Changing the Fundamental Parameters of the Universe

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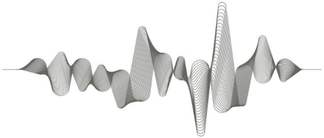
Outline

Motivation for this Project

Bringing Fundamental Physics to Everyday Life is a project that focuses on understanding the fundamental constants of nature and their impact on the Universe at various time frames. The goal is to construct accessible representations of the universe at different times showing the effects of varying these constants such as the speed of sound.



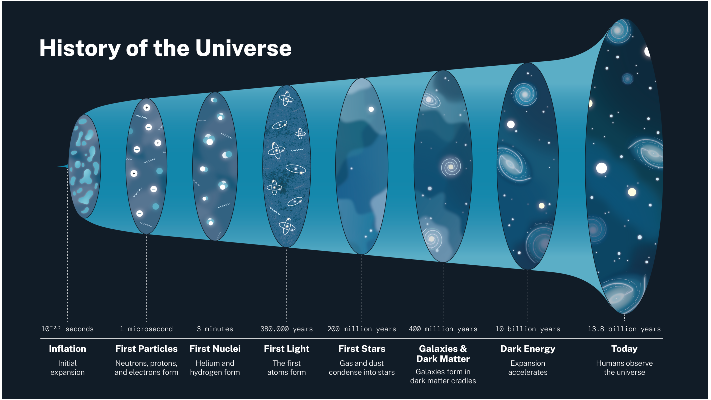
Credit: *VectorStock*

Why we Chose the Speed of Sound?

- We began by examining the speed of sound as it is a concept that many people are familiar with from their everyday lives (Doppler effect, echoes, etc). We wanted to investigate what aspects of the universe might be different if it had a different value, and how this value could be changed.
- In order to understand when in the early universe it might have an effect, we must first understand the timeline of the universe

Universe Evolution

- The early universe had two important eras the matter dominated era and the radiation dominated era.
- The radiation dominated era had 5 epochs consisting of the Planck, Grand Unified Theory, Quark, Lepton, and Nuclear epochs.
- The matter dominated era consisted of the atomic, galactic and the stellar epoch.

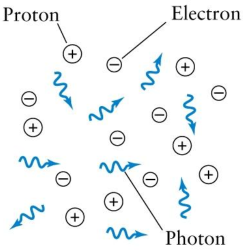


Credit: *NASA Universe Basics*

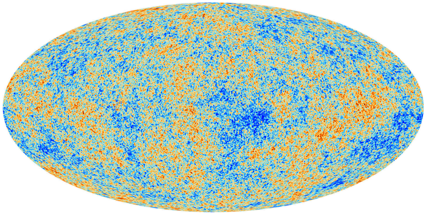
Nucleosynthesis

- At times less than one second after the Big Bang, the universe was a hot ($>> 10^{10}$K) rapidly expanding plasma. Nucleons were outnumbered by more than a billion to one, and there were essentially no composite nuclei.
- At one second, temperature was around 10^{10}K. The amount of D, ^{3}H, ^{3}He and ^{4}He began to increase, but were still present only in amounts governed by nuclear statistical equilibrium.
- After five minutes, the universe was cool enough for composite nuclei to be stable. Most neutrons were in ^{4}He nuclei and most protons remained free, due to proton/neutron asymmetry.

Cosmic Microwave Background



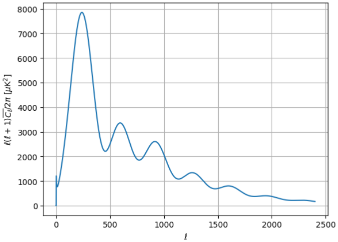
Credit: *University of Alberta*

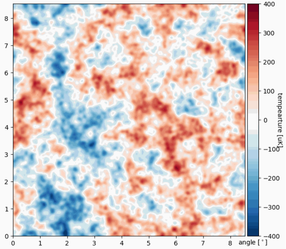


Credit: *ESA - Planck Mission*

- Around the period of recombination the universe was at approximately 3000K
- As the universe cooled neutral atoms started to form which meant radiation could decouple from charged particles such as electrons
- Photons stopped getting scattered and the their mean free path increased
- The last time they scattered formed the surface of last scattering

- Temperature anisotropies in the CMB are described by spherical harmonics
- $C_\ell = \langle |a_{\ell m}|^2 \rangle$.
- $C_\ell \ell(\ell+1)/2\pi$ refers to the power of the fluctuations at each multipole number



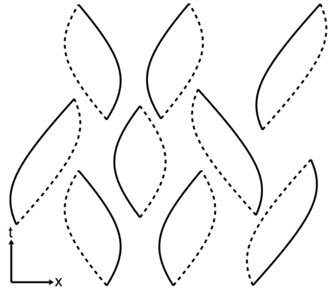


(Syksy Rasanen, 2015)

link

Primordial Fluctuations

- It is believed that the origin of all structures in the early universe is due to quantum fluctuations during the inflationary epoch.
- Quantum fluctuations occur on small spatial and temporal timescales, so they can be swept up in the expanding universe.
- This causes gravitational potential wells to form.



Quantum fluctuations. Source: Edward L Wright 2008

Photon Baryon Soup

- Gravitational wells would attract matter and light. Dark matter has no pressure, so primordial plasma is typically treated as a baryon-photon fluid.
- Baryons fall into the gravitational wells and are compressed, but this creates outward radiation pressure from photons. The pressure becomes so great, that the plasma expands.

Fluctuations in expanding space. Source: Edward L Wright 2008

Sound waves

- Hence, we have pressure (sound) waves. Via the definition of the speed of sound, we have:

$$c_s^2 = \frac{\partial P}{\partial \rho} \qquad \rho = \rho_b + \rho_\gamma$$

- The radiation pressure is due to photons. For photons that bounce back, this scales as 1/3 of the energy density. $P = \frac{1}{3}\rho_\gamma c^2$

$$\therefore c_s = \left(\frac{dP_\gamma}{d\rho_\gamma}\frac{\partial \rho_\gamma}{\partial \rho}\right)^{1/2} = \frac{c}{\sqrt{3}}\left[\frac{1}{1+\frac{\partial \rho_b}{\partial \rho_\gamma}}\right]^{1/2}$$

Sound waves

- We need to introduction the scale factor a(z), where z is the redshift, which accounts for the effect that cosmic inflation has on distances. Doing so, we have:

$$\frac{\partial \rho_b}{\partial \rho_\gamma} = \frac{\partial \rho_b}{\partial a}\frac{\partial a}{\partial \rho_\gamma}$$

- The scale factor scales like a^{-4} for the energy density of the photons and like a^{-3} for the baryon density. Note: $a(0)$ means that we use the present-day value. So, we can use the following relations:

$$\rho_b = \overline{\rho_b}(z) = \overline{\rho_{b,0}}a^{-3}$$

$$\rho_\gamma = \overline{\rho_\gamma}(z) = \overline{\rho_{\gamma,0}}a^{-4},$$

$$\therefore \frac{\partial a}{\partial \rho_\gamma} = \frac{1}{\frac{\partial \rho_\gamma}{\partial a}} = \frac{1}{-4\overline{\rho_{\gamma,0}}a^{-5}},\ \Omega\ \frac{\partial \rho_b}{\partial a} = -3\overline{\rho_{b,0}}a^{-4}.$$

Sound waves

$$\frac{\partial \rho_b}{\partial \rho_\gamma} = \frac{-3\overline{\rho_{b,0}}a^{-4}}{-4\overline{\rho_{\gamma,0}}a^{-5}} = \frac{3\overline{\rho_{b,0}}}{4\overline{\rho_{\gamma,0}}}\frac{1}{a(z)} = \frac{3}{4}\frac{\rho_b(z)}{\rho_\gamma(z)}.$$

$$c_s = \frac{c}{\sqrt{3}}\left(\frac{4\rho_\gamma}{4\rho_\gamma + 3\rho_b}\right)^{1/2}.$$

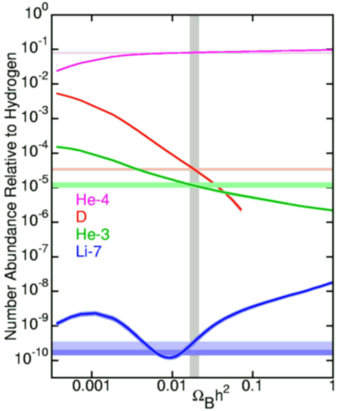
Evidently, the speed of sound increases or decreases depending on the photon and baryon densities. We decided to investigate the effects of varying the baryon densities at Nucleosynthesis and Recombination.

Changing ρ_b during Nucleosynthesis

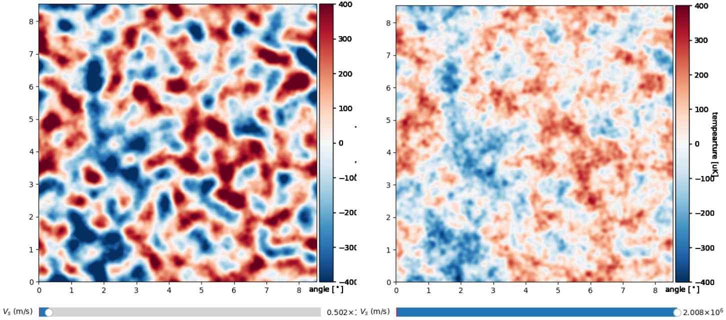
- The effects of changing the baryon density on the nuclear reactions during nucleosynthesis would be immense, changing the structure of the entire universe.
- If ρ_b is lower, there are less protons and neutron available for nuclear reactions.
- If ρ_b is higher, there are more protons and neutrons available so more reactions can occur.
- Predicting the exact changes can be difficult, but there exists software such as PArthENoPE and CAMB which can take the baryon density as an input parameter and plot the BBN predicted abundances of light elements relative to the abundance of H.
- They use algorithms that factor in nuclear reaction cross-sections, reaction rates, external heat baths, etc.

Changing ρ_b during Nucleosynthesis

- $\Omega_B h^2$ is the baryon density parameter, defined as $\frac{\rho_b}{\rho_{crit}}$.
- ρ_{crit} refers to the critical baryon density - the density needed to create enough gravitational attraction to halt the expansion of the universe.
- $h = \frac{\mathrm{H_0}}{(100\mathrm{kms^{-1}Mpc^{-1}})}$ is the Hubble parameter.



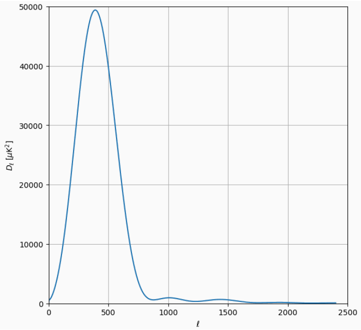
How did the Cosmic Microwave Background Change?

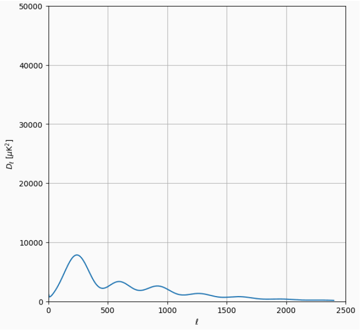


Website

- $c_s = \frac{c}{\sqrt{3}}\left(\frac{4\rho_\gamma}{4\rho_\gamma + 3\rho_b}\right)^{1/2}$.
- The physical baryon density can be related to the critical baryon density as $\rho_b = \rho_c \Omega_b$.
- As we decrease the speed we can see that the baryonic density increases.
- The hot and cold spots become more intense due to deeper gravitational wells

- The odd numbered peaks represent the maximal density oscillations and the even numbered peaks represent the minimal density oscillations
- The first peak corresponds to the maximum compression, and as baryonic density increases, this peak increases





▸ Website

Further Implications in the Universe

- Let's revisit the scale factor, $a(z)$. This characterises the size of the universe at a given time compared to a reference time.
- The Friedmann equations are a set of fundamental equations in cosmology that describe the evolution of the universe within the framework of the Friedmann-Lemaître-Robertson-Walker (FLRW) metric.
- These equations operate under the assumptions of the cosmological principle: On a large scale, the universe is homogeneous and isotropic.
- The first Friedmann equation is:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi \mathrm{G}}{3}\rho - \frac{kc^2}{a^2}$$

Further Implications

- H_0 refers to the Hubble 'constant' *today* i.e. when $z = 0$, $a(0) = 1$. Using this, the first Friedmann equation can be used to write:

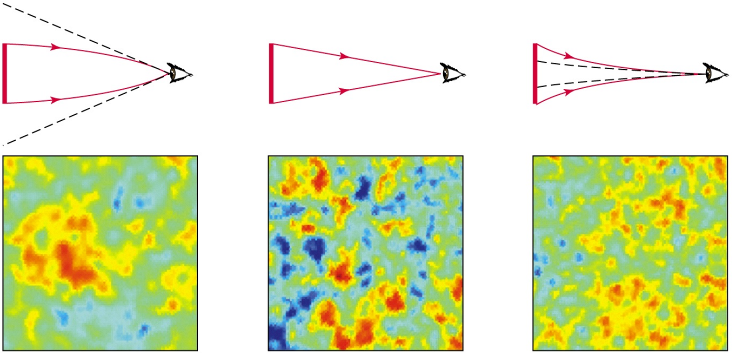
$$\dot{a} = H_o \sqrt{\Omega_r / a^2 + \Omega_m / a + \Omega_k + \Omega_v / a^2}$$

- The Ω terms refer to the density parameters ($\frac{\rho}{\rho_{crit}}$) of radiation (Ω_r) and matter (Ω_m), the vacuum energy density parameter (Ω_v) and a 'curvature term' ($\Omega_k = 1 - \Omega_m - \Omega_r - \Omega_v$).
- Evidently, varying ρ_b (and thus varying Ω_m) could have a number of effects depending on which terms in this equations remain constant. If the density terms remain constant, then the expansion rate of the universe would change.

Further Implications

- However, what if we kept all terms except Ω_k constant, and varied ρ_b? This would mean that the curvature of space would change, which would directly affect many physical phenomena.
- In a flat universe, $\Omega_k = 1$. This space has Euclidean geometry, which we are used to.
- In an open universe, $\Omega_k < 1$. This space has negative curvature; parallel lines diverge.
- In a closed universe, $\Omega_k > 1$. This space has positive curvature; parallel lines will converge.

Further Implications



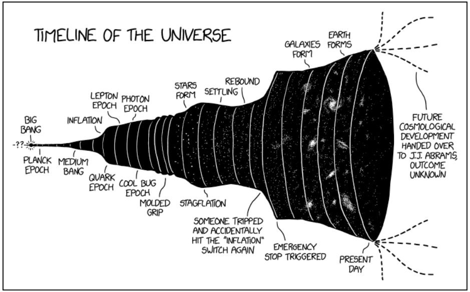
a If universe is closed, "hot spots" appear larger than actual size

b If universe is flat, "hot spots" appear actual size

c If universe is open, "hot spots" appear smaller than actual size

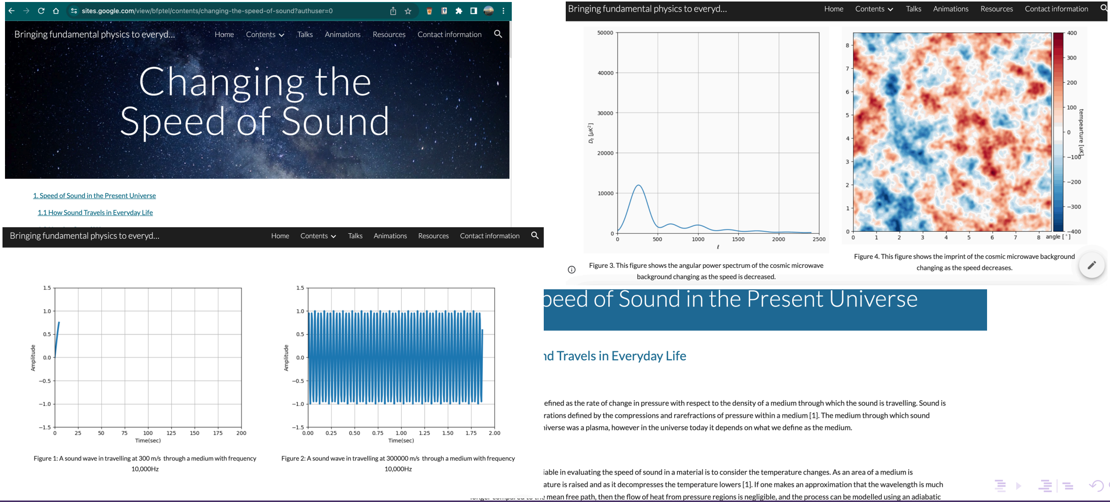
What will we do Next?

- We hope to connect the implications or to propagate one change in the speed throughout the evolution of the universe
- We will investigate the implications of changing the baryon density further in the matter era such as the stellar epoch or the galactic epoch



Credit: *Explain XKCD*

Working on the Website



Conclusion

- The aim of this project was learning about how the fundamental parameters affect our universe and creating information regarding this subject accessible to people outside of physics.
- We have created animations and accessible information on the website and we will continue to create and learn more!
- We would like to thank our supervisor Dr. Venus Keus and the organisers of the 2023 DIAS internships.

Questions?

Temperature Anisotropies Described by Spherical Harmonics

$$\frac{\delta T}{T}(\theta,\phi) = \sum a_{\ell m} Y_{\ell m}(\theta,\phi)$$

- $\frac{\delta T}{T}(\theta,\phi)$ is defined as the temperature anisotropies defined as a function on a sphere
- $Y_{\ell m}(\theta,\phi)$ refers to the spherical harmonics and they form an orthonormal set of functions over the sphere
- $a_{\ell m}$ are the coefficients and they represent a deviation from the average

$$a_{\ell m} = \int Y^*_{\ell m}(\theta,\phi)\frac{\delta T}{T}(\theta,\phi)d\Omega$$

back

- Temperature anisotropies are of a Gaussian nature and thus the expectation value $\langle a_{\ell m} \rangle = 0$
- The amplitude is defined as the variance ($\langle |a_{\ell m}|^2 \rangle$)

$$C_\ell = \langle |a_{\ell m}|^2 \rangle = \frac{1}{2\ell + 1} \sum_m \langle |a_{\ell m}|^2 \rangle$$

- The angular power spectrum C_ℓ is related to the contribution of the multipole ℓ to the temperature variance as,

$$\langle \frac{\delta T}{T}(\theta, \phi)^2 \rangle = \sum_\ell \frac{2\ell + 1}{4\pi} C_\ell$$

Observed Angular Spectrum

- From the theoretical angular power spectrum, $\langle |a_{\ell m}|^2 \rangle$ defines the temperature anisotropies
- Since only one set of $a_{\ell m}$ can be observed for the CMB imprint the observed angular spectrum is defined differently as below,

$$\widehat{C_\ell} = \frac{1}{2\ell + 1} \sum_m |a_{\ell m}|^2 .$$

- The variance of the observed temperature anisotropies is the average of $(\frac{\delta T}{T}(\theta, \phi))^2$ over the celestial sphere

$$\frac{1}{4\pi} \int \left(\frac{\delta T}{T}(\theta, \phi) \right)^2 d\Omega = \sum_\ell \frac{2\ell + 1}{4\pi} \widehat{C_\ell} .$$

(Syksy Rasanen, 2015)