Baryon Acoustic Oscillations and the Canadian Hydrogen Intensity Mapping Experiment

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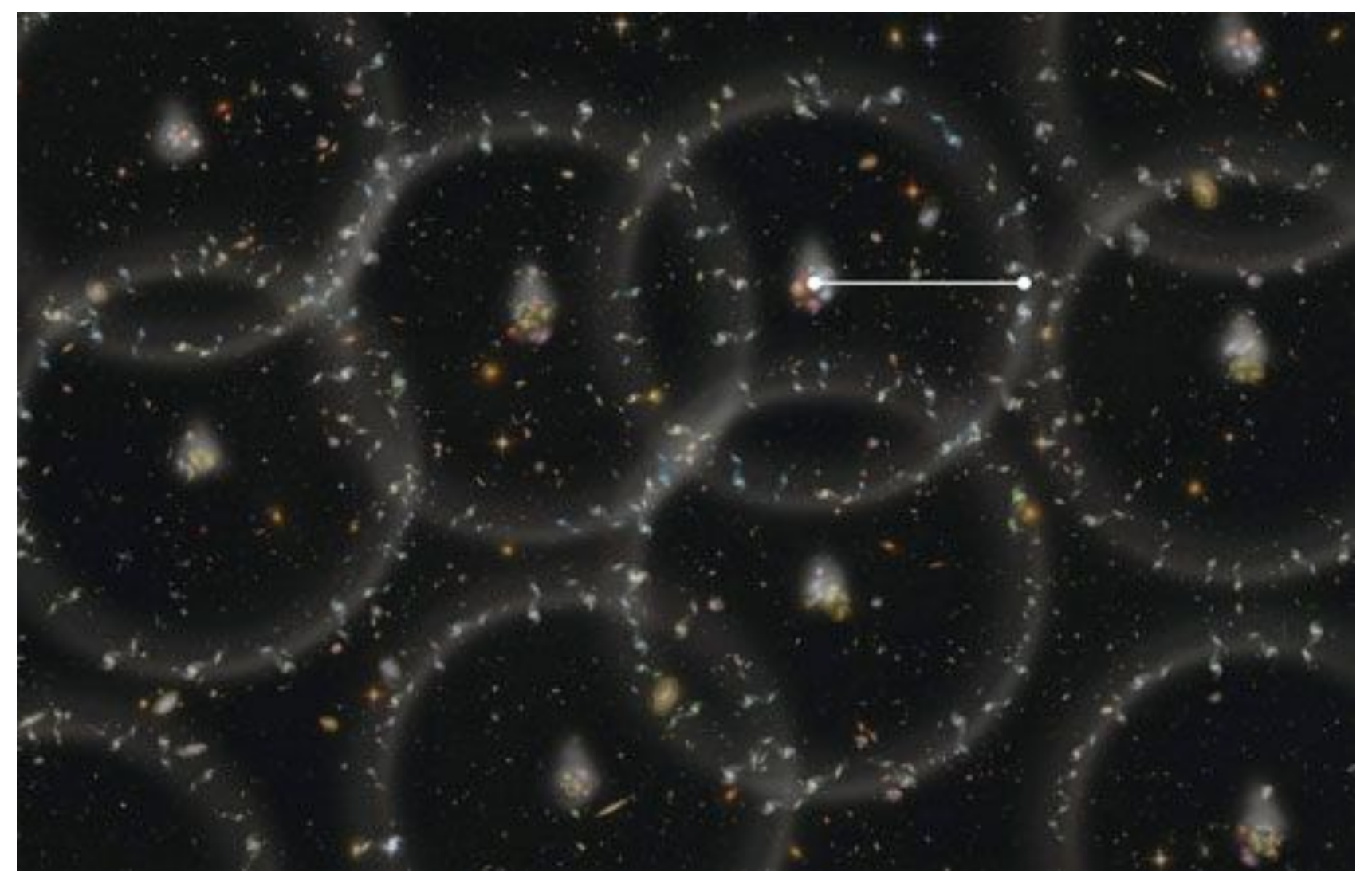
Introduction

This poster will explore the characteristic length scales that are generated by baryon acoustic oscillations (BAOs) in the era of recombination of the early universe. Specifically, it will focus on how the Canadian Hydrogen Intensity Mapping Experiment (CHIME) is applying hydrogen intensity mapping to probe the BAO scale at a range of previously unexplored redshifts.

What are BAOs?

BAOs originate from the early universe prior to the era of photon decoupling. In this hot, dense state, the majority of matter in the universe was comprised of high energy photons, protons, and electrons constantly scattering off of each other. Being tightly coupled, the “fluid” comprised of these particles behaved relatively similarly to standard fluids. Due to density fluctuations in weakly-interacting dark matter, this fluid would generally congregate around regions of higher density. In this state, the fluid would undergo acoustic oscillations, alternating between being compressed due to the potential well of the dark matter, and being expanded due to the increase of pressure in the fluid during compression.



A visualization of shells of acoustic standing waves [1]

BAOs as a Standard Ruler

The length scale of a maximally compressed fluid is well constrained by its acoustic speed, which is 1/sqrt(3) times the speed of light. Thus, BAOs can provide a characteristic length scale of the baryon-photon fluid during photon decoupling. After decoupling, the baryons, electrons and photons no longer behave as a collective fluid. The photons stream off into the expanding universe, with atomic hydrogen left behind in distinctly sized shells of higher or lower density. This size, known as the sound horizon size, is approximately 0.145Mpc, and has evolved due to the expansion of the universe, and can therefore provide a length scale to measure the rate of expansion and scale factor over time.

References

[1] E. Wright, “Listening for the Size of the Universe,” Baryon Acoustic Oscillation Cosmology, 2014. [Online]. Available: http://www.astro.ucla.edu/~wright/BAO-cosmology.html. [Accessed: 08-Apr-2021].

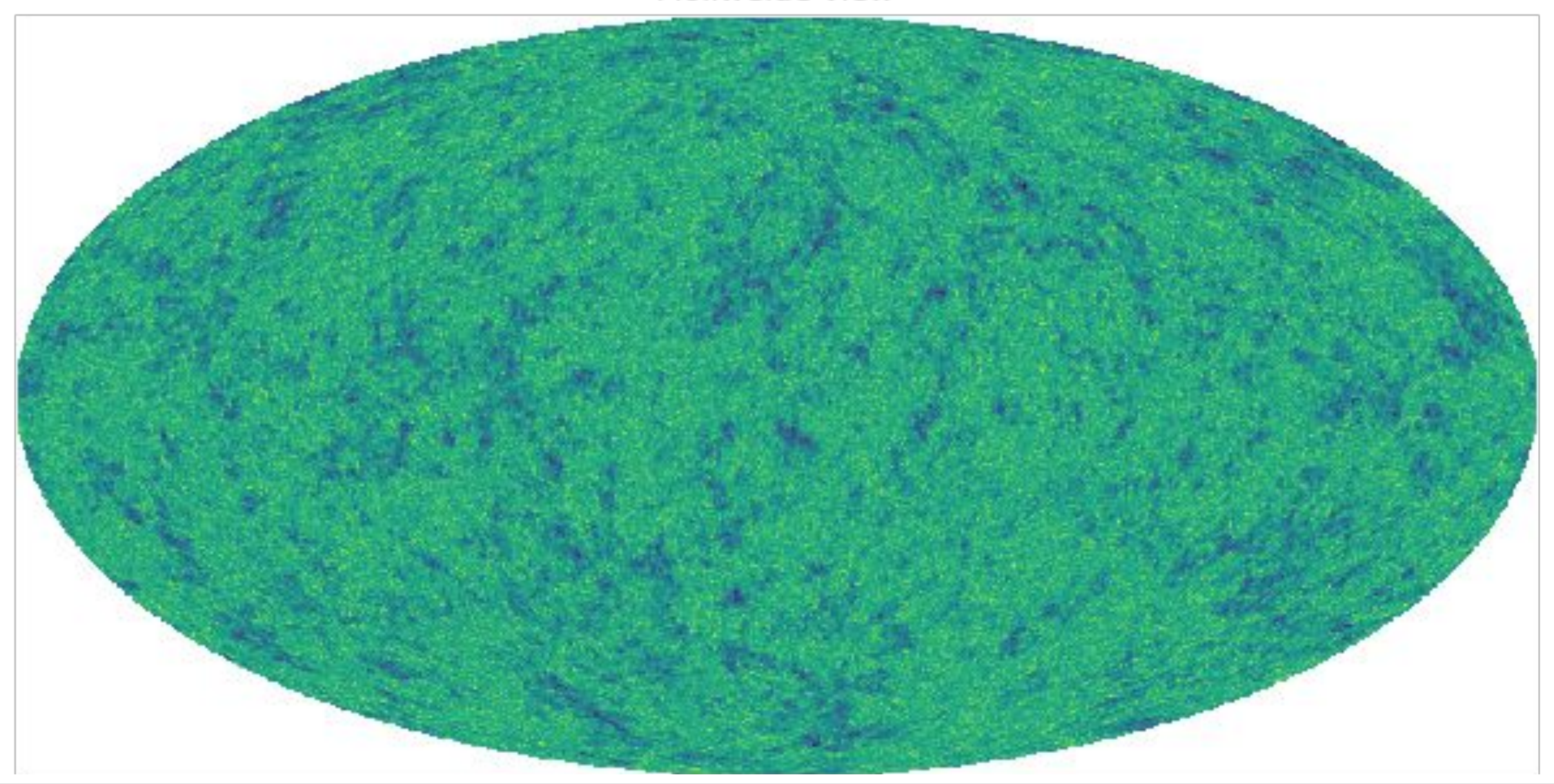
[2] L. B. Newburgh, G. E. Addison, M. Amiri et al. “Calibrating CHIME: a new radio interferometer to probe dark energy,” Ground-based and Airborne Telescopes V, 2014.

[3] CHIME Experiment. [Online]. Available: https://chime-experiment.ca/en. [Accessed: 08-Apr-2021].

Hydrogen Intensity Mapping

Traditionally, the presence of BAO shells were detected using galaxy redshift surveys. By determining angular position as well as redshift for a large number of galaxies, statistical analysis can be applied to determine if there is a preferred separation distance between galaxies. However, at larger redshifts, luminous sources such as galaxies become scarce. A way to obtain information on the large-scale structure of the universe at these high redshifts, is to probe the density of hydrogen in the universe directly. This can be done by investigating the intensity of the 21-centimeter hydrogen spectra line over a large volume of the universe. This line is caused by a minute energy transition that occurs in neutral hydrogen when an electron with parallel spin to its proton “flips” to become antiparallel. Hydrogen intensity (HI) mapping simply creates a low-resolution 3D map of the hydrogen density in the universe by investigating the intensity of the 21-cm signal at different redshifts.

The image below is a Mollweide projection of simulated hydrogen density values at redshift z=1, obtained from Dr. Richard Shaw who is currently working on HI mapping at CHIME, with the monopole (average density) removed.



CHIME

CHIME is an interferometric radio telescope located in Penticton that has no moving parts. CHIME consists of five adjacent “half pipe” dishes that are oriented north-to-south to allow the telescope to survey a large volume of the night sky as the Earth rotates [2]. The relevant frequencies of the 21-centimeter hydrogen line that CHIME is designed to investigate are between 400 - 800MHz. This corresponds to a redshift of approximately 0.8 - 2.5, allowing it to probe the universe’s expansion around where dark energy began to dominate the energy density of the universe. Through the investigation of hydrogen density via the 21-cm line, CHIME is able to view the BAO scale at multiple epochs in the history of the universe. This will result in a 3D HI map that can be analysed to constrain the state parameter for dark energy. The rest of this poster conducts statistical analyses on the simulated 3D HI map, which is a simplified version of a density map that could be generated from CHIME data.

A photo of CHIME [3]

Statistical Analysis

The preferred method to determine the distribution of matter in an intensity map is a correlation function. This function describes, given any point on the HI map, the likelihood of finding a similarly over or under-dense region within a certain distance. An autocorrelation function can be found between points at a constant redshift that lie on a celestial sphere. This function can be obtained from the angular power spectrum of the density map (spatial frequency, rather than temporal). Using spherical harmonic transforms, the density map can be rewritten as:

$$f(\theta,\varphi) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} a_{lm}Y_{lm}(\theta,\varphi) \qquad (1)$$

Where *f* is the density map and Y_{lm} are spherical harmonic functions. a_{lm} can be converted into the multipole moments, which contain the same information as the power spectrum, using equation 2.:

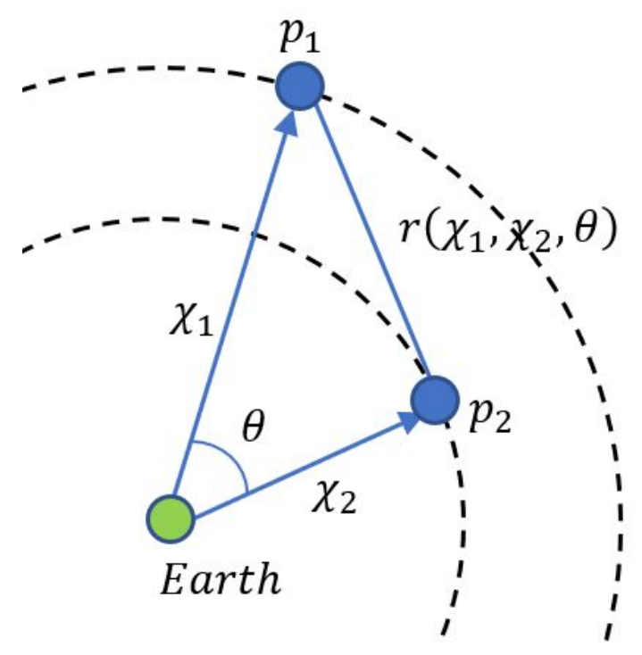
$$C_l = \frac{1}{2l+1}\sum_{m=-l}^{l}|a_{lm}|^2 \qquad (2)$$

Then, since CHIME investigates not just a single redshift, but rather a number of redshifts, richer information can be found by converting the 2D (in spherical space) multipole moments into a 3D correlation function involving both radial and angular separation. This can be done by using cross-correlation between redshift pairs along with a Legendre transform at multiple angles of separation:

$$C(\chi_1,\chi_2,\theta) = \sum_{l=0}^{\infty}(2l+1)C_l(\chi_1,\chi_2)P_l(\cos(\theta)) \qquad (3)$$

Where χ_1 and χ_2 are the comoving distance in Mpc/h, and θ is the angular separation between the points. $C(\chi_1, \chi_2, \theta)$ is the correlation function, and $C_l(\chi_1, \chi_2)$ are now the multipole moments for the cross-correlation between two maps at a pair of redshift values. The cross power spectrum describes the power shared by the maps at the two redshifts. The separation distance, *r* is computed simply using the cosine law in equation 4, and the figure also shows this visually.

$$r(\chi_1,\chi_2,\theta) = \sqrt{\chi_1^2, +\chi_2^2 - 2\chi_1\chi_2\cos(\theta)} \qquad (4)$$



The result of this analysis on the simulated data visualized in panel 2 of the poster are shown below. The figures plot the 2-point correlation function in 3D versus comoving separation between the points. The small bump in correlation around 100 Mpc/h occurs due to BAOs in the early universe.