DISCREPANCY IN THE VALUE OF THE COSMOLOGICAL SOUND HORIZON

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The comoving size of the sound horizon can be determined in two ways. It can be found empirically with Cepheid-calibrated Type 1a Supernovae or calculated within the standard model of cosmology. The first method is independent of assumptions about the components of the universe while the second uses data to constrain cosmological parameters according to the ΛCDM model. This paper presents constraints on the empirically-determined sound horizon using Cepheid-calibrated Supernovae and BAO (Baryon Acoustic Oscillation) data both using the ΛCDM model (Lambda Cold Dark Matter) as a basis for the behavior of the universes expansion and using a non-parametric method. Both of these values of the sound horizon are significantly smaller than the ΛCDM-calculated value. This discrepancy could mean there are more systematic errors in the Supernovae data than previously thought, but as observations become more and more accurate, there is strong evidence that the standard model of cosmology is missing something. We argue that the best way to decrease the value of the model calculated sound horizon is to increase the expansion rate before recombination. This could be accomplished by adding a dark radiation component in early times.

I. INTRODUCTION

The universe is composed of baryonic matter, dark matter, photons, neutrinos, and dark energy. The relative amounts of each of these components has changed over the course of the universe's expansion. Shortly after the Big Bang, the radiation component dominated. As the universe expanded the radiation density decreased the most rapidly, allowing matter to become the most abundant. Today the cosmological constant, Λ, dominates as its density remains fixed despite expansion. This is commonly referred to as 'dark energy.' Though roughly 95% of the universe is made of the dark matter and dark energy about which we know very little, until recently it was thought that this current understanding of the universe was highly accurate. The relative densities of each component and their effects on the expansion history of the universe are summarized in the ΛCDM model. However, recent data releases and analyses suggest this model may be incomplete.

Prior to recombination, the universe was hot and ionized. Quantum fluctuations in the nearly homogeneous plasma resulted in sound waves that propagated radially outwards until recombination occurred. The universe cooled and became neutral. At this time, photons were decoupled from matter and continued to stream outwards, leaving overdensities of both baryons and dark matter in spherical shells surrounding the initial fluctuations. The sound horizon is the distance these sound waves traveled through the plasma before decoupling took place. As the universe continued to expand, these overdense regions ended up with more mass and subsequently more galaxies than underdense regions.

Figure 1:

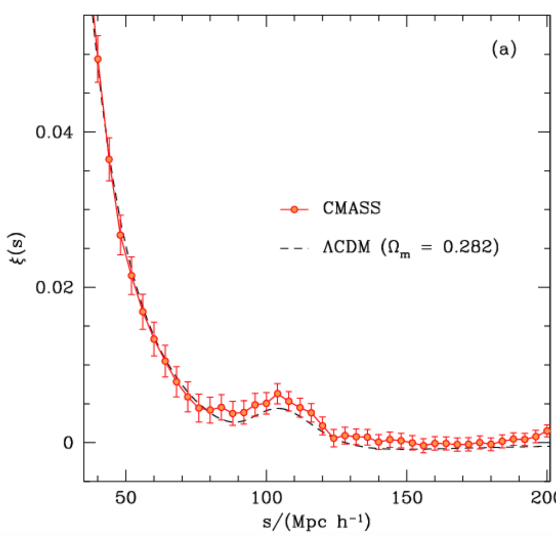
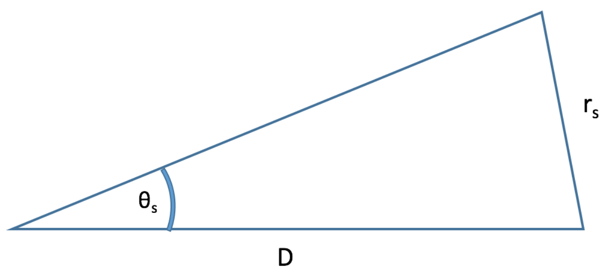


Figure 1: Two-point galaxy correlation function from Sanchez et al. showing two-point correlation of galaxies of similar redshift from the BOSS CMASS survey plotted as a function of Megaparsecs scaled by h, the Hubble parameter divided by 100 Mpc.

Today we see the signature of the sound horizon in the two-point galaxy correlation function. The peak in the above histogram (Figure 1) corresponds with the size of the comoving sound horizon. We can easily measure the angular separation between two galaxies of similar redshift, so if we know how far away they are from the Earth (the angular diameter distance), we can use simple geometric arguments to calculate the size of the sound horizon. Figure 2 shows an enlarged representation of how the sound horizon (r_s) and the angular diameter distance (D) are related. Since the angle θ_s is small, we can use the small angle approximation to get that $\theta_s(z) = \frac{r_s}{D(z)}$.

Figure 2:



To calculate the sound horizon, one must know the distance to galaxies at similar redshifts in order to figure out the ratio of r_s to D. We use Baryon Acoustic Oscillation data to constrain this ratio and Type 1a Supernovae to figure out the value of r_s. This calculation can be done under the assumption that the expansion of the universe can be described by the current version of the ΛCDM model or without assuming a form for the expansion history. Both methods result in a value of the sound horizon much smaller than the value calculated theoretically through the ΛCDM model alone. The discrepancy of 2.8σ for the ΛCDM-assumption model and of 2.6σ for the non-parametric model could mean there is a missing feature of our current model of the expansion history of the universe. Since the values from observations are much lower than those from the model, we must change the model to lower its predicted value of the sound horizon. The best way to accomplish this without changing other crucial features of the model is by adding in another radiation component in the early expansion history. This would increase the expansion rate prior to recombination, decreasing the model sound horizon.

II. MODELING THE DATA

Measuring the distances to these characteristic galaxies is done using the classical distance ladder in which Cepheid variable stars are used to calibrate the distance measurements to Type 1a Supernovae. This paper uses Baryon Acoustic Oscillation (BAO) data which acts as a standard ruler, measuring angular distances between characteristic galaxies from the peak of Figure 1. This data comes from the BOSS survey and reports the ratio of the angular diameter distance ($D_A(z)$) to the sound horizon (r_s), divided by a fiducial value of the sound horizon. Because the dataset reports $D_A(z)/\ r_s$ (Eq. 1), any number of models for $D_A(z)$ can be fit to the data by just inputting a different value of r_s (Figure 3). To better constrain r_s, we use Supernovae data from Scolnic et al. 2018 that reports the distance modulus, μ (Eq. 2), which can be used to determine the luminosity distance, $D_L(z)$ (Eq. 3).

(1): $D_A(z)/r_s = \frac{c}{r_s} \int_0^z \frac{dz}{H(z)} = \alpha_{BAO} \int_0^z \frac{dz}{H(z)/H_0}$
where $\alpha_{BAO} \equiv$ c$/(r_s H_0)$, H_0 is the Hubble constant, z is redshift, and H(z) is the Hubble paramenter as a function of redshift

(2): $\mu = M_b + 5log(\frac{D_L(z)}{\ell_{SN}}) + 25$

(3): $\frac{D_L(z)}{1+z}\ \frac{1}{\ell_{SN}} = \frac{c}{\ell_{SN}} \int_0^z \frac{dz}{H(z)} = \alpha_{SN} \int_0^z \frac{dz}{H(z)/H_0}$
where $\alpha_{SN} \equiv$ c$/(\ell_{SN} H_0)$, c is the speed of light, and ℓ_{SN} is a parameter used to scale the distance modulus, μ

Converting D_L to D_A using $D_L(z) = (1+z)D_A(z)$ and combining the two datasets, the value of the sound horizon is better constrained (Figure 4). These two datasets along with a constraint on the value of H_0 (Riess et al. 2018) are combined in order to determine the value of the sound horizon.

Figure 3:

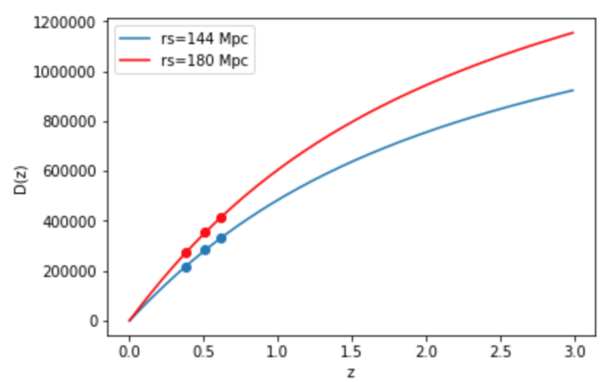
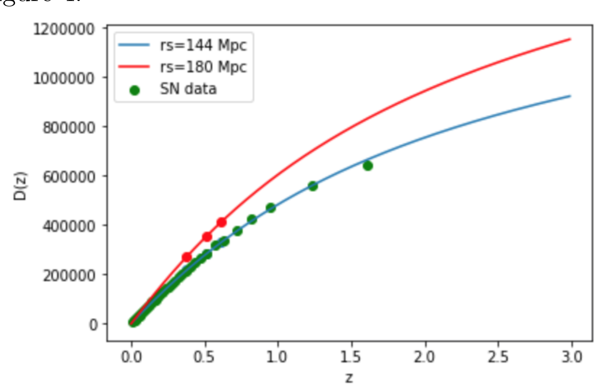


Figure 4:



III. METHODS

The BAO and SNe data values of D_A and D_L respectively are compared to predicted values in order to construct a likelihood and perform a Markov Chain Monte Carlo (MCMC). This requires the input of a form of H(z). One method, the ΛCDM-assumption form of H(z) gives:

$$\text{H(z)} = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + \rho_\nu(z)/\rho_c + \Omega_\gamma(1+z)^4}$$

The set of parameters is then $\{\alpha_{BAO}, \alpha_{SN}, \Omega_m, H_0\}$. The non-parametric version uses 5 initial values of H(z) at z=[0,.2,.57,.8,1.3] to construct a model-independent form of H. The parameters for this method were $\{\alpha_{BAO}, \alpha_{SN}, H_0, H_1, H_2, H_3, H_4\}$ where $H_i = H(z_i)$. We then construct log likelihoods for the two datasets of the form:

$$L = -\frac{1}{2}(Model - Data)C^{-1}(Model - Data)^T$$

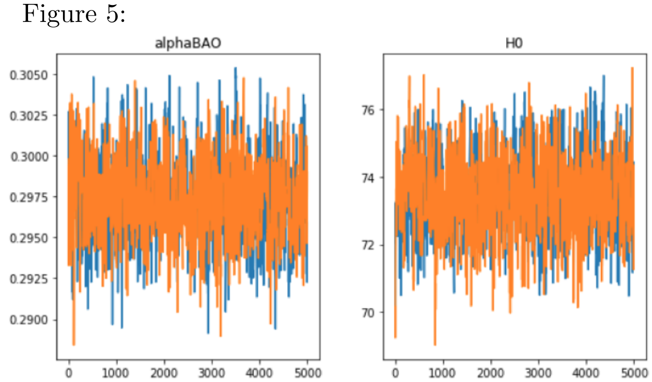
where C is the covariance error matrix.

Both methods also include a likelihood for the value of H_0 of the form:

$$L = -\frac{1}{2}\frac{(Model-Data)^2}{error^2}$$

We performed a Markov Chain Monte Carlo (MCMC) using the Cosmoslik code written by Marius Millea. The sampler chosen was the Metropolis-Hastings sampler, and the three chains were run in MPI. After drawing 10,000 samples, with steps being made roughly 1/10 of the time, the three chains converged onto values of H_0, Ω_m, α_{BAO}, and α_{SN} for both methods, along with values of H(z) for each of the five z values for the non-parametric method. A few selected trace plots are shown in Figure 5. We were then able to find the derived quantity of r_s using $r_s = \frac{c}{r_s H_0}$ from these results.

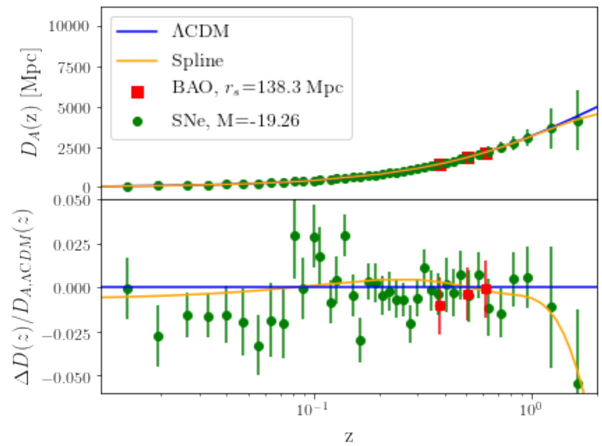
Figure 5:



IV. RESULTS

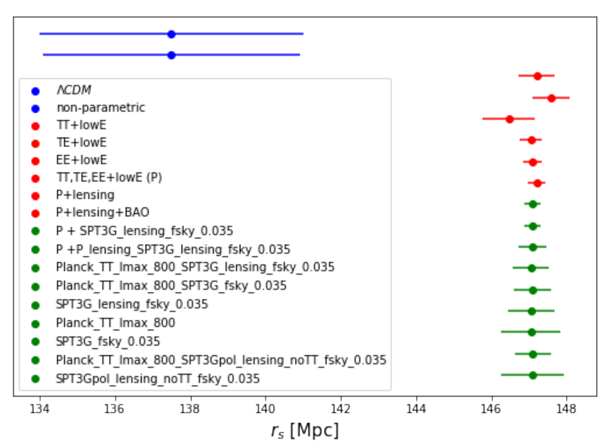
My analysis resulted in values of r_s=137.6±3.45 for the model with ΛCDM assumptions and r_s=138.1±3.59 for the non-parametric model. Figure 6 shows how both the ΛCDM and non-parametric (spline) models fit well with the data. The ΛCDM model does not follow the data as well at higher redshift (z), but given the larger error bars of the SNe data, both models can be considered representative of the data. The resulting values of are close together and both between 2σ and 3σ away from the model calculations.

Figure 6:



An r_s of 138.3 was used in Figure 3 to calibrate the BAO data, but there is not much difference when using 138.1 or 137.6. Slight changes to these values were reported after running the chain through for a longer period of time, again showing a difference of 2-3σ with the model calculations. Figure 7 is a visual representation of the spread in values. The blue bars on the left are the values of the sound horizon produced by the ΛCDM assumption model and the spline model with their respective error bars. All of the red and green bars are values of the sound horizon produced by different combinations of datasets and assumptions to get different model-produced values. It is clear that all of the model values are significantly larger than the two values produced by the data.

Figure 7:



V. CONCLUSIONS

The significant difference in values of the sound horizon from model calculations and empirical determinations signifies either a problem with the systematic error calculations of the datasets or a problem with the standard model of cosmology. As the Planck survey produced more accurate distance measurements of a larger set of SNe than previously obtained, the theoretical side of the discrepancy is facing question. In order to reconcile the two values, the expansion rate of the universe prior to recombination must be increased. One possible method of doing this that many favor is adding another radiation component in our description of the early universe.

VI. FUTURE WORK

After demonstrating how large the difference in sound horizon calculations between data and theory is, the next step is to figure out how to adjust the ΛCDM model. Using the fact that the ratio of the diffusion scale and the sound horizon must remain constant, we can place constraints on the radiation component of the universe. This could help point to what type of particle the missing radiation could be comprised of. One idea is that the missing radiation is another species of neutrino.

VII. CITATIONS AND REFERENCES

M. Millea, URL https://github.com/marius311/cosmoslik.

Riess, A. G., Casertano, S., Kenworthy, D., Scolnic, D., and Macri, L. 2018a, ArXiv e-prints. arXiv: 1810.03526

Sanchez, et al. 2012, ArXiv e-prints. arXiv:1203.6616

Scolnic, D. M., Jones, D. O., Rest, A., et al. 2018, ApJ, 859, 101. doi: 10.3847/1538-4357/aab9bb. arXiv: 1710.00845