

The Accuracy of Λ CDM as a Dark Matter Model

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ABSTRACT: For decades, the Lambda-Cold Dark Matter (Λ CDM) model has achieved impressive consistency with cosmological observations regarding the density of cold dark matter (CDM) and its influence on baryonic (ordinary) matter in the universe. Despite the confident data preference for Λ CDM— for which it is now acknowledged as the current Standard Cosmological Model— there are significant discrepancies which challenge the model-data agreement. Such disagreements are apparently overlooked, implying an inaccurate assumption of an ideal agreement between Λ CDM and all cosmological data. In this review, we aim to emphasize a realistic discussion of the Λ CDM model as a successful yet imperfect dark matter model. We invite evaluation on the model's coherence, addressing one of its notable discrepancies, the S_8 tension, discussing discordant values of parameters Ω_m (Omega-m) and S_8 in relation to Λ CDM's understanding of cold dark matter (CDM), and recalling attempts at modification which highlight certain limitations to the theory.

KEYWORDS: Physics and Astronomy, Astronomy and Cosmology, Dark Matter, Small-Scale Problems, Λ CDM Model.

■ Introduction

Dark matter is a renowned cornerstone in astrophysics and cosmology. For nine decades since its discovery, observations of large-scale structures in the late and early universe have been conducted to gather data on its properties, density (abundance), and influence on baryonic (ordinary) matter.¹⁻⁶ The first statistical evidence suggesting its existence is credited to Fritz Zwicky, whose research on the redshifts of galaxy clusters in 1930 revealed discrepancies between their predicted and observed masses, hinting at the presence of an unidentified, invisible mass called 'dark matter'.²⁻⁵ Following revolutionary discoveries on flat galaxy rotation curves in the 1970s by numerous pioneers, including Ken Freeman, David Rogstad, and Seth Shostak, the presence of dark matter and its fundamental role in the formation and evolution of cosmological structures began to gain acceptance in cosmology.^{5,7-9}

Simultaneously, various cosmological theories on different models of dark matter have been developed alongside ongoing research. The Cold Dark Matter (CDM) model is one prominent example, first proposed in 1982 by James Peebles, describing all dark matter as consisting of 'cold', slow-moving, weakly interacting massive particles (WIMPs), non-baryonic dark matter particles that interact weakly with electromagnetic radiation.^{5,6,10} During the late 20th century, original concepts, including the CDM model, were consolidated into the basis of the Lambda-Cold Dark Matter (Λ CDM) model.^{5,6,11-14} Additionally, the Λ CDM model incorporates a cosmological constant, denoted as Λ (Lambda): first introduced by physicist Albert Einstein in his field equations of general relativity as a counteractive force to gravity, which is associated with dark energy and represents the constant dominating force accelerating the expansion of the universe.^{1,5,6,11-14} With dark energy (Λ) combined, cold dark matter (CDM) accounts for approximately 95% of the mass-energy density (total mass and energy) in

the universe, an integral component in describing the content and structure of the universe.^{1,5,6,11-14}

The Λ CDM model has now become accepted as the modern paradigm, considered to be one of the most accurate prevailing cosmological models at present for its impressive consistency with data from large-scale observations, notably: the Planck Mission Survey on the Cosmic Microwave Background (CMB), remnants of electromagnetic radiation (light) dating back to the earliest observable period of the universe roughly 13.8 billion years ago; or the Dark Energy Spectroscopic Instrument (DESI) Survey on Baryon Acoustic Oscillations (BAOs), sound waves from the early universe that cause fluctuations in the density of baryonic (ordinary) matter.^{1,12,15-17}

Yet, disagreements between Λ CDM and such data, particularly the S_8 tension, are inadequately mentioned, which provides an incomplete understanding of its coherence in describing dark matter.¹¹ While the model still provides a valid approximation of it, such inconsistencies and limitations ought to be taken into consideration to achieve a more viable theory.^{2,11,12}

This paper aims to dispel potential bias regarding the Λ CDM model, analyzing its comprehensive accuracy in representing dark matter by recalling discrepancies with observations and evaluating the Λ CDM model's clarity in conflicts. In Section 2, we summarize and examine the Ω_m discrepancy and the S_8 tension, introducing past attempts to modify the Λ CDM framework to improve its accuracy, which further exemplify these problems. Finally, we conclude in Section 3 with a brief discussion on how such conflicts within the Λ CDM theory could be explored in hopes of alleviating the model.

■ Results and Discussion

Ω_m Discrepancy:

The Ω_m discrepancy represents discrepant values of Ω_m , the parameter for the ratio of total matter density (the frac-

tion that matter constitutes the total mass-energy density in the universe).^{18,19} The Λ CDM model predicts a value of $\Omega_m = 0.3$, indicating that all matter accounts for 30% of the total mass-energy content of the universe, whereas the remaining 70% is attributed to Λ (dark energy).^{11,18-20}

A comprehensive study of dark matter models and large-scale structure data conducted by Gawiser and Silk yields results suggesting that large-scale data prefer alternative dark matter models to the Λ CDM model (see Figures 1 and 2).^{11,20} The Automatic Plate Measuring (APM) galaxy power spectrum (a survey on the distribution of galaxies in the universe), in particular, provided the most prominent discrimination. In their analysis, the Λ CDM model is ruled inconsistent with the data at 99% confidence, showing a steeper correlation function (the probability of galaxy distribution compared to a random distribution) than that predicted by the model with conventional Λ CDM parameters of $\Omega_m = 0.3$.^{11,20} According to their data, an alternative dark matter model, the Cold-Hot Dark Matter (CHDM) model, with parameters of $\Omega_m = 1$ (where $\Omega_m = 1$ suggests that all matter accounts for 100% of the total mass-energy density), is the most consistent model with APM.^{11,20} Although due to the current overwhelming evidence for a low matter density in the universe, exemplified by the existence of dark matter, $\Omega_m = 1$ is not viable; nevertheless, the significant discrepancy between the Λ CDM model and APM data still suggests a potential systematic error in the Λ CDM model regarding the density of matter (baryonic matter and CDM) in the universe.^{11,20}

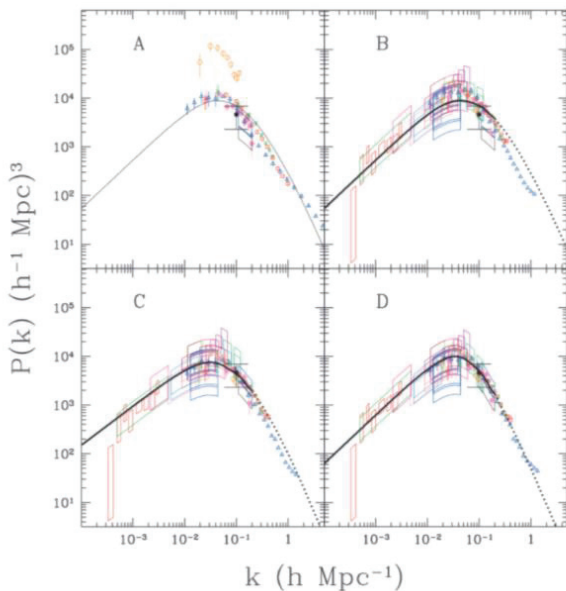


Figure 1: Figure 1 shows a comparison between a compilation of uncorrected large-scale structure observations and dark matter models: SCDM (Standard Cold Dark Matter model) (solid curve: represented using a solid line for clarity in visualizations) (A); SCDM (B); TCDM (Tilted Cold Dark Matter model) (C); and CHDM (Cold-Hot Dark Matter model) (D), where CHDM is the best fit model with agreement even on nonlinear scales (where linear equations used to describe structural formation on large scales no longer apply to the structural formation of the universe on smaller scales, such as individual galaxies). The featured CHDM model with parameter $\Omega_m = 1$ shows better agreement with APM measurements in comparison with alternative models of lower Ω_m parameters, possibly hinting at a higher mass-energy density in the universe; although, a precise density of $\Omega_m = 1$ is unlikely. The featured

large-scale structure data are indicated as such: present-day abundance of clusters (black boxes) and measurements on their evolution (blue boxes); APM measurements (blue triangles); Las Campanas (Las Campanas Distant Cluster Survey, a redshift survey on cluster number distribution) (red squares); IRAS (Infrared Astronomical Satellite, a comprehensive infrared all-sky survey) (pink filled circles); APM clusters (orange circles); and SSRS2+CfA2 (Southern Sky Redshift Survey 2 and Center for Astrophysics Redshift Survey 2, two early galaxy redshift surveys on the large-scale structure of the universe) (green crosses).^{20,21} Image Credit: [20]

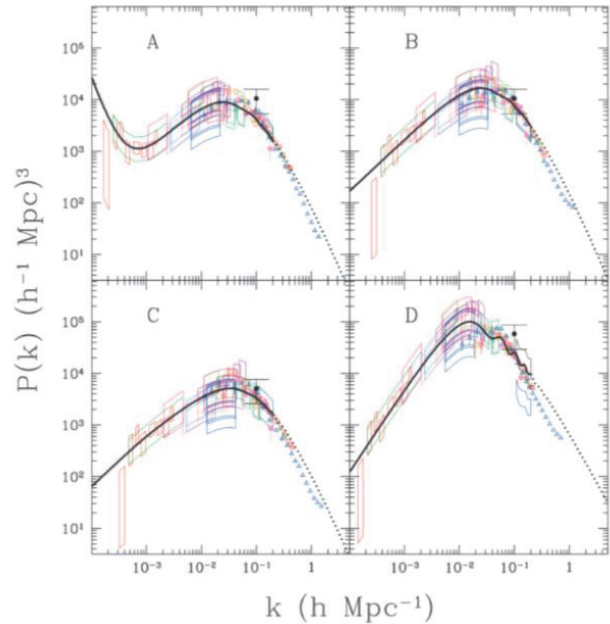


Figure 2: Figure 2 shows an equivalent comparison between large-scale structure data and alternative dark matter models: OCDM (Open Cold Dark Matter Model) (A); Λ CDM (B); CDM (Cold Dark Matter Model) (C); and BCDM (Baryonic Cold Dark Matter) (D), where there is a prominent discrepancy between Λ CDM and APM.^{11,20} The featured Λ CDM model with parameters $\Omega_m = 0.3$ is in worse agreement with APM measurements in comparison to the CHDM model ($\Omega_m = 1$), leading to the suggestion of potential systematic inaccuracies in the Λ CDM model in determining the mass-energy density of the universe. Image Credit: [11]

Furthermore, quantitative analysis conducted by Colgáin *et al.* on parameters for Ω_m provided by the Dark Energy Spectroscopic Instrument (DESI) collaboration based on baryon acoustic oscillations (BAOs) (fluctuations in the density of baryonic matter) confirms an ‘unexpected’ value of

$$\Omega_m = 0.67^{+0.18}_{-0.17} \quad \text{Credit [22]}$$

which is less drastic, but a notable difference from the Λ CDM model predicted value $\Omega_m = 0.3$.^{11,22}

According to the APM survey, large-scale structure does not prefer the Λ CDM model to alternatives such as the Cold-Hot Dark Matter (CHDM) model.²⁰ Thus, in consideration of the main foreign component of the CHDM model, Hot Dark Matter (HDM), an alternative type of dark matter theorized to move at or near the speed of light, a study by Gawiser considers the possibility of incorporating HDM into the Λ CDM model to see if the agreement between the model and large-scale structure data improves.¹¹ Within this modified Λ CDM framework, it is assumed that Hot Dark Matter (HDM) coexists alongside Cold Dark Matter (CDM) (see Figure 3).

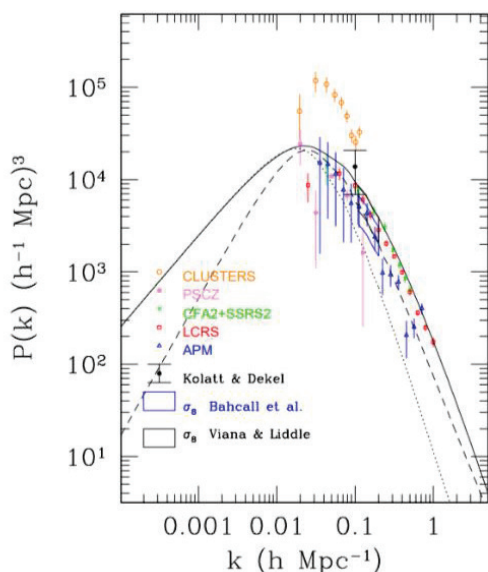


Figure 3: Figure 3 shows a comparison of various large-scale structure data with the following dark matter models: Λ CDM (solid); Λ CHDM (Lambda-Cold-Hot Dark Matter) ($\Omega_\nu = 0.1$ and $n = 1.0$) (dotted); and Λ CHDM ($\Omega_\nu = 0.1$ and $n = 1.5$) (dashed), indicating a worse fit with both Λ CHDM models.¹¹ The recurring disagreement between modified Λ CDM models and APM measurements again may alternatively point to systematic errors and biases within APM as opposed to a data preference for CHDM, given the nonviability of a high matter density in the universe as theorized in the CHDM framework ($\Omega_m = 1$). Image Credit: [11]

Ultimately, the fit becomes worse, but these results allow setting an upper limit on the mass of the most massive particle of dark matter, implying further evidence for the current assumption of a low dark matter density.

Simultaneously, this also reveals that APM is susceptible to systematic errors and limitations, posing challenges in accurately determining the masses and properties of galaxy clustering in the universe. Its use of photographic plates and projection methods in measurements led to uncertainties in estimations due to limitations in sensitivity and accuracy.

S8 Tension:

The S8 tension refers to discrepancies between the predicted and observed amplitudes of matter fluctuations (clustering of matter) in the present-day universe.^{12,23-25} Recent studies on the CMB identify evidence of a “cosmological-scale” inconsistency where weak lensing measurements yield lower S8 values than those inferred from the Λ CDM framework, suggesting that the distribution of matter in the universe is more uniform than what is predicted by the model.^{1,12,24,26-30} This conflict with the Λ CDM model’s limited understanding of how dark matter influences the large-scale structure of the universe is a testament to the reality that the Λ CDM model’s understanding of dark matter is incomplete.^{1,12,24,26-30}

This was particularly evident in the Planck Mission Survey, which refers to a series of satellite observations conducted on the CMB with three data releases, the most recent release being from 2018.^{1,6}

The Planck satellite observations provide the most precise measurements to date, particularly at large scales, and thus data yielded from Planck CMB constitutes a significant por-

tion of cosmological insight into the evolution of the universe, particularly the history of its expansion and matter dispersion, two aspects of its evolution thought to be influenced by the presence of dark energy and dark matter respectively.^{1,6,11} Large-scale observations of the CMB have been impressively consistent with the Λ CDM model for decades, and thus the model is praised for its consistency with CMB data. Simultaneously, inaccuracies of the Λ CDM model regarding S8 value measurements are inadequately addressed.^{11,12}

The observed abundance of galaxy clusters through CMB observations and weak lensing measurements (where subtle gravitational lensing from galaxies or clusters is analyzed to imply data on the distribution of dark matter) are two common methods that are applied to measure the value of S8 (see figures 4 and 5).¹²

Refined S8 values derived from the constrained Planck 2018 (PR4) dataset reveal an S8 tension with a deviation of 2.2σ :

$$S8 = 0.819 \pm 0.014 \quad \text{Credit: [12]}$$

which is a notable discrepancy.^{12,29} Furthermore, S8 values obtained from a joint cosmic shear analysis (a collective study of data obtained from weak-lensing measurements) conducted by the Dark Energy Survey and Kilo-Degree Survey collaboration, suggest a less drastic deviation of 1.3σ :^{12,30}

$$S8 = 0.790 \quad \begin{matrix} -0.018 \\ +0.014 \end{matrix} \quad \text{Credit: [12]}$$

Nevertheless, the S8 tension is prompting further refinement of the model itself as well as measurement techniques to rule out biases and systematic errors.^{12,27}

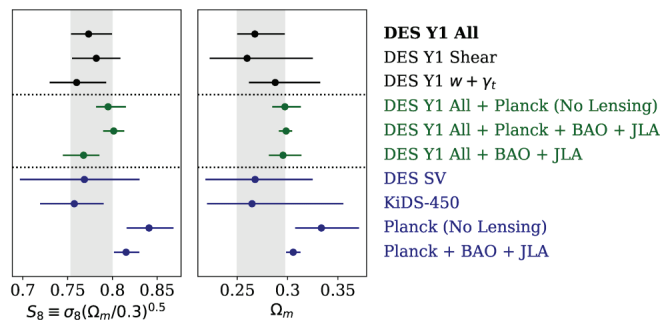


Figure 4: Figure 4 shows results for S8 values derived from the Λ CDM model compared with results from constrained samples of Dark Energy Survey (DES) (a survey of the large-scale structure of the universe aimed to provide constraints for dark energy parameters), Kilo-Degree Survey (KiDS) (a large-scale survey focused on analyzing weak gravitational lensing particularly in relation to dark matter), and Planck CMB data, indicating the inconsistency of observed S8 parameter results.^{31,32} The figure shows notable deviations in several datasets—particularly DES and KiDS—and the Λ CDM best-fitting value, suggesting lower S8 parameters than predicted. DES Y1 refers to the first year observations of DES; DES SV the Science Verification analysis; JLA Supernova Ia Analyses; and BAO observational data on baryon acoustic oscillations (fluctuations in baryonic matter densities caused by acoustic oscillations from the early universe).³³ Image Credit: [33]

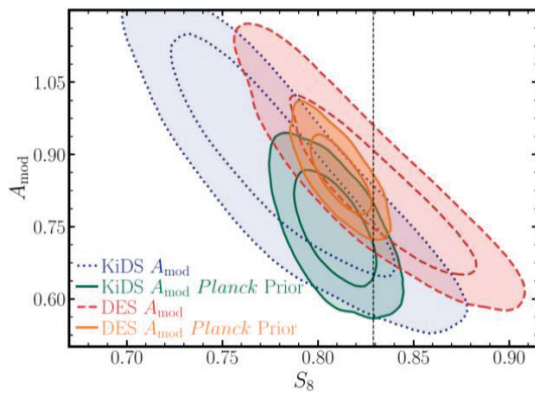


Figure 5: Figure 5 shows the high discrepancy between S_8 and the phenomenological parameter A_{mod} (a modifier to S_8 , typically used as a parameter that quantifies the consistency between Planck CMB data and other large-scale structure datasets), indicating an S_8 tension between results from Planck and other surveys. The horizontal dashed line indicates the Planck Λ CDM best-fitting value of $S_8 = 0.828$; the red DES statistics (with 68% and 95% constraints) and orange DES statistics incorporated with prior data from Planck CMB; and the KiDS equivalents in blue and green, respectively.²⁷ Data obtained from both KiDS and DES demonstrate lower predicted S_8 values than the Λ CDM best-fitting value, again highlighting the tension. Image Credit: [27]

Various methods of modifying the Λ CDM model have been attempted to resolve the S_8 tension, yet so far, few proposals are well known, let alone widely accepted.²³ We briefly discuss one such attempt, presented by astrophysicist Jamie Farnes: a modified version of the Λ CDM model that takes into account a hypothetical negative mass consisting of incorporated dark matter and dark energy, as a potential explanation for the discrepant distribution of matter in the universe.³⁴ The model predicts that the continuously generated negative mass could substitute as a force resembling the cosmological constant, helping to resolve our lack of understanding of the potential interactions between dark matter and dark energy, which may be influencing the more even distribution.³⁵

When values derived from simulations are reconciled with modern cosmological observations, however, this theory reveals a discrepancy between parameter predictions for Ω_m and Ω_Λ (representing the density parameters for matter and dark energy respectively), implying that the cosmological constant is likely positive as opposed to being driven by a negative mass, and therefore that there are other unaccounted implications to our understanding of dark matter and the S_8 tension.³⁵

This is true if a lower value of S_8 is assumed to be the main indicator of the tension. On the contrary, some sources suggest a higher S_8 value than expected, leading to further uncertainty and possibly hinting at a new, different S_8 tension.^{12,35}

■ Conclusion

From re-examining conflicts between the Λ CDM model and observational data, we have found that while modifications to the model do not yet resolve such disagreements, these discrepancies provide further indication to support our understanding of dark matter, suggesting key areas to improve the consistency of parameters within the model. Overall, it can be observed that the S_8 tension is an indicator that dark matter

may interact with dark energy, and the Ω_m discrepancy problem still recalls current evidence for a low dark matter density.

Furthermore, they suggest that just as the Λ CDM model's agreement with observational data may not be ideal, there may be systematic inaccuracies within measurement methods. APM, for example, could be argued as an outdated method for observation, and presents a challenge in accurately determining galaxy cluster masses and clustering properties due to the limitations of its data and analysis methods.

The introduction of alternative dark matter models or the advancement of accurate observation methods will be crucial in the coming decades, either expanding the potential of the Λ CDM model or rendering it incompetent as a dark matter model. Ongoing research on new dark matter particles—neutrinos, for example— as well as the implementation of improved cosmological surveys, may provide further insight for a more detailed and accurate structure of large-scale structures in the universe.

Our concluding emphasis is that Λ CDM, while likely the most accurate and prevalent Standard Cosmological Model by far, remains a theory with non-negligible limitations that are constantly challenged and developed alongside the advancement of research.

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■ Data Availability

No new data has been analyzed or generated in support of this paper.

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