

Cosmological parameter estimation from CMB and X-ray clusters after Planck (postprint)

Authors: Jian-Wei Hu, Rong-Gen Cai, Zong-Kuan Guo, Bin Hu

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Abstract

We update the cosmological parameter estimation for three non-vanilla models by a joint analysis of CCCP X-ray cluster, the newly released Planck CMB data as well as some external data sets, such as baryon acoustic oscillation measurements from the 6dFGS, SDSS DR7 and BOSS DR9 surveys, and Hubble Space Telescope H0 measurement. First of all, we find that X-ray cluster data sets strongly favor a non-zero summed neutrino mass at more than 3 confidence level in these non-vanilla models. And then, we reveal some tensions between X-ray cluster and Planck data in some cosmological parameters. For the matter power spectrum amplitude σ_8 , X-ray cluster data favor a lower value compared with Planck. Because of the strong σ_8 degeneracy, this tension could be beyond 2 confidence level when the summed neutrino mass m is allowed to vary. For the CMB lensing amplitude A_L , the addition of X-ray cluster data results in a 3 deviation from the vanilla model. Furthermore, Planck+X-ray data prefer a large Hubble constant and phantom-like dark energy equation of state, which are in 2 tension with those from WMAP7+X-ray data. Finally, we find that these tensions/discrepancies could be relaxed in some sense by adding a 9% systematic shift in the cluster mass functions.

Full Text

Cosmological Parameter Estimation from CMB and X-ray Clusters After Planck

Jian-Wei Hu,¹ Rong-Gen Cai,² Zong-Kuan Guo,³ Bin Hu⁴

^{1,2,3}State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, P.O. Box 2735, Beijing 100190, China

⁴Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, 2333 CA Leiden, The Netherlands

Abstract

We update cosmological parameter constraints for three non-vanilla models through a joint analysis of CCCP X-ray cluster data, the newly released Planck CMB data, and external datasets including baryon acoustic oscillation measurements from 6dFGS, SDSS DR7, and BOSS DR9 surveys, as well as Hubble Space Telescope H_0 measurements. First, we find that X-ray cluster data strongly favor a non-zero summed neutrino mass at more than 3σ confidence level in these non-vanilla models. We also reveal tensions between X-ray cluster and Planck data for several cosmological parameters. For the matter power spectrum amplitude σ_8 , X-ray cluster data prefer a lower value compared to Planck. Due to the strong σ_8 - Σm degeneracy, this tension can exceed the 2σ confidence level when the summed neutrino mass Σm is allowed to vary. For the CMB lensing amplitude A , adding X-ray cluster data results in a 3σ deviation from the vanilla model. Furthermore, Planck+X-ray data prefer a large Hubble constant and phantom-like dark energy equation of state, which are in 2σ tension with those from WMAP7+X-ray data. Finally, we find that these tensions/discrepancies can be partially relaxed by introducing a 9% systematic shift in the cluster mass functions.

Keywords: cosmology, neutrino mass, galaxy clusters

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1 Introduction

The Planck Collaboration recently released initial cosmology products based on the first 15.5 months of Planck operations. Their results strongly support the standard 6-parameter Λ CDM model (hereafter the “vanilla” model), with significantly improved parameter constraints, including a highly significant deviation from scale invariance in the primordial power spectrum of curvature perturbations. However, some base cosmological parameters and derived quantities differ substantially from previous determinations, such as the present Hubble parameter H_0 and the lensing amplitude A . Among these tensions, the most controversial concerns the H_0 value. On one hand, Planck results disagree with recent direct measurements from the Hubble Space Telescope (HST) Key Project and Type Ia supernovae observations via the magnitude-redshift relation (e.g., the Union2.1 compilation). On the other hand, they show excellent agreement with geometric constraints from several baryon acoustic oscillation (BAO) surveys. Additionally, recent work re-analyzing the Planck primary CMB data found that the 217 GHz \times 217 GHz detector set spectrum used in the Planck analysis is responsible for some of this tension.

Numerous efforts have been made to reveal or reconcile tensions between low-redshift geometric measurements and Planck data.

Beyond CMB observations, large-scale structure (LSS) surveys on various scales,

including galaxies and galaxy clusters, provide valuable cosmological information. A complete understanding of our universe's structure requires agreement between theoretical predictions and observations across different spatial and temporal scales. While CMB maps primarily encode information on large spatial scales and high redshifts, LSS distributions reveal structure formation laws resulting from gravitational instability on relatively small scales and low redshifts. As the most massive virialized structures in the universe, galaxy clusters are ideal probes of matter distribution on large scales. In the dark matter structure formation scenario, baryonic matter traces the dark matter halo distribution. When baryonic gas falls into gravitational potential wells, it heats to $\sim 10^7$ K and emits X-rays, allowing galaxy clusters to be identified through their X-ray flux. The Chandra Cluster Cosmology Project (CCCP) uses X-ray indicators to observe clusters from a catalog detected in ROSAT PSPC surveys covering 400 square degrees of sky. Thanks to Chandra's high resolution, high-quality X-ray data for samples up to redshift $z = 0.9$ have been obtained, enabling determination of the galaxy cluster mass function and cosmological parameter estimation.

Solar and atmospheric neutrino oscillation measurements indicate that neutrinos have mass but cannot provide absolute mass values. Cosmological observations can place strong constraints on the summed neutrino mass through its cosmological effects. Neutrino masses affect the CMB power spectrum mainly through the early integrated Sachs-Wolfe effect, modify the late-time expansion rate of the universe (affecting BAO), and suppress the abundance of galaxy clusters by smearing mass over the neutrino free-streaming scale. The Planck team adopted a normal hierarchy for neutrino masses with $\Sigma m = 0.06$ eV as their baseline model and found a significant discrepancy between Planck data and galaxy cluster abundances. This tension can be relaxed by increasing the summed neutrino mass, as neutrino free-streaming reduces small-scale clustering. Therefore, in our analysis the summed neutrino mass is always allowed to vary freely.

This paper focuses on cosmological parameter estimation for three non-vanilla models using Planck+WP+BAO+HST data combined with CCCP X-ray clusters. The paper is organized as follows: Section 2 describes the datasets and methodology, Section 3 presents results for three non-vanilla models and reveals tensions between X-ray cluster and Planck data, and Section 4 concludes.

2 Data and Methodology

The total Planck CMB temperature power-spectrum likelihood is divided into low- ($l < 50$) and high- ($l \geq 50$) parts. This division arises because the central limit theorem ensures that the distribution of CMB angular power spectrum C in the high- regime can be well approximated by Gaussian statistics, whereas the low- distribution is non-Gaussian. Consequently, the Planck team employs two different methodologies to construct the likelihood. For the low- part, the likelihood exploits all Planck frequency channels from 30 to 353 GHz, separating the cosmological CMB signal from diffuse Galactic foregrounds through a

physically motivated Bayesian component separation technique. For the high-part, the team uses a correlated Gaussian likelihood approximation based on fine-grained angular cross-spectra derived from multiple detector combinations between the 100, 143, and 217 GHz frequency channels, marginalizing over power-spectrum foreground templates.

To break the well-known parameter degeneracy between reionization optical depth τ and scalar spectral index n_s , the Planck team adopts the low- l WMAP polarization likelihood (WP).

We also incorporate X-ray cluster data from the CCCP project, which measures the cluster mass function using a high-redshift ($0.4 < z < 0.9$) subsample of 37 objects from the 400 square degree survey and a low-redshift ($z < 0.2$) subsample of 49 brightest clusters from the all-sky survey. The likelihood construction follows the standard derivation of the Poisson distribution of cluster mass. The likelihood function implicitly depends on cosmological parameters through the cluster mass function model (reflecting the growth, normalization, and shape of the density perturbation power spectrum), the cosmological volume-redshift relation determining the survey volume, and the distance-redshift and mass-temperature relations. Details of likelihood construction and systematic uncertainty control are described in the literature.

To break parameter degeneracies, we additionally use external datasets including BAO measurements from 6dFGS, SDSS DR7, and BOSS DR9 surveys, and HST Key Project H_0 measurements.

Previous work found that adding X-ray cluster data yields non-zero detection of active or sterile neutrino mass (Σm_ν or m_s) with high statistical significance for various 8-parameter models, including active/sterile neutrino mass and effective neutrino number N_{eff} . X-ray data also leads to significant deviation in σ_8 (the matter power spectrum amplitude on $8 h^{-1}$ Mpc scales) from the Planck result: without X-ray clusters, Planck favors a larger σ_8 value, while joint analysis yields a lower value. Therefore, we explore tensions between Planck and CCCP X-ray cluster data using several 8-parameter models including effective neutrino number N_{eff} , constant dark energy equation of state w , present spatial curvature Ω_K , and lensing amplitude A_L . We focus on neutrino mass constraints, so the summed neutrino mass is always allowed to vary freely. We restrict ourselves to one-parameter extensions to the baseline Λ CDM + Σm_ν model, as listed in Table 1.

We compute CMB angular and matter power spectra using the public Einstein-Boltzmann solver CAMB and explore the cosmological parameter space with a Markov Chain Monte Carlo sampler (CosmoMC). For Planck, we use the Planck Likelihood Code (PLC/clik) available at the Planck Legacy Archive, and for CCCP we use the likelihood grids from the literature.

3 Results

This section extracts information from CCCP X-ray cluster data (hereafter denoted CL_{CCCP}). We first investigate constraints on summed neutrino mass from Planck+WP+BAO+HST data (hereafter PWBH) combined with CL_{CCCP}, then reveal tensions in cosmological parameters between these datasets.

3.1 Σm Results

We first examine the summed neutrino mass Σm . Solar and atmospheric oscillation observations set a lower bound ($\Sigma m \geq 0.06$ eV) for standard three neutrino species. Beyond local observations, neutrino mass information can be obtained through indirect measurements on cosmological scales via two main approaches. One uses secondary CMB anisotropies generated in the deep matter-dominated epoch, such as weak lensing effects. However, these anisotropies are small compared to the primordial signal, so current CMB experiments provide only loose upper bounds (e.g., $\Sigma m < 0.66$ eV from Planck+ACT+SPT). The other approach utilizes large-scale structure tracers such as the matter power spectrum, selected cluster counts, and cosmic shear. These tomographic measurements provide relatively stringent constraints, though results vary among projects due to systematic noise and theoretical non-linearities. For example, CL_{CCCP} and selected Sunyaev-Zel'dovich galaxy cluster counts from Planck and SPT report non-zero detection of summed neutrino mass with significant evidence, while other galaxy surveys like WiggleZ improve upper bounds but find no significant deviation from zero.

Given these considerations, we use CL_{CCCP} data for joint analysis of summed neutrino mass Σm with related parameters including effective neutrino number N_{eff} , dark energy equation of state w , and spatial curvature Ω_K . Results with and without CL_{CCCP} are listed in Tables 2 and 3, with corresponding 2D likelihood contours shown in Figure 1.

Our main results are as follows. First, Table 2 shows more than 3σ detection of summed neutrino mass for these three non-vanilla models when CL_{CCCP} data are included:

$$\Sigma m = 0.46 \pm 0.12 \text{ (68\%; + } N_{\text{eff}}\text{: PWBH + CL)}$$

$$\Sigma m = 0.55 \pm 0.10 \text{ (68\%; + } w\text{: PWBH + CL)}$$

$$\Sigma m = 0.45 \pm 0.12 \text{ (68\%; + } \Omega_K\text{: PWBH + CL)}$$

Moreover, as noted in the literature, CL_{CCCP} data sets contain a systematic error in hydrostatic mass measurements of $\delta M/M \approx 0.09$. Accounting for this mass function correction yields reduced mean values for summed neutrino mass:

$$\Sigma m = 0.39 \pm 0.09 \text{ (68\%; + } w\text{: PWBH + CL + 9\%Mass)}$$

[Figure 1: see original paper]

3.2 A_L and σ_8 Results

We now examine models including A_L and σ_8 , where the latter is treated as a derived parameter from the primordial curvature perturbation amplitude. First considering parameter degeneracies, Figure 2 shows only a tiny correlation between Σ_m and A_L , so constraints on A_L in $\Lambda\text{CDM}+\Sigma_m+A_L$ and $\Lambda\text{CDM}+A_L$ models are very similar (see Table 5). For example, using PWBH+CL we obtain:

$$A_L = 1.37 \pm 0.11 \text{ (68\%; } \Lambda\text{CDM} + A_L: \text{PWBH} + \text{CL})$$

For comparison, Table 5 also lists $\Lambda\text{CDM}+A_L$ results without CL, which are consistent with Planck results:

$$A_L = 1.22 \pm 0.10 \text{ (68\%; } \Lambda\text{CDM} + A_L: \text{PWB})$$

Comparing these results shows that CL leads to even larger deviation of A_L from unity (the vanilla model value). Additionally, Table 4 shows that with 9% cluster mass correction, tension with the vanilla model can be mildly reconciled:

$$A_L = 1.28 \pm 0.10 \text{ (68\%; } w\text{CDM} + \Sigma_m + A_L: \text{PWBH} + \text{CL} + 9\%\text{Mass})$$

Turning to the matter power spectrum amplitude σ_8 , Figure 2 reveals a significant anti-correlation between σ_8 and Σ_m . This occurs because non-relativistic, massive, weakly-interacting neutrinos behave as warm/hot dark matter, suppressing fluctuations on scales smaller than their thermal free-streaming length. Consequently, this correlation leads to relatively low σ_8 values when Σ_m is allowed to vary (see Figure 3 and Table 5). Using PWBH+CL data, our results give:

$$\sigma_8 = 0.7894 \pm 0.0070 \text{ (68\%; } \Lambda\text{CDM} + A_L: \text{PWBH} + \text{CL})$$

$$\sigma_8 = 0.7550 \pm 0.0139 \text{ (68\%; } \Lambda\text{CDM} + \Sigma_m + A_L: \text{PWBH} + \text{CL})$$

In the 6-parameter ΛCDM model, the Planck collaboration reported $\sigma_8(\Omega_m/0.27)^{0.3} = 0.784 \pm 0.027$ using Planck+WP+BAO+BBN+CL, consistent with our results. Figure 3 shows that results with CL (blue curve) are in 2σ tension with those without CL data (red curve):

$$\sigma_8 = 0.8162 \pm 0.0119 \text{ (68\%; } \Lambda\text{CDM} + A_L: \text{PWB})$$

Similar to A_L , a 9% cluster mass correction can reconcile tension with Planck:

$$\sigma_8 = 0.7639 \pm 0.0198 \text{ (68\%; } w\text{CDM} + \Sigma_m + A_L: \text{PWBH} + \text{CL} + 9\%\text{Mass})$$

[Figure 2: see original paper]

[Figure 3: see original paper]

3.3 H_0 and w Results

This subsection examines two background parameters: the Hubble constant H_0 and dark energy equation of state w .

First, Table 2 shows that without 9% mass correction to CL data, a larger H_0 value is favored. For the w CDM+ Σm model:

$$H_0 = 74.0 \pm 2.1 \text{ (68\%; +w: PWBH + CL)}$$

After adding this correction, the mean H_0 value is pulled back slightly for the same model:

$$H_0 = 72.0 \pm 1.3 \text{ (68\%; +w: PWBH + CL + 9\%Mass)}$$

Second, when dark energy equation of state w is treated as a free parameter instead of spatial curvature Ω_K , a larger H_0 emerges (see left panel of Figure 4). This is due to the H_0 - w correlation illustrated in the right panel of Figure 4.

Third, for consistency checking we include results from joint analysis of WMAP7 and CL data. The right panel of Figure 4 clearly shows a 2σ tension in the parameter plane between Planck+WP+BAO+HST+CL (blue) and WMAP7+BAO+HST+CL (green) data.

Beyond these H_0 discrepancies, our results favor a phantom-like dark energy equation of state:

$$w = -1.39 \pm 0.12 \text{ (68\%; +w: PWBH + CL)}$$

We emphasize that this phantom value is not caused by including CL data. The middle column of Table 3 shows that even without X-ray cluster data, the dark energy equation of state deviates from -1 by more than 2σ :

$$w = -1.33 \pm 0.15 \text{ (68\%; +w: PWBH)}$$

Furthermore, removing HST data (using only Planck+WP+BAO) eliminates significant deviation from $w = -1$:

$$w = -1.31 \pm 0.23 \text{ (68\%; +w: PWB)}$$

Due to the well-known H_0 - w correlation, this result partially reflects tension between HST and Planck on the Hubble parameter H_0 as found in previous work. Finally, the 9% mass correction can also relax tension in w with the Λ CDM model:

$$w = -1.23 \pm 0.06 \text{ (68\%; +w: PWBH + CL + 9\%Mass)}$$

[Figure 4: see original paper]

4 Conclusions

We have presented updated cosmological parameter estimates for three 8-parameter non-vanilla models using Planck, WMAP7, BAO, HST, and CCCP X-ray datasets. First, we found that X-ray cluster data strongly favor a non-zero summed neutrino mass with more than 3σ confidence level in these models, consistent with recent literature. Massive neutrinos inhibit structure growth below their thermal free-streaming scale during structure formation,

leading to reduced σ_8 values that improve consistency with X-ray cluster data. Additionally, we revealed tensions between X-ray cluster and Planck data for several cosmological parameters including the matter power spectrum amplitude σ_8 , lensing amplitude A_L , constant dark energy equation of state w , and Hubble parameter H_0 .

For σ_8 , X-ray cluster data prefer a relatively low value compared to Planck. Due to the σ_8 - Σ_m degeneracy, this tension can exceed 2σ confidence level when Σ_m is allowed to vary. For the CMB lensing amplitude A_L , adding X-ray cluster data worsens its deviation from unity (the vanilla model value) and results in more than 3σ discrepancy. Because of the correlation between H_0 and w , X-ray cluster data prefer a large Hubble constant and quite negative dark energy equation of state. We also found a 2σ tension in the H_0 - w plane between Planck+WP+BAO+HST+CL and WMAP7+BAO+HST+CL data.

Finally, we emphasize that these tensions/discrepancies can be partially reduced by introducing a 9% shift in cluster mass functions. Resolving these tensions will likely require either identifying currently unknown systematic effects in at least one of these datasets or new physics.

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