Cosmological Constraints on Neutrino Masses in Light of JWST Red and Massive Candidate Galaxies (Postprint)

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Full Text

Preamble

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Cosmological Constraints on Neutrino Masses in Light of JWST Red and Massive Candidate Galaxies

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Abstract

The overabundance of red and massive candidate galaxies observed by the James Webb Space Telescope (JWST) implies efficient structure formation or large star formation efficiency at high redshift $z \sim 10$. In the scenario of low or moderate star formation efficiency, because massive neutrinos tend to suppress the growth of structure in the universe, JWST observations tighten the upper bound on neutrino masses. Assuming Λ cold dark matter cosmology and a star formation efficiency $\in [0.05, 0.3]$ (flat prior), we perform joint analyses of Planck+JWST and Planck+BAO+JWST, obtaining improved constraints $\sum m_\nu < 0.196$ eV and $\sum m_\nu < 0.111$ eV at 95% confidence level, respectively. Based on these assumptions, the inverted mass ordering, which implies $\sum m_\nu > 0.1$ eV, is excluded by Planck+BAO+JWST at 92.7% confidence level.

Key words: (cosmology:) cosmological parameters -galaxies: abundances -galaxies: formation -neutrinos

1. Introduction

The standard hot big bang cosmology predicts a cosmic neutrino background (CνB), which decoupled from the thermal bath in the early universe at a temperature ~MeV. The subsequently redshifted momenta of CνB follow an ultra-relativistic Fermi-Dirac distribution with negligible chemical potential and an effective temperature $1.95(1 + z)$ K, where z denotes the cosmological redshift. Although direct detection of CνB is yet unrealistic, the existence of CνB has been indirectly confirmed by observations of primordial abundances of light elements and the cosmic microwave background (CMB). The mass-squared differences between the three mass eigenstates have been measured in neutrino flavor oscillation experiments [**?**, **?**]. These experiments constrain the sum of masses of three neutrino species, $\sum m_\nu$, to be > 0.06 eV for the normal mass ordering $m_1 \sim m_2 \ll m_3$, and > 0.10 eV for the inverted mass ordering $m_3 \ll m_1 \approx m_2$. Distinguishing between the two mass-ordering scenarios, and hence obtaining accurate measurements of the sum of neutrino masses, are important for understanding the origin of neutrino masses.

At $z \approx 1100$ where primary CMB anisotropies are generated, the background temperature is $T \approx 3000$ K ≈ 0.3 eV. For $\sum m_\nu \gtrsim 0.3$ eV, neutrino masses will impact the primary CMB via the early integrated Sachs-Wolfe effect. In the late universe, massive neutrinos act as a hot dark matter component, which tends to suppress the growth of large-scale structure at small scales ($\lesssim 100$ Mpc) and alter the CMB lensing effect. The third-generation CMB experiment Planck mission constrained the total neutrino masses to be $\sum m_\nu < 0.241$ eV (TTTEEE+lowE+lensing) at 95% confidence level (CL) in the standard Λ cold dark matter (ΛCDM) model [**?**]. Further including baryon acoustic oscillation

(BAO) data, which breaks the degeneracy between neutrino masses and the background expansion history of the universe, pushes the upper limit of neutrino masses to $\sum m_\nu < 0.121$ eV (95% CL). This upper bound already puts inverted mass ordering under pressure (excluded at 90.2% CL).

Standard cosmological structure and galaxy formation are recently challenged by red and massive candidate galaxies from the James Webb Space Telescope (JWST). [?] found six candidate massive galaxies (stellar mass 10^{10} solar masses) at $7.4 \lesssim z \lesssim 9.1$. This finding suggests that either the star formation efficiency (SFE) significantly exceeds typical values in low-redshift galaxies, or the halo mass function is about 2σ higher than the prediction of the standard ΛCDM cosmology [?, ?, ?, ?, ?]. Although a large SFE cannot be theoretically excluded [?, ?], a large SFE at $z \gtrsim 7$ tends to enhance UV radiation from galaxies, causing a faster reionization process that is in tension with observations [?, ?, ?]. For this reason, we adopt the more widely accepted conservative assumption of SFE $\lesssim 0.1$ and discuss cosmological implications. Because massive neutrinos tend to suppress the number of massive halos in which massive galaxies are born, a large $\sum m_\nu$ increases the tension between the ΛCDM model and JWST data. Thus, adding JWST data to current cosmological analysis, as the present work aims to do, helps tighten the upper bound on neutrino masses.

This paper is organized as follows. Section 2 constructs the likelihood of massive galaxy counting and describes the numerical tool for likelihood evaluation. In Section 3 we apply the likelihood to the [?] data and obtain Planck+JWST and Planck+BAO+JWST joint constraints on $\sum m_\nu$. Section 4 discusses and concludes.

2. Likelihood of Massive Galaxy Counting

The aim of this section is to extend the likelihood of massive galaxy counting from [?], which we sketch below, to massive neutrino models.

To assess the impact of massive neutrinos on galaxy formation, we adopt the extended Press-Schechter ellipsoidal collapse model [?, ?, ?] to compute the expected abundance of dark matter halos. It predicts the halo mass function, which is the comoving halo number density per mass interval, to take the form:

$$\frac{dn}{d\ln M} = \frac{\bar{\rho}}{M} f(\nu) \frac{d\nu}{d\ln M}$$

where $\bar{\rho}$ is the average background density and $\nu = \delta_c/\sigma(M,z)$, where $\delta_c = 1.686$ corresponds to the critical linear overdensity and $\sigma(M,z)$ is the mass fluctuation at scale M. The simulation-calibrated $f(\nu)$ factor is given by:

$$f(\nu) = A\sqrt{\frac{2a}{\pi}}\left[1+(\nu^2)^{-p}\right]\nu e^{-a\nu^2/2}$$

with $a = 0.707$, $A = 0.322$, and $p = 0.3$ [?]. For massive halos we assume that the fraction of baryonic mass in a massive dark matter halo is $f_b \equiv \Omega_b/\Omega_m$, where Ω_b and Ω_m are the baryon and matter abundance parameters. The stellar mass M_* is then connected to the halo mass $M_{\rm halo}$ via $M_* = \epsilon f_b M_{\rm halo}$, where ϵ is the SFE. This relation allows conversion of a stellar-mass threshold $M_{*,\rm cut}$ to a halo-mass threshold $M_{\rm halo,cut}$. Assuming each massive halo hosts a massive central galaxy, we can write the expected number of massive galaxies above the stellar-mass threshold and in a selected comoving volume as:

$$\langle N_{\rm th}\rangle = f_{\rm sky}\int_{z_{\rm min}}^{z_{\rm max}} dz \frac{dV}{dzd\Omega}\int_{M_{\rm halo,cut}}^{\infty} dM_{\rm halo}\frac{dn}{d\ln M_{\rm halo}}$$

where the selected comoving volume is defined by the redshift interval $[z_{\rm min}, z_{\rm max}]$ and the sky fraction $f_{\rm sky}$. Following [?] we take $z_{\rm min} = 7$ and $z_{\rm max} = 10$. The survey area is 38 arcmin^2, which gives $f_{\rm sky} = 2.56 \times 10^{-7}$. The comoving volume per redshift interval per solid angle, $dV/dzd\Omega$, is specified by the cosmology. For the spatially flat ΛCDM model:

$$\frac{dV}{dzd\Omega} = \frac{c}{H_0}\frac{(1+z)^2}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

where c, Ω_m, and H_0 are the speed of light, the total matter (CDM + baryon + neutrinos) abundance parameter, and the Hubble constant, respectively.

At $z \lesssim 10$, massive neutrinos become non-relativistic and contribute a small ($\sim 10^{-3}$) fraction to the total energy budget of the universe. However, the correction to Equation (4) due to neutrino masses, namely the volume effect, is still negligible for our analysis. The major impact of neutrino masses is on the matter power spectrum, whose integration gives $\sigma(M, z)$ in Equation (1). Figure 1 shows the dependence of the halo mass function, evaluated at $z = 8.5$ (the center of the redshift bin used in the likelihood), on the sum of neutrino masses.

The stellar mass and redshift uncertainties propagate to the uncertainty in $N_{\rm obs}$, the number of observed galaxies above the stellar mass threshold and within the selected volume. Meanwhile, due to cosmic variance and Poisson shot noise, the theoretical prediction of $N_{\rm obs}$ is also probabilistic. The likelihood of the theory is then characterized by the probability of finding $N_{\rm obs}$ given $N_{\rm th}$, which is $P(N_{\rm obs}|N_{\rm th})$.

The distribution function $P(N_{\rm th})$ is based on the cosmological model and the star formation efficiency. For the purpose of using rare-object statistics, we are only interested in the $\langle N_{\rm th}\rangle \lesssim O(1)$ case, where $N_{\rm th}$ approximately follows a Poisson distribution. The expectation-value parameter of the Poisson distribution, denoted as λ, has an uncertainty due to cosmic variance [?]. Marginalizing over the cosmic variance of λ that is denoted as σ_λ, we obtain the distribution function of $N_{\rm th}$:

$$P(N_{\rm th}) = \int d\lambda \frac{\lambda^{N_{\rm th}} e^{-\lambda}}{N_{\rm th}!} \frac{1}{\sqrt{2\pi}\sigma_\lambda} \exp\left[-\frac{(\lambda - \langle N_{\rm th}\rangle)^2}{2\sigma_\lambda^2}\right]$$

where $\sigma_\lambda = \langle N_{\rm th}\rangle$ for Poisson shot noise and $\sigma_\lambda = \langle N_{\rm th}\rangle^{5/8}$ for cosmic variance [?]. In the right panel of Figure 2 we show the derived data, namely $P(N_{\rm obs})$ for the 13 candidate galaxies from [?], and the theoretical $P(N_{\rm th})$ for two representative values SFE = 0.1 and SFE = 0.3, respectively. For the case of SFE = 0.1, there is tension between theory and data, as the theory prefers a smaller number of massive galaxies ($N < 2$) than what the data indicates ($N \geq 2$). For SFE = 0.3, the theory is well consistent with the data as $P(N_{\rm th})$ is comparable to or greater than $P(N_{\rm obs})$ for all N values.

The distribution function $P(N_{\rm obs})$ is obtained by randomly sampling stellar masses and redshifts of the candidate galaxies with the summary statistics given in [?], and counting the number of galaxies in the selected volume. The precise values of $P(N_{\rm obs})$ rely on the functional form of the systematic errors of the stellar masses and redshifts of the galaxy candidates. We adopt the triangular distribution function, which is shown to be a more conservative estimation than smooth distributions, e.g., the skew-normal distribution. See [?] for a more detailed description of the algorithm and its theoretical explanation.

We integrate the cosmological linear perturbation Boltzmann solver CAMB [?, ?] into the calculator in [?]. As shown in the left panel of Figure 2, the expected number of massive galaxies $\langle N_{\rm th}\rangle$ decreases with the sum of neutrino masses, while other cosmological parameters ($\Omega_m = 0.3158$, $\Omega_b = 0.04939$, $h = 0.6732$, $A_s = 2.101 \times 10^{-9}$, $n_s = 0.9661$) are fixed at the Planck best-fit values [?]. The reduced Hubble constant h is defined by $H_0 = 100h$ km s^{-1} Mpc^{-1}; Ω_m and Ω_b are the total matter (CDM + baryon + neutrinos) and baryon abundances; A_s and n_s are the amplitude and spectral index of the primordial power spectrum.

3. Results

For the given set of observed galaxy candidates and selected volume ($7 \lesssim z \lesssim 10$ and survey area 38 arcmin^2), the cosmology-dependent $P(N_{\rm th})$ in Equation (5) gives a likelihood of cosmological parameters and SFE. For more detailed information about the data set, such as the redshifts and stellar masses of the candidate galaxies, we refer readers to [?].

Due to degeneracy between cosmological parameters, JWST data alone cannot give a meaningful constraint on $\sum m_\nu$. We therefore analyze Planck+JWST and Planck+BAO+JWST jointly by performing importance sampling with the Planck and Planck+BAO Monte Carlo Markov chains from the Planck Legacy Archive (https://pla.esac.esa.int/pla/). The base parameters, on which flat priors are assumed, are the baryon density $\Omega_b h^2$, the CDM density $\Omega_c h^2$, the reionization optical depth τ, the angular extension of sound horizon on the last scattering surface θ, the sum of neutrino masses $\sum m_\nu$, the primordial power spectrum parameters $\ln A_s$ and n_s, and the SFE. Before doing cosmological analysis, we must assume a prior on SFE. Unless otherwise stated, we focus our study on a low or moderate SFE, namely a flat prior SFE $\in [0.05, 0.3]$, though other options will also be briefly discussed.

The constraints on some key parameters (base or derived), before and after incorporating JWST likelihood, are shown in Table 1 for comparison. The 95% CL upper bound of $\sum m_\nu$ is improved by 19% (without BAO) and 8% (with BAO), respectively. Although the improvement is modest, the inclusion of JWST data pushes the upper bound to $\sum m_\nu < 0.111$ eV, very close to the $\sum m_\nu > 0.1$ eV limit implied by inverted mass ordering. Integrating over the posterior distribution of $\sum m_\nu$, we find that the inverted mass ordering is excluded by Planck+BAO+JWST at 92.7% CL.

The addition of JWST data also impacts σ_8, the root mean square of density fluctuations in a top-hat spherical window with radius $8h^{-1}$ Mpc. This is because the suppression effect due to neutrino masses is degenerate with the amplitude of matter density fluctuations. This degeneracy can be clearly seen in the left panel of Figure 3, which shows the marginalized 1σ and 2σ contours of $\sum m_\nu$ and σ_8. In the right panel of Figure 3 we show the well-known geometric degeneracy between $\sum m_\nu$ and H_0, which allows the inclusion of BAO (or any other geometric probes at low redshift) to significantly improve the CMB-alone constraint on neutrino masses. The figures are made with the publicly available GetDist package [**?**].

The solid and filled contours in Figure 4 show the marginalized 1σ, 2σ, and 3σ constraints on SFE and $\sum m_\nu$. Although seemingly the upper bound of $\sum m_\nu$ tightens when SFE is lower, this is not the case. This is because the likelihood is very sensitive to SFE, and thus the contours vary significantly when we change the prior on SFE. For example, when the upper bound of SFE is changed to 0.2, the contours become the orange dashed lines in the figure. When we marginalize over SFE, the upper bound of $\sum m_\nu$ does not change much. See also Table 2 for concrete numbers.

By varying the prior on SFE, we also find an interesting phenomenon: as Table 2 shows, the best improvement of the $\sum m_\nu$ bound is achieved around SFE ~ 0.2. Physically this is because a very small SFE makes the likelihood approach a cosmology-independent constant $P \to P(N_{\rm obs} = 0)$, interpreting all candidate galaxies as false detections due to systematic errors in redshift and mass, while a very large SFE makes the likelihood approach another cosmology-independent constant $P \to 1$, where the theoretical prediction significantly exceeds the observed number of galaxies.

4. Conclusions and Discussion

In this work, we incorporate massive neutrinos into the numerical tool in [?] to evaluate the likelihood of massive galaxy counting. At the current stage, JWST candidate galaxies alone cannot constrain cosmology. However, the addition of JWST massive galaxy counting to joint analyses with Planck or Planck+BAO improves the upper bound on neutrino masses by a few percent and puts the inverted mass ordering under more pressure.

While the Planck+BAO+JWST constraint gives the most stringent upper bound on neutrino masses, the results are still very model-dependent. In particular, our results rely on the SFE prior at $z \sim 7$, namely SFE ≤ 0.3. If a larger SFE ≥ 0.4, which is unlikely in the usual scenario of galaxy formation and evolution, is assumed, the likelihood becomes insensitive to cosmology and can no longer improve the $\sum m_\nu$ constraint.

However, there are alternative scenarios where an enhanced SFE at high redshift does not accelerate the reionization process and therefore remains consistent with observations. For example, [?] considered large SFE ($\gtrsim 0.4$) at high redshift and warm dark matter in the keV mass range. In this picture, warm dark matter has no impact on the abundance of very massive halos and only suppresses the low-mass end of the halo mass function. In other words, keV warm dark matter reduces the number of low-mass galaxies that emit UV photons. This effect cancels the enhancement of UV radiation from each galaxy due to large SFE and keeps the cosmic reionization history in line with observations. There are also other options, such as fuzzy dark matter, which can suppress the abundance of small halos and galaxies and lead to the same phenomenon [?].

Other cosmological probes—type Ia supernovae, local distance-ladder measurements of H_0, weak gravitational lensing, redshift-space distortion, etc.—may also tighten the current upper bound on neutrino masses (see e.g., [?] and discussion therein). Ideally, one would like to combine all available data and push the bound on $\sum m_\nu$ to its best limit. However, at the current stage, these cosmological probes, including JWST high-z massive candidate galaxies, may suffer from unknown systematics [?, ?, ?, ?]. It is thus not favorable to add too many cosmological data sets into the pool at once, and caution should be taken for cosmological bounds on neutrino masses. Nevertheless, the growing JWST data bring hope to cross-check constraints on neutrino masses from very different perspectives (tail statistics, perturbation-based, non-linear physics).

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Note: Figure translations are in progress. See original paper for figures.