

# Implications of the Stellar Mass Density of High- $z$ Massive Galaxies from JWST on Warm Dark Matter (Postprint)

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**Date:** 2024-02-01T00:00:00+00:00

## Abstract

A significant excess of the stellar mass density at high redshift has been discovered from the early data release of James Webb Space Telescope (JWST), and it may require a high star formation efficiency. However, this will lead to large number density of ionizing photons in the epoch of reionization (EoR), so that the reionization history will be changed, which can arise tension with the current EoR observations. Warm dark matter (WDM), via the free streaming effect, can suppress the formation of small-scale structure as well as low-mass galaxies. This provides an effective way to decrease the ionizing photons when considering a large star formation efficiency in high- $z$  massive galaxies without altering the cosmic reionization history. On the other hand, the constraints on the properties of WDM can be derived from the JWST observations. In this work, we study WDM as a possible solution to reconcile the JWST stellar mass density of high- $z$  massive galaxies and reionization history. We find that, the JWST high- $z$  comoving cumulative stellar mass density alone has no significant preference for either CDM or WDM model. But using the observational data of other stellar mass density measurements and reionization history, we obtain that the WDM particle mass with keV and star formation efficiency parameter in  $2\sigma$  confidence level can match both the JWST high- $z$  comoving cumulative stellar mass density and the reionization history.

## Full Text

### Preamble

Research in Astronomy and Astrophysics, 24:015009 (7pp), 2024 January © 2023. National Astronomical Observatories, CAS and IOP Publishing Ltd. Printed in China and the U.K. <https://doi.org/10.1088/1674-4527/ad0864>

Implications of the Stellar Mass Density of High- $z$  Massive Galaxies from JWST on Warm Dark Matter

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Received 2023 June 9; revised 2023 October 12; accepted 2023 October 30; published 2023 December 13

## Abstract

A significant excess of the stellar mass density at high redshift has been discovered from the early data release of the James Webb Space Telescope (JWST), which may require a high star formation efficiency. However, this would lead to a large number density of ionizing photons in the epoch of reionization (EoR), altering the reionization history and creating tension with current EoR observations. Warm dark matter (WDM), via the free-streaming effect, can suppress the formation of small-scale structure as well as low-mass galaxies. This provides an effective way to decrease the ionizing photon budget when considering large star formation efficiency in high- $z$  massive galaxies, without altering the cosmic reionization history. Conversely, constraints on WDM properties can be derived from JWST observations. In this work, we investigate WDM as a possible solution to reconcile the JWST stellar mass density of high- $z$  massive galaxies with reionization history. We find that the JWST high- $z$  comoving cumulative stellar mass density alone shows no significant preference for either CDM or WDM models. However, using observational data from other stellar mass density measurements and reionization history, we obtain that a WDM particle mass of  $m_W = 0.22^{+0.13}_{-0.06}$  keV and star formation efficiency parameter  $f_0 = 0.16^{+0.07}_{-0.05}$  can match both the JWST high- $z$  comoving cumulative stellar mass density and the reionization history at the  $2\sigma$  confidence level.

**Key words:** Cosmology -(cosmology:) dark matter -(cosmology:) large-scale structure of universe

## 1. Introduction

High-redshift (high- $z$ ) galaxies play a crucial role in the Epoch of Reionization (EoR), considered the final phase transition of the Intergalactic Medium (IGM) in cosmic history. Studying high- $z$  galaxies allows us to achieve a deeper understanding of early galaxy formation and evolution, as well as the cosmic reionization history. The launch of the James Webb Space Telescope (JWST) opens a new era for studying the Universe, particularly high-redshift objects

(Finkelstein et al. 2022, 2023). JWST's early observational data release provides valuable information about the properties of high- $z$  galaxies, which may challenge current galaxy formation theory under the  $\Lambda$ CDM model (Menci et al. 2022; Naidu et al. 2022a, 2022b; Boyle-Kolchin 2023; Mason et al. 2023; Mirocha & Furlanetto 2023).

In particular, Labbé et al. (2023) identified six galaxies with stellar masses  $M_* = 10^{10} \sim 10^{11} h^{-1} M_\odot$  at  $7.4 \lesssim z \lesssim 9.1$  using the JWST Cosmic Evolution Early Release Science sample detected by the JWST/NIRCam instrument. The corresponding comoving cumulative stellar mass density is about 20 times higher at  $z \sim 8$  and about three orders of magnitude higher at  $z \sim 9$  than predictions from standard  $\Lambda$ CDM cosmology star formation theory based on previous observations (Stark et al. 2013; Song et al. 2016; Bhatawdekar et al. 2019; Kikuchi-hara et al. 2020; Stefanon et al. 2021). This huge abundance excess may be due to issues of galaxy selection, measurements of galaxy stellar mass and redshift, dust extinction, and sample variance (Endsley et al. 2022; Ferrara et al. 2022; Adams et al. 2023; Ziparo et al. 2023). However, if this result is confirmed by future spectroscopic observations, such as follow-up observations by JWST/NIRSpec, it would pose a significant challenge to the  $\Lambda$ CDM model.

Numerous efforts have attempted to resolve this tension, including primordial non-Gaussianity in the initial conditions of cosmological perturbations (Biagetti et al. 2023); rapidly accreting primordial black holes (Liu & Bromm 2022; Yuan et al. 2023); Fuzzy Dark Matter (FDM) (Gong et al. 2023); axion miniclusters or primordial black holes (Hütsi et al. 2023); cosmic strings (Jiao et al. 2023); a gradual transition in the stellar Initial Mass Function (Trinca et al. 2023); and modified  $\Lambda$ CDM power spectrum (Padmanabhan & Loeb 2023; Parashari & Laha 2023).

A direct way to explain the Labbé et al. (2023) observation theoretically is by enhancing the star formation efficiency  $f_*$ . While some previous observations prefer a low star formation efficiency ( $f_* < 0.1$ ), since  $f_*$  depends on complex astrophysical processes that remain unclear, it is theoretically possible to have larger  $f_*$  at high redshifts. However, assuming large  $f_*$  at high- $z$ , while potentially resolving tension with JWST observations, may create new problems. Higher star-forming efficiency at high- $z$  would significantly increase the total number of ionizing photons in the EoR, potentially ending reionization much earlier and creating tension with EoR history observations (Hinshaw et al. 2013; Planck Collaboration et al. 2020). A possible solution is to enhance the formation rate of massive galaxies while simultaneously suppressing the formation of low-mass galaxies. A mass-dependent star formation efficiency  $f_*(M)$  can suppress star formation in small halos, but may still be insufficient to reduce the substantial tension.

Gong et al. (2023) proposed using FDM to solve this problem. FDM, with an extremely low particle mass of  $10^{-27} \lesssim m_a \lesssim 10^{-19}$  eV, can suppress the abundance of low-mass haloes via effective quantum pressure arising from its galaxy-scale de Broglie wavelength, successfully explaining both JWST and EoR

observations. In this work, we investigate warm dark matter (WDM) as an alternative solution and explore the implications for WDM properties using JWST data. In the WDM scenario, WDM particles with masses of a few keV are much lighter than standard CDM particles, allowing them to remain relativistic for longer in the early universe and retain non-negligible thermal velocity dispersion. This thermal velocity dispersion causes a free-streaming effect, enabling WDM particles to escape from high-density regions and resulting in suppressed structure growth on small scales (Blumenthal et al. 1982; Bode et al. 2001; de Vega & Sanchez 2012). Consequently, the abundance of low-mass haloes and galaxies is significantly suppressed, motivating us to consider WDM as a solution to explain the JWST observations (Labbé et al. 2023). In this work, we assume a flat universe with  $\Omega_m = 0.3153$ ,  $\Omega_b = 0.0493$ ,  $h = 0.6736$ ,  $\sigma_8 = 0.811$ ,  $n_s = 0.9649$  (Planck Collaboration et al. 2020).

## 2.1. WDM Halo Mass Function

To analyze the impact of WDM on halo abundance, we calculate the halo mass function. A conventional choice is obtained from the ellipsoidal collapse model (Press & Schechter 1974; Sheth & Tormen 1999; Sheth et al. 2001; Cooray & Sheth 2002), which can be expressed as:

$$\frac{dn}{d \ln M} = \frac{\bar{\rho}}{M} f(\nu) \frac{d \ln \sigma^{-1}}{d \ln M}$$

where  $M$  is the halo mass,  $\bar{\rho}$  is the mean comoving matter density, and

$$f(\nu) = A \sqrt{\frac{2q}{\pi}} [1 + (\nu^2)^{-p}] \nu \exp\left(-\frac{q\nu^2}{2}\right).$$

Here  $p = 0.3$ ,  $q = 0.707$ ,  $A = 0.2161$  are parameters derived from simulations, and  $\nu(M) = \delta_c / \sigma(M)$ .

In the CDM case, we assume the critical overdensity is independent of mass scale, with  $\delta_c$  as the critical overdensity barrier for collapse, derived analytically as  $\delta_c \approx 1.686$  for spherical collapse of CDM. In the WDM case, the free-streaming effect allows WDM particles to escape from collapsing regions, making WDM collapse more difficult on small scales. Barkana et al. (2001) studied collapse thresholds for WDM through spherical collapse simulations, finding that when halo mass is below a characteristic mass scale, the collapse threshold increases rapidly with decreasing mass. Benson et al. (2013) provided a fitting function to describe the mass dependence of  $\delta_c$  as:

$$\delta_c(M) = \delta_c^{\text{CDM}} \left[ 1 + \alpha \exp\left(-\frac{M}{M_J}\right) \right],$$

where  $\alpha = 0.809 \exp(-2.3M/M_J)$ , and  $M_J$  is the effective Jeans mass of WDM as defined by Barkana et al. (2001):

$$M_J = 2.6 \times 10^8 M_\odot \left( \frac{1 \text{ keV}}{m_W} \right)^{-1.85} \left( \frac{1+z}{3000} \right)^{1.85}.$$

Here  $z_{\text{eq}} \approx 3400$  is the redshift of matter-radiation equality,  $g_W = 1.5$  is the effective number of degrees of freedom for the spin-1/2 fermion, and  $\alpha(M) = 0.809 \exp(-2.3M/M_J)$  is an auxiliary fitting function.

The variance  $\sigma(M)$  can be calculated as the variance of the linear matter overdensity field when smoothed on a comoving scale  $R$ :

$$\sigma^2(R) = \int_0^\infty \frac{k^2 dk}{2\pi^2} P_{\text{lin}}(k) W^2(kR),$$

where  $W(kR) = 3[\sin(kR) - kR \cos(kR)]/(kR)^3$  is the Fourier transform of a spherical top-hat filter window function. We can rewrite  $\sigma(R)$  in terms of mass by relating the comoving scale  $R$  with the mass enclosed within this scale as  $M = 4\pi\bar{\rho}R^3/3$ .  $P_{\text{lin}}(k)$  is the linear matter power spectrum, representing both CDM and WDM linear power spectra in this study.

Since WDM can suppress matter clustering on small scales via the free-streaming effect, the WDM linear matter power spectrum can be calculated following Bode et al. (2001):

$$P_{\text{WDM}}(k) = T_W^2(k) P_{\text{CDM}}(k).$$

The CDM linear power spectrum  $P_{\text{CDM}}(k, z)$  is obtained from CAMB (Lewis et al. 2000), and the transfer function  $T_W(k)$  is assumed to be redshift-independent, given by fitting parameters  $\mu = 1.12$ ,  $\nu = 1.0$ .

In Figure 1 [Figure 1: see original paper] we show the halo mass functions for both WDM and CDM cases at redshift  $z = 8$ , demonstrating that the abundance of low-mass halos is strongly suppressed by WDM free-streaming. Consequently, the contribution of ionizing photons from low-mass galaxies is also suppressed, allowing a larger number density for massive galaxies without altering the reionization history.

## 2.2. Stellar Mass Density and Reionization History

After obtaining the halo mass function, the comoving cumulative halo mass density with halo mass greater than  $M$  can be estimated by:

$$\rho_h(> M) = \int_M^\infty dM' M' n(M').$$

By considering the  $M_*$ - $M$  relation  $\langle M_* \rangle = f_*(M)M$ , the cumulative stellar mass density with stellar mass larger than  $M_*$  can be written as:

$$\rho_*( > M_*) = \int_{M_{\min}}^{\infty} dM f_*(M) M n(M, z).$$

The star formation efficiency  $f_*$  can be considered a mass-dependent quantity. In this work, we assume a double power-law form for  $f_*(M)$ , following Mirocha et al. (2017):

$$f_*(M) = 2f_0 \left[ \left( \frac{M}{M_p} \right)^{\alpha_{\text{lo}}} + \left( \frac{M}{M_p} \right)^{\alpha_{\text{hi}}} \right]^{-1},$$

where  $f_0$  is the star formation efficiency at its peak mass  $M_p$ , and  $\alpha_{\text{lo}}$  and  $\alpha_{\text{hi}}$  describe the power-law indices at low and high masses. In our work, we adopt  $M_p = 2.8 \times 10^{11} M_{\odot}$ ,  $\alpha_{\text{lo}} = 0.49$  and  $\alpha_{\text{hi}} = -0.61$ . The parameter  $f_0$  will be adjusted to match the JWST data.

Star formation efficiency is tightly related to the emission of ionizing photons and can thus change the cosmic reionization history. We explore the reionization history by investigating the redshift evolution of the hydrogen volume filling factor  $Q_{\text{HII}}(z)$ , solving the differential equation (Madau et al. 1999; Wyithe & Loeb 2003):

$$\frac{dQ_{\text{HII}}}{dz} = \frac{\dot{n}_{\text{ion}}}{\bar{n}_H} - \alpha_B C_{\text{HII}} \bar{n}_H (1+z)^3 Q_{\text{HII}} \frac{dt}{dz}.$$

Here we set the escape fraction  $f_{\text{esc}} = 0.1$  (Sun et al. 2021),  $\bar{n}_H$  is the mean number density of hydrogen (both neutral and ionized) atoms today,  $C_{\text{HII}} = 3.0$  is the clumping factor of ionized gas (Kaurov & Gnedin 2015) assumed to be redshift-independent,  $\alpha_B$  is the Case B recombination coefficient, and  $T_{\text{HII}}$  is the kinetic temperature. We set  $T_{\text{HII}} = 2 \times 10^4$  K as a constant (Robertson et al. 2015), giving  $\alpha_B = 2.5 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$ .

The total ionization fraction  $x_e$  can be estimated by assuming helium has the same first-stage ionization fraction as hydrogen:

$$x_e = \frac{2Q_{\text{HII}}}{1 + Y_{\text{He}}},$$

where  $Y_{\text{He}} = 0.25$  is the helium abundance. The ionizing photon emission rate per unit comoving volume  $\dot{n}_{\text{ion}}$  can be estimated by:

$$\dot{n}_{\text{ion}}(z) = f_{\text{esc}} N_{\text{ion}} \int_{M_{\min}}^{\infty} dM f_*(M) M n(M, z) / t_{\text{SF}},$$

where  $N_{\text{ion}} \approx 4000$  is the total ionizing photon number a stellar baryon can produce throughout its lifetime for typical Population II galaxies (Leitherer et al. 1999; Vázquez & Leitherer 2005; Leitherer et al. 2010, 2014).  $t_{\text{SF}}$  is the star formation timescale, equal to 10% of the Hubble time at redshift  $z$  (Wyithe & Loeb 2006; Lidz et al. 2011).  $M_{\text{min}}$  represents the minimum halo mass corresponding to a virial temperature  $T_{\text{vir}}$ , above which halos can sustain effective cooling via the Ly $\alpha$  transition (Barkana & Loeb 2001):

$$M_{\text{min}} = 10^8 M_{\odot} \left( \frac{T_{\text{vir}}}{10^4 \text{ K}} \right)^{3/2} \left( \frac{\mu}{0.61} \right)^{-3/2} \left( \frac{\Omega_m(z)}{\Omega_m(0)} \right)^{-1/2} \left( \frac{\Delta_c}{18\pi^2} \right)^{-1/2} (1+z)^{-3/2},$$

where  $\mu = 0.61$  is the mean molecular weight,  $\Omega_m(z)$  is the matter density fraction at redshift  $z$ , and  $\Delta_c = 18\pi^2 + 82d - 39d^2$  with  $d = \Omega_m(z) - 1$ . We set  $T_{\text{vir}} = 10^4$  K to obtain the corresponding  $M_{\text{min}}$  at each redshift.

In Equation (14), the shape of  $f_*(M)n(M, z)$  mainly determines the contribution of ionizing photons from galaxies of different masses. In the CDM model, low-mass galaxies make a significant contribution, but in the WDM case, since low-mass galaxy formation is suppressed by the WDM free-streaming effect, ionizing photons are dominated by massive galaxies.

Additionally, the optical depth of cosmic microwave background (CMB) scattering provides a good probe for characterizing the reionization history, estimated by:

$$\tau(z) = \int_0^z dz' \frac{c}{H(z')} \sigma_T \bar{n}_H (1+z')^3 x_e(z'),$$

where  $\sigma_T = 6.65 \times 10^{-25} \text{ cm}^2$  is the Thomson scattering cross-section.

### 3. Result

In Figure 2 [Figure 2: see original paper], we present the comoving cumulative stellar mass density at redshift  $z = 8$  and  $z = 9$  for different WDM masses and the CDM case. We find that both WDM and CDM can be consistent with JWST data when the star formation efficiency  $f_0 = 0.16$ . However, comparing with previous measurements (e.g., Hubble Ultra-Deep Field, Spitzer/Infrared Array Camera, Keck Observatory) at low stellar mass regions (Stark et al. 2013; Song et al. 2016; Bhatawdekar et al. 2019; Kikuchihara et al. 2020; Stefanon et al. 2021), the CDM model significantly overpredicts the stellar mass density in this region, as too many low-mass galaxies form under such high star formation efficiency. The WDM model's advantage is that it strongly suppresses low-mass galaxy formation and can match measurements in both low-mass and high-mass regions. As a reference, we also show results varying the star formation efficiency parameter with  $m_W = 0.6$  keV as an orange hatched region.

As discussed in Section 2.2, we can verify our results by investigating the impact on cosmic reionization history. We calculate the optical depth  $\tau$  as a function of redshift for WDM and CDM models, shown in the left panel of Figure 3 [Figure 3: see original paper], and compare with 9-year WMAP (Hinshaw et al. 2013) and Planck 2018 (Planck Collaboration et al. 2020) results. The model with  $m_W = 0.6$  keV shows good agreement with Planck 2018 measurements.

In the right panel of Figure 3, we present our calculation of the neutral hydrogen fraction characterized by  $1 - Q_{\text{HII}}$  as a function of redshift. Observational constraints on the neutral hydrogen fraction from various methods are also shown for comparison, including Ly $\alpha$  forest dark fraction (McGreer et al. 2015), Ly $\alpha$  emitters (Ota et al. 2008), Ly $\alpha$  equivalent width distribution (Mason et al. 2018, 2019; Hoag et al. 2019), Ly $\alpha$  galaxy clustering (Sobacchi & Mesinger 2015), Ly $\alpha$  emitter fraction (Dijkstra et al. 2011; Stark et al. 2011), QSO damping wing (Davies et al. 2018; Greig et al. 2019), and GRB damping wing absorption (Totani et al. 2006). The WDM model with  $m_W = 0.6$  keV and  $f_0 = 0.16$  (shown by the orange hatched region) is in good agreement with these observational data. Our results indicate that a model with  $m_W \sim 0.6$  keV can match both the high-redshift comoving cumulative stellar mass density and the reionization history.

We also sample the posterior distribution of model parameters using the Markov Chain Monte Carlo (MCMC) method with the Cobaya package (Torrado & Lewis 2019, 2021). Flat priors are used for the two model parameters with  $0.1 \leq m_W/\text{keV} \leq 3.0$  and  $0.01 \leq f_0 \leq 0.5$ . Since JWST data alone provides no effective constraint, we constrain parameters using cumulative stellar mass density data from both JWST and previous measurements at  $z = 8$  and 9, and also consider reionization history data, including optical depth measured by Planck and neutral hydrogen fraction measured by various observations (see data in Figures 2 and 3).

We present the constraint results in Figure 4 [Figure 4: see original paper]. As shown by red contours, when considering only cumulative stellar mass density data from JWST and previous measurements, the constraint favors a large  $m_W$  and small  $f_0$ , similar to the CDM case, or a small  $m_W$  and large  $f_0$ . The 1D probability distribution functions of the two parameters are shown in red curves, yielding  $m_W > 0.35$  keV ( $2\sigma$ ). When including reionization history data, we find the constraint on  $m_W$  is significantly improved, with  $m_W = 0.22^{+0.13}_{-0.06}$  keV ( $1\sigma$ ) and  $f_0 = 0.16^{+0.07}_{-0.05}$  ( $1\sigma$ ), and only large  $m_W > 0.39$  keV ( $2\sigma$ ) is favored.

We note that this result may have some tension with previous studies. For example, using UV luminosity functions of high-redshift galaxies, a lower limit of  $m_W \gtrsim 2.9$  keV can be obtained (Schultz et al. 2014; Menci et al. 2016; Corasaniti et al. 2017; Rudakovskiy et al. 2021). A similar result can be derived using the global 21 cm signal detected by the Experiment to Detect the Global Epoch of Reionization Signature observation (Bowman et al. 2018), where WDM models with  $m_W \lesssim 3$  keV can be ruled out (Chatterjee et al. 2019). In these works, a low star formation efficiency (e.g.,  $f_0 \sim 0.01$ ) is always assumed, derived

from Hubble Space Telescope (HST) and other telescope observations, which may differ from the result implied by JWST data from Labbé et al. (2023), which may favor higher star formation efficiency with  $f_0 \sim 0.16$ . In Figures 1–3, we plot results for the WDM model with  $m_W = 3$  keV for comparison. The WDM model with  $m_W = 3$  keV has a suppression mass scale  $\sim 10^7 M_\odot$  and obviously cannot fit the reionization history data with large star formation efficiency ( $f_0 = 0.16$ ). A small star formation efficiency with  $f_0 \sim 0.01$  is needed to match reionization data, but then the JWST data shown in Figure 2 cannot be matched, just like the CDM case. Additionally, Enzi et al. (2021) derived a lower limit of  $m_W > 6.048$  keV by combining strong gravitational lensing, Ly $\alpha$  forest, and Milky Way satellite abundance, which depends on the low-mass dark halo mass function and clearly challenges our model. In our low WDM mass case, formation of dark halos below  $10^9 \sim 10^{10} M_\odot$  is strongly suppressed, which may be challenging to explain the existence of low-mass galaxies in the Milky Way (McConnachie 2012; Newton et al. 2018). Hence, the inconsistency in WDM particle mass between our result and previous studies likely stems from inconsistency between JWST data and other previous observations.

We should note that there are indeed arguments regarding the data from Labbé et al. (2023). For instance, Prada et al. (2023) found that their galaxy formation model can explain the UV luminosity function measured by JWST (Naidu et al. 2022b; Donnan et al. 2023; Harikane et al. 2023) and HST (Oesch et al. 2018; Bouwens et al. 2021; Kauffmann et al. 2022), and their predictions for star formation rate and stellar mass at  $z \sim 8.5$  match well with observations of spectroscopically confirmed galaxies (Bouwens et al. 2022; Fujimoto et al. 2023; Heintz et al. 2023; Williams et al. 2023). They claim that the stellar mass-to-light ratio during early epochs could not have reached such high values as reported by Labbé et al. (2023). Chen et al. (2023) discussed three sources of uncertainty in counting massive galaxies at high- $z$ , including cosmic variance, errors in stellar mass estimates, and backslash contributions. They found each can significantly affect estimation of stellar mass density at high- $z$ . Additionally, photometric redshift estimation (Adams et al. 2023) and dust extinction (Ferrara et al. 2022; Ziparo et al. 2023) are important factors requiring careful calibration in data analysis. Therefore, follow-up spectroscopic observations (especially by JWST/NIRSpec) are likely necessary for further confirmation of these data.

#### 4. Conclusion

Unexpectedly high stellar mass densities of massive galaxies at  $z = 8$  and  $9$  have been found in early JWST observations, which may indicate high star formation efficiency and could be in tension with current cosmic reionization history measurements. We propose that the WDM model may provide a solution and explore the implications for WDM particle properties. Since WDM can suppress low-mass halo formation through free-streaming effects, the number of small galaxies and thus ionizing photons is effectively reduced. Therefore, in this scenario, the reionization history would remain unchanged even with high

star formation efficiency for high- $z$  massive galaxies.

After comparing our WDM model predictions with JWST data (at high stellar masses) and other high- $z$  galaxy observations (at low stellar masses), CMB optical depth measurements from Planck, and neutral hydrogen fraction measurements of the IGM from various methods, we employ MCMC methods to fit these observational data and find that a WDM model with  $m_W = 0.22^{+0.13}_{-0.06}$  keV is in good agreement with all observational data at 95.5% confidence level.

We note that this result still has large uncertainties and may change with adopted models and observational data. On one hand, there may be significant uncertainties in our current theoretical models and parameters regarding WDM, optical depth, and reionization history, which could substantially alter the derived WDM particle mass. On the other hand, early release JWST data need further confirmation through follow-up spectroscopic observations, especially with JWST/NIRCam. If higher quality data can be obtained from future JWST observations, we should be able to place more reliable and tighter constraints on WDM particle mass and achieve a better understanding of dark matter nature and galaxy formation processes.

## Acknowledgments

We acknowledge support from the National Key R&D Program of China No. 2022YFF0503404, 2020SKA0110402, MOST-2018YFE0120800, NSFC-11822305, NSFC-11773031, NSFC-11633004, NSFC-11473044, NSFC-11973047, the CAS Project for Young Scientists in Basic Research (No. YSBR-092), and Chinese Academy of Sciences grants QYZDJ-SSW-SLH017, XDB 23040100, and XDA15020200. This work is also supported by science research grants from the China Manned Space Project with NO.CMS-CSST-2021-B01 and CMS-CSST-2021-A01.

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