

Article

The Impact of Stellar Initial Mass Function on the Epoch of Reionization: Insights from Semi-Analytic Galaxy Modeling

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Abstract: The adequate choice of stellar initial mass function (IMF) is crucial when studying high- z galaxy formation and the epoch of reionization (EoR) models. We employ the semi-analytical galaxy model L-GALAXIES2020 and the dark matter simulation MILLENNIUM-II, in combination with the BPASS spectral model, to investigate the effects of different stellar IMFs on the properties of high- z galaxies and their ionizing photon budget during EoR. We find that different stellar IMFs lead to different SED of high- z galaxies, and thus different ultraviolet luminosity functions (UVLF) and budgets of ionizing photons for EoR. Specifically, at $z < 10$, the UVLF with Salpeter and Chabrier IMF models are closer to the observed results, while at $z > 10$, the ones with a Top-Heavy model are more consistent with the JWST observations. The increase in the upper limit of star mass within stellar IMF from $100 M_{\odot}$ to $300 M_{\odot}$ results in the increase in the UVLF and the ionizing photon number density.

Keywords: cosmology; reionization; galaxies; evolution; high redshift; method; semi-analysis



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1. Introduction

In the early stages of the Big Bang, the baryonic matter in the Universe was hot and dense. As the Universe expanded and cooled, the primordial plasma recombined to form the neutral atoms ~ 380 thousand years after the Big Bang, denoting the beginning of cosmic dark ages [1]. After the formation of the first galaxies and first stars [2], their radiation started to ionize and heat the neutral gas; finally, the hydrogen in the Universe became fully ionized at $z \simeq 5 \sim 6$ [3–6]. This process is known as the Epoch of Reionization (EoR). The radiation sources that can emit a sufficient number of ionizing photons ($h\nu \geq 13.6$ eV) to ionize the intergalactic medium (IGM) [7] are believed to be the first stars (i.e., Population III, Pop III) formed in the early Universe [8,9], the high- z galaxies [10–12], and the mini-quasars and/or normal quasars (QSO) [13–15]. Jiang et al., 2022 [16] have confirmed for the first time that the contribution of QSOs to EoR can be negligible by measuring the ultraviolet (UV) ionizing photons emitted from high- z QSOs, indicating that the high- z galaxies should be the primary contributors of the ionizing photons for EoR. Some theoretical and observational studies (e.g., [17–19]) also confirmed that stars and galaxies formed in the early Universe are the primary radiation sources driving reionization.

In theoretical studies, semi-analytical models and hydrodynamic simulations are being widely used to explore the formation of high- z galaxies and their radiative properties. However, there are some uncertainties in estimating the ultraviolet luminosity function (UVLF) and the total budget of ionizing photons emitted by these high- z galaxies, e.g.,

with the Stellar Population Synthesis (SPS) models that are adopted to estimate this [20]. The stellar initial mass function (IMF) is an important parameter within SPS models which characterizes the number distribution of stars as functions of mass; thus, it is indispensable for deciphering the fundamental properties of galaxies, e.g., luminosity, color, and chemical enrichment [21]. The public SPS models, e.g., BC03 [22], YEPS [23,24], M05 [25], STARBURST99 [26,27], and BPASS [28], can help us to compute the stellar populations and galaxy properties under different stellar IMF assumptions, as well as their effects on galaxy luminosity and chemical enrichment. For example, the BPASS [29] and BC03 [22] models have included different IMFs, e.g., Salpeter, Chabrier, Kroupa, Scalo, and top-heavy IMF, with different upper limits of star mass, i.e., $100 M_{\odot}$ and $300 M_{\odot}$. The SPS models with different stellar IMF assumptions can lead to significant differences in estimating the stellar mass of galaxies from observations [30,31]. Additionally, the stellar IMF is important to predict the merger rate of Pop III binary black holes [32] and the portrayal of star formation history [33]. It is also important to predict the ionizing photon emission rates of high- z galaxies within the simulations [20,34]. Note that the shape and evolution of stellar IMF within high- z galaxies may deviate from the typical form of the local universe (e.g., Salpeter or Chabrier) [35,36]. The lower metallicity of high- z galaxies can alter the physical conditions of star formation, potentially leading to a Top-Heavy IMF [37,38]. Additionally, differences in gas density, turbulence, and intense star formation activities in high- z galaxies can further influence the stellar IMF [39]. If the stellar IMF in high-redshift galaxies is biased towards massive stars, the emission rate of ionizing photons will be increased significantly, which then affects the process of cosmic reionization [40,41].

The Hubble Space Telescope (HST) and the James Webb Space Telescope (JWST) have already observed a large number of high- z galaxy samples (e.g., Bouwens et al., 2021 [42]; Donnan et al., 2023 [43]; Harikane et al., 2023 [44]; Leung et al., 2023 [45]; Finkelstein et al., 2023 [46]; McLeod et al., 2024 [47]; Harikane et al., 2024 [48]; Donnan et al., 2024 [49]; Adams et al., 2024 [50]). Although JWST has dramatically improved the detection of high- z galaxies, the assumptions of stellar IMF still leads to significant uncertainties in the ionizing photon budget [34]. In our previous work [51], we quantitatively analyzed the impact of different SPS models on the properties of high- z galaxies and the ionizing photon budget during the EoR by assuming the same IMF. We found that the effects of different SPS models on the UVLF are small, while they predict significantly different ionizing photon budgets, e.g., the BPASS model predicts the highest ionizing photon number density, which is twice that of the YEPS model. The binary stars also increase the ionizing photon budget by $\sim 40\%$. In this work, we will use the semi-analytical galaxy model (SAM) to study the impact of different IMF on the properties of high- z galaxies and the ionizing photon budget during the EoR.

The structure of this paper is as follows: Section 2 introduces the dark matter simulation and SPS models adopted in the SAM. Section 3 presents the results of properties of high- z galaxies and the ionizing photon budget during the EoR. Section 4 summarizes and discusses the conclusions. Throughout this work, we adopt the *PLANCK* cosmological parameters [52]: $\Omega_{\Lambda} = 0.685$, $\Omega_m = 0.315$, $\Omega_b = 0.049$, $h = 0.673$, $\sigma_8 = 0.829$, and $n_s = 0.965$.

2. Method

We use the semi-analytical galaxy model L-GALAXIES2020 [53] to simulate the formation and evolution of high- z galaxies, while the merger trees are from the Millennium-II simulation (MS-II, [54]). The SPS models adopted are the Binary Population and Spectral Synthesis with different IMFs (BPASS, [28]).

2.1. SAM Model

The L-GALAXIES model has been continuously developed for ~ 35 years and has become a prominent tool to investigate galaxy formation and evolution [55–57]. This model includes most known physical processes of galaxy formation, such as gas cooling, stellar formation, galaxy mergers, supernova feedback, and AGN feedback [58]. It starts with merger trees from the dark matter simulations to track hierarchical assembly. Baryonic matter falls into these halos due to gravity; then, the shock heats up the gas to the virial temperature and the hot gas cools onto the galactic disk or becomes a hot atmosphere. The cold gas within interstellar medium partitions into atomic and molecular components, while the star formation occurs primarily in the molecular gas, driven by the H_2 cooling. The feedback of supernovae reheats and ejects gas and AGN feedback suppresses cooling in massive galaxies; both of them reduce or quench the star formation of galaxies. Galaxy mergers trigger starbursts and black hole growth. Furthermore, the L-GALAXIES also include the chemical enrichment from supernovae explosion, the tidal effects and ram pressure stripping on satellite galaxies, and SPS and dust extinction to predict observable properties of galaxies.

We adopt the new version L-GALAXIES2020 [53] to simulate the formation and evolution of high- z galaxies, in which the SPS model adopted is the BPASS [28], while other parameters are the default ones, as in Henriques et al., 2020 [53]. Compared to the L-GALAXIES2015 version [58], in L-GALAXIES2020, the galactic disks are spatially resolved into 12 concentric rings [59], allowing for a description of the distributions of atomic and molecular gas, stellar mass, and metals along the radius.

2.2. Dark Matter Simulations

The Millennium-II simulation (MS-II, [54]) is a large-scale N -body simulation under the Λ CDM cosmological model, which utilized the GADGET code [60] and output a total of 68 snapshots during the process from $z = 127$ to 0, and 23 of them are at $z > 5$. Its box size is $100 h^{-1} \text{Mpc}$ with 2160^3 dark matter particles. Its minimum halo mass is $1.38 \times 10^8 h^{-1} M_\odot$, i.e., 20 dark matter particles. The resolution is adequate to statistically study the properties of high- z galaxies, while their contribution to the ionizing photon budget during EoR might be underestimated due to the lack of faint galaxies. MS-II constructs halo groups with the Friends-Of-Friends (FOF) algorithm [61] and employs the SUBFIND algorithm [62] to identify the self-bound substructures within each FOF group.

2.3. Stellar Initial Mass Function

The stellar initial mass function (IMF) determines the distribution of stellar masses, which affects the chemical enrichment and evolution of galaxies [63]. Stanway et al., 2016 [29] constructed the distribution of IMF in the BPASS model [28] as a broken power law function (BPL) similar to the Salpeter IMF [64]:

$$N \propto \int_{0.1}^{M_1} \left(\frac{M}{M_\odot} \right)^{\alpha_1} dM + M_1^{\alpha_1} \int_{M_1}^{M_{\max}} \left(\frac{M}{M_\odot} \right)^{\alpha_2} dM, \quad (1)$$

where $M_1 = 0.5 M_\odot$, α_1 is the power index of IMF for the mass range $0.1 M_\odot$ to M_1 and α_2 is the power index of IMF for the mass range M_1 to $M_{\max}$. In this work, we adopt the SPS results of BPASS version v2.2.1 [28] including binary stars, since it is widely believed that the SPS models with binary stars are more consistent with theoretical and observational results (e.g., Wilkins et al., 2016 [20]; Han et al., 2020 [65]; Yung et al., 2020 [66]; Ma et al., 2022 [67]; Seeyave et al., 2023 [34]; Liu et al., 2024 [51]). The binary proportion of stars varies with their mass. Specifically, $\sim 80\%$ of massive stars ($M > 5 M_\odot$) are binaries, the binary proportion of medium stars ($0.7 M_\odot < M < 5 M_\odot$) is $\sim 50\%$, while the binary

stars among low-mass stars ($M < 0.7 M_{\odot}$) are negligible due to their small size and large main sequence lifetime. We apply the results of four IMF models from BPASS within L-GALAXIES2020, i.e., Salpeter IMF [64], Scalo IMF [68], Chabrier IMF [69], and Top-heavy IMFs [70–72]. It should be noted that the Chabrier IMF model adopted in BPASS follows the prescription of Chabrier (2003) [69], with an exponential cut-off at the low-mass end ($\leq 1 M_{\odot}$) and a power law distribution at the high-mass end ($> 1 M_{\odot}$) [28]. For each IMF model, we include two cases of mass upper limit, i.e., $100 M_{\odot}$ and $300 M_{\odot}$. Table 1 lists the values of α_1 , α_2 and $M_{\max}$ within eight IMF models adopted in this work.

Table 1. The parameters of 8 IMF models applied in this work. The first column contains the adopted model number in BPASS version v2.2.1. The second column contains the names of the 8 IMF models. The third column contains the power index α_1 of the mass distribution within range $0.1-M_1$. The fourth column contains the power index α_2 of the mass distribution within range $M_1-M_{\max}$. The last column contains the upper limit $M_{\max}$ of star mass within stellar IMF.

Model	IMF	α_1 ($0.1-M_1$)	α_2 ($M_1-M_{\max}$)	$M_{\max}$ ($M_{\odot}$)
170-100	Scalo ^a	−1.30	−2.70	100
170-300	Scalo ^b	−1.30	−2.70	300
chab100	Chabrier ^a	−	−2.30	100
chab300	Chabrier ^b	−	−2.30	300
135-100	Salpeter ^a	−2.35	−2.35	100
135-300	Salpeter ^b	−2.35	−2.35	300
100-100	Top-Heavy ^a	−1.30	−2.00	100
100-300	Top-Heavy ^b	−1.30	−2.00	300

The names of these models in BPASS are as follows: 170-100, 170-300, chab100, chab300, 135-100, 135-300, 100-100, and 100-300 model; we label them as Scalo^a, Scalo^b, Chabrier^a, Chabrier^b, Salpeter^a, Salpeter^b, Top-Heavy^a, and Top-Heavy^b, where ^a denotes the mass upper limit of IMF $100 M_{\odot}$ and ^b is $300 M_{\odot}$. The SPS SEDs from the BPASS model have stellar age range from 1 Myr to 100 Gyr at 13 metallicity values ($Z = 10^{-5}, 10^{-4}, 10^{-3}, 2 \times 10^{-3}, 3 \times 10^{-3}, 4 \times 10^{-3}, 6 \times 10^{-3}, 8 \times 10^{-3}, 10^{-2}, 1.4 \times 10^{-2}, 2 \times 10^{-2}, 3 \times 10^{-2}$, and 4×10^{-2}), with flux units in luminosity per angstrom ($L/\text{\AA}$) normalized to $10^6 M_{\odot}$. Their wavelength range is from 1 to 100,000 $\text{\AA}$ with a sampling interval of 1 $\text{\AA}$. As a reference, we present the SPS SEDs from a BPASS model of eight IMFs at four metallicities and four ages in Appendix A.

3. Result

In Section 3.1, we present the SEDs of high- z galaxies from L-GALAXIES2020 simulations with eight different IMFs. Section 3.2 shows the luminosity functions of high- z galaxies. The predicted ionizing photon number density and ionizing photon emission efficiency are in Section 3.3.

3.1. SED of High- z Galaxies

The SED of one galaxy has abundant information about its properties, e.g., the star formation history (SFH), the dust component, and the chemical abundance [21]. L-GALAXIES 2020 first linearly interpolates the SPS SEDs at different ages and metallicities, then scales them by stellar mass, and finally sums the contributions at all ages to obtain the SED of galaxies. In Figure 1, we present the average SEDs of high- z galaxies from L-GALAXIES2020 simulations with eight IMF models. As a reference, the number of galaxies is $\sim 10^6$ at $z = 6$. To compare with the input SPS SEDs as shown in Figure A1, the SEDs of high- z galaxies in Figure 1 are normalized by the stellar mass of galaxies.

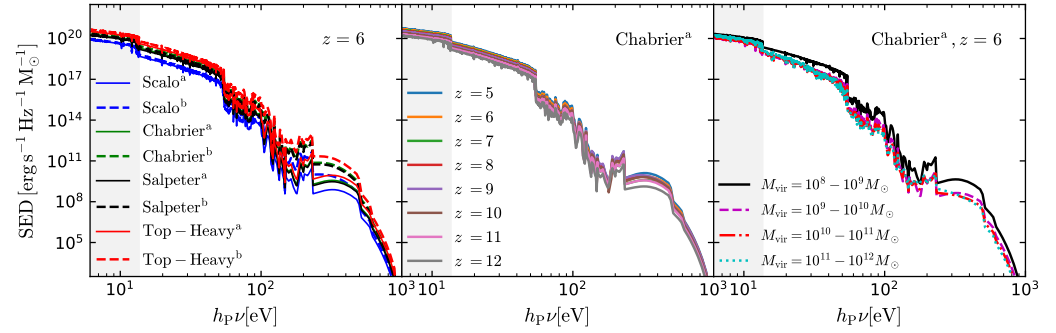


Figure 1. Stellar mass normalized SEDs of high- z galaxies. **Left panel:** average SEDs of galaxies from 8 IMF models at $z = 6$, i.e., Scalo^a model (blue solid line), Scalo^b model (blue dashed line), Chabrier^a model (green solid line), Chabrier^b model (green dashed line), Salpeter^a model (black solid line), Salpeter^b model (black dashed line), Top-Heavy^a model (red solid line), and Top-Heavy^b model (red dashed line). **Middle panel:** average SEDs of galaxies from Chabrier^a model at $z = 5$ (blue line), 6 (orange line), 7 (green line), 8 (red line), 9 (purple line), 10 (brown line), 11 (pink line), 12 (gray line). **Right panel:** average SEDs of galaxies within four halo mass ranges from Chabrier^a model at $z = 6$, i.e., $M_{\text{vir}} = 10^8 - 10^9 M_{\odot}$ (black solid line), $M_{\text{vir}} = 10^9 - 10^{10} M_{\odot}$ (magenta dashed line), $M_{\text{vir}} = 10^{10} - 10^{11} M_{\odot}$ (red dash-dot line), and $M_{\text{vir}} = 10^{11} - 10^{12} M_{\odot}$ (cyan dotted line). Gray shading indicates locations where $h_p \nu < 13.6$ eV.

The left panel of Figure 1 shows the average SEDs of galaxies with eight IMF models at $z = 6$. In the full wavelength range, the average SED of galaxies with the Top-Heavy model is significantly higher than those with other IMF models. With the upper limit of star mass $100 M_{\odot}$ in the IMF, the average SED luminosity of galaxies with the Chabrier^a model is slightly lower than that of the Top-Heavy^a model, followed by the Salpeter^a model, and the Scalo^a model has the lowest luminosity. Specifically, compared to the Salpeter^a model, the Chabrier^a model shows a 20.9% increase, the Top-Heavy^a model shows a 132.5% increase, and the Scalo^a model shows a 62.5% decrease. When the upper limit of star mass in IMF is increased to $300 M_{\odot}$, all four IMF models show a noticeable increase in the average SED luminosity of galaxies in the full wavelength range. It should be noted that the average SED of galaxies with the Salpeter^b model is slightly higher than the one with Chabrier^a model but still lower than that of the Chabrier^b model. The middle panel of Figure 1 displays the average SED of galaxies with the Chabrier^a model at $z = 5$ to 12. We can see that the SED of high- z galaxies does not vary significantly with decreasing z , with differences of luminosity $\sim 15\%$. The right panel of Figure 1 presents the average SED of galaxies within four halo mass ranges from the Chabrier^a model at $z = 6$, i.e., $M_{\text{vir}} = 10^8 - 10^9 M_{\odot}$, $10^9 - 10^{10} M_{\odot}$, $10^{10} - 10^{11} M_{\odot}$, and $10^{11} - 10^{12} M_{\odot}$. We can see that the SED of galaxies within massive halos ($> 10^9 M_{\odot}$) is slightly lower than that of low-mass halo ($< 10^9 M_{\odot}$), which may be related to the stellar age and metallicity of the galaxies. It is worth noting that the SED of $M_{\text{vir}} = 10^{11} - 10^{12} M_{\odot}$ is slightly higher than that of $M_{\text{vir}} = 10^9 - 10^{10} M_{\odot}$ and $M_{\text{vir}} = 10^{10} - 10^{11} M_{\odot}$, probably due to their smaller stellar age than the latter ones. As shown in Figure A2, the average stellar mass weighted age of galaxies decreases as the halo mass increases. By comparing with the Figure A1, we can see that the SEDs of high- z galaxies within the UV band are dominated by the young stars, i.e., those with age < 100 Myr, and the SEDs of high- z galaxies do not evolve too much with the decreasing z , consistent with the results of Liu et al., 2024 [51].

3.2. UVLF of the Galaxy

The rest frame UVLF and its evolution with z are important tracers of the galaxy properties over cosmic time [73]. We show the UVLF ϕ with the eight IMF models at 8 z s

from $z = 5$ to 12 in Figure 2. The absolute magnitude of galaxies at $\lambda = 1500 \text{ \AA}$ is computed as follows:

$$M_{1500, AB} = -\frac{5}{2} \log_{10} \left(\frac{F_{1500}}{4\pi R^2} \right) - 48.6, \quad (2)$$

where F_{1500} is the flux of galaxies at $\lambda = 1500 \text{ \AA}$ and distance $R = 10 \text{ pc}$. Note that we do not include dust absorption effects on the UV luminosity, which might reduce the UVLF at low- z and bright end. As a comparison, we present some observational results of UVLF from the HST and JWST telescope in Figure 2. Note that the observations by the HST (e.g., Finkelstein2015 [74]; Bouwens2021 [42]) are at $\lambda = 1600 \text{ \AA}$, while those of JWST (e.g., Donnan2023 [43]; Harikane2023 [44]; Leung2023 [45]; McLeod2024 [47]; Finkelstein2023 [46]; Harikane2024 [48]; Donnan2024 [49]; Adams2024 [50]) are at $\lambda = 1500 \text{ \AA}$.

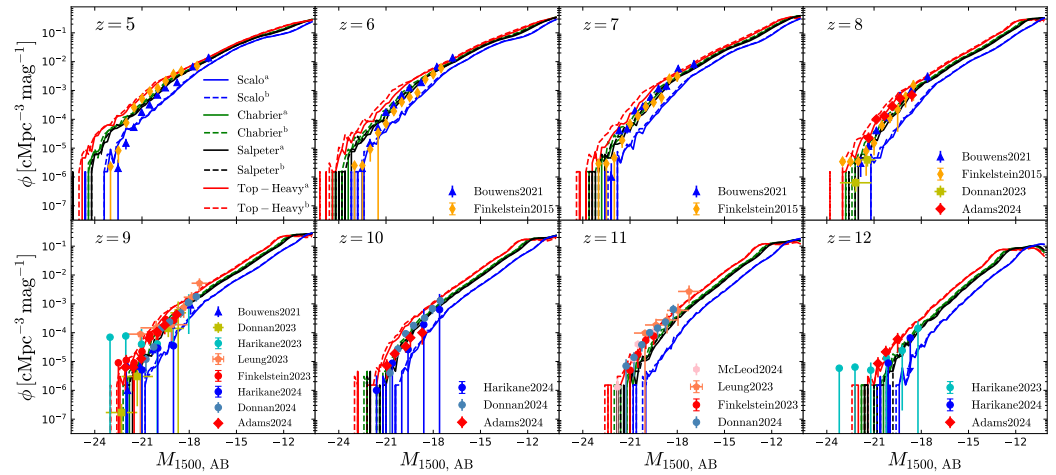


Figure 2. UVLF (ϕ) at rest frame wavelength ($\lambda = 1500 \text{ \AA}$) for the 8 IMF models, i.e., Scalo^a model (blue solid line), Scalo^b model (blue dashed line), Chabrier^a model (green solid line), Chabrier^b model (green dashed line), Salpeter^a model (black solid line), Salpeter^b model (black dashed line), Top-Heavy^a model (red solid line), and Top-Heavy^b model (red dashed line). From **left to right** and **top to bottom**, the ϕ s are at $z = 5, 6, 7, 8, 9, 10, 11$, and 12 , respectively. The observational data points are from Bouwens2021 [42] (blue up triangle), Finkelstein2015 [74] (orange diamond), Donnan2023 [43] (yellow square), Harikane2023 [44] (cyan circle), Leung2023 [45] (coral pentagon), McLeod2024 [47] (pink hexagon), Finkelstein2023 [46] (red circle), Harikane2024 [48] (blue circle), Donnan2024 [49] (steelblue circle), and Adams2024 [50] (red rhomboid). Note that the observations of Bouwens2021 [42] are at $\lambda = 1600 \text{ \AA}$, while others are at $\lambda = 1500 \text{ \AA}$.

As shown in Figure 2, with the same upper limit of star mass $100 M_{\odot}$ in the IMF, the amplitude of UVLF from the Top-Heavy^a model is the largest in four IMF models at all eight z s; the ones of the Chabrier^a model and the Salpeter^a model are similar and both lower than that of the Top-Heavy^a model, and the one of the Scalo^a model is the smallest. When the star mass upper limit of IMF is increased to $300 M_{\odot}$, the amplitudes of the UVLF from all four IMF models increase slightly, but not very significantly, which is consistent with the SED of high- z galaxies shown in Figure 1. As z increases, the differences in the amplitude of UVLF ϕ from the different IMF models gradually increases at the faint end (e.g., $M_{1500, AB} > -15$), while their differences are roughly constant at the bright end (e.g., $M_{1500, AB} < -18$).

To further quantify the differences in the different IMF models, we calculate the χ^2 values of the UVLF from eight IMF models compared to the observations:

$$\chi^2 = \sum \frac{(\phi_{\text{obs}} - \phi_{\text{sim}})^2}{\sigma_{\text{obs}}^2}, \quad (3)$$

where ϕ_{obs} is the observed ϕ , ϕ_{sim} is the simulated ϕ , and σ_{obs} is the 1- σ error of ϕ_{obs} . The χ^2 results at $z = 9$ to 12 are shown in Table 2. At $z = 9$, the Chabrier^a model is the best fit with the UVLF observations; then, the Salpeter^b models are the best. At $z = 10$, the Chabrier^b model is the best, followed by the Chabrier^a model. At $z = 11$, the Top-Heavy^b model is the best, followed by the Top-Heavy^a model. At $z = 12$, the best-fit model is the Top-Heavy^b model, followed by the Top-Heavy^a model. We can then conclude that at $z \leq 10$ the UVLFs from the Salpeter and Chabrier models are closer to the observational results, while at $z > 10$ the ones of the Top-Heavy model are more consistent with the JWST observations. This is consistent with some recent theoretical works [75–78], which denotes that a top-heavy stellar IMF is necessary to explain the observations.

Table 2. χ^2 of UV LF ϕ from 8 IMF models compared to the observations at $z = 9, 10, 11$, and 12.

z	Scalo ^a	Scalo ^b	Chabrier ^a	Chabrier ^b	Salpeter ^a	Salpeter ^b	Top-Heavy ^a	Top-Heavy ^b
9	134.49	131.57	75.29	81.95	84.14	76.03	173.71	226.94
10	120.74	117.78	42.09	38.25	59.09	46.29	72.08	142.16
11	90.38	90.16	73.99	60.10	80.27	77.61	46.99	36.97
12	36.25	34.93	31.26	30.00	31.11	31.13	20.81	16.58

3.3. Budget of Ionizing Photons

To correctly calculate the number of ionizing photons produced by high- z galaxies, we rerun the L-GALAXIES2020 simulations, in which we employ the integrated SED (iSED) over the stellar age (i.e., the time from the birth of stars to the output z s). The iSED can include the effects of the full SFH of galaxies [79]. The number of ionizing photons (n_{ion}) from galaxies is then computed as $n_{\text{ion}} = \int \frac{L_{\nu}}{h_{\text{p}}\nu} d\nu$, where L_{ν} is the iSED of galaxies computed by L-GALAXIES2020, h_{p} is the Planck constant, and ν is the frequency of photons. The integration is carried out within the frequency band of $13.6 \text{ eV} < h_{\text{p}}\nu < 2 \text{ keV}$. The cosmic volume averaged by the ionizing photons N_{ion} (i.e., number density of the ionizing photon) is then $N_{\text{ion}} = \sum n_{\text{ion}} / V_{\text{box}}$, where the sum $\sum$ is for all the galaxies, and V_{box} is the comoving volume of MS-II simulation.

In Figure 3, we show the evolution of N_{ion} with z for eight IMF models. With the upper limit of star mass $100 M_{\odot}$ in the IMF, at the same z s, the Top-Heavy^a model has the highest N_{ion} , followed by the Chabrier^a model. The Salpeter^a model has a slightly lower N_{ion} compared to the Chabrier^a model, while the Scalo^a model has the lowest N_{ion} . When the star mass upper limit in the IMF is increased to $300 M_{\odot}$, the N_{ion} in all four IMF models is increased by $\sim 19.50\%$ (Scalo), $\sim 29.97\%$ (Top-Heavy), $\sim 27.80\%$ (Salpeter), and $\sim 28.30\%$ (Chabrier), respectively. It is important to note that our simulations cannot properly resolve galaxies with stellar mass $< 10^6 M_{\odot}$ due to the limit of resolution, i.e., the minimal halo mass $1.38 \times 10^8 h^{-1} M_{\odot}$. The budget of ionizing photons might be underestimated due to the lack of faint galaxies.

In Figure 4, we show the average ionizing photon emission efficiency ζ_{ion} of galaxies with specific stellar mass and redshift from eight IMF models, which is defined as $\zeta_{\text{ion}} = \frac{\dot{n}_{\text{ion}}}{F_{1500}}$, where $\dot{n}_{\text{ion}}$ is the ionizing photon emissivity of galaxies. We also present some of the recent measurements of ζ_{ion} , e.g., Sun2023 [80], Tang2023 [81], Whitley2024 [11], while for the other, ones one can refer to the recent paper by Simmonds [82]. With the upper limit of star mass $100 M_{\odot}$ in the IMF, the galaxies with the same stellar mass from the Top-Heavy^a model have the highest ζ_{ion} , followed by the Chabrier^a model. The Salpeter^a model has a slightly lower ζ_{ion} compared to the Chabrier^a model, while the Scalo^a model has the lowest ζ_{ion} . When the star mass upper limit in the IMF is increased to $300 M_{\odot}$, the ζ_{ion} in all four IMF models is increased. From Figure 4, our simulated ζ_{ion} values agree with the observations, e.g., Sun2023 [80], but are different with other studies, e.g., Tang2023 [81]

and Whittler2024 [11]. We note that our average ζ_{ion} cannot fully capture the diversity of galaxies, while the observations might only represent some specific galaxies.

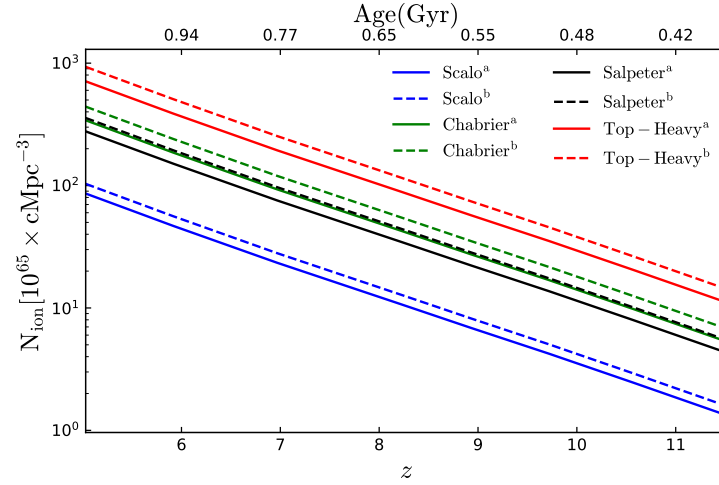


Figure 3. Redshift evolution of volume averaged ionizing photon number density N_{ion} from 8 IMF models, i.e., Scalo^a model (blue solid line), Scalo^b model (blue dashed line), Chabrier^a model (green solid line), Chabrier^b model (green dashed line), Salpeter^a model (black solid line), Salpeter^b model (black dashed line), Top-Heavy^a model (red solid line), and Top-Heavy^b model (red dashed line). It also shows the age of the universe at redshift.

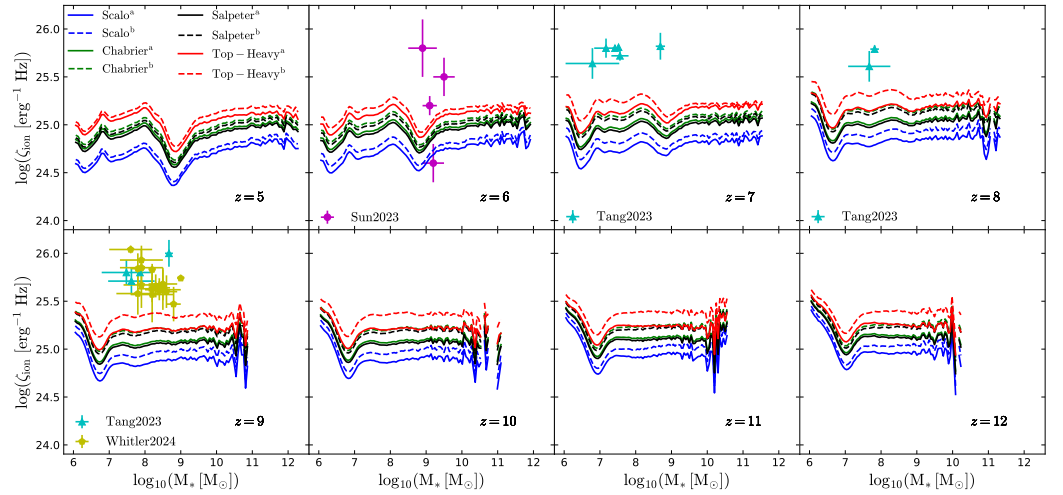


Figure 4. Ionizing photon production efficiency ζ_{ion} from 8 IMF models, i.e., Scalo^a model (blue solid line), Scalo^b model (blue dashed line), Chabrier^a model (green solid line), Chabrier^b model (green dashed line), Salpeter^a model (black solid line), Salpeter^b model (black dashed line), Top-Heavy^a model (red solid line), and Top-Heavy^b model (red dashed line). From left to right and top to bottom, the eight panels are the results at $z = 5, 6, 7, 8, 9, 10, 11$, and 12 , respectively. The observational data points are from Whittler2024 [11] (yellow pentagon), Tang2023 [81] (cyan triangle), and Sun2023 [80] (magenta circle).

4. Discussion and Conclusions

The stellar IMF is an important parameter within SPS models. The different selection of a stellar IMF can lead to significant differences in the estimation of galaxy properties. In this work, we use the semi-analytical galaxy model L-GALAXIES2020 to study the impact of four classical IMFs (i.e., Scalo, Chabrier, Salpeter, and Top-Heavy) on the high- z galaxies and the ionizing photon budget during EoR, considering both the star mass upper limit of IMF $100 M_{\odot}$ and $300 M_{\odot}$.

We find that the SED of high- z galaxies is sensitive to the adopted IMFs. Specifically, the SED of high- z galaxies from the Top-Heavy^a model is highest, followed by the Chabrier^a model, which is slightly higher than the Salpeter^a model, and the one of the Scalo^a model is the lowest. These discrepancies are crucial to understand EoR, as they affect the estimated ionizing photon budget. When the star mass upper limit of IMF is increased to $300 M_{\odot}$, the SED amplitudes of all models increase.

The UVLF at a wavelength of $1500 \text{ \AA}$ of high- z galaxies ARE consistent with their SED. The UVLF of Chabrier^a and Salpeter^a model are similar, while the one of Top-Heavy^a model is higher, and the Scalo^a model has the lowest UVLF. When the star mass upper limit of IMF is increased to $300 M_{\odot}$, the UVLF of all four IMF models are not significantly changed. At $z < 10$, the UVLF from the Salpeter and Chabrier models are closer to the observations, while at $z > 10$, the one from the Top-Heavy model is more consistent with the JWST observations. This may suggest that a top-heavy IMF is necessary to explain the high- z galaxies [75–78].

The ionizing photon number density N_{ion} and ionizing photon emission efficiency ζ_{ion} are also sensitive to the IMF models. The ones of the Top-Heavy model are the highest at all z s, while the ones of the Scalo model are the lowest. The increase of the star mass upper limit of IMF from $100 M_{\odot}$ to $300 M_{\odot}$ results in slightly higher N_{ion} and ζ_{ion} , because a larger population of high-mass stars significantly enhances the production of ionizing photons, consistent with the conclusions of Shivaeei et al., 2018 [83] and Seeyave et al., 2023 [34].

In the recent literature, some papers have examined the impact of the IMF on the properties of high- z galaxies and ionizing radiation from perspectives, such as the semi-empirical and SPS model [35,84], the combination of SAMs and hydrodynamic simulations [85], and observational data from JWST [86,87]. These works reveal that IMF variations can explain the UV excess phenomena in high- z galaxies and significantly affect the ionizing photon budget. In this work, we statistically analyze the effects of different IMFs on high- z galaxy properties and ionizing photon production using high resolution N -body simulation and L-GALAXIES2020. Our results demonstrate that the Top-Heavy IMF model is more consistent with recent observations at $z \geq 11$ (e.g., Adams2024 [50]), and different IMF models and a star mass upper limit of IMF significantly affect ionizing photon production.

The SAM models are efficient for studying high- z galaxy formation and evolution, but they have limitations due to the simplified assumptions and parameter uncertainties. These models may not fully capture the real physical processes, and their parameters can lead to uncertainties on galaxy properties at different redshifts and galaxy masses. In this paper, we primarily focus on the impact of different IMF, while other factors are fixed. The stellar IMF might correlate with or be degenerate against, e.g., metallicity or stellar age, and we may have potentially ignored their interactions in this work. The different IMF can also lead to different supernovae explosion rates and thus change the SFR and the stellar mass of galaxies, while we do not include these effects in this paper. Furthermore, we adopt the values of free parameters in L-GALAXIES2020 that are fitted with the low- z observations, while they might be different at $z > 6$. All these effects might affect the estimation of UVLF and the budget of the ionizing photons. We will explore these processes using the MCMC (Markov Chain Monte Carlo) technique in future works in order to find the best fit for all the observations, e.g., UVLF, stellar mass function, and optical depth, measured by the Planck telescope. In summary, the different IMFs have significant impacts on the properties of high- z galaxies and the ionization budget during the EoR. With more and more observations released by the JWST telescope, it is possible to precisely measure the IMF models during EoR in the near future.

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Appendix A. SPS SED of 8 IMF Models from BPASS

Figure A1 presents the SEDs from BPASS of eight IMF models at the same metallicity and age. With the same age and metallicity, the amplitudes of the SEDs decrease with increasing power law index of IMF. With the same power law index, the SEDs with star mass upper limit of $300 M_{\odot}$ within IMF are slightly higher compared to the ones with $100 M_{\odot}$. At the same age, the SEDs with different IMF models are not very sensitive to the metallicity. However, with the same metallicity, all the SEDs of the eight IMF models decrease with increasing age. Meanwhile, the differences of the SEDs from the eight IMF models become much smaller as age increases, e.g., at age 1 Gyr, the SEDs of the eight IMFs have no visible differences from Figure A1. It is worth noting that the Top-Heavy models show a slightly higher SED than the other models at different ages, e.g., at 1 Myr and 10 Myr, while they become consistent with the other models as age increases.

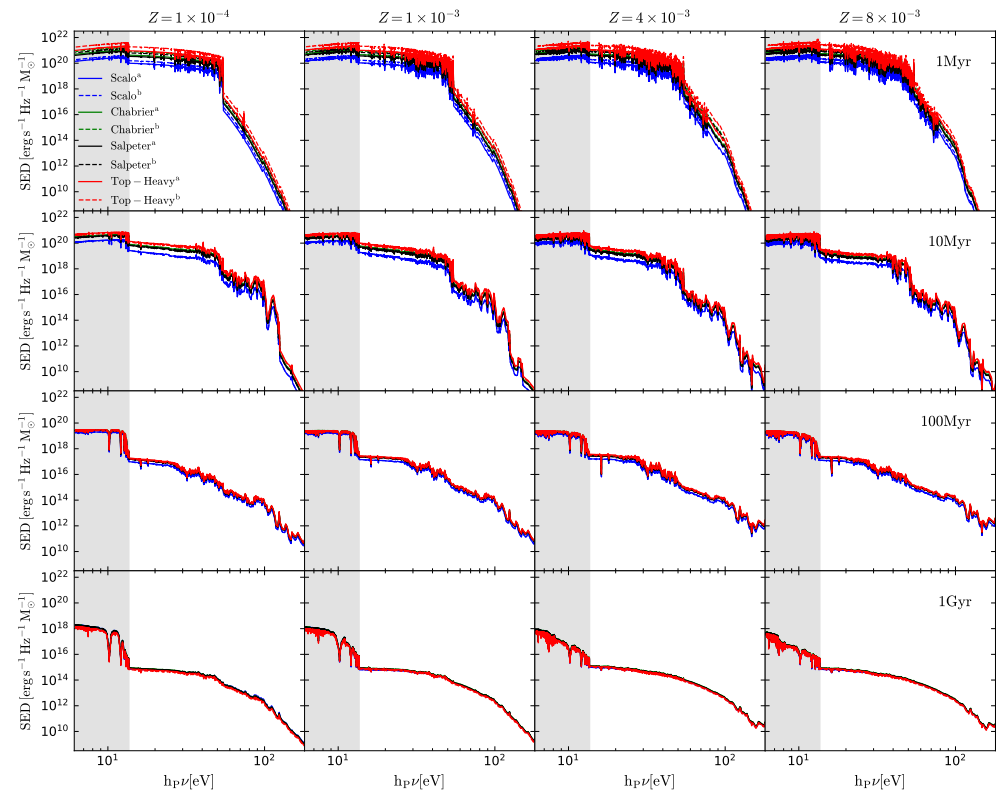


Figure A1. Stellar mass normalized SEDs of different IMF models, where each spectrum corresponds to a Simple Stellar Population (SSP). Specifically, the models include the Scalo^a model (blue solid line), Scalo^b model (blue dashed line), Chabrier^a model (green solid line), Chabrier^b model (green dashed line), Salpeter^a model (black solid line), Salpeter^b model (black dashed line), Top-Heavy^a model (red solid line), and Top-Heavy^b model (red dashed line), at metallicity $Z = 10^{-4}$, 10^{-3} , 4×10^{-3} , and 8×10^{-3} (from left to right), and age 1 Myr, 10 Myr, 100 Myr, and 1 Gyr (from top to bottom). The gray area denotes the region of $h_p\nu < 13.6$ eV.

Appendix B. Mass Weighted Galaxy Age

Figure A2 presents the distribution of stellar mass weighted stellar age of galaxies from the L-GALAXIES2020 simulation versus halo mass at $z = 6$. The average stellar mass weighted stellar age of galaxies decreases with the increasing of halo mass. The metallicity of galaxies increases with the increasing of halo mass, i.e., the more massive galaxies tend to have higher metallicity.

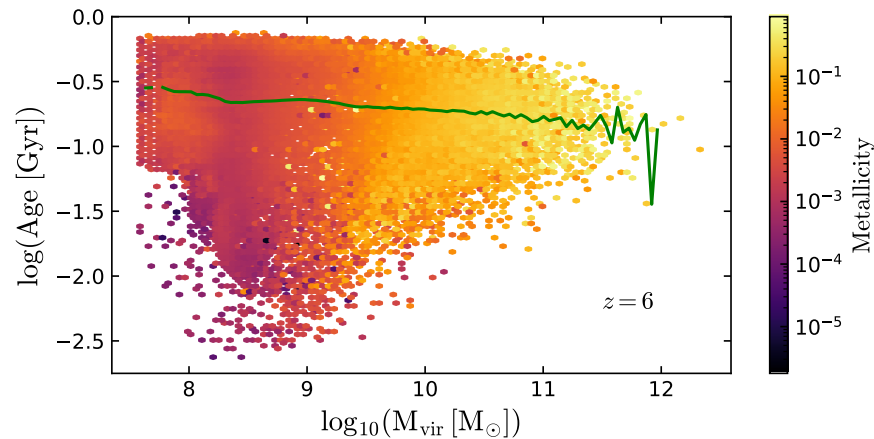


Figure A2. Distribution of stellar mass weighted age of galaxies at $z = 6$ versus halo mass. The green line represents the average values. The data points are color-coded due to the metallicity.

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