Confronting predictions of the galaxy stellar mass function with observations at high redshift


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Confronting predictions of the galaxy stellar mass function with observations at high redshift

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ABSTRACT

We investigate the evolution of the galaxy stellar mass function at high redshift \((z \geq 5)\) using a pair of large cosmological hydrodynamical simulations: MassiveBlack and MassiveBlack-II. By combining these simulations, we can study the properties of galaxies with stellar masses greater than \(10^8 M_\odot h^{-1}\) and (comoving) number densities of \(\log_{10}(\phi [\text{Mpc}^{-3} \text{dex}^{-1} h^{-3}]) > -8\). Observational determinations of the galaxy stellar mass function at very high redshift typically assume a relation between the observed ultraviolet (UV) luminosity and stellar mass-to-light ratio which is applied to high-redshift samples in order to estimate stellar masses. This relation can also be measured from the simulations. We do this, finding two significant differences with the usual observational assumption: it evolves strongly with redshift and has a different shape. Using this relation to make a consistent comparison between galaxy stellar mass functions, we find that at \(z = 6\) and above the simulation predictions are in good agreement with observed data over the whole mass range. Without using the correct UV luminosity and stellar mass-to-light ratio, the discrepancy would be up to two orders of magnitude for large galaxies \((>10^{10} M_\odot h^{-1})\). At \(z = 5\), however, the stellar mass function for low-mass galaxies \((<10^9 M_\odot h^{-1})\) is overpredicted by factors of a few, consistent with the behaviour of the UV luminosity function, and perhaps a sign that feedback in the simulation is not efficient enough for these galaxies.

Key words: galaxies: high-redshift -- galaxies: luminosity function, mass function -- galaxies: stellar content.

1 INTRODUCTION

The observational exploration of the high-redshift \((z > 2)\) Universe has been driven, over the past 10–15 years, predominantly by deep Hubble Space Telescope (HST) surveys. Deep Advanced Camera for Surveys (ACS) observations alone (e.g. of the Hubble Ultra Deep Field [HUDF]) permitted the identification of a large number of galaxies at \(z = 2–6\) (e.g. Bunker et al. 2004; Beckwith et al. 2006; Bouwens et al. 2007). While some galaxies at \(z > 7\) were identified using ACS and near-infrared (near-IR) Camera and Multi-Object Spectrometer (NICMOS) observations (e.g. Bouwens et al. 2008) or ground-based imaging (e.g. Bouwens et al. 2008; Ouchi et al. 2009; Hickey et al. 2010), the very high redshift Universe was only truly opened up by the installation of Wide Field Camera 3 (WFC3) in 2009. WFC3 near-IR (1.0–1.6 μm) observations allow the identification of star-forming galaxies to \(z = 7–8\) (e.g. Bouwens et al. 2010, 2011b; Bunker et al. 2010; Oesch et al. 2010; Wilkins et al. 2010, 2011a; Lorenzoni et al. 2011) and potentially even to \(z \sim 10\) (Bouwens et al. 2011a; Oesch et al. 2012).

By combining ACS optical and NICMOS or WFC3 near-IR imaging with Spitzer Infrared Array Camera (IRAC) observations, it becomes possible to probe the rest-frame ultraviolet–optical (UV–optical) spectral energy distributions (SEDs) of galaxies at \(z = 4–8\) (e.g. Eyles et al. 2005; Gonzalez et al. 2012). Rest-frame optical photometry is crucial to accurately determine stellar masses (e.g. Eyles et al. 2007; Stark et al. 2009; Labbé et al. 2010; González et al. 2011, 2012). With a sufficiently large, well-defined sample of galaxies it is possible to study the galaxy stellar mass demographics, and in particular the galaxy stellar mass function (GSMF; e.g. González et al. 2011, 2012). The GSMF is a fundamental description of the galaxy population and is defined as the number density of galaxies per logarithmic stellar mass bin. The first moment of the GSMF corresponds to the cosmic stellar mass density.
Here we use state-of-the-art cosmological hydrodynamical simulations of structure formation (MassiveBlack and MassiveBlack-II) to investigate their predictions of the GSMF and compare it with current constraints. These runs are large, high-resolution simulations, with more than 65.5 billion resolution elements used in a box of roughly cubic gigaparsec scales (for MassiveBlack), making it by far the largest cosmological smooth particle hydrodynamics (SPH) simulation to date with ‘full physics’ of galaxy formation (meaning here an inclusion of radiative cooling, star formation, black hole growth and associated feedback physics) ever carried out. The combination of the two simulations allows us to probe galaxies with stellar masses greater than $10^7 M_\odot h^{-1}$ and (comoving) number densities of $\log_{10}(\rho(Mpc^{-3} dex^{-3} h^3)) > -8$, a range well matched with current observations at high redshift.

This paper is organized as follows. In Section 2, we introduce the MassiveBlack and MassiveBlack-II simulations. In Section 3, we explore the predicted evolution of the GSMF, how both the intrinsic and observed luminosities correlate with the stellar mass-to-light ratio, and in Section 3.5 compare GSMFs to recent observations. Finally, in Section 4 we present our conclusions.

Throughout this work, magnitudes are calculated using the AB system (Oke & Gunn 1983). We assume Salpeter (1955) stellar initial mass function (IMF), i.e. $\xi(m) = dN/dm \propto m^{-2.35}$.

## 2 MassiveBlack AND MassiveBlack-II

### 2.1 Simulation runs: MassiveBlack and MassiveBlack-II

Our new simulations (see Table 1 for the parameters of the simulation) have been performed with the cosmological TreePM-SPH code $P$-GADGET, a hybrid version of the parallel code GADGET2 (Springel 2005) which has been extensively modified and upgraded to run on the new generation of Petaflop-scale supercomputers (e.g. machines like the upcoming Bluewaters at NCSCA). The major improvement over previous versions of GADGET is in the use of threads in both the gravity and SPH part of the code which allows the effective use of multi-core processors combined with an optimum number of MPI task per node. The MassiveBlack simulation contains $N_{\text{part}} = 2 \times 3200^3 = 65.5$ billion particles in a volume of $533$ Mpc $h^{-1}$ on a side with a gravitational smoothing length $\epsilon = 5.0$ kpc $h^{-1}$ in comoving units. The gas and dark matter particle masses are $m_g = 5.7 \times 10^7 M_\odot$ and $m_{DM} = 2.8 \times 10^9 M_\odot$, respectively. The simulation has currently been run from $z = 159$ to 4.75 (beyond our original target redshift of $z = 6$). For this massive calculation, it is currently prohibitive to push it to $z = 0$ as this would require an unreasonable amount of computational time on the world’s current fastest supercomputers. The simulated redshift range probes early structure formation and the emergence of the first galaxies and quasars.

MassiveBlack-II (see Khandai et al., in preparation for an overview) is a smaller volume but the mass and spatial resolution are better than MassiveBlack by a factor of 25 and 2.7, respectively. The smaller volume means that a smaller part of the high-mass function can be sampled and that in the mass range where it overlaps with MassiveBlack it can be used to check for convergence as well as to extend our predictions towards the low-mass end. This is the largest volume ever run at this resolution with a final redshift of $z = 0$.

These runs contain gravity and hydrodynamics but also extra physics (subgrid modelling) for star formation (Springel & Hernquist 2003), black holes and associated feedback processes (Di Matteo et al. 2008, 2012). The cosmological parameters used were the amplitude of mass fluctuations $\sigma_8 = 0.8$, spectral index $n_s = 0.96$, cosmological constant parameter $\Omega_m = 0.74$, mass density parameter $\Omega_m = 0.26$, baryon density parameter $\Omega_b = 0.044$ and $h = 0.72$ (Hubble’s constant in units of 100 km s$^{-1}$ Mpc$^{-1}$; WMAP5) for MassiveBlack. For MassiveBlack-II we instead used $\Omega_\Lambda = 0.725$ and $\Omega_m = 0.275$ (according to WMAP7).

Catalogues of galaxies are made from the simulation outputs by first using a friends-of-friends groupfinder and then applying the SUBFIND algorithm (Springel 2001) to find gravitationally bound subhaloes. The stellar component of each subhalo consists of a number of star particles, each labelled with a mass and the redshift at which the star particle was created.

To generate the SED, and thus broad-band photometry, of each galaxy we sum the SEDs of each star particle (weighted by the particle mass). The SED of each star particle is generated using the PEGASE.2 stellar population synthesis (SPS) code (Fioc & Rocca-Volmerange 1997, 1999) taking their ages and metallicities into account. Nebula (continuum and line) emission is also added to each star particle SED, though this has a negligible effect on the UV photometry considered in this work. In addition, we apply a correction for absorption in the intergalactic medium using the standard Madau et al. (1996) prescription (though again this has a negligible effect on this work). Throughout this work, we measure the broad-band UV luminosity using an idealized rest-frame top-hat filter at $\lambda = 1500 \pm 200$ Å. A rest-frame filter is chosen to allow a consistent comparison between samples at different redshifts. The shape of this filter is selected for convenience, but closely reflects the profile of near-IR bandpasses which are available to measure the rest-frame UV flux at high redshift.

We note that our work is complementary to the recent simulation predictions of the GSMFs of Jaacks et al. (2012), who compare results for a suite of smaller simulations to the González et al. (2011, 2012) observational data. Our work differs in extending to a lower redshift, correcting for the effect of an evolving ratio of UV luminosity to mass-to-light ratio, and also for the inclusion of supermassive black hole formation and feedback in our simulations. We discuss the Jaacks et al. (2012) results further below.

### 3 THE GALAXY STELLAR MASS FUNCTION

Measuring the GSMF from outputs of the MassiveBlack and MassiveBlack-II simulations is straightforward, given that the total masses of star particles in each galaxy are known. Before making a comparison to observational data, however, we must remember that observed UV luminosities were used (e.g. González et al. 2011, 2012) to compute the published observed GSMFs. This means examining the relationship between UV luminosity and stellar mass-to-light ratio in the simulation and using this information in our

<table>
<thead>
<tr>
<th>Run</th>
<th>$N_{\text{part}}$</th>
<th>$L_{\text{box}}$ (Mpc $h^{-1}$)</th>
<th>$\epsilon$ (kpc $h^{-1}$)</th>
<th>$z_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MassiveBlack</td>
<td>$2 \times 3200^3$</td>
<td>533</td>
<td>5.0</td>
<td>4.75</td>
</tr>
<tr>
<td>MassiveBlack-II</td>
<td>$2 \times 1792^3$</td>
<td>100</td>
<td>1.85</td>
<td>0</td>
</tr>
</tbody>
</table>
Galaxy stellar mass function from simulations

The evolution of the \( M > 10^8 \, M_\odot \) GSMF from \( z = 10 \) to 5 predicted by MassiveBlack and MassiveBlack-II is shown in Fig. 1. The shape of the simulated GSMF is a declining distribution with mass and, at least at \( z = 5 \), exhibits a sharp cut-off at high masses. Values of the number density \( \phi \) are also given in Table 2 in various logarithmic mass intervals.

Fig. 1 also demonstrates the evolution in the normalization of the GSMF. At \( z = 10 \) there are only \( \sim 500 \) galaxies with stellar masses \( > 10^8 \, M_\odot \) in the MassiveBlack-II volume (106 Mpc\(^3\)), while at \( z = 5 \) this has increased to \( \sim 135,000 \) (\( \times 270 \)). The shape of the GSMF also evolves strongly; while the number of galaxies with masses \( > 10^8 \, M_\odot \) increases by a factor of 270 from \( z = 10 \) to 5, the number of galaxies with masses \( > 10^{10} \, M_\odot \) increases by a factor of 5000.

The evolution of the simulated GSMF is stronger than that exhibited by the UV luminosity function (LF). This reflects the fact that the average UV mass-to-light ratio of galaxies also increases \( z = 10 \) to 5 (as demonstrated in Section 3.3).

3.2 Observational estimation of the galaxy stellar mass function

By combining HST optical and near-IR observations (from ACS and NICMOS or WFC3) with Spitzer IRAC photometry, it is possible to measure the rest-frame UV–optical SEDs of high-redshift galaxies. Rest-frame optical photometry is vital to determine accurate stellar masses. Several studies have recently attempted to measure the stellar masses of high-redshift Lyman-break selected galaxies (e.g. Eyles et al. 2007; Stark et al. 2009; Labbé et al. 2010; González et al. 2011, 2012). With a sufficiently large sample and a handle on the incompleteness issues, it is also possible to study the GSMF (e.g. Stark et al. 2009; Labbé et al. 2010; González et al. 2011, 2012).

3.3 The relation between UV luminosity and the stellar mass-to-light ratio in simulations

As noted above, the González et al. (2011, 2012) study uses the distribution of stellar masses and UV luminosities measured at \( z = 4 \) to effectively convert the observed UV LF into a GSMF. To make a proper simulation prediction, we must take into account any difference between the relation between UV luminosity and the stellar mass-to-light ratio used by González et al. (2011, 2012) and that in the simulations.

Fig. 2 shows the relationship between the intrinsic UV luminosity \( L_{1500} \) and mass-to-light ratio \( M/L_{1500} \) at \( z \in \{5, 6, 7, 8, 9, 10\} \) predicted by MassiveBlack-II. This relationship is (over the full mass range) approximately flat (i.e. the intrinsic mass-to-light ratio is constant) and is significantly different from the \( M/L_{1500, \text{obs}} \propto L_{1500}^{0.7} \) relation found by González et al. (2011, 2012). Jaacks et al. (2012) plotted the rest-frame UV magnitude against stellar mass in their simulations, also finding a flatter relationship than that used by González et al. (2011, 2012). The lower panel of Fig. 2 shows that the relationship between the intrinsic UV luminosity and stellar mass-to-light ratio also varies strongly with redshift, increasing by 0.6 dex from \( z = 10 \) to 5.

It is also interesting to note from Fig. 2 that it appears the intrinsic UV luminosity of galaxies with \( L_{1500} > 10^{23} \) erg s\(^{-1}\) h\(^{-1}\) can alone be used to estimate the stellar mass with an accuracy of \( \approx 50 \) per cent. This contrasts sharply with the low-redshift Universe where star formation has terminated in many systems (particularly massive ellipticals) rendering the UV luminosity to be negligible. The strong correlation between UV luminosity and stellar mass reflects the fact that virtually all galaxies at high redshift (in the MassiveBlack and MassiveBlack-II simulations) continue to actively form stars.

3.4 The effect of dust attenuation

The González et al. (2011, 2012) relation is however based on the observed (i.e. dust attenuated luminosities) as opposed to the intrinsic luminosities (as used in Fig. 2). Attenuation due to dust both decreases the UV luminosity (i.e. \( L_{1500, \text{obs}} < L_{1500} \)) and increases the stellar mass-to-light ratio (i.e. \( M/L_{1500, \text{obs}} > M/L_{1500} \)) relative to their intrinsic values. A positive correlation between luminosity and dust attenuation would then introduce a positive correlation between \( M/L_{1500, \text{obs}} \) and the observed UV luminosity.

1 Though the power-law fit is not used to determine the GSMF.
The measurement of dust attenuation at high redshift is challenging. Far-IR observations, and optical emission lines, are generally inaccessible for the bulk of the galaxy population at high redshift leaving only the UV continuum slope $\beta$ as a diagnostic (e.g. Meurer et al. 1999; Wilkins et al. 2012a). A number of recent studies have attempted to constrain the relationship between $\beta$ and the observed UV luminosity at high redshift though with some conflicting results (e.g. Stanway, McMahon & Bunker 2005; Bouwens et al. 2009, 2012, Wilkins et al. 2011b; Dunlop et al. 2012; Finkelstein et al. 2012). Bouwens et al. (2009), Wilkins et al. (2011b) and Bouwens et al. (2012) find an increase in $\beta$ with observed luminosity. Dunlop et al. (2012) and Finkelstein et al. (2012), on the other hand, found little evidence of the variation of $\beta$ with luminosity (see Wilkins et al., submitted for a detailed comparison).

Adopting the relationship(s)$^2$ between $\beta$ and luminosity found by Bouwens et al. (2012) and utilizing the Meurer et al. (1999) calibration (between the observed UV continuum slope $\beta$ and UV attenuation), we can determine the relationships between the observed UV luminosity ($L_{1500, \text{obs}}$) and observed mass-to-light ratio at $z \in \{5, 6, 7\}$ as predicted by MassiveBlack and MassiveBlack-II. These are shown in Fig. 3. The most significant change (relative to that found for the intrinsic luminosities and mass-to-light ratios) is that the relationship between $L_{1500, \text{obs}}$ and $M/L_{1500, \text{obs}}$ is no longer approximately constant but is instead strongly positively correlated, at least at $M_{1500, \text{obs}} < -19.5$. At $M_{1500, \text{obs}} < -19.5$ the slope of this relation is $\gamma = 0.5 \pm 0.8$ (where $\gamma$ is defined such that $M/L_{1500, \text{obs}} \propto L^{\gamma}$) (cf. $\gamma = 0.7$ found by González et al. 2011, 2012 at $z = 4$). This suggests that the physical cause of the strong observed correlation between UV luminosity and mass-to-light ratio is caused almost solely by the correlation of dust attenuation with luminosity. At lower luminosities the relation flattens ($\gamma < 0.2$). This arises due to the diminishing effect of dust at lower luminosities, i.e. the $L_{1500, \text{obs}} - M/L_{1500, \text{obs}}$ begins to reflect the (virtually flat) intrinsic relation.

$^2$If a luminosity-invariant dust correction was assumed, the shape of the observed UV luminosity–mass-to-light ratio relation would remain the same (though the average observed mass-to-light ratio would increase).

**Table 2.** The number density (in units of Mpc$^{-3}$ dex$^{-1}$ h$^{-3}$) of galaxies in various logarithmic mass intervals ($9.5, 10.0) = 9.5 \leq \log_{10}(M) < 10.0$, where $M$ has units $M_\odot h^{-1}$) for $z \in \{5, 6, 7, 8, 9, 10\}$. Where there are no objects within the mass interval, the number density is replaced by an upper limit corresponding to $n < 1$ (i.e. $\phi < 1/V$).

<table>
<thead>
<tr>
<th>Mass interval</th>
<th>$\log_{10}((M_\odot h^{-1}))$</th>
<th>$z = 5$</th>
<th>$z = 6$</th>
<th>$z = 7$</th>
<th>$z = 8$</th>
<th>$z = 9$</th>
<th>$z = 10$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MassiveBlack</td>
<td>Volume = (533 Mpc h$^{-1}$)$^3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[9.5, 10.0)</td>
<td>-2.85</td>
<td>-3.50</td>
<td>-4.25</td>
<td>-5.13</td>
<td>-6.07</td>
<td>-7.88</td>
<td></td>
</tr>
<tr>
<td>[10.0, 10.5)</td>
<td>-3.69</td>
<td>-4.46</td>
<td>-5.35</td>
<td>-6.43</td>
<td>-7.88</td>
<td>-8.18</td>
<td></td>
</tr>
<tr>
<td>[10.5, 11.0)</td>
<td>-4.55</td>
<td>-5.46</td>
<td>-6.80</td>
<td>-7.88</td>
<td>-8.18</td>
<td>-8.18</td>
<td></td>
</tr>
<tr>
<td>[11.0, 11.5)</td>
<td>-6.23</td>
<td>-7.88</td>
<td></td>
<td>-8.18</td>
<td>-8.18</td>
<td>-8.18</td>
<td></td>
</tr>
<tr>
<td>[11.5, 12.0)</td>
<td>-8.18</td>
<td></td>
<td>-8.18</td>
<td>-8.18</td>
<td>-8.18</td>
<td>-8.18</td>
<td></td>
</tr>
<tr>
<td>MassiveBlack-II</td>
<td>Volume = (100 Mpc h$^{-1}$)$^3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[8.0, 8.5)</td>
<td>-0.70</td>
<td>-1.06</td>
<td>-1.46</td>
<td>-1.92</td>
<td>-2.44</td>
<td>-3.03</td>
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</tr>
<tr>
<td>[8.5, 9.0)</td>
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<td>-1.69</td>
<td>-2.15</td>
<td>-2.69</td>
<td>-3.31</td>
<td>-4.06</td>
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</tr>
<tr>
<td>[9.0, 9.5)</td>
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<tr>
<td>[9.5, 10.0)</td>
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<td>-3.37</td>
<td>-4.12</td>
<td>-4.80</td>
<td>-5.70</td>
<td>-6.00</td>
<td></td>
</tr>
<tr>
<td>[10.0, 10.5)</td>
<td>-3.57</td>
<td>-4.27</td>
<td>-4.74</td>
<td>-5.70</td>
<td>-6.00</td>
<td>-6.00</td>
<td>-6.00</td>
</tr>
<tr>
<td>[10.5, 11.0]</td>
<td>-4.40</td>
<td></td>
<td>-6.00</td>
<td></td>
<td>-6.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2.** The relationship between the intrinsic UV luminosity and stellar mass-to-light ratio at $z \in \{5, 6, 7, 8, 9, 10\}$ predicted from MassiveBlack-II. In both panels, the points denote the median value of the mass-to-light ratio in each luminosity bin. In the upper panel, the 2D histogram shows the density of sources on a linear scale and the error bars show the range encompassing the central 68.2 per cent of the galaxies. The arrow in the upper panel shows the effect of dust attenuation (the labels denote values of $A_{1500}$). The dashed line in both panels shows $M/L_{1500} \propto L^{0.7}$ which provides a good fit to the distribution used by González et al. (2011, 2012) to determine stellar masses from observed UV luminosities.
The flattening of the relation between the simulated UV lumino-
sity and stellar mass-to-light ratio at high luminosities essen-
tially reflects the good overall agreement between the sim-
ulations as compared to that of González et al. (2011, 2012). This
MTOL sample shows a much closer correspondence to the simu-

7 GSMF comes from Labbé et al. 2010 but is also presented in
importantly however is the strong redshift evolution: from a dif-
ference in the shape of the simulated and observed GSMFs. More
ratio at low luminosities does go some way to explaining the dif-
ficulty to reconcile observationally without requiring the application of a much larger
correction described above) and construct a GSMF. These GSMFs are shown at z ∈ {5, 6, 7} in Fig. 4. We also show in Fig. 4 the
GSMFs predicted by MassiveBlack/MassiveBlack-II and those determined by González et al. (2011, 2012) at z ∈ {5, 6, 7} (the z ∼ 7
GSMF comes from Labbé et al. 2010 but is also presented in

From an examination of Fig. 4, it is clear that the B07/B11 + MB
MTOL sample shows a much closer correspondence to the sim-
ulated UV LF and the observations, at least at high luminosities.
The flattening of the relation between L_{1500,obs} and the mass-to-light
ratio at low luminosities does go some way to explaining the dif-
ficulty in the presence of feedback, restricting star formation to molecular
gas or modifying the cooling function has very little effects on the

3.5 Comparison with observations
We are now in position to compare the MassiveBlack and
MassiveBlack-II results to observations. We follow a procedure sim-
ilar to that of González et al. (2011, 2012) but using the simulated
relation between UV luminosity and mass-to-light ratio. We con-
struct a volume-limited sample (referred to below as ‘B07/B11 + MB
MTOL’) of galaxy UV luminosities using the Bouwens et al. (2007,
2011b) observed UV LFs. We then convert the observed UV lumi-
nosity of each galaxy to a stellar mass using the relation between
luminosity and stellar mass-to-light ratio (M/L_{1500,obs}) predicted by
the MassiveBlack-II simulation (combined with the empirical dust
correction described above) and construct a GSMF. These GSMFs are shown at z ∈ {5, 6, 7} in Fig. 4. We also show in Fig. 4 the
gSMFs predicted by MassiveBlack/MassiveBlack-II and those de-
determined by González et al. (2011, 2012) at z ∈ {5, 6, 7} (the z ∼ 7 GSMF comes from Labbé et al. 2010 but is also presented in

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ficulty in the presence of feedback, restricting star formation to molecular
gas or modifying the cooling function has very little effects on the

Figure 3. The relationship between the dust attenuated (observed) UV
luminosity and stellar mass-to-light ratio at z ∈ {5, 6, 7} predicted from
MassiveBlack-II and using Bouwens et al. (2012) to relate dust attenuation
to the observed UV luminosity. The points denote the median value of
the mass-to-light ratio in each bin, while the vertical error bars (at z = 5)
denote the 68.2% confidence interval. The diagonal lines denote
M/L_{1500,obs} ∝ L^{\gamma} for γ = {0.1, 0.2, . . . , 1.0}. The dashed line denotes
γ = 0.7.

Figure 4. The GSMF predicted by MassiveBlack (dashed lines) and
MassiveBlack-II (solid lines) compared with observations at z ∈ {5, 6, 7} (top, middle and bottom panels, respectively). The open symbols in each panel show the prediction for the GSMF using the Bouwens et al. (2007, 2011b) observed UV LF and a relationship between stellar mass and luminosity derived from MassiveBlack-II. The filled grey points show the GSMF from González et al. (2011, 2012), which was estimated using a non-evolving relationship between UV luminosities and stellar mass-to-light ratios. Note that the units now implicitly assume h = 0.7.

the GSMF declines to high masses, this would cause the number
density of sources at any mass to be overestimated.

We also note from Fig. 4 that at z = 5 (and to a lesser extent
at z = 6) this process does not fully reconcile the GSMF at low
masses. At z = 5, MassiveBlack-II overpredicts the faint end of the
UV LF relative to the observations of Bouwens et al. (2007) by
around a factor of 5 at M_{1500} = −18. This is difficult to reconcile
observationally without requiring the application of a much larger
completeness correction. It therefore suggests that the discrepancy
has its roots in the MassiveBlack/MassiveBlack-II modelling as-
sumptions. This disagreement occurs in low-mass galaxies which are much less affected by active galactic nucleus (AGN) feedback and hence more sensitive to the details of the star formation model and stellar feedback. For example, our model does not include any
10^8 10^9 10^10 10^11
log M_\ast [M_\odot]
Observed GSMF
Gonzalez et al. (2011)
B07/B11 + MB MTOL
Simulated GSMF (z=5.0)
MassiveBlack-II
-1 0 1
M_\ast /L_{1500}\,\, h^{-3}\,\, Mpc^{-1}\,\, d^{-1}
-4 -3 -2 -1
z=5.0
z=6.0
z=7.0
Observed GSMF
Gonzalez et al. (2011)
B07/B11 + MB MTOL
Simulated GSMF (z=6.0)
MassiveBlack-II
-1 0 1
M_\ast /L_{1500}\,\, h^{-3}\,\, Mpc^{-1}\,\, d^{-1}
-4 -3 -2 -1

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Comparing to the simulation results of Jaacks et al. (2012) (which do not include AGN modelling), we see a similar disagreement with observations at low mass. At the high-mass end, we have shown that correcting for the evolution of the relationship between UV luminosity and mass-to-light ratio brings the observations and simulations into agreement, and this would also be likely to work for the Jaacks et al. results. Finally, it is also worth noting that the González et al. (2011, 2012) GSMF evolves only very mildly from $z = 5$ to 7. Indeed, the stellar mass density (which is the first moment of the GSMF) of galaxies with $> 10^5 \, M_\odot$ is virtually flat at $z = 5$–7. This is surprising given that all the galaxies contributing to the GSMF at these redshifts/masses are likely actively forming stars (by virtue of being UV selected) and suggest either the high-redshift GSMF is overestimated or the lower redshift GSMF is underestimated.

4 CONCLUSIONS

We have investigated the high-redshift ($z = 5–10$) evolution of the GSMF using a pair of large cosmological hydrodynamic simulations MassiveBlack and MassiveBlack-II. Over the redshift range $z = 10–5$, we find both the normalization and shape of the GSMF evolve strongly with the number density of massive galaxies ($> 10^8 \, M_\odot$) increasing by a factor of around 300.

By combining HST optical and near-IR observations (from ACS, NICMOS and WFC3) with near-IR IRAC photometry from the Spitzer Space Telescope, it is possible to identify and measure the stellar masses of galaxies at very high redshift, and thus constrain the GSMF (e.g. González et al. 2011, 2012). While the simulated GSMF at $z = 5$ provides reasonable agreement with the González et al. (2011, 2012) observations at $> 10^5 \, M_\odot$ at low masses and at $z > 5$ there is a significant discrepancy. The disagreement at low masses at $z = 5$ is also reflected in the UV LF at low luminosities. However, at $z > 5$ the discrepancy appears to arise due to a difference in the assumed relationship between the observed UV luminosity and mass-to-light ratio. González et al. (2011, 2012) apply a relationship calibrated at $z \sim 4$; however, we find that the relation, while having a similar form (i.e. the mass-to-light ratio is positively correlated with the observed UV luminosity), evolves strongly with redshift. Applying a calibration based on the simulated distribution of UV luminosities and stellar masses to the observed UV LF yields GSMFs which closely reflect those predicted by the simulations. This simply reflects the good agreement between the observed and simulated intrinsic UV LFs.

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