Lessons on early structure formation from a mature galaxy cluster observed at cosmic noon

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1 INTRODUCTION

A grand challenge for modern astrophysics is to constrain star and galaxy formation in the first billion years of cosmic history (Loeb & Furlanetto 2013). This is in particular the case for the first, so-called Population III (Pop III), stars and galaxies formed at $z \gtrsim 10$, which are believed to have distinct features compared with their present-day counterparts (reviewed by e.g. Bromm & Yoshida 2011; Bromm 2013). Future facilities, such as the James Webb Space Telescope (JWST) and the Einstein Telescope (ET), are expected to directly probe this formative epoch (e.g. Appleton et al. 2009; Pawlik et al. 2011; Zackrisson et al. 2017; Jeon & Bromm 2019; Basu-Zych et al. 2019; Maggiore et al. 2020). However, before they come into operation, we have to rely on indirect observations and empirical constraints.

A traditional indirect approach is ‘stellar archaeology’, where clues to the earliest star-forming environments are derived from local ($z \sim 0$) observations of extremely metal poor (EMP) stars ([Fe/H] < −3; e.g. Frebel & Norris 2015; Ji et al. 2015). For instance, the non-detection of metal-free stars in the Milky Way place constraints on the low-mass end ($\lesssim 0.8$ $M_\odot$) of the Pop III initial mass function (IMF) (Hartwig et al. 2015; Magg et al. 2019), while the abundance patterns of observed EMP stars constrain the higher-mass ($\gtrsim 10$ $M_\odot$) regime of the Pop III IMF, as well as the properties of the first supernovae (Ishigaki et al. 2018). Another probe that has become promising recently is the 21-cm signal from high-$z$ neutral hydrogen, encoding the Lyman-$\alpha$ and X-ray fields powered by the first stars and galaxies (e.g. Mirocha & Furlanetto 2019; Fialkov & Barkana 2019; Qin et al. 2020). As a specific example, Schauer et al. (2019b) found that Pop III star formation in minihaloes ($M_{\text{halo}} \sim 10^6$ $M_\odot$) is required to explain the timing ($z \sim 17$) of the 21-cm absorption signal potentially detected by the Experiment to Detect the Global Epoch of Reionization Signature (EDGES; Bowman et al. 2018). Each approach is subject to uncertainties, such as turbulent metal mixing in the formation pathways of EMP stars, or the escape fraction of Lyman-$\alpha$ photons. It is therefore important to harness new probes to complement the existing ones.

In this work, we consider mature galaxy clusters at cosmic noon ($z \sim 2$) to constrain early star and structure formation, e.g. IDCS J1426.5+3508 ($z = 1.75$; Stanford et al. 2012), JKCS 041 ($z = 1.8$; Andreon et al. 2014; Newman et al. 2014), Cl J1449+0856 ($z = 2$; Gobat et al. 2013; Strazzullo et al. 2016), and XLSSC 122 ($z = 1.98$; Mantz et al. 2018; Willis et al. 2020). These clusters are the most massive virialized structures in the Universe ($\sim 3 – 4$ Gyr after the Big Bang, such that their oldest constituent post-starburst galaxies (i.e. red-sequence cluster members) probe...
star formation histories at much earlier times \((z \gtrsim 10)\), here, we consider XLSSC 122 to demonstrate our basic approach, given the cluster’s clear post-starburst red-sequence members with ages of \(t_{\text{age}} \sim 2.4 - 3.1\) Gyr. We construct an idealized stellar population model, based on the standard extended Press-Schechter (EPS) formalism (Sec. 2), to derive new constraints on early star formation parameters and dark matter (DM) physics from the age distribution of stars within the XLSSC 122 red sequence (Sec. 3), as measured by the Hubble Space Telescope (HST; Willis et al. 2020). We summarize our findings and discuss future directions in Section 4.

2 STELLAR POPULATION MODEL

The cluster XLSSC 122 is observed at \(z_{\text{obs}} = 1.98\) (Willis et al. 2020), X-ray observations show that it has a virial mass of \(M_2 \sim 10^{14} M_\odot\), a virial (physical) radius of \(r_{200} \approx 1.5 r_{200} \approx 440\) kpc, and a sound-crossing time of \(t_{\text{cr}} \sim 3.3 \times 10^8\) yr (Mantz et al. 2018). To connect the observed luminosity-weighted posterior age distribution of (red-sequence) galaxies in XLSSC 122 to star and structure formation at higher redshifts \((z \gtrsim 13)\) with a simple but flexible model, we employ the standard EPS formalism (Mo et al. 2010) to estimate halo abundances. We further make the following assumptions and approximations:

- XLSSC was formed at \(z_2 \gtrsim 2.8\), i.e. 3 sound-crossing timescales before the observed epoch \((t_{\text{cr}} \sim 3.3 \times 10^8\) yr\)\(^1\).
- Star formation in progenitor haloes older than \(t_{\text{age}} \gtrsim 2.98\) Gyr (corresponding to formation at \(z_1 \gtrsim 13\)) is unaffected by environmental effects/cosmic variance, and reflects the average star formation efficiency in the early Universe.
- In such high-\(z\) haloes, star formation is episodic on timescales smaller than the average halo mass bin size of \(\sim 50\) Myr, such that the luminosity-weighted posterior age distribution of galaxies in XLSSC 122 is a good approximation to the underlying stellar age distribution, assuming a universal mass-to-light ratio.

The observational input comes from the last four bins in the stellar age distribution of XLSSC 122 assuming no dust absorption \((A_V = 0\), see fig. 4 of Willis et al. 2020\), corresponding to the four redshift bins: \(z_1 \sim 12.6 - 13.6, 13.6 - 14.8, 14.8 - 16.3\) and \(16.3 - 18.4\) (with Planck cosmological parameters, see Sec. 3.1), contributing \(\approx 0.275, 0.124, 0.025\) and \(0.004\) of the total stellar mass/luminosity, respectively. Here we focus on the \(A_V = 0\) model, as it predicts the oldest stellar ages (up to \(z \sim 18\)), most relevant for the first galaxies and stars. We build a simple stellar population model for XLSSC 122 with minimum parameters, as described below. With this model, information on high-\(z\) star formation and DM physics can be extracted by matching the observed stellar mass (in galaxies) within a given age range to the model predictions.

Under the episodic star formation assumption, the mass of stars formed in haloes within the mass range \(M_i \sim M_1 + \delta M_1\) and redshift bin \(i \equiv (z_{2,i} - \Delta z_{2,i}/2; z_{1,i} + \Delta z_{1,i}/2)\) is \(\Delta M_{i,p} = \eta(z_{1,i}, M_i)\Delta n_p(z_{1,i}, M_i) M_i \delta M_1\) \((1)\), where \(\eta \equiv \Delta M_i/\Delta M_{\text{halo}} = \eta(z, M_{\text{halo}})\) is the instantaneous halo star formation efficiency (HSFE, the average mass of newly-formed stars per increase in halo mass), and \(\Delta n_p(z_{1,i}, M_i)\) is the number of progenitor haloes of XLSSC 122 per unit halo mass in the mass range \([M_1; M_1 + \delta M_1]\), formed in redshift bin \(i\). For simplicity, we estimate \(\Delta n_p(z_{1,i}, M_i)\) with \(\Delta n_p(z_{1,i}, M_i) = n_p(z_{1,i} - \Delta z_{1,i}/2; z_1 + \Delta z_{1,i}/2)\) \((2)\), where \(n_p(z_{1,i} \lesssim M_2) \equiv dN/dM_1\) is the cluster progenitor mass function at \(z_1\), which only depends on cosmology, reflected in the linear power spectrum \(P(k)\). Here, we calculate the progenitor mass functions with the standard EPS formalism, without imposing any corrections based on cosmological simulations, which allows us to take into account different cosmologies self-consistently. Fig. 1 shows four examples of \(n_p\) for the standard lambda cold dark matter (LCDM) cosmology and three fuzzy dark matter (FDM) models (see Sec. 3.3 for details).

![Figure 1](image_url)

We parameterize \(\eta(M_1)\) as follows: (i) \(\eta = \eta_0\) is constant for \(M_1 > M_{\text{low}} = 10^{10} M_\odot\), and (ii) \(\eta\) exhibits (broken) power-law behavior between \(M_{\text{low}}\), the peak mass \(M_{\text{peak}} = 3 \times 10^{12} M_\odot\), and the high-mass reference point \(M_{\text{high}} = 10^{14} M_\odot\) (see Fig. 2 for examples). We set \(\eta(M_{\text{peak}}) = 0.02\).

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\(^1\) Hydrodynamical simulations of gas in a forming cluster indicate that virial equilibrium is achieved within a minimum of 2 to 3 sound-crossing timescales (Roettiger et al. 1998). We adopt \(\Delta t_{\text{gas}} = 3t_{\text{cr}}\) as a conservative estimate of the delay time between cluster formation and observation. In general, lower \(\Delta t_{\text{gas}}\) leads to higher HSFE, but the variation is minor (within 30%) for \(\Delta t_{\text{gas}} \lesssim 3t_{\text{cr}}\).

\(^2\) \(n_p(z_{1,i} \lesssim M_2) \equiv \#\) number of haloes in the mass range \([M_1; M_1 + \delta M_1]\) at \(z_1\) that end up in a halo of a mass \(M_2\) at \(z_2\).
and $\eta(M_{\text{high}}) = 0.001$, independent of redshift, based on the abundance matching results at $z = 2$ (Behroozi et al. 2019). Here we assume that $\eta$ is constant at the low-mass end for simplicity, in agreement with the semi-analytical analysis of Mirocha & Furlanetto (2019) to explain the EDGES 21-cm absorption signal (Bowman et al. 2018). Note that at $z \gtrsim 13$, haloes with $M_1 \lesssim 10^{10}$ (8) $M_\odot$ contribute $\gtrsim 99.9$ (90)% of the total mass of progenitor haloes, such that the behavior of $\eta$ at $M_1 \gtrsim 10^{10}$ $M_\odot$ is unimportant for star formation at such high redshifts, i.e. $\eta \approx \eta_0$ for $z > 13$. Nevertheless, $\eta$ at the high-mass end is important for determining the total stellar mass $M_{\text{stars, tot}}$ in XLSSC 122 at $z_{\text{obs}} \approx 2$. In our case, $M_{\text{stars, tot}} = M_{\text{stars}}(z) \gtrsim 10^{11}$ $M_\odot$, according to Behroozi et al. (2019).

Finally, given equations (1) and (2), observation and theory is bridged with

$$f_{\text{stars, tot}} = \int_{M_{\text{th}}}^{M_2} \Delta n_\nu(z_{\text{th}}, M_2) \eta(z_{\text{th}}, M_2) dM_1 \ .$$

On the left-hand side (observation), $f_1$ is the fraction of stars formed at redshift bin $i$, while on the right side (theory), there are two unknown/degenerate star formation parameters: $\eta_0(z_{\text{th}})$ and $M_{\text{th}}$, which is the minimum halo mass for star formation. With equation (3), constraints on $M_{\text{th}}$ and $\eta_0(z_{\text{th}})$ can be derived for any given cosmology embodied by the progenitor mass function $n_\nu(z_{\text{th}}, M_1, M_2)$.

We have thus connected the observed age distribution of galaxies/stars to two key theoretical ingredients: cosmology ($n_\nu$) and star formation model ($\eta_0$ and $M_{\text{th}}$), which are degenerate to some extent. In a full Bayesian model, the joint posterior distributions of model parameters could be derived once the statistical properties of observational data and priors are available. We defer such complex treatment to future work. Instead, in the following section, we explore the bounds on individual parameters separately, by fixing a subset of them to existing constraints.

### 3 CONSTRAINTS ON STAR FORMATION AND DARK MATTER PHYSICS

#### 3.1 Cold dark matter

To begin with, we apply equation (3) to the standard $\Lambda$CDM cosmology with $Planck$ parameters: $\Omega_m = 0.3089$, $\Omega_b = 0.0486$, $H_0 = 67.74$ km s$^{-1}$ Mpc$^{-1}$, $\sigma_8 = 0.8159$, $n_s = 0.9667$, and $N_{\text{eff}} = 3.046$ (Planck Collaboration et al. 2016). The corresponding linear power spectrum $P_{\text{CDM}}(k)$ is obtained from the PYTHON package COLOSSUS$^3$ (Diemer 2018). The resulting constraints on $M_{\text{th}}$ and $\eta_0$ are shown in Fig. 3, represented by the curves for different redshift bins in $M_{\text{th}} - \eta_0$ space. Generally, the observed stellar mass of a certain age (corresponding to a given redshift bin) is more sensitive to $\eta_0$ than $M_{\text{th}}$ (for $\nu_{\text{streaming}} \lesssim 3\sigma$), such that 1 dex variation in $M_{\text{th}}$ corresponds to less than 0.5 dex variations in $\eta_0$, especially for $z_1 \lesssim 15$.

The degeneracy of $\eta_0$ and $M_{\text{th}}$ can be broken by further information on either one of them. For illustration, we consider the constraints on $M_{\text{th}}$ from the cosmological simulations in Schauer et al. (2019a) with different levels of baryon-DM streaming motion (i.e. $\nu_{\text{streaming}} = 0$, 1, 2, 3$\sigma$), and the upper limits on $\eta_0$ from abundance matching at $z \leq 2$ (Behroozi et al. 2019) and reionization (see the next subsection). If we fix $M_{\text{th}}$ to the mass above which more than 50% of haloes can form stars, using the results in Schauer

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3. https://bdiemer.bitbucket.io/colossus/
The extrapolated value of $\eta_0$ at $z \sim 20$ from our results agrees well with the estimations in SA19\(^6\) and LB20 for $\nu < 4$ peaks, showing that HSFE is typically low (\(\sim 10^{-4}\)) for Pop III stars in minihaloes. This is required to not imprint the 21-cm absorption signal at a redshift ($z \gtrsim 20$) higher than observed. Note that similar values ($\sim 10^{-4} - 10^{-3}$) are also found in the recent cosmological simulation from Skinner & Wise (2020). However, in MJ19 and the star forming FOF haloes of LB20, the HSFE is almost constant at a higher level (\(\sim 10^{-3}\)) at $z \sim 10-20$. The detailed analysis of semi-numerical simulations, taking into account the escape fraction of UV photons, also infers that $\eta_0 \sim 10^{-3}$ from the observed 21-cm absorption signal (Fialkov & Barkana 2019; Qin et al. 2020). In our case, $\eta_0 \sim 10^{-2}$ at $z \sim 14-16$, but it rises to $10^{-2}$ at $z \sim 13$. The rapid evolution of $\eta_0$ may be caused by the fact that XLSSC is likely formed in an overdense region (i.e. at a $\nu \gtrsim 4$ peak).

Note that for LB20, the HSFE based on star forming FOF haloes is higher by a factor of $\sim 3 - 9$ than that derived from the EPS formalism for $\nu < 4$ peaks (see the orange shaded region in Fig. 4, representing the range in values for the two HSFE methods)\(^7\). The discrepancies between SA19 and Fialkov & Barkana (2019); Qin et al. (2020) may be caused by different estimations of host halo abundances and treatments for the escape fraction of Lyman-\(\alpha\) photons. As significant uncertainties also exist in the input stellar age distribution of XLSSC (Willis et al. 2020), we do not expect the discrepancies found here to have statistical significance. Nevertheless, they indicate that caution is necessary when comparing the results from observations, semi-analytical models and simulations.

3.2 Upper limit from reionization

Another bound on the HSFE can be set by reionization, thus providing a consistency check for our analysis, and also constraining the underlying structure formation history (see the next subsection). We derive an upper limit on $\eta_0$ from reionization as follows. First, we define the completion of reionization as the moment when the number of ionizing photons per hydrogen atom reaches two (So et al. 2014),

$$V_C J_{M_{\text{H}_b}} M_{\eta_0}(M) dM \text{ (as a function of redshift), where } V_C \text{ is the simulation volume, } \eta_0(M) \text{ the EPS halo number density per unit mass, } J_{M_{\text{H}_b}} \text{ the critical mass for } \nu = 4 \text{ peaks, } \sigma(M_{\text{crit}}) \equiv \delta_c/4, \text{ and } M_{\text{th}} = 1.63 \times 10^{6} \rho_{C} \text{ according to SA19. Note that the HSFE calculated in this way is lower than that defined for all simulated FOF haloes (i.e. } \eta_0 = \Delta M_{\text{star}}/\Delta \left( \sum_j M_{\text{halo},j} \right), \text{ } M_{\text{halo},j} > M_{\text{th}} \text{) by a factor of } 2, \text{ reflecting the well-known discrepancies between the EPS halo mass functions and those measured in simulations.}

\(^6\) Schauer et al. (2019a) also use the EPS formalism in their analysis, so that their definition of ‘halo’ is consistent with the one adopted in this work.

\(^7\) This implies that for low-mass haloes at high-$z$, where the delay time between halo and star formation is non-negligible, most haloes do not host stars at a given snapshot. That is to say, the HSFE measured in star forming haloes is not representative for the entire halo population, and must be diluted if the average should be taken over all haloes.

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4 https://bitbucket.org/gfcstanford/rockstar/src/master/

5 In detail, $\eta_0 = \Delta M_{\text{star}}/\Delta M_{\text{coll}}(\nu < 4)$ with $M_{\text{coll}}(\nu < 4) = V_c J_{M_{\text{H}_b}} M_{\eta_0}(M) dM$
such that
\[
\frac{2 X_{\text{H}} \rho_0}{m_{\text{H}}} = N_{\text{Ion}} \eta f_{\text{esc}} \times \int_{M_{\text{min}}}^{\infty} M [n_h(t_{\text{Ion}}) - n_h(t_{\text{Ion}} - t)] dM,
\]
where \( X_{\text{H}} = 0.76, \rho_0 = 3H_0^2 / (8\pi G) \) is the average baryon density, \( \eta = \eta(t_{\text{Ion}}, M) \) the HSFE parameterized by \( \eta(t_{\text{Ion}}, M) \) at \( z_{\text{Ion}} \), \( M_{\text{min}} = 2.5 \times 10^7 M_\odot / [1 + z_{\text{Ion}} / 10]^{-3/2} \) the atomic cooling threshold, and \( n_h(t) \equiv n_h(t, M) \) the halo mass function at time \( t \). Further, \( t_{\text{Ion}} \) is the age of the Universe at the end of reionization corresponding to \( z_{\text{Ion}}, t_* \sim 10 \) Myr and \( N_{\text{Ion}} = 10^{12} \) s^{-1} \( M_\odot \) are the lifetime of O/B stars and luminosity of ionizing photons per unit stellar mass for Population II stars\(^8\) (which dominate at \( z \gtrsim 18 \), see e.g. Liu & Bromm 2020), and \( f_{\text{esc}} \) is the effective escape fraction. Then we assume that \( \eta(t_{\text{Ion}}, M) \gtrsim \eta_0(z_1) \) for \( z_1 \gtrsim 13 \), such that the upper limit on \( \eta(t_{\text{Ion}}, M) \) to not complete reionization before \( z_{\text{Ion}} \) is also the upper limit on \( \eta_0(z_1) \), which can be derived by equation (4) given \( f_{\text{esc}} \) and \( z_{\text{Ion}} \). Here we adopt \( z_{\text{Ion}} = 6 \), and consider the range \( f_{\text{esc}} \sim 0.1 - 0.7 \) with \( f_{\text{esc}} = 0.3 \) the fiducial value, based on the simulations of So et al. 2014 (see also Paardekooper et al. 2015).

As shown in Fig. 3 and 4, the inferred \( \eta_0 \) at \( z_1 \gtrsim 13 \) is lower than the upper limits set by abundance matching and reionization for \( \psi_{\text{stream}} \lesssim 2 \psi \), which accounts for \( \approx 99 \% \) of the cosmic volume, further demonstrating that our results are consistent with existing constraints. Overall, we confirm the emerging picture that star formation began early in cosmic history, but was initially quite inefficient, with a ramp up towards a late epoch of reionization.

### 3.3 Fuzzy dark matter

Given \( M_{\text{th}} \) and the upper limit on \( \eta_0 \) either from abundance matching or reionization, our model can also place constraints on the underlying structure formation history (captured by \( n_p \) and \( n_v \)), governed by DM physics. As an example, we consider the fuzzy dark matter (FDM) scenario, parameterized by the mass of ultra-light particles, \( m_a \), whose linear power spectrum is given by (Hu et al. 2000)

\[
P_{\text{FDM}}(k) = T^2_{\text{FDM}}(k) P_{\text{CDM}}(k),
\]

\[
T_{\text{FDM}}(k) = \cos(x_3(k))[1 + x_3^2(k)],
\]

\[
x_3(k) = 1.61 (m_a c^2 / 10^{-22} \text{ eV})^{1/8} (k/k_{\text{eq}}) \text{ Mpc}^{-1},
\]

\[
k_{\text{eq}} = 9 (m_a c^2 / 10^{-22} \text{ eV})^{1/2} \text{ Mpc}^{-1}.
\]

As shown in Hirano et al. (2018), star formation can significantly be delayed to occur in more massive structures in FDM models, compared with standard ΛCDM. Therefore, the mass of old stars in XLSSC 122 can constrain the parameter \( m_a \), once \( \eta_0 \) and \( M_{\text{th}} \) are known. For simplicity, we now consider all the redshift bins together\(^9\) for stars/galaxies older than 2.98 Gyr, which accounts for \( \approx 0.43 \) of the total stellar mass, and rewrite equation (3) at \( z_1 \approx 12.7 \) as

\[
M_{\text{old}} = \frac{M_2}{M_{\text{th}}} n_p(M_1) \eta_0(M_1) \eta(M_1) dM_1,
\]

where \( n_p(M_1) = n_p(z_1, M_1, z_2, M_2) \) (see Fig. 1), and \( M_{\text{old}} = M_{\text{old}}(M_{\text{tot}}) \). There exists a lower limit \( M_{\text{min}} \) below which the above equation (6) cannot be satisfied with reasonable \( M_{\text{th}} \) and \( \eta_0 \), when structure formation is delayed to lower redshifts \( z \lesssim 21 \) \( z_1 \approx 12.7 \).

To derive a conservative estimate for this lower limit, we set \( M_2 \), to the lowest threshold value of \( \approx 5 \times 10^5 M_\odot \), which is the minimum mass of star formation in Schauer et al. (2010a) with no streaming motion\(^10\), and \( \eta_0 \) to the (fiducial) upper limit from reionization \( \eta_{0,\text{max}} \) (with \( f_{\text{esc}} = 0.3 \)), given by equation (4). Note that here both the halo mass function \( n_h \) and the progenitor mass function \( n_p \) depend on \( m_a \), so that equations (3) and (5) must be solved together for \( \eta_{0,\text{max}} \).

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\(^8\) Here we neglect the contribution of Pop III stars to completing reionization at \( z_{\text{Ion}} \sim 6 \), as Pop III star formation will be significantly suppressed by external Lyman-Werner and ionizing photons, as well as metal enrichment. Previous studies have found that the Pop III contribution to the ionizing photon budget is \( \lesssim 10\% \) (e.g. Greif & Bromm 2006; Wise et al. 2011; Paardekooper et al. 2015).

\(^9\) Actually \( \eta_0 \) here stands for the cumulative HSFE for \( z \gtrsim z_1 \approx 12.7 \). We assume that the HSFE generally increases with decreasing redshift before reionization, so that the cumulative HSFE should be smaller than the instantaneous one at a given redshift. Therefore, our constraints on \( m_a \) should be regarded conservative when any upper limit on the instantaneous HSFE is adopted.

\(^10\) It turns out that \( \eta_{0,\text{min}} \) is not sensitive to \( M_{\text{th}} \) for \( m_a \lesssim 10^{-20} \text{ eV}/c^2 \), the contribution from minihaloes (\( M_{\text{halo}} \lesssim 10^7 M_\odot \)) to the total stellar mass formed at \( z \gtrsim z_1 \approx 12.7 \) is negligible (see Fig. 5).
and $m_{a,\text{min}}$. Carrying out these steps, we find $\eta_{\text{max}} \simeq 0.016$ and $m_{a,\text{min}} \simeq 5 \times 10^{-21} \text{ eV}/c^2$.

This approach is further illustrated in Fig. 5 in terms of the cumulative stellar mass $M_*(> M_1)$, where FDM models with $M_1(> M_\text{halo}) < M_\text{old}$ are ruled out. If we adopt $\eta = 0.025$, which is the local ($z \lesssim 2$) upper limit from abundance matching (Behroozi et al. 2019), equation (6) can be solved independently to give a weaker constraint on FDM of $m_{a,\text{min}} \simeq 2.5 \times 10^{-21} \text{ eV}/c^2$. Using the reionization upper limit with $f_{\text{esc}} = 0.1$ leads to an even weaker constraint of $m_{a,\text{min}} \simeq 6 \times 10^{-22} \text{ eV}/c^2$ for $\eta_{\text{max}} \simeq 0.091$, which is unphysical, as it would imply that $\sim 60\%$ of baryons end up in stars. Interestingly, our constraints on FDM inferred from the cluster XLSSC 122 are consistent with those based on the EDGES 21-cm absorption signal (Bowman et al. 2018), e.g. $m_{a,\text{min}} \simeq 5 \times 10^{-21} \text{ eV}/c^2$ in Lidz & Hui (2018) and $m_{a,\text{min}} \simeq 8 \times 10^{-21} \text{ eV}/c^2$ in Schneider (2018).

4 SUMMARY AND CONCLUSIONS

We demonstrate a new approach of indirectly constraining early star and structure formation via mature galaxy clusters at cosmic noon ($z \sim 2$), using the cluster XLSSC 122 as an example ($z_{\text{obs}} = 1.98$). Based on the age distribution of galaxies/stars in XLSSC 122 (neglecting dust extinction) measured by HST photometry (Willis et al. 2020), and its halo properties from X-ray observations (Mantz et al. 2018), we infer a rapid evolution of the halo formation efficiency (HSFE, $\eta \equiv (\Delta M_*)/(\Delta M_\text{halo})$) at $z \sim 13 - 18$. Specifically, we derive a fit $\eta \simeq 2.7 \times 10^{-3 - 0.37(z-15)}$ for low-mass haloes ($M_\text{halo} \lesssim 10^{10} \text{ M}_\odot$) that host the first stars and galaxies. Our results generally agree with semi-analytical models based on 21-cm absorption and cosmological simulations, giving $\eta_0 \sim 10^{-4}$ to a few $10^{-3}$ at $z \sim 13 - 20$ (Mirocha & Furlanetto 2019; Schauer et al. 2019b; Fialkov & Barkana 2019; Qin et al. 2020; Skinner & Wise 2020; Liu & Bromm 2020). However, such rapid evolution is unique to our model, likely caused by the fact that XLSSC is formed in an overdense region, corresponding to a $\nu \gtrsim 4$ peak.

We also place new constraints on the mass of ultra-light bosons in fuzzy dark matter models of $m_a \lesssim 5 \times 10^{-21} \text{ eV}/c^2$, from the abundance of star forming galaxies at $z \gtrsim 13$ in the merger tree of XLSSC 122. This is comparable to existing constraints $m_a \lesssim 5 \sim 8 \times 10^{-21} \text{ eV}/c^2$ (Lidz & Hui 2018; Schneider 2018).

However, significant uncertainties in the inferred stellar age distribution of XLSSC 122, as the posterior age distributions of individual galaxies are broad ($\sim$ Gyr). This is typical for photometry-inferred ages (see fig. 7-8 in Andreon et al. 2014 and extended data fig. 2-3 of Willis et al. 2020). The age distribution is also sensitive to the underlying stellar population parameters assumed for SED fitting (e.g. IMF, metallicity and star formation history), especially the assumption on dust absorption (Willis et al. 2020). We here focus on the zero-dust absorption ($A_V = 0$) model that predicts major star formation to occur around $z \sim 12$ and extend to $z \sim 18$, while in models with dust absorption (e.g. $A_V = 0.3$ and 0.5) the stellar population is shifted to lower redshifts ($z \sim 6 - 13$), becoming less relevant to the first stars and galaxies.

Besides, it remains unknown whether XLSSC 122 is an extreme case or a typical galaxy cluster at $z \sim 2$. Therefore, our results should be regarded as tentative and for illustration purpose. Nevertheless, more comprehensive results will be obtained if our approach is extended to a large sample of clusters or field post-starburst galaxies at cosmic noon, with a full statistical framework in which observational uncertainties are properly propagated to the inferred star/structure formation parameters. There is thus a strong case for systematic observational campaigns to identify galaxy clusters at cosmic noon and to characterize their member galaxies.

On the theoretical side, we use the standard EPS formalism for simplicity and flexibility in the current work, which defines haloes differently from cosmological simulations. This introduces an additional layer of complexity for bridging theory and observation, given that simulations are needed to implement the detailed physics of star and galaxy formation, such as primordial chemistry, cooling and stellar feedback. In future work, merger trees constructed from simulations should be used to calculate the progenitor mass functions of clusters. That approach does not only remove the ambiguity in halo definition but also enables one to account for cosmic variance. We may also use more physically motivated models of the HSFE that allow variation with halo mass at $M_\text{halo} \lesssim 10^{10} \text{ M}_\odot$, reflecting the different modes of early star formation in atomic cooling haloes ($M_\text{halo} \gtrsim 10^7 \text{ M}_\odot$) and molecular cooling minihaloes ($M_\text{halo} \sim 10^5 \text{ M}_\odot$).

Overall, we begin to probe the earliest epoch of star and galaxy formation with the tantalizing hints provided by pioneering observations, such as the ones discussed here. Soon, we will be able to complement this with direct observations of active star formation at the highest redshifts, together contributing to the emerging model of the first stars and galaxies.

ACKNOWLEDGMENTS

Support for this work was provided by NASA through the NASA Hubble Fellowship grant HST-HF2-51418.001-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS5-26555.

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