Reionisation: the role of Globular Clusters

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Abstract. In this talk I discuss the role of proto-globular clusters as the dominant sources of radiation that reionised hydrogen in the intergalactic medium (IGM) at redshift $z \sim 6$. Observations at lower redshift indicate that only a small fraction, $\langle f_{\text{esc}} \rangle$, of hydrogen ionising radiation emitted from massive stars can escape unabsorbed by the galaxy into the IGM. High redshift galaxies are expected to be more compact and gas rich than present day galaxies, consequently $\langle f_{\text{esc}} \rangle$ from their disks or spheroids might have been very small. But if the sites of star formation in the galaxies are off-centre and if the star formation efficiency of the proto-clusters is high, then the mean $\langle f_{\text{esc}} \rangle$ calculated for these objects only, is expected to be close to unity.

Here I argue that this mode of star formation is consistent with several models for globular clusters formation. Using simple arguments based on the observed number of globular cluster systems in the local universe and assuming that the oldest globular clusters formed before reionisation and had $\langle f_{\text{esc}} \rangle \sim 1$, I show that they produced enough ionising photons to reionise the IGM at $z \sim 6$. I also emphasise that globular cluster formation might have been the dominant mode of star formation at redshifts from 6 to 12.

1. Introduction

In this talk, using simple arguments, I emphasise the important cosmological role of globular cluster (GC) formation at high-redshift. I show that the formation of GCs may have been the dominant mode of star formation near the epoch of reionisation and have contributed significantly to it. The material presented in this talk is based on published work by Ricotti & Shull (2000) and Ricotti (2002).

Observation of Ly$\alpha$ absorption systems toward high-redshift quasars (Becker et al. 2001) indicate that the redshift of reionisation of the intergalactic medium (IGM) is $z_{\text{rei}} \sim 6$. The recent result from the WMAP satellite (Kogut et al. 2003) of an early epoch of reionisation will not be addressed in this talk. The reader can refer to Ricotti & Ostriker (2003a,b) if interested in this topic.

A key ingredient in determining the effectiveness by which galaxies photoionise the surrounding IGM is the parameter $\langle f_{\text{esc}} \rangle$, defined here as the mean fraction of ionising photons escaping from galaxy halos into the IGM. Cosmological simulations and semi-analytical models of IGM reionisation by stellar sources find that, in order to reionise the IGM by $z = 6 - 7$, the escape fraction from galaxies must be relatively large: $\langle f_{\text{esc}} \rangle \gtrsim 10\%$ assuming a Salpeter initial mass function (IMF) and the standard ΛCDM cosmological model. The assumption of a universal star formation efficiency (SFE) is consistent with the observed values of the star formation rate (SFR) at $0 < z < 5$ and total star
budget at $z = 0$. However, the assumption of a constant $\langle f_{\text{esc}} \rangle$ does not seem to be consistent with observations. An escape fraction $\langle f_{\text{esc}} \rangle \sim 1$ is required for reionisation at $z \sim 6$ but the ionising background at $z \sim 3$ is consistent with $\langle f_{\text{esc}} \rangle \lesssim 10\%$ [Bianchi et al. 2001]. Small values of $\langle f_{\text{esc}} \rangle$ at $z \lesssim 3$ are also supported by direct observations of the LyC emission from Lyman-break and starburst galaxies. Giallongo et al. (2002) find an upper limit $\langle f_{\text{esc}} \rangle < 16\%$ at $z \sim 3$ (but see Steidel et al. 2001) and observations of low-redshift starbursts are consistent with $\langle f_{\text{esc}} \rangle$ upper limits ranging from a few percent up to 10\% (Hurwitz et al. 1997; Deharveng et al. 2001).

Theoretical models (e.g., Dove et al. 2000) for the radiative transfer of ionising radiation through the disk layer of spiral galaxies similar to the Milky Way find $\langle f_{\text{esc}} \rangle \sim 6\%$. At high redshift the mean value of $\langle f_{\text{esc}} \rangle$ is expected to decrease almost exponentially with increasing redshift (Ricotti & Shull 2000; Wood & Loeb 2000); at $z > 6$, $\langle f_{\text{esc}} \rangle \lesssim 0.1 - 1\%$ even assuming star formation rates typical of starburst galaxies. The majority of photons that escape the halo come from the most luminous OB associations located in the outermost parts of the galaxy. Indeed, Ricotti & Shull (2000) have shown that changing the luminosity function of the OB association and the density distribution of the stars has major effects on $\langle f_{\text{esc}} \rangle$ (see their Figs. 8 and 9).

A star formation mode, in which very luminous OB associations form in the outer parts of galaxy halos, may explain the large $\langle f_{\text{esc}} \rangle$ required for reionisation. Globular clusters are possible observable relics of such a star formation mode. Their age is compatible with formation at reionisation or earlier. Because of their large star density they survived tidal destruction and represent the most luminous tail of the luminosity distribution of old OB associations. In § 3.1 I show that several models for the formation of proto-GCs imply an $\langle f_{\text{esc}} \rangle \sim 1$. I will also show that the total amount of stars in GCs observed today is sufficient to reionise the universe at $z \sim 6$ if their $\langle f_{\text{esc}} \rangle \sim 1$. This conclusion is reinforced if the GCs we observe today are only a fraction, $1/f_{\text{di}}$, of primordial GCs as a consequence of mass segregation and tidal stripping.

In § 2.1 I briefly review a few observational properties and in § 3.1 formation theories of GCs that motivate the assumption of $\langle f_{\text{esc}} \rangle \sim 1$; in § 4.1 I discuss the model assumptions in light of GC observations and present the results. In § 5 I present my conclusions.

2. Condensed review on GC systems

Most galaxies have a bimodal GCs distribution indicating that luminous galaxies experience at least two major episodes of GCs formation. The bulk of the globulars in the main body of the Galactic halo appear to have formed during a short-lived burst ($\sim 0.5 - 2$ Gyr) that took place about 13 Gyr ago. This was followed by a second burst associated with the formation of the galactic bulges.

The method for determining the absolute age of GCs is based on fitting the observed colour-magnitude diagram with theoretical evolutionary tracks. The systematics in the evolutionary model and the determination of the cluster distance are the major sources of errors. Recent determinations of the absolute age of old GCs find $t_{\text{gc}} = 12.5 \pm 1.2$ Gyr [Chaboyer et al. 1998], consistent with radioactive dating of a very metal-poor star in the halo of our galaxy.
Relative ages of Galactic GCs can be determined with greater accuracy, since many systematic errors can be eliminated. In our Galaxy $\Delta t_{gc} = 0.5$ Gyr, but differences in age between GC systems in different galaxies could be $\Delta t_{gc} \sim 2$ Gyr (Stetson et al. 1996).

The GC specific frequency is defined as the number, $N$, of GCs per $M_V = -15$ of parent galaxy light, $S_N = N \times 10^{0.4(M_V+15)}$ (Harris & van den Bergh 1981). The most striking characteristic is that $S_N$(Ellipticals) > $S_N$(Spirals). $S_N = 0.5$ in Sc/Ir galaxies (Harris, 1991), $S_N = 1$ in spirals of types Sa/Sb, and $S_N = 2.5$ in field ellipticals (Kundu & Whitmore 2001). Converting to luminosity $\left(L_V/L_\odot = 10^{-0.4(M_V-4.83)}\right)$ we have $N = (L/L_\odot)S_N/8.55 \times 10^7$. I can therefore calculate the efficiency of GC formation defined as,

$$\epsilon_{gc} = \frac{M_{gc}}{M} = \frac{f_{di}Nm_{gc}}{M} = \frac{S_N f_{di}}{(M/L)_V} \times 0.00585,$$

where $M_{gc}$ is the total mass of the GC system, $m_{gc} = 5 \times 10^5$ $M_\odot$ is the mean mass of GCs today, $M$ is the stellar mass and $(M/L)_V$ is the mass to light ratio of the galaxy. In the next paragraph we show that, because of dynamical evolution, $m_{gc}$ and $N$ are expected to be larger at the time of GC formation than today. Therefore, the parameter $f_{di} \geq 1$ is introduced to account for dynamical disruption of GCs during their lifetime.

The IMF of GCs is not known. The present mass function is known only between 0.2 and 0.8 $M_\odot$, since high-mass stars are lost because of two-body relaxation and stellar evolution processes. Theoretical models show that the shape is consistent with a Salpeter-like IMF. The mean metallicity of old GCs is $Z \sim 0.03$ $Z_\odot$. One of the most remarkable properties of GCs is the uniformity of their internal metallicity $\Delta [Fe/H] \lesssim 0.1$. This implies that the bulk of the stars that constitute a GC formed in a single monolithic burst of star formation. A typical GC emits $S \approx 3 \times 10^{53}$ s$^{-1}$ ionising photons in a burst lasting 4 Myrs: about 300 times the ionising luminosity of largest OB associations in our Galaxy.

During their lifetime GCs lose a large part of their initial mass or are completely destroyed by internal and external processes. Numerical simulations show that about 50%–90% of the mass of GCs is lost due to external processes, depending on the host galaxy environment, initial concentration and IMF of the proto-GCs (Chernoff & Weinberg 1990; Gnedin & Ostriker 1997). Many of the low-metallicity halo field stars in the Milky-Way could be debris of disrupted GCs. The mass in stars in the halo is about 100 times the mass in GCs. Therefore the parameter $f_{di}$, defined in §2, could be as large as $f_{di} = 100$. Overall $f_{di}$ is not well constrained since it depends on unknown properties of the proto-GCs. According to results of N-body simulations $f_{di}$ should be in the $f_{di} \sim 2 - 10$ range.

3. Why is $\langle f_{esc} \rangle \sim 1$ plausible for GCs?

I discuss separately two issues: (i) the $\langle f_{esc} \rangle$ from the gas cloud in which the GC forms, and (ii) the $\langle f_{esc} \rangle$ through any surrounding gas in the galaxy.

(i) The evidence for $\langle f_{esc} \rangle \sim 1$ comes from the observed properties of present-day GCs. The fact that they are compact self-gravitating systems with
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low and uniform metallicity points to a high efficiency of conversion of gas into stars. A longer timescale of star formation would have enriched the gas of metals and the mechanical feedback from SN explosions would have stopped further star formation. If \( f_\text{s} \approx 10\% \) of the gas is converted into stars in a single burst (with duration \(< 4 \text{ Myr}\)) at the centre of a spheroidal galaxy, following the simple calculations shown in Ricotti & Shull (2000) [see their eq. (18)] at \( z = 6 \) we have, \( f_\text{esc} = 1 - 0.06(1 - f_\text{s})^2/f_\text{s} \approx 50\% \).

(ii) The justification for \( \langle f_\text{esc} \rangle \sim 1 \) is model dependent but in general there are two main arguments: a) the high efficiency of star formation \( f_\text{s} \), and b) the sites of proto-GC formation in the outermost parts of the galaxy halo. In the “cosmological objects model” (30 < \( z_f \) < 7) of Peebles & Dicke (1968) GCs form with efficiency \( f_\text{s} \approx 100\% \), implying \( \langle f_\text{esc} \rangle = 1 \) (note that such a high \( f_\text{s} \) is not found in numerical simulations of first object formation (Ricotti et al. 2002a,b)). In “hierarchical formation models” (10 < \( z_f \) < 3) (Harris & Pudritz 1994; McLaughlin & Pudritz 1996, e.g.) GCs form in the disk or spheroid of galaxies with gas mass \( M_g \sim 10^7 - 10^9 \text{ M}_\odot \). Compact GCs survive the accretion by larger galaxies while the rest of the galaxy is tidally stripped. Assuming that 1–10 GCs form in a galaxy with \( M_g \sim 10^7 - 10^8 \text{ M}_\odot \) implies \( f_\text{s} \sim 10\% \) and therefore \( \langle f_\text{esc} \rangle \geq 50\% \). \( \langle f_\text{esc} \rangle \) is larger if proto-GCs are located off-centre (e.g., if they form from cloud-cloud collisions during the galaxy assembly) or if part of the gas in the halo is collisionally ionised as a consequence of the virialization process. In models such as the “super-shell fragmentation” (\( z_f < 10 \)) of Taniguchi et al. (1999) or the “thermal instability” (\( z_f < 7 \)) of Fall & Rees (1985), \( \langle f_\text{esc} \rangle \approx 1 \) since proto-GCs form in the outermost part of an already collisionally ionised halo.

In summary, since \( \langle f_\text{esc} \rangle \) depends strongly on the luminosity of the OB associations and on their location, proto-GCs, being several hundred times more luminous than Galactic OB associations, should have a comparably larger \( \langle f_\text{esc} \rangle \).

4. Method and Results

In this section I estimate the number of ionising photons emitted per baryon per Hubble time, \( N_{\text{ph}} \), by GC formation. In §4.1 I derive \( N_{\text{ph}} \) assuming that all GCs observed at \( z = 0 \) formed in a time period \( \Delta t_\text{gc} \) with constant formation rate. In §4.2 I use the Press-Schechter formalism to model more realistically the formation rate of old GCs.

| Type | \( \omega_\text{s} \) (%) | \( S_N \) | \( (M/L)_V \) | \( \epsilon_\text{gc} \) (%) |
|------|----------------|--------|--------------|-----------------|
| Sph  | 6.5\(^{+2.4}_{-2.3}\) | 2.4 ± 0.4 | 5.4 ± 0.3 | 0.26 ± 0.06 |
| Disk | 2\(^{+1.5}_{-0.5}\) | 1 ± 0.1 | 1.82 ± 0.4 | 0.32 ± 0.1 |
| Irr  | 0.15\(^{+0.15}_{-0.05}\) | 0.5 | 1.33 ± 0.25 | 0.22 ± 0.04 |
| Total| 9\(^{+5.9}_{-3.5}\) | - | - | 0.3 ± 0.07 |
4.1. The simplest estimate

I start by estimating the fraction, \( \omega_{gc} \), of cosmic baryons converted into GC stars. By definition \( \omega_{gc} = \omega_\ast \epsilon_{gc} \), where \( \omega_\ast \) is the fraction of baryons in stars at \( z = 0 \) and \( \epsilon_{gc} \) is the efficiency of GC formation defined in §2. In all the calculations I assume \( \Omega_b = 0.04 \). In Table 1 I summarise the star census at \( z = 0 \) according to Persic & Salucci (1992) and I derive \( \epsilon_{gc} \) using eq. (1), assuming \( f_{di} = 1 \). Using similar arguments McLaughlin (1999) finds a universal efficiency of globular cluster formation \( \epsilon_{gc} = (0.26 \pm 0.05)\% \), in agreement with the simpler estimate presented here. It follows that \( \omega_{gc} = \frac{f_{di}}{\Delta t_{gc}} (2.7^{+2.3}_{-1.7} \times 10^{-4}) \) at \( z = 0 \).

The total number of ionising photons per unit time emitted by GCs is \( \eta \omega_{gc} f_{gc} / \Delta t_{gc} \), where \( \eta \) is the number of ionising photons emitted per baryon converted into stars, and \( \omega_{gc} \approx 2.1 \omega_{gc} \) takes into account the mass loss due to stellar winds and SN explosions adopting an instantaneous-burst star formation law. GCs did not recycle this lost mass since they formed in a single burst of star formation. \( \eta \) depends on the IMF and on the metallicity of the star. I calculate \( \eta \) using a Salpeter IMF and star metallicity \( Z = 0.03 Z_\odot \) (see §2.) with Starburst99 code (Leitherer et al. 1999), and find \( \eta = 8967 \). The number of ionising photons per baryon emitted in a Hubble time at \( z = 6 \) is,

\[
N_{ph}^e = \eta \omega_{gc} f_{H}(z = 6) / \Delta t_{gc} = \frac{f_{di}}{\Delta t_{gc} (\text{Gyr})},
\]

where I have assumed \( \langle f_{esc} \rangle = 1 \) and Hubble time at \( z = 6 \) \( t_H = 1 \pm 0.1 \) Gyr. I expect \( 1 \leq f_{di} \lesssim 100 \) and \( 0.5 \lesssim \Delta t_{gc} \lesssim 2 \) Gyr. A conservative estimate of \( f_{di} \approx 2 \) and \( \Delta t_{gc} \approx 2 \) Gyr \((i.e., 10 < z_f < 3)\) implies \( f_{di}/\Delta t_{gc} \approx 1 \). The IGM is reionised when \( N_{ph} = C_{\text{HI}} \), where \( C_{\text{HI}} = \langle n_{\text{HI}}^2 \rangle / \langle n_{\text{HI}} \rangle^2 \) is the ionised IGM clumping factor. According to the adopted definition of \( \langle f_{esc} \rangle \), \( C_{\text{HI}} = 1 \) for a homogeneous IGM, or \( 1 \lesssim C_{\text{HI}} \lesssim 10 \) taking into account IGM density fluctuations producing the Ly\( \alpha \) forest (Miralda-Escudé et al. 2000; Gnedin 2000). The estimate from eq. (2) is rather rough because I have implicitly assumed that the SFR is constant during the period of GC formation \( \Delta t_{gc} \). A more realistic SFR as a function of redshift requires assuming a specific model for the formation of GCs. I try to address this question in the next section.

4.2. Using the Press-Schechter formalism

I assume that the formation rate of stars or GCs in galaxies is proportional to the merger rate of galaxy halos (each galaxy undergoes a major star burst episode when it virializes). Using the Press-Schechter formalism I calculate,

\[
\frac{d\omega_{gc}(z)}{dt} = A \int_{M_1}^{M_2} d\Omega(M_{dm}, z) \frac{d\ln M_{dm}}{dt}, \quad (3)
\]

\[
\frac{d\omega_{\ast}(z)}{dt} = B \int_{M_m}^{\infty} d\Omega(M_{dm}, z) \frac{d\ln M_{dm}}{dt}, \quad (4)
\]
where $\Omega(M_{dm}, z) d\ln(M_{dm})$ is the mass fraction in virialized dark matter halos of mass $M_{dm}$ at redshift $z$. I determine the constants $A$ and $B$ by integrating eqs. (3)-(4) with respect to time, and assuming $\omega_{gc} = 0.1\%$ (i.e., $f_{di} = 2$) and $\omega_{*} = 1.4\%$ at $z = 0$ (the factor 1.4 takes into account the mass loss due to stellar winds and SN explosions adopting a continuous star formation law). I assume that GCs form in halos with masses $M_1 < M_{dm} < M_2$. The choice of $M_1$ and $M_2$ determine the mean redshift, $z_f$, and time period, $\Delta t_{gc}$, for the formation of old GCs. In order to be consistent with observations I consider three cases: case (i) halos with virial temperature $2 \times 10^4 < T_{vir} < 5 \times 10^4$ K; case (ii) $5 \times 10^4 < T_{vir} < 10^5$ K; and case (iii) $10^5 < T_{vir} < 5 \times 10^5$ K. In case (i), (ii) and (iii) $\Delta t_{gc} = 2.2, 3.7$ and 5.2 Gyr, respectively, and the GC formation rate has a peak at $z = 7.5, 6$ and 4.6, respectively. Disk and spheroid stars form in halos with $M_{dm} > M_m$. At $z > 10$ I assume that the first objects form in halos with $M_m$ corresponding to a halo virial temperature $T_{vir} = 5 \times 10^3$ K. At $z < 10$ only objects with $T_{vir} > 2 \times 10^4$ K can form (see [Ricotti et al. 2002b]).

The comoving star formation rate, given by $\dot{\rho}_* = \bar{\rho} \omega_{*}$, where $\bar{\rho} = 5.51 \times 10^9$ M$_\odot$

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1By definition $\int_0^\infty \Omega(M_{dm}, z) d\ln(M_{dm}) = 1$. I find the following values of the constants $A = 1.3\%, 1.6\%, 0.6\%$ for cases (i), (ii) and (iii) respectively (see text) and $B = 12\%$. 

Figure 1. (left) The thin solid line in the top panel shows the comoving SFR of galaxies as a function of time in our model. The thick solid, dashed and short-dashed lines show the SFR of GCs for cases (i), (ii) and (iii), respectively (assuming $f_{di} = 2$). The bottom panel shows the stellar mass budget (in units of the baryon abundance), $\omega_{*}$, as a function of time. The segment with arrows is a visual aid to compare the GC contribution, $\omega_{gc}$, (assuming $f_{di} = 20$) to $\omega_{*}$ around $z \sim 6$. (right) Emissivity (photons per baryon per Hubble time) as a function of redshift. The thick solid, dashed and short-dashed lines show the contribution of GCs for cases (i), (ii) and (iii), respectively (assuming $f_{di} = 2$). The thin lines show the contribution of galaxies assuming a realistic $\langle f_{esc} \rangle = 0.1 \times \exp[-z/2]$ (solid) and a constant $\langle f_{esc} \rangle = 5\%$ (dashed). [Plots from Ricotti (2002).]
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The mean baryon density at $z = 0$, is shown in Fig. 1(left). The points show the observed SFR from Lanzetta et al. (2002).

In Fig. 1(right) I show $N_{ph}$ for GCs (thick lines) and for galaxies (thin lines) defined as,

$$N_{ph}^{gc} = \eta f_{di} \frac{d\omega_{gc}^f}{dt} t_H(z),$$

$$N_{ph}^* = \eta \langle f_{esc} \rangle \frac{d\omega_{f}^*}{dt} t_H(z).$$

The thick solid, dashed and short-dashed lines show $N_{ph}^{gc}$ for case (i), (ii) and (iii), respectively. For comparison, I show (thin solid line) $N_{ph}^*$ assuming $\langle f_{esc} \rangle = 0.1 \times \exp[-z/2]$, derived theoretically by Ricotti & Shull (2000) and normalised to fit the observed values (squares) of $N_{ph}^*$ at $z = 2, 3, 4$ (Miralda-Escudé et al. 2000). The thin dashed line shows $N_{ph}^*$ assuming constant $\langle f_{esc} \rangle = 5\%$.

5. Conclusions

The observed Lyman break galaxies at $z \sim 3$ are probably the most luminous starburst galaxies of a population that produced the bulk of the stars in our universe. Their formation epoch corresponds to the assembly of the bulges of spirals and ellipticals. Nevertheless the observed upper limit on $\langle f_{esc} \rangle$ from Lyman break galaxies, $\langle f_{esc} \rangle \lesssim 10\%$, may be insufficient to reionise the IGM according to numerical simulations. Ferguson et al. (2002), using different arguments based on the presence of an older stellar population, also noticed that the radiation emitted from Lyman break galaxies at $z > 3$ was insufficient to reionise the IGM assuming a continuous star formation mode.

I propose that GCs during their formation may have produced enough ionising photons to reionise the IGM. Assuming $f_{di} = 2$ (i.e., during their evolution GCs have lost half of their original mass), I find a stellar mass fraction in GCs, $\omega_{gc}^f \approx 0.1\%$, small compared to the total stellar budget $\omega_f^* \sim 10\%$ at $z = 0$. But GCs are about 12-13 Gyr old and, if they formed between $5 < z < 7$ (in about 0.5 Gyr), the expected total $\omega_f^*$ formed during this time period is about $\omega_f^* \sim 1\%$, only 10 times larger than $\omega_{gc}^f$. Assuming $f_{di} = 20$, expected from the results of N-body simulations, I find $\omega_f^* \approx 1\%$, suggesting that GC formation is an important mode of star formation at high-redshift. The star formation mode required to explain the formation of GCs suggests an $\langle f_{esc} \rangle \sim 1$ from these objects. This is because the mean $\langle f_{esc} \rangle$ is dominated by the most luminous OB associations and GCs are extremely luminous, emitting $S \sim 3 \times 10^{53}$ s$^{-1}$ ionising photons in bursts lasting only 4 Myrs. Moreover, according to many models, GCs form in the hot, collisionally-ionised galaxy halo, from which all the ionising radiation emitted can escape into the IGM. Therefore it is not too surprising, if GCs started forming before $z = 6$, that their expected contribution to reionisation is significant. I find that the number of ionising photons per baryon emitted in a Hubble time at $z = 6$ by GCs is $N_{ph}^{gc} = (5.1^{+1.3}_{-3.2}) f_{di}/\Delta t_{gc} > 1$, therefore sufficient to reionise the IGM even if we assume $f_{di} = 1$. Here, $\Delta t_{gc} \sim 0.5 - 2$.

Mpc$^{-3}$ is the mean baryon density at $z = 0$, is shown in Fig. 1(left). The points show the observed SFR from Lanzetta et al. (2002).

In Fig. 1(right) I show $N_{ph}$ for GCs (thick lines) and for galaxies (thin lines) defined as,
is the period of formation of the bulk of old GCs in Gyrs. Using simple calculations based on Press-Schechter formalism [see Fig. 1 (right)] I find that, if galaxies have \( \langle f_{\text{esc}} \rangle < \sim 5\% \), GC contribution to reionisation is important. If GCs formed by thermal instability in the halo of \( T_{\text{vir}} \sim 10^5 \) K galaxies (case (iii)), the ionising sources have a large bias (\( i.e. \), they form in rare peaks of the initial density field). Therefore, the mean size of intergalactic \( \text{H}^\text{II} \) regions before overlap is large and reionisation is inhomogeneous on large scales.

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