Low-Metallicity Star Formation:
From the First Stars to Dwarf Galaxies
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Searching for Pop III stars and galaxies at high redshift

Daniel Schaerer[1,2]

[1]Geneva Observatory, University of Geneva, 51, Ch. des Maillettes, CH-1290 Versoix, Switzerland

[2]Laboratoire d'Astrophysique de Toulouse-Tarbes, Université de Toulouse, CNRS, 14 Avenue E. Belin, F-31400 Toulouse, France

Abstract. We review the expected properties of Pop III and very metal-poor starbursts and the behaviour the Lyα and He II λ1640 emission lines, which are most likely the best/easiest signatures to single out such objects. Existing claims of Pop III signatures in distant galaxies are critically examined, and the searches for He II λ1640 emission at high redshift are summarised. Finally, we briefly summarise ongoing and future deep observations at $z > 6$ aiming in particular at detecting the sources of cosmic reionisation as well as primeval/Pop III galaxies.

Keywords. galaxies: high-redshift, galaxies: stellar content, (cosmology:) early universe

1. Introduction

Finding the first stars and galaxies remains a major observational challenge in astrophysics. Searches for metal-free (Pop III) or extremely metal-poor individual stars or for ensembles of stars (clusters, proto-galaxies, populations of galaxies, etc.) are ongoing both nearby (Pop III stars in the halo of our Galaxy), and in galaxies out to the highest redshifts currently known.

Astronomers have been quite inventive in searching for Pop III or metal-poor stars, exploiting many possible direct and indirect signatures; some of these methods will be discussed below. A more detailed account on primeval galaxies, some of the physics related to these objects, an overview on searches etc. is presented in the lectures of Schaerer (2007).

Although some studies may have found signatures of Pop III stars, none of those claims is very strong (see discussion below), and my personal opinion – taking a somewhat conservative attitude – is that Pop III stars still remain to be found. However, there is good hope that this goal should be reached in the near future with current or forthcoming instrumentation, as I will sketch below.

2. Expected properties of Pop III and very metal-poor populations

Many authors have modeled the evolution of Pop III stars in the 1980s and before. Since then the interest in these stars has been revived, and new generations of models computed. Subsequently I will use predictions from the stellar evolution and non-LTE atmosphere models as well as the evolutionary synthesis models computed by Schaerer (2002, 2003). For a detailed description of the input physics and references to earlier work the reader is referred to these papers.

One of the main distinctive features of Pop III stars is their extreme compactness close to and on the zero age main sequence (ZAMS), implying much higher effective temperatures (up to $\sim$ 100 kK) than usual. For a given mass this leads to a considerable

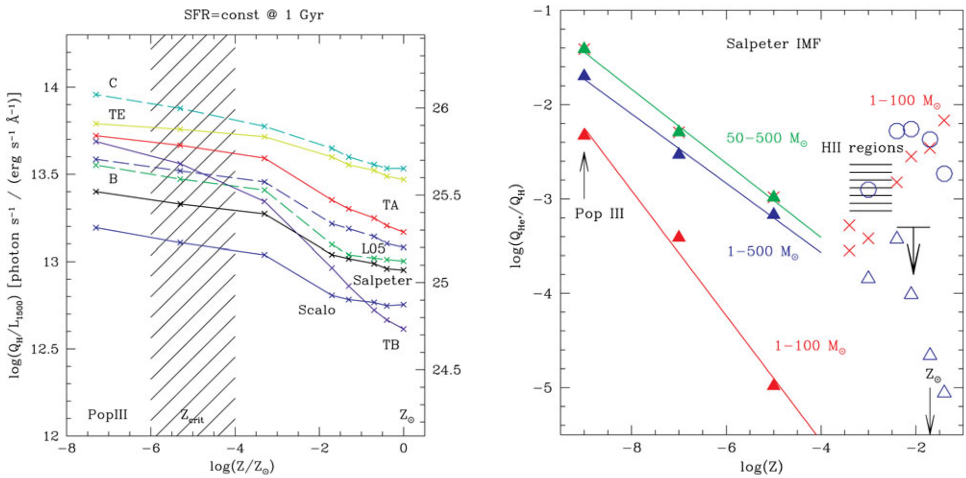

Figure 1. Left: Predicted ionising photon flux as a function of metallicity for different IMFs. The ionising output is normalised here to the UV luminosity. The shaded area labeled $Z_{\rm crit}$ indicates the domain where the typical stellar mass / IMF may change (cf. Schneider *et al.* 2004). **Right:** Dependence of the hardness of the ionising flux, expressed by $Q_{\rm He^+}/Q_H$, on metallicity and IMF. Figure from Schaerer (2003).

increase of the ionising flux and to a much harder ionising spectrum (cf. Tumlinson *et al.* 2001, Schaerer 2002). In addition, if the conditions in metal-poor environments favour the formation of massive stars (cf. Bromm & Larson 2004, and contributions by Abel, Bromm, Tan, and others in these proceedings), the integrated spectrum of young, zero and very low metallicity stellar populations can be quite different than that of populations at "normal" metallicities, as shown e.g. by Schaerer (2002, 2003). In particular, the strong Lyα line emission and the presence of nebular He II emission lines are probably the best/easiest features to search for very metal-poor and Pop III objects.

For example in Figure 1 (left) we show the increase of the ionising (Lyman continuum) photon flux Q_H normalised to the UV continuum luminosity with decreasing metallicity for different IMFs (Salpeter, Scalo; B, C as in Schaerer 2003, and other IMFs). For a fixed IMF the increase from solar to zero metallicity is typically a factor of 2; assuming that more extreme IMFs may be valid for Pop III, this increase can be up to a factor ~ 10 (compared to solar and Salpeter). Note that this prediction also depends on the exact star-formation (SF) history, which affects, in particular, the UV continuum output. The right panel of Fig. 1 shows the increase of the hardness of the ionising flux, expressed by the ratio of He^+ to H ionising flux, $Q_{\rm He^+}/Q_H$, with decreasing metallicity.

As already mentioned, the strong Lyman continuum flux at low metallicities implies a strong intrinsic Lyα emission (cf. Schaerer 2002, 2003). For example, the *maximum Lyα equivalent width* predicted for an integrated stellar population increases from $\sim$ 200-300 Å to 500-1000 Å or even larger (depending on the IMF) from solar to zero metallicity, as shown in Fig. 2. Of course it must be reminded that after its emission inside the ionised region surrounding the starburst, Lyα photons are scattered and may be absorbed, thereby altering the intrinsic value of W (see e.g. Schaerer 2007).

The increase of the hardness of the ionising radiation shown in Fig. 1 (right) translates into the increase of He II recombination lines, such as He II λ1640, shown in Fig. 2 (right). For obvious reasons their strength depends on the exact SF history, age, and in particular

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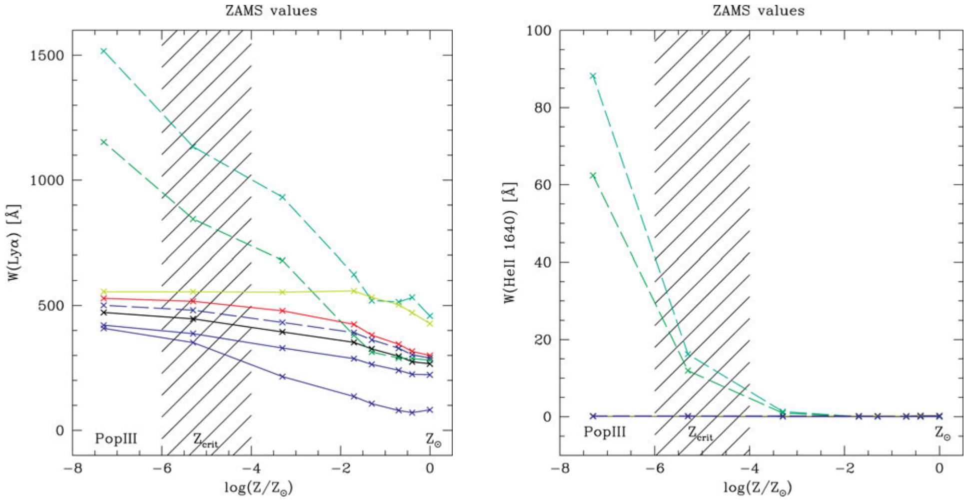

Figure 2. Left: Predicted maximum value of $W(\mathrm{Ly}\alpha)$ as a function of metallicity and IMF (same colors as Fig. 1). **Right:** Same as left for W(He II λ1640). See discussion in text.

on the IMF, as shown by these figures (see also Schaerer 2003). While clearly a promising signature of very metal-poor populations as pointed out earlier†, this strong sensitivity to the presence of the most massive stars – i.e. to the IMF and age – may complicate the interpretation of He II lines, especially when dealing with non-detections (cf. below).

Once the properties of individual Pop III clusters or galaxies are known, important questions are of course how many such objects are expected and what is their distribution, e.g. in mass and luminosity? Answering these questions requires in particular a description of the transport and mixing of metals to determine the duration (locally) of Pop III SF events. Several authors have addressed this using different approaches (e.g. Scannapieco *et al.* 2003, Yoshida *et al.* 2004, Tornatore *et al.* 2007). The predicted Pop III SF rate, defined by SF in regions with $Z < Z_{\rm crit}$, as a function of redshift from the recent computations of Tornatore *et al.* (2007) is shown in Fig. 3. Predicted number counts from Choudhury & Ferrara (2007) are shown in Fig. 5 for illustration.

3. Have we found Pop III?

It is possible that galaxies containing Pop III or very metal-poor stars have already been found in different samples. Here I will critically examine some of these results.

3.1. *Have we found Pop III in Lyman Break Galaxies?*

For example, Jimenez & Haiman (2006) have recently proposed an explanation to several apparent puzzles concerning Lyman Break Galaxies (LBGs) and related objects at $z \sim$ 3–4. They propose that their stellar populations contain $\sim$ 10–30 % of primordial stars, which would explain the observed He II λ1640 emission in LBGs, the existence of some

† Caveat: He II λ1640 emission can also of different origin (stellar cf. Sect. 3.1, AGN or shocks) and nebular He II is observed in some normal H II regions (see e.g. Thuan & Izotov 2005) or in other peculiar objects (cf. Fosbury *et al.* 2003 and discussion in Schaerer 2003b).

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galaxies with very high W(Lyα), the excess of Lyman continuum flux seen in some LBGs, and the nature of Lyα blobs.

Although the idea to tackle simultaneously four problems is in principle attractive, the proposed solution is probably not unique and not the most likely one, and some of the 4 problems may not be robust observationally. First, the strength of the He II λ1640 line in the composite spectrum of LBGs is quite modest ($W(1640) = 1.3 \pm 0.3$ Å), and small enough to be explained by Wolf-Rayet stars in normal stellar populations (cf. models of Schaerer & Vacca 1998, and Brinchmann *et al.* 2008). Furthermore the observed line is broad, as observed in Wolf-Rayet stars. Second, the existence of a population of galaxies at $z \sim$ 4–5 with high Lyα equivalent widths found by the LALA survey, does not seem to be confirmed by other groups or is at least very uncertain (see Sect. 3.2). Third, other explanations are proposed for extended Lyα blobs (e.g. Matsuda *et al.* 2007). Finally, the proposed explanation may also have difficulties with mixing time scales (Pan & Scalo 2007). The excess of Lyman continuum flux in some LBGs remains still puzzling (see also Shapley *et al.* 2006, Iwata *et al.* 2008)

3.2. *Have we found Pop III in Lyα emitters?*

A few years ago Malhotra & Rhoads (2002) found Lyα emitters (LAE) at $z \sim 4.5$ with an unusual Lyα equivalent width distribution from their LALA survey. They suggested that their large fraction of objects with a high W(Lyα) ($>$ 200-300 Å) could be due to very metal-poor or Pop III objects, a very unusual IMF, or to AGN. Follow-up observations of these objects have been undertaken, also at X-rays, and several papers have already adressed these results (see discussion in Schaerer 2007). The AGN hypothesis has been rejected (Wang *et al.* 2004). Deep spectroscopy aimed at detecting other emission lines, including the He II λ1640 line indicative of a Pop III contribution (cf. Sect. 4), have been unsuccessful (Dawson *et al.* 2004), although the achieved depth may not be sufficient. If taken at face value, the origin of these high W(Lyα) remains thus unclear. However, there is some doubt on the reality of these equivalent widths measured from NB and broad-band imaging, or at least on them being so numerous even at $z = 4.5$. First of all the objects with the highest W(Lyα) have very large uncertainties since the continuum is faint or non-detected. Second, the determination of W(Lyα) from a NB and a centered broad-band filter (R-band in the case of Malhotra & Rhoads 2002) may be quite uncertain, e.g. due to unknowns in the continuum shape, the presence of a strong spectral break within the broad-band filter etc. (see Hayes & Oestlin 2006 for a quantification, and Shimasaku *et al.* 2006). Furthermore other groups have not found such high W objects (e.g. Hu *et al.* 2004, Ajiki *et al.* 2003 and compilation in Verhamme *et al.* 2008) suggesting also that this may be related to insufficient depth of the LALA photometry.

Recently Shimasaku *et al.* (2006) and Dijkstra & Wyithe (2007) have again, used W(Lyα) distributions to argue for a non-negligible contribution of Pop III stars in LAEs, this time in objects at $z \geqslant 5.7$. In fact the *observed* restframe values of W(Lyα) LAE samples at $z = 5.7$ and 6.5 obtained with SUBARU are considerably lower than those of Malhotra & Rhoads at $z = 4.5$, and only few objects show $W^{\rm rest}_{\rm obs}$(Lyα)$\gtrsim$200 Å, the approximate limit expected for "normal" stellar populations (cf. Fig. 2). However, if the IGM transmission T_α affects half of the Lyα line, as often assumed (see also Hu *et al.* 2004), this would imply true intrinsic equivalent widths $2/T_\alpha$ times higher than the observed value, i.e. typically 4 times higher at $z = 5.7$! For this reason Shimasaku *et al.* suggest that these may be young galaxies or objects with Pop III contribution. Based on this reasoning and on modeling the Lyα luminosity function and IGM transmission, Dijkstra & Wyithe (2007) argue for the presence of $\sim$ 4–10 % of Pop III SF in $\sim$ half of Lyα selected galaxies and in few percent of i-drop galaxies at $z \gtrsim$ 5.7.

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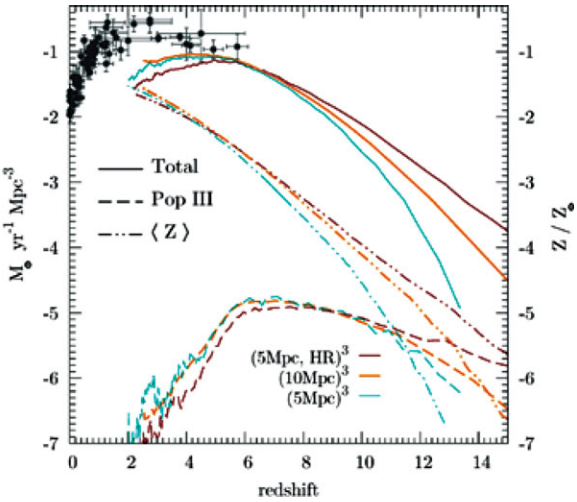

Figure 3. Predicted SFR density and average metallicity as a function of redshift showing the contribution of Pop III (defined as metallicity $Z < Z_{\rm crit}$, cf. above) and other stars. Recently Nagao *et al.* (2008) have derived $SFRD_{\rm PopIII} \lesssim 5.\,10^{-6}$ $M_\odot$ yr^{-1} Mpc^{-3} at $4.0 \lesssim z \lesssim 4.6$ close to the predicted value at this redshift. Figure from Tornatore *et al.* (2007).

Although possible, this conclusion rests strongly on the assumption that the IGM transmission (due to individual or overlapping Lyα forest clouds) really cuts out a significant fraction of the Lyα line emerging from the galaxy. This is by no means clear, e.g. since it implies the need for cold gas close (and/or infalling) to the galaxies, which has not been observed yet. E.g. in the LBG cB58 studied in depth, Savaglio *et al.* (2002) find no Lyα absorption close to the galaxy (at $\Delta v \lesssim$ 2000 km s^{-1}). Also Verhamme *et al.* (2008) find no need for IGM absorption in their Lyα profile modeling of LBG/LAE at $z \sim$ 3–5. Furthermore, absorbing a fraction of Lyα by the IGM is even more difficult if the intrinsic Lyα profile emerging from the galaxy is already redshifted (and asymmetric), as expected if outflows are as ubiquitous as in LBGs at lower redshift. Assessing these important issues remains to be done. In the meantime conclusions depending strongly on corrections to the observed Lyα equivalent widths (or LF) should probably be taken with caution.

4. Searches for He II emission

Several groups have tried to use the expected He II λ1640 emission (cf. Sect. 2) to search for Pop III stars, so far with no positive detection. However, the limits obtained from most recent survey begin to provide interesting constraints.

4.1. *Upper limits from individual objects or composite spectra*

Follow-up spectroscopy of LALA sources by Dawson *et al.* (2004) (cf. Sect. 3.2) have yielded an upper limit of W(Lyα) $<$ 25 Å (3 σ) and He II λ1640/Ly$\alpha <$ 0.13–0.20 at 2–3 σ from their composite spectrum (11 objects). Nagao *et al.* (2005) searched for He II λ1640 with deep spectroscopy of one strong Lyα emitter at $z = 6.33$. Currently the lowest limit on He II emission is that measured by Ouchi *et al.* (2008) in composite spectra of 36 and 25 $z = 3.1$ and 3.7 LAEs. They reach I(He II λ1640)/I(Lyα) $<$ 0.02 and 0.06 (3σ) at

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these two redshifts, which translates to $\log(Q_{\mathrm{He}^+}/Q_H) < -1.9$ and < -1.4 respectively†. Although no definite conclusions can be drawn from that, comparison with Fig. 1 (right) show that these limits are already close to the maximum or slightly below the predicted values for metal-free populations with IMFs including very massive stars.

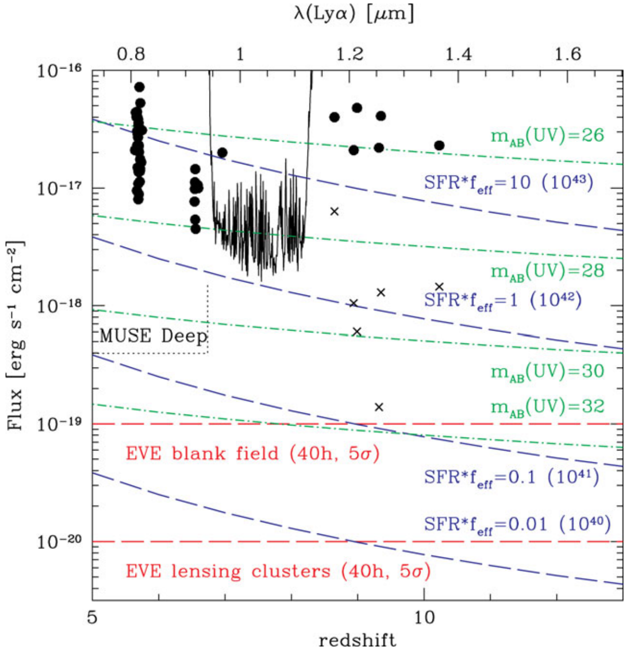

Figure 4. Observed Lyα flux as a function of redshift (observed wavelength on top) achieved with 10m class telescopes. Observations from Shimasaku *et al.* (2006), Kashikawa *et al.* (2006), and Ota *et al.* (2008) at $z = 5.7$, 6.5, and 7, as well as the $z \sim 8.5$ to 10 lensed candidates of Stark *et al.* (2007) are shown by the filled circles (observed fluxes, and crosses: intrinsic fluxes for lensed objects). The black line shows the flux limit from deep NIRSPEC/Keck spectroscopy of Richard *et al.* (2008) from 0.95 to 1.1 μm. Blue dashed lines show the fluxes corresponding to values of SFR$\times f_{\mathrm{eff}}$ from 0.01 to 10 $\mathrm{M}_\odot$ yr^{-1}, where f_{eff} denotes the effective Lyα transmission, including the IGM transmission and other possible losses, e.g. inside the galaxy. Green dash-dotted lines show the expected Lyα flux for star-forming galaxies with rest-frame UV continuum magnitudes from 26 to 32 in the AB system, assuming $f_{\mathrm{eff}} = 1$. In both cases the conversion to Lyα flux was computed assuming a standard SFR calibration based on Kennicutt (1998) and case B. Deep observations with MUSE, a 2nd generation instrument for the VLT, and observations with EVE, a proposed multi-object spectrograph for the E-ELT, will allow to push the current limits down by $\sim$ 1–2 magnitudes!

4.2. *The first constraint on the He* II $\lambda 1640$ *flux density at high redshift*

Using an original approach combining narrow/intermediate-band filters to select dual Lyα + He II λ1640 emitters at $z \sim 4.0$ and 4.6, Nagao *et al.* (2008) have carried out a survey of 875 arcmin^2 using SUBARU in the Subaru Deep Field (see also Nagao, these proceedings, for more details). No such dual emitters were found, down to a flux limit of $(6-7) \times 10^{-18}$ erg s^{-1} cm^{-2} for He II λ1640. With some assumptions on the IMF and using the models of S03, the observed flux limits translate to an upper limit for the Pop III SFR of $\gtrsim 2$ $\mathrm{M}_\odot$ yr^{-1}, and a SFR density of $SFRD_{\mathrm{PopIII}} \lesssim 5.10^{-6}$ $\mathrm{M}_\odot$ yr^{-1}

† The approximate translation between line ratios and ionising flux ratios is $Q_{\mathrm{He}^+}/Q_H = 0.6\, I(\mathrm{He\ II}\ \lambda 1640)/I(\mathrm{Ly}\alpha)$ (cf. S03).

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Mpc^{-3} at $4.0 \lesssim z \lesssim 4.6$ (Nagao *et al.* 2008). Interestingly this first Pop III SFR density determination turns out to be very close to the theoretical prediction of Tornatore *et al.* (2007) shown in Fig. 3. Clearly further work and deeper observations are required to track the elusive Population III at high-redshift and future theoretical work may provide a more detailed/accurate picture of the expectations.

5. Ongoing and future deep observations at $z > 6$

The impressive depth – down to few times 10^{-18} erg s^{-1} cm^{-2} – reached already in emission line searches with SUBARU, VLT, and Keck is illustrated in Fig. 4, where Lyα measurements and upper limits obtained in the visible and near-IR domain are compiled. In the case of lensed galaxies the intrinsic depths can be considerably larger, as e.g. shown for the candidate high-z galaxies of Stark *et al.* (2007). In several cases of $z > 6$ galaxies or candidates, spectroscopic follow-up observations have already been undertaken to search for various emission lines, including the potential Pop III indicator He II λ1640 discussed above (e.g. Pelló *et al.* 2005, Stark *et al.* 2007, Richard *et al.* 2008, in preparation).

Since the average metallicity of galaxies must decrease with increasing redshift, searches for primeval galaxies and/or Pop III galaxies are also naturally focussed towards the highest redshift. At the same time galaxy searches at $z > 6$ are also of great interest to identify the sources of cosmic reionisation.

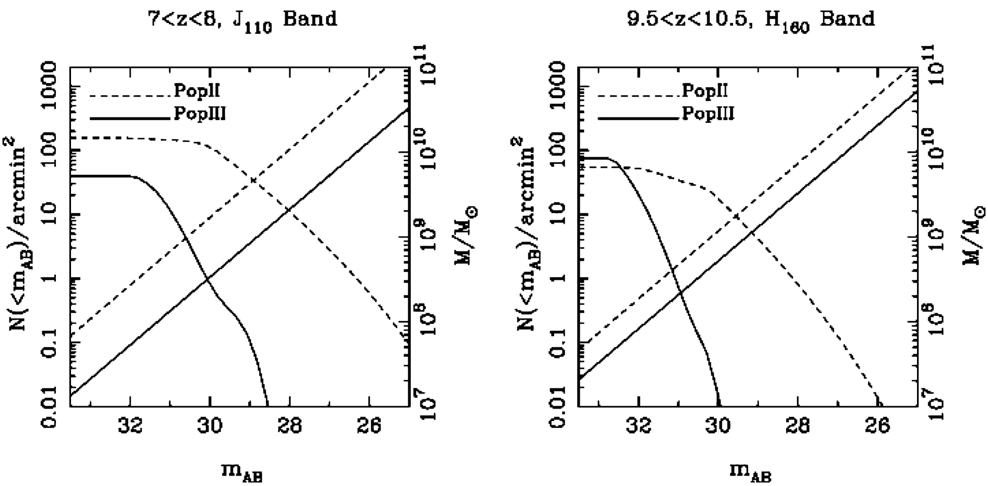

Figure 5. Predicted (cumulative) number density of "normal" (Pop II) and Pop III dominated sources for $z \sim 7.5$ (left) and $z \sim 10$ (right). Figure from Choudhury & Ferrara (2007).

Reviewing the status of galaxy searches/observations at $z > 6$ is beyond the scope of the present contribution. For an overview see e.g. Schaerer (2007 and references therein). The most recent results from searches for $z > 7$ galaxies are presented by Bouwens *et al.* (2008) and Richard *et al.* (2008), who use surveys in blank fields or fields with massive galaxy clusters benefiting from strong gravitational lensing. At the bright end of the LF the number density of galaxies at $z \gtrsim 7$, and hence also the total SFR density, remains controversial (cf. Richard *et al.* 2006, Bouwens *et al.* 2008). At fainter magnitudes ($m_{AB} \gtrsim 27$) the results from these two approaches (blank fields and lensing clusters) give consistent number densities (see Richard *et al.* 2008). The lensing cluster technique allows one to extend the observations to the faintest levels, currently down to an effective magnitude of $m_{AB} \sim$ 29–30. Clearly the two techniques, one with an additional gain in

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depth by lensing over a small area and the other over wide fields, are complementary and both approaches will likely play an important role in finding distant, primeval, maybe even Pop III dominated objects.

The lensing studies show a source density of 3–100 arcmin$^{-2}(\Delta z = 1)^{-1}$ for $7 < z < 8$ from $m_{AB} = 28$ to 30 (Richard *et al.* 2008). This source density is also in agreement with the theoretical predictions from Stiavelli *et al.* (2004) and Choudhury & Ferrara (2007), shown in Fig. 5 . If spectroscopy of objects down to magnitudes of 30 or even 32 become feasible with extremely large telescopes (cf. Fig. 4) this means that we should expect very high source densities, e.g. several hundred objects(!) in a field of view of several arcmin^2 as foreseen for ELT instruments. High multiplex multi-object spectrographs reaching with an optical and near-IR coverage up to $\sim 1.7\mu$m, such as EVE proposed for the E-ELT, should therefore be very efficient in detecting Lyα and He II λ1640 lines up to redshift 13 and 9.4 respectively. Great progress can be expected from searches for the sources of cosmic reionisation and primeval/Pop III galaxies in the fairly near future!

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