# Reionization and Metal Enrichment by the First Stars

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**KITP, UC Santa Barbara; October 29, 2002**

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# CURRENT CONCORDANCE MODEL

From a wide variety of observations probing different physical scales:

$\Omega_B \sim 0.04$ (Light element abundances, high-$z$ D measurements)
$\Omega_{\rm Lum} \sim 0.01$ (Multi-wavelength obsvns. of luminous baryons)
$\Omega_M \sim 0.3$ (Galaxy clusters, galaxy rotation curves, weak lensing)
$\Omega_\Lambda \sim 0.7$ (High-$z$ SNe)
h $\sim$ 0.7 (Direct measurement, CMB, large-scale structure)
$\Omega_{\rm tot} \sim 1$ (CMB, large-scale structure, high-z SNe)
Age of universe $\sim$ 14 billion yr
(Some of the above, and ages of oldest objects in Galaxy)

# SIGNIFICANCE OF THE FIRST STARS

- **In the currently favored adiabatic CDM paradigm, the first galaxies are thought to form at redshifts, $z \sim 30$–$50$, and the first stars at $z \sim 10$–$30$.**

- **The formation sites of the first stars are not well understood, because the extent of the radiative feedback from early luminous sources is an unresolved topic. It is unclear whether the primary coolant for star formation within individual high-$z$ halos is molecular hydrogen ($H_2$) or hydrogen line cooling.**

- **The first stars are expected to be cosmologically significant, from at least two sets of observational results: hydrogen reionization, and the metal enrichment of the Ly$\alpha$ clouds in the intergalactic medium (IGM) by $z \sim 3$.**

- **Thus, understanding the evolution of stars is important in studies of the high-$z$ universe. There should be a strong correlation between the integrated stellar output of metals and ionizing radiation.**

- **Examining the connection between these two effects is critical for at least two problems: the degree to which the same population of early stars may have influenced reionization and the IGM enrichment, and the accurate calculation of the IGM metallicity from observations of absorption lines corresponding to specific metal ionization states, which depends on the assumptions made for the ionizing photon background.**

# BACKGROUND ON REIONIZATION

- **Observations of the spectra of distant quasars and galaxies have revealed that the intergalactic medium (IGM) was highly ionized by redshifts, $z$, $\sim 6$.**

- **From degree and sub-degree anisotropy in current CMB temperature data, $\tau_{\rm reion} \leq 0.3$ ($z_{\rm reion} \leq 25$ for $h = \Omega_\Lambda = 0.7$). Satellite experiments such as *MAP* and *Planck* will place far stronger limits on such parameters.**

- **The ionizing sources can be a variety of astrophysical objects: stars, QSOs, proto-galaxies, and related processes, e.g., cosmic rays, supernovae, galactic winds. Leading scenarios at present involve photoionization by stars or mini-QSOs.**

- **Much work, numerical and semi-analytic, on various reionization scenarios has been done in the last decade, partly motivated by the many observational signatures of reionization which can potentially be detected in the near future.**

- **The epoch of H–reionization:**
  **$z \sim$ 6–20 (theoretical models)**
  **$z \sim$ 6–25 (observational limits)**

- **Current data imply that H I reionization may occur not far beyond $z \sim 6 - 7$, and He II reionization at $z \sim 3$.**

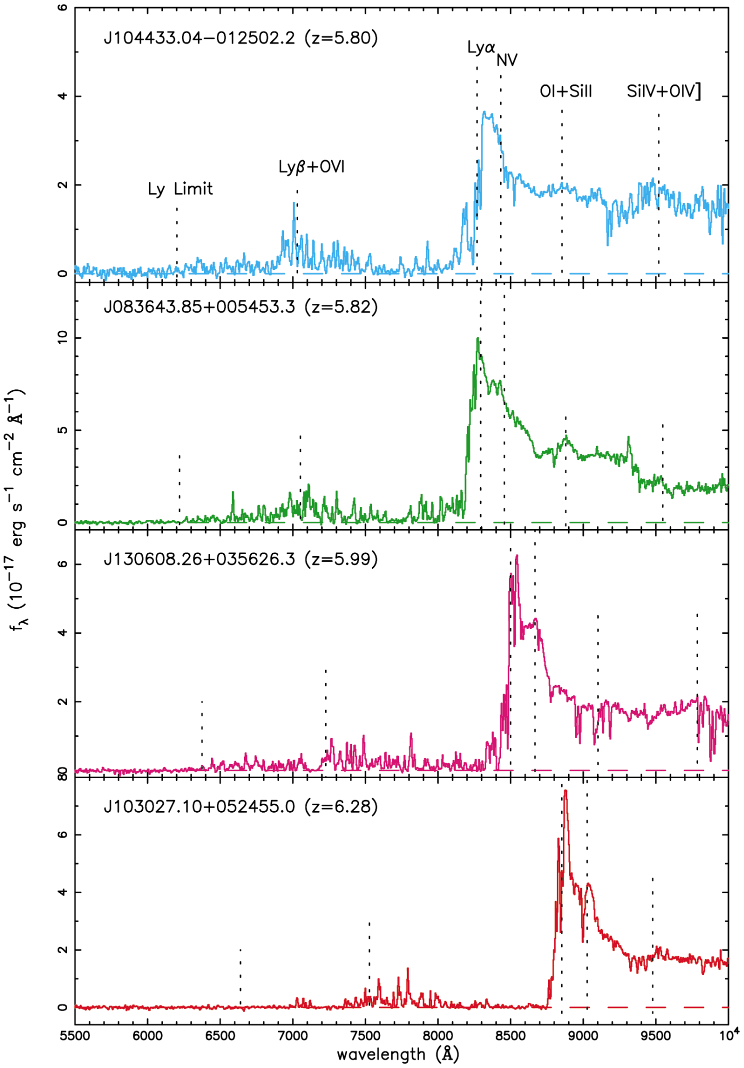


FIG. 1.—Optical spectra of $z \gtrsim 5.8$ quasars observed with Keck/ESI in the observed frame. The spectra have been smoothed to 4 Å pixel$^{-1}$ and have been normalized to the observed $z$-band flux. The spectrum of SDSS 1044−0125 has been taken from Fan et al. (2000). In each spectrum, the expected wavelengths of prominent emission lines, as well as the Lyman limit, are indicated by the dashed lines.

$\lambda$1402 feature is detected at ~9800 Å, but it is difficult to fit its profile because of the weakness of the line and possible absorption lines nearby. We therefore adopt a redshift of $5.99 \pm 0.02$ for SDSS 1306+0356.

In the spectrum of SDSS 1306+0356, we notice a strong absorption feature at ~7130 Å, where over ~80 Å there is no detectable flux. The rest-frame equivalent width is ~15 Å, typical for a damped Lyα system, at a redshift of $z_{\rm abs} = 4.86$. A strong absorption feature is detected at $\lambda = 9080$ Å, corresponding to C IV absorption at the same redshift. This feature is double peaked in absorption, consistent with the $\lambda\lambda$1548, 1551 components of the C IV doublet, although the signal-to-noise ratio is low at that wavelength. This system, if confirmed by high-S/N spectroscopy, is the highest-redshift damped Lyα system known (the previous record holder was at $z = 4.47$, Péroux et al. 2001; Dessauges-

# Evidence for Reionization at z ∼ 6.3 from SDSS:

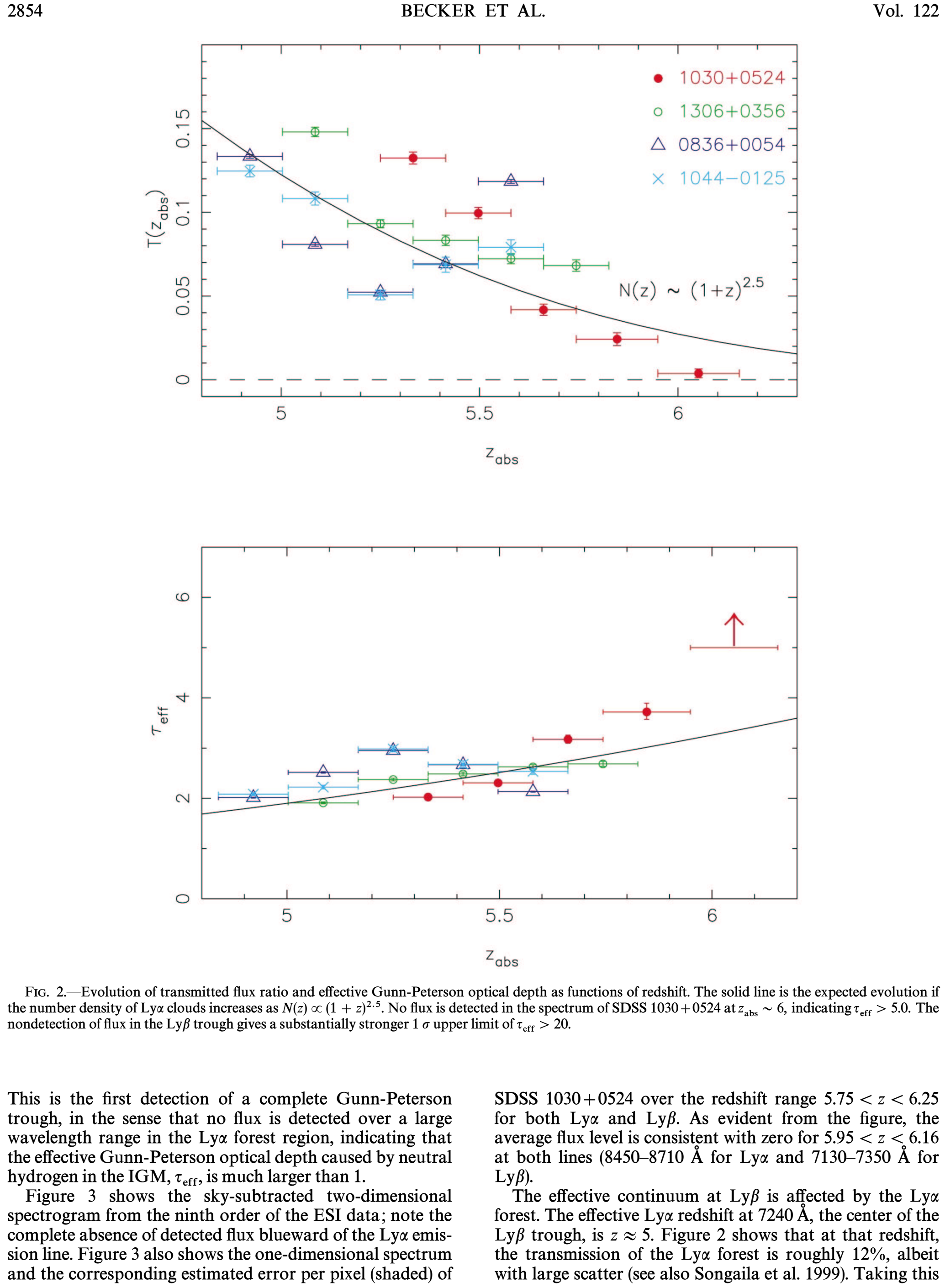


FIG. 2.—Evolution of transmitted flux ratio and effective Gunn-Peterson optical depth as functions of redshift. The solid line is the expected evolution if the number density of Ly$\alpha$ clouds increases as $N(z) \propto (1+z)^{2.5}$. No flux is detected in the spectrum of SDSS 1030+0524 at $z_{abs} \sim 6$, indicating $\tau_{eff} > 5.0$. The nondetection of flux in the Ly$\beta$ trough gives a substantially stronger 1 $\sigma$ upper limit of $\tau_{eff} > 20$.

This is the first detection of a complete Gunn-Peterson trough, in the sense that no flux is detected over a large wavelength range in the Ly$\alpha$ forest region, indicating that the effective Gunn-Peterson optical depth caused by neutral hydrogen in the IGM, $\tau_{eff}$, is much larger than 1.

Figure 3 shows the sky-subtracted two-dimensional spectrogram from the ninth order of the ESI data; note the complete absence of detected flux blueward of the Ly$\alpha$ emission line. Figure 3 also shows the one-dimensional spectrum and the corresponding estimated error per pixel (shaded) of SDSS 1030+0524 over the redshift range $5.75 < z < 6.25$ for both Ly$\alpha$ and Ly$\beta$. As evident from the figure, the average flux level is consistent with zero for $5.95 < z < 6.16$ at both lines (8450–8710 Å for Ly$\alpha$ and 7130–7350 Å for Ly$\beta$).

The effective continuum at Ly$\beta$ is affected by the Ly$\alpha$ forest. The effective Ly$\alpha$ redshift at 7240 Å, the center of the Ly$\beta$ trough, is $z \approx 5$. Figure 2 shows that at that redshift, the transmission of the Ly$\alpha$ forest is roughly 12%, albeit with large scatter (see also Songaila et al. 1999). Taking this

# THE ROLE OF STARS IN REIONIZATION

**• Optical and radio surveys indicate a decline in the large bright QSO population's space density up to $z \sim 6.3$ beyond a peak at $z \sim 3$. If this is real, QSOs are less likely to be sources of HI reionization.**

**• Stars create the first metals in the universe, and could account for the persistent metallicity ($Z \sim 0.003 Z_\odot$) seen in Ly$\alpha$ clouds up to $z \sim$ 3–4. 75% of absorbers with HI column density $\geq 3 \times 10^{14}$ cm$^{-2}$ show C IV absorption: the Ly$\alpha$ forest is "ubiquitously" enriched by $z \sim 3$. The conversion to the associated ionizing radiation shows that the first stars must have played a significant part in reionization. Furthermore, line widths of C IV, Si IV, N V, and C II indicate that these systems are photoionized rather than collisionally ionized.**

**• Indications from high-$z$ quasar spectra of a soft component to the UV background at $z \sim 3$, consistent with a stellar ionizing spectrum. Further evidence from observed C IV/Si IV ratio of a transition at $z \sim 3$ from a soft to hard ionizing UV background.**

**• The observational evidence for the delayed reionization of He II (at $z \sim 3$) relative to H I (at $z \sim 6$–$7$) has usually been taken to be consistent with the higher ionization potential and shorter recombination time of He II relative to H I. Sources of He II reionization were thought to likely be quasars, which have relatively hard ionizing spectra relative to that from stars of metallicity down to about $10^{-5}$.**

**• However, recent work has revealed that metal-free stars differ dramatically from their lowest-$Z$ counterparts in producing a significant amount of He II ionizing photons during their main-sequence phase.**

# REVIEW OF STELLAR EVOLUTION

- **The critical factors that determine a star's fate (structure and evolution) are its mass and initial chemical composition.**

- **The lifetime of stars goes roughly as the inverse cube of the star's mass, with some dependence on the progenitor metallicity, $Z$.**

- **All of the ionizing radiation and most of the created metals (elements heavier than $^4$He) come from the massive stars ($\geq 10\ M_\odot$) in the stellar initial mass function (IMF).**

- **As we progress from solar-$Z$ stellar populations to lower $Z$s, the general trend is for the massive stars to get hotter and bluer (greater ionizing radiation) and to have lower post-SN integrated metal yield.**

- **For a present-day IMF, elements like oxygen, neon, magnesium, silicon and sulphur (alpha elements) come from short-lived massive stars, whereas elements like carbon are created by longer-lived intermediate-mass (3–6 $M_\odot$) stars.**

- **Thus, the various probes of stellar activity, e.g., generated metals, ionizing photons, etc., are themselves highly dependent on the progenitor metallicity, altering the nature of these constraints with the average enrichment of starforming regions and hence with redshift.**

# PROPERTIES OF THE FIRST STARS

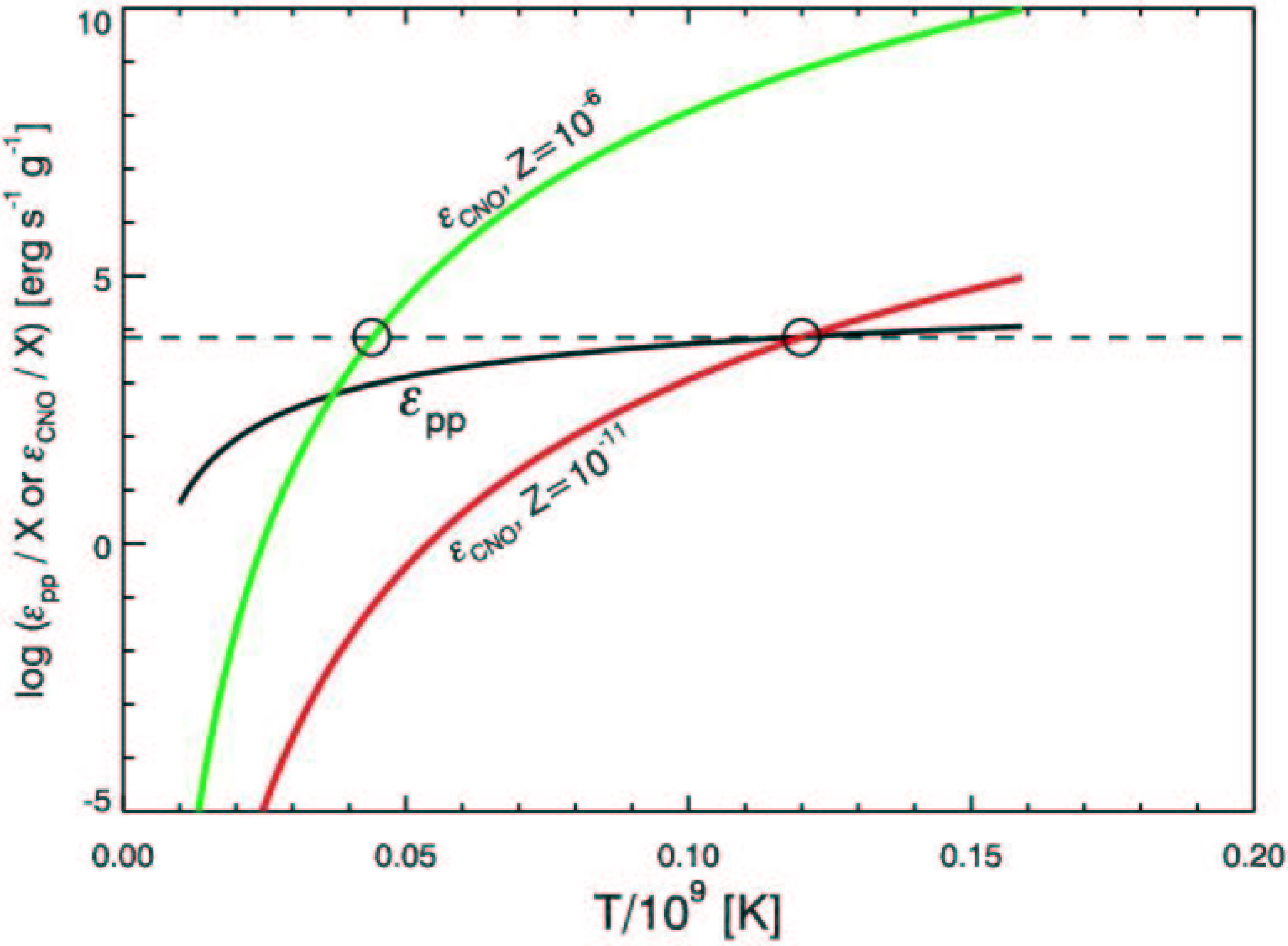
- The first generations of stars are expected to be metal-free in composition (Population III), and to have fundamentally different evolutionary properties relative to their finite-metallicity counterparts.

- Studies of such stars have remained theoretical in nature to date, as they are undetected in observational searches for them in our own Galaxy and at high redshift. Yet such stars must have existed at some point in the past – the question is how long such an epoch of metal-free star formation lasted, and what, if any, observable consequences it had?

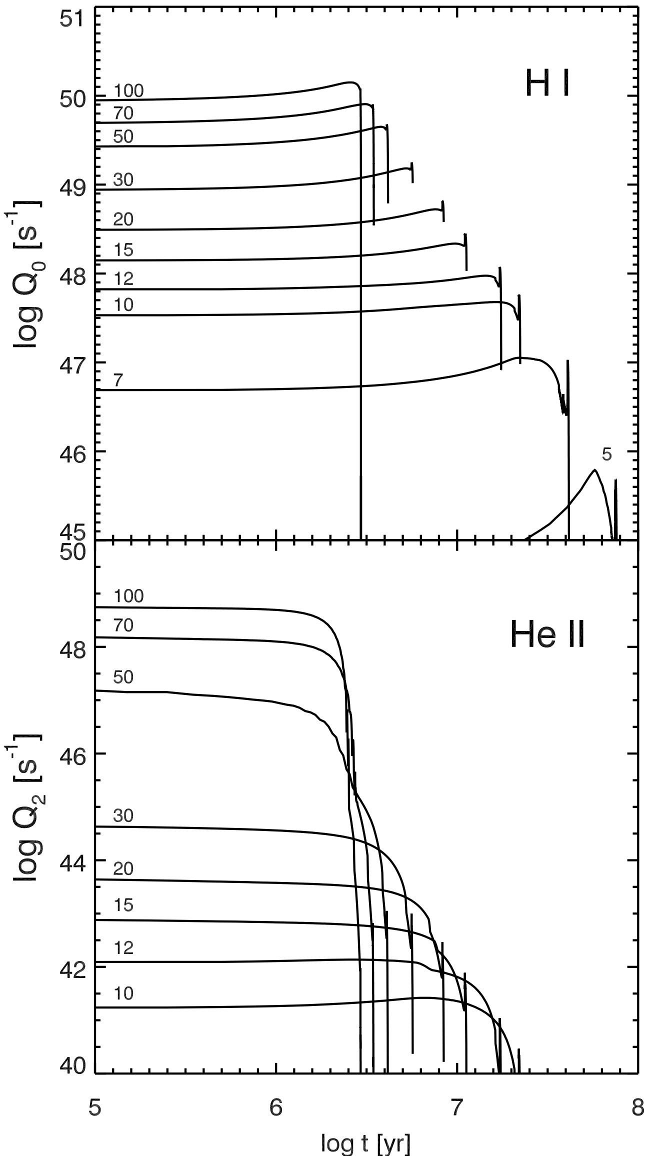
- The Colorado group (Tumlinson & Shull 2000) has constructed evolving, synthetic spectra for stellar populations of Pop. III stars. The grid of evolutionary tracks range over stellar masses of 1–100 $M_\odot$, and assume no mass loss.

- As these stars have no metals, their thermonuclear fuel source is the p–p chain rather than the more efficient CNO cycle, which drives the core temperatures to much higher values. Consequently, they are hotter, smaller and emit harder radiation.

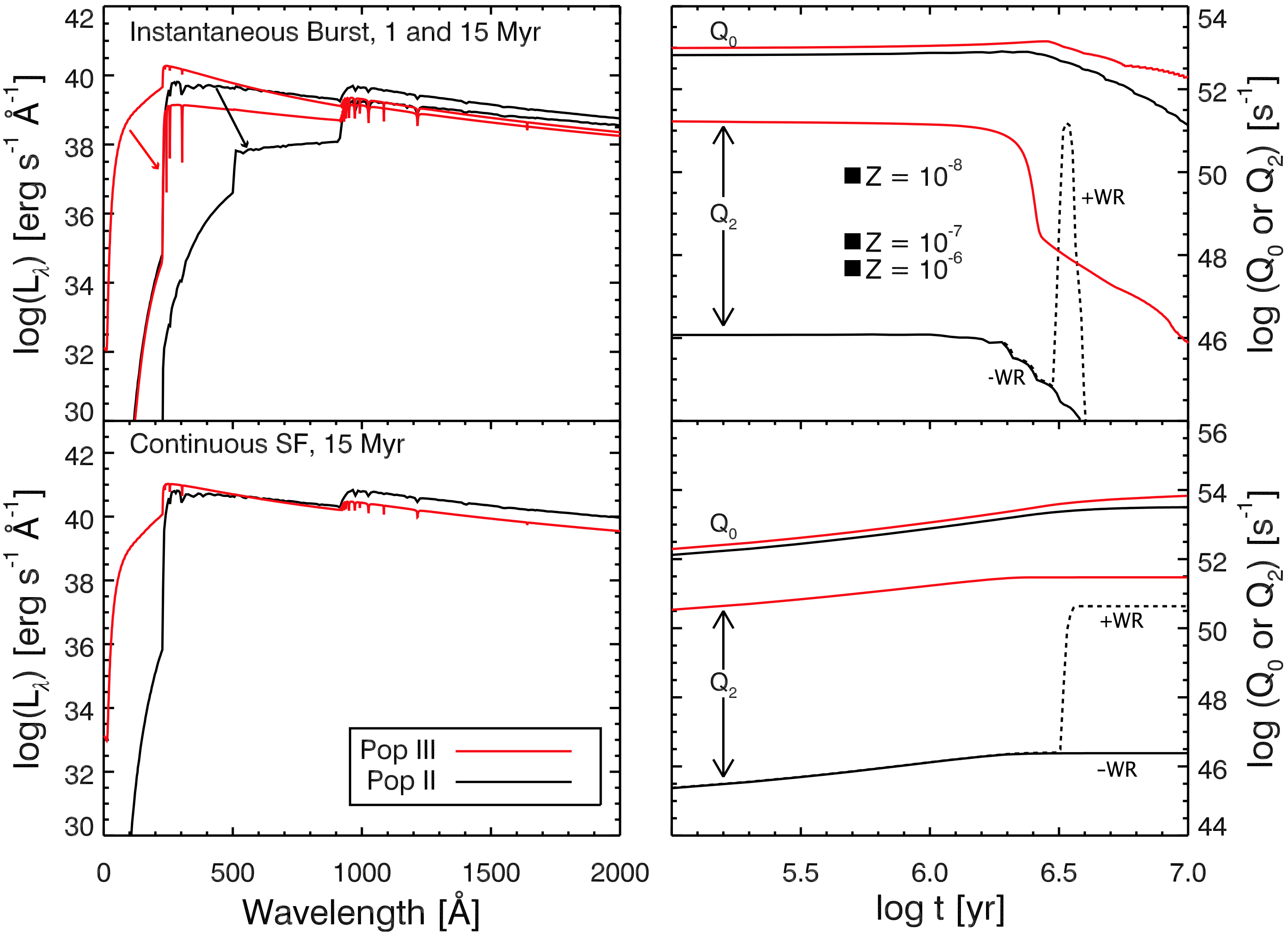
**Energy generation rates ($\epsilon$) illustrate why metal-free stars must attain unusually high temperatures to support their mass against gravity. The black curve shows the pp rate for a typical H mass fraction $X = 0.7$. The green and red curves show the CNO rate for a fiducial low metallicity and for Pop III, respectively. The horizontal dashed line marks a typical rate for the interior of a massive ($M > 20\ M_\odot$) star. The circles mark the points where the respective burning processes produce the desired total $\epsilon$.**



**Ionizing photon production rates $Q_0$ (1 Ryd; upper panel) and $Q_2$ (4 Ryd; lower panel) for individual stars. The tracks are labeled with their stellar mass in $M_\odot$.**



**The evolving composite spectra and IMF-weighted cluster $Q_0$, $Q_2$ for a synthetic stellar cluster of total mass $10^6$ $M_\odot$ that forms stars in a Salpeter IMF between 1–100 $M_\odot$. For comparison with Pop. II stellar spectra, we use the tracks from Leitherer et al. (1999; STARBURST package) for $Z = 0.001$ stars. This does not include nebular emission.**



- **Pop. III stars are roughly twice as hot as Pop. II stars.** **Relative to Pop. II, the Pop. III stellar cluster emits 60% more H I ionizing photons and $10^5$ more He II ionizing photons during its lifetime.**

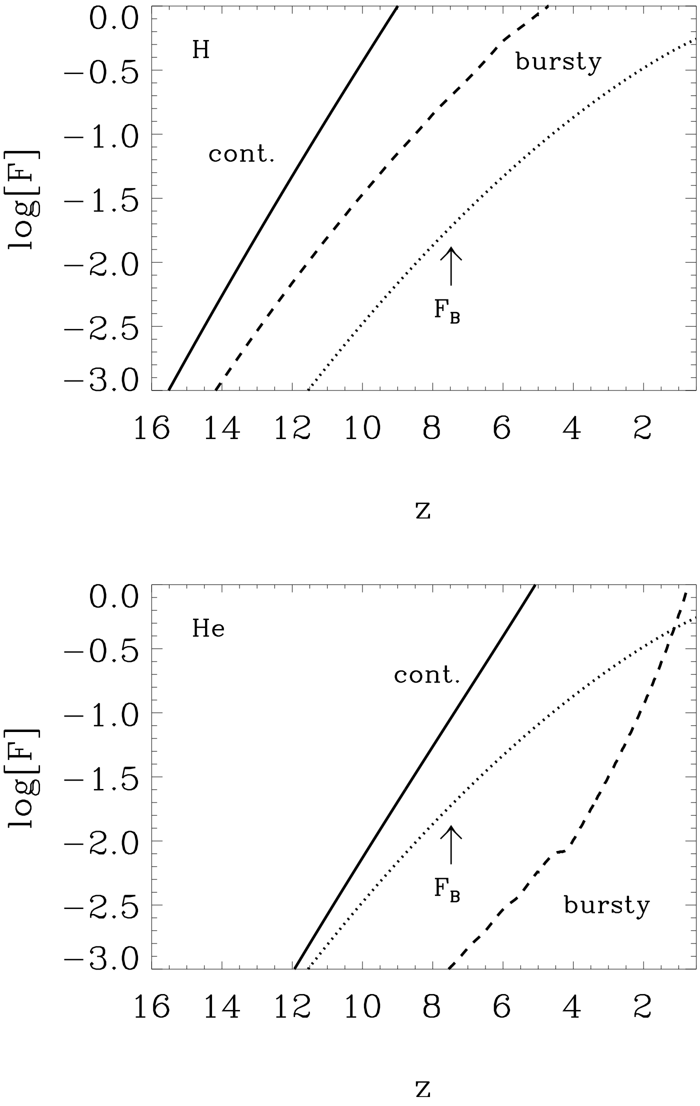
# POP. III STARS AND REIONIZATION

- In order to assess the effect of Pop. III stars on the high-$z$ IGM, we use the semi-analytic stellar reionization model described in Venkatesan (2002).

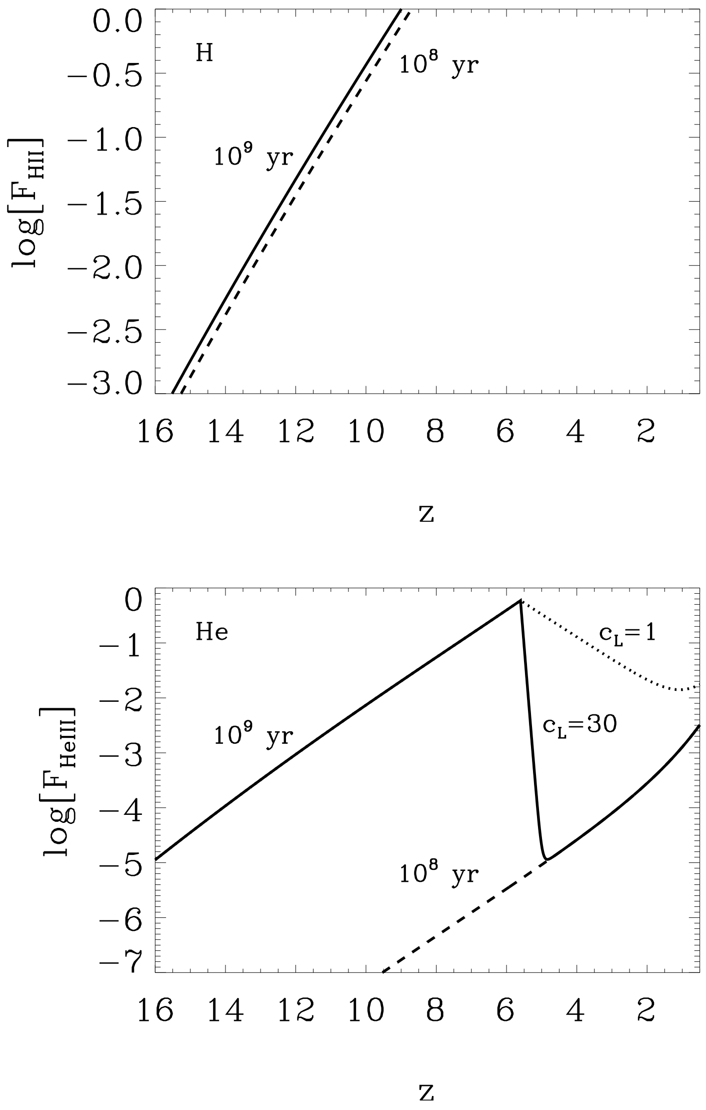
- The assumed cosmology is, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_B = 0.04$, $h = 0.7$, $Y_{\rm He} = 0.24$; also, assume a scale-invariant primordial scalar matter power spectrum ($n = 1$), normalized to $\sigma_8 = 0.9$ at the present epoch for a top-hat window function and transfer functions from Eisenstein and Hu (1998). The fraction of baryons in collapsed halos at a given redshift is calculated using the Press-Schecter formalism; IGM clumping is included in the form of a spatially averaged clumping factor. Set $f_\star = 0.05$ (the fraction of baryons in galaxy halos forming stars), and the escape fraction of ionizing photons from halos to the IGM, $f_{esc} = 0.05$ (0.025) for H I (He II).

- Displayed are the volume-weighted filling factors of H II and He III; reionization is defined as the epoch of overlap of ionized regions around individual sources. This generally precedes the epoch when the transmission-weighted opacity becomes negligible, corresponding to the disappearance of the GP trough in the IGM. The latter represents the end of the gradual process of inhomogeneous reionization, coinciding with the disappearance of the last neutral regions in highly overdense or clumped portions of the high-$z$ IGM.

**The redshift evolution of the fraction of baryons in star-forming halos $F_\mathrm{B}$ (dotted lines), and the volume filling factors of H II and He III, $F_\mathrm{HII}$ and $F_\mathrm{HeIII}$, for $\sigma_8 = 0.9$, $\Omega_b = 0.04$, $h = 0.7$, $n = 1.0$, $\Omega_\Lambda = 0.7$, $\Omega_\mathrm{M} = 0.3$, $c_L = 30$, $f_\star = 0.05$, $f_\mathrm{esc}^\mathrm{H} = 0.05$, $f_\mathrm{esc}^\mathrm{He} = 0.025$. Upper and lower panels display $F_\mathrm{HII}$ and $F_\mathrm{HeIII}$, with solid and dashed lines in each panel representing continuous and bursty star formation respectively with evolving Pop III spectra.**



Upper and lower panels display $F_{\mathrm{HII}}$ and $F_{\mathrm{HeIII}}$ respectively for continuous star formation. Solid and dashed lines in each panel represent Pop III spectra switching to Pop II at times corresponding to ages of the universe of $10^9$ and $10^8$ yr. For $F_{\mathrm{HeIII}}$, an additional case is shown with a dotted line, where Pop III spectra switch to Pop II at $10^9$ yr with the assumption of a homogeneous IGM ($c_L = 1$) at $z < 5.6$. This is intended to mimic the fate of low-density regions in the IGM subsequent to partial ionization.



**Pop III alone:**

$z_{\rm reion}$(H) $\sim$ 9.0 (4.7), $z_{\rm reion}$(He II) $\sim$ 5.1 (0.7) for continuous (bursty) modes of star formation.
Consistent with current observational values of $z_{\rm reion,H}$ $\sim$ 6 and $z_{\rm reion,He}$ $\sim$ 3.

**Pop III/II:**

$z_{\rm reion}$(H) $\sim$ 9.0 (8.7) for Pop III star formation lasting for $10^9$ ($10^8$) yr.
He II never reionizes completely, but reaches a maximum He III ionization fraction of $\sim 8.9 \times 10^{-3}$ (0.6) at $z \sim 0$ (5.6) for the duration of Pop III star formation being $10^8$ ($10^9$) yr.

# CONNECTING REIONIZATION AND METAL PRODUCTION

- Diagnostics that relate the generation of ionizing photons and metal yields from stars include: the number of ionizing photons per baryon in the universe ($N_{\rm Lyc}/b$), and the conversion efficiency of energy produced in rest mass of metals to energy released in the H-ionizing continuum (Madau & Shull 1996):

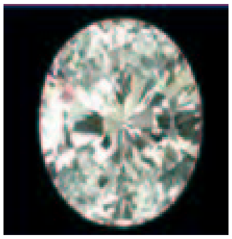
$$\eta_{\rm Lyc} = {\rm E}\ (h\nu \geq 13.6\ {\rm eV})/(M_Z c^2) \simeq 0.002$$

Note that this value of $\eta_{\rm Lyc}$ is valid for massive stars only ($M \geq 8 M_\odot$). Applying either of the above to the IGM metallicity is subject to several uncertainties, such as the escape fraction of photons to the IGM, progenitor stars' $Z$, metal transport mechanism, feedback effects, etc.

- As a rough calculation, combine two observational constraints:
H-reionization occurs before $z \sim 6$, and the IGM at $z \sim 3$ has an average enrichment, detected in carbon, of $\sim 10^{-2} Z_\odot$. Also, assume that most of the baryons at $z \sim 3$ are in the Lyman-$\alpha$ clouds, as indicated by numerical simulations.

- If the same population of stars enriched the IGM and reionized the universe, then $f_\star \sim$ 1–2 % is required, for continuous star formation. Furthermore, $N_{\rm Lyc}/b \sim 10$ (Miralda-Escude & Rees 1997). Both these estimates are quite reasonable.

# CONSISTENCY OF THE CARBON CONNECTION

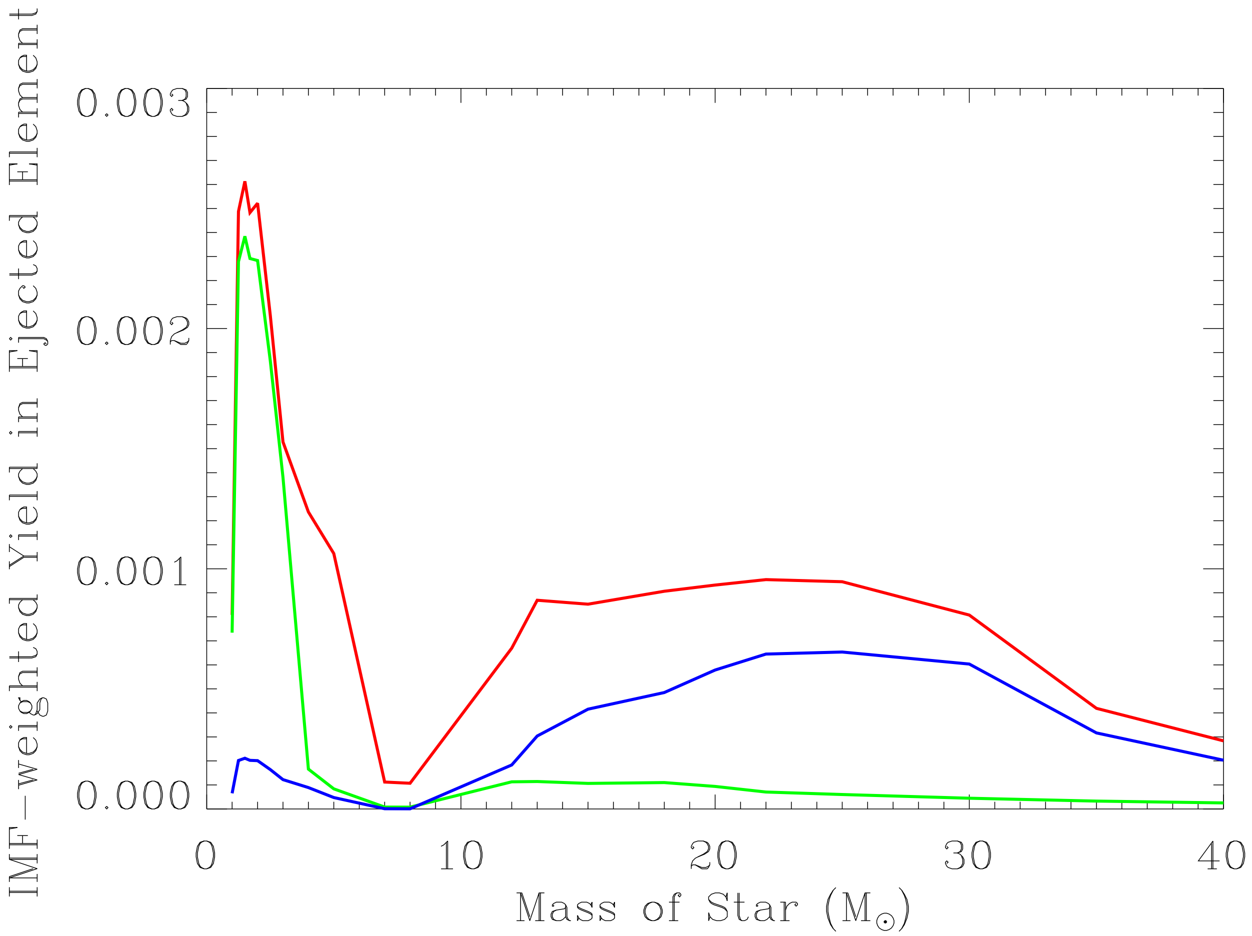


- **In principle, there should be a relatively unambiguous connection between the effects of ionizing photons and metal production from the first stars on the IGM.**

- **Two potential problems with consistently normalizing such stellar activity through the degree of carbon enrichment: ionizing photons come from massive stars ($\geq$ 10 $M_\odot$), while carbon is produced dominantly by 2–6 $M_\odot$ stars. Thus, different regions of the IMF are being probed, and may not be mutually constraining if the IMF was different in the past. Second, for burst-driven star formation (not continuous), there is an issue of timescales; most of the carbon is produced an order of magnitude in time AFTER the epoch of ionizing photons and Type II SNe associated with massive stars. Important to address how the carbon is expelled from individual halos and distributed so ubiquitously in the IGM, if not via winds/outflows driven by Type II SNe.**

— **Total yield in metals**
— **Yield in $^{16}$O**
— **Yield in $^{12}$C**

**Yields from van den Hoek & Groenewegen (1997) and Woosley & Weaver (1995), for $Z = 0.001$ stars in a Salpeter IMF.**



# ETA AS A FUNCTION OF METALS/METALLICITY

**_A priori_, we expect that a better index of stellar activity would be the number of ionizing photons per dominant alpha-element generated by massive stars, such as oxygen; this will provide a more consistent connection, if one exists, between the reionizing stars and the IGM-enriching stars.**

| | $Z = 0$ | $Z = 0.001$ | $Z = Z_\odot$ |
|---|---|---|---|
| $\eta_{\mathrm{Lyc,Z}}$ | 0.075 | 0.008 | 0.004 |
| $\eta_{\mathrm{Lyc,C}}$ | 0.45 | 0.088 | 0.048 |
| $\eta_{\mathrm{Lyc,O}}$ | 0.19 | 0.013 | 0.007 |

The conversion efficiency of rest mass in metals, carbon and oxygen to ionizing radiation for stellar masses $\geq 8$ M$_\odot$, as a function of progenitor metallicity, $Z$.

**As $Z$ decreases, the number of stellar ionizing photons increase, and the stellar yield in metals, individual or total, decreases, leading to a net decline in $\eta$ with rising $Z$. The table shows that $\eta_{\mathrm{Lyc}}$ can vary significantly with the metallicity of the progenitor star, and also with the element with respect to which it is defined.**

# Re-examine the calculation of $N_{\rm Lyc}/b \sim 10$:

$$N_{\rm Lyc}/b = (E_{\rm Lyc}/b)/< E_{\rm Lyc} >$$
$$= (\eta_{\rm Lyc} < Z_{\rm IGM} > m_p c^2)/< E_{\rm Lyc} >$$
$$\sim 0.002 \times 10^{-4}\ (1\ {\rm GeV}/20\ {\rm eV}) \sim 10$$

- To apply this to the IGM carbon abundance, we must define $\eta_{\rm Lyc}$ with respect to the carbon yield $M_C c^2$, rather than the rest mass energy of the total metal yield, from massive stars. Using spectral templates of the Colorado Pop. III stellar clusters, and yields for $Z = 0$ massive stars from Woosley & Weaver (1995), $\eta_{\rm Lyc,C} \simeq 0.454$. This results in:

$$N_{\rm Lyc}/b \sim 700\ !$$

- This implies that either Pop. III stars made a negligible contribution to the carbon detected at $z \sim 3$, or that in enriching the IGM, they generated a tremendous amount of ionizing radiation.

- Until measurements of a variety of elements are shown to be consistent with $< Z_{\rm IGM} >$ as measured in carbon, conversion diagnostics as described above must be applied with caution as an index of stellar activity.

# SUMMARY

- Metal-free (Pop. III) stars are significant sources of hard photons at high redshifts, and must have existed at some point in the past. A Pop. III stellar cluster, relative to Pop. II, emits 60% more H I ionizing photons and $10^5$ more He II ionizing photons during its lifetime.

- For the currently favored cosmology, Pop III stars can be cosmologically significant for reionization, particularly for He II. Depending on how long such a phase of star formation lasts, this could result in full or partial hydrogen AND helium reionization at early epochs. Thus, He II may reionize more than once.

- The relation between the integrated ionizing radiation and metal output from the first stars is complicated by the strong dependence on progenitor metallicity alone, outside of other factors. Massive Pop. III stars are, however, unlikely to be the source of the carbon detected in the IGM at $z \sim 3$.

- If star formation occurred in bursts, it is unclear how to relate ionizing stellar activity (from short-lived massive stars) to the carbon abundance in the IGM (from intermediate-mass stars). The transport of carbon to the IGM also becomes problematic. The detection of elements which are the products of massive stars, e.g., oxygen or silicon, in absorption-line systems at $z \geq 3$, and a comparison of the values of $Z_{\rm IGM}$ implied by their abundances with that measured in carbon should help to consistently address whether the reionizing stellar population generated the metals observed in the high-$z$ IGM.

# LOOKING AHEAD

- What is the duration of metal-free star formation at early epochs, before self-pollution of starforming regions occurs and irrevocably alters the emerging ionizing spectrum of new generations of stars?

- If the IGM He II was not completely reionized by Pop. III stars, the temperature evolution and chemistry of the IGM prior to $z \sim 6$ will be altered by the presence of copious 4-rydberg photons.

- If HI reionization does occur relatively late ($z \sim 6$–$7$), then Ly$\alpha$ will not be a good probe of the $z \geq 6$ IGM. But certain metal absorption lines, e.g., C IV, Si IV, longward of Ly$\alpha$ are still potentially useful, and are important targets for NGST.

- Observational searches for metal-free stars:
NGST may detect nebular emission and He II recombination lines from Pop. III stars in the first galaxies at $z \geq 5$ (Tumlinson et al. 2001; Oh et al. 2001), or if the first stars were extremely massive, $M \geq 100$ $M_\odot$ (Bromm et al. 2001, Schneider et al. 2002).