

Upper limit on the
Lyman continuum flux
escaping from $z \sim 3$
galaxies

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- and others

What is the problem?

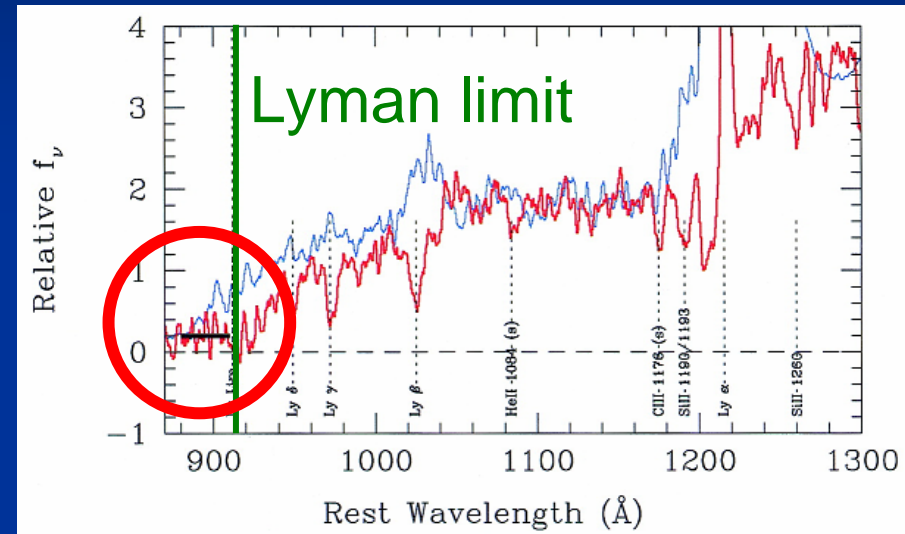
- Cosmic HI reionization epoch
 - End at $z \sim 6$ (Becker et al.2001)
 - Start at $z \sim 20$ (Kogut et al.2003)
- We have some reionization histories.
 - assume the escape fraction and so on.
- How much is **the escape fraction**?
 - Can the ionizing photons escape from galaxies efficiently, if galaxies are the main source?
- We will discuss the escape of Lyman continuum from galaxies.

Theoretical approach?

- The problem is well-defined theoretically:
 - just solving the Lyman continuum transfer through the galactic ISM.
 - However, the results strongly depend on the assumption: the amount of neutral gas (i.e. scale of the system), and the configuration of gas and stars (e.g., clumpiness of gas).
- **Observational constraints!!**

Lyman continuum from galaxies

- All the attempts for the direct detection of the Lyman continuum have failed to date, except for Steidel et al. (2001) who succeeded in detecting the continuum in the composite spectrum of 29 *very blue* Lyman break galaxies at $\langle z \rangle = 3.4$.



Steidel et al.(2001), red line: the composite spectrum of 29 Lyman break galaxies at $z \sim 3.4$.



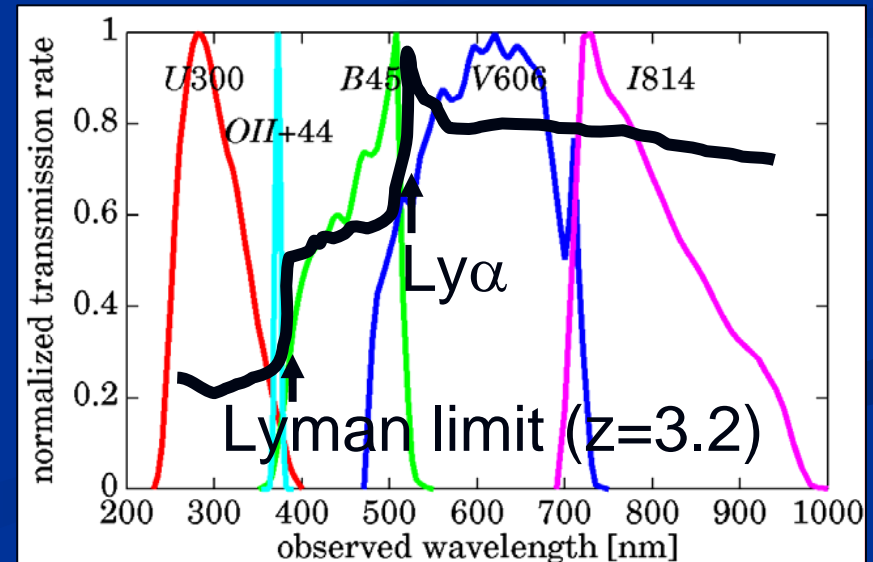
very large escape?

Our approach

- Narrow-band photometry
 - **better sensitivity** than spectroscopy
 - close to the Lyman limit (smaller IGM opacity)
 - very important for high- z galaxies
 - select galaxies with an appropriate redshift

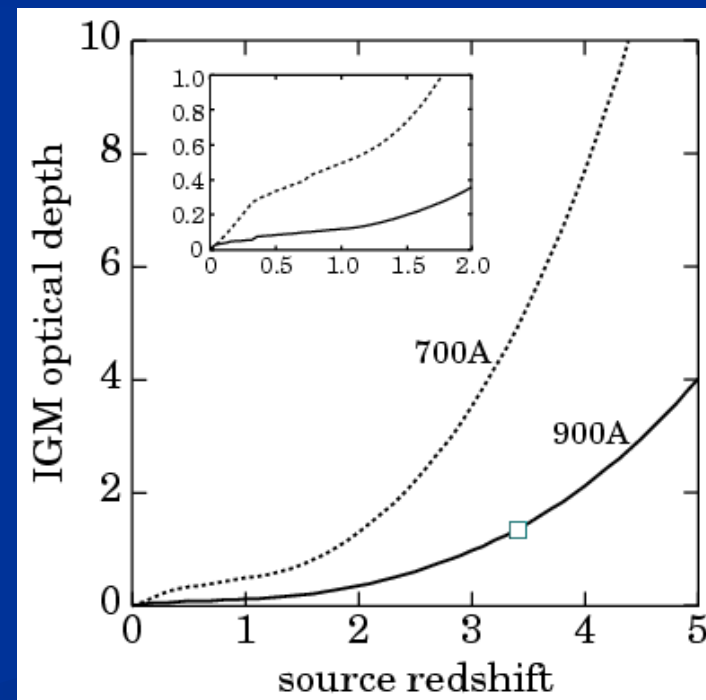
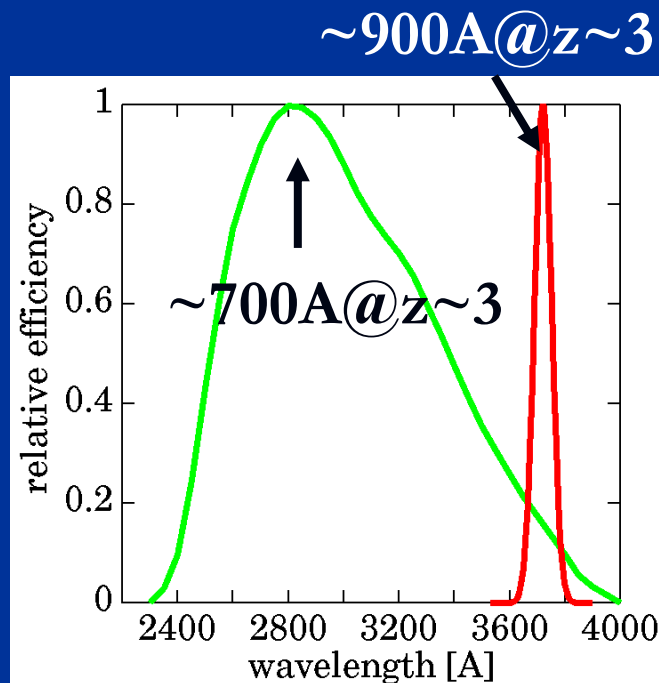
to avoid any contamination of nonionizing photons.

- The redshift criterion for the *OII+44* filter of VLT/FORS is $z > 3.2$.



U-band is not useful.

- IGM opacity increases rapidly as decreasing the wavelength.



Observations

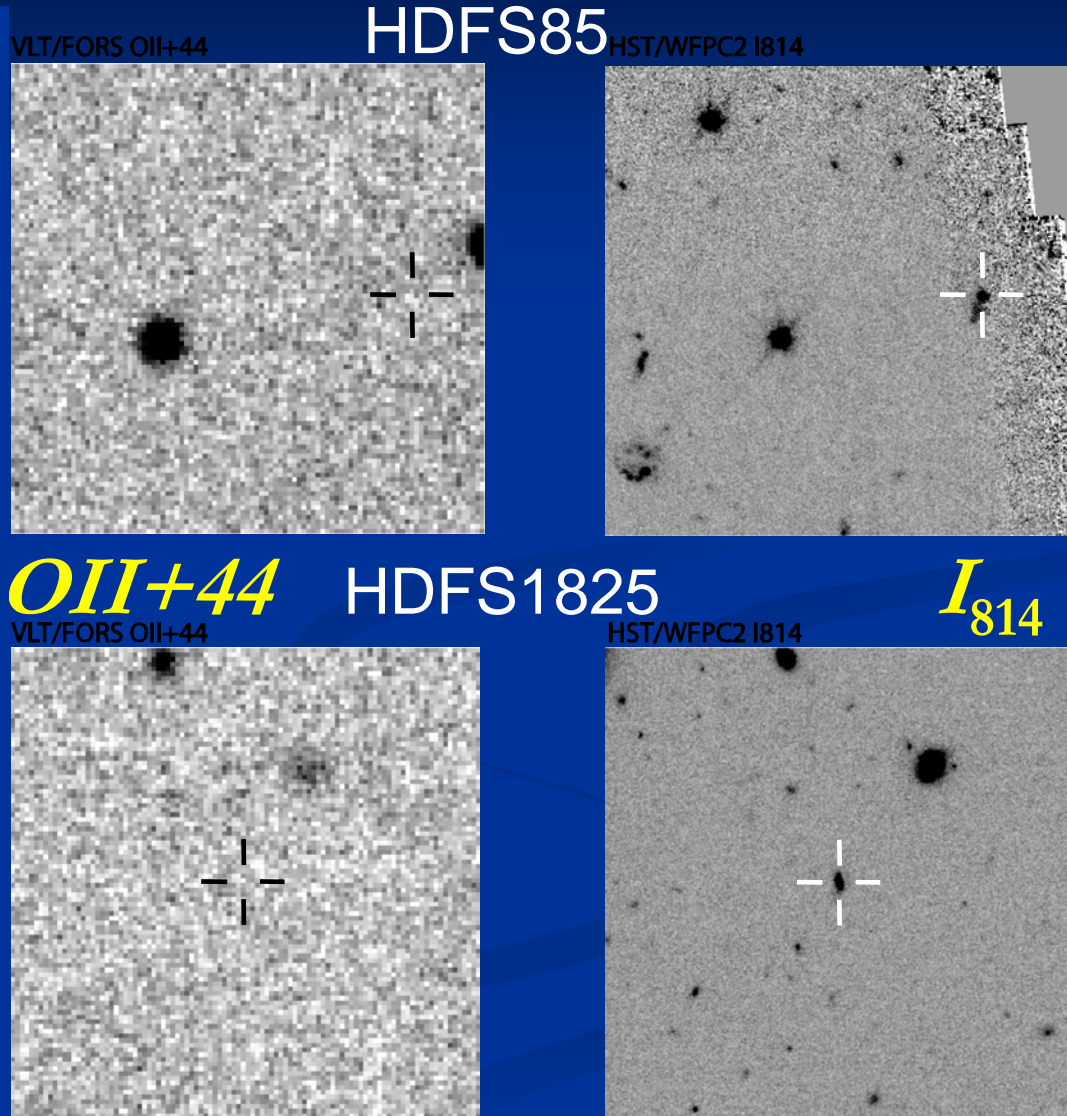
- We spent ~ 11 h exposure (on-source) toward the HDF-S field through the narrow-band filter, *OII*+44 (central wavelength ~ 372 nm), with the VLT/FORS1.
- At the same time, we performed the spectroscopy with the VLT/FORS2 to know the accurate redshift of galaxies expected to be at $z \sim 3$ based on the photometric redshift catalog of Labbé et al.(2003).
- Unfortunately, only two galaxies with an appropriate redshift ($z > 3.2$) were left in our sample because of unexpected systematic overestimation of the photometric redshift catalog (see discussions in Iwata et al. 2005).

Observational results

HDFS	85	1825
z_{sp}	3.170	3.275
<i>OII+44</i>	<44.9	<39.8
U_{300}	<102	<42.1
B_{450}	392	182
V_{606}	699	405
I_{814}	860	504

Unit of the photometric data is nJy.
 ID of galaxies and U , B , V , I
 photometric data are taken from
 Casertano et al.(2000).
 Upper limits are 3- σ .

1 July 2005



Reionizing The Universe

LC-to-UV luminosity ratio

	z	$L_{\text{LC}}^{\text{obs}}$	$L_{\text{LC}}^{\text{esc}}$	$L_{\text{UV}}^{\text{obs}}$	$(L_{\text{LC}}/L_{\text{UV}})^{\text{esc}}$
Inoue et al. NB photometry	3.2	$<1.0e28$ erg/s/Hz	$<5e28$ erg/s/Hz	$1.3e29$ erg/s/Hz	<0.4
Steidel et al. composite spectrum	3.4	$9.0e27$ erg/s/Hz	$4e28$ erg/s/Hz	$1.6e29$ erg/s/Hz	0.3
Giallongo et al. long-slit spectrum	3.0	$<1.7e28$ erg/s/Hz	$<6e28$ erg/s/Hz	$4.0e29$ erg/s/Hz	<0.2
Malkan et al. BB photometry	1.1	$<6.8e26$ erg/s/Hz	$<1e27$ erg/s/Hz	$1.2e29$ erg/s/Hz	<0.008

NOTE: $L_{\text{LC}}^{\text{obs}} = L_{\text{LC}}^{\text{esc}} \exp(-\tau_{\text{IGM}})$; $L_{\text{UV}}^{\text{obs}} = L_{\text{UV}}^{\text{esc}}$

Absolute escape fraction

	z	$(L_{\text{LC}}/L_{\text{UV}})^{\text{esc}}$	A_{UV}	f_{esc}
Inoue et al. NB photometry	3.2	<0.4	2 mag	<20%
Steidel et al. composite spectrum	3.4	0.3	<u>0.3 mag</u>	<u>60%</u>
Giallongo et al. long-slit spectrum	3.0	<0.2	3 mag	<3%
Malkan et al. BB photometry	1.1	<0.008	2 mag	<0.4%

NOTE: $f_{\text{esc}} = (L_{\text{LC}}/L_{\text{UV}})^{\text{esc}} / (L_{\text{LC}}/L_{\text{UV}})^{\text{int}} 10^{-0.4A(\text{UV})}$; $(L_{\text{LC}}/L_{\text{UV}})^{\text{int}} = 0.3$

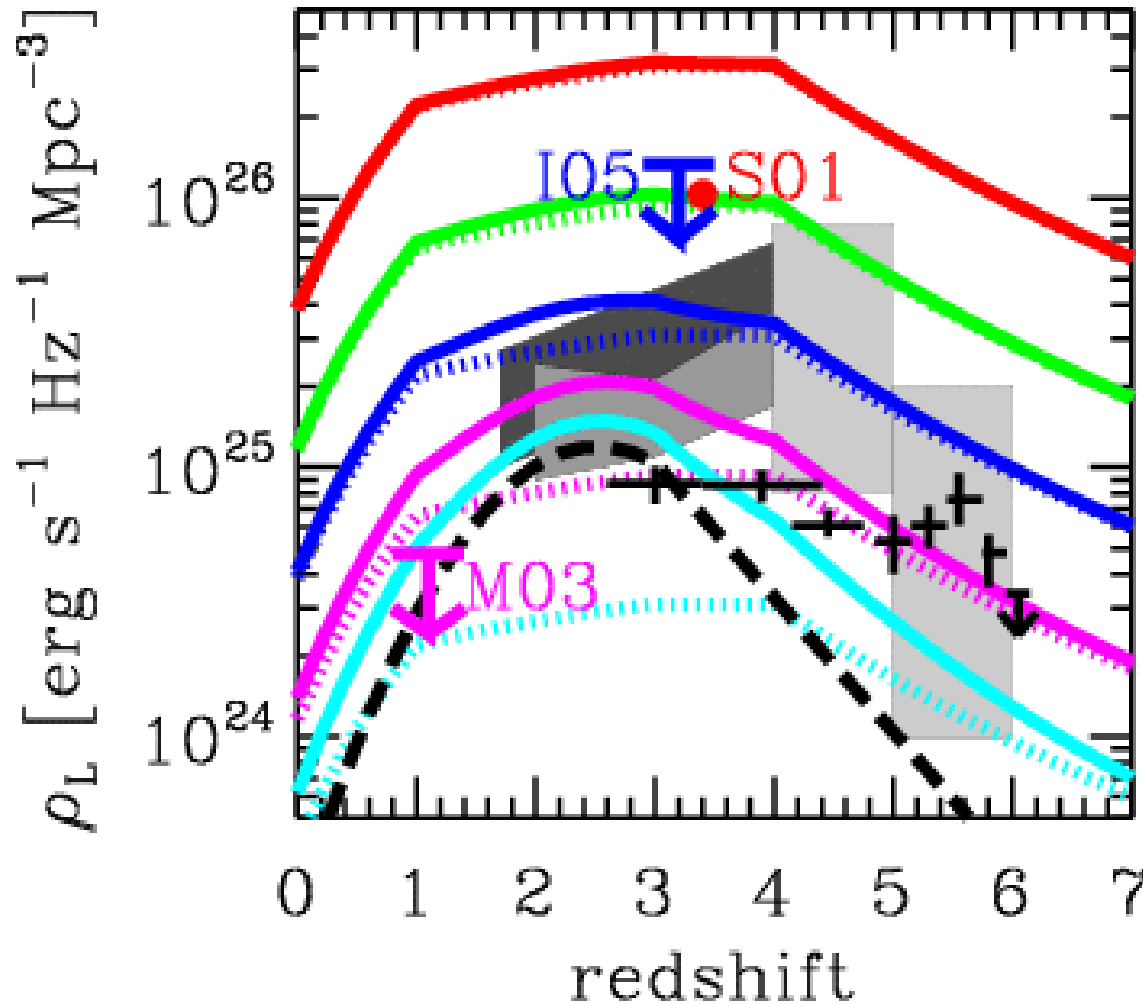
Galactic LC emissivity

- Because of the dust correction, absolute escape fraction is very uncertain.
- Directly from the observed galactic UV emissivity, the escaping LC-to-UV luminosity ratio allows us to estimate the **galactic LC emissivity** without any additional corrections!

$$\rho_{\text{LC}}^{\text{gal}} = \left(\frac{L_{\text{LC}}}{L_{\text{UV}}} \right)_{\text{esc}} \rho_{\text{UV}}^{\text{gal}}$$

- We assume the UV emissivity by Bouwens et al. (2005).

LC emissivity evolution



- Total
- - - QSOs
- galaxies
- ($L_{\text{LC}}/L_{\text{UV}}$)_{esc}
= 1.0 (red),
0.3 (green),
0.1 (blue),
0.03 (magenta),
0.01 (cyan)

Other data from
 Scott et al.(2000),
 Fan et al.(2002),
 Bolton et al.(2005),
 Hiroi et al. in prep.

Implication to the EoR

- Required LC emissivity to keep the Universe ionized at $z=10$ (depending on the spectral slope):

$$\rho_{\text{LC}}^{\text{crit}}(z=10) \approx 10^{25-26} [\text{erg s}^{-1} \text{ Hz}^{-1} \text{ Mpc}^{-3}]$$

* fast recombination is assumed.

- Expected LC emissivity by an extrapolation (cf. Bouwens et al. 2005) :

$$\rho_{\text{LC}}^{\text{exp}}(z=10) \approx 2 \times 10^{24} \left(\frac{L_{\text{LC}} / L_{\text{UV}}}{0.1} \right) [\text{erg s}^{-1} \text{ Hz}^{-1} \text{ Mpc}^{-3}]$$

- **Need other populations?**

New data coming soon!

- Next VLT observations have been allocated in this period (75A).
- We have 18 galaxies with a good redshift in the FOV of the VLT/FORS1 toward the FORS Deep Field.
- Expected upper limit on the **escaping LC-to-UV luminosity ratio is ~ 0.1** in a stacked image.
- We will **detect the escaping LC flux from individual galaxy** if the escape fraction is as large as reported by Steidel et al. (2001).

Conclusions

- We did not find any significant escape of Lyman continuum from two Lyman break galaxies (LBGs) at $z \sim 3$ by the narrow-band photometry with VLT.
- Narrow-band photometry can put a good constraint on the escape fraction of individual typical LBGs at $z \sim 3$.
- The two LBGs have a small *absolute* escape fraction, less than 20% (with a large uncertainty by dust).
- For the moment, the sample size is too small to conclude that many LBGs have a small escape fraction.
- Cosmic Lyman continuum emissivity is estimated directly from the observed UV emissivity.
- Next observations with the VLT have been already allocated. New constraints are coming soon!