The Epoch of Reionization:

Astrophysical Constraints

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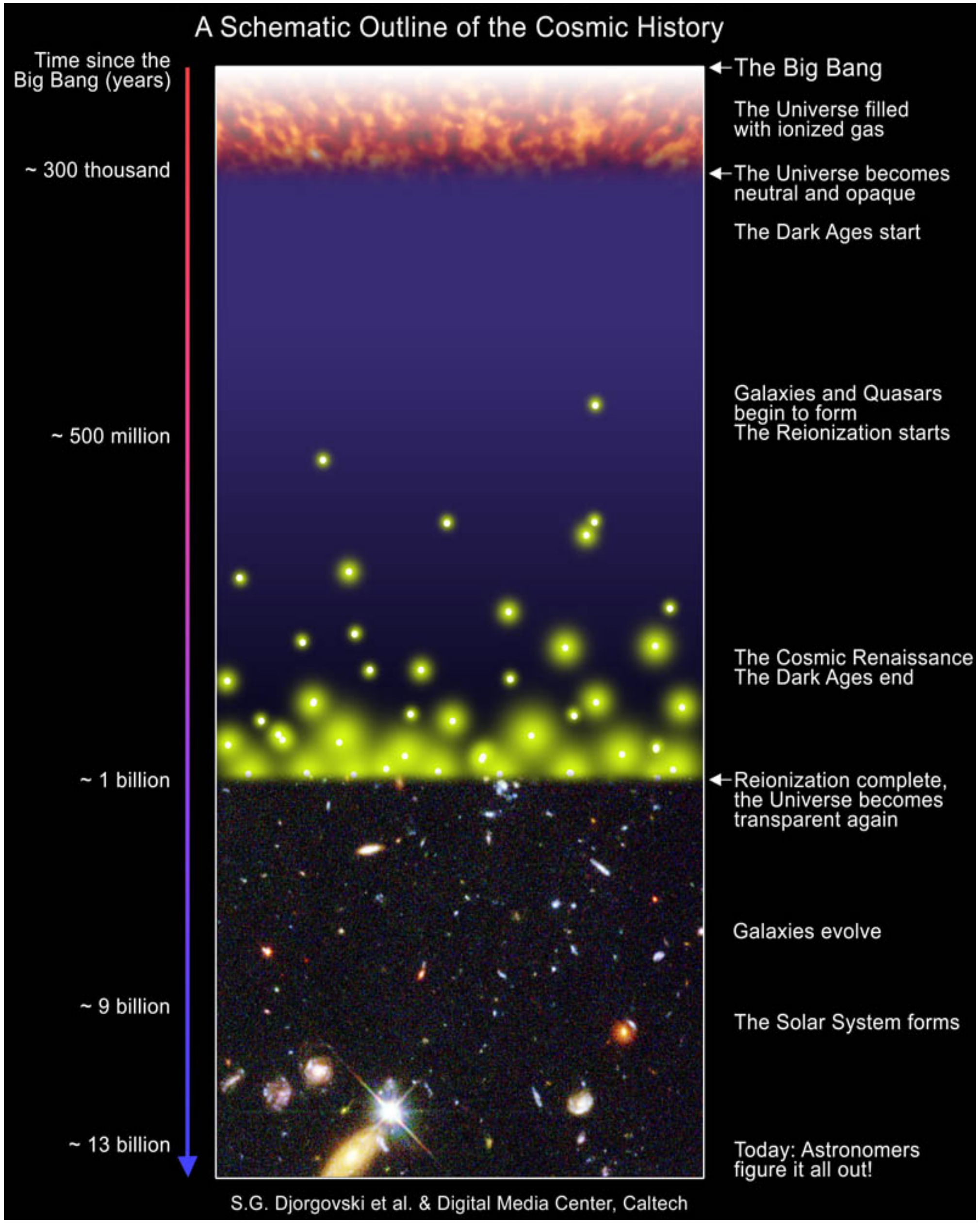
Overview

- The “dark age” of the Universe
- Gunn-Peterson test
- Evolution of Lyα optical depth
- Abundance of Lyα emitters
- Photoionization rates from QSO proximity effect
- The highest redshift QSO
- Constraints from IGM temperature
- Comparison of astrophysical and cosmological constraints

The "dark ages"

- During an extended era of the cosmic history the Universe was a very dark place, pervaded mainly by neutral HI gas. On the contrary, today it is populated by astrophysical sources (stars, galaxies, AGNs) and the HI has almost disappeared from the IGM (containing 90% of H), surviving only in some collapsed structures.

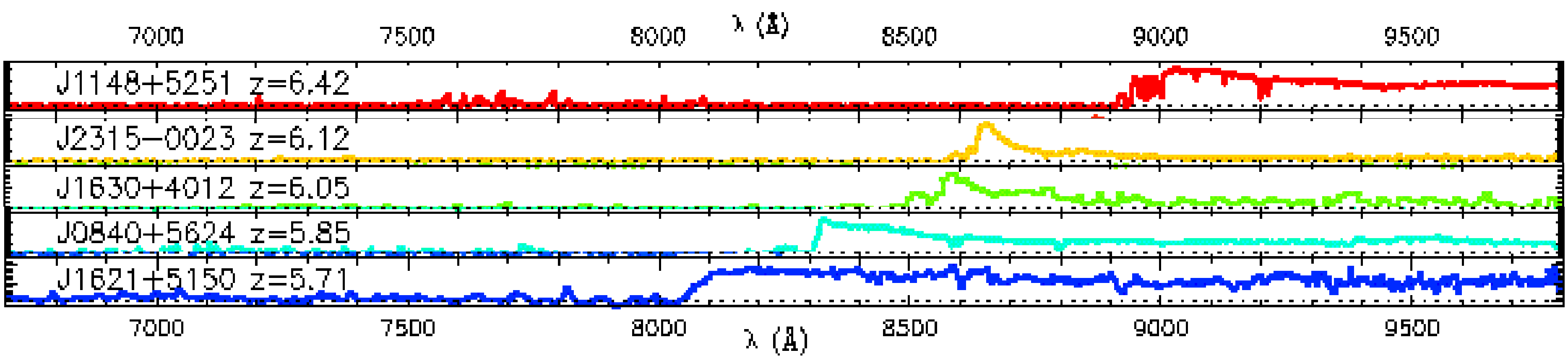
- The disappearance of HI was due to its transition to ionized state, the reionization. When and how it occurred, what were the sources providing enough ionizing photons to achieve it?



Gunn-Peterson test

- HI is very efficient in absorbing radiation at the wavelengths of resonant transitions to ionized states. Lack of complete absorption by the IGM of Lyα photons emitted from quasars provides firm evidence that the Universe has been reionized (Gunn&Peterson65).

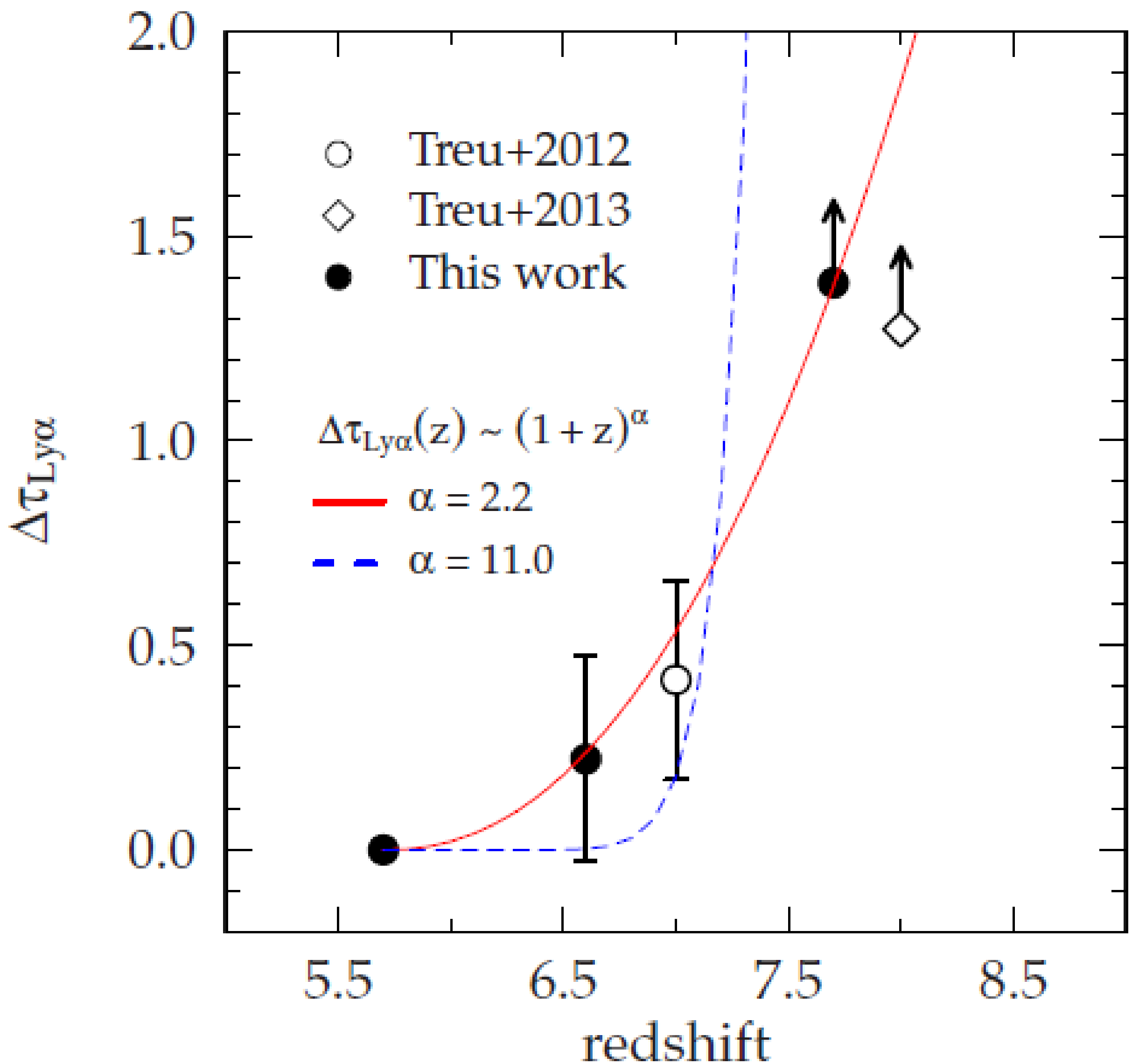
- Detection of almost complete Lyα absorption in the spectra of distant quasars may suggest that the end of reionization epoch occurred around z~6 (Fan+06). However, the high efficiency of HI in Lyα (or even high-order transitions Lyβ, Lyγ) absoprtion allows only to look for final stages of reionization, since one has complete absorption in presence of tiny fraction of HI (~0.1%).



Evolution of Ly-alpha optical depth

- Anyway, recent data on evolution of Lyα optical depth show a sharp increase for z>6, that could be indicative of a dramatic rise in the HI fraction of the IGM (Treu+13; Faisst+14).

- A similar conclusion is supported by the study of l.o.s. variations in the IGM Lyα optical depth (Becker+14).

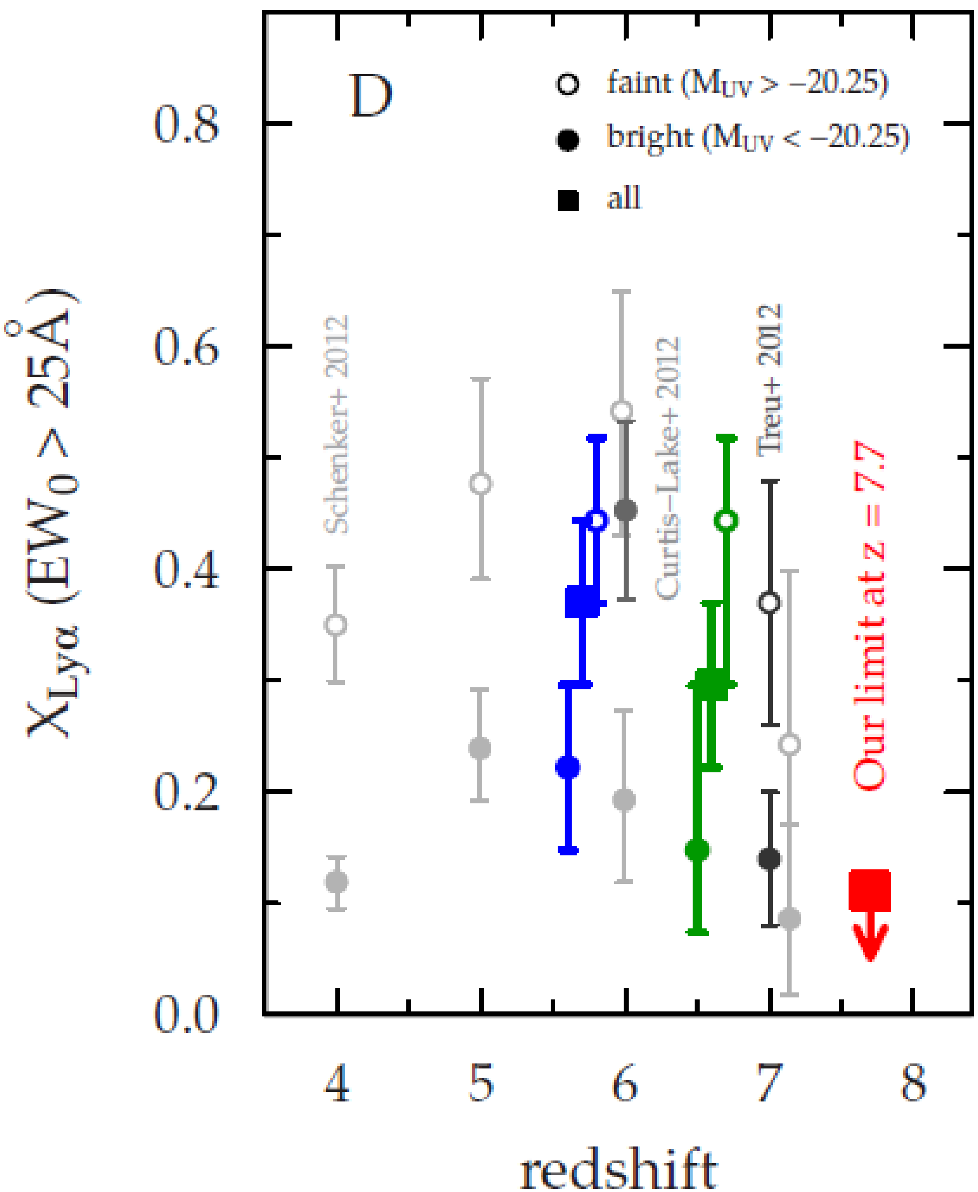


Abundance of Ly-alpha emitters

- A decrease of the LAE fraction is expected when the IGM becomes partly neutral. Data indicate a drop of a factor ~4 for z>6 (Faisst+14, Mathee+14).

- Lower limits on the neutral HI fraction around 50-70% at z~7.7 are inferred, while no LAEs in a deep 10 deg^2 survey at z~8.8 with spectroscopic follow-up is found.

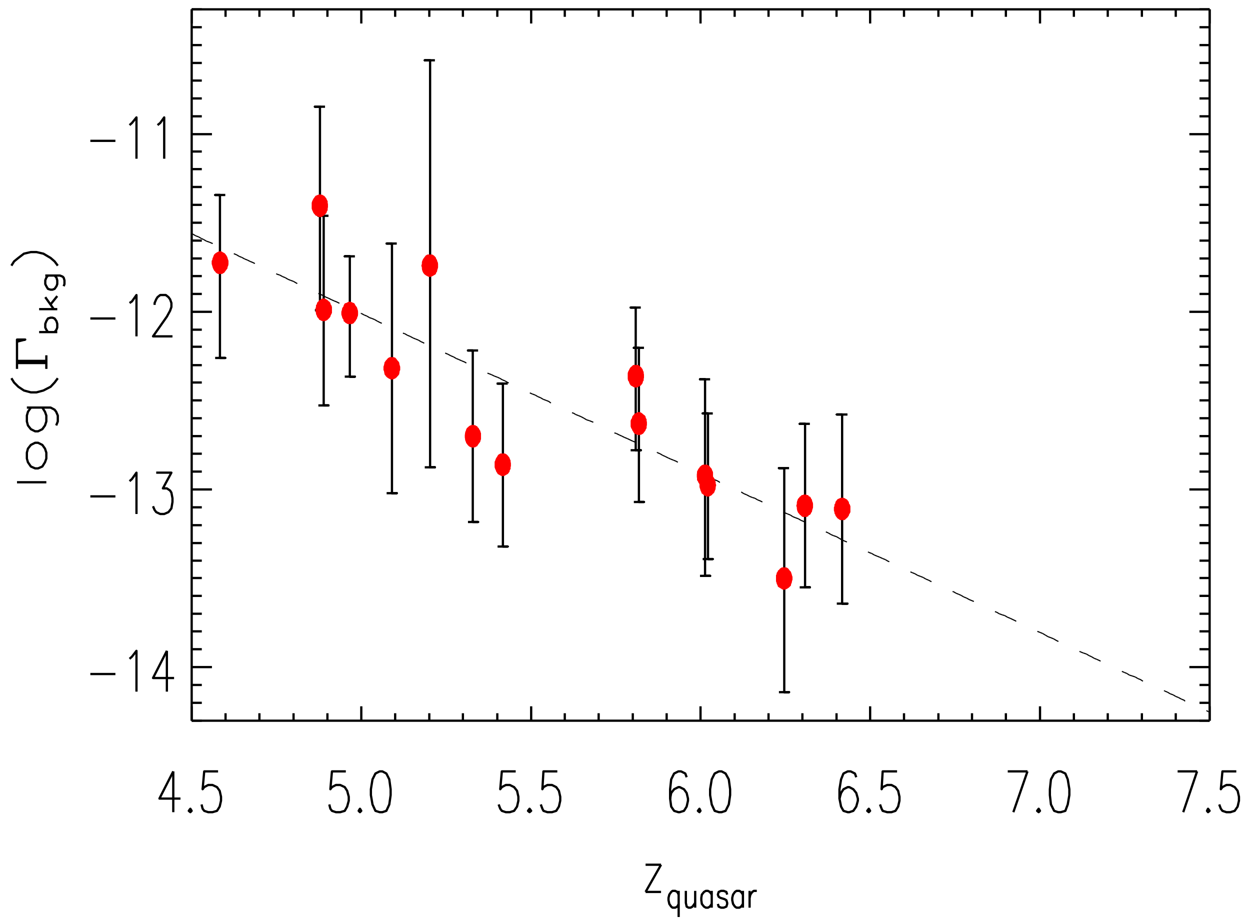
- Similar info from size evolution of Lyα halos (?!) at z>6 (Momose+14)



Decrease of photoionization rate

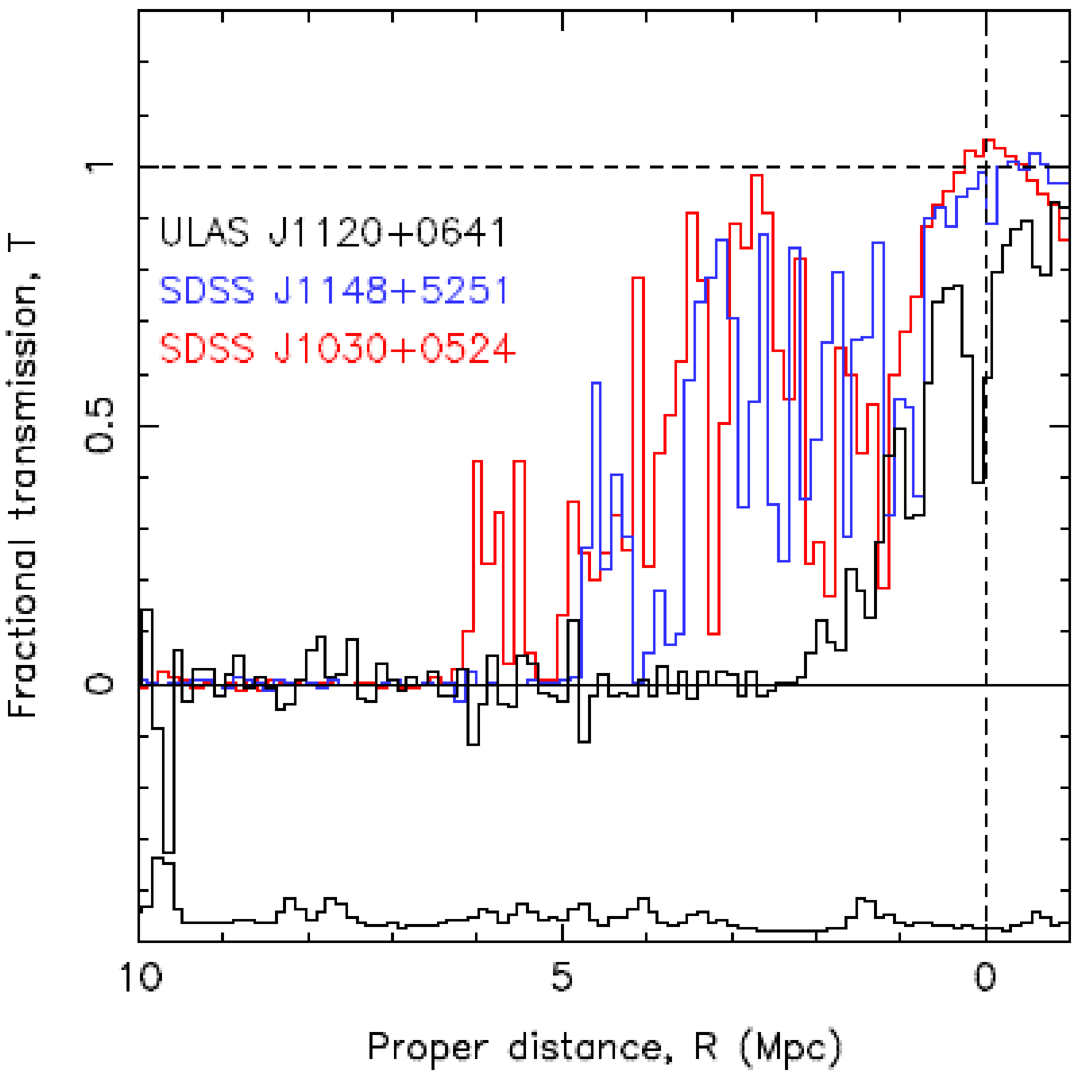
- Consistent results are found from the complementary approach, by looking at the production rate of ionizing photons estimated from the "proximity effect", i.e., the relative lack of Lyα absorption in the vicinity of a QSO (Carlswell+82).

- A decrease of the HI photoionization rate is found from z~4.5 to z~6.5 (Calverley+11). Since the ionizing emissivity is already quite low at z~6 (~1.5 ionizing photons per H atom), unless the trend changes at higher z, the onset of reionization appears unlikely to occur much before z~6.5.



Highest-redshift QSOs: transmission profiles

- The Ly-alpha transmission profile of the highest-redshift QSO ULAS J112001.48 +064124.3 at z~7.1 is strikingly different from that of two lower redshift z~6.3-6.4 SDSS counterparts. It features a measured near-zone radius of ~1.9 Mpc, a factor of ~3 smaller than is typical for QSOs at z~6-6.5 (Mortlock+11).

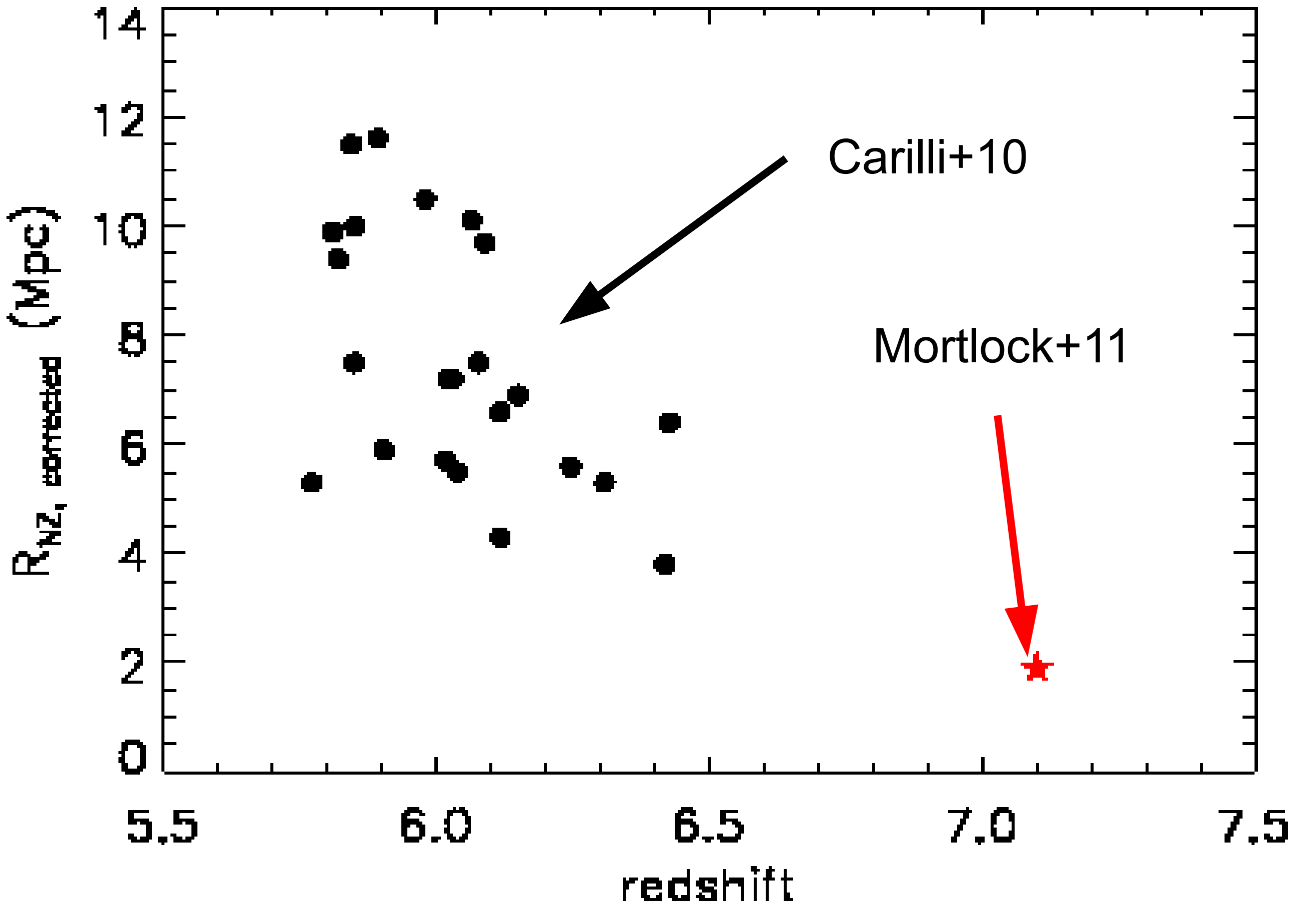


Highest-redshift QSOs: sizes of QSO near zone

- Declining extent of QSO near zone (Mortlock+11, Bolton+11)

$$R \propto (1+z)^{-1}\, f_{\rm HI}^{-1/3}$$

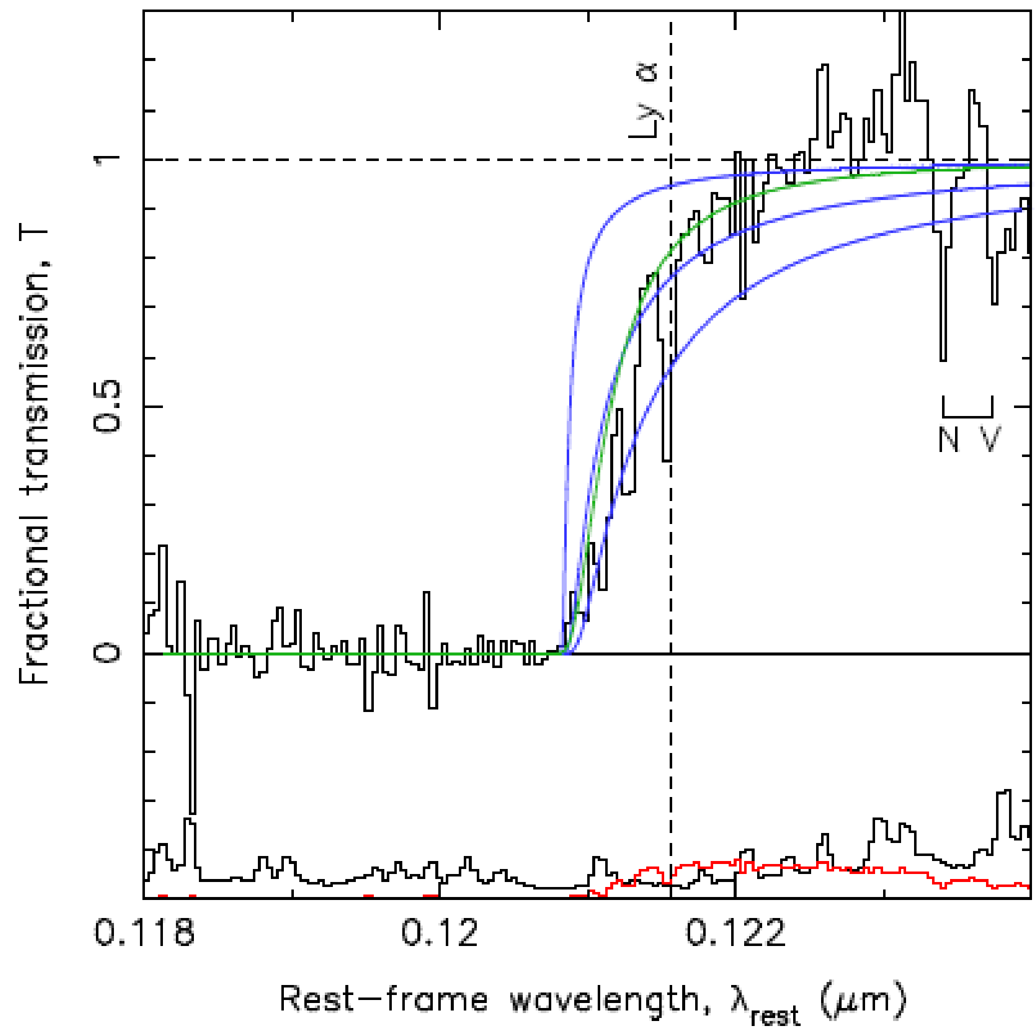
suggests higher-z QSOs live in an IGM whose HI fraction is much higher.



Btw, the UV bright age of ULAS... is estimated around $10^{6\text{-}7}$ yr, implying that it has grown its $>10^9\ M_{sun}$ mass during a previously obscured phase!

Highest-redshift QSOs: transmission profiles

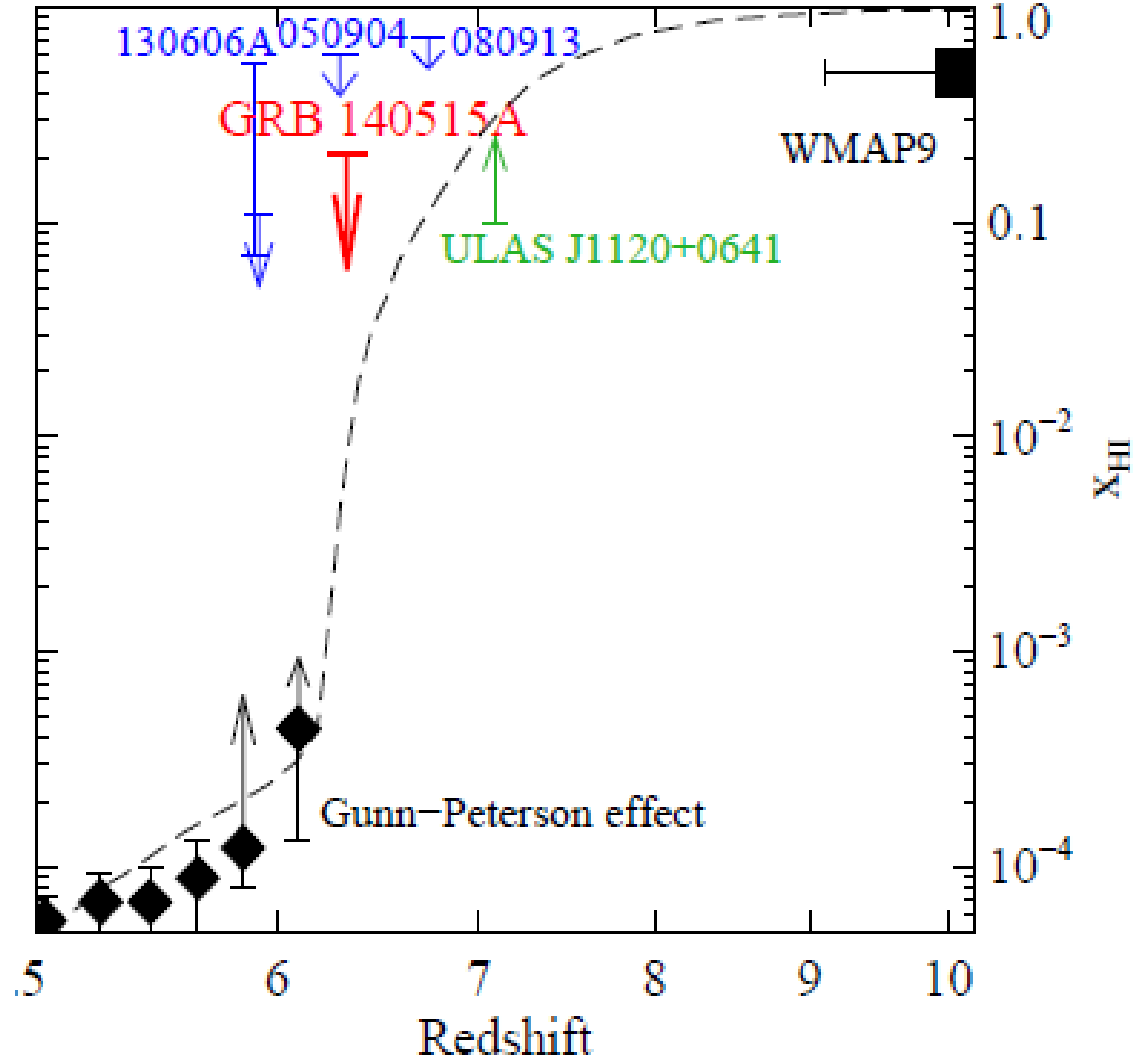
- Blue lines show the Lyα damping wing of the IGM for neutral fraction f_{HI} = 0.1,0.5,1.0 (from top to bottom), assuming a sharp ionization front at 2.2 Mpc. Green curve shows the absorption profile of a damped Ly-α absorber with column density 4 10^{20} cm^{-2} located 2.6 Mpc in front of the QSO. If the absorption is due to the IGM, this requires $0.1<f_{HI}<1$, a quite substantial HI fraction (Mortlock+11).



Highest-redshift GRB afterglows

- High redshift GRBs with their bright afterglow can be also exploited as probes of cosmic reionization, dispensing with some of the complications inherent to QSO observations .

- Extreme dropoff in transmission profile of GRB140515A at z~6.3 is inconsistent with a substantial HI fraction at these redshift (e.g., Chornock+13+14, Totani+14).



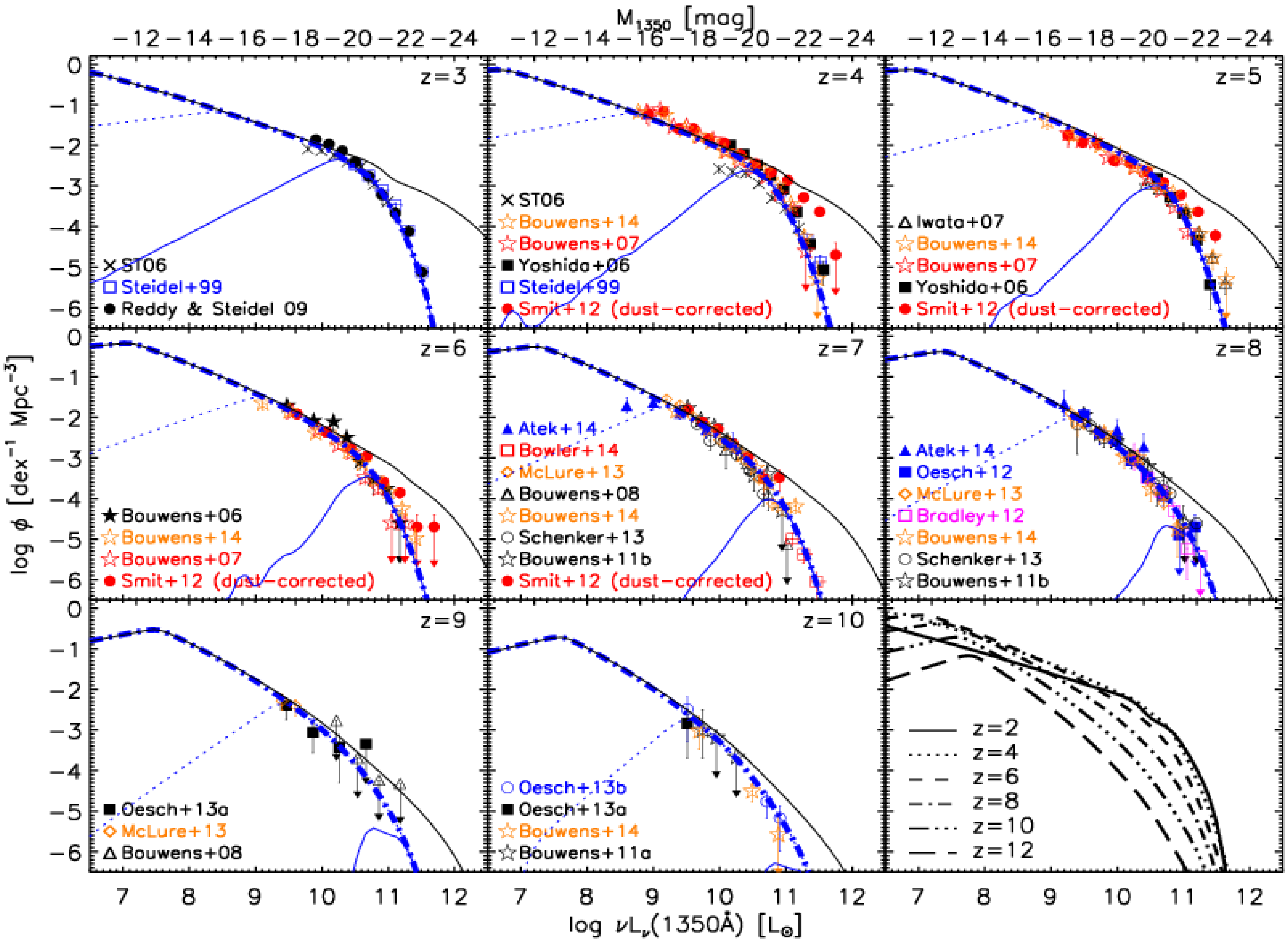
Contraints from high-z UV luminosity function

- Other estimates of the production rate of ionizing photons come from determination of the UV luminosity function (LF) taking advantage of the fact that even a Universe full of HI is transparent throughout most of the spectrum (apart from resonant lines).

- Ultradeep observations have provided measurements of the non-ionizing LFs up to z~10 (Bouwens+11, Bradley+12, Schenker+13, McLure+13, Finkelstein+14) . Extrapolating these information to the ionizing UV suggest that galaxies can keep the Universe fully ionized up to z~6, but they have can hardly do so at z>7 unless the faint end of the LFs is very steep and/or the escape fraction of ionising photons is high (Robertson+13, Cai+14, Ishigaki+14).

Remark: Although QSOs and (bright) AGNs are effective UV emitters, their space density declines very rapidly at z>3 and therefore have no significant role in the H reionization process in the early stages (Becker+13).

Contraints from high-z UV luminosity function



Contraints from high-z UV luminosity function

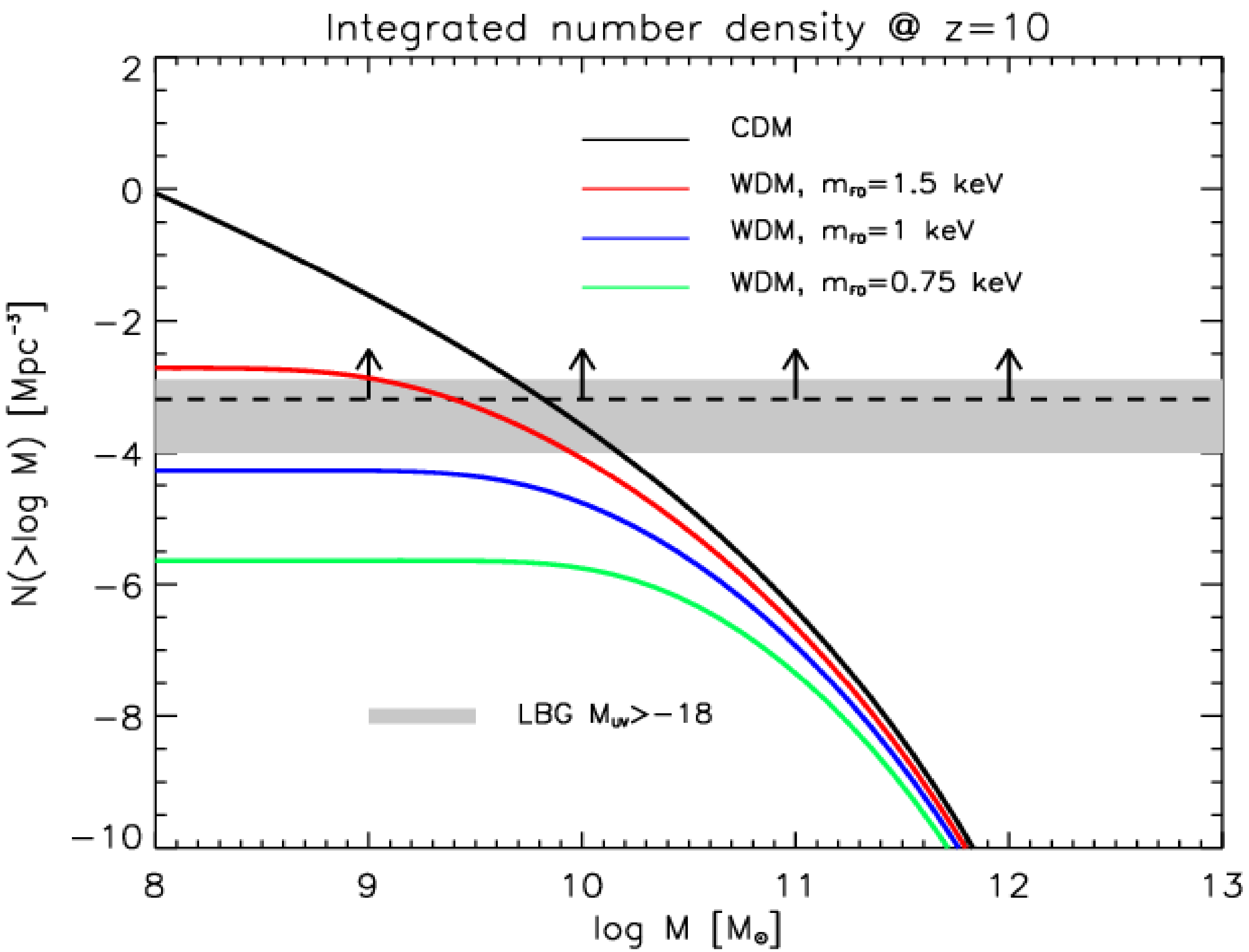
- Self-consistent models for chemical evolution and dust-enrichment, that determine the duration of the UV-bright phase, imply that the already measured LFs at $z \geq 7$ are associated to halo masses down to $M_h \approx 10^{10}\ M_\odot$.

- The contributions of lower M_h objects is very unlikely to yield a steep faint end of the LF because heating processes (SN explosions, radiation from massive low-metallicity stars and, possibly, stellar winds) reduce the SFR in low-mass halos (e.g., Pawlik & Schaye 2009; Hambrick et al. 2011; Finlator et al. 2011a; Krumholz & Dekel 2012; Pawlik et al. 2013; Wyithe & Loeb 2013; Sobacchi & Mesinger 2013) and completely suppress it below a critical halo mass, M_{crit}, which may be $>10^9$ $M_\odot$.

- Tension with galaxy counts in the local Universe: star formation in small halos at high $z>6$ will imply tens of bound satellites in the Milky Way, and hundreds in the Local Group (Boylan-Kolchin+14) at $z=0$.

Contraints from high-z UV luminosity function

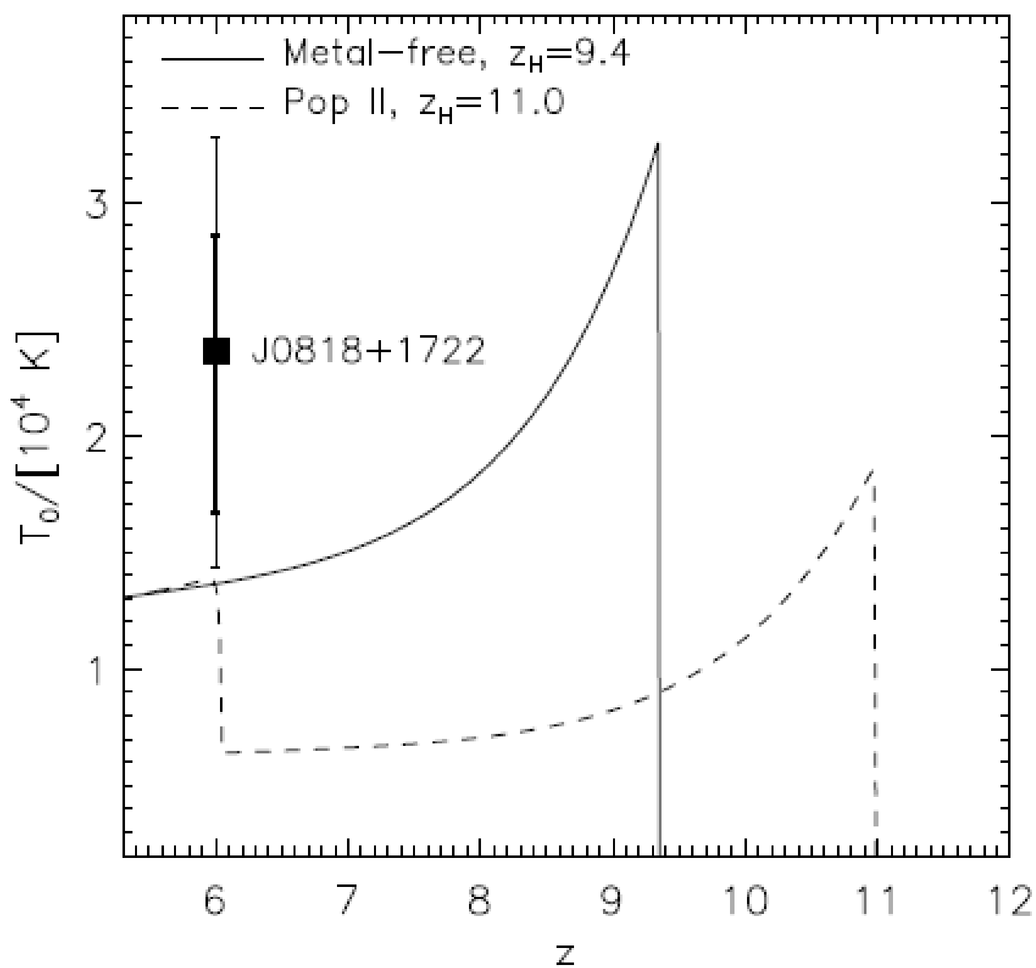
- Aside issue: constraints on the shape of the primordial perturbation spectrum (e.g., WDM-like, (e.g., Pacucci+13, Stark+14, Maio & Viel 14).



Contraints from IGM temperature

- The reionization also raises the IGM temperature (e.g., Miralda-Escude&Rees94). The heated gas retains some memory of the process since its cooling time is long.

- Bolton+10 investigated the IGM temperature around z~6 QSO by analysing the Doppler widths of the Lyα absorption lines. For SDSS J0818+1722 $T \sim 23600^{+5000}_{-6900}$ K is found. If reionization is driven by sources with soft spectra (typical of pop II stars) then the constraint z<9 is obtained, while if it is driven by a population of massive, metal-free stars featuring very hard ionizing spectra, a tighter upper limit z<8.4 is found.



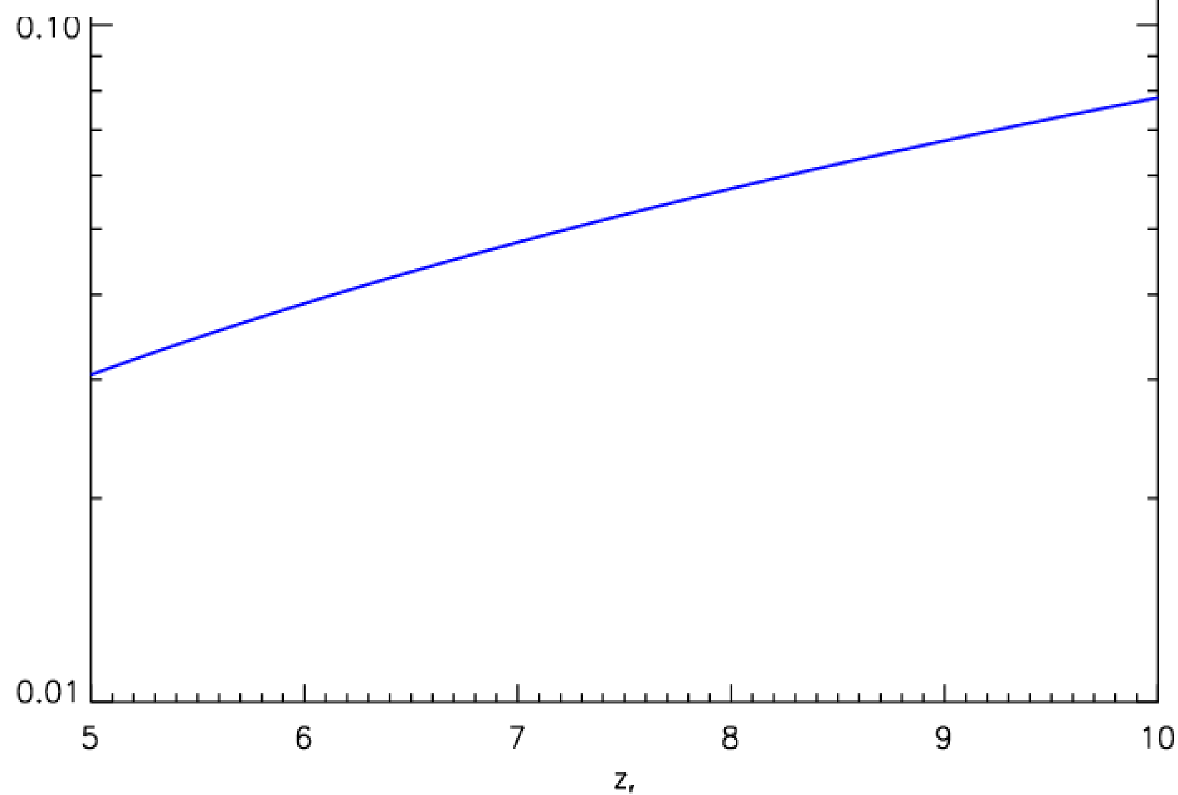
Electron scattering optical depth

- Assuming a Universe fully ionized up to a redshift z_r , the effective electron scattering optical depth can be written

$$\tau_{\rm es} = \int_0^{z_r} {\rm d}z\, \frac{n_e\, \sigma_{\rm T}\, c}{(1+z)\, H(z)} = 0.00123\, \frac{[\Omega_M\, (1+z_r)^3 + \Omega_\Lambda]^{1/2} - 1}{\Omega_M} + 0.002$$

where the last term accounts for extra-scattering from He++ at z<3.

z	$\tau_{\rm es}$
6.0	0.0388
6.5	0.0432
7.0	0.0478
7.5	0.0525



Tension between astrophysical and cosmological constraints

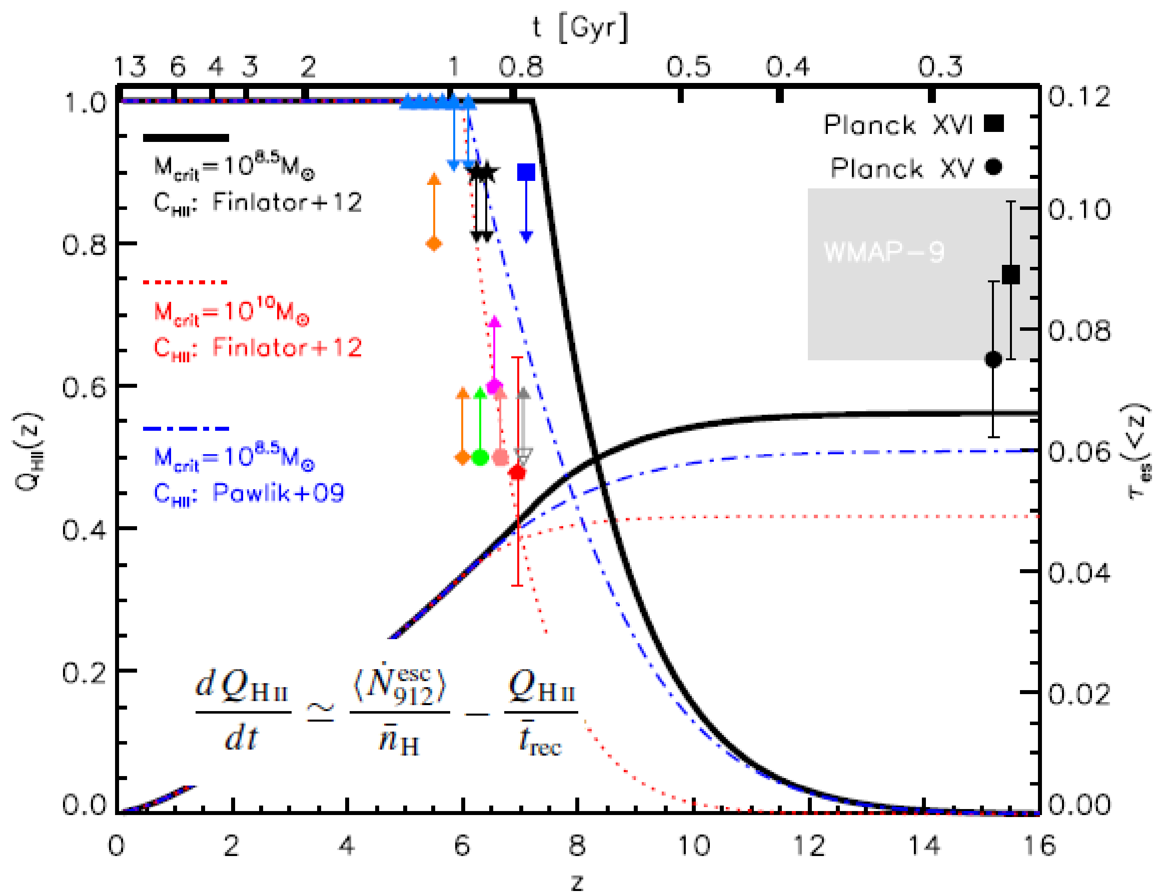
- Another major, complementary probe of reionization is provided by the CMB.

  CMB photons interact via inverse Compton interaction with ionized plasma, producing various effects. The most informative is a bump on the CMB polarization power spectrum on large angular scales, at multipoles $l \sim z_r^{1/2}$ with an amplitude $\sim \tau_{es}$.

- Optical/UV data imply $\tau_{es} \sim 0.04$ and unless high-redshift galaxies have unexpected properties $\tau_{es} \sim < 0.07$.

- These values are significantly lower than those from WMAP pol. and Planck T data $\tau_{es} \sim 0.089^{+0.012}_{-0..014}$

  (Planck Coll. 14)



Conclusions

- Optical/UV data imply essentially complete IGM ionization up to z=6–6.5, that assuming a Planck cosmology entail $\tau_{es} > 0.04$.

- Several observational indications and theoretical arguments (constraining in particular the faint end of the UV luminosity functions) concur in suggesting a fast increase of the neutral fraction above z>6.5, so that the additional contributions to τ_{es} should be small ($\lesssim 0.02$).

- This is somewhat in conflict with the current cosmological constraints from the *WMAP* and *Planck* CMB experiments, that point toward values $\tau_{es} \gtrsim 0.08$, based on *WMAP* polarization. If the analysis of *Planck* polarization will decrease τ_{es} to values in agreement with the astrophysical ones, this will allow to derive key constraints on the properties of galaxies of low luminosities at high redshifts, on properties of the first stars, on how the reionization actually proceeded.

Conclusions

- Otherwise, more exotic sources must be considered:

  -) pop III stars (and star-clusters)

  -) extremely luminous SNe

  -) miniquasars

  -) annihilating or decaying dark matter

  -) ..

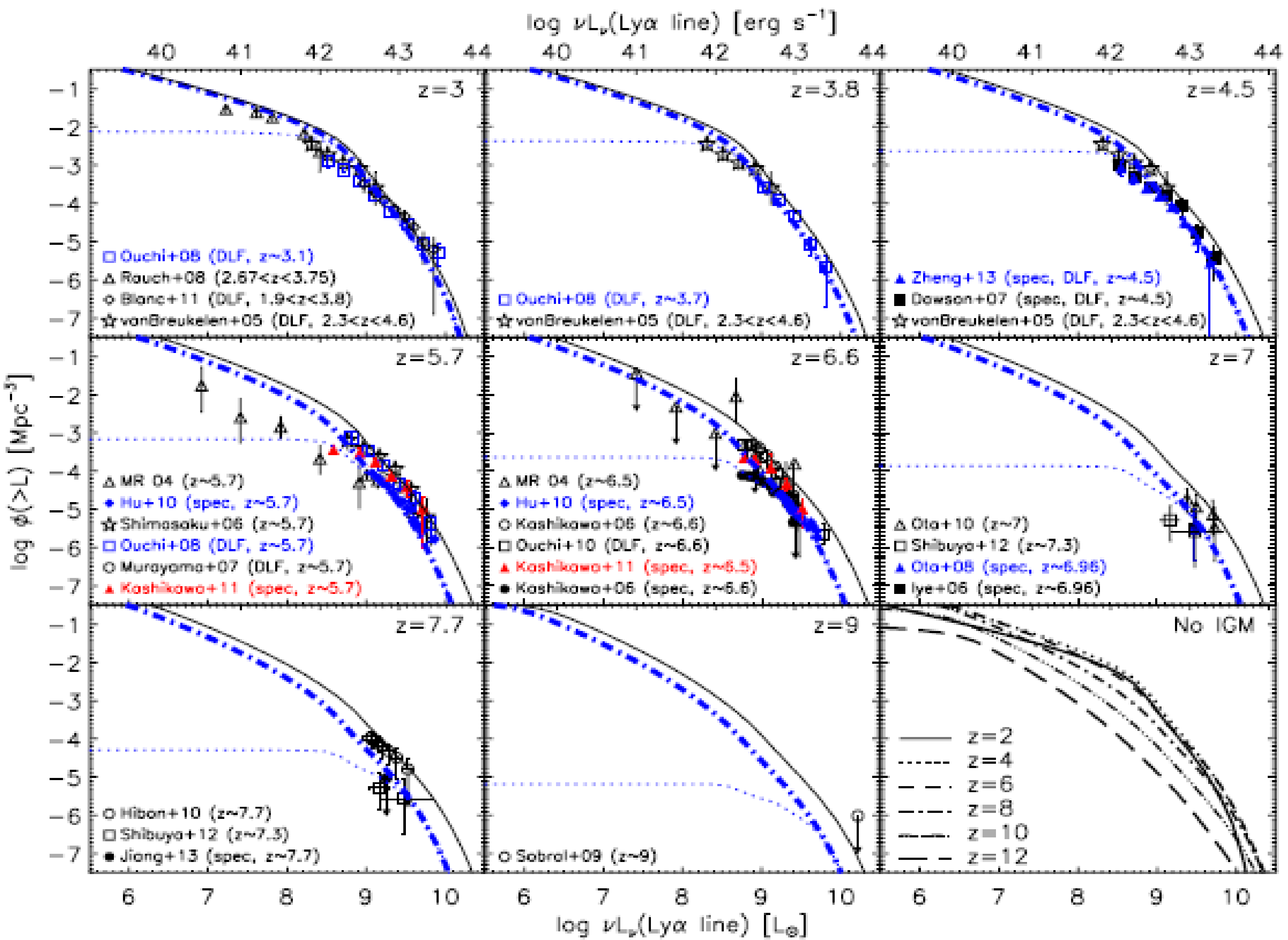
- To clarify our picture of the reionization process, promising future observational perspectives will be provided by:

  -) ultradeep NIR-mid IR observations of the *James Webb Space Telescope* at high redshift (e.g., Windhorst+13).

  -) 21 cm line emission from the H hyperfine spin transition during the cosmic dawn (Field59, Madau+97) → LOFAR, SKA (e.g., Mellema+14)

Bonus slide I

- Lyman-alpha emission $L_{\rm Ly\alpha}^{\rm obs} \simeq 4.36\times 10^{42}\left(\frac{\dot M_\star}{M_\odot\,{\rm yr}^{-1}}\right)\times f_{912}^{\rm dust}\,(1-f_{912}^{\rm H\,I})\,f_{\rm Ly\alpha}^{\rm dust}\,f_{\rm Ly\alpha}^{\rm IGM}\,{\rm erg\,s^{-1}}.$



Bonus slide II

- Ionization $\dot{N}_{912}^{\rm esc} = \dot{N}_{912}^{\rm int} f_{912}^{\rm esc} = k_{\rm ion} \dot{M}_\star f_{912}^{\rm esc}$ photons s^{-1}