Sources of Reionization and the Changing Neutrality of the IGM

Piero Madau
UCSC

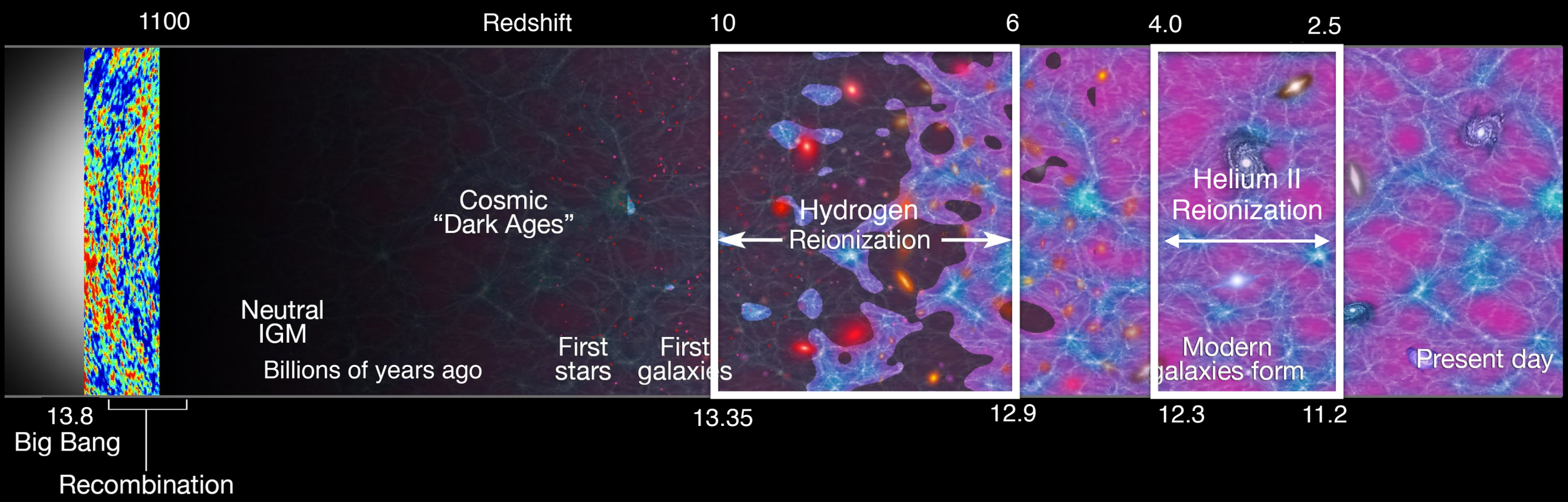
KICC 10th

The transformation of cold intergalactic H I into a highly ionized warm plasma marks the end of the *cosmic dark ages* and the beginning of the *age of galaxies*.

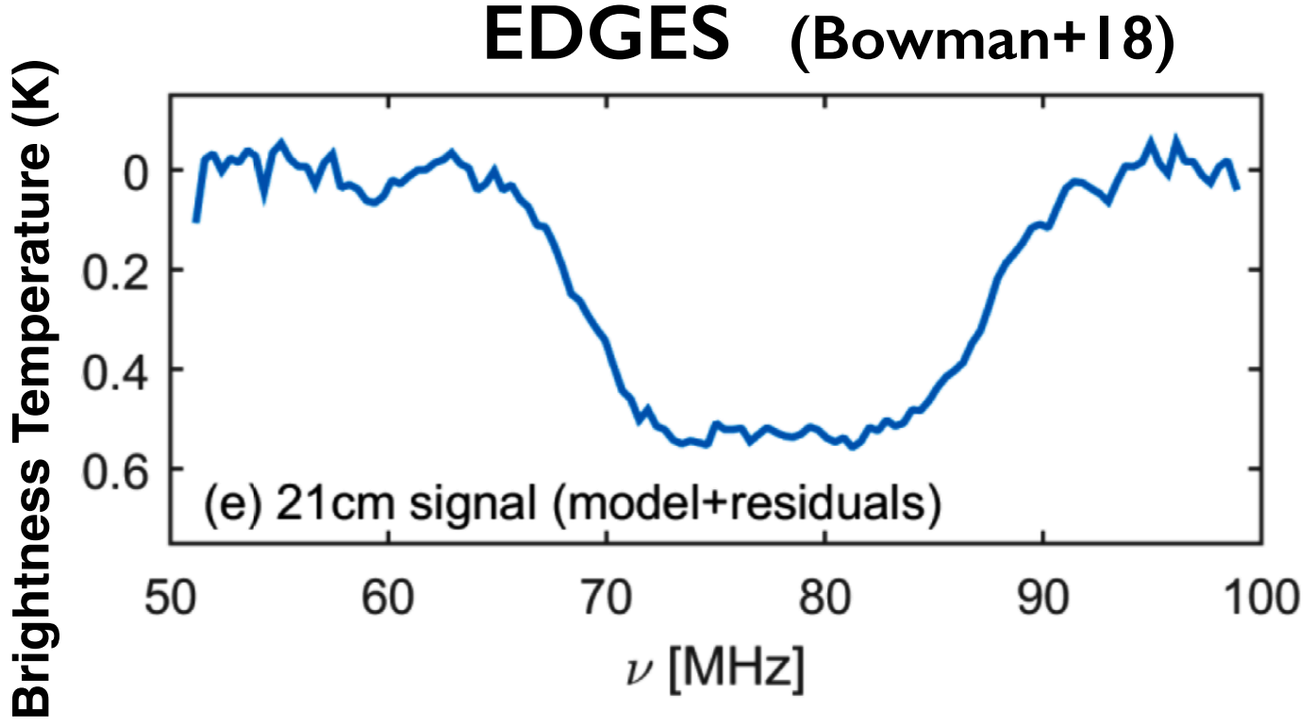
As in any crime investigation, we need to understand the *what*, *when*, *and how* in order to unravel the true story behind the last major "*phase transition*" of the gaseous Universe.

As in any crime investigation, *plot twists, shifting blame*, and *complications* have added tension to the story.

A brief history of Reionization

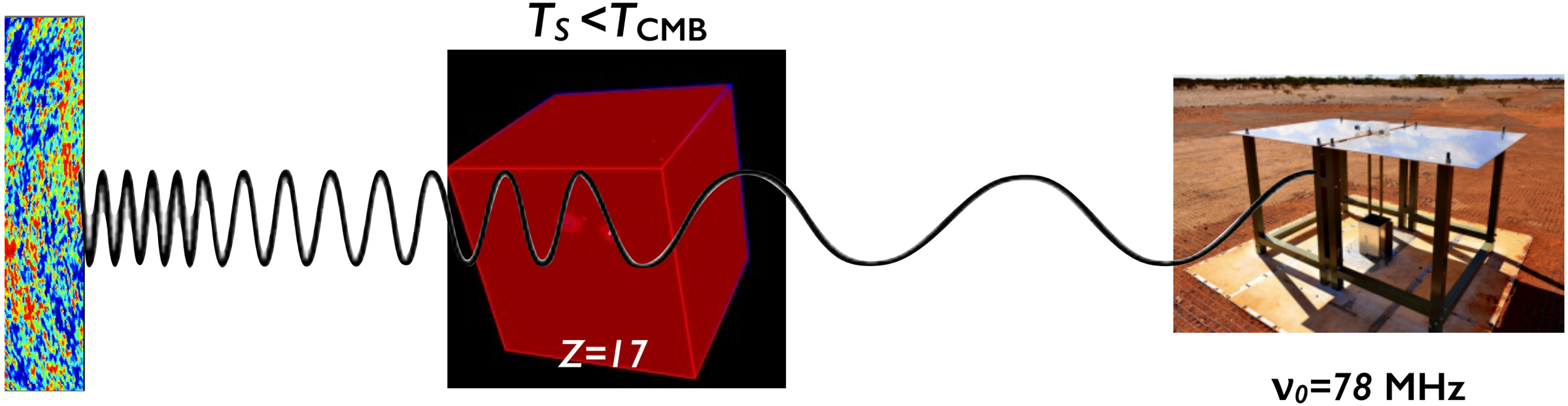


When does reionization start?



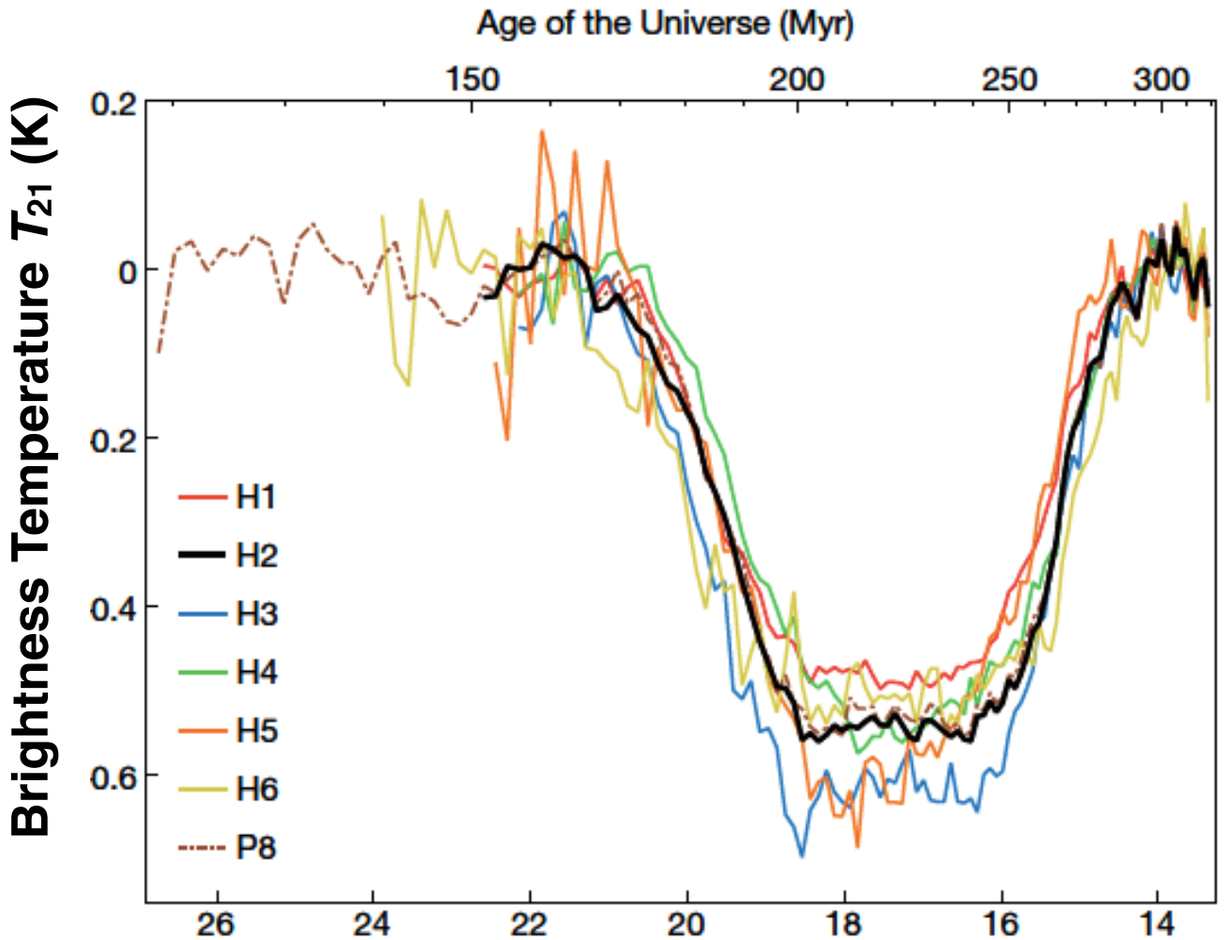
$$T_{21} \propto x_{\rm HI}\left(1-\frac{T_{\rm CMB}}{T_S}\right)$$

(assumes no excess radio background!)



CMB acts as backlight

H I imprints all-sky 21-cm *absorption* signal



At z≲40, only *resonant scattering of ambient Lyα radiation* can mix the hyperfine levels, *unlock* T_S from T_{CMB}, and make H I *visible* against the CMB:

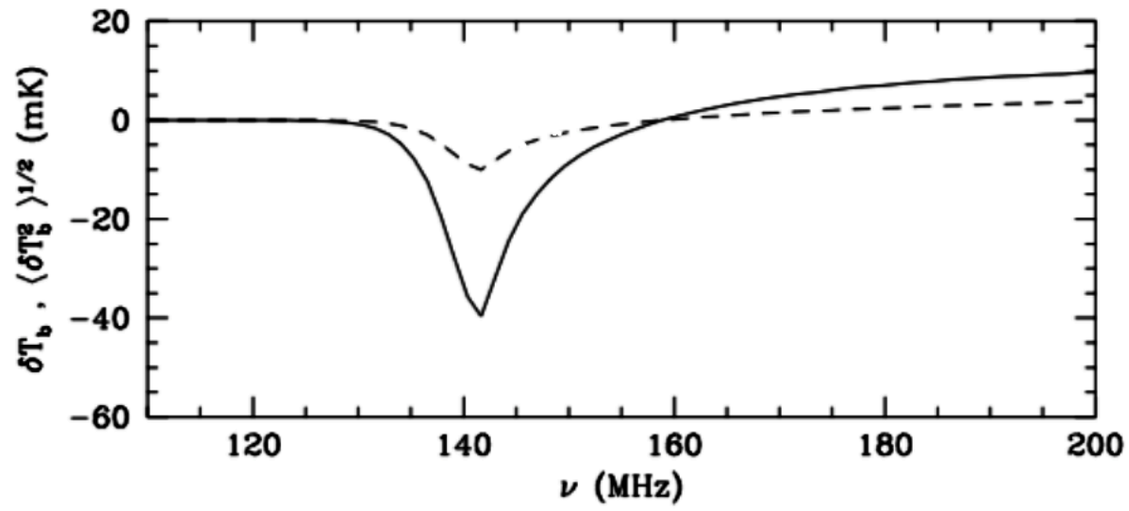
efficient unlocking:* ≥ *0.1 Lyα phot (H atom)$^{-1}$

THE ASTROPHYSICAL JOURNAL, 528:597–606, 2000 January 10

RADIO SIGNATURES OF H I AT HIGH REDSHIFT: MAPPING THE END OF THE "DARK AGES"

PAOLO TOZZI,[1,2] PIERO MADAU,[1,3] AVERY MEIKSIN,[4] AND MARTIN J. REES[3]

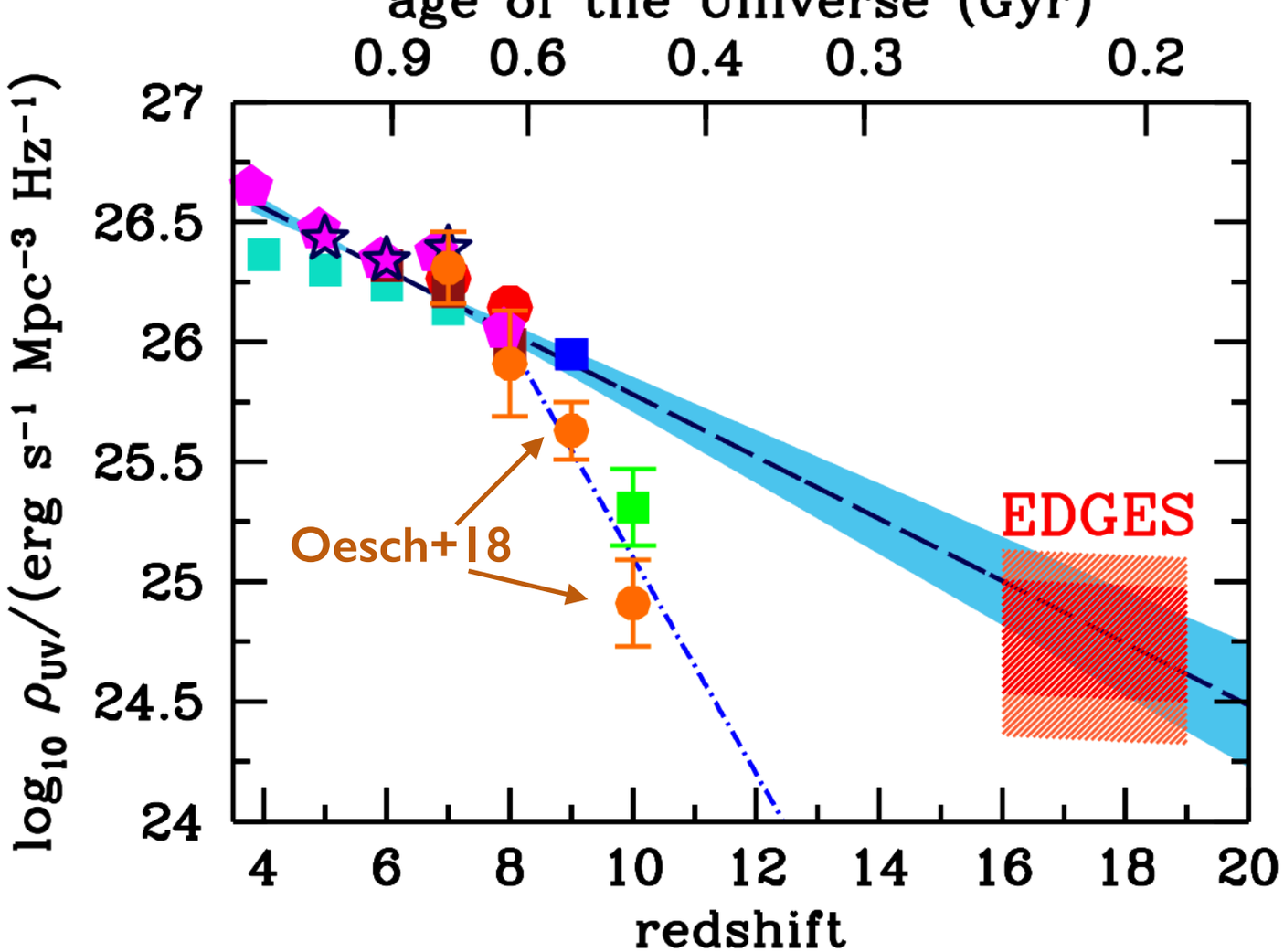
Received 1999 March 10; accepted 1999 August 23



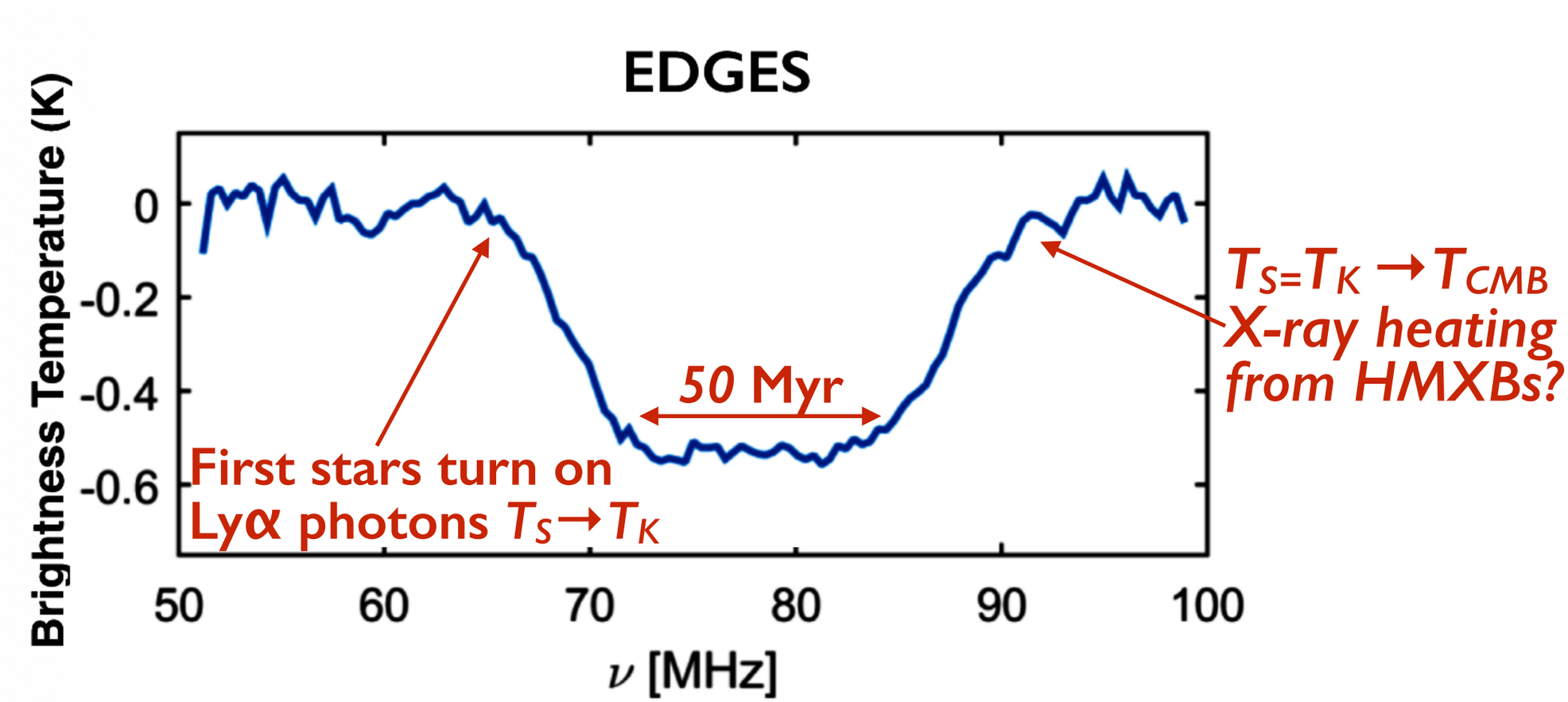
FIRST, METAL-POOR STELLAR SYSTEMS?

A 21-cm signal at *z~18* is consistent with an extrapolation of the declining galaxy UV luminosity density measured at *4 < z < 9* by deep HST observations. ***A substantially enhanced SFR density or new exotic sources of UV photons are not required by the EDGES detection.***

☛ galaxy *light* builds up at a *steady* rate over the first Gyr of cosmic history?



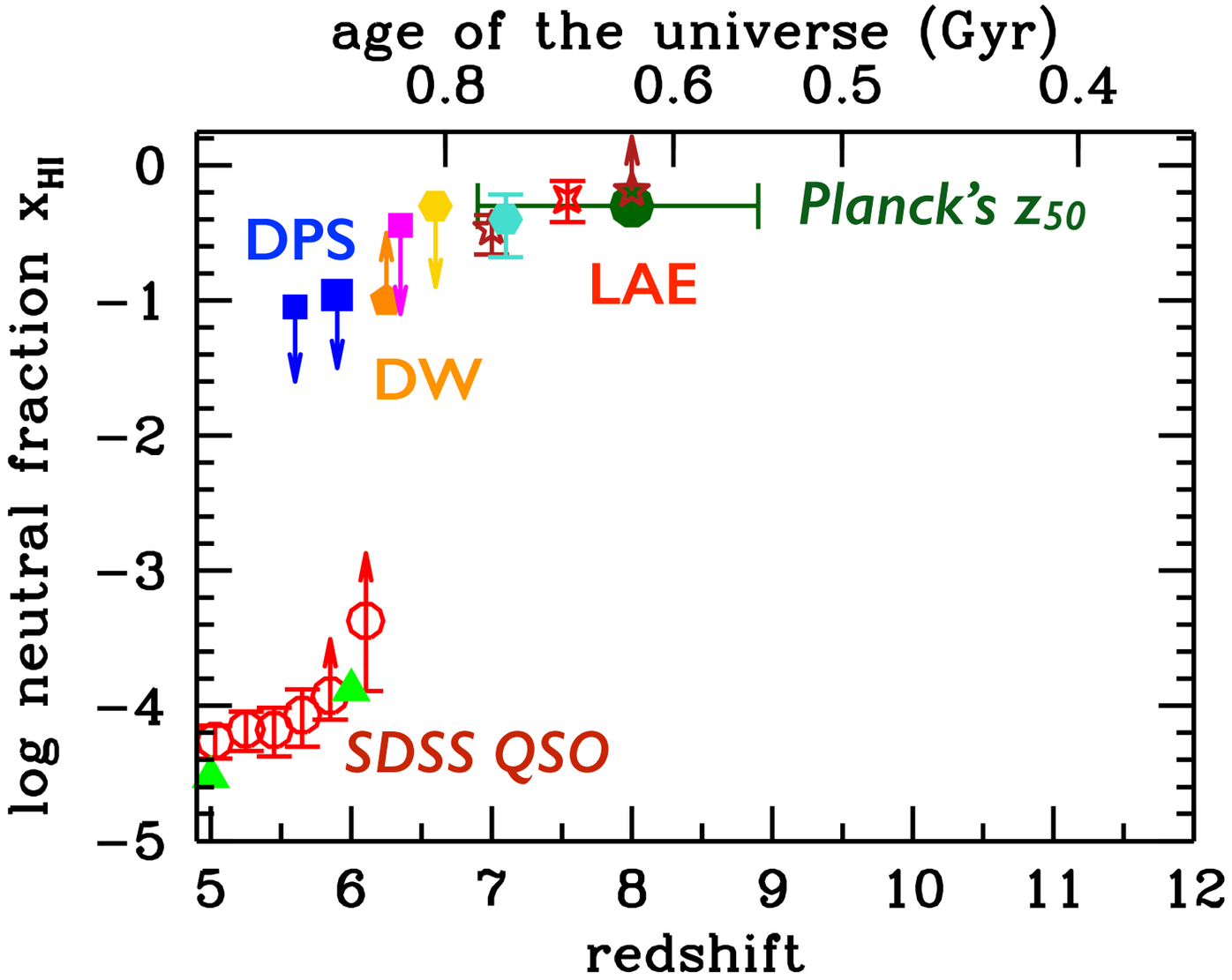
X-RAYS AT COSMIC DAWN?

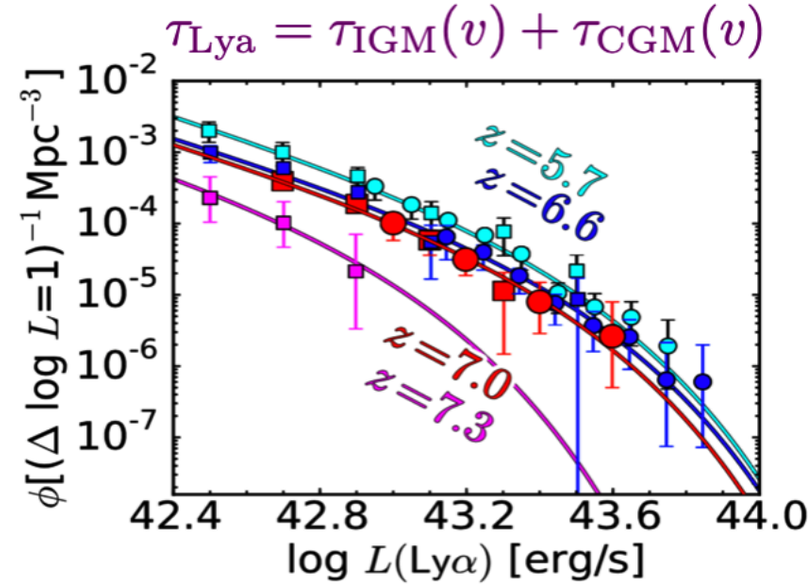


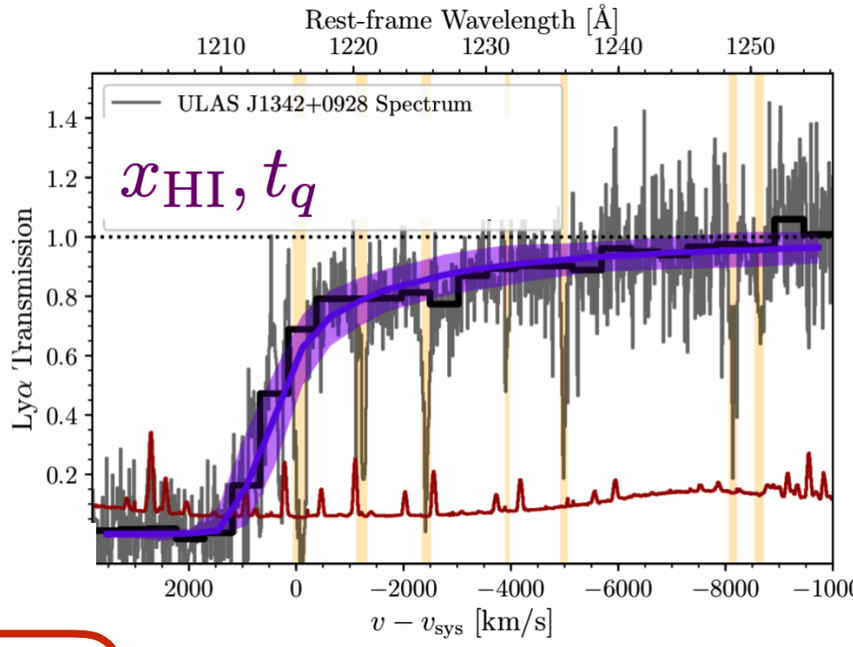
Δt = preferred formation timescale of HMXBs after SF episode.

M33 (Garofali+2018, HST+Chandra): $\Delta t \sim 40$ Myr (delayed onset associated with NS+Be stars).

CHANGING NEUTRALITY OF THE IGM





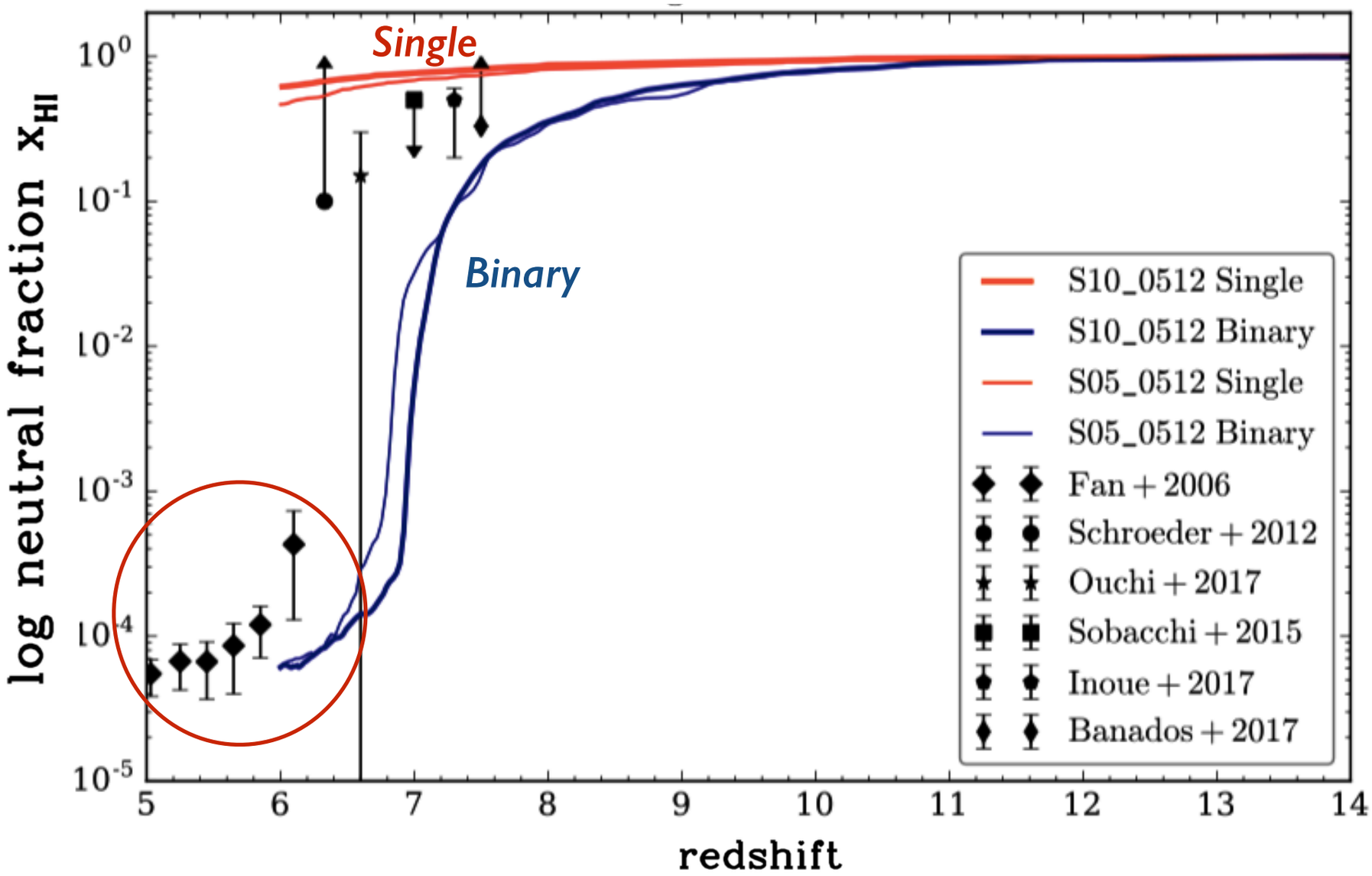


Reionization was completed (hydrogen became 99% ionized) at z~6, and above z~10 hydrogen was less than 10% ionized.

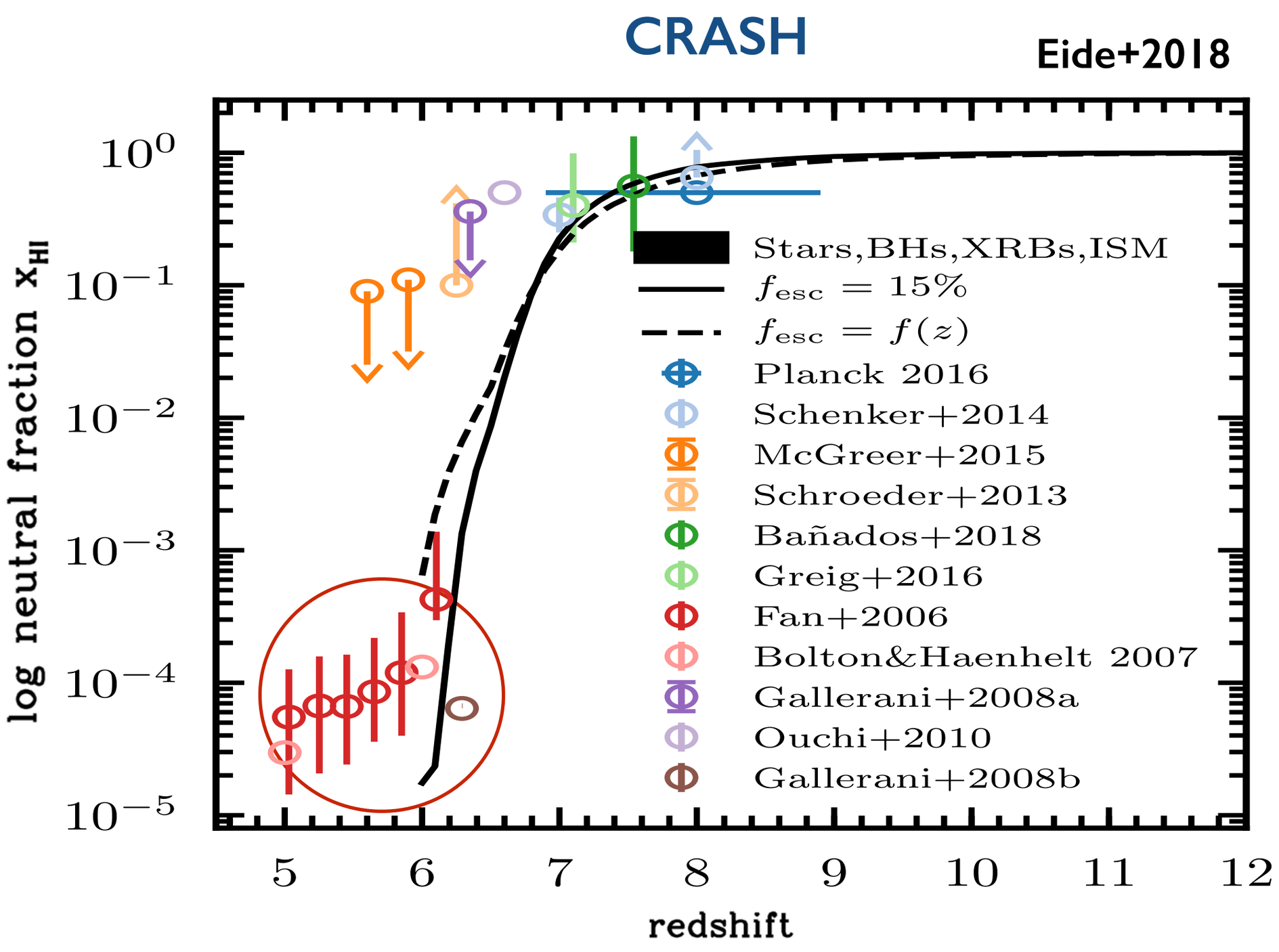
RADIATIVE TRANSFER SIMULATIONS

SPHINX

Rosdahl+2018



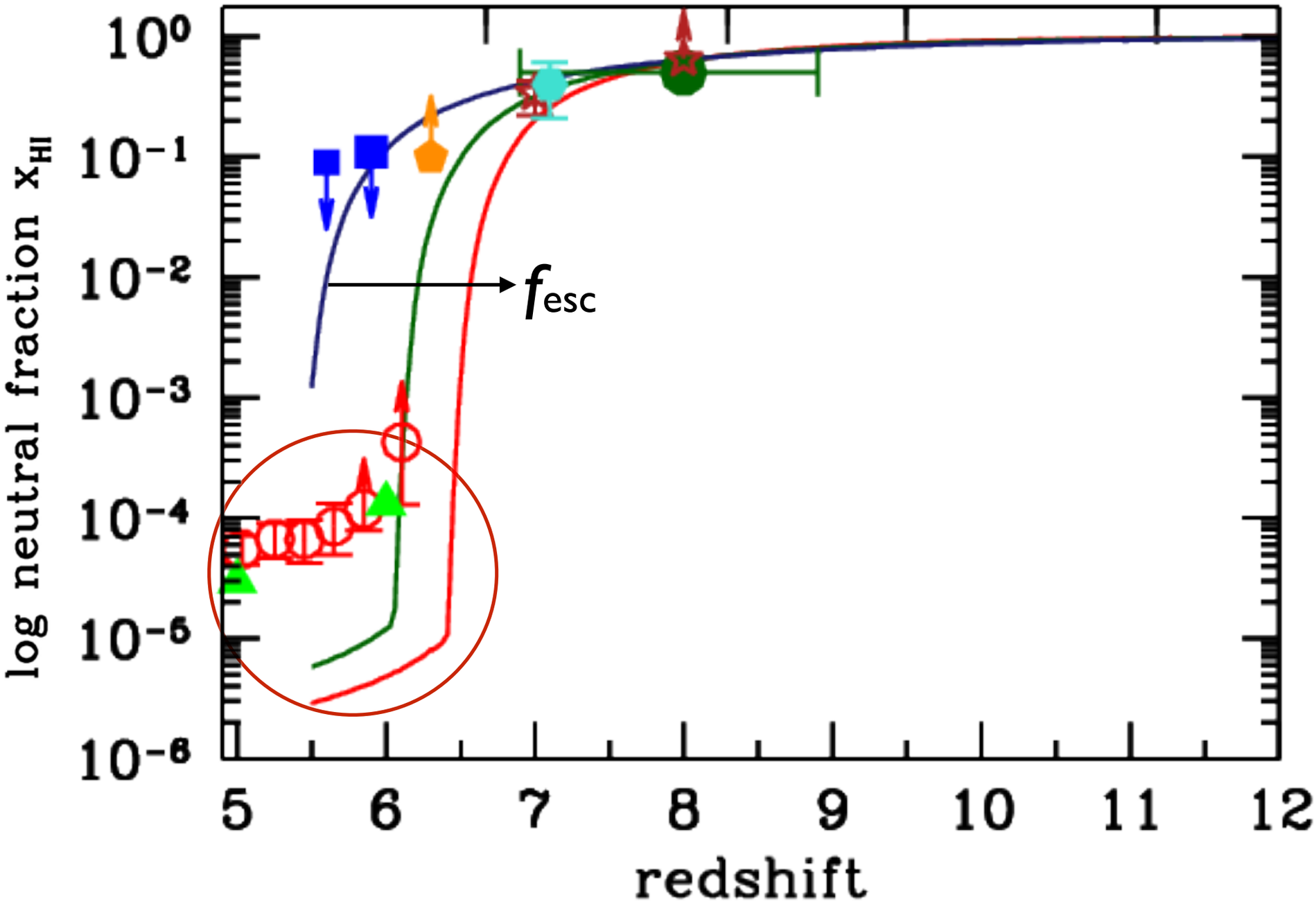
RADIATIVE TRANSFER SIMULATIONS



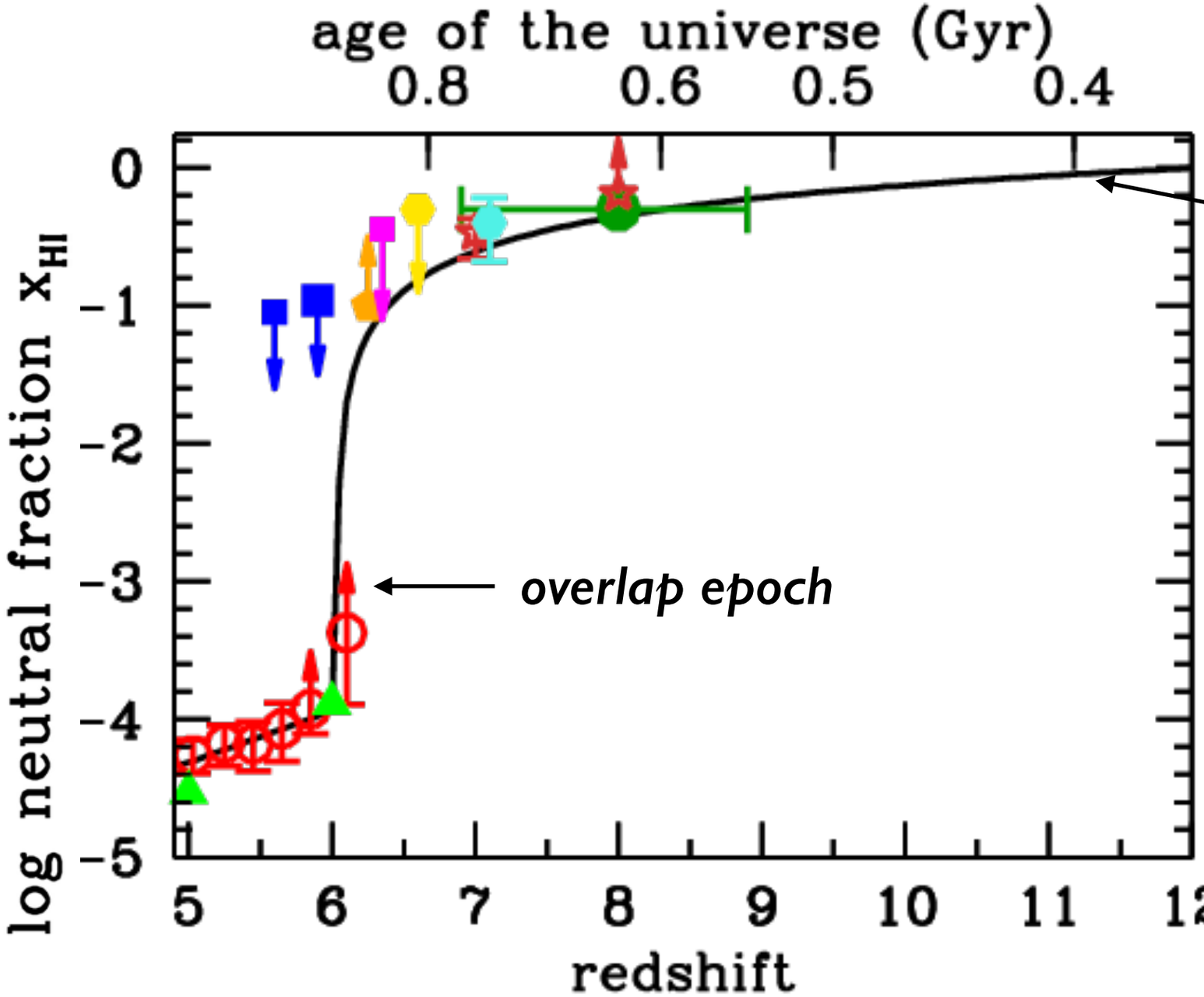
RADIATIVE TRANSFER SIMULATIONS

SCORCH

Trac+2018

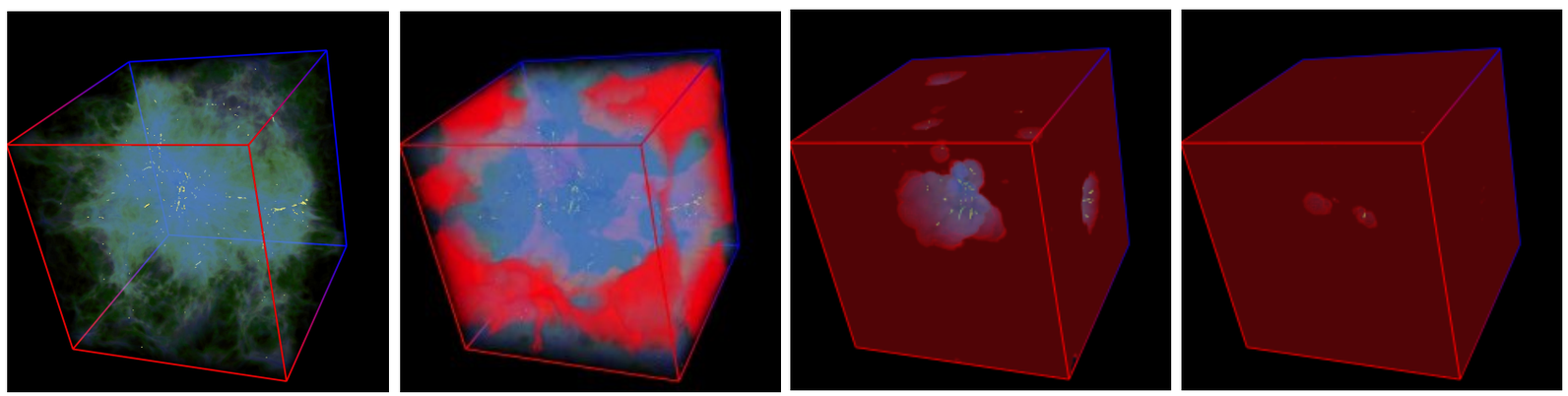


A Concordance Reionization History?

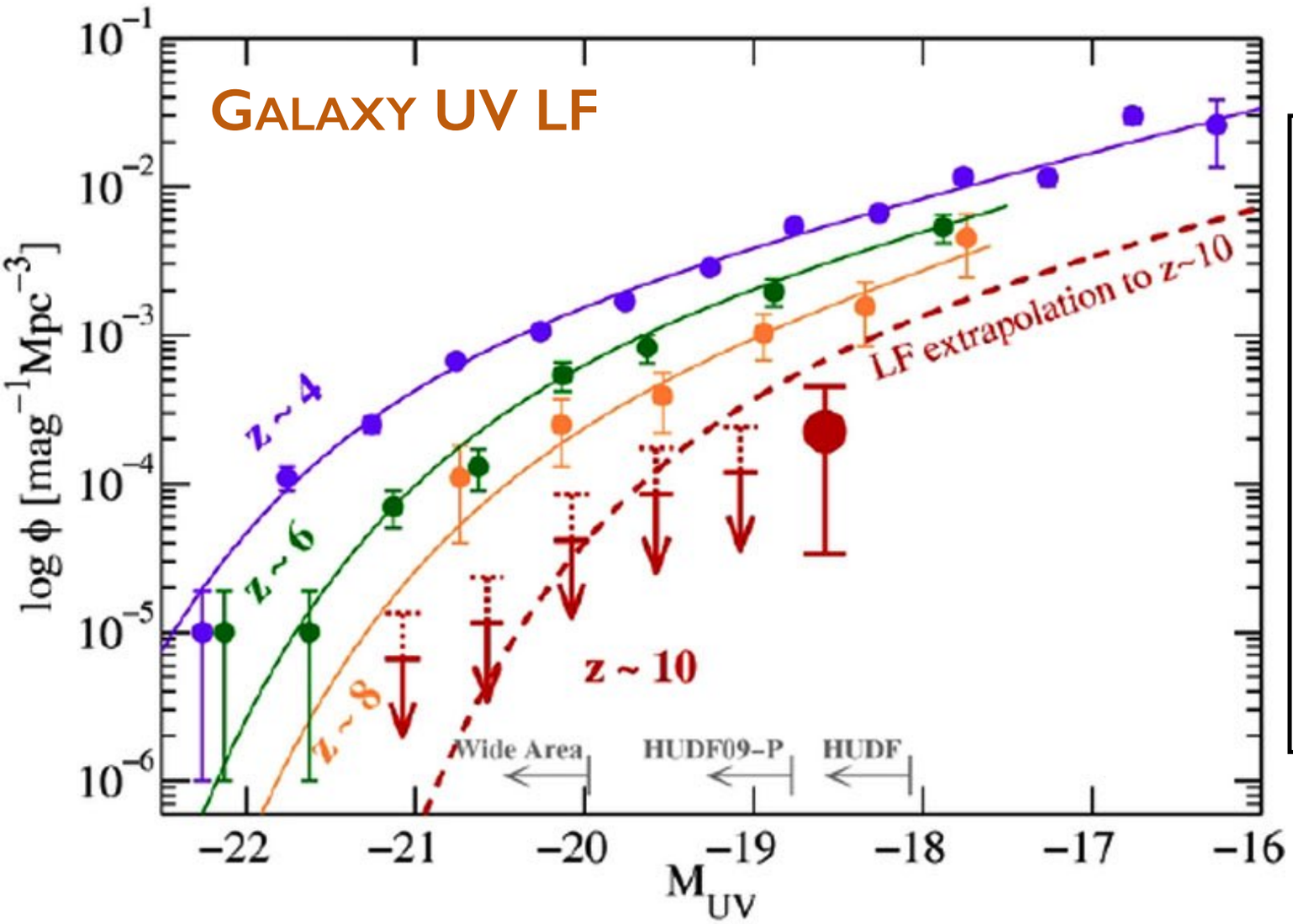


model

$$\frac{\dot{n}_{\rm ion}}{n_{\rm H}} = 3\,{\rm LyC\ phot\ Gyr}^{-1}$$



SOURCES OF UV PHOTONS: SF GALAXIES



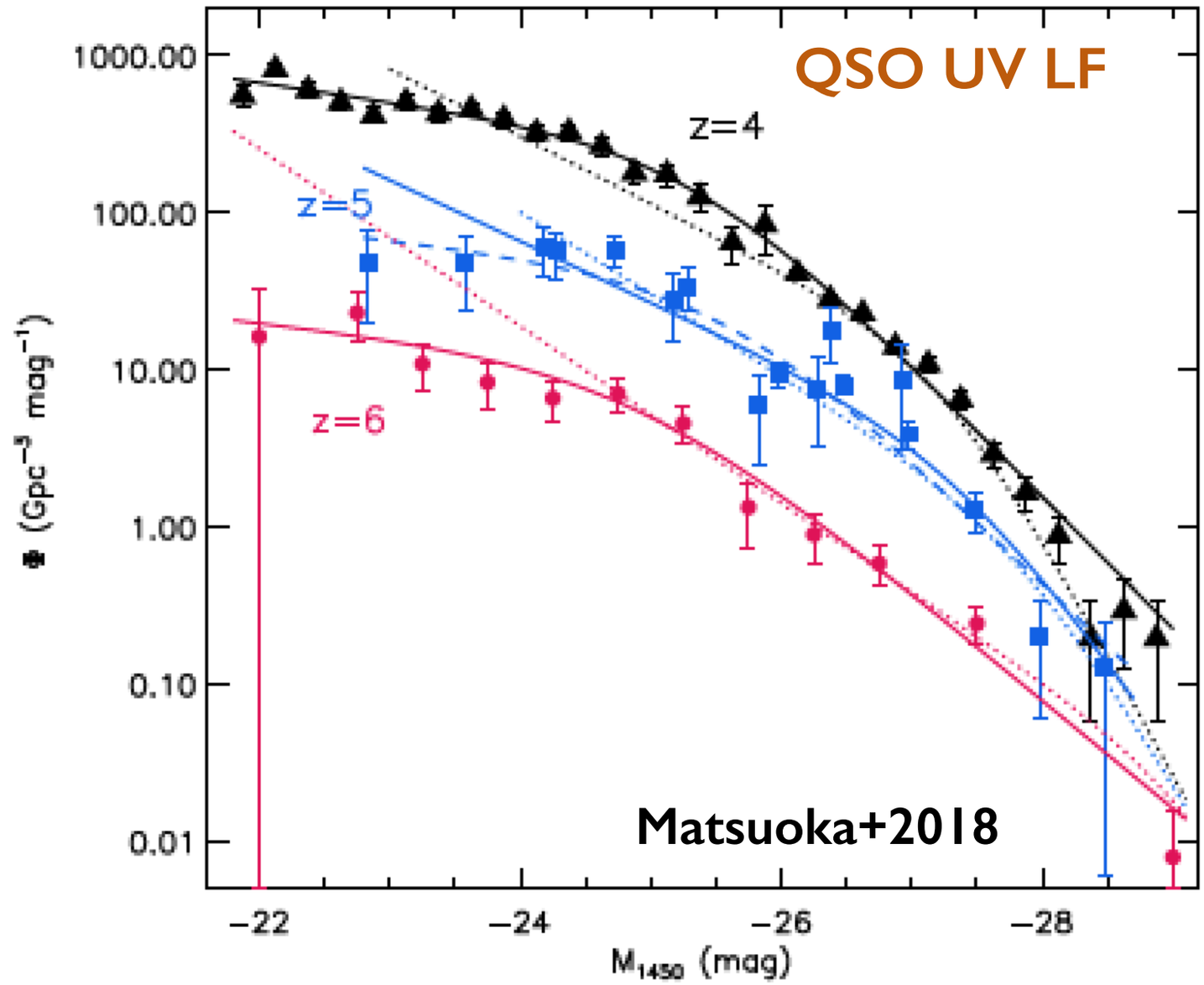
✓ Plenty of high-z SF galaxies.

✓ Soft FUV spectra.

✗ Small f_{esc} at $z<4$.

✗ Produce "*uniform*" UVB in post-reionization era.

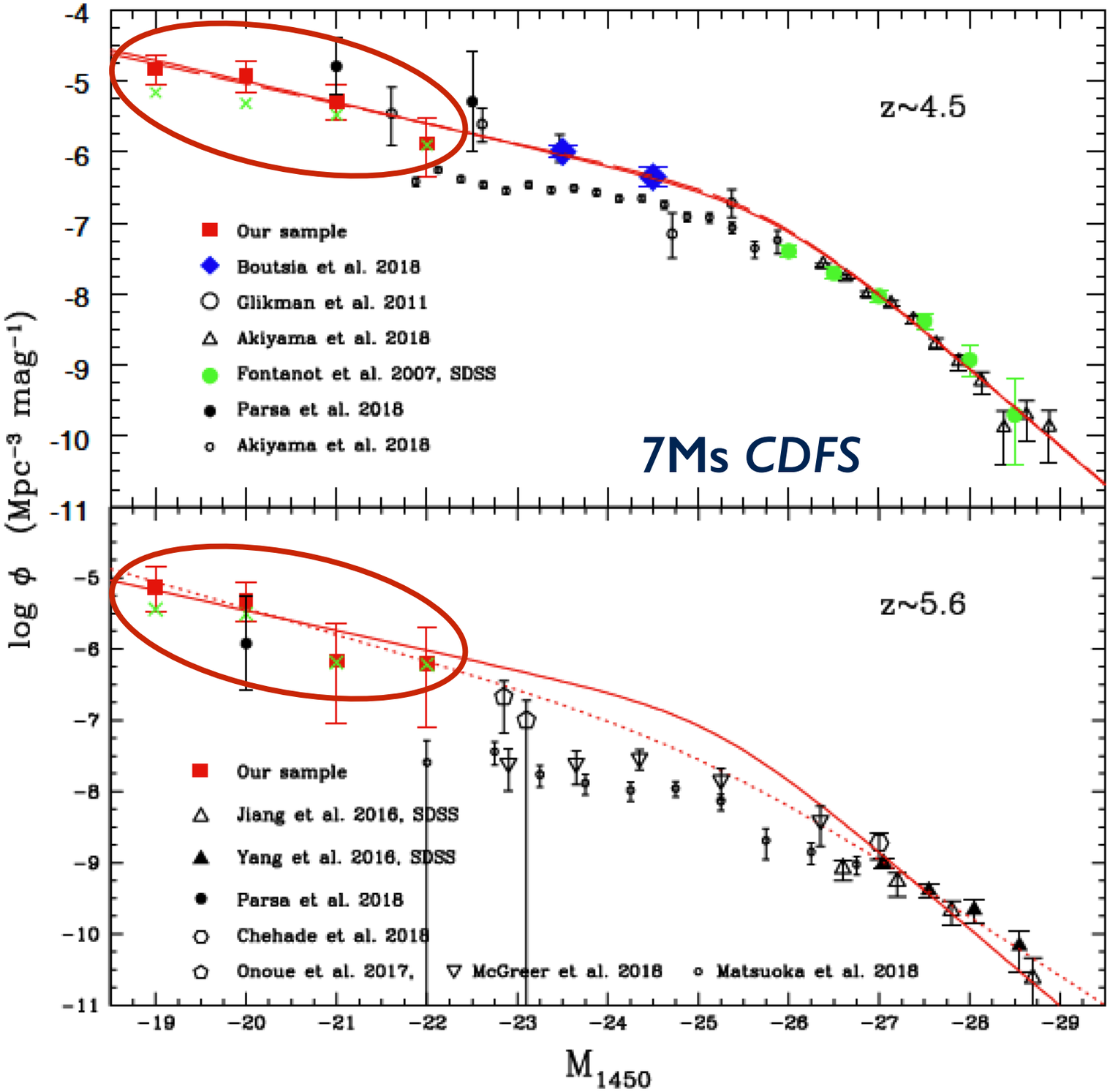
SOURCES OF UV PHOTONS: QUASARS

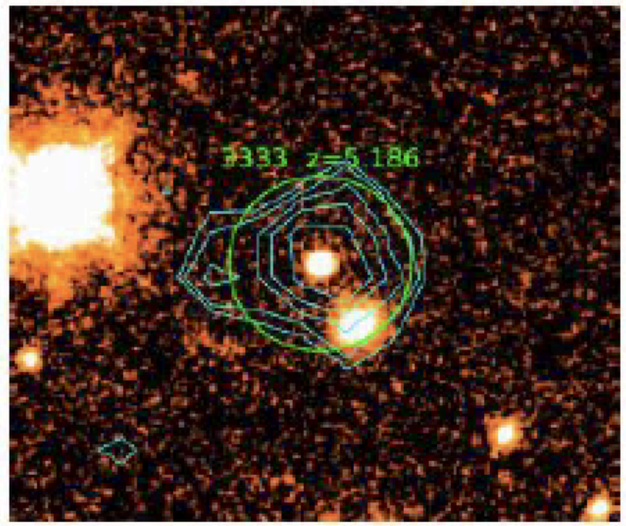


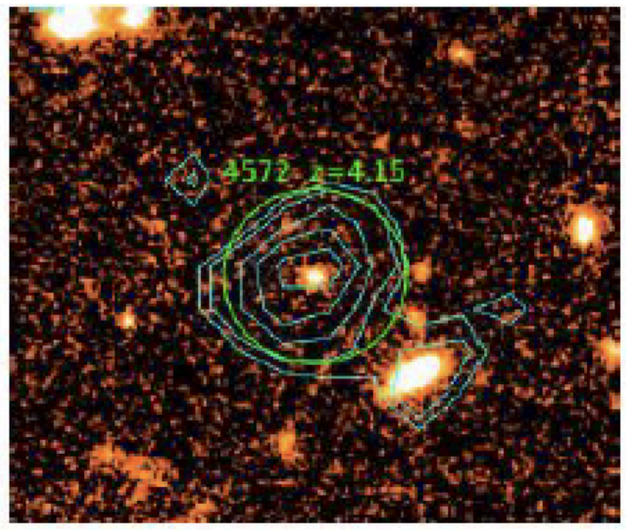
- ✓ Escape fractions $f_{esc} \sim 1$.
- ✓ Hard FUV spectra ⇨ HeII reionization at z<4.
- ✓ Produce *fluctuating* UVB in post-reionization era.
- ✗ Rare at z>5.
- ✗ Large population of z>5 AGNs reionizes HeII early and produces high T_{IGM}.

FAINT AGNS CONTROVERSY

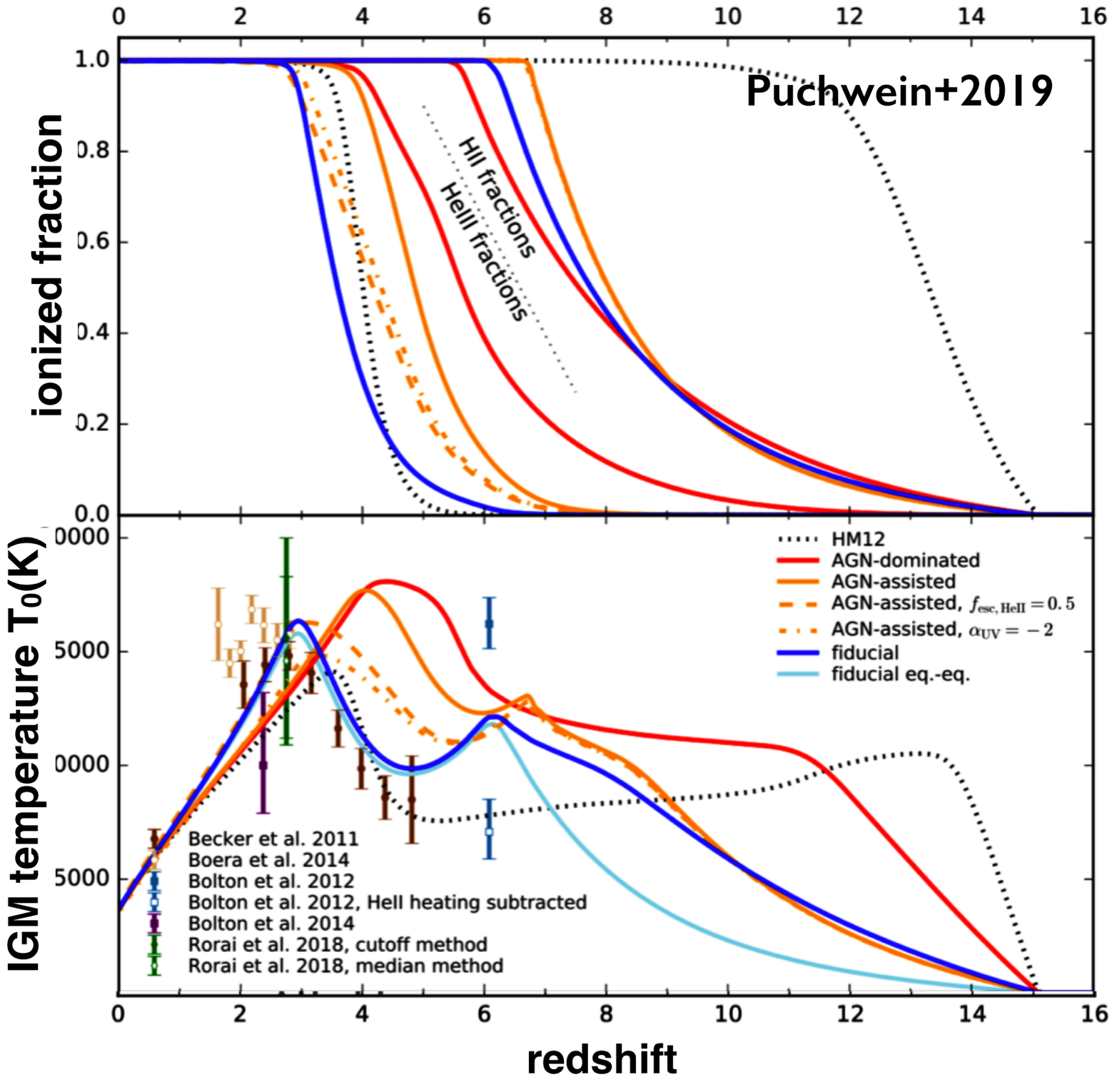
Giallongo+2019







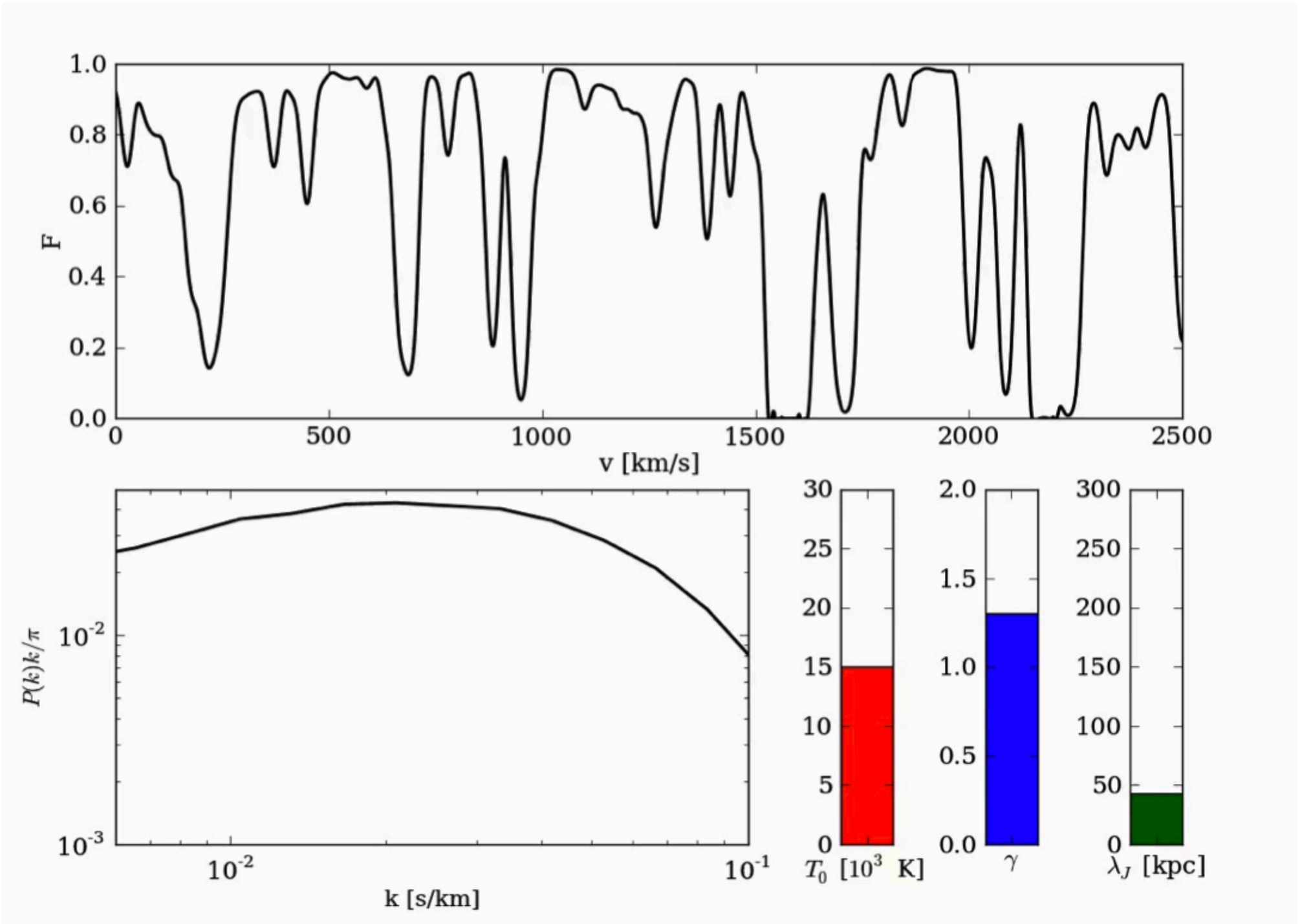
THE IGM THERMAL HISTORY



A source of information about processes that injected vast amounts of energy into this gas on relatively short timescales

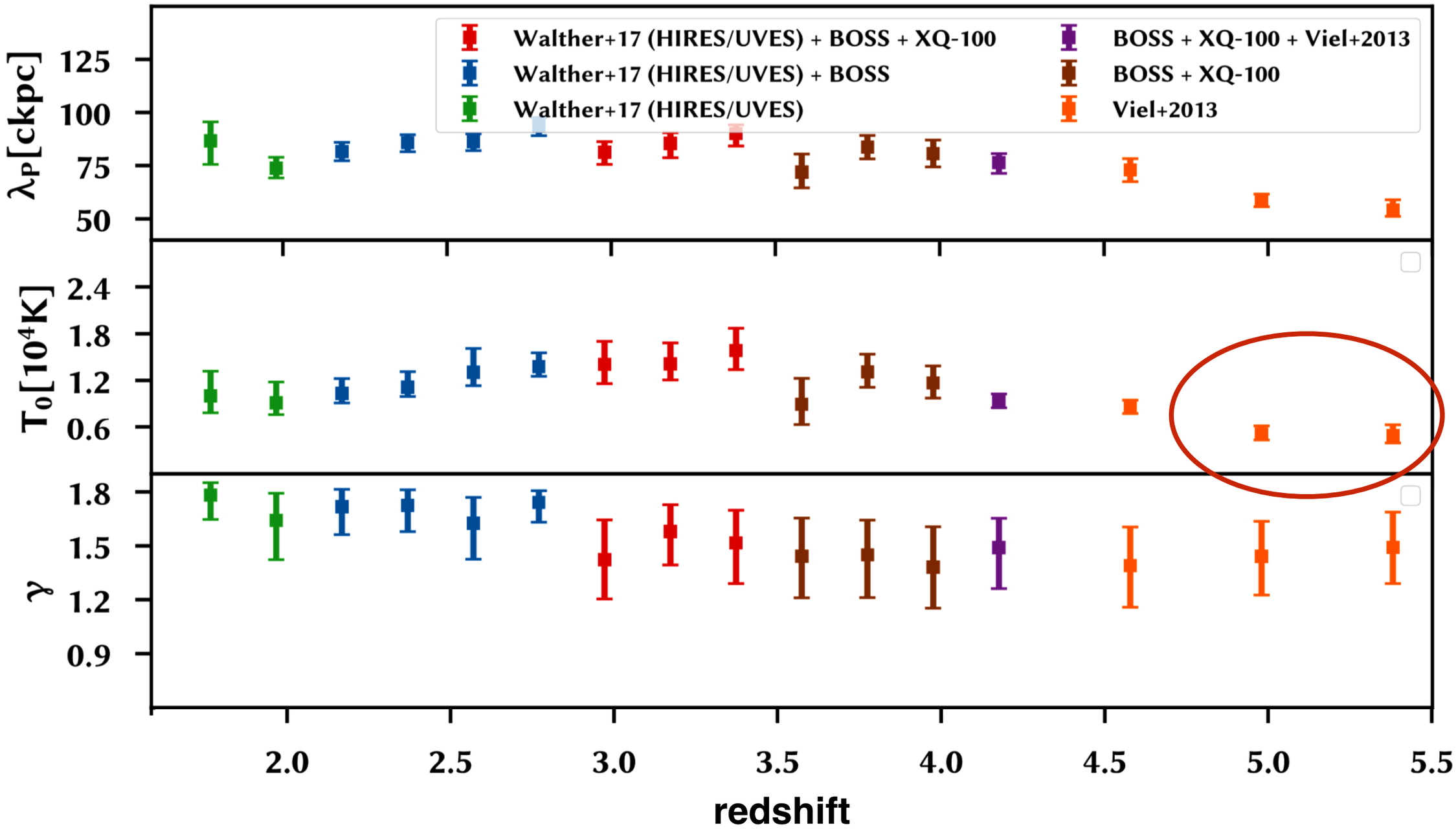
➪ search of any *footprint* of either H I or He II reionization.

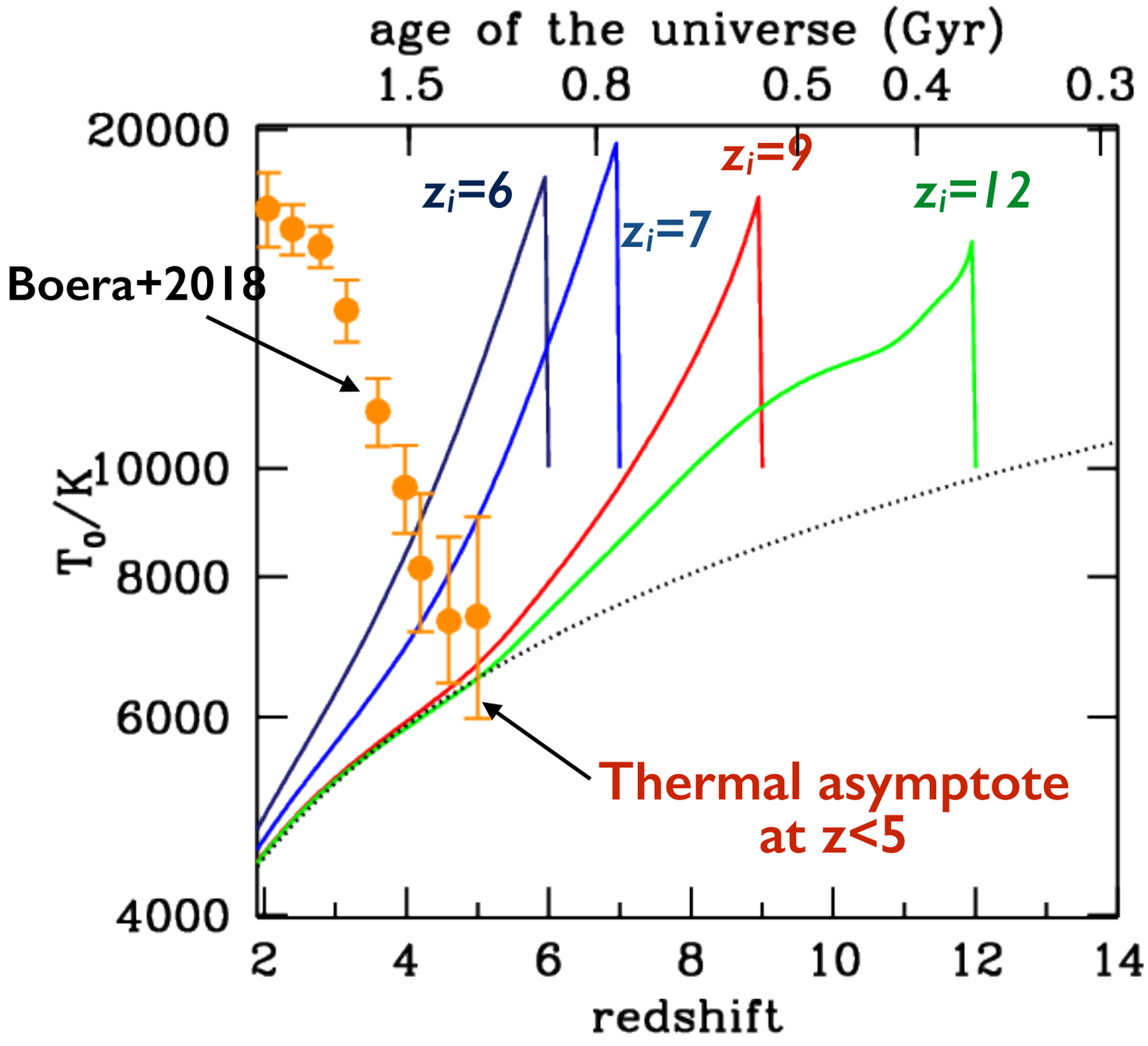
RIPPLES IN THE COSMIC WEB



Credit: Rorai

THE TEMPERATURE OF THE IGM





H-photoheating only: late reionization histories result in $T_{IGM} \gtrsim$ *8,000* K at z~*5*!

Temperature evolution for gas at mean density

$$\frac{dT_0}{dt} = -2HT_0 + \frac{T_0}{\mu}\frac{d\mu}{dt} + \frac{2\mu m_p}{3k_B\bar{\rho}_b}(\mathcal{H} - \Lambda)$$

When does reionization start and when is it over?

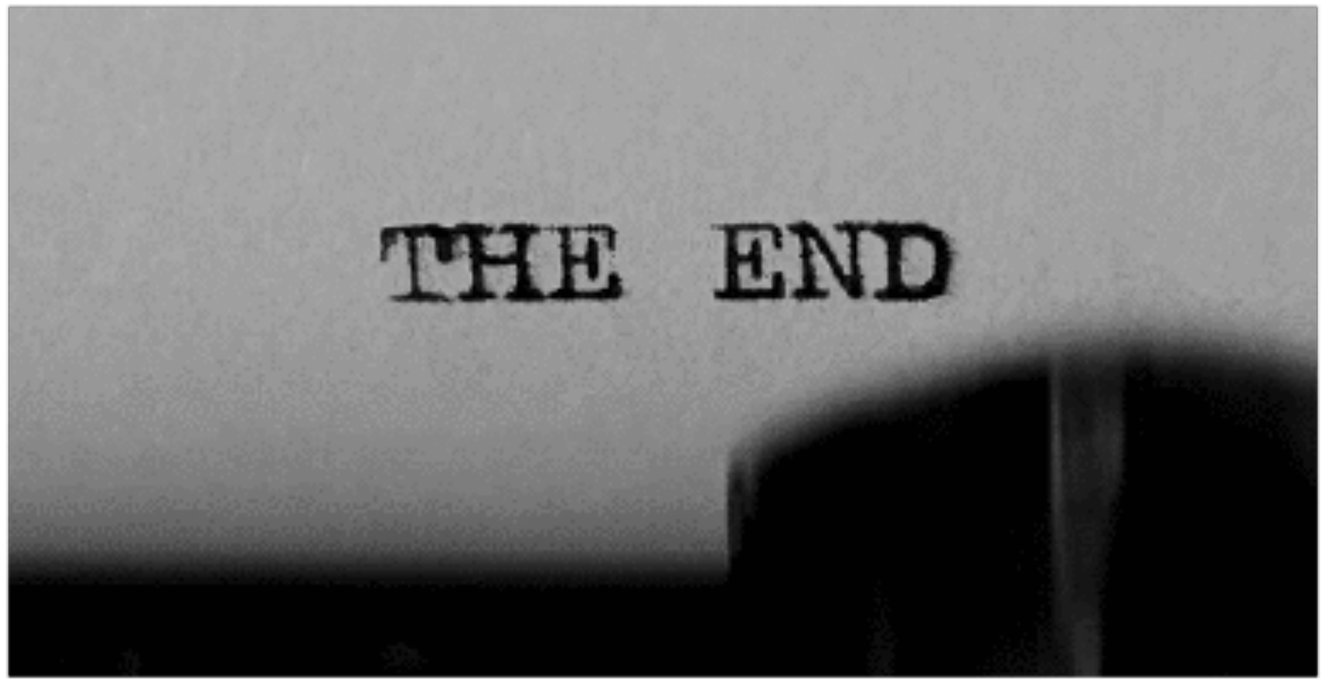
What are the sources of ionizing radiation: galaxies, AGNs, or something more exotic?

Do X-rays pre-heat the IGM and impact the 21-cm signal from First Light?

What is the imprint of reionization on the temperature and pressure of the $z<6$ IGM?

How does reionization affect the use of the Lyman-alpha forest as a cosmological probe (e.g. as a test of WDM vs. CDM)?

What is its back-reaction on galaxy formation?


THE END