Definitive Determination of Galaxy Luminosity Functions at Energies Above the Hydrogen Ionization Edge, Covering 11 Billion Years of Evolution

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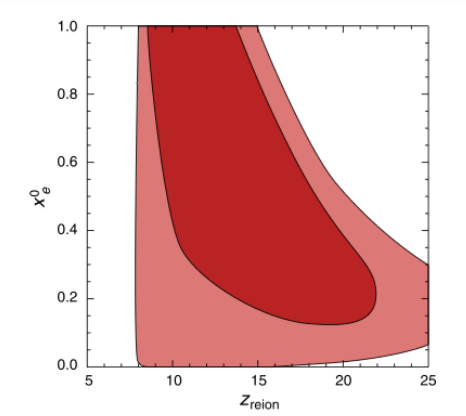
Project Lyman

(white paper for astro2010 McCandliss et al. 2009)

- How did the universe become ionized?
  - Stars or quasars? (or exotica?)
  - Does the escape of ionizing photons depend on:
    - Luminosity? Mass? Metallicity? Redshift?
  - Do low-z analogs exist of the faint high-z galaxies?
  - Can Lyα escape fraction serve as a proxy for LyC escape fraction? $N_{Ly\alpha} = \frac{2}{3} N_{LyC} f_{Ly\alpha} (1 - f_{esc}) e^{-\tau}$
- Use low z observations to inform high z observations of reionization epoch by JWST

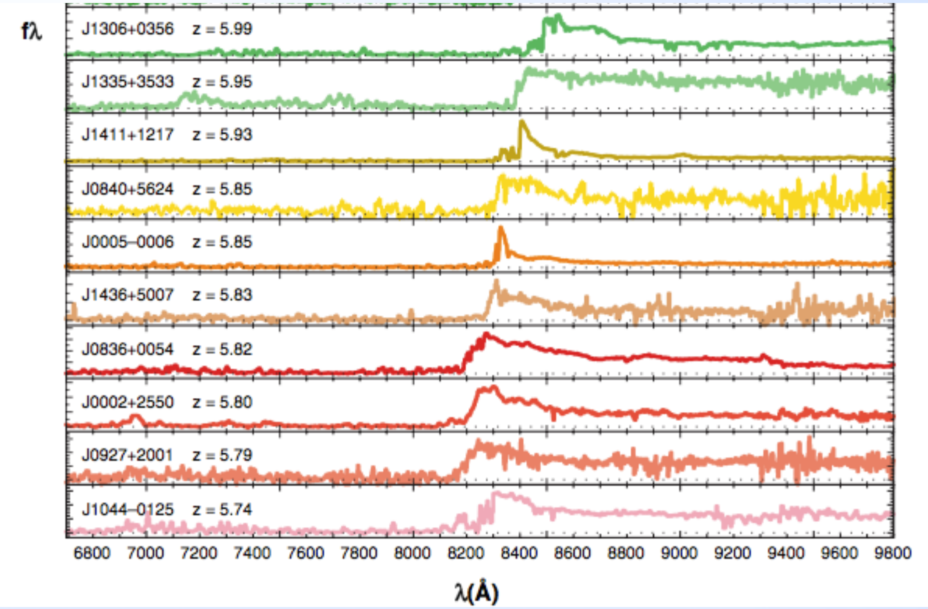
We know the Universe is Ionized

- Thomson scattering of CMB photons by free electrons creates polarization detected by WMAP
  - Indicates that reionization started at redshifts $z > 11$



Spergel et al. 2007
Confidence intervals for ionization fraction x_e as a function of redshift.

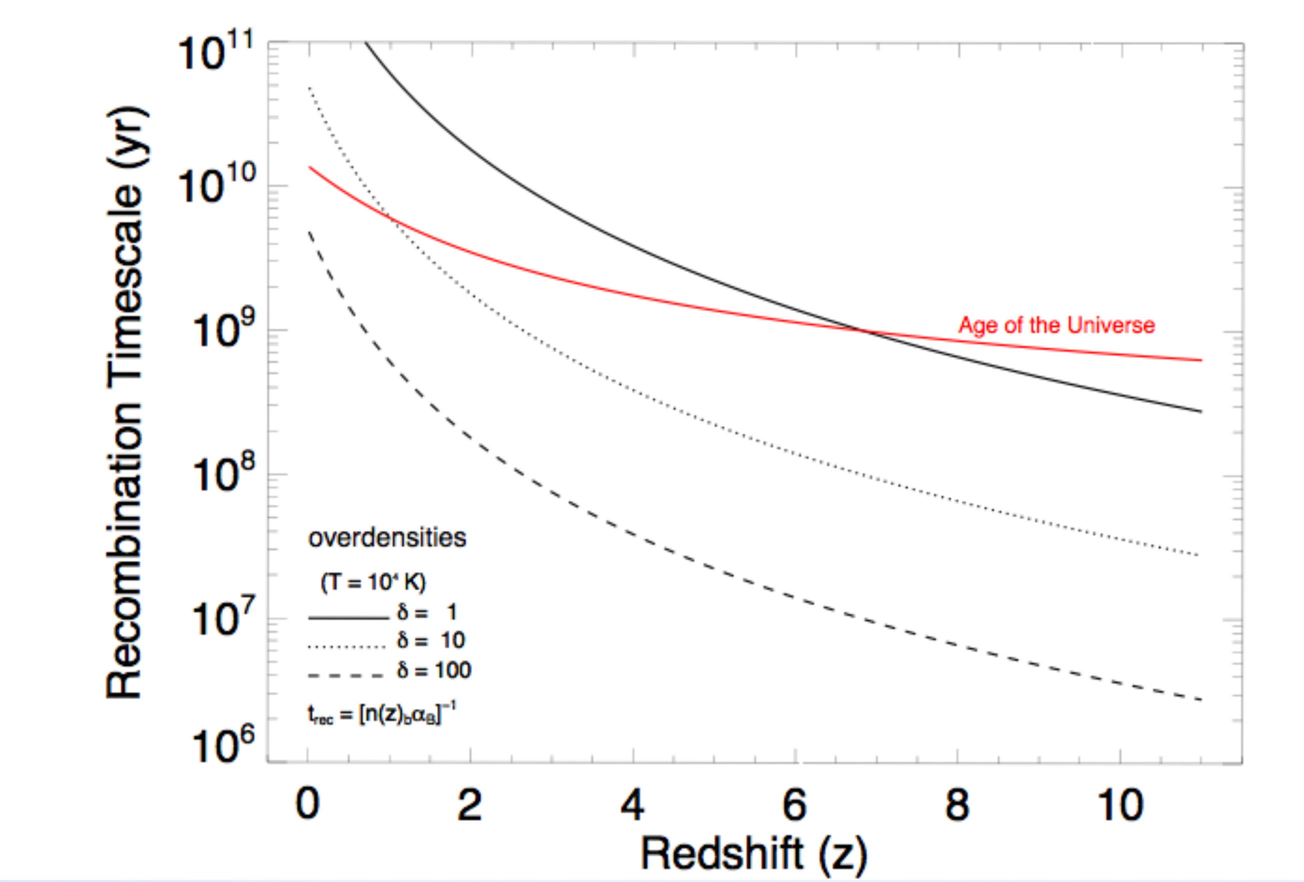
- Break up of black Hydrogen absorption troughs in Sloan Digital Sky Survey QSO
  - Indicates that reionization was mostly complete around $z \sim 6$



Fan, Carilli and Keating 2006

Hydrogen Recombination Timescales

Overdensity and the Metagalactic Ionizing Background



Timing and duration of the reionization epoch is crucial to the emergence and evolution of structure in the universe.

Low numbers of Lyα forest lines at low z suggest a non-zero LyC escape fractions at low redshift. (Kollmeier et al. 2014)

The fundamental question is:
How is reionization initiated and sustained?

Reionization Requires
One Ionizing Photon for Each Baryon

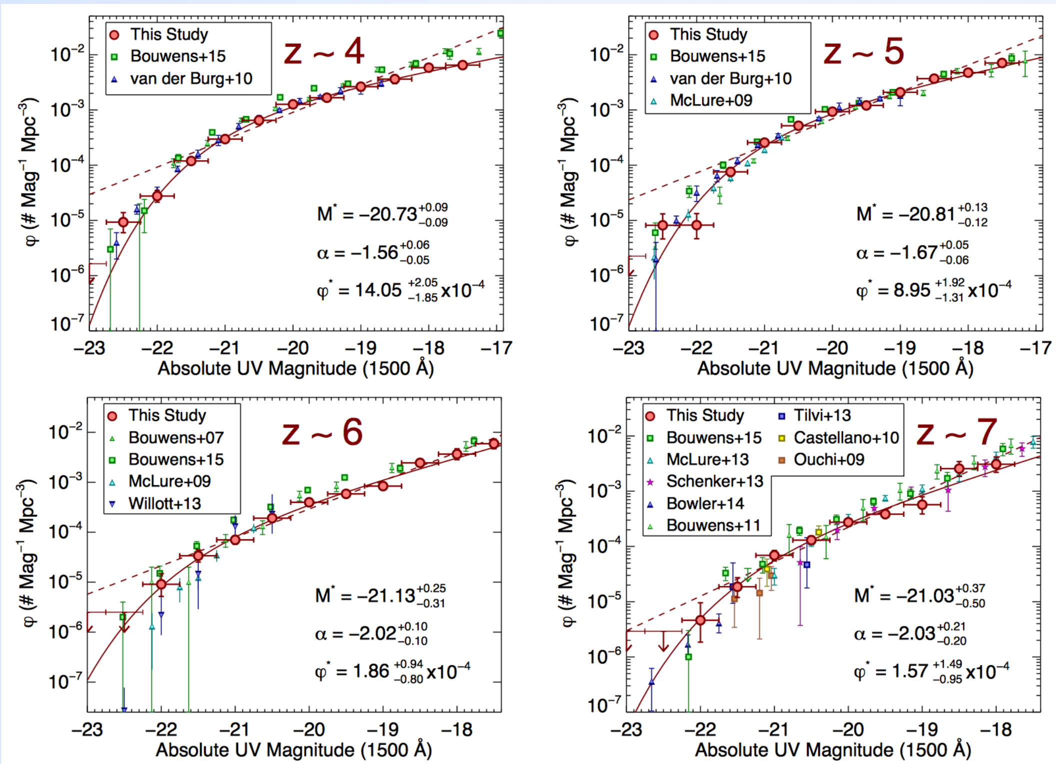
- Critical Star-formation rate
  - (Madau et al. 1999, Pawlik et al. 2015)

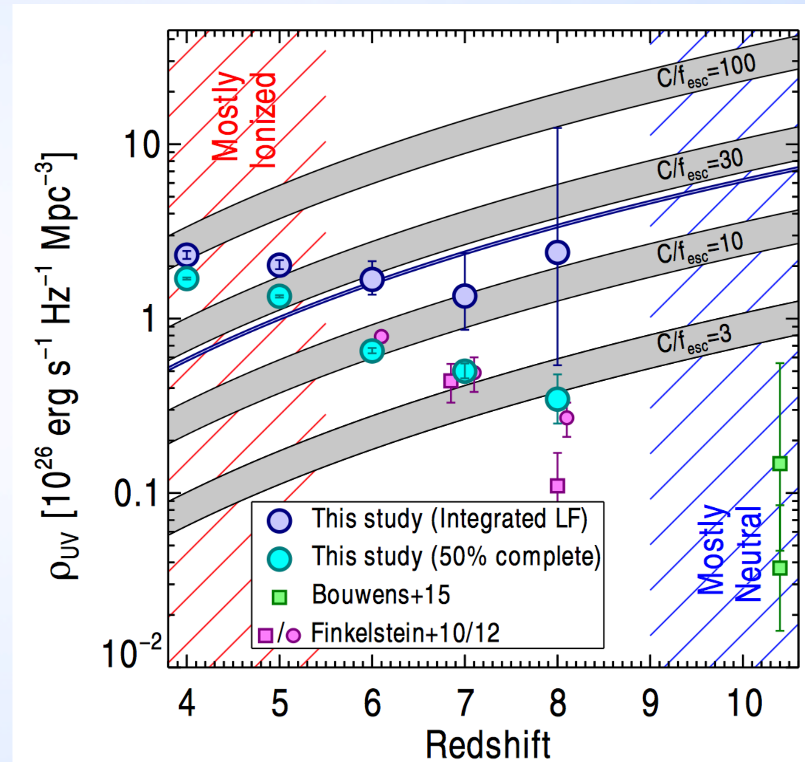
$$\rho_{cr}^{SFR} \approx 0.013 M_{\odot}\, yr^{-1}\, Mpc^{-3} \left(\frac{C}{5}\right)\left(\frac{0.2}{f_{LyC}^{e}}\right)\left(\frac{1+z}{7}\right)^{3}$$

- Clumping factor $C \equiv \langle \varrho^2_b \rangle_{IGM} / \langle \varrho_b \rangle^2$
- Escape fraction of ionizing photons f^e_{LyC}
  - Universally acknowledged as most uncertain

LyC escape from the smallest (faintest) galaxies is thought to power reionization

- Depends on extrapolation of faint end slope to M_{1500} = -13, C=3, f^{e}_{LyC}= 13%





Finkelstein et al. 2015

The Photon Underproduction Crisis

THE ASTROPHYSICAL JOURNAL LETTERS, 789:L32 (5pp), 2014 July 10

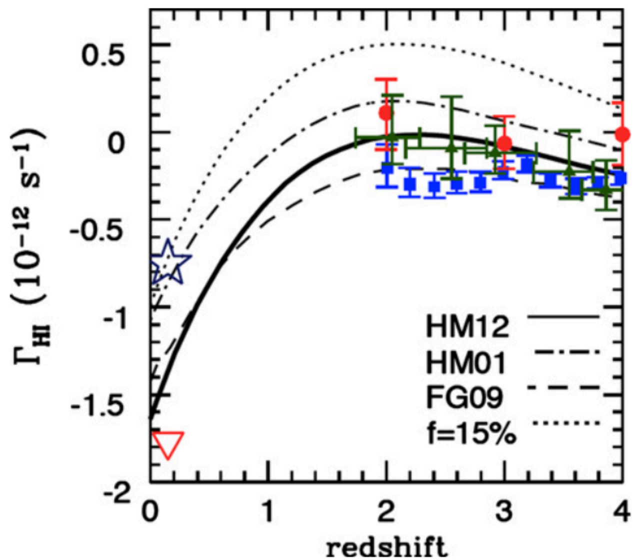


Figure 1. Photoionization rate as a function of redshift for the HM12, HM01 UVB (solid, dot-dashed) compared to observations at $z = 2$–4 (circles: Bolton & Haehnelt 2007, triangles: Becker et al. 2007, and squares: Faucher-Giguère et al. 2008) and the value we infer from our Lyα forest modeling at $z = 0.1$ (open star). The red triangle shows the low-redshift upper limit inferred by Adams et al. (2011) from non-detection of Hα emission in UGC 7321. The dashed line shows an alternative UVB model from Faucher-Giguère et al. (2009). The dotted line shows a model, discussed in Section 4.1, with a constant galaxy escape fraction $f_{esc} = 15\%$.

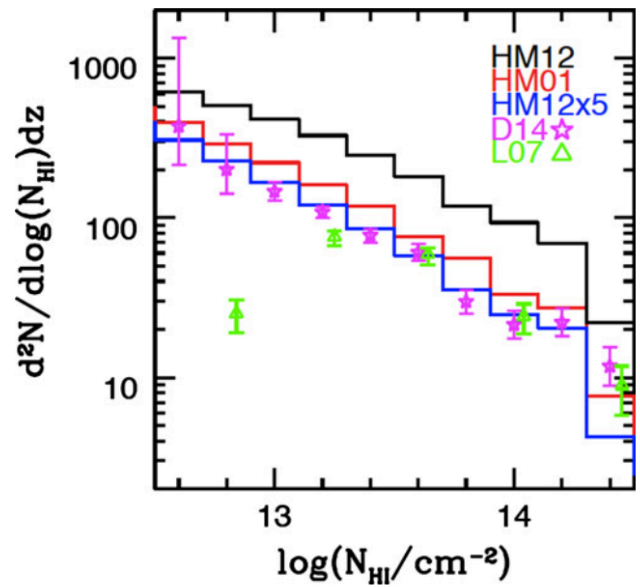
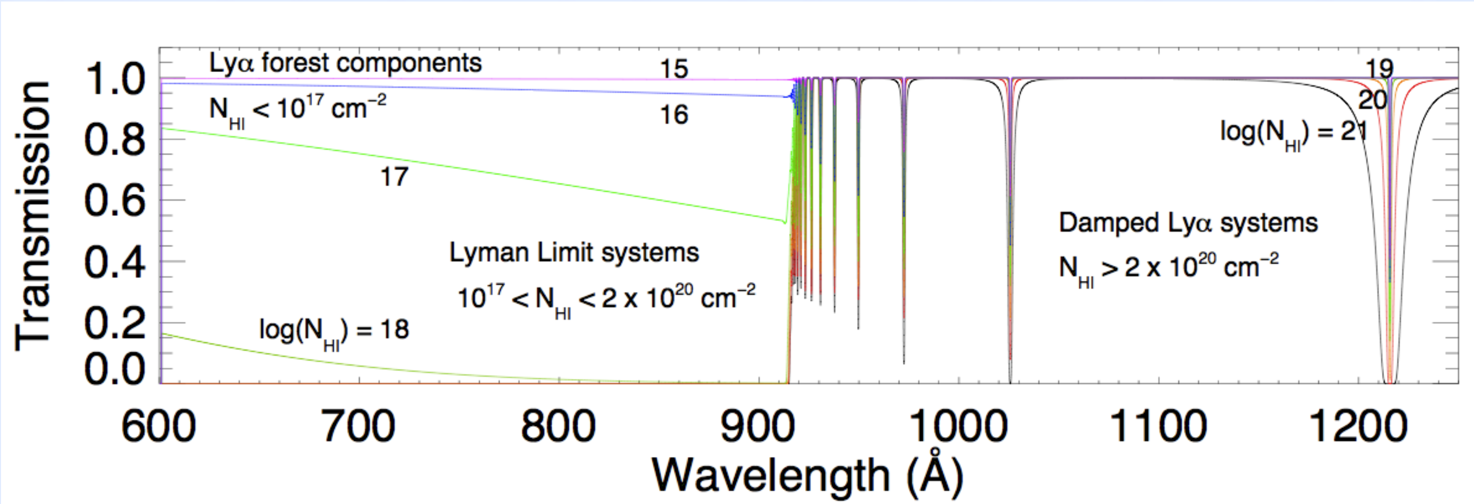


Figure 2. Column density distribution in the low-redshift IGM. Black (red) line shows the column density distribution determined from simulations adopting the HM12 (HM01) UVB estimates. The magenta data points shown are from COS observations from Danforth et al. (2014), while green symbols show the data from Lehner et al. (2007). The blue line shows a model in which HM12 is "boosted" by a constant factor of five (HM12 $\times$ 5).

LyC (and Lyα) Escape is a Great Mystery

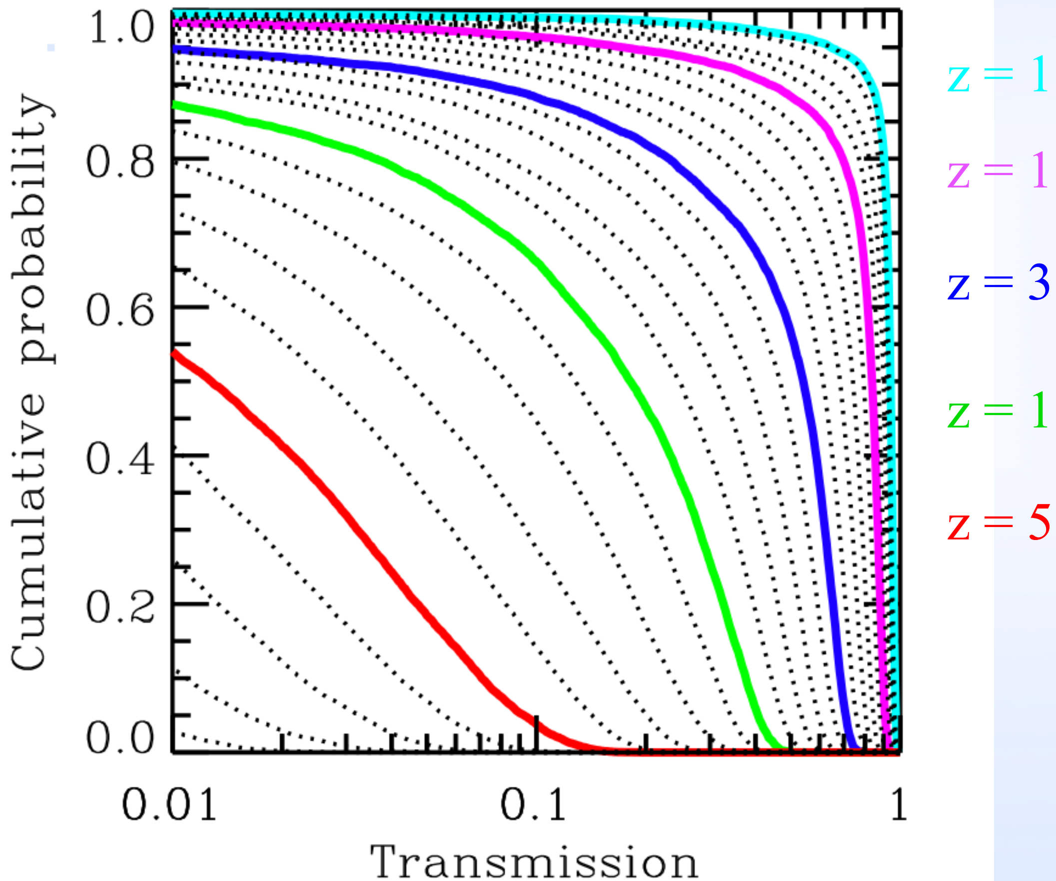


- Most star forming galaxies are optically thick to LyC photons ($n_{HI}>10^{20}$cm^2), **which should trap all ionizing radiation and prevent escape**
  - $\tau_{\lambda<912} = N_{HI}\, 6.3 \times 10^{-18} (\lambda/912)^3$
  - $\tau_{Ly\alpha} = N_{HI}\, 6.3 \times 10^{-14}$ (Vdop = 12 km s^{-1})
- Theoretical suggestions for f_{esc}, $f_{Ly\alpha}$:
  - LyC escape aided by galaxy porosity; low density, high ionization voids created by supernovae or integrated winds from stellar clusters
  - Lyα escape aided by velocity gradients and resonance scattering in a multi-phase media
- **Observations desperately needed to ground the models**

Detections of LyC leak at z > 3 are frustrated by Lyman Limit Systems (thickening of the Lyα forest)

Probability that the intergalactic transmission of the LyC is greater than the abscissa

Inoue and Iwata (2008)



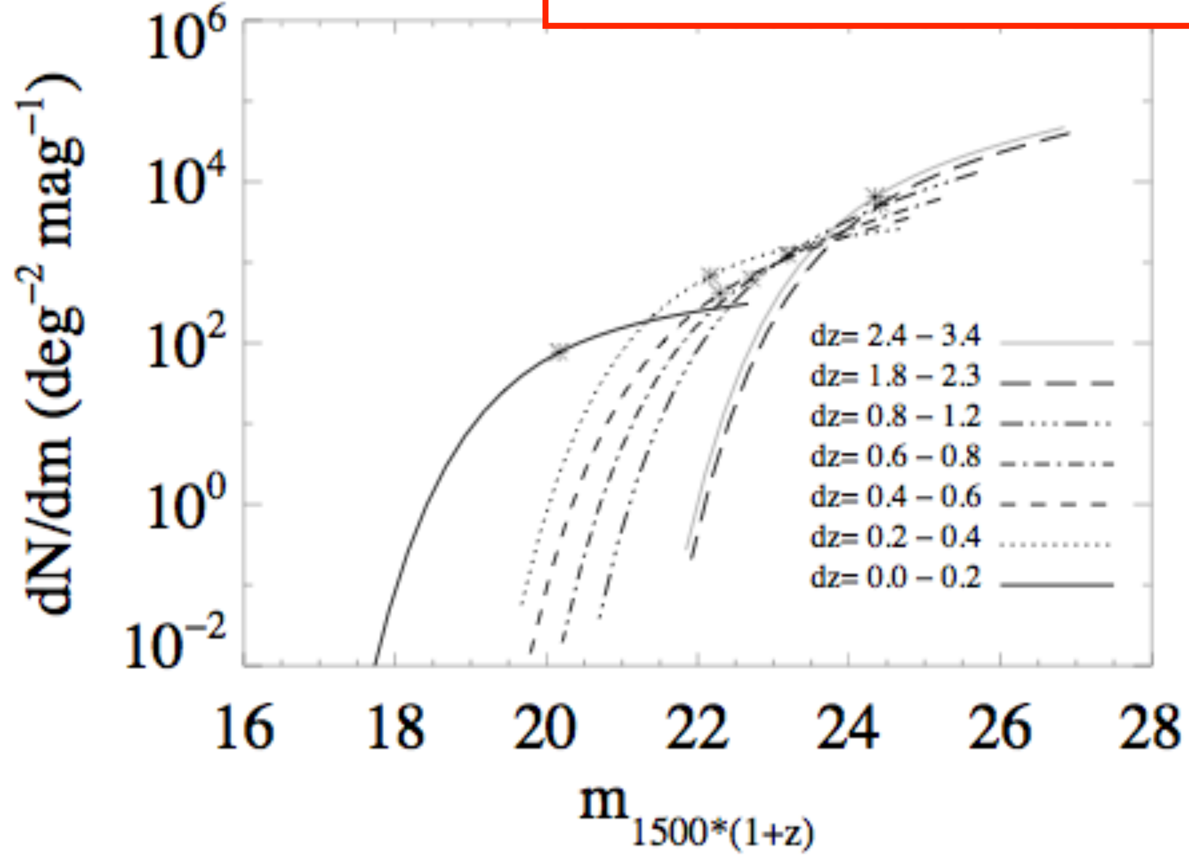
Detecting escaping Lyman continuum photons is a problem for UV/Optical

Far-UV has the advantage of small Ly limit system corrections

Evolution of Galaxy UV luminosity function

0 < z < 3 (Arnouts et al 2005)

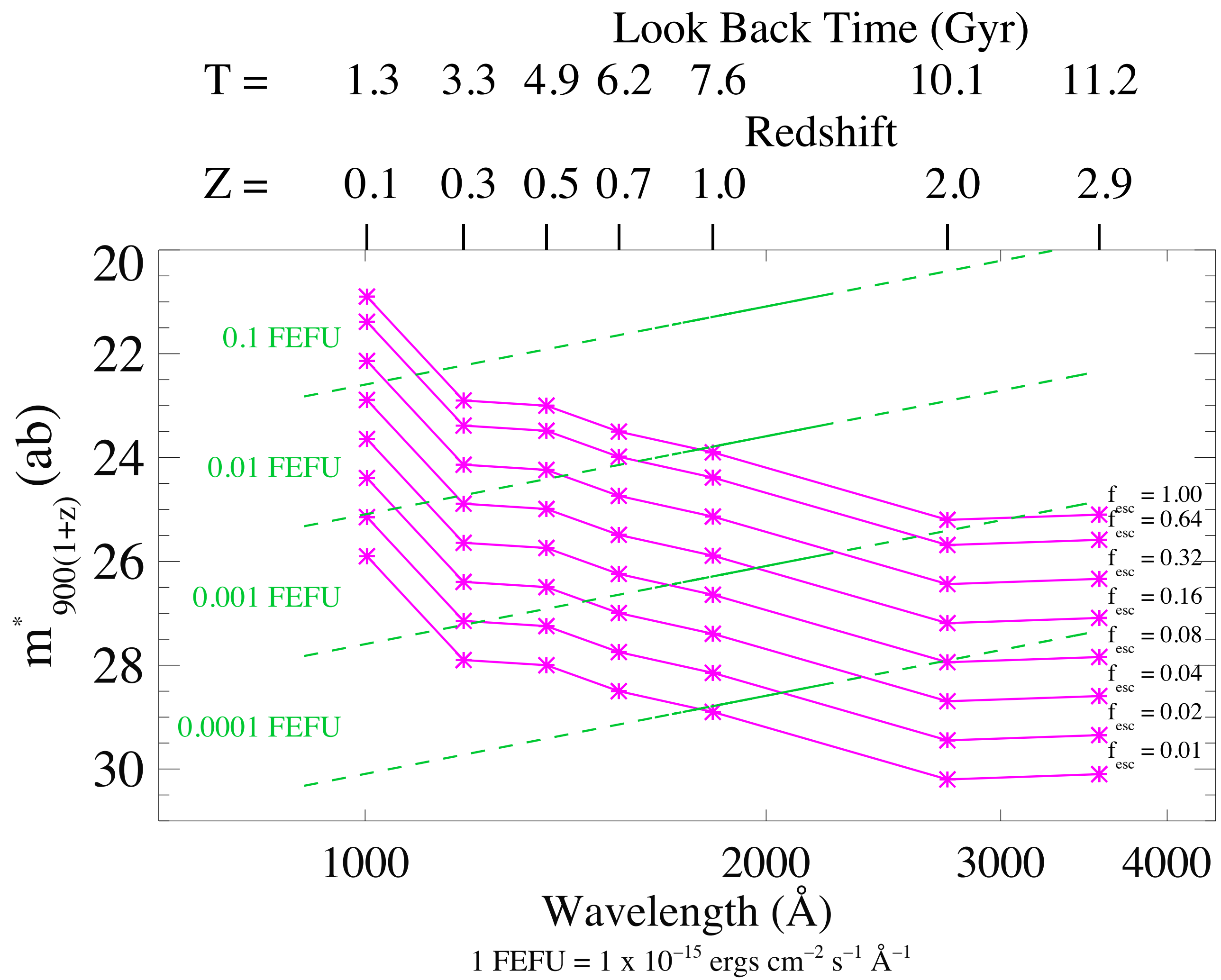
$$m^{*}_{900(1+z)} = m^{*}_{1500(1+z)} + \delta m^{1500}_{900} + \delta m_{esc}$$



There are 100's to 10,000's of galaxies per square degree per magnitude with $24 > m^{*}_{1500(1+z)} > 20$

LyC Observation Requirements for L^*_{uv} galaxies

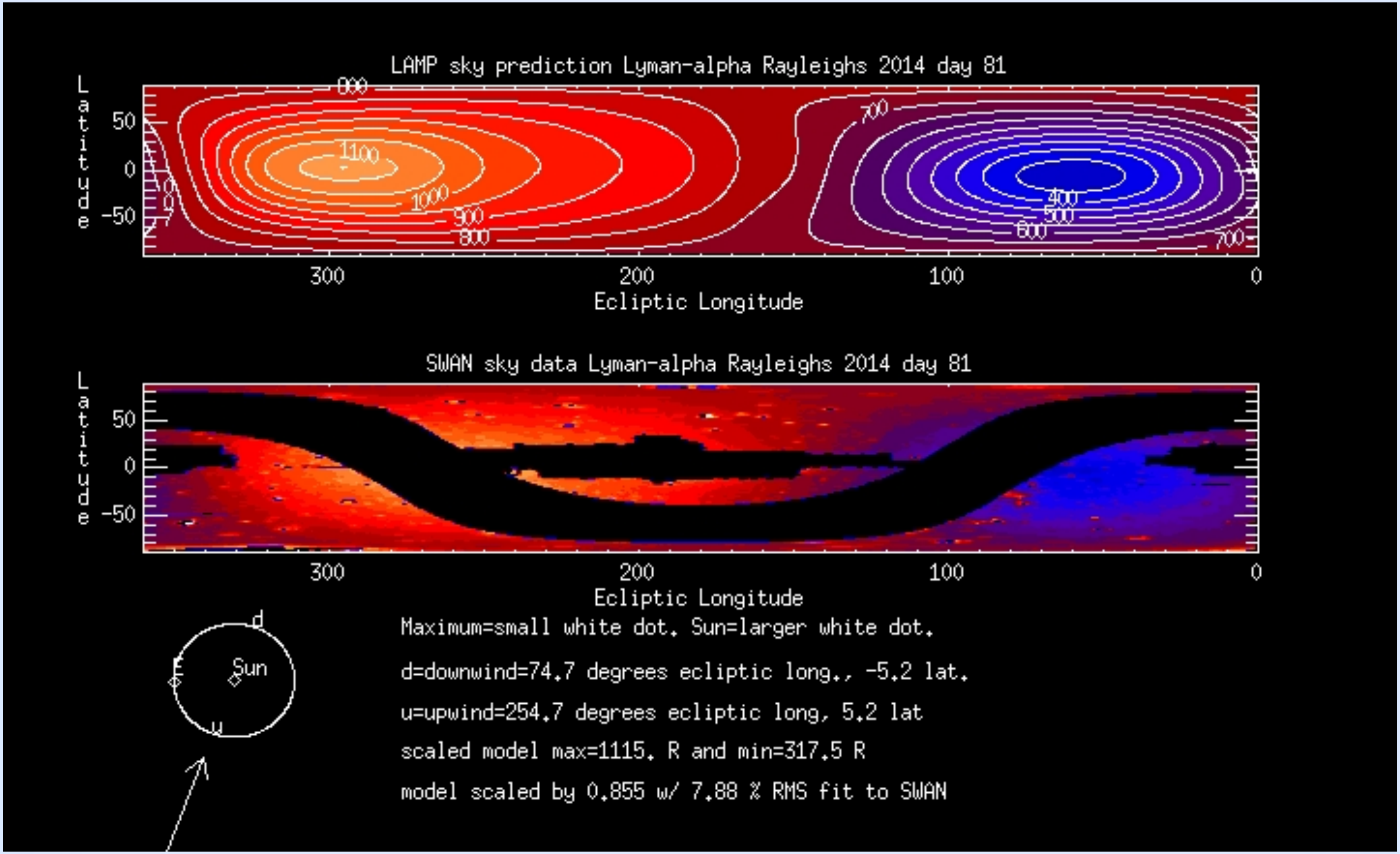
(McCandliss et al. 2008, 2012)



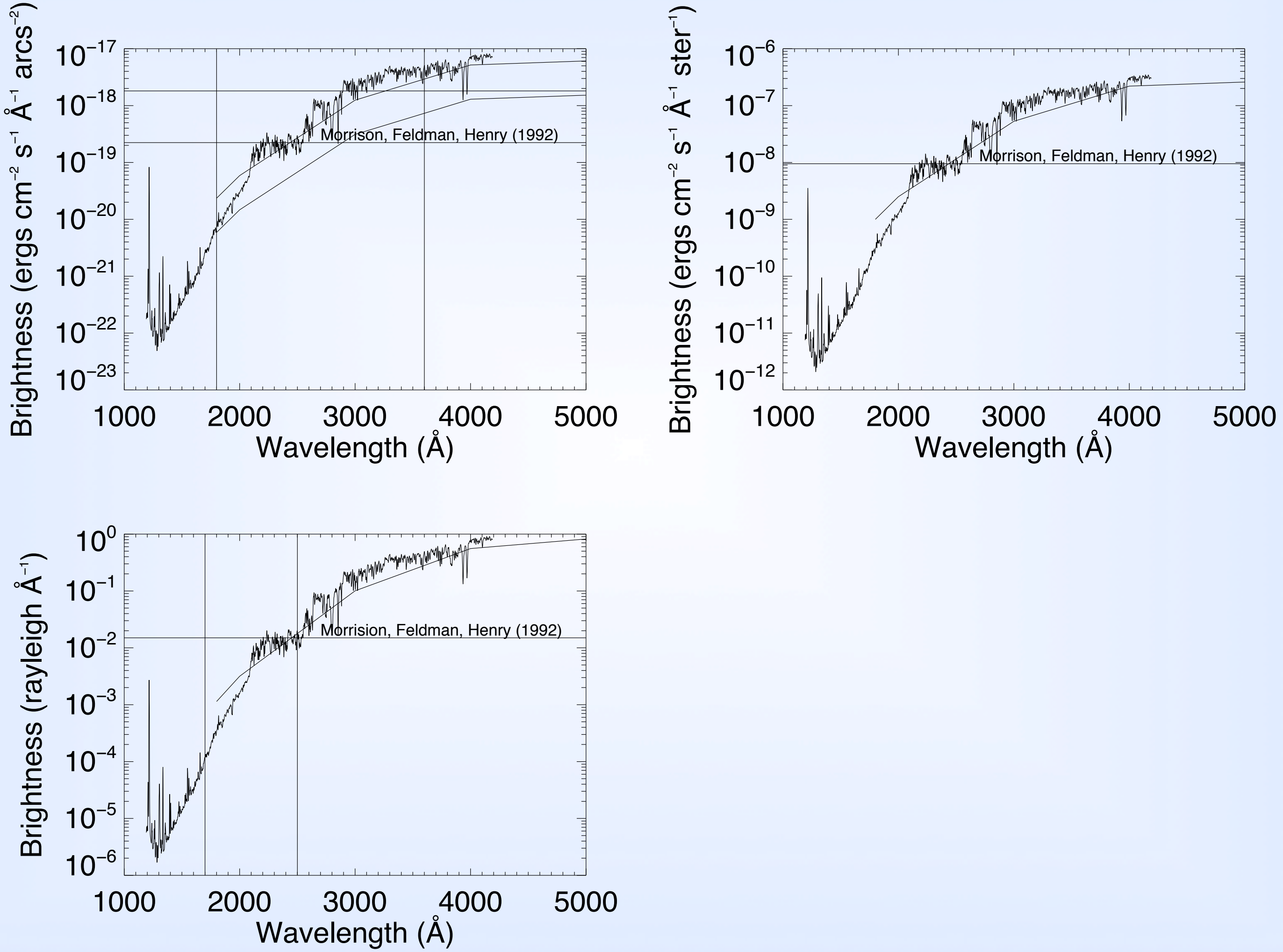
Requirements Flowdown for LyC Luminosity Function Evolution Determination

- Objects $0 < z \approx 3$
- Faint end $f^{e}_{LyC} < 1\%$
  - $f_{900(1+z)} = 10^{-20}$ erg cm^{-2} s^{-1} Å^{-1} representative flux
    - Requires A_{eff} T $\Delta\lambda \approx 2.5 \times 10^{9}$ cm^{2} s Å at 2000 Å for S/N =5 in 5hrs
  - 25 objects per luminosity bin per redshift interval will yield rms deviation for each point ≈ 20%
- Angular sample > 1 degree
  - Beat down cosmic variance
- Angular resolution on star-forming cluster scales ~ 30 pc
- Redshifts for all objects
- These criteria can be met with a diffraction limited 12 meter aperture at f/24.
  - A 2 arcminute FOV requires a detector that is 170 x 170 mm^{2}
- Such a telescope could be compatible with a Habitable-Exoplanet Imaging mission.

Backgrounds: Interplanetary Lyα



Backgrounds: Zodiacal

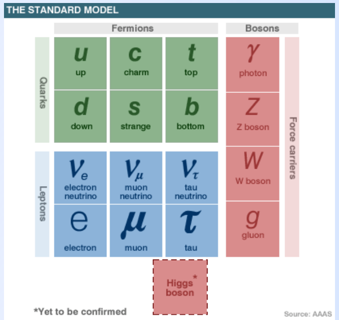


LyC Science Questions

1) How does f^{e}_{LyC} evolve with redshift?
2) What are the relative contributions of star-forming galaxies, AGN and quasars to the MIB over the past 11 Gyrs ($z < 3$)?
3) What local and global environmental factors aid escape?
   - Gas, dust, metallicity, clumpiness of interstellar medium, velocity fields, intergalactic neighborhood, star formation history, luminosity, mass
4) Are there local relic analogs to the sources of reionization?
   - High escape fraction at EoR
   - Low escape fraction before EoR is complete
5) What is the relation between Lyα and LyC escape?
   - This is critical to the JWST key project seeking the source(s) of reionization.

Emergence of Complexity:

Organization Themes for Cosmic Birth to Living Earth 12 m



- How does Complexity Emerge from a universe of fundamentally indistinguishable particles?
- Themes of Emergence

  - Emergence of structure and radiation — Wofford, Calzetti, Rafelski, Howk, Tumlinson, McCandliss
  - Emergence of elements, molecules, dirt — Andersson, Hartigan, Worford, Roederer
  - Emergence of life — Harris, France

Big BOSS in Space

Baryon Acoustic Oscillations Lyα forest and Lyα emission (LAE)

- Know a lot about Lyα forest and LAE $7 > z > 2$
- Huge ground based fiber spectrographs are coming
  - BOSS(s), HETDEX, Subaru Prime Focus Spectrograph
  - Concentrating on detecting BAO at $3 > z > 2$
- Less known about Lyα forest and LAE at $z < 2$
- $z < 2$ "dark energy sweet spot", where accelerated expansion is manifest
- dN/dz in forest (see Penton et al. 2004, Williger et al. 2005, Weymann et al. 1998)
  - ~ 100 for columns of 13 < N(H I) < 14
  - ~ 30 for columns of 14 < N(H I) < 17