UV Luminosity Functions at $z > 6$ predicted by Semi-Analytic Models and Implications for Reionization

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Can galaxies ionize the Universe?

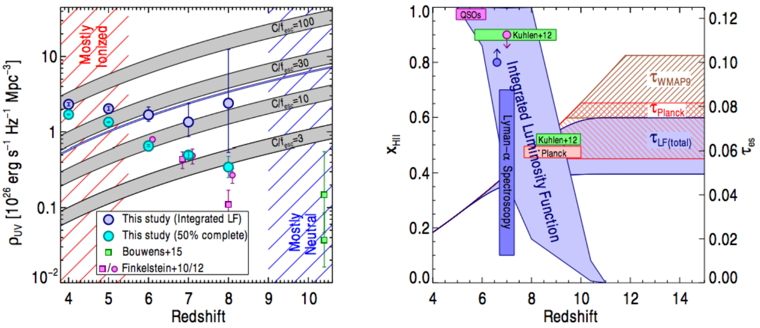


Figure : (Left) Specific luminosity density ρ_{UV}. (Right) ionized volume fraction (X_{HII}) vs redshift. [Finkelstein et al. 2015 (fig.20)]

Can galaxies *below current detection limits* ionize the Universe?

Studies extrapolating these faint, undetected populations show that they are indeed able to ionize the Universe!

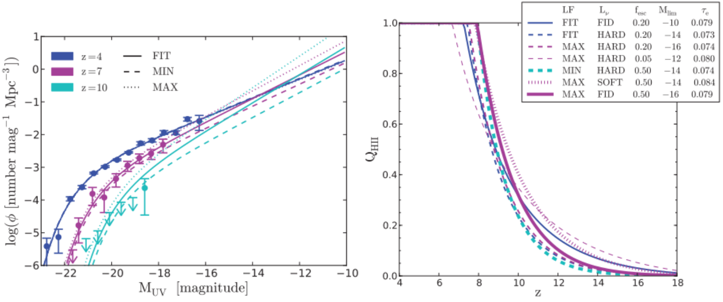
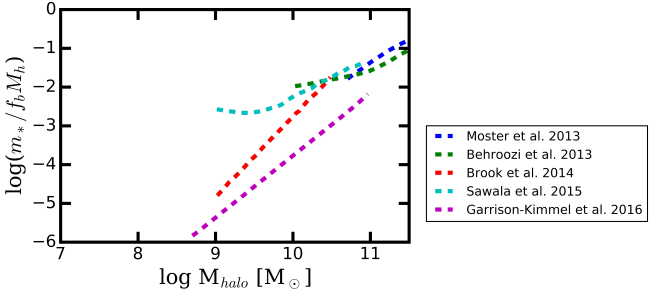


Figure : (Left) LFs extrapolated from observations. (Right) calculated ionized volume fraction (Q_{HII}) vs. redshift. [Kuhlen & Faucher-Giguere 2012 (fig.2 & 5)]

Introduction: The Current Puzzle

Can the current models predict this galaxy population?

- The early universe is dominated by low mass halos.
- They are inefficient at making stars in the local universe.
- Star formation efficiency within is the key to cosmic reionization.



Introduction: Scientific Goals

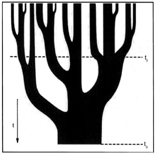
- To reconcile the tension in star formation efficiency between early and recent times in low-mass galaxies.
  - it needs to be more efficient at early times ($z > 6$) in order to fully ionize the Universe
  - but become less efficient at later times to avoid over-producing dwarf galaxies
- Can we develop a model for galaxy formation and cosmic reionization that simultaneously satisfies constraints at all redshifts?

Introduction: Our Approach

1. Semi-Analytic Models (SAMs) for sample galaxy populations (Somerville et al. 2008, 2012, 2015; Lu 2014)
2. Cosmic reionization history with analytic model (Kuhlen & Faucher-Giguere 2012)
3. Explore parameter space by coupling our model with a Markov chain Monte Carlo (MCMC) machinery
4. Compare with a self-consistent, high-resolution hydrodynamic simulation + radiative transport

Introduction: Semi-Analytic Models (SAMs) of Galaxy Formation

- Why SAMs?
  - Computationally efficient
  - Can easily handle up to millions of halos
  - Can achieve very high mass-resolution in large volumes, and are capable of running to $z = 0$
  - Able to simultaneously track many physical processes
  - Excellent tool for probing the parameter space
- How does it work?
  - Use dark matter halo merger trees as backbone
  - Analytic or empirical recipes to track the properties of the galaxies inside these halos



SAMs: Somerville Model

Standard recipes (Somerville 2002, 2008, 2012)

- cosmological gas accretion & cooling
- stellar driven winds $\dot{m}_{rh} = \alpha_{LD} \left(\frac{V_{disk}}{200 km\ s^{-1}} \right)^{-\beta_{LD}}$
- stellar population synthesis (Bruzual & Charlot 2003) and dust attenuation (Charlot & Fall 2000)
- etc.

Here are few updated recipes in the latest Somerville model (Somerville, Popping, & Trager 2015)

- formation of molecular hydrogen (Gnedin & Kravtsov 2011)
- H_2-based empirical star-formation recipe (Bigiel et al. 2008)

SAMs: Lu Model

The Lu model is coupled to an MCMC machinery, which can systematically explore the parameter space under available observational constraints (Lu et al. 2012, 2014).

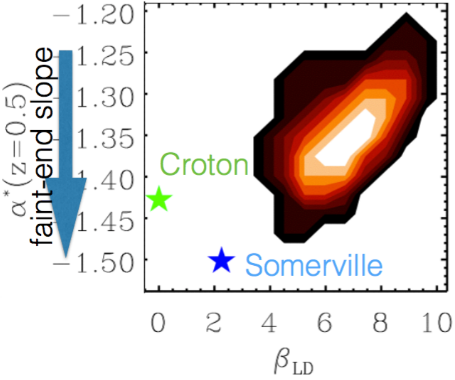


Figure : Stellar feedback parameter β_{LD} vs. LF faint-end slope α^*. Contour shows the confidence levels from the Lu model using MCMC (Lu et al. 2014). Stars denote the prediction and parameter choice of the Somerville and Croton models.

High-z Luminosity Functions (LFs)

LFs predicted by the latest SAMs, notice the disagreement in the faint-end slope probably due to the choice of feedback parameter β_{LD}.

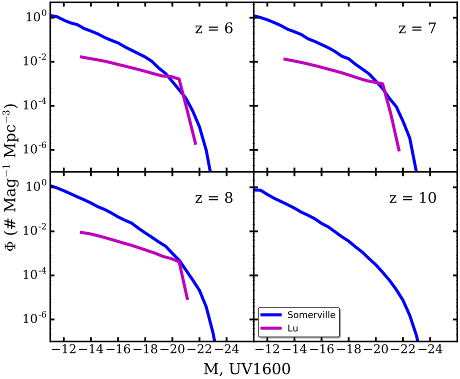


Figure : Comparison of the luminosity functions at $z = 6$, 7, 8, and 10 predicted by the Somerville model and the Lu model.

High-z Luminosity Functions (LFs)

The LFs predicted by SAMs are highly consistent with hydrodynamic simulations and observations!

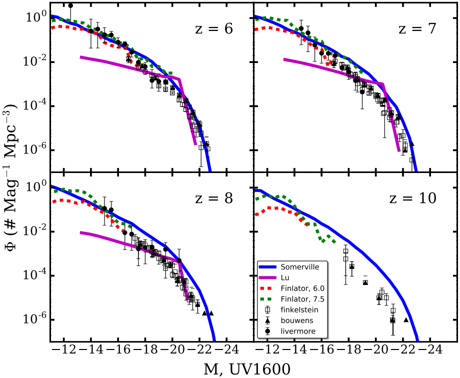


Figure : Luminosity functions at $z = 6$, 7, 8, and 10. SAMs predictions (blue: Somerville, purple: Lu) compared to high resolution hydrodynamic simulations (dashed: Finlator et al. 2011, 2015) and observation (markers: Bouwens et al. 2014, Finkelstein et al. 2015, Livermore et al. 2016)

Fast! Analytic Reionization Model

We use a simple analytic reionization model [*e.g. Kuhlen & Faucher-Giguere 2012*] to efficiently forecast the cosmic reionization history.

- reionization equation:

$$\frac{dQ_{\rm HII}}{dt} = \frac{\dot{n}_{\rm ion}}{\bar{n}_{\rm H}} - \frac{Q_{\rm HII}}{\bar{t}_{\rm rec}} \qquad \rightarrow Q_{\rm HII}(z)$$

- ionizing emissivity ($\frac{\#\text{ of photons}}{\text{unit time}\times\text{unit volume}}$):

$$\dot{n}_{\rm ion}^{\rm com} = \int_{M_{\rm lim}}^{\infty} dM_{\rm UV}\phi(M_{\rm UV})\gamma_{\rm ion}(M_{\rm UV})f_{\rm esc}$$

- volume averaged recombination time:

$$\bar{t}_{\rm rec} \approx 0.93\ {\rm Gyr}\left(\frac{C_{\rm HII}}{3}\right)^{-1}\left(\frac{T_0}{2\times10^4{\rm K}}\right)^{0.7}\left(\frac{1+z}{7}\right)^{-3}$$

- Thomson scattering optical depth for the CMB:

$$\tau_{\rm e} = \int_0^{\infty} dz \frac{c(1+z)^2}{H(z)} Q_{\rm HII}(z)\sigma_{\rm T}\bar{n}_{\rm H}(1+\eta Y/4X)$$

Fast! Analytic Reionization Model: Results

Using the LFs predicted by SAMs, and by assuming some fixed f_{esc}, we calculated the evolution of neutral volume and the Thomson optical depth to the CMB.

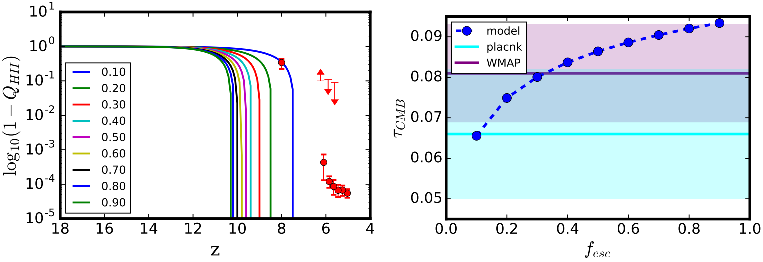


Figure : (Left) Neutral volume fraction vs, z, compared to observational constraints in red markers (Bouwens et al. 2015). (Right) τ_{CMB} vs. f_{esc}, compared to the Planck (cyan) and WMAP (purple) measurements.

Upcoming Work: Highlight

We will use the Lu model (with MCMC) to explore the interplay between stellar feedback physics and reionization.

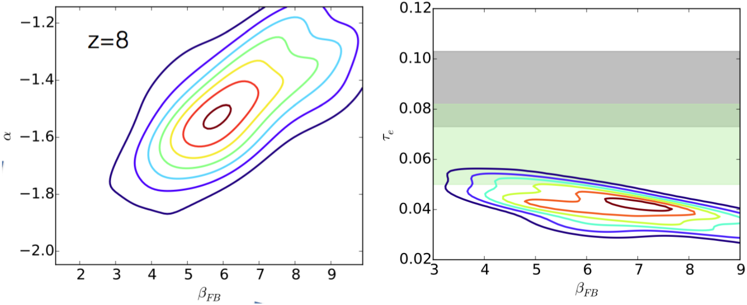


Figure : (Left) LF faint-end slope vs. SN feedback parameter. (Right) CMB optical depth vs. SN feedback parameter. The contours show the posterior confidence levels from such model. (Lu et al. 2011, 2014)

Upcoming Work

- Parameter calibration using MCMC
  Collaborator: Dr. Yu Lu (Carnegie Observatories)
  - SN Feedback Parameters
  - UV escape fraction (f_{esc})
- vary f_{esc} based on galaxy physical parameters using results from high-resolution numerical simulation
  (e.g. FiBY - Paardekooper et al. 2015)
- Self-consistent treatment of reionization
  - Spatially resolved reionization simulation
  - Progression & topology of reionization
  - HI intensity map / topographic map

Summary

- The SAMs predicted high-redshift luminosity functions are in good agreement with many studies. Such predictions are crucial to forecast many future JWST observations.

- Even by making simple assumptions for model parameters, the reionization model outputs show great agreement with observations and other theoretical studies.

- Our model result shows that galaxies are very likely to be the ones reionized the Universe.