Modelling the properties of star-forming galaxies at high redshifts

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Advanced 21-cm Cosmology Workshop
NISER, Bhubaneswar

December 20 , 2023

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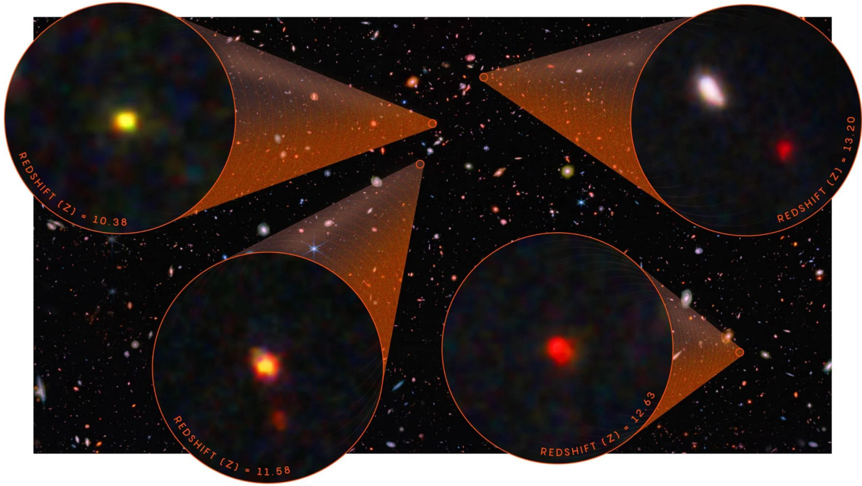
Galaxies in the Epoch of Reionization (z ~ 6 - 15)

- Cosmic Reionization is closely tied to large scale structure formation in our universe
  - ➢ A direct consequence of the formation of the first structures and sources
  - ➢ Also affects subsequent structure formation.

- Several uncertainties about EoR (e.g., timing, progress, topology) stems from our incomplete understanding of early galaxy formation and the properties of the earliest galaxies

- Many current and upcoming optical/infrared telescopes (HST, JWST, Subaru, TMT etc) will **directly** detect galaxies in the EoR.

- Complementarily, EoR galaxies can be studied through their effect on the intergalactic medium ⇒ **HI 21-cm studies**



Credits : Samuel Velasco (Quanta Magazine)

Probing EoR with high-z galaxies

Galaxy Luminosity Function (LF)

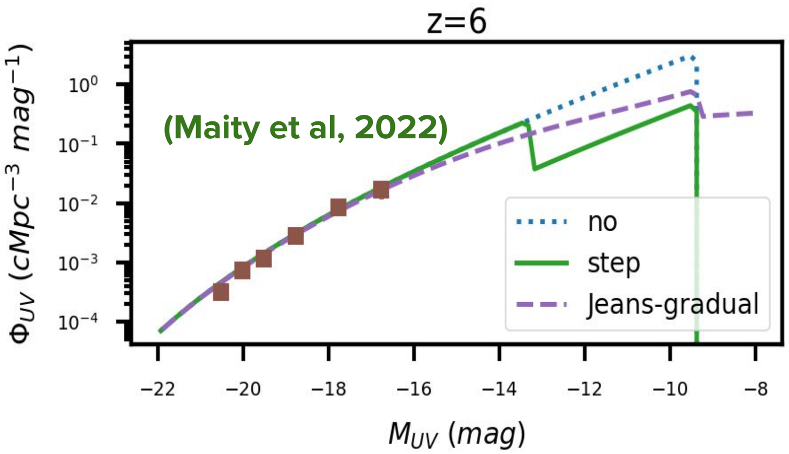
- The UV LF is dependent on the star-formation activities in galaxies

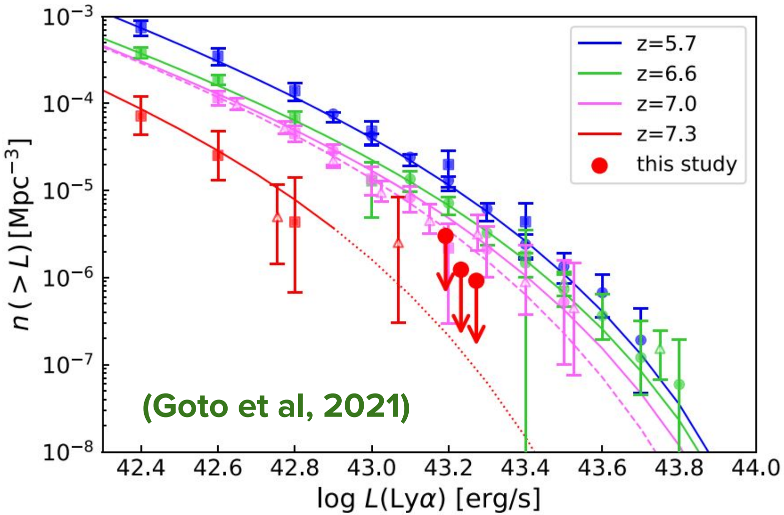
- Star-formation is sensitive to feedback arising due to reionization heating
  ⇒ affects **faint-end** slope of the UV LF

- Ly-α emission from galaxies is expected to be absorbed due to presence of HI

  ⇓

  Evolution of the 'observed' Ly-α LF of LAEs at high-z as cosmic reionization progresses





Motivation : New Insights into early galaxy formation by JWST

- A surprisingly high number density of UV bright and massive galaxies at early redshifts ($z \geq 10$) detected by James Webb Space Telescope (JWST)

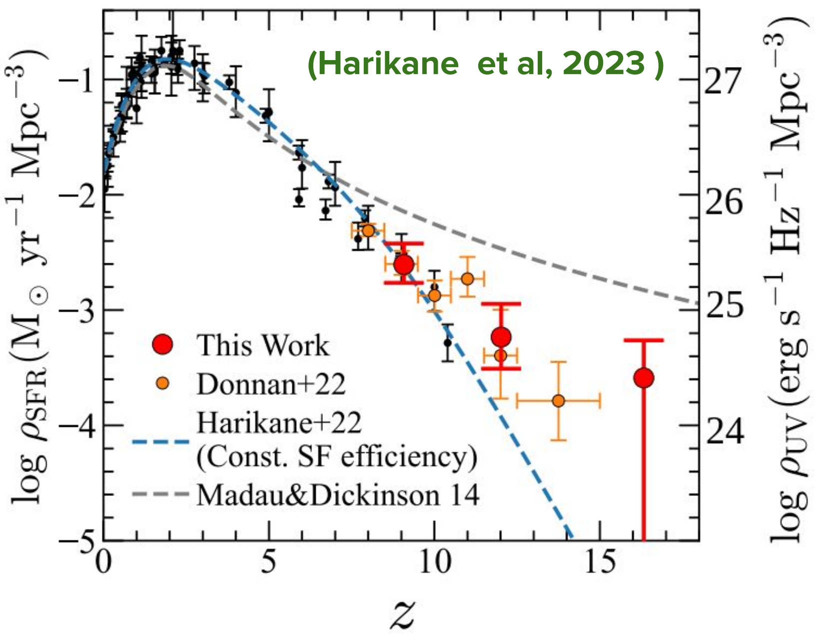
- A variety of possibilities advanced to explain it :

  Cosmological Solutions

  ➢ Higher number density of dark matter halos than that predicted by ΛCDM ?

  Astrophysical Solutions

  ➢ Very high star formation efficiency at high-z ?
  ➢ Top-heavy initial mass function ?
  ➢ Pop-III stars / low dust content at high-z ?
  ➢ High magnification bias ?



- Theoretically important to understand the origin and implications of this “ excess ” ! !

Motivation : What does this mean for cosmic reionization ?

- High SFRD at $z > 10$ $\Rightarrow$ More no. of ionizing photons available at high-z ??
- UV background (UVB) radiation heats up HI gas in low-mass halos of $M_h < 10^8$–$10^9\,M_\odot$ suppressing star-formation during the EoR and post-EoR epochs.
- Most halos ($\lesssim 10^9\,M_\odot$) at $z \sim 13$ are not affected by the UVB at the pre-EoR, while the similar halos at $z < 9$ experience strong UVB suppression in their star formation.
- Essential to jointly track the progress of galaxy formation and reionization in a self-consistent manner.
- UV Luminosity $\propto$ $f_*(M_h, z)$

  Reionization History $\propto$ $f_*(M_h, z) \times f_{esc}(M_h, z)$

  Possible to constrain the escape fraction f_{esc} of UV ionizing photons from galaxies

A semi-analytical model for UV LF of high-z galaxies - I

- Dark matter forms the skeleton on which galaxies form and grow
- **DM Halo**

$$M_h$$

$$f_*(M_h) = f_*(M_h)\left(\frac{M_h}{10^{10}M_\odot}\right)^{\alpha_*}$$

Stellar Mass

$$M_*(M_h) = f_*(M_h)\left(\frac{\Omega_b}{\Omega_m}\right)M_h$$

$$t_*(z) = c_*\,t_H(z)$$

(See also : Park et al, 2019 , Sun et al 2016)

Star Formation Rate

$$SFR(M_h, z) = \frac{M_*(M_h)}{t_*(z)} = \frac{f_{*,10}}{c_*}H(z)\left(\frac{M_h}{10^{10}M_\odot}\right)^{\alpha_*}\left(\frac{\Omega_b}{\Omega_m}\right)M_h$$

$$\kappa_{UV} = \frac{SFR(M_h, z)}{L_{UV}}$$

1500Å UV Luminosity

$$L_{UV}(M_h)$$

A semi-analytical model for UV LF of high-z galaxies - II

- The standard $L_{UV} - M_h$ relation has the following dependencies

$$L_{UV}^{\text{nofb}} = F\left(\mathcal{K}_{fid,UV}\,;\,\varepsilon_{*10,\,UV}\,;\,\alpha_*\,;\,M_h\,;\,z\right)\,M_h \quad ; \qquad \varepsilon_{*10,UV} = \frac{f_{*,10}}{c_*}\,\frac{1}{\mathcal{K}_{UV}/\mathcal{K}_{fid,UV}}$$

- The $L_{UV} - M_h$ relation gets modified in presence of radiative feedback processes.

$$L_{UV}^{\text{nofb}} = G\left(f_{gas}\,;\,\mathcal{K}_{fid,UV}\,;\varepsilon_{*10,\,UV}\,;\,\alpha_*\,;\,M_h\,;\,z\right)\,M_h \quad ; \qquad f_{gas}(M_h) = 2^{-M_{crit}/M_h}$$

(Sobacchi et al 2013 , Hutter et al 2021)

- The UVLF Φ_{UV} can then be obtained from the HMF using the respective $L_{UV}\left(M_h\right)$ relation.

- The globally averaged UV Luminosity Function can be written as

$$\Phi_{\text{UV}}^{\text{total}}(\text{M}_{\text{UV}}, z) = Q_{II}(z)\;\Phi_{\text{UV}}^{\text{fb}}(\text{M}_{\text{UV}}, z) + [1 - Q_{II}(z)]\;\Phi_{\text{UV}}^{\text{fb}}(\text{M}_{\text{UV}}, z)$$

(Choudhury & Dayal 2019 , Maity et al 2022)

Connecting to the reionization history - $Q_{II}(z)$

- The number of ionizing photons in the IGM per unit time per unit comoving volume

$$\dot{n}_\gamma(z) = \text{Fraction of photons that escape into IGM} \times \text{No. of ionizing photons per unit mass of stars} \times \text{Amt. of stars formed per unit time per unit com. volume}$$

$$f_{esc}(M_h) \qquad \eta_{\gamma *} \qquad \dot{\rho}_*(M_h)$$

$$f_{esc}(M_h) = f_{esc,10}\left(\frac{M_h}{10^{10} M_\odot}\right)^{\alpha_{esc}}$$

- The globally averaged ionizing photon production rate density is then computed as

$$\dot{n}_\gamma(z) = Q_{II}(z)\, \dot{n}_{\gamma,\mathrm{II}}(z) + [1 - Q_{II}(z)]\, \dot{n}_{\gamma,\mathrm{I}}(z)$$

(Dayal et al 2017)

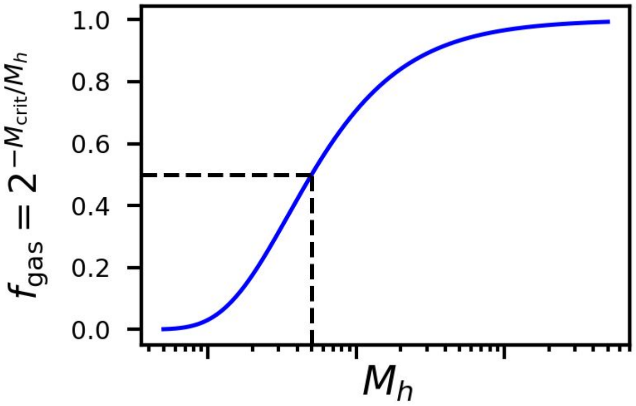
- The reionization history is constructed by solving the equation -

$$\frac{dQ_{II}}{dz} = \underbrace{\frac{\dot{n}_\gamma}{\bar{n}_H}\frac{dt}{dz}}_{\text{Source}} - \underbrace{\chi_{He}(z)\, \bar{n}_H (1+z)^3 \alpha_B(T_e)\, \mathcal{C}\, Q_{II}}_{\text{Recombination}} \frac{dt}{dz}$$

Source **Recombination**

The free parameters of our semi-analytical model

- M_{crit} Critical halo mass below which radiative feedback effects are dominant.

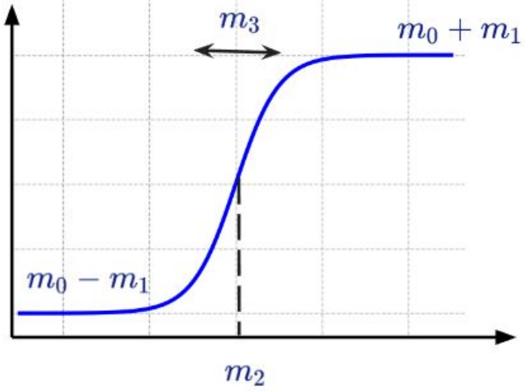


- $\varepsilon_{esc,10}$ α_{esc} Normalisation and power-scaling of the halo mass - dependent UV escape fraction

- Redshift evolution of the normalisation & power-law scaling of the halo mass dependent UV radiation / star-formation efficiency

$$\log_{10} \varepsilon_{*10,UV}\ (z) = f_0 + f_1 \tanh\left(\frac{z - f_2}{f_3}\right)$$

$$\alpha_*(z) = a_0 + a_1 \tanh\left(\frac{z - a_2}{a_3}\right)$$



$$y(x) = m_0 + m_1 \tanh\left(\frac{x - m_2}{m_3}\right)$$

Observational Datasets and Parameter Estimation

- **Observational Constraints Used :**
  - ➢ Galaxy UV luminosity functions at six redshift bins over $6 \leq z \leq 13.2$ from various HST and JWST surveys (Bouwens et al , 2021 ; Harikane et al, 2023 ; Donnan et al , 2023 ; Bouwens et al 2023)
  - ➢ Thompson scattering optical depth of CMB photons (Planck Collab. , 2020)

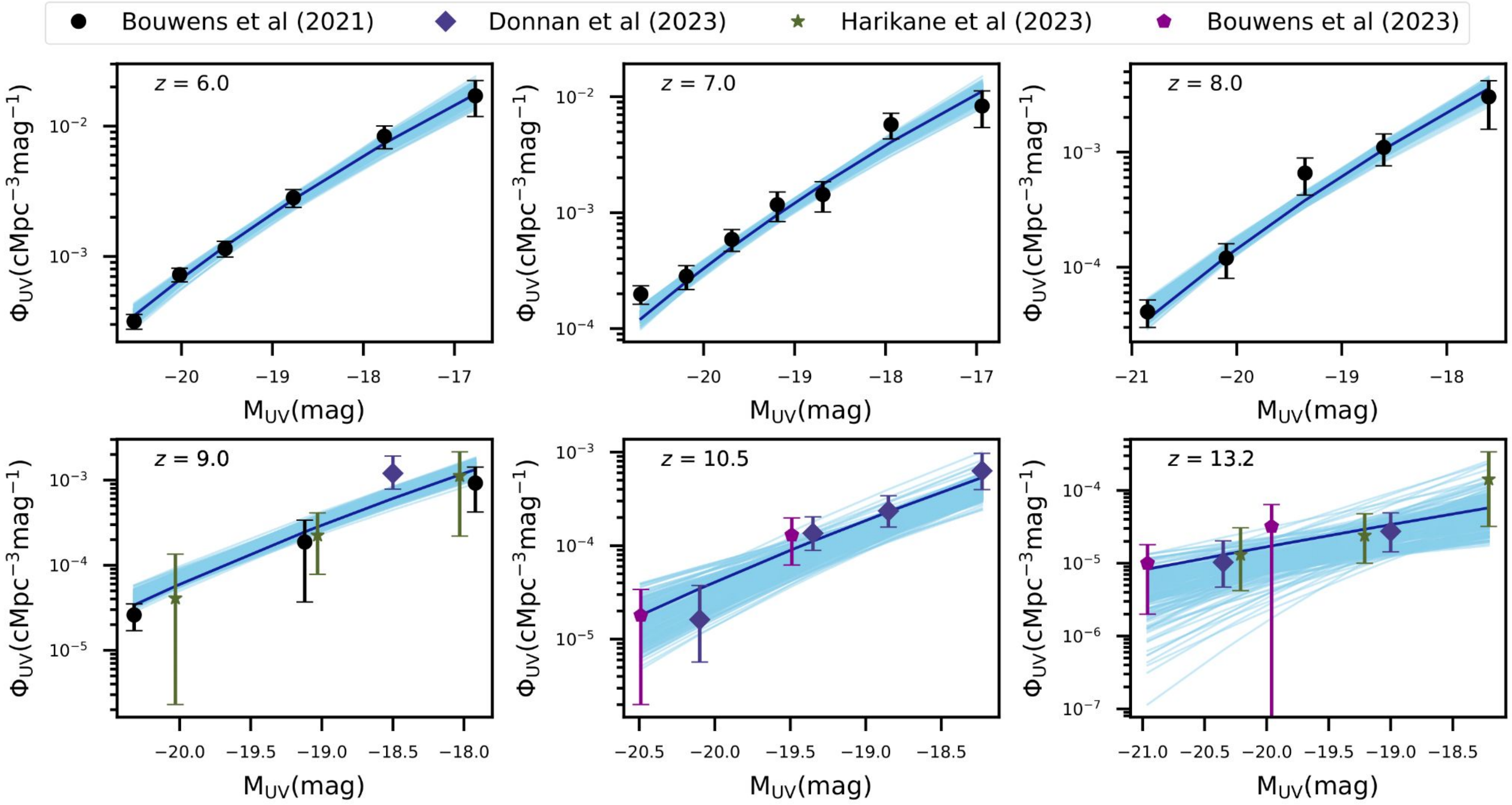
    $$\tau_{el} = 0.054 \pm 0.007$$

  - ➢ Global neutral hydrogen fraction Q_{HI} in the IGM at different cosmic epochs
    - ■ $5.4 \leq z \leq 6$: Analysis of QSO spectra from X-Shooter and ESI (Gaikwad et al , 2023)
    - ■ $z \leq 7$: Ly-α damping-wing obs. towards high-z quasars , Damping-wing measurements towards a stacked sample of UV luminous galaxies from the JWST (Davies et al , 2018 ; Greig et al 2021 ; Umeda et al 2023)

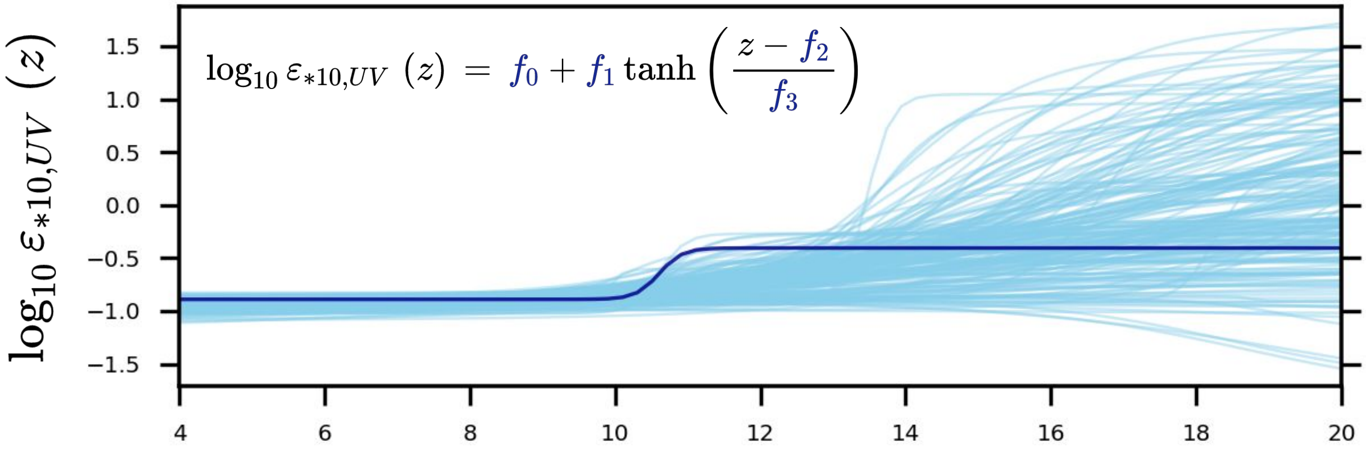
- Free parameters were constrained against these datasets using a Bayesian approach

- Posterior distribution of the free parameters was obtained using the MCMC sampler in the publicly available `COBAYA` package

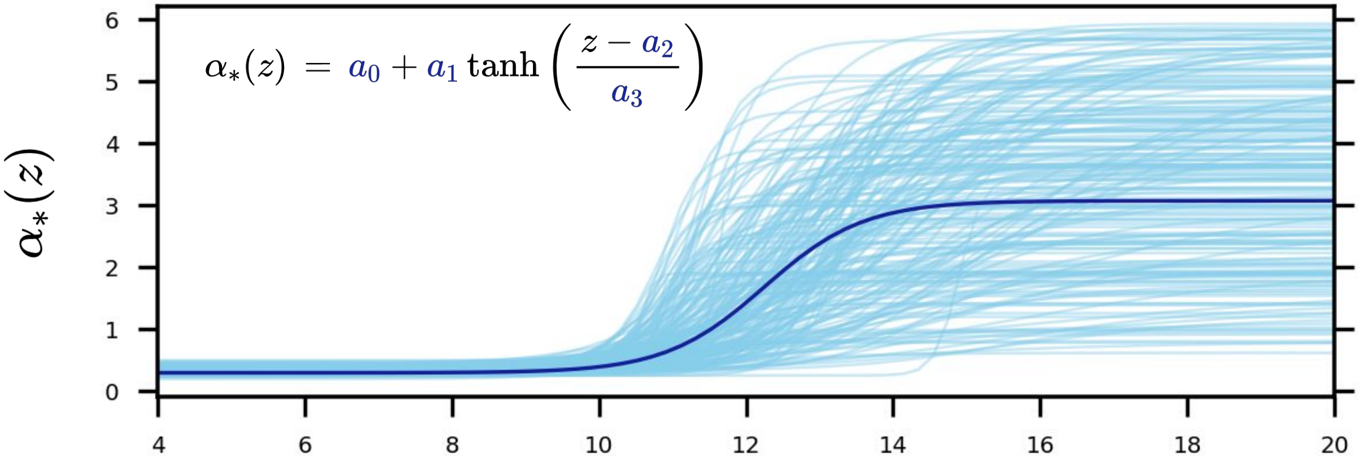
Comparison of model UVLFs to the data



Results : The UV / SF efficiency parameters

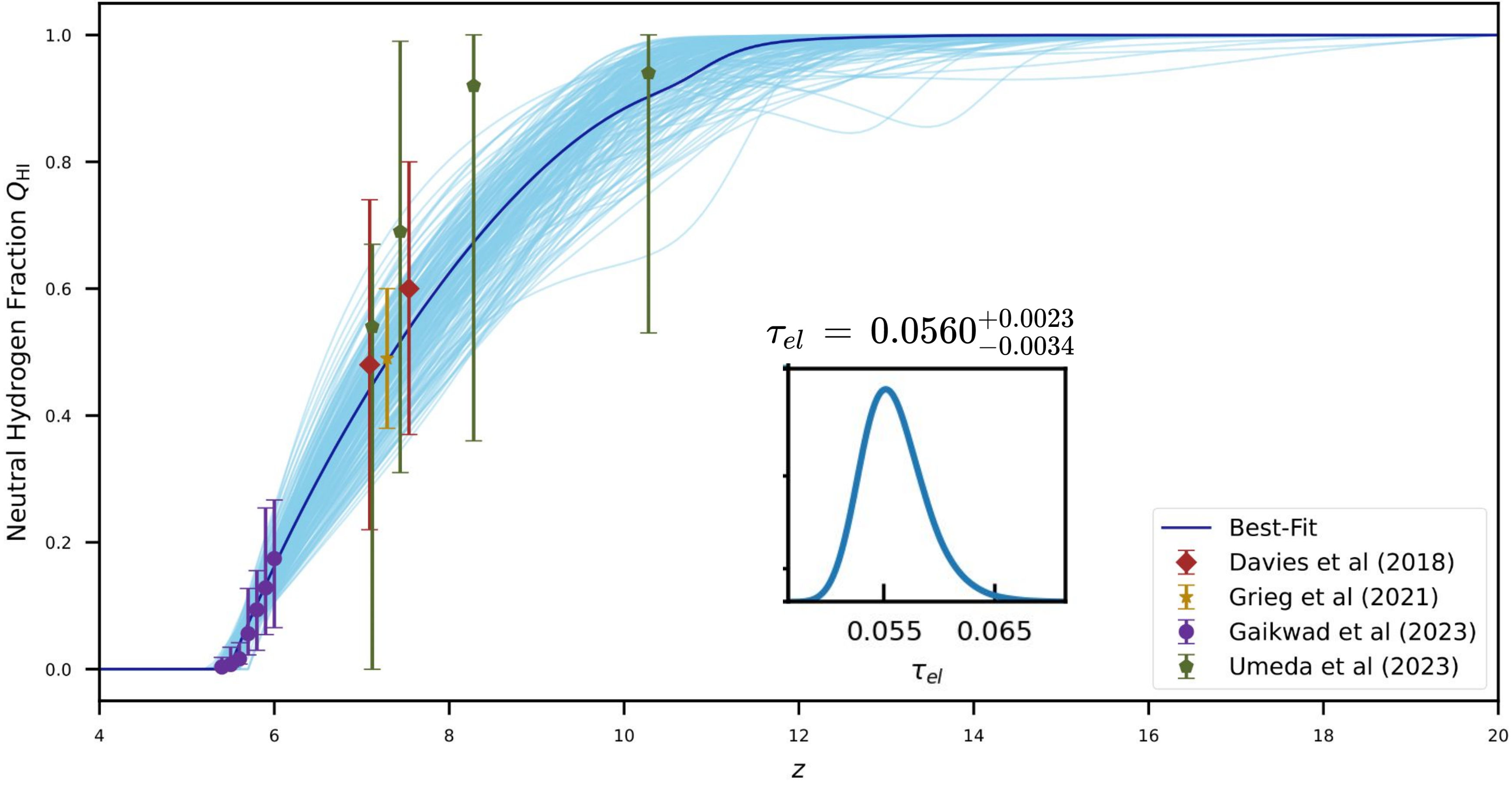


$$f_0 - f_1 = -0.958^{+0.073}_{-0.045}$$
$$f_0 + f_1 = 0.30^{+0.75}_{-1.0}$$
$$f_2 = 15.0^{+3.7}_{-4.5}$$
$$f_3 = 4.2^{+1.3}_{-3.8}$$



$$a_0 - a_1 = 0.338^{+0.046}_{-0.052}$$
$$a_0 + a_1 = 3.5^{+1.7}_{-1.3}$$
$$a_2 = 12.50^{+0.75}_{-1.7}$$
$$a_3 = 1.42^{+0.34}_{-1.1}$$

Comparison of reionization model to the data

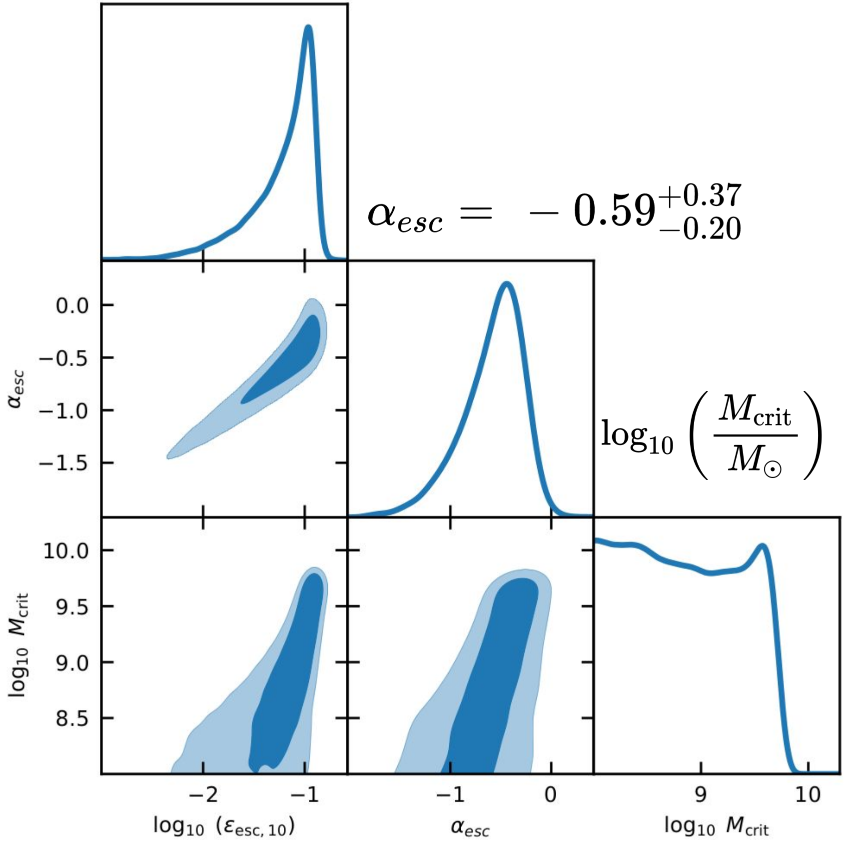


Results : The UV escape fraction

$$\log_{10}\ (\varepsilon_{\mathrm{esc},10}) = -1.23^{+0.370}_{-0.096}$$

$$\alpha_{esc} = -0.59^{+0.37}_{-0.20}$$

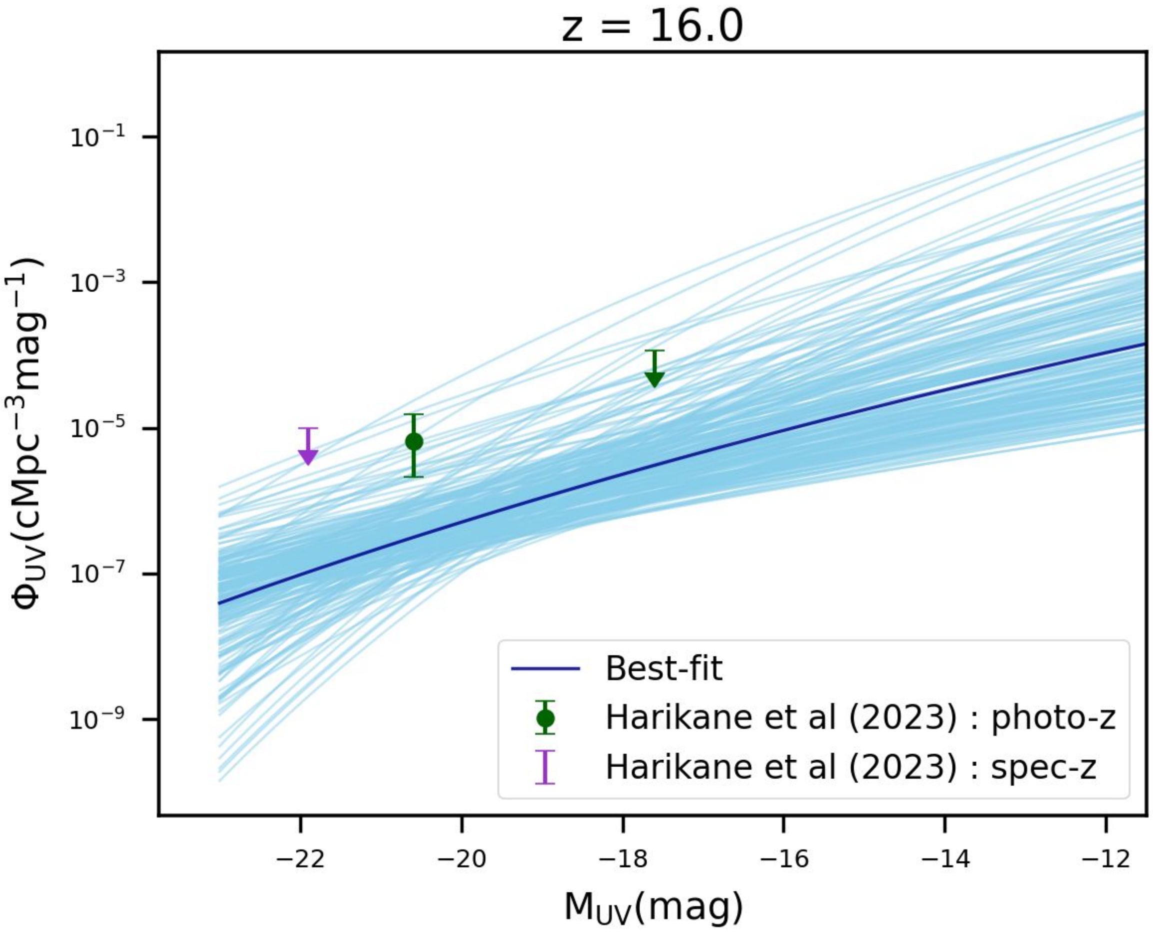
$$\log_{10}\left(\frac{M_{\mathrm{crit}}}{M_\odot}\right) < 9.18$$



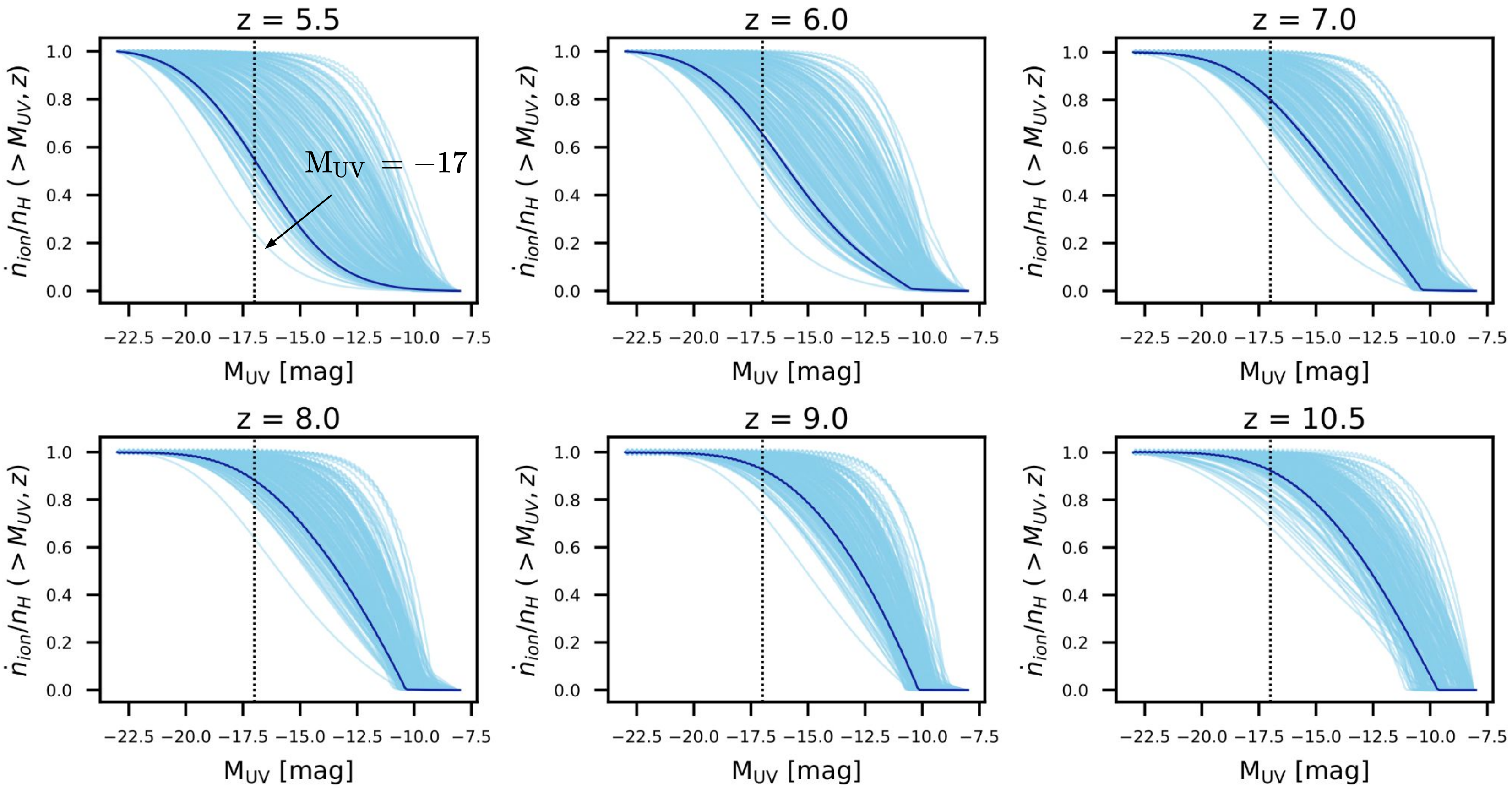
$$f_{esc}(M_h) = f_{esc,10}\left(\frac{M_h}{10^{10}M_\odot}\right)^{\alpha_{esc}}$$

- Low mass galaxies have higher UV escape fractions
- Halos with $M_{halo} < 10^{9.67}\ M_\odot$ are most affected by radiative feedback effects during the EoR

Results : The model-predicted UVLF at z ~ 16



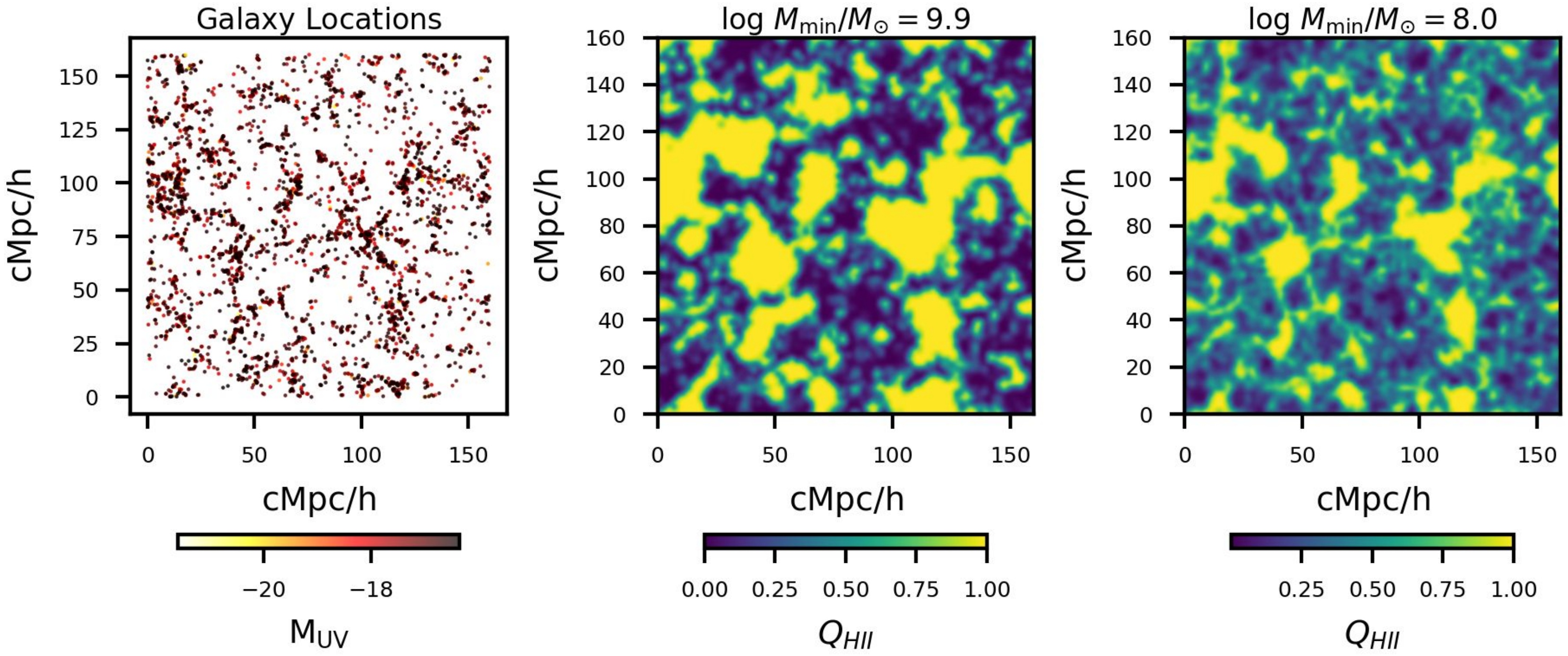
Results : Census of the ionizing photon budget



The fainter set of galaxies contribute the bulk (≥ 50%) of ionizing photons at all stages of EoR

What next ??

- Fluctuations in the ionized field contain much **MORE** information about the EoR sources as compared to only the globally averaged quantities.



Representative ionization maps for two different source populations having the same global ionization fraction

Ionisation map was generated using SCRIPT

Summary

- Our model UVLFs are in agreement with observations at all redshifts where data are currently available.

- An enhancement in the star-formation efficiency and/or UV luminosity per stellar mass formed is indeed required to reconcile with the recent JWST UVLF estimates at $z \geq 11$, as also found by a number of other studies.

- UV emission from galaxies residing inside DM halos with $M_{halo} < 10^{9.67} M_{\odot}$ is strongly affected by radiative feedback from the EoR.

- Our models are consistent with the currently available EoR constraints if the UV escape fraction $f_{esc}(M_h)$ is parameterised by a *power-law* relationship

- In our models, f_{esc} decreases with increasing M_h, having a modest value of 6% for $10^{10} M_{\odot}$, and the bulk of the ionizing photons seem to be produced by the fainter population of galaxies.

BACKUP SLIDES