Modelling the properties of star-forming galaxies at high redshifts

Anirban Chakraborty

National Centre for Radio Astrophysics (NCRA-TIFR), Pune, India

(with Prof. Tirthankar Roy Choudhury)

arXiv:2404.02879

A. Chakraborty & T. Roy Choudhury, JCAP (2024), in press

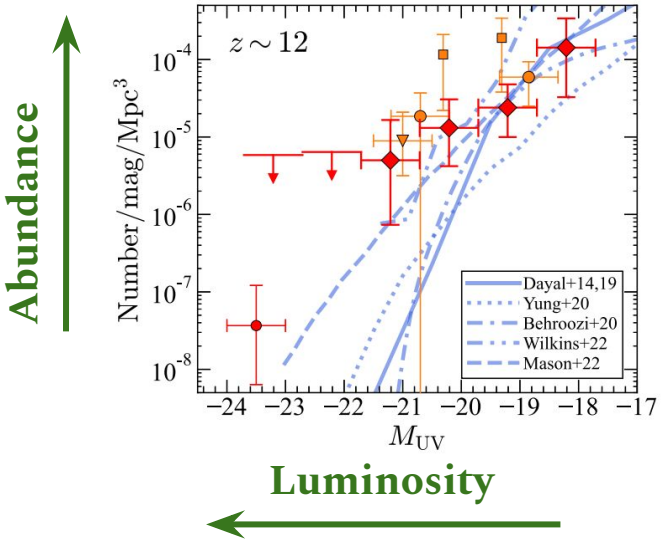
SKA CD/EoR Science Team Meeting

July 18 , 2024

NCRA • TIFR

New Insights into early galaxy formation enabled by JWST

- A surprisingly high number density of UV bright and massive galaxies at z ≥ 10 found by JWST



(Harikane et al, 2023)

Cosmological Solutions : More number of DM halos than in ΛCDM ?

Astrophysical Solutions : Higher star formation ? Top-heavy IMF / Pop-III stars? Less dust? AGNs?

- Understand the implications of this " excess " for other large scale processes like reionization !!!

Modelling the UV Luminosity Function of high-z galaxies

- **DM Halo Mass Function**
  Number density of DM halos per unit mass

  Galaxy Halo Connection

  $L_{UV}\left(M_h\right)$

  Galaxy UV Luminosity Function : Φ_{UV}
  Number density of galaxies per unit UV luminosity (1500 Å)

Modelling the UV Luminosity Function of high-z galaxies

- **DM Halo Mass Function**
  Number density of DM halos per unit mass

  Galaxy Halo Connection

  $L_{UV}\,(M_h)$

  Galaxy UV Luminosity Function : Φ_{UV}
  Number density of galaxies per unit UV luminosity (1500 Å)

- **Halo Mass** M_h

  SF efficiency $f_*(M_h)$

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

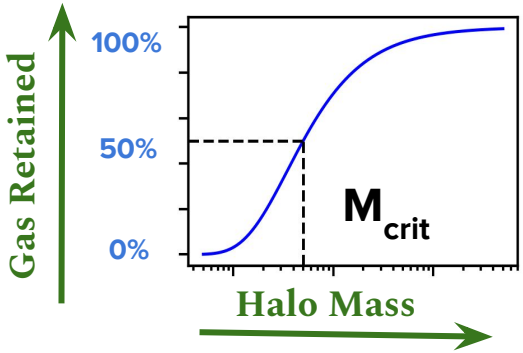
  Star Formation Rate $\dot{M}_*$

  $\mathcal{K}_{UV}$

  UV Luminsoity (1500 Å) $L_{UV}^{\rm nofb}$

In already **ionized** regions, radiative feedback will deplete the gas reservoir of low-mass halos, reducing their SFR

$$L_{UV}^{\rm fb} = f_{gas}(M_h)\, L_{UV}^{\rm nofb}$$



Modelling the UV Luminosity Function of high-z galaxies

- **DM Halo Mass Function**
  Number density of DM halos per unit mass

  Galaxy Halo Connection

  $$L_{UV}\,(M_h)$$

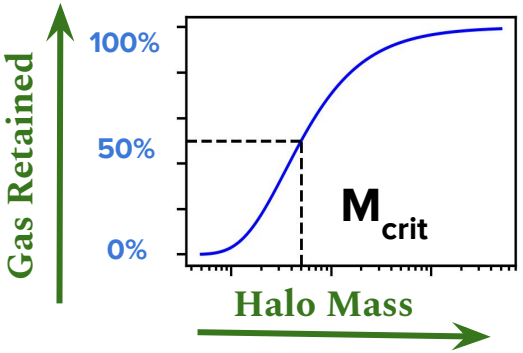
  Galaxy UV Luminosity Function : Φ_{UV}
  Number density of galaxies per unit UV luminosity (1500 Å)

- **Halo Mass** M_h — **SF efficiency** $f_*(M_h)$ → **Star Formation Rate** $\dot{M}_*$ — $\mathcal{K}_{UV}$ → **UV Luminsoity (1500 Å)** $L_{UV}^{\rm nofb}$

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

In already **ionized** regions, radiative feedback will deplete the gas reservoir of low-mass halos, reducing their SFR

$$L_{UV}^{\rm fb} = f_{gas}(M_h)\, L_{UV}^{\rm nofb}$$



- The globally averaged UV Luminosity Function can be written as

$$\Phi_{\rm UV}^{\rm total} = Q_{II}(z)\,\Phi_{\rm UV}^{\rm fb} + [1 - Q_{II}(z)]\,\Phi_{\rm UV}^{\rm nofb}$$

Ionized regions **Neutral regions**

Connecting to the reionization history

- For UVLF calculations, need to solve for global ionization fraction : Q_{II}

Fractional volume filled with ionized hydrogen

No. of ionizations per unit time

Rate of recombinations

$$\frac{dQ_{II}}{dt} = \frac{\dot{n}_\gamma(z)}{\bar{n}_H} - \frac{Q_{II}}{t_{rec}(z)}$$

$$Q_{II}\,\dot{n}_\gamma^{\rm fb}(z) + [1 - Q_{II}]\,\dot{n}_\gamma^{\rm nofb}(z)$$

No. of ionizing photons in the IGM per unit time

Escape Fraction

No. of ionizing photons per unit mass of stars

Amt of stars formed per unit time

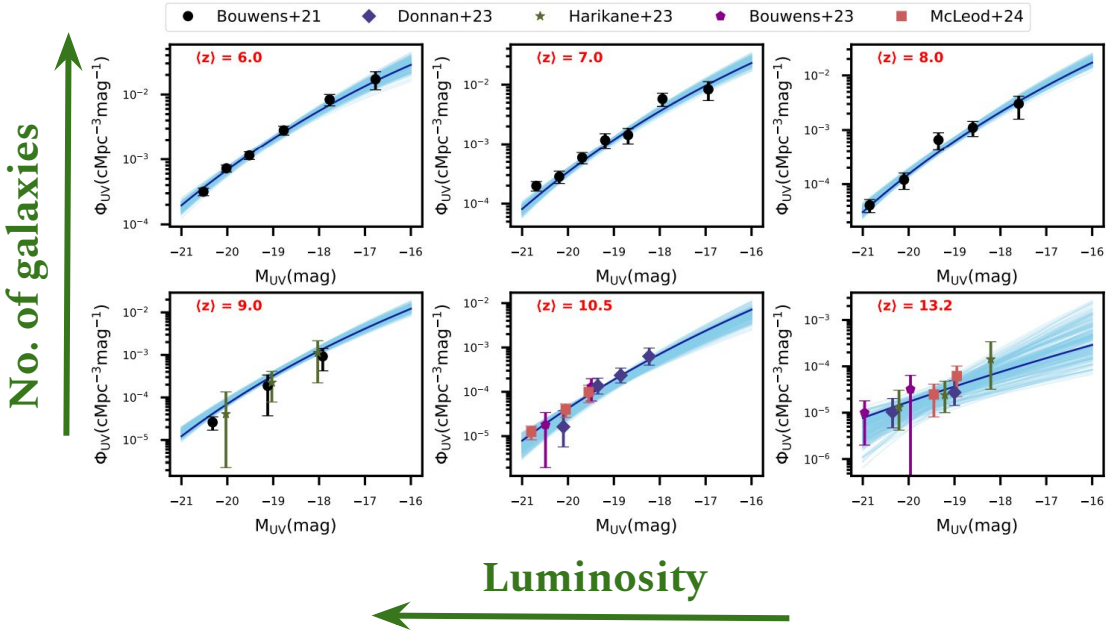
$$\dot{n}_\gamma^{\rm region}(z) = f_{esc}(M_h) \times \eta_{\gamma *} \times \dot{M}_*^{\rm region}(M_h) \times \text{No. of halos}$$

Stellar spectra was obtained using STARBURST99 code

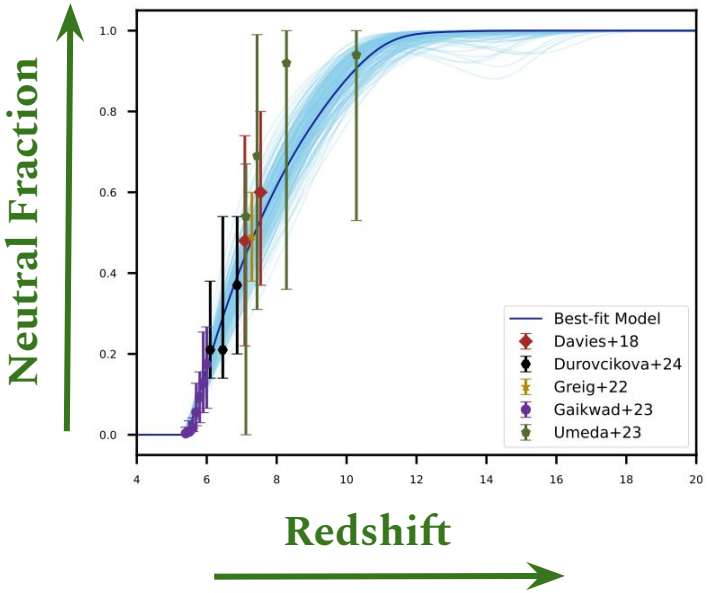
Comparison with observations and parameter inferences

- Free parameters were constrained against the following obs. datasets using a Bayesian approach

[A] *Galaxy UVLF over 6 ≤ z ≤ 13.25 from HST + JWST.*



[B] *Global IGM Neutral Hydrogen Fraction*



[C] *Thompson Scattering of CMB photons by free electrons produced during reionization*

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

Results: The astrophysical properties of high-z galaxies

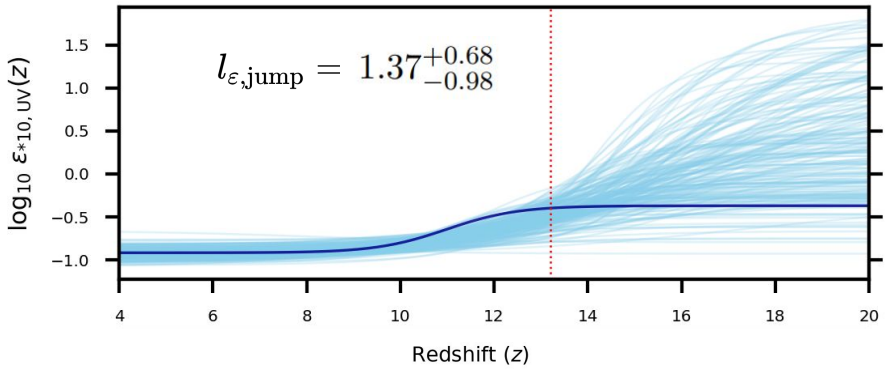
- $$L_{UV} \propto \varepsilon_{*10,UV}(z) \left(\frac{M_h}{10^{10} M_\odot} \right)^{\alpha_*(z)}$$

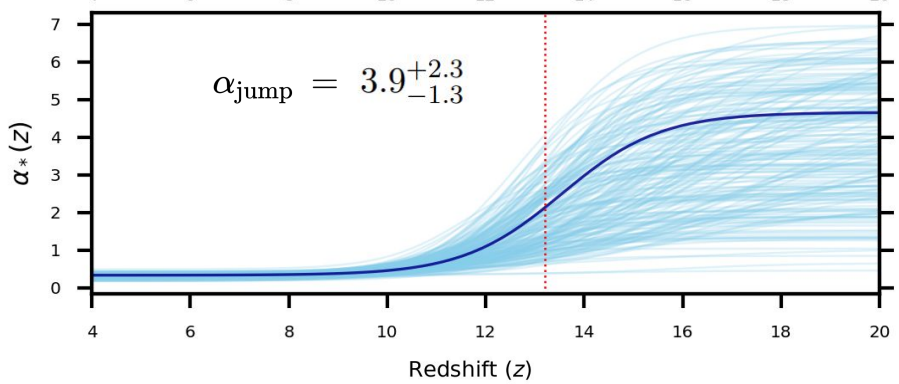
SF efficiency

SF timescale

$$\varepsilon_{*10,UV} = \frac{f_{*,10}}{c_*} \left(\frac{\mathcal{K}_{UV}}{\mathcal{K}_{fid,UV}} \right)^{-1}$$

L_{UV} per SFR





High f_*? Less efficient feedback?

Bursty star formation history ?

Top heavy IMF ?

Results: The astrophysical properties of high-z galaxies

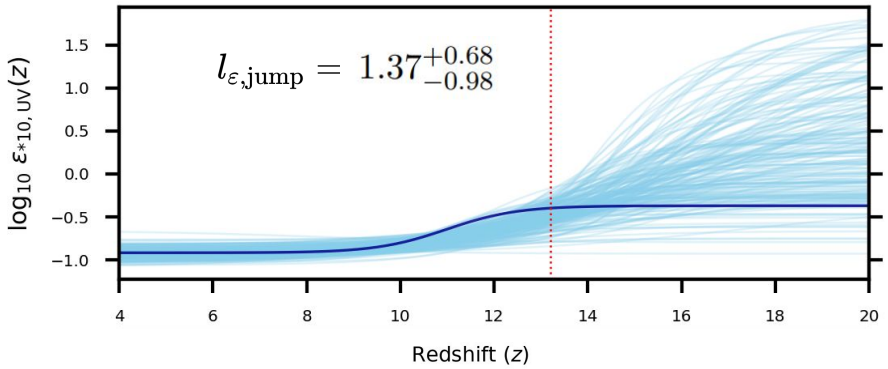
- $$L_{UV} \propto \varepsilon_{*10,UV}(z)\left(\frac{M_h}{10^{10}M_\odot}\right)^{\alpha_*(z)}$$

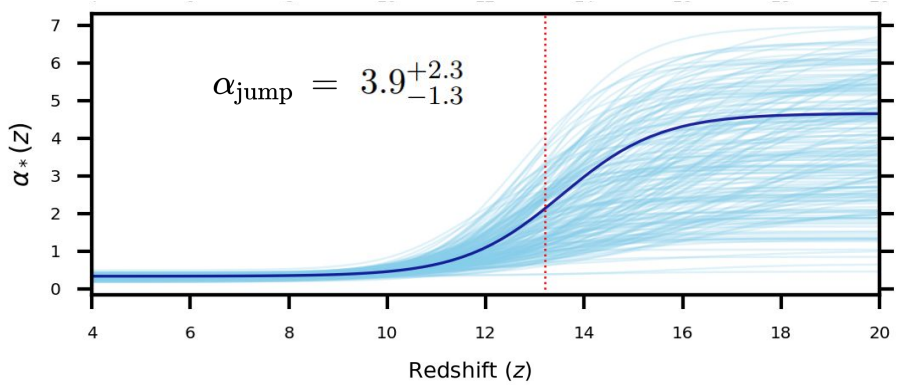
SF efficiency

SF timescale

$$\varepsilon_{*10,UV} = \frac{f_{*,10}}{c_*}\left(\frac{\mathcal{K}_{UV}}{\mathcal{K}_{fid,UV}}\right)^{-1}$$

L_{UV} per SFR





High f_*? Less efficient feedback? *Bursty star formation history ?* *Top heavy IMF ?*

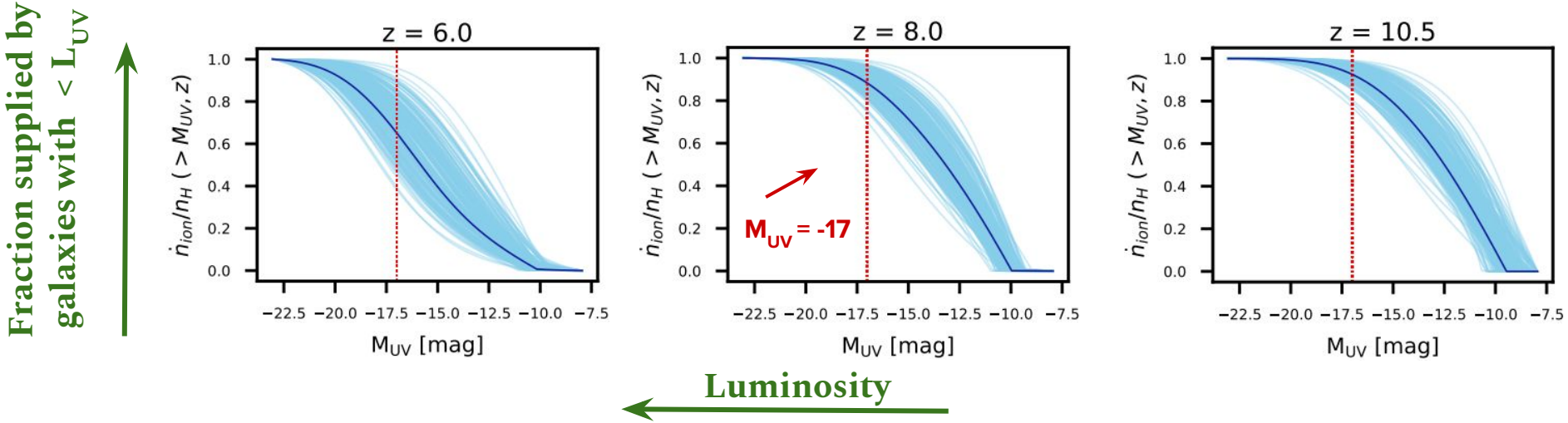
- $$f_{esc}(M_h) = f_{esc,10}\left(\frac{M_h}{10^{10}M_\odot}\right)^{\alpha_{esc}}$$ ⇨ $$\alpha_{esc} = -0.38^{+0.19}_{-0.16}$$ $$f_{\mathrm{esc},10} \approx 11\% \left(\frac{\xi_{\mathrm{ion}}}{10^{25.23}\ \mathrm{erg^{-1}\ Hz}}\right)^{-1}$$

Low mass galaxies have higher LyC escape fractions

Implications and predictions from the model

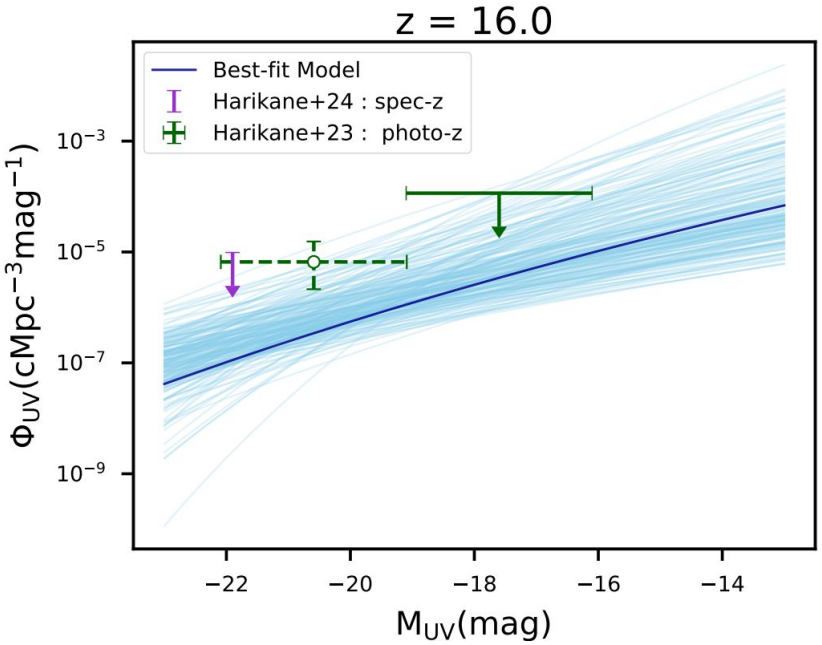
- ***What kind of galaxies drive cosmic reionization ?***

The **fainter** set of galaxies provide the bulk (≥ 50%) of ionizing photons all throughout the EoR



Implications and predictions from the model

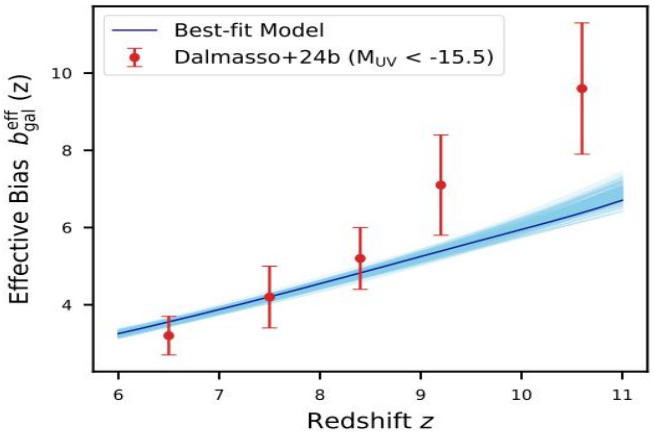
- *What kind of galaxies drive cosmic reionization ?*
- *How many galaxies are there at the very early times (z ~ 16) ?*



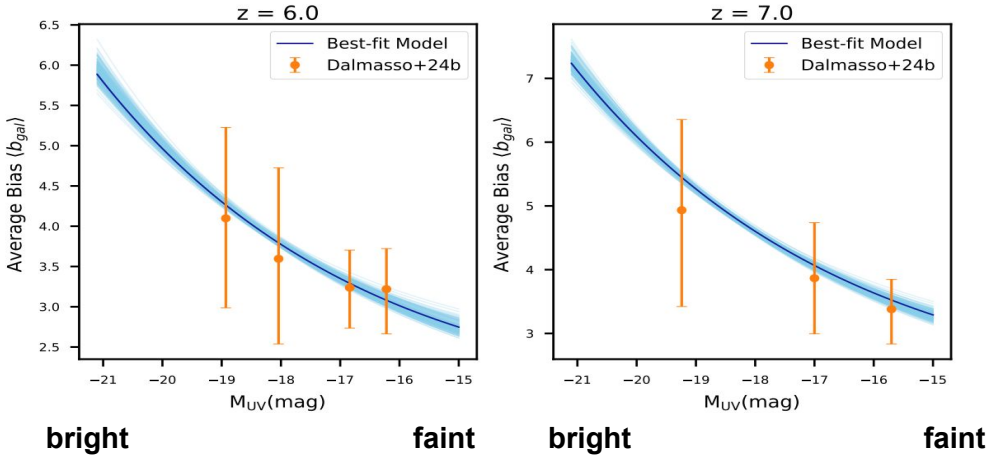
Implications and predictions from the model

- *What kind of galaxies drive cosmic reionization ?*
- *How many galaxies are there at the very early times (z ~ 16) ?*
- *How are the early galaxies distributed spatially ?*

Number-weighted linear bias of galaxies



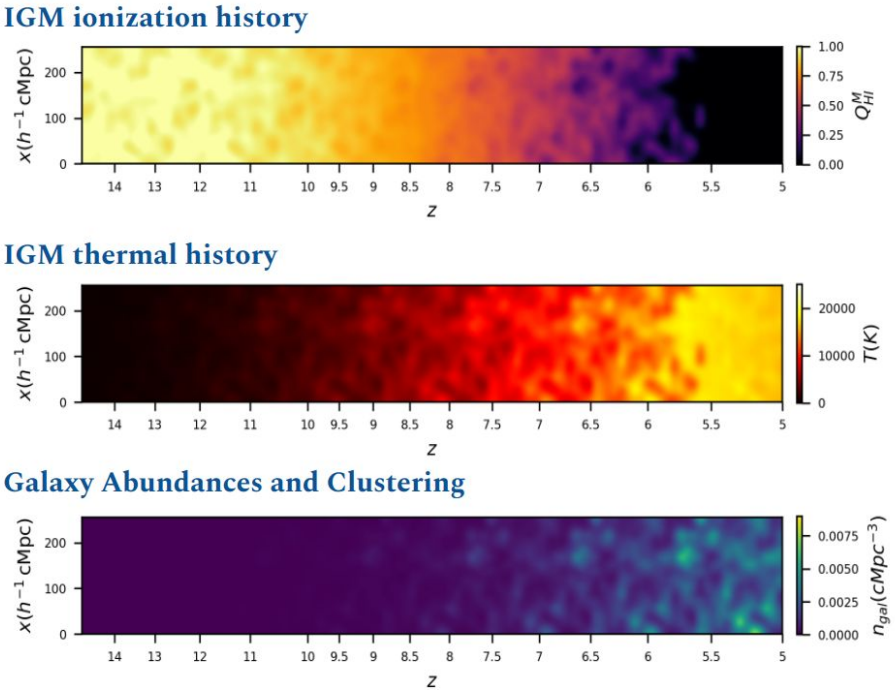
The average linear bias of galaxies at a given redshift



The way forward ....

- Implemented this galaxy formation model into a semi-numerical reionization code named **SCRIPT** : Semi-numerical *C*ode for *R*e*I*onization with *P*ho*T*on-conservation

(Choudhury et al, 2018 ; Maity et al, 2023)



Mass-averaged Neutral Fraction

IGM Temperature

Number density of bright set of UV galaxies

Applications :

21cm-Galaxy Cross Correlations

Galaxy clustering at high-z

Lyman-alpha forest

+++

Summary

- We developed an ***analytical*** model to **jointly** explain the evolution of the galaxy UVLFs over $6 < z < 15$ and the ionization state of the IGM.
- Effects of reionization feedback on low-mass galaxies are self-consistently accounted.
- The model was used to infer the properties of high-z galaxies by comparing its outputs with the latest JWST and IGM observations.
- The model is also able to reasonably predicts other galaxy observables at high redshifts.
- The galaxy framework has now been integrated into a ***semi-numerical*** reionization code **SCRIPT**, enabling many **more** interesting science explorations for the EoR

Thank you

arXiv:2404.02879
A. Chakraborty & T. Roy Choudhury, JCAP (2024), in press

Email : anirban@ncra.tifr.res.in