Modelling star-forming galaxies during the Epoch of Reionization in the JWST era

Anirban Chakraborty

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

(with Prof. Tirthankar Roy Choudhury)

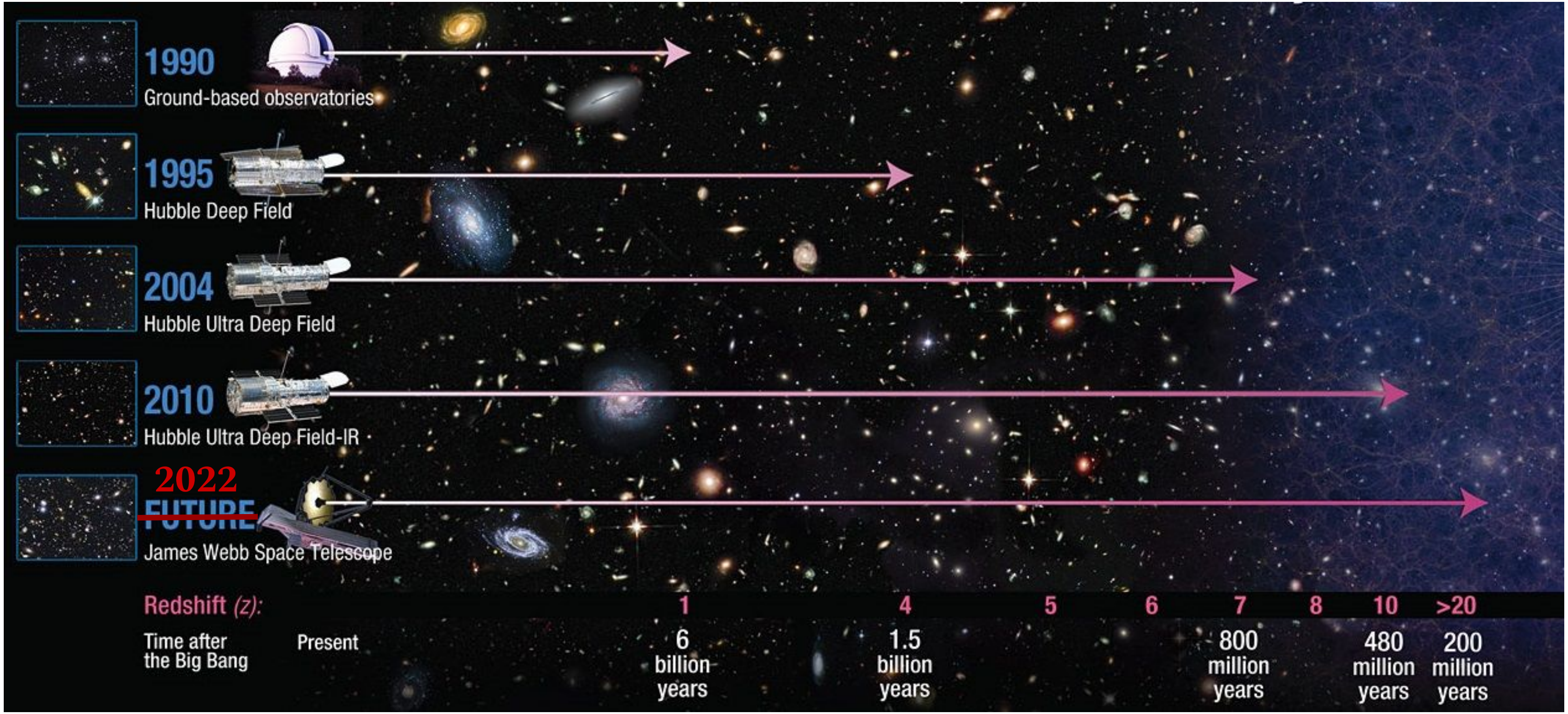
A. Chakraborty & T. Roy Choudhury, JCAP (2024) : arXiv:2404.02879
A. Chakraborty & T. Roy Choudhury (submitted, JCAP) : arXiv:2503.07590

Radio Cosmology and Continuum Observations in the SKA Era: A Synergic View
ICTS-TIFR Bangalore, April 10, 2025

NCRA • TIFR

New Insights into early galaxy formation enabled by JWST

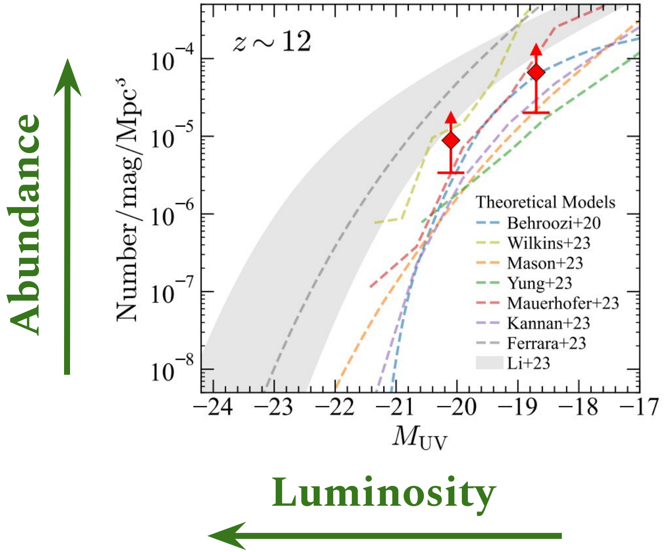
- JWST has pushed the frontiers of observational study of galaxies back to much earlier epochs



(Credit : HST Press Release Archives)

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, 2024)

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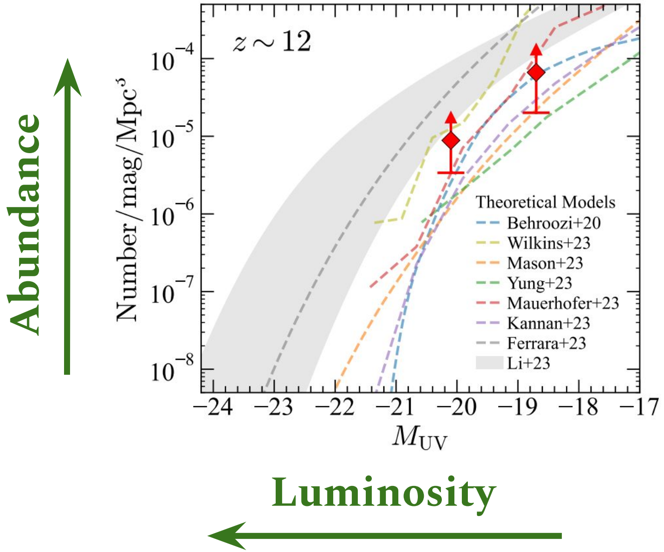

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Cosmological Solutions : More no. of DM halos than in ΛCDM ? Modifications to power spectrum ?

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

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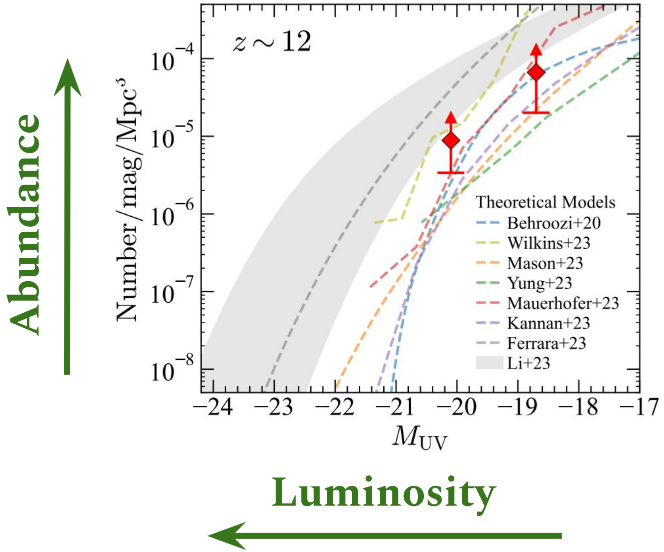

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Cosmological Solutions : More no. of DM halos than in ΛCDM ? Modifications to power spectrum ?

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)

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Halo Mass M_h

SF efficiency $f_*(M_h)$ →
SF timescale $t_* = c_* \, t_H\left(z\right)$

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

$\mathcal{K}_{UV}$ →
UV light per SFR

UV Luminsoity L_{UV}^{nofb}

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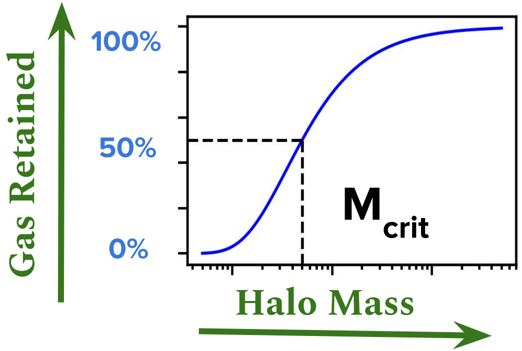
Halo Mass M_h — **SF efficiency** $f_*(M_h)$, **SF timescale** $t_* = c_*\, t_H\left(z\right)$ → **Star Formation Rate** $\dot{M}_*$ — $\mathcal{K}_{UV}$, **UV light per SFR** → **UV Luminsoity** $L_{UV}^{\rm nofb}$

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

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



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Halo Mass — **Star Formation Rate** — **UV Luminsoity**

M_h - - - - → $\dot{M}_*$ - - - - → L_{UV}^{nofb}

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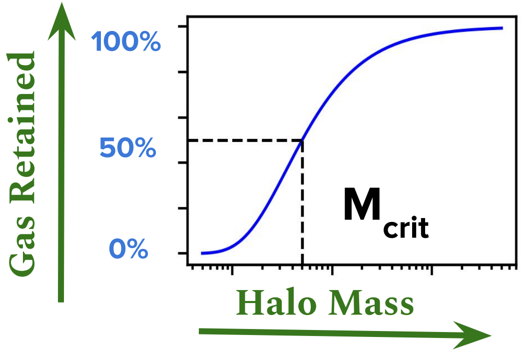

- The globally averaged UV Luminosity Function can be written as

$$\Phi_{\text{UV}}^{\text{total}} = \underbrace{Q_{\text{HII}}(z)\, \Phi_{\text{UV}}^{\text{fb}}}_{\text{Ionized regions}} + \underbrace{\left[1 - Q_{\text{HII}}(z)\right] \Phi_{\text{UV}}^{\text{nofb}}}_{\text{Neutral regions}}$$

Ionized regions **Neutral regions**

Connecting to the reionization history

- For UVLF calculations, need to solve for global ionization fraction : $Q_{\rm HII}$

Growth of ionized regions — No. of ionizations per unit time — Rate of recombinations

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

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$$\dot{n}_\gamma(z) \rightarrow Q_{\rm HII}\,\underbrace{\dot{n}_\gamma^{\rm fb}(z)}_{\text{Ionized regions}} + [1 - Q_{\rm HII}]\,\underbrace{\dot{n}_\gamma^{\rm nofb}(z)}_{\text{Neutral regions}}$$

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No. of ionizing photons in the IGM per unit time = Escape Fraction x No. of ionizing photons per unit mass of stars x Amt of stars formed per unit time x No. of halos

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

Stellar spectra obtained using STARBURST99 code

Comparison with observations and parameter inferences

- In total, the **baseline** model has 9 free parameters that determines :
  - ➢ Production efficiency of UV radiation as a function of halo mass and redshift.

$$L_{\rm UV} \propto \varepsilon_{*10,\rm UV}(z) \left(\frac{M_h}{10^{10} M_\odot}\right)^{\alpha_*(z)} \qquad \varepsilon_{*10,\rm UV} = \frac{f_{*,10}}{c_*}\left(\frac{\mathcal{K}_{\rm UV}}{\mathcal{K}_{\rm fid,UV}}\right)^{-1}$$

  - ➢ Escape fraction of ionizing photons escaping as a function of halo mass.

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

  - ➢ The characteristic halo mass (in $M_\odot$) below which effects of radiative feedback are severe.

$$M_{\rm crit}$$

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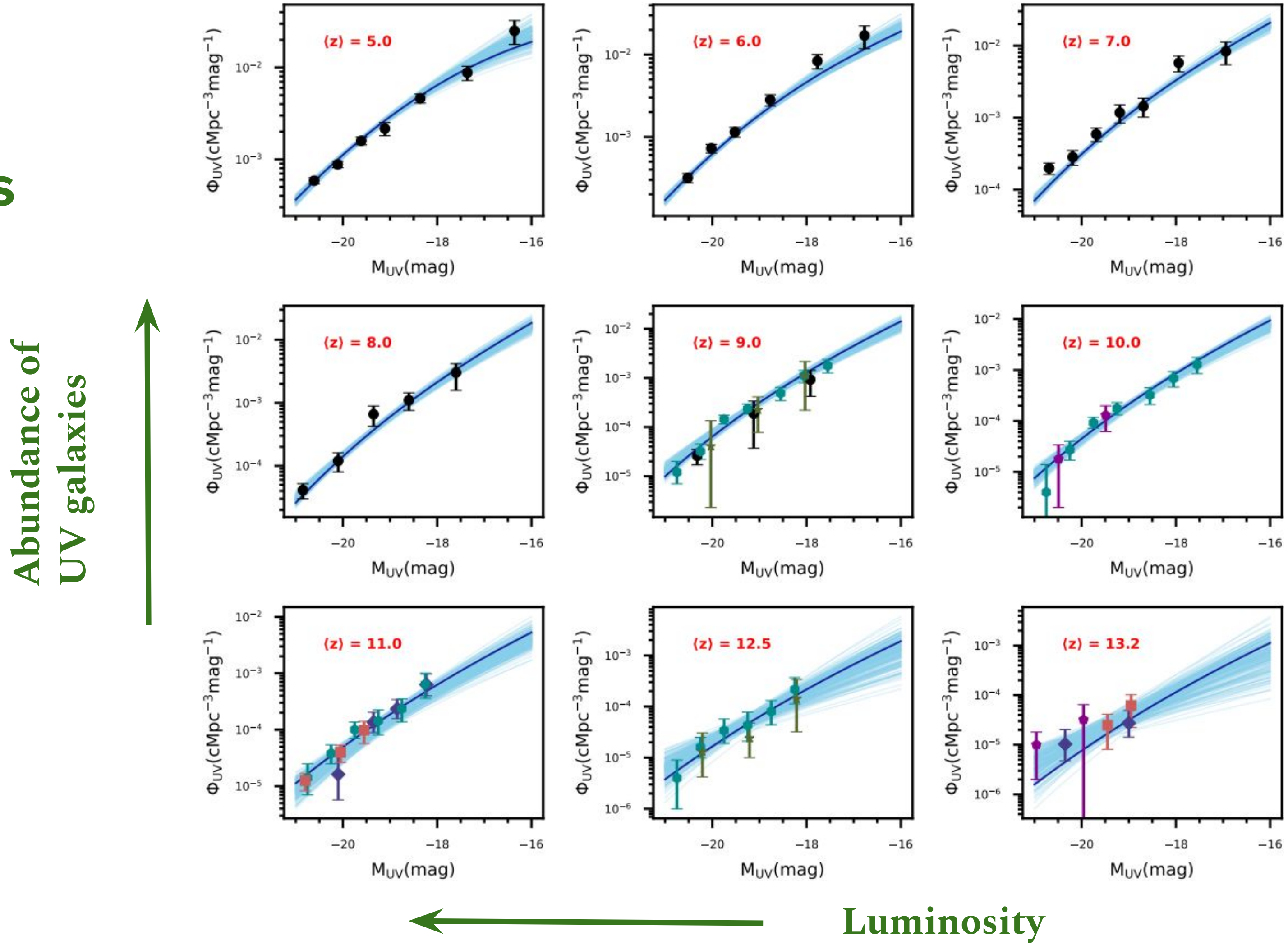
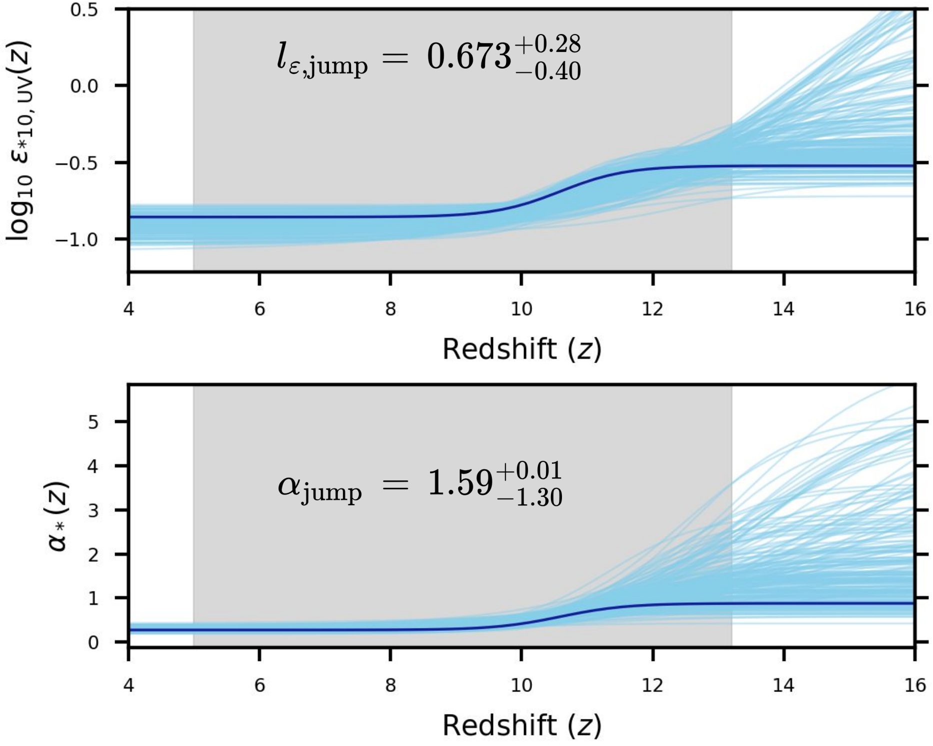
- Constraints obtained by fitting the model predictions to various observations **simultaneously**
  - ➢ Galaxy UV luminosity function at 9 different redshift bins over $5 < z < 15$ from JWST and HST.
  - ➢ Globally averaged neutral hydrogen fraction at various redshifts.
  - ➢ Thompson Scattering of CMB photons by free electrons produced during reionization.

Comparison with galaxy observations



Increased efficiency of UV emission in galaxies at high-z



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

SF efficiency

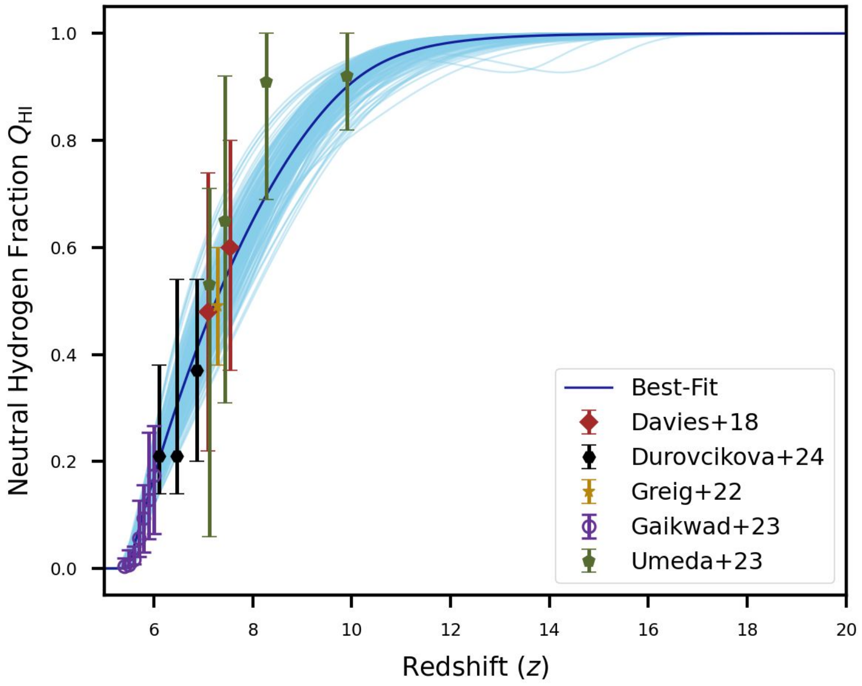
L_{UV} per SFR

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

SF timescale

- High SFE ? Less efficient feedback ?
  (e.g., Dekel et al 2023)
- Bursty star formation history ?
  (e.g., Mason et al 2023)
- top heavy IMF / Pop-III stars ?
  (e.g., Trinca et al 2023)

Comparison of baseline model with reionization observations



- Preference for low-mass galaxies to have higher LyC escape fractions

$$f_{esc}(M_h) = f_{esc,10}\left(\frac{M_h}{10^{10} M_\odot}\right)^{-0.18^{+0.14}_{-0.11}}$$

$$\text{with } f_{esc,10} \approx 15\% \left(\frac{\xi_{ion}}{10^{25.23} \text{erg}^{-1}\text{Hz}}\right)^{-1}$$

- Reionization driven by the **fainter** population of galaxies (M_{UV} < - 17)

- Radiative feedback affects haloes lighter than $10^{10.07}$ $M_\odot$ severely

Predictions of galaxy bias from the baseline model

- Determine the galaxy bias using the constructed galaxy-halo connection

$$b_{\rm gal}^{\rm fb}(M_{\rm UV}, z) = b_{\rm halo}\left(M_h(M_{\rm UV})\Big|_{\rm fb}, z\right)$$
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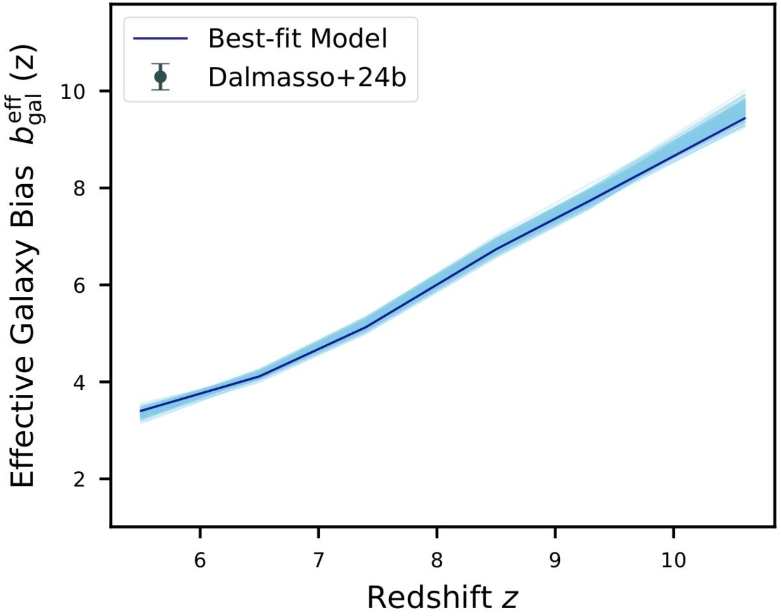

- **Number-weighted linear bias of galaxies at a redshift**

$$b_{\rm gal}^{\rm eff}(z) = \frac{\int_{M_{\rm UV,min}}^{M_{\rm UV,max}} {\rm d}M_{\rm UV}\, \{Q_{\rm HII}(z)\, b_{\rm gal}^{\rm fb}(M_{\rm UV}, z)\, \Phi_{\rm UV}^{\rm fb} + [1 - Q_{\rm HII}(z)]\, \Phi_{\rm UV}^{\rm nofb}\, b_{\rm gal}^{\rm nofb}(M_{\rm UV}, z)\}}{\int_{M_{\rm UV,min}}^{M_{\rm UV,max}} {\rm d}M_{\rm UV}\, \{Q_{\rm HII}(z)\, \Phi_{\rm UV}^{\rm fb} + [1 - Q_{\rm HII}(z)]\, \Phi_{\rm UV}^{\rm nofb}\}}$$

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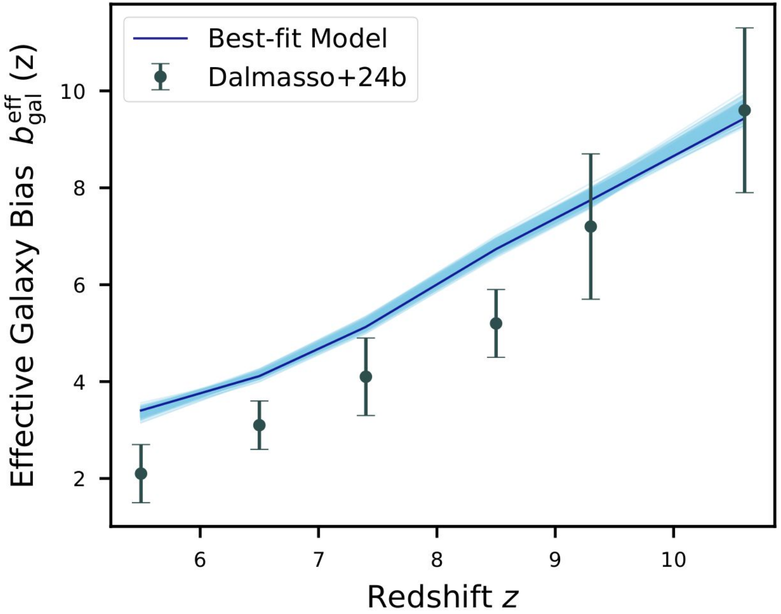

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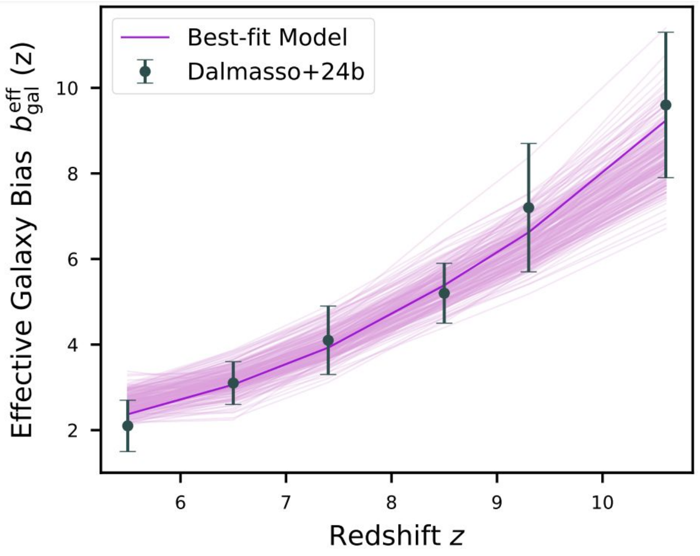
What does it take to match the galaxy bias observations ?



Galaxy UVLFs ?

+

Reionization observations

$Q_{HI}(z)$ and τ_{el}

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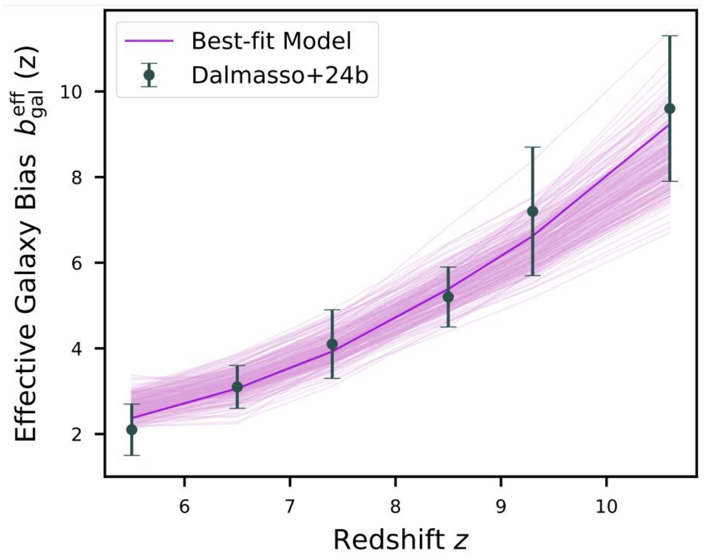
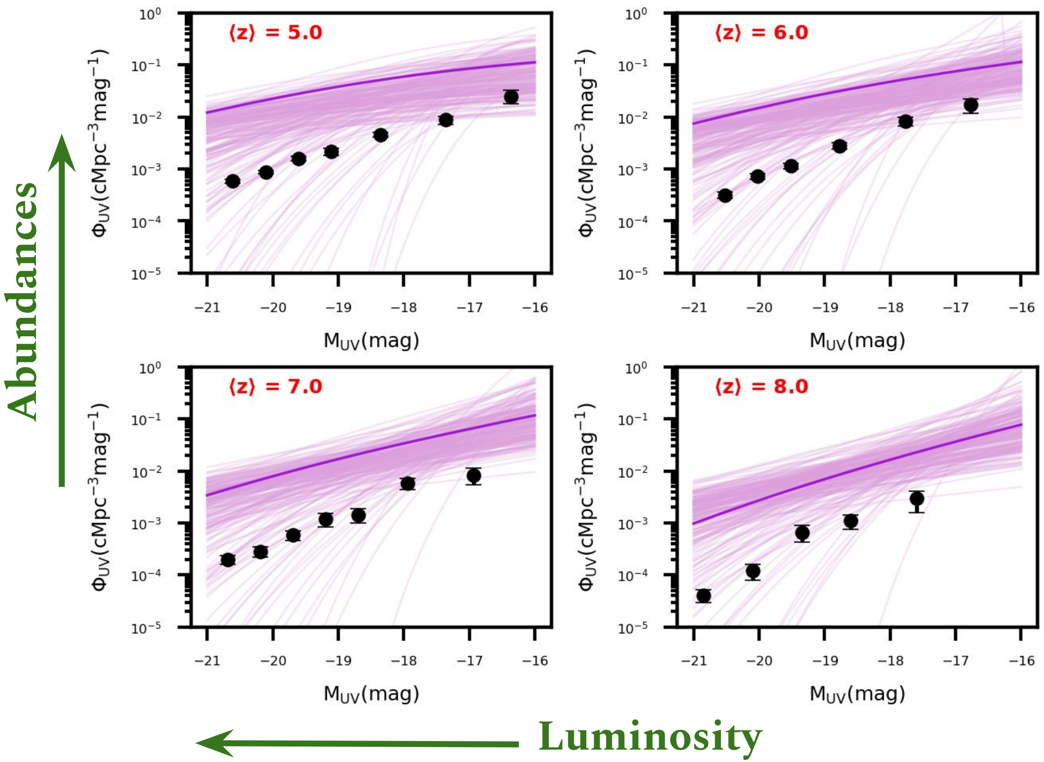




Reionization observations

Q_{HI} (z) and τ_{el}

BUT ... a surplus of UV galaxies !!!

To the rescue : A duty cycle for galaxies

- Only a fraction of the underlying galaxy population is observable (at a given time)

- Duty Cycle $\epsilon_{DC}\ (M_h\ , z)$ $\Longrightarrow$ How likely it is that we will observe the galaxy hosted by a given halo at a particular redshift ??

To the rescue : A duty cycle for galaxies

- Only a fraction of the underlying galaxy population is observable (at a given time)

- Duty Cycle $\epsilon_{DC}\ (M_h\ , z)$ $\Longrightarrow$ How likely it is that we will observe the galaxy hosted by a given halo at a particular redshift ??

- *Assume :* Only halos that formed within some given preceding time interval Δt can possibly host a detectable UV-bright galaxy

(Trenti et al, 2010)

$$\epsilon_{DC}(t_*, M_h, z) = \frac{\delta n\,(\Delta t = t_*)}{n}$$

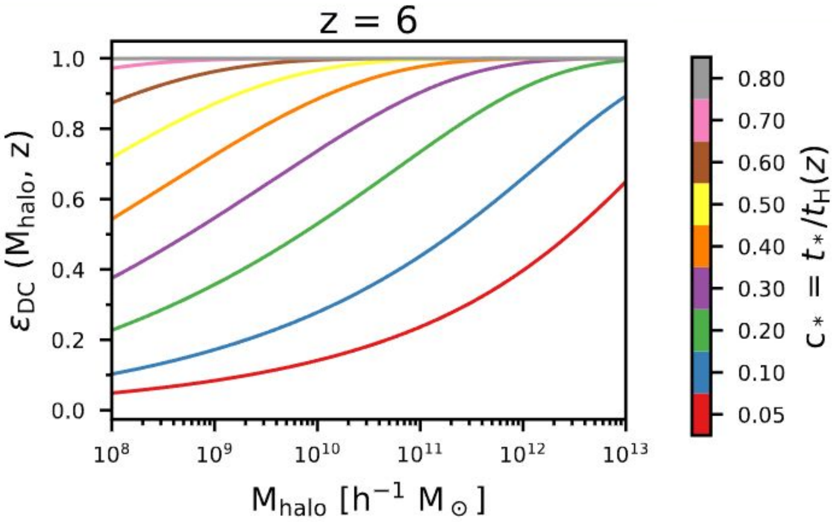
$$= \frac{\int_{M_h}^{+\infty} [n(M_h', z) - n(M_h', z_{t_*})]\ dM_h'}{\int_{M_h}^{+\infty} n(M_h', z)\ dM_h'}$$

$$t_* = t_H(z) - t_H(z_{t_*})$$

The duty cycle prescription

$$\epsilon_{DC}(t_*, M_h, z)$$

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



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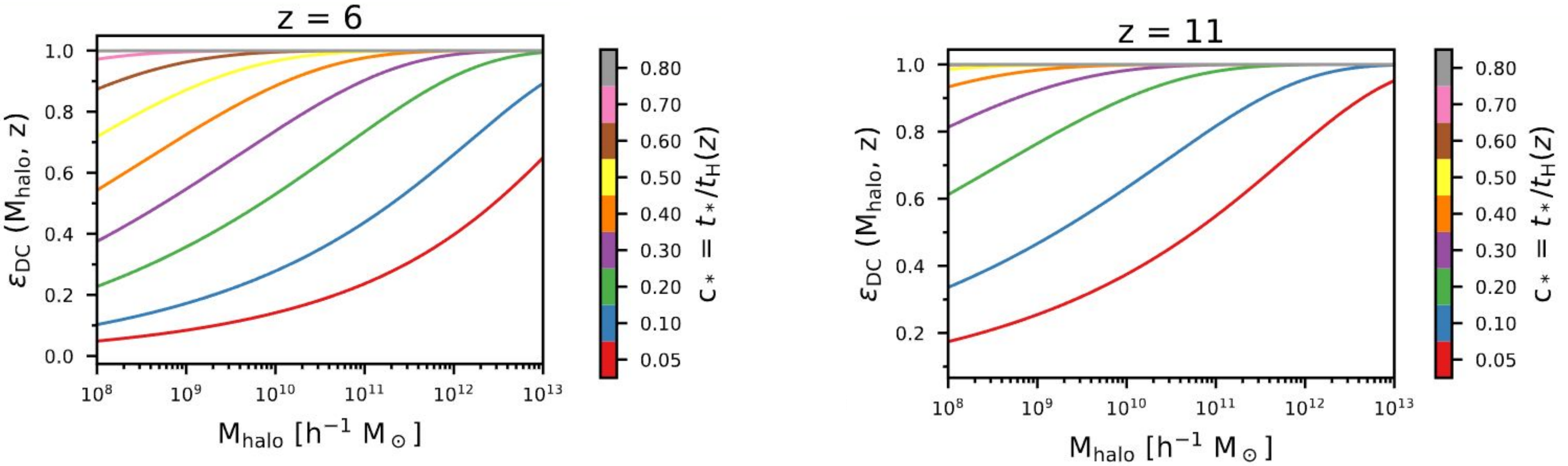


- Higher for massive halos and higher values of c_* at fixed redshift
- Higher at early times (i.e., high redshifts) at fixed halo mass and c_*

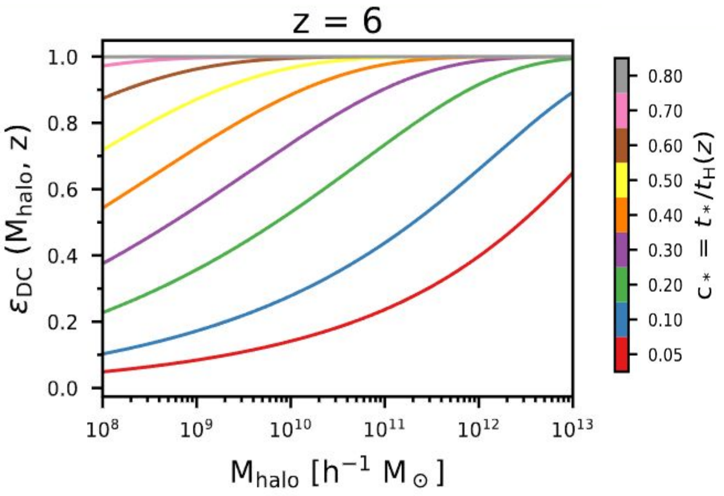
Extending the baseline model with a duty cycle

- At a given redshift, smaller value of c_* implies

  >> haloes are now comparatively brighter →

$$L_{UV} = \frac{1}{\mathcal{K}_{\rm UV}} \frac{f_*(M_h, z)}{c_* \, t_H(z)} \frac{\Omega_b}{\Omega_m} M_h$$

  >> but, equally less likely to be UV-visible since their duty cycles are lower →



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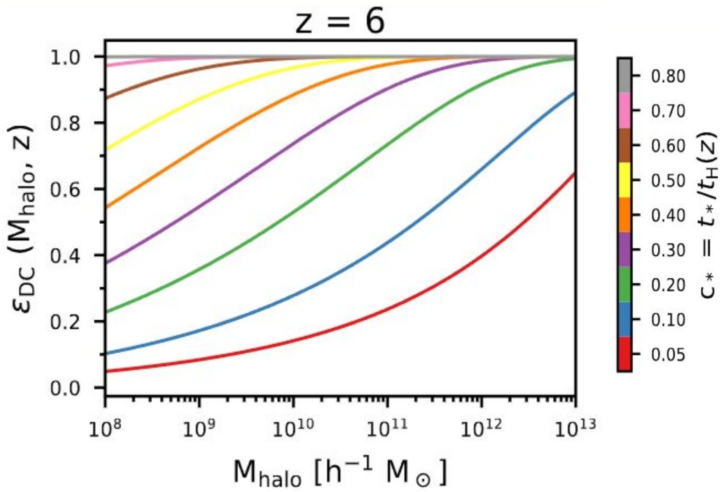


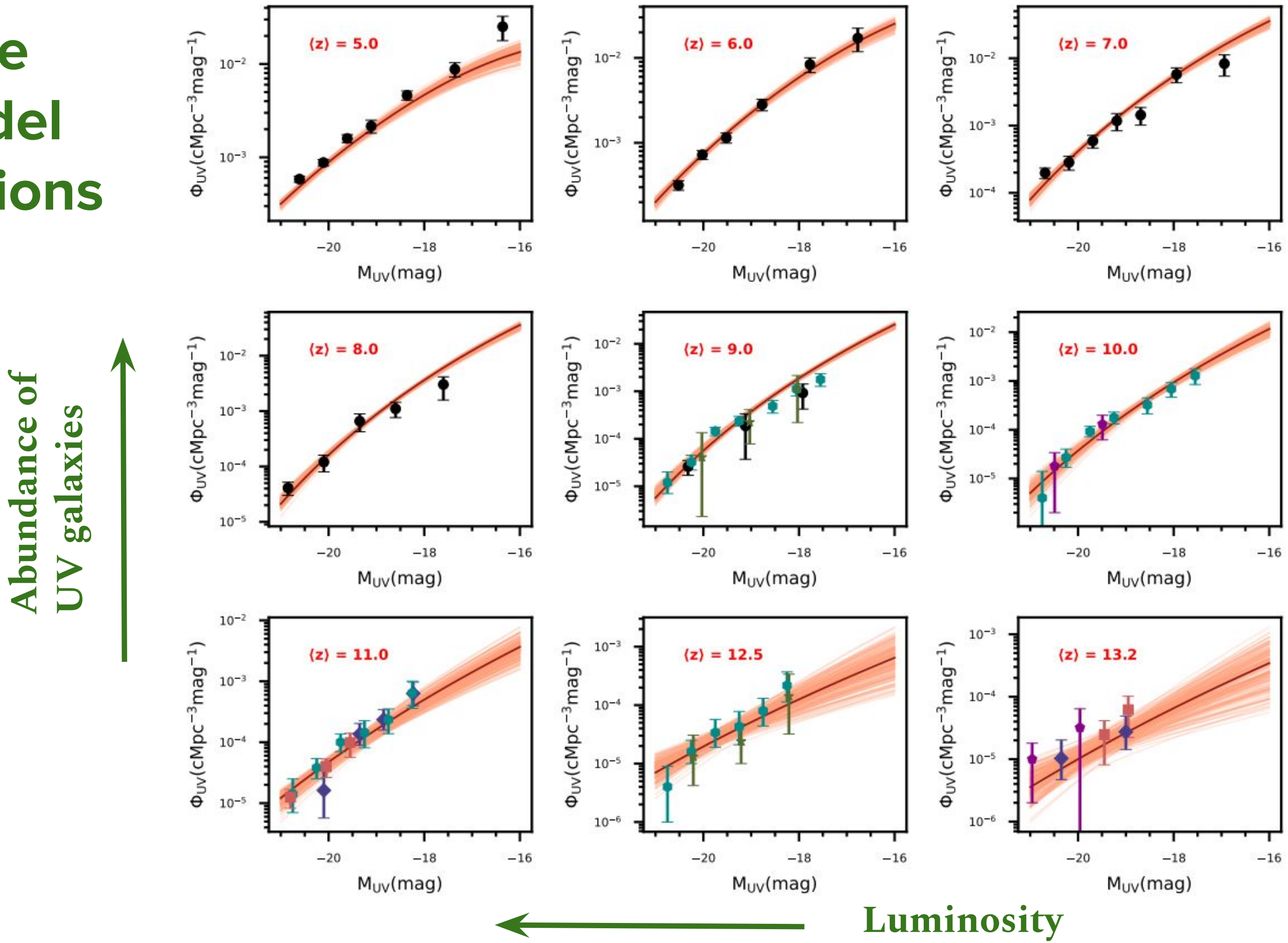
- Breaks degeneracy (to some extent) in the prescription for production efficiency of UV radiation

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

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

$$c_*(z) = \min\left[0.5\,,\ c_{*,6}\left(\frac{1+z}{7}\right)^{\beta_{c*}}\right]$$

Comparing the extended model with observations



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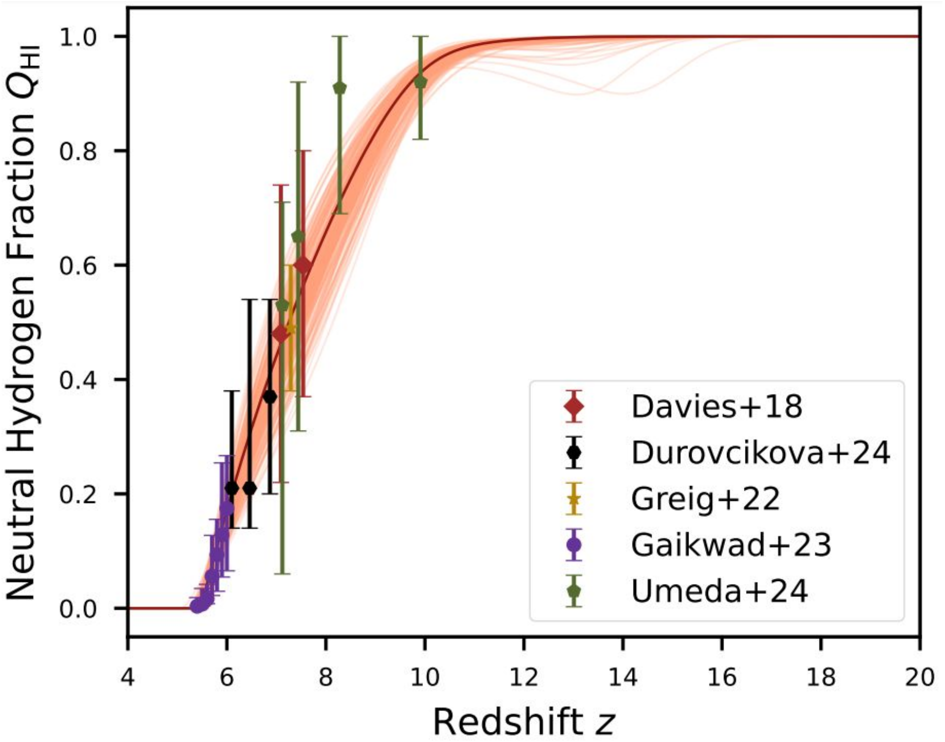
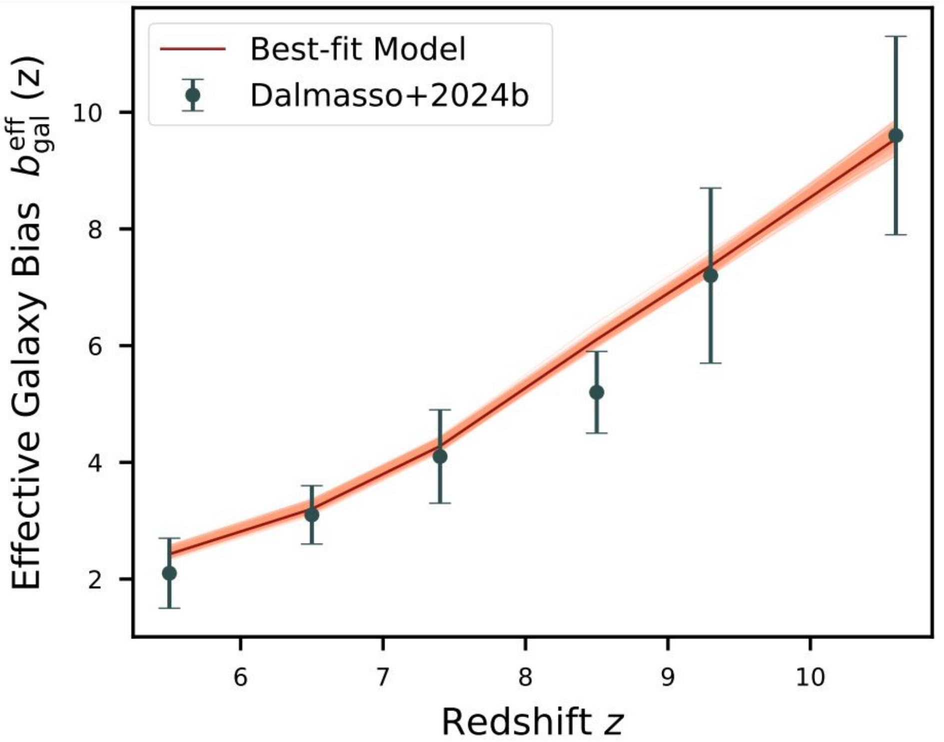
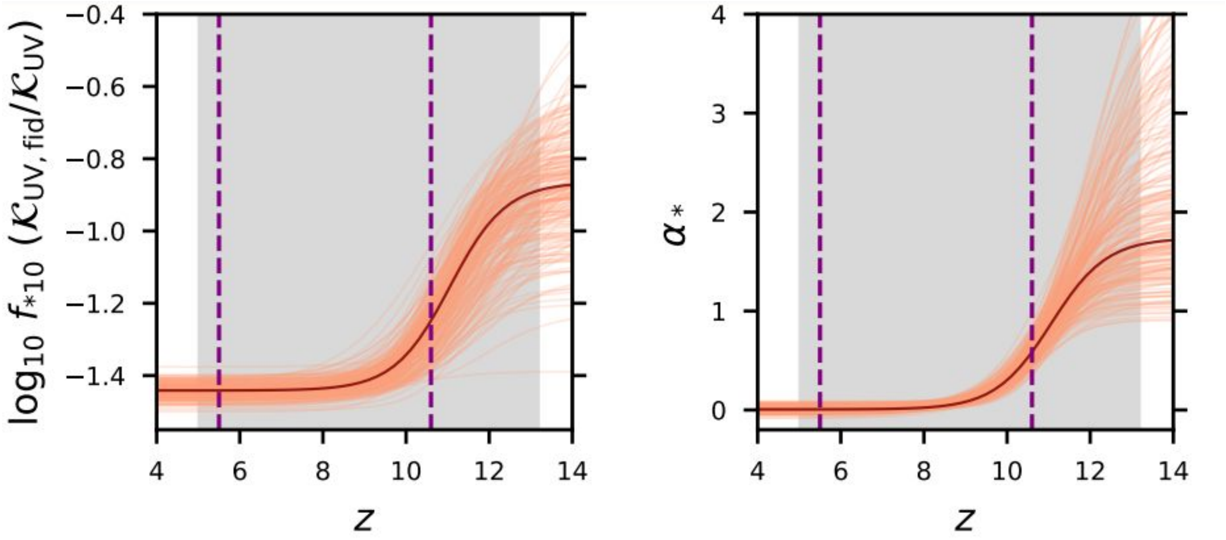




Insights on astrophysical properties from the extended model

Redshifts with gal-bias data

Redshifts with gal-UVLF data



- Increased efficiency of star formation at z > 10

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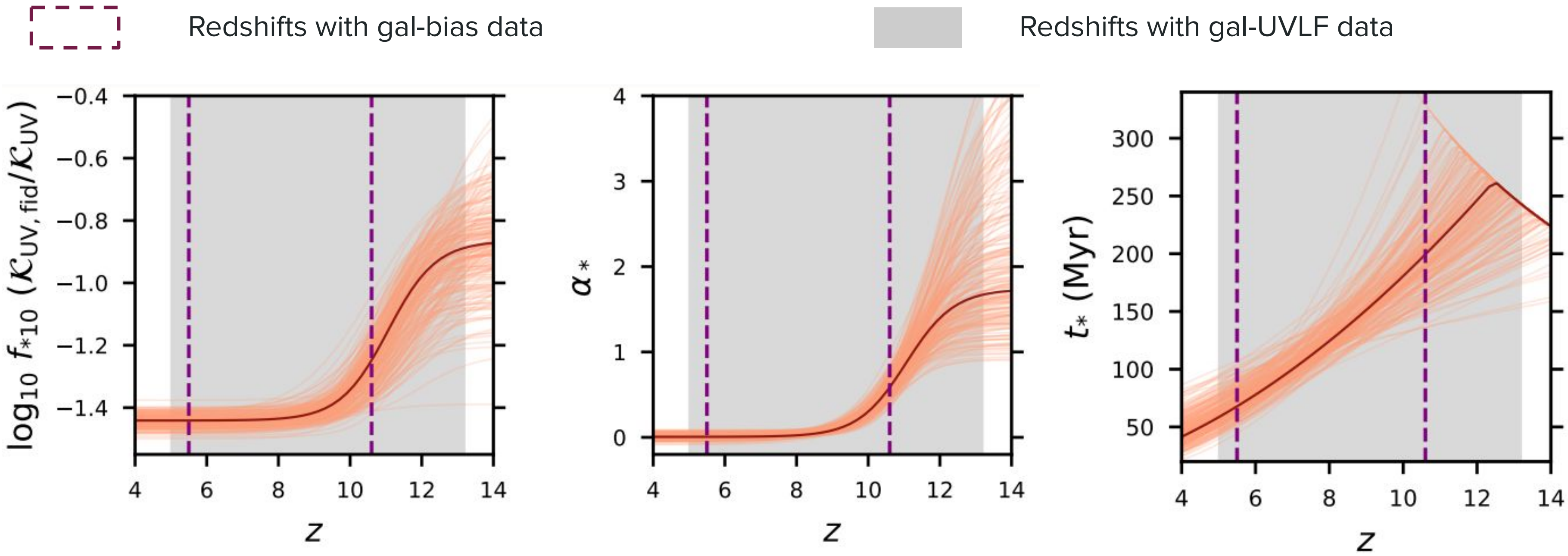

- Increased efficiency of star formation at $z > 10$
- Decreasing duty cycle at $z < 10$

- A mass-independent constant $f_{esc} \simeq 12\ \%$ aligns with current reionization constraints

What has been done ...

UV Luminosity Functions

&

Clustering

$$\Downarrow$$

$$f_*(M_h).\left(\frac{\kappa_{\mathrm{UV,fid}}}{\kappa_{\mathrm{UV}}}\right) \;\; \& \;\; c_*$$

SF efficiency **light-to-mass** **SF timescale**

Other Implications : Evolution of sSFR

UV Luminosity Functions
&
Clustering

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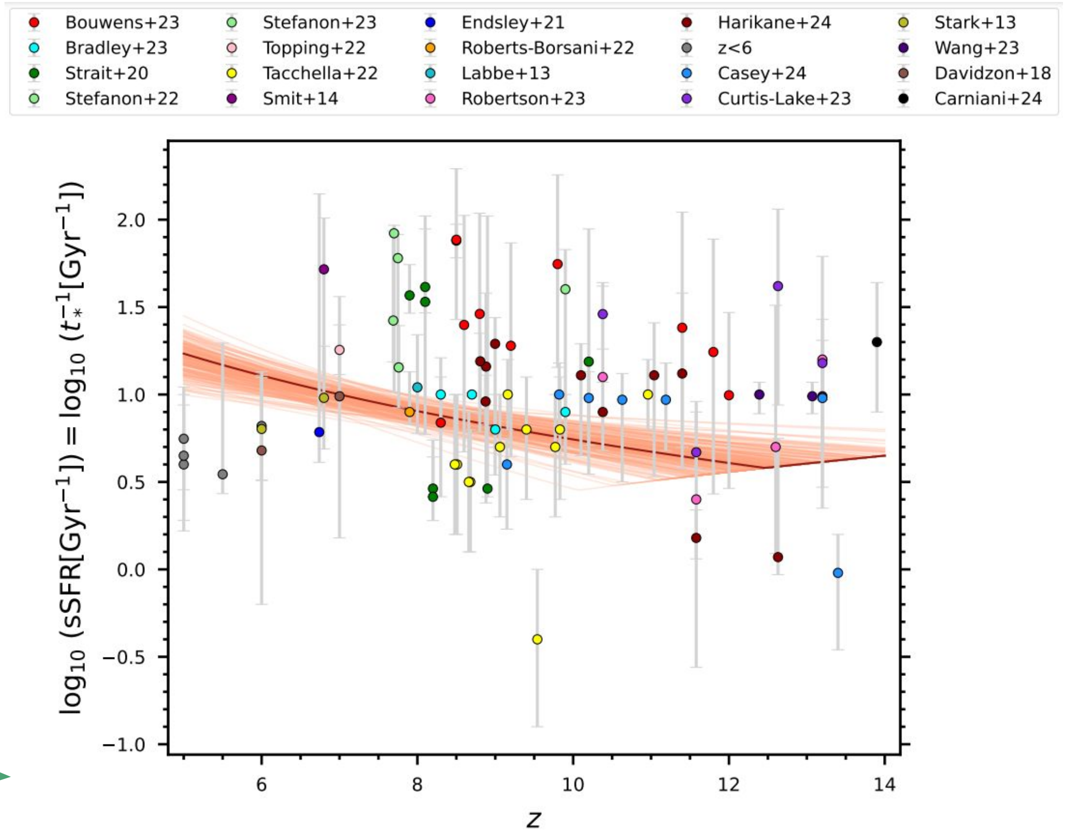

Other Implications : Galaxy Stellar Mass Function

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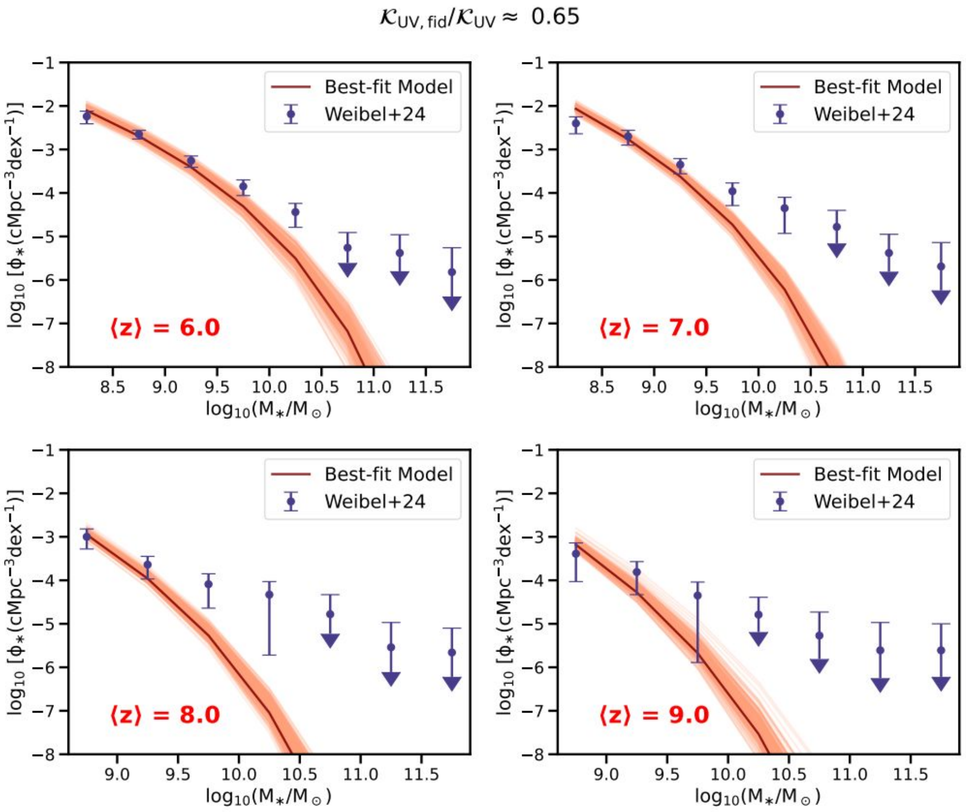

$$f_* \approx 5\% \text{ at } z < 10$$

Summary

- We developed an ***analytical*** model to **jointly** explain the evolution of the galaxy UVLFs over $5 < z < 14$ and the ionization state of the IGM.
- Effects of reionization feedback on low-mass galaxies are self-consistently accounted.
- The theoretical predictions were compared with the latest JWST galaxy and IGM observations.
- An **enhancement** in the **star-formation efficiency** and/or **UV light-to-mass ratio** of galaxies is necessary to match JWST UVLF measurements at $z > 10$.
- **Faint, low-mass galaxies** with **higher LyC escape fractions** drive cosmic reionization
- Incorporating an **evolving mass-dependent duty cycle** prescription to the model helps in correctly reproducing JWST galaxy bias measurements in the range of $5.5 < z < 11$.
- Galaxy clustering measurements are crucial for **breaking degeneracies in the galaxy-halo connection** inferred solely from galaxy UV luminosity functions.