

### BRIDGING THE GAP BETWEEN COSMIC DAWN AND EPOCH OF REIONIZATION<sup>\*</sup>

Not until the empirical resources are exhausted, need we pass on to the dreamy realms of speculation.

– Edwin Powell Hubble

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As already mentioned, the measurements of the 21-cm global signal at z > 15 by the EDGES collaboration (Bowman et al., 2018b) provide the constraints on cosmic dawn. On the other hand, currently, there are several observational global constraints on reionization at  $z \gtrsim 5$ , including measurements of the volume-averaged neutral hydrogen fraction of the IGM using different techniques such as the evolution in Lyman- $\alpha$  and

<sup>\*</sup>This chapter is adapted from the paper, ""Bridging the Gap between Cosmic Dawn and Reionization favors Faint Galaxies-dominated Models" by Bera et al. (2022).

Lyman- $\beta$  forests (Fan et al., 2001; White et al., 2003; McGreer, Mesinger, and D'Odorico, 2015) and Lyman- $\alpha$  emitters (Ouchi et al., 2010; Zheng et al., 2011; Mesinger et al., 2014; Sobacchi and Mesinger, 2015; Mason et al., 2019), the optical depth to Thomson scattering of cosmic microwave background (CMB) photons as measured by Planck Collaboration et al. (2020b), and the ionizing emissivity constraints as compiled by Becker and Bolton (2013). Inferred from the EDGES signal, Madau (2018) have derived a constraint on the early star formation and shown that it is consistent with an extrapolation of UV measurements at lower redshifts (4 < z < 9). While there have been many theoretical (see e.g., Hills et al., 2018; Bradley et al., 2019; Singh and Subrahmanyan, 2019; Sims and Pober, 2020) and observational works (see e.g., Singh et al., 2022) suggesting that the measured profile by EDGES is not of astrophysical origin, it remains crucial to understand what implications such a detection might have on cosmic dawn and reionization. In particular, could additional constraints be placed on the role of faint and bright galaxies during these epochs if the measurement holds? In the light of the recent successful launch of the James Webb Space Telescope (JWST) and the growing observational efforts to detect the 21-cm signal during cosmic dawn, many high-redshift constraints are expected, and hence it is currently a scientific priority to ask the question: What is required to bridge the gap between cosmic dawn and reionization?

We here use a semi-analytical approach coupled with a Markov Chain Monte Carlo (MCMC) sampler to explore the range of scenarios and models that are mostly consistent with the combined constraints from cosmic dawn and reionization. Since all considered constraints are globally-averaged quantities, a semi-analytical approach is sufficiently accurate while also being much faster than using reionization simulations where numerical limitations in the resolution, box size, sub-grid physics, and radiation transport prescriptions complicate the interpretability and feasibility of parameter explorations (e.g. Mesinger, Furlanetto, and Cen, 2011; Hassan et al., 2017; Vogelsberger et al., 2020; Wu, McQuinn, and Eisenstein, 2021). To obtain insights on the role of faint and bright galaxies, we use a physically motivated source model for the ionization rate ( $R_{ion}$ ) that was derived from radiative transfer simulations (Finlator et al., 2015; Hassan et al., 2016).

This parameterization assumes a non-linear relation between the ionization rate and the halo mass  $R_{\rm ion} \propto M_h^{C+1}$ , where C = 0 corresponds to a linear relation, as is typically assumed in many semi-numerical models of reionization via the efficiency parameter (Mesinger, Furlanetto, and Cen, 2011). In addition to the C parameter, we aim to constrain the most debated parameter in reionization models, namely, the escape fraction of ionizing photons  $f_{\rm esc}$ . Harnessing the MCMC framework, our aim is to explore the joint  $C-f_{\rm esc}$  parameter space to determine the range of models that naturally reproduce the combined constraints from reionization and cosmic dawn. Finally, we aim to study the implications these constraints might have on galaxy evolution during these early formation epochs.

This chapter is organized as follows: we describe our empirical source model in section 5.1 and calibrate it to cosmic dawn (EDGES) constraints in section 5.2. We then constrain our model to several reionization observables in section 5.3. Further, we calibrate our source model jointly to both cosmic dawn and reionization in section 5.4. Finally, we summarise our findings in section 5.5.

#### 5.1 Source model

In this section, we discuss the details of the source model considered in this work. To study the role of different populations of galaxies, we consider a physically motivated source model that was derived in Hassan et al. (2016) from the radiative transfer simulations of reionization described in Finlator et al. (2018). In this model, the ionization rate  $R_{ion}$  is parameterized as a function of halo mass ( $M_h$ ) and redshift (z). The mass dependence of  $R_{ion}$  is analogous to the Schechter function, which can be characterized as a power law on the bright end and an exponential cut-off on the faint end. The redshift dependence follows a simple power law. This parameterization of  $R_{ion}$  accounts for the non-linear dependence on halo mass, which can be expressed as follows:

$$\frac{R_{\rm ion}}{M_h} = A \left(1+z\right)^D \left(\frac{M_h}{B}\right)^C \exp\left[-\left(\frac{M_h}{B}\right)^{-3}\right],\qquad(5.1)$$

where A, B, C, and D are free parameters, and their best-fit values were obtained by calibrating to radiative transfer simulations. We refer the reader to Hassan et al. (2016) for more details about the derivation of this model. We now discuss the physical meaning of these free parameters. Parameter A acts as an amplitude of  $R_{ion}$ , which scales the ionizing emissivity over the entire halo mass range at a given redshift by the same amount. Parameter B determines the minimum halo mass, which can be thought of as the quenching mass scale due to feedback from star formation and photoionization heating. Parameter C quantifies the slope of the  $R_{ion}-M_h$  relation, which controls the contribution of different mass scales to the total emissivity. Lastly, parameter D accounts for the redshift dependence of ionization rate for a given halo mass.

Having defined our source model  $R_{ion}$ , we adopt the Sheth and Tormen (1999b) halo mass function  $(\frac{d_n}{d_M})$ , which provides the number density of halos per unit halo mass, to compute the cosmic evolution of the global quantities governing reionization and comic dawn. In this work, we consider the halo mass range from  $10^5$  to  $10^{15}$  M<sub> $\odot$ </sub> to account for the contribution from all source populations including the most faint halos.

The most interesting parameters of this source model are the B and C parameters



Figure 5.1: **Top panel:** The ionization rates for different C values at  $z \sim 17$  (solid) and  $z \sim 6$  (dashed) while fixing other parameters to values of  $A = 10^{40} \,\mathrm{M}_{\odot}^{-1} \mathrm{s}^{-1}$ ,  $B = 10^8 \,\mathrm{M}_{\odot}$ , and D = 2.28 as derived from radiative transfer simulations (Hassan et al., 2016). This shows that positive and negative C correspond to higher ionization rate efficiencies from massive and low-mass halos, respectively. **Bottom panel:** The ionization rates multiplied by the Sheth–Tormen halo mass function for different values of B, while keeping the other parameters fixed at  $A = 10^{40} \,\mathrm{M}_{\odot}^{-1} \mathrm{s}^{-1}$ , C = -0.5, and D = 2.28. The B parameter represents the minimum halo mass  $(M_{h,\min})$  considered in the model.

since they allow us to draw conclusions about the role of different source populations during cosmic dawn and reionization. Therefore, we set the amplitude  $A = 10^{40} \,\mathrm{M}_{\odot}^{-1} \mathrm{s}^{-1}$ and redshift index D = 2.28, following the calibration to radiative transfer simulations (for more details see Hassan et al., 2016)<sup>†</sup> throughout. To illustrate how the source model parameters (B and C) affect the  $R_{\rm ion}-M_h$  relation, in Figure 5.1 we show several  $R_{\rm ion}$ models with different C and B values at cosmic dawn ( $z \sim 17$ , solid) and reionization  $(z \sim 6, \text{dashed})$ . As mentioned earlier, the C parameter (top panel) scales the ionization rate ( $R_{\rm ion})$  as a function of halo mass following  $R_{\rm ion}\,\propto\,M_h^{C+1}.$  In the top panel of Figure 5.1, C = 0 (red curves) corresponds to a linear relation. However, in the case of C = 2 (blue curves), the emissivity increases with halo mass and hence favors a relatively larger contribution from more massive halos than low-mass halos, and vice versa for the case of C = -2 (green curves), where reionization is dominated by lowmass halos. While this depends on the photon escape fraction, under the assumption of a mass-independent escape fraction, the intrinsic  $R_{\rm ion}$  increases by several orders of magnitude from low to high mass halos as seen in Figure 5.1. In the bottom panel, we show the impact of varying the *B* parameter, which sets the minimum halo mass scale.

# 5.2 Source model calibration to cosmic dawn (EDGES) constraints

As previously mentioned, our goal is to find the possible range of models that can reproduce the existing observational constraints during cosmic dawn and reionization. To do so, we first calibrate our source model parameters (C, B) to the intrinsic UV luminosity density ( $\rho_{\rm UV}$ ) inferred from the EDGES signal in the redshift range  $z \sim 5-20$ , where the function  $\log_{10}[\rho_{\rm UV}/(\text{erg s}^{-1} \text{ Mpc}^{-3} \text{ Hz}^{-1})] = (26.30 \pm 0.12) + (-0.130 \pm 0.018)(z-6)$ is the best fit as compiled by Madau (2018).

Using our source model, we compute the UV luminosity density as follows. First, the ionization rate  $R_{ion}$  (Equation 5.1) can be converted to a star-formation rate (SFR) by

<sup>&</sup>lt;sup>†</sup>We have varied the A and D parameters to reproduce several observations using MCMC and found similar values. Hence, fixing these parameters has a minimal impact on the presented results.



Figure 5.2: **Top panel:** Several posterior distributions derived using the UV luminosity density (Madau, 2018) including constraints for three different redshift ranges, namely z > 16 (representing cosmic dawn only, green), z < 10 (during reionization only, red), and  $z \sim 5$ –20 (cosmic dawn and reionization, by combining the full redshift range, blue). **Bottom panel:** Comparison between several UV luminosity densities calculated from  $R_{\text{ion}}$  with the inferred parameter values using MCMC. This figure indicates that fitting to z > 16 favors more negative C values, which implies stronger contributions from low-mass (faint) galaxies.

accounting for a stellar metallicity-dependent parameterization of the ionizing photon flux  $Q_{ion}$  following:

$$SFR = R_{ion}(M_h, z)/Q_{ion}(Z).$$
(5.2)

The sub-solar metallicity-dependent parameterization is provided by Finlator, Davé, and Özel (2011):

$$\log Q_{\rm ion}(Z) = 0.639(-\log Z)^{1/3} + 52.62 - 0.182, \qquad (5.3)$$

where  $Q_{ion}$  is in units of s<sup>-1</sup> (M<sub> $\odot$ </sub> yr<sup>-1</sup>)<sup>-1</sup>. This form of  $Q_{ion}$  is consistent with the equilibrium values measured by Schaerer (2003) assuming a Chabrier (2003) initial mass function (IMF). We also adopt the Madau and Fragos (2017) redshift evolution of the mass-weighted metallicity (Z) given by:

$$\log\left(Z/Z_{\odot}\right) = 0.153 - 0.074 \, z^{1.34} \,. \tag{5.4}$$

The SFR can then be written in terms of the UV luminosity density  $L_{\rm UV}$  (Kennicutt, 1998; Madau, Pozzetti, and Dickinson, 1998) as follows:

SFR[M<sub>☉</sub> yr<sup>-1</sup>] = 
$$1.25 \times 10^{-28} L_{\rm UV}$$
[ergs s<sup>-1</sup> Hz<sup>-1</sup>]. (5.5)

The global  $\rho_{\rm UV}$  is obtained by integrating  $\int L_{\rm UV} \frac{\mathrm{d}n}{\mathrm{d}m} \mathrm{d}m$  over the entire mass range at different redshifts.

We now constrain our source model parameters (B and C) to the Madau (2018) UV luminosity evolution using EMCEE, which is an affine-invariant ensemble sampler for MCMC (Foreman-Mackey et al., 2013). We assume a flat prior in the range:  $\log(B/M_{\odot}) \in$ [5, 10] and  $C \in [-5, 5]$ . Our task is to find the range of models that minimizes the following multivariate  $\chi^2$  distribution:

$$\chi^{2} \equiv \sum_{z} \frac{(\rho_{\rm UV,model}(z) - \rho_{\rm UV,obs}(z))^{2}}{2 \, (\sigma_{\rho_{\rm UV,obs}}(z))^{2}} \,.$$
(5.6)

In the top panel of Figure 5.2 we show several posterior distributions of the parameters B and C by considering different epochs, namely, cosmic dawn (z > 16, green),

Parameters	z > 16	z < 10	$z \sim 5 - 20$
$\log_{10} \mathbf{B}$	$6.34_{-0.80}^{+0.69}$	$8.49^{+0.16}_{-0.17}$	$7.67_{-0.15}^{+0.07}$
С	$-6.43^{+3.78}_{-9.0}$	$-0.11\substack{+0.04\\-0.05}$	$-0.34^{+0.03}_{-0.03}$

Table 5.1: Best-fit values of photon escape fraction ( $f_{esc}$ ) and power dependence on halo mass (C).

Note. – The other model parameters are fixed to values obtained by fitting to radiative transfer simulations ( $A = 10^{40} \,\mathrm{M_{\odot}^{-1} s^{-1}}$  and D = 2.28, see Hassan et al., 2016).

reionization (z<10, red), and the combination of cosmic dawn plus reionization ( $z\sim5-$ 20, blue). The dark and light shaded contours correspond to  $1\sigma$  and  $2\sigma$  levels, respectively. From the 1-dimensional probability distribution function (PDF) of the B parameter (i.e.  $M_{h,\min}$ ) it is clear that the minimum halo mass or the mass cut-off varies between  $\sim 10^{6-8} \,\mathrm{M_{\odot}}$ . It is also evident that calibrating the model to reproduce higher-z  $\rho_{\rm UV}$  constraints (z > 16) favors models with lower mass cut-offs ( $\sim 10^6 \,{\rm M_{\odot}}$ ) and vice versa. Likewise, a more negative C is preferred to match with higher-z constraints. As discussed before, the negative value of C and the low value of B both suggest that the low-mass (faint) halos play an important role in reproducing the extrapolated  $\rho_{\rm UV}$ constraints. Overall, using  $\rho_{\rm UV}$  measurements in the entire redshift range (z ~ 5–20) provides much tighter posterior contours than constraining to either z > 16 or z < 10. This is mainly due to the number of redshift bins used in each case. Since the time duration in the redshift range of z = 16-20 is shorter than that of z = 5-20 or z = 5-10, more redshift bins exist in the latter than the former, and hence more constraining power is expected. Each of the best-fit values with  $1\sigma$  errors is provided in Table 5.1 for the three scenarios. In the bottom panel of Figure 5.2, we compare the  $\rho_{\rm UV}$  evolution predictions from these three models with the Madau (2018)  $\rho_{\rm UV}$  evolution. Shaded areas

show the 1 $\sigma$  confidence levels which are obtained by translating the parameter 1 $\sigma$  levels from Table 5.1 into constraints on  $\rho_{\rm UV}$ . All models are within the 1 $\sigma$  level of the  $\rho_{\rm UV}$ constraints over the relevant redshift ranges. This figure clearly demonstrates that a stronger contribution from low-mass halos is required to reproduce the  $\rho_{\rm UV}$  constraints inferred from EDGES during cosmic dawn (green curve). This is in agreement with the picture that massive halos are rare and biased toward later formation times, whereas low-mass halos are predominant at these early epochs. This can be seen in the bottom panel of Figure 5.1, where the maximum halo mass during reionization (z = 6, dashed) is about 2 orders of magnitude higher than during cosmic dawn (z = 17, solid).

Since our aim is to bridge the gap between cosmic dawn and reionization, we will fix the B (i.e.  $M_{h,\min}$ ) parameter to the value obtained by calibrating the source model to the  $\rho_{\text{UV}}$  constraints over the entire redshift range (z = 5-20). Nevertheless, we will keep the halo mass power-law index parameter (C) as a free parameter to explore its correlations with the escape fraction of ionizing photons ( $f_{\text{esc}}$ ), and to test whether similar values can be derived by adding reionization constraints, which we discuss next.

### 5.3 Constraining the source model for key reionization observables

We consider three key reionization observables to place constraints on our source model parameters, namely the ionizing emissivity, IGM neutral fraction, and Thomson optical depth to the CMB. In addition to the halo mass power-law index parameter (C) we also vary the fraction of ionizing photons ( $f_{esc}$ ) that successfully escapes the remaining neutral hydrogen clumps and dust extinction in the interstellar medium (ISM) and circumgalactic medium (CGM) to contribute to the IGM ionization process. In this work, we assume a constant  $f_{esc}$  at all redshifts, since our  $R_{ion}$  function (Equation 5.1) already accounts for redshift and mass dependence. We assume a flat prior in the range:  $f_{esc} \in [0, 1]$ and  $C \in [-10, 10]$ , and combine different data using a multivariate Gaussian likelihood (similar to Equation 5.6).



Figure 5.3: Posterior distributions for the escape fraction of ionizing photons  $f_{\rm esc}$  and power-law index C as constrained by the ionizing emissivity ( $\dot{N}_{\rm ion}$ ; left), IGM neutral fraction ( $x_{\rm HI}$ ; right), and Thomson optical depth ( $\tau$ ; bottom). The orange line in each plot denotes the value of C parameter obtained in Table 5.1 for  $z \sim 5-20$ , for reference. The emissivity and optical depth do not provide tight constraints on our parameters, due to the large uncertainties. The IGM neutral fraction measurements provide tighter constraints on our parameters and favor models with low  $f_{\rm esc}$  and positive C values, suggesting that reionization is driven by massive (bright) galaxies.

#### 5.3.1 The ionizing emissivity, $\dot{N}_{ion}$

The integrated emission rate density of ionizing photons, or ionizing emissivity ( $N_{ion}$ ), is a measure of the total number of ionizing photons per second per volume that escape from all ionizing sources to the IGM. In our case, the ionizing emissivity is related to the ionization rate ( $R_{ion}$ ) as follows:

$$\dot{N}_{\rm ion}[{\rm s}^{-1}{\rm Mpc}^{-3}] = f_{\rm esc} \int R_{\rm ion}(M_h, z) \frac{{\rm d}n}{{\rm d}M_h} {\rm d}M_h , \qquad (5.7)$$

where  $\frac{d_n}{dM_h}$  is the Sheth and Tormen (1999b) differential halo mass function, which gives the number density of halos in the mass range of M and M + dM per unit comoving volume. We constrain our source model parameters (C,  $f_{esc}$ ) to the Becker and Bolton (2013) ionizing emissivity constraint at z = 4.75 of  $\log_{10}[\dot{N}_{ion}/(10^{51} \text{ photons s}^{-1} \text{ Mpc}^{-3})] = -0.014^{+0.454}_{-0.355}$ .

In the top panel of Figure 5.3, we show the  $f_{\rm esc}-C$  joint posterior distribution constrained to match the ionizing emissivity measurement. This shows that the  $\dot{N}_{\rm ion}$  measurement alone cannot place a tight constraint on these parameters due to the large uncertainty. However,  $\dot{N}_{\rm ion}$  data favors models with higher  $f_{\rm esc}$  and more negative C, leading to a stronger contribution from low-mass halos. Similar parameter constraints were found in our earlier work on calibrating semi-numerical simulations to reionization observables (Hassan et al., 2017). The best-fit value of C parameter obtained in the previous section for  $z \sim 5$ -20 is also within the  $1\sigma$  level as shown by orange horizontal line in Figure 5.3.

#### 5.3.2 The IGM neutral fraction, $x_{\rm HI}$

We compute the reionization history from our models as follows. The rate of change in the ionized fraction of intergalactic hydrogen ( $x_{HII}$ ) is given by (Madau, Haardt, and Rees, 1999),

$$\frac{\mathrm{d}x_{\mathrm{HII}}}{\mathrm{d}t} = \frac{\dot{N}_{\mathrm{ion}}}{\bar{n}_{\mathrm{H}}} - \frac{x_{\mathrm{HII}}}{\bar{t}_{\mathrm{rec}}} \,. \tag{5.8}$$

The first term describes the growth as a ratio between comoving ionizing emissivity  $(\dot{N}_{\rm ion})$  and volume-averaged comoving number density of intergalactic hydrogen  $\bar{n}_{\rm H}$ , which is given by

$$\bar{n}_{\rm H} = X \Omega_{b,0} \rho_{\rm crit,0} / m_{\rm H} \,. \tag{5.9}$$

Here, X is the cosmic hydrogen mass fraction (0.76),  $\rho_{\text{crit},0}$  is the present-day critical density, and  $m_{\text{H}}$  is the mass of a hydrogen atom. The second term models the sink of ionizing photons, where the recombination time-scale for the IGM is given by

$$t_{\rm rec} = \left[ C_{\rm HII} \alpha_{\rm A} (1 + Y/4X) \bar{n}_{\rm H} (1 + z)^3 \right]^{-1} \,. \tag{5.10}$$

Here,  $C_{\rm HII}$  is the redshift-dependent clumping factor, which we adopt from Pawlik, Schaye, and Dalla Vecchia (2015). This clumping factor accounts for the overall density fluctuations in ionized medium, which boosts recombination rate by a factor up to ~ 5 near the end of reionization, predominantly contributed by ionized medium in the vicinity of halos. The Y denotes the helium mass fraction (0.24) and  $\alpha_{\rm A}$  is the case A recombination coefficient ( $4.2 \times 10^{-13} \,{\rm cm}^3 \,{\rm s}^{-1}$ ), corresponding to a temperature of  $10^4 \,{\rm K}$ (Kaurov and Gnedin, 2014). Having computed the reionization history, we now constrain our source model parameters to the IGM neutral fraction measurements given in Table 5.2.

In the right panel of Figure 5.3, we show the parameter constraints given the above combination of IGM neutral fraction data. The  $x_{\rm HI}$  data provides the tightest constraints, with a clear tendency for the data to favor models with low  $f_{\rm esc}$  and positive C parameters. This implies that massive (bright) galaxies-dominated models are preferred. The low  $f_{\rm esc}$  value (1%) found here is a consequence of the non-linear relation between  $R_{\rm ion}$  and  $M_h^C$  through the C parameter, where an anti-correlation between  $f_{\rm esc}$  and C is observed. However, we find that the resulting C value is not within the range reported in Table 5.1, hence we combine different constraints in the next section to understand the degeneracy between  $f_{\rm esc}$  and C. Using the same source model in semi-numerical simulations of reionization, we have previously found that  $f_{\rm esc} = 4\%$  is sufficient to match the reionization observations (Hassan et al., 2016), which is still within the  $2\sigma$  level of

Redshift(z)	Constraints	Observables	References	
5.9	$\leq 0.06 \pm 0.05$	Ly- $\alpha$ and Ly- $\beta$ forest dark fraction	McGreer, Mesinger, and D'Odorico (2015)	
7.0	$0.59\substack{+0.11 \\ -0.15}$	Ly- $lpha$ EW distribution	Mason et al. (2018)	
7.09	$0.48\pm0.26$		Davies et al. (2018)	
7.5	$0.21\substack{+0.17 \\ -0.19}$	QSO damping wings	Greig, Mesinger, and Bañados (2019)	
7.54	$0.60^{+0.20}_{-0.23}$		Davies et al. (2018)	
7.6	$0.88^{+0.05}_{-0.10}$	Lyman-break galaxies emitting Ly- $\alpha$	Hoag et al. (2019)	

Table 5.2: IGM neutral hydrogen fraction measurements.

the current constraints based on updated observational data. We also find a lower  $f_{\rm esc}$  value since our current analysis includes contributions from the wider halo mass range of  $10^{5-15}$  M<sub> $\odot$ </sub> as opposed to  $10^{8-12}$  M<sub> $\odot$ </sub> in Hassan et al. (2016). Such low  $f_{\rm esc}$  values have been favored in several works (Gnedin, Kravtsov, and Chen, 2008; Wise et al., 2014; Ma et al., 2015; Carucci and Corasaniti, 2019; Rosdahl et al., 2022; Yeh et al., 2022). However, it is worth noting that in this work, we consider a constant  $f_{\rm esc}$ , and defer exploring the impact of assuming mass and/or redshift dependent  $f_{\rm esc}$  to future works.

#### 5.3.3 Thomson optical depth, $\tau$

The optical depth is a measure of the scattering of CMB photons by free electrons produced by reionization. Given a reionization history, it is straightforward to obtain the Thomson scattering optical depth ( $\tau$ ) as follows:

$$\tau = \int_0^\infty dz \frac{c(1+z)^2}{H(z)} x_{\rm HII}(z) \,\sigma_T \,\bar{n}_{\rm H} \left(1 + Y/4X\right),\tag{5.11}$$

where  $\sigma_T$  is the Thomson cross-section and c is the speed of light. This optical depth can also be used to constrain the timing of reionization, where lower/higher  $\tau$  corresponds

Parameters		Constraints	EoR	CD+ EoR	
	$\dot{N}_{\rm ion}(z=4.75)$	$x_{\rm HI}(z = 5.9 - 7.6)$	au	$\dot{N}_{\rm ion} + x_{\rm HI} + \tau$	$ \rho_{\rm UV} + \dot{N}_{\rm ion} + x_{\rm HI} + \tau $
$\mathbf{f}_{\mathrm{esc}}$	$0.68^{+0.23}_{-0.34}$	$0.01\substack{+0.02\\-0.01}$	$0.68^{+0.22}_{-0.33}$	$0.02\substack{+0.02 \\ -0.01}$	$0.36^{+0.02}_{-0.02}$
С	$-0.90\substack{+0.76\\-2.13}$	$0.73^{+0.22}_{-0.19}$	$-2.31^{+1.43}_{-3.06}$	$0.56\substack{+0.19 \\ -0.17}$	$-0.29^{+0.02}_{-0.02}$

Table 5.3: Best-fit values of photon escape fraction ( $f_{esc}$ ) and power dependence on halo mass (C).

Note. – The A and D parameters are fixed to values obtained by calibration to radiative transfer simulations ( $A = 10^{40} \,\mathrm{M_{\odot}^{-1} s^{-1}}$ , D = 2.28, see Hassan et al. 2016), and B to the derived value from fitting to  $\rho_{\rm UV}$  in the entire redshift range  $z \sim 5-20 \,(\log(B/\mathrm{M_{\odot}}) = 7.67)$ , see Table 5.1).

to later/earlier reionization redshifts, respectively.

In the bottom panel of Figure 5.3, we show the resulting posterior distribution of fitting to the measured value of  $\tau = 0.054 \pm 0.007$  from Planck Collaboration et al. (2020b). Similar to the case with  $\dot{N}_{\rm ion}$  (left panel),  $\tau$  alone does not place tight constraints on our parameters due to the large uncertainty that is consistent with a broad range of reionization histories. The tendency to favor models with high  $f_{\rm esc}$  and negative C is also seen. However, allowing much more negative C, as compared to values derived from  $\dot{N}_{\rm ion}$  data is suggesting that a stronger contribution from low-mass halos is needed to reproduce the Planck Collaboration et al. (2020b)  $\tau$  in our model. The constraints placed on the C parameter using  $\rho_{\rm UV}$  data for  $z \sim 5$ -20 is consistent with constraints obtained by calibrating to Planck Collaboration et al. (2020b)  $\tau$  at 1–2 $\sigma$  level as shown by orange horizontal line.



Figure 5.4: Comparison between the combined constraints from reionization, EoR  $(\dot{N}_{\rm ion}, x_{\rm HI}, \tau)$  in blue, and by adding cosmic dawn to reionization, CD ( $\rho_{\rm UV}$  from EDGES) + EoR ( $\dot{N}_{\rm ion}, x_{\rm HI}, \tau$ ) in red. The dark and light shaded contours correspond to the  $1\sigma$  and  $2\sigma$  levels, respectively. This demonstrates that adding cosmic dawn constraints shifts contours towards higher  $f_{\rm esc}$  and negative C parameters. This suggests that low-mass (faint) galaxies play a major role in bridging the gap between cosmic dawn and reionization.



Figure 5.5: **Upper:** Redshift evolution of the ionizing emissivity,  $N_{ion}$ , as predicted by our models, EoR (solid blue) and CD+EoR (solid red) along with the observational constraint by (Becker and Bolton, 2013). Dotted blue and red curves show the THESAN-HIGH and THESAN-LOW simulations, respectively. **Middle:** The neutral hydrogen fraction,  $x_{HI}$ , as compared to data listed in Section 5.3.2. **Lower:** The Thomson optical depth,  $\tau$ , as compared to the Planck Collaboration et al. (2020b) measurement (black line) with  $1\sigma$  uncertainty (grey shaded region). Massive galaxies-dominated models (blue) favor a gradually increasing emissivity which in turn produces a later onset of reionization, more sudden and shorter duration, and lower optical depth. Faint galaxies-dominated models (red) favor a nearly flat emissivity evolution with the opposite characteristics.

# 5.4 Constraining the source model to reionization and cosmic dawn

We now turn our attention to the main goal of this work, which is to determine the range of models that can successfully reproduce reionization and cosmic dawn constraints. For reionization, we consider all measurements, from the previous section, which include the  $\dot{N}_{\rm ion}$ ,  $x_{\rm HI}$ , and  $\tau$  data. As mentioned earlier, the only existing constraint during cosmic dawn comes from the EDGES detection at  $z \sim 17$ , from which Madau (2018) have been able to place constraints on the UV luminosity density  $\rho_{\rm UV}$  (see §5.2). We now constrain our source model to reionization only constraints ( $\dot{N}_{ion} + x_{HI} + \tau$ ), and combined reionization and cosmic dawn constraints ( $\dot{N}_{\rm ion}+x_{\rm HI}+\tau+\rho_{\rm UV}$  ). We refer to the former as  $EoR(\dot{N}_{ion} + x_{HI} + \tau)$ , and to the latter as CD(EDGES) +  $EoR(\dot{N}_{ion} + x_{HI} + \tau)$ . We compare the two resulting posterior distributions in Figure 5.4. Blue and red correspond to reionization only (EoR) and cosmic dawn plus reionization (CD+EoR), respectively. In both cases, combined observations place tight constraints on our parameters but in different parts of the parameter space. Comparing with Figure 5.3, the reionization combined observations (blue, EoR) are mainly driven by the reionization history measurements ( $x_{\rm HI}$ ). This shows that constraining to reionization observations favors models with low  $f_{\rm esc}$ and positive C, indicating that massive galaxies play a major role to drive reionization. On the other hand, constraining to both reionization and cosmic dawn observations (red, CD+EoR) favors models with high  $f_{esc}$  and negative C, suggesting that low-mass galaxies play a dominant role to bridge the gap between these two epochs. This is represented by the diagonal shift from the blue to red contours once the cosmic dawn constraint ( $\rho_{\rm UV}$ from EDGES) is added to the likelihood. All best-fit parameters and their  $1\sigma$  confidence intervals are listed in Table 5.3.

In Figure 5.5, we present predictions based on these best-fit parameters for the ionizing emissivity (top), reionization history (middle), and cumulative optical depth (bottom) from the EoR (blue) and CD+EoR (red) models. Shaded regions reflect the  $1\sigma$  uncertainty of the derived constraints (see Table 5.3). In each panel, we add the relevant observations used in the MCMC analysis. We then compare our predictions with results from the THESAN project (Kannan et al., 2022; Garaldi et al., 2022; Smith et al., 2022), which provides a suite of radiation-magneto-hydrodynamic simulations that self-consistently evolve reionization on large-scales ( $L_{\text{box}} = 95.5 \text{ cMpc}$ ) and resolve the majority of ionizing sources responsible for it ( $m_{\text{gas}} = 5.82 \times 10^5 \text{M}_{\odot}$ ) with galaxy formation physics based on the state-of-the-art IllustrisTNG model (Vogelsberger et al., 2014a; Vogelsberger et al., 2014b; Marinacci et al., 2018; Naiman et al., 2018; Nelson et al., 2018; Springel et al., 2018; Pillepich et al., 2018). Specifically, we compare with the THESAN-HIGH and THESAN-LOW simulation runs (dotted curves), where reionization is mainly driven by high-mass and low-mass galaxies, respectively.

In the upper panel of Figure 5.5, we compare our predictions for the ionizing emissivity evolution with the THESAN runs (based on the ray-tracing escape fraction calculations of Yeh et al., 2022) and Becker and Bolton (2013) measurements. Our models (EoR, CD+EoR) and the different THESAN runs are consistent within the 1–2 $\sigma$  levels of the observations. The emissivity evolution in the EoR model (blue) gradually increases towards decreasing redshifts as more massive halos form. This is a consequence of the positive C value inferred by reionization observations, which leads to stronger contributions from massive halos. On the other hand, the CD+EoR model (red) infers a negative C value, which gives more weight to the low-mass halos. This results in a higher  $N_{\rm ion}$ predicted by the CD+EoR model as compared to the EoR model predictions at high redshifts ( $z \gtrsim 10$ ). As more massive halos form at lower redshifts ( $z \lesssim 10$ ), the EoR model produces higher  $N_{\rm ion}$  than the CD+EoR model, where the emissivity in the latter starts to decrease due to the negative C value. This leads to a flatter emissivity evolution in the CD+EoR model (red). Besides observations, our different models produce emissivity histories that are consistent with model predictions from the THESAN simulations. Our EoR and CD+EoR models show similar emissivity evolution to the THESAN-HIGH and THESAN-LOW, respectively since the models share similar assumptions.

In the middle panel of Figure 5.5, we show a reionization history comparison be-

tween our models and the THESAN runs against observationally inferred measurements. As with the emissivity, we see similar reionization histories between EoR/CD+EoR models and THESAN-HIGH/THESAN-LOW simulations, respectively. Reionization begins earlier in faint galaxies-dominated models (CD+EoR, THESAN-LOW) than in bright galaxiesdominated models (EoR, THESAN-HIGH), since faint (bright) galaxies are predominant (rare) at high redshift. Reionization is also more gradual (longer duration) in faint galaxiesdominated models, whereas bright galaxies-dominated scenarios yield a more sudden (shorter duration) neutral-to-ionized transition of the Universe. This earlier onset of reionization in the CD+EoR and THESAN-LOW models translates to a higher cumulative optical depth, as seen in the bottom panel of Figure 5.5, that is consistent within the  $1-2\sigma$ levels of the Planck Collaboration et al. (2020b) measurements. On the other hand, the sudden (late) reionization history in the massive galaxies-dominated models (EoR and THESAN-HIGH) produces a lower optical depth that is also consistent with the  $1\sigma$  level of the data. In addition, our EoR model is in agreement with the late reionization models presented in Kulkarni et al. (2019), which reproduce the large-scale opacity fluctuations measurements (Becker et al., 2018).

To test whether our present models (EoR, EoR+CD) provide plausible predictions in terms of star formation, we calculate the star-formation efficiency,  $f_*$  using Equations 1 and 4 in Sun and Furlanetto (2016). In case of EoR model, we find that it is ~ 10% at  $M_{\rm h} = 10^9 \,\rm M_{\odot}$  and then increases with halo mass. On the contrary, the efficiency peaks at 1% for our CD+EoR model and then decreases with increasing halo mass as this model favors a greater contribution from faint galaxies. The  $f_*$  evolution at  $z \sim 8$ in Sun and Furlanetto (2016) lies between the predicted  $f_*$  in our models. We further compute the star-formation timescales ( $t_{\rm SF}$ ) in our models using the approximate relation, SFR =  $f_* \frac{\Omega_{\rm b}}{\Omega_{\rm m}} \frac{M_{\rm h}}{t_{\rm SF}}$ . We find that it increases/decreases with  $M_{\rm h}$  in the EoR/EoR+CD models, respectively. For both of our models, the average  $t_{\rm SF}$  is about ~ 1 Gyr, consistent with commonly assumed values in traditional star formation models (e.g. Springel and Hernquist, 2003). It is worth mentioning that our models are calibrated to the globally averaged quantities, and hence we do not expect our models to reproduce detailed instantaneous observables such as the star formation rate functions (SFRF) or UV luminosity functions (UVLF) at different redshifts. For instance, we find that our EoR (CD+EoR) model over (under) -produces the SFRF at  $z \sim 7$  and 8 as compared to Smit et al. (2012) star formation rate functions. However, our CD+EoR model which is calibrated to all observables is broadly in good agreement with the Madau and Dickinson (2014) cosmic star formation densities at low redshifts. As demonstrated by the CD+EoR model, it is entirely possible to reconcile the different observational constraints from the cosmic dawn to post-reionization using faint galaxies-dominated models of reionization, without the need to invoke new physics/exotic sources to explain the potential detection by EDGES.

#### 5.5 Summary

We have presented a detailed analysis to explore the conditions by which the controversial EDGES detection (Bowman et al., 2018b) is consistent with reionization and postreionization measurements including the ionizing emissivity ( $\dot{N}_{\rm ion}$ ), IGM neutral hydrogen fraction ( $x_{\rm HI}$ ), and Thomson optical depth ( $\tau$ ) measurements. To account for the EDGES detection during cosmic dawn, we use the inferred constraint on the UV luminosity density ( $\rho_{\rm UV}$ ) following Madau (2018), which is consistent with a simple extrapolation of deep Hubble Space Telescope (HST) observations of 4 < z < 9 galaxies.

Using a semi-analytical framework of reionization with a physically-motivated source model (Hassan et al., 2016) coupled with MCMC likelihood sampling, our key findings are as follows:

- Calibrating our source model  $R_{ion}$  to cosmic dawn constraints ( $\rho_{UV}$  from EDGES) favors models with negative C values. This indicates that a stronger contribution from low-mass (faint) galaxies is required to reproduce the inferred  $\rho_{UV}$  constraints from EDGES (see Figure 3.2 and Table 5.1).
- Constraining our source model  $R_{ion}$  to different reionization observables is mainly

driven by the IGM neutral fraction measurements where models with low  $f_{\rm esc}$  and positive C values are favored. This suggests that massive (bright) galaxies play the major role to drive reionization (see Figures 5.3 and 5.4 and Table 5.3).

- Further constraining our source model  $R_{\rm ion}$  to both reionization ( $N_{\rm ion} + x_{\rm HI} + \tau$ ) and the cosmic dawn constraint ( $\rho_{\rm UV}$  from EDGES) favors models with high  $f_{\rm esc}$ and negative C values. This implies that low-mass (faint) galaxies would play a crucial role to bridge the gap between cosmic dawn and reionization (see Figure 5.4 and Table 5.3).
- Massive (bright) galaxies-dominated models produce an increasing emissivity that results in a later onset of reionization, more sudden and shorter reionization duration, and lower optical depth (see Figure 5.5). Low-mass (faint) galaxies-dominated models result in a flatter emissivity evolution with the opposite reionization history characteristics.

It is worth mentioning several limitations to this work. First, the inferred  $\rho_{\rm UV}$  values from EDGES compiled by Madau (2018) do not take into account the depth nor shape of the detected profile, but rather the constraints are imposed by the required Wouthuysen-Field coupling strength on UV radiation backgrounds at the detection redshift. As mentioned in Madau (2018), accounting for the amplitude might require new physics, which in turn might alter our finding. We leave accounting for the whole properties of the detected profile to future works. Second, we use a linear relationship between SFR and  $L_{\rm UV}$  in the entire redshift range (z = 5-20), that has been derived from low redshift. This SFR- $L_{\rm UV}$  relation might not be linear at high redshift and assuming a different form might change our results quantitatively. Third, due to the high degeneracies between the  $R_{\rm ion}$  parameters, we have fixed the amplitude A and redshift dependence Dto values found in Hassan et al. (2016) by calibrating to radiative transfer simulations of reionization. We have checked the results when A is included as a free parameter, and found relatively the same value obtained in Hassan et al. (2016). The parameter D might not be the same at different redshifts due to evolution in galactic feedback. However, we have obtained our fit from radiative transfer simulations using data from z = 6-12, and it has been shown that the observed SFR function parameters show a weak dependence on redshift in Smit et al. (2012). Hence, we do not expect a qualitative change in our results if D is varied. Fourth, the quantitative results might be different if the A, B, and D parameters were fixed to different values. Nevertheless, the qualitative result (high/low redshift data prefers models with more negative/positive C and higher/lower  $f_{\rm esc}$ , respectively) would be similar. Fifth, our models have been adjusted to match the globally averaged quantities. As a result, we observe that the EoR and CD+EoR model overproduces and underproduces the observables, such as the star formation rate functions or UV luminosity functions respectively. We leave to future works to perform a detailed analysis to calibrate our models to all global and local quantities, including the SFRF and UVLF at different redshifts using the recently high redshift data by JWST and the previous HST low redshift data.

It is worth noting that calibrating our models to a different  $\tau$  value,  $\tau = 0.0627^{+0.0050}_{-0.0058}$ , as recently determined by de Belsunce et al. (2021), and to the updated measurements of  $\dot{N}_{\rm ion}$  by Becker et al. (2021), does not alter our findings. In summary, our results demonstrate that it is entirely possible to reproduce both cosmic dawn and reionization constraints with faint galaxies-dominated models without requiring new physics or exotic sources as our models with deduced parameters align well with the star formation efficiencies and time scales that have been reported in previous literature. Our results shed additional light on the roles of faint and bright galaxies during cosmic dawn and reionization, which can be tested by upcoming JWST surveys.