

Narrowing the discovery space of the cosmological 21-cm signal using multi-wavelength constraints

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ABSTRACT

The cosmic 21-cm signal is a promising probe of the early Universe, owing to its sensitivity to the thermal state of the neutral intergalactic medium (IGM) and properties of the first luminous sources. Here, we constrain the 21-cm signal and infer IGM properties using the Population II galaxy parameters derived in a previous study through multiwavelength synergies. This includes high-redshift UV luminosity functions (UVLFs) from *Hubble Space Telescope* (*HST*) and *James Webb Space Telescope* (*JWST*), cosmic X-ray and radio backgrounds (CXB and CRB), the SARAS 3 global 21-cm signal non-detection, and HERA 21-cm power spectrum upper limits. From CXB and HERA data, we infer the IGM kinetic temperature to be $T_K(z = 15) \lesssim 7.7$ K, 2.5 K $\lesssim T_K(z = 10) \lesssim 66$ K, and 20 K $\lesssim T_K(z = 6) \lesssim 2078$ K at 95 per cent credible interval. Similarly, CRB and HERA data limit the radio emission efficiency of galaxies, giving $T_{\text{rad}}(z = 15) \lesssim 47$ K, $T_{\text{rad}}(z = 10) \lesssim 51$ K, and $T_{\text{rad}}(z = 6) \lesssim 101$ K. These constraints, strengthened by UVLFs from *HST* and *JWST*, enable the first *lower bound* on the cosmic 21-cm signal. We infer an absorption trough of depth -201 mK $\lesssim T_{21,\text{min}} \lesssim -68$ mK at $z_{\text{min}} \approx 10$ –16, and a power spectrum of 8.7 mK² $\lesssim \Delta_{21}^2(z = 15) \lesssim 197$ mK² at $k = 0.35$ hMpc⁻¹. Our results highlight the power of multiwavelength synergies in constraining the early Universe. While promising for upcoming 21-cm experiments, the results depend on our assumption of a redshift-independent X-ray and radio efficiency of galaxies and on the exclusion of a flexible model for Population III stars.

Key words: galaxies: high-redshift – galaxies: star formation – (cosmology:) dark ages, reionization, first stars – (cosmology:) early Universe.

1 INTRODUCTION

The 21-cm signal, tracing the evolution of neutral hydrogen across cosmic time, has long been recognized as a promising probe of the early Universe since its earliest theoretical predictions (e.g. D. A. Varshalovich & V. K. Khersonskii 1977; C. J. Hogan & M. J. Rees 1979; D. Scott & M. J. Rees 1990; P. Madau, A. Meiksin & M. J. Rees 1997; P. Tozzi et al. 2000). The evolution of the global (sky-averaged) 21-cm signal is predicted to pass through distinct phases: an initial absorption trough due to collisional coupling in a cooling intergalactic medium (IGM) during the Dark Ages (e.g. P. Tozzi et al. 2000; A. Loeb & M. Zaldarriaga 2004); a deeper absorption feature driven by Lyman-alpha coupling (the Wouthuysen–Field effect; S. A. Wouthuysen 1952; G. B. Field 1958) during the Cosmic Dawn, sourced by early metal-free Population III stars (e.g. H. Yajima & S. Khochfar 2015; T. Gessey-Jones et al. 2022) or early Population II galaxies (e.g. X. Chen & J. Miralda-Escudé 2004; R. Barkana & A. Loeb 2005); weakening of the signal due to heating of the neutral

IGM by X-ray sources (e.g. J. R. Pritchard & S. R. Furlanetto 2007; X. Chen & J. Miralda-Escudé 2008); and eventual disappearance of neutral hydrogen driving the signal towards zero during the Epoch of Reionization (EoR; e.g. see reviews by S. R. Furlanetto, S. P. Oh & F. H. Briggs 2006; J. R. Pritchard & A. Loeb 2012; A. Mesinger 2019). However, the strength and timing of these phases are highly sensitive to the physical properties of the early Universe, and uncertainties in key parameters – such as the star formation efficiency (SFE), X-ray luminosity of high-redshift galaxies, and possible excess radio background, translate into a wide range of plausible 21-cm signal models.

The field has seen a rapid growth in the past decade, both on the theoretical and observational fronts. The reported EDGES detection of a deep absorption signal at $\nu \sim 78$ MHz (J. D. Bowman et al. 2018) spurred a large number of theoretical studies focused on understanding the implications of its unusual depth and spectral shape. Exotic dark matter (DM) models (R. Barkana 2018; A. Fialkov, R. Barkana & A. Cohen 2018; H. Liu & T. R. Slatyer 2018; J. B. Muñoz & A. Loeb 2018), superconducting cosmic strings (R. Brandenberger, B. Cyr & R. Shi 2019), or primordial black holes

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(S. J. Clark et al. 2018; A. Hektor et al. 2018; S. Mittal et al. 2022) have all been proposed to explain the signal, while conventional astrophysical models have invoked an enhanced radio background sources from galaxies (A. Ewall-Wice et al. 2018; C. Feng & G. Holder 2018; J. Mirocha & S. R. Furlanetto 2019; I. Reis, A. Fialkov & R. Barkana 2020). Meanwhile, a number of experiments are underway to verify the tentative detection¹ such as SARAS (S. Singh et al. 2022, which has refuted the EDGES observation based on independent observational data at 2σ confidence), REACH (E. Lera Acedo et al. 2022), MIST (R. A. Monsalve et al. 2024), RHINO (P. Bull et al. 2024), PRIZM (L. Philip et al. 2019), and others,² with many already deployed and collecting data. Alongside this, measurements of the 21-cm signal spatial fluctuations (power spectrum) are being attempted by a number of interferometric arrays. In particular, the strongest limits so far from recent observations by HERA (HERA Collaboration et al. 2023), LOFAR (R. Ghara et al. 2025; F. G. Mertens et al. 2025), and MWA (C. D. Nunhokee et al. 2025) have been able to place the first limits on the presence of a heated IGM at $z \lesssim 11$, while other observations continue to push the high-redshift frontier (e.g. NenuFAR; S. Munshi et al. 2025).

Meanwhile, the field of high-redshift galaxy formation has also seen a rapid growth, with the advent of the *James Webb Space Telescope* (*JWST*; J. P. Gardner et al. 2006) and its deep surveys. These surveys have revealed a wealth of information about the early Universe, including an abundance of bright galaxies at redshifts $z \gtrsim 10$ (e.g. D. Austin et al. 2023; M. Castellano et al. 2023; G. C. K. Leung et al. 2023; Y. Harikane et al. 2023a; S. L. Finkelstein et al. 2024; K. N. Hainline et al. 2024; B. Robertson et al. 2024; P. G. Pérez-González et al. 2025; L. Whitler et al. 2025), beyond what is expected from extrapolations of the UV luminosity functions (UVLFs) at lower redshifts. In order to resolve this apparent discrepancy, modifications to standard galaxy formation models have been suggested, including a top-heavy initial mass function of early stars (e.g. K. Inayoshi et al. 2022; Y.-Y. Wang et al. 2023; A. Trinca et al. 2024; A. Hutter et al. 2025), an increased SFE (e.g. A. Dekel et al. 2023; M. Boylan-Kolchin 2025; J. Dhandha et al. 2025; V. Mauerhofer et al. 2025; R. S. Somerville et al. 2025), or star formation variability/stochasticity (e.g. C. A. Mason, M. Trenti & T. Treu 2023; J. Mirocha & S. R. Furlanetto 2023; G. Sun et al. 2023b; A. Kravtsov & V. Belokurov 2024).

As we enter the era of next-generation telescopes with the Square Kilometer Array (L. Koopmans et al. 2015, aiming to directly probe neutral hydrogen during the EoR and Cosmic Dawn) and the Athena X-ray Observatory (K. Nandra et al. 2013, aiming to probe hot gas and X-ray populations at high- z), the synergy between multiwavelength observations and theoretical models is becoming increasingly important. Alongside this, advancements in Bayesian inference methods have made it possible to perform multidimensional, statistically rigorous inference of astrophysical parameters (e.g. D. Prelogović & A. Mesinger 2023; A. Saxena et al. 2023; D. Prelogović & A. Mesinger 2024), especially combining multiwavelength data (e.g. J. Mirocha & S. R. Furlanetto 2019; Y. Qin et al. 2020; A. Chatterjee, T. R. Choudhury & S. Mitra 2021; J. Dorigo Jones et al. 2023; D. Breitman et al. 2024; S. Pochinda

et al. 2024; P. H. Sims et al. 2025; O. Zvi Katz, D. Redigolo & T. Volansky 2025). In this work, we build on the simulations and Bayesian analysis performed in J. Dhandha et al. (2025), where we placed strong constraints on key astrophysical parameters of the early Universe such as the SFE of Pop II galaxies, and X-ray and radio emission efficiency of galaxies at $z \gtrsim 6$. We extend the analysis to infer the kinetic temperature and radio background temperature of the neutral IGM, and derive stringent limits on the 21-cm global signal and power spectrum within the context of our astrophysical model.

The paper is organized as follows. In Section 2, we describe the astrophysical model used in our simulations (Section 2.1), the five observables of interest that we calculate in the simulations (Section 2.2), the multiwavelength observational data used to constrain the models (Section 2.3), the Bayesian analysis framework used for inference (Section 2.4), and a summary of the astrophysical parameter constraints from J. Dhandha et al. (2025, Section 2.5). In Section 3, we present the results of our analysis, including the neutral IGM temperature (Section 3.1), and the 21-cm signal (Section 3.2). We discuss the model dependency and caveats of our work in Section 3.3, and finally conclude in Section 4.

2 METHODOLOGY

2.1 Astrophysical model

We use the seminumerical code 21cmSPACE (A. Fialkov et al. 2012, 2013; E. Visbal et al. 2012; A. Fialkov, R. Barkana & E. Visbal 2014)³ to generate 30 000 cosmological simulations of the early Universe. The simulations are described in detail in J. Dhandha et al. (2025), but we summarize the key aspects here. The simulations consist of periodic boxes of cosmological volume ($128 \times 3 \text{ cMpc}$)³, spanning the redshift range $z = 50$ to $z = 6$. Large-scale overdensity fields δ and baryon-DM streaming velocity v_{bc} (D. Tseliakhovich & C. Hirata 2010) are initialized using CAMB (A. Lewis & A. Challinor 2011) and evolved linearly through time, while the gas kinetic temperature T_K and ionized fraction x_e are initialized using RECFAST (S. Seager, D. D. Sasselov & D. Scott 2011) and evaluated at each time-step. DM haloes are modelled using the hybrid halo mass function (HMF) $dn(M_h, z|\delta, v_{bc})/dM_h$ of D. Tseliakhovich, R. Barkana & C. M. Hirata (2011) (see also R. Barkana & A. Loeb 2004). Star formation takes place in these haloes above the cooling threshold quantified by M_{crit} , which is affected by the minimum virial circular velocity for star formation V_c (free parameter), as well as v_{bc} suppression (A. Fialkov et al. 2012; J. B. Muñoz et al. 2022), inhomogeneous Lyman–Werner feedback (A. Fialkov et al. 2013; J. B. Muñoz et al. 2022) and photoheating feedback (E. Sobacchi & A. Mesinger 2013; A. Cohen, A. Fialkov & R. Barkana 2016). Star formation begins with a single burst of Pop III stars as haloes cross M_{crit} with an efficiency $f_{*,\text{III}}$, followed by a period of recovery due to supernovae feedback t_{delay} (M. Magg et al. 2022) that delays gas collapse into Pop II stars. As we focus on Pop II modelling in this work and J. Dhandha et al. (2025, but see Section 3.3.3 for more on this caveat), we fix these parameters to $f_{*,\text{III}} = 0.2$ per cent and $t_{\text{delay}} = 30 \text{ Myr}$, further assuming a log-flat IMF in the mass range $2\text{--}180 M_{\odot}$ (T. Gessey-Jones et al. 2022, 2025).

¹In addition to observational attempts, several papers have suggested potential instrumental systematics as the cause for the deep, flattened Gaussian signal (e.g. R. Hills et al. 2018; R. F. Bradley et al. 2019; S. Singh & R. Subrahmanyan 2019; P. H. Sims & J. C. Pober 2020).

²See github.com/JitenDhandha/21cmExperiments for a comprehensive list of 21-cm experiments.

³For a description of the code and relevant development papers, see cosmicdawnlab.com/21cmSPACE.

Pop II star formation proceeds with a halo-mass and redshift-dependent efficiency introduced in J. Dhandha et al. (2025):

$$f_{*,\text{II}}(\mathbf{x}, M_h, z) = \tilde{f}_{*,\text{II}} \begin{cases} 0 & M_h < M_{\text{crit}} \\ \frac{\log(M_h/M_{\text{crit}})}{\log(M_{\text{atm}}/M_{\text{crit}})} & M_{\text{crit}} \leq M_h < M_{\text{atm}} \\ 1 & M_{\text{atm}} \leq M_h < M_{\text{high}} \\ \left(\frac{M_h}{M_{\text{high}}}\right)^{\alpha_*} & M_{\text{high}} \leq M_h \end{cases} \quad (1)$$

where $M_{\text{atm}} \propto (1+z)^{-3/2}$ is the atomic cooling threshold, and the turning point $M_{\text{high}}(z)$ is defined as

$$M_{\text{high}}(z) = M_0 \left(\frac{1+z}{7}\right)^{-\beta_*}. \quad (2)$$

The turning point determines the transition between a constant SFE of low-mass haloes and a power-law SFE of high-mass haloes, and $\beta_* > 0$ captures an enhancement of the stellar mass fraction at high- z for a fixed halo mass M_h (see fig. 1 of J. Dhandha et al. 2025). The Pop II star formation is averaged over a time-scale of $t_{*,\text{II}} = 0.2H(z)^{-1}$, where $H(z)^{-1}$ is the Hubble time at redshift z (equation 1 in J. Dhandha et al. 2025) to get the Pop II star formation rate per halo ($\dot{M}_{*,\text{II}}$), or the HMF-integrated star formation rate density $\dot{\rho}_{*,\text{II}}(\mathbf{x}, z)$ in each cell. The fully flexible Pop II SFE is thus governed by four free parameters: $\tilde{f}_{*,\text{II}}$, M_0 , α_* , and β_* .

In order to model the radiative transfer from stellar/galactic sources, we calculate the specific emissivity $\epsilon(\mathbf{x}, \nu, z)$ in the Lyman band (responsible for the Ly α coupling of the 21-cm signal and Ly α heating; e.g. I. Reis, A. Fialkov & R. Barkana 2021), as well as X-ray and radio bands (described below). They are propagated throughout the simulation via window functions. Of particular interest in this work are the X-ray emissions, likely sourced by low-metallicity high-mass X-ray binaries (HMXBs) at high redshifts (e.g. T. Fragos et al. 2013b; B. D. Lehmer et al. 2016). We assume the X-ray luminosity per unit energy is proportional to the halo SFR as in local star-burst galaxies (e.g. H. J. Grimm, M. Gilfanov & R. Sunyaev 2003; B. D. Lehmer et al. 2010; S. Mineo, M. Gilfanov & R. Sunyaev 2012a; S. Mineo et al. 2014)⁴:

$$\frac{\hat{L}_X(E)}{\text{SFR}} = f_X \times (3 \times 10^{40} \text{ erg s}^{-1} \text{ M}_{\odot}^{-1} \text{ yr}) \hat{\epsilon}_X(E), \quad (3)$$

where $\hat{\epsilon}_X(E)$ is the X-ray SED (normalized to 1) from T. Fragos et al. (2013b, the mean model at $z = 15.34$ in the energy range 0.2–95 keV including interstellar absorption) in units of eV^{-1} . The luminosity normalization is chosen such that it matches the theoretical prediction for low-metallicity HMXBs (T. Fragos et al. 2013a, b; B. D. Lehmer et al. 2021). We further assume that Pop II and Pop III X-ray binaries have the same normalization, i.e. $f_X = f_{X,\text{II}} = f_{X,\text{III}}$ (varied as a free-parameter), as well as the same SED. Thus, the comoving X-ray emissivity can be calculated as $\epsilon_X(\mathbf{x}, E, z) = (\hat{L}_X(E)/\text{SFR}) \times \dot{\rho}_{*,\text{II+III}}(\mathbf{x}, z)$. The X-rays contribute to both heating, as well as ionization of the IGM (e.g. J. P. Ostriker & N. Y. Gnedin 1996; A. Venkatesan, M. L. Giroux & J. M. Shull 2001; J. R. Pritchard & S. R. Furlanetto 2007; M. McQuinn & R. M. O’Leary 2012).

Similar to the X-ray emissivity, we model the radio luminosity per unit frequency of galaxies at high- z as (G. Gürkan et al. 2018; J.

Mirocha & S. R. Furlanetto 2019; I. Reis et al. 2020):

$$\frac{L_r(\nu)}{\text{SFR}} = f_r \times (10^{22} \text{ W s}^{-1} \text{ Hz}^{-1} \text{ M}_{\odot}^{-1} \text{ yr}) \left(\frac{\nu}{150 \text{ MHz}}\right)^{-0.7}, \quad (4)$$

where the spectral index is typical for radio synchrotron emissions, and the normalization is with respect to present-day radio galaxies (M. J. Hardcastle et al. 2016; G. Gürkan et al. 2018). Like X-rays, we assume the same emission for both Pop II and Pop III stars, i.e. $f_r = f_{r,\text{II}} = f_{r,\text{III}}$ (and vary it as a free parameter).

The emissivities thus calculated are then used to determine the heating and ionization rates of the IGM. The evolution of the kinetic/matter temperature T_K is governed by the balance between heating and cooling processes (e.g. S. R. Furlanetto et al. 2006; A. Mesinger, S. Furlanetto & R. Cen 2011):

$$\frac{dT_K}{dz} = \frac{2T_K}{1+z} + \frac{2T_K}{3(1+\delta)} \frac{d\delta}{dz} - \frac{dx_e}{dz} \cdot \frac{T_K}{1+x_e} \quad (5)$$

$$- \frac{2}{3k_B(1+f_{\text{He}}+x_e)} (Q_X + Q_{\text{Compton}} + Q_{\text{Ly}\alpha}), \quad (6)$$

where f_{He} is the helium fraction, and x_e is the free electron fraction. In the above equation, the terms (from left to right) account for cooling due to Hubble/adiabatic expansion and structure formation, and heating due to change in number of ionized particles, X-rays (Q_X), Compton scattering (Q_{Compton}) and Ly α photons ($Q_{\text{Ly}\alpha}$, accounting for multiple scattering effects, I. Reis et al. 2021).

We compute the ionization by UV photons from galaxies and X-rays using the excursion set formalism commonly used in seminumerical simulations (S. R. Furlanetto, M. Zaldarriaga & L. Hernquist 2004). A region of the simulation is considered to be ionized if it satisfies

$$\exists R < R_{\text{mfp}}, \quad \text{s.t.} \quad \zeta_{\text{ion}} f_{\text{coll}}(\mathbf{x}, R) > 1 - x_{e,\text{oth}}(\mathbf{x}, R). \quad (7)$$

Here, ζ_{ion} is the ionization rate per baryon (varied as a free parameter), R_{mfp} is the maximum mean free path of ionizing photons (B. Greig & A. Mesinger 2015; A. Cohen et al. 2017) set to 50 cMpc (e.g. J. S. B. Wyithe & A. Loeb 2004; Y. Qin et al. 2021; Y. Zhu et al. 2023), and $f_{\text{coll}}(\mathbf{x}, R)$ is the fraction of baryons collapsed into galaxies averaged over a volume of radius R centred at \mathbf{x} . If the above criterion is not satisfied, the cell is considered to have a two-phase IGM with partial ionization. The ionizations from long range agents like X-rays are encapsulated in the final term:

$$\frac{dx_{e,\text{oth}}(\mathbf{x}, z)}{dz} = \frac{dt}{dz} [\Lambda_{\text{ion},X} - \alpha_B n_{\text{H}}(\mathbf{x}) x_{e,\text{oth}}^2], \quad (8)$$

where $\Lambda_{\text{ion},X}$ is the X-ray ionization rate per baryon, α_B is the case-B recombination coefficient, and $n_{\text{H}}(\mathbf{x})$ is the large-scale hydrogen number density. The neutral fraction is then given by $x_{\text{HI}}(\mathbf{x}) = 1 - x_e = 1 - \zeta_{\text{ion}} f_{\text{coll}}(\mathbf{x}) - x_{e,\text{oth}}(\mathbf{x})$.

The astrophysical model described in this section thus consists of eight free parameters, listed in Table 1. The priors are chosen to be broad enough to cover the range of astrophysical models that can be expected at high- z , while also being physically motivated (e.g. a V_c of 4.2 km s^{-1} corresponds to the molecular cooling threshold). Furthermore, in place of ζ_{ion} , we use τ_{CMB} (which is calculated in post processing) to quantify the reionization history and directly sample this derived parameter in our Bayesian analysis (following previous works, e.g. H. T. J. Bevins et al. 2024; S. Pochinda et al. 2024).

2.2 Observables of interest

The 21-cm signal is sensitive to the astrophysical processes described above, and can be quantified through the sky-averaged global signal $T_{21}(z)$, or the power spectrum $\Delta_{21}^2(k, z)$. The strength of the signal is

⁴The bolometric luminosity per star formation rate (L_X/SFR) often used in literature is just the integrated luminosity over the X-ray SED, i.e. $\int \hat{L}_X(E)/\text{SFR} dE$.

Table 1. Astrophysical parameter priors used in J. Dhandha et al. (2025) and this work. The parameters $\{V_c, \tilde{f}_{\star, \text{II}}, M_0, \alpha_\star, \beta_\star\}$ describe the star-forming properties of early galaxies, while $\{\tau_{\text{CMB}}, f_X, f_r\}$ describe their radiative properties (in particular, their ionizing, X-ray, and radio emission efficiencies). We use the derived parameter τ_{CMB} instead of ζ_{ion} to quantify the reionization history, allowing us to use *Planck 2018* constraints on the optical depth as our prior, and allow for a wide prior to remain agnostic to early/late reionization scenarios (e.g. S. Asthana et al. 2024; W. Elbers 2025).

Parameter	Prior	Minimum	Maximum
V_c	Log-uniform	4.2 km s ⁻¹	100 km s ⁻¹
$\tilde{f}_{\star, \text{II}}$	Log-uniform	10 ⁻⁴	10 ^{-0.3}
M_0	Log-uniform	2 × 10 ⁸ M _⊙	10 ¹¹ M _⊙
α_\star	Uniform	0	2
β_\star	Uniform	0	5
τ_{CMB}	Uniform	0.033	0.075
f_X	Log-uniform	10 ⁻³	10 ³
f_r	Log-uniform	10 ⁻¹	10 ⁵

given by the differential brightness temperature (e.g. P. Madau et al. 1997; S. R. Furlanetto et al. 2006; J. R. Pritchard & A. Loeb 2012):

$$T_{21}(\mathbf{x}, z) = (1 - e^{-\tau_{21}(\mathbf{x}, z)}) \frac{T_S(\mathbf{x}, z) - T_{\text{rad}}(\mathbf{x}, z)}{1 + z}, \quad (9)$$

where τ_{21} is the 21-cm radiation optical depth, T_S is the spin temperature, and T_{rad} is the radio background temperature at the rest-frame 21-cm wavelength at redshift z . In regions of the Universe where $T_S > T_{\text{rad}}$, the signal is seen in emission (and in absorption otherwise). The spin temperature T_S is given by the balance between collisional and radiative processes, and is defined as

$$T_S(z)^{-1} = \frac{x_{\text{rad}} T_{\text{rad}}^{-1} + x_\alpha T_C^{-1} + x_c T_K^{-1}}{x_{\text{rad}} + x_\alpha + x_c}, \quad (10)$$

where we have suppressed the spatial dependence in the equation for brevity. The terms x_{rad} ⁵, x_α and x_c are the relative coupling strengths to the CMB, Ly α background via the Wouthuysen-Field coupling mechanism (S. A. Wouthuysen 1952; G. B. Field 1958), and collisional processes, respectively (e.g. E. M. Purcell & G. B. Field 1956; B. Zygelman 2005).

Averaging over the sky at a particular frequency (or in case of simulations, the brightness temperature field at a particular redshift) gives us the global signal:

$$T_{21}(z) = \langle T_{21}(\mathbf{x}, z) \rangle_x. \quad (11)$$

On the other hand, the power spectrum $P_{21}(k, z)$, which quantifies the spatial fluctuations of the brightness temperature field, is defined as

$$\langle \tilde{T}_{21}(\mathbf{k}, z) \tilde{T}_{21}^*(\mathbf{k}', z) \rangle = (2\pi)^3 \delta^D(\mathbf{k} - \mathbf{k}') P_{21}(k, z). \quad (12)$$

where $\tilde{T}_{21}(\mathbf{k}, z)$ is the Fourier transform of $T_{21}(\mathbf{x}, z)$. For consistency with other works, we define the dimensionless power spectrum:

$$\Delta_{21}^2(k, z) = (k^3/2\pi^2) P_{21}(k, z) \quad (13)$$

to quantify the spatial fluctuations of the 21-cm signal in this work.

Due to the versatile nature of the 21-cm signal and its sensitivity to the astrophysical processes described above, it can be used in conjunction with other observables of the early Universe. The diffuse X-ray background and radio background seen today are complementary probes setting upper limits on radiative efficiencies

of galaxies at high- z (A. Fialkov et al. 2017; J. Mirocha et al. 2025). Following previous works (e.g. S. Pochinda et al. 2024; J. Dhandha et al. 2025), we define the present-day angle-averaged X-ray specific intensity from sources at $z > 6$ as (e.g. J. R. Pritchard & S. R. Furlanetto 2007):

$$J_X(E, z = 0) = \frac{1}{4\pi} \int_{z'=6}^{\infty} \epsilon_X(E', z') e^{-\tau_X(E', z')} \left| \frac{cdt}{dz'} \right| dz', \quad (14)$$

where $E' = E(1 + z')$ is the energy at emission redshift z' , $\epsilon_X(E', z')$ is the comoving X-ray emissivity defined in the previous section (but averaged across the simulation box), and $\tau_X(E', z')$ is the X-ray optical depth. We can further define the integrated intensity in an energy band E_{band} as:

$$S_X(E_{\text{band}}) = \int_{E_{\text{band}}} J_X(E, z = 0) dE \quad (15)$$

for direct comparison with broad-band Chandra (and other) X-ray observations. Similarly, we define the radio background temperature seen today as (e.g. A. Ewall-Wice, T.-C. Chang & T. J. W. Lazio 2020; I. Reis et al. 2020)⁶:

$$T_{\text{rad}}(\nu, z = 0) = T_{\text{CMB}} + \frac{c^2}{2k_B \nu^2 4\pi} \int_{z'=6}^{\infty} \epsilon_r(\nu', z') \left| \frac{cdt}{dz'} \right| dz', \quad (16)$$

where the second term accounts for the present-day angle-averaged radio specific intensity from sources at $z' > 6$, and $\nu' = (1 + z')$ is the frequency at emission redshift z' , and radio photons are assumed to be free-streaming (i.e. negligible absorption or scattering since the optical depth is $\ll 1$). Observations of radio excess at < 10 GHz (e.g. D. J. Fixsen et al. 2011; J. Dowell et al. 2017) can help constrain the radio emissivity of galaxies at high- z , by setting upper limits on their contribution to the radio background observed today.

In J. Dhandha et al. (2025), UVLFs were introduced as a new output in 21CMSPACE to derive constrain on the SFE of high-redshift galaxies using *Hubble Space Telescope* (*HST*) and *JWST* observations. The UVLF measures the number density of galaxies per unit magnitude in the ultraviolet band, defined as $\lambda_{\text{UV}} \equiv 1500 \text{ \AA} \pm 50 \text{ \AA}$. In order to model the UVLF, we employ a framework that uses the hybrid HMF described in Section 2.1 (e.g. J. Park et al. 2019):

$$\Phi(\mathbf{x}, M_{\text{UV}}, z) = (1 + \delta(\mathbf{x})) \frac{dn(\mathbf{x}, M_h, z)}{dM_h} \left| \frac{M_h}{M_{\text{UV}}} \right|, \quad (17)$$

where the $(1 + \delta)$ factor accounts for the conversion of the HMF from Lagrangian space to Eulerian space (see, e.g. A. Mesinger et al. 2011; D. Tselikhovich et al. 2011; J. B. Muñoz 2023). To evaluate the final term in the above equation, we map the host halo mass M_h to the UV magnitude M_{UV} of the galaxy contained within, using the SFR–UV relation:

$$\dot{M}_{\star, \text{II}}(\mathbf{x}, M_h, z) = \kappa_{\text{UV}} \times L_{\text{UV}}(\mathbf{x}, M_h, z), \quad (18)$$

where $\kappa_{\text{UV}} = 1.15 \times 10^{-28} \text{ M}_\odot \text{ yr}^{-1} \text{ erg}^{-1} \text{ s}^{-1} \text{ Hz}$ (P. Madau & M. Dickinson 2014). This value assumes a continuous star formation history and a Salpeter IMF spanning the mass range 1–100 M_⊙. In the early Universe, the UV luminosity may be dominated by a stellar population that is strongly metallicity dependent or top-heavy in stellar mass (e.g. R. S. Klessen & S. C. O. Glover 2023). We use the above κ_{UV} for consistency with other works in the literature, and leave a self-consistent, spatially varying and time-evolving Pop II spectra

⁶Note that in the absence of an explicit ν variable, $T_{\text{rad}} = T_{\text{rad}}(\nu_{21}, z)$, the radio temperature at the rest-frame 21-cm wavelength at a given redshift, as used in equation (9) and for the rest of the paper.

⁵We assume $x_{\text{rad}} = (1 - e^{-\tau_{21}})/\tau_{21} \approx 1$ in this work, which is valid in the optically thin limit $\tau_{21} \rightarrow 0$ at the redshifts of interest.

Table 2. Summary of the datasets used in J. Dhandha et al. (2025) and this work, and their different combinations for joint analysis. The first five rows show individual datasets (in case of CXB and CRB, the UVLF is included as explained in Section 2.4), while the latter four rows show the joint analysis cases. The ‘Joint w/o UVLF’ is similar to the analysis in S. Pochinda et al. (2024), although we use a different SFE model and exclude Pop III free parameters. This case is included to show the importance of the UVLFs in early Universe constraints, as demonstrated in J. Dhandha et al. (2025). The ‘Joint w/o high- z UVLF’ case is useful to assess how our knowledge of the 21-cm signal has changed with the advent of *JWST* observations (i.e. how *HST*-inferred fixed SFE models change our conclusions). Finally, since the SARAS 3 data includes nuisance parameters to subtract the radio foregrounds (that we marginalize over in our results), we also show a ‘Joint w/o SARAS 3’ case to allow for the case that the foreground fit is inaccurate.

Fit type	21-cm global signal	21-cm power spectra	UVLFs		Cosmic X-ray bg.	Cosmic radio bg.
	(SARAS 3, 2022)	(HERA, 2023)	$z \leq 10$ (<i>HST</i> ; B21) [†]	$z > 10$ (<i>JWST</i> ; D24)	(Chandra + others)	(LWA1 + others)
UVLF			✓	✓		
UVLF + CXB			✓	✓	✓	
UVLF + CRB			✓	✓		✓
HERA		✓				
SARAS 3	✓					
Joint w/o UVLF	✓	✓			✓	✓
Joint w/o high- z UVLF	✓	✓	✓		✓	✓
Joint w/o SARAS 3		✓	✓	✓	✓	✓
Joint	✓	✓	✓	✓	✓	✓

Note. [†] Technically, the $z \leq 10$ UVLFs contain both *HST* determinations from B21 at $z = 6-9$ and *JWST* determinations from D24 at $z = 9, 10$, but we refer to it as ‘*HST*’ for simplicity. The data in this redshift range prefers a redshift-independent SFE, which is consistent with pre-*JWST* findings of constant SFE models.

calculation to future work. However, we do include an analytic dust model to correct for the attenuation of the UV luminosity, which is expected to be crucial at $z \lesssim 10$ where *HST* data is strongest. The dust distribution across galaxies can be quantified using their UV spectral slope β as a proxy (e.g. infrared excess and β relation of G. R. Meurer, T. M. Heckman & D. Calzetti 1999), which depends on the intrinsic UV luminosity of the galaxy as well as the redshift. Here, we use the $\beta(M_{\text{UV}}^{\text{dust}}, z)$ fit from R. J. Zhao & S. R. Furlanetto (2024) which combines observations from *HST* (R. J. Bouwens et al. 2014) and *JWST* (M. W. Topping et al. 2024), making it applicable across a wide redshift range. The dust attenuation can thus be thought as mapping $M_{\text{UV}}^{\text{dust-free}}(z) \rightarrow M_{\text{UV}}^{\text{dust}}(M_{\text{UV}}^{\text{dust-free}}, z)$. In this calibration, the attenuation is negligible at $z \gtrsim 10$ and for faint galaxies that are insufficiently dust-rich. The above calculations are performed in each pixel to get the UVLF at 3 cMpc scale, and then averaged across the simulation volume to capture the statistics of large-scale surveys.

2.3 Observational datasets

Having computed the astrophysical observables of interest, we now describe the data used in our joint analysis. We use five observational datasets, following the analysis in S. Pochinda et al. (2024) and J. Dhandha et al. (2025), as summarized below.

(i) **21-cm global signal non detection** from SARAS 3: We use global sky temperature measurements from SARAS 3 (T. Jishnu Nambissan et al. 2021; S. Singh et al. 2022) to constrain the global 21-cm signal directly, in the redshift range $z \approx 15-25$ (or $\nu \approx 55-85$ MHz). The data consists of 15 hours of observations from its deployment in southern India, and is calibrated to remove any radio-frequency interference, receiver systematics, and environmental thermal emissions. We fit the data with a 6th order log-log polynomial as the Galactic and extragalactic foreground model:

$$\log_{10}(T_{\text{fg}}(\nu)/\text{K}) = \sum_{i=0}^6 a_i [\mathcal{f}_{\text{N}}(\log_{10}(\nu/\text{MHz}))]^i \quad (19)$$

and a thermal noise term as done in previous works (e.g. H. T. J. Bevens et al. 2022; S. Singh et al. 2022; H. T. J. Bevens et al. 2024). In the above equation, \mathcal{f}_{N} is a function that normalizes the log-frequency

to the range $[-1, 1]$. We marginalize over the foreground + noise parameters in our Bayesian analysis (e.g. H. T. J. Bevens et al. 2024; T. Gessey-Jones et al. 2024; S. Pochinda et al. 2024) when discussing constraints on the astrophysical parameters. The residuals, although quite sensitive to the foreground fit, are generally of the order of $\sim 200-300$ mK.

(ii) **21-cm power spectrum upper limits** from HERA Phase 1: In addition to the global signal, we use 21-cm power spectrum limits from HERA Phase 1 observations (HERA Collaboration et al. 2023). These are the most stringent upper limits to date—using data from 94 nights of observations with 34–41 antennas—at redshifts $z \approx 7.9$ and $z \approx 10.4$ in the wavevector range $k \approx 0.2-0.4 \text{ h Mpc}^{-1}$. We use the frequency bands least contaminated by RFI (Band 1 in Field D, and Band 2 in Field C) and decimate neighbouring k -bins to remove correlations. Since foreground avoidance is employed, only residual systematics need to be marginalised over, which we do using the likelihood function from HERA Collaboration et al. (2023).

(iii) **Cosmic X-ray background (CXB)**: The diffuse X-ray background is expected to contain contributions from unresolved faint point sources such as AGN and galaxies, diffuse emission from the hot IGM, as well as redshifted emission from unresolved X-ray binaries in the early Universe—the latter being the focus of this study. We use CXB flux measurements from Chandra (R. C. Hickox & M. Markevitch 2006) and the collated data from Table 1 of F. A. Harrison et al. (2016). This includes measurements from HEAO (F. E. Marshall et al. 1980; D. E. Gruber et al. 1999), BeppoSAX (F. Frontera et al. 2007), INTEGRAL (E. Churazov et al. 2007) and Swift BAT (M. Ajello et al. 2008).

(iv) **Cosmic radio background (CRB)**: Similar to the CXB, the unresolved diffuse radio background (after removal of Galactic foregrounds and CMB) is expected to contain contributions from unresolved radio galaxies at low and high- z . We use the CRB data collated in Table 2 of J. Dowell & G. B. Taylor (2018), which includes measurements from LWA1 Low Frequency Sky Survey (40–80 MHz; J. Dowell et al. 2017), ARACDE2 (3–11 GHz; D. J. Fixsen et al. 2011), and other single frequency experiments at 22 MHz (R. S. Roger et al. 1999), 46 MHz (H. Alvarez et al. 1997; K. Maeda et al. 1999), 408 MHz (C. G. T. Haslam et al. 1982; M.

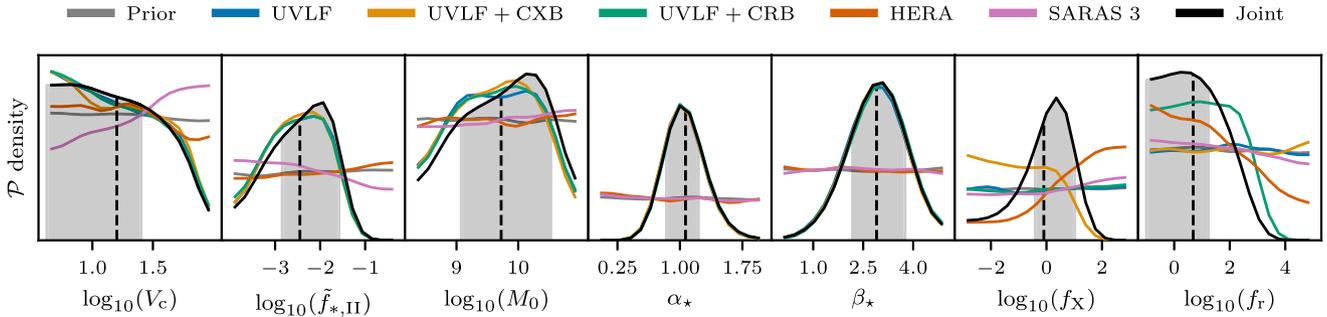


Figure 1. 1D marginal posterior probability distributions (PDFs) of the seven astrophysical parameters (marginalizing over τ_{CMB} since it remains prior-dominated) from the individual and joint analysis. The constraints shown here are the same as in J. Dhandha et al. (2025), except for the case of CXB + UVLF and CRB + UVLF which are new to this work. In case of α_* and β_* , all data sets containing UVLF lie on top of each other. The vertical black dashed line and grey shaded region show the weighted posterior mean and the 68 per cent credible interval (CI), respectively, for the joint analysis. For the special cases of the joint analysis, see Fig. A1.

Remazeilles et al. 2015), and 1420 MHz (P. Reich, J. C. Testori & W. Reich 2001).

(v) **UVLFs from *HST/JWST*:** We use multifield *HST* derived UVLF determinations from R. J. Bouwens et al. (2021, see their Table 4) in the redshift range $z = 6 - 9$, and *JWST* derived UVLFs from C. T. Donnan et al. (2024, see their Table 2) in the redshift range $z = 9 - 14.5$. The former contains 1946 sources from HUDF/XDF and parallel fields, BORG/HIPPIES, five CANDELS fields, HFF and parallel fields, and observations from the ERS program (see their Table 1). The latter contains 2548 sources from PRIMER, NGDEEP and JADES fields. We do not use more datasets at high- z to minimize source-overlap (which would artificially shrink error bars) and to avoid systematic differences between analysis pipelines. Nonetheless, C. T. Donnan et al. (2024) is broadly consistent with other *JWST*-based UVLF measurements (e.g. G. C. K. Leung et al. 2023; P. G. Pérez-González et al. 2023; N. J. Adams et al. 2024; D. J. McLeod et al. 2024; B. Robertson et al. 2024), lending further confidence to their findings and our results.

(vi) **CMB optical depth (τ_{CMB}) from *Planck 2018*:** We indirectly use the CMB optical depth as a constraint by adopting a uniform prior on the reionization history of 3σ around the measured *Planck 2018* value of $\tau_{\text{CMB}} = 0.054 \pm 0.07$ (Planck Collaboration VI 2020), i.e. $\tau_{\text{CMB}} \in [0.033, 0.075]$ as shown in Table 1. This ensures that our reionization histories are not too extreme, while also allowing for a wide range of astrophysical models.

2.4 Joint Bayesian analysis

In order to derive the constraints on the astrophysical parameters described in Section 2.1 using our collection of observational datasets, we use the Bayesian nested-sampling package POLYCHORD (W. J. Handley, M. P. Hobson & A. N. Lasenby 2015a, b). Under the Bayesian statistical framework, we define a likelihood function for each observable such that $\mathcal{L}(\theta) = P(\mathcal{D}|\theta)$ is the probability of the data \mathcal{D} given the parameters θ . This can then be combined with a *prior* probability distribution $\pi(\theta)$ to obtain the *posterior* distribution $\mathcal{P}(\theta) = P(\theta|\mathcal{D})$:

$$\mathcal{P}(\theta) = \frac{\mathcal{L}(\theta)\pi(\theta)}{\mathcal{Z}}, \quad (20)$$

where $\mathcal{Z} = P(\mathcal{D}) = \int \mathcal{L}(\theta)\pi(\theta)d\theta$ is the Bayesian evidence. The Bayesian inference allows us to marginalize over nuisance parameters (e.g. SARAS 3 foreground parameters), and obtain posterior

distributions for the astrophysical parameters of interest. Furthermore, assuming statistical independence of the observables, we can write the joint likelihood as a product of all the individual likelihoods:

$$\mathcal{L}_{\text{Joint}} = \mathcal{L}_{\text{SARAS 3}} \times \mathcal{L}_{\text{HERA}} \times \mathcal{L}_{\text{CXB}} \times \mathcal{L}_{\text{CRB}} \times \mathcal{L}_{\text{UVLF}}. \quad (21)$$

or a subsets of these, depending on the analysis. We use upper limit likelihoods for the CXB, CRB and HERA datasets (e.g. see Appendix A of W. Li et al. 2019), a Gaussian likelihood for SARAS 3 including a noise term σ_{S3} , and a two-piece Gaussian likelihood for the UVLF data to account for asymmetric errors (see J. Dhandha et al. 2025, for more details). All likelihoods include uncertainties on the data, as well as on our model predictions (a 20 per cent error floor on simulation accuracy + additional emulator errors).

2.5 Astrophysical constraints from J. Dhandha et al. (2025)

We use the nested sampling runs from J. Dhandha et al. (2025) for the most part. They were performed by training neural network emulators on the observables of interest output by 21CMSPACE⁷, and then efficiently sampling the parameter space using POLYCHORD. However, the case CXB and CRB datasets are different, since we also include UVLF data for both. The diffuse X-ray and radio backgrounds are sensitive to the SFR of galaxies (i.e. $\propto \text{SFR} \times f_{\text{X}}$ and $\text{SFR} \times f_{\text{r}}$), and the UVLF data breaks the degeneracy between the SFE, and f_{X} or f_{r} , anchoring the former to observationally determined values. This yields more accurate constraints on f_{X} and f_{r} compared to previous works like S. Pochinda et al. (2024) and T. Gessey-Jones et al. (2024) that do not use UVLFs, and is one of the main results in J. Dhandha et al. 2025 (see also Y. Qin et al. 2020; J. Dorigo Jones et al. 2023, who arrive at a similar conclusion).

Table 2 summarizes the combinations of data sets used in this work, and Fig. 1 shows the corresponding 1D marginal posterior probability distributions (PDFs) for the minimum virial circular velocity for star formation in DM haloes V_c , SFE parameters $\tilde{f}_{*,\text{II}}$, M_0 , α_* , β_* , and the X-ray and radio emission efficiencies f_{X} and f_{r} . A similar plot for the special cases of the joint analysis is shown in Fig. A1 to assess how sensitive our constraints are to the inclusion of *JWST* data or to the SARAS 3 foreground fit. Since we use the joint constraints from J. Dhandha et al. (2025) to derive IGM properties and the 21-cm

⁷Each simulation takes roughly $\sim 2-4$ h while emulators can evaluate an observable on the order of 1–10 ms (e.g. H. T. J. Bevins et al. 2021).

Table 3. Joint constraints from J. Dhandha et al. (2025) on the seven astrophysical parameters $\{V_c, \tilde{f}_{\star, \text{II}}, M_0, \alpha_{\star}, \beta_{\star}, f_X, f_r\}$ using all the observational datasets, shown here for ease of reference. The errors are quoted at 68 per cent (95 per cent) CI. around the weighted mean.

Parameter	Constraint
$\log_{10}(V_c/\text{km/s})$ $\Rightarrow V_c$ (km/s)	$\lesssim 1.40$ (1.79) $\gtrsim 25.2$ (62.0)
$\log_{10}(\tilde{f}_{\star, \text{II}})$	$-2.4^{+0.9}_{-0.4}$ $\left(\begin{smallmatrix} +1.0 \\ -1.2 \end{smallmatrix}\right)$
$\log_{10}(M_0/M_{\odot})$	$9.7^{+0.8}_{-0.6}$ $\left(\begin{smallmatrix} +1.1 \\ -1.2 \end{smallmatrix}\right)$
α_{\star}	$1.1^{+0.2}_{-0.2}$ $\left(\begin{smallmatrix} +0.4 \\ -0.4 \end{smallmatrix}\right)$
β_{\star}	$2.9^{+0.9}_{-0.7}$ $\left(\begin{smallmatrix} +1.5 \\ -1.6 \end{smallmatrix}\right)$
$\log_{10}(f_X)$ $\Rightarrow \log_{10}(L_X/\text{SFR}/\text{erg s}^{-1} M_{\odot}^{-1} \text{ yr})$ $\Rightarrow f_X$	$-0.10^{+1.12}_{-0.31}$ $\left(\begin{smallmatrix} +1.33 \\ -2.22 \end{smallmatrix}\right)$ $40.4^{+1.1}_{-0.3}$ $\left(\begin{smallmatrix} +1.3 \\ -2.2 \end{smallmatrix}\right)$ $0.8^{+9.7}_{-0.4}$ $\left(\begin{smallmatrix} +16.3 \\ -0.8 \end{smallmatrix}\right)$
$\log_{10}(f_r)$ $\Rightarrow f_r$	$\lesssim 1.23$ (2.39) $\gtrsim 16.9$ (243.7)

signal, we summarize the key findings here and refer the reader to the aforementioned work for more details.

The minimum virial circular velocity for star formation V_c is constrained by a combination of SARAS 3 and UVLFs. The former has a weak preference for higher values of V_c so as to delay WF coupling and the onset of the 21-cm absorption signal to outside the SARAS 3 band,⁸ while the latter sets strong upper limits on V_c by direct detection of faint galaxies at $M_{\text{UV}} \lesssim -18$ by *HST/JWST* (see e.g. O. Zvi Katz et al. 2025). The SFE parameters on the other hand, $\tilde{f}_{\star, \text{II}}, M_0, \alpha_{\star}$, and β_{\star} , are entirely constrained by UVLFs. The halo mass dependence of the SFE is inferred to be $\alpha_{\star} \approx 1.1$ (consistent with $M_{\star} \propto M_{\text{H}}^2$; S. Tacchella et al. 2018), while the redshift evolution, given by $[(1+z)/7]^{-\beta_{\star}}$ is inferred to have a non-monotonic behaviour. The UVLFs show a preference for $\beta_{\star} \lesssim 1.4$ at $z \lesssim 10$ (i.e. minimal evolution, consistent with pre-*JWST* *HST*-based inferences; e.g. R. J. Bouwens et al. 2015; Y. Harikane et al. 2018; S. Tacchella et al. 2018), and $\beta_{\star} \approx 3.6$ (enhanced SFE in the early Universe; e.g. A. Dekel et al. 2023; M. Boylan-Kolchin 2025; R. S. Somerville et al. 2025). The joint analysis gives an intermediate evolution of $\beta_{\star} \approx 2.9$.

The X-ray and radio radiative efficiencies f_X and f_r (defined in equations 3 and 4) are constrained at the upper end of their respective priors by the upper limits on the diffuse CXB and CRB. HERA provides a secondary contribution to both constraints; it disfavors low values of f_X by requiring efficient heating at $z \lesssim 11$ to suppress the 21-cm signal, and disfavors high values of f_r which would otherwise lead to excess radio build-up, deepening the signal. Fig. A1 shows how the constraints on f_X and f_r are strengthened by the inclusion of the UVLF data.⁹

We tabulate the full joint constraint in Table 3. The case of f_X

⁸This constraint is highly sensitive on the foreground model parameters, as we shall discuss in Section 3.2.2.

⁹Although the constraints on f_X and f_r depend on UVLFs, they are robust to the choice of including or excluding high- z galaxies at $z \gtrsim 10$. This is because the largest contribution to diffuse X-ray and radio backgrounds comes from galaxies at $z \sim 6$ where the SFE (in particular β_{\star}) parameter is anchored (as defined in equation (2)). This is clear by the match of black and dashed light-blue curves in Fig. A1.

- Fragos + 13 (0.2 – 95 keV)
- ☐ Mineo + 12 (0.5 – 8 keV)
- ☐ Brorby + 16 (0.5 – 8 keV)
- ☐ Lehmer + 16 (2 – 10 keV)
- ☐ Fornasini + 19 (2 – 10 keV)
- ☐ Saxena + 21 (2 – 10 keV)
- ☐ MWA (Nunhokee + 25, < 2 keV)
- ☐ HERA (+23, 21cmMC, < 2 keV)

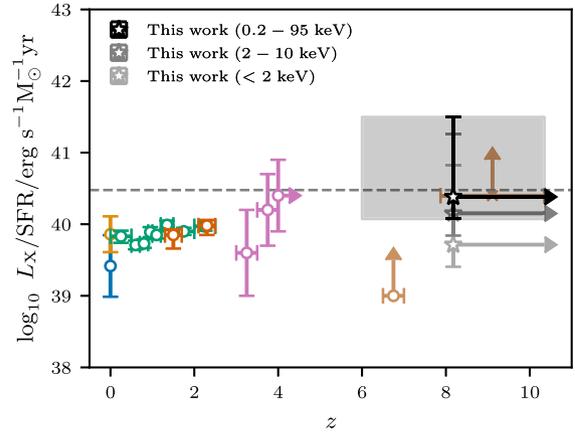


Figure 2. Constraints on the X-ray luminosity per unit SFR, L_X/SFR , from *Chandra* observations of star-forming galaxies in the local Universe (S. Mineo et al. 2012a; M. Brorby et al. 2016) and at low-redshifts (B. D. Lehmer et al. 2016; F. M. Fornasini et al. 2019), and 21-cm experiment inferred limits at high-redshifts (HERA Collaboration et al. 2023; C. D. Nunhokee et al. 2025). We put constraints at $\log_{10}(L_X/\text{SFR}/\text{erg s}^{-1} M_{\odot}^{-1} \text{ yr}) = 40.4^{+1.1}_{-0.3}$ (68 per cent CI) in this work from CXB contributions at $z \gtrsim 6$ and 21-cm power spectrum limits from HERA at $z \lesssim 10.35$ (hence the grey shaded region). The arrows towards high- z reflect our assumption of a fixed L_X/SFR relation during the early epochs. Since different works assume different SEDs (e.g. the energy range considered) which can change our constraints from CXB, a direct comparison is non-trivial but we convert the luminosity in the full X-ray band, 0.2–95 keV, to 2–10 keV and <2 keV for a relative comparison of the luminosity in the different energy bands.

is of particular interest as it is a key parameter in determining the thermal state of the IGM at $z \gtrsim 6$. The joint analysis gives $\log_{10}(f_X) = -0.10^{+1.12}_{-0.31}$ $\left(\begin{smallmatrix} +1.33 \\ -2.22 \end{smallmatrix}\right)$ or equivalently $f_X = 0.8^{+9.7}_{-0.4}$ $\left(\begin{smallmatrix} +16.3 \\ -0.8 \end{smallmatrix}\right)$ at 68 per cent (95 per cent) CI. This implies that the behaviour of high- z galaxies is consistent with predictions of low metallicity HMXBs ($f_X = 1$; T. Fragos et al. 2013b) and higher than that of local star-burst galaxies (S. Mineo et al. 2012b), and we disfavour $f_X \gtrsim 17$ at 95 per cent CI. These constraints correspond to $\log_{10}(L_X/\text{SFR}/\text{erg s}^{-1} M_{\odot}^{-1} \text{ yr}) = 40.4^{+1.1}_{-0.3}$ $\left(\begin{smallmatrix} +1.3 \\ -2.2 \end{smallmatrix}\right)$ at 68 per cent (95 per cent) CI, as shown in Fig. 2, where we place our results in the context of other works for comparison. In particular, those using only 21-cm power spectrum upper limits have inferred higher values predicting a more heated IGM compared to our results (e.g. J. C. Pober et al. 2015; HERA Collaboration et al. 2023; R. Ghara et al. 2025), as we shall discuss more in the next section.

3 RESULTS

The joint constraints on the astrophysical parameters described in Section 2.5 allow us to derive various properties of the IGM and star formation in the early Universe. In order to visualize these functional constraints, we load the POLYCHORD posterior samples (which are of order tens of thousands in number) using ANESTHETIC (W. Handley 2019) and compress them to $N \sim 500$ samples of equal weights.¹⁰ These samples are then used to compute the functional posteriors of

¹⁰Although we compress the posterior samples to $N \sim 500$ to make plotting tractable, all histograms or statistics are derived from the full posterior

the quantities of interest via emulators, trained in a similar manner to J. Dhandha et al. (2025), as we shall describe in the following sections.

3.1 Constraints on IGM and star formation

We first discuss the constraints on the kinetic temperature of the neutral IGM (T_K), the radio background temperature (T_{rad}), the 21-cm spin temperature (T_S), the Pop II star formation rate density (SFRD; $\dot{\rho}_{*,\text{II}}$) and the neutral IGM fraction (x_{HI}) in the redshift range $z = 6-30$. All quantities are trained on 21CMSPACE outputs using the TENSORFLOW (M. Abadi et al. 2016) based package GLOBALEMU (H. T. J. Bevens et al. 2021), with a test/train split of 1/9, a learning rate of 10^{-3} , and the tanh activation function (except for the $\dot{\rho}_{*,\text{II}}$ emulator which has a ReLU activation function). The T_K , T_S , and T_{rad} emulators have an architecture of 4 hidden layers with 32 nodes each, $\dot{\rho}_{*,\text{II}}$ emulator has 4 hidden layers with 16 nodes each, and the x_α and x_{HI} emulators have 3 hidden layers with 32 nodes each, all yielding an error of $\lesssim 10$ per cent at 65th percentile of the test data in log-space.

We show the posteriors from the joint constraints for each of the above quantities in Fig. 3, and describe them in detail below:

(i) **Kinetic temperature of neutral IGM**, T_K (first row, the left panel of Fig. 3): As the main source of IGM heating in our models is via X-rays from low metallicity HMXBs (although we do include Ly α heating which can be important for weak X-ray efficiencies), the constraints on T_K are dictated by the constraint on f_X . By tightly constraining the X-ray heating efficiency of galaxies from both ends of the prior, the joint analysis favours a late heating scenario in which the neutral IGM remains largely adiabatically cooled¹¹ at $z = 15$ ($5.0 \text{ K} \lesssim T_K \lesssim 7.7 \text{ K}$), reaches modest temperatures by $z = 10$ ($2.5 \text{ K} \lesssim T_K \lesssim 66 \text{ K}$), and is assuredly heated above the adiabatic limit at $z = 8$ ($3.7 \text{ K} \lesssim T_K \lesssim 350 \text{ K}$) and $z = 6$ ($20 \text{ K} \lesssim T_K \lesssim 2078 \text{ K}$) at 95 per cent CI. Indeed, we do not rule out a weakly heated IGM even at low redshifts (the so-called ‘cold reionization scenario’) on account of high f_X being disfavoured by UVLF + CXB data, except towards the end of the EoR at $z = 6$ when $T_K \gtrsim T_{\text{CMB}} = 19 \text{ K}$. These results, tabulated in Table 4, are in good agreement with the IGM evolution inferred in P. Madau & T. Fragos (2017) who use an empirical model calibrated using SFRDs and the CXB (although we allow for a wider range of values; e.g. they infer $300 \text{ K} \lesssim T_K(z = 6) \lesssim 600 \text{ K}$). Our results also generally agree with the inference from PAPER (J. C. Pober et al. 2015; B. Greig et al. 2016, $T_K \gtrsim 6 \text{ K}$ at $z = 8.4$, although at 60 per cent CI.), and LOFAR (R. Ghara et al. 2025, $T_K \gtrsim 4.4 \text{ K}$ at $z = 9.1$), but are less consistent with HERA+23 (HERA Collaboration et al. 2023, $T_K \gtrsim 13 \text{ K}$ at $z = 7.9$ at 95 per cent CI.). It is worth noting that the HERA+23 analysis using 21cmMC does not include Ly α heating, which is included in our analysis. Since the aforementioned works use 21-cm power spectrum upper limits without including CXB data, they infer higher f_X values and thus allow for a more heated IGM. Similarly, previous analyses, using 21CMSPACE (T. Gessey-Jones et al. 2024; S. Pochinda et al. 2024) that include both HERA and CXB data, do not include UVLFs and thus have weaker upper limits on f_X and consequently T_K . The joint constraints here improve upon them, providing a more complete picture of the heated IGM during

the EoR. Furthermore, at $z \lesssim 7$, the recent limits and analysis from MWA (C. D. Nunhokee et al. 2025) provide evidence for a heated IGM at those epochs, but since they are less constraining than HERA, we find comfortable agreement with their results.

To illustrate the results further, we plot the posterior distribution of T_K at $z = 6, 8, 10$ and $z = 15$ in Fig. 4 (top row), clearly showing the contribution of the CXB data in constraining high T_K ¹²

(ii) **Radio background temperature at rest-frame 21-cm wavelength**, $T_{\text{rad}}(\nu_{21})$ (first row, right panel of Fig. 3): The radio background temperature, as sourced by the CMB and radio galaxies in our model, is determined by the emission efficiency f_r . The joint analysis favours $f_r \lesssim 16.9$ (243.7) at 68 per cent (95 per cent) CI, with contributions from UVLF + CRB and HERA data. Hence, we infer upper limits of $T_{\text{rad}} \lesssim 47 \text{ K}, 51 \text{ K}, 67 \text{ K}$ and 101 K at $z = 15, 10, 8$ and $z = 6$ respectively at 95 per cent CI, as shown in Table 4.

(iii) **21-cm spin temperature**, T_S (second row of Fig. 3): Once star-forming galaxies become abundant in the Universe (as informed by *HST* and *JWST*), the 21-cm spin temperature T_S couples to the matter temperature T_K via Ly α radiation from galaxies (see discussion on x_α constraints later). The constraints from the joint analysis are tabulated in Table 4 and also shown in the second row of Fig. 4. The conclusions are similar to that of T_K , and although the T_S constraints are useful in their own regard, we observe the 21-cm signal in contrast to the radio background. Thus the most informative quantity is the ratio of the spin temperature to the radio background temperature T_S/T_{rad} , as shown in the second row, right panel of Fig. 3. The joint analysis gives us a striking result. With efficient coupling and a weakly heated IGM at $z \lesssim 15$, there is definitive contrast between T_S and T_{rad} as evidenced by the $T_S/T_{\text{rad}} \lesssim 1$ at $z \approx 12.5$. This has important implications for the 21-cm signal and its detectability, and we discuss this in detail in Section 3.2. At lower redshifts, $z \lesssim 10.5$, we infer a similar T_S/T_{rad} to HERA+23 (HERA Collaboration et al. 2023, although we allow for lower values on account of weaker heating).

(iv) **Pop II SFRD**, $\dot{\rho}_{*,\text{II}}$ (third row, left panel of Fig. 3): As described in Section 2.5, the Pop II SFE is constrained by the UVLF data (see Fig. 7 in J. Dhandha et al. 2025, for the functional posteriors), and shows preference for redshift independence at $z \lesssim 10$ and a strong redshift evolution at $z \gtrsim 10$. The SFRD evolution inferred from the joint analysis, which is a compromise between the two redshift regimes, sits above the *HST* and *JWST* observations of Lyman-break galaxies $z \lesssim 15$ (e.g. R. J. Bouwens et al. 2015; C. T. Donnan et al. 2024). This is expected as the SFRD shown in Fig. 3 is the total SFRD of Pop II star-forming galaxies, including DM haloes down to the minimum circular velocity, V_c . This can be as low as $M_h \sim 10^6 M_\odot$ at $z = 15$ and $M_h \sim 10^5 M_\odot$ at $z = 30$ for molecular cooling haloes, well outside the faintest observable magnitudes. As an example, assuming a SFE of 100 per cent, this would correspond to magnitudes of $M_{\text{UV}} \sim -11.5$ and $M_{\text{UV}} \sim -10$, respectively, in the absence of lensing magnification. A more direct comparison to *HST/JWST* observations would be to infer the SFRD by integrating the UVLF at $M_{\text{UV}} < -17$ (as in fig. 9 of J. Dhandha et al. 2025). SFRD inferred from gamma-ray bursts (M. D. Kistler et al. 2013), which are sensitive to obscured star formation unlike *HST/JWST* observations, are also consistent with our results in Fig. 3. Recent

distribution compressed to the ‘maximum channel capacity’ (see ANESTHETIC documentation for details).

¹¹For reference, the adiabatic cooling limit as plotted/mentioned throughout this work is $T_{K,\text{adiabatic}}(z) \approx 50.67 \text{ K} \times (1+z)^2/(1+50)^2$.

¹²Note that the since CXB and UVLF data are combined in the analysis here, there is *some* heating even with the lowest f_X due to guaranteed star formation. It is only when there is very low SFE (or equivalently SFR, which UVLFs disfavour) combined with weak heating that the adiabatic prior limit is recovered.

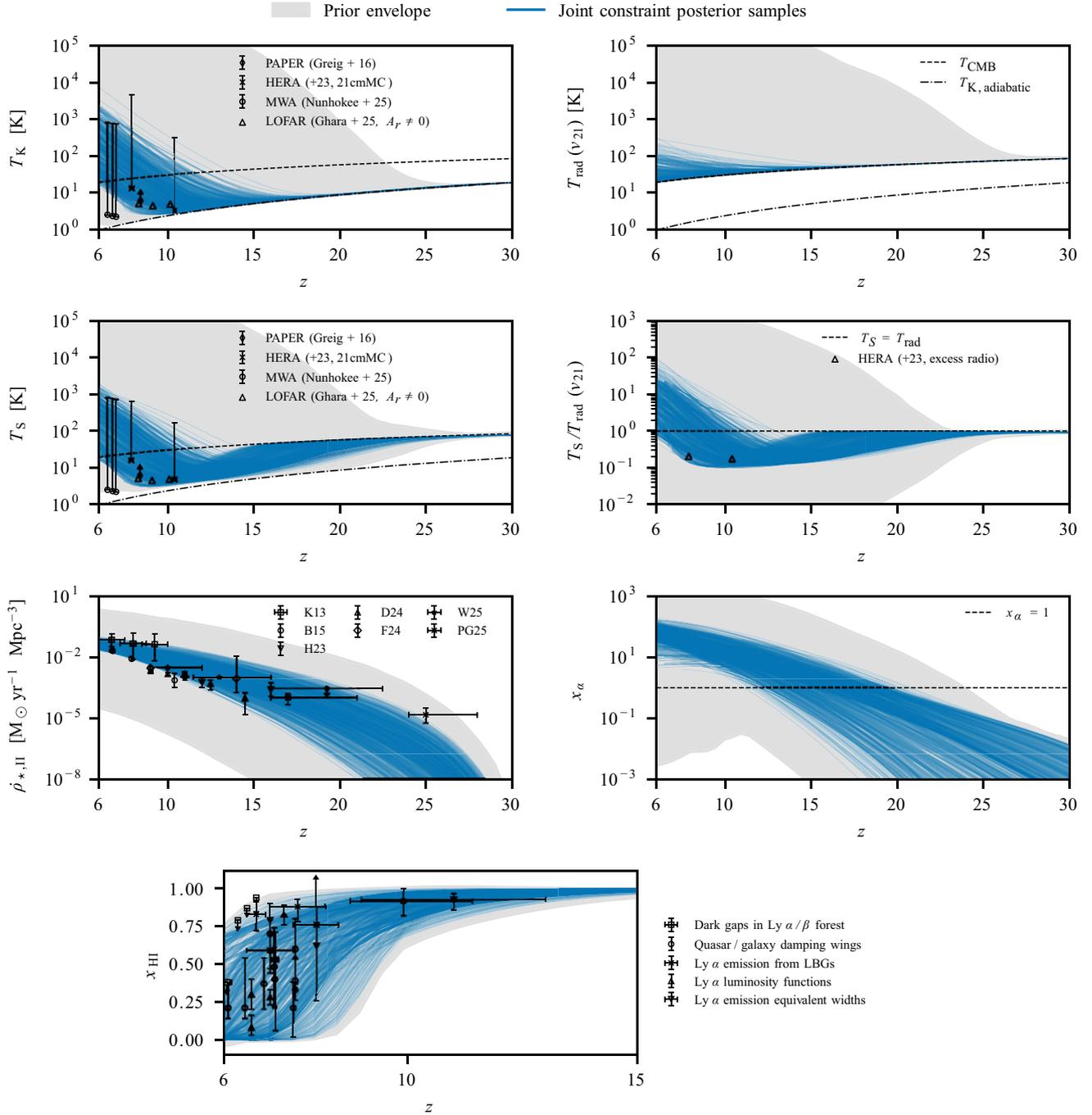


Figure 3. Evolution of various quantities related to the IGM and star formation in the redshift range $z \approx 6-30$. The panels from top-left to bottom-right show the kinetic temperature of neutral IGM (T_K), the radio background temperature at the rest-frame 21-cm wavelength (T_{rad}), the spin temperature (T_S), the ratio of spin to radio background temperature (T_S/T_{rad}), the Pop II star formation rate density (SFRD, $\dot{\rho}_{*,\text{II}}$), and the neutral IGM fraction (x_{HI}) at the bottom. The grey regions show the priors in this functional space, while the solid lines are $N \sim 500$ samples from the joint posterior distribution. In the top panels, we also show the latest constraints on neutral IGM T_K from PAPER (J. C. Pober et al. 2015; B. Greig, A. Mesinger & J. C. Pober 2016), HERA+23 (HERA Collaboration et al. 2023), LOFAR (R. Ghara et al. 2025, their $A_r \neq 0$ model), MWA (C. D. Nunhokee et al. 2025). In case of the HERA+23 constraints, we plot the results from their 21cmMC model (generated using 21CMFAST; A. Mesinger et al. 2011) for T_K and excess radio model (generated using 21CMSPACE) for T_S/T_{rad} . We also plot the same constraints for T_S , assuming $T_S = T_K$ for MWA (although not stated explicitly in their work, it is reasonable to assume saturated WF coupling at $z \lesssim 7$). In the panel for the SFRD $\dot{\rho}_{*,\text{II}}$, we show various inferences from literature using *HST/JWST* UVLFs (R. J. Bouwens et al. 2015; Y. Harikane et al. 2023a; C. T. Donnan et al. 2024; S. L. Finkelstein et al. 2024; P. G. Pérez-González et al. 2025; L. Whitler et al. 2025), and gamma-ray bursts (M. D. Kistler, H. Yuksel & A. M. Hopkins 2013). Finally, in the bottom panel for neutral fraction x_{HI} , we show constraints from dark gaps in Ly α/β forest (I. D. McGreer, A. Mesinger & V. D’Odorico 2015; X. Jin et al. 2023), from Ly α damping wings (B. Greig et al. 2017; E. Bañados et al. 2018; F. B. Davies et al. 2018; B. Greig, A. Mesinger & E. Bañados 2019; F. Wang et al. 2020; J. Yang et al. 2020; H. Umeda et al. 2024; D. Ďurovčíková et al. 2024), fraction of Lyman-break galaxies showing Ly α emission (C. A. Mason et al. 2018; A. Hoag et al. 2019; C. A. Mason et al. 2019; P. Bolan et al. 2022), from Ly α luminosity functions (A. M. Morales et al. 2021; Y. Ning et al. 2022), and from Ly α equivalent width distributions (M. Nakane et al. 2024). In this work, we do not constrain x_{HI} anymore than the flat 3σ prior on τ_{CMB} from *Planck*2018, hence the overlap of grey shaded region and blue lines, but we show a variety of constraints from literature for completeness and to highlight the uncertainty in EoR evolution.

Table 4. Constraints on the IGM kinetic temperature T_K , spin temperature T_S , and adiabatic cooling limit $T_{K,\text{adiabatic}}$ (top section); and on the radio background temperature $T_{\text{rad}}(\nu_{21})$, $T_S/T_{\text{rad}}(\nu_{21})$, and CMB temperature T_{CMB} (bottom section) at $z = 6, 8, 10, 12.5, 15$. For each quantity, we show the prior range and the posterior range, both at 95 per cent confidence interval (CI). The numbers in bold for the T_S/T_{rad} column highlight the optimistic predictions for the observability of the 21-cm signal.

Redshift	T_K (K)		T_S (K)		$T_{K,\text{adiabatic}}$ (K) Value
	Prior	95 per cent CI	Prior	95 per cent CI	
$z = 6$	[2.5, 165043.8]	[19.8, 2077.9]	[2.7, 40110.9]	[19.0, 1258.1]	1.0
$z = 8$	[1.7, 106530.4]	[3.7, 349.5]	[2.7, 25677.9]	[4.3, 359.2]	1.6
$z = 10$	[2.4, 49516.9]	[2.5, 66.2]	[3.2, 11624.1]	[3.1, 73.3]	2.4
$z = 12.5$	[3.6, 6956.2]	[3.6, 16.0]	[4.4, 2939.6]	[4.5, 19.0]	3.6
$z = 15$	[5.0, 704.8]	[5.0, 7.7]	[5.6, 578.3]	[6.4, 33.9]	5.0

Redshift	$T_{\text{rad}}(\nu_{21})$ (K)		$T_S/T_{\text{rad}}(\nu_{21})$		T_{CMB} (K) Value
	Prior	95 per cent CI	Prior	95 per cent CI	
$z = 6$	≤ 93900.5	≤ 101.0	[0.0, 592.7]	[0.8, 54.7]	19.1
$z = 8$	≤ 43163.3	≤ 66.5	[0.0, 222.0]	[0.2, 11.9]	24.5
$z = 10$	≤ 18636.8	≤ 50.5	[0.0, 172.0]	[0.1, 2.2]	30.0
$z = 12.5$	≤ 5891.6	≤ 44.7	[0.0, 55.0]	[0.1, 0.5]	36.8
$z = 15$	≤ 1652.7	≤ 46.8	[0.0, 11.1]	[0.1, 0.8]	43.6

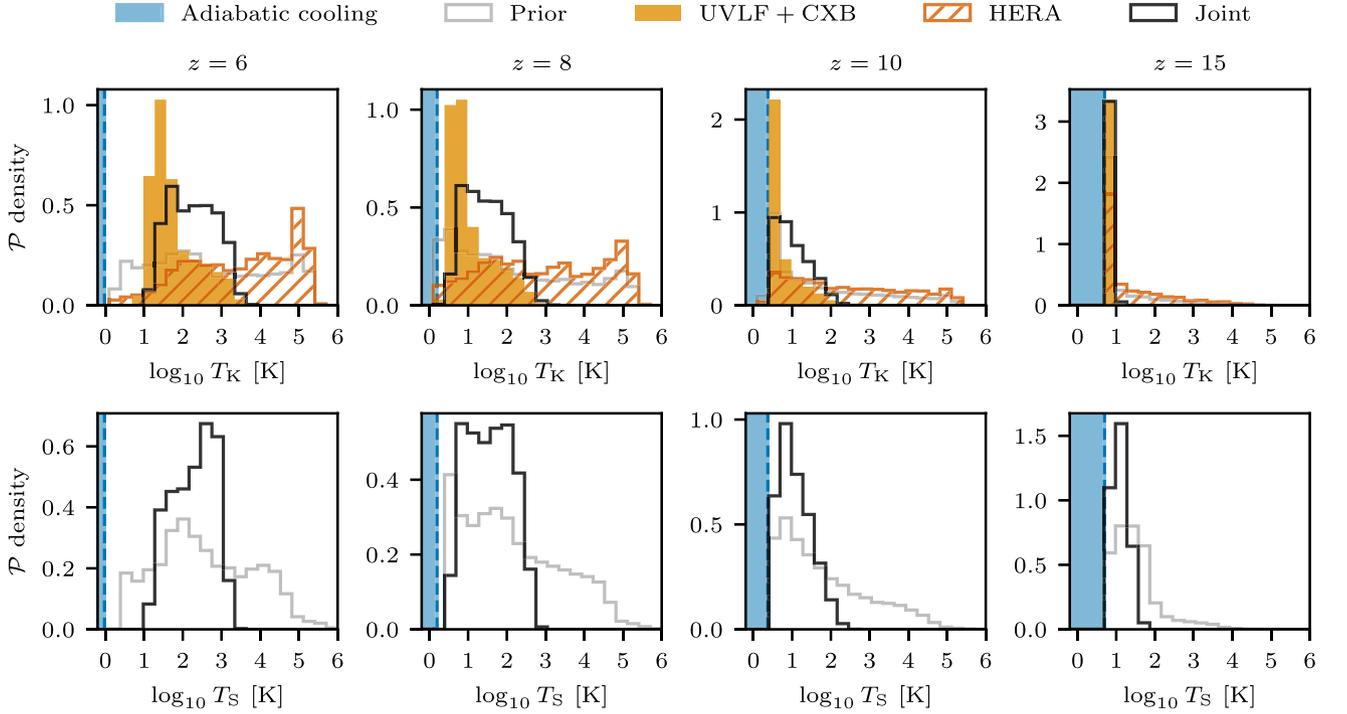


Figure 4. PDFs of the IGM kinetic temperature T_K (top row) and spin temperature T_S (bottom row) at $z = 6, 8, 10$, and $z = 15$ in the joint analysis. Note that the histograms are not from one simulation, but denote many realizations of the Universe with different astrophysical parameters sampled from the posterior. The blue region denotes the adiabatic cooling limit, while the grey and black histograms are the prior and joint posteriors from our models and analysis respectively. The constraints on T_K are driven by a combination of UVLF + CXB data disfavoring high f_X values (shown in solid yellow histogram), and HERA disfavoring low f_X values (shown in hatched orange histograms). It can be seen that we only get marginal heating at $z \gtrsim 15$, while it is guaranteed at $z \lesssim 8$.

estimates suggest that dust-obscured star formation can account for as high as ~ 40 per cent of all star formation at $z \sim 6$ (L. Barrufet et al. 2025).

(v) **Ly α coupling**, x_α (third row, right panel of Fig. 3): The Ly α flux from Pop II star-forming galaxies facilitates the WF coupling of the spin temperature T_S to the kinetic temperature of the IGM T_K , quantified by the coupling coefficient as defined in equation (10), and becomes saturated when $x_\alpha \gg 1$. We derive constraints

of $x_\alpha \gtrsim 0.1, 0.8, 4.8, 11.2$ and 13.3 at $z = 15, 12.5, 10, 8$ and $z = 6$ respectively at 95 per cent CI.

(vi) **Neutral IGM fraction**, x_{HI} (bottom panel of Fig. 3): We do not constrain the ionization of the IGM in our models anymore than the prior, which is set to be uniformly sampled from 3σ around the *Planck 2018* optical depth $\tau_{\text{CMB}} \in [0.033, 0.075]$. Of all data sets, the only one with the potential to constrain the neutral fraction is the 21-cm power spectrum limits from HERA. HERA marginally prefers a

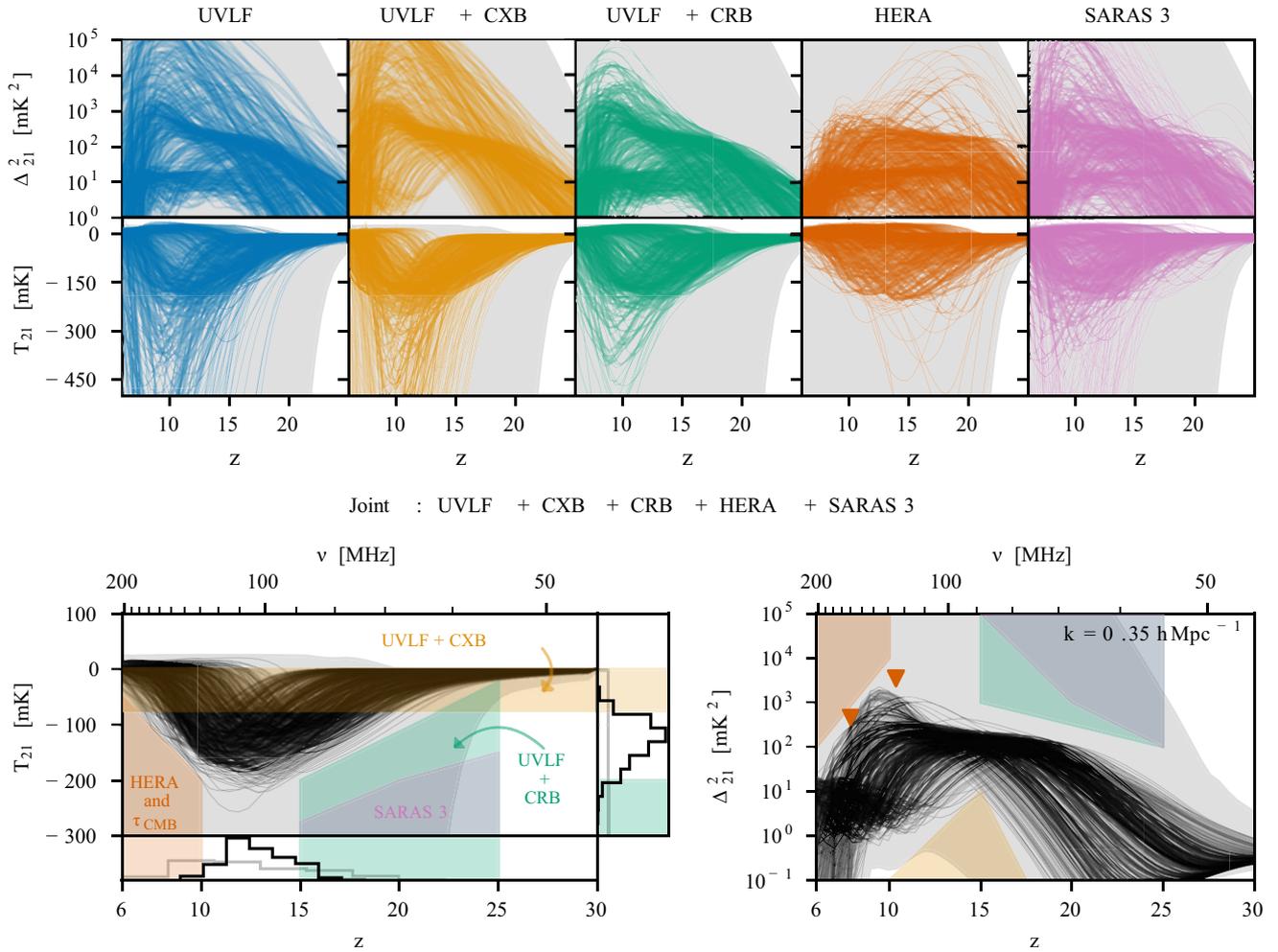


Figure 5. Constraints on the 21-cm global signal T_{21} and power spectrum Δ_{21}^2 from the individual data sets (top row) and the joint analysis (bottom row). The grey regions show the prior space, while the solid lines are $N \sim 500$ samples from the respective posterior distributions. In the joint constraint panels, we highlight qualitatively regions of the prior space (as the filled coloured regions) that are disfavoured by the different data sets. The global signal panel also show histograms of the redshift/timing (along x -axis) and depth (along y -axis) of the absorption trough minima, while the power spectrum panel shows the 21-cm power spectrum limits from HERA (HERA Collaboration et al. 2023, in orange). Most notably, via the constraints on heating efficiency f_X and IGM temperature T_K from the UVLF + CXB data, we find a non-vanishing global signal and power spectrum at $z \sim 10 - 15$ (see Section 3.2 for quantified constraints). For the special cases of joint analysis where we exclude certain data sets, see Fig. A2.

higher τ_{CMB} (i.e. early reionization at $z \approx 8$) as an alternative solution to the vanishing 21-cm power spectrum in extremely weak heating cases ($f_X \lesssim 0.1$, which is why the f_X PDF does not fall to zero at the low end of the prior in Fig. 1). Beyond this degeneracy, HERA is no more informative than the *Planck 2018* prior on x_{HI} , hence, we retrieve a prior-dominated posterior. We comment on the prospects for future work in this realm in Section 3.3.4.

3.2 Constraints on 21-cm global signal and power spectrum

The constraints on the IGM temperature T_K and the radio background temperature T_{rad} are crucial for understanding the 21-cm signal. In order to quantify the 21-cm signal constraints, we improve upon the emulators for the 21-cm global signal and power spectrum from J. Dhandha et al. (2025) by re-training them with updated architectures. The former is re-trained with an architecture of 4 hidden layers with 32 nodes each (instead of 16 nodes each as used in the earlier work), still GLOBALEMU with a test/train split of 1/9. The new emulator has a root-mean squared error of 9.1 mK at 68th percentile of the

test data.¹³ The latter is re-trained with the same architecture as the previous work and with SCIKIT-LEARN's MLPRegressor, but with an increased redshift range of $z = 6 - 30$ (instead of $z = 7 - 11$ used earlier), yielding an error of $\lesssim 20$ per cent for all k and z bins.

Fig. 5 shows the constraints on the 21-cm global signal and power spectrum at $z = 6 - 30$ for each dataset in the top row, and the joint analysis in the bottom row. In particular, the figure highlights the regions of the function space that are constrained by each of the data sets used in this work.

The UVLF data on its own only rules out very early, deep global signals at $z \gtrsim 15$ (arising from very high SFE) and very low amplitude power spectra at $z \approx 10 - 15$ (arising from very low SFE). These extreme cases are disfavoured by anchoring star formation to the range allowed by the galaxy abundances (i.e. UVLF

¹³For test data signals that have absorption amplitude of $T_{21,\text{min}}$ smaller than -50 mK, the RMSE is 5 mK at 68th percentile. This is consistent with a ~ 10 per cent emulator error, which is smaller than the assumed seminumerical errors of ~ 20 per cent.

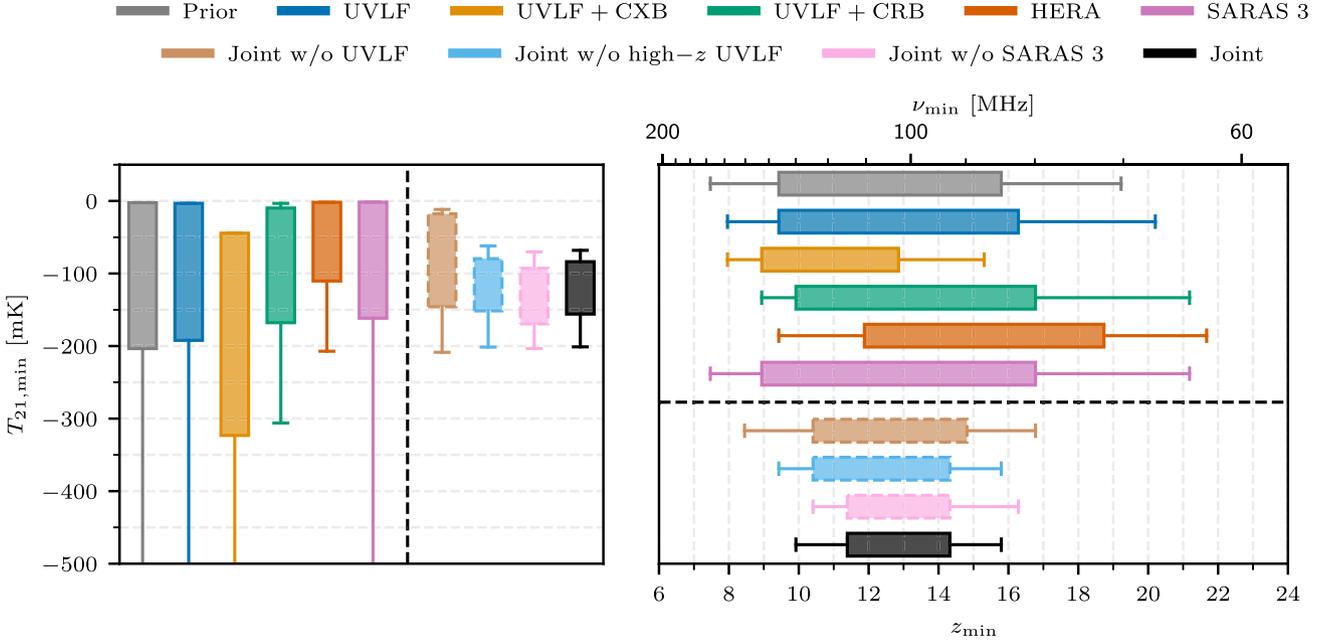


Figure 6. Another way to quantify the global signal constraints from individual datasets and joint analysis shown in Figs 5 and A2. The plot shows the depth (signal amplitude; left panel) and timing (redshift; middle panel) of the 21-cm global signal absorption trough, with the dashed black line separating the joint cases. The box-plots here show the 68 per cent CI (boxes) and 95 per cent CI (whiskers) of the prior and posterior distributions.

observations). Building on this, the UVLF + CXB data combination provides a strong constraint on how efficient the heating can be before it is in conflict with the diffuse X-ray background limits. This rules out very shallow global absorption signals and suppressed power spectra at $z \sim 10 - 15$. The UVLF + CRB combination, on the other hand, rules out high f_r and thus deep signals due to an excess radio background sourced by efficient radio galaxies, which has implications for deep signals at $z \gtrsim 15$. HERA, in contrast to UVLF + CXB, prefers a heated IGM to suppress high power spectra (and consequently global signal amplitude) at $z \lesssim 11$. SARAS 3 prefers to push deep global signals outside of the redshift range $z \approx 15-25$ (and thus disfavors high power spectra at early times). One way to achieve this is to disfavor efficient star formation in molecular cooling haloes that cause an early onset of the absorption signal (i.e. low V_c).¹⁴

The case of joint analysis is most interesting because it provides stringent (however, model-dependent) constraints on the 21-cm signal. In the global signal panel of Fig. 5, the histograms along the x and y axes show the timing and depth of the absorption trough respectively. The constraints predict the global signal absorption trough to lie at $9.9 \lesssim z_{\min} \lesssim 15.8$ (or equivalently $130 \text{ MHz} \lesssim \nu_{\min} \lesssim 85 \text{ MHz}$) with a depth of:

$$\begin{aligned} -156 \text{ mK} &\lesssim T_{21,\min} \lesssim -84 \text{ mK} \text{ at 68 per cent CI,} \\ -201 \text{ mK} &\lesssim T_{21,\min} \lesssim -68 \text{ mK} \text{ at 95 per cent CI,} \end{aligned}$$

and $T_{21,\min} < -278 \text{ mK}$ and $T_{21,\min} > -33 \text{ mK}$ are ruled out at 99.99 per cent CI. We also show these constraints in the form of box-plots in Fig. 6, for all individual and joint data sets, and in the

form of a ‘discovery space’ map ($T_{21,\min}$ versus z_{\min}) in Fig. 7 for the joint analysis.

The power spectrum panel of Fig. 5 shows $\Delta_{21}^2(z)$ in the k -bin where HERA limits are strongest ($k \approx 0.35 \text{ hMpc}^{-1}$). Most interestingly, we infer a non-vanishing power spectrum at $z = 15$ of:

$$\begin{aligned} 50 \text{ mK}^2 &\lesssim \Delta_{21}^2(z = 15) \lesssim 157 \text{ mK}^2 \text{ at 68 per cent CI,} \\ 8.7 \text{ mK}^2 &\lesssim \Delta_{21}^2(z = 15) \lesssim 197 \text{ mK}^2 \text{ at 95 per cent CI.} \end{aligned}$$

We also constrain the power spectrum at $z = 8, 10, 20, 25$ as tabulated in Table 5. The power spectrum at $z = 8$ and $z = 10$ is also non-vanishing, but the constraints are weaker, while the power spectrum $z = 20$ and $z = 25$ is consistent with zero, but with informative upper limits. The joint analysis thus provides a lower limit on the 21-cm global signal depth and a non-vanishing power spectrum that is not prior-limited. This is a significant step forward in our understanding of the expected range of 21-cm signals.

Thus, we have constrained the 21-cm signal within our model parametrization, and, for the first time, inferred a lower limit on the global signal depth and non-vanishing power spectrum that is not prior-limited. These constraints would not be possible without the inclusion of the UVLF data, as shown in brown in Figs 6 and A2 (top-row), and indeed provide an optimistic view of the 21-cm signal at high- z . Before we discuss the caveats of this inference, we test the robustness of these constraints by performing the joint analysis without the high- z UVLF data from *JWST*, and without the SARAS 3 data which relies on proper foreground subtraction.

3.2.1 In the absence of high- z UVLFs

In light of the abundance of bright galaxies seen by *JWST* at $z \gtrsim 10$, there is increasing interest in the impact of how different galaxy formation models affect our understanding of the 21-cm signal (e.g. A. Chatterjee, P. Dayal & V. Mauerhofer 2023; S. Libanore et al.

¹⁴Deep signals resulting from excess radio background are mildly disfavoured by SARAS 3 as shown in the marginalized PDF for f_r in Fig. 1. We expect that this constraint would be strengthened if SARAS 3 data were combined with UVLF data, so that degenerate low SFE—high f_r combinations are ruled out.

Table 5. Constraints on the 21-cm global signal T_{21} (minimum absorption) and power spectrum Δ_{21}^2 at $k = 0.35 h \text{ Mpc}^{-1}$ at selected redshifts. For each quantity, we show the prior range (at 95 per cent CI) and the joint posterior range (at 68 per cent and 95 per cent CI). The numbers in bold highlight the optimistic predictions for the observability of the 21-cm signal.

Quantity	Prior	21-cm global signal (in mK)	
		68 per cent CI	95 per cent CI
$T_{21,\min}$	$[-3796, -2] \text{ mK}$	$[-156, -84] \text{ mK}$	$[-201, -68] \text{ mK}$
z_{\min}	$[7.5, 19.2]$	$[11.4, 14.3]$	$[9.9, 15.8]$
ν_{\min}	$[168, 70] \text{ MHz}$	$[115, 93] \text{ MHz}$	$[130, 85] \text{ MHz}$
Quantity	Prior	21-cm power spectrum (in mK^2)	
		68 per cent CI	95 per cent CI
$\Delta_{21}^2(z = 8)$	$[0, 4.15 \times 10^5]$	$[0.004, 16.4]$	$[0.004, 180]$
$\Delta_{21}^2(z = 10)$	$[0.18, 1.21 \times 10^6]$	$[0.47, 179]$	$[0.47, 1020]$
$\Delta_{21}^2(z = 15)$	$[0.06, 1.86 \times 10^5]$	$[50, 157]$	$[8.7, 197]$
$\Delta_{21}^2(z = 20)$	$[0.005, 3070]$	$[0.01, 35]$	$[0.01, 80]$
$\Delta_{21}^2(z = 25)$	$[0.051, 19.3]$	$[0.056, 0.90]$	$[0.056, 6.2]$

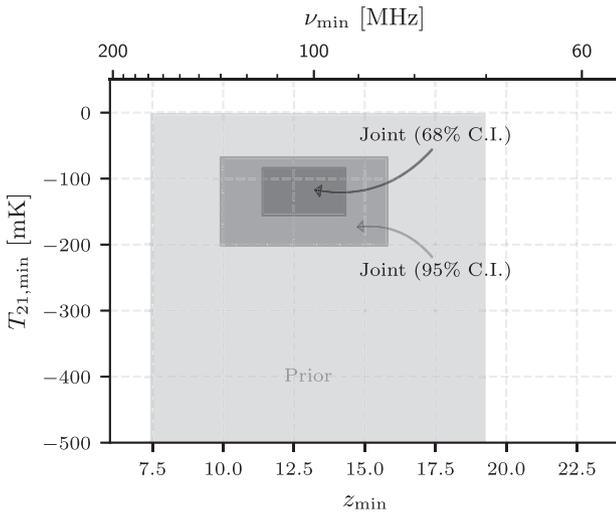


Figure 7. A ‘treasure map’ of the discovery space for the 21-cm global signal absorption trough with the priors in light grey (at 95 per cent CI), and the joint posterior (at 68 per cent and 95 per cent CI, as annotated) in darker grey. The exact values are shown in Table 5.

2024; A. Acharya et al. 2025). The results presented in this work do not change much in the absence of high- z UVLFs ($z \gtrsim 10$), as shown in light-blue in Figs 6 and A2. This is expected even though the constraint on β_* changes, meaning the SFE evolves with redshift. The SFRD and UVLFs are still sensitive to β_* , but the constraints on f_X and f_r from the diffuse X-ray and radio backgrounds respectively largely come from galaxies at $z \sim 6$, where β_* has no effect (see footnote 9). There is a marginal shift in the median global signal trough by $\Delta z \sim 0.5$ to lower z , which is consistent with the analysis of S. Libanore et al. (2024) in their ‘feedback-free burst’ model for galaxies (which is similar to our redshift-dependent enhancement of the SFE). This is because a fixed SFE that is not enhanced in the early Universe means a less efficient WF coupling at high- z , and thus a later onset of the absorption signal.

3.2.2 In the absence of SARAS 3

As described in Section 2.3, our Bayesian likelihood for the SARAS 3 data employs a sixth-order log–log polynomial to model the Galactic and extragalactic foreground. Evidently, a small shift in any of

the polynomial coefficients can lead to large (tens of mK level) changes in the global signal posteriors that can bias our astrophysical parameter constraints. This was demonstrated in J. Dhandha et al. (2025, fig. C3), where the leading polynomial coefficients are degenerate with the constraint on V_c . Thus, we perform a joint analysis without the SARAS 3 data to ensure a wrong choice of foreground model is not affecting our results, shown in light-pink in Figs 6 and A2. The constraint on the global signal depth remains unaffected, but the timing shifts by $\Delta z \sim 0.5$ to higher z . This is because the weak constraint on models with low V_c , disfavouring molecular cooling haloes, disappears (see the first panel of Fig. A1) and star formation can begin earlier, leading to an earlier onset of the absorption signal.

3.3 Model dependency and caveats

The results presented in this work offer promising constraints on the 21-cm signal and optimistic prospects for its detection. *However, they do not constitute an indirect detection of the 21-cm signal.* They are model-dependent inferences based on our astrophysical parametrization and come with some assumptions and caveats. In particular, we highlight how our results may change with different assumptions about the X-ray emissions and inclusion of a flexible Pop III star formation model.

3.3.1 X-ray emission at high- z

Our knowledge of high- z galaxies and their X-ray emission properties is still limited. Thus the lower limit on the 21-cm signal (driven by UVLF + CXB data) is dependent on the X-ray model. The assumptions we make about the X-ray emissions in this work include:

(i) *X-ray emissions are dominated by HMXBs.* Due to their short lifetimes, formation in high (or bursty) star-forming and low metallicity environments, they are expected to dominate the X-ray emissions at $z \gtrsim 6$ (T. Fragos et al. 2013b; B. D. Lehmer et al. 2016; P. Madau & T. Fragos 2017). With the recent observations of *JWST* showing an increasing population of AGN at earlier times (e.g. I. Juodžbalis et al. 2023; Y. Harikane et al. 2023b; Á. Bogdán et al. 2024; S. Fujimoto et al. 2024; R. Maiolino et al. 2024, albeit many without X-ray detections), the contribution of AGN to the X-ray background at high- z remains uncertain (in particular, understanding the X-ray quiet ‘Little Red Dots’ discovered by *JWST*; e.g. K. N. Hainline et al. 2025). Furthermore, other sources of heating, such as

cosmic rays produced by Pop II and Pop III supernovae may be able to heat the IGM above the CMB temperature by $z \sim 10$ already (S. Sazonov & R. Sunyaev 2015; N. Leite et al. 2017; R. Jana, B. B. Nath & P. L. Biermann 2019; T. Gessey-Jones et al. 2023), which we do not explore in this work.

(ii) *X-ray SED is fixed across cosmic time.* We assume that the X-ray SED of HMXBs is fixed to T. Fragos et al. (2013b, their mean model at $z = 15.34$) in the energy range 0.2–95 keV, which is a relatively hard spectrum. Since the X-ray SED slope and minimum/maximum energy cut-offs remain essentially unconstrained so far (e.g. S. Pochinda et al. 2024; O. Zvi Katz et al. 2025), a softer spectrum (from hot ISM instead of HMXBs, e.g. F. Pacucci et al. 2014) may be able to provide more heating efficiency whilst avoiding exceeding the CXB limits. This has been explored previously in A. Fialkov et al. (2017), including both soft and hard X-ray SEDs and contributions from high- z quasars, but using only CXB data as opposed to the multiwavelength data used in this work.

(iii) *L_X/SFR is constant over cosmic time,* scaled by the free parameter f_X (normalized to the theoretical prediction for low metallicity HMXBs from T. Fragos et al. 2013b) that we constrain. Assuming this star formation scaling, the X-ray emissions integrated across the simulation volume and time (accounting for redshifting spectra) contribute to the diffuse CXB at $z = 0$. The largest contributions come from galaxies at the lowest redshift ($z \sim 6$) in our simulations where the SFRD is largest (anchored by the UVLF data) and spectra are redshifted the least. Hence, the f_X constraint from CXB is most robust for populations close to $z \sim 6$. The constraints become increasingly weaker on the higher- z populations, where the spectra are redshifted and star-forming galaxies contribute less to the CXB. In particular, we expect our 21-cm signal constraints to be affected if the L_X/SFR relation strongly depends on the metallicity as stellar populations evolve from primordial metallicities of $Z/Z_\odot < 10^{-6}$ to $\sim 10^{-2}$ over cosmic time. This regime lies outside of observed ranges, but there is growing evidence of a strong metallicity dependence (e.g. V. M. Douna et al. 2015; M. Brorby et al. 2016; F. M. Fornasini et al. 2019; B. D. Lehmer et al. 2024), especially when considering Pop III stars which can be $\times 100$ more efficient in X-ray emissions than Pop II stars (N. S. Sartorio et al. 2023, see discussion on Pop III stars later). This would imply that heating is more efficient at higher- z , thus suppressing the 21-cm signal. H. D. Kaur et al. (2022) quantify this effect by comparing Pop II stellar models with two different $L_X/\text{SFR} - Z$ relations, one constant (T. Fragos et al. 2013b) and the other steeply increasing with metallicity (M. Brorby et al. 2016). The suppression in the global signal in the latter model compared to the former is $\delta \sim 25$ mK for a signal of depth ~ 70 mK. Thus, our lower limit at 95 per cent CI of a similar depth would decrease in such a model, but the *prospect* for placing such a lower limit still remains.

3.3.2 Radio emission at high- z

Our model disfavors a strong radio background at high- z , inferring an upper limit of $T_{\text{rad}}(\nu_{21}) \lesssim 100$ K at $z = 6$, and $\lesssim 50$ K at $z > 10$ (see Table 4), meaning that exotic astrophysical models of deep 21-cm signals are ruled out. This is conditional on our choice of radio SED (which is fixed to a synchrotron power law), and the same caveat that applies to the constant L_X/SFR relation also applies to the L_r/SFR relation. Galaxies at high- z may have a steeper spectral index (J. Delhaize et al. 2017, favouring shallower signals), or higher radio luminosities (allowing for deeper signals). However, since radio emissions are largely unabsorbed in the IGM, it is hard to build up

a large radio background without exceeding the constraints from LWA1/ARCADE2. As also pointed out in J. Cang et al. (2025), the only way to allow for a large radio background at high- z is to introduce an ad-hoc z_{cutoff} below which radio emissions are quenched (e.g. I. Reis et al. 2020; S. Sikder, R. Barkana & A. Fialkov 2024) or to allow for them to be sourced by Pop III galaxies that are sterilized by a growing Lyman-Werner background (e.g. J. B. Muñoz et al. 2022), which leads onto our next caveat.

3.3.3 Exclusion of Pop III stars

There is growing interest in the modelling of Pop III stars, and their observational prospects for *JWST* (see e.g. B. Liu et al. 2024, and references within). 21CMSPACE employs a flexible Pop III model that allows for a range of Pop III star formation efficiencies, IMFs (T. Gessey-Jones et al. 2022, 2025) and SED models (B. Liu et al. 2025; J. Wasserman et al. 2025). As explained in Section 2.1, the focus of our prior work (J. Dhandha et al. 2025) was on Pop II star formation constraints which this work builds on. Thus, we fix the Pop III SFE to $f_{\star, \text{III}} = 0.2$ per cent, the time for Pop II star formation to recover after Pop III SNe to $t_{\text{delay}} = 30$ Myr (M. Magg et al. 2022), a log-flat IMF in the mass range 2–180 M_\odot , and the stellar modelling from T. Gessey-Jones et al. (2022).

Including a range of Pop III models in our analysis, as has been done in other recent works (e.g. T. Gessey-Jones et al. 2024; S. Pochinda et al. 2024; O. Zvi Katz et al. 2025), may change the constraints. In particular, allowing for early WF coupling (via high Pop III SFE or strong Ly α emitting SED, both of which are poorly constrained; e.g. H. Yajima & S. Khochfar 2015; Y. Qin et al. 2020; T. Gessey-Jones et al. 2022; J. B. Muñoz et al. 2022); early heating (through an elevated $f_{X, \text{III}}$, as opposed to a fixed f_X for both populations; e.g. J. Mirocha et al. 2018; N. S. Sartorio et al. 2023; T. Gessey-Jones et al. 2025; E. M. Ventura et al. 2025); or a strong radio emitting population (via $f_{r, \text{III}}$; e.g. J. Cang et al. 2025), would indeed give rise to different 21-cm signals. Additionally, more extreme rotational Pop III stars can even have a strong impact on the EoR by causing an early reionization scenario through their strongly ionizing SEDs (B. Liu et al. 2025; J. Wasserman et al. 2025). This would suppress the signal by ~ 10 –20 per cent at $z \sim 15$.

We expect, conditional on the radio foreground fit, that SARAS 3 would disfavour efficient Pop III star formation since the global signal absorption trough would fall in the $z = 15 - 25$ range, where the SARAS 3 non-detection lies (e.g. see Fig. 2 of S. Pochinda et al. 2024). Otherwise, like in our constraints, it would favour higher V_c values pushing star formation to sufficiently large atomic cooling haloes that form at later times, thus making Pop III star formation at high- z less likely. Recently, H. Lazare, D. Sarkar & E. D. Kovetz (2024) showed that including molecular cooling galaxies can decrease the inferred X-ray emission efficiency of atomic cooling galaxies when using HERA data. This allows for deeper, more extended absorption signals (within the SARAS 3 limits) which would bolster our optimistic predictions.

3.3.4 Comment on reionization

There are a plethora of constraints on the reionization history of the Universe, some of which are plotted in Fig. 3 (bottom panel). We have used the most conservative of these constraints in this work, a flat 3σ prior on the optical depth τ_{CMB} from *Planck 2018* (Planck Collaboration VI 2020). The models presented here are thus agnostic to late or early reionization scenarios. We use a simple

parametrization of the ionizing efficiency of galaxies ζ_{ion} that is fixed in both redshift and halo mass, despite the SFE being allowed to vary along both those variables. Whether such a model is realistic is outside the scope of this work, and we thus leave out the focus on ionization during EoR here. Nonetheless, since $\zeta_{\text{ion}} \propto f_{\star} f_{\text{esc}}$, the increased SFE at large halo masses may be compensated by a lower escape fraction (as large haloes are more resilient to SNe clearing channels of low density gas for ionizing photons to escape, e.g. H. Xu et al. 2016; J. S. W. Lewis et al. 2020; S. J. Mutch et al. 2024).

In future works, we hope to explore more flexible models for the ionizing properties of galaxies. This includes escape fractions (and their redshift/halo mass dependencies), clumping factors, ionizing emissivities – all of which are subsumed into ζ_{ion} in this work due to their degenerate nature, but have been recently introduced in 21CMSPACE in (B. Liu et al. 2025, for Pop III stars). This would allow us to not only explore varied reionization histories, but also build towards a more complete model of the astrophysical properties of galaxies at $z \gtrsim 6$ by including various reionization datasets (such as in Y. Qin et al. 2021, 2025; P. H. Sims et al. 2025; O. Zvi Katz et al. 2025), giving tighter constraints on the vanishing of the global signal and power spectrum at the end of the EoR.

4 CONCLUSIONS

In this work, we constrain various properties of the neutral IGM at high-redshifts ($z \gtrsim 6$), including the kinetic temperature T_{K} , radio background temperature $T_{\text{rad}}(\nu_{21})$, the 21-cm spin temperature T_{S} , and consequently the 21-cm global signal and power spectrum. This follows from our previous work, J. Dhandha et al. (2025), where we constrained the astrophysical properties of early Pop II galaxies using a combination of multiwavelength observations. This includes high-redshift UVLFs from *HST* and *JWST*, cosmic X-ray and radio backgrounds (CXB and CRB), 21-cm global signal non-detection from SARAS 3, 21-cm power spectrum upper limits from HERA, and CMB optical depth from *Planck 2018* as a prior on our reionization history. Our main findings on the evolution of the IGM and the 21-cm signal are summarized below:

(i) Using CXB data (in conjunction with UVLFs) and HERA upper limits, we constrain the evolution of the neutral IGM temperature T_{K} and find that the IGM is heated to at most $T_{\text{K}} \sim 7.7$ K at $z = 15$ at 95 per cent credible interval (CI). At lower redshifts, it is heated to 2.5 K $\lesssim T_{\text{K}} \lesssim 66$ K at $z = 10$ and 20 K $\lesssim T_{\text{K}} \lesssim 2078$ K at $z = 6$ (as shown in Fig. 4 and Table 4).

(ii) Using CRB data (in conjunction with UVLFs) and HERA upper limits, we constrain the radio background temperature at the rest-frame 21-cm wavelength, $T_{\text{rad}}(\nu_{21})$, to $\lesssim 47$ K at $z = 15$ and $\lesssim 51$ K at $z = 10$ (compared to $T_{\text{CMB}} = 43.6$ K and 30.0 K respectively), reaching a maximum of $T_{\text{rad}} \lesssim 101$ K at $z = 6$ (compared to $T_{\text{CMB}} = 19.1$ K). These constraints rule out exotic models of radio galaxies producing deep 21-cm signals at $z \gtrsim 15$.

(iii) The combination of the above constraints in our joint analysis yields a constraint on the ratio of the 21-cm spin temperature to the radio background temperature, $T_{\text{S}}/T_{\text{rad}} \lesssim 0.5\text{--}0.8$ at $z = 12.5\text{--}15$. This has strong implications for the observability of the 21-cm signal.

(iv) We place the first lower limits on the 21-cm global signal absorption amplitude of -201 mK $\lesssim T_{21,\text{min}} \lesssim -68$ mK at 95 per cent CI, at $z \approx 10\text{--}16$. Furthermore, we rule out a depth of $\gtrsim -33$ mK at 99.99 per cent CI. The joint analysis also provides a lower limit on the 21-cm power spectrum at $z = 15$ and $k = 0.35$ hMpc $^{-1}$ of 8.7 mK $^2 \lesssim \Delta_{21}^2 \lesssim 197$ mK 2 at 95 per cent CI, as shown in Fig. 5.

(v) The above constraints assume that the same L_{X}/SFR and L_{r}/SFR relation holds for both Pop II and Pop III galaxies, and is fixed across redshifts. Furthermore, we do not include a flexible Pop III stellar model in this work (instead fixing their parameters to a some fiducial values). Although we expect our constraints on the 21-cm signal to change with a broader model, the prospects for placing such lower bounds on the 21-cm signal using multiwavelength synergies remain promising.

(vi) The results are robust to the inclusion/exclusion of high- z UVLF data from *JWST*, except for a marginal shift in the timing of the absorption trough to earlier epochs by $\Delta z \sim 0.5$ if they are included. Similarly, the inclusion of SARAS 3 does not significantly change the constraints except allowing for marginally earlier absorption trough, by $\Delta z \sim 0.5$, if excluded.

As the 21-cm community awaits independent verification of the EDGES global signal results (J. D. Bowman et al. 2018), and power spectrum experiments continue to place increasingly stringent upper limits (HERA Collaboration et al. 2023; F. G. Mertens et al. 2025; S. Munshi et al. 2025; C. D. Nunhokee et al. 2025), our work guides future observations by providing the first lower limit on the 21-cm signal, thus narrowing the discovery space. Our results also showcase the power of joint analyses using multiwavelength data sets, which can be extended in the future to include Population III parameters (e.g. H. Lazare et al. 2024; S. Pochinda et al. 2024; J. Cang et al. 2025; T. Gessey-Jones et al. 2025; O. Zvi Katz et al. 2025), or combined with other synergetic data sets from measurements of the neutral IGM fraction (e.g. Y. Qin et al. 2021, 2025; P. H. Sims et al. 2025), CMB observations (e.g. Q. Ma et al. 2018; P. La Plante et al. 2020; K. E. Kunze 2023; M. Zhou et al. 2025), line intensity mapping experiments (e.g. C. Heneka, A. Cooray & C. Feng 2017; C. S. Murmu, S. Majumdar & K. K. Datta 2021; G. Sun et al. 2023a; H. Fronenberg & A. Liu 2024) or cosmic near-infrared background measurements (e.g. X.-C. Mao 2014; G. Sun et al. 2021, 2025), to build a complete, self-consistent picture of the early Universe.

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DATA AVAILABILITY

The 30 000 simulations performed using 21CMSPACE, the trained emulators, the POLYCHORD chains, and other analysis scripts used in

this work can all be made available upon reasonable request to the corresponding author.

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APPENDIX A: SPECIAL CASES OF THE JOINT ANALYSIS

Fig. A1 shows the constraints on the astrophysical parameters from the joint analysis, similar to Fig. 1, but for special cases where we exclude specific datasets, and Fig. A2 shows the 21-cm global signal and power spectrum constraints.

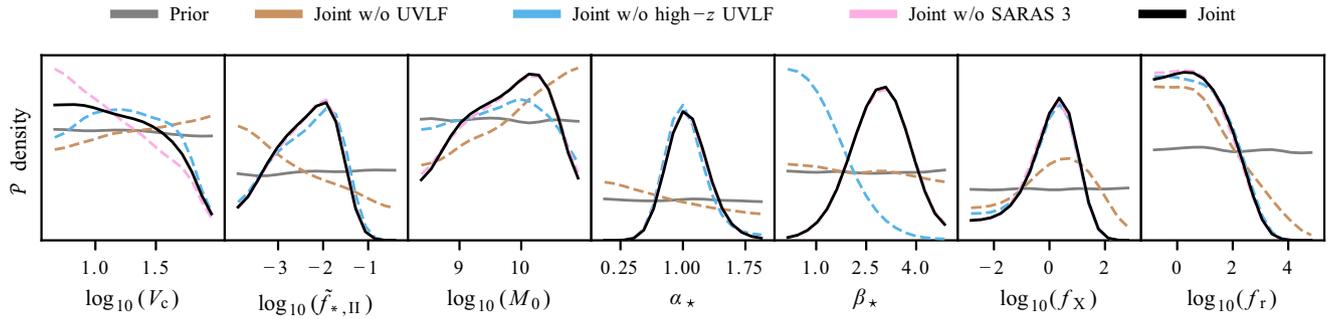


Figure A1. Same as Fig. 1, but for special cases of the joint analysis where we exclude specific data sets. Qualitatively, the inclusion of UVLF data is crucial for constraining the SFE and for more accurate constraints on f_X and f_r . The inclusion of high- z UVLF data gives preference to a redshift-evolving SFE (i.e. $\beta_* > 0$). Finally, SARAS 3 data disfavours efficient star formation in molecular cooling haloes (i.e. low V_c).

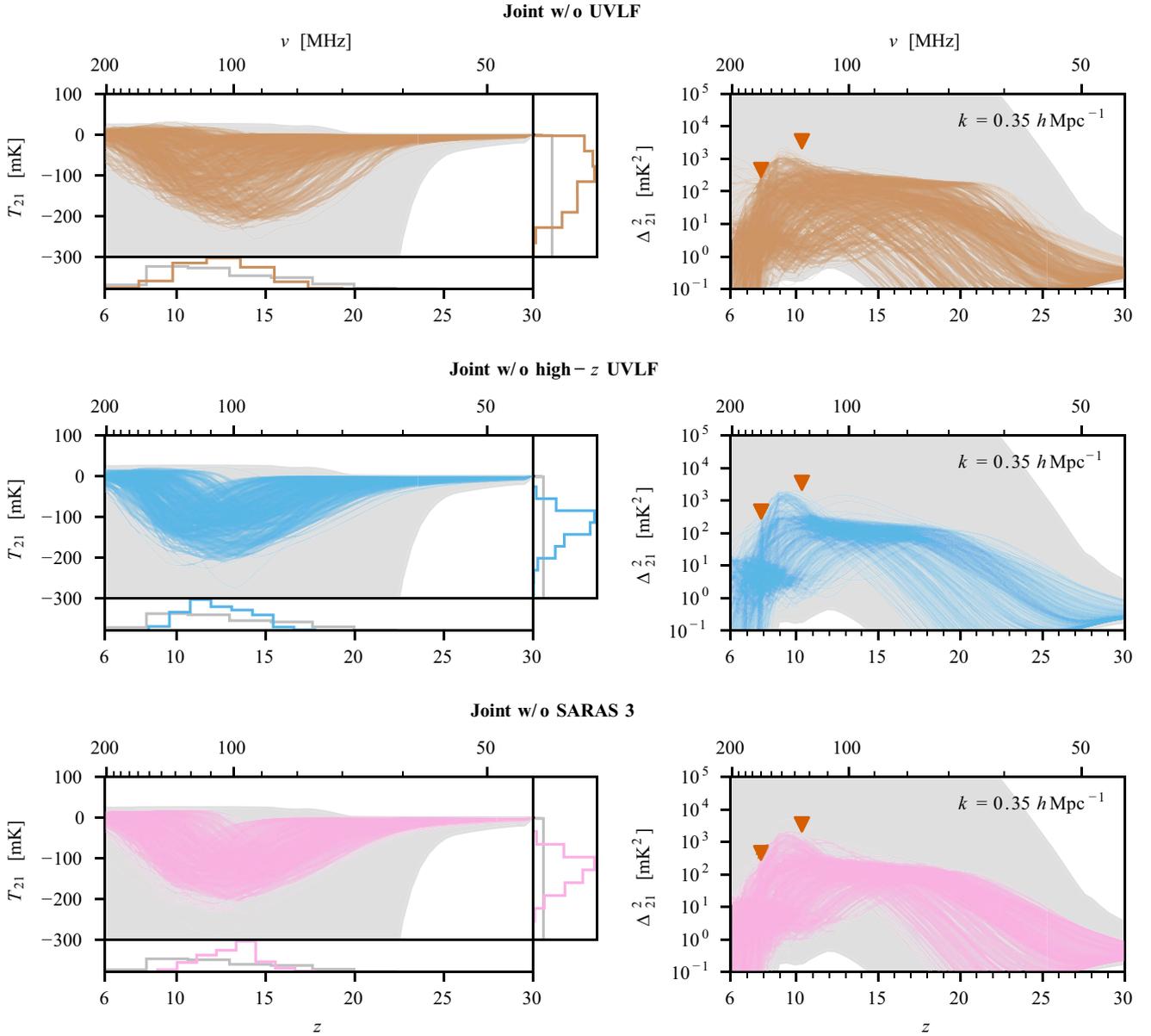


Figure A2. Same as the bottom row of Fig. 5, but for special cases of the joint analysis where we exclude specific data sets.

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