Exploring the Cosmic Reionization using an efficient SCRIPT

Barun Maity, *NCRA-TIFR*

collaborators: **Tirthankar Roy Choudhury (NCRA-TIFR), Aseem Paranjape (IUCAA)**

@Shedding new light on the first billion years of the Universe, Merseille, France

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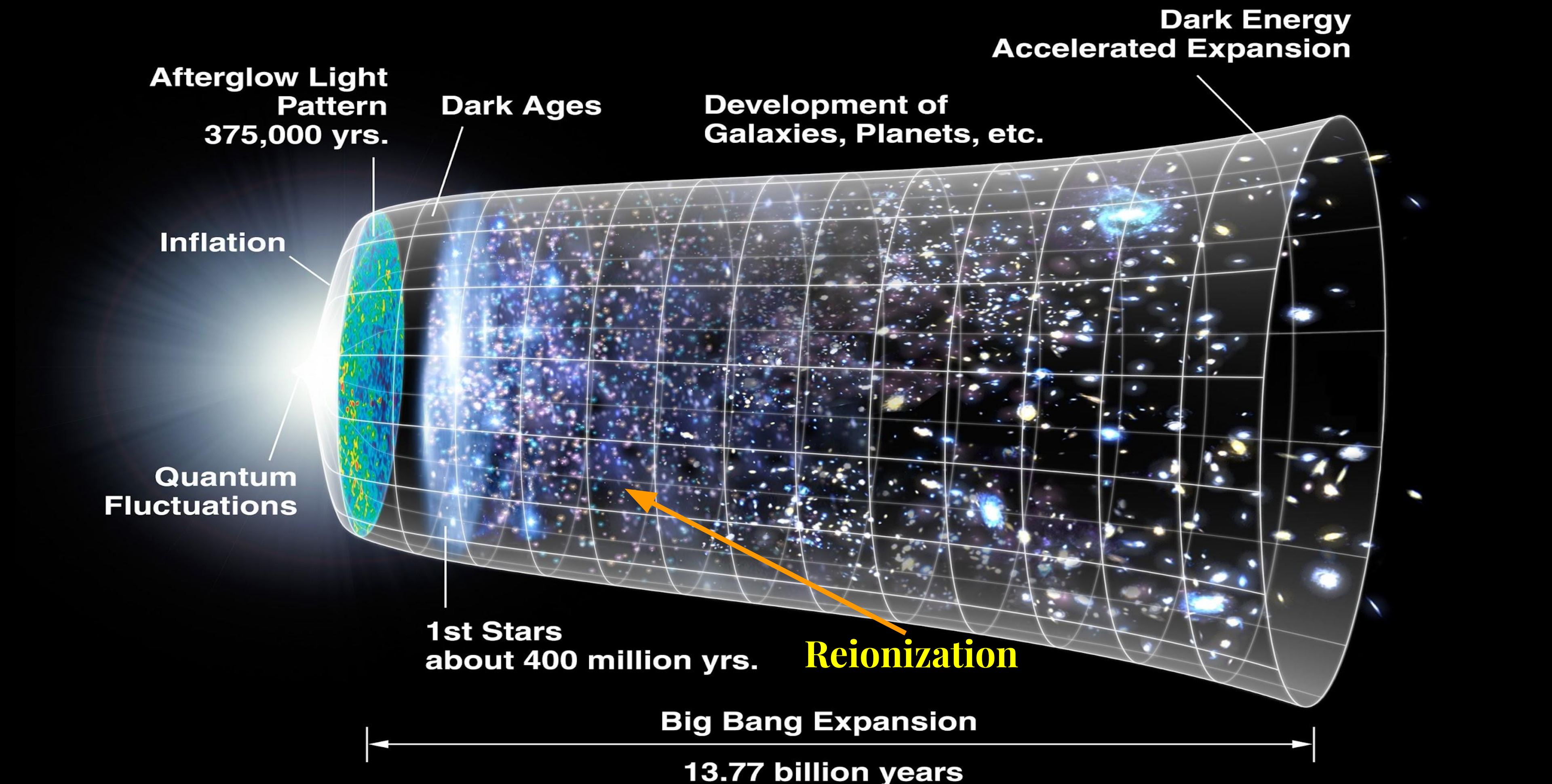
History of the Universe

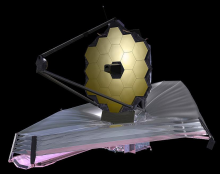


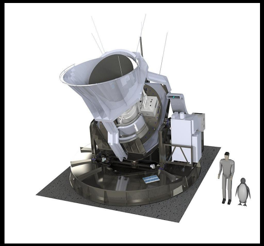
Courtesy: *NASA / WMAP Science Team*

Motivations behind the work

- **Uncertainties:** precise reionization end, duration, nature of ionizing sources, etc ???

- **Bright Observational Prospects:**
  - UV luminosity functions *(HST, JWST, TMT etc.);*
  - Quasar absorption spectra *(JWST, GMT etc.);*
  - CMB observations *(CMB-S4, Simons obs etc.);*
  - Redshifted 21 cm signal *(SKA, HERA, LOFAR, MWA etc.);*



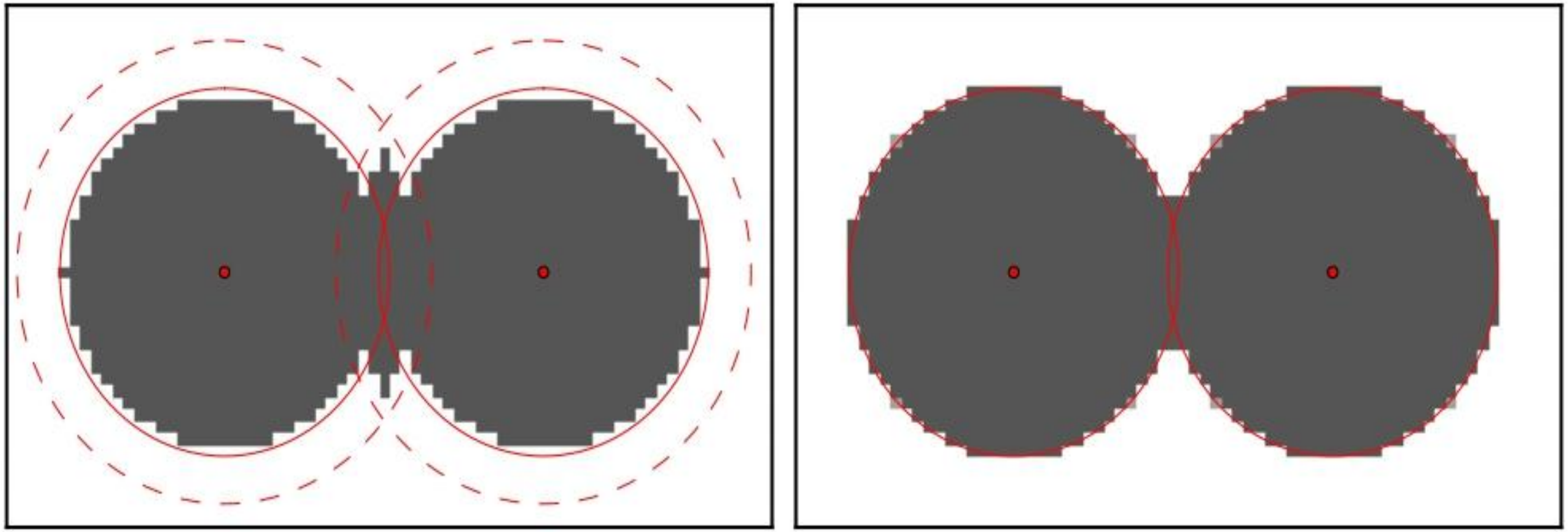


- **Importance of Thermal Evolution:** check the prospects of thermal history of the IGM as a tracer of reionization.

- **Constraining parameter spaces:** efficient modelling ***(including various inhomogeneities)*** is needed to correctly interpret the observational data and constrain different uncertain parameters. (need of semi numerical models)

What is SCRIPT?

- **SCRIPT: S*emi Numerical* C*ode for* R*eion*I*zation with* P*ho*T*on Conservation***



Photon number non-conserved

Photon number conserved

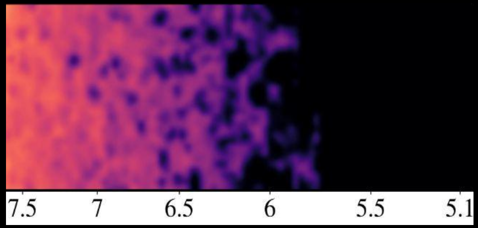
- Provides large scale convergence of power spectra with respect to the resolutions.

(Choudhury & Paranjape, MNRAS, 2018)

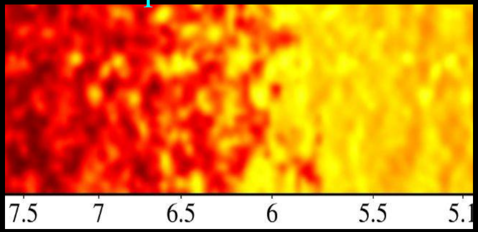
Physical Processes during Reionization

- ***Thermal Evolution of IGM:*** Reionization is associated with subsequent heating of the medium.

Ionization evolution



Temperature evolution



- ***Inhomogeneous Recombinations:*** Track the density evolution and ionization history of each cell in our simulation box to compute the recombination number density.

(Choudhury et al, 2009; Sobacchi & Mesinger, 2013)

Free Parameter $\Rightarrow$ C_{HII} ***(Clumping factor)***

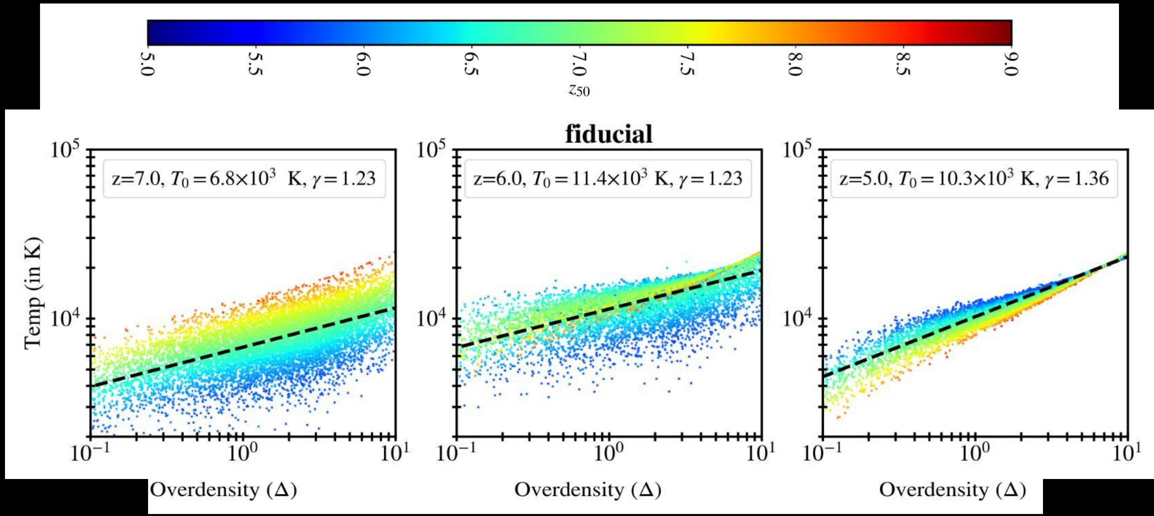
- ***Radiative Feedback:*** Inefficient star formation in lower mass halos due to excess radiation pressure *(a consequence of reionization heating).*

(Gnedin 2000; Illiev et al, 2007; Sobacchi & Mesinger, 2013)

Minimum threshold mass: temperature dependent ($\propto T^{3/2}$)

Temperature of low-density IGM

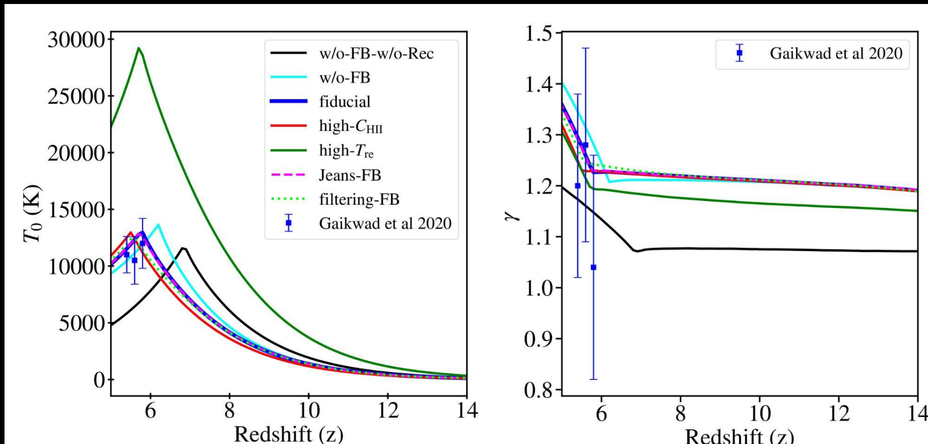
- Use subgrid physics to model low density IGM temperature.
- Shows a power law correlation between temperature and overdensity.
  $(T = T_0 \Delta^{\gamma-1})$
- Recombination is important in achieving the correlation.



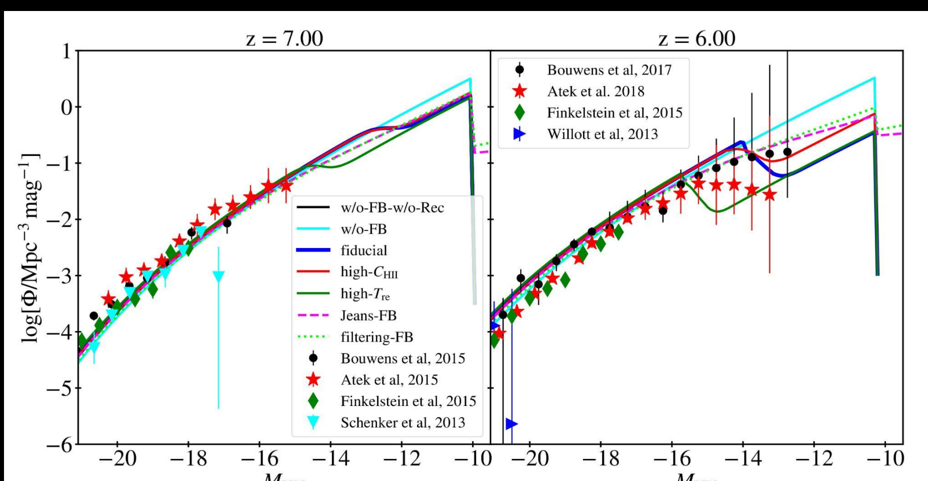
(Maity & Choudhury, MNRAS, 2022a)

A variety of observables:

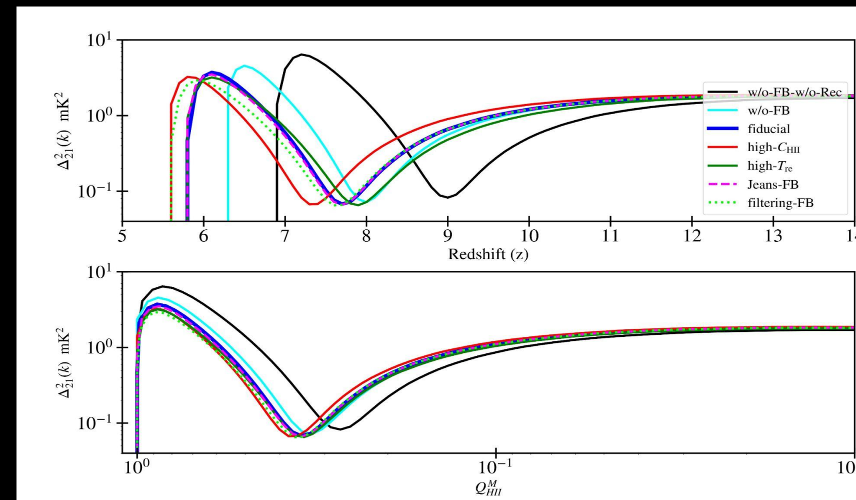
Temperature at low density IGM



UV Luminosity Functions



21 cm power spectra



(Maity & Choudhury, MNRAS, 2022a)

Parameter Explorations

- ***Free Parameters:***

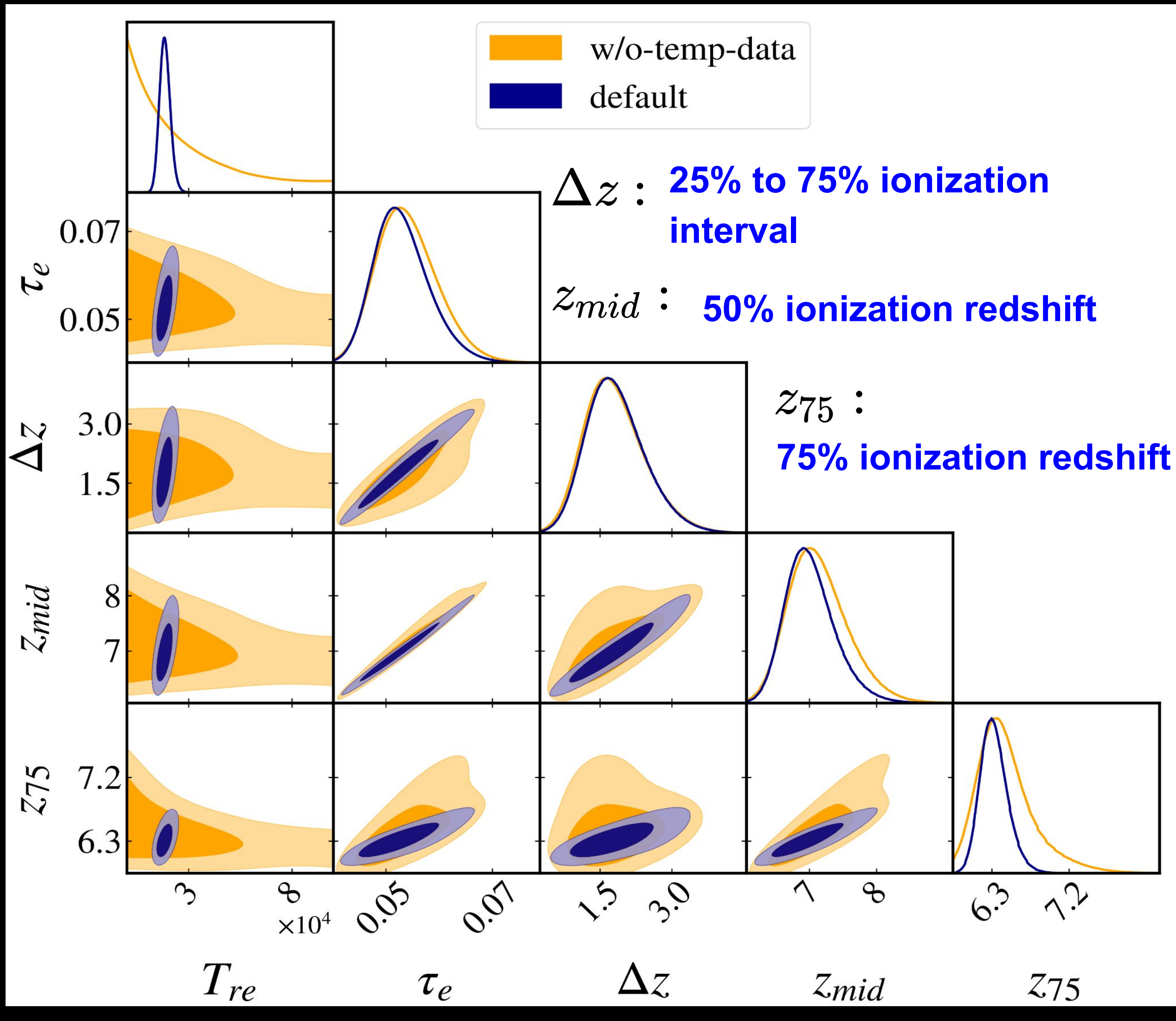
	Priors
Ionizing Efficiency: $\zeta(z) = \zeta_0 \left(\frac{10}{1+z}\right)^{\alpha}$	$\log \zeta_0 : [0, \infty]$ $\alpha : [-\infty, \infty]$
Escape fraction: $f_{esc}(M) = f^0_{esc} \left(\frac{M}{10^9 M_\odot}\right)^{\beta}$	$f^0_{\rm esc} : [0, 1]$ $\beta : [-1, 0]$
Reionization Temperature: T_{re}	$T_{\rm re} : [10^3, 10^5] K$

- ***Observational Constraints:***
  - **Model independent constraints on global ionization fraction** ***(McGreer et al, 2011)***
  - **CMB scattering optical depth** ***(PLANCK, 2018)***
  - **UV luminosity functions at redshifts 6 & 7** ***(Bouwens et al, 2015,2017)***
  - **Low density IGM temperature estimates** ***(Gaikwad et al, 2021)***
  - **Reionization is end by z=5.3** ***(Zhu et al, 2021; Bosman et al 2021)***

Parameter Exploration

- Reionization temperature increment is well constrained by the low density IGM temperature estimates.

- Improves the bounds on other parameters.



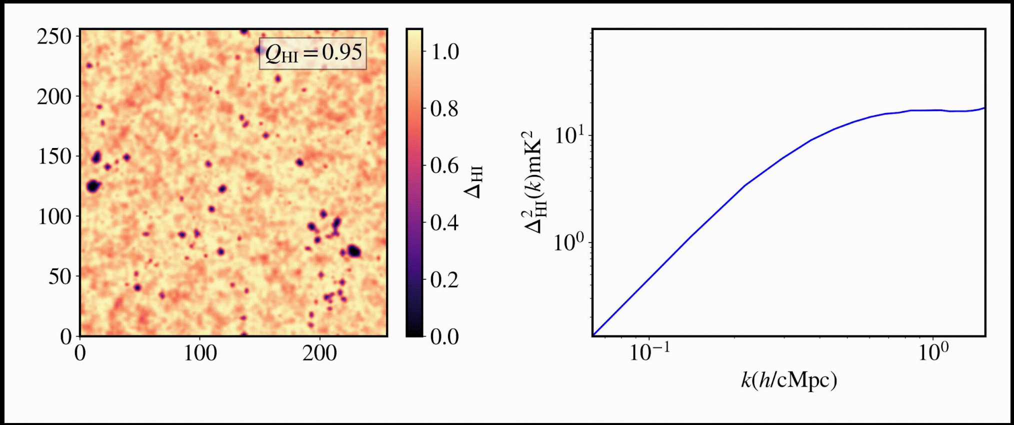
(Maity & Choudhury, MNRAS, 2022b)

Prospects of 21cm power spectra

- Start with the basic model without any recombination/feedback effects.

- Two free parameters
  - ionizing efficiency ζ
  - minimum threshold mass $M_{\rm min}$

An example of ionization snapshot using SCRIPT



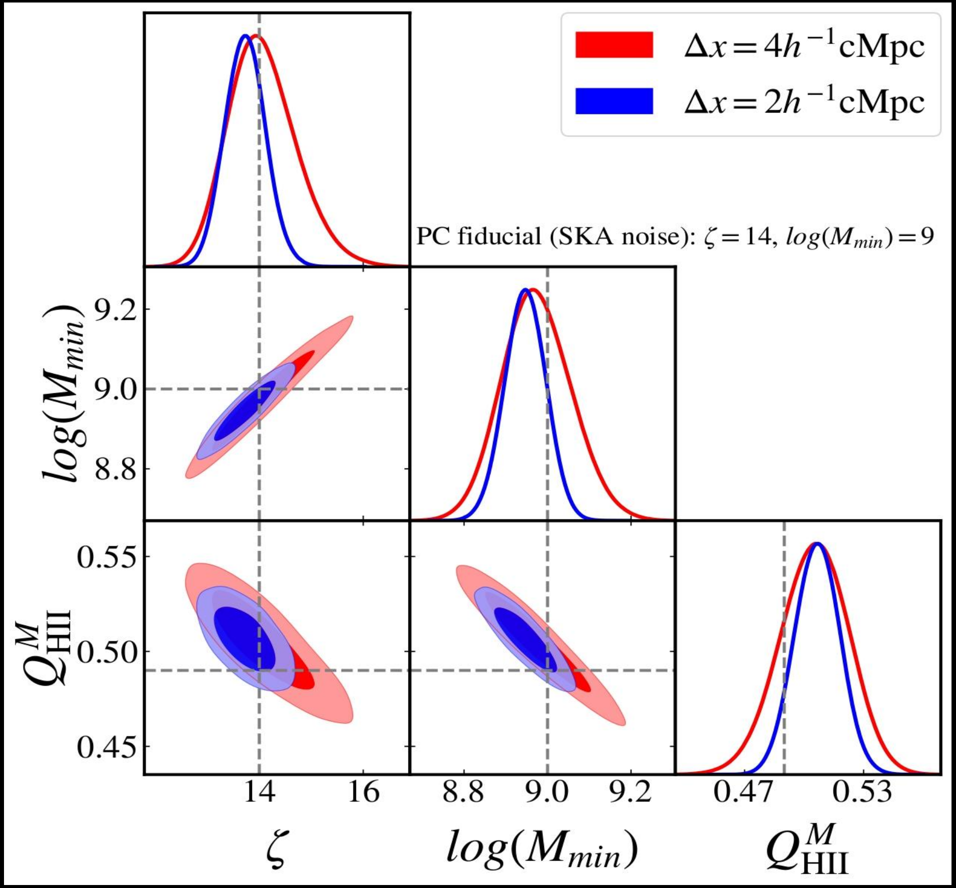
- Derived constraints on mass averaged ionization fraction $Q^M_{\rm HII}$

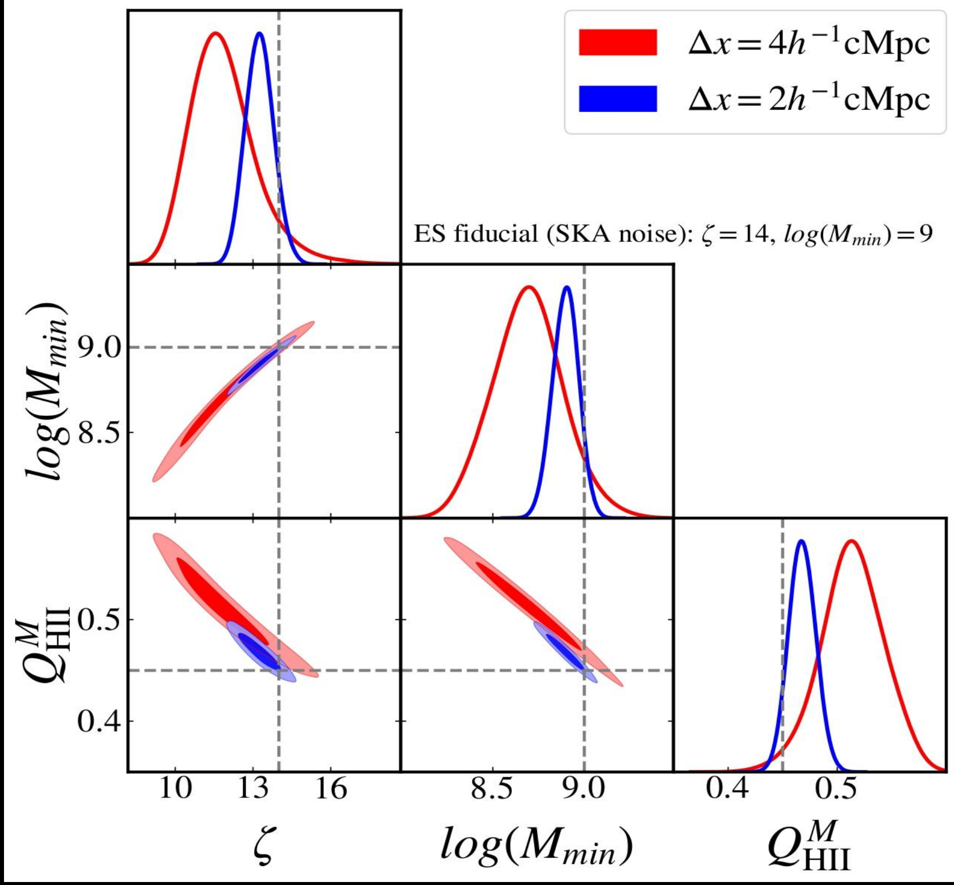
- Try to recover the input parameters from 21 cm mock power spectra independently with photon conserving model and excursion based approach.

Parameter Recoveries with 21 cm mocks

A comparison at z=7.0

(Maity & Choudhury, MNRAS, 2023)



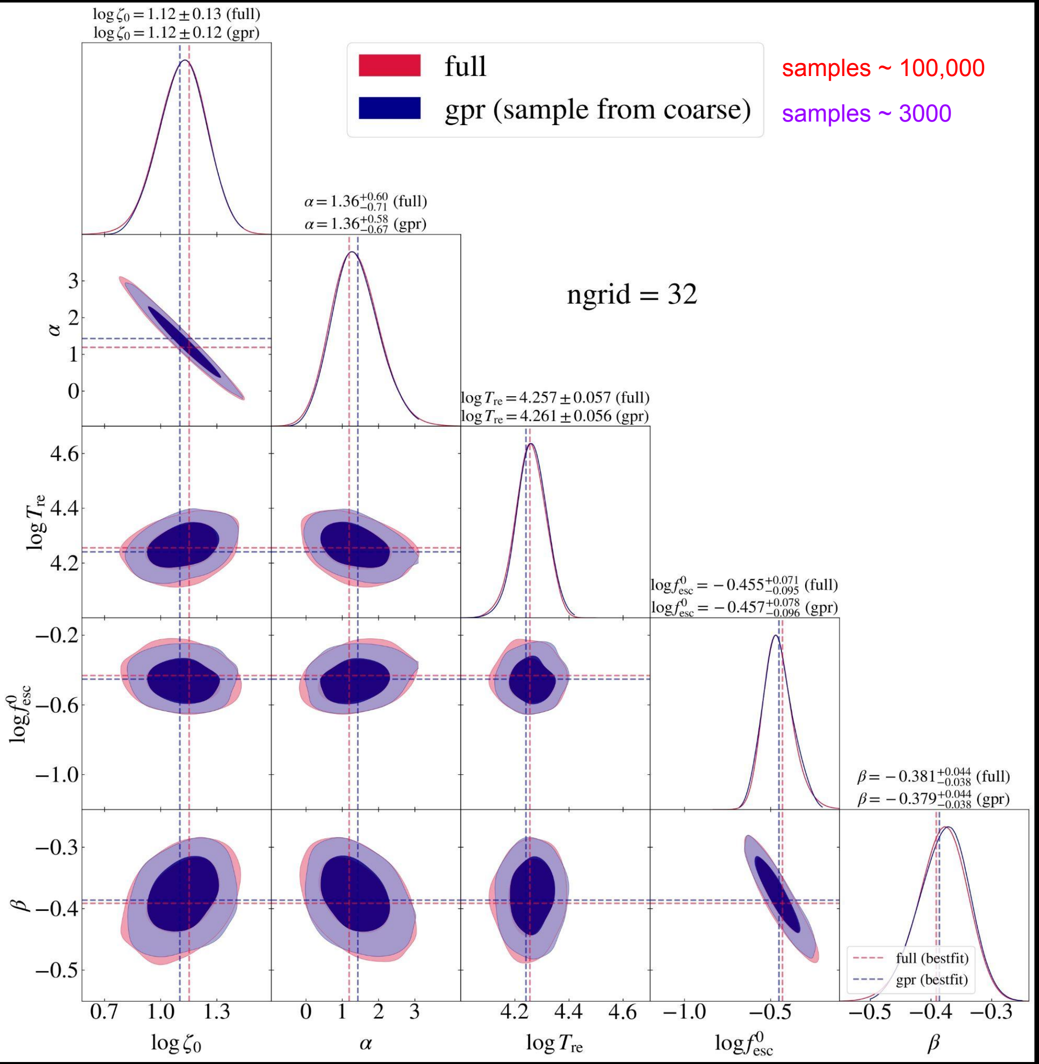


Quest for more efficient exploration

Likelihood Interpolator: A way out?

- Use coarse sample of parameter space (chi-square and parameters).
- Build up *likelihood interpolator* with coarse samples using Gaussian Process Regression (GPR). ***(Paranjape, 2022)***
- Fast MCMC with the interpolator.

(Maity, Paranjape & Choudhury, submitted to MNRAS, 2023)



Summary:

- Probing the thermal and ionization history of the universe
  - We probe the thermal evolution of IGM which is necessary to model radiative feedback.
  - We model the effects of inhomogeneous recombination during reionization using SCRIPT.
  - We check the effects on a variety of observables.
  - We can also use the low density IGM temperature estimates as a potential probe of reionization.
- Constraining the reionization era with available observations
  - The inclusion of temperature data tightens the parameter spaces.
  - Our default step feedback model prefers a late reionization end.
- Prospects of 21cm power spectra as a tracer of reionization
  - Photon number conservation can play a crucial role to correctly interpret the data.
  - Our simple model can reproduce the ionization state from the realistic mock.
- Quest is on for more efficient parameter exploration

Future Plans…

- Addition of more observables (like Ly-alpha power spectra)
- Extend the applicability of SCRIPT towards higher redshifts via modelling cosmic dawn physics (i.e x-ray heating, Ly-alpha coupling…)
- Simultaneous exploration of Cosmic Dawn and Epoch of Reionization

CD Observables:

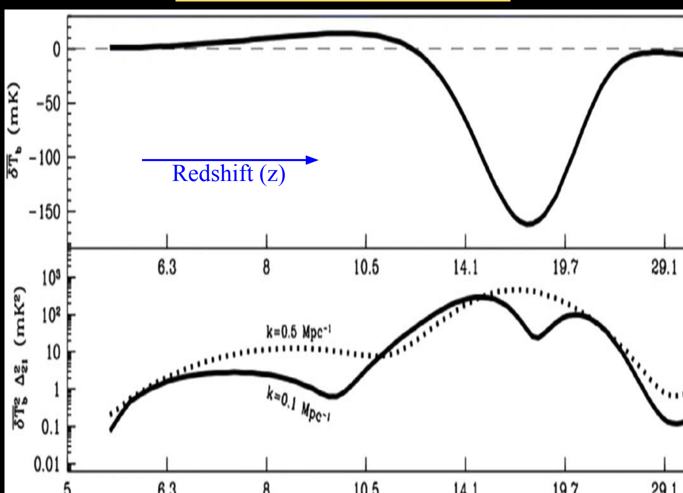


Image Credit: *Koopmans et al, 2021*

EoR Observables:

UV LF, low density IGM Temperature, CMB scattering optical depth, Ly-alpha…