TORRCH

Field-level reconstruction of reionization morphology from galaxy tracers

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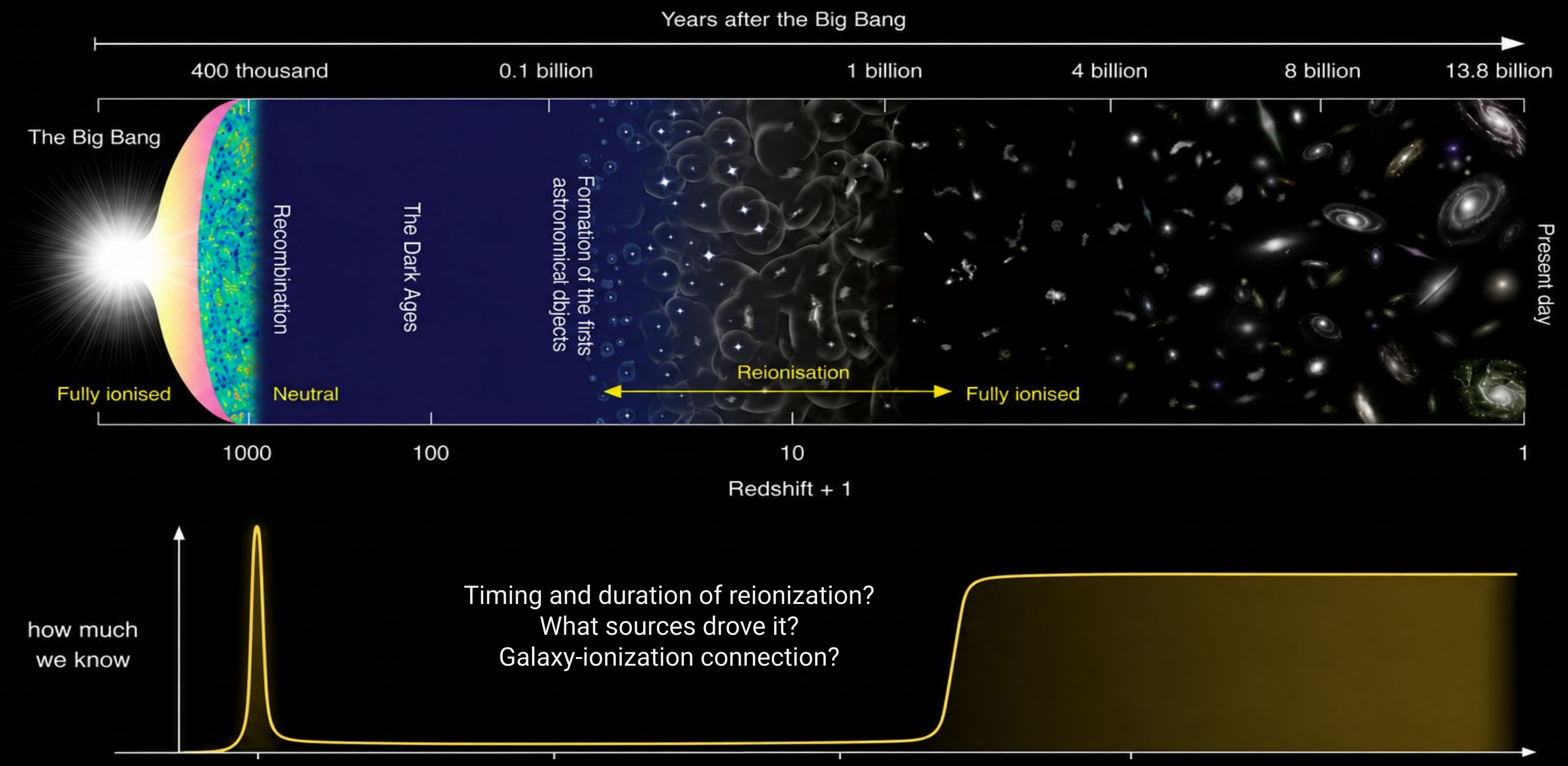
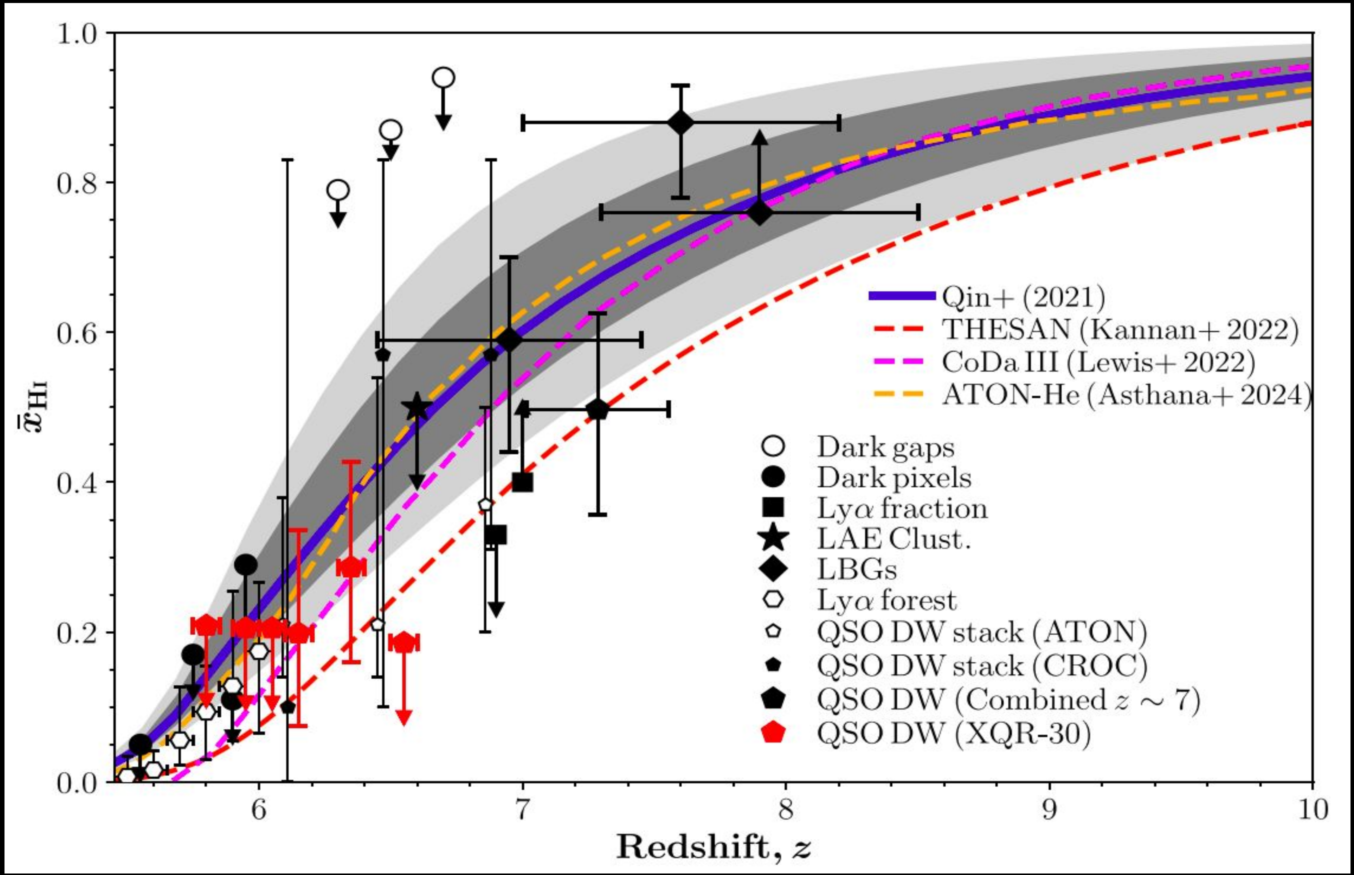
Reionization: A pivotal but poorly understood phase transition

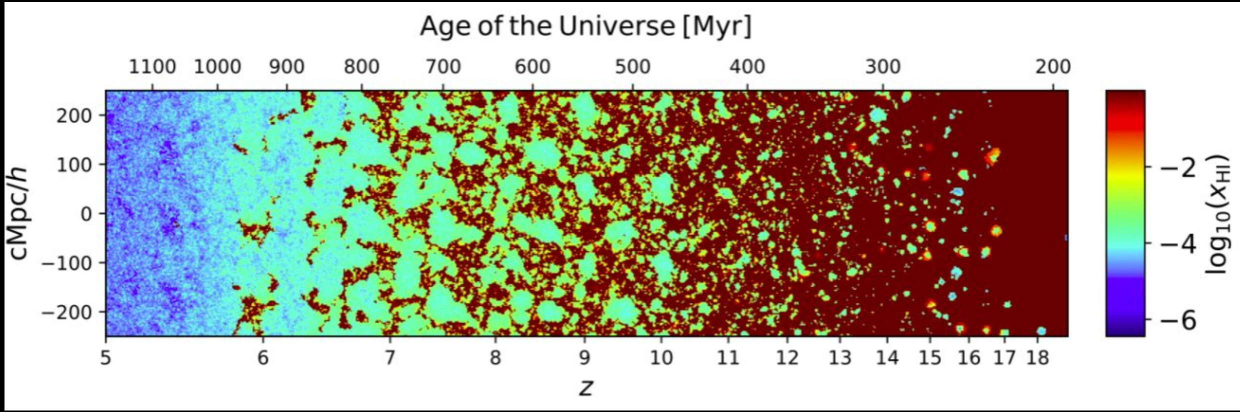


Our view of Reionization is still mostly global



Greig+2024

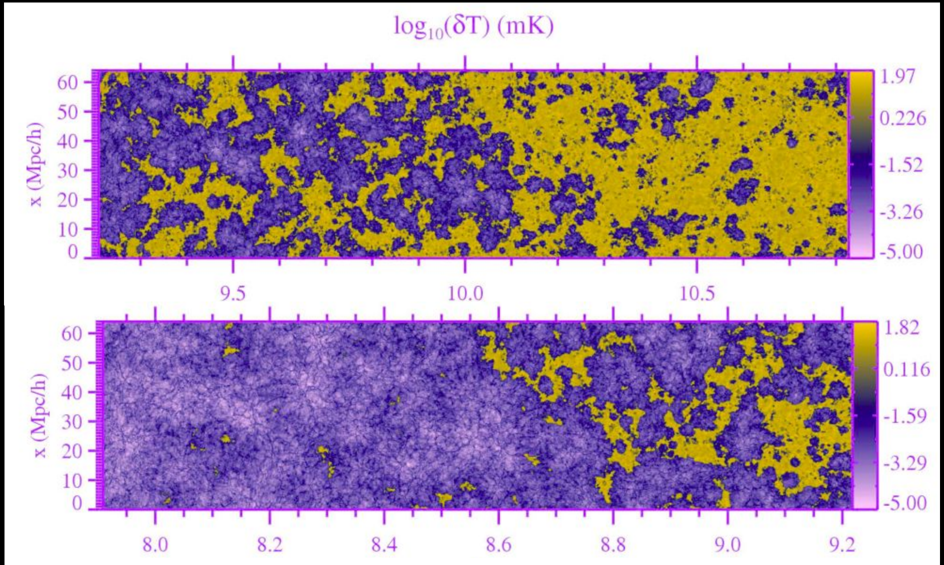
The Global Average Hides a Patchy Reionization Field



Asthana et al. 2024

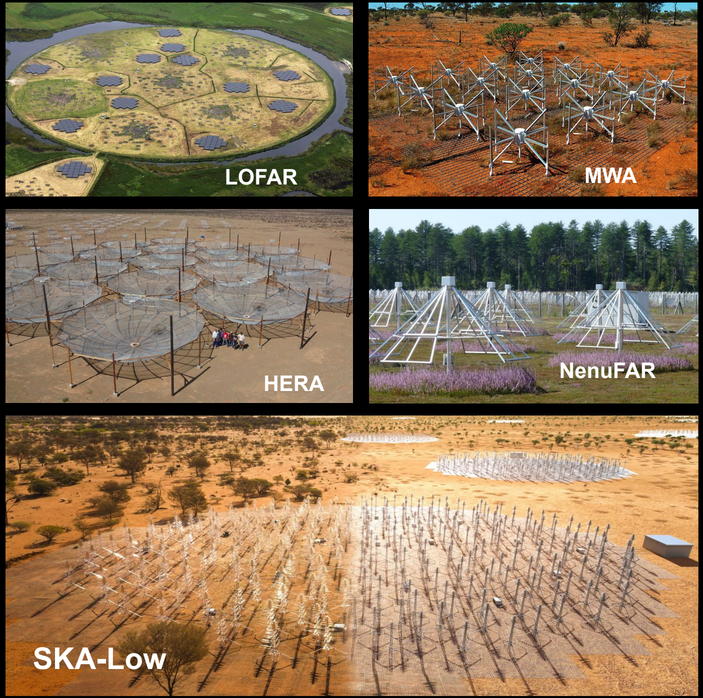
Morphology of the patchy reionization process is crucial in understanding what drove Reionization

The Next Frontier is Reionization Tomography



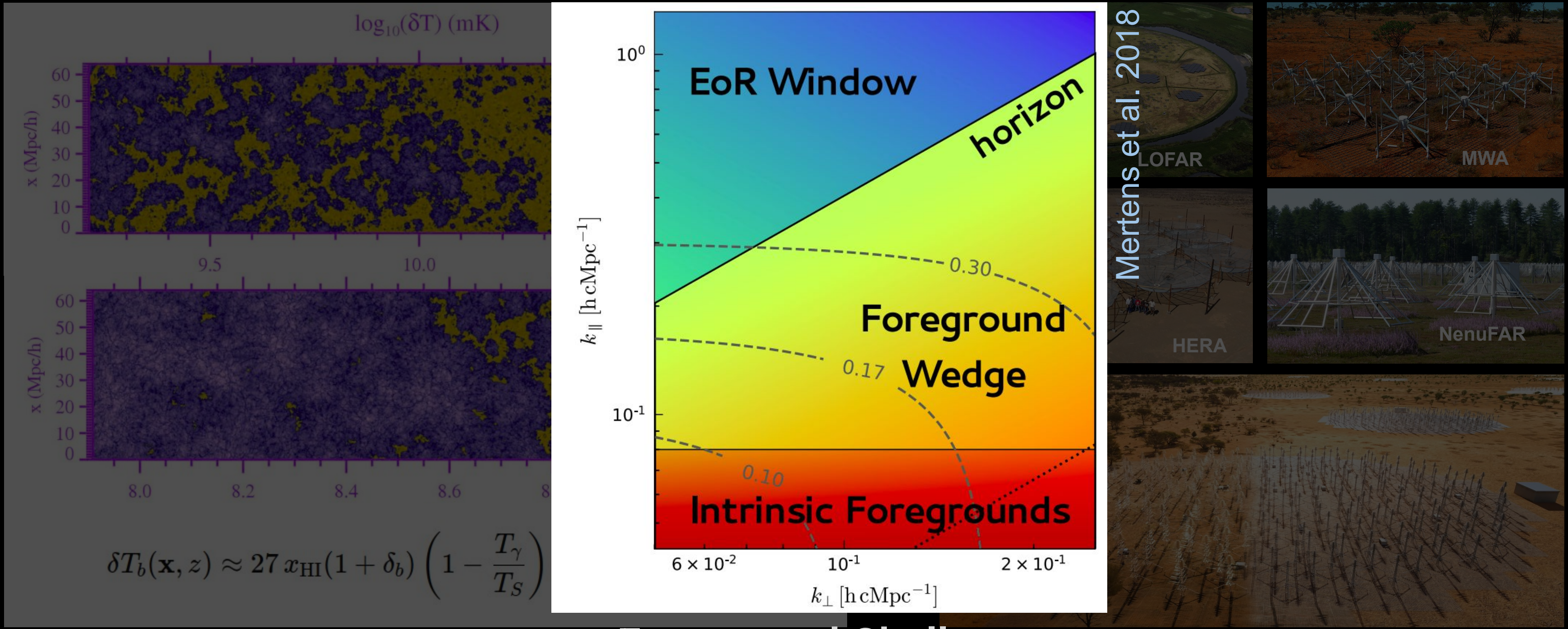
$$\delta T_b(\mathbf{x}, z) \approx 27\, x_{\rm HI}(1+\delta_b)\left(1-\frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\ \mathrm{mK}$$

Furlanetto et al. 2009



Major 21-cm experiments are pushing reionization studies beyond global averages and toward morphological studies and spatial mapping.

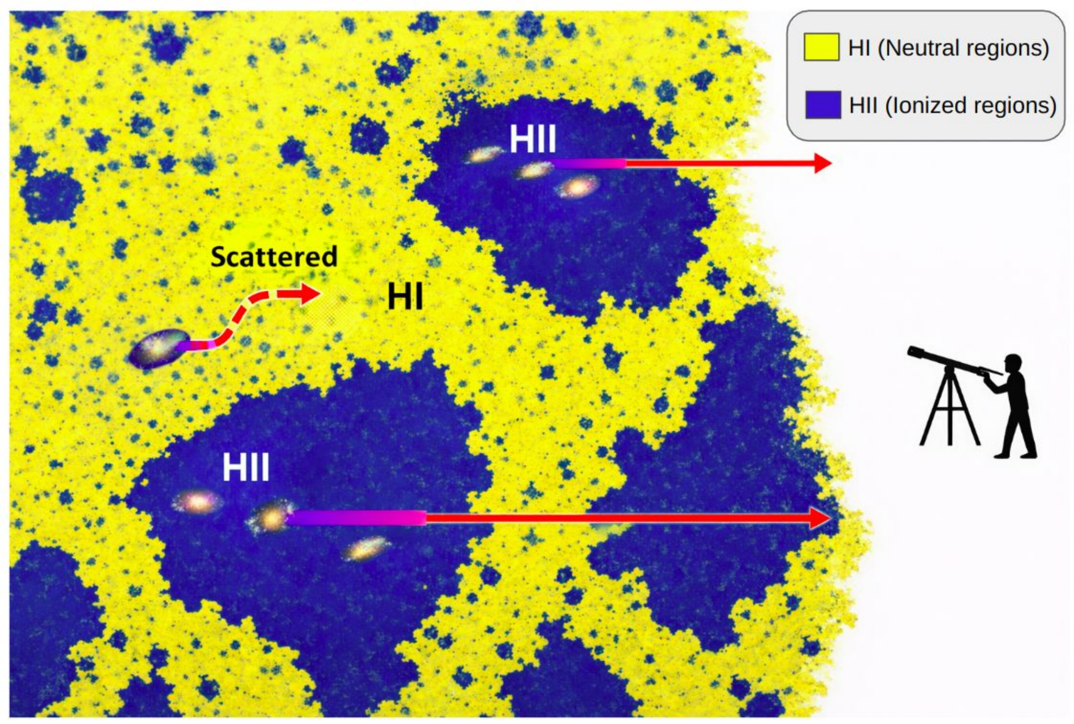
The Next Frontier is Reionization Tomography



Foreground Challenge

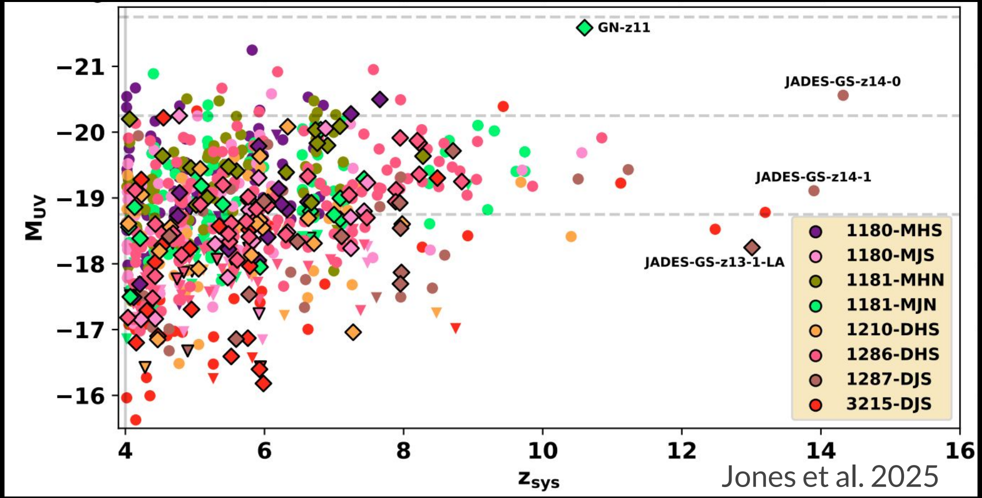
Major 21-cm experiments are pushing reionization studies beyond global averages and toward morphological studies and spatial mapping.

Galactic tracers of the Ionization Field



Lyman-α Emitters (LAEs)

Large sample of LAEs now available for Reionization studies!



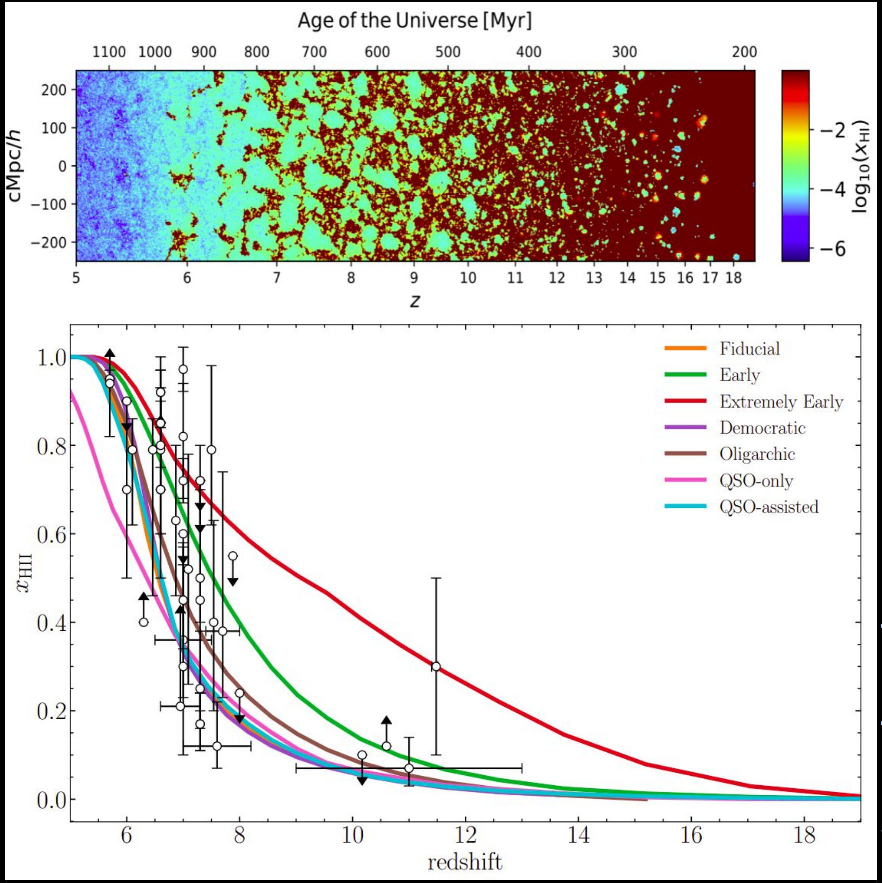
Survey	Instrument	Redshift Range	Area (deg^2)
SILVERRUSH	Subaru/HSC (NB)	2.2–7.3	~25
PFS-SSP	Subaru/PFS	5.7-6.6	~15
DAWN	NEWFIRM (NB)	7.7	~1
MUSE-Wide	VLT/MUSE (IFU)	2.9–6.7	~0.03
MUSE-HUDF	VLT/MUSE (IFU)	2.9–6.7	~0.003
LAGER	DECam (NB964)	6.9	~3
CIDER	NB964/NB1008	6–7.5	-
WERLS	Keck/MOSFIRE+LRIS	6–8	~0.7
MOONS	VLT/MOONS (Multi-object)	6–8.5	~1–2
CEERS	JWST/NIRSpec	6–9	~0.03
JADES	JWST/NIRSpec+NIRCam	5.8–8.0	~0.05
COSMOS-Web	JWST/NIRCam	6–11	0.54
Roman Grism	Roman Space Telescope	6–10+	~16

Field-level reconstruction of reionization from LAEs?

Step 1: Reionization Simulations

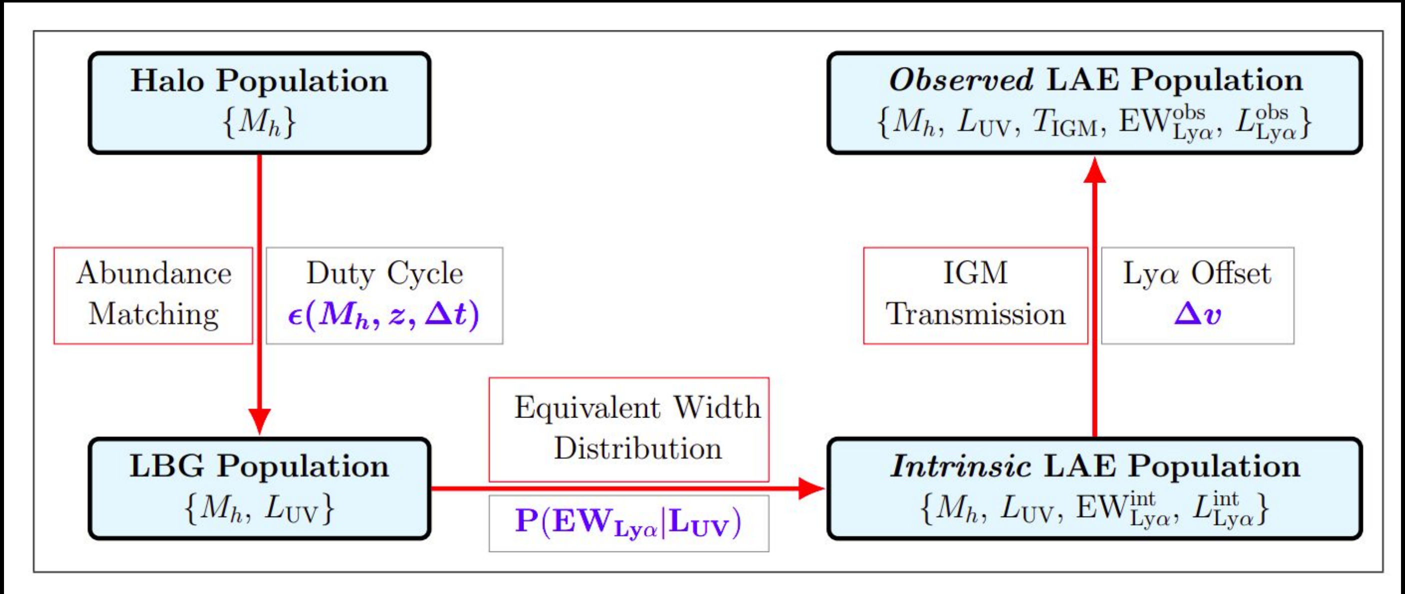
- P-GADGET3 for the hydrodynamic simulation (SHERWOOD Relic): $(160h^{-1}\mathrm{cMpc})^3$, 2 x 2048^3 particles

- ATON (Aubert & Teyssier 2008) and ATON-HE (Asthana et al. 2024b):
  Radiative transfer code for the thermal and ionization fields.



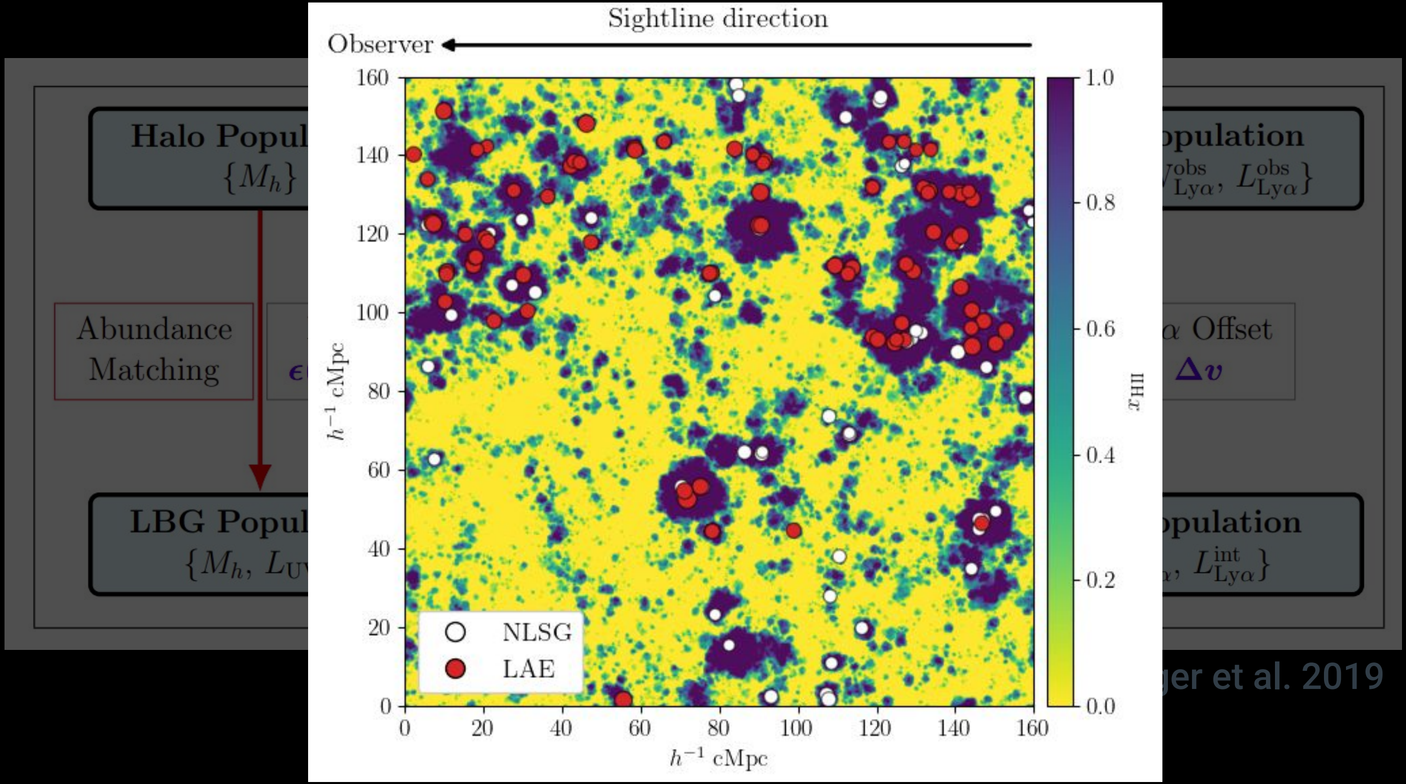
Maitra et al. 2025b

Step 2: Forward model for the LAEs



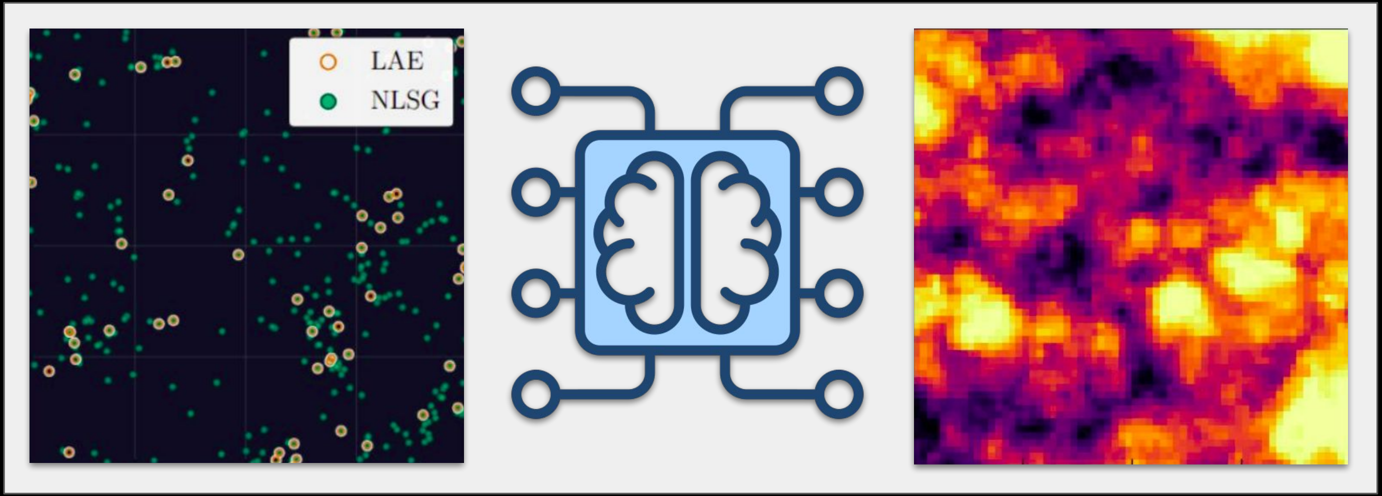
Weinberger+2019, Maitra+2025b

Step 2: Forward model for the LAEs

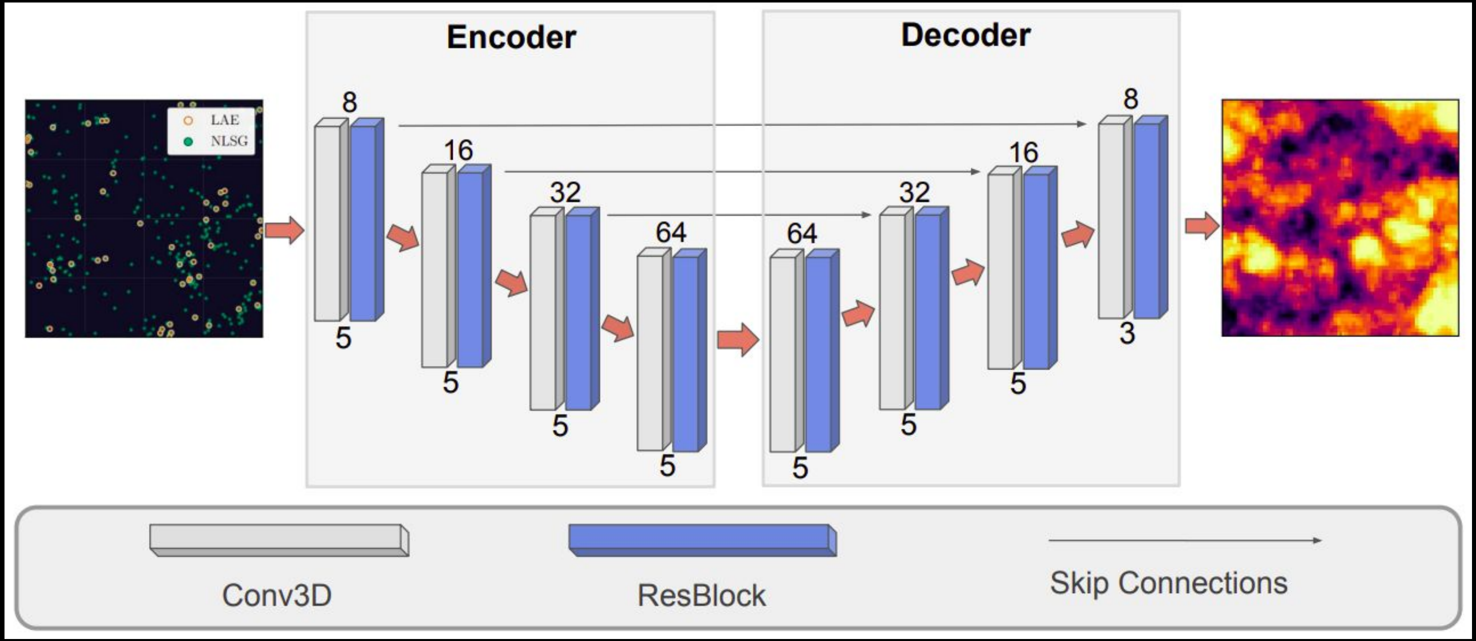


ger et al. 2019

Step 3: An intelligent tool for the tomographic inversion



TORRCH: TOmographic Reconstruction of the Reionization of Cosmic Hydrogen with Lyα emitters and non-Lyα-selected galaxies (z=7.14) [Maitra et al. 2026]



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Training sample:

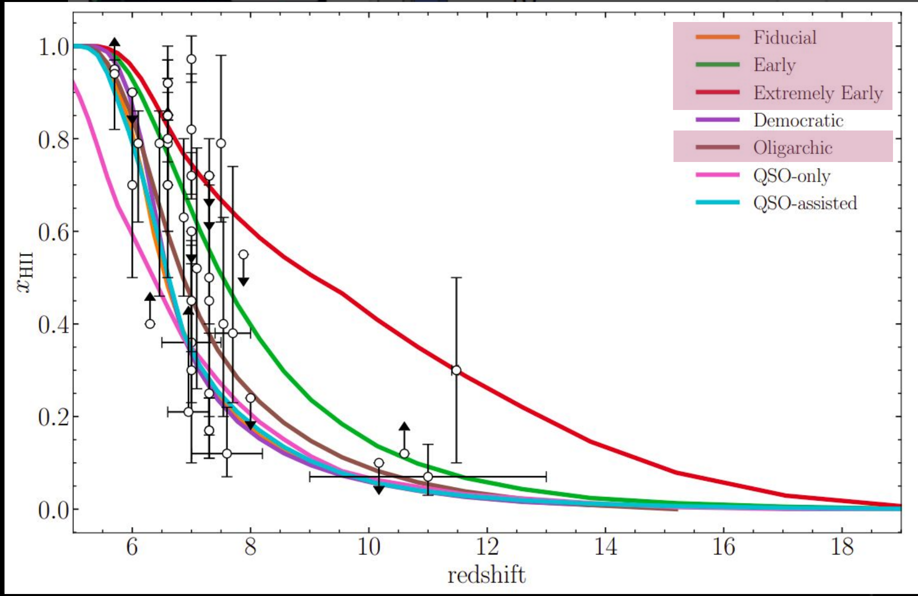

Table 1. Configurations of the three galaxy surveys considered in this work.

Survey type	$\log(L_{\rm Ly\alpha}/{\rm erg\,s^{-1}})$ cut	$M_{\rm UV}$ cut	Tracers included
Deep	> 41.5	< -18	LAEs + NLSGs
Shallow	> 42.5	< -19	LAEs + NLSGs
LAE-only	> 42.5	–	LAEs only

Loss | Heteroscedastic β-NLL

• $\hat{\mu}(\mathbf{x}) \equiv \hat{x}_{\rm HI}(\mathbf{x})$ (ionization field) • $\log \hat{\sigma}^2(\mathbf{x})$ (learned variance)

$$\mathcal{L}_{\beta\text{-NLL}} = \mathrm{sg}\left[\sigma^{2\beta}\right]\left[\frac{(x_{\rm HI}-\mu)^2}{2\sigma^2} + \frac{1}{2}\log\sigma^2\right]$$

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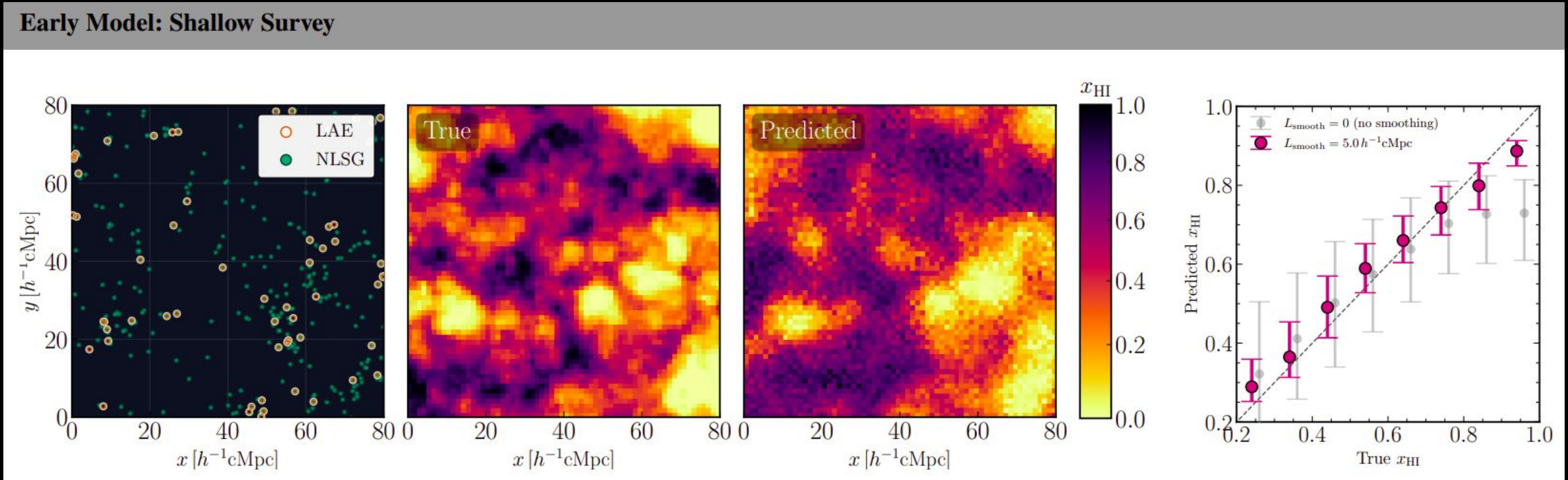
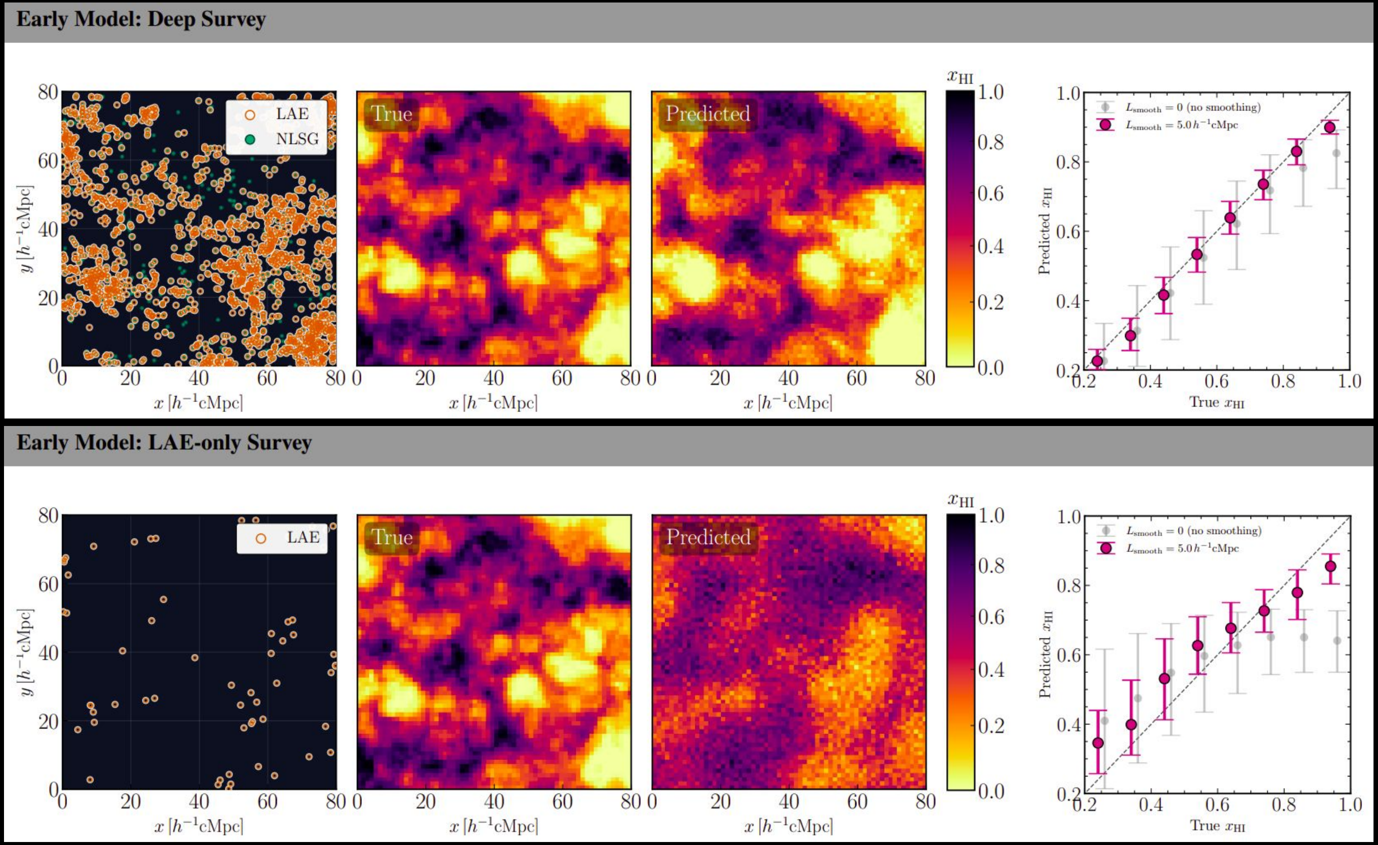
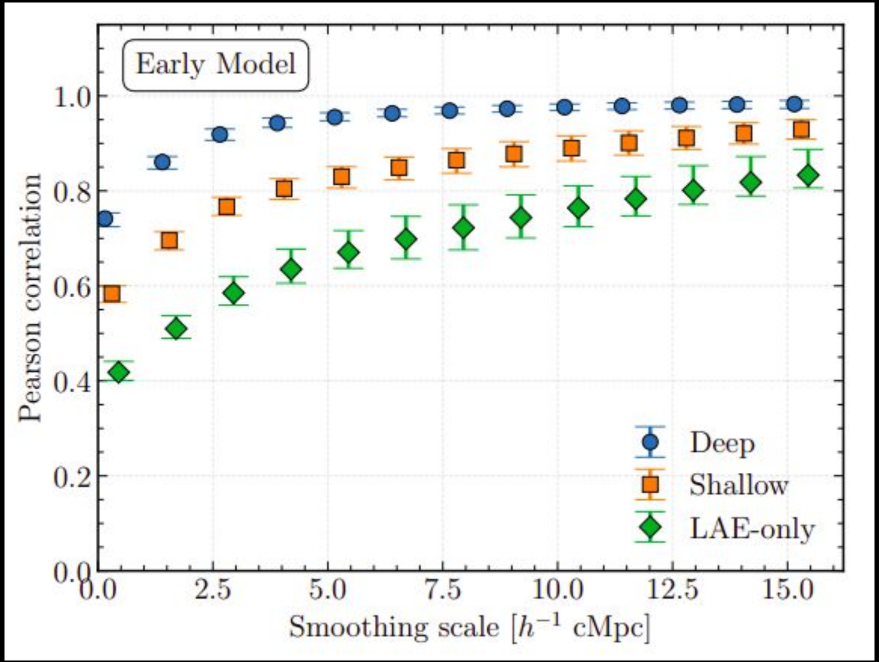


2D Projection with 30h^{-1}cMpc thickness.

TORRCH: TOmographic Reconstruction of the Reionization of Cosmic Hydrogen with Lyα emitters and non-Lyα-selected galaxies (z=7.14) [Maitra et al. 2026]



Reconstruction fidelity improves with scale



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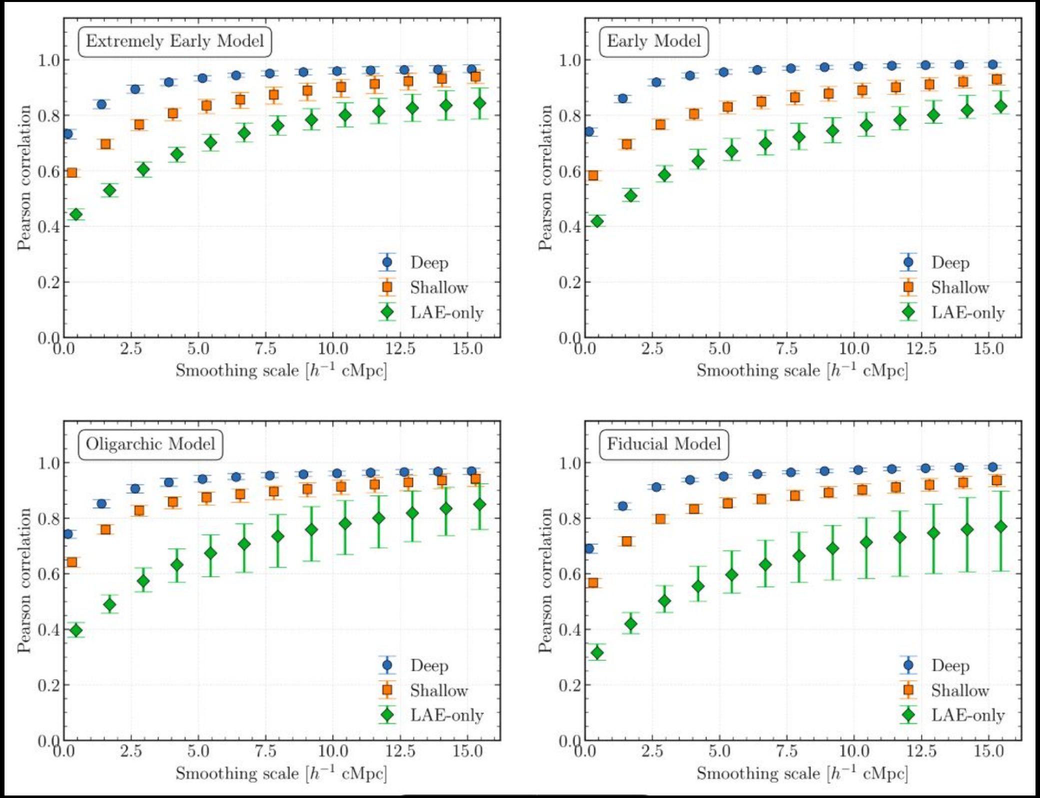
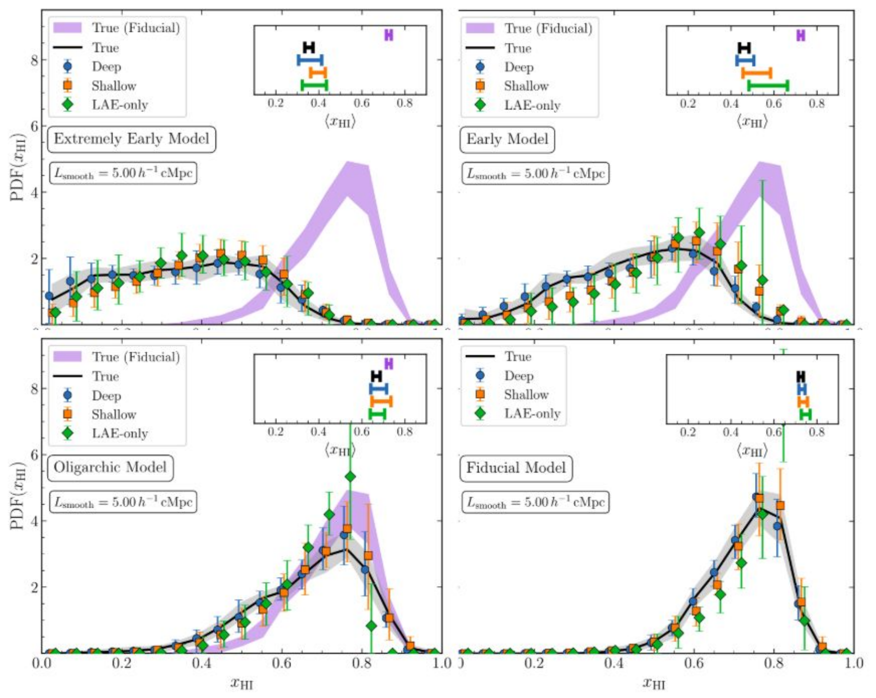
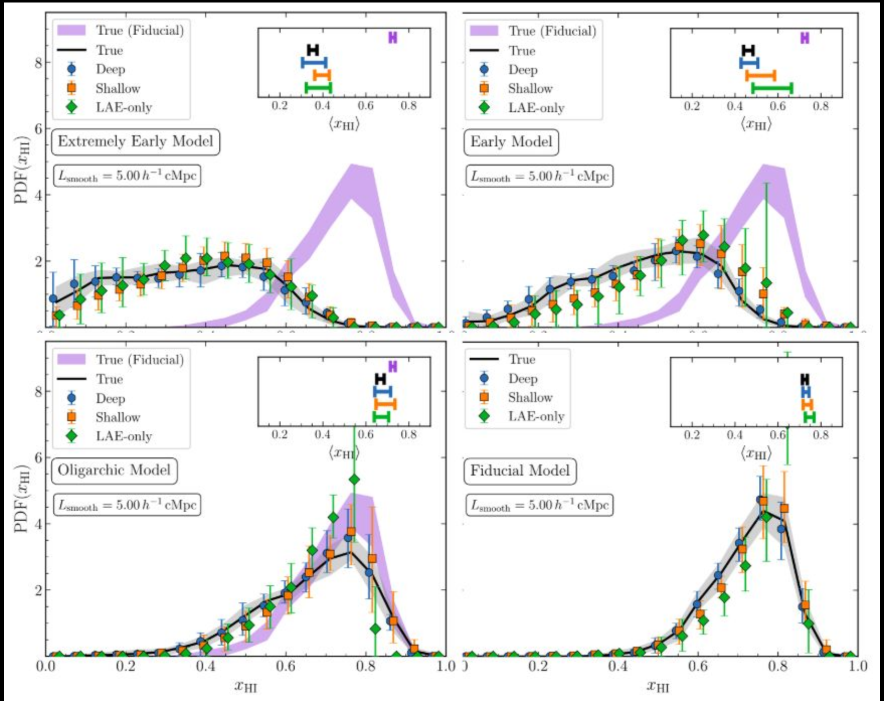


The summary statistics are well reproduced

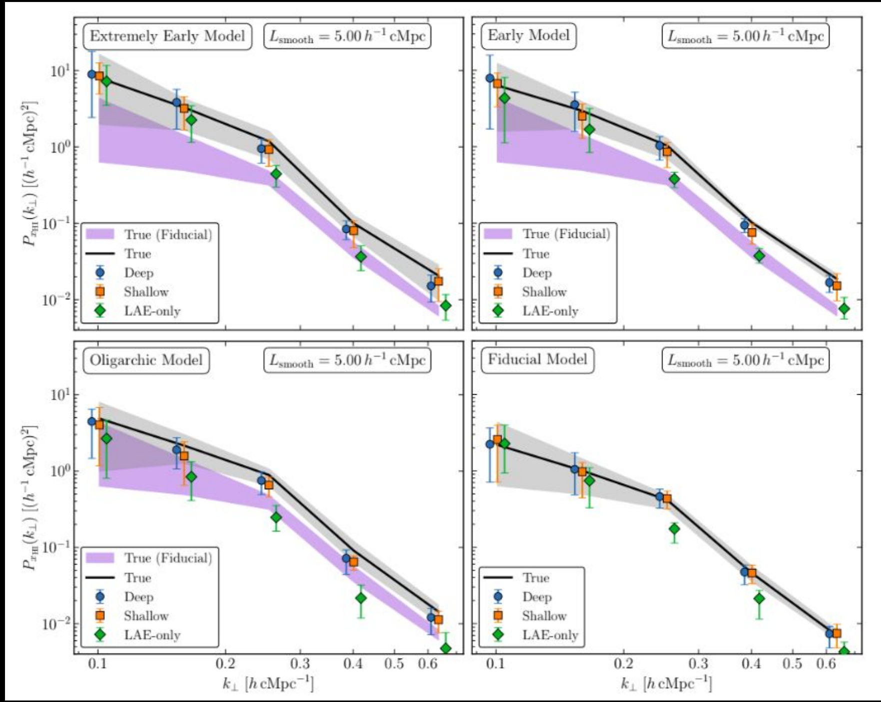


Probability distribution function

The summary statistics are well reproduced

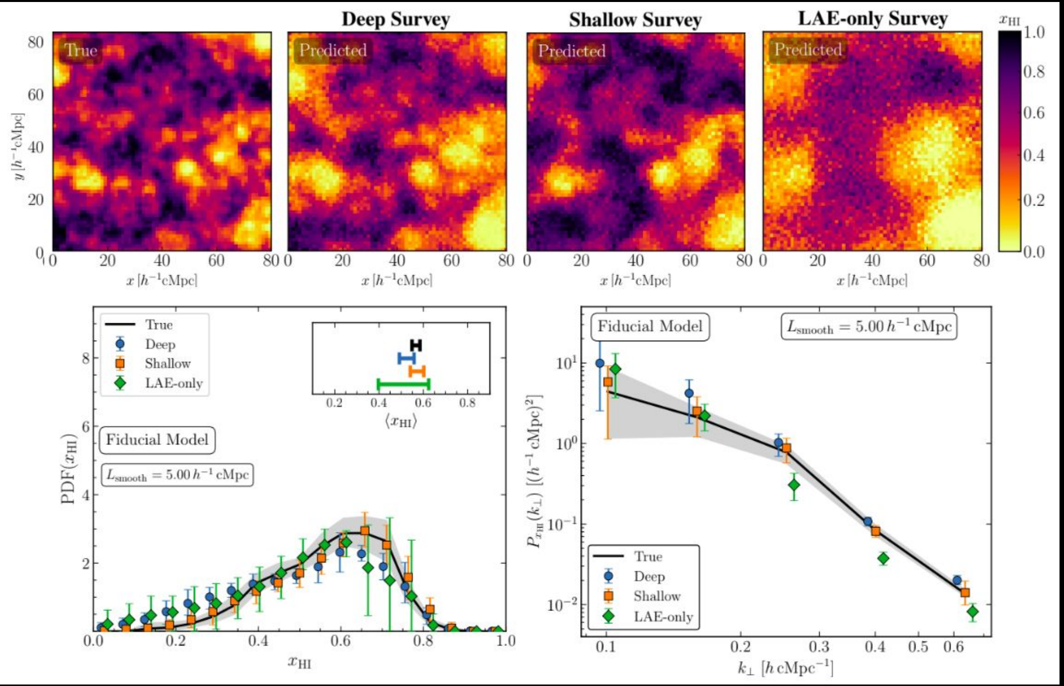


Probability distribution function



Power spectrum

Robustness check



Network trained at z=7.14 tested on z=6.6.

What we are currently working on

Modeling


Martin Haehnelt
KICC


James Bolton
U. Nottingham


Girish Kulkarni
TIFR


Laura Keating
U. Edinburgh


Matteo Viel
SISSA


Raghunathan
Srianand, IUCAA


Supriyo Saha
TIFR


Jahaan Thakkar
TIFR

- Intrinsic Lyα Luminosity/profile modeling.
- Larger simulation boxes.

Observation


Romain Meyer
Geneva Observatory


Koki Kakiichi
U. Copenhagen


Masami Ouchi
U.Tokyo


Hiroya Umeda
U.Tokyo


Yuta Kageura
U.Tokyo

- Data acquisition: JWST, Subaru
- Modeling the data systematics.

Machine Learning


Jatin Batra
TIFR


Dheeraj Nagaraj
Google DeepMind


Vipul Arora
KU Leuven


Parthe Pandit
IIT Bombay

- Reliable uncertainty estimation for predictions.
- Posterior with Generative algorithms.