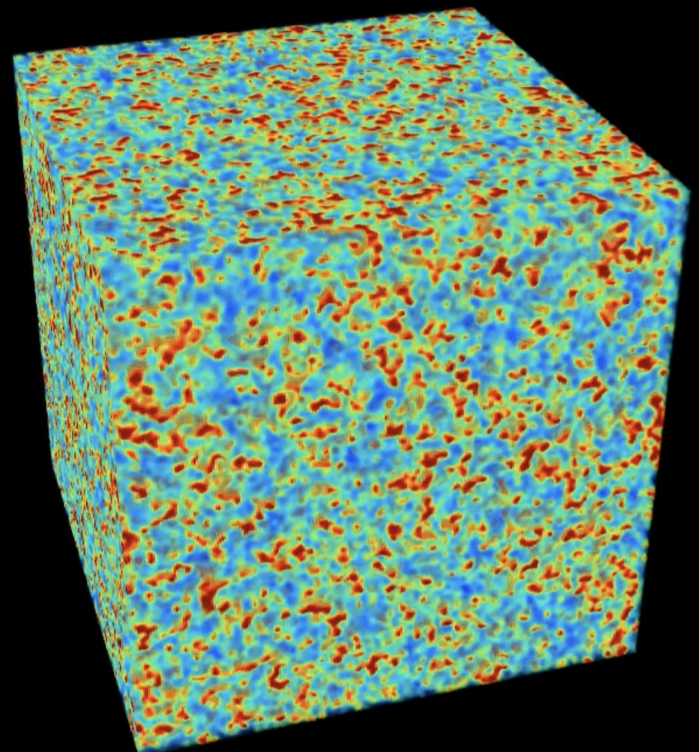
Inference of Reionization Parameters and Reconstruction of Cosmological Initial Density Field with Observations from the Epoch of Reionization

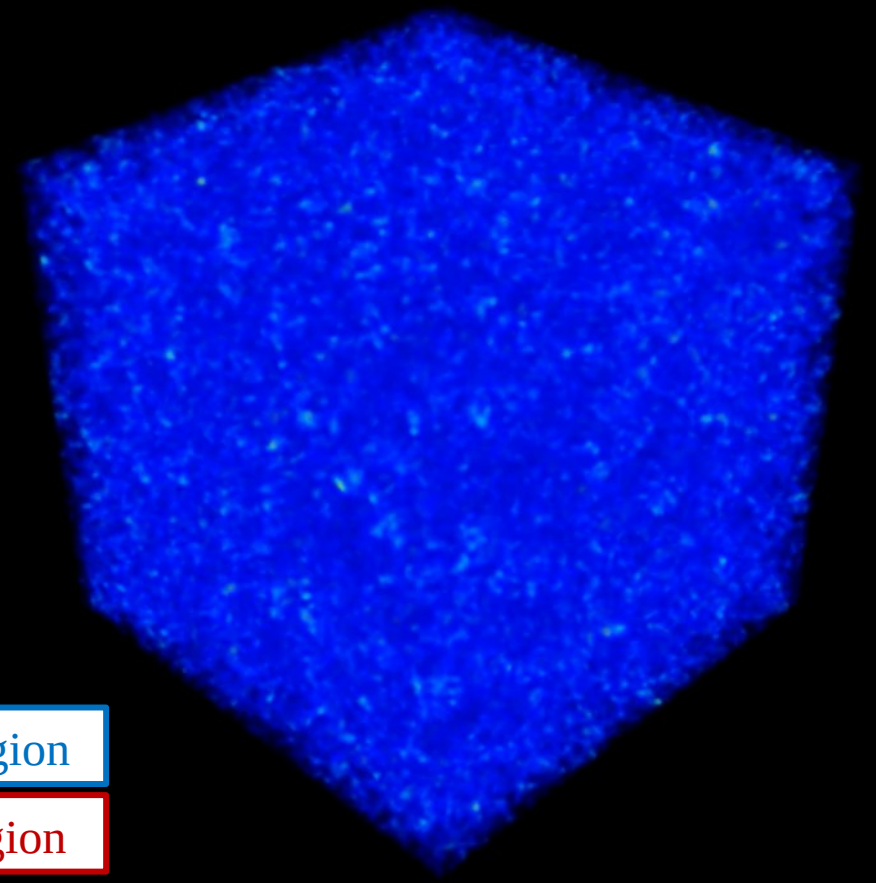
Yi Mao （茅奕）
Department of Astronomy
Tsinghua University （清华大学）

The 11th KIAS Workshop
on Cosmology and Structure Formation
October 28, 2024
Hilton Hotel, Gyeongju



清華大學天文系
Department of Astronomy, Tsinghua University

z=15.062 Epoch of Reionization (EoR)



HII
1.00
0.750
0.500
0.250
0.00

Blue: H I region

Red: H II region

Movie: Meng Zhou and Yi Mao using SIRIUS

Infant Universe
filled with ionized gas

380,000 years old

Dark Ages
filled with neutral gas

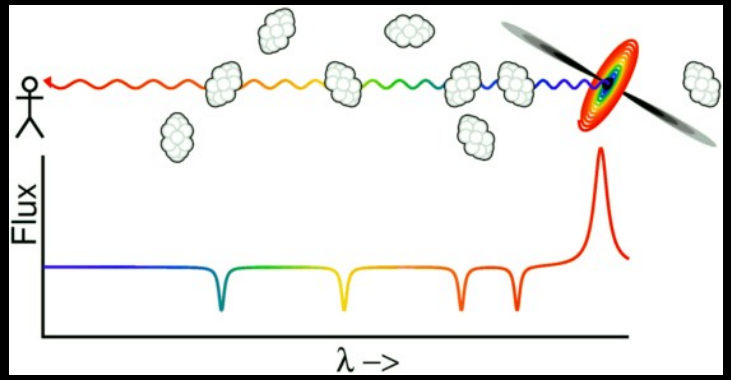
100,000,000 years old
First galaxies form
H atoms reionized
Epoch of Reionization
21 cm Line

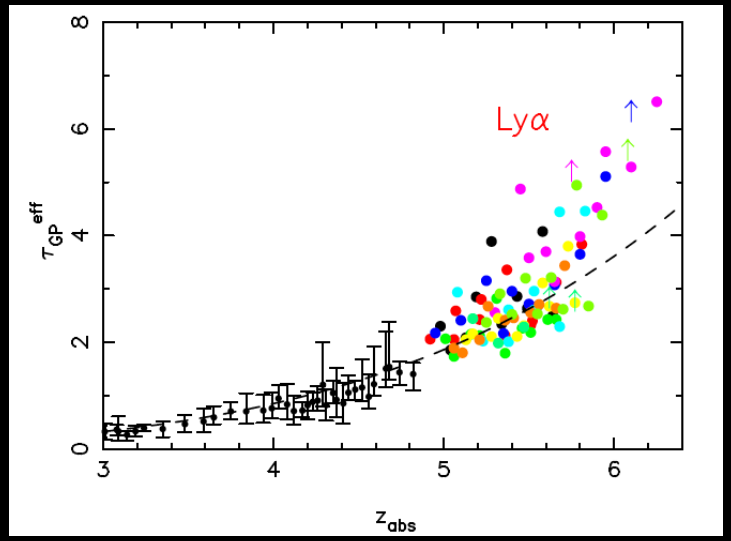
1,000,000,000 years old
Reionization ends

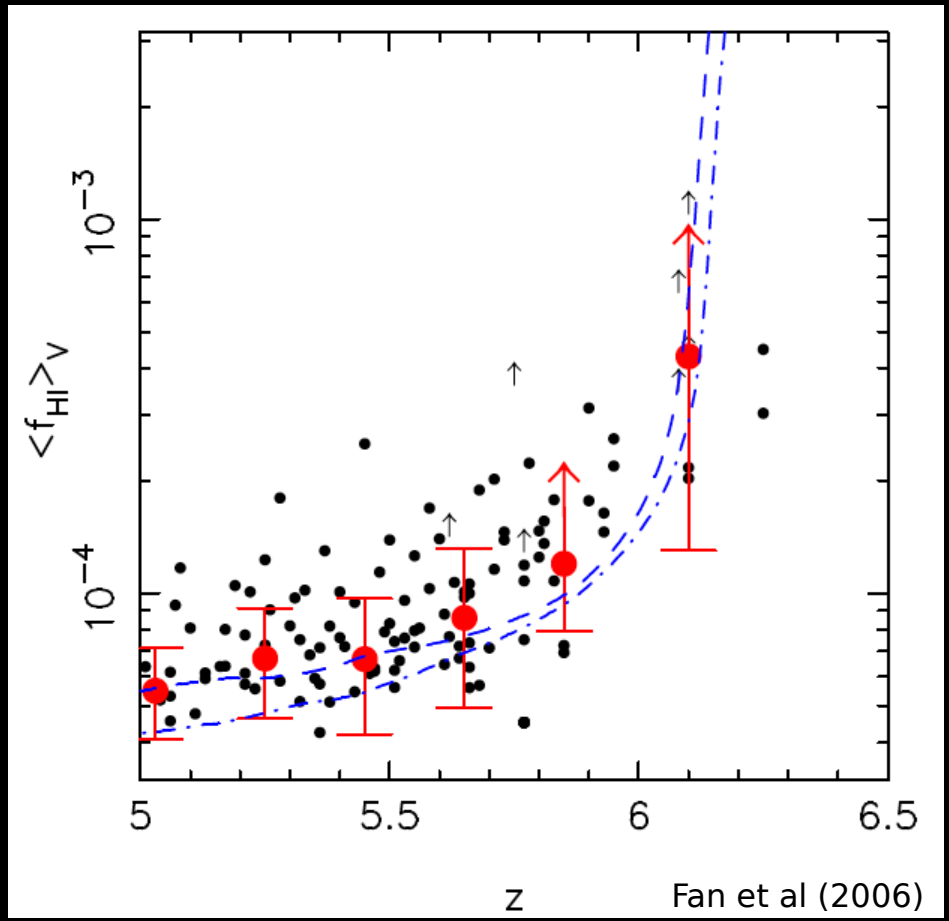
Today 13.8 Billion years

Indirect Probes of Cosmic Reionization

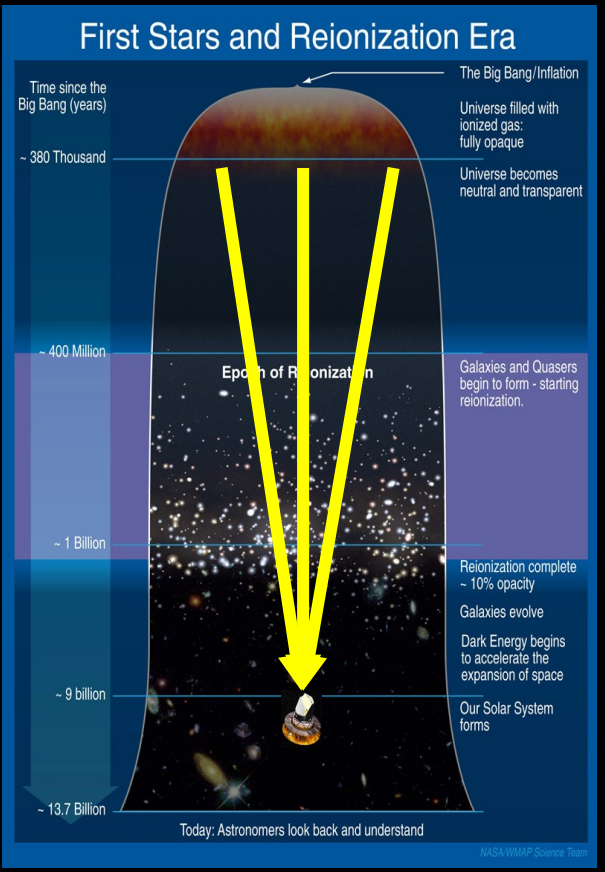
Cosmic Probe of EoR 1 - Lyα Forest: Reionization completed at z ~ 6



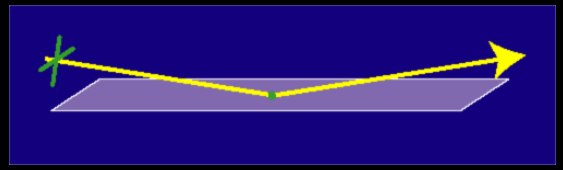


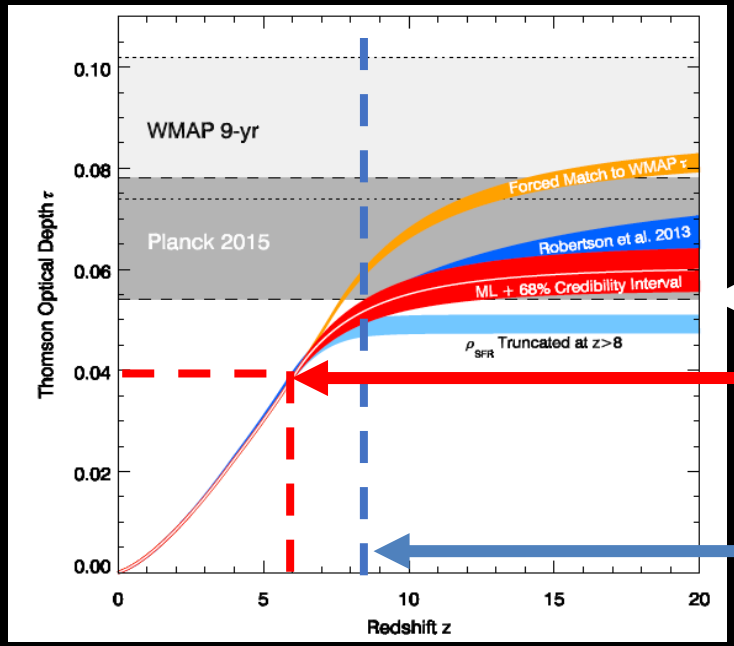


Cosmic Probe of EoR 2 - CMB: Reionization is an extended process



Credit: NASA/WMAP Science Team





Robertson et al. (2015)

$$\tau_{es} = \int \sigma_T \, n_e \, d\ell$$

$$\tau = 0.058 \pm 0.012$$

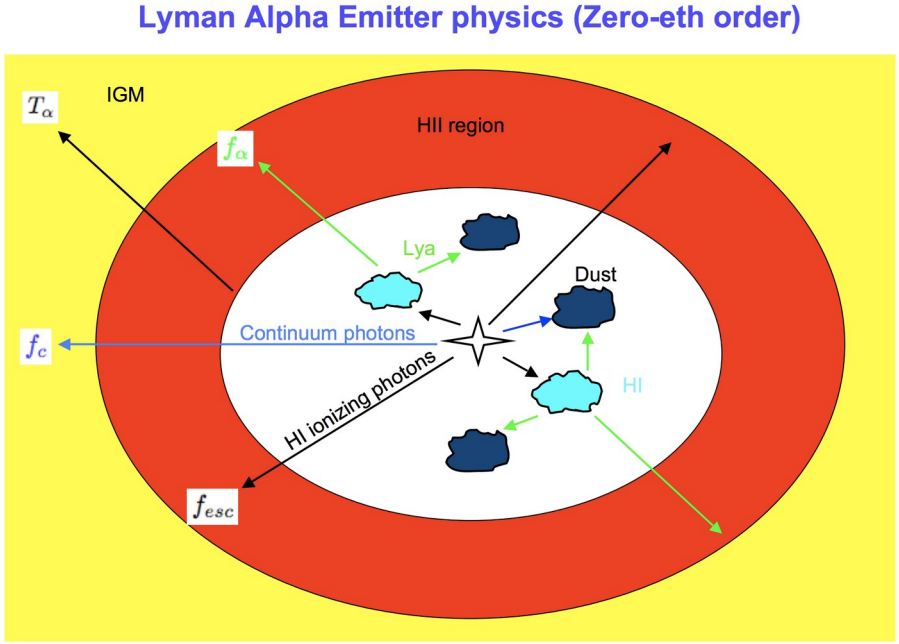
Planck 2016 (TT + lowP/HFI)

4% CMB photons could have been scattered by the fully ionized IGM at z<6

If reionization would be instantaneous, then

$z_{re} = 8.5^{+1.0}_{-1.1}$ (Planck 2016

Cosmic Probe of EoR 3 - Lyα Emitters: inhomogeneous and patchy reionization



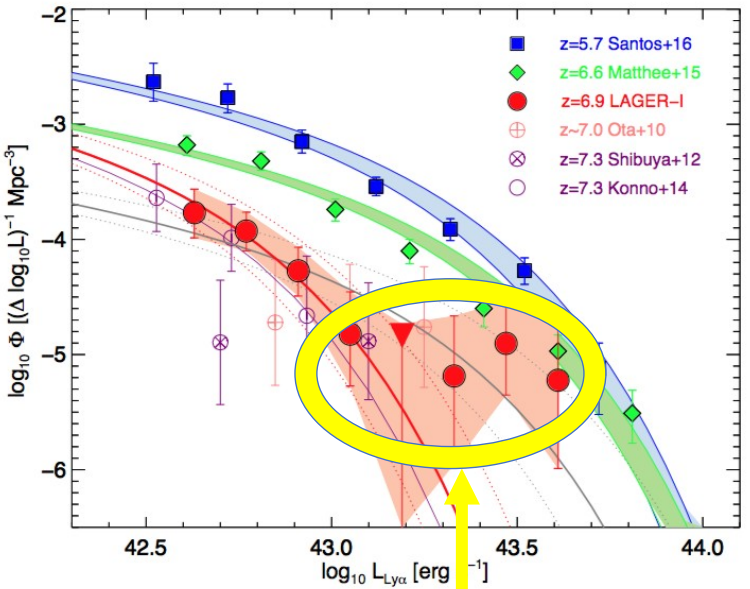
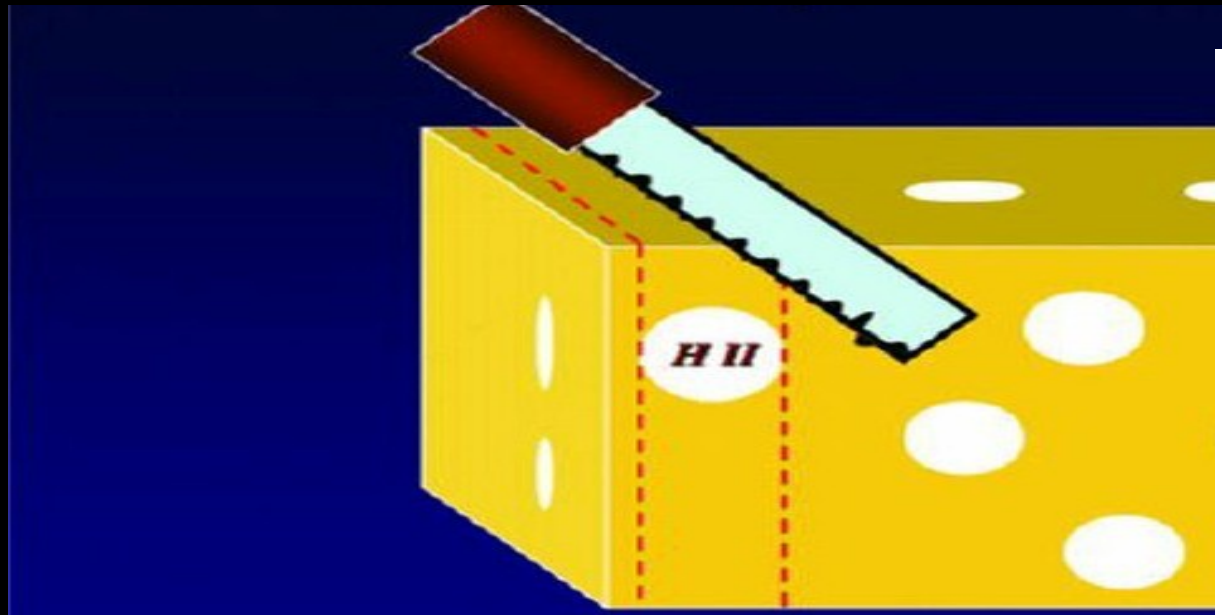


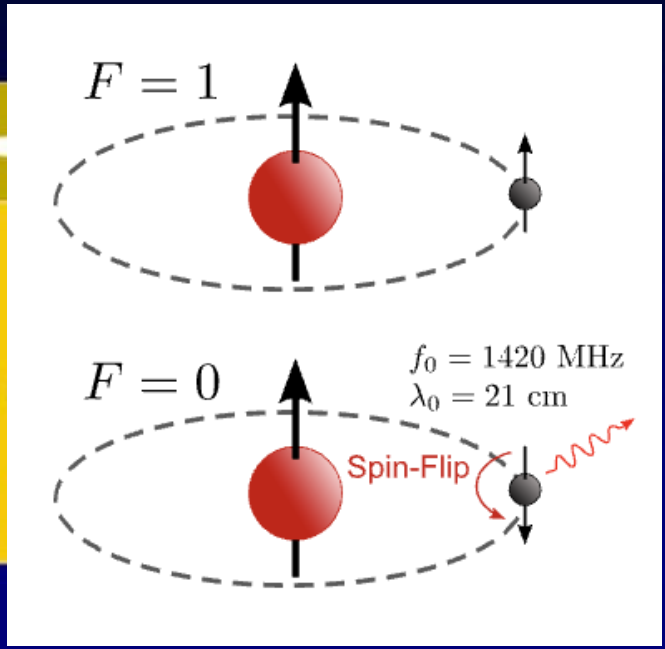
Figure 2. The Lyα LFs of LAE surveys at $z \sim [5.7, 6.6, 7, 7.3]$.

Bump at bright end indicates large HII bubbles, where Hubble flow, galactic inflow/outflow can bring Lyα photons out of resonance.

LAGER collaboration (Zheng et al. 2017)

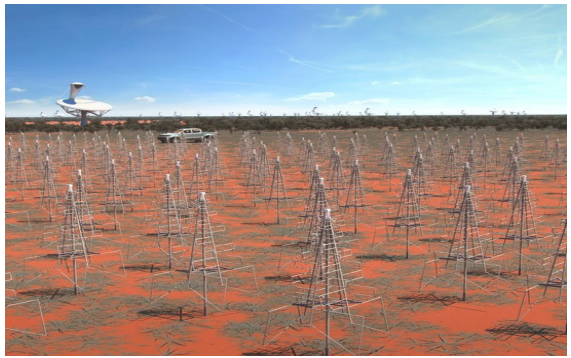
Ionized and Neutral Hydrogen



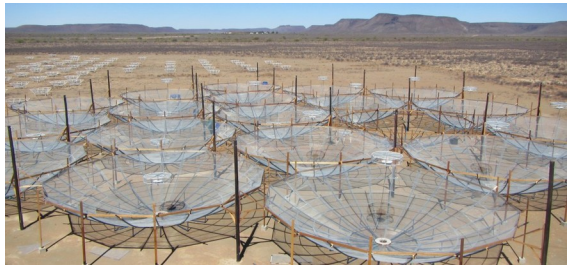


H I 21 cm Line

Interferometers *will* measure power spectrum *and* images



SKA （Square Kilometre Array）
Phase I ~1 Billion euros



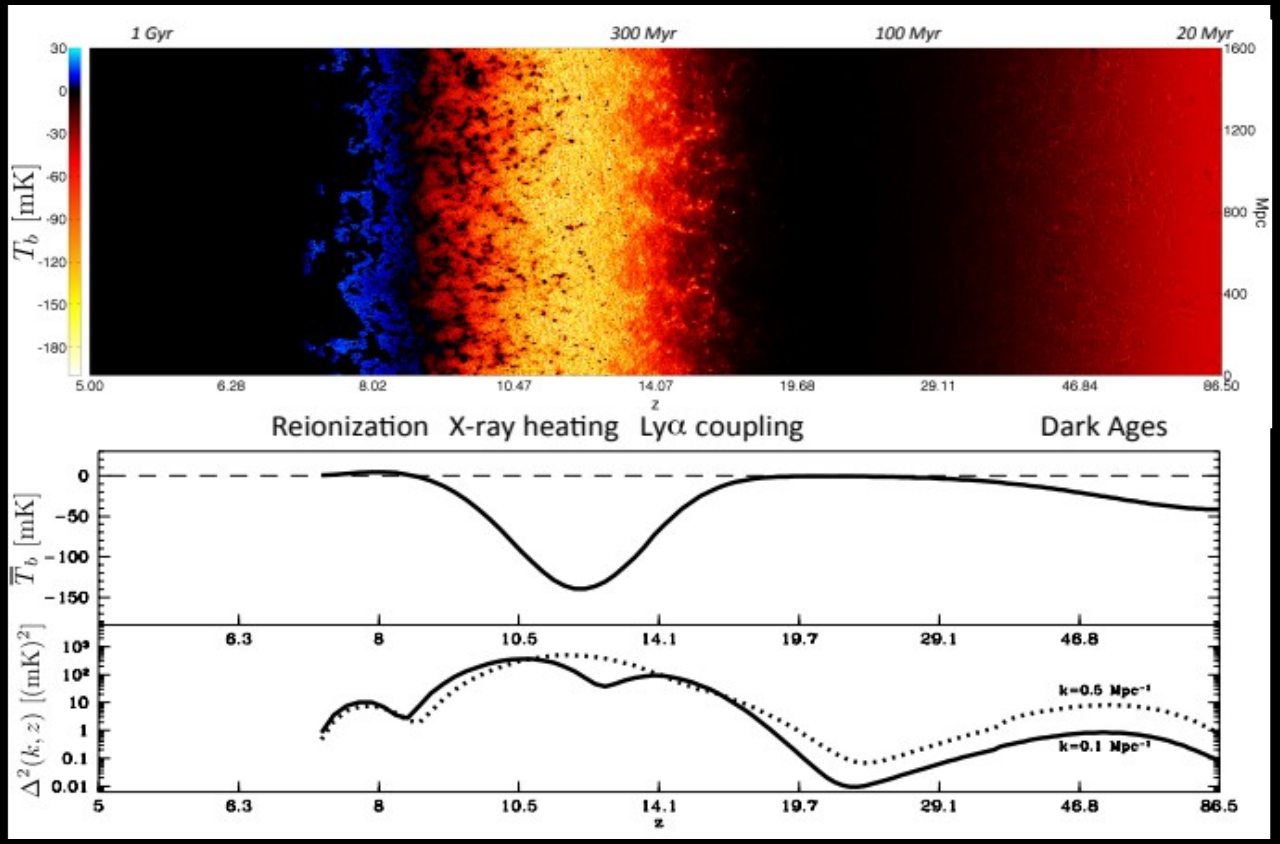
HERA

Data Analysis in 21 cm observations

- Calibration
- RFI flagging (in visibility measurement)
- Image making
- Foreground subtraction
- Scientific interpretation

Inference of reionization parameters from 21 cm signals

Extract astrophysical information from cleaned data



Images

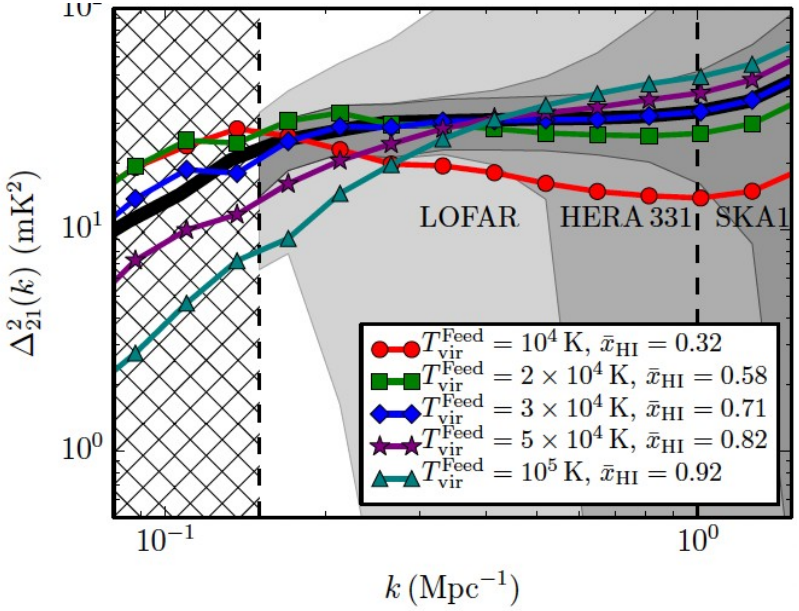
Global Signal

Power Spectrum

A. Liu & R. Shaw

Parameter Estimation using 21 cm Power Spectrum

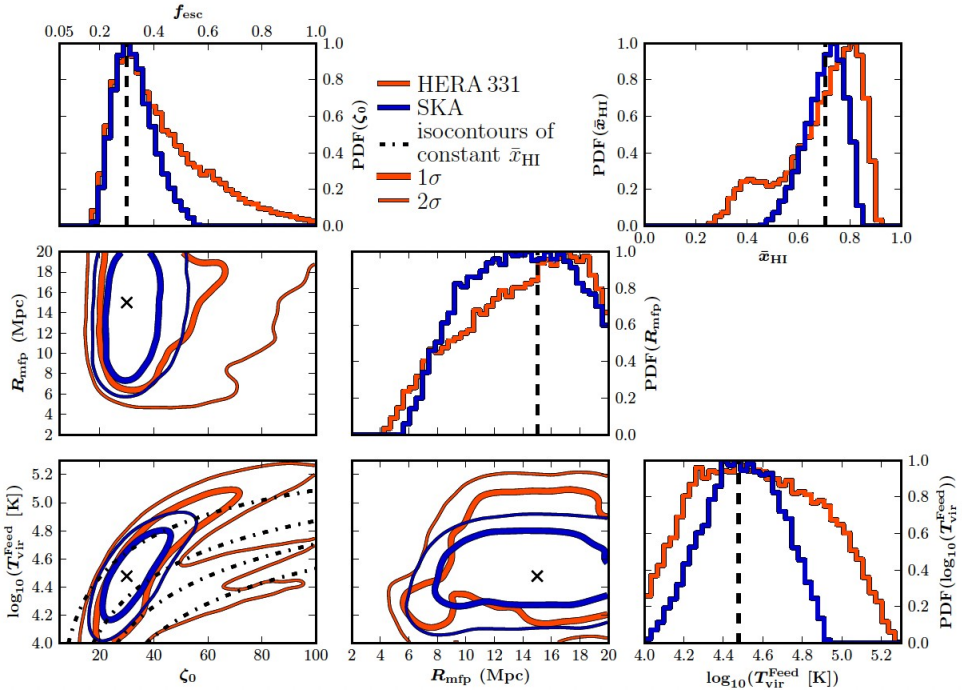
21cm Power Spectrum



Reionization Parameters

ζ the ionizing efficiency

the minimum virial temperature of halos that host ionizing sources



Bayesian inference of reionization model parameters with conventional MCMC method (`21CMMC` code)

Greig & Mesinger, 2015, MNRAS

Parameter Estimation using 21 cm Power Spectrum

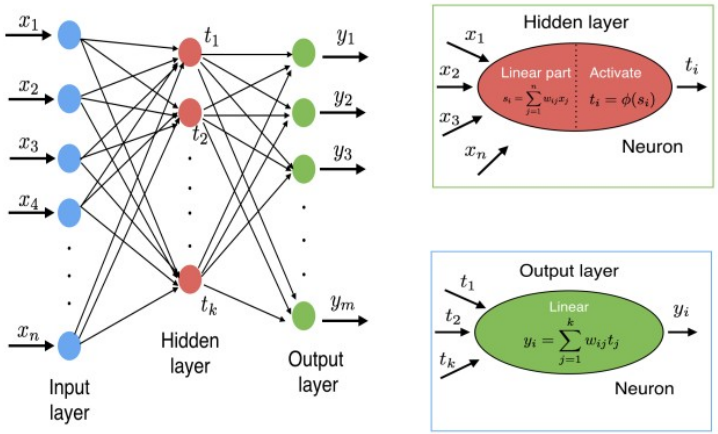


Figure 1. Typical architecture of an artificial neural network. The architecture of the ANN consists of an input layer, a hidden and an output layer of neurons. Each neuron connects the neurons in the next layer.

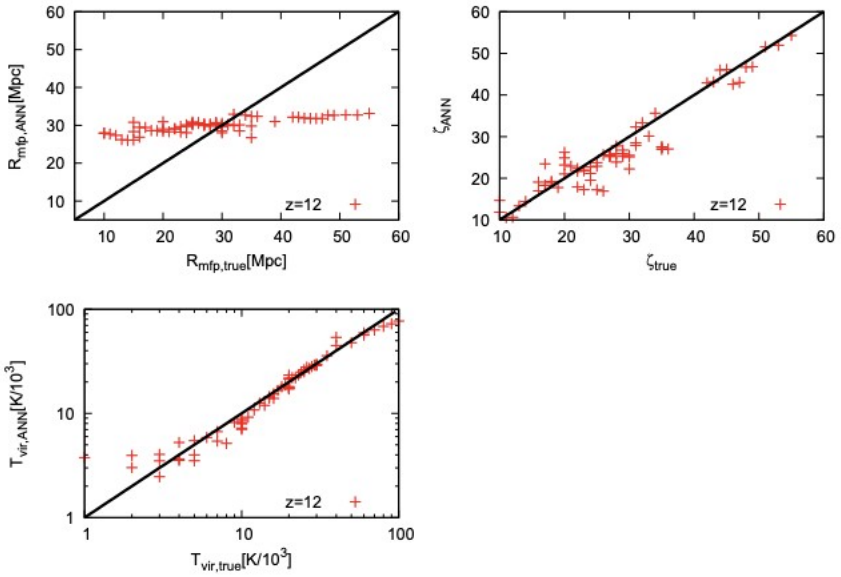
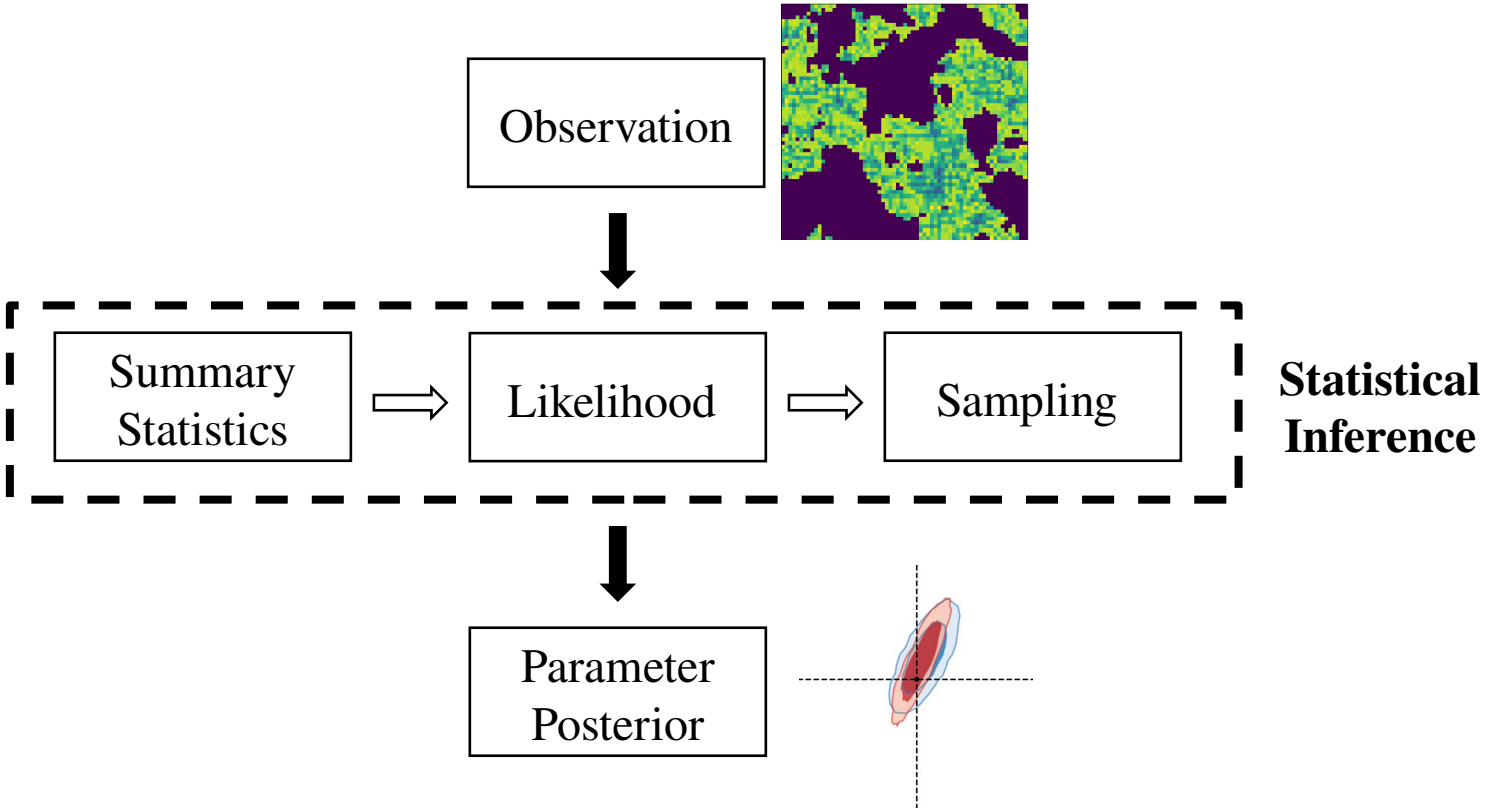


Figure 4. The EoR model parameter values computed by the ANN from the PS against the values used in the simulation at z=12. Note that the result for the Virial temperature is plotted

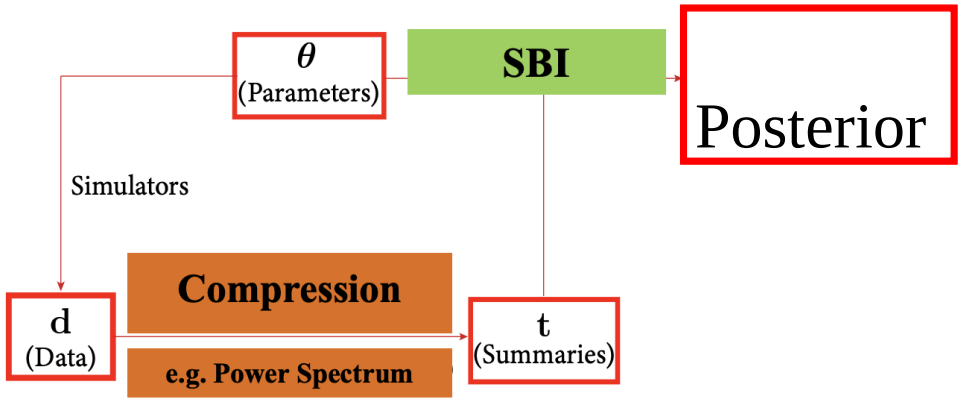
Estimation of reionization model parameters with artificial neural networks
(note: point estimate, not posterior inference)

Shimabukuro & Semelin, 2017, MNRAS

Statistical Inference in Cosmology



Simulation-Based Inference



1. Generative Way (density estimation likelihood-free inference, DELFI):

Zhao, **YM**, et al 2022a,2022b, 2023

$$\{\theta, t\} \xrightarrow{\text{Density Estimator}} P(t|\theta) \xrightarrow{\text{Prior}} \boldsymbol{P(\theta|t) \propto P(t|\theta) P(\theta)}$$

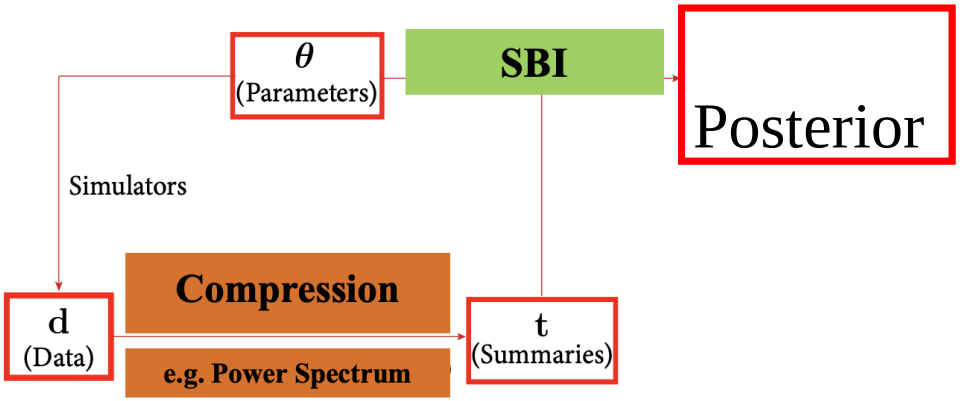
Bayes' Theorem

Discriminative Way (Neural Ration Estimation, NRE):

Ce, **YM**, et al In prep

$$\{\theta, t\} \xrightarrow{\text{Ratio estimation}} r(\theta, t) = \frac{P(t \vee \theta)}{P(t)} \xrightarrow{\text{Prior}} \boldsymbol{P(\theta|t) = r(\theta, t) P(\theta)}$$

Simulation-Based Inference



1. Generative Way (density estimation likelihood-free inference, DELFI):

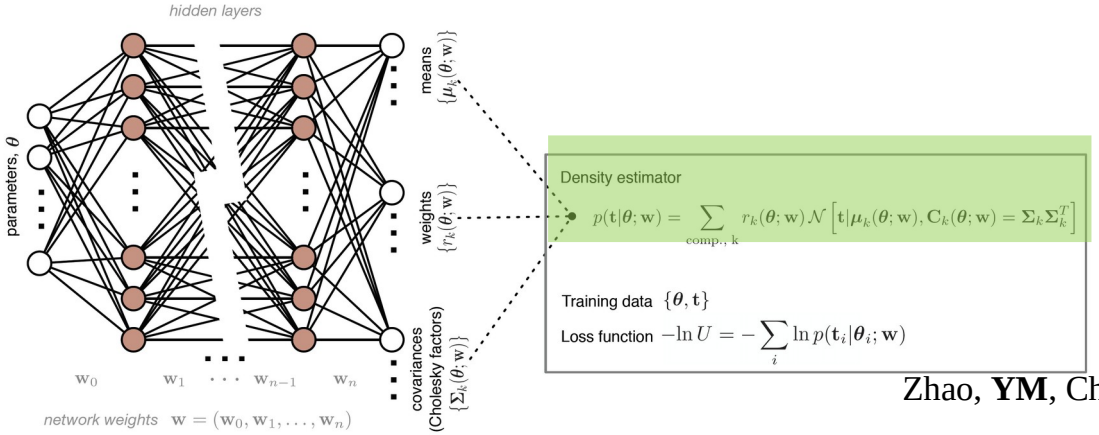
Zhao, YM, et al 2022a,2022b, 2023

$$\{\theta, t\} \xrightarrow{\text{Density Estimator}} P(t|\theta) \xrightarrow{\text{Prior}} \boldsymbol{P(\theta|t) \propto P(t|\theta) P(\theta)}$$

Mixture Density Network (MDN)

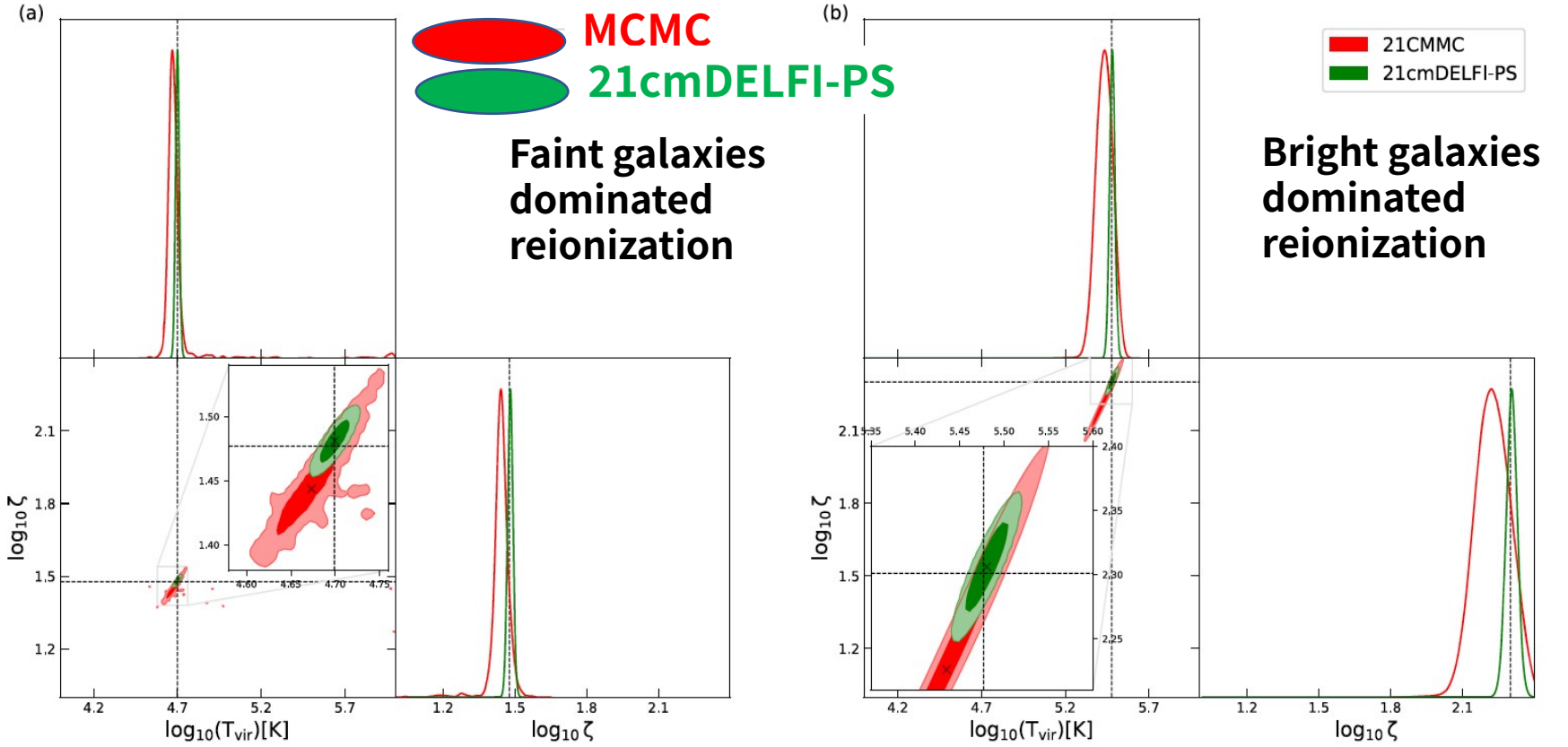
Bayes' Theorem

An example of Neural Density Estimators (NDEs)



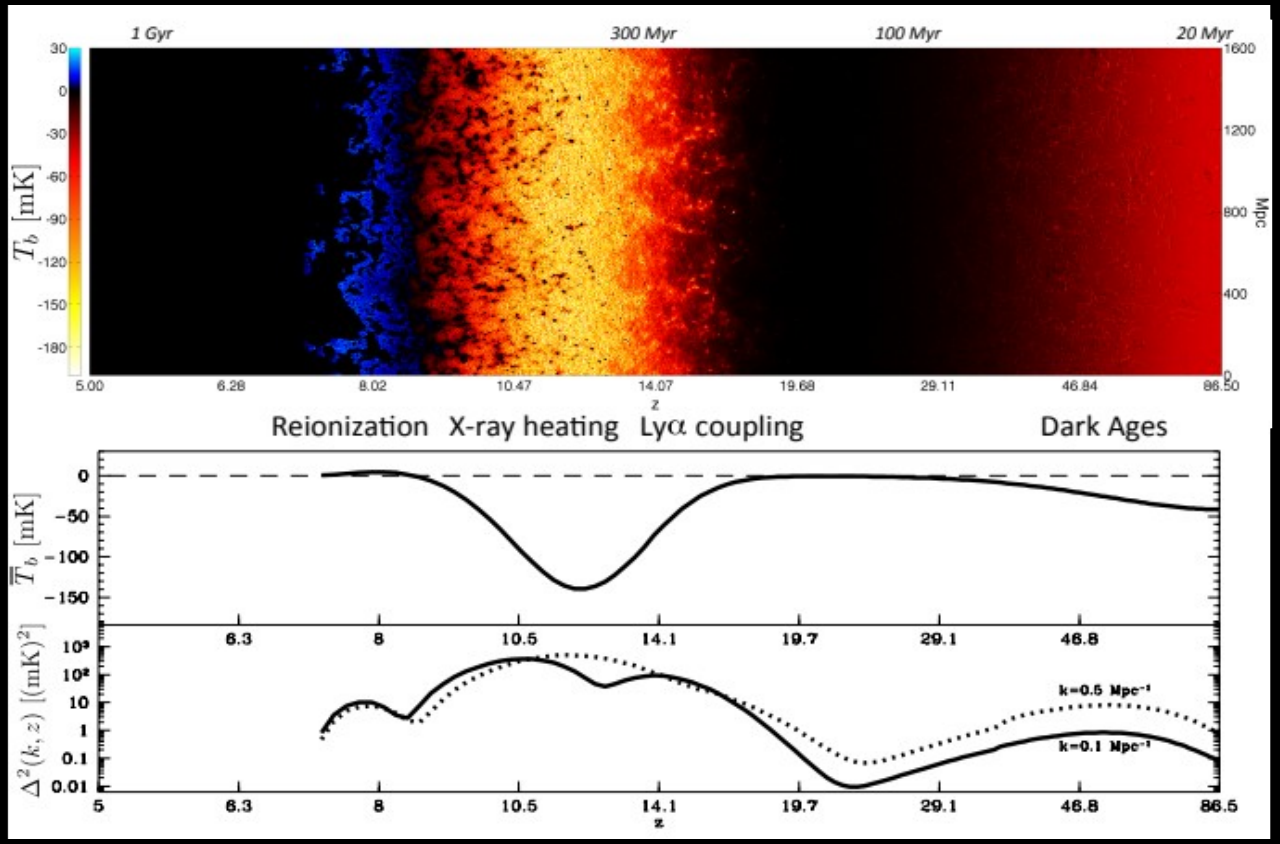
Zhao, **YM**, Cheng & Wandelt, 2022a, ApJ (arXiv:arXiv:2105.03344)

Inference of reionization model parameters from *21 cm power spectrum*



Zhao, **YM** & Wandelt, 2022b, ApJ (arXiv:2203.15734)

Extract astrophysical information from cleaned data



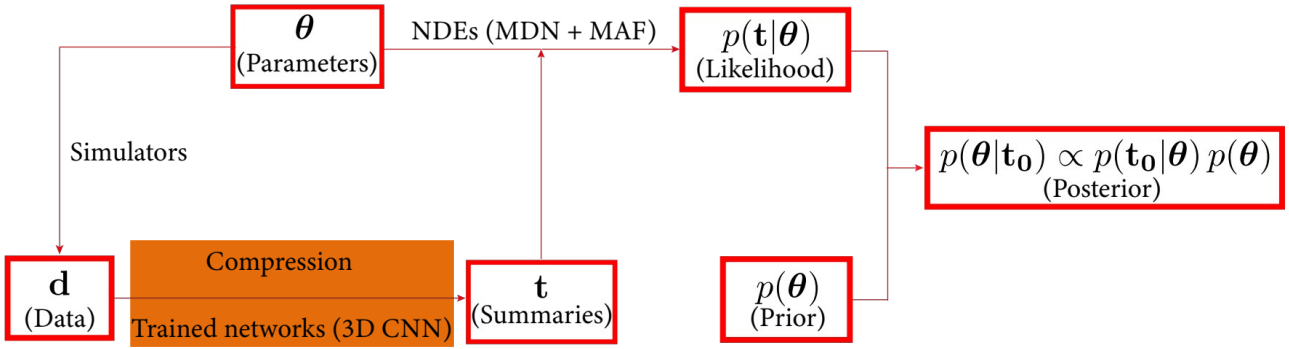
Images

Global Signal

Power Spectrum

A. Liu & R. Shaw

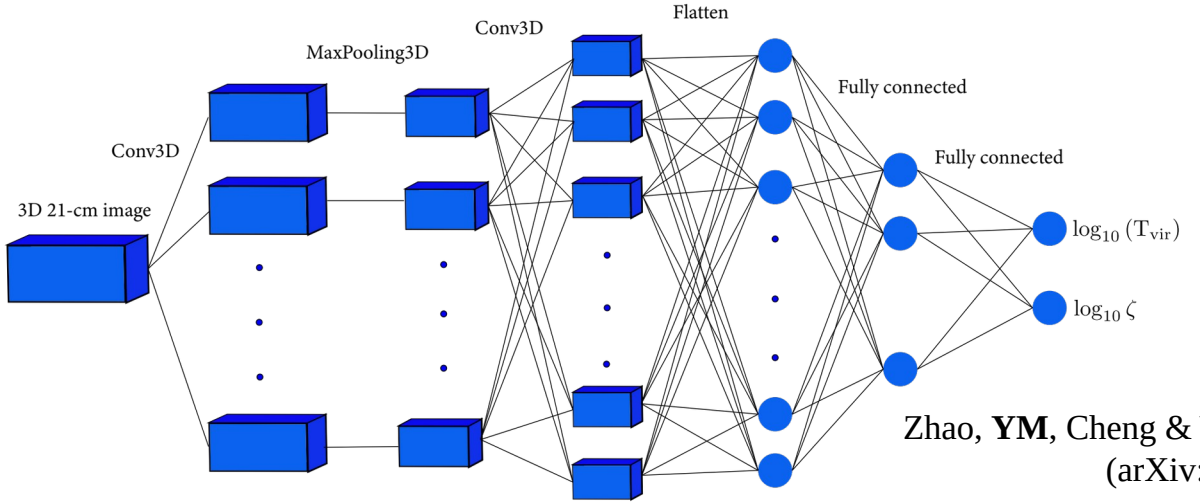
Likelihood-free Bayesian inference





Xiaosheng Zhao (now postdoc at JHU)

Structure of Convolutional Neural Networks (CNN)

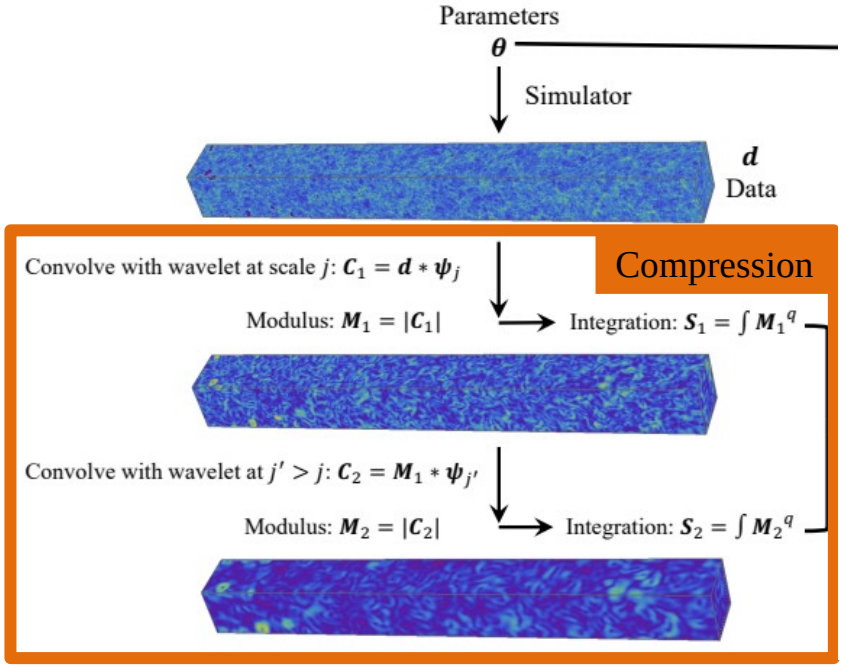


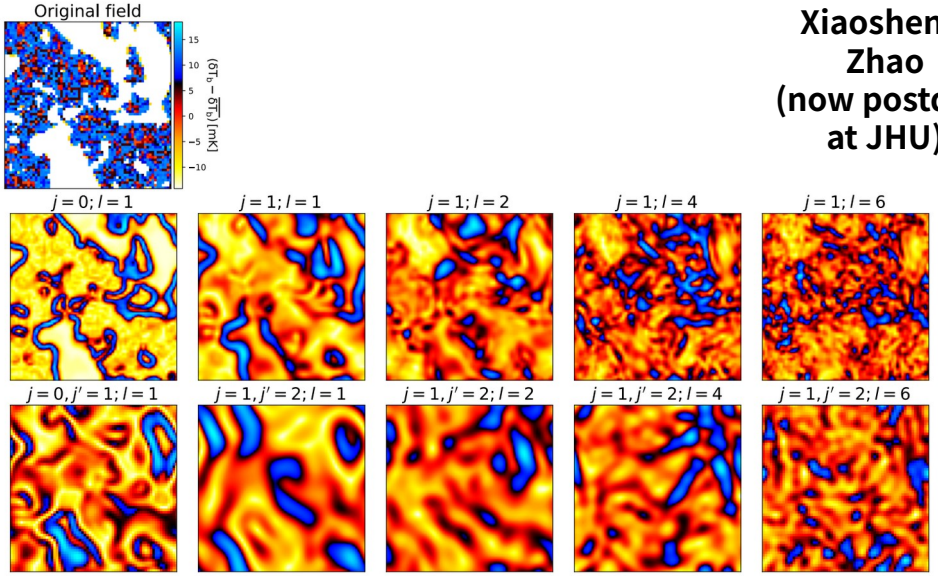
Zhao, **YM**, Cheng & Wandelt, 2022a, ApJ (arXiv:arXiv:2105.03344)

Minimum virial temperature of haloes that host star-forming galaxies

UV Ionizing efficiency of galaxies.

Likelihood-free Bayesian inference





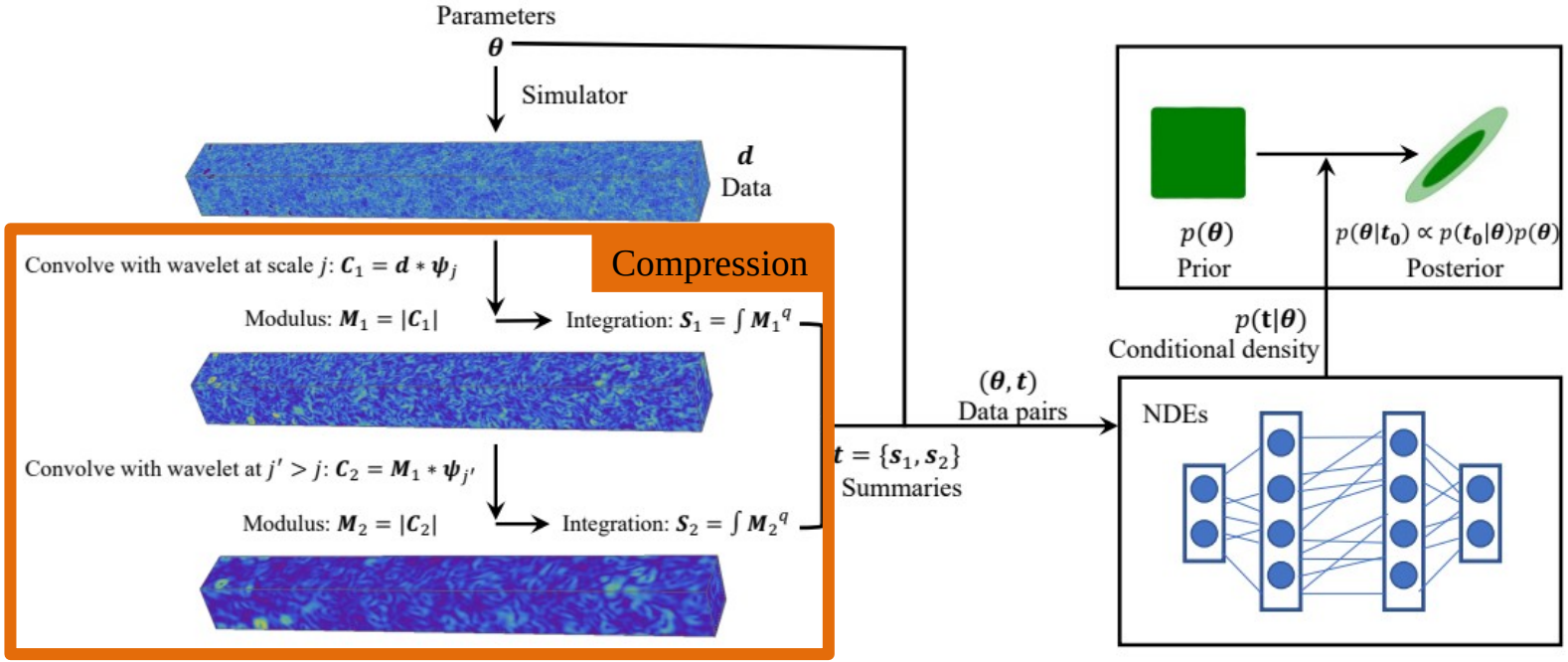


Xiaosheng Zhao (now postdoc at JHU)

Solid harmonic wavelet scattering transform (**SHWST**)

Zhao, **YM**, Zuo & Wandelt, ApJ 2024 (arXiv: 2310.17602)

Likelihood-free Bayesian inference



Solid harmonic wavelet scattering transform (**SHWST**)



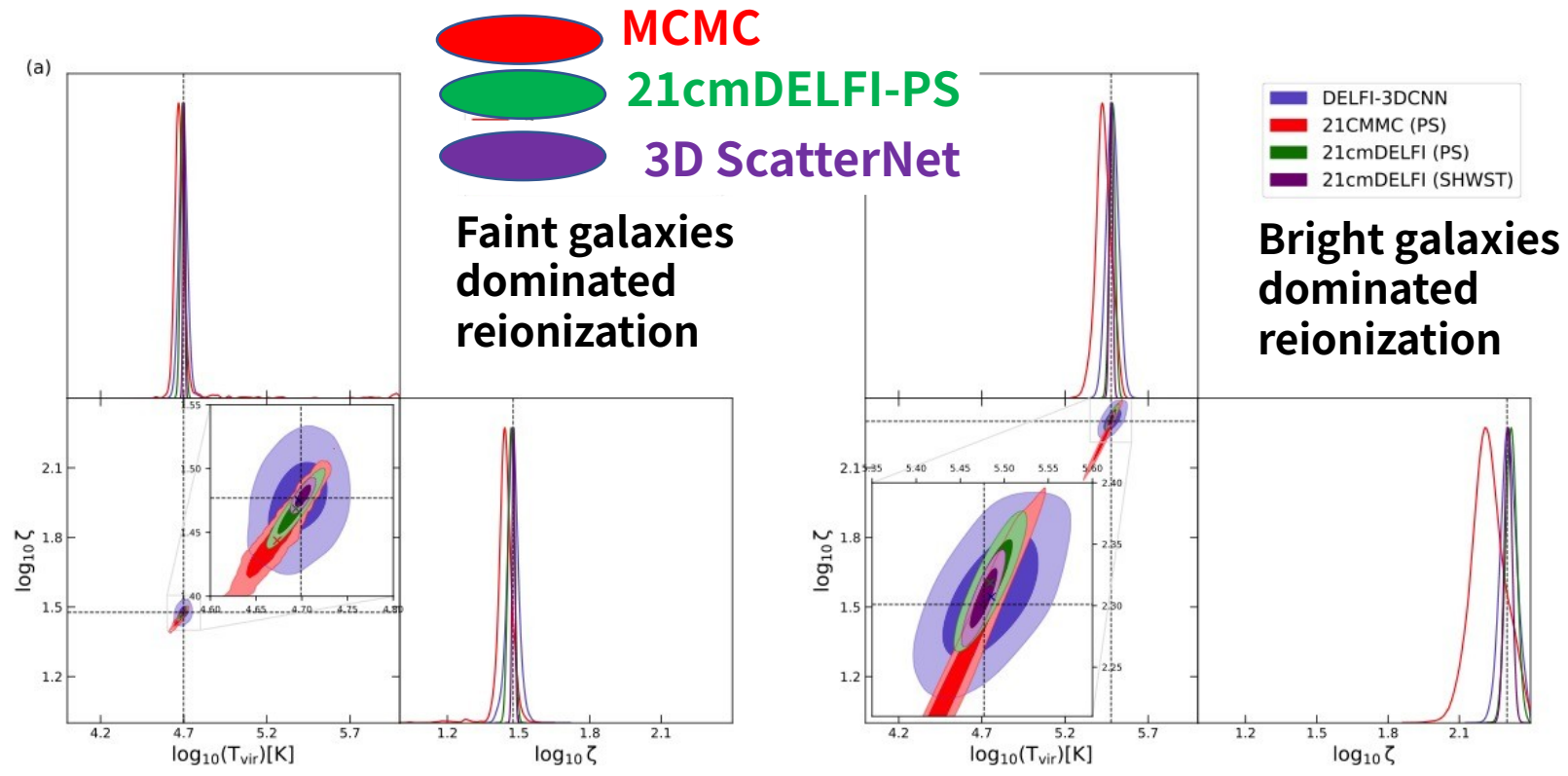
Xiaosheng Zhao (now postdoc at JHU)

Zhao, **YM**, Zuo & Wandelt, ApJ 2024 (arXiv: 2310.17602)

Inference of reionization model parameters from 21 cm *lightcone 3D images*

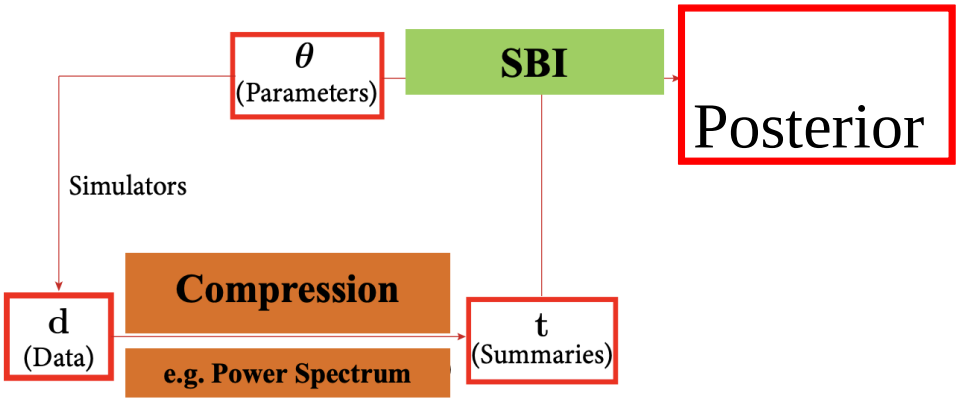


Xiaosheng Zhao (now postdoc at JHU)



Zhao, **YM**, Zuo & Wandelt, ApJ 2024 (arXiv: 2310.17602)

Simulation-Based Inference



iscriminative Way (Neural Ration Estimation, NRE):

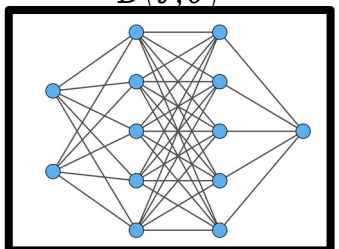
Ce, **YM**, et al
In prep

$$\{\theta,t\} \xrightarrow{\text{Ratio estimation}} r(\theta,t)=\frac{P(t\vee\theta)}{P(t)} \xrightarrow{\text{Prior}} \boldsymbol{P(\theta|t)=r(\theta,t)P(\theta)}$$

$$P(\theta,t)=P(t|\theta)P(\theta)$$

$$\boldsymbol{P(\theta)P(t)}$$

$$\{\theta,t\} \xrightarrow{\textbf{Classifier}} D(t,\theta)$$



$$\max_{D} E_{p(\theta,t)} \text{¿ ¿}$$

$$r|\theta,t)=\frac{P(x\vee t)}{P(t)}$$

$$\boldsymbol{D^{*}(t,\theta)=\frac{r(\theta,t)}{r(\theta,t)+1}}$$

Comparison between two SBI methods



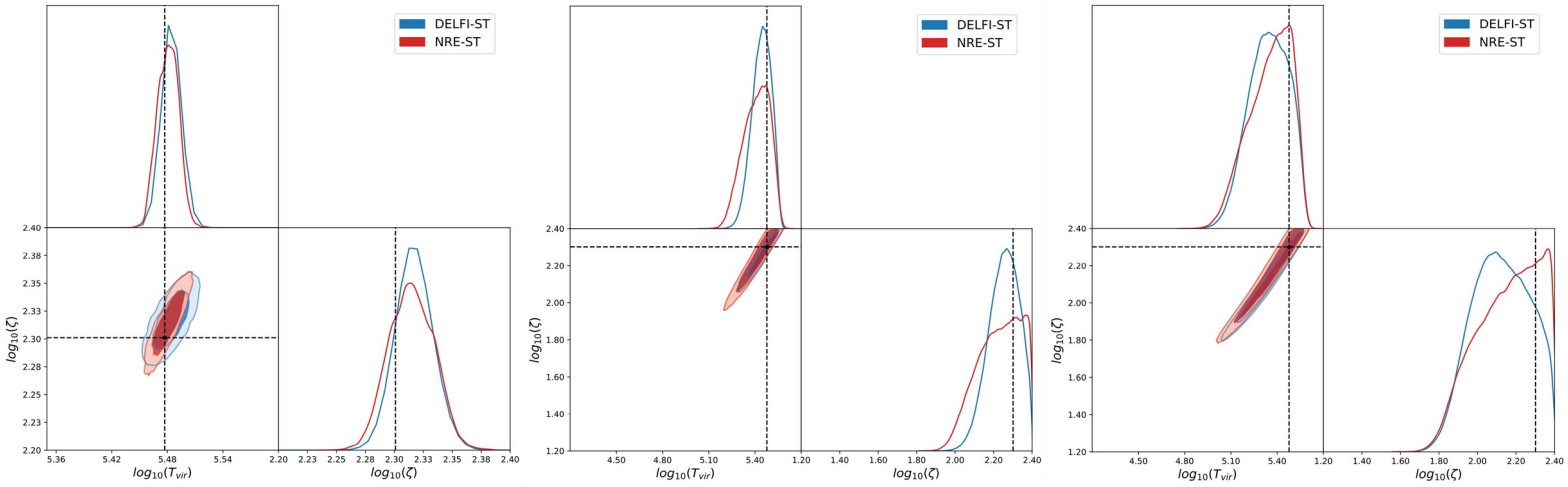
Ce Sui

Pure Signal

+ Thermal Noise

+Residual Foreground

Bright Galaxy Model



Ce, **YM**, et al. in prep

What else can we learn about the EoR than just constraining reionization *model* parameters?

We can reconstruct the initial density fields

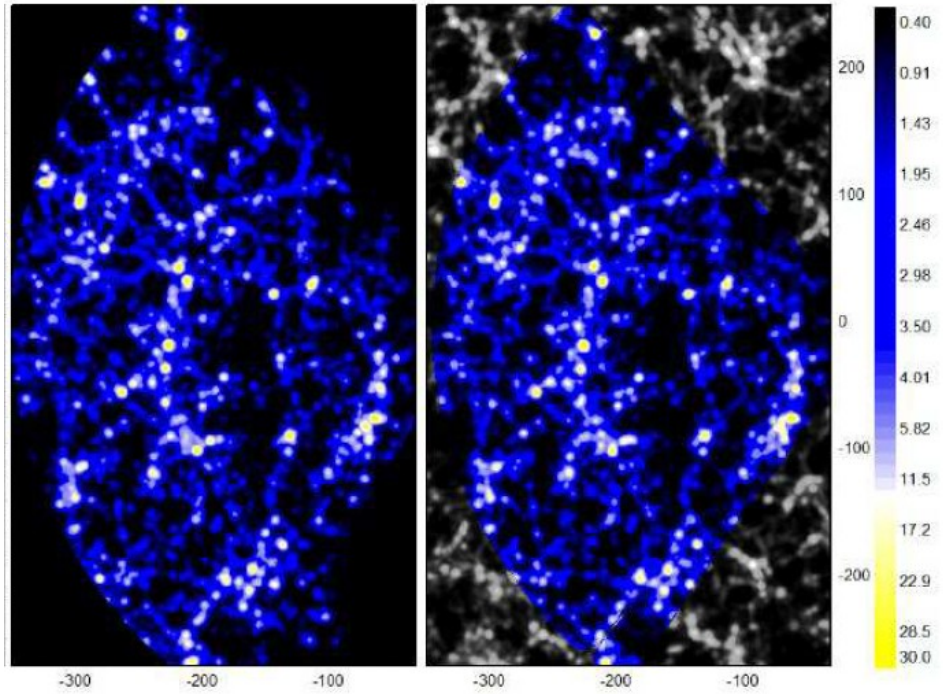
Local Universe:

ELUCID (Wang et al 2013)

BORG (Jasche & Wandelt 2013)

….

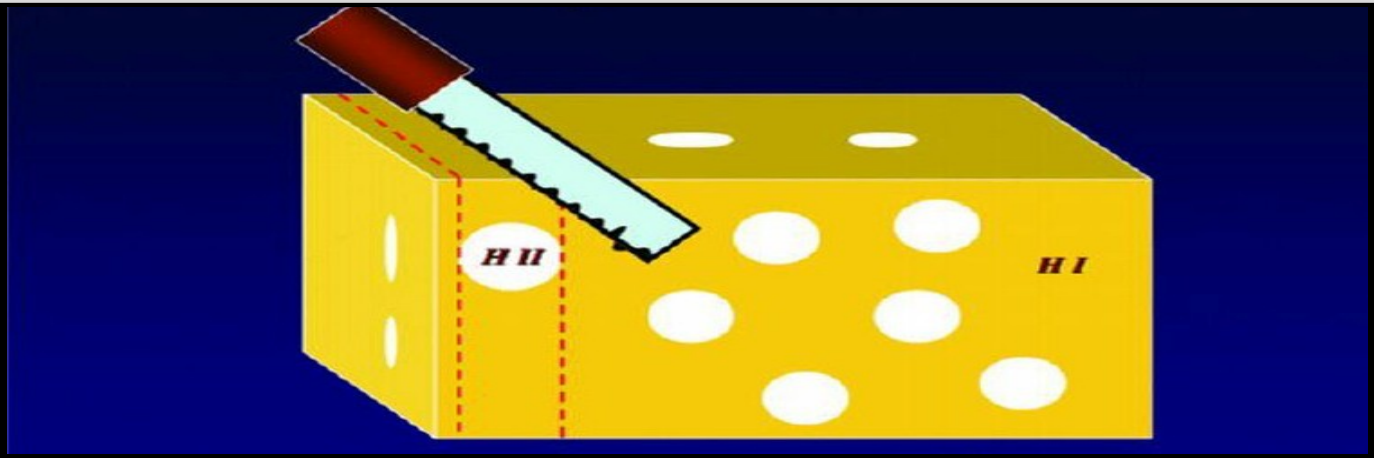
$P(\delta^{\rm ini}|\delta^{\rm galaxy})$ + Hamiltonian Monte Carlo



“observed” “resimulated”

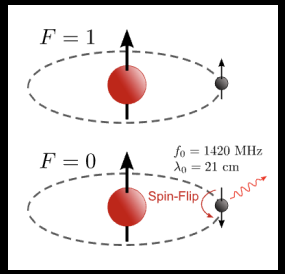
Wang et al 2013

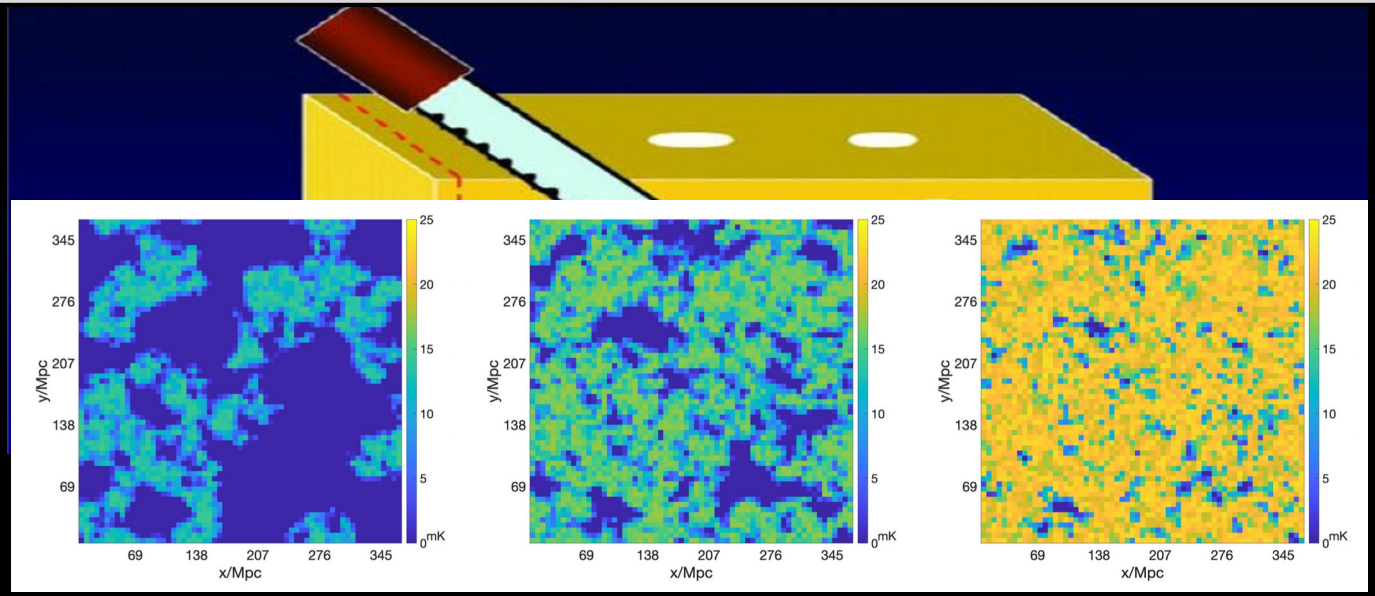
We can reconstruct the initial density fields *from high-redshift observations*



We can reconstruct the initial density fields *from high-redshift observations*

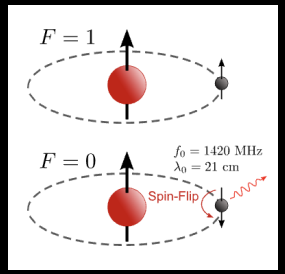
H I 21 cm intensity mapping



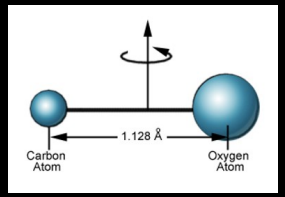


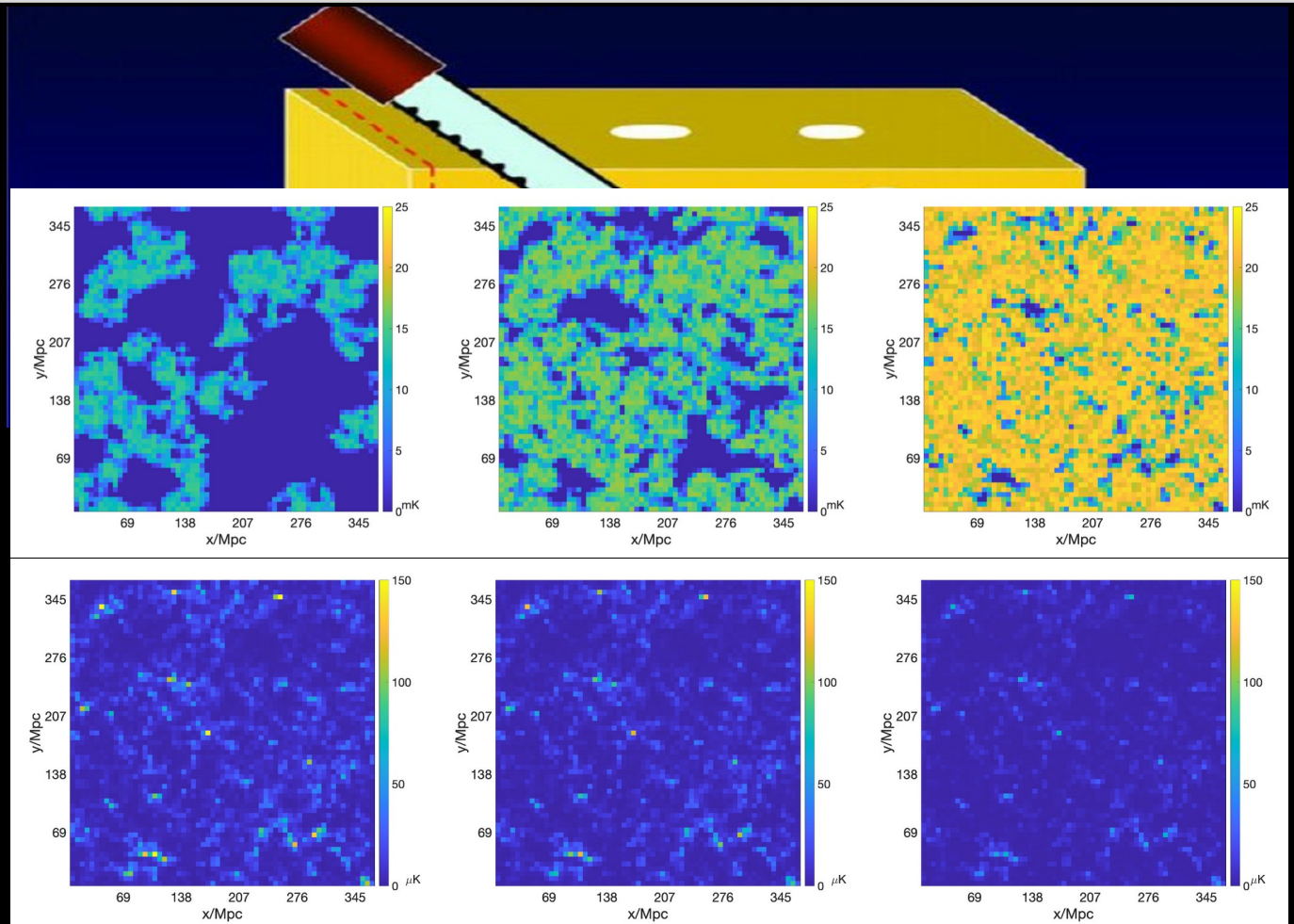
We can reconstruct the initial density fields *from high-redshift observations*

H I 21 cm intensity mapping



Molecular line intensity mapping





We can use line intensity mappings

Minimize Cost Function ~ Maximize Likelihood

$$\phi \to 0 \qquad \{\delta^{\rm ini,rec}\} \to \{\delta^{\rm ini,true}\}$$

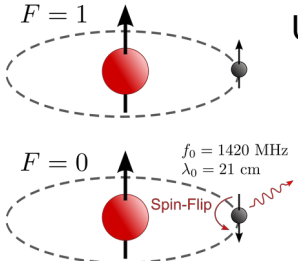
Resimulated LIM Mock (input) LIM

$$\phi\left(\delta^{\rm ini}\right) = C_{\rm cost} \sum_{j,\alpha} \frac{\left(T^{\rm mod}_{j,\alpha} - T^{\rm inp}_{j,\alpha}\right)^2}{2\left(\sigma^{\rm N}_{j}\right)^2} w_j$$

Weight

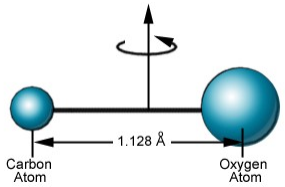
j: 21cm and CO : pixels

Uncertainty



21cm: neutral region

CO (1→0): ionized region



Zhou and **YM**, ApJ 2024 (arXiv:2311.14940)



Meng Zhou (now postdoc at NAOC)

We employ the *conjugate gradient* to minimize the cost function.



Meng Zhou (now postdoc at NAOC)

Here is the overall algorithm:

Starting from an arbitrary point $\boldsymbol{x}_0$.

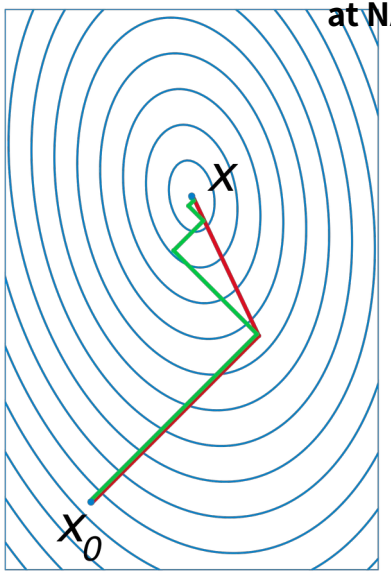
Calculate the gradient, and set $\boldsymbol{g}_0 = \boldsymbol{h}_0 = -\nabla f(\boldsymbol{x}_0)$.

Start iteration until convergence:

Perform line minimization along $\boldsymbol{h}_i$ to obtain $\boldsymbol{x}_{i+1}$.

Calculate the gradient vector $\boldsymbol{g}_{i+1} = -\nabla f(\boldsymbol{x}_{i+1})$.

Determine the new direction $\boldsymbol{h}_{i+1} = \boldsymbol{g}_{i+1} + \gamma_i \boldsymbol{h}_i$.



Zhou and **YM**, ApJ 2024 (arXiv:2311.14940)

Analytical gradients agree with numerical results.



Meng Zhou

Excursion Set model of reionization (ESMR):

$$T_{21\mathrm{cm}}(\mathbf{x}) \sim x_{\mathrm{HI}}(\mathbf{x})[1+\delta(\mathbf{x})]$$

$$x_{\mathrm{HI}}(\mathbf{x}) = \begin{cases} 0, & \text{if } \zeta f_{\mathrm{coll},R}(\mathbf{x}) > 1 \\ 1.0 - \zeta f_{\mathrm{coll},R_{\mathrm{min}}}(\mathbf{x}), & \text{otherwise} \end{cases}$$

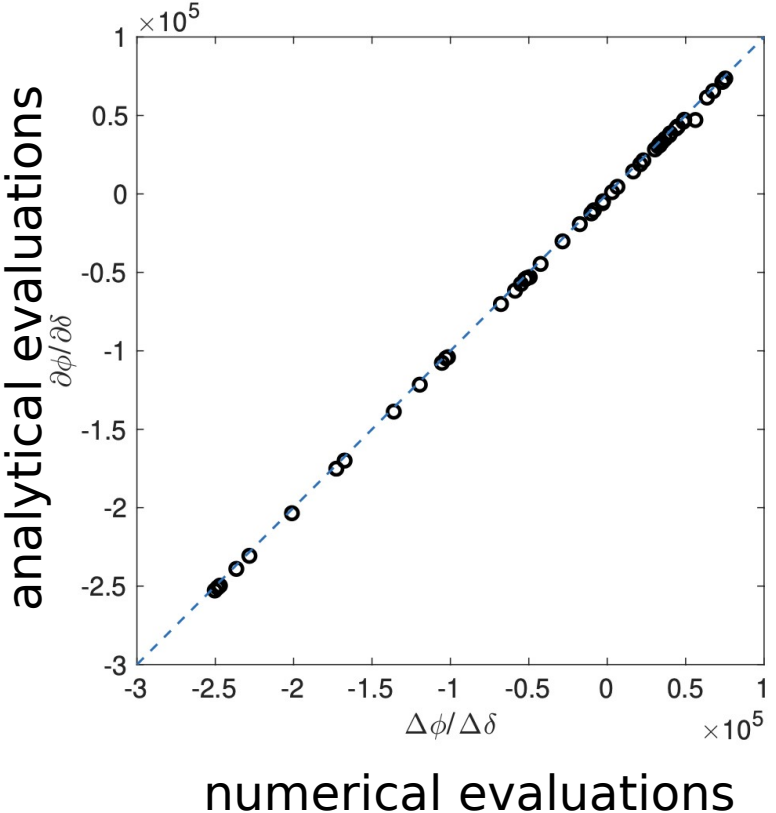
Empirical L~SFR model:

$$T_{\mathrm{CO}}(\mathbf{x}) \sim f_{\mathrm{coll},R_{\mathrm{min}}}(\mathbf{x})[1+\delta(\mathbf{x})]$$

$$\frac{\partial\phi}{\partial\delta^{\mathrm{ini}}} \sim \frac{\partial\phi}{\partial T_j} * \frac{\partial T_j}{\partial\delta} * \frac{\partial\delta}{\partial\delta^{\mathrm{ini}}}$$

ESMR

Zel'dovich approximation



Zhou and **YM**, ApJ 2024 (arXiv:2311.14940)

We can reconstruct the initial density fields *from high-redshift observations*



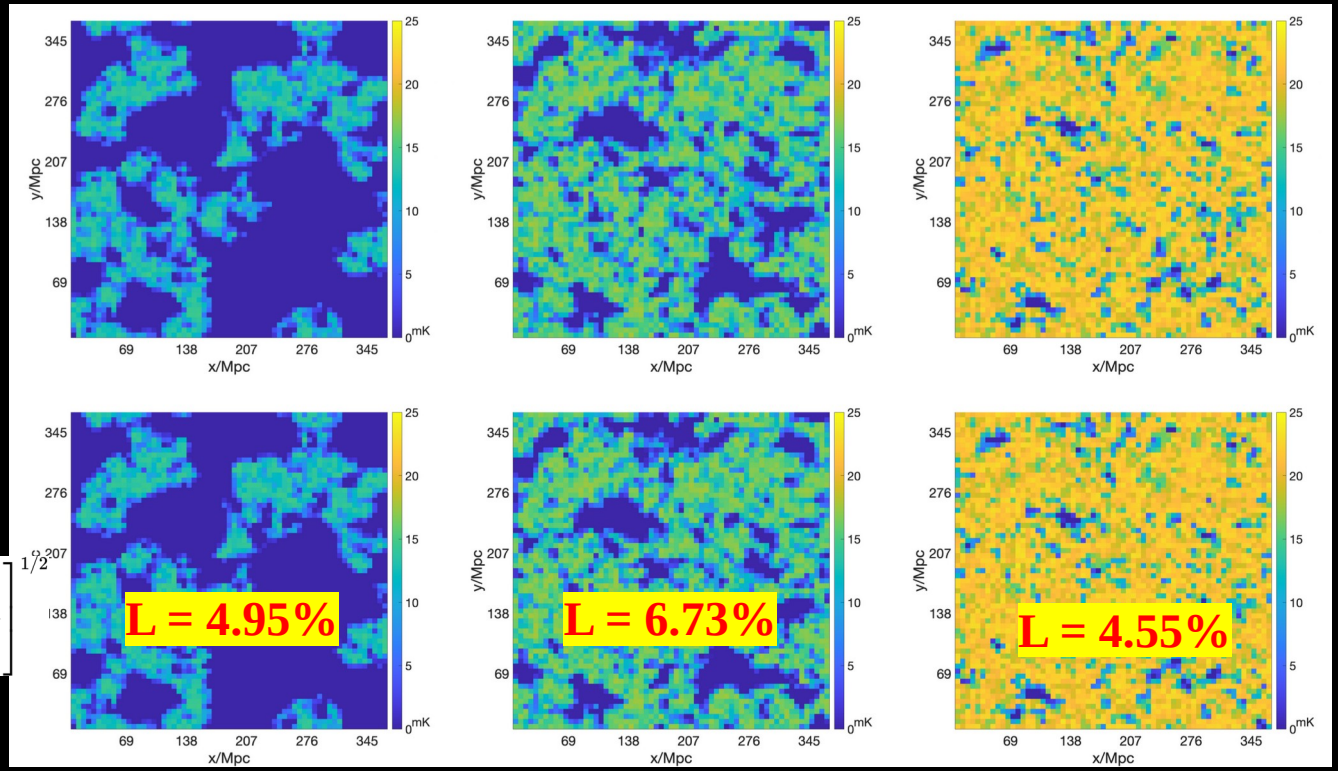
Meng Zhou (now postdoc at NAOC)

H I 21 cm intensity mapping

z=7.56, x_{HI} = 0.25 **z=8.20, x_{HI} = 0.50** **z=9.54, x_{HI} = 0.75**

Input maps

Resimulated maps



$$L_{\rm tot} = \left[\frac{1}{2N_p}\sum_{j,\alpha}\frac{\left(T^{\rm mod}_{j,\alpha}-T^{\rm inp}_{j,\alpha}\right)^2}{\left(\sigma^{\rm S}_j\right)^2}\right]^{1/2}$$

Zhou and **YM**, ApJ 2024 (arXiv:2311.14940)

We can reconstruct the initial density fields *from high-redshift observations*



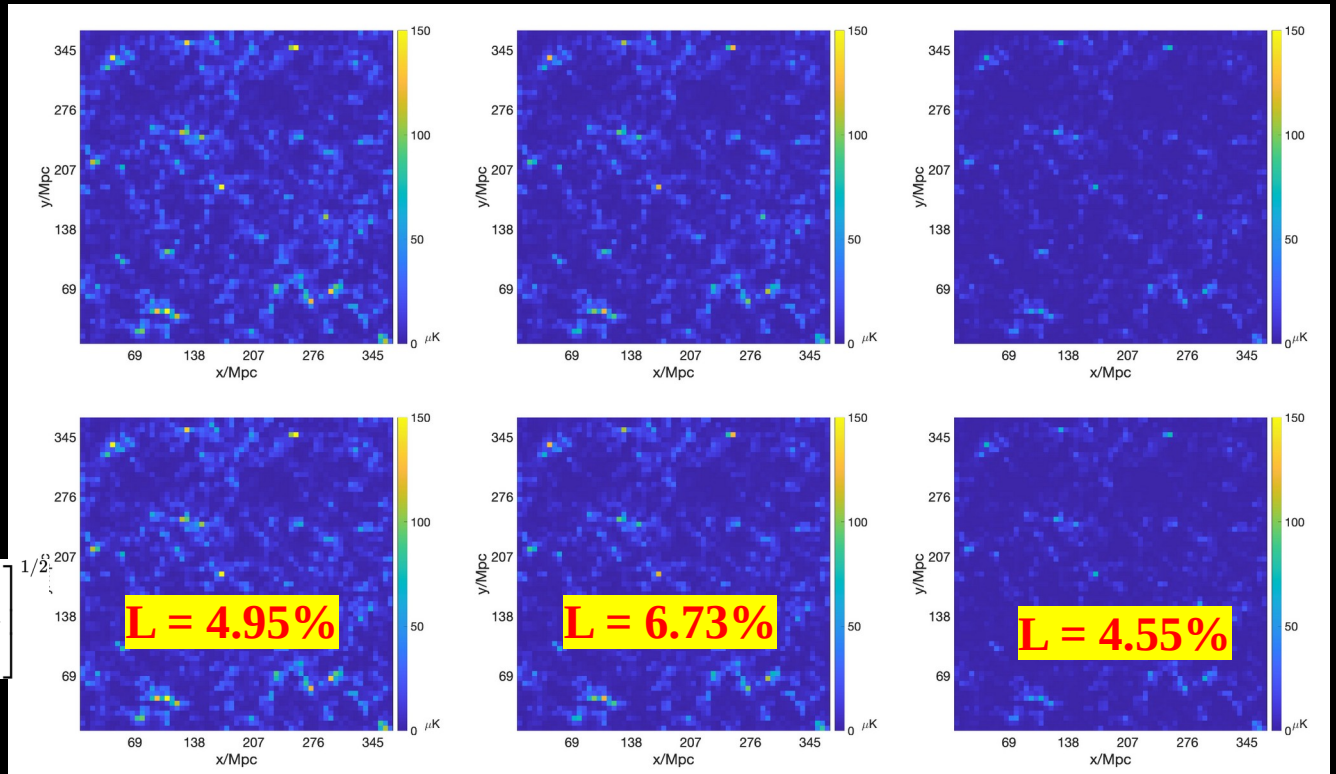
Meng Zhou (now postdoc at NAOC)

CO line intensity mapping

z=7.56, x_{HI} = 0.25 | **z=8.20, x_{HI} = 0.50** | **z=9.54, x_{HI} = 0.75**

Input maps

Resimulated maps



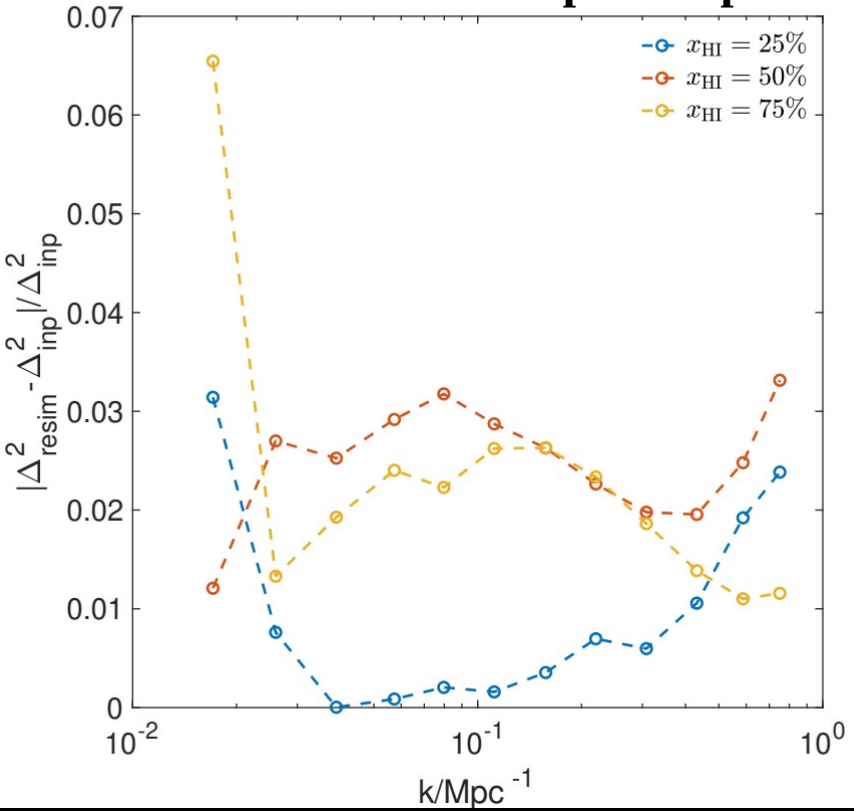
$$L_{\rm tot} = \left[\frac{1}{2N_p} \sum_{j,\alpha} \frac{\left(T^{\rm mod}_{j,\alpha} - T^{\rm inp}_{j,\alpha}\right)^2}{\left(\sigma^{\rm S}_j\right)^2} \right]^{1/2}$$

Zhou and **YM**, ApJ 2024 (arXiv:2311.14940)

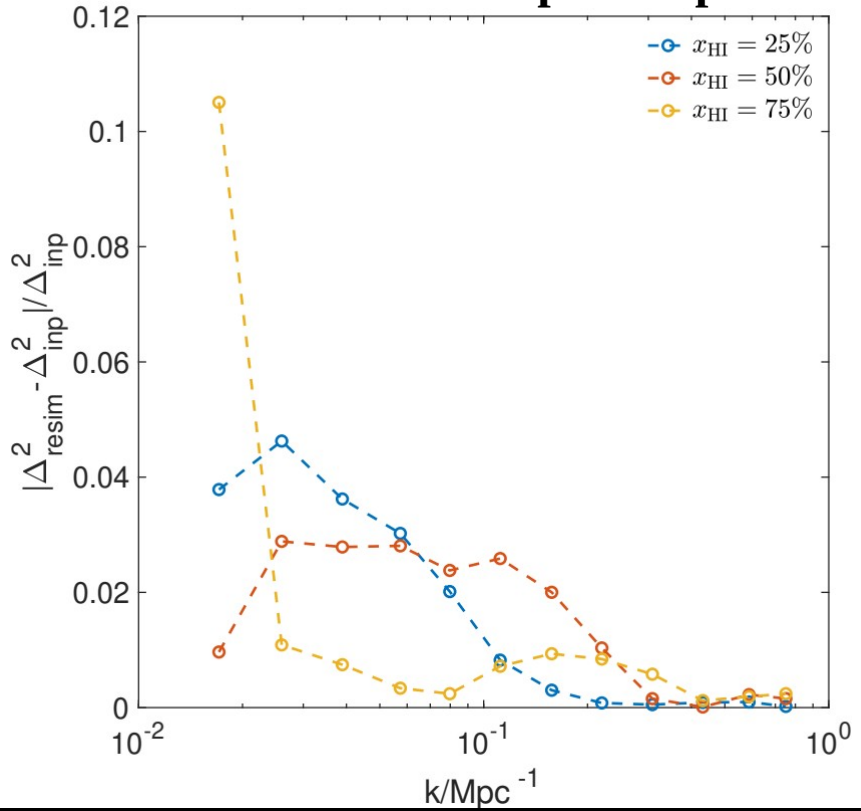
We can reconstruct the initial density fields *from high-redshift observations*



Relative error of 21cm power spectrum



Relative error of CO power spectrum



Zhou and **YM**, ApJ 2024
(arXiv:2311.14940)

The reconstructed power spectrum is <4% error in most cases.

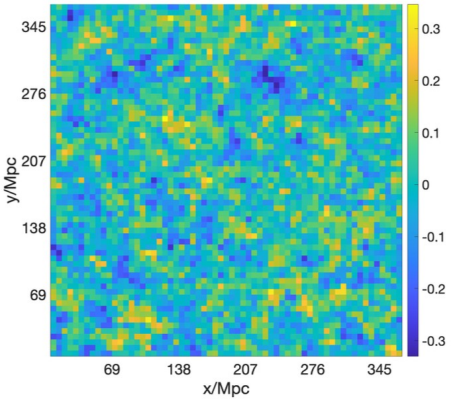
We can reconstruct the initial density fields *from high-redshift observations*



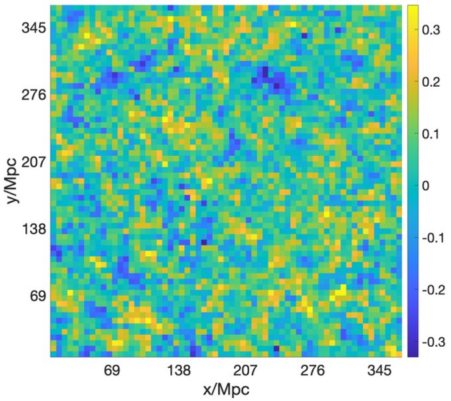
Meng Zhou (now postdoc at NAOC)

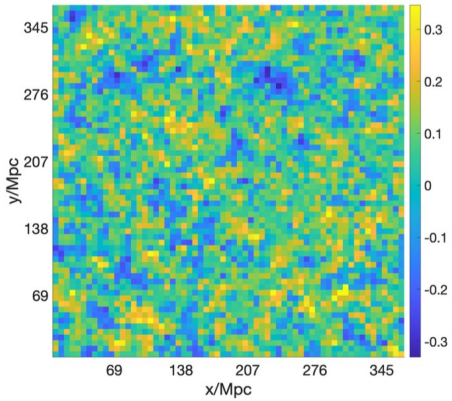
Zhou and **YM**, ApJ 2024
(arXiv:2311.14940)

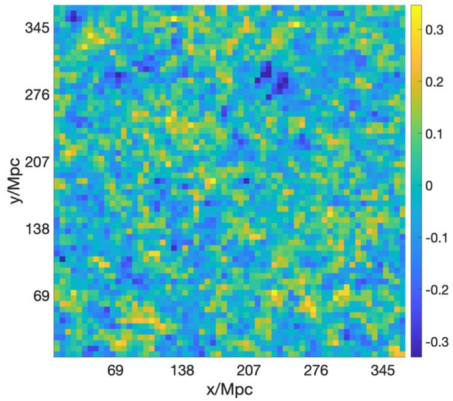
True initial overdensity field



Reconstructed initial overdensity field



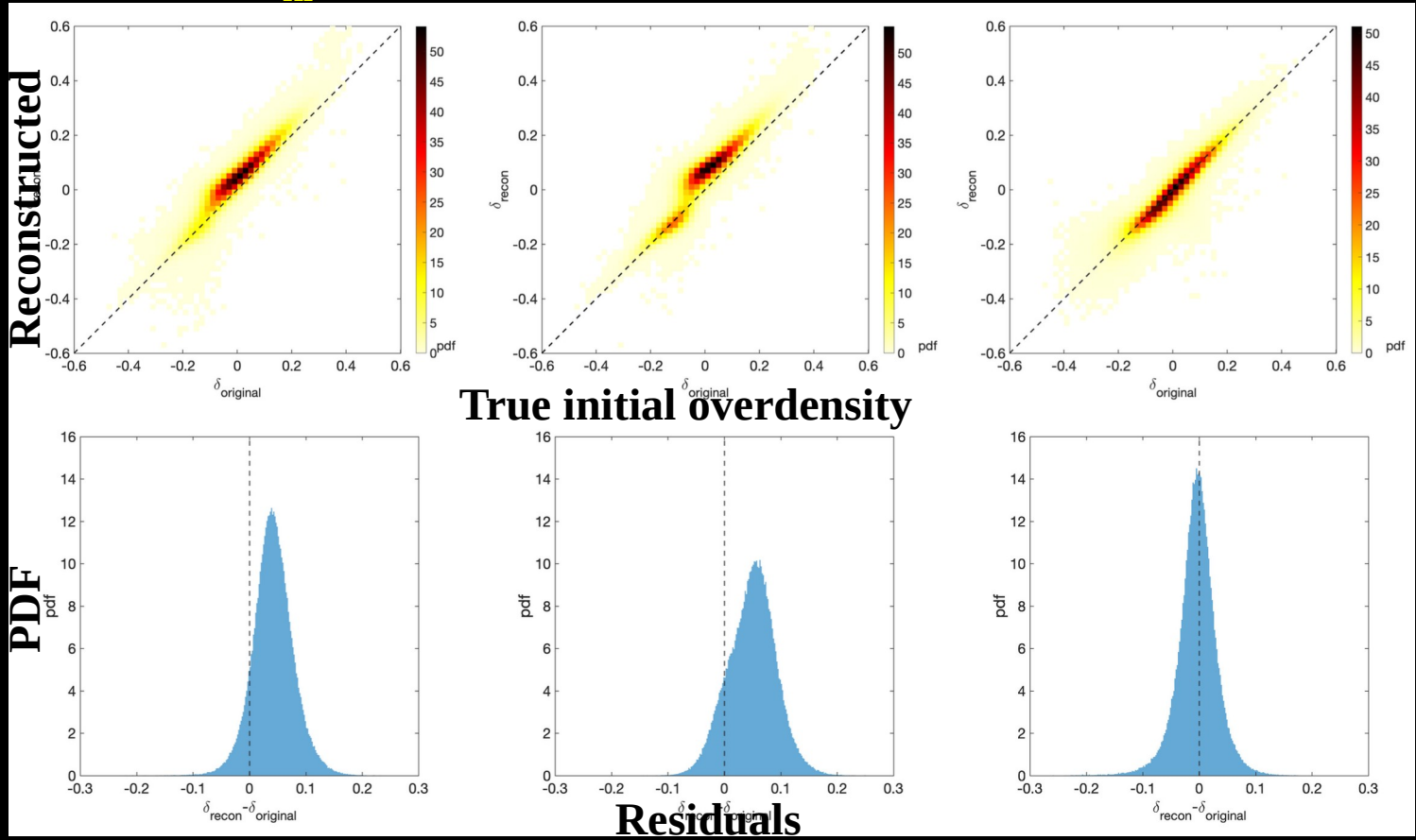




From observations at: $z=7.56$, $x_{HI} = 0.25$ $z=8.20$, $x_{HI} = 0.50$ $z=9.54$, $x_{HI} = 0.75$

We can reconstruct the initial density fields *from high-redshift observations*

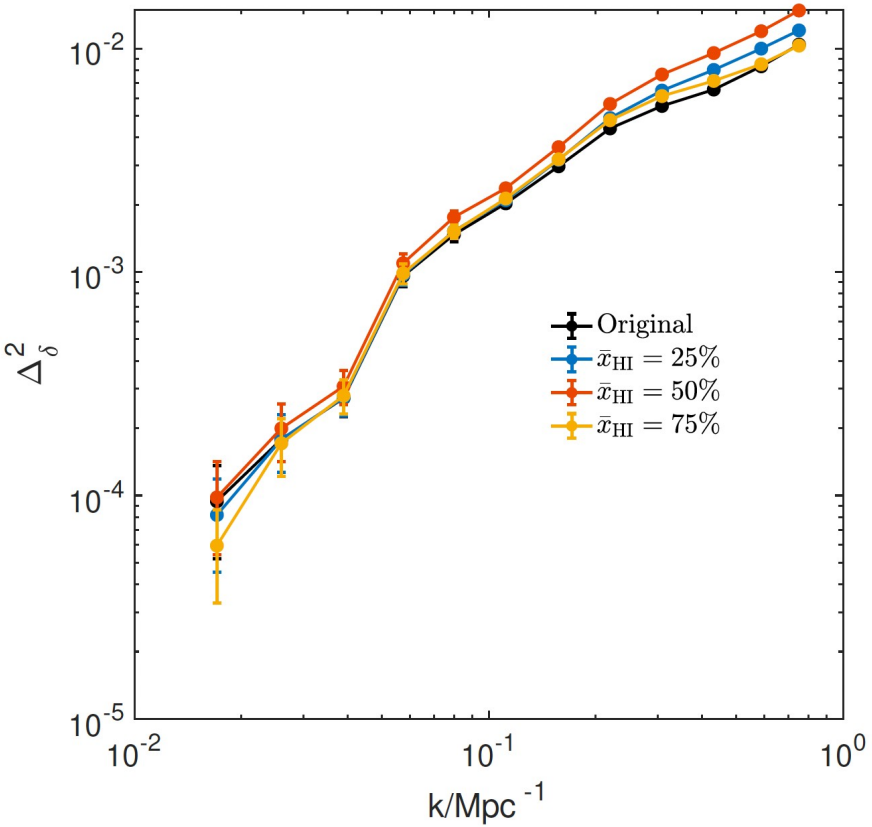
From observations at: $z=7.56$, $x_{HI} = 0.25$ $z=8.20$, $x_{HI} = 0.50$ $z=9.54$, $x_{HI} = 0.75$



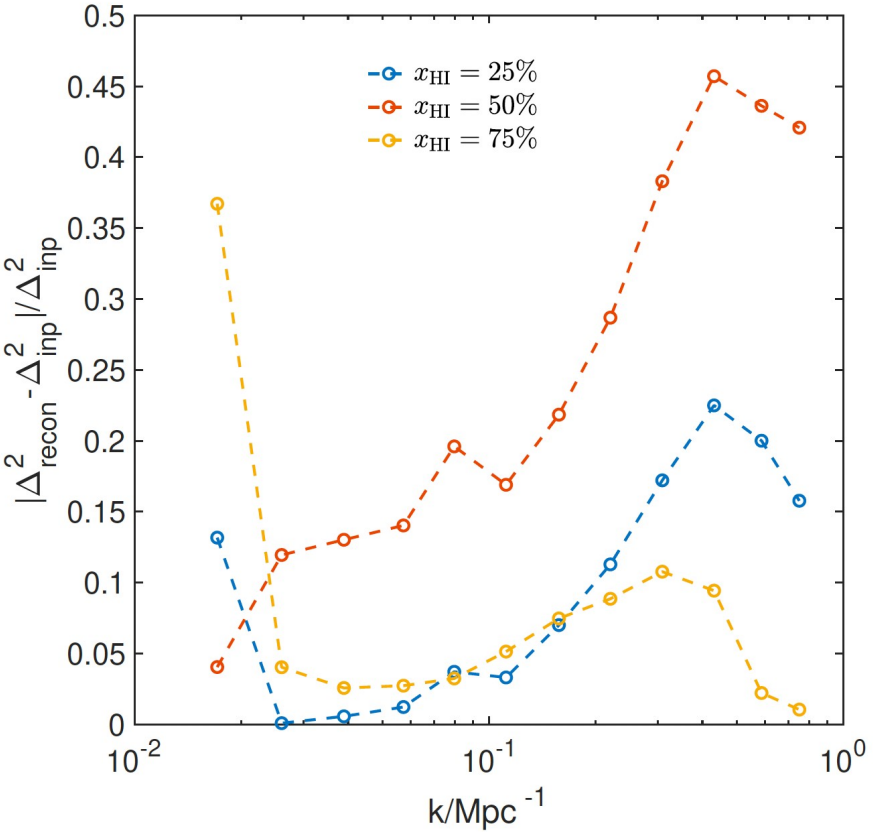
Zhou and **YM**, ApJ 2024
(arXiv:2311.14940)

We can reconstruct the initial density fields *from high-redshift observations*

Power spectrum of initial overdensity



Relative error of initial overdensity power spectrum



Zhou and **YM**, ApJ 2024 (arXiv:2311.14940)

Summary

- We exploit the Simulation-based Inference (SBI) to perform the posterior inference of reionization parameters, both from 21 cm power spectrum and from 21 cm lightcone images.

- We can reconstruct the cosmological initial density fields from the 21 cm and CO intensity mapping during the epoch of reionization. We develop a method based on conjugate gradients, which can successfully reconstruct the initial density fields with a goodness less than 7% at all stages of reionization.