SKA Data Challenge 3

Foreground removal update from SKACH team

SKACH

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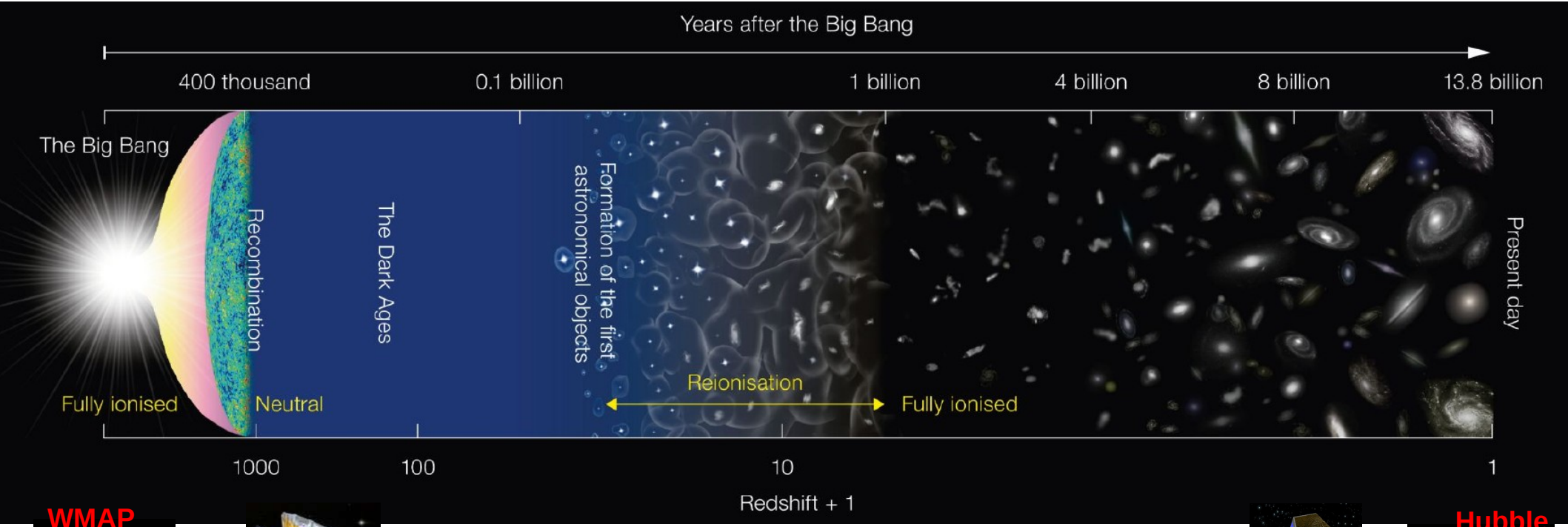
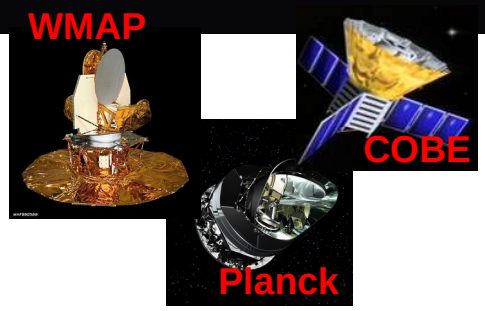
Andrei Mesinger
David Prelogović

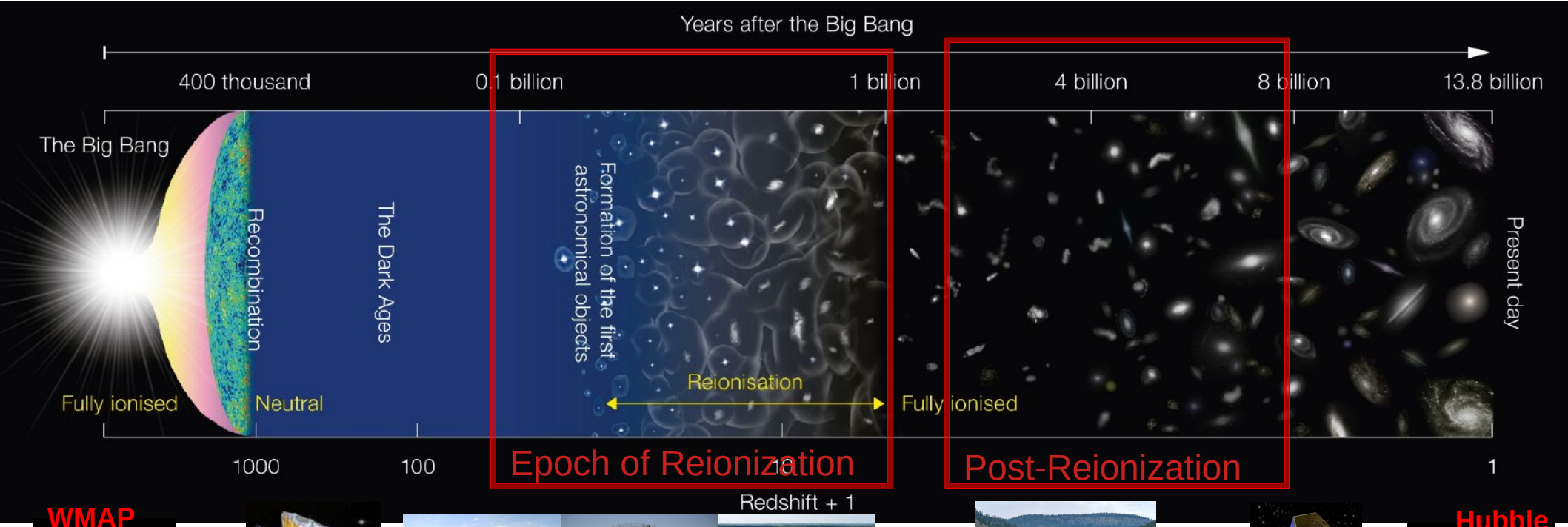
Cosmology with Radio Interferometric Experiments

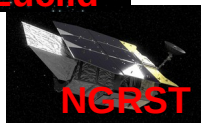




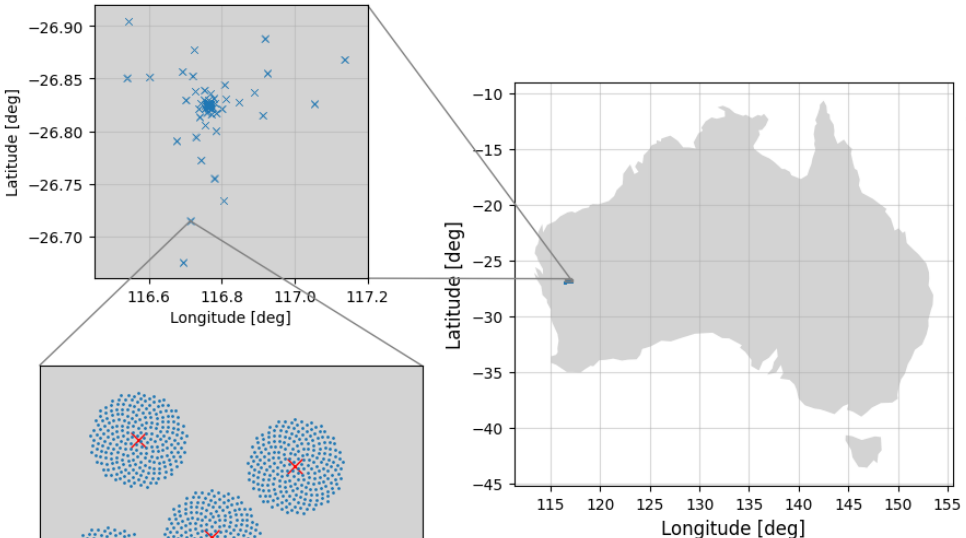
Current cosmology is inferred by either lager scale or local cosmological constraints

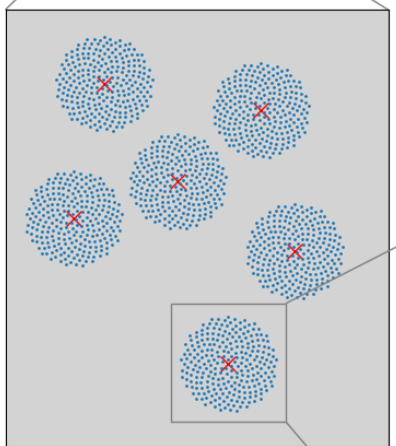
Cosmology with Radio Interferometric Experiments

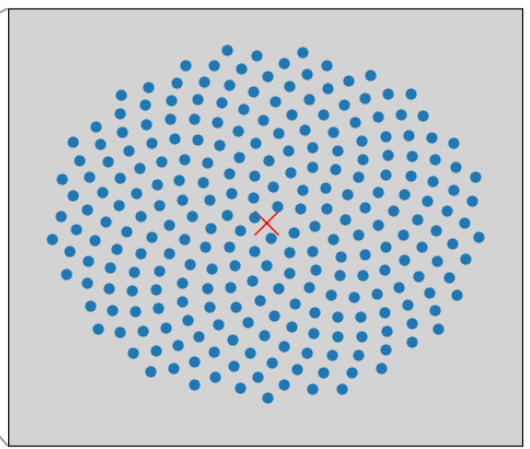




Square Kilometre Array (SKA-Low)







Final layout of the SKA-Low stations and **start of the construction** on the 5th of December 2022.

- 512 stations, each with 128 antennas
- Maximum baseline ~65 km, station diameter 35 m
  - FoV = 10 deg with 16 arcsec resolution
- Frequency range between 50 to 350 MHz (z = 27 – 5)

Ongoing Radio Experiments

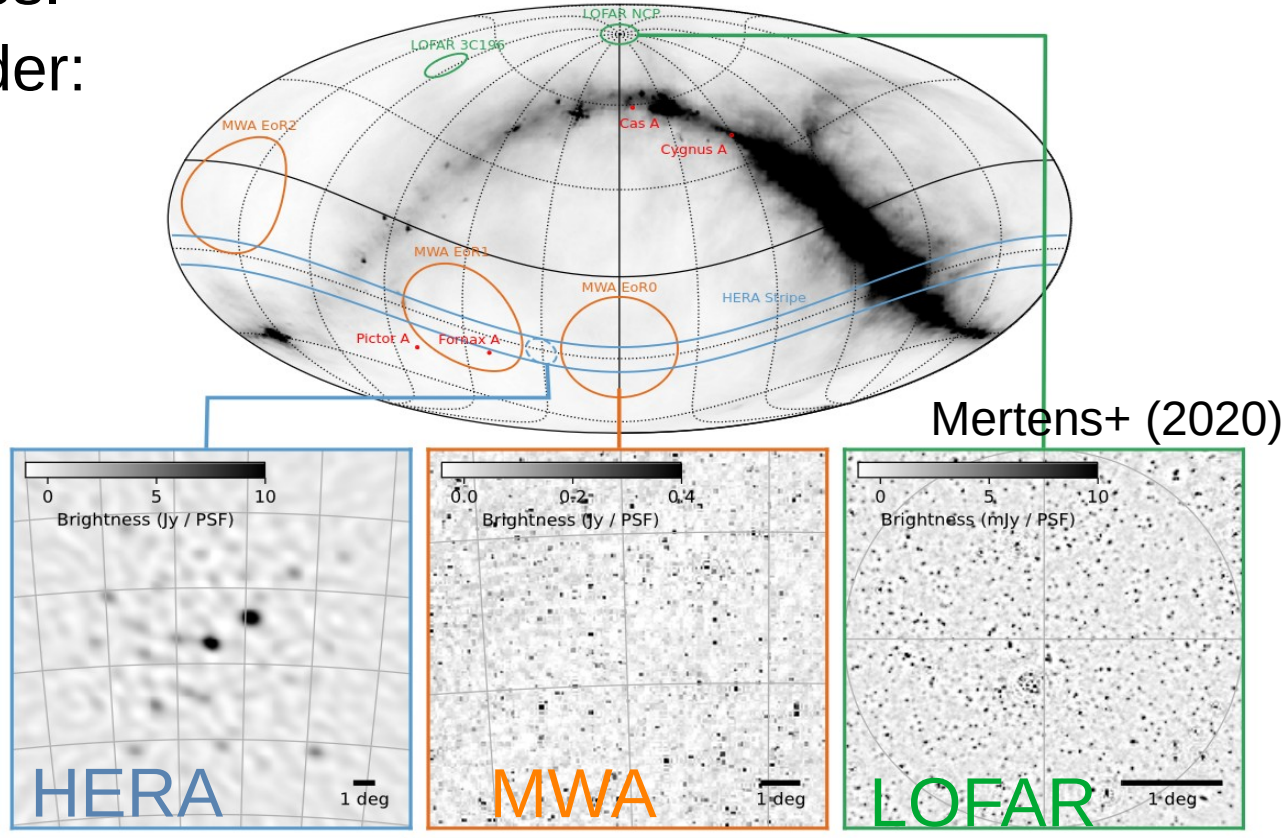
Emission at low frequency of the Galactic foreground sky and radio extra-galactic point sources.

Results form SKA pathfinder:

- HERA

- MWA

- LOFAR



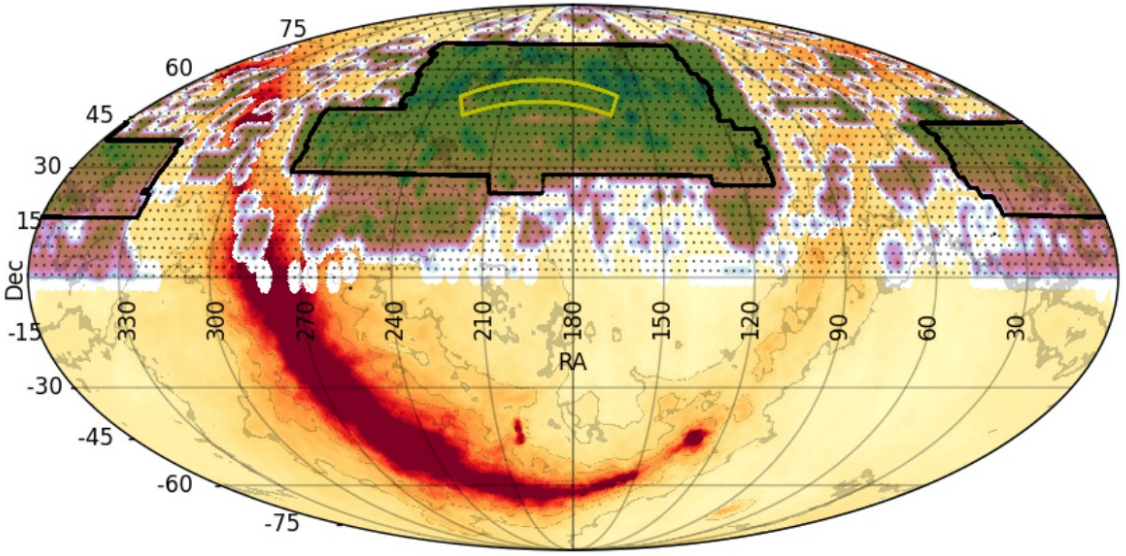
Mertens+ (2020)

Ongoing Radio Experiments

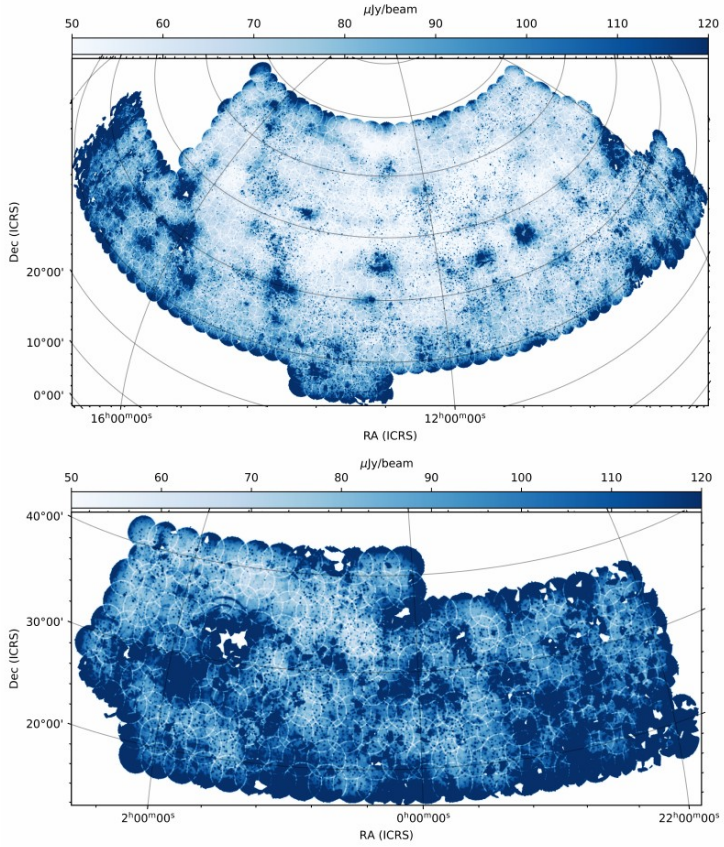
LOFAR is covering 27% of North sky avoiding the Galactic plane.

Recent data release of the **LoTTS-DR2** observation:

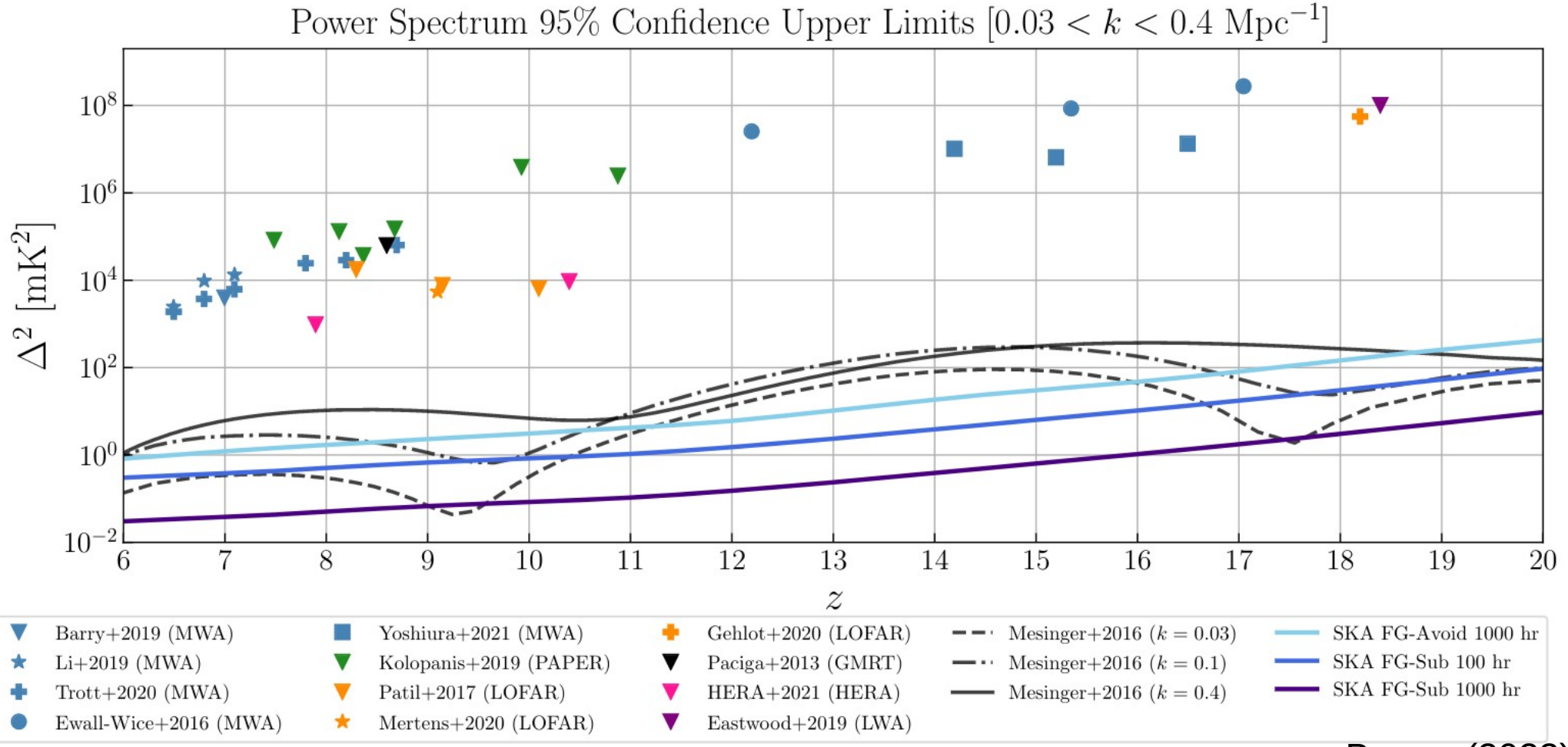
- High Band Antenna: 120 – 168 MHz
- 3.4 hrs obervation (7.6PB)



Shimwell+ (2022)

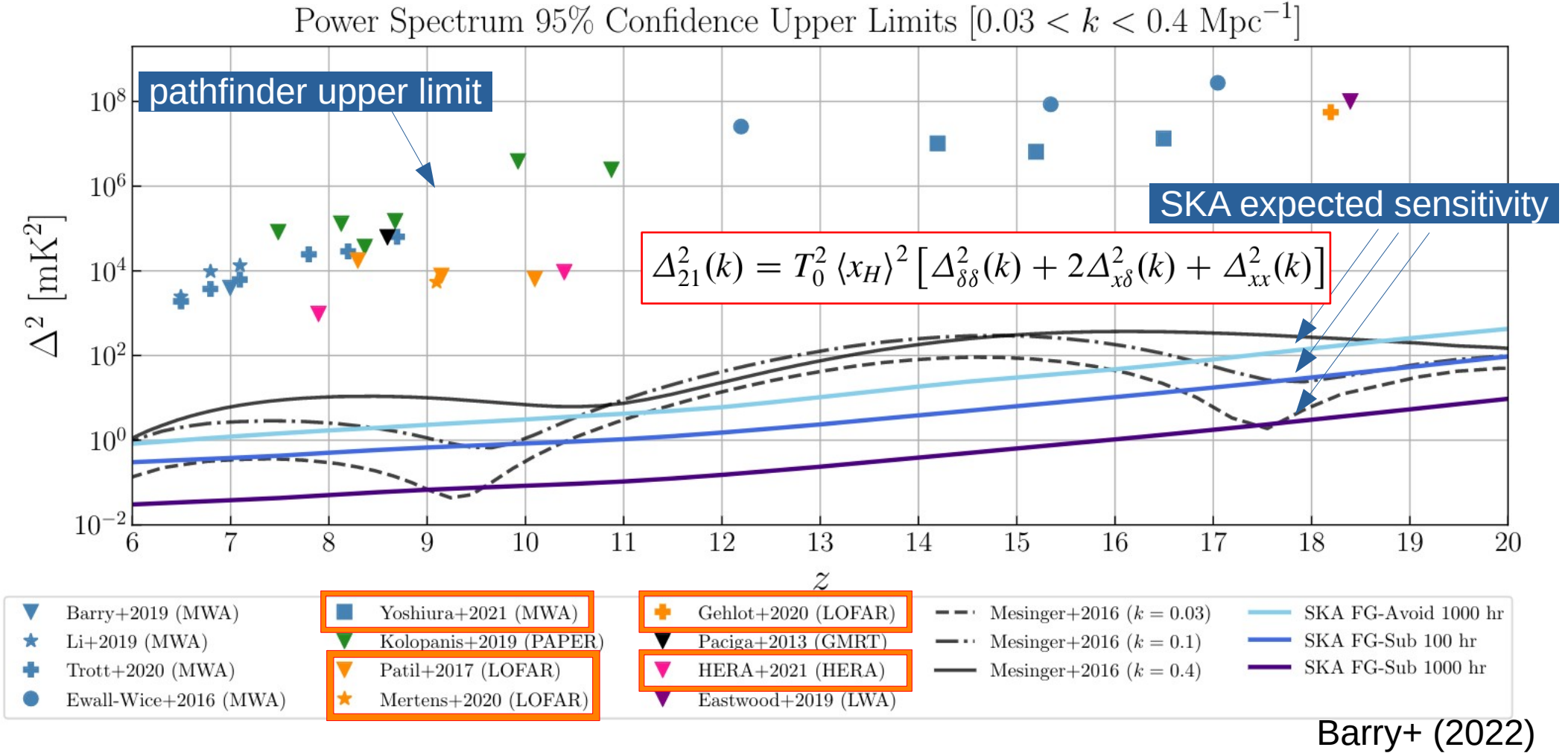


Constrains on the 21-cm Power Spectrum



Barry+ (2022)

Constrains on the 21-cm Power Spectrum



Barry+ (2022)

The 21-cm Signal During EoR

$$\delta T_b = 28\text{mK}\,(1+\delta)\,x_{\text{HI}}\left(1-\frac{T_{CMB}}{T_{spin}}\right)\left(\frac{\Omega_b h^2}{0.0223}\right)\sqrt{\left(\frac{1+z}{10}\right)\left(\frac{0.24}{\Omega_m}\right)}\left[\frac{H(z)/(1+z)}{\mathrm{d}v_{\parallel}/\mathrm{d}r_{\parallel}}\right]$$

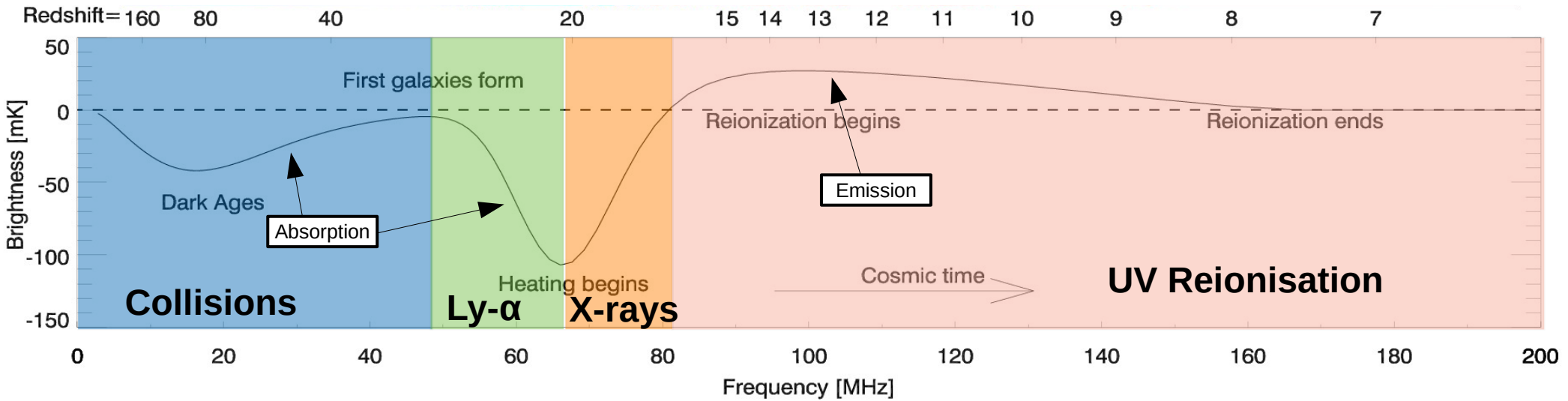
Gas density distribution

Hydrogen Neutral fraction

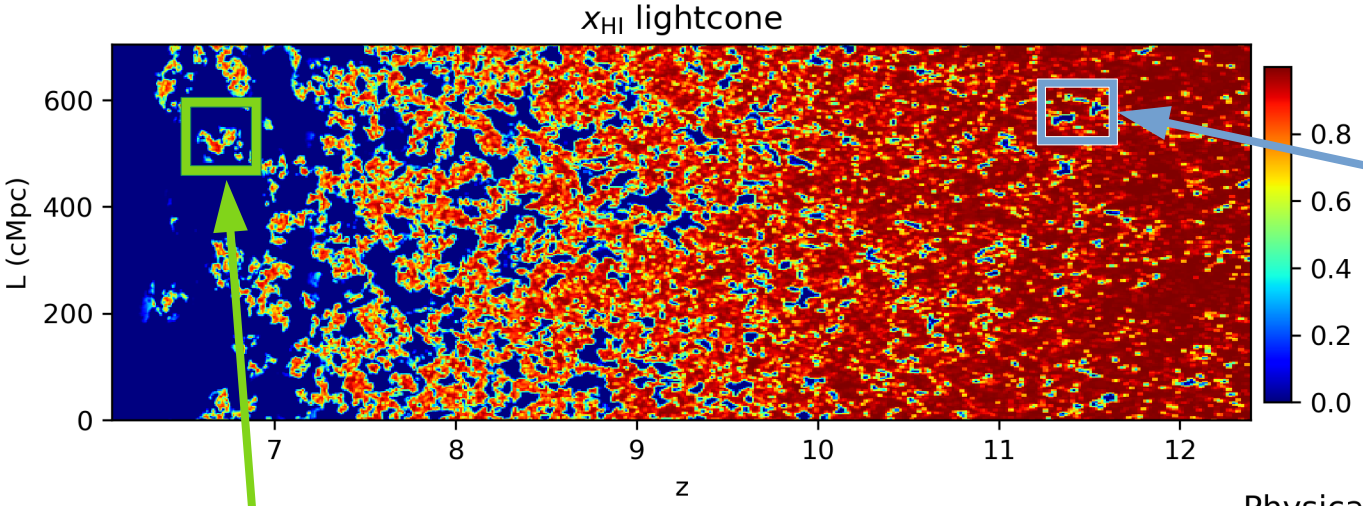
Spin temperature

Cosmology

L.o.S velocity



The 21-cm Signal During EoR

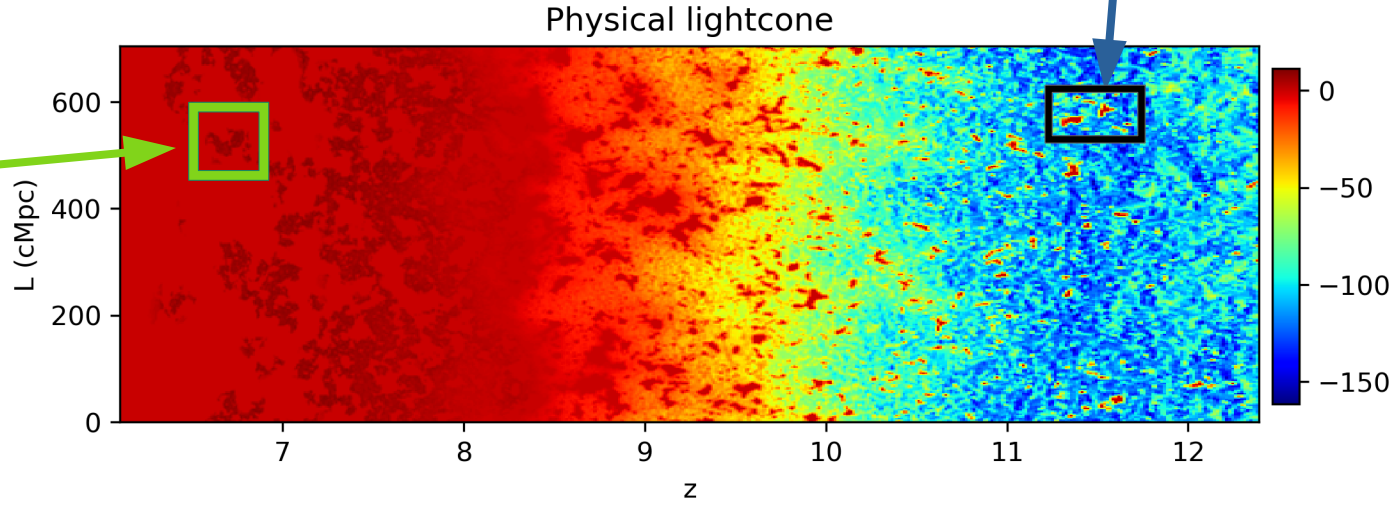


$T_S \ll T_{CMB} \Longrightarrow \delta T_b \ll 0\,\mathrm{mK}$

21-cm in emission in cold IGM

21-cm emission = Neutral hydrogen

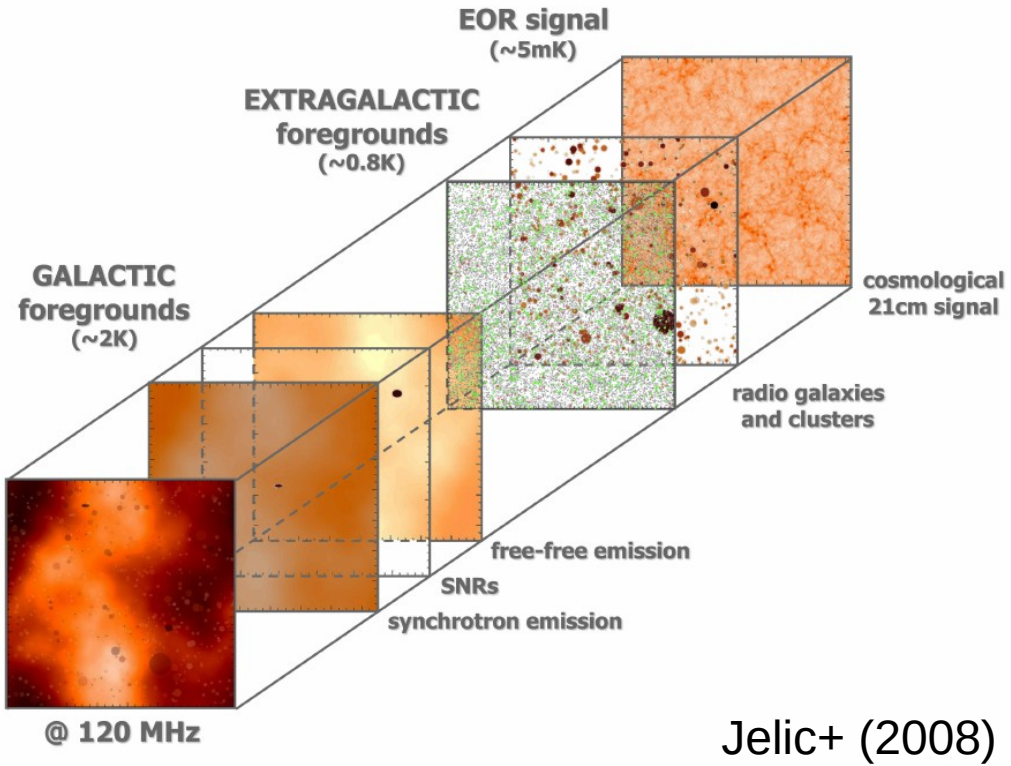
$\delta T_b \propto x_{\rm HI}(z)$



Tomographic Imaging of the 21-cm signal

SKA1-Low tomographic images of redshifted 21-cm signal challenges:

- Instrumental noise (signal ~ 5 K)
- Foreground emission (signal ~ 1 - 1000 K)
- Antennas gain errors
- Ionospheric refraction effects
- Radio frequency interference
- And more ...

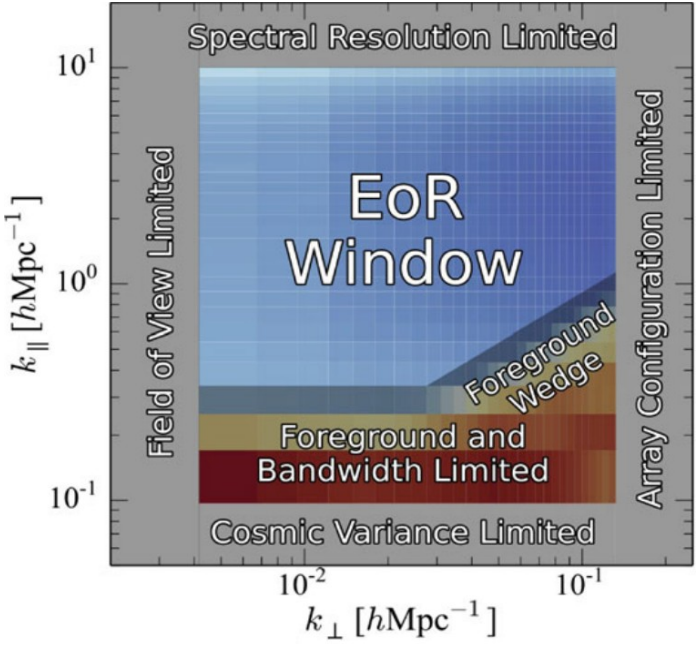


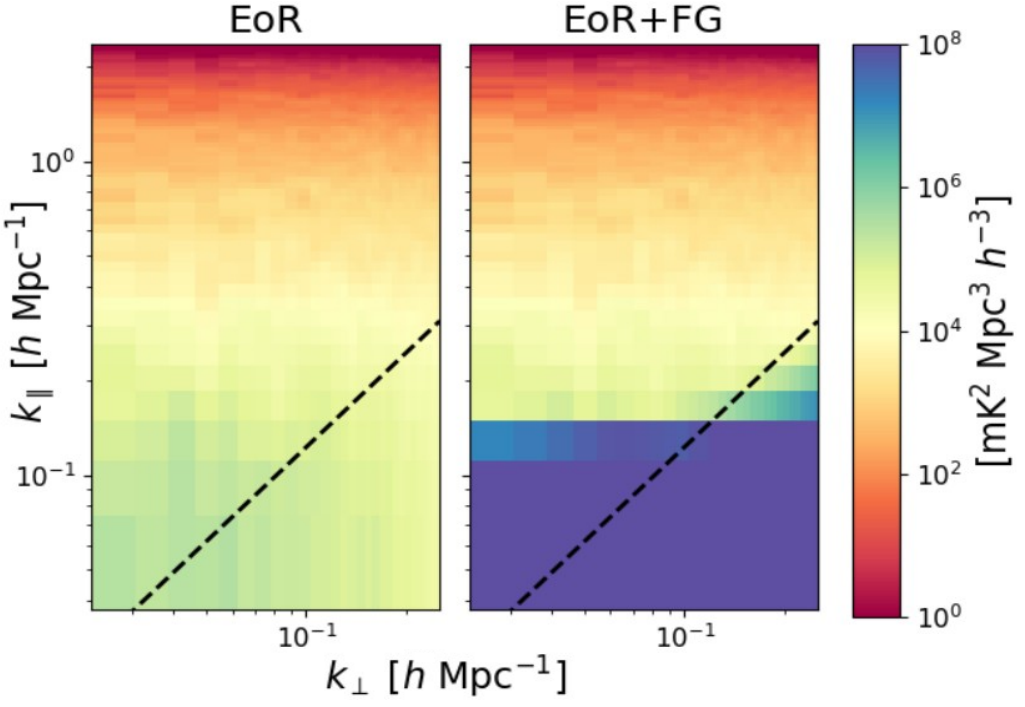
Jelic+ (2008)

Contamination from Galactic & extra-galactic Foregrounds

Most **foregrounds** have **frequency smooth spectra** compared to the 21-cm signal.

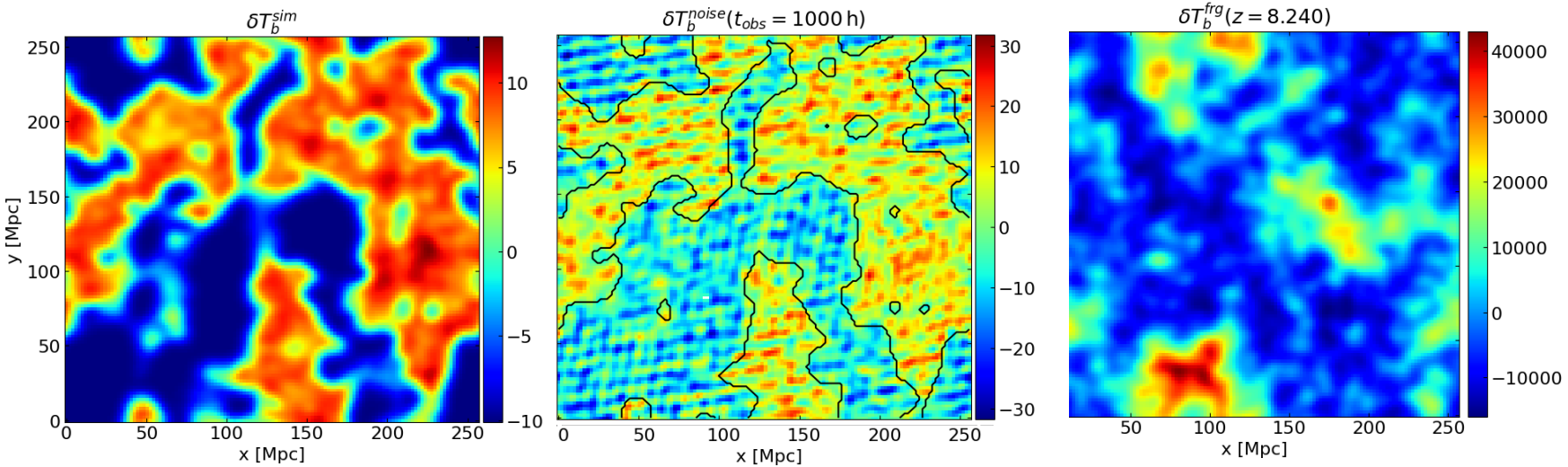
From 2D power spectra, remove $k_\perp$ - $k_\parallel$ modes that are contaminated by the foregrounds as a **avoidance technique** or model them for **substraction**.





Mock Data for 21-cm Observation

Currently we can create EoR mock observation with a combination of numerical models for 21-cm, systematic noise and Galactic foreground.

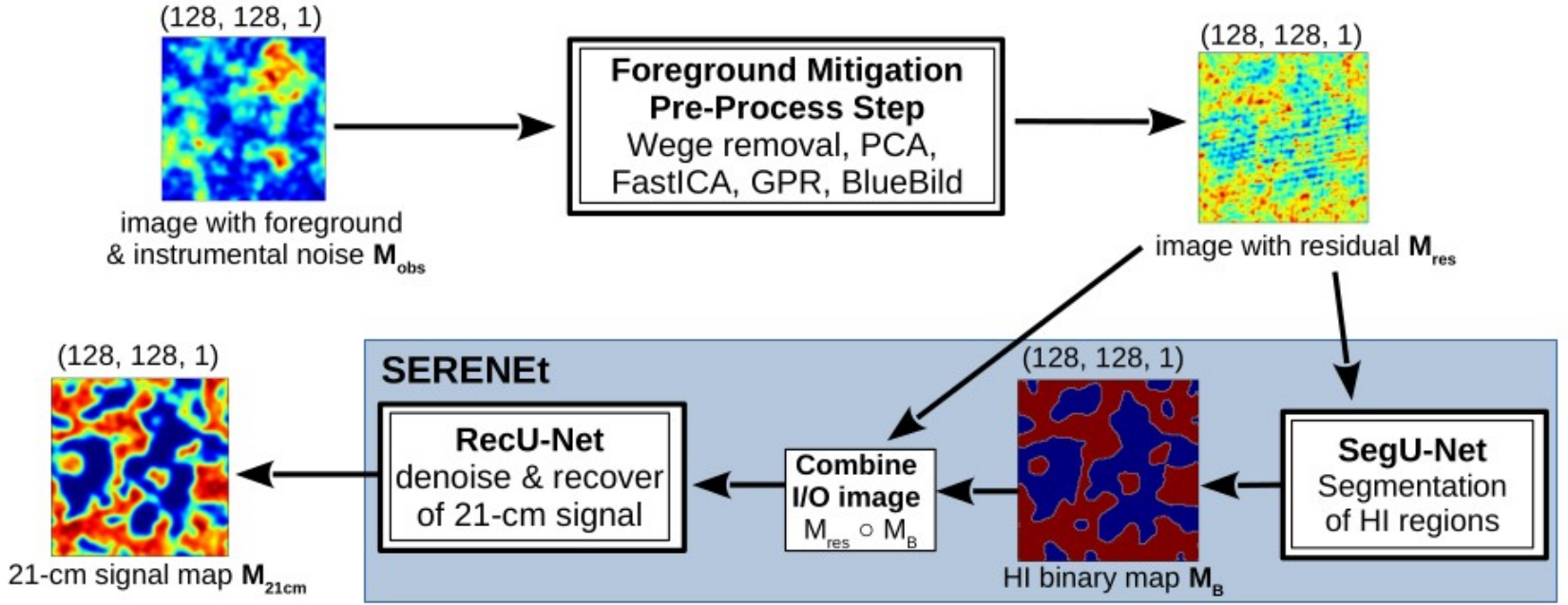


<u>Goal:</u>

pipelines to recover differential brightness and the distributon of netural hydrogen from mock observations.

SERENEt
SEgmentation and **RE**gression **NEt**work

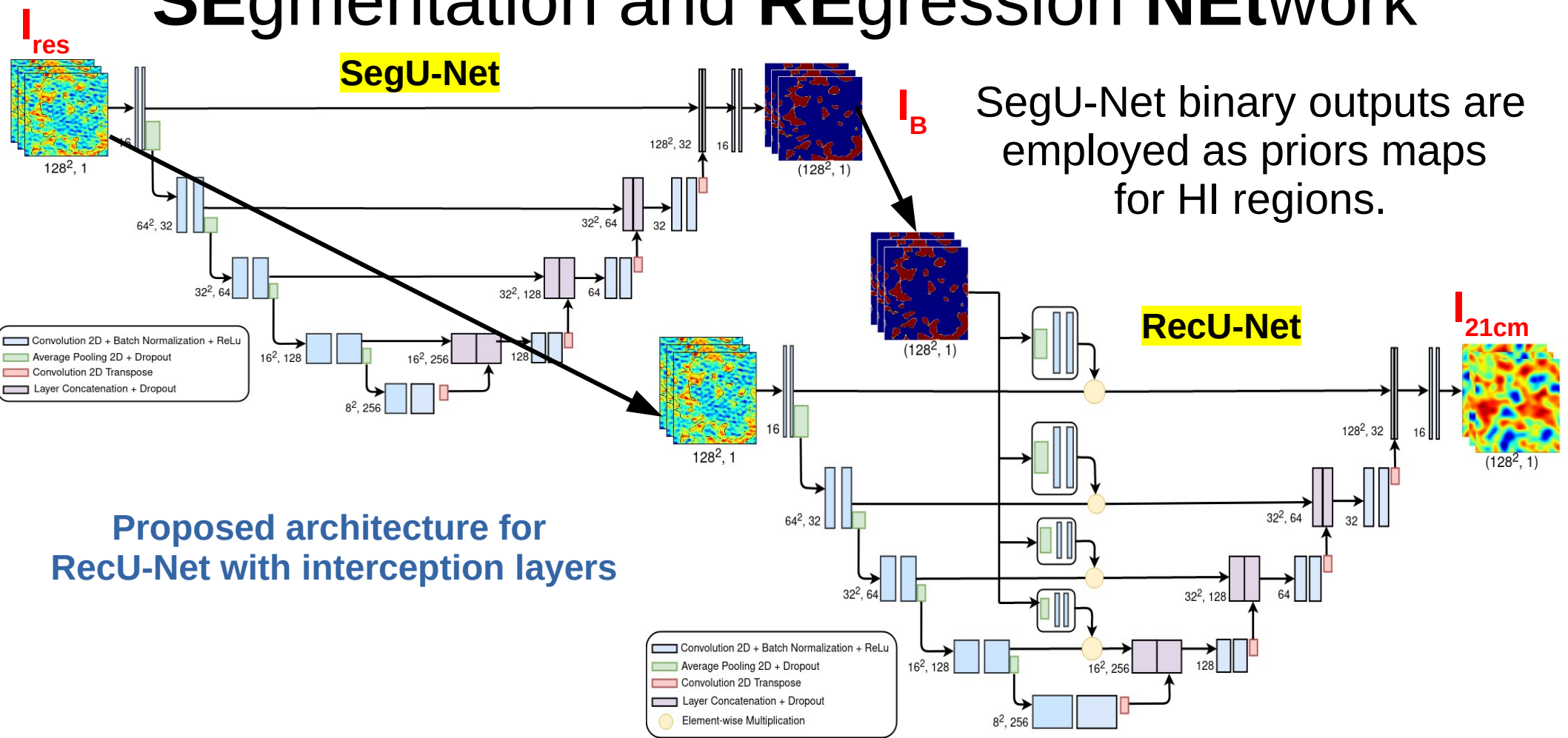
Combine the predicted binary maps of **SegU-Net** as additional input of **Rec-Unet** training step in order to include prior in the network training.



SKACH large HPC **70k hybrid-h** allocation projects at Pitz Daint at CSCS

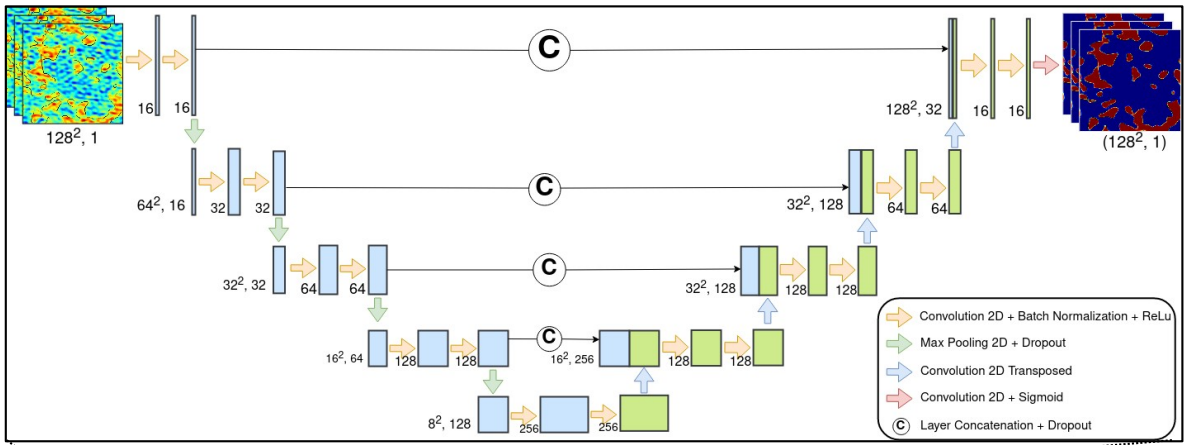
SERENEt

SEgmentation and REgression NEtwork

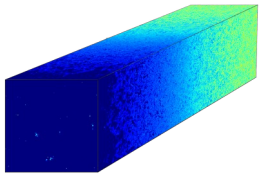


SegU-Net: Segmentation with U-Net
(Bianco+ 2021, 2023)

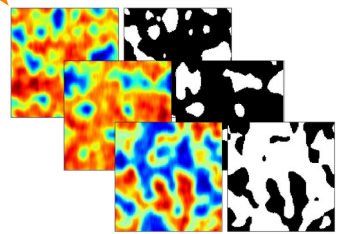
- U-Net:
  Network with interconnected encoder/decoder layers



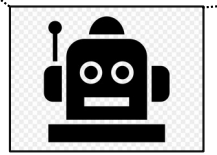
add PCA pre-process step that decreases image dynamic range



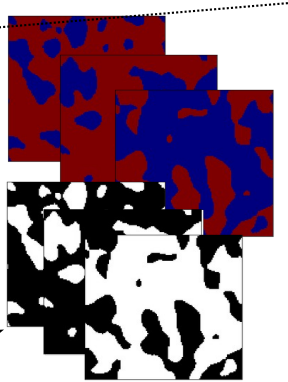
21cm tomography dataset



(z, ν_{obs})
21cm signal = image
x_{HI} field = mask



SegU-Net
(2.5M trainable params.)



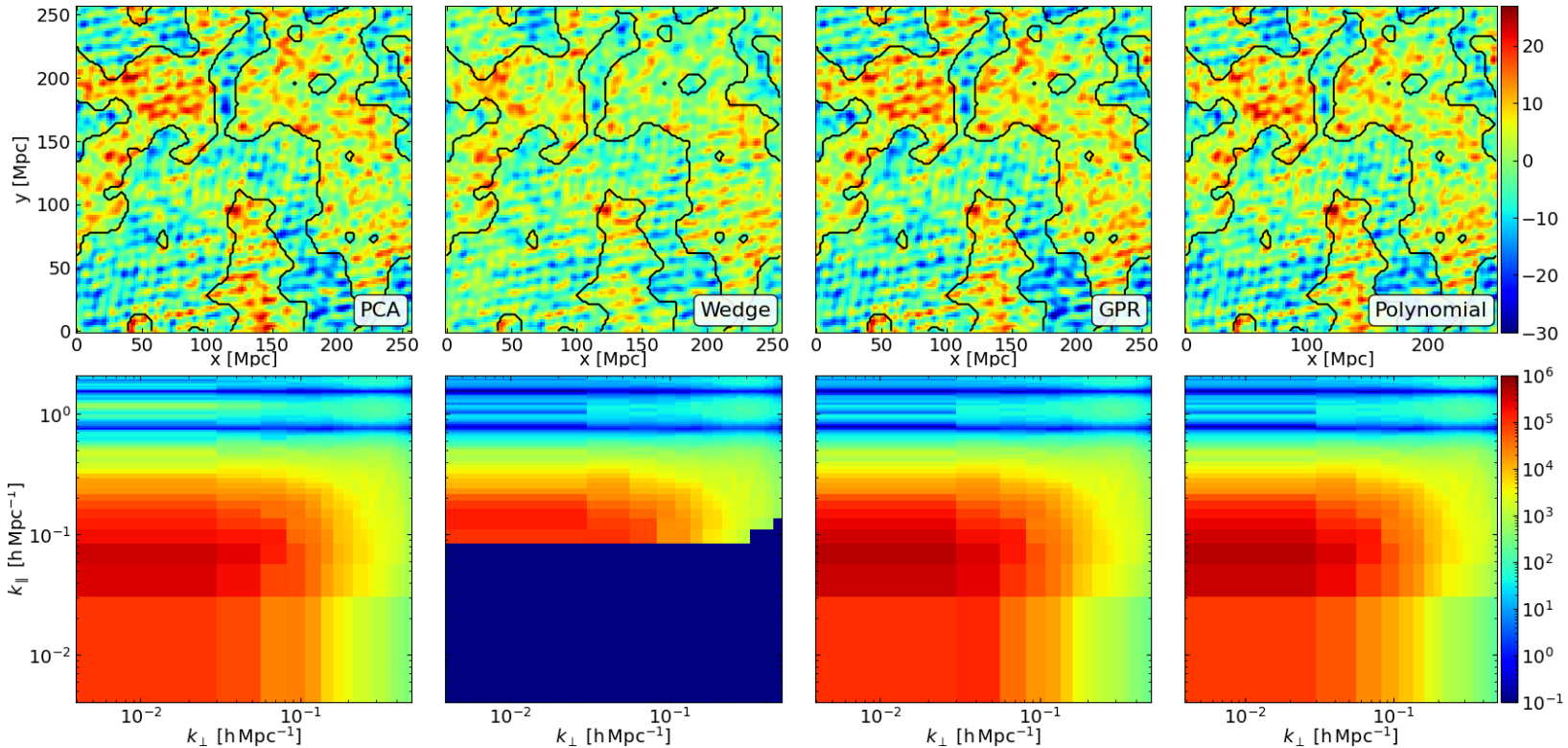
Compare Prediction/True mask

$\mathcal{L}(y, \hat{y})$

Calculate Loss

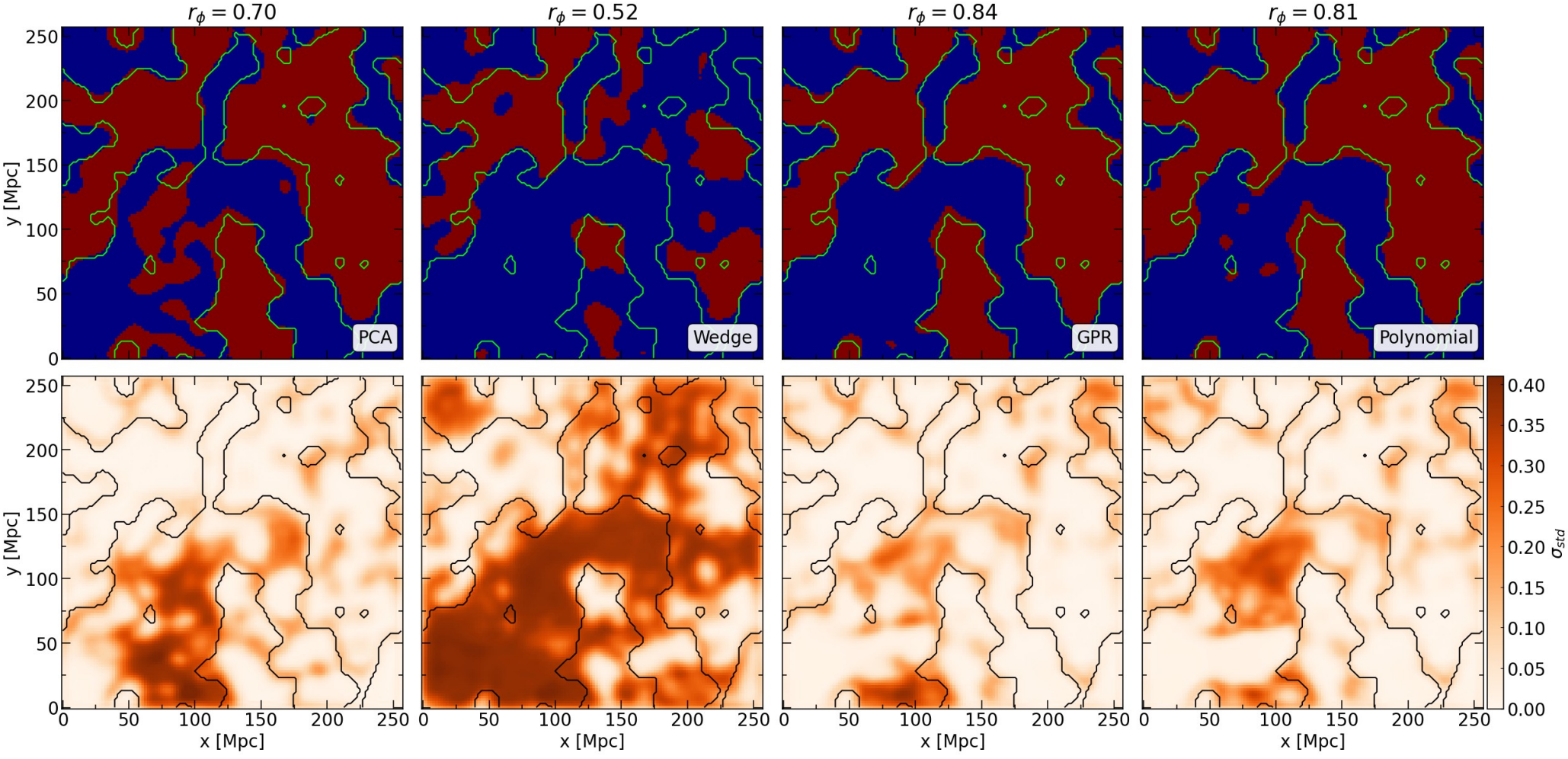
Pre-process:
Foreground Mitigation & Avoidance

We employ 3 mitigation and 1 avoidance techniques, Bianco+ 2023



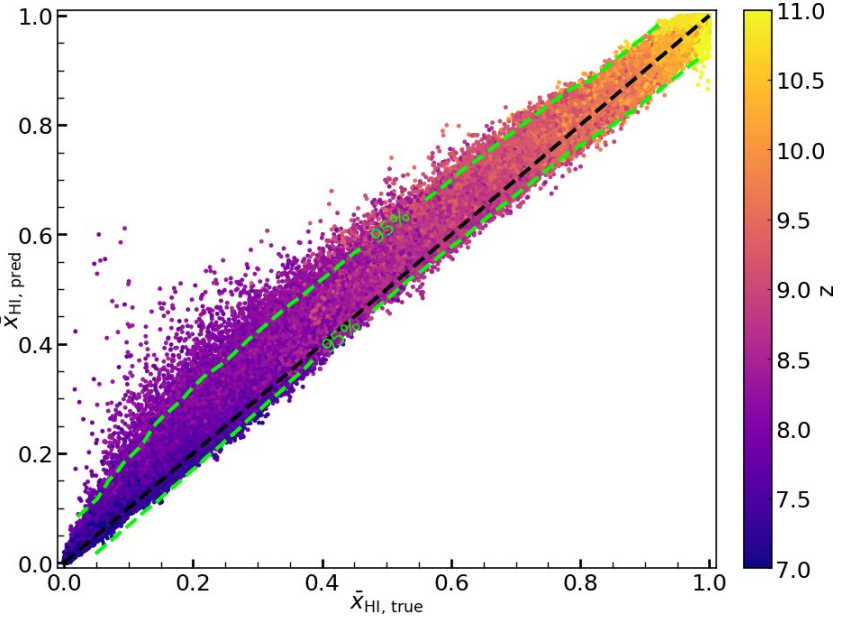
PCA Wedge GPR Polynomial

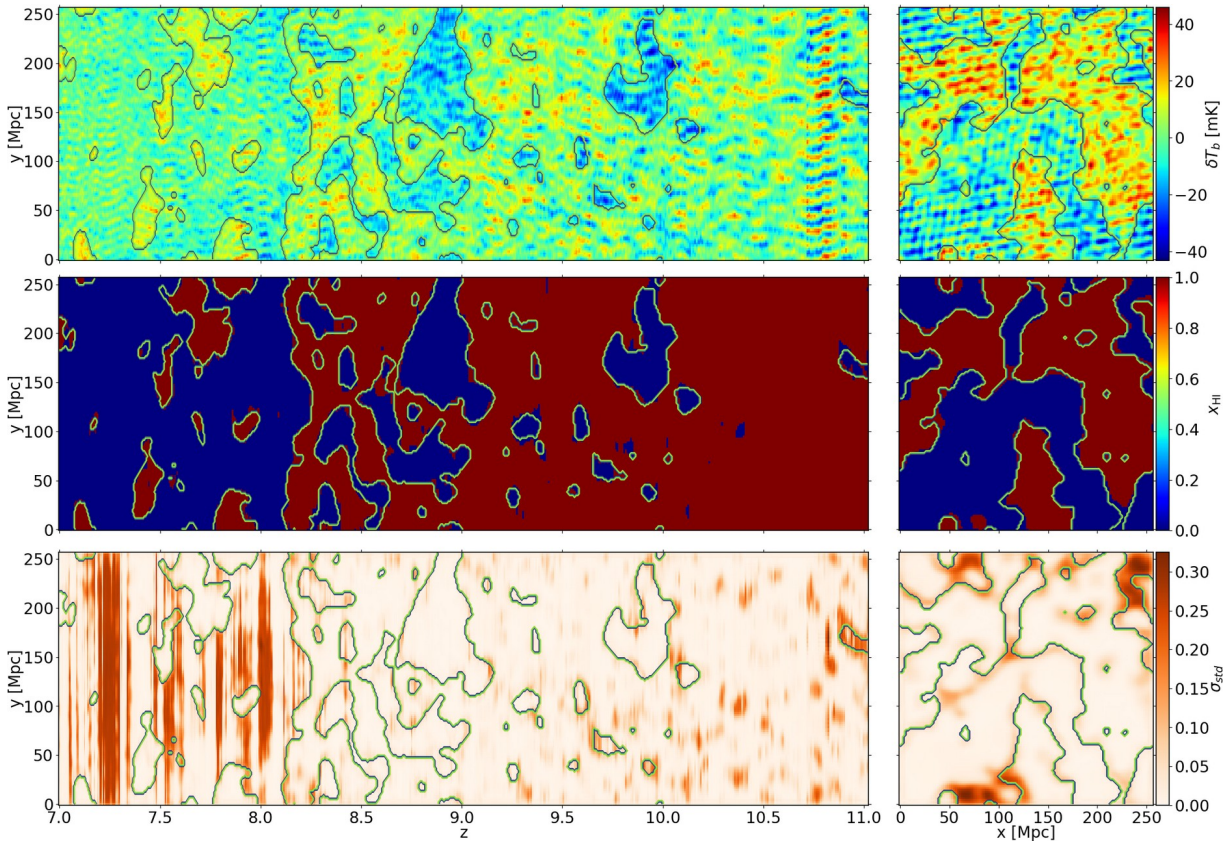
SDC3: General Annoucment



SegU-Net:
Tomographic Data & Reionization History

z_c	pre-process	$\overline{x}_{\rm HI}$
8.24	Ground Truth	**0.45**
	all z PCA	0.48 ± 0.07
	PCA	0.49 ± 0.11





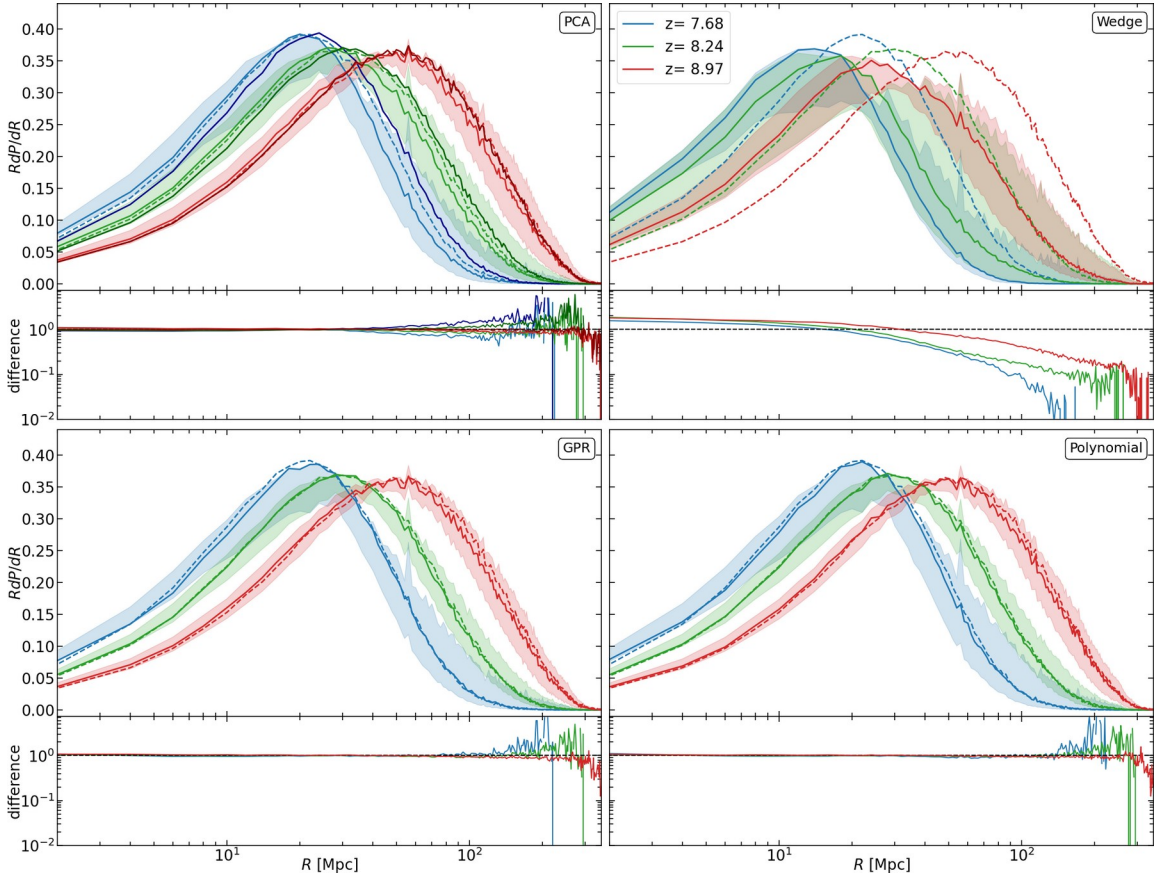
SegU-Net: HI size distribution

The Island (HI regions) size distribution is an powerfull probe of the reionization process. (21-cm non-Gaussianity)

$$\overline{R}_C(z) = \int_{R_{\min}}^{\infty} R \, \frac{dP}{dR}(z) \, dR$$

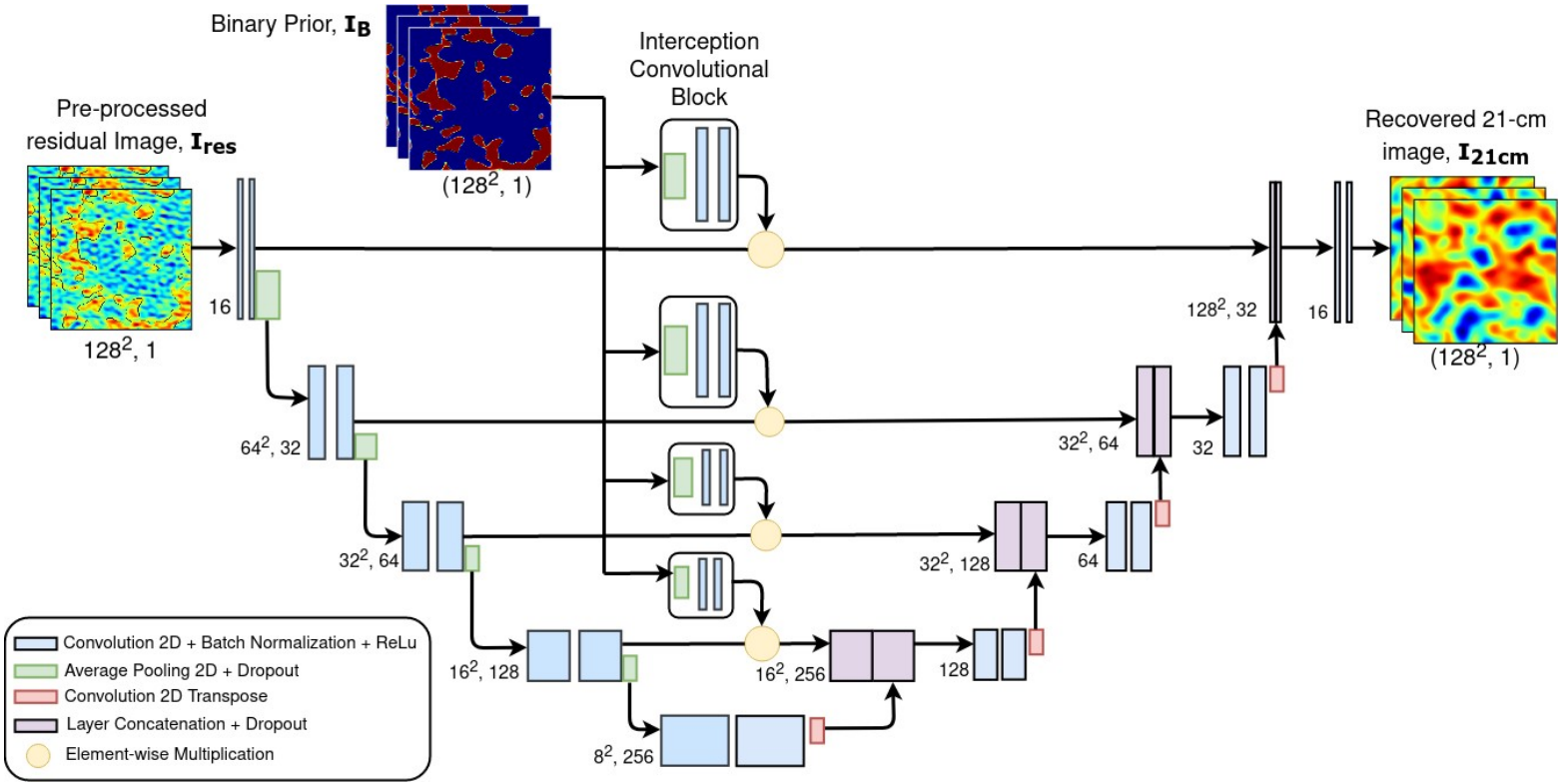
SegU-Net results:

z_c	pre-process	$\overline{R}_C$ [cMpc]
8.24	Ground Truth	**29.54**
	all z PCA	$31.37^{+3.09}_{-3.93}$
	PCA	$27.65^{+9.13}_{-6.12}$
	Wedge	$15.20^{+24.13}_{-6.18}$
	GPR	$29.14^{+5.26}_{-4.89}$
	Polynomial	$29.21^{+5.83}_{-5.21}$



RecU-Net: Recover 21-cm with U-Net

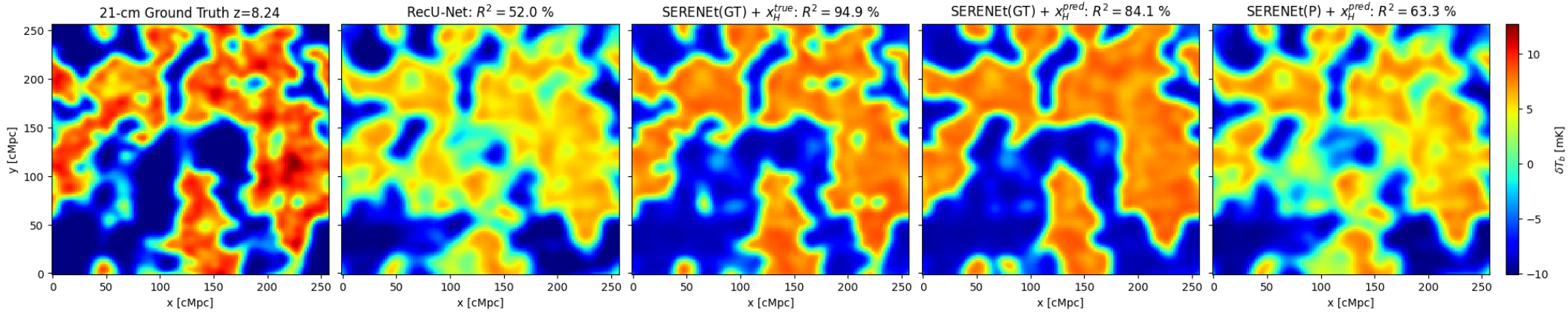
(Bianco+ in prep.)



U-Net architecture with intercepting convolution block to process the binary prior map from SegU-Net

SERENEt: Recover of 21-cm Signal

Recovered 21-cm signal for EoR for image at z = 8.25 (x_{HI}~0.5)



Best performing setup consider:

- Train SERENEt with the prior binary ground truth: **SERENEt(GT)**
- Real application requires the prredicted binary map from SegU-Net for the prediction: **SERENEt(GT) + x^{pred}_H**

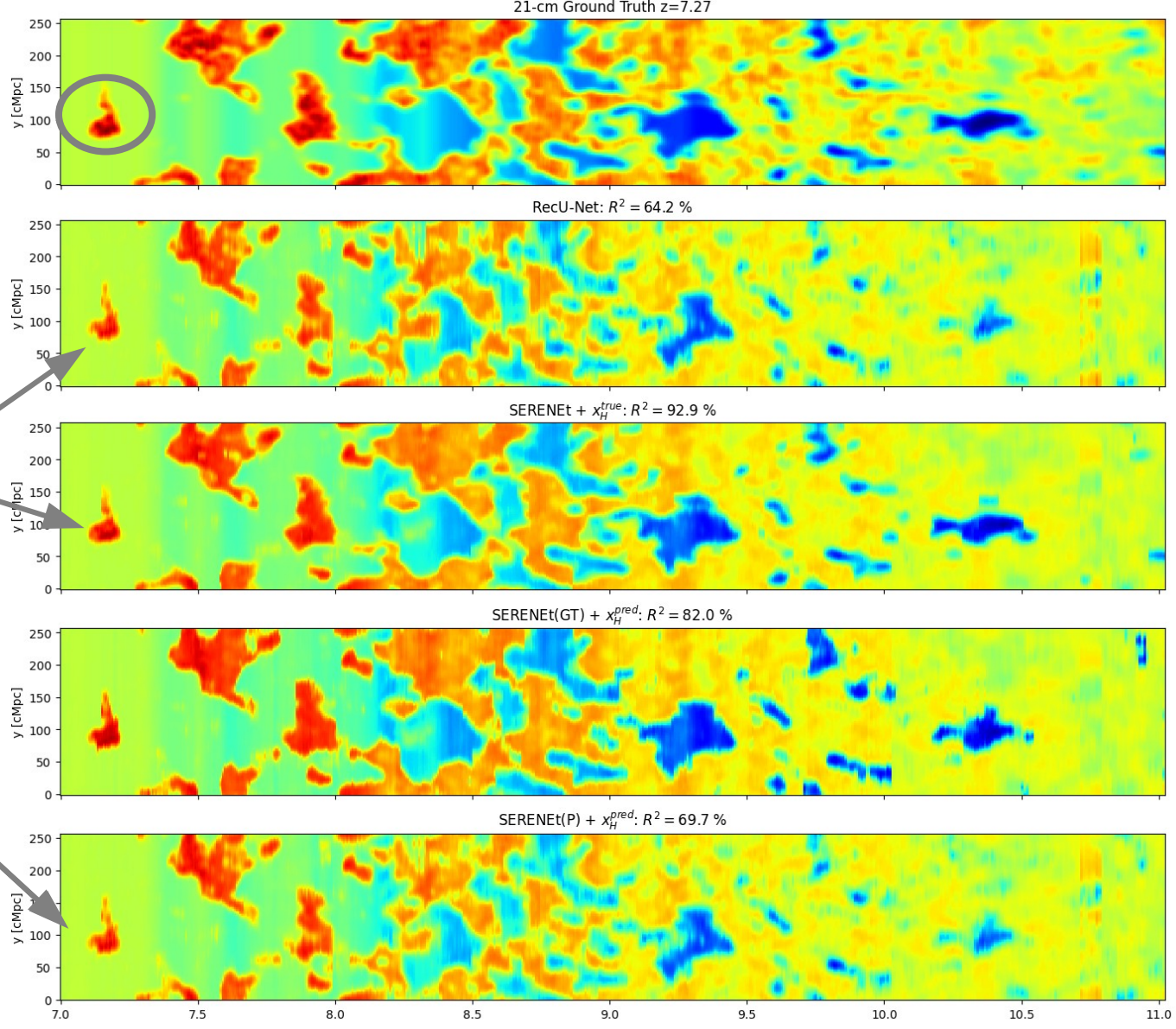
SERENEt

Limitation at lower redshift and decrease in accuracy for:

SERENEt(GT) + x^{pred}_H

When compared to

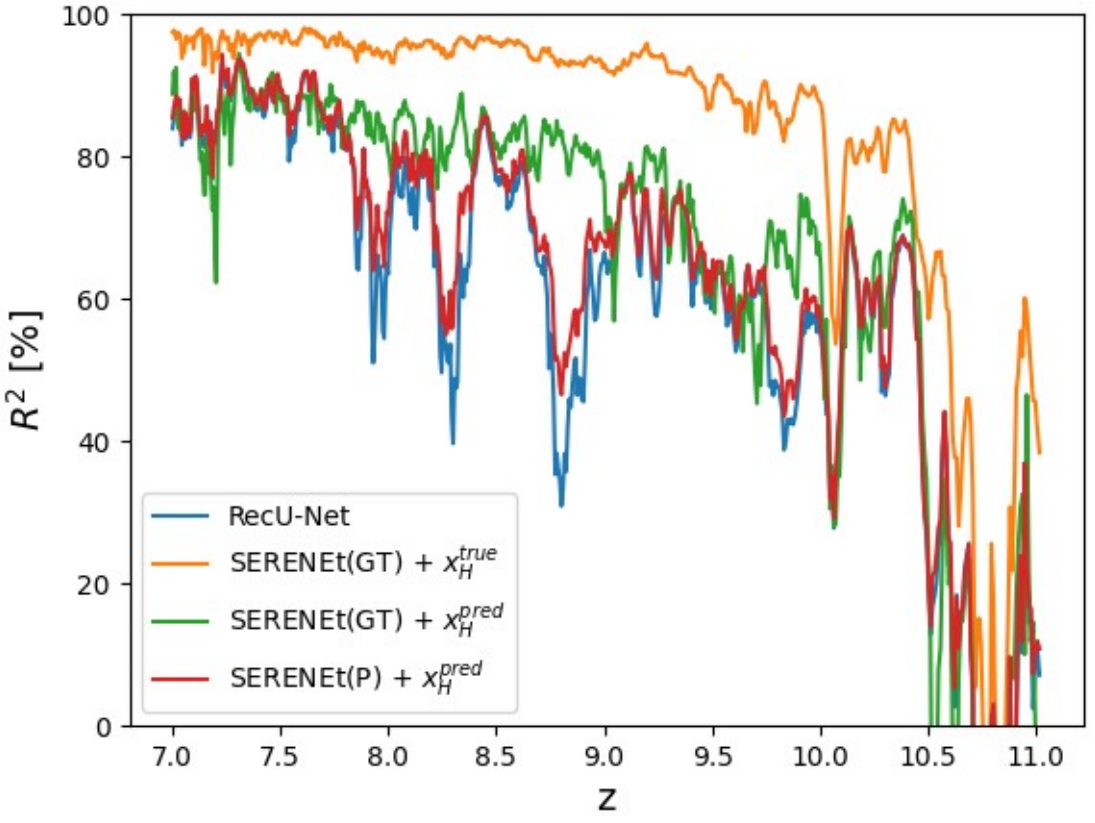
RecU-Net or
SERENEt(P) + x^{pred}_H



SERENEt: Recover of 21-cm Signal

Coefficient of determination (R^2 score) redshift evolution as a temporary Figure of Merit metric (FoM):

- **SERENEt(GT) + x^{true}_H**
  upper limit based on best pric
  binary map (ground truth)
- **SERENEt(GT) + x^{pred}_H**
  next best results when compared to **RecU-Net** or **SERENEt(P) + x^{pred}_H**



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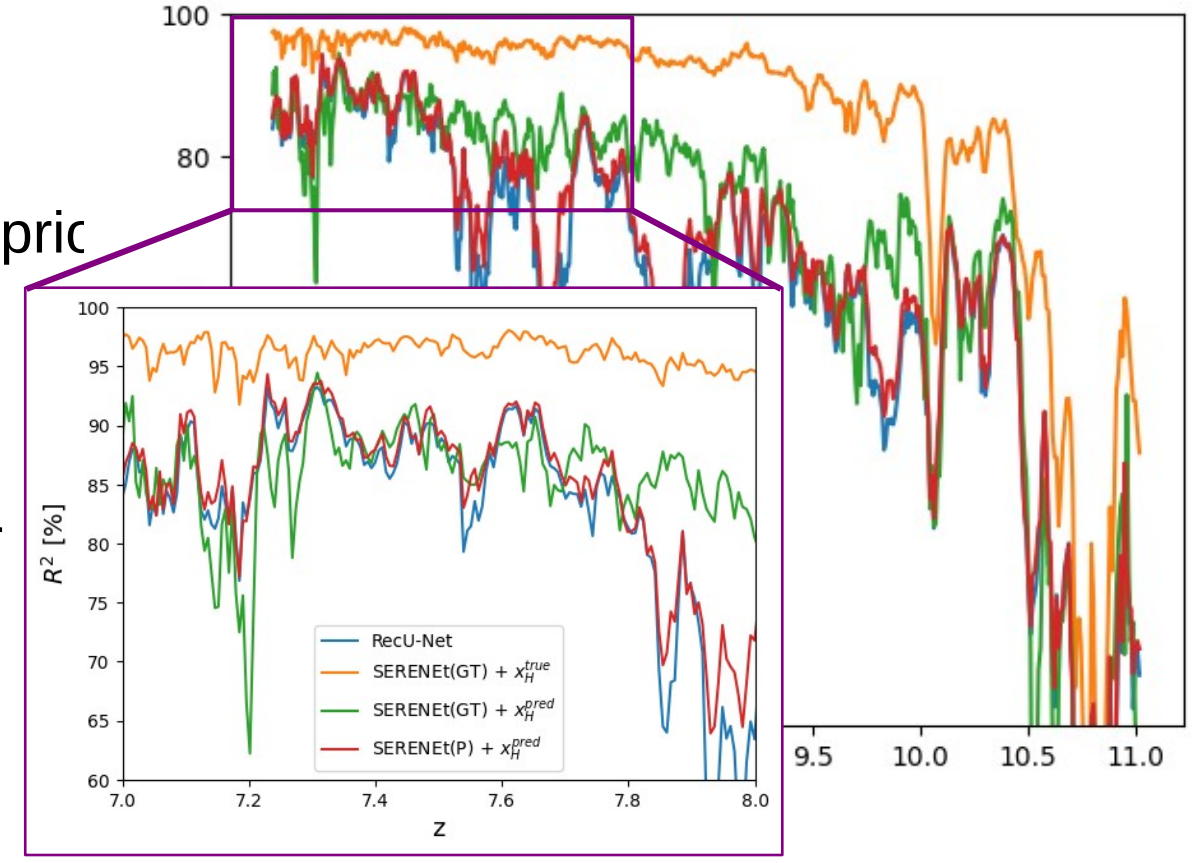
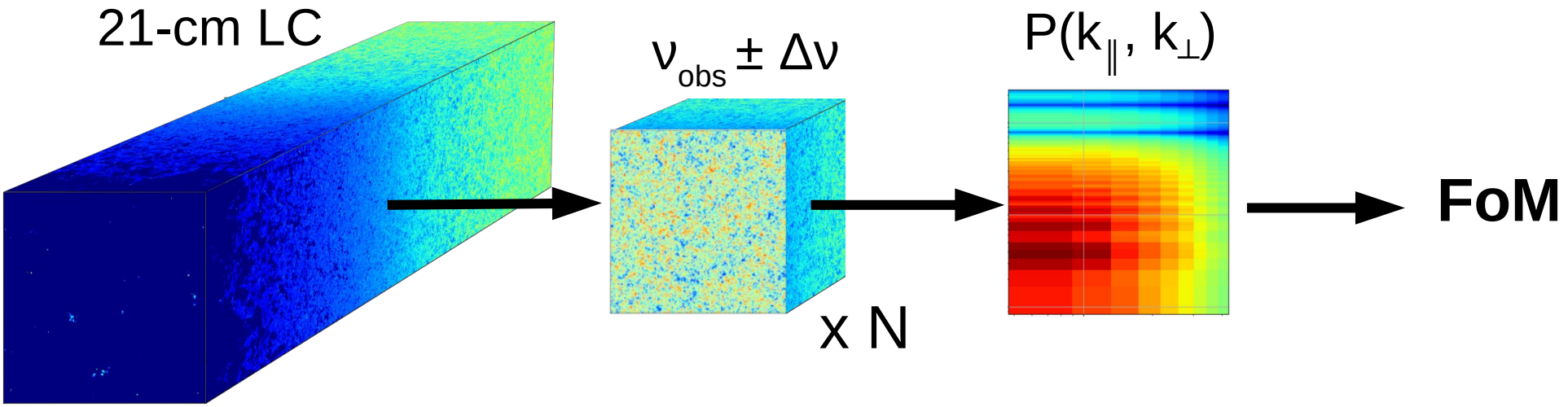


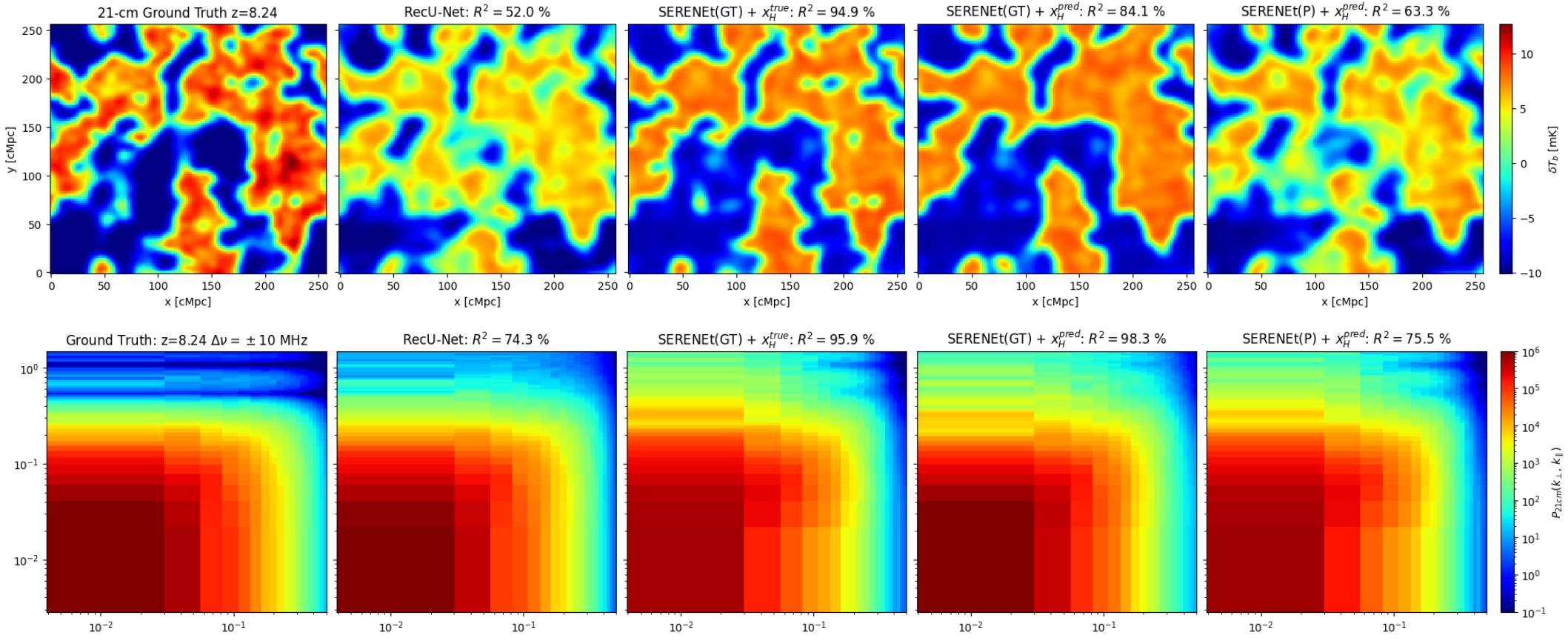
SDC3 Scoring System

The Figure of Merit (FoM) based on *"metric distance"* between the true and recovered spectra for **N sub-volumes** at a central frequency ν_{obs} and width $\Delta\nu$



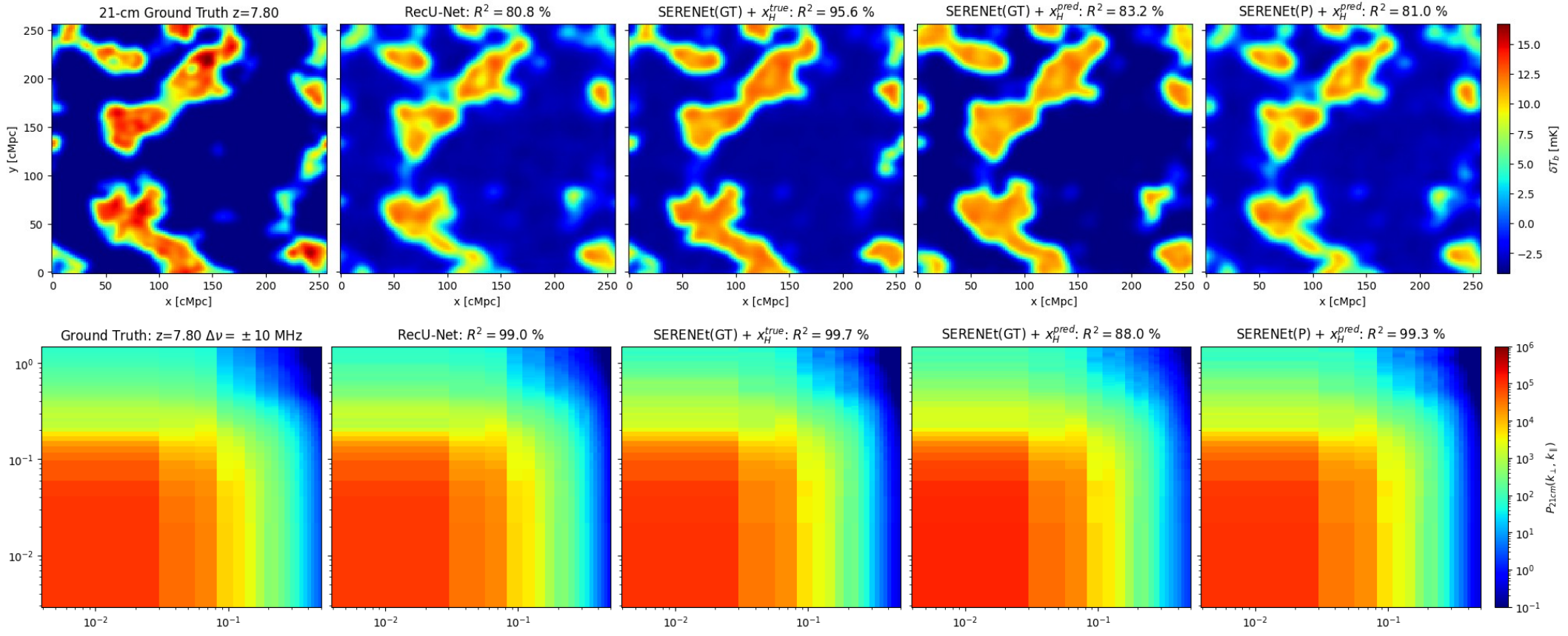
SERENEt: Recover of 21-cm Signal

Recovered 21-cm signal for EoR for lightcone subvolume centered at redshift **z = 8.25** (x_{HI}~0.5) and Δν +/- 10 MHz

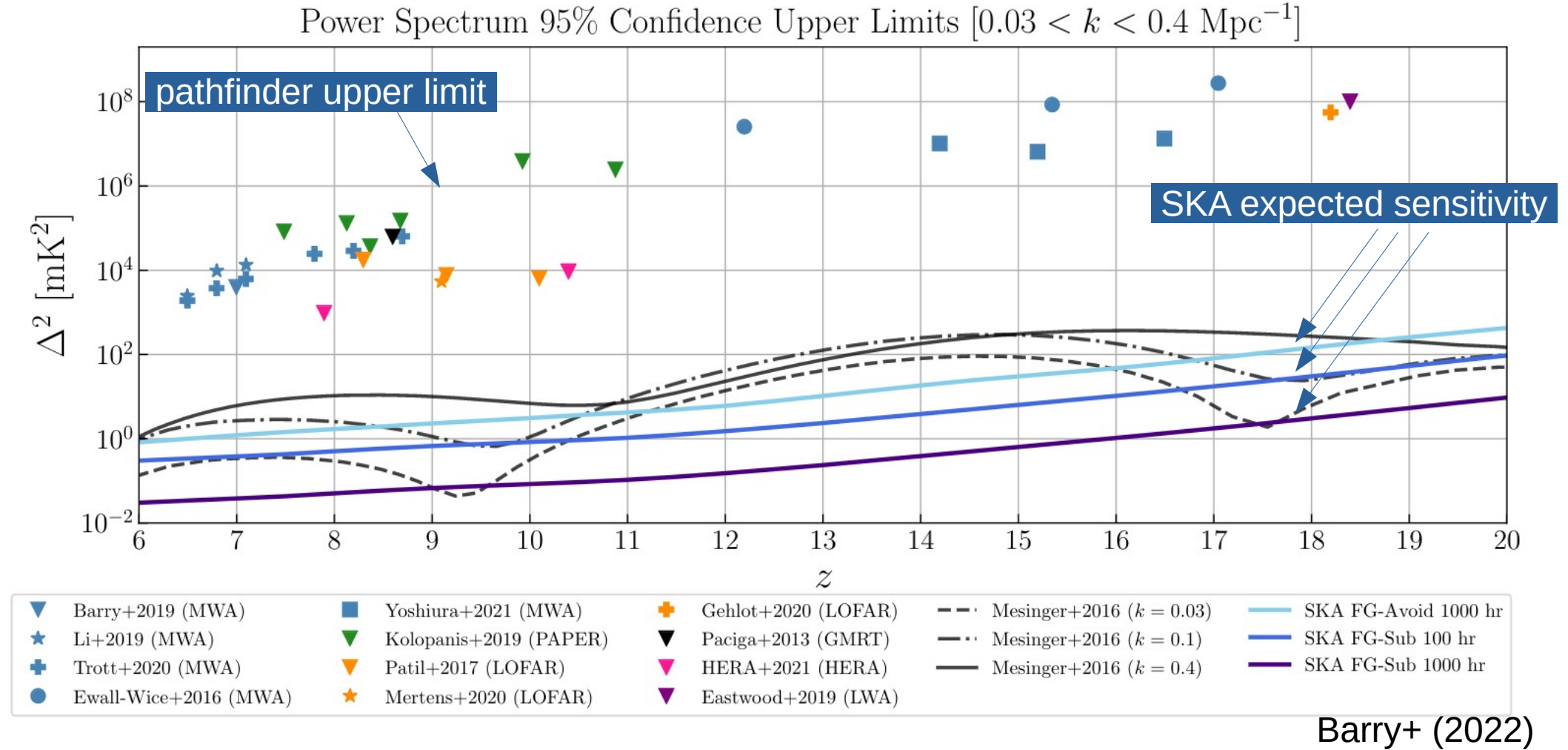


SERENEt: Recover of 21-cm Signal

Recovered 21-cm signal for EoR for lightcone subvolume centered at redshift **z = 7.8** (x_{HI}~0.3) and Δν +/- 10 MHz



SERENEt: Comparison with Current Data



Barry+ (2022)

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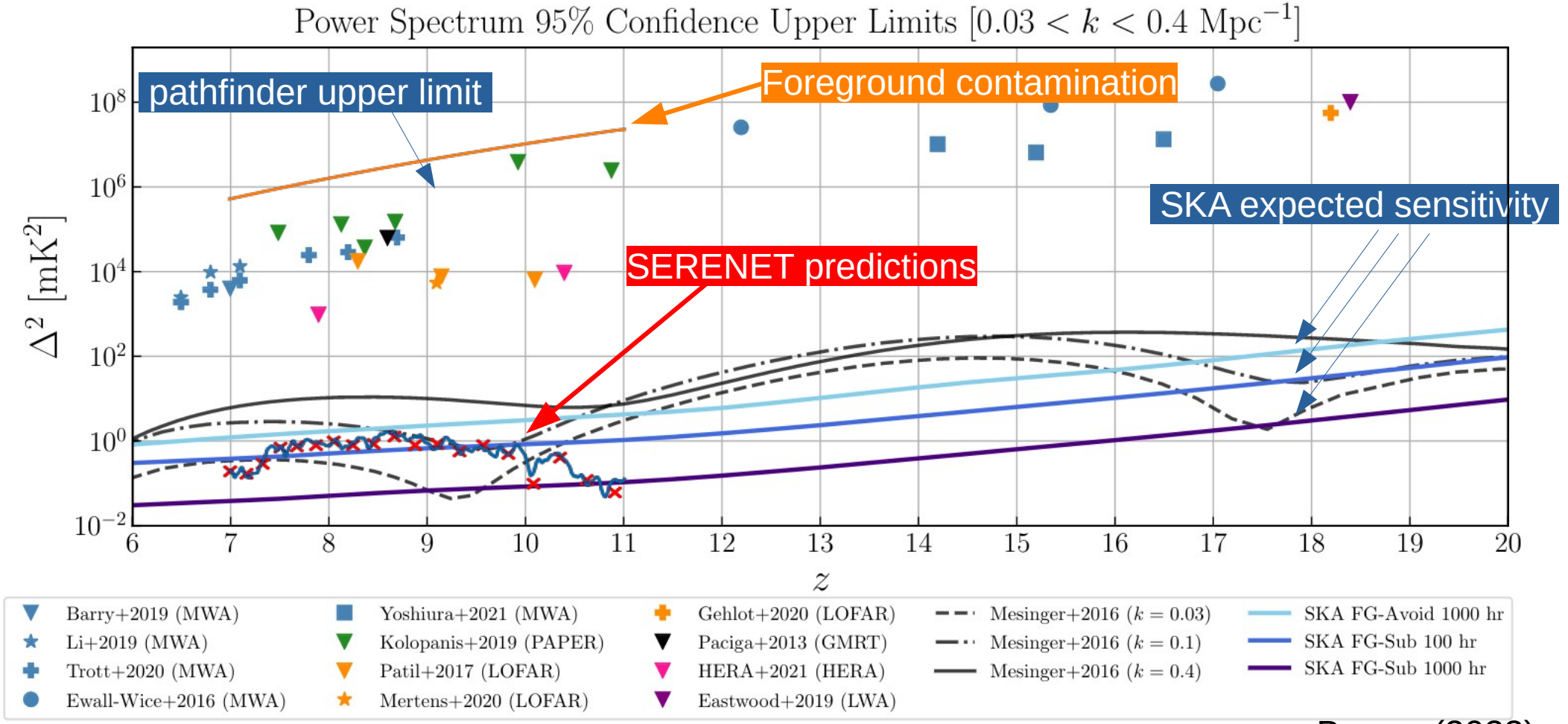


Barry+ (2022)

Thanks

Support Slides

Mesinger+ (2016)

$\delta(\mathbf{r}, z)$: Dark matter density fluctuations depends on structure formation

$x_{\mathrm{HI}}(z)$: Volume neutral fraction depends on SFH in the early Universe

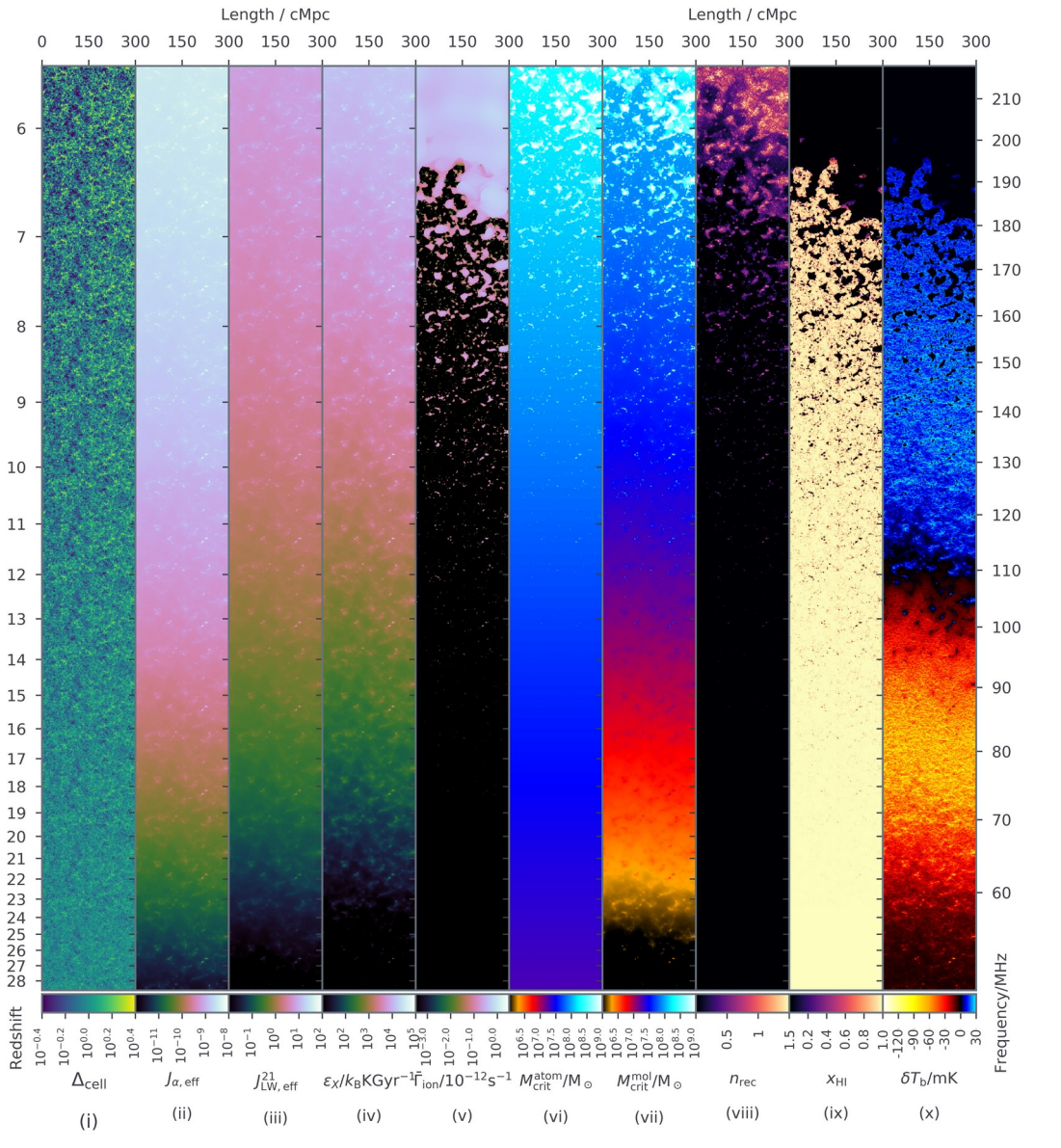
$$T_S^{-1} = \frac{T_{CMB}^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

$x_\alpha \propto J_\alpha(z)$

Wouthuysen-Field effect (Lyα pumping)

$$x_c = x_c^{HH} + x_c^{eH} + x_c^{pH}$$

Collision coupling



Mesinger+ (2016)

$\delta(\mathbf{r}, z)$: Dark matter density : fluctuations depends on structure formation

$x_{\rm HI}(z)$: Volume neutral fraction depends on SFH in the early Universe

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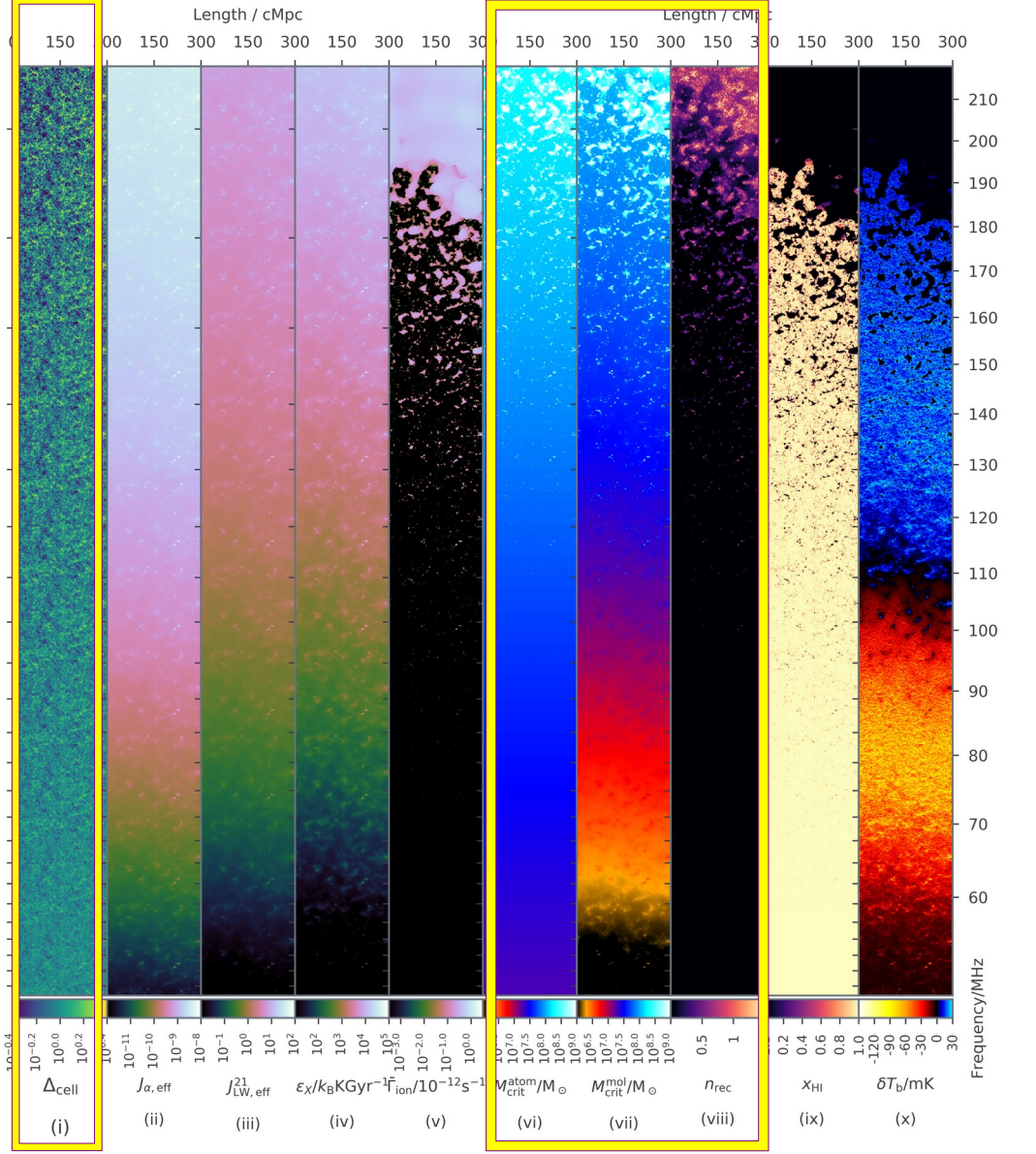
$x_\alpha \propto J_\alpha(z)$

Wouthuysen-Field effect (Lyα pumping)

$$x_c = x_c^{HH} + x_c^{eH} + x_c^{pH}$$

Collision coupling



Mesinger+ (2016)

$\delta(\mathbf{r}, z)$: Dark matter density fluctuations depends on structure formation

$x_{\rm HI}(z)$: Volume neutral fraction depends on SFH in the early Universe

$$T_S^{-1} = \frac{T_{CMB}^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

$x_\alpha \propto J_\alpha(z)$

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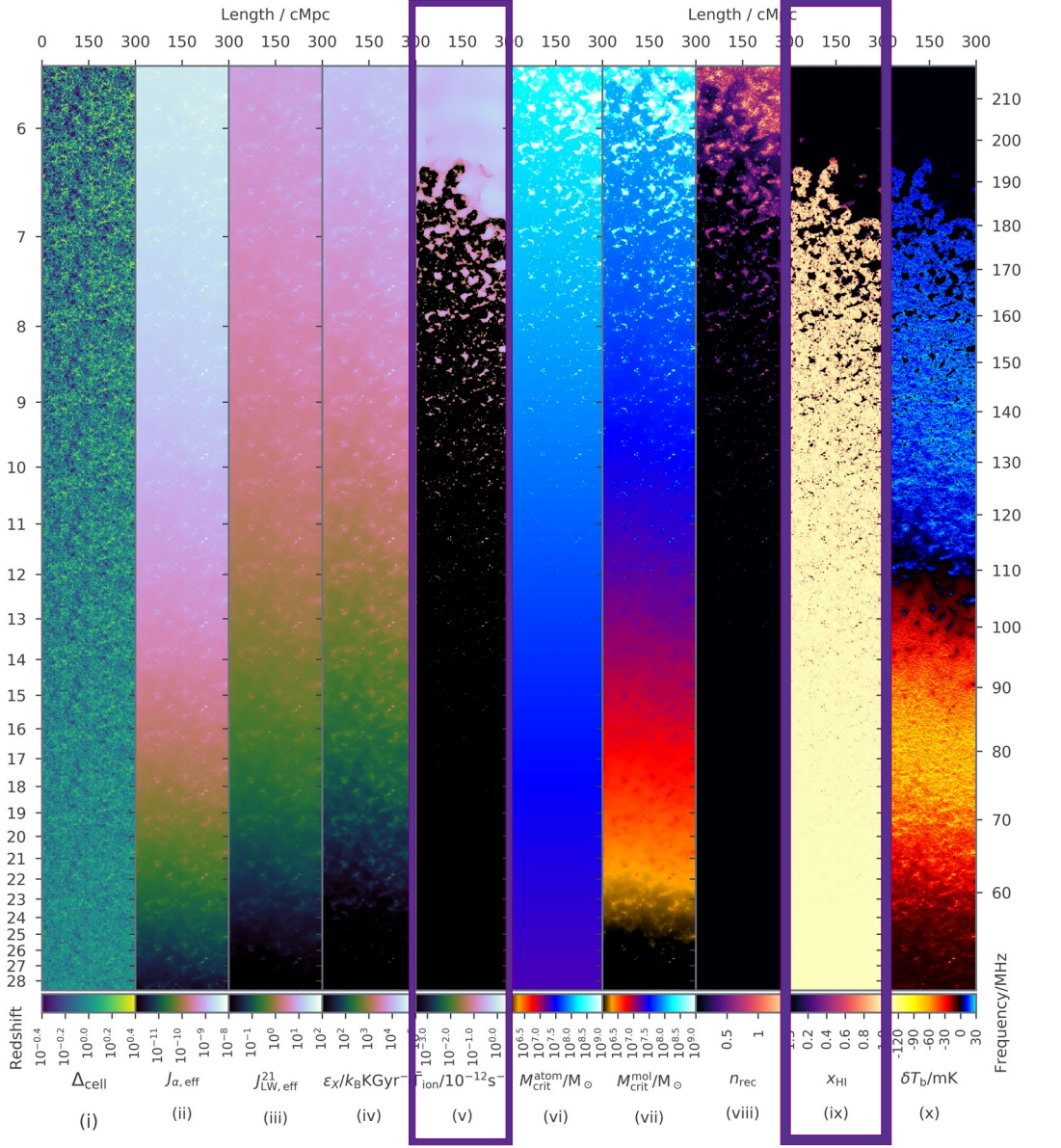

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