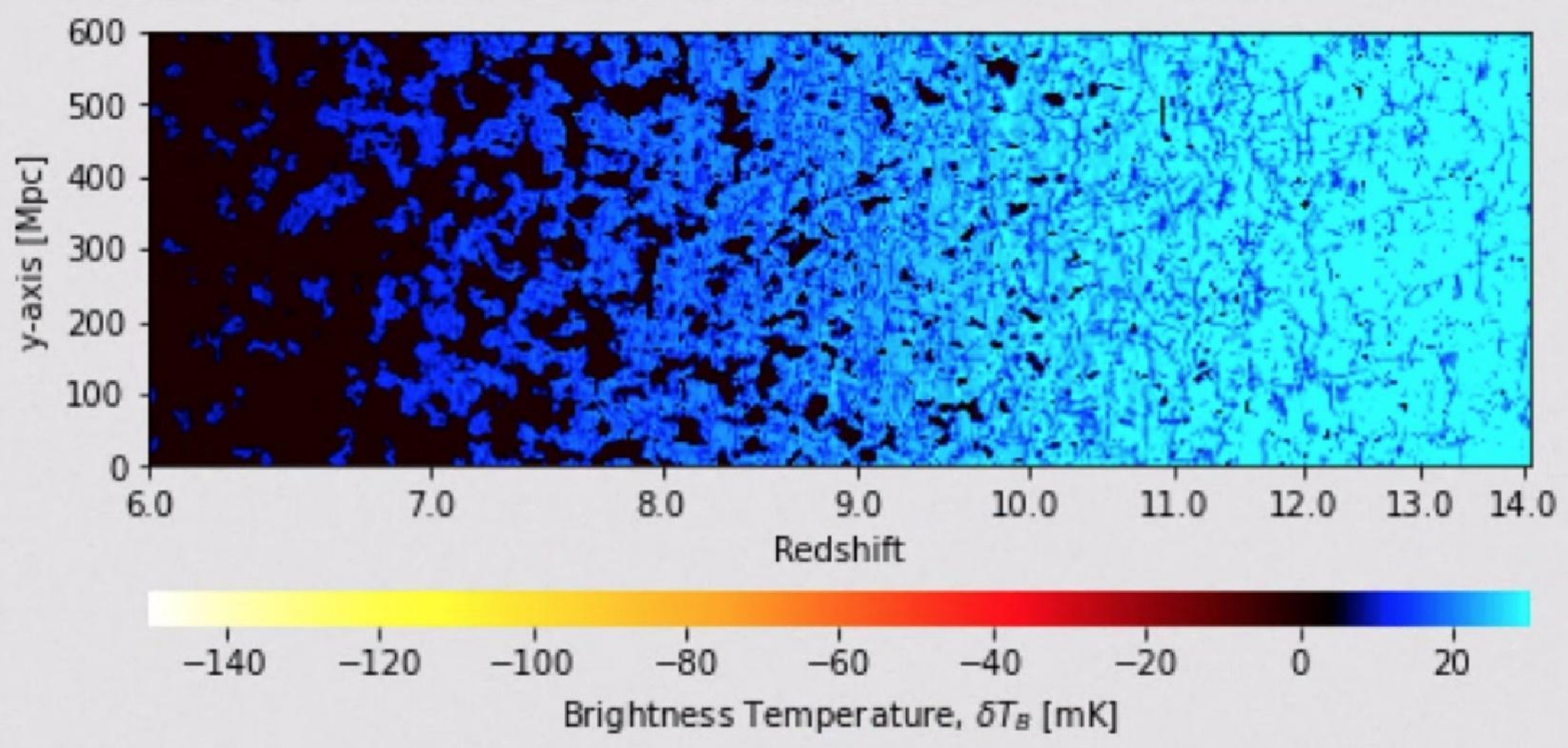
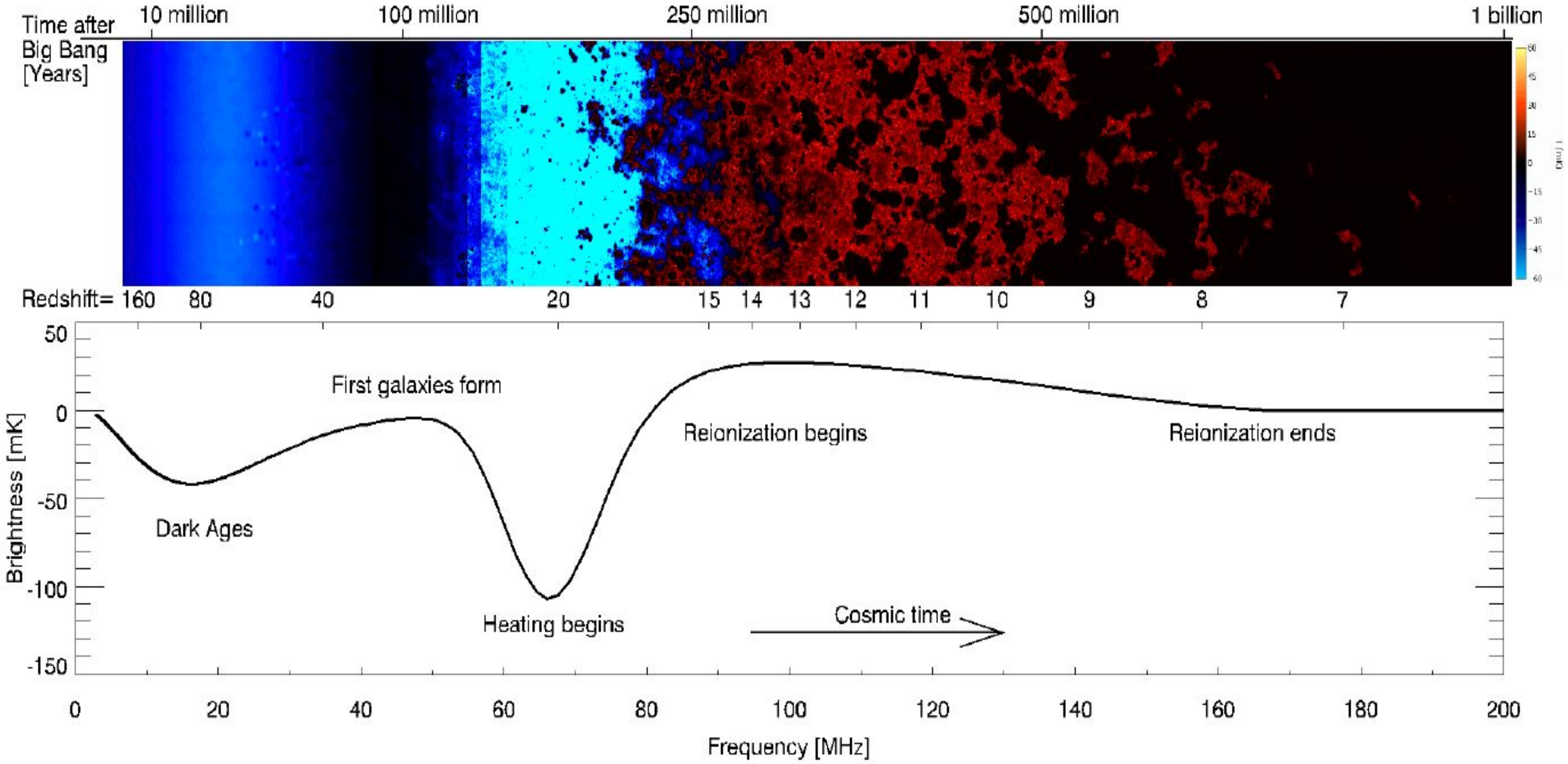
Experimenting with 21cmFAST for future radio observations

Cristiano Sabiu



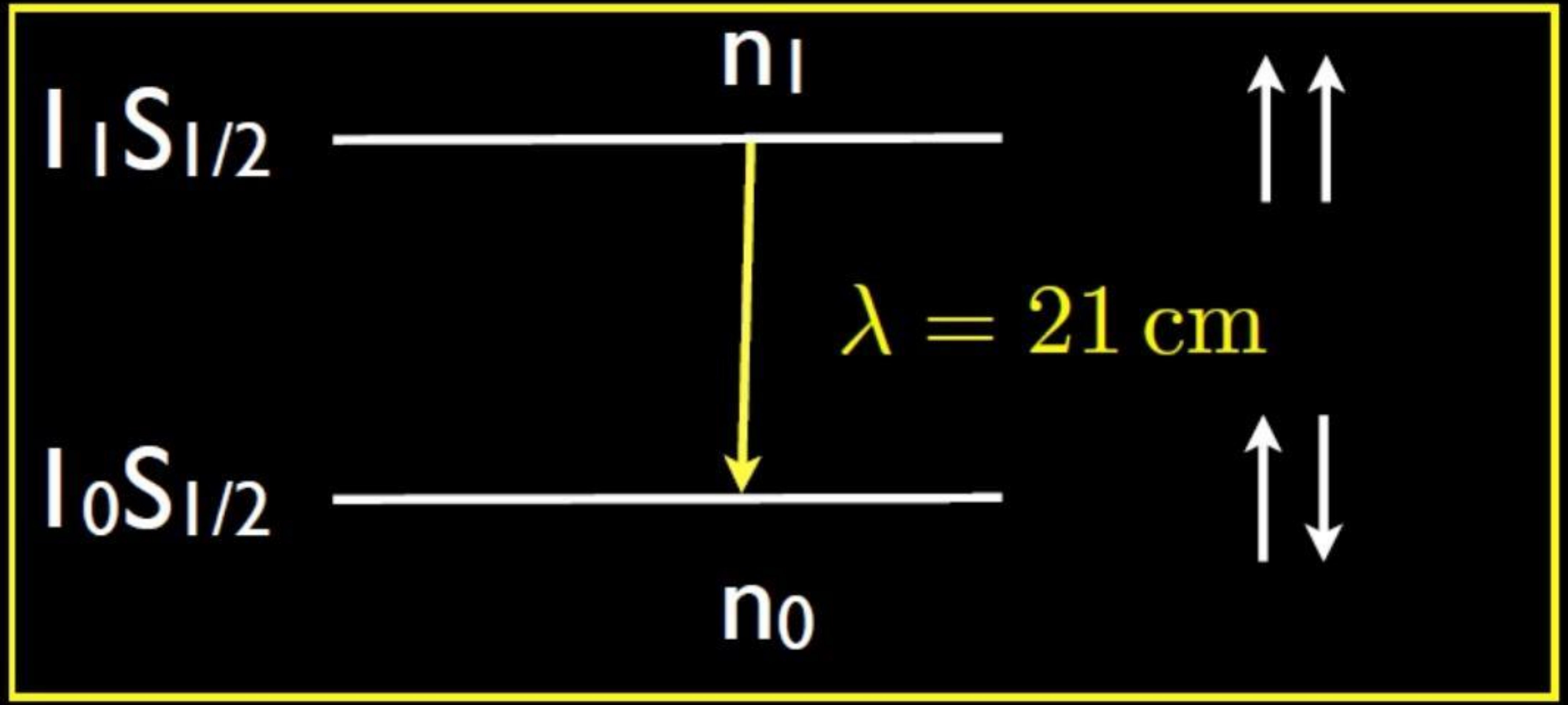
CPLUOS Group Meeting
5/3/2021

Cosmic Reionization History



$$\nu_{21cm} = 1,420,405,751.768 \pm 0.001\,\mathrm{Hz}$$

Hyperfine transition of neutral hydrogen



Spin temperature describes relative occupation of levels

$$n_1/n_0 = 3\exp(-h\nu_{21\mathrm{cm}}/kT_s)$$

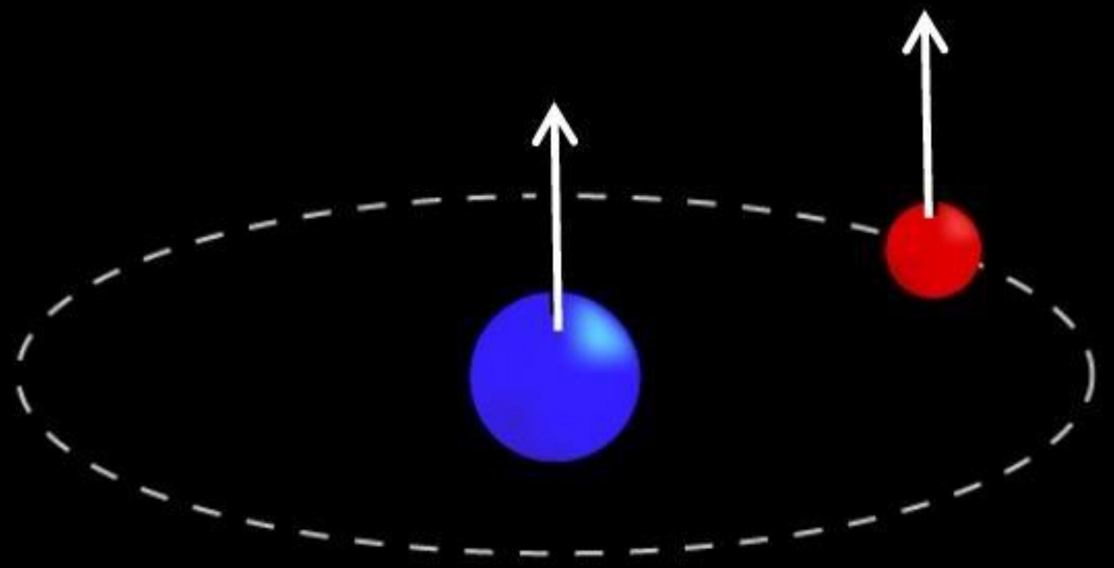
Useful numbers:

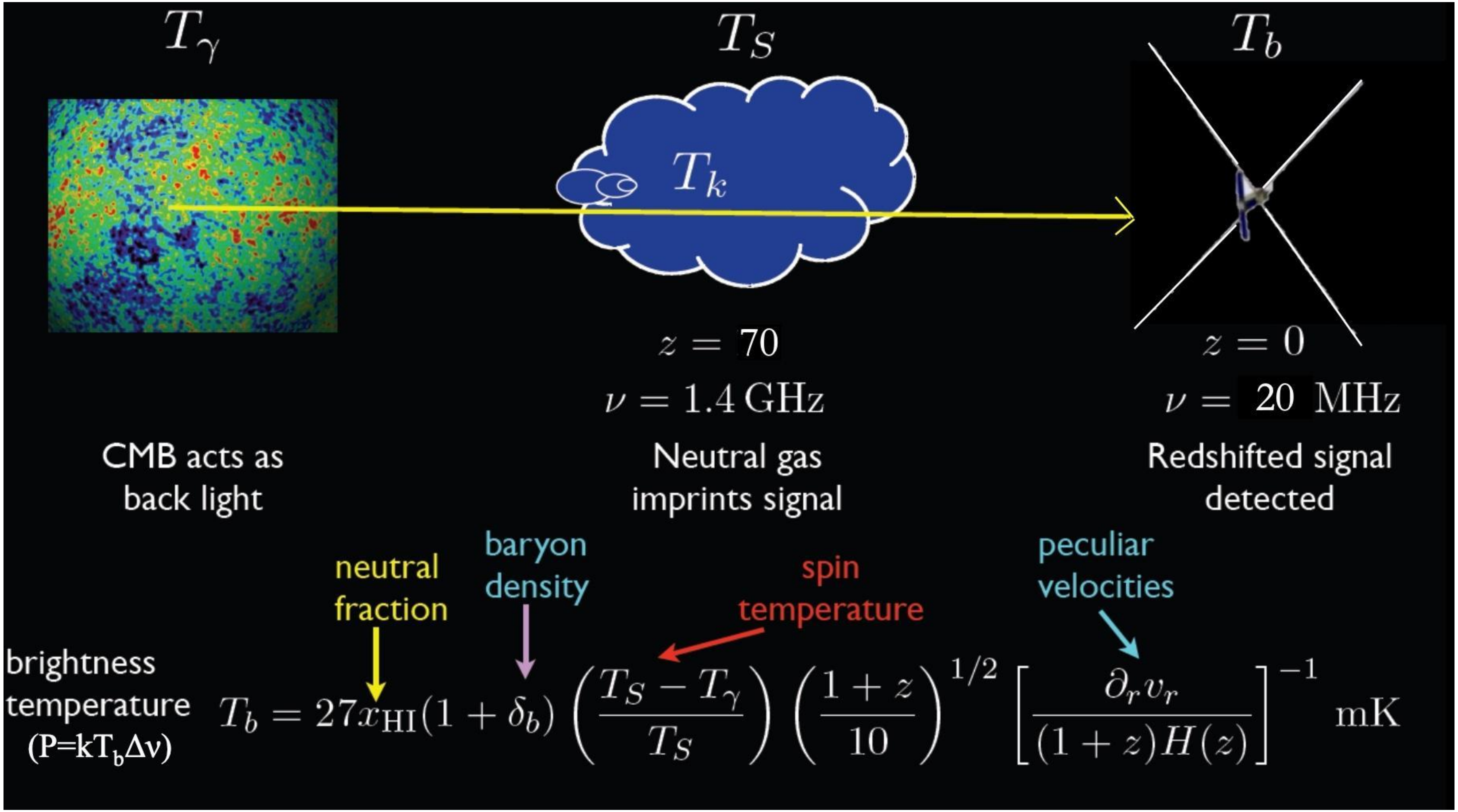
$200\,\mathrm{MHz} \rightarrow z = 6$
$100\,\mathrm{MHz} \rightarrow z = 13$
$70\,\mathrm{MHz} \rightarrow z \approx 20$
$40\,\mathrm{MHz} \longrightarrow z \approx 35$

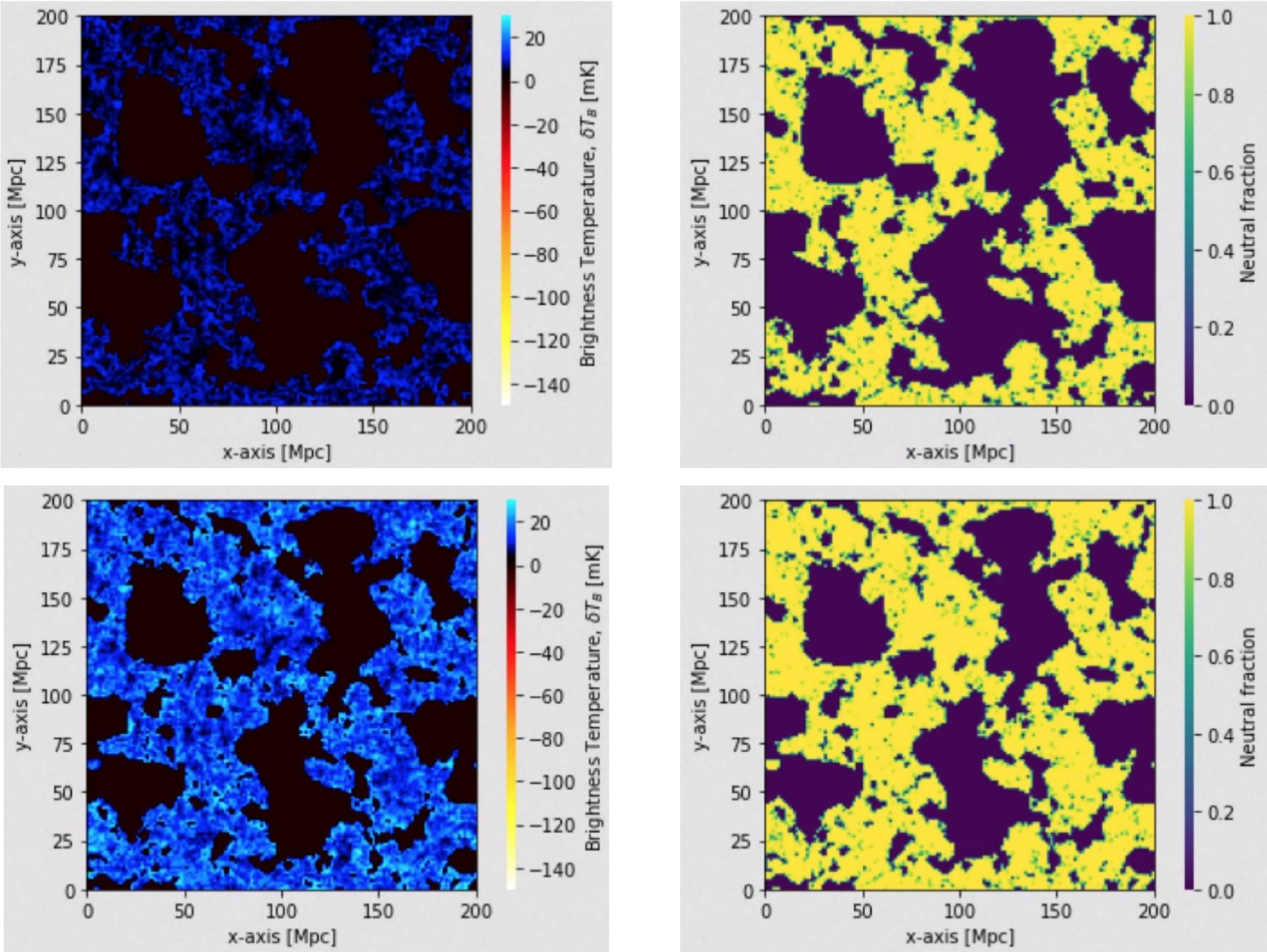
$t_{\mathrm{Age}}(z=6) \approx 1\,\mathrm{Gyr}$

$t_{\mathrm{Age}}(z=10) \approx 500\,\mathrm{Myr}$

$t_{\mathrm{Age}}(z=20) \approx 150\,\mathrm{Myr}$



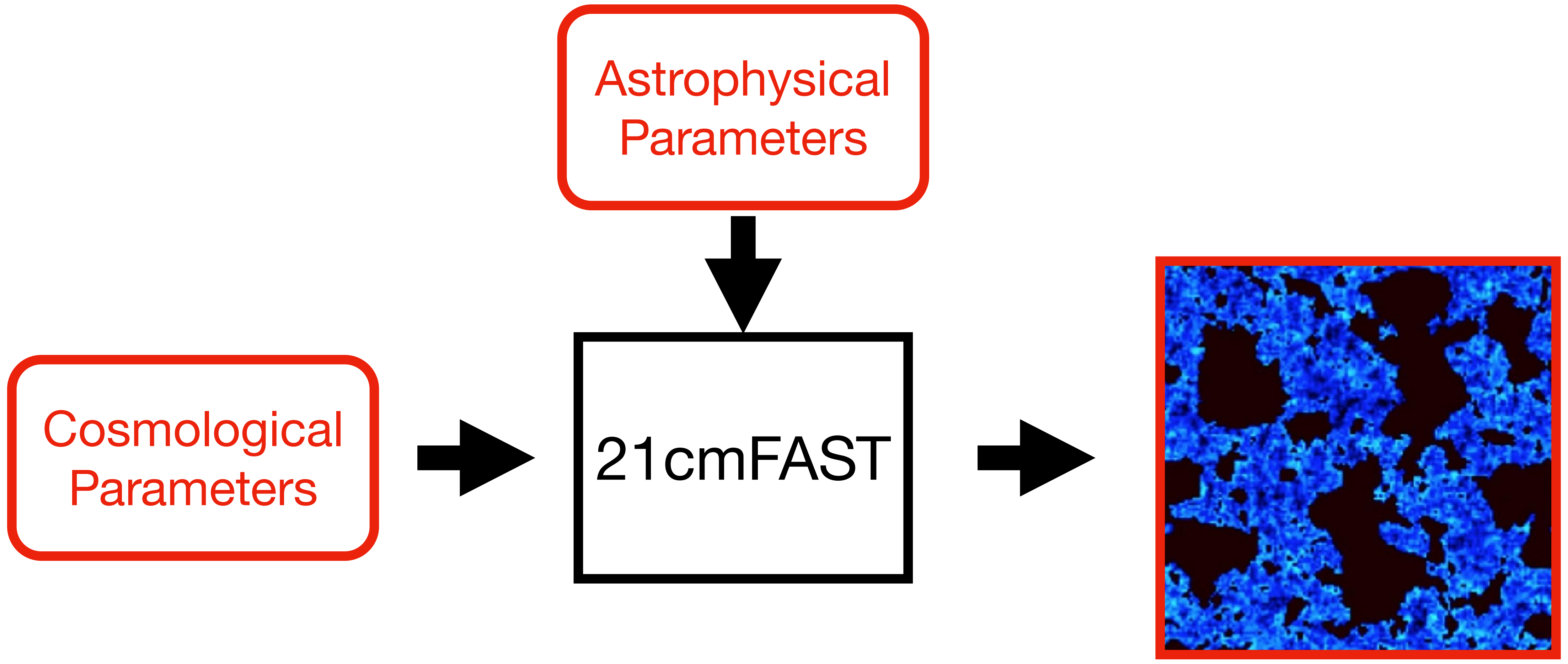

T_γ
T_S
T_b
T_k
$z = 70$
$\nu = 1.4\,\mathrm{GHz}$
$z = 0$
$\nu = 20\,\mathrm{MHz}$
CMB acts as back light
Neutral gas imprints signal
Redshifted signal detected
neutral fraction
baryon density
spin temperature
peculiar velocities
brightness temperature
($P=kT_b\Delta\nu$)
$T_b = 27 x_{\mathrm{HI}}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1}\,\mathrm{mK}$



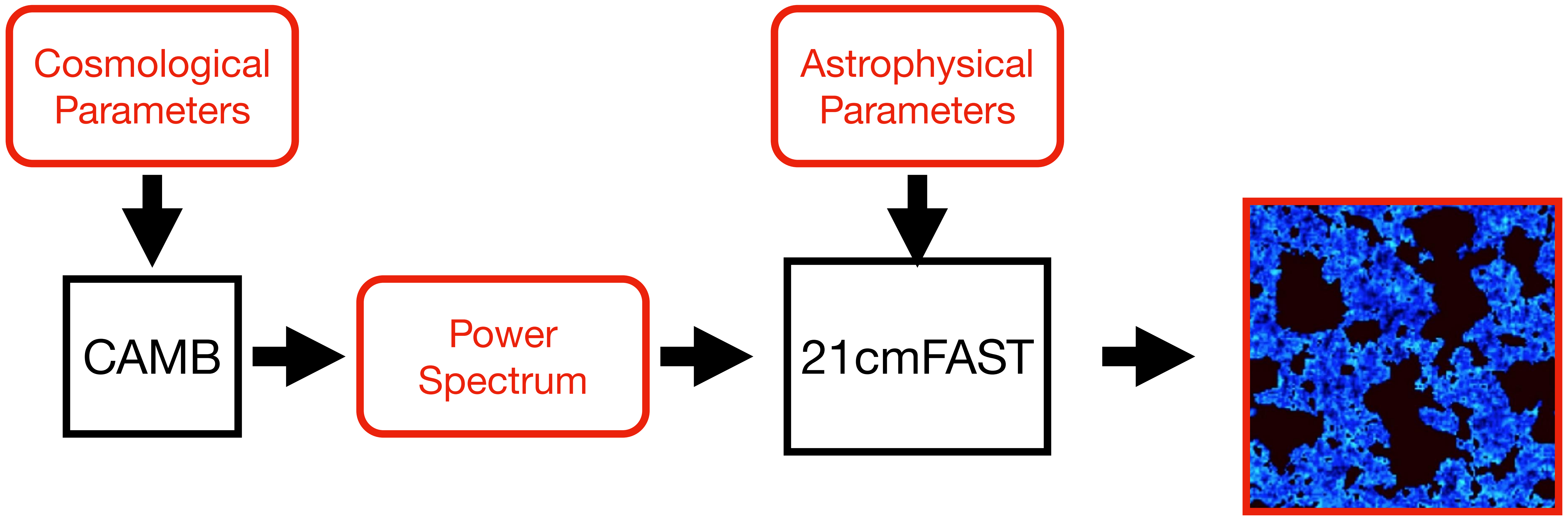
Low baryon fraction

High baryon fraction

Pipeline

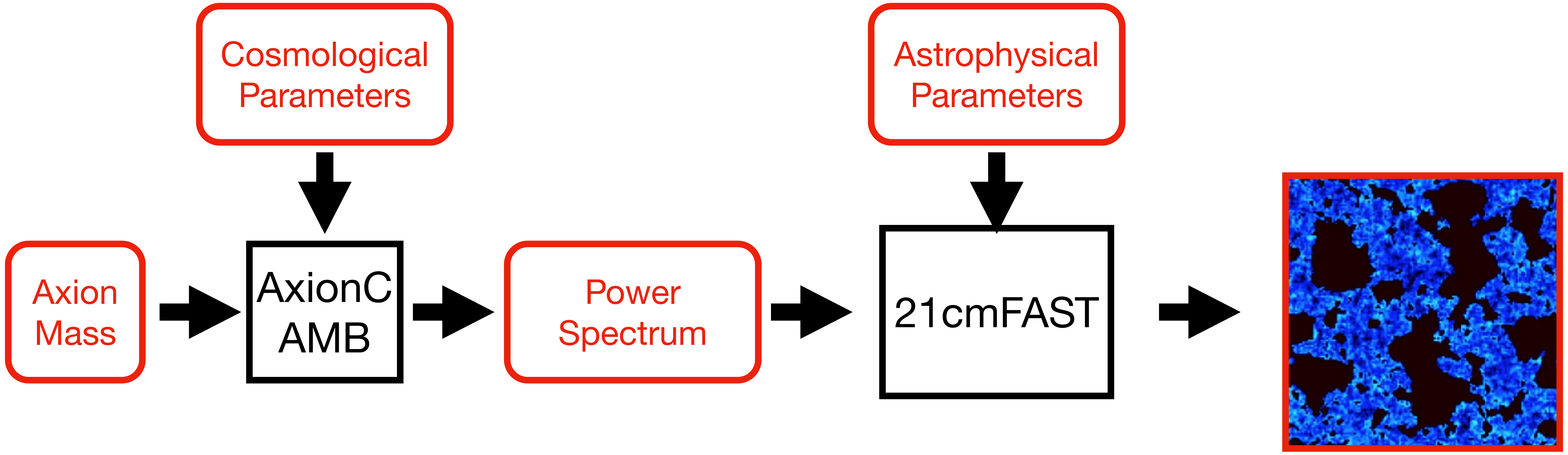

Astrophysical Parameters
Cosmological Parameters
21cmFAST

Pipeline



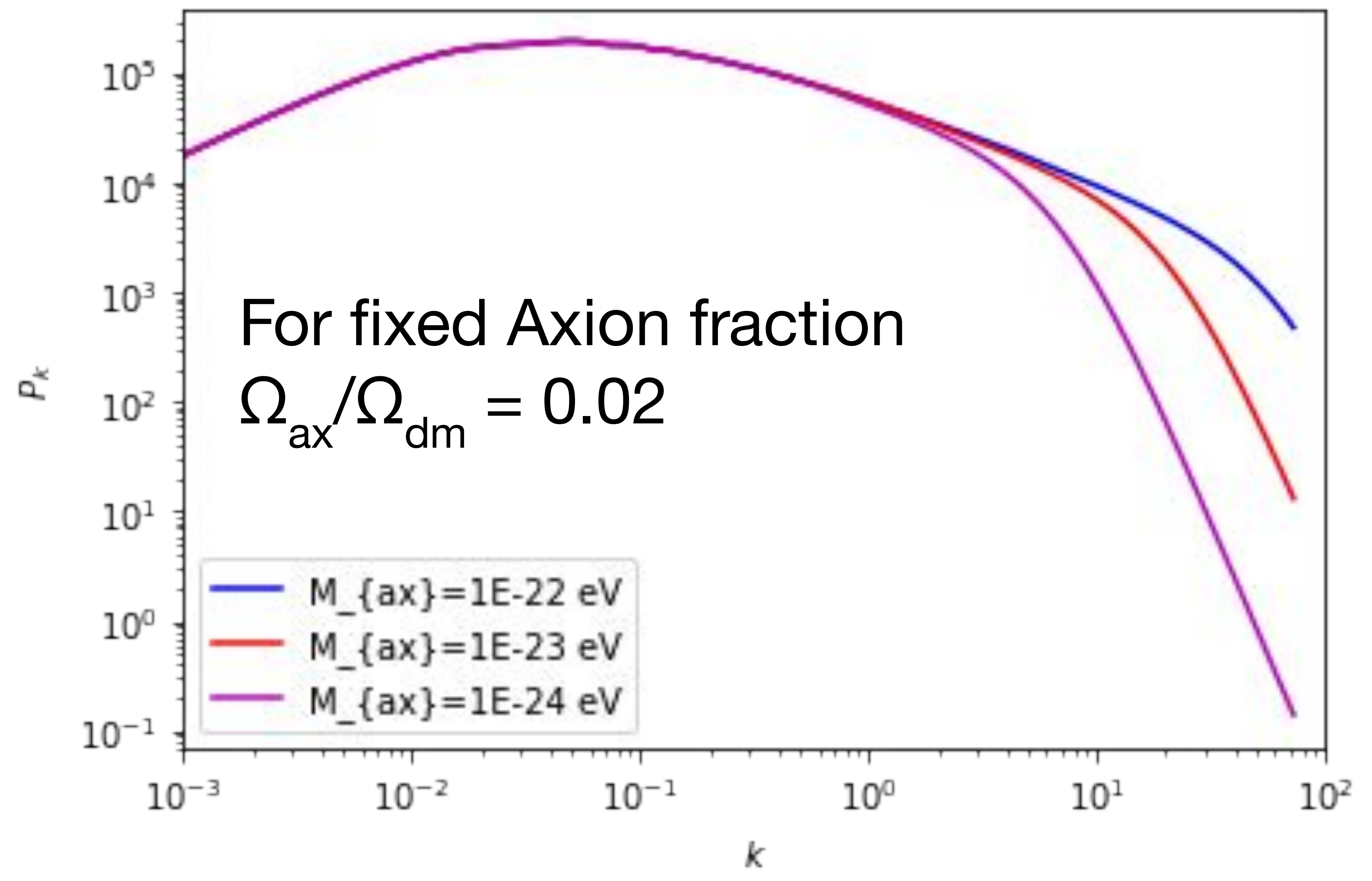
Thanks to Jaehong Park (KIAS), I can now run 21cmFAST with a custom Power Spectrum

Pipeline

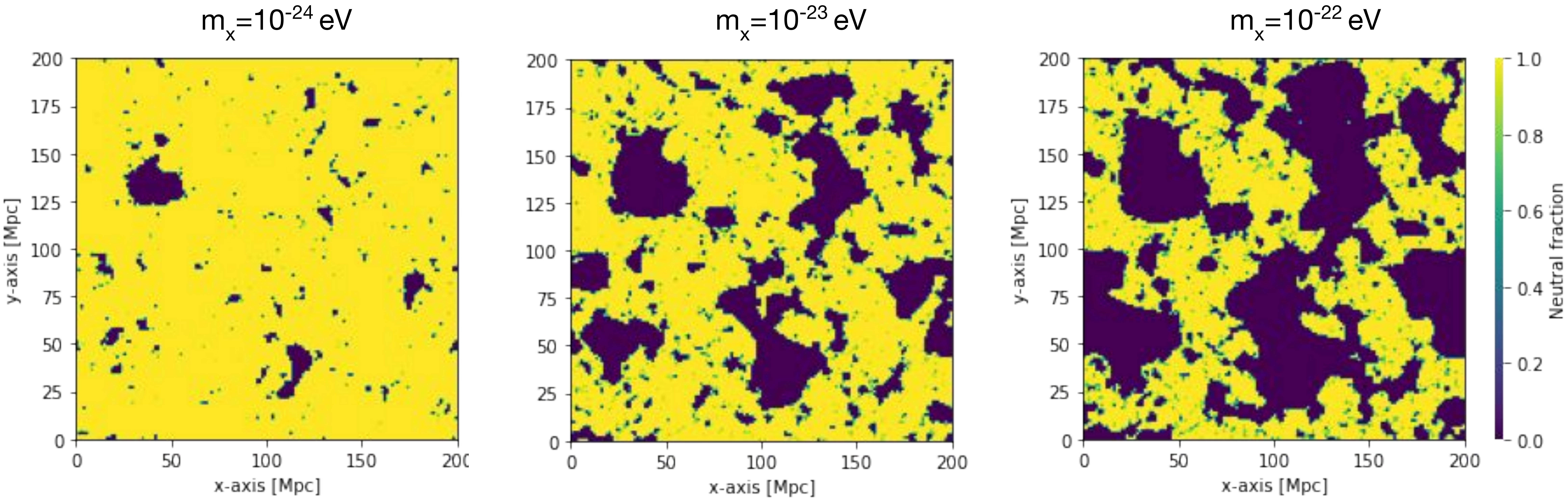


With Kenji Kadota (IBS, Daejeon) we want to see the effect of Axion particles on early structure formation

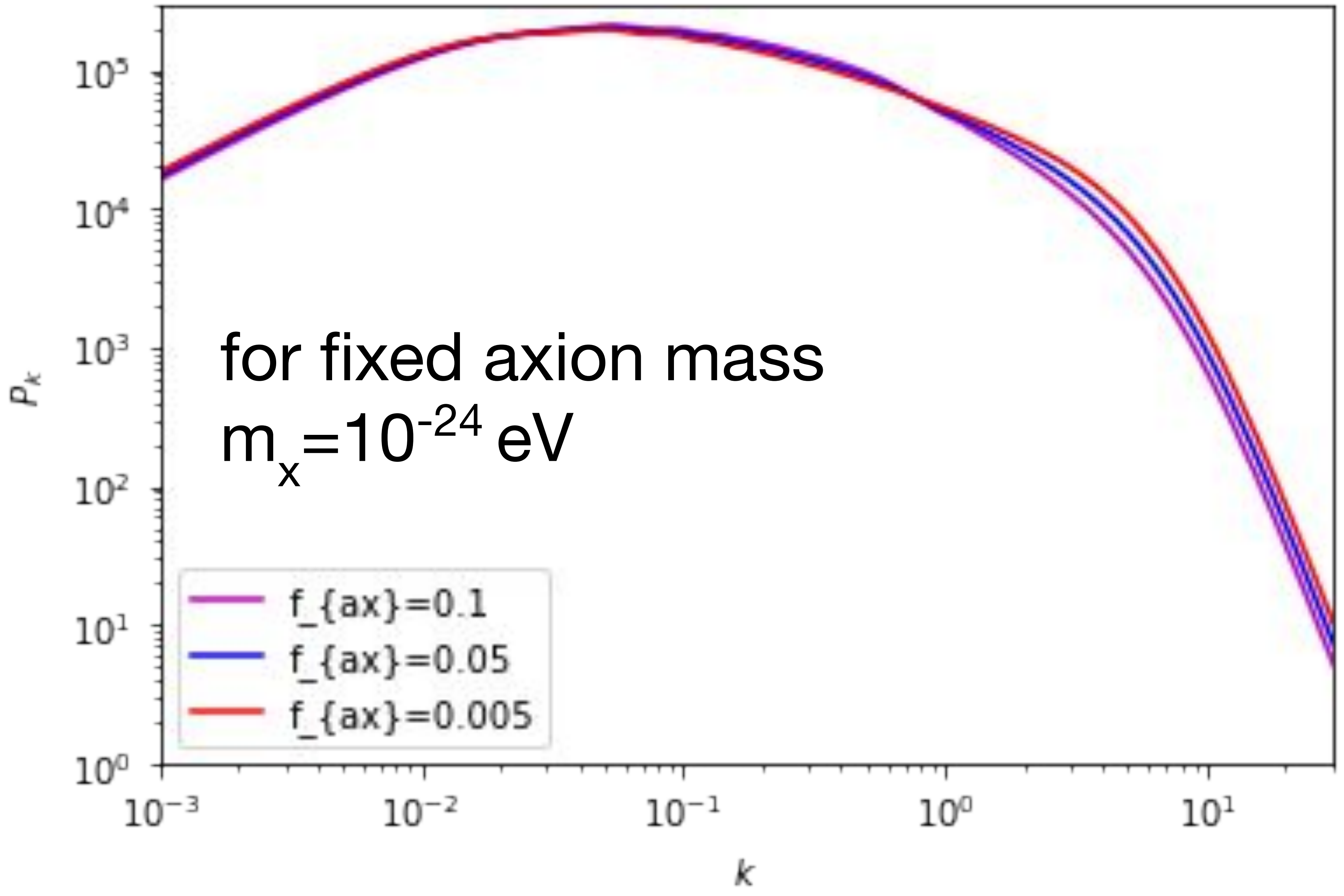
Varying Axion Mass



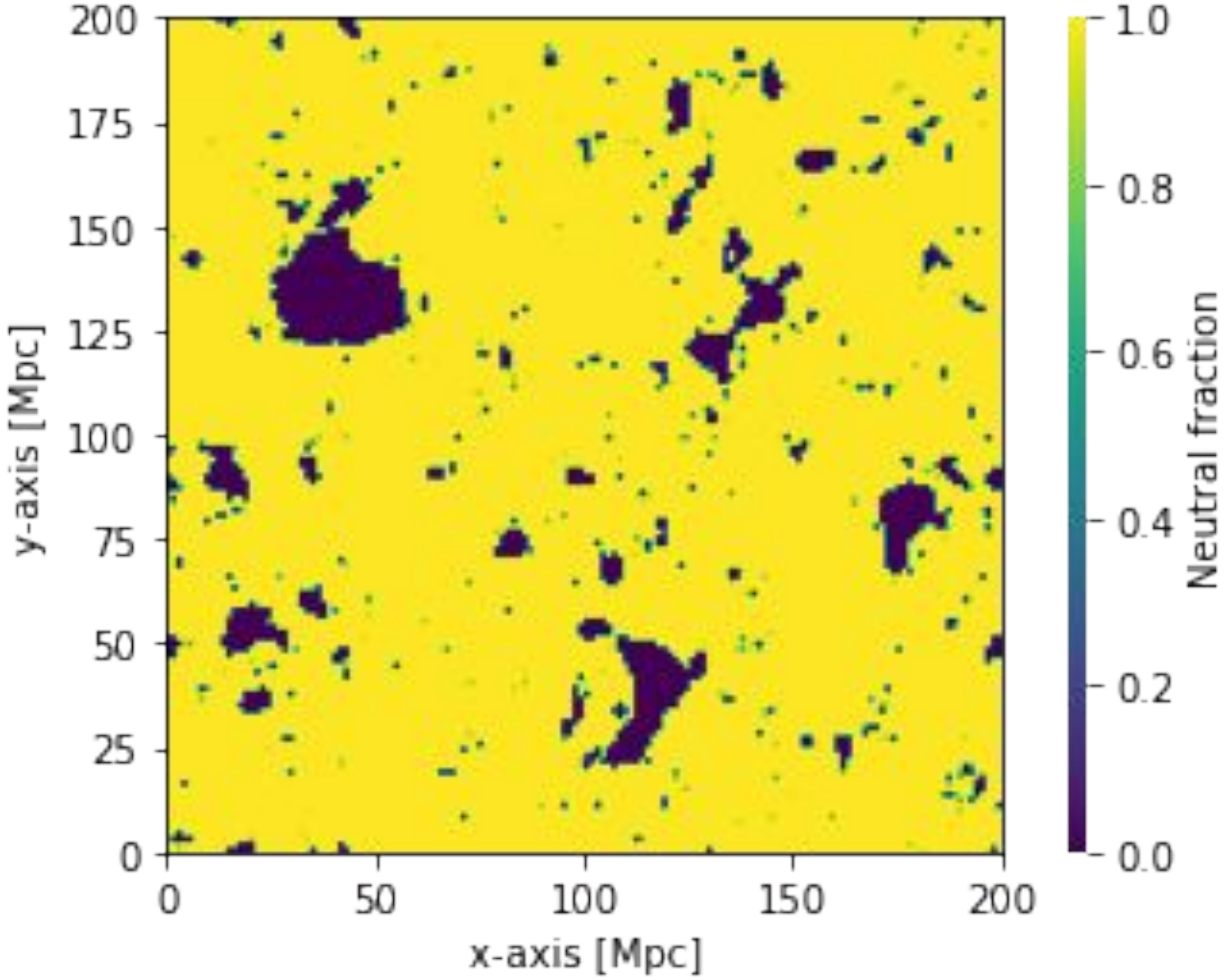
for $m_x<10^{-24}$ eV neutral hydrgen intact at z=8.0



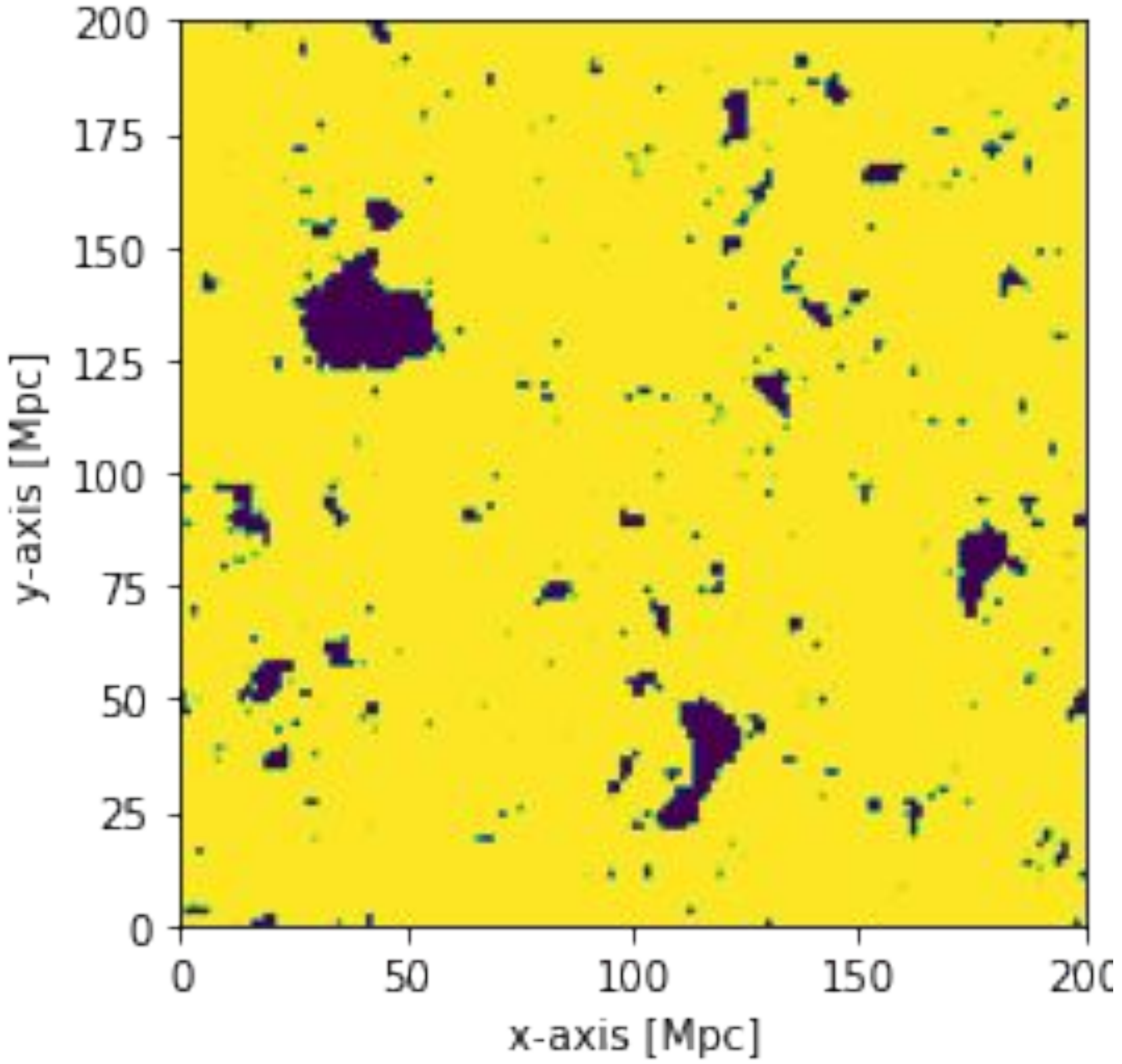
Varying Axion Fraction



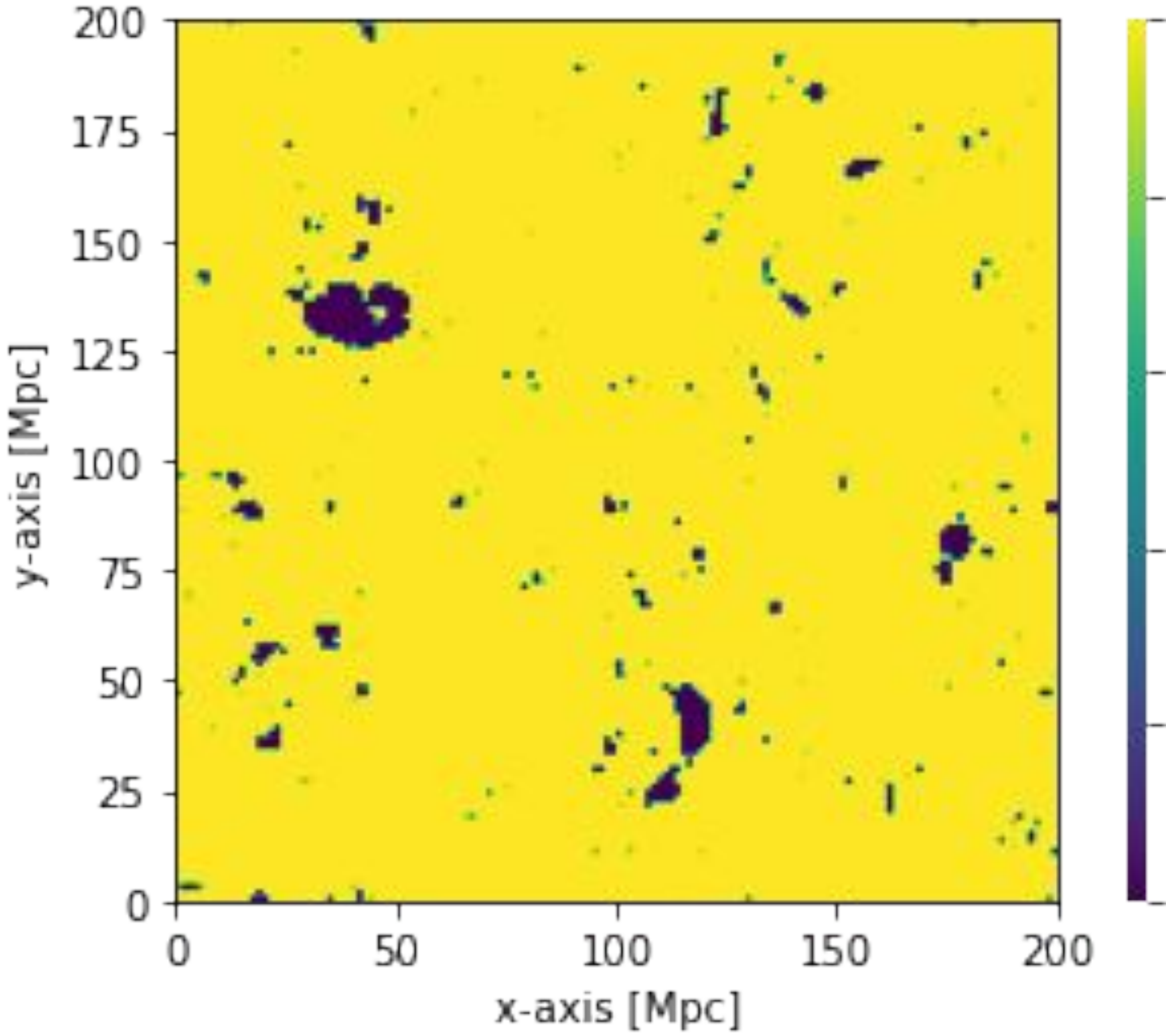
Ω_{ax}/Ω_{dm} = 0.005



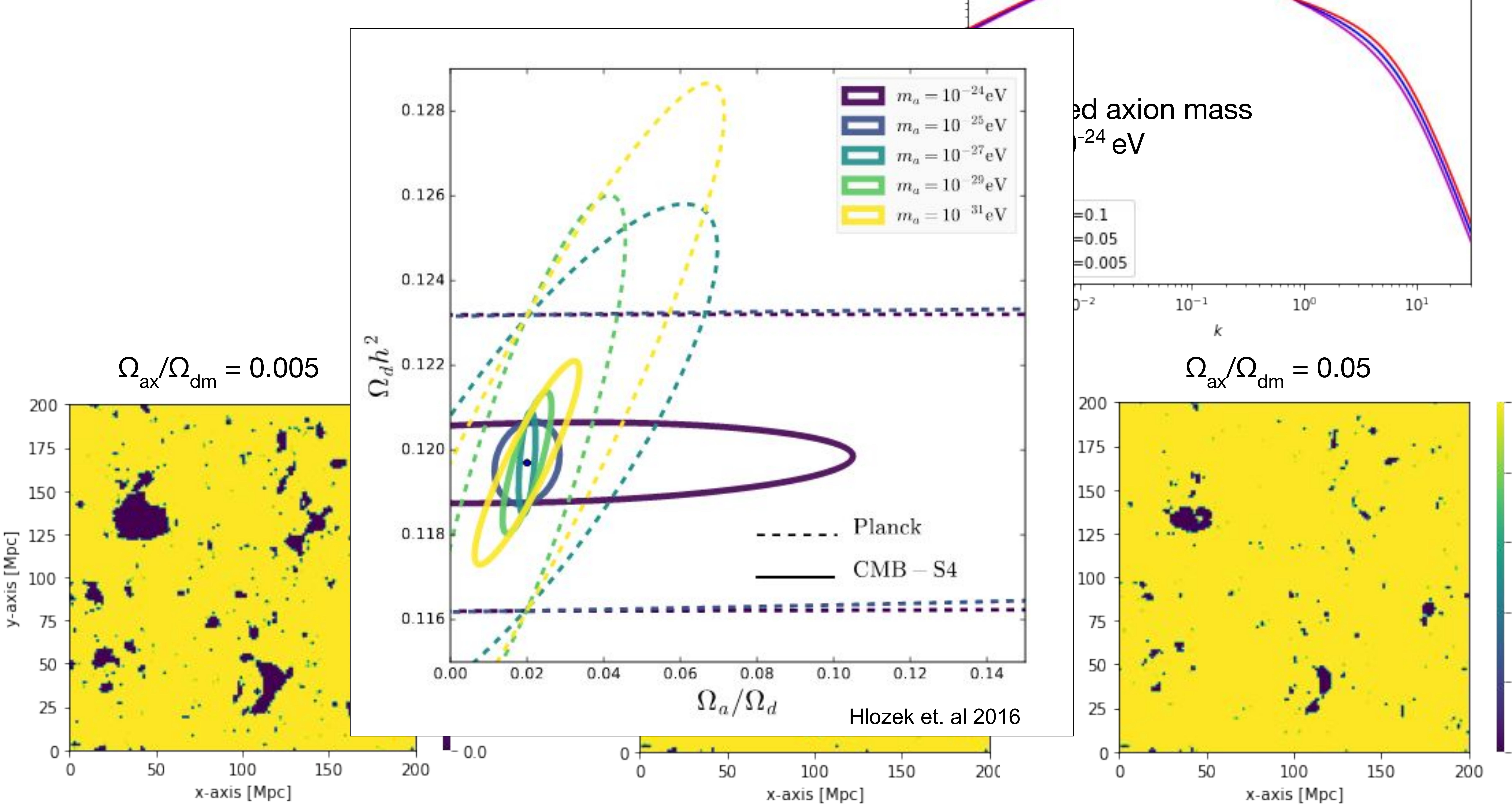
Ω_{ax}/Ω_{dm} = 0.02



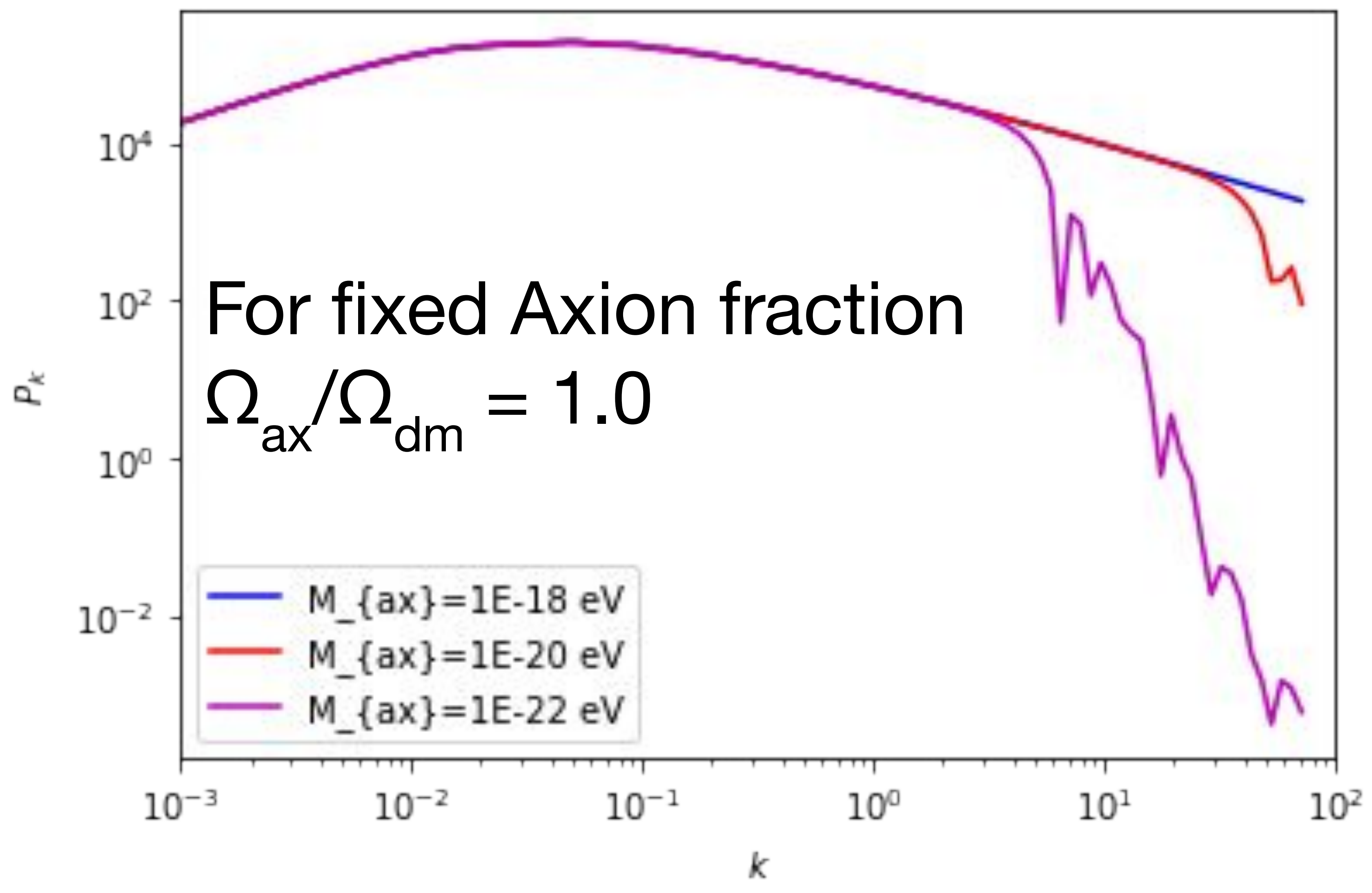
Ω_{ax}/Ω_{dm} = 0.05



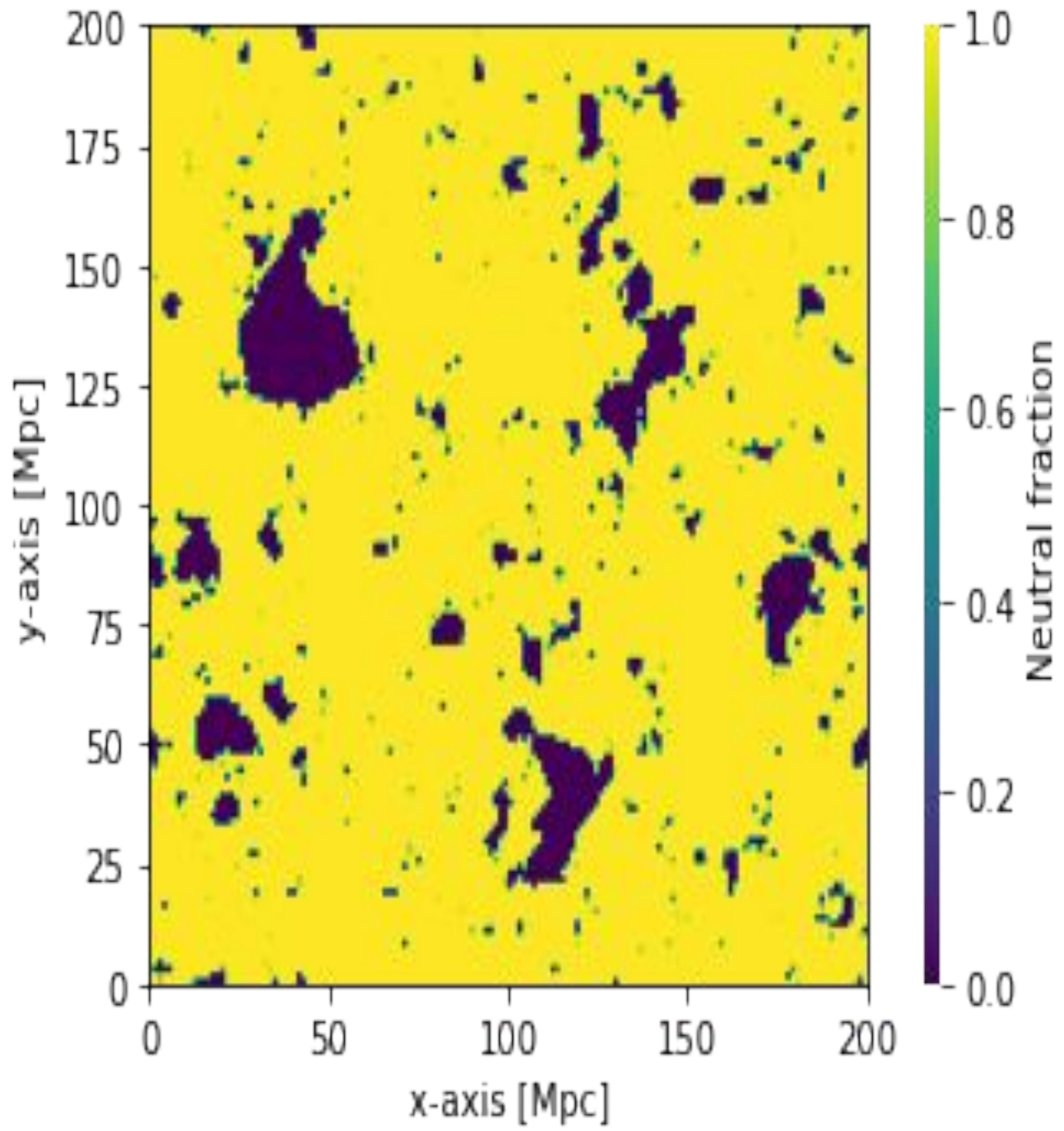
Varying Axion Fraction



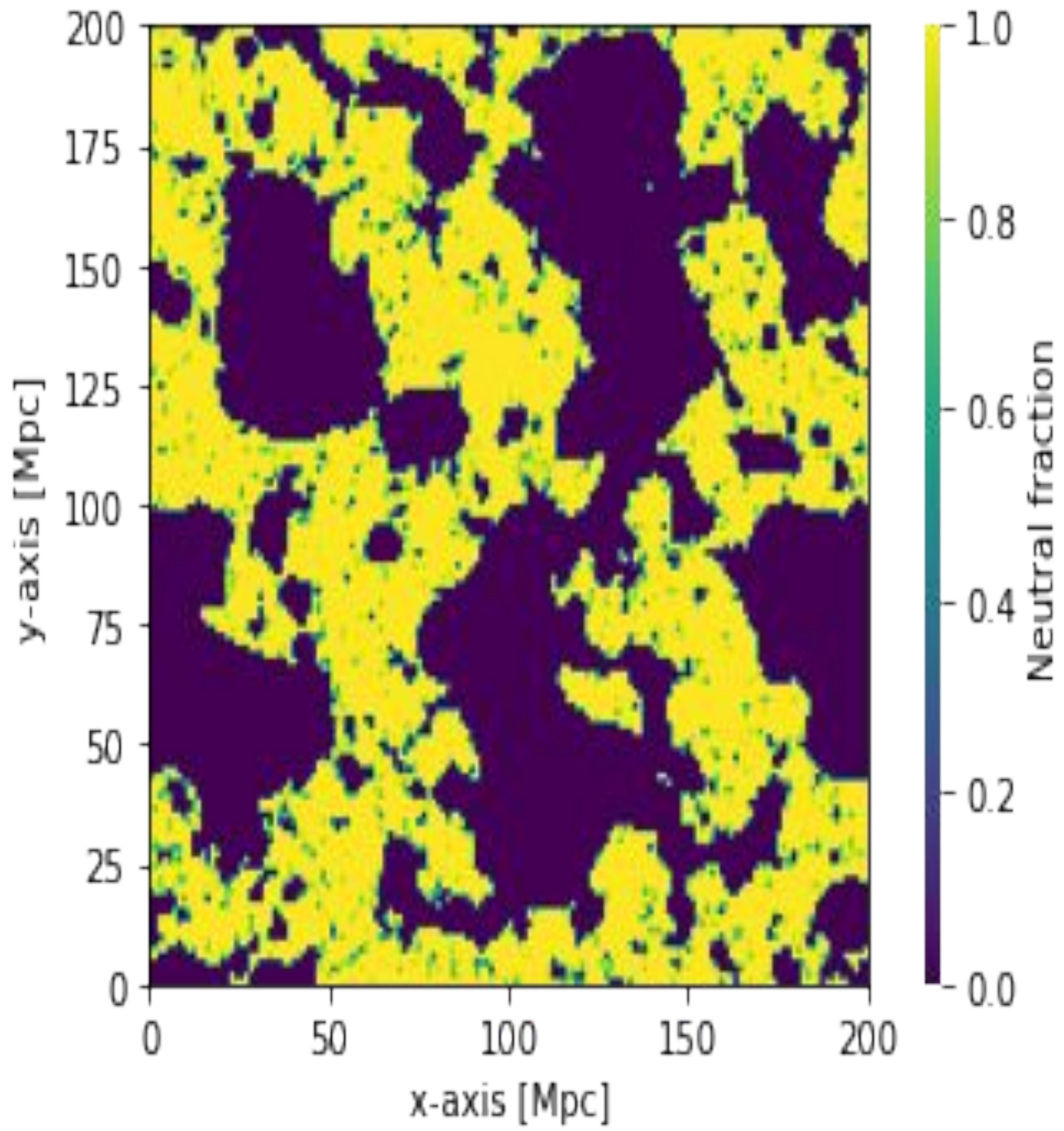
Varying Axion Mass (Axion only DM component)



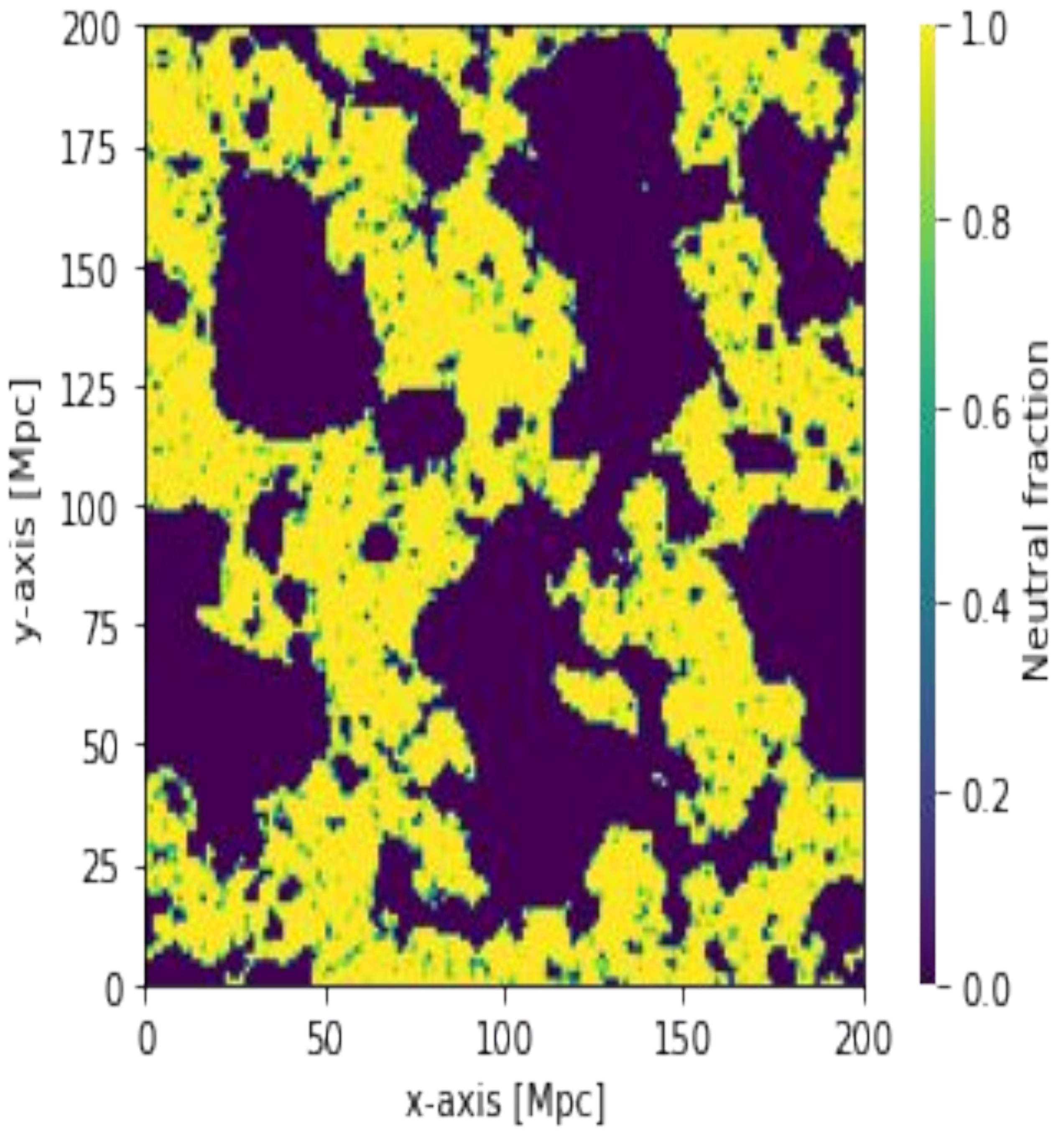
$m_x=10^{-22}$ eV



$m_x=10^{-20}$ eV

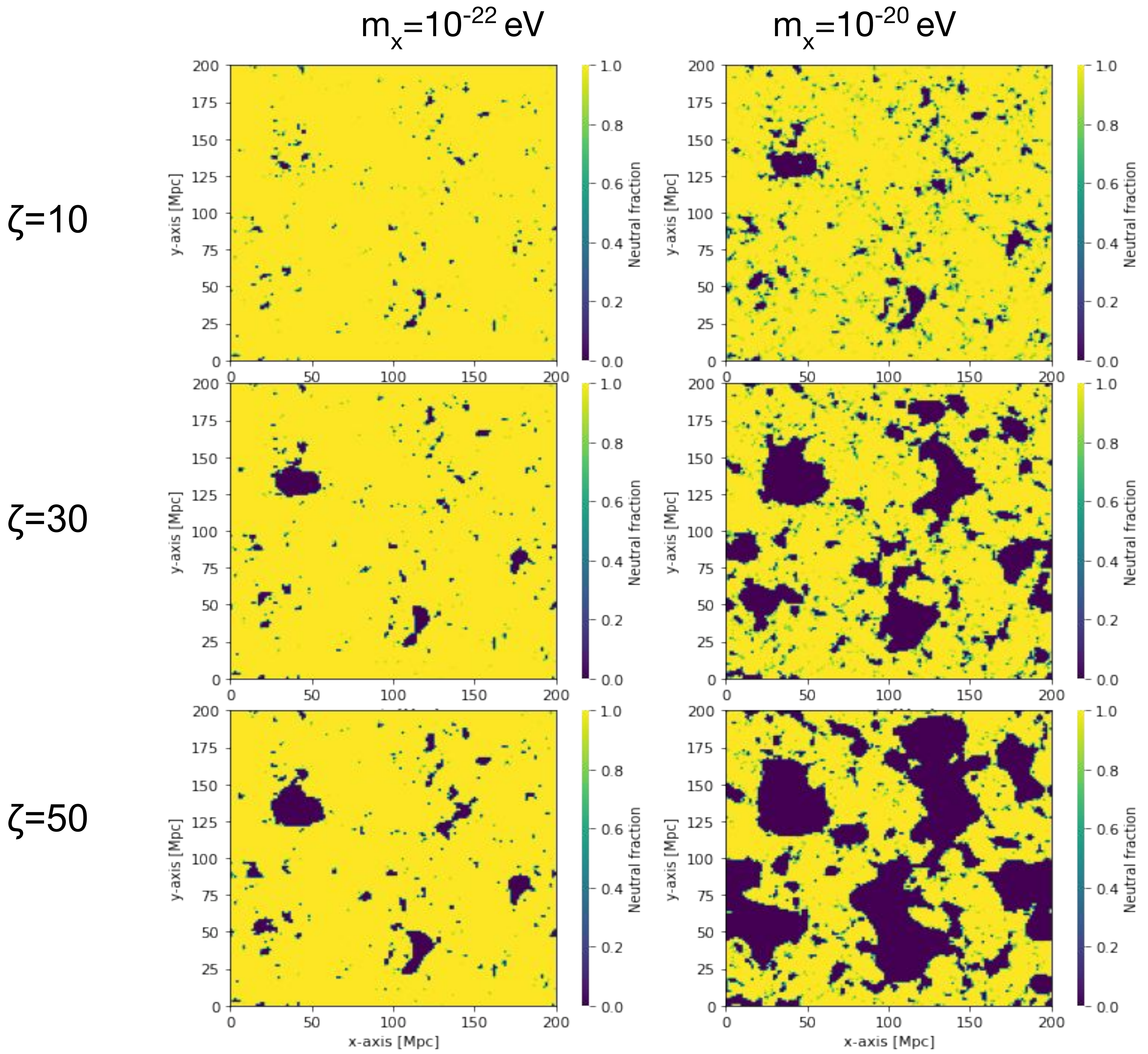


$m_x=10^{-18}$ eV



Varying Nuisance Parameters: Ionization Efficiency

ζ,the ionizing efficiency: ζ is the combination of several parameters related to ionizing photons escaping from high redshift galaxies and is defined as $\zeta=fesc f{*} N\gamma/(1+nrec)$. Here, fesc is the fraction of ionizing photons escaping from galaxies into the IGM and f∗ is the fraction of baryons locked into stars. These parameters are extremely uncertainat high redshift. Nγ is the number of ionizing photons produced per baryon in stars and nrecis the mean recombination rate per baryon.In our calculation, we explore a range of 10≤ζ≤60 following the work of Shimabukuro & Semelin (2017)



Varying Nuisance Parameters: T_{vir}

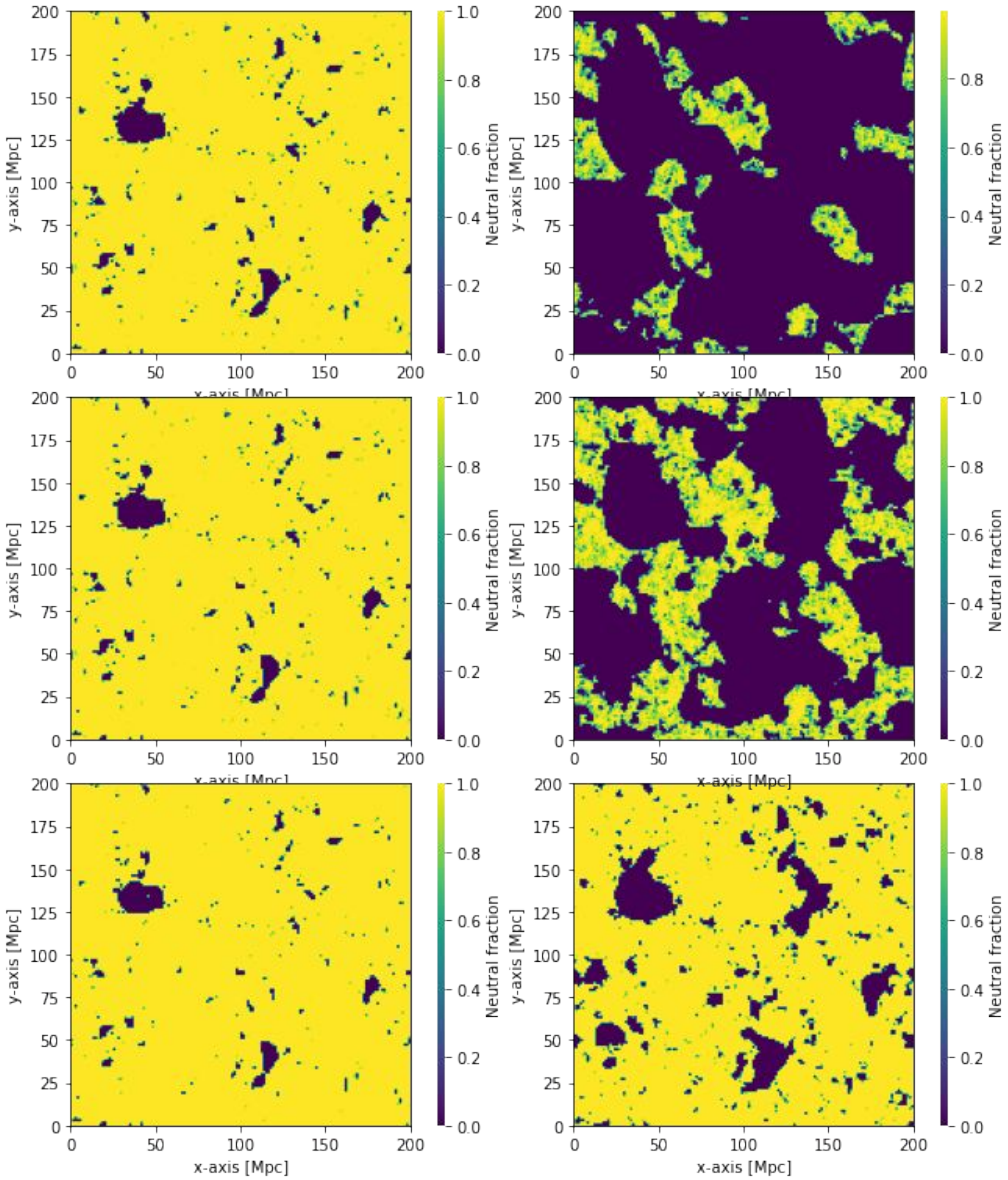
T_{vir},the minimum virial temperature of haloes producing ionizing photons: T_{vir} parameterizes the minimum mass of haloes producing ionizing photons during the EoR. Typically, T_{vir} is chosen to be 10^4K, corresponding to the temperature above which atomic cooling becomes effective. T_{vir} parameterizes the physics of star formation in high redshift galaxies. In haloes with virial temperature>10^4K atomic cooling is sufficient to trigger gravothermal instability and thus star formation.

$m_x=10^{-22}$ eV $\quad$ $m_x=10^{-20}$ eV

$T_{vir}=10^3$

$T_{vir}=10^4$

$T_{vir}=10^5$



Varying Nuisance Parameters: R_{mfp}

I now changed to brightness temperature (observable)

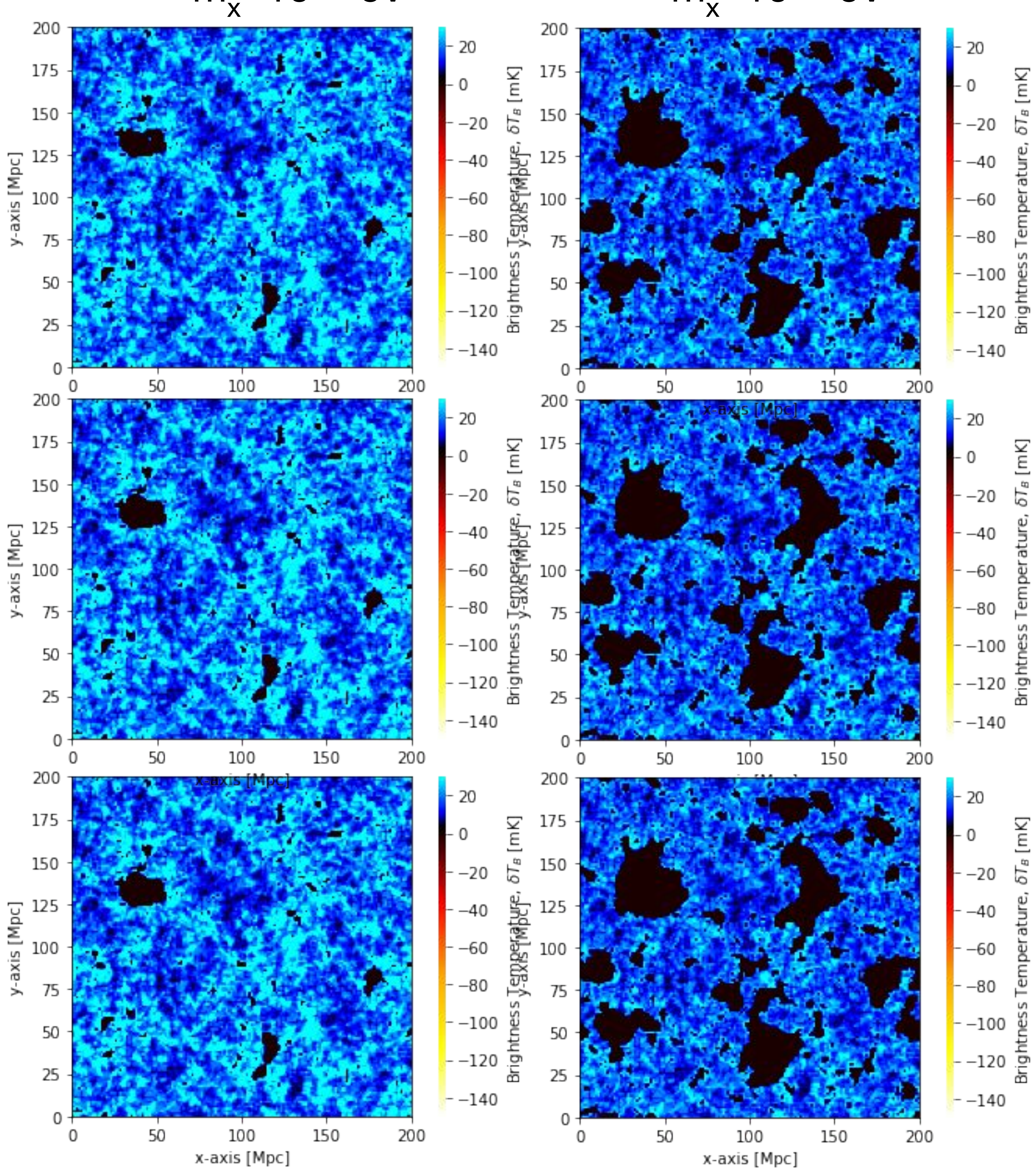
R_{mfp},the mean free path of ionizing photons: The propagation of ionizing photons through the ionized IGM strongly depends on the presence of absorption systems and the sizes of ionized regions are determined by the balance between sinks and sources of ionizing photons. Physically, the mean free path of ionizing photons corresponds to the typical distance traveled by photons within ionized regions before they are abosorbed and is determined by the number density and the optical depth. In our calculation, we explore R_{mfp}=10-60 Mpc

$m_x=10^{-22}$ eV | $m_x=10^{-20}$ eV

R_{mfp}=10

R_{mfp}=30

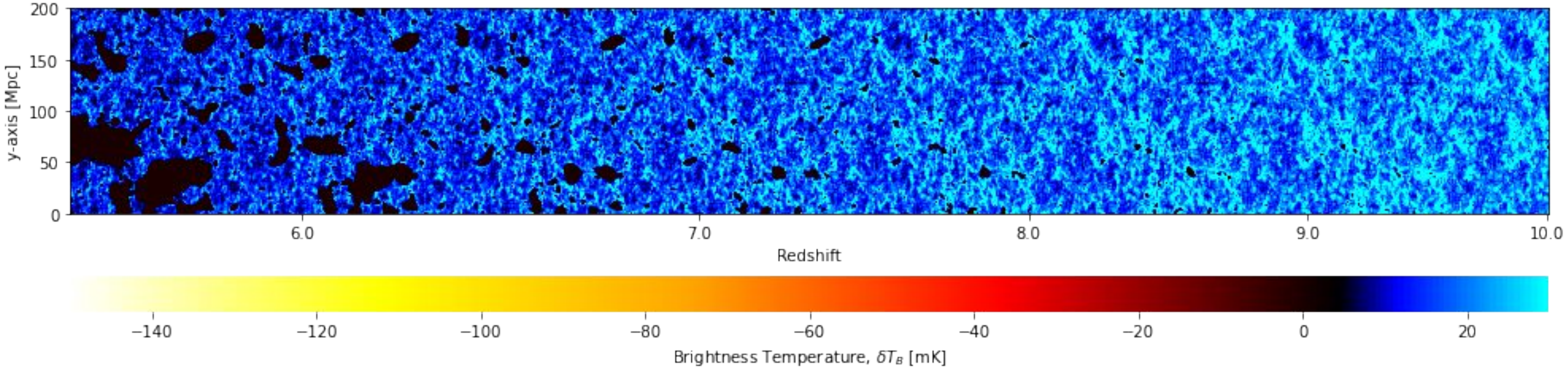
R_{mfp}=60



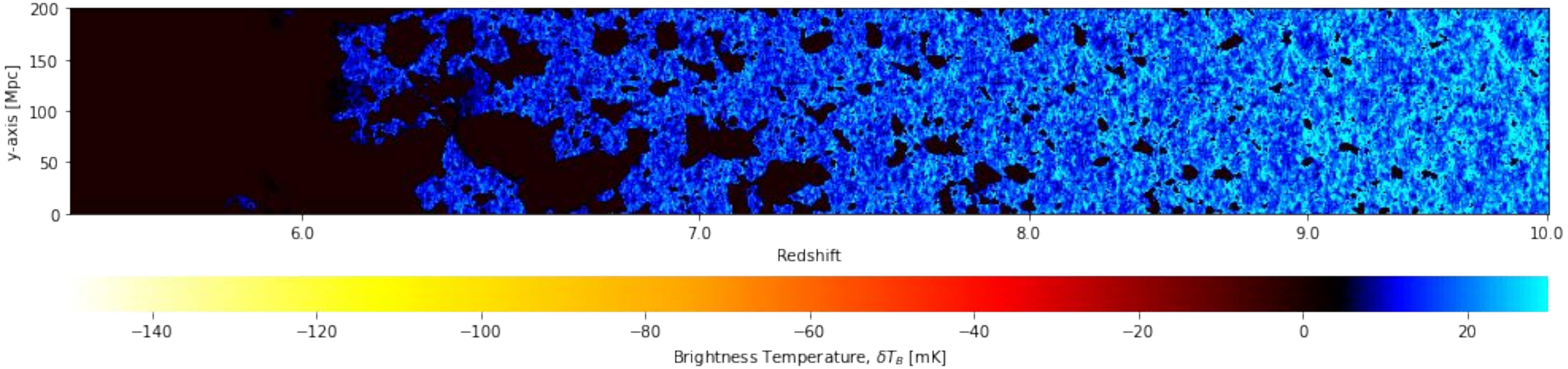
Redshift Evolution of the Brightness Temperature

$\lambda_{obs}=\lambda_{emit}(1+z)$

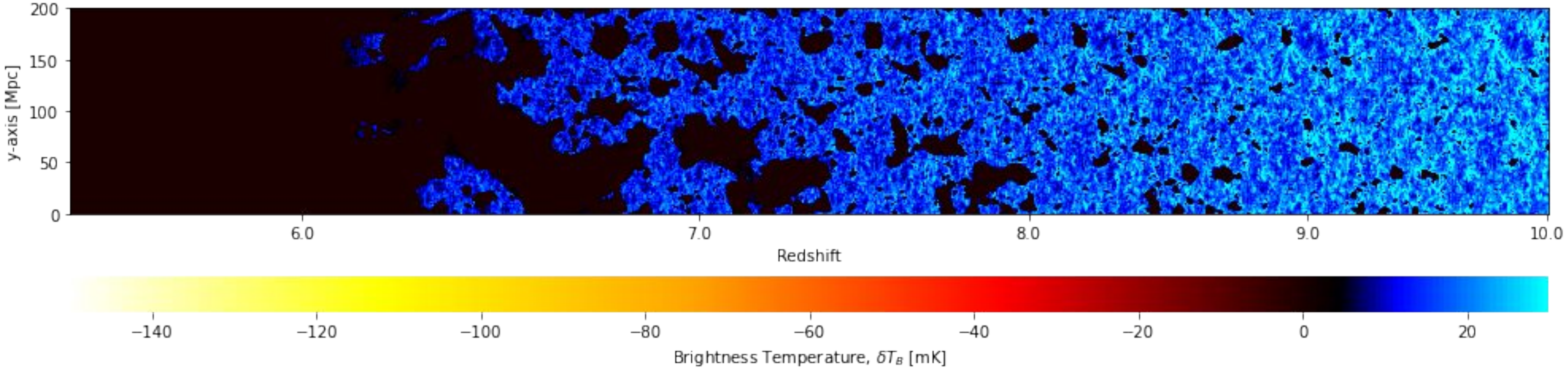
$m_x=10^{-22}$ eV



$m_x=10^{-21}$ eV



$m_x=10^{-20}$ eV



Towards Realistic Images

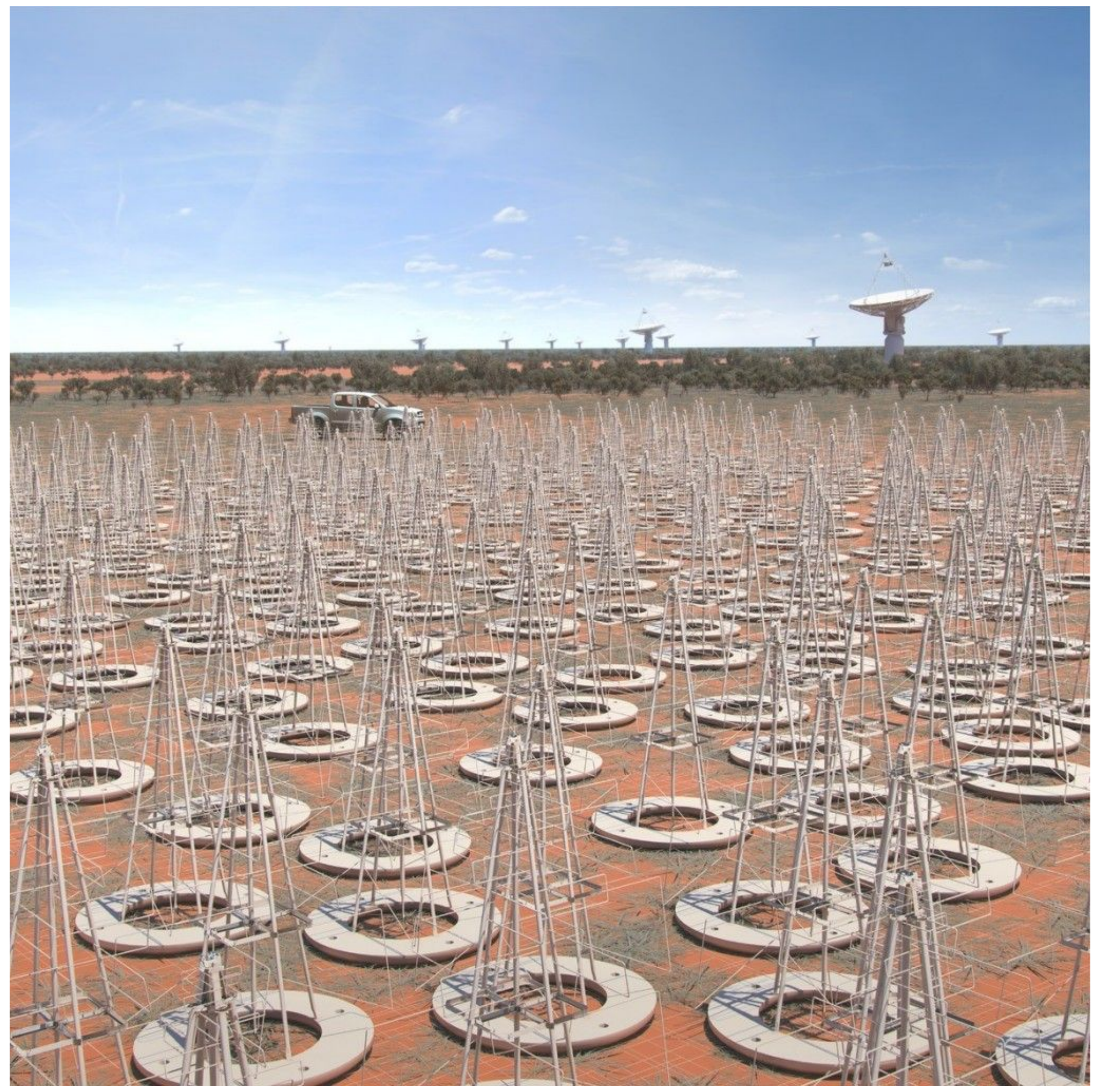
Following the SKA Desgin Plan: https://www.skatelescope.org/wp-content/uploads/2012/07/SKA-TEL-SKO-DD-001-1_BaselineDesign1.pdf

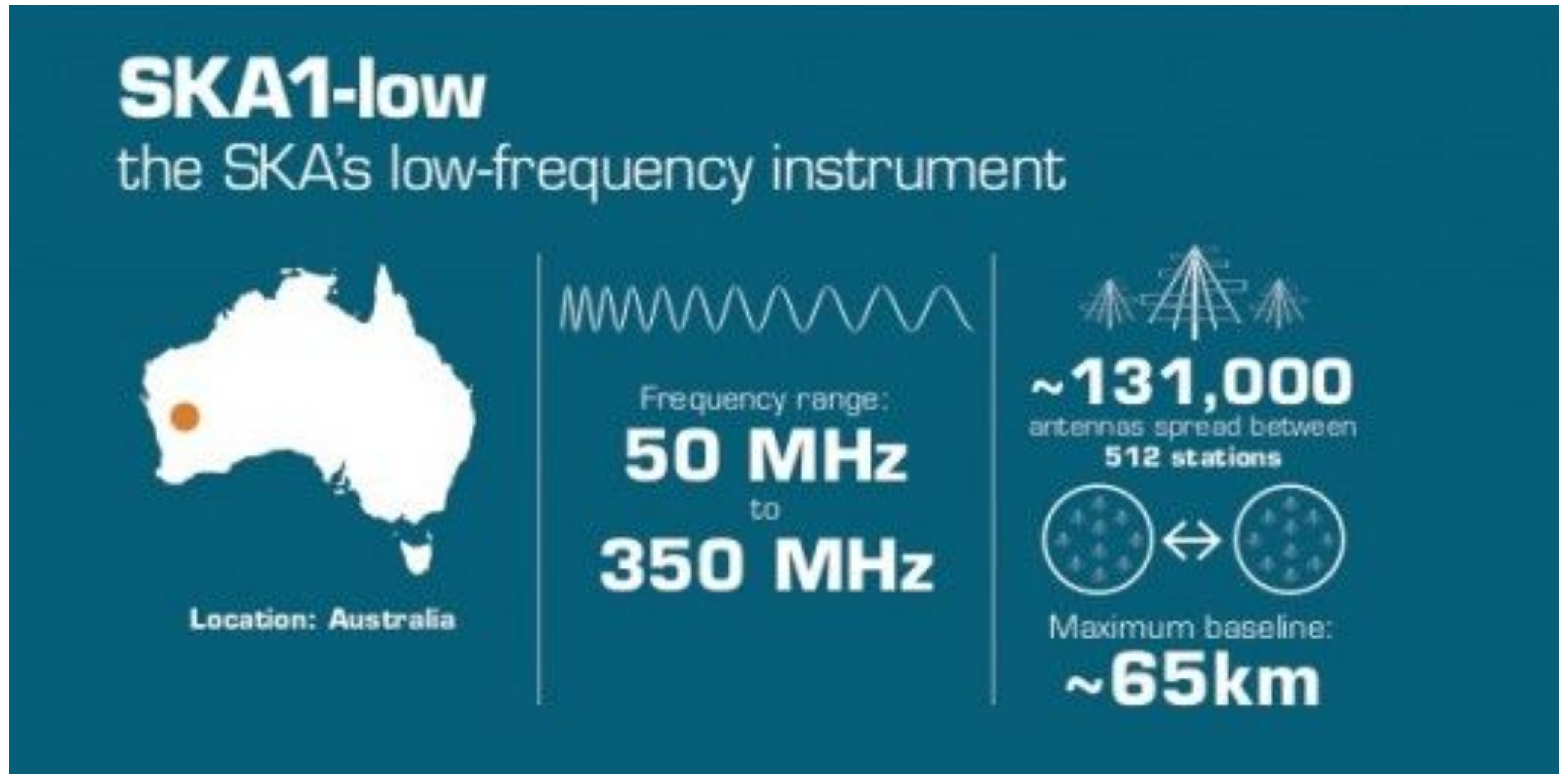
and the methodology of McQuinn, etal 2007

		FAST	MeerKAT	WSRT	Arecibo	ASKAP	SKA1-survey	SKA1-low	SKA-mid
A_{eff}/T_{sys}	m^2/K	1250	321	124	1150	65	391	1000	1630
FoV	deg^2	0.0017	0.86	0.25	0.003	30	18	27	0.49
Receptor Size	m	300	13.5	25	225	12	15	35	15
Fiducial frequency	GHz	1.4	1.4	1.4	1.4	1.4	1.67	0.11	1.67
Survey Speed FoM	$deg^2\, m^4\, K^{-2}$	2.66×10^3	8.86×10^4	3.84×10^3	3.97×10^3	1.27×10^5	2.75×10^6	2.70×10^7	1.30×10^6
Resolution	arcsec	88	11	16	192	7	0.9	11	0.22
Baseline or Size	km	0.5	4	2.7	225	6	50	50	200
Frequency Range	GHz	0.1 – 3	0.7 - 2.5, 0.7 - 10	0.3 – 8.6	0.3 - 10	0.7-1.8	0.65-1.67	0.050 – 0.350	0.35-14
Bandwidth	MHz	800	1000	160	1000	300	500	250	770
Cont. Sensitivity	$\mu Jy\text{-}hr^{-1/2}$	0.92	3.20	20.74	0.89	28.89	3.72	2.06	0.72
Sensitivity, 100 kHz	$\mu Jy\text{-}hr^{-1/2}$	82	320	830	89	1582	263	103	63
SEFD	Jy	2.2	8.6	22.3	2.4	42.5	7.1	2.8	1.7

100kpc at z=5

$3 < z_{H1} < 27$





Sample Variance

We also want an expression for the contribution to $\boldsymbol{C}$ that is due to sample variance. For a 3D window function $W(\hat{\boldsymbol{n}}, \nu) = A_\nu(\hat{\boldsymbol{n}}) f_{\hat{n}}(\nu)$, if we assume that different pixels indexed by $\boldsymbol{u}$ are uncorrelated, the covariance matrix of the 21 cm signal $\tilde{I}^{21}$ is

$$C^{SV}(\boldsymbol{k}_i, \boldsymbol{k}_j) = \langle \tilde{I}^{21}(\boldsymbol{u}_i)^* \tilde{I}^{21}(\boldsymbol{u}_j) \rangle \approx \delta_{ij} \int d^3\boldsymbol{u}' \left|\tilde{W}(\boldsymbol{u}_i - \boldsymbol{u}')\right|^2 P^{21}_{\Delta T}(\boldsymbol{u}'), \quad (20)$$

where we have used the fact that $\langle \Delta T^{21}(\boldsymbol{u}') \Delta T^{21}(\boldsymbol{u}) \rangle = P_{\Delta T}(\boldsymbol{u}) \delta^3(\boldsymbol{u}' - \boldsymbol{u})$ and the definition of visibility (eq. [11]). We can simplify $\boldsymbol{C}^{SV}$ further:

$$C^{SV}(\boldsymbol{k}_i, \boldsymbol{k}_j) \approx P^{21}_{\Delta T}(\boldsymbol{u}_i) \frac{\lambda^2 B}{A_e} \delta_{ij} \quad (21)$$

$$\approx P^{21}_{\Delta T}(\boldsymbol{k}_i) \frac{\lambda^2 B^2}{A_e x^2 y} \delta_{ij}, \quad (22)$$

Detector Noise

For upcoming arrays, $\boldsymbol{C}$ will be dominated by the detector noise on most scales. The rms detector noise fluctuation per visibility of an antennae pair after observing for a time t_0 in one frequency channel is (Rohlfs & Wilson 2004)

$$\Delta V^N = \frac{\lambda^2 T_{sys}}{A_e \sqrt{\Delta\nu t_0}}, \quad (13)$$

$$\tilde{I}^N(\boldsymbol{u}) = \sum_{i=1}^{B/\Delta\nu} V^N(u, v, \nu_i) \exp(2\pi i \nu_i \eta) \Delta\nu \quad (14)$$

$$= \sum_{i=1}^{B/\Delta\nu} V'^N(u, v, \nu_i) \Delta\nu, \quad (15)$$

$$C^N_{1b}(\boldsymbol{u}_i, \boldsymbol{u}_j) = \langle \tilde{I}^N(\boldsymbol{u}_i)^* \tilde{I}^N(\boldsymbol{u}_j) \rangle_{1\ \text{baseline}} = \left\langle \left[\sum_{m=1}^{B/\Delta\nu} V'^N(\boldsymbol{u}_i, \nu_m) \Delta\nu\right]^* \left[\sum_{l=1}^{B/\Delta\nu} V'^N(\boldsymbol{u}_j, \nu_l) \Delta\nu\right] \right\rangle$$

$$= B\Delta\nu (\Delta V^N)^2 \delta_{ij} \quad (16)$$

$$= \left(\frac{\lambda^2 B T_{sys}}{A_e}\right)^2 \frac{\delta_{ij}}{B t_0}. \quad (17)$$