University of Zurich[UZH]

BEoRN : a fast and flexible framework to simulate the 21cm signal during cosmic dawn and reionisation

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with Sambit Giri and Aurel Schneider

Structure of the presentation

- 1- Introducing BEoRN : publicly available and user-friendly python 21cm code
- 2- What type of cosmic dawn and reionisation signals are expected given current constraints from high-z observation ?
- 3- Description of the Halo Model (HM) approach for 21cm
- 4- Cosmological forecast for SKA using the Halo Model

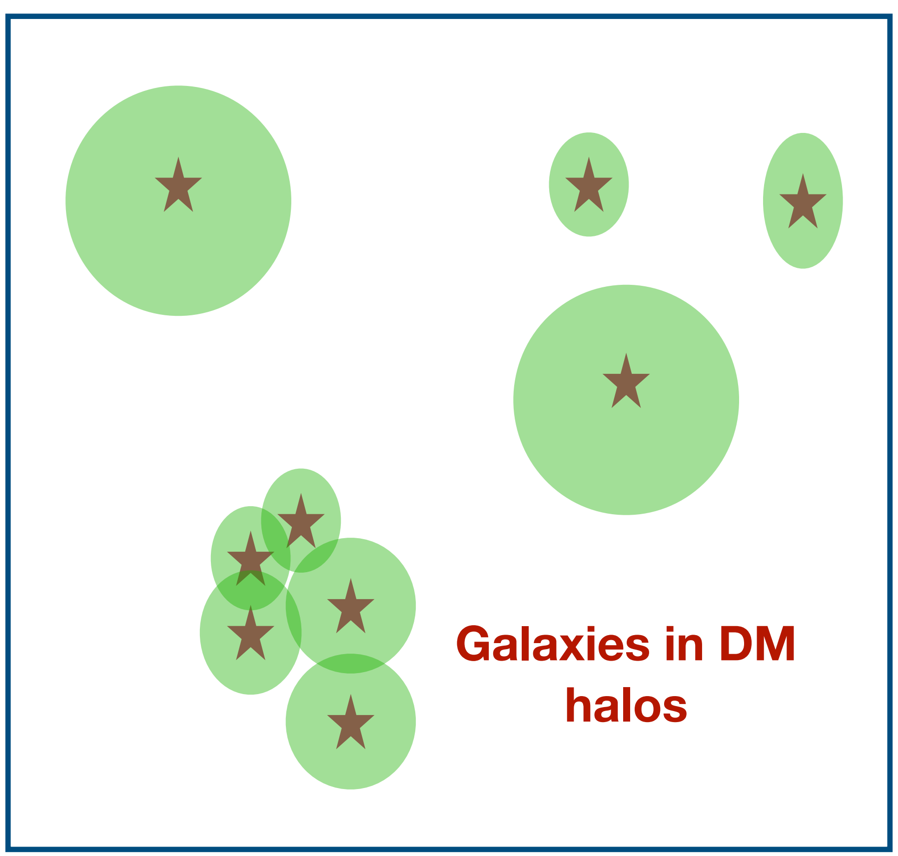
Modelling the 21cm signal : BEoRN

(**B**ubbles during the **E**poch **o**f **R**eionisation **N**umerical simulator)

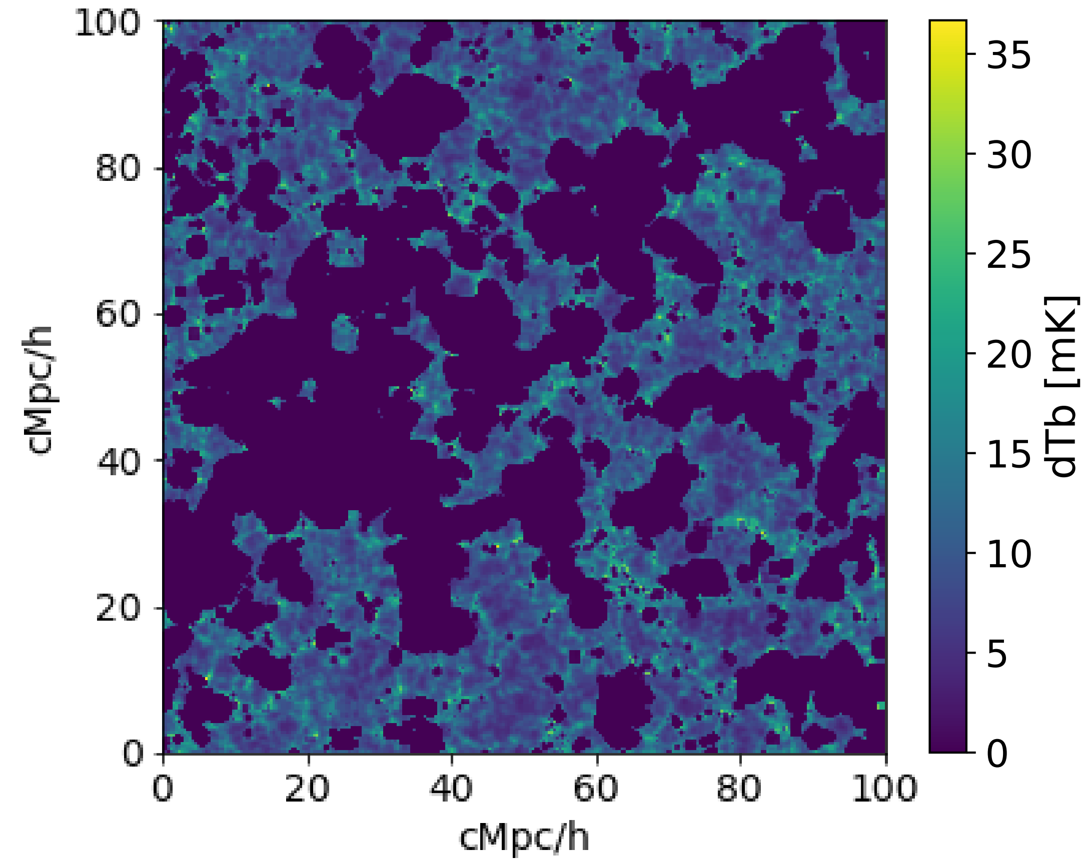
Methodology : based on source distribution and 1D radial profiles

Radial profiles (xHII, Tk, ly-alpha)

Cosmological volume

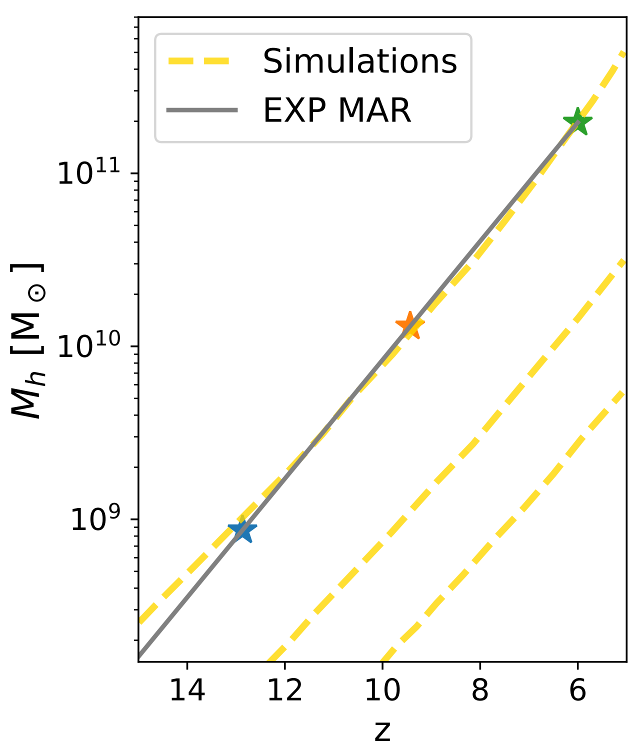


Ionisation, temperature, dTb maps

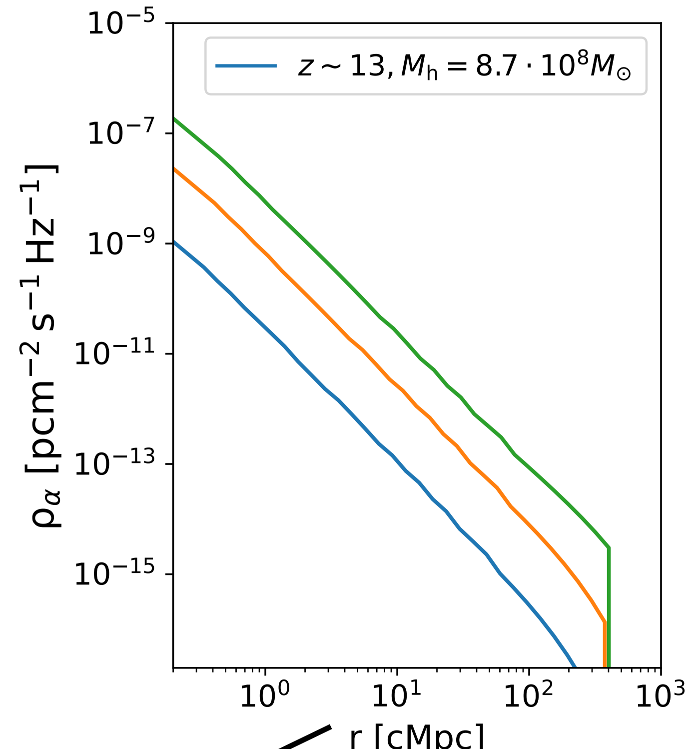


1D radial profiles

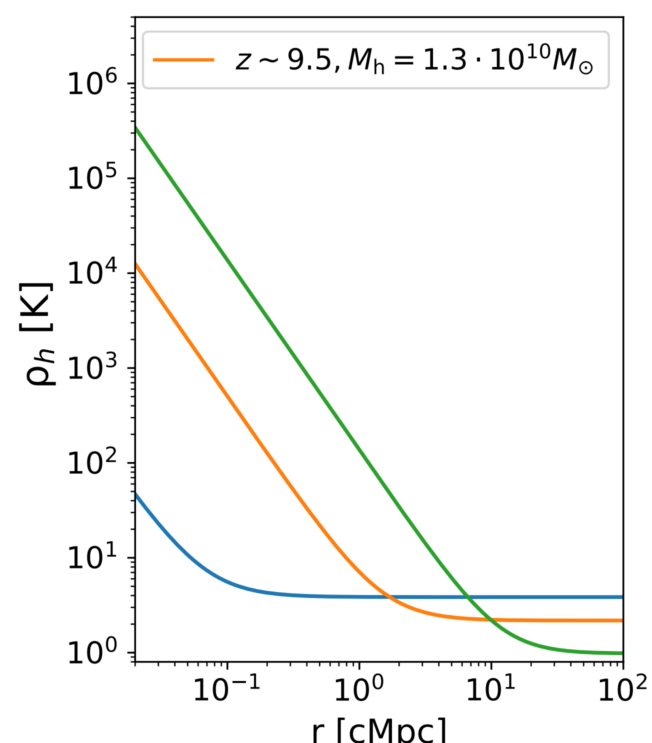
Halo growth



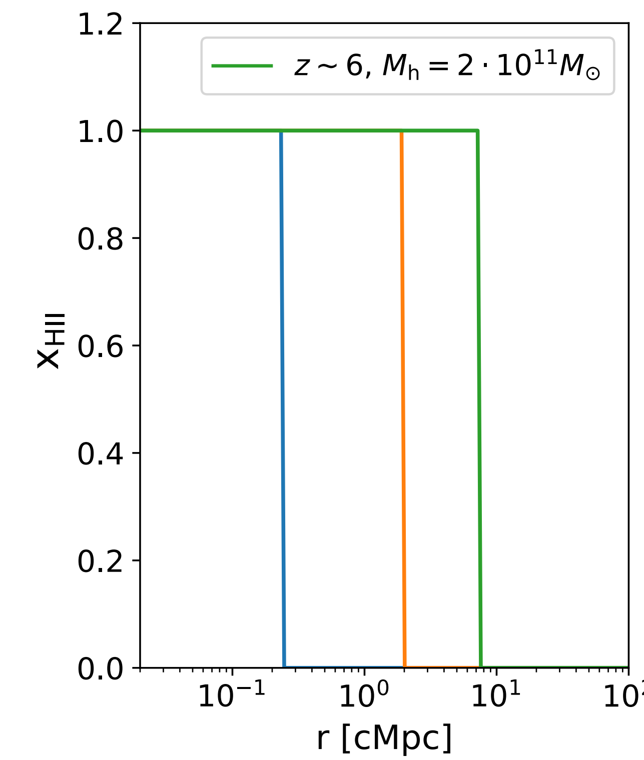
Ly-a flux



Temperature (Tk)



Ionisation (xHII)



$$\rho_\alpha(r|M_h,z) = \frac{1}{4\pi r^2}\sum_{n=2}^{n_m} f_n \epsilon_\alpha(\nu') f_*(M_h(z'))\dot{M}_h(z')$$

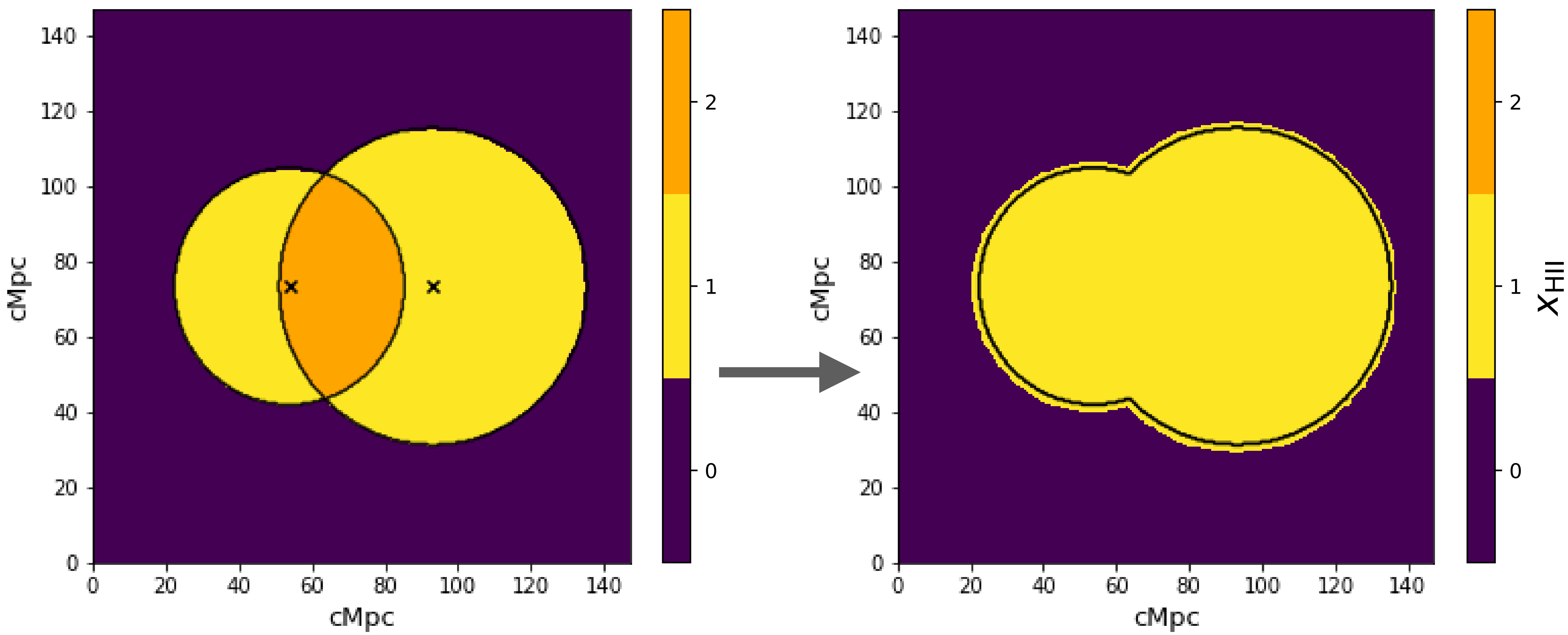
$$\frac{3}{2}\frac{d\rho_h(r|M_h,z)}{dz} = \frac{3\rho_h(r|M_h,z)}{(1+z)} - \frac{\rho_{\mathrm{xray}}(r|M_h,z)}{k_{\mathrm{B}}(1+z)H(z)}$$

$$\frac{dV}{dt} = \frac{\dot{N}_{\mathrm{ion}}(t)}{\bar{n}_H^0} - \alpha_B \frac{C}{a^3}\bar{n}_H^0 V,$$

Barkana & Loeb (2001)

Overlap of 1D radial profiles

- Ionisation bubbles: Redistribute “overionised” pixels to the nearest grid points



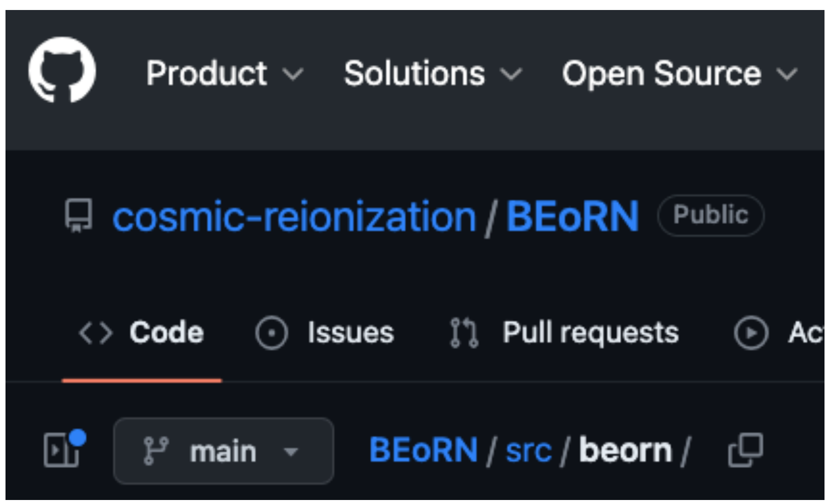
BEoRN

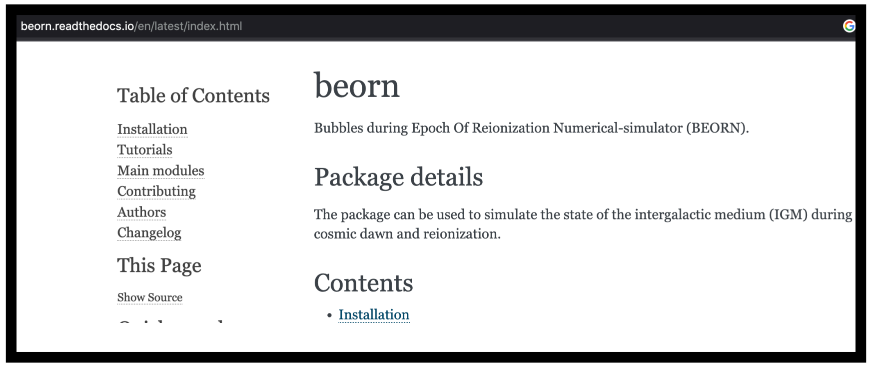
*(**B**ubbles during the **E**poch **o**f **R**eionisation **N**umerical simulator)*

Publicly available, flexible, user-friendly

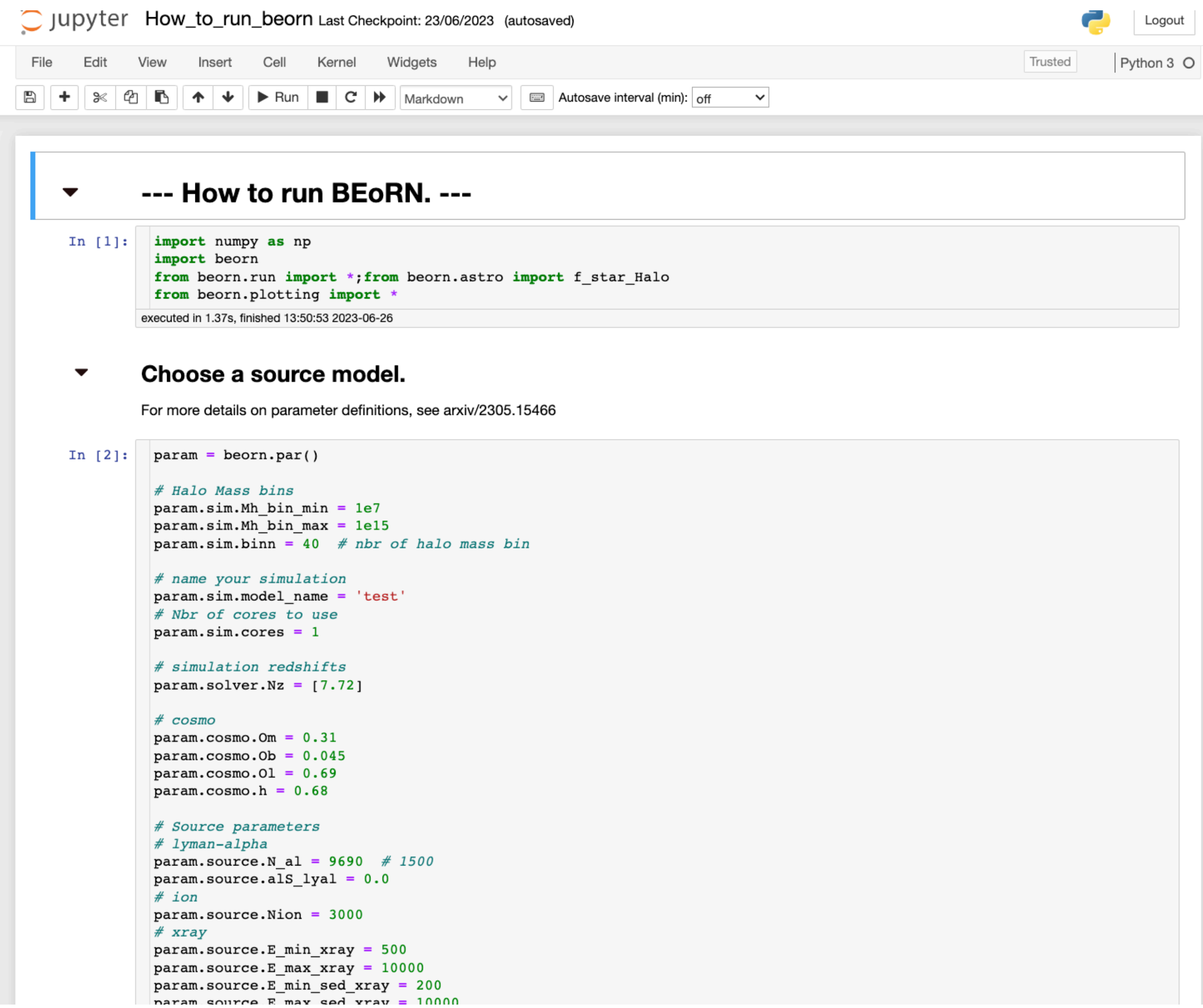
https://github.com/cosmic-reionization/BEoRN

Readthedoc and example Jupyter notebook





(in development)



2- What kind of cosmic dawn and reionisation signals can we expect given current constraints from high-z observations ?

Realistic simulation of the 21cm signal

Pipeline :

1. Run N-body

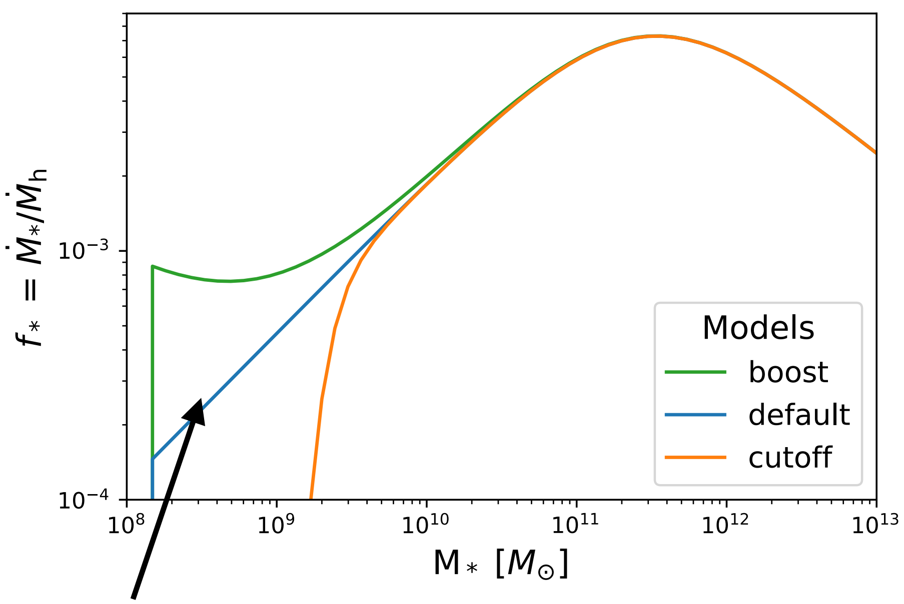
N-body sim :
Lbox: 147cMpc
2048^3 particles
Mpart = 10^7 Msol/h

2. Calibrate astrophysical parameters (f*, fesc, x-ray amplitude) to observation (UV luminosity fct, estimate of xHII, low-z HMXB observation)

3. Run BEoRN

3 realistic scenarios : source parameters

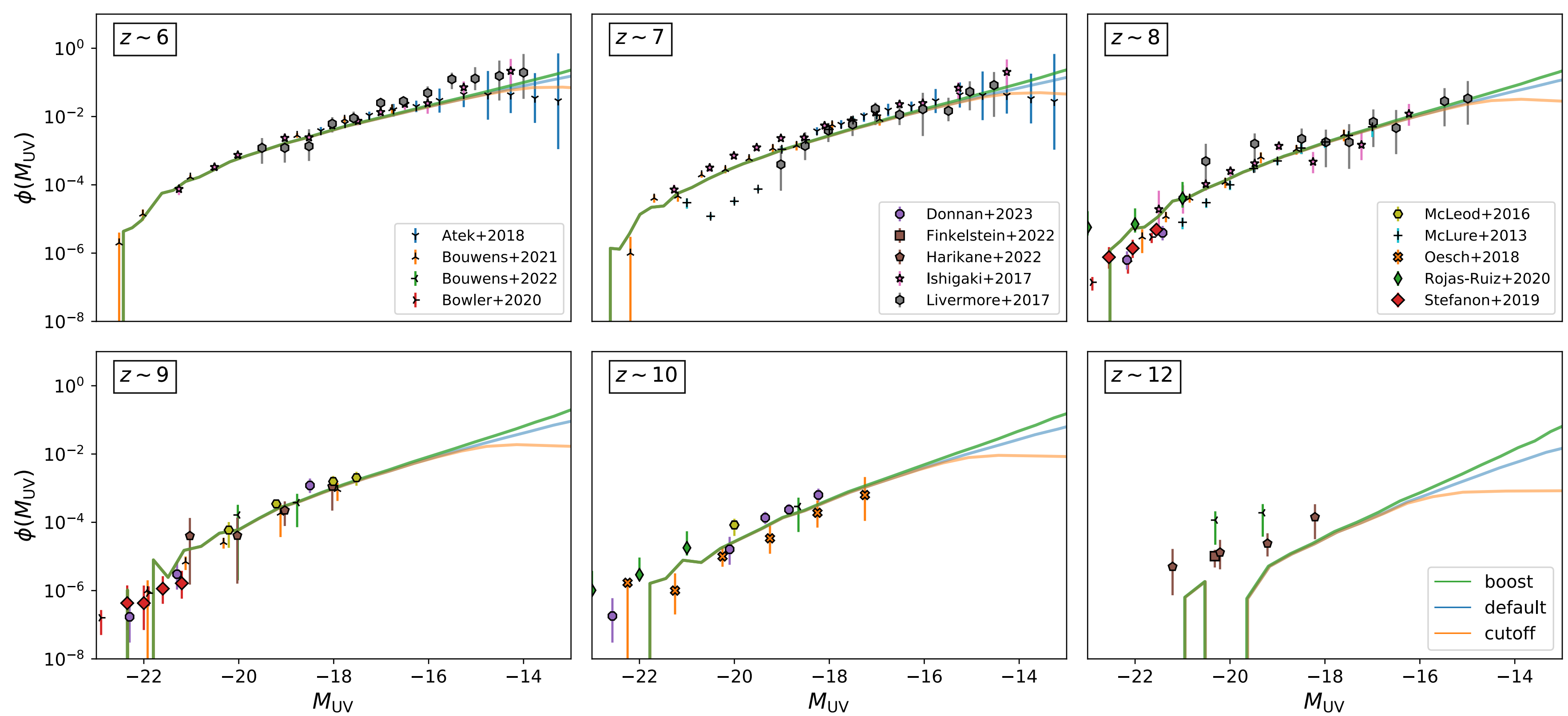
Stellar-to-halo



Unconstrained at small scales

The UV **luminosity function** constraints the **stellar-to-halo relation**

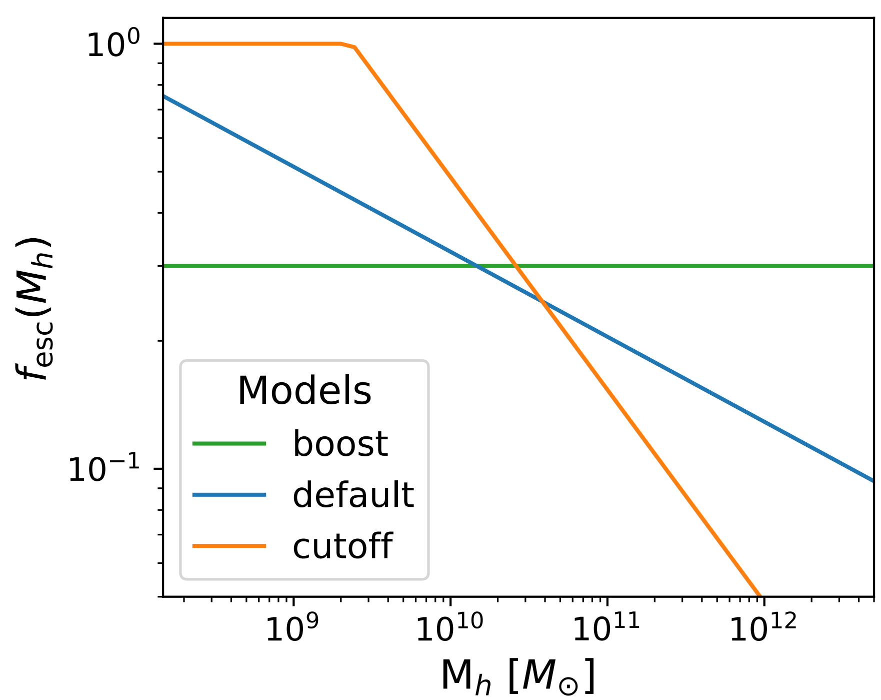
Luminosity function : theory vs data



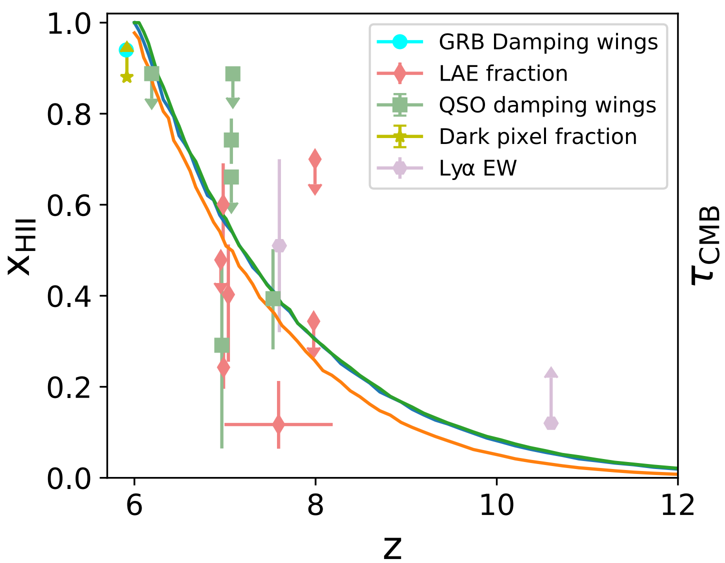
3 realistic scenarios : source parameters

Estimates of xHII: put constraints on the **escape fraction** of ionising photons

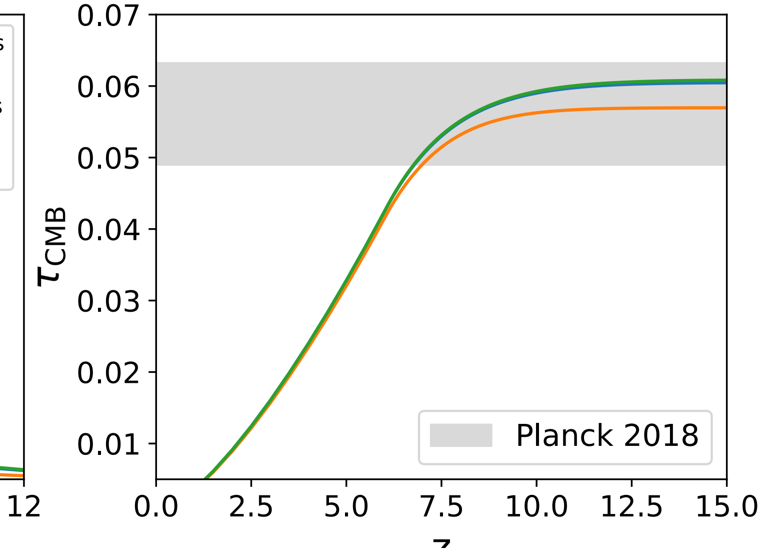
Escape fraction



Reionisation history



CMB



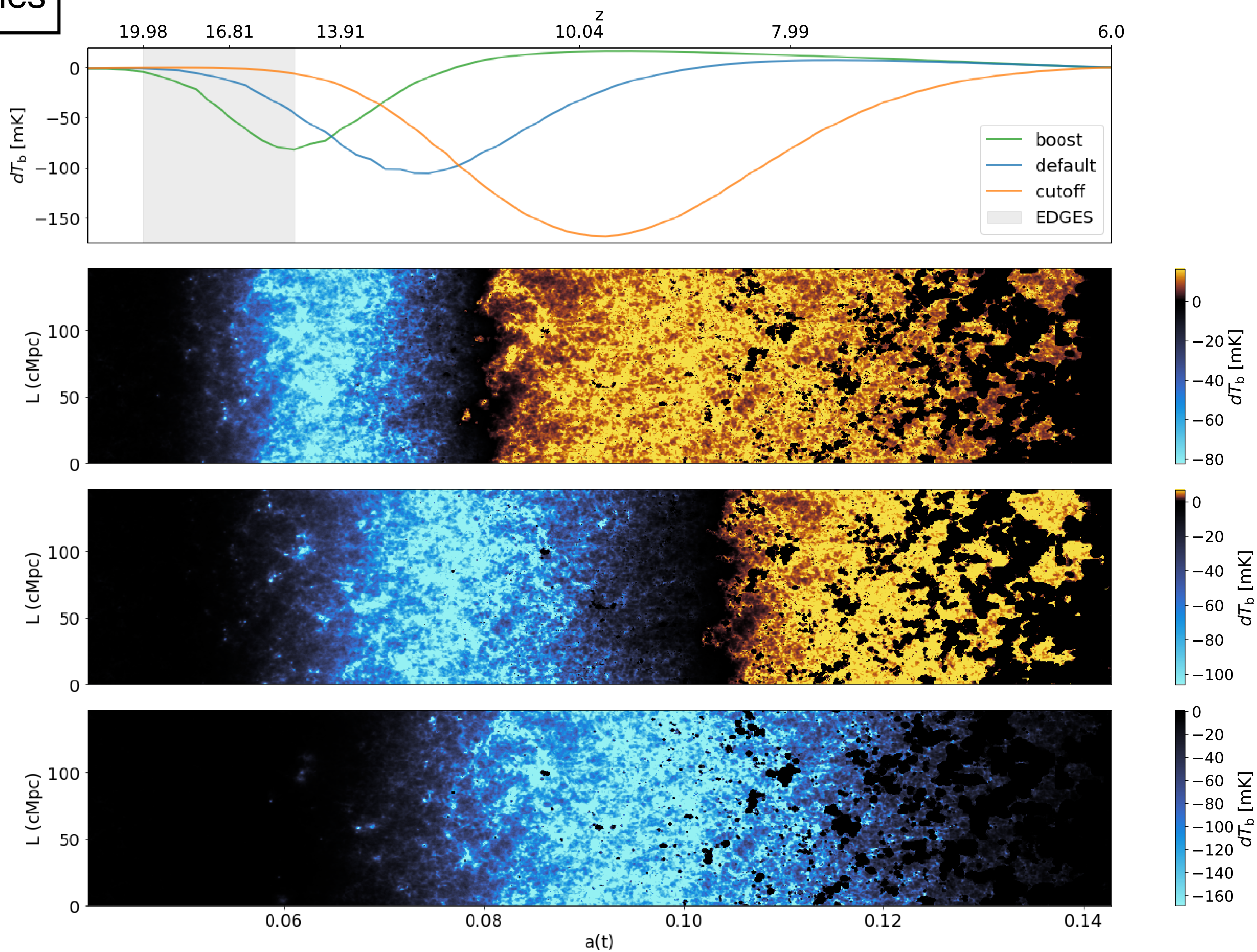
X-ray parameters :

$$c_X = 10^{40.5}\ \mathrm{erg\ s^{-1} yr}\ M_\odot^{-1}$$

The true normalisation of the x-ray spectrum is highly uncertain —> we vary fX = 0.1, 1, 5 (cutoff, default, boost)

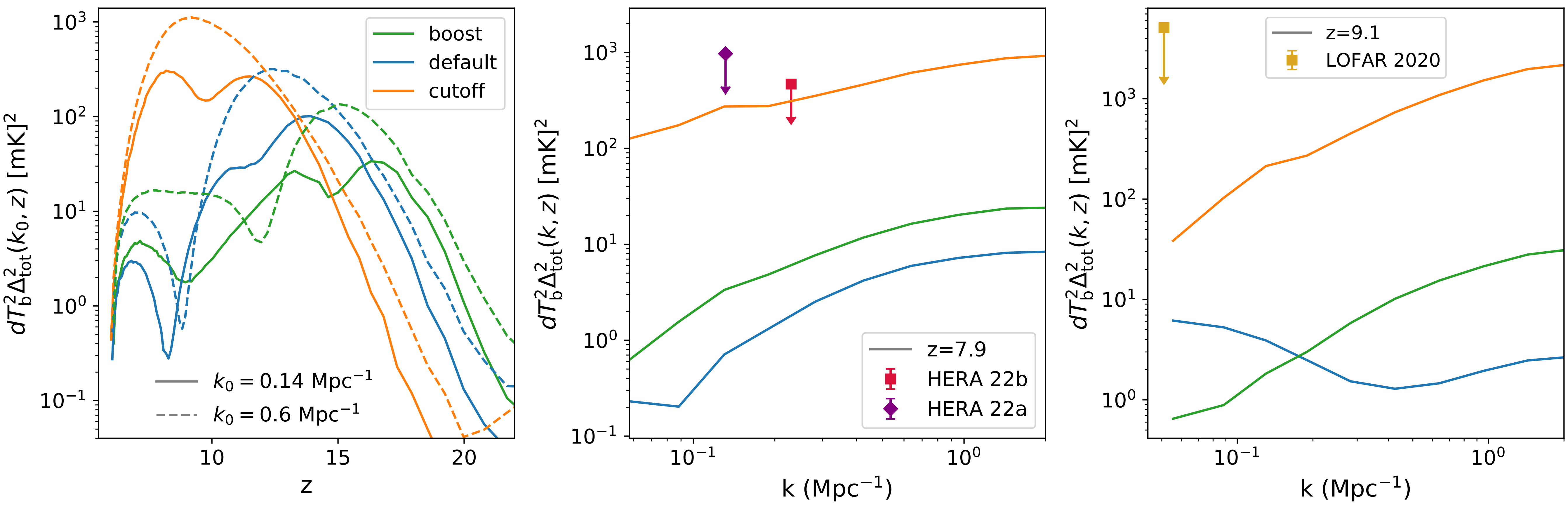
3 realistic scenarios for the Cosmic Dawn

Lightcones



3 realistic scenarios for the Cosmic Dawn

21cm signal (Power spectrum)



—> Large variety of 21cm signal still allowed by current observation

3- Halo Model approach for 21cm

(A fast analytical method to compute the 21cm power spectrum in ~sec)

(Schneider, Giri, Mirocha 2011.12308)

(Schneider, TS, Giri 2302.06626)

The Halo model (HM) implementation of BEoRN

(Analytical calculation of the 21cm PS)

How it works :

*1- Express dTb perturbations as a function of **matter** (b), **Ly-α** (α), **Tk** (T) and **xHII** (r) perturbations*

$$dT_\mathrm{b} \propto (1 - x_\mathrm{HII})(1+\delta_\mathrm{b})(1 - \frac{T_\gamma}{T_\mathrm{k}})(\frac{x_\alpha}{1+x_\alpha})$$

$$dT_\mathrm{b} = \overline{T}_{21}(1+\delta_{21})$$

$$x_\alpha = \overline{x}_\alpha(1+\delta_\alpha)$$

$$T_\mathrm{k} = \overline{T}_\mathrm{k}(1+\delta_\mathrm{T})$$

$$x_\mathrm{HII} = \overline{x}_\mathrm{HII}(1+\delta_r)$$

*To first order in **Ly-α** (α) and **Tk** (T) :*

$$\longrightarrow \delta_{21} = \beta_r\delta_r + \beta_b\delta_b + \beta_T\delta_T + \beta_\alpha\delta_\alpha + \beta_r\beta_b\delta_r\delta_b + \beta_r\beta_T\delta_r\delta_T + \beta_r\beta_\alpha\delta_r\delta_\alpha - \delta_{dv}$$

(Schneider, Giri, Mirocha 2011.12308)

(Schneider, TS, Giri 2302.06626)

Halo model (HM) implementation of BEoRN

(Analytical calculation of the 21cm PS)

How it works :

2- Compute auto and cross PS using HM formalism, replacing NFW by **1D radiation flux profiles :**

$$P_{21}^{(\mathrm{lin})} = P_{r,r} + P_{b,b} + P_{T,T} + P_{\alpha,\alpha} + 2\left(P_{r,b} + P_{r,T} + P_{r,\alpha} + P_{b,T} + P_{b,\alpha} + P_{T,\alpha}\right)$$

X,Y Individual fields :
(**b**) : matter
(**α**): Ly-α ,
(**T**) : Tk
(**r**) : xHII

$$P_{XY}^{1\mathrm{h}}(k,z) = \frac{\beta_X \beta_Y}{(\bar{\rho} f_{\mathrm{coll}})^2} \int dM \frac{dn}{dM} \tilde{f}_*^2 M^2 |u_X||u_Y|,$$

$$P_{XY}^{2\mathrm{h}}(k,z) = \frac{\beta_X}{(\bar{\rho} f_{\mathrm{coll}})} \int dM \frac{dn}{dM} \tilde{f}_* M |u_X| b_X \times \frac{\beta_Y}{(\bar{\rho} f_{\mathrm{coll}})} \int dM \frac{dn}{dM} \tilde{f}_* M |u_Y| b_Y \times P_{\mathrm{lin}}$$

$$P_{XY}(k,z) = P_{XY}^{1\mathrm{h}}(k,z) + P_{XY}^{2\mathrm{h}}(k,z),$$

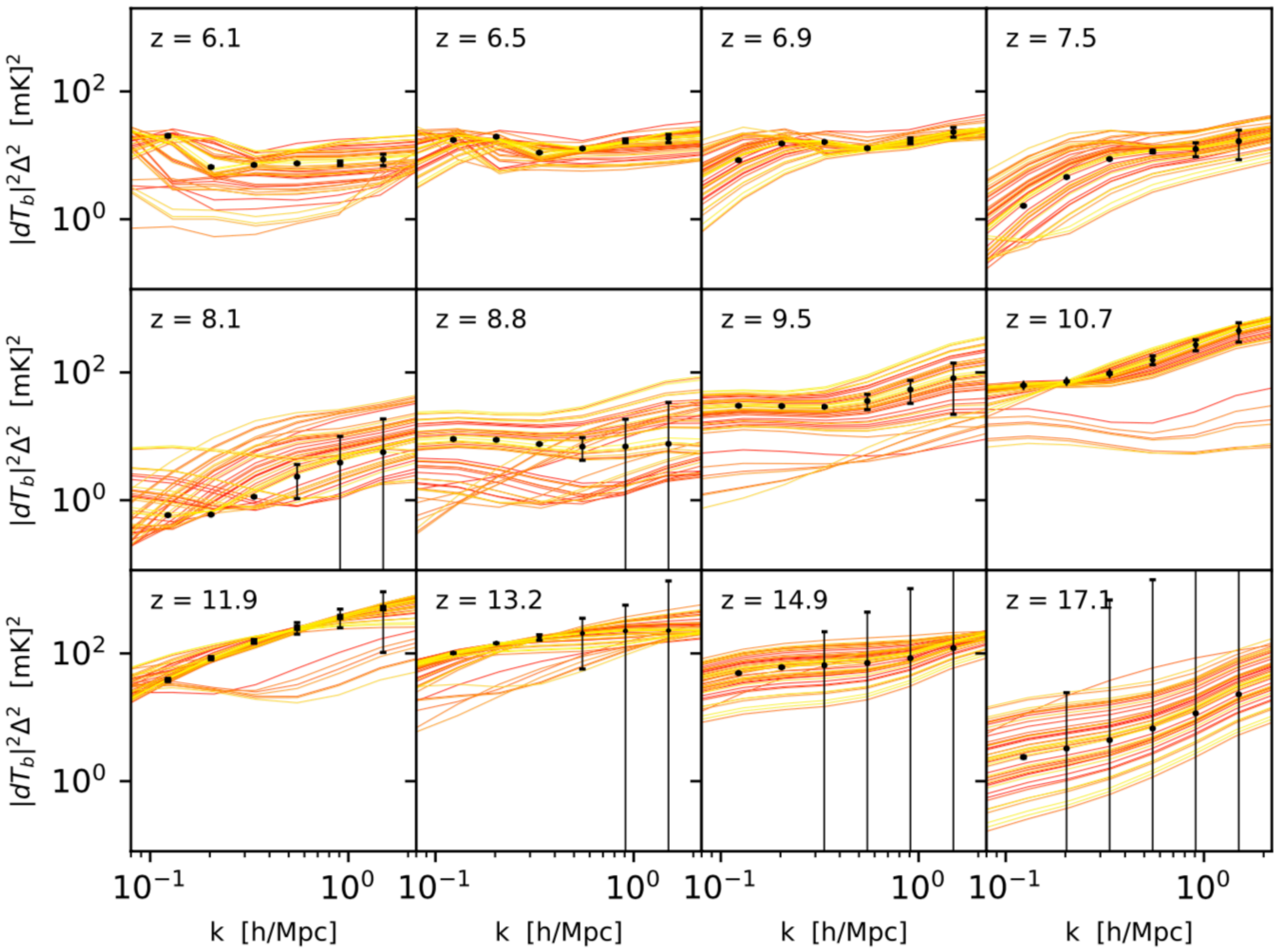
Ingredients :
-**Plin**
-**bX** : halo matter bias
-**uX** : 1D profiles
-**dn/dM** : HMF

→ Computes P21 in ~20 sec

4- Cosmological forecast for SKA using the HM approach

Results : Cosmological forecast for SKA using the HaloModel

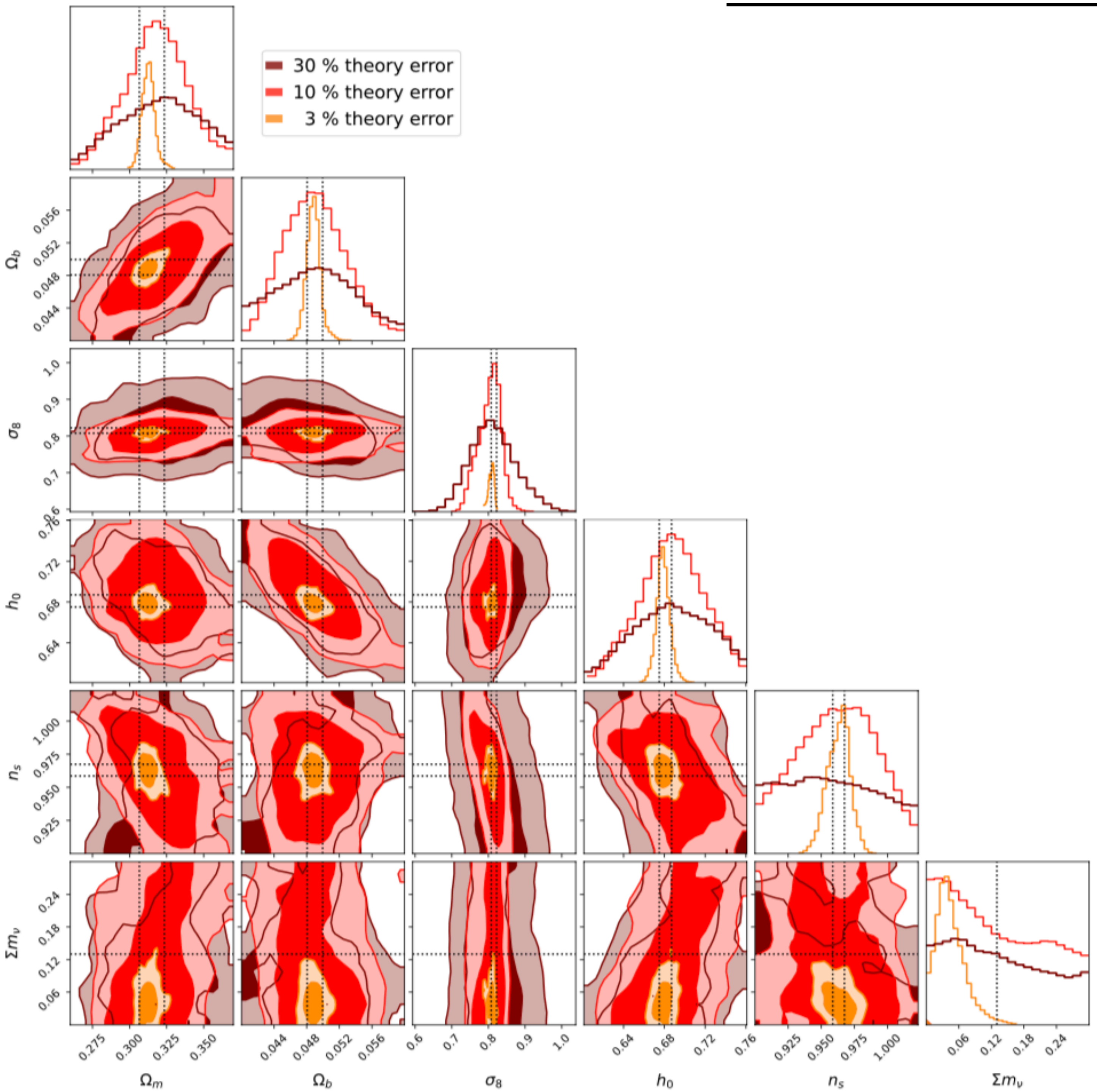
Mock Power Spectrum data (1000h):



- Foreground : scale cut (keep 0.1<k<1.5 h/Mpc)
- Instrumental noise (SKA-low 512 antennae)
- Sample variance

Results : Cosmological forecast for SKA using the HaloModel

MCMC inference :



-Add a “theory” error

$$\sigma^2_{\rm tot} = \sigma^2_{\rm obs} + \sigma^2_{\rm th}, \qquad \sigma_{\rm th} = c_{\rm th} P_{\rm obs},$$

-Vary 13 parameters (cosmo + astro)

Parameter name	Acronym	mock value	prior range
Matter abundance	Ω_m	0.315	[0.27, 0.37]
Baryon abundance	$\Omega_{\rm b}$	0.049	[0.04, 0.06]
Scalar amplitude	A_s $[10^{-9}]$	2.07	[1.0, 3.5]
Hubble parameter	h	0.68	[0.6, 0.8]
Spectral index	n_s	0.963	[0.90, 1.02]
Neutrino masses	Σm_ν [eV]	0.06	[0.0, 0.5]
Amplitude of f_*	$f_{*,0}$	0.1	[0.01, 1.0]
Slope of f_*	γ_2	0.5	[-0.79,-0.19]
Truncation of f_*	M_t $[{\rm M}_\odot/{\rm h}]$	10^8	[3.2e6, 3.2e9]
Amplitude of $f_{\rm esc}$	$f_{{\rm esc},0}$	0.1	[0.01, 1.0]
Slope of $f_{\rm esc}$	$\alpha_{\rm esc}$	0.5	[0,1]
Ampl. of X-ray rad.	f_X	1.0	[0.01,10]
Min X-ray energy	$E_{\rm min}$ [keV]	0.5	[0.3, 2.0]

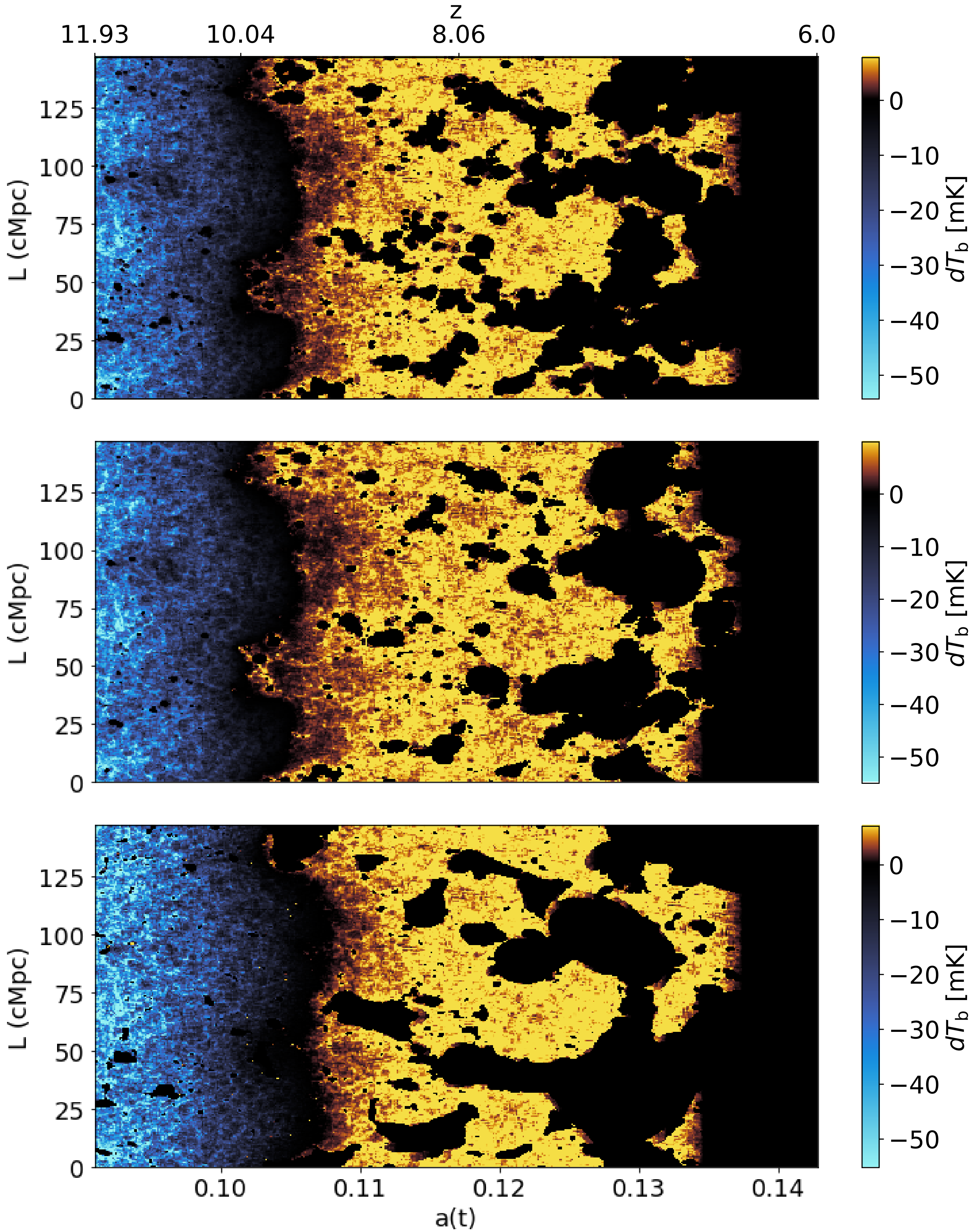
Conclusions

- BEoRN is publicly available and user friendly : https://github.com/cosmic-reionization/BEoRN

- The 21-cm clustering signal is a powerful complementary probe with other high-z observations

- Assuming 3% theory error, we can expect to get constraints competitive with Planck, an independent estimate of h0 and S8 in a new redshift range, and a direct constraint on neutrino masses.

Comparison between bubble, sem-num, and excursion set :

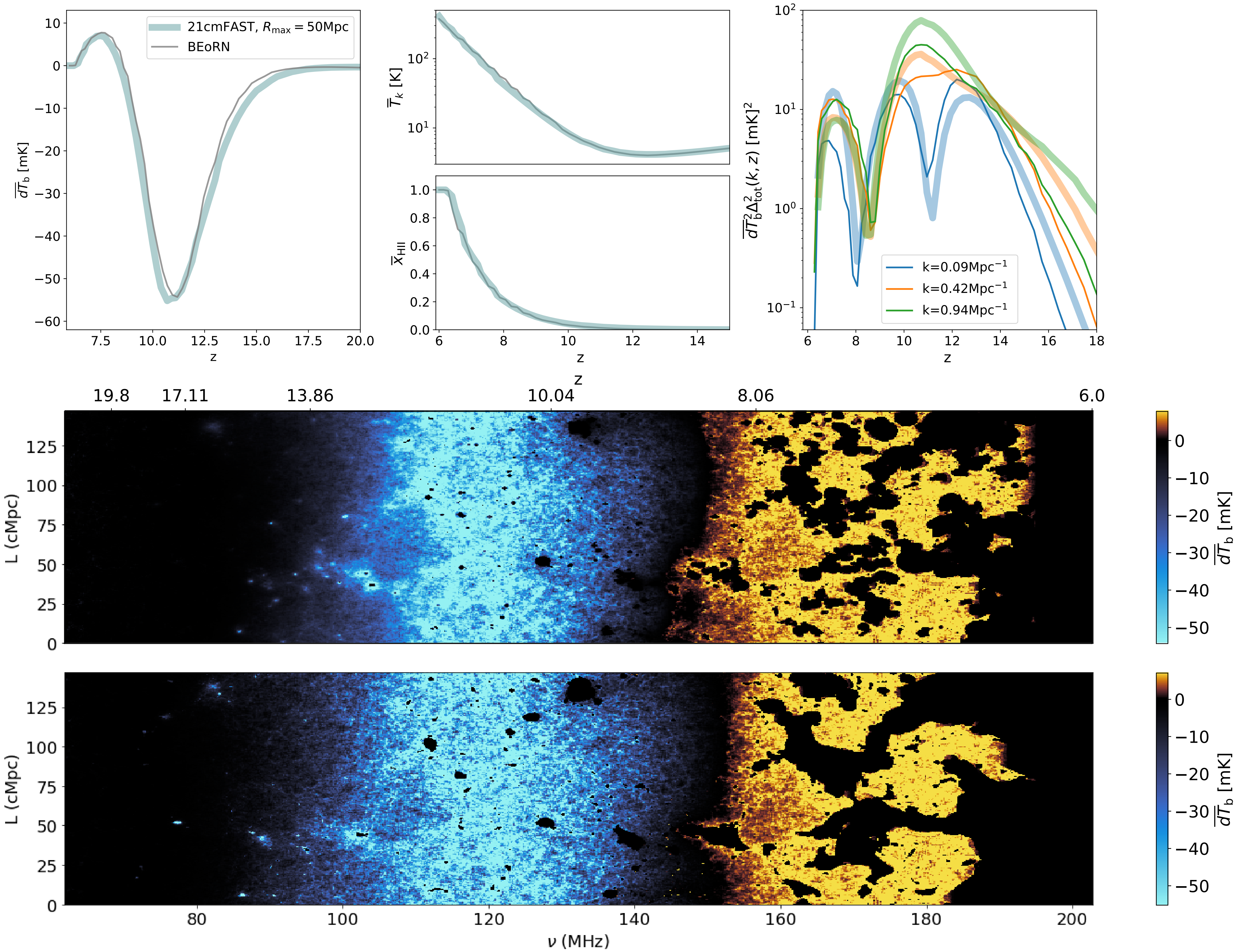


Bubbles (BEoRN)

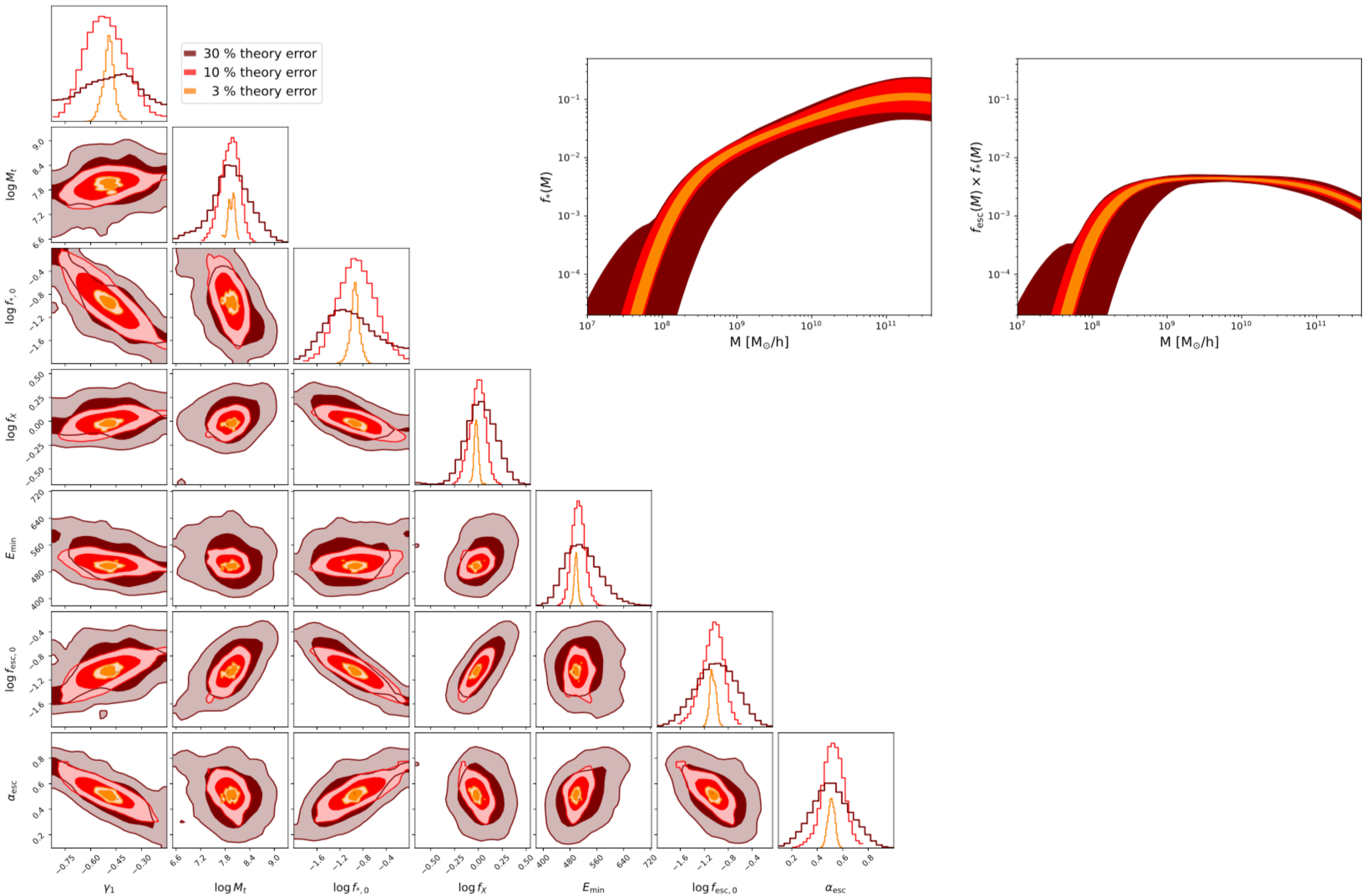
Sem-Num (halo based, Majumdar 2014)

Excursion Set (21cm FAST)

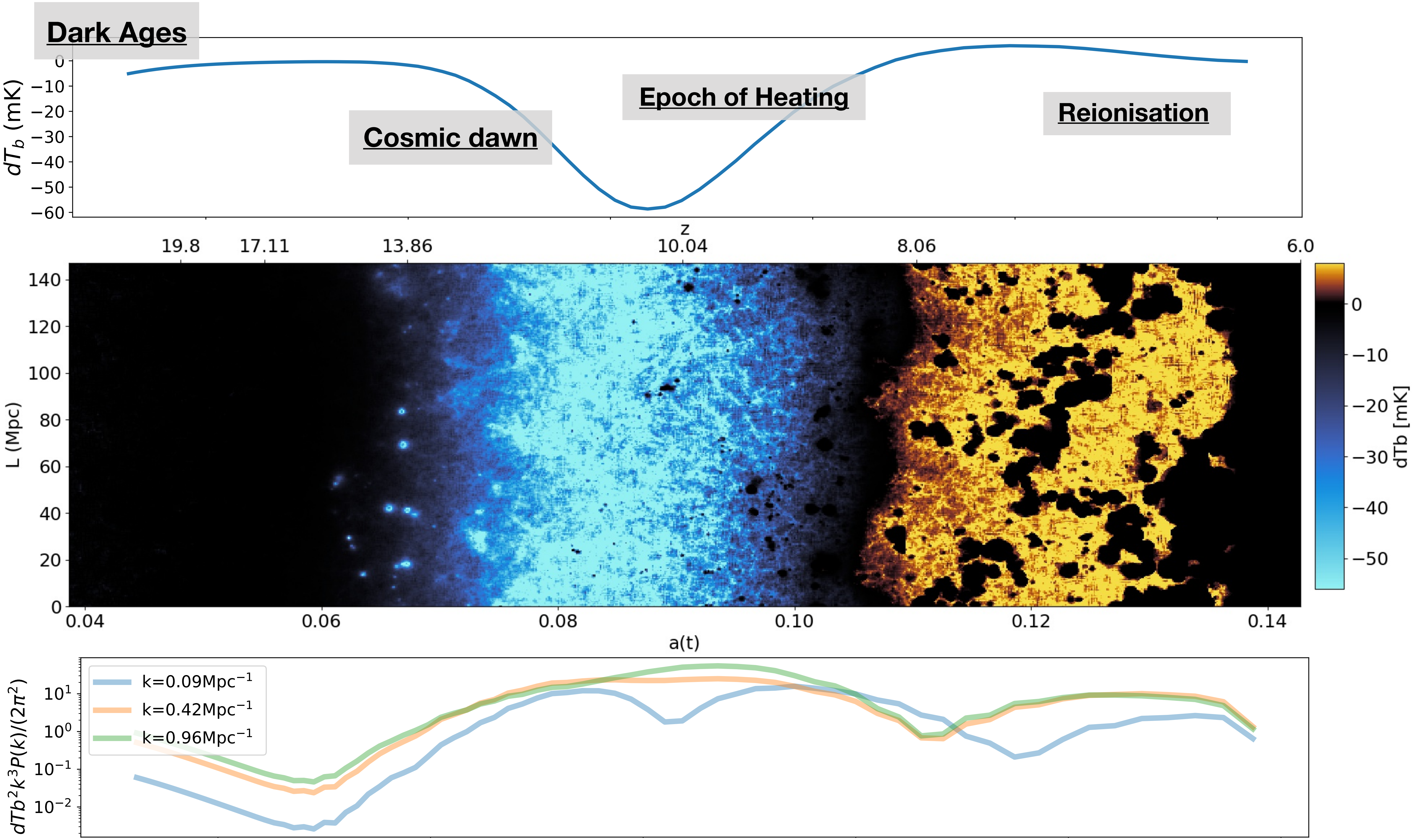
Comparison BEoRN/21cmFAST



SKA forecast on astrophysics (marginalising over cosmology)



Final product : 3D dTb maps, power spectrum

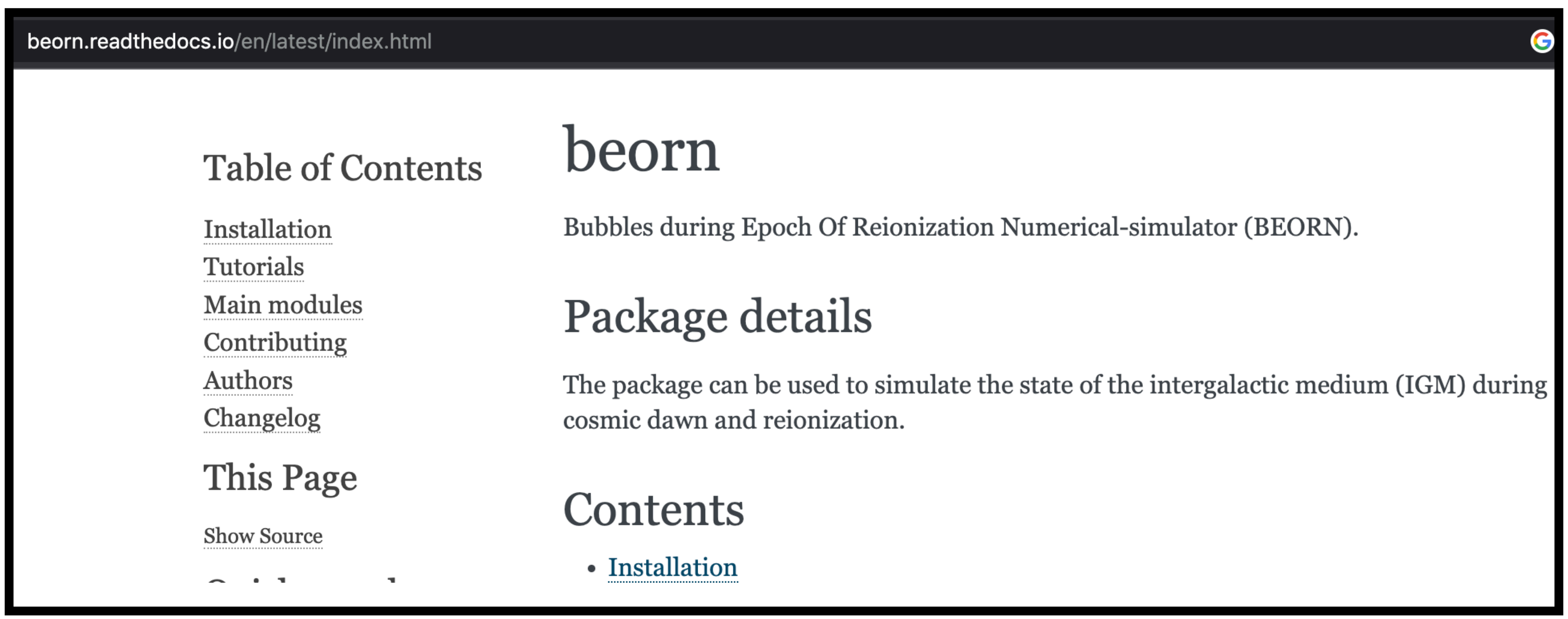


~200Myr **~1Gyr**

BEoRN

(**B**ubbles during the **E**poch **of** **R**eionisation **N**umerical simulator)

Publicly available, flexible, user-friendly


beorn.readthedocs.io/en/latest/index.html

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beorn

Bubbles during Epoch Of Reionization Numerical-simulator (BEORN).

Package details

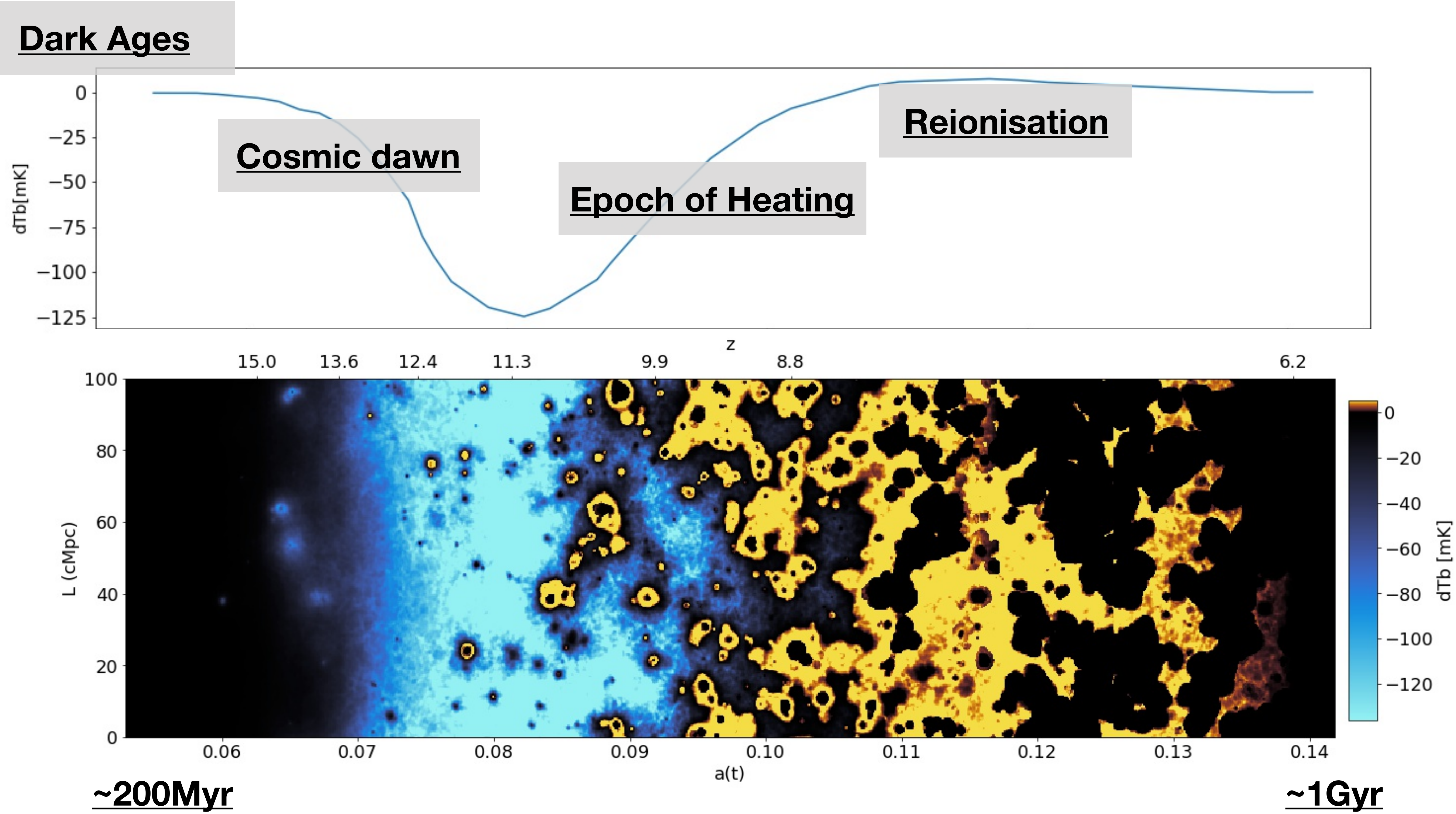
The package can be used to simulate the state of the intergalactic medium (IGM) during cosmic dawn and reionization.

Contents

- Installation

(in development)

Outcome of the code



To go further

- Need Fast gravity solver/halo finder algorithms

- More accurate galactic SED (pop.II/pop.III stars)

- Modelling of X-ray sources (Qasars/ HMXBs)

- Constraints on the ionising photon escape fraction.

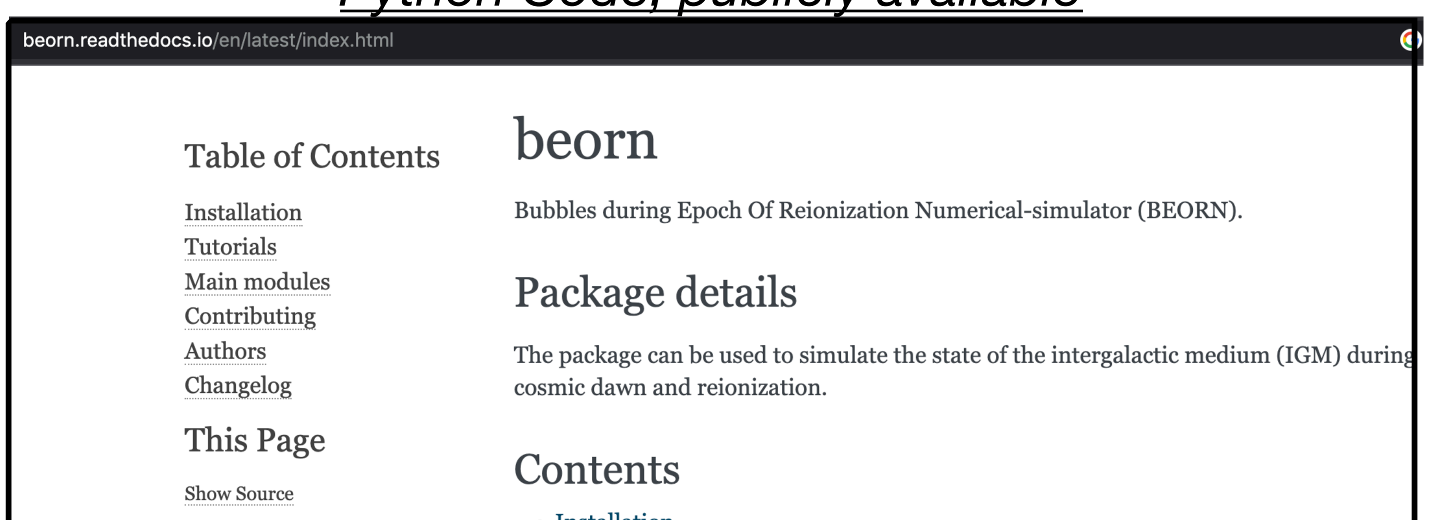
Modelling the 21cm signal : BEoRN

(**B**ubbles during the **E**poch **o**f **R**eionisation **N**umerical simulator)

Methodology :

1. Use N-body or LPT solver to evolve the non-linear matter field
2. Identify DM halos
3. Populate halos with galactic sources
4. Compute 1D profiles for temperature, ionisation and Ly-α flux
5. Paint the profiles on 3D grids.

Python Code, publicly available



(in development)