# A fast and accurate method to generate 3D 21cm maps from cosmic dawn to reionisation

T.Schaeffer, S.Giri, A.Schneider

## I . Introducing the code : BEORN (Bubbles during the EoR Numerical solver)

*Fully written in python, parallelised and very modular*

## II . Using emulators to speed-up

## III . Comparison with other work

# Introducing the code : BEORN

Goal : produce 21cm brightness 3D maps from cosmic dawn to the end of reionisation

Method : analogous to BEARS/GRIZZLY code —>paint ionisation and temperature profiles around galactic source, at the center of DM halos (*BEARS* : R.M.Thomas 2008 , *GRIZZLY* : R,Ghara 2017)

Ingredients:

DM density field + halo catalogs from N-body simulations (pkdgrav + rockstar)

Source model (f_star, f_esc, SED,  )

1D radiative transfer solver for Tk and xHII profiles

# The code step by step

**1. Use N body simulation (pkdgrav) for the density field and halo catalogs (rockstar)**

2 .Choose a source model (fst, fesc, sed..)

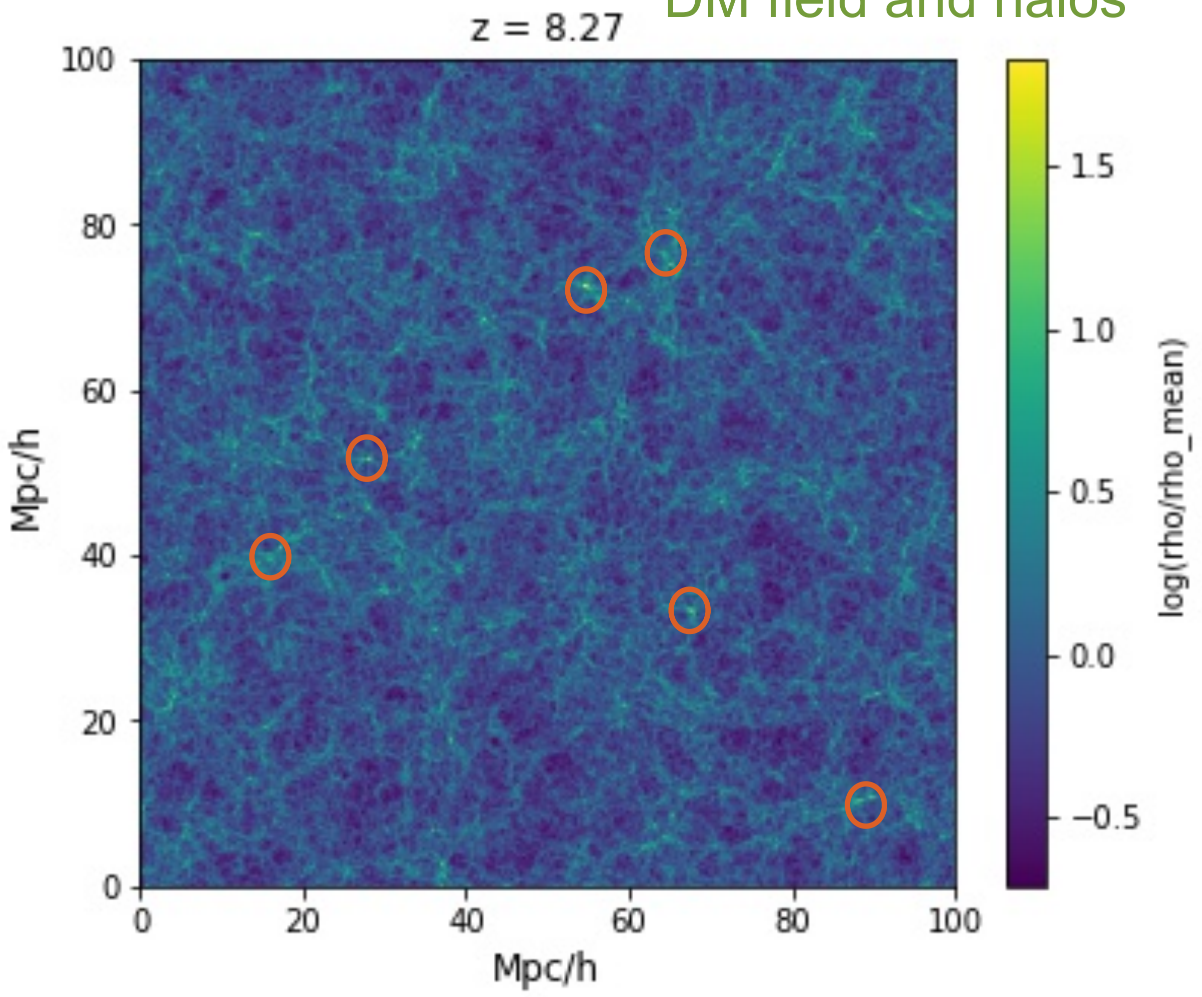
3 . Compute Tk and xHII profiles for a range of halo masses from z~25 to z~6, following halo growth

4 .Paint profiles around sources to get Tk and xHII maps

5 . Account for bubbles overlap

6. Compute dTb maps from Tk and xHII

DM field and halos



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## From halos to galaxies

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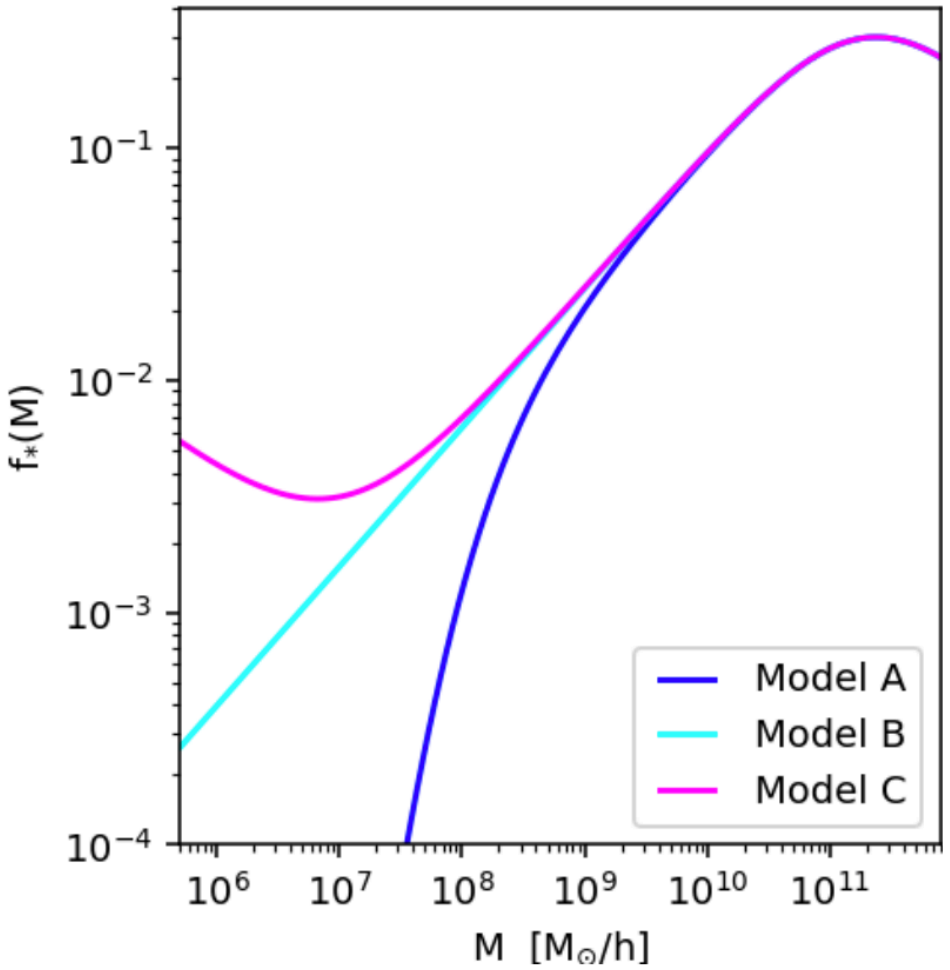

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## IGM ionisation state

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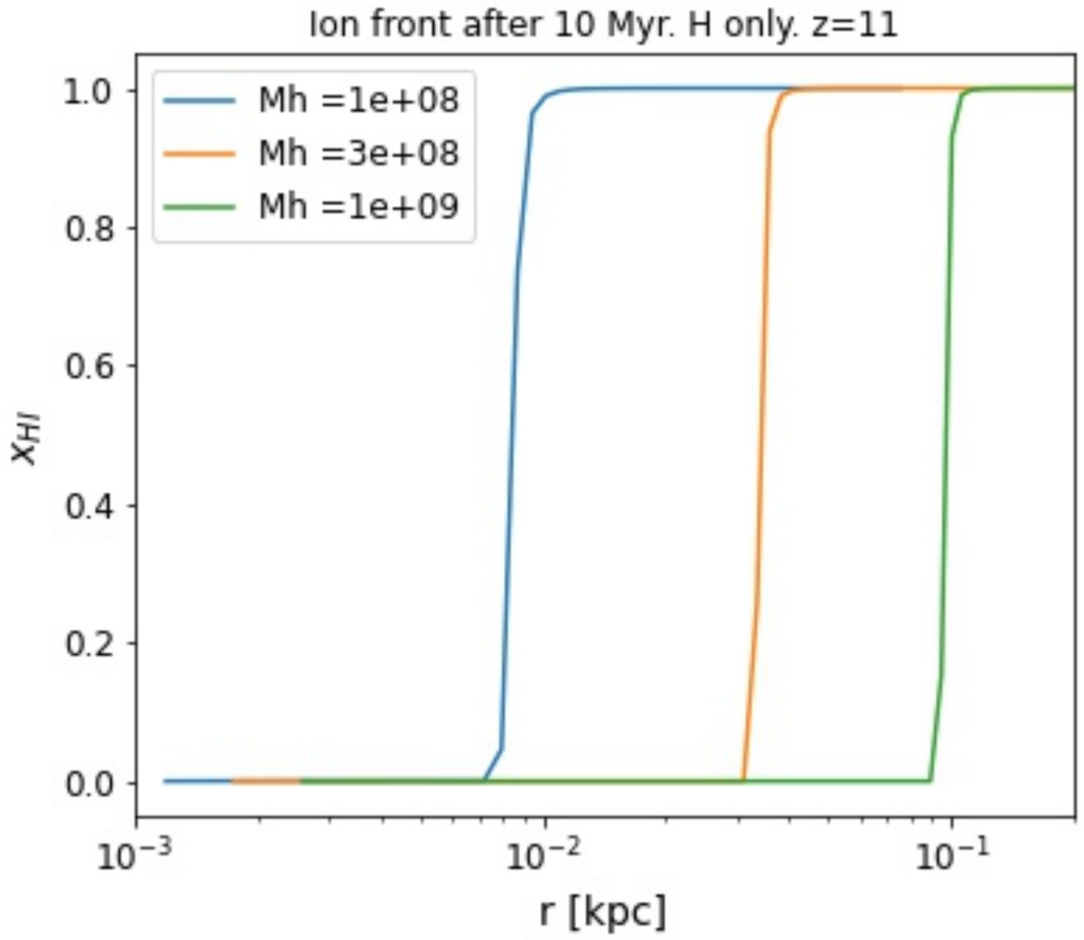

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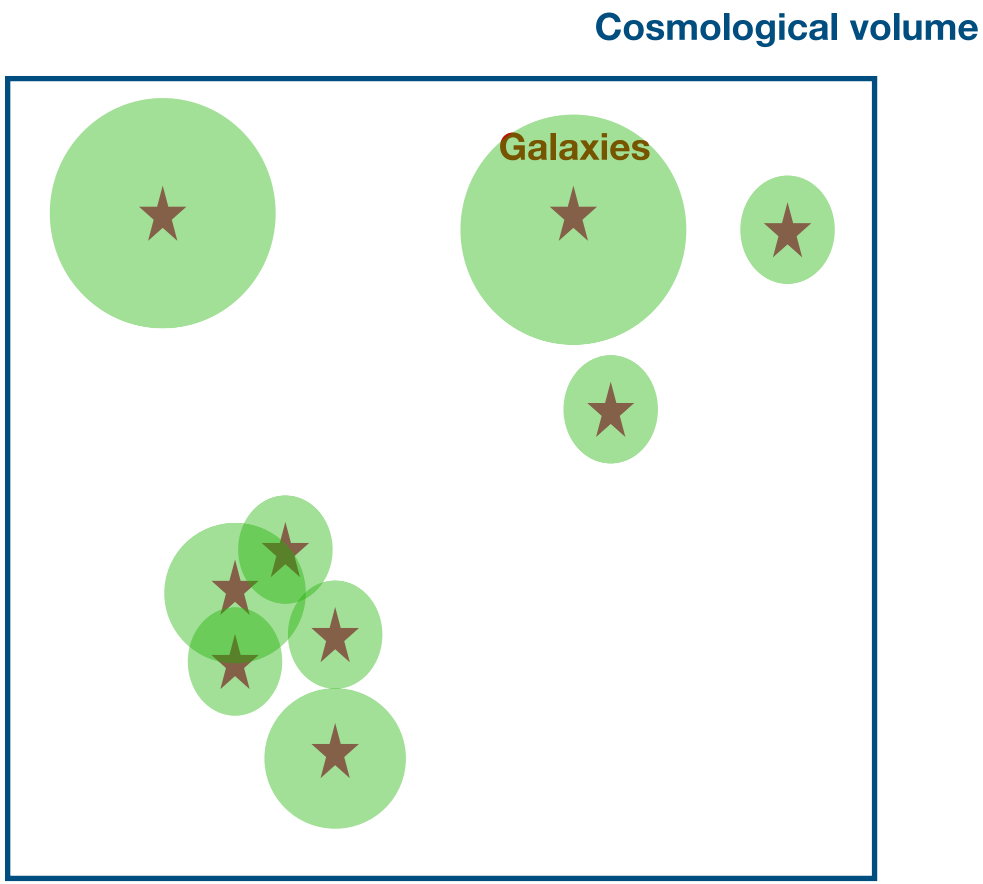

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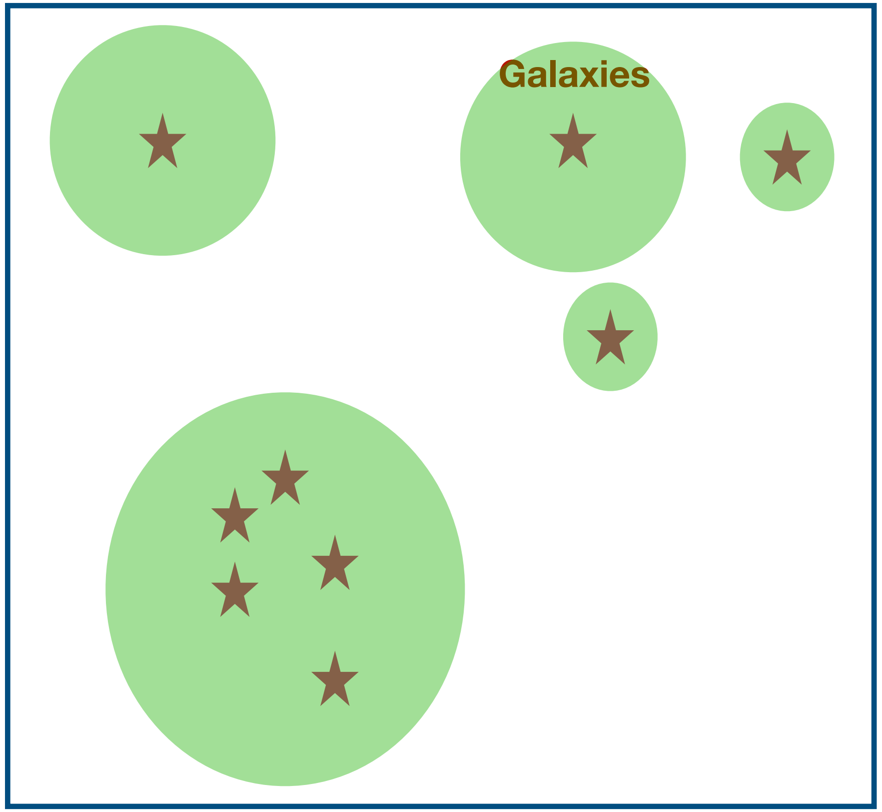
Cosmological volume



# The code step by step

21cm Brightness maps

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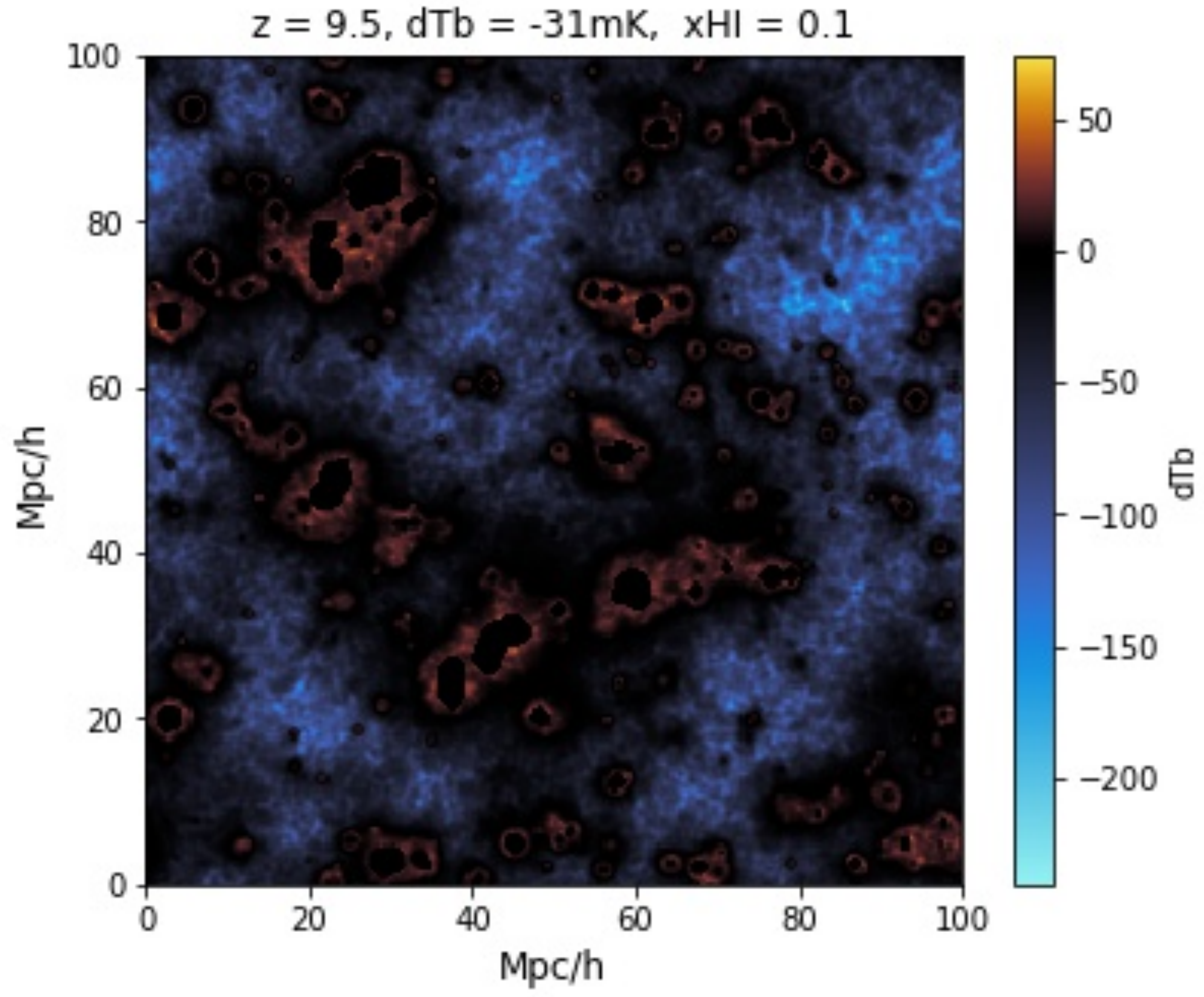
**6. Combine Tk and xHII to get dTb maps**



# Photon propagation

- Photons are produced by galactic sources : need a **source model**

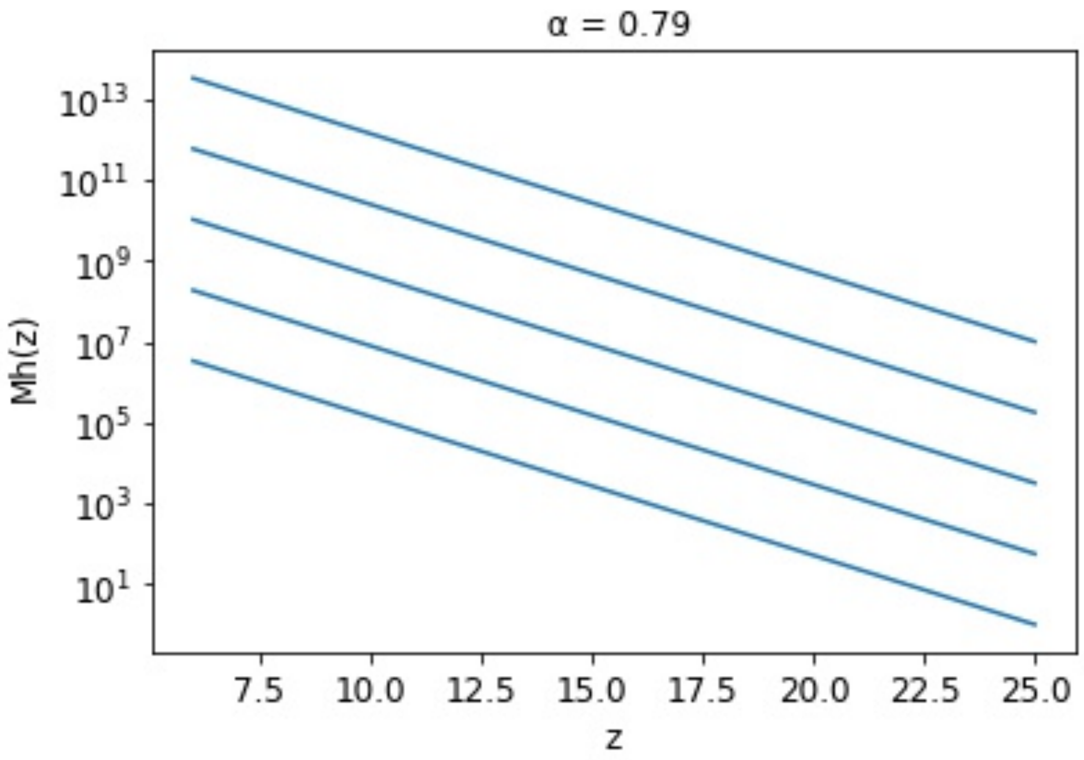
- They heat and ionise the IGM gas : need a model for the **IGM baryon density**

# Source modelling (from halos to photons)

- Use merger trees to fit the halo mass accretion rate:

$$M_{\rm ac}(M, z) = M \exp\left[\alpha(z_0 - z)\right]$$

*(A.Schneider 2020)*



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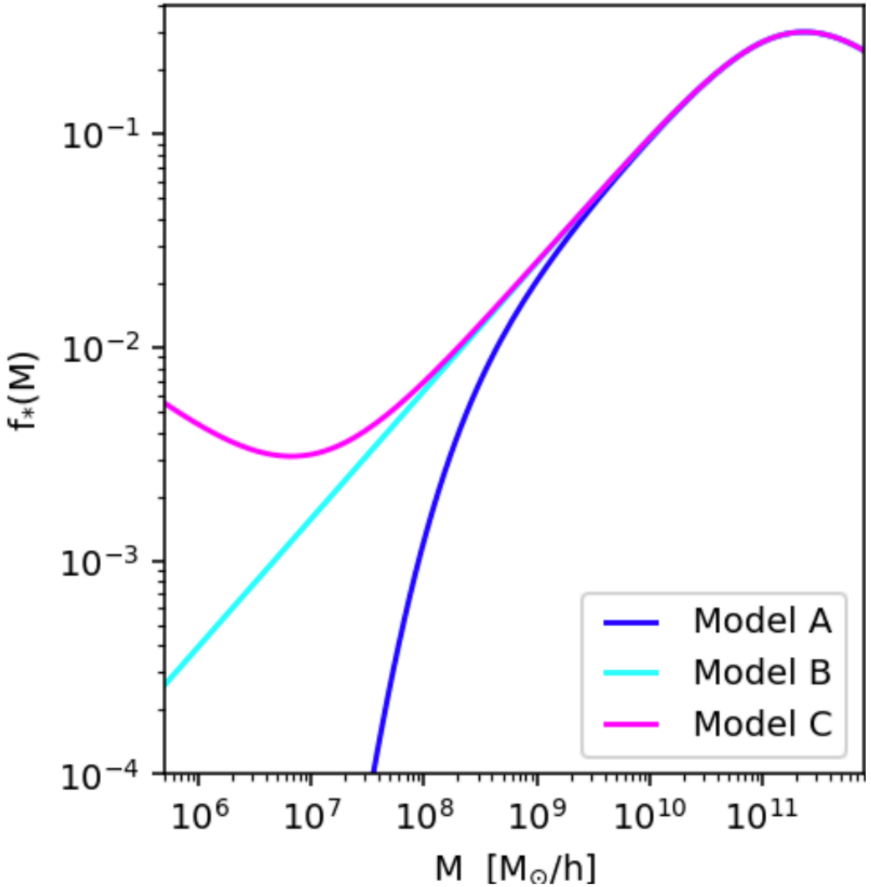
$$f_*(M) \equiv \dot{M}_*/\dot{M}_{\rm ac}$$



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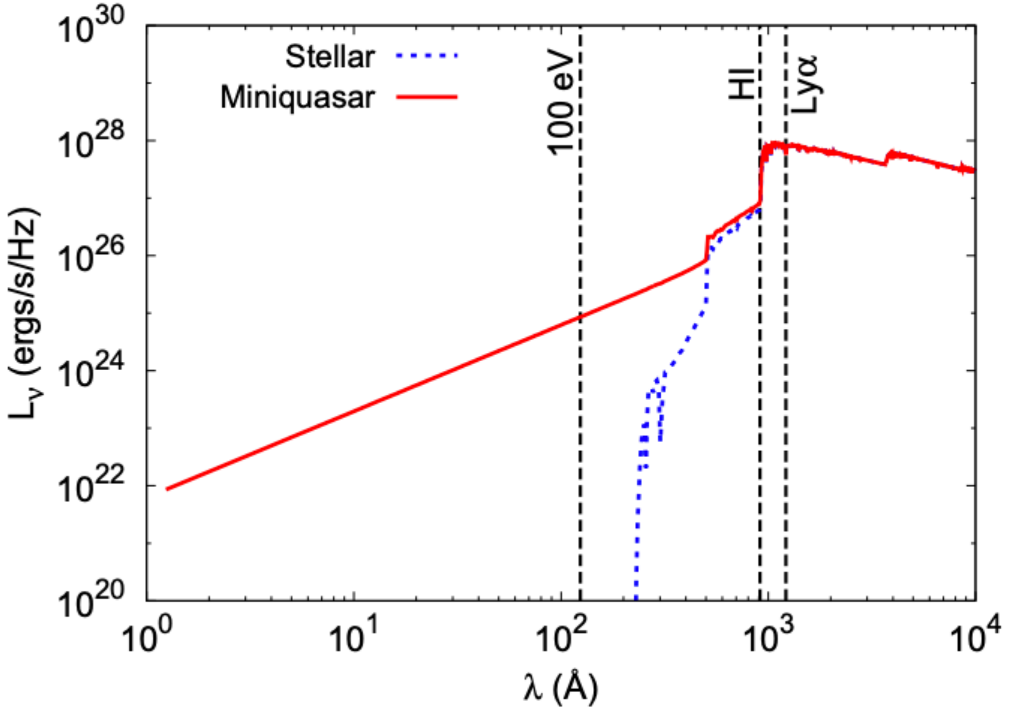
- Galactic spectra : flexible parametrisation in Ly-α, ion, Xray bands

*Ghara et al 2015*



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*Mapelli et al 2015*

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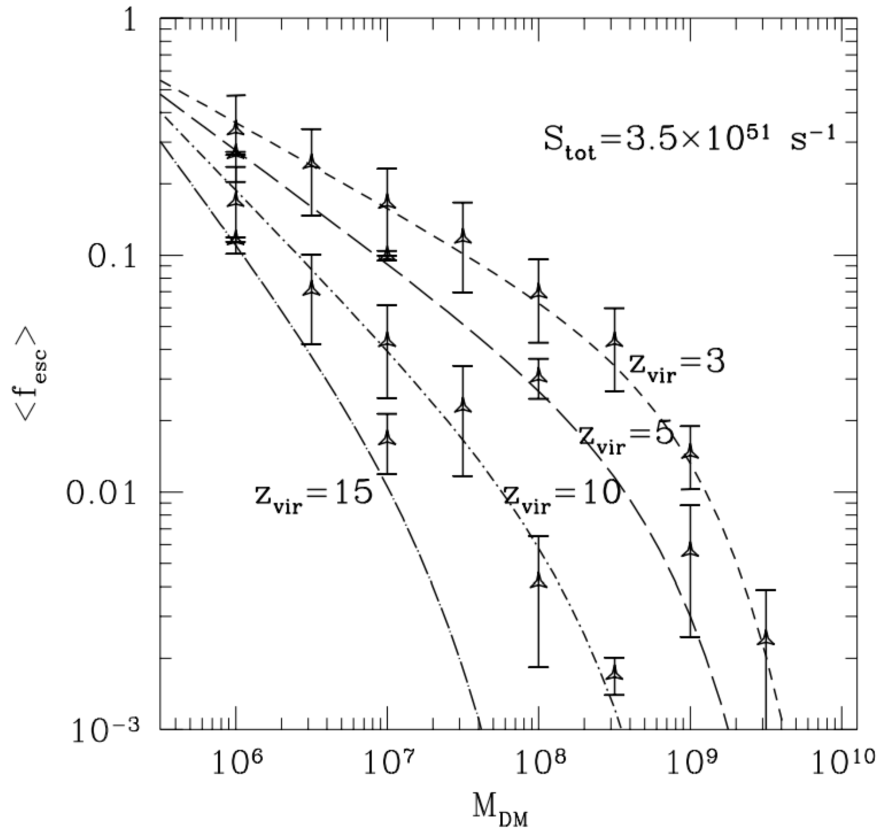
- Galactic spectra : flexible parametrisation in Ly-α, ion, Xray bands

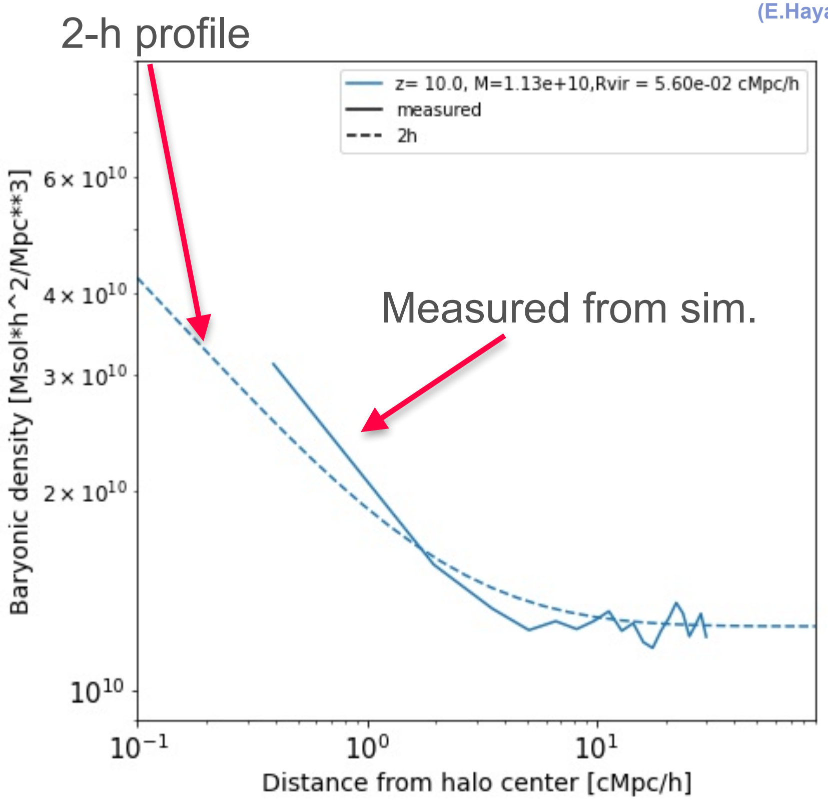
- Assume that a fraction f_esc of ionising photons reach the IGM (inside halos gas is fully ionised).



# Halo environment and mass binning

- Use an analytical fit (**2-halo profile**) for the non uniform baryon density in the IGM : $\rho_{2\mathrm{h}}(r) = [b(\nu)\xi_{\mathrm{lin}}(r) + 1]\,\Omega_m \rho_{\mathrm{crit}}$

(E.Hayashi & S.White 2008)



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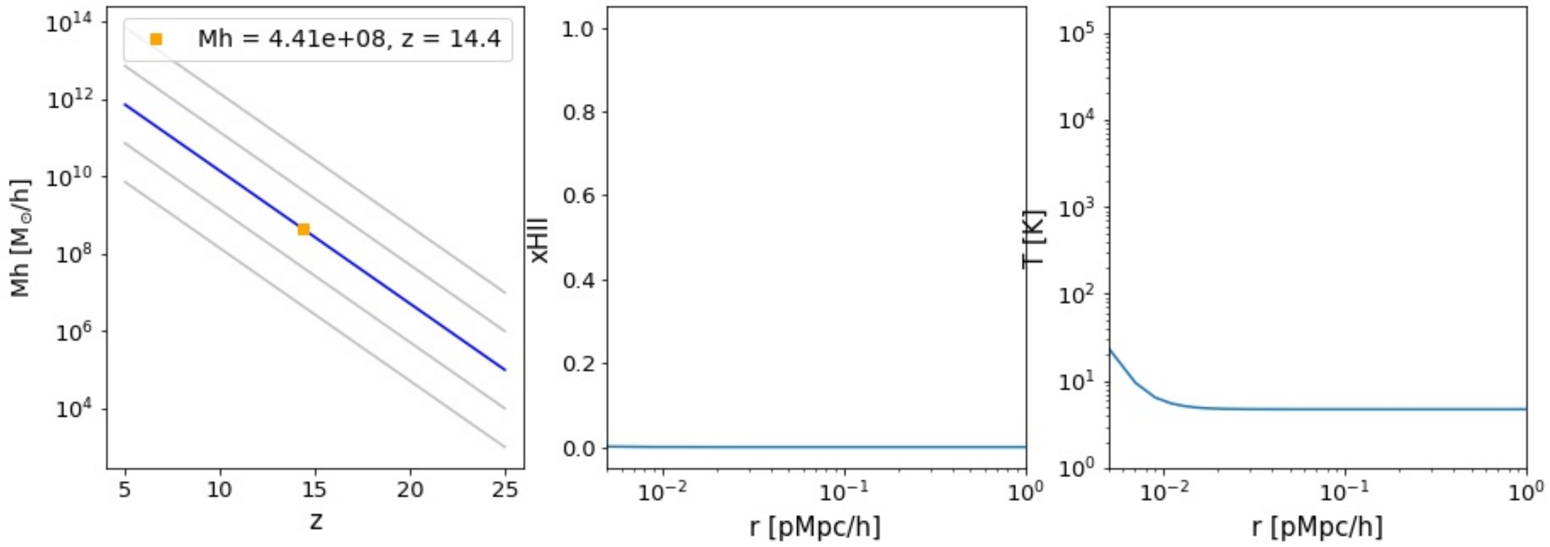

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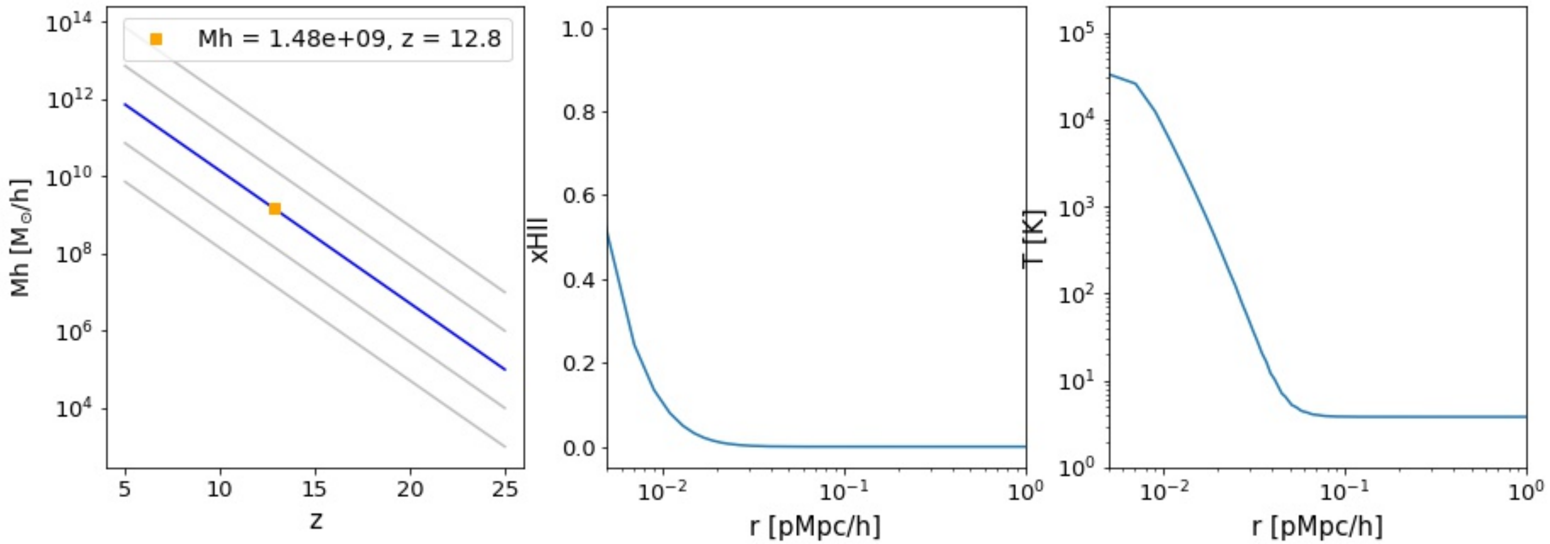

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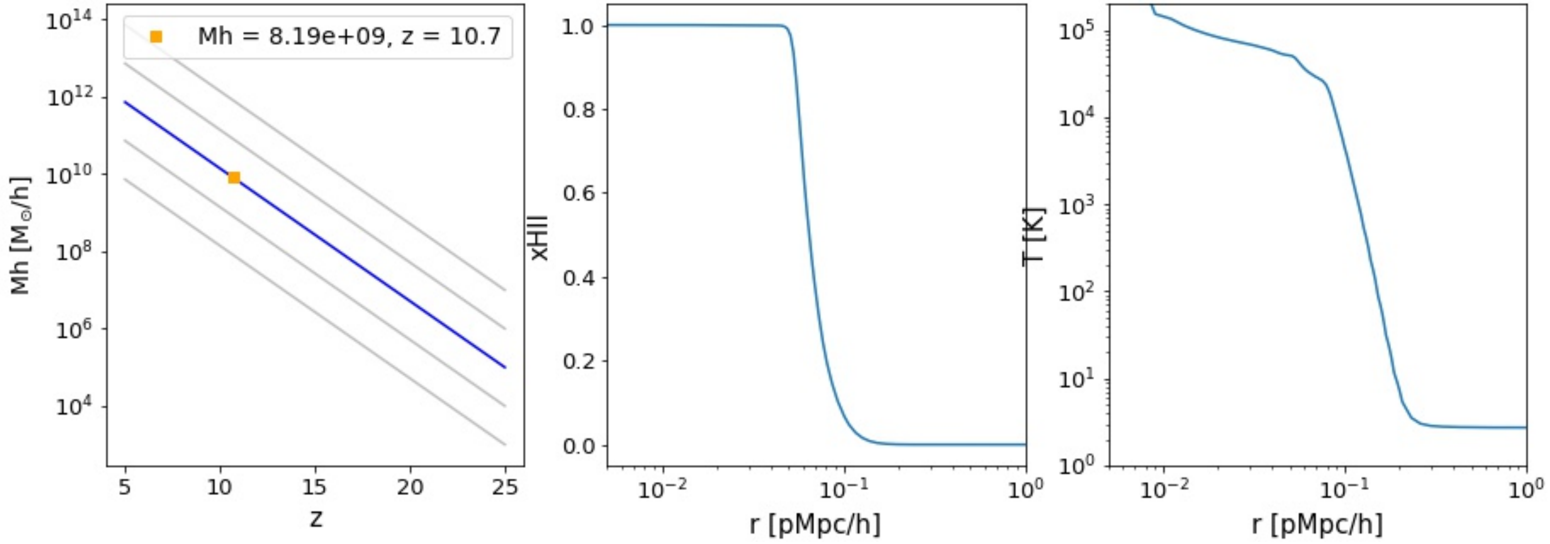


# Heat and ionisation equations

3 options :

- **Simple model : Strömgren sphere + simplified heat equation**
- Coupled heat/ionisation equation with Hydrogen only
- Full ion/heat equation including Helium

$$\frac{dV}{dt} = \frac{1}{\bar{n}_H^0} \frac{d\,N_\gamma}{dt} - \alpha_B \frac{C}{a^3} \bar{n}_H^0 V$$

*Barkana & Loeb 2001*

$$\frac{3}{2} \frac{dT_k(\mathbf{x}, z)}{dz} = \frac{T_k(\mathbf{x}, z)}{\rho(\mathbf{x}, z)} \frac{d\rho(\mathbf{x}, z)}{dz} - \frac{\Gamma_h(\mathbf{x}, z)}{k_B(1+z)H}$$

*Schneider & Giri 2021*

# Heat and ionisation equations

3 options :

- Simple model : Stromgren sphere + simplified heat equation

- **Coupled heat/ionisation equation with Hydrogen only**

- **Full ion/heat equation including Helium**

$$\frac{\mathrm{d}n_{\mathrm{H_{II}}}}{\mathrm{dt}} = \Gamma_{\mathrm{H_I}} n_{\mathrm{H_I}} - \alpha_{\mathrm{H_{II}}} n_{\mathrm{e}} n_{\mathrm{H_{II}}}$$

$$\Gamma_{\mathrm{He_I}} n_{\mathrm{He_I}} + \beta_{\mathrm{He_I}} n_{\mathrm{e}} n_{\mathrm{He_I}},$$

$$\frac{\mathrm{d}n_{\mathrm{He_{II}}}}{\mathrm{dt}} = -\beta_{\mathrm{He_{II}}} n_{\mathrm{e}} n_{\mathrm{He_{II}}} - \alpha_{\mathrm{He_{II}}} n_{\mathrm{e}} n_{\mathrm{He_{II}}} + \alpha_{\mathrm{He_{III}}} n_{\mathrm{e}} n_{\mathrm{He_{III}}} - \xi_{\mathrm{He_{II}}} \mathrm{n_e} n_{\mathrm{He_{II}}},$$

$$\frac{\mathrm{d}n_{\mathrm{He_{III}}}}{\mathrm{dt}} = \Gamma_{\mathrm{He_{II}}} n_{\mathrm{He_{II}}} + \beta_{\mathrm{HeII}} n_{\mathrm{e}} n_{\mathrm{He_{II}}} - \alpha_{\mathrm{He_{III}}} n_{\mathrm{e}} n_{\mathrm{He_{III}}},$$

$$\frac{3}{2}\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{k\mathrm{T_e} n_{\mathrm{B}}}{\mu}\right) = f_{\mathrm{Heat}} \sum_{i=\mathrm{H\,I,HeI,He\,II}} n(i) \int \sigma_{\mathrm{i}}(E - E_{\mathrm{i}}) N(E;r;t) \frac{\mathrm{d}E}{E} + \frac{\sigma_{\mathrm{s}} n_{\mathrm{e}}}{m_{\mathrm{e}} c^2} \int N(E;r;t)(E - 4k_{\mathrm{B}}\mathrm{T})\,\mathrm{d}E - \sum_{i=\mathrm{H\,I,He\,I,He\,II}} \zeta_{\mathrm{i}} n_{\mathrm{e}} n(i)$$

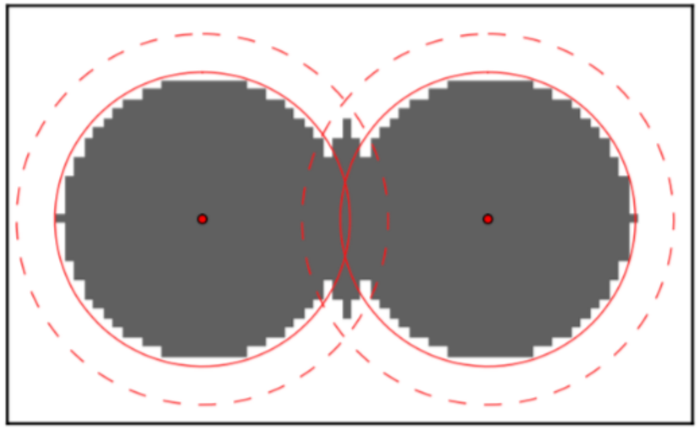
…… (collision terms + cooling)

# The time-consuming step : dealing with bubbles overlaps

-Identify connected regions with xHII>0

-Identify 1st, 2nd, 3rd layer of closest pixels around the surface

-Spread the excess ionisation fraction equally among the closest pixels



*Choudhury et al 2018*

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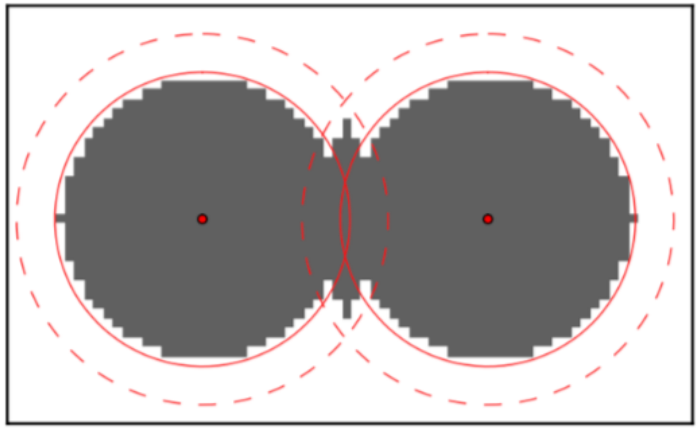

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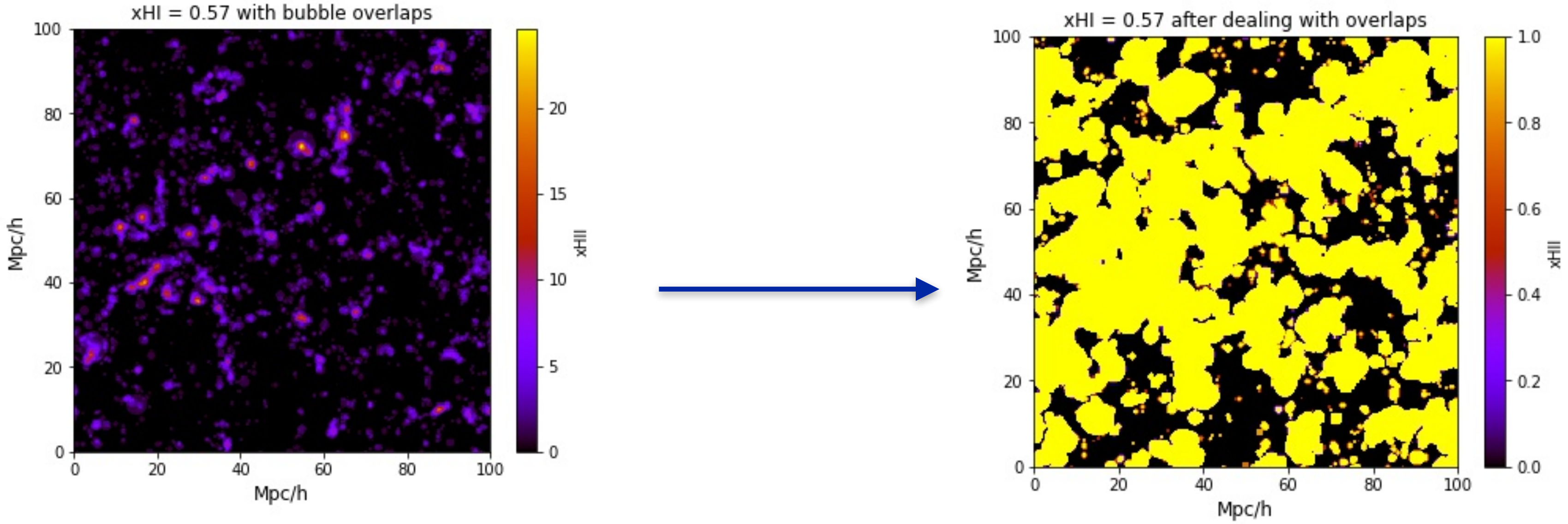
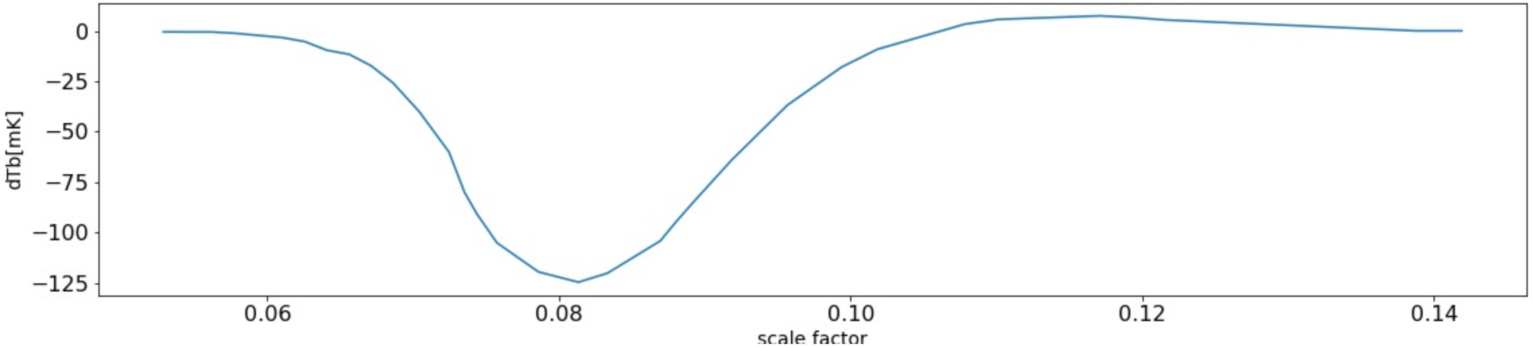
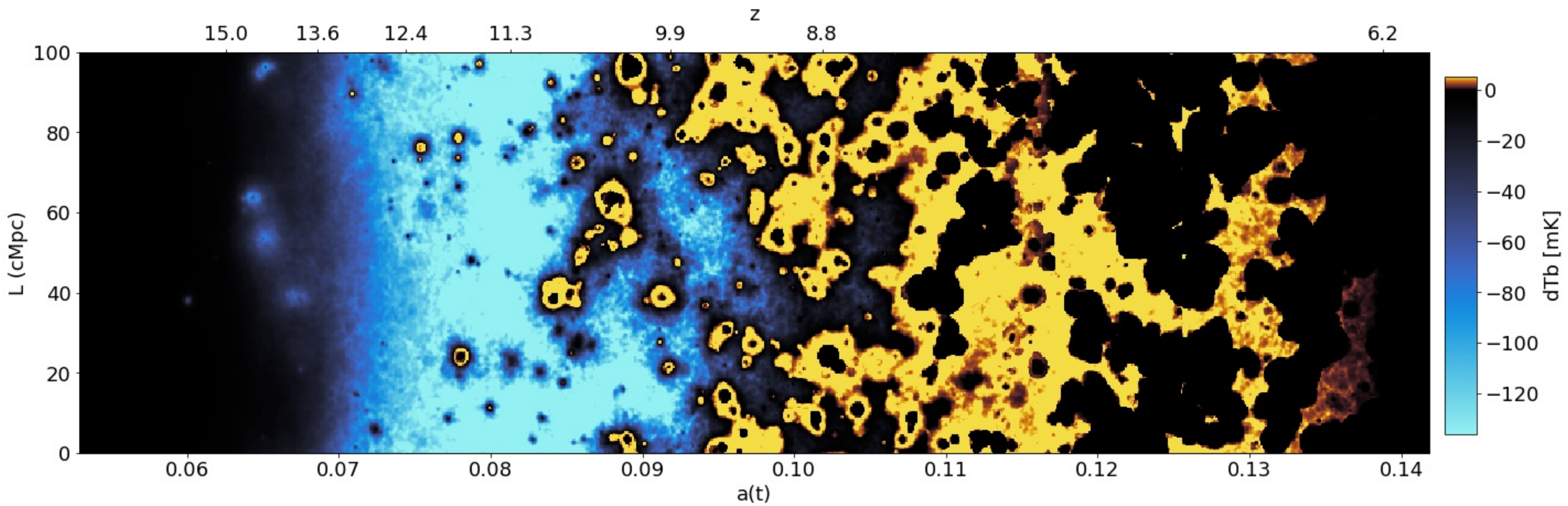


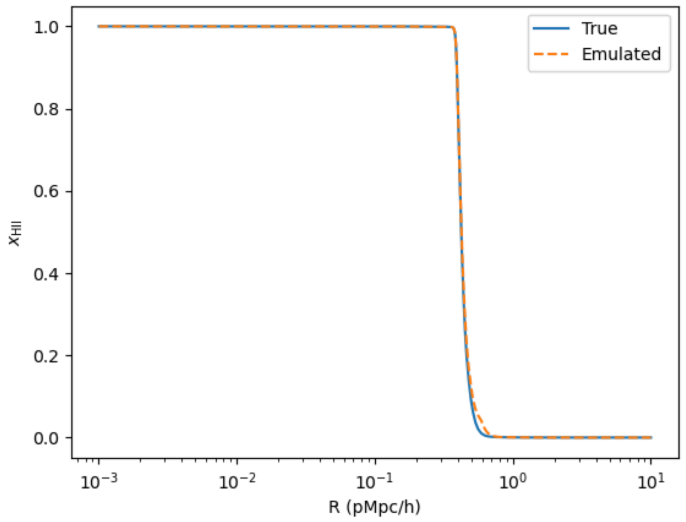
# Outcomes : 3D maps and light cone

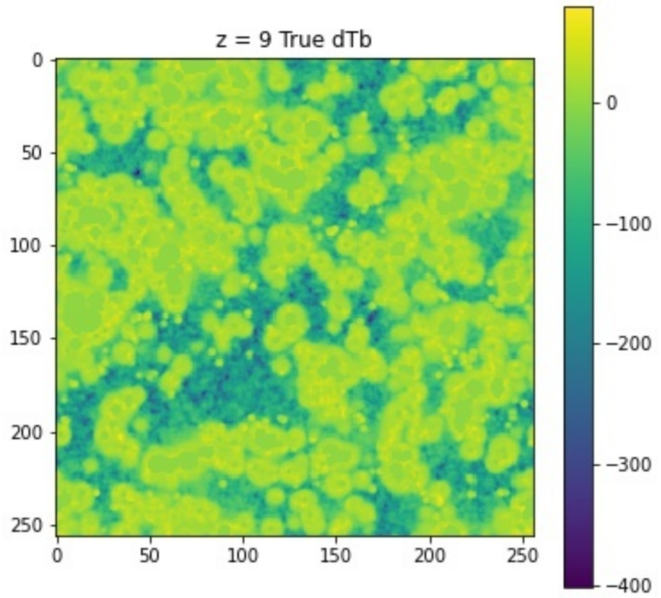


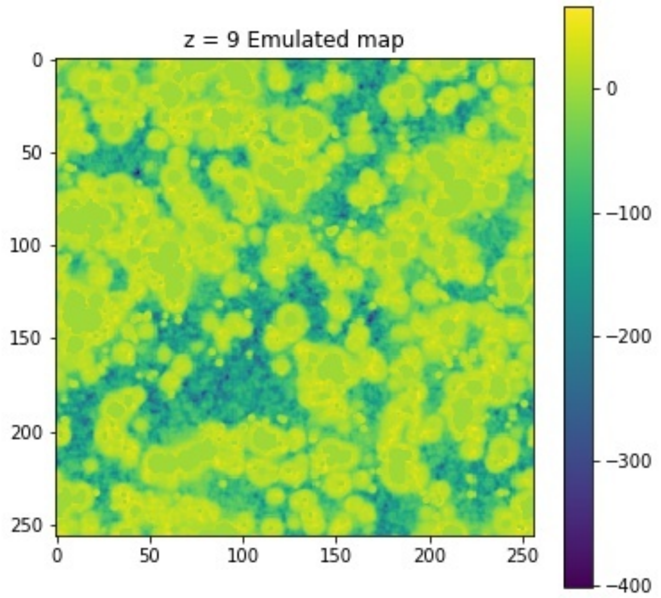



# II. Speeding up the procedure for parameter inference

- Emulate the profile calculation : compute profiles for a set of values of the source parameters, using Latin Hypercube sampling, and use an emulator to interpolate



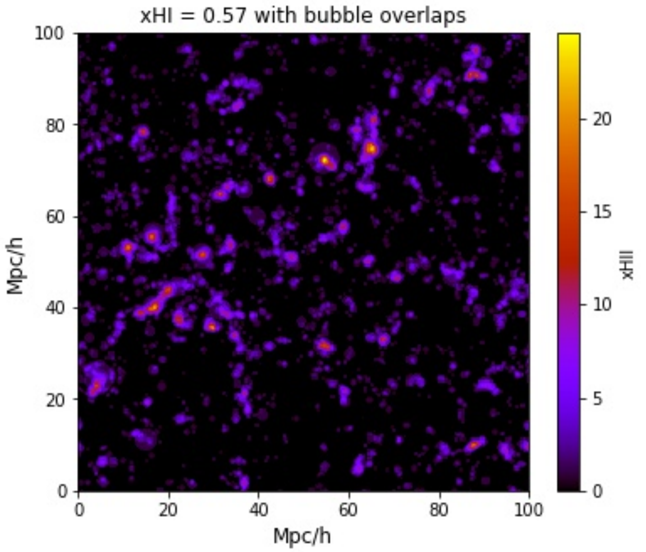



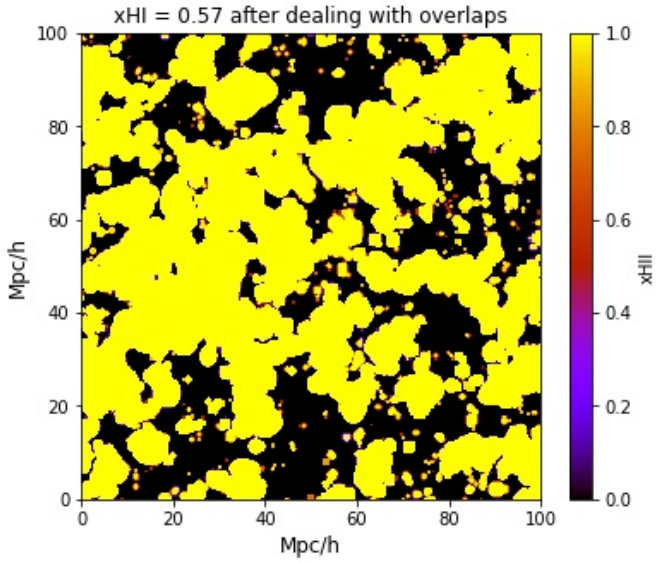
# II. Speeding up the procedure for parameter inference

- Done : Emulate the profile calculation : compute profiles for a set of values of the source parameters, using Latin Hypercube sampling, and use an emulator to interpolate

- Next step : Emulate the procedure to account for bubble overlap



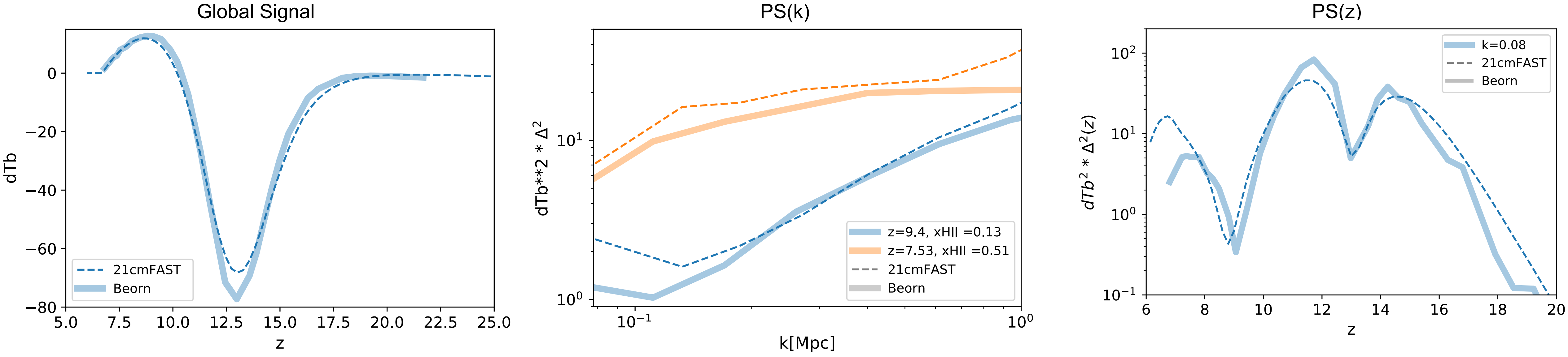

Order ~sec with the emulator (instead of ~5min for a 256**3 grid)



# III. Comparison with other work

Comparing with **21cmFAST**, for a model with *flat fstar*, with a *cutoff* at *Mt = 10**9 Msol*

Box size 100Mpc, 1024**3 particles.



# Questions ?