Interpretation framework for SKA observations

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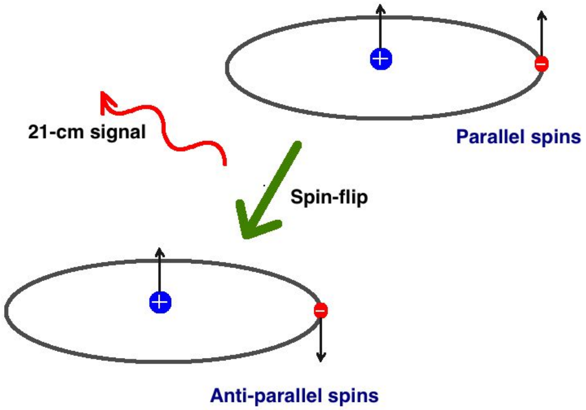
21-cm signal to be observed by SKA

$$\delta T_{\mathrm{b}} \propto x_{\mathrm{HI}}(1+\delta)\left(1-\frac{T_{\mathrm{CMB}}}{T_{\mathrm{S}}}\right)$$

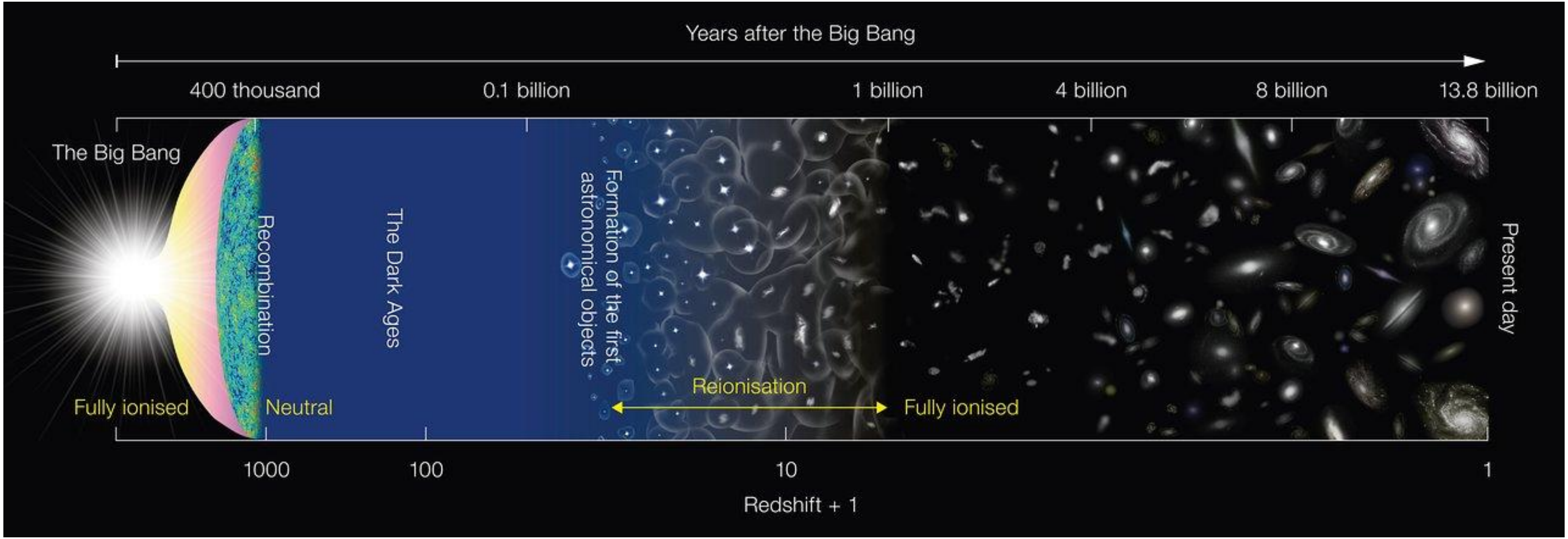
Neutral hydrogen

Baryon density

Spin temperature



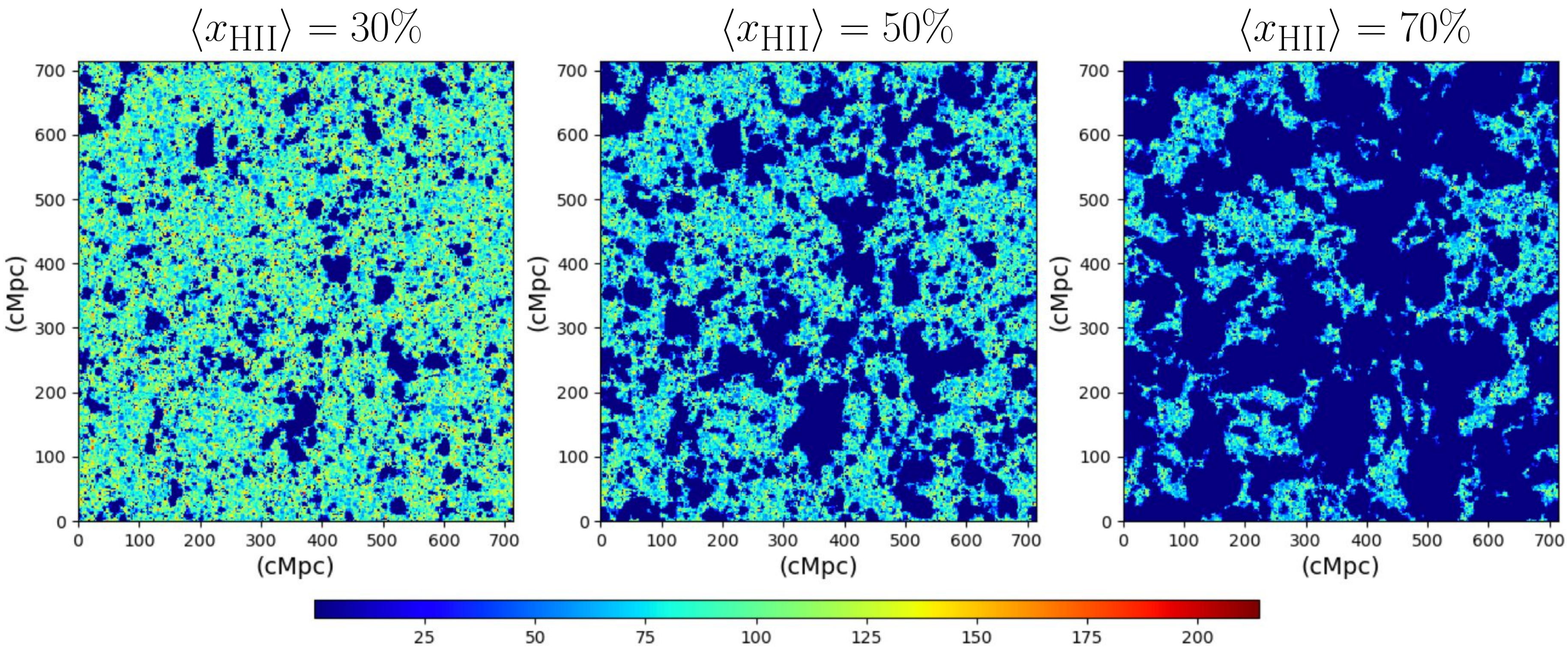
Different epochs of the Universe



~100 MHz ~200 MHz

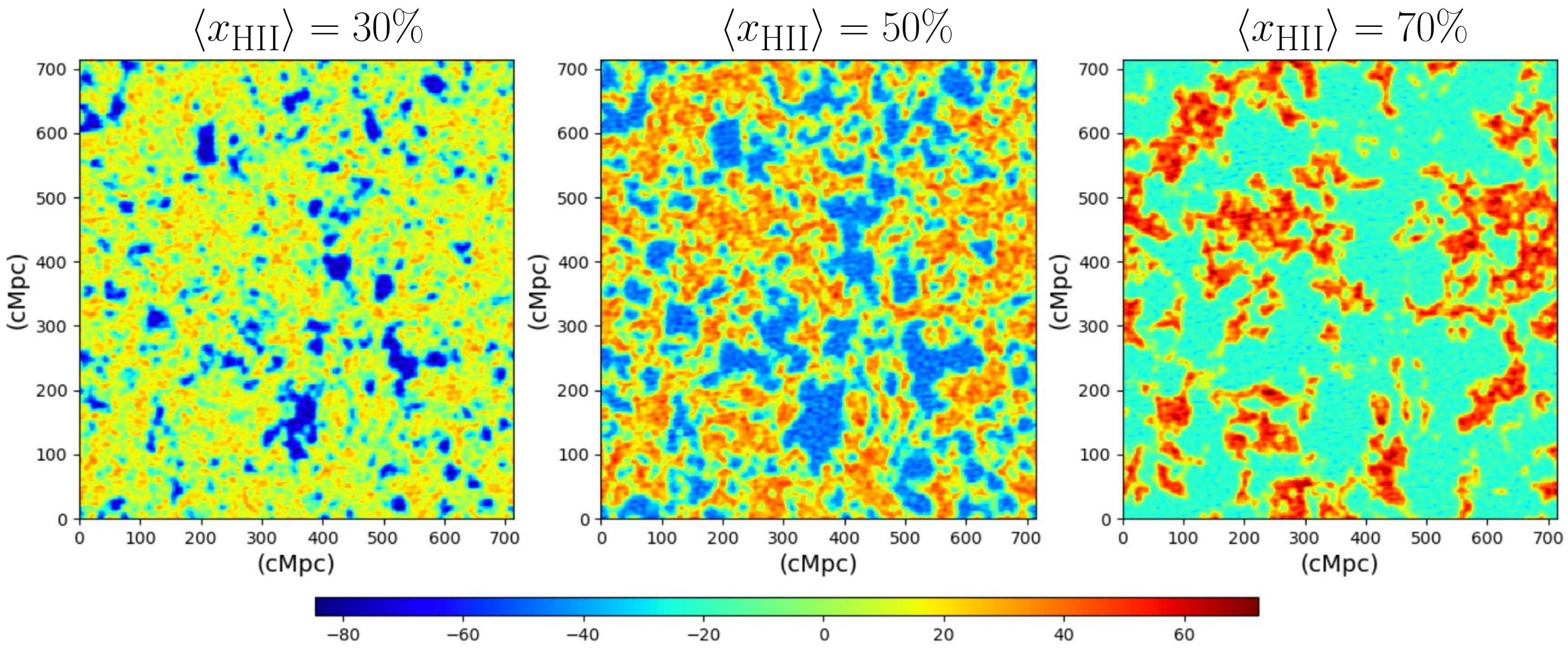
Credit: NAOJ

Reionization seen with the 21-cm signal



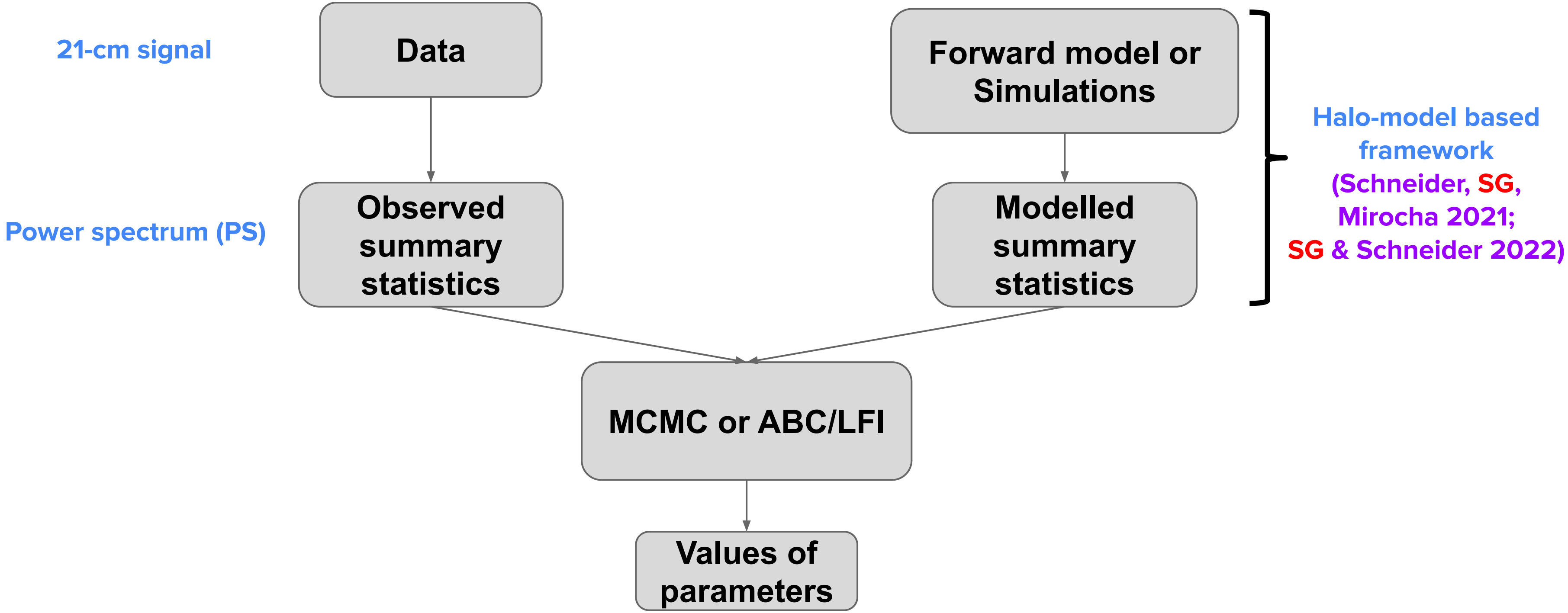
Radiative transfer simulation (e.g. SG+2019b; SG & Mellema 2021)

Simulated SKA images

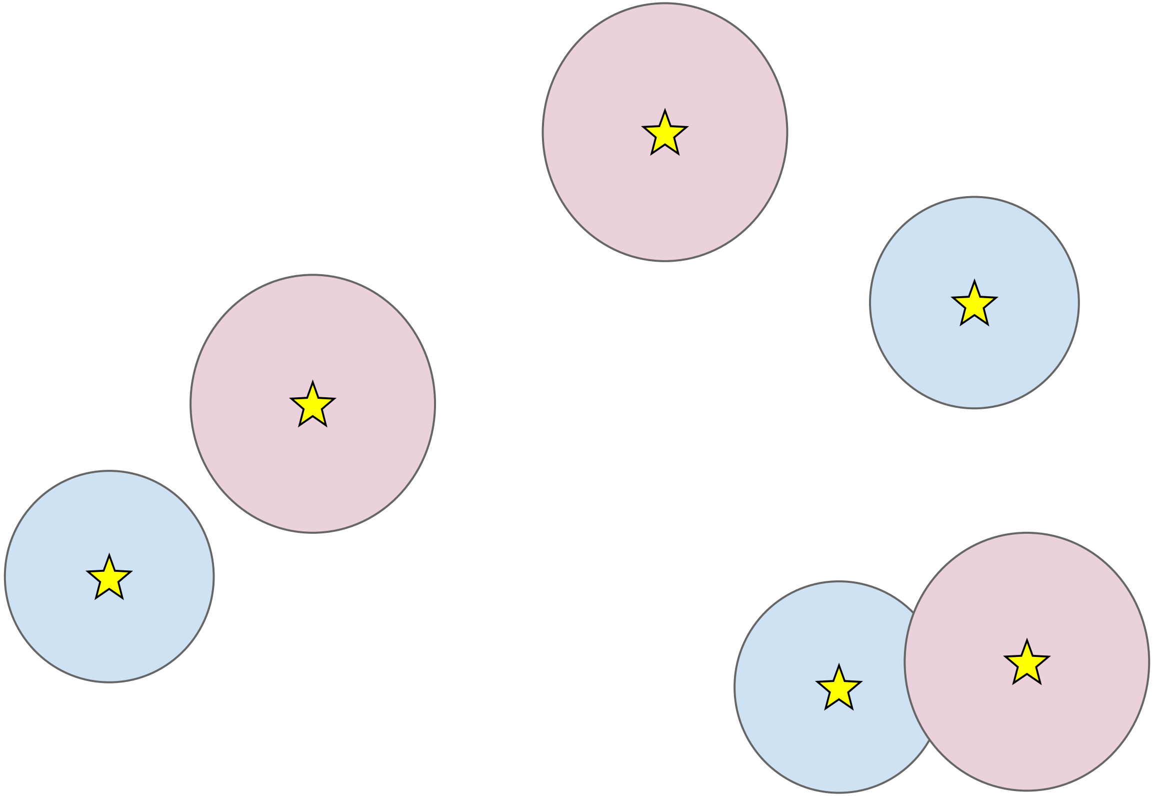


Instrumental effects using Tools21cm (e.g. SG+2018b; SG+2020)

Inference from 21-cm observations

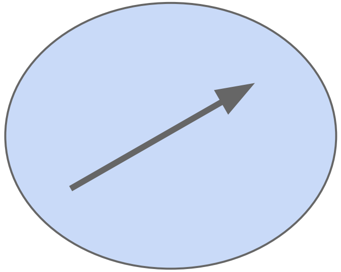


Halo model

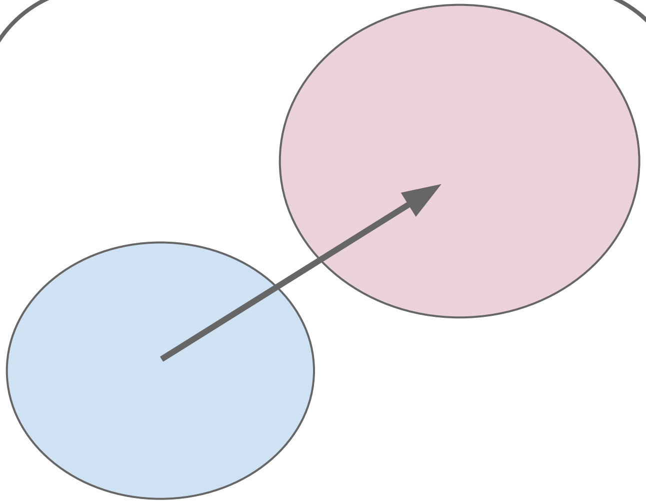


Seljak (2000)
Cooray & Sheth (2002)
...

Halo model: power spectrum



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



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

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

Ingredients for the halo model

Linear power spectrum

Halo mass function

Mass accretion

Halo bias

Stellar to halo mass relation

Flux profiles

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

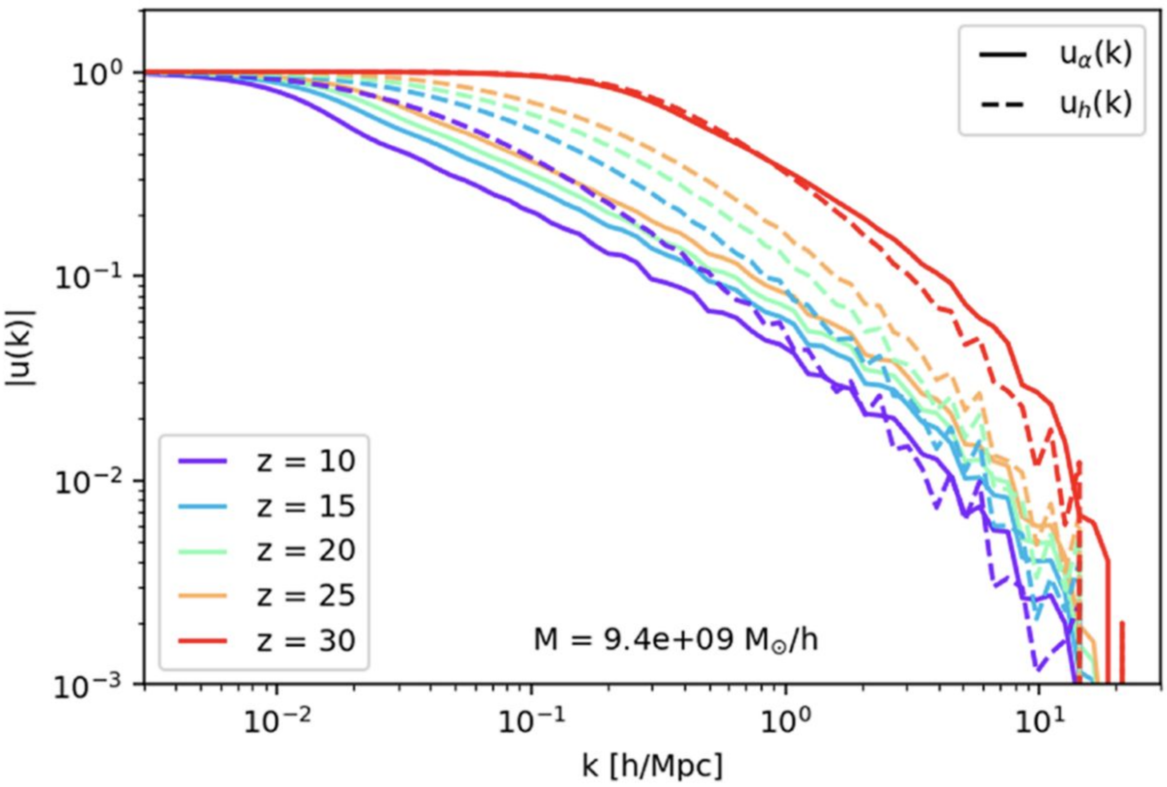
$$P^{2\,\mathrm{h}}_{XY}(k,z) = \frac{\beta_X}{(\bar{\rho} f_{\mathrm{coll}})}\int dM \frac{dn}{dM}\tilde{f}_* M |u_X| b_X$$

$$\times \frac{\beta_Y}{(\bar{\rho} f_{\mathrm{coll}})}\int dM \frac{dn}{dM}\tilde{f}_* M |u_Y| b_Y \times P_{\mathrm{lin}},$$

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

$$\tilde{f}_\star(M) = \frac{1}{M_{\mathrm{ac}}}\int f_\star(M)\dot{M}_{\mathrm{ac}}dt$$

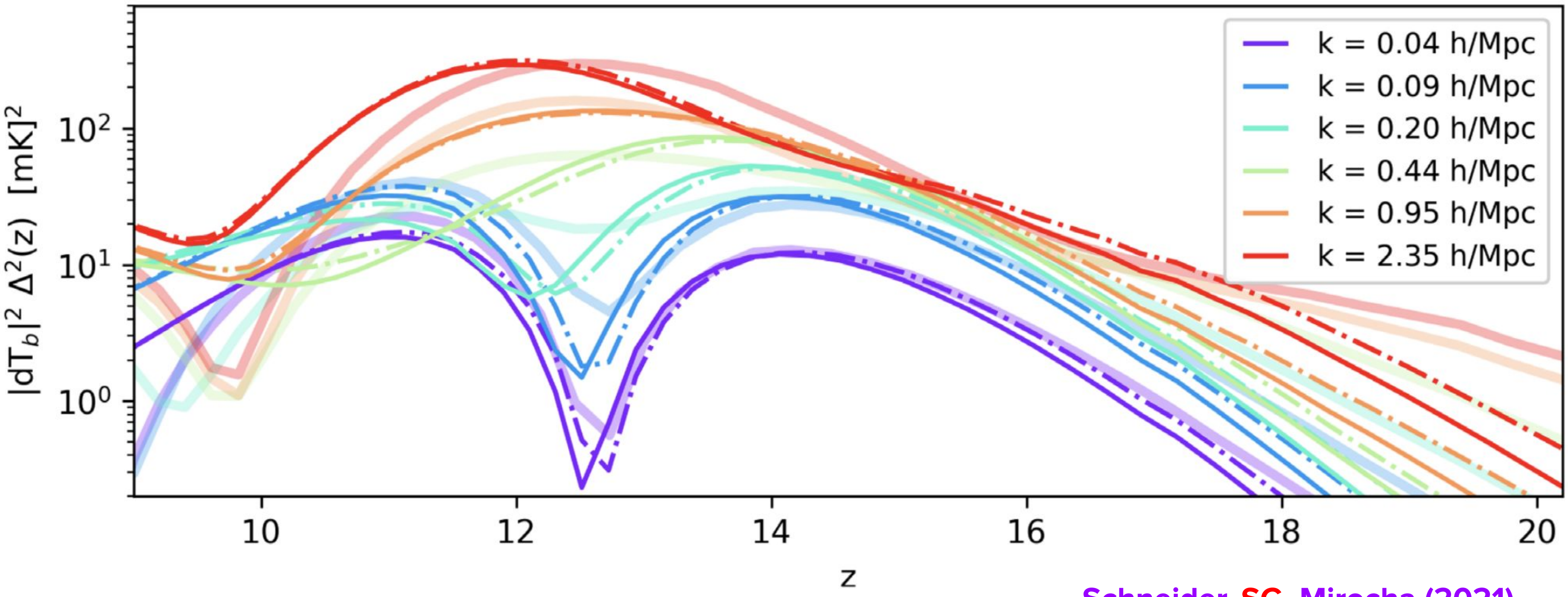
Flux profiles



$$P_{21} = P_{\alpha\alpha} + P_{hh} + P_{pp} + P_{bb} + 2(P_{\alpha h} + P_{\alpha p} + P_{\alpha b} + P_{hp} + P_{hb} + P_{pb}) + \frac{2}{3}(P_{\alpha m} + P_{hm} + P_{pm} + P_{bm}) + \frac{1}{5}P_{mm}.$$

Schneider, SG, Mirocha (2021)

Validity of the approach



Schneider, SG, Mirocha (2021)

Constraining mixed dark matter models with SKA

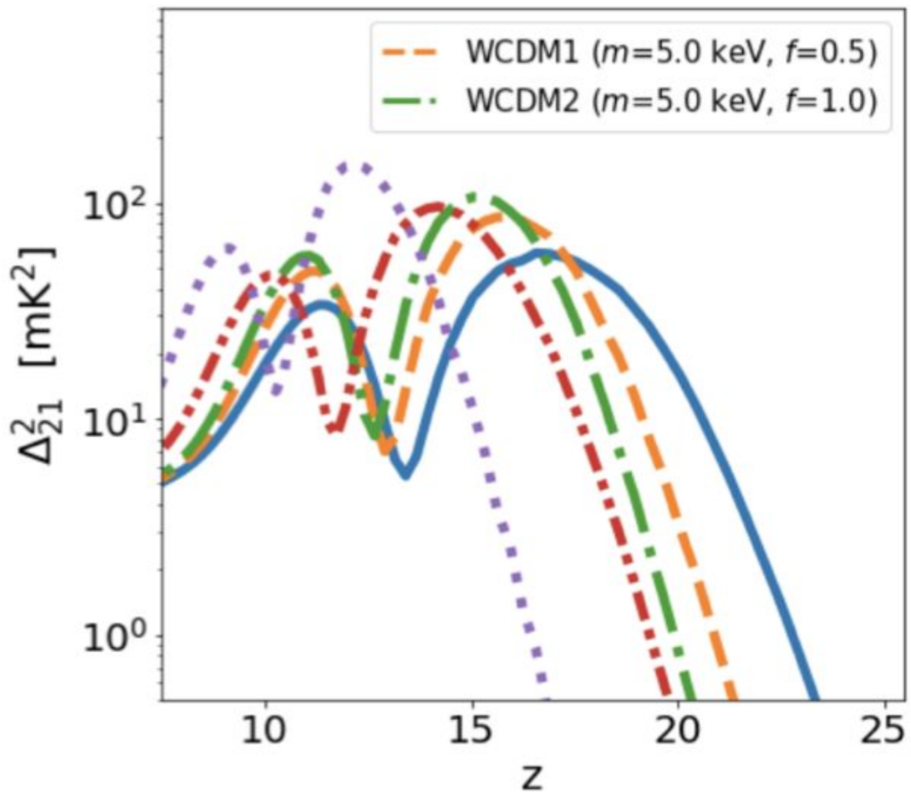
Contains a mixtures of two components

- Cold DM
- Non-cold: WDM/FDM

$$f_{n\mathrm{DM}} = \frac{\Omega_{n\mathrm{DM}}}{\Omega_{n\mathrm{DM}} + \Omega_{n\mathrm{DM}}}$$

f_{nDM} < 20% (Boyarsky+2009)

Evolution of power spectra

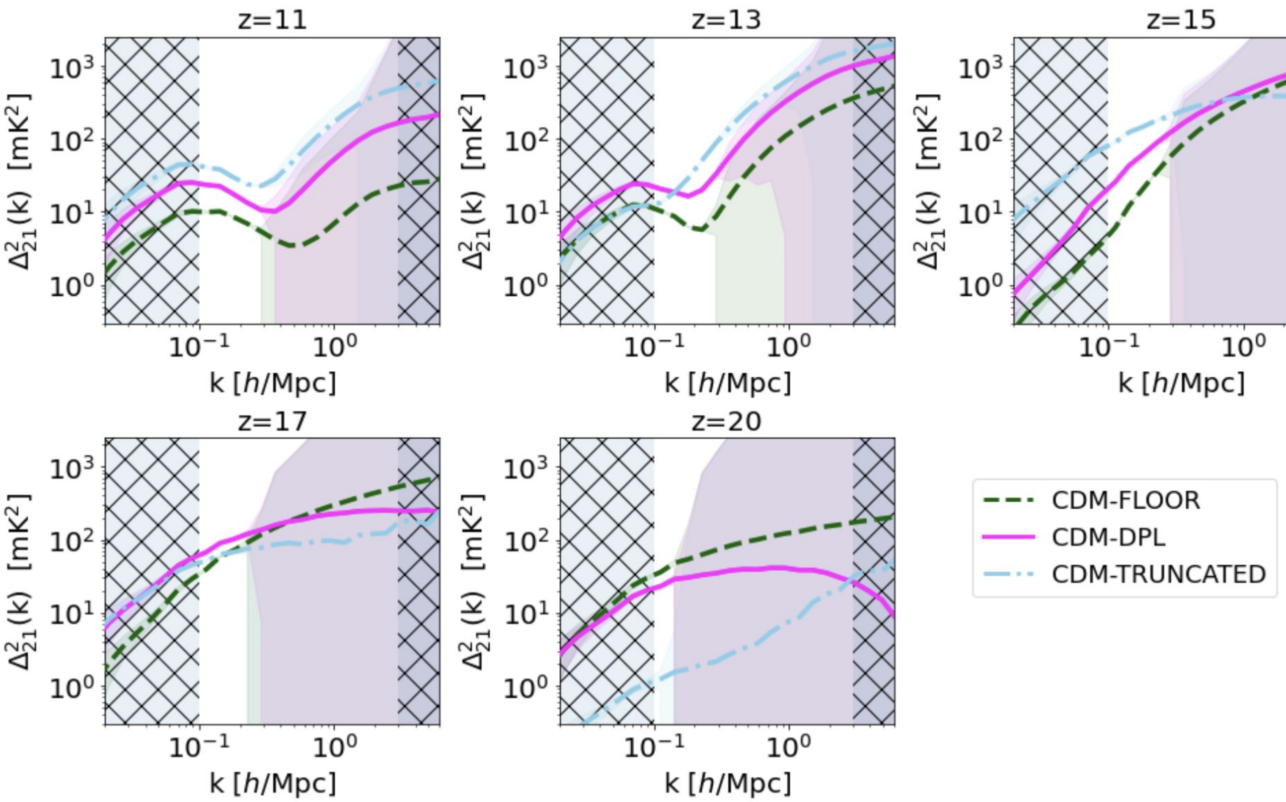


WCDM1 (m=5.0 keV, f=0.5)
WCDM2 (m=5.0 keV, f=1.0)
WCDM3 (m=0.1 keV, f=0.05)
WCDM3 (m=0.1 keV, f=0.10)

k∼0.1 h/Mpc

(SG & Schneider 2022)

Mock observation at cosmic dawn

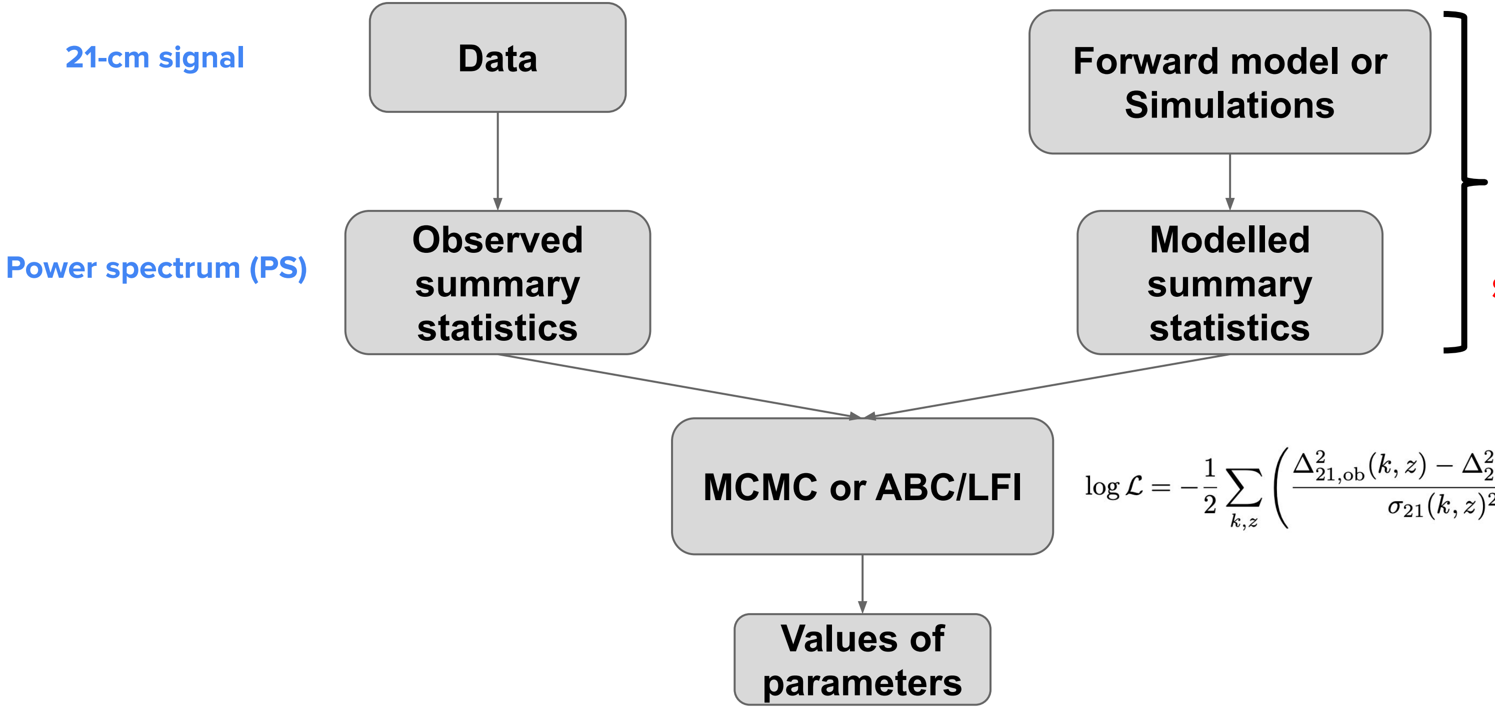


1000 hour observations

Instrumental effects are calculated using Tools21cm (SG+2020)

(SG & Schneider 2022)

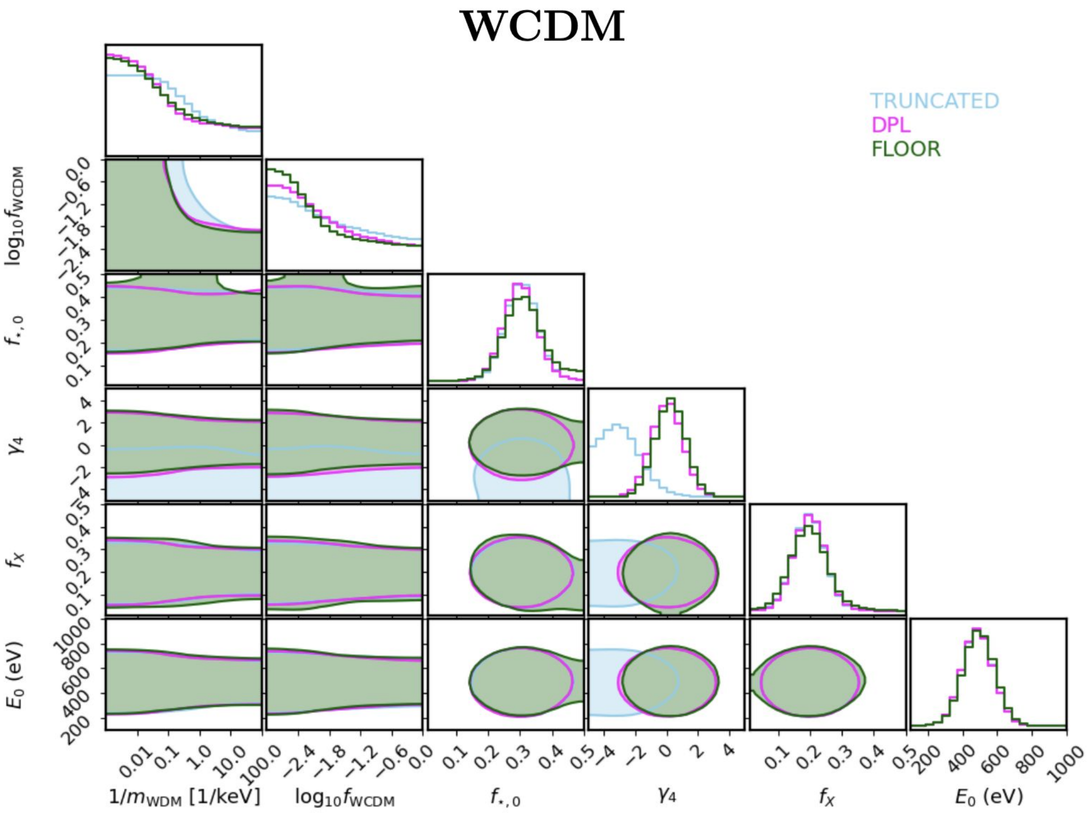
Inference from 21-cm observations



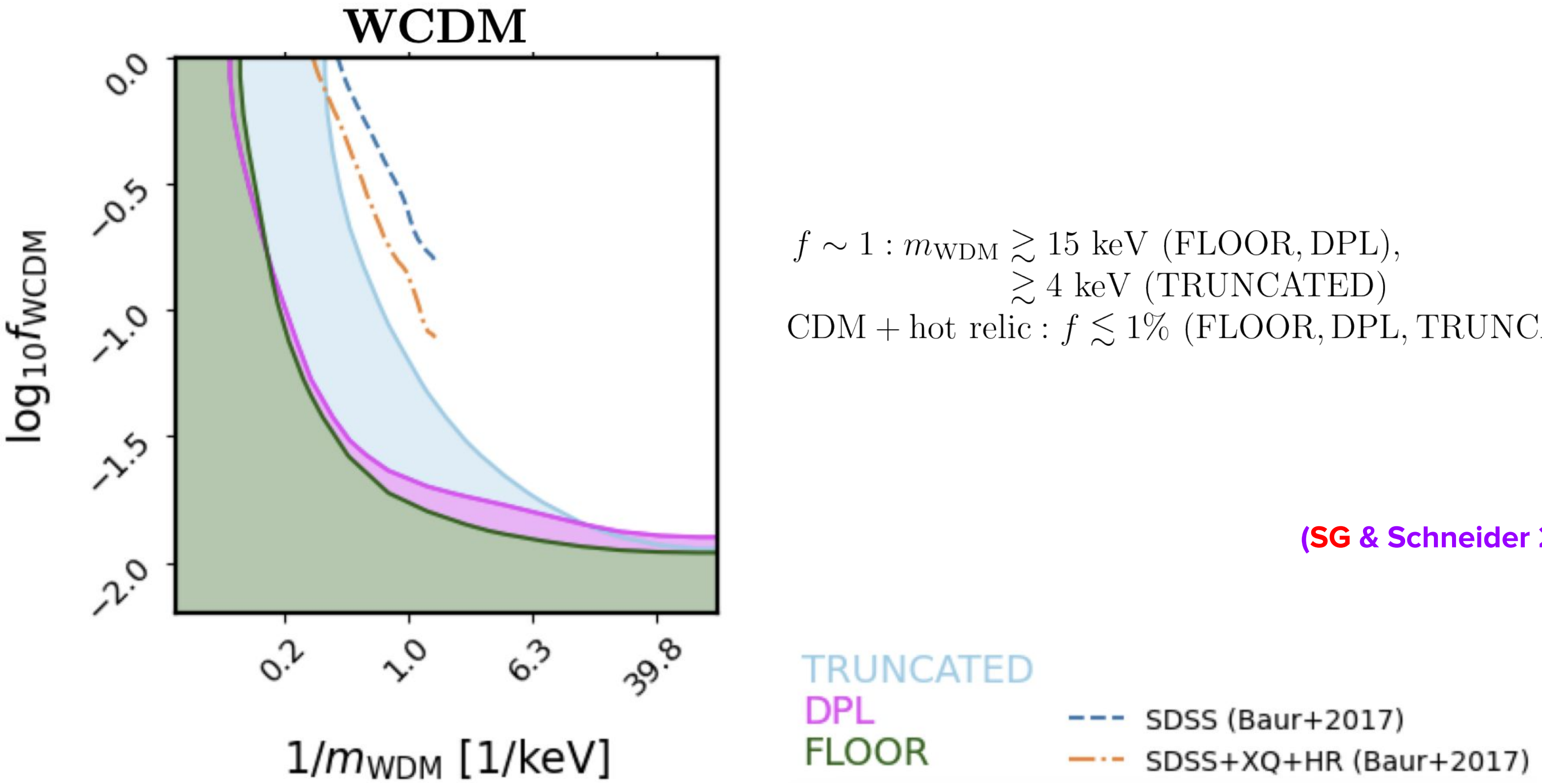
Halo-model based framework (Schneider, SG, Mirocha 2021; SG & Schneider 2022)

$$\log \mathcal{L} = -\frac{1}{2}\sum_{k,z}\left(\frac{\Delta^2_{21,\mathrm{ob}}(k,z) - \Delta^2_{21,\mathrm{th}}(k,z)}{\sigma_{21}(k,z)^2}\right)^2$$

Corner showing the posterior distribution



Constraints on cold + warm DM



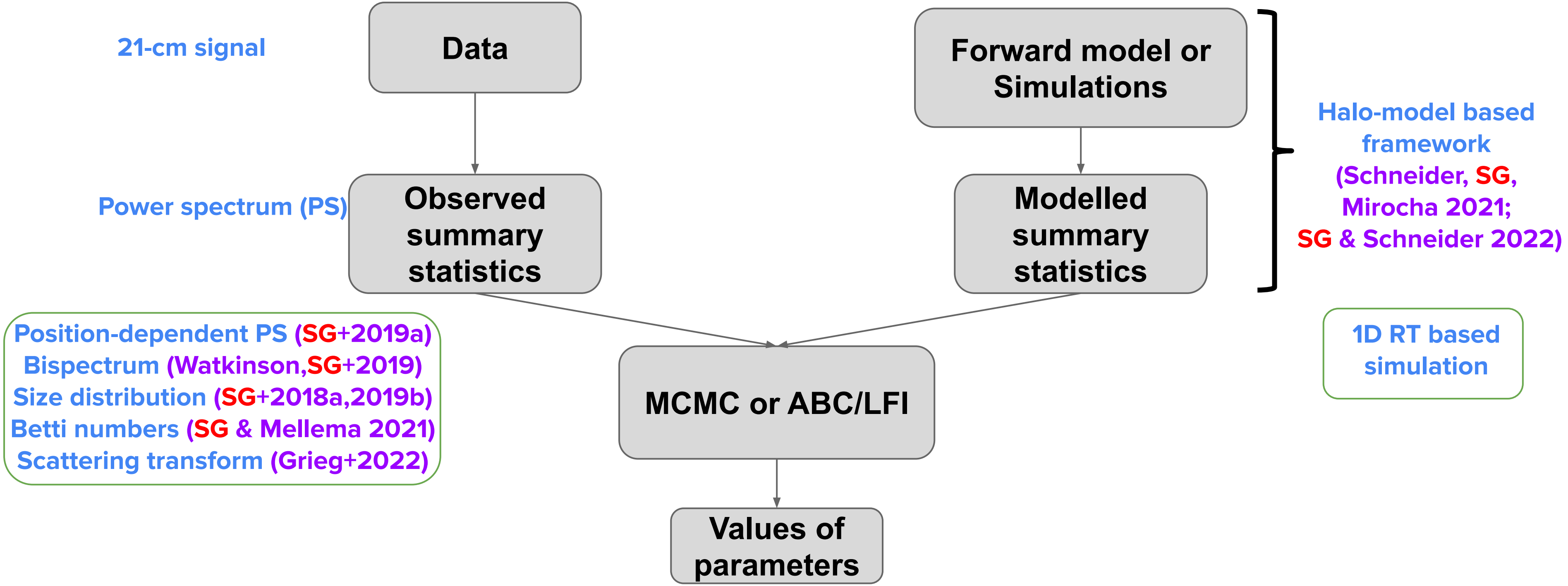
$$f \sim 1 : m_{\rm WDM} \gtrsim 15 \text{ keV (FLOOR, DPL)}, \quad \gtrsim 4 \text{ keV (TRUNCATED)}$$
$$\text{CDM + hot relic} : f \lesssim 1\% \text{ (FLOOR, DPL, TRUNCATED)}$$

(SG & Schneider 2022)

Fast simulations to go beyond the power spectrum

Timothée Schaefer
PhD student

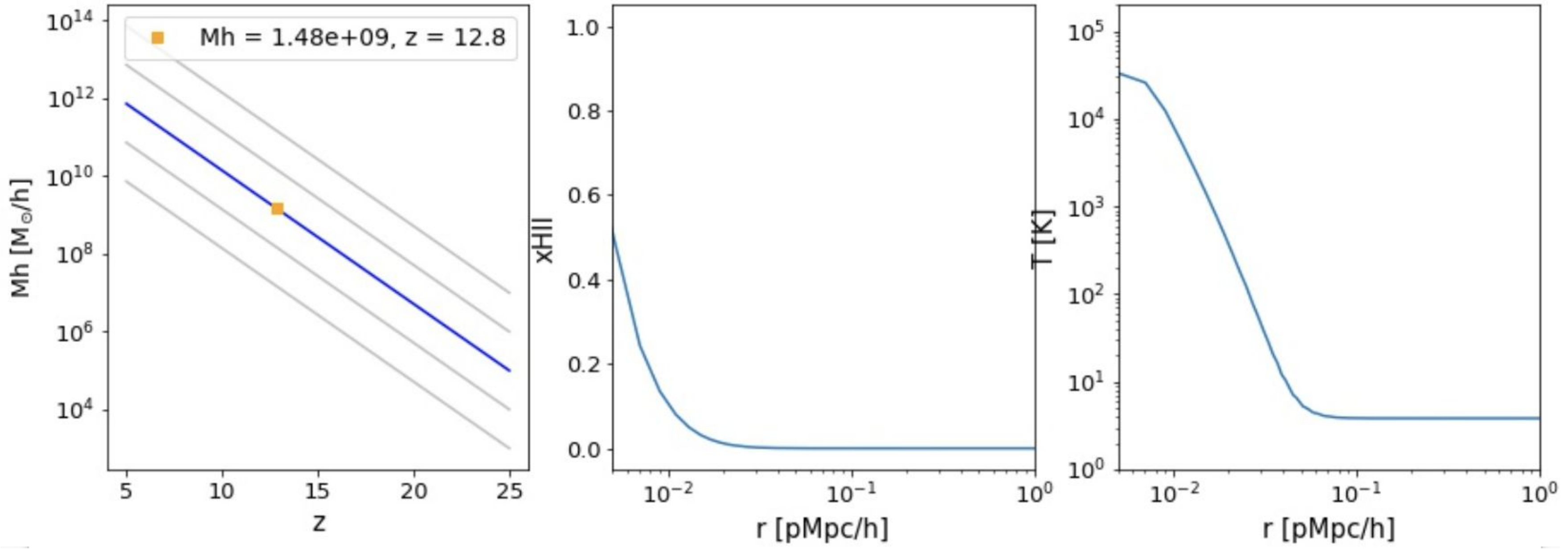
Inference from 21-cm observations



Simulation framework

1D radiative Transfer solver:

Pre-compute the profile for a range of halo mass at z>25, assuming a galaxy model, and following the halo growth.



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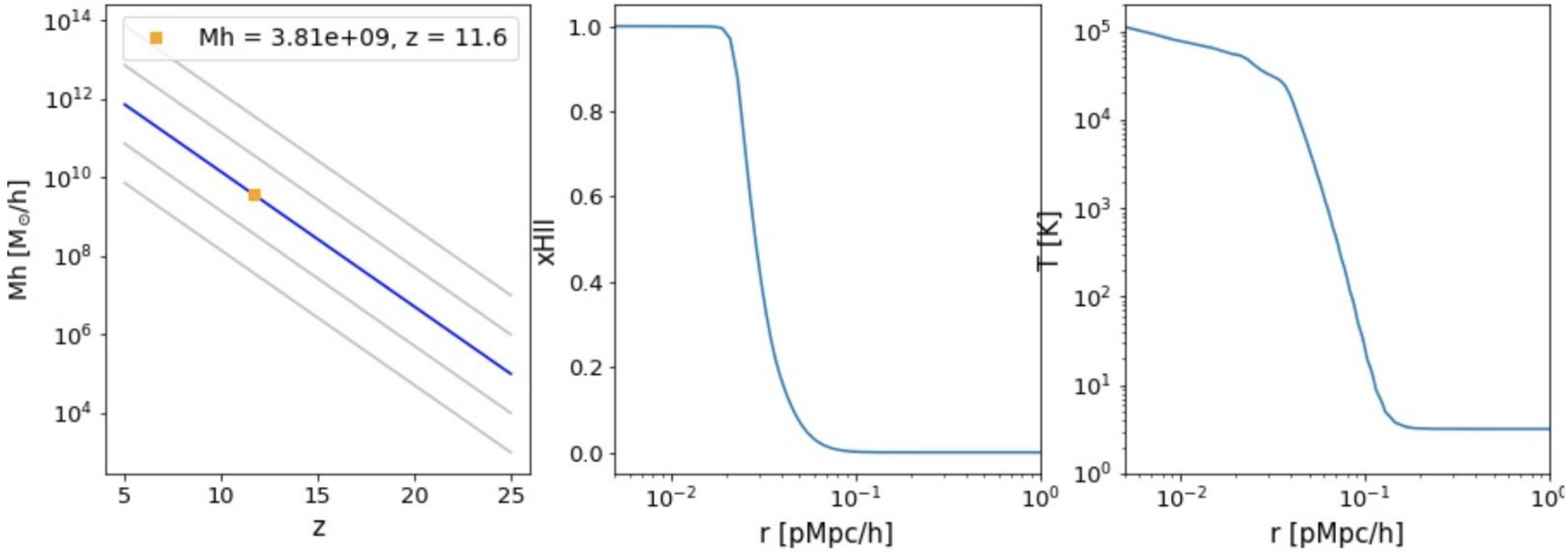
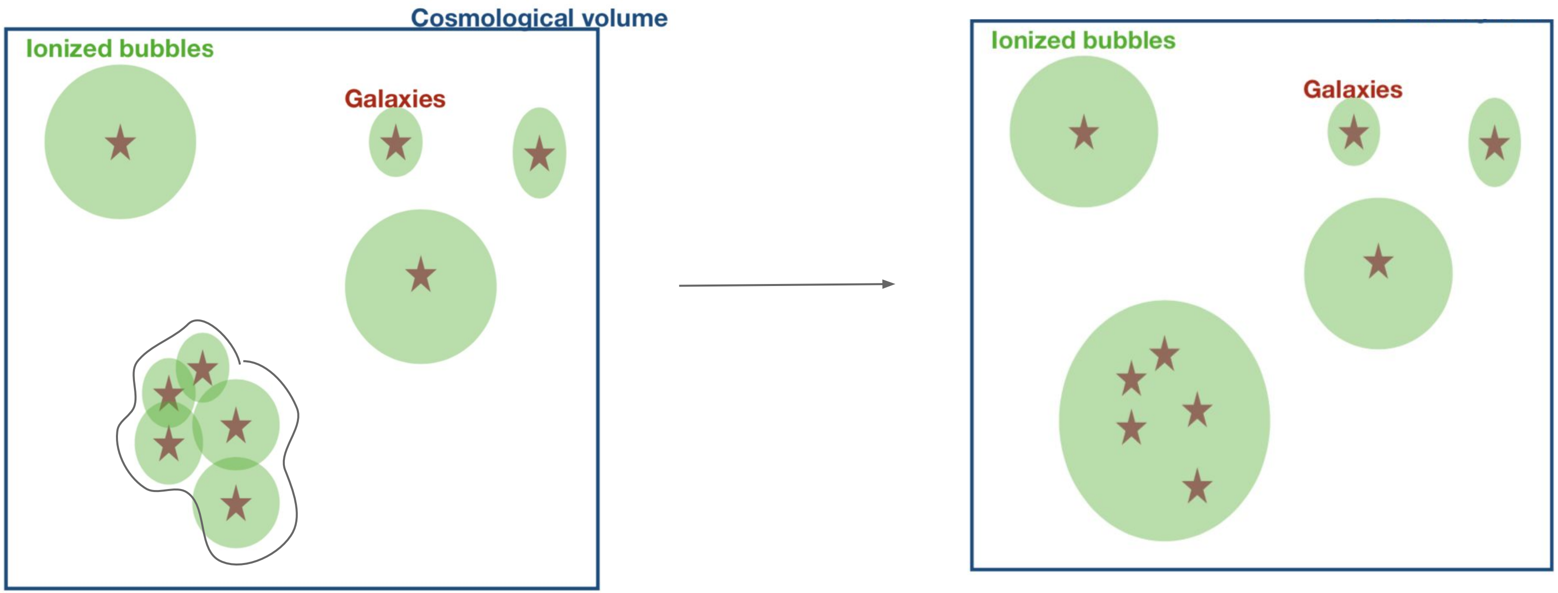


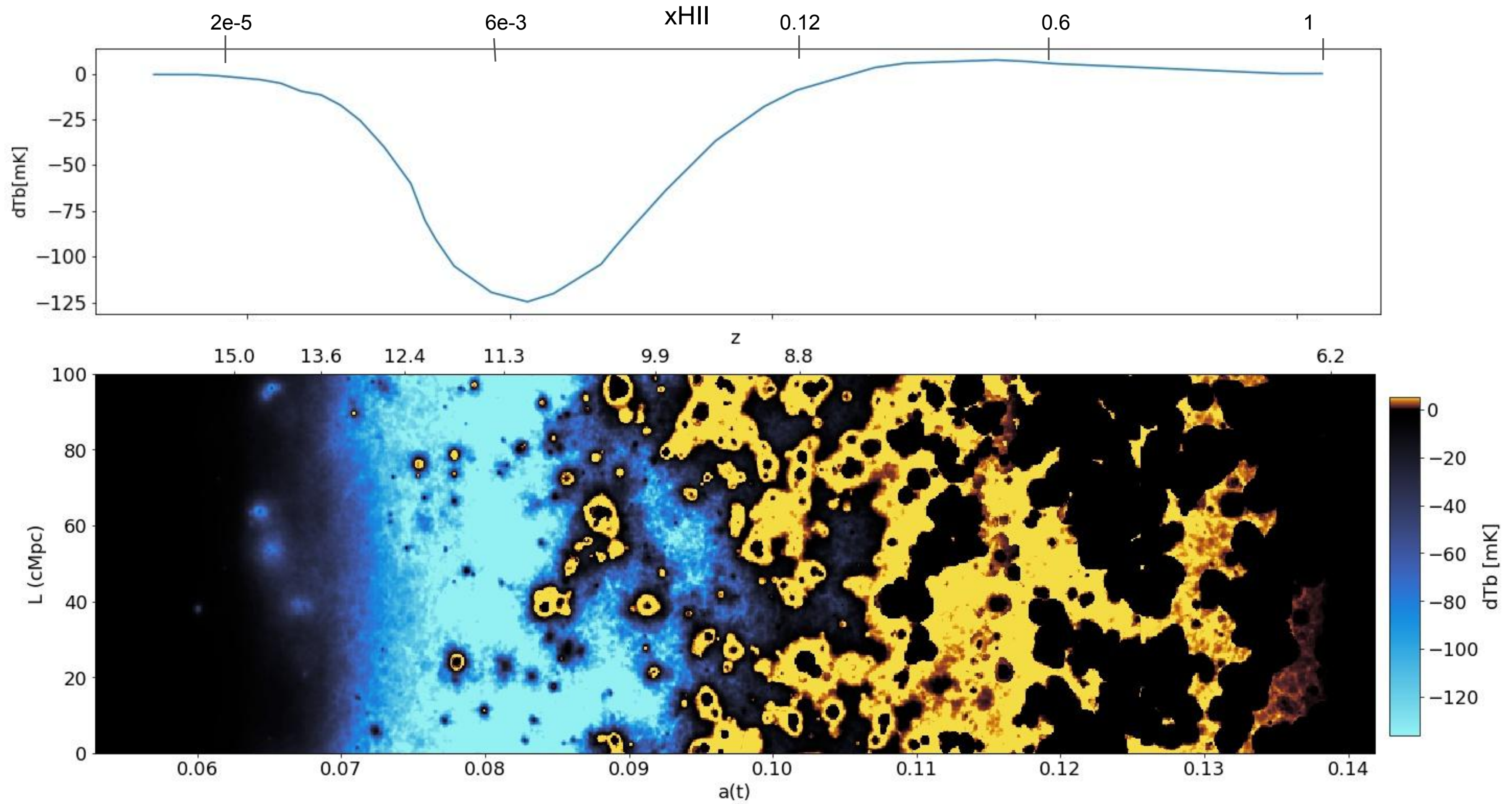
Overlap of ionized bubbles :

-Identify connected ionized regions

-Spread the excess ionisation fraction at the boundary of the regions



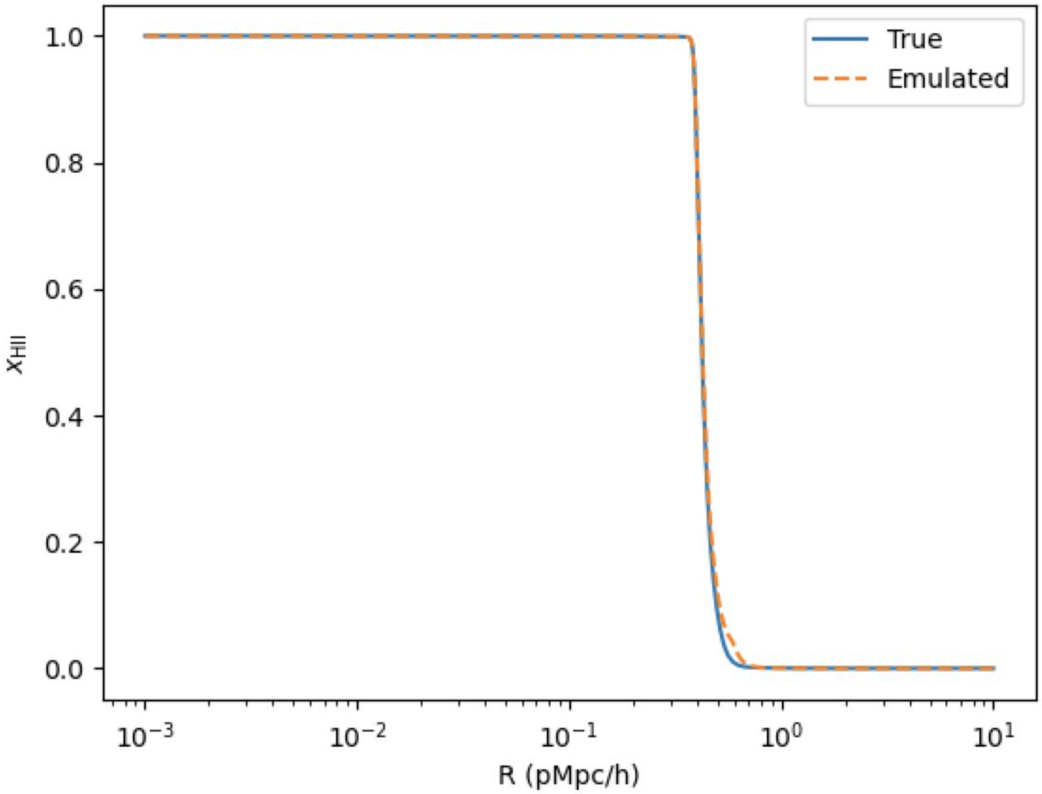
21-cm light-cone



Computation time (single core)

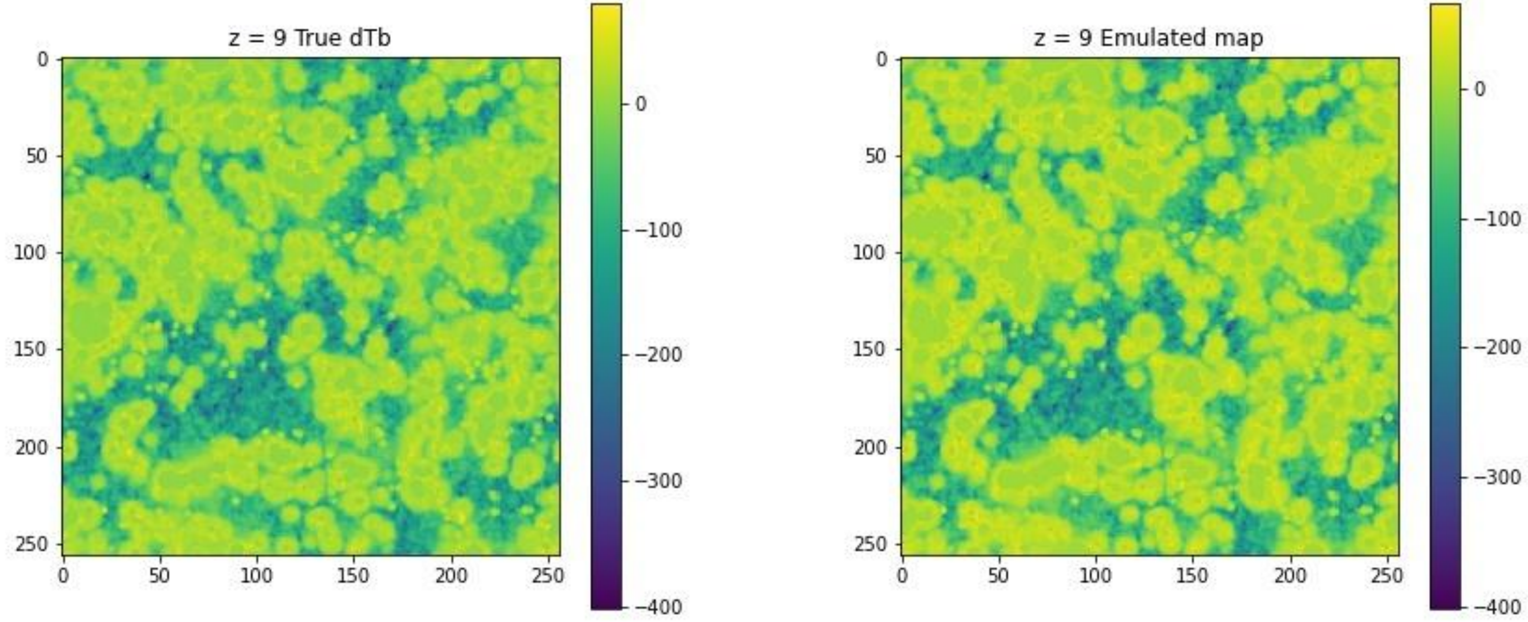
- Profile calculations for 1 set of parameters for full halo catalogues at all redshifts: ~15 minutes
- Painting profiles on each N-body snapshots:
  ~1 minutes (128^3 mesh) or ~10 minutes (256^3 mesh)

Emulation of the profiles



Solver runtime: ∼15 minutes
Emulator runtime: ∼10 ms

Painted profiles using emulator



Next steps to speed up the profile painting

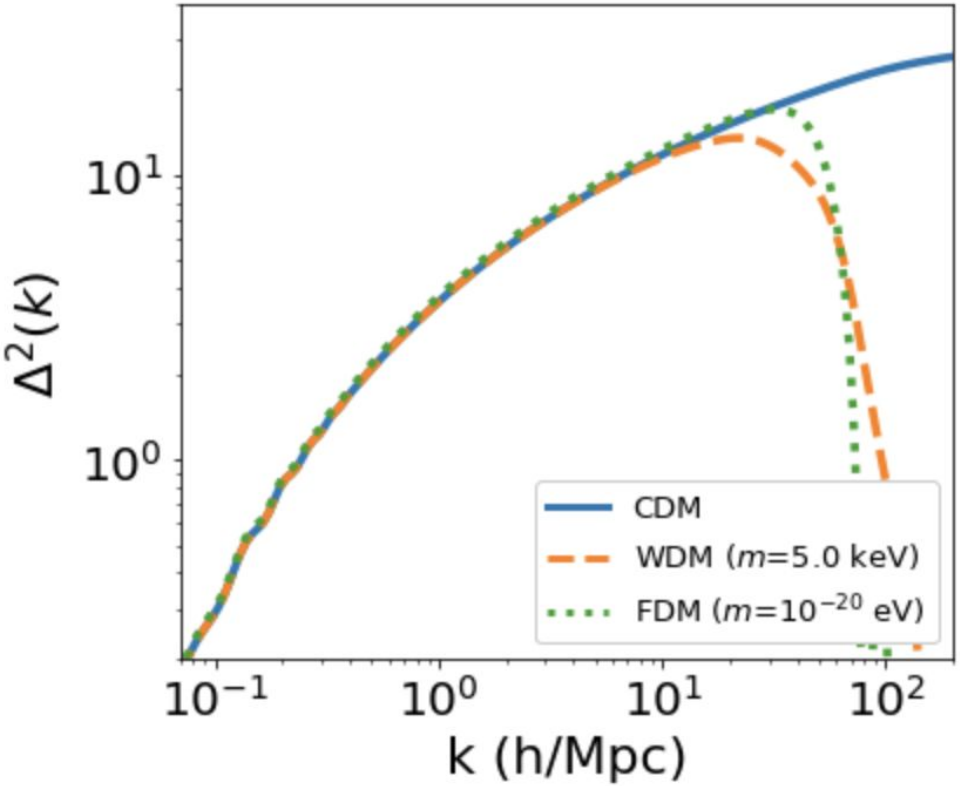
- Use **GPUs** (ongoing): ∼100 times faster
- Use **Machine learning**: expect ≲1 second

Summary

- Halo-model based approach gives a fast and flexible way of exploring many cosmological and astrophysical models
- We can put constraints on non-cold dark matter models using SKA observations of the cosmic dawn
- We are developing a very fast simulation code (Timothee)
- Final interpretation framework will be able to analyse any summary statistics derived SKA observations
- Field-level inference by forward-modelling telescope effects with Tools21cm

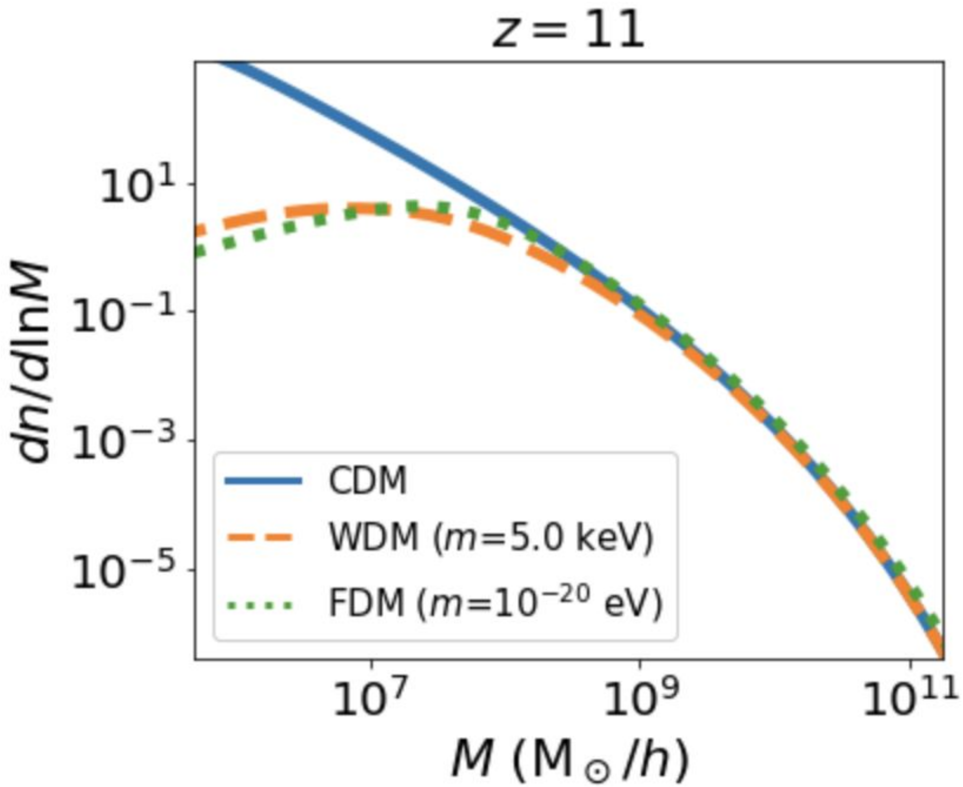
Back-up slides

Linear power spectra



z = 0

Halo mass function



$$\frac{\mathrm{d}n}{\mathrm{d}\ln M} = -\frac{\bar{\rho}}{M}\nu f(\nu)\frac{\mathrm{d}\ln\sigma}{\mathrm{d}\ln M} ,$$

$$M = \frac{4\pi}{3}\bar{\rho}(cR)^3$$

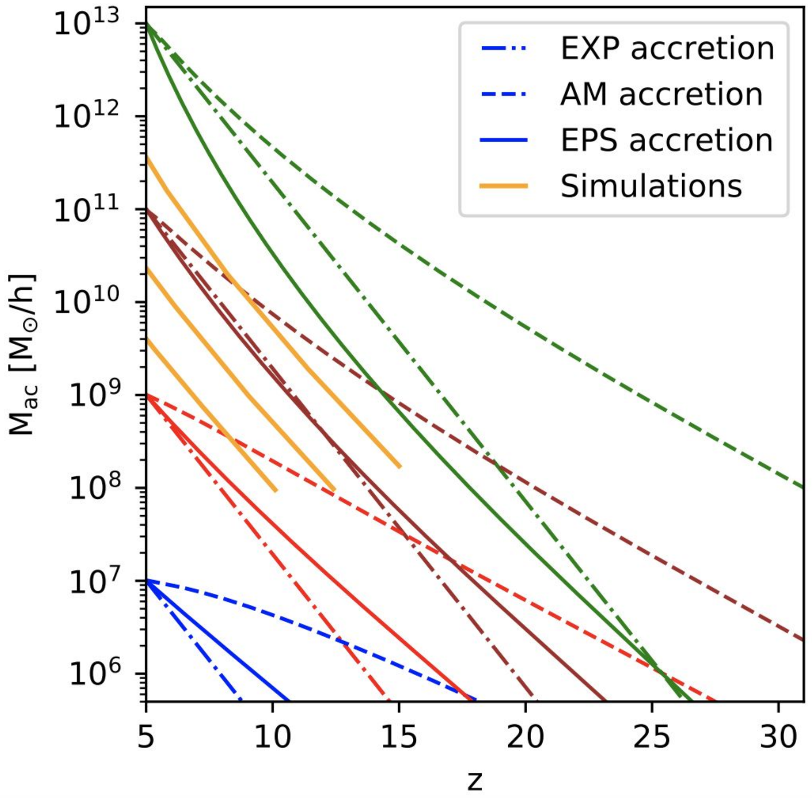
$$f(\nu) = A\sqrt{\frac{2q\nu}{\pi}}(1+\nu^{-p})e^{-q\nu/2}$$

$$\sigma^2(R,z) = \int \frac{\mathrm{d}k^3}{(2\pi)^3}P_{\mathrm{lin}}(k)\mathcal{W}(k|R)$$

$$\mathcal{W}(k|R) = \frac{1}{1+(kR)^\beta} .$$

Leo+2018

Mass accretion rate

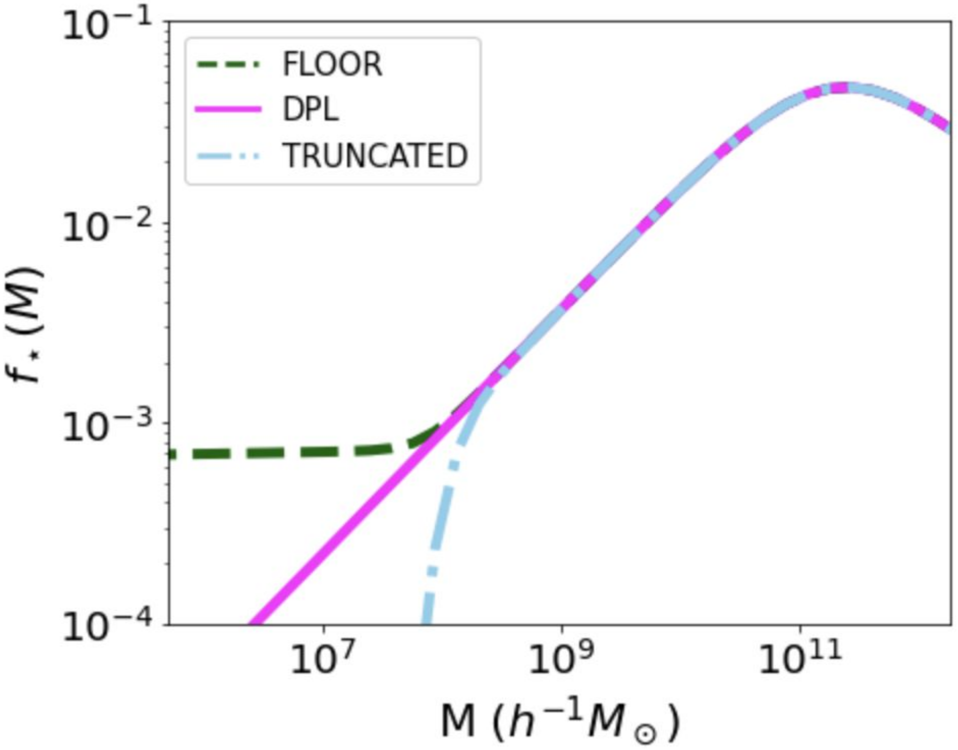


Halo bias

$$b(M) = 1 + \frac{q\nu - 1}{\delta_c(z)} + \frac{2p}{\delta_c(z)[1 + (q\nu)^p]}\,.$$

Cooray & Sheth (2002)

Stellar to halo mass relation



$$f_*(M) = \frac{2(\Omega_b/\Omega_m)f_{*,0}}{(M/M_p)^{\gamma_1} + (M/M_p)^{\gamma_2}} \times S(M)$$

$$S(M) = [1 + (M_t/M)^{\gamma_3}]^{\gamma_4},$$

(SG & Schneider 2022)

Fast and accurate method to obtain dTb maps :

1 . Density field and halo growth :

-Use N-body sim (*pkdgrav*) for the **density field** and **halo catalogs** (*rockstar*)

-Use merger trees to fit the halo **mass accretion rate** (MAR) : $M_{\rm ac}(M,z) = M \exp\left[\alpha(z_0 - z)\right]$

2 . Sources of radiation:

- Relate halo growth to star formation rate via a double power law: $f_*(M) \equiv \dot{M}_*/\dot{M}_{\rm ac}$

- Parameterize in a flexible way the galaxy spectra in ionising, Xray, and Lyman-alpha bands (power laws and/or black body)

3 . IGM thermal and ionisation state :

- Assume spherical symmetry : solve 1D coupled RT equations, following the halo growth, from cosmic dawn to the end of reionisation (z<6).

4 . dTb maps :

- Paint Temperature and Ionisation profiles around each halo of the catalog.

- Spread the excess ionisation fraction where bubbles overlaps