Interpreting the high-redshift 21-cm signal observations

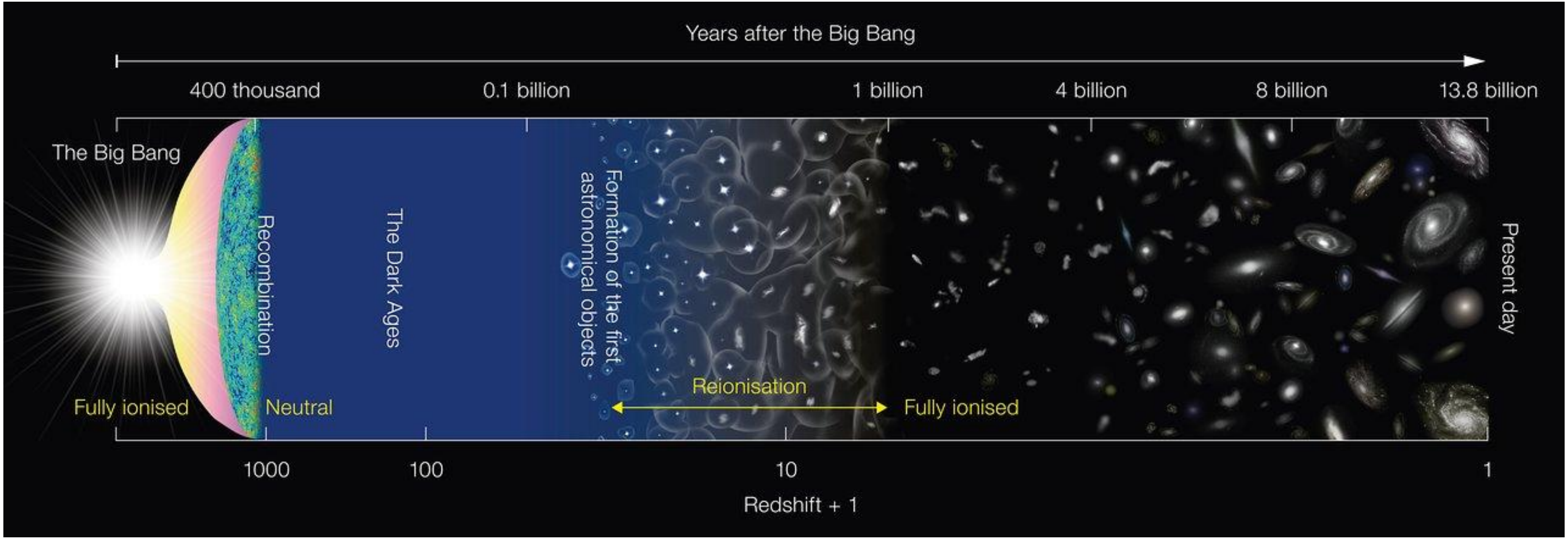
Sambit Giri

Universität Zürich[UZH]

Outline

- Basics of 21-cm signal
- Constraints from current 21-cm observations
- Forecast for upcoming observations
    - Halo model based framework

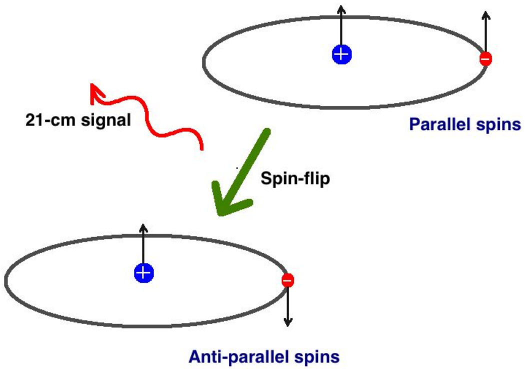
Timeline of the Universe



~100 MHz ~200 MHz

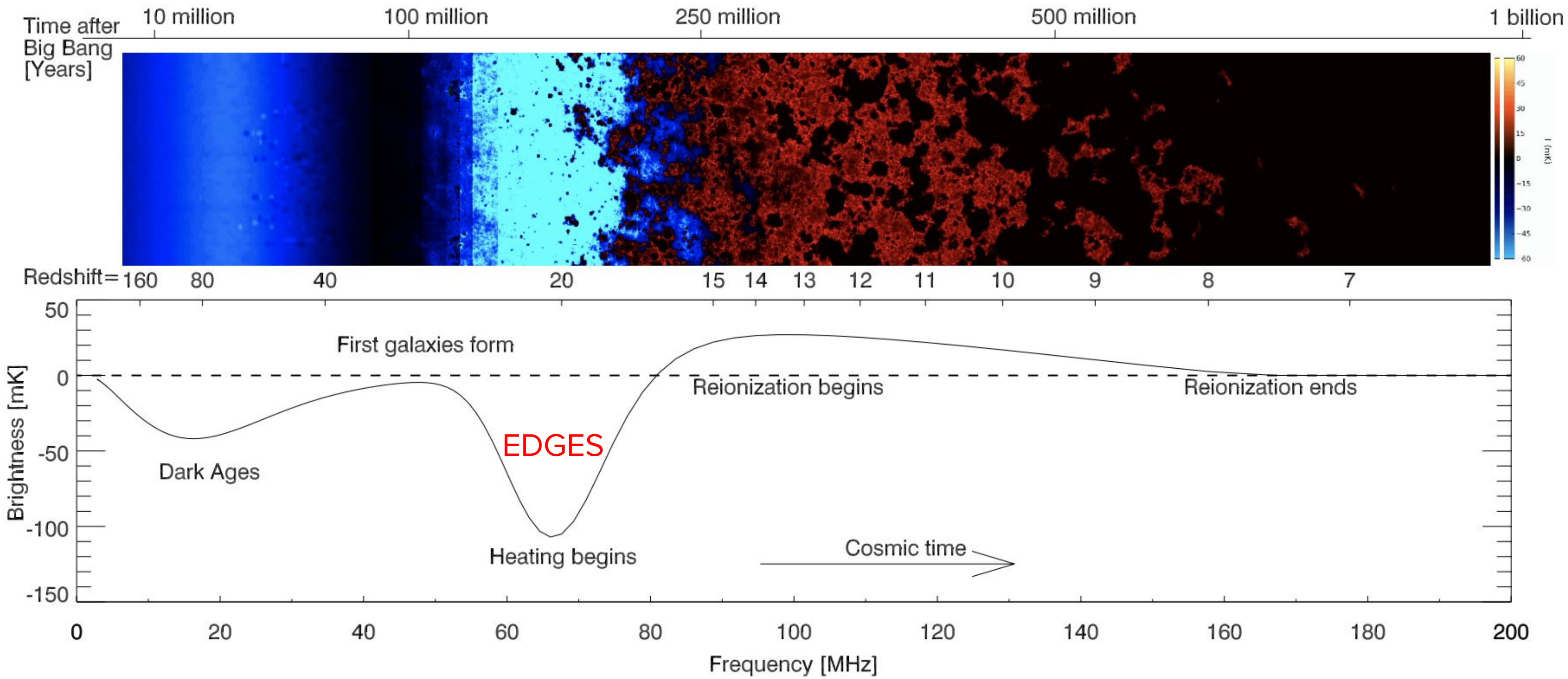
Credit: NAOJ

Observing the intergalactic medium

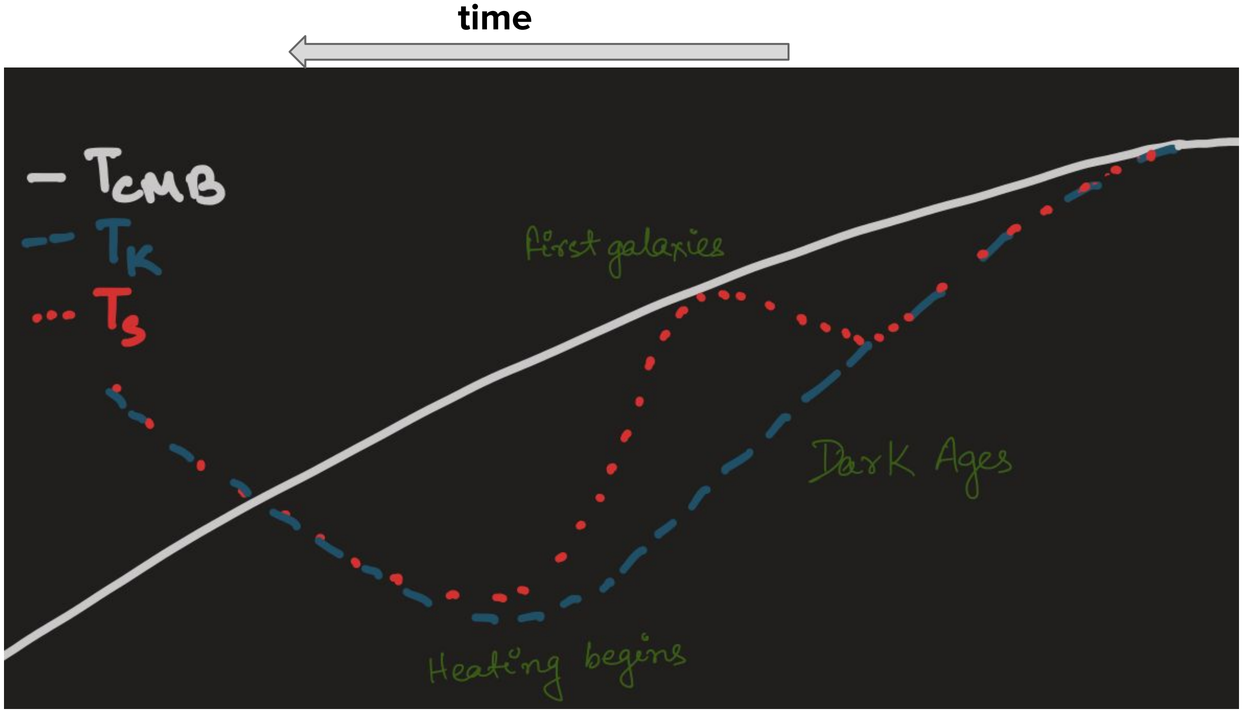


$$\delta T_b \propto x_{\rm HI}(1+\delta_b)\left(1-\frac{T_{\rm CMB}}{T_{\rm S}}\right)$$

Observing the intergalactic medium

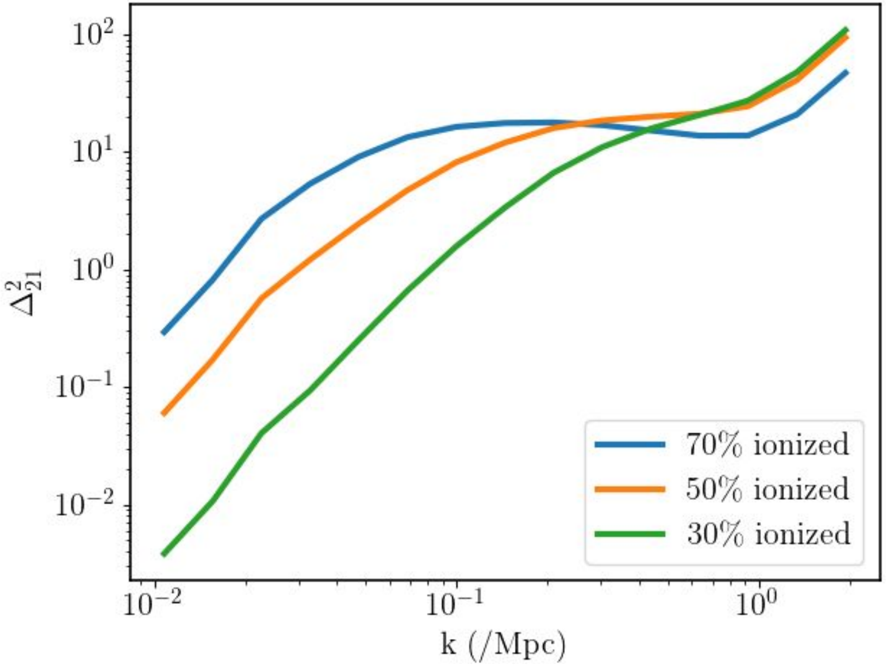


Spin temperature



$$\delta T_b \propto \left(1 - \frac{T_{\rm CMB}}{T_{\rm S}}\right)$$

Power spectrum

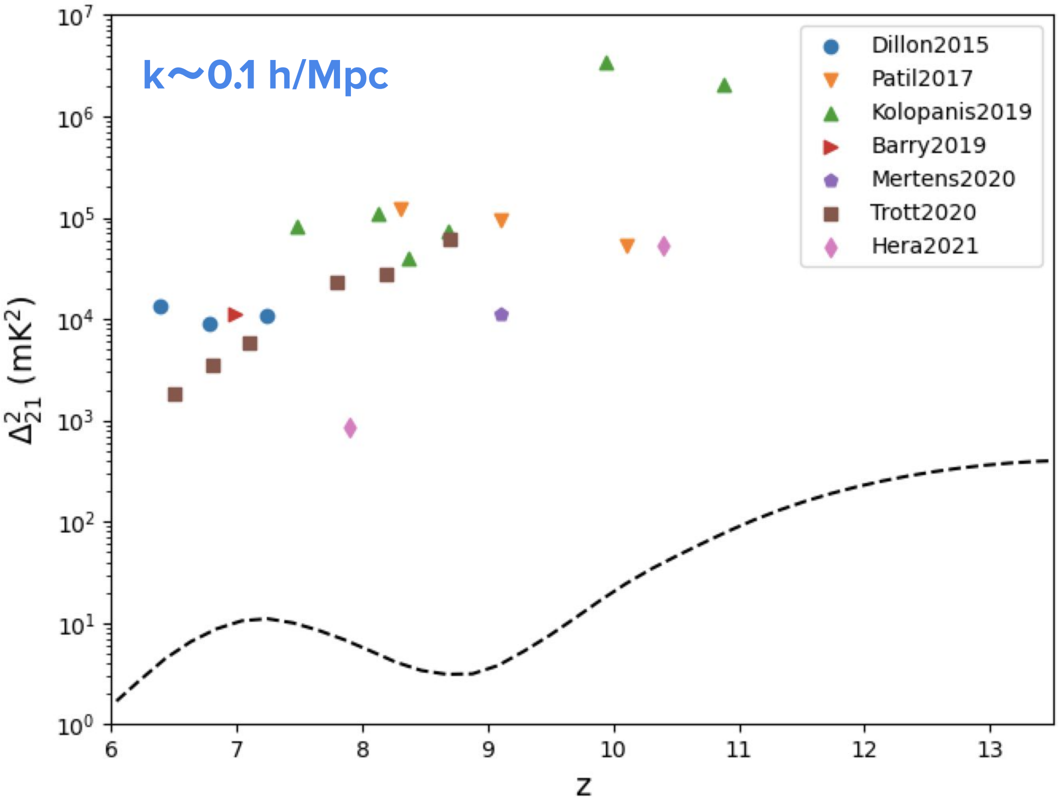


Observed by
LOFAR, MWA, HERA, SKA, etc.

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

$$\Delta^2_{21}(k) = \frac{k^3}{2\pi^2}\langle \delta T_b(k)^* \delta T_b(k)\rangle$$

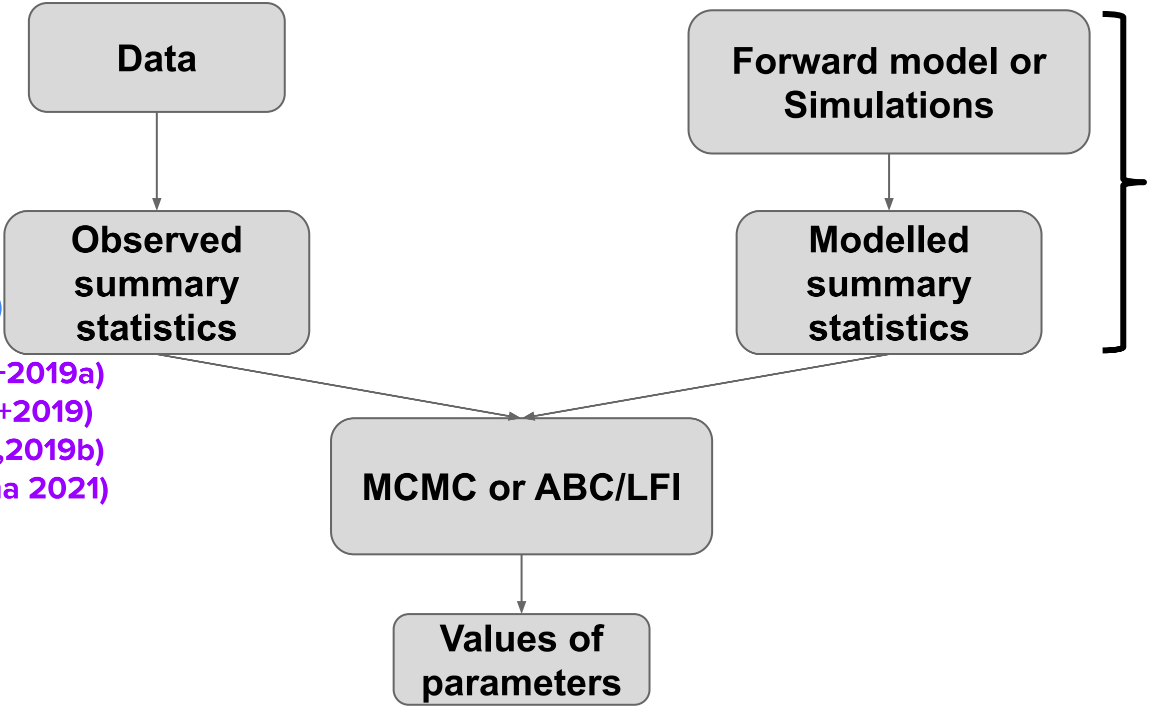
Current 21-cm signal observations



Inference from 21-cm observations

21-cm signal

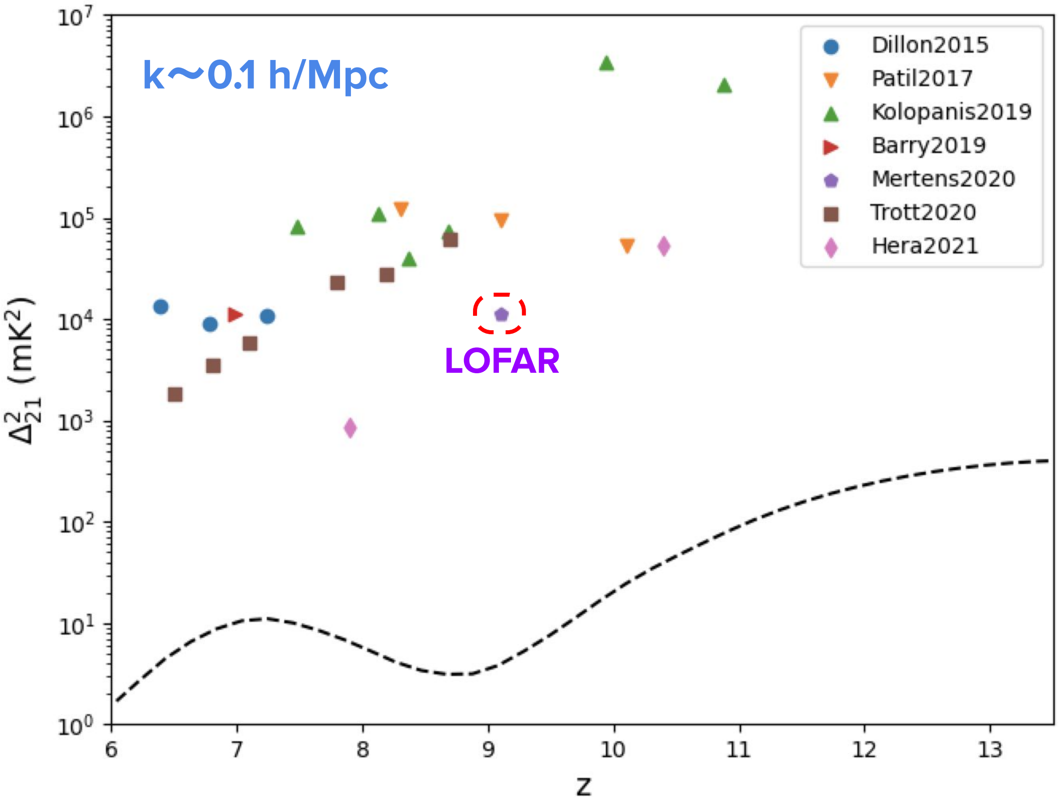
Global signal
Power spectrum (PS)
Position-dependent PS (SG+2019a)
Bispectrum (Watkinson,SG+2019)
Size distributions (SG+2018,2019b)
Betti numbers (SG & Mellema 2021)



Emulators
(Ghara,SG+2020)

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

Constraints from upper limits



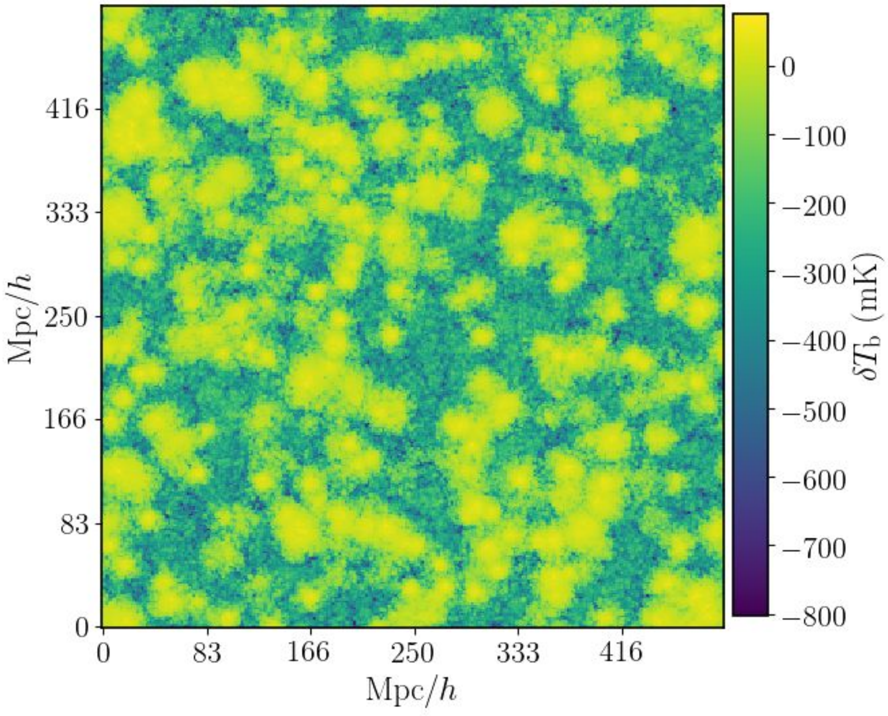
We need models which boosts large scale fluctuations in 21-cm signal

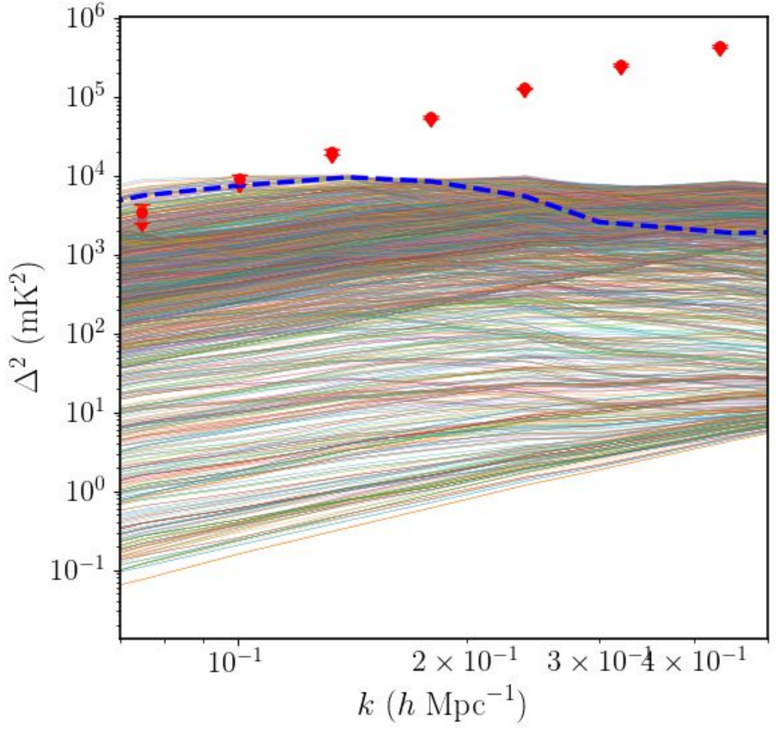
$$\delta T_{\rm b} \propto x_{\rm HI}(1+\delta)\left(1-\frac{T_{\rm CMB}}{T_{\rm S}}\right)$$

To zeroth order, these fluctuations are scales of ∼50 Mpc.
To achieve such fluctuations, we need extreme source models.

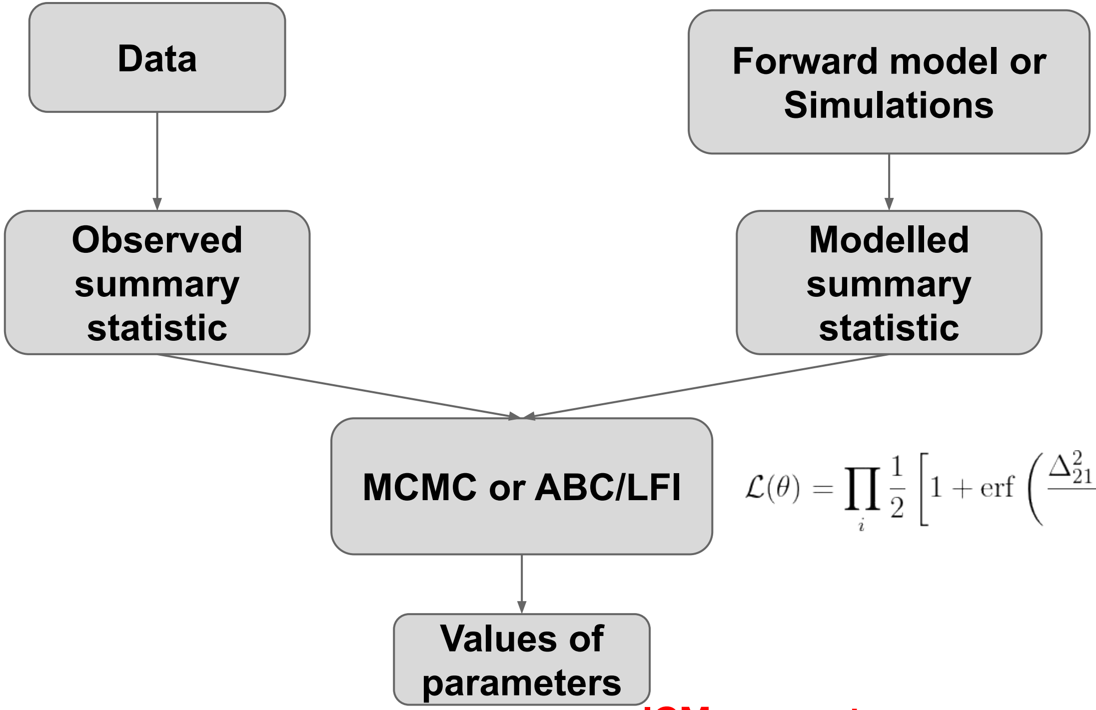
Simulated models at z=9.1

(Ghara,SG+2020)





Inference from 21-cm observations



Upper limits

GRIZZLY code (Ghara,Mellema,SG+2018)

Surrogate model or Emulator

$$\mathcal{L}(\theta) = \prod_i \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\Delta^2_{21}(k_i) - \Delta^2_{\mathrm{m}}(k_i,\theta)}{\sqrt{2}\sigma(k_i)}\right)\right]$$

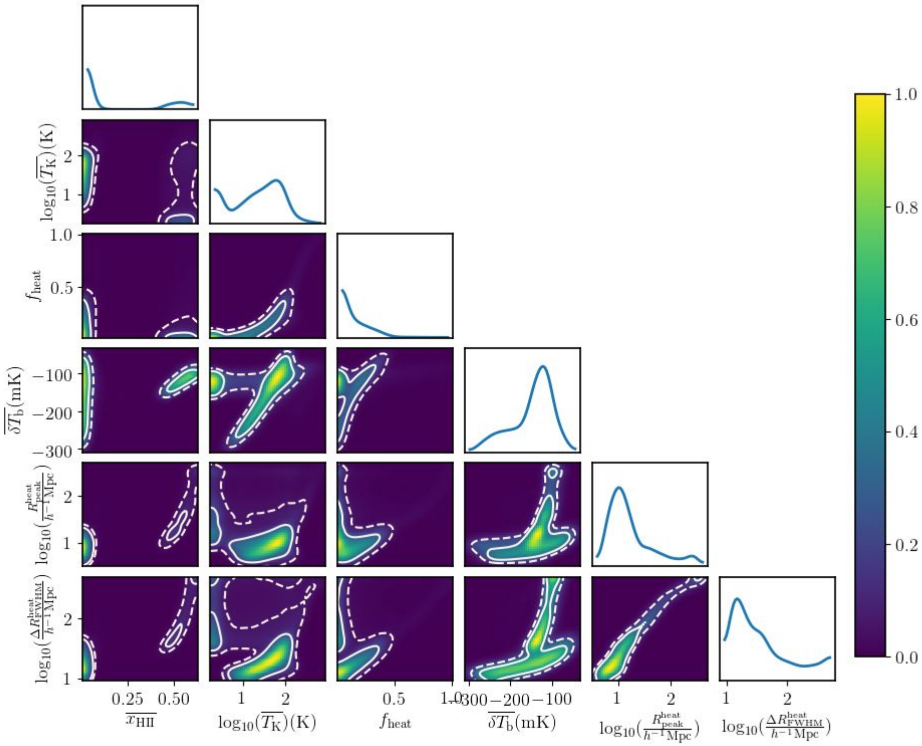
IGM parameters

IGM parameters

Average ionization fraction	$\overline{x_{\mathrm{HII}}}$
Average gas temperature	$\overline{T_{\mathrm{K}}}$ (K)
Fraction of heated region	f_{heat}
Global 21-cm signal	$\overline{\delta T_{\mathrm{b}}}$ (mK)
Peak of the heated bubble PDF	$R_{\mathrm{peak}}^{\mathrm{heat}}$ (h^{-1}Mpc)
Width of the heated bubble PDF	$\Delta R_{\mathrm{FWHM}}^{\mathrm{heat}}$ (h^{-1}Mpc)

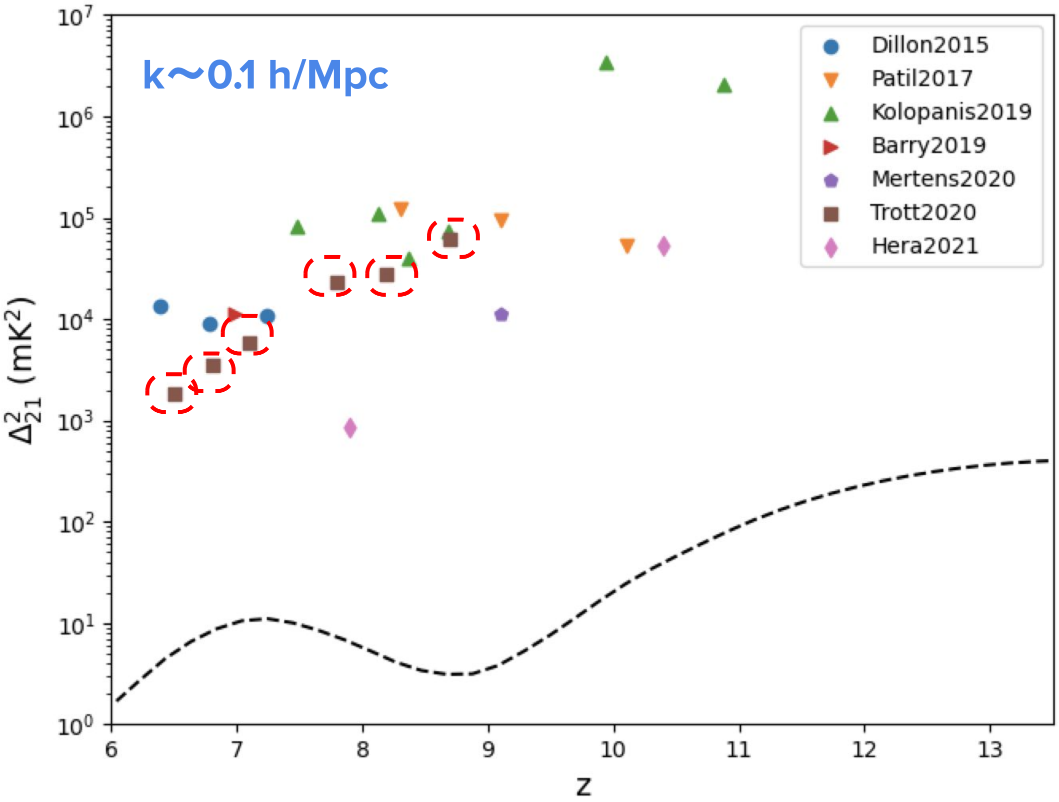
Excluded IGM parameters

(Ghara,SG+2020)



IGM Parameters of non-uniform T_S scenario	95% credible interval of the excluded models
$\overline{x_{HII}}$	[0, 0.08], [0.45, 0.62]
$\overline{T_K}$ (K)	[7.41, 158.48], [2.10, 3.55]
f_{heat}	[0, 0.34]
$\overline{\delta T_b}$ (mK)	[−234.15, −65.53]
R_{peak}^{heat} (h^{-1}Mpc)	[3.50, 69.82]
ΔR_{FWHM}^{heat} (h^{-1}Mpc)	[0, 113.76]

MWA 21-cm signal observations

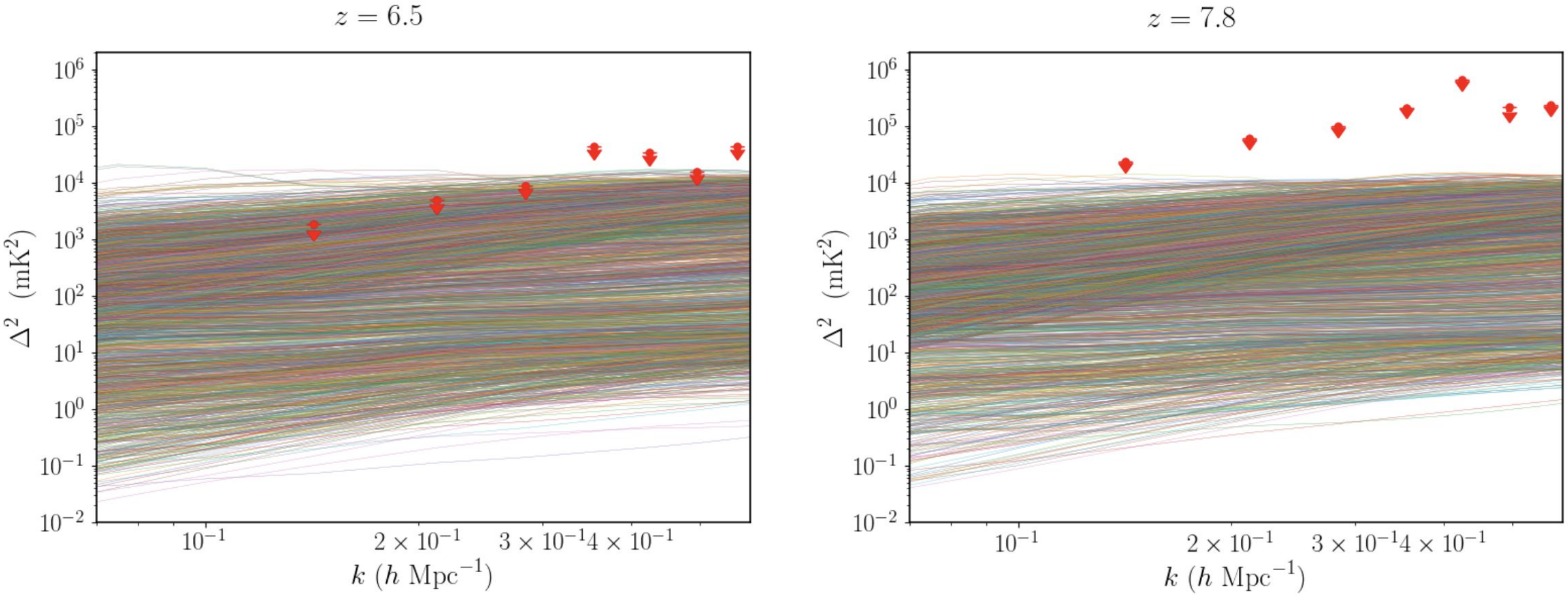


$$\delta T_b \propto x_{\rm HI}(1+\delta_b)\left(1-\frac{T_{\rm CMB}}{T_{\rm S}}\right)$$

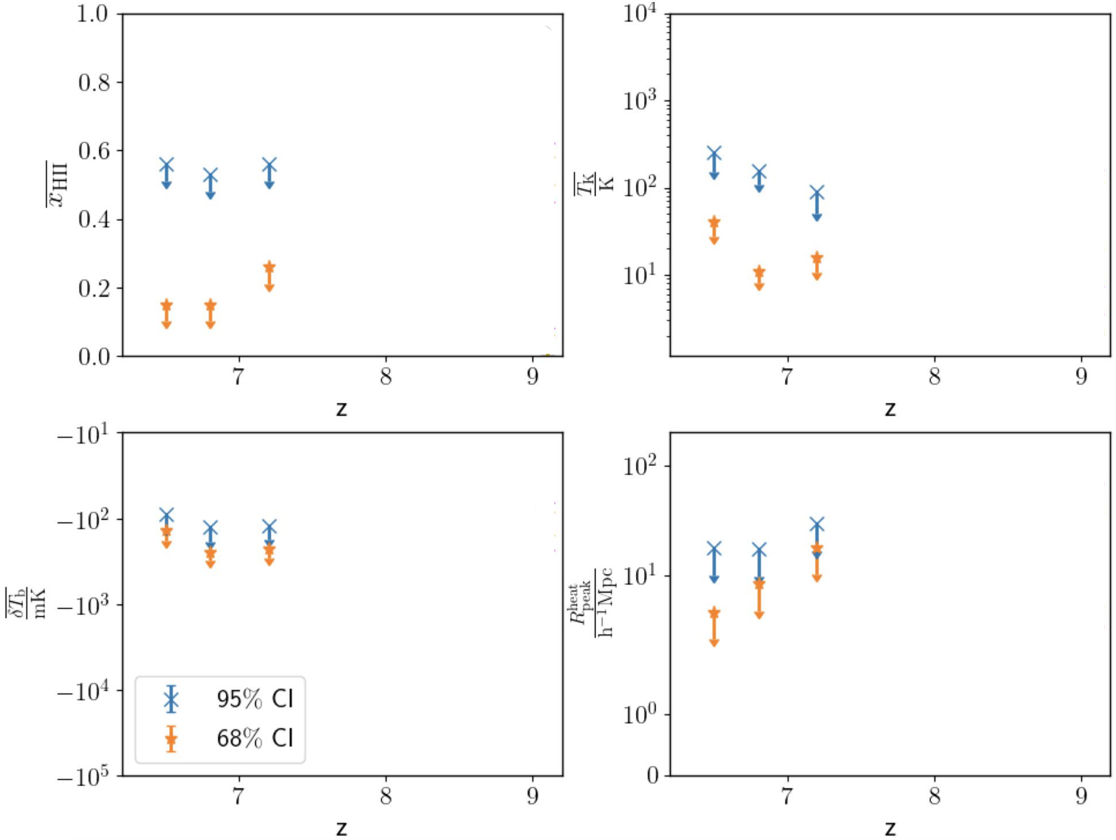
$$\Delta^2_{21}(k) = \frac{k^3}{2\pi^2}\langle \delta T_b(k)^* \delta T_b(k)\rangle$$

Simulated models

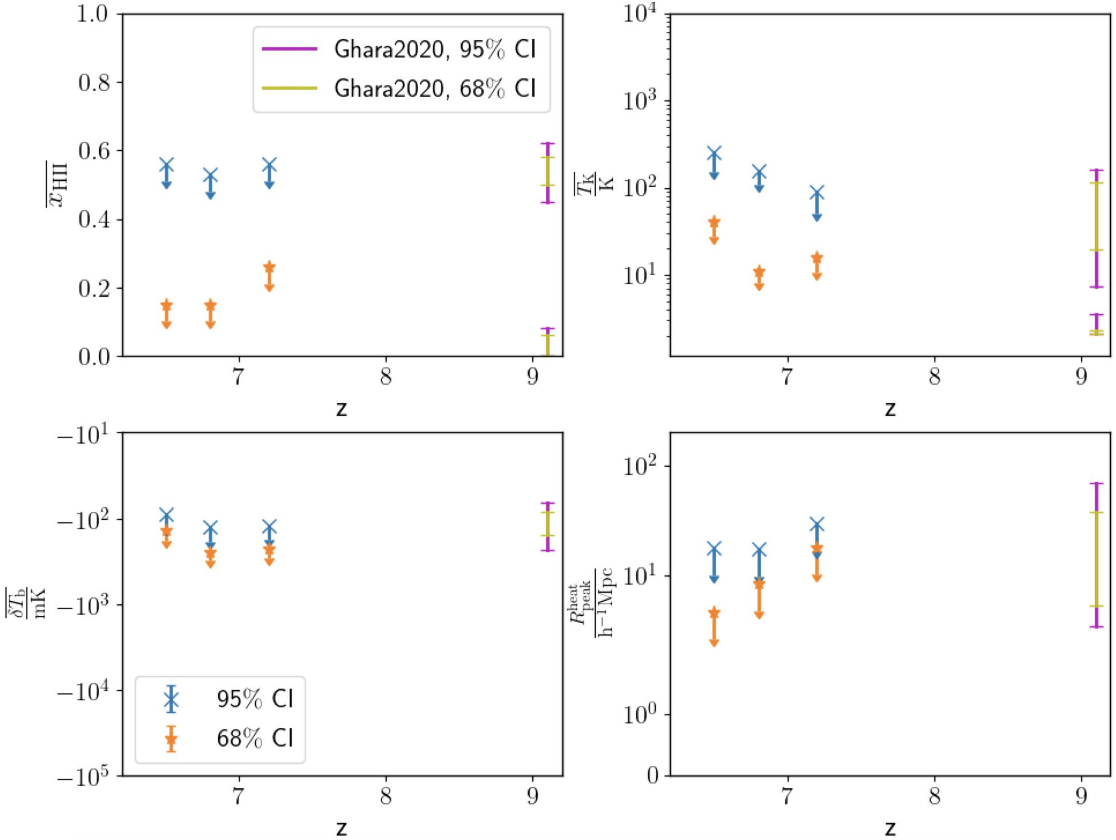
(Ghara,SG+2021)



Excluded IGM parameters

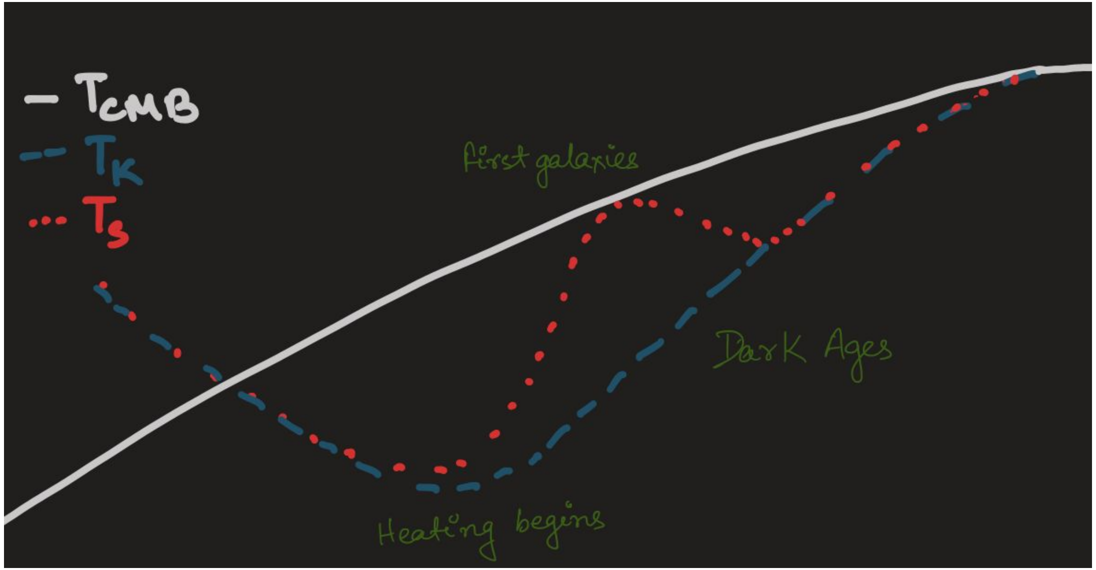


Excluded IGM parameters



Excess radio background

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



Excess radio background

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

Model parameter

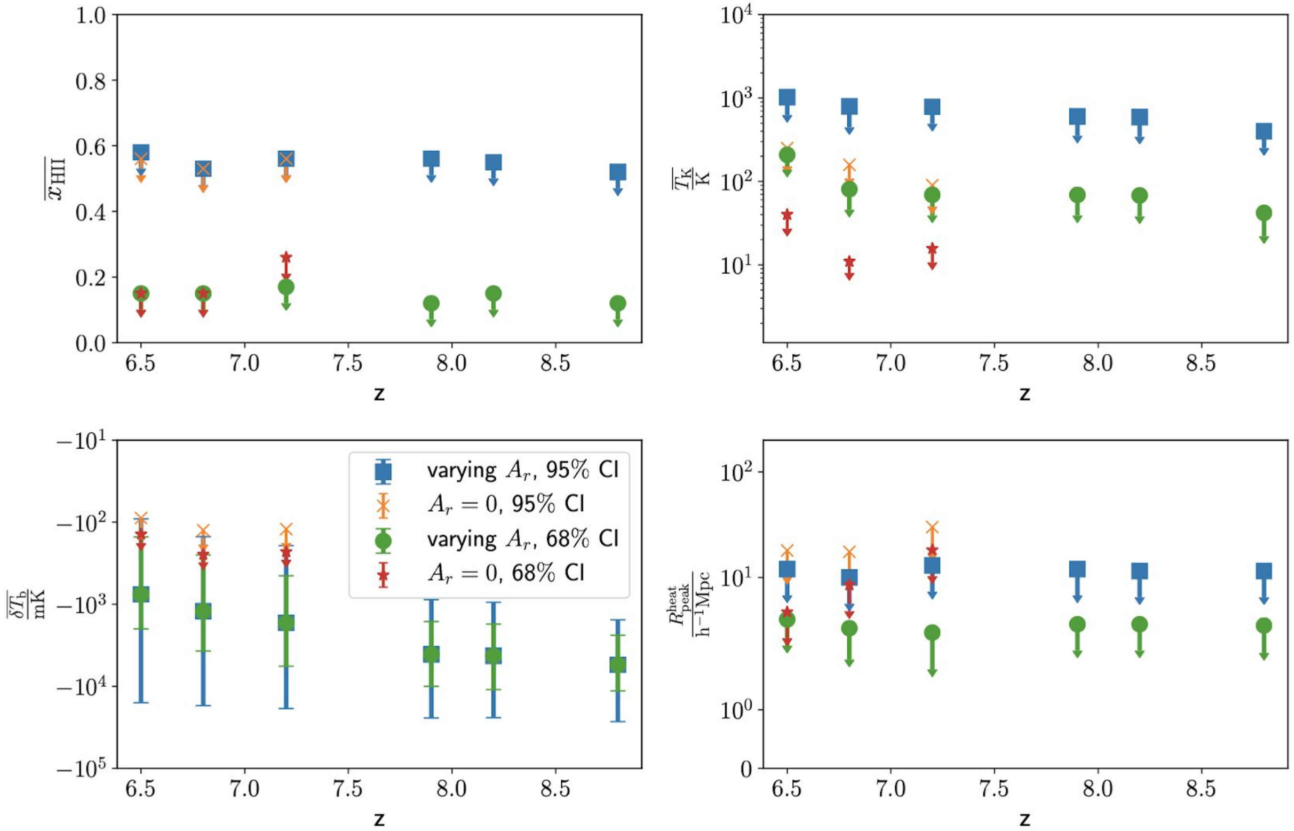
$$T_{\rm rad} = T_{\rm CMB}(1+z)\left[1 + A_{\rm r}\left(\frac{\nu_{\rm obs}}{78\ {\rm MHz}}\right)^{\beta}\right]$$

Fialkov & Barkana 2019
Mondal...SG+2020

$$\beta = -2.6$$

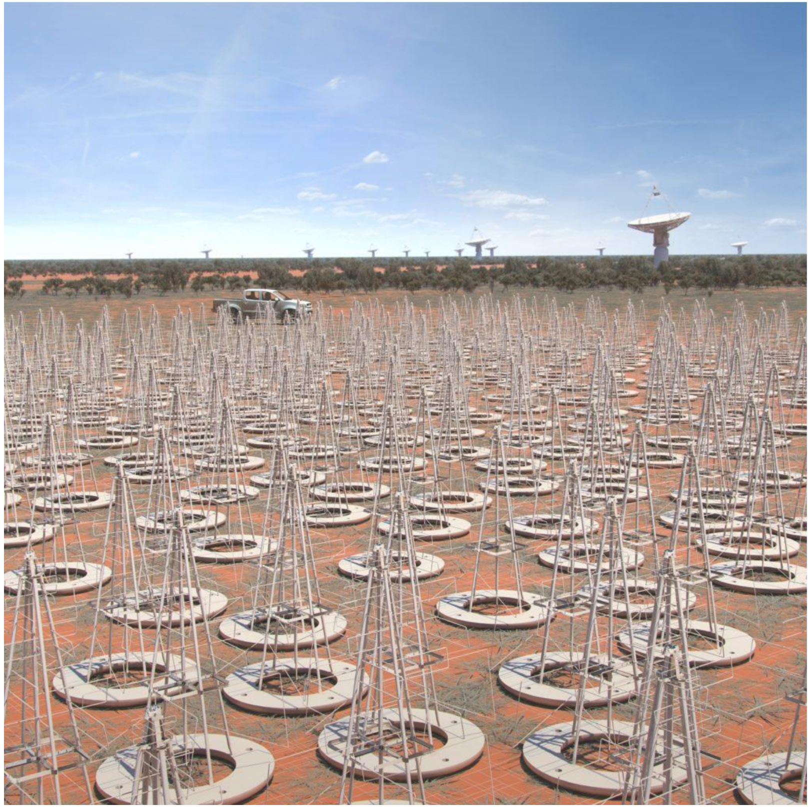
Value that agrees with LWA1 observations (Dowell & Taylor 2018)

Excluded IGM states with excess radio background



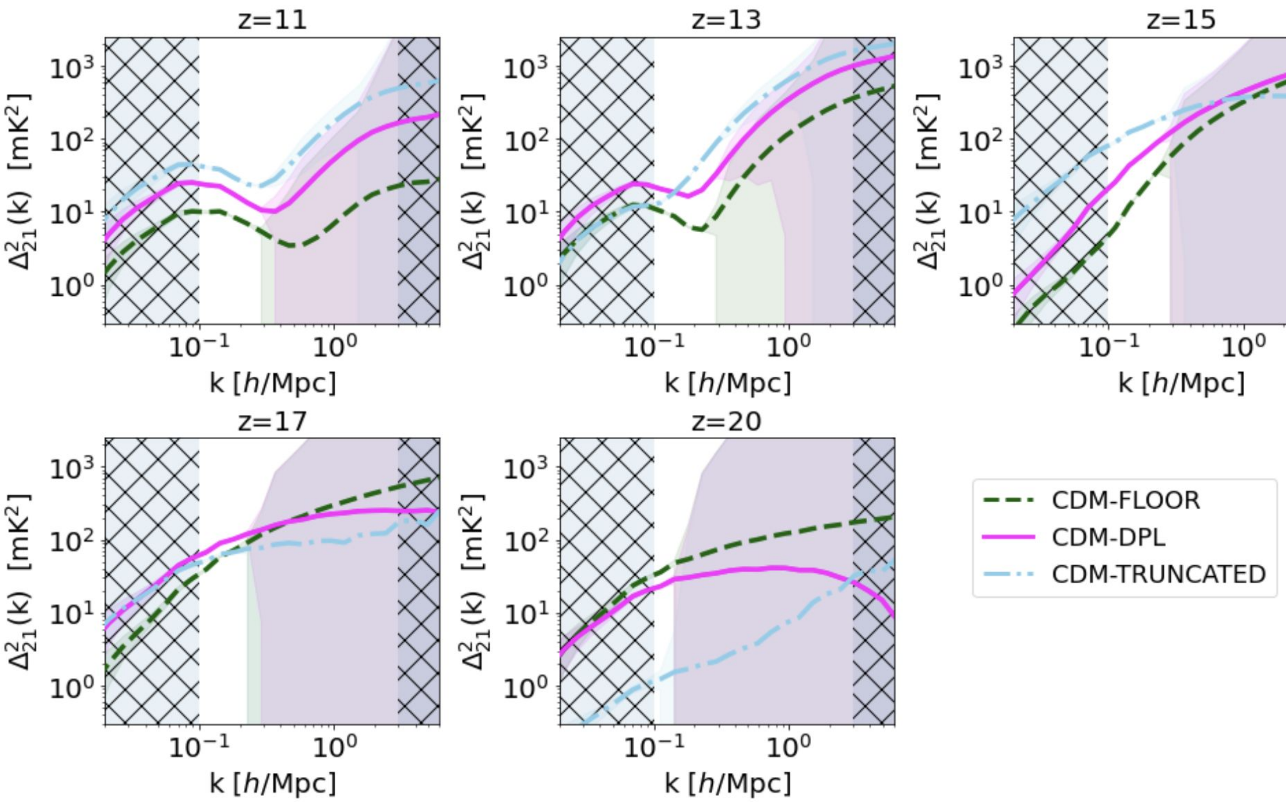
(Ghara,SG+2021)

Forecast study: SKA-Low



Credit: SKA Organisation

Mock observation at cosmic dawn

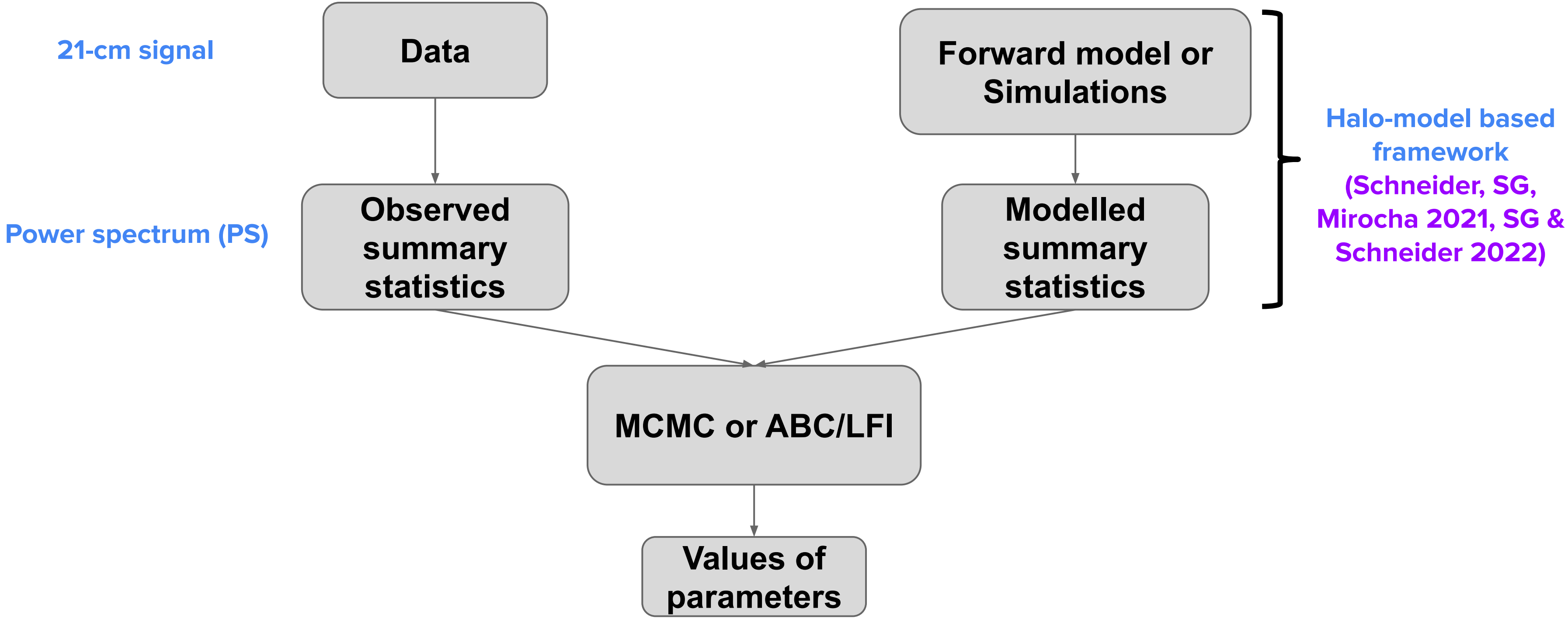


1000 hour observations

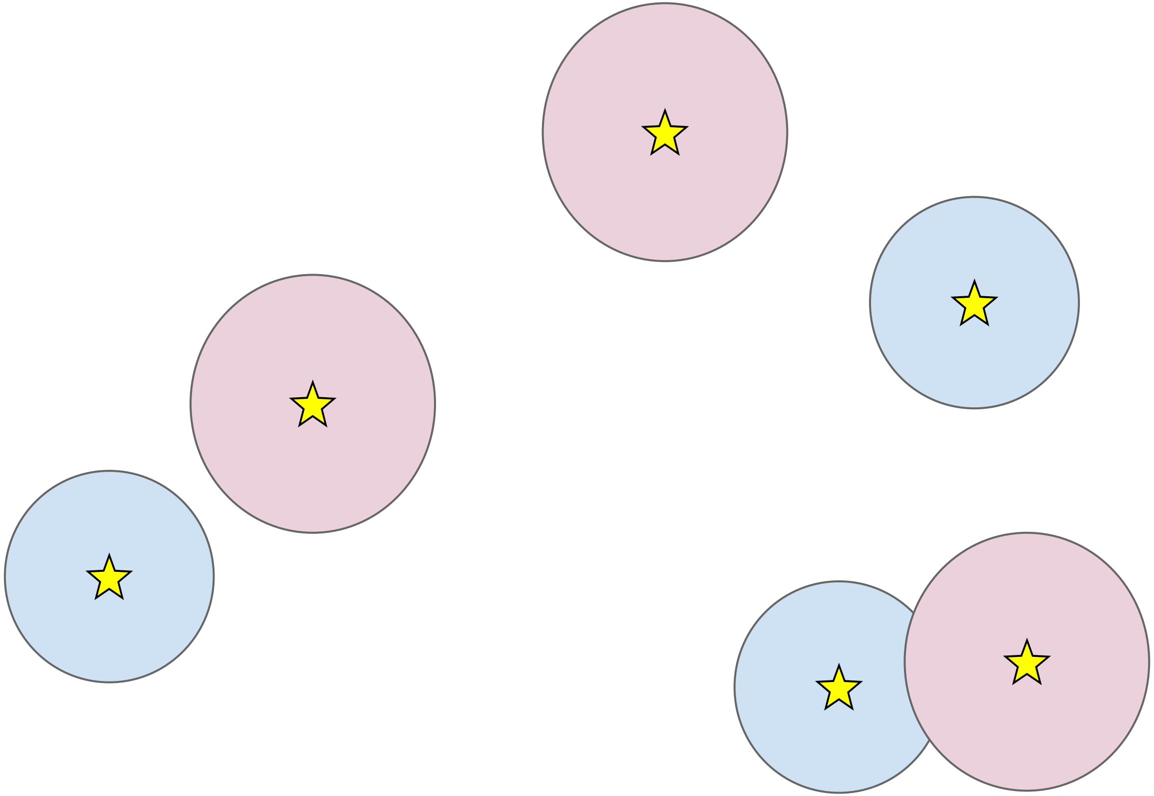
Instrumental effects are calculated using Tools21cm (SG+2020)

(SG & Schneider 2022)

Inference from 21-cm observations

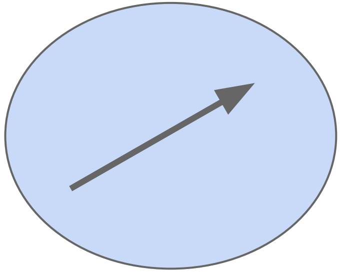


Halo model

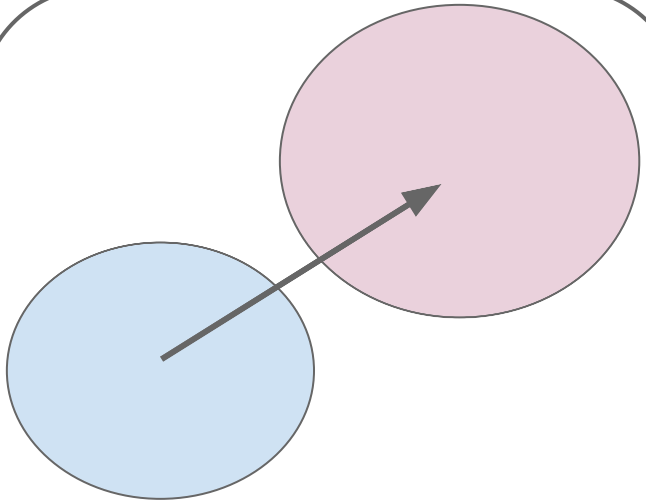


Seljak (2000)
Cooray & Sheth (2002)
...

Halo model: power spectrum



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



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

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

Ingredients for the halo model

Linear power spectrum

Halo mass function

Mass accretion

Halo bias

Stellar to halo mass relation

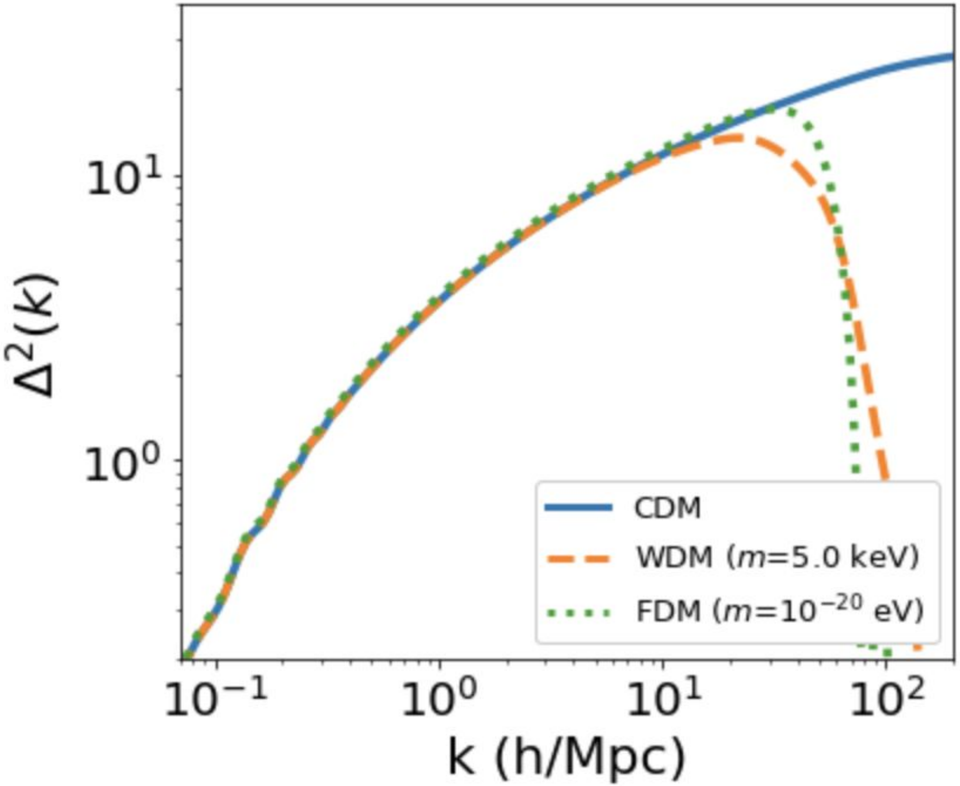
Flux profiles

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

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

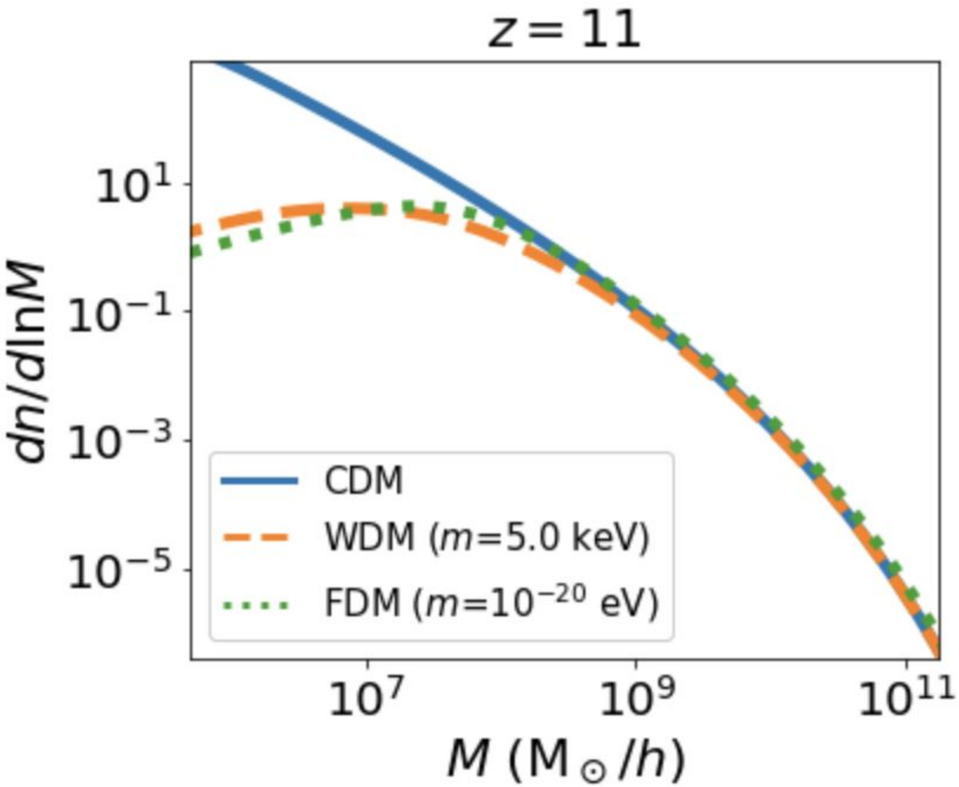
$$P_{XY}(k,z) = P^{1\,\mathrm{h}}_{XY}(k,z) + P^{2\,\mathrm{h}}_{XY}(k,z),$$

Linear power spectra



z = 0

Halo mass function



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

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

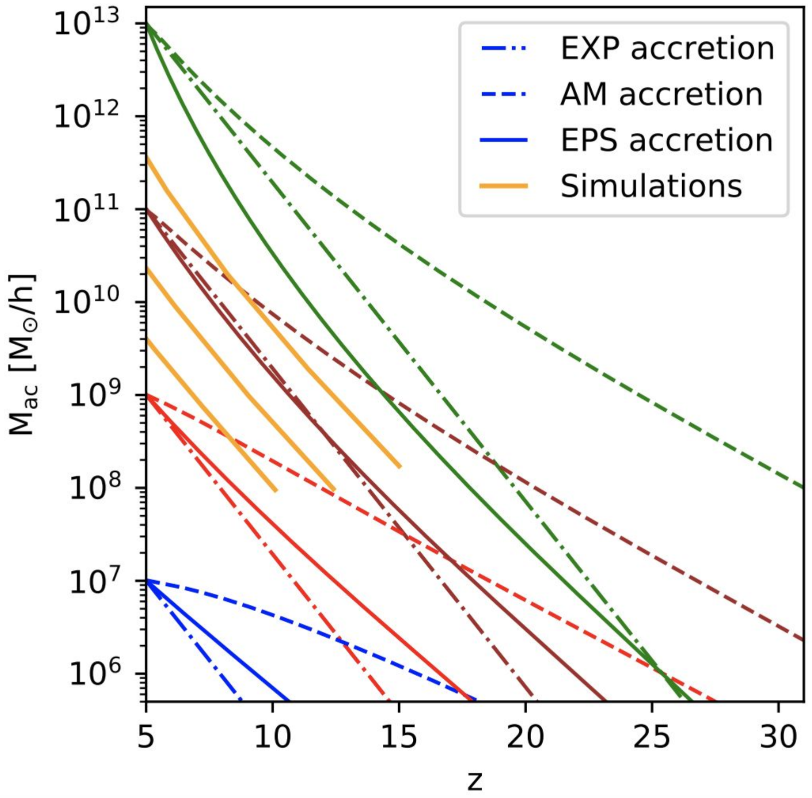
$$f(\nu) = A\sqrt{\frac{2q\nu}{\pi}}(1+\nu^{-p})e^{-q\nu/2}$$

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

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

Leo+2018

Mass accretion rate

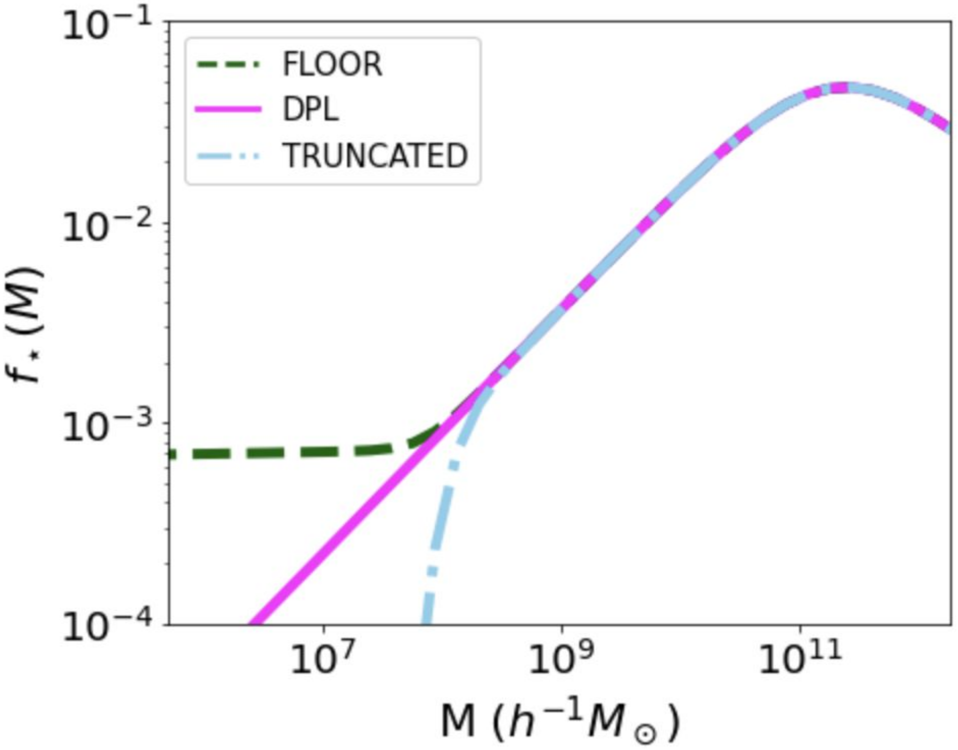


Halo bias

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

Cooray & Sheth (2002)

Stellar to halo mass relation

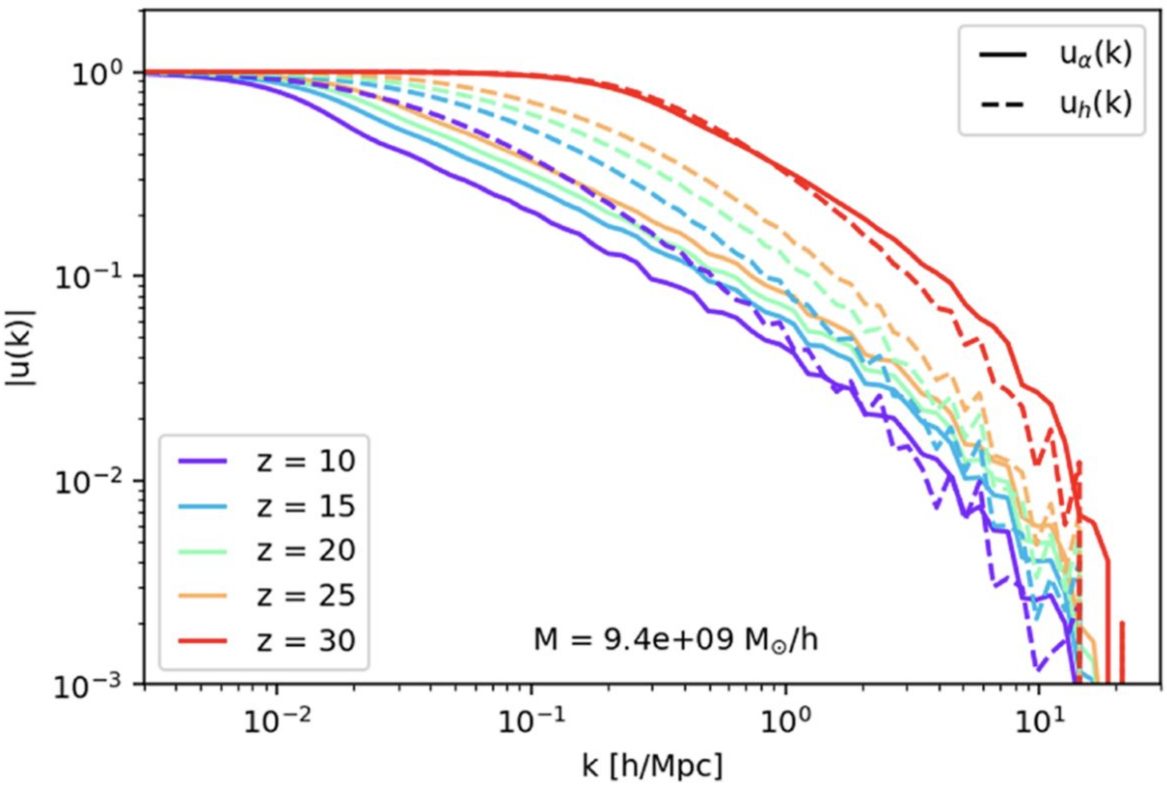


$$f_*(M) = \frac{2(\Omega_b/\Omega_m) f_{*,0}}{(M/M_p)^{\gamma_1} + (M/M_p)^{\gamma_2}} \times S(M)$$

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

(SG & Schneider 2022)

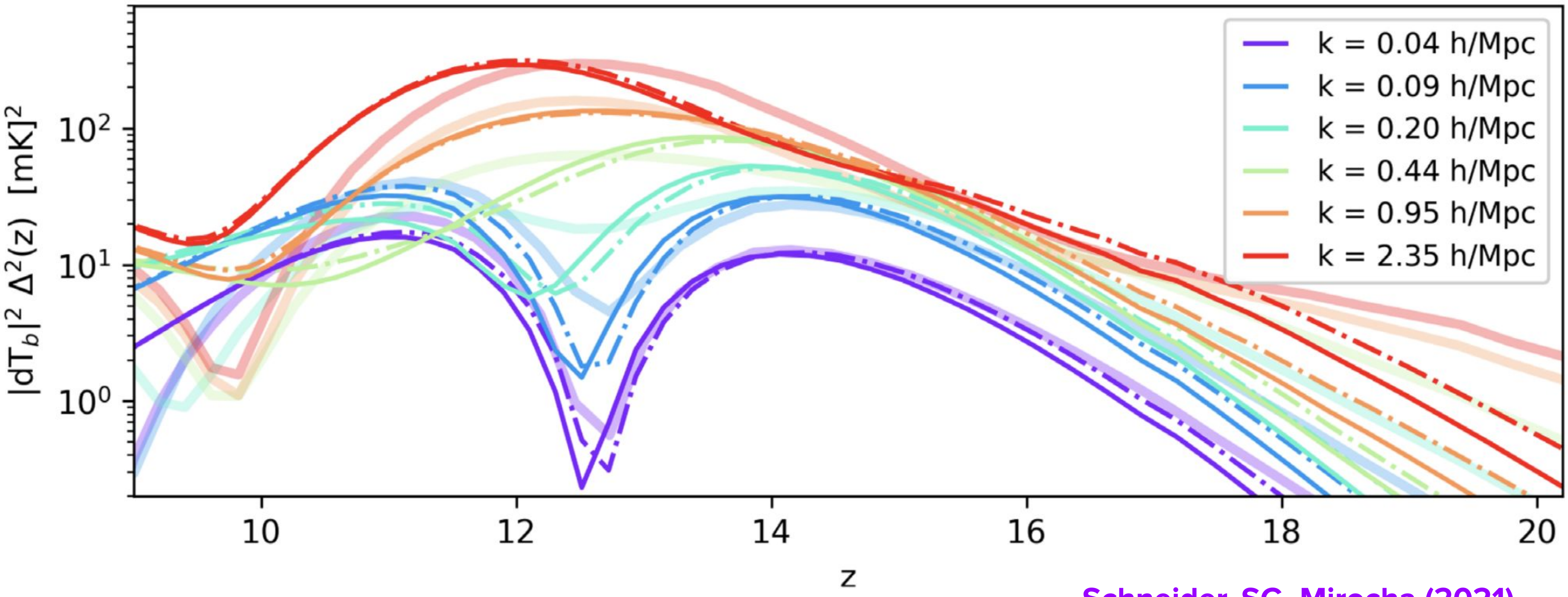
Flux profiles



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

Schneider, SG, Mirocha (2021)

Validity of the approach



Schneider, SG, Mirocha (2021)

Constraining mixed dark matter models

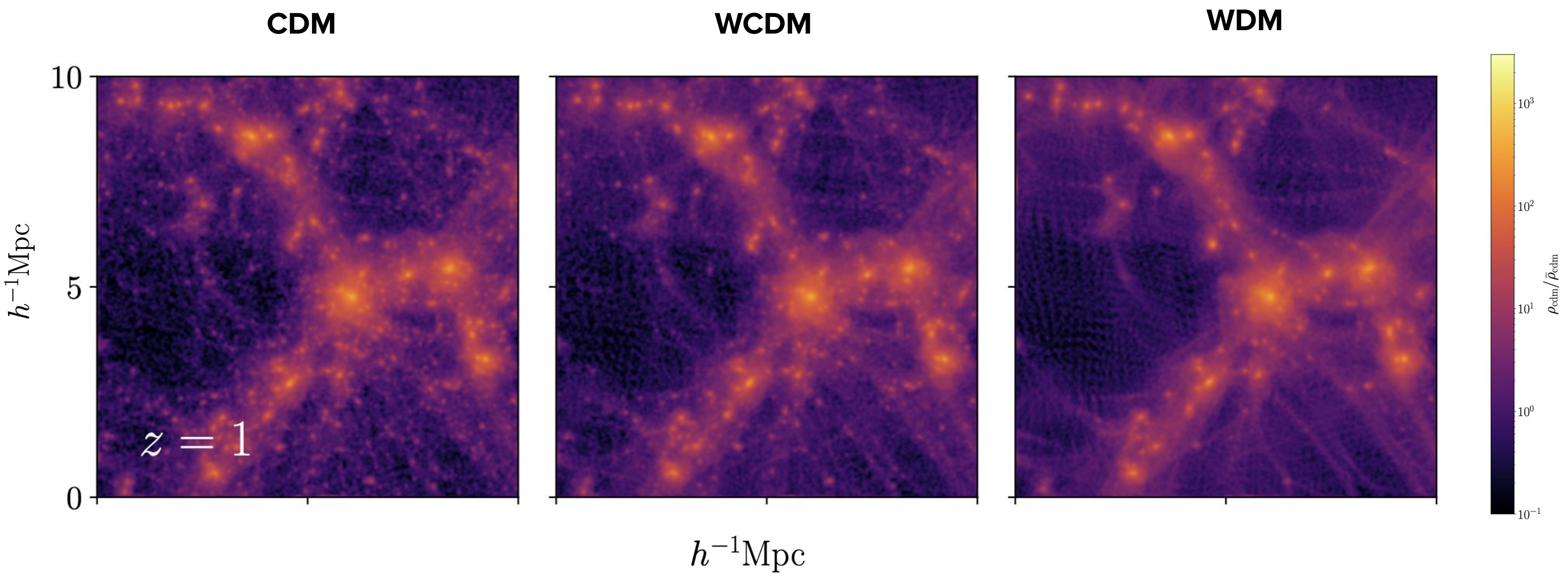
Contains a mixtures of two components

- Cold DM
- Non-cold: WDM/FDM

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

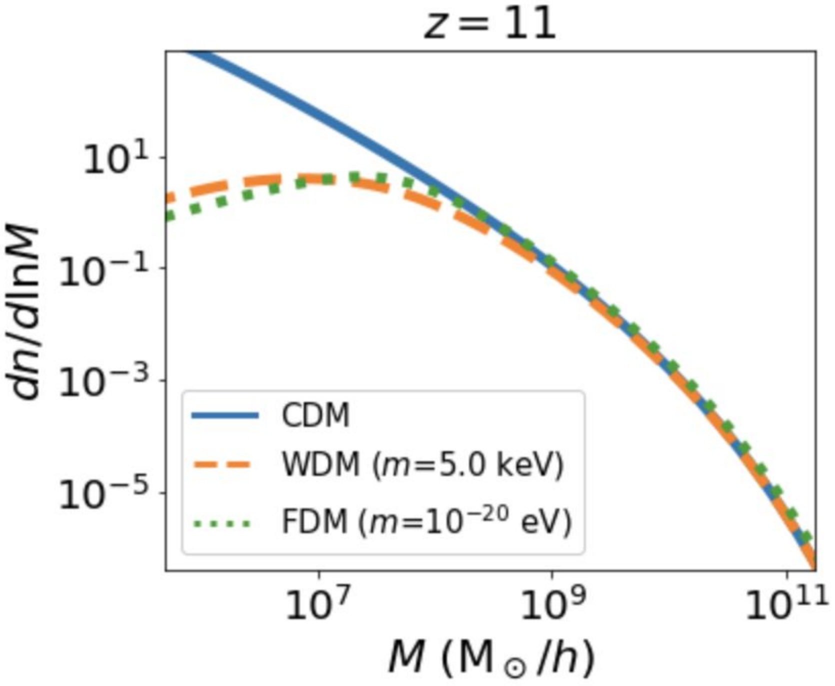
$f_{nDM} < 20\%$ (Boyarsky+2009)

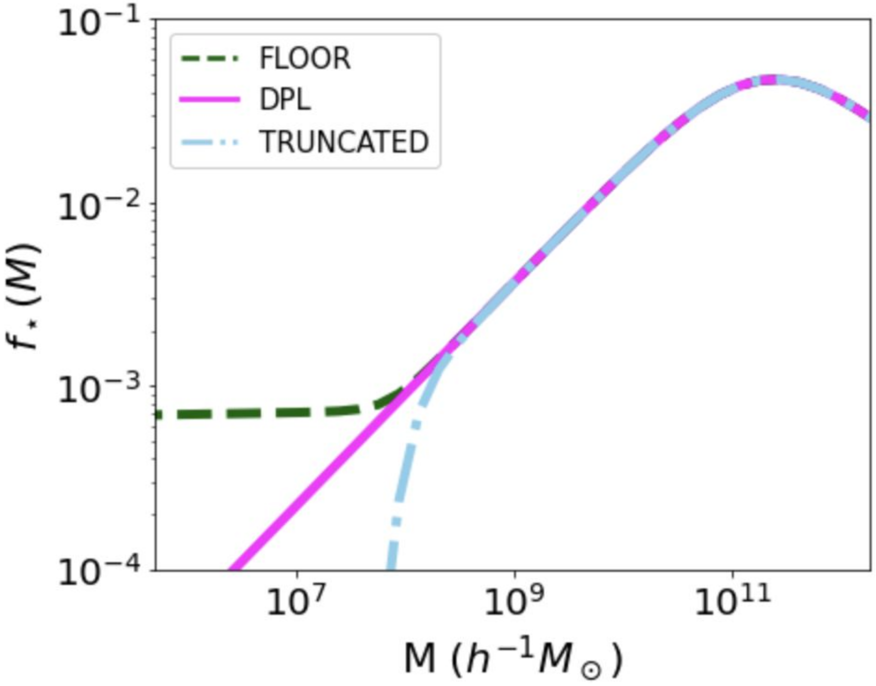
Snapshots of Cold-Warm dark matter



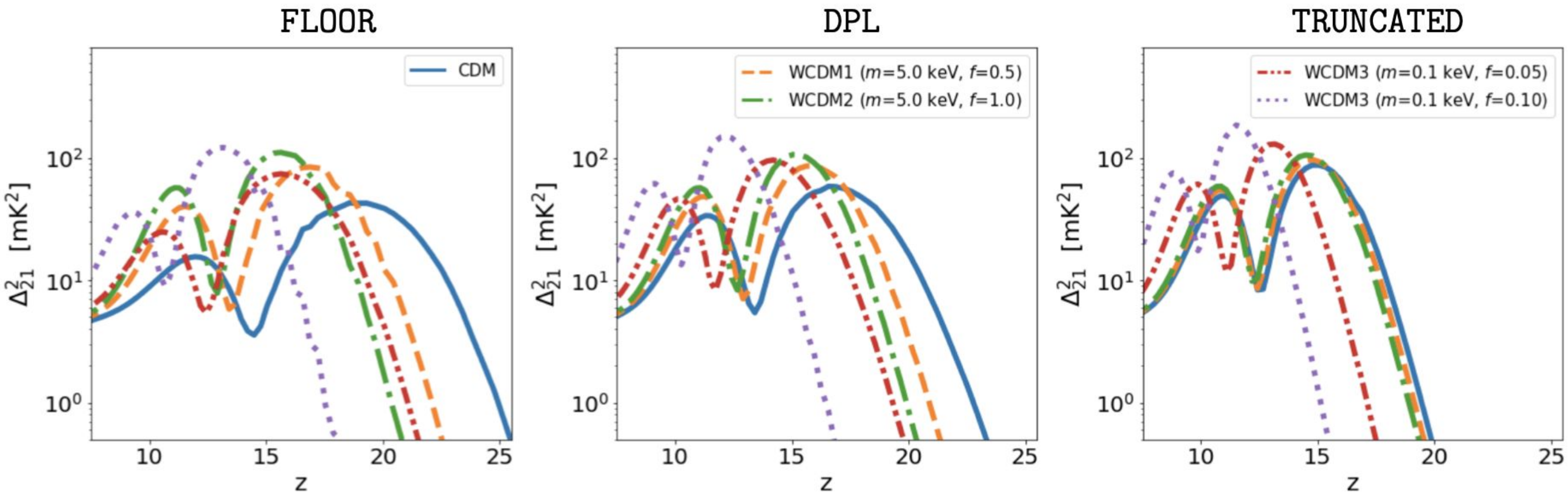
Parimbelli, Scelfo,SG+2021

Constraining dark matter models

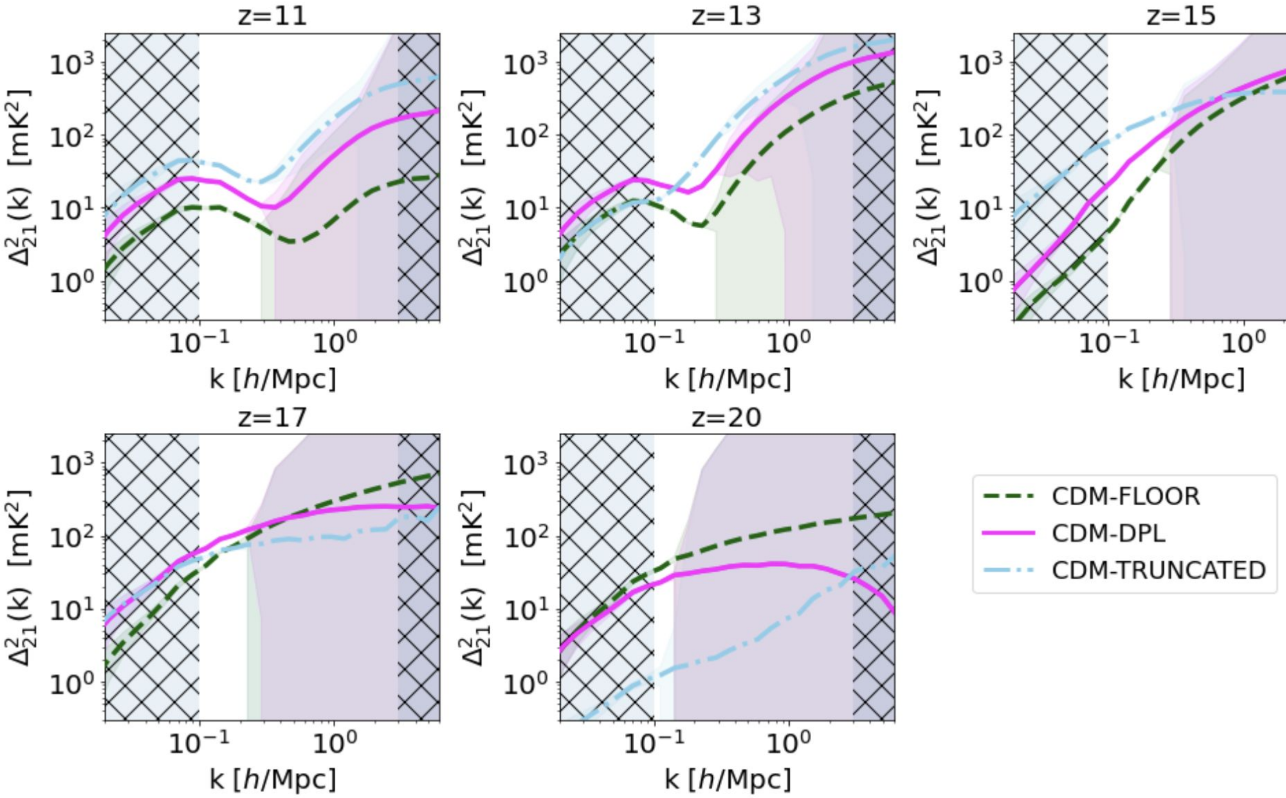




Evolution of power spectra

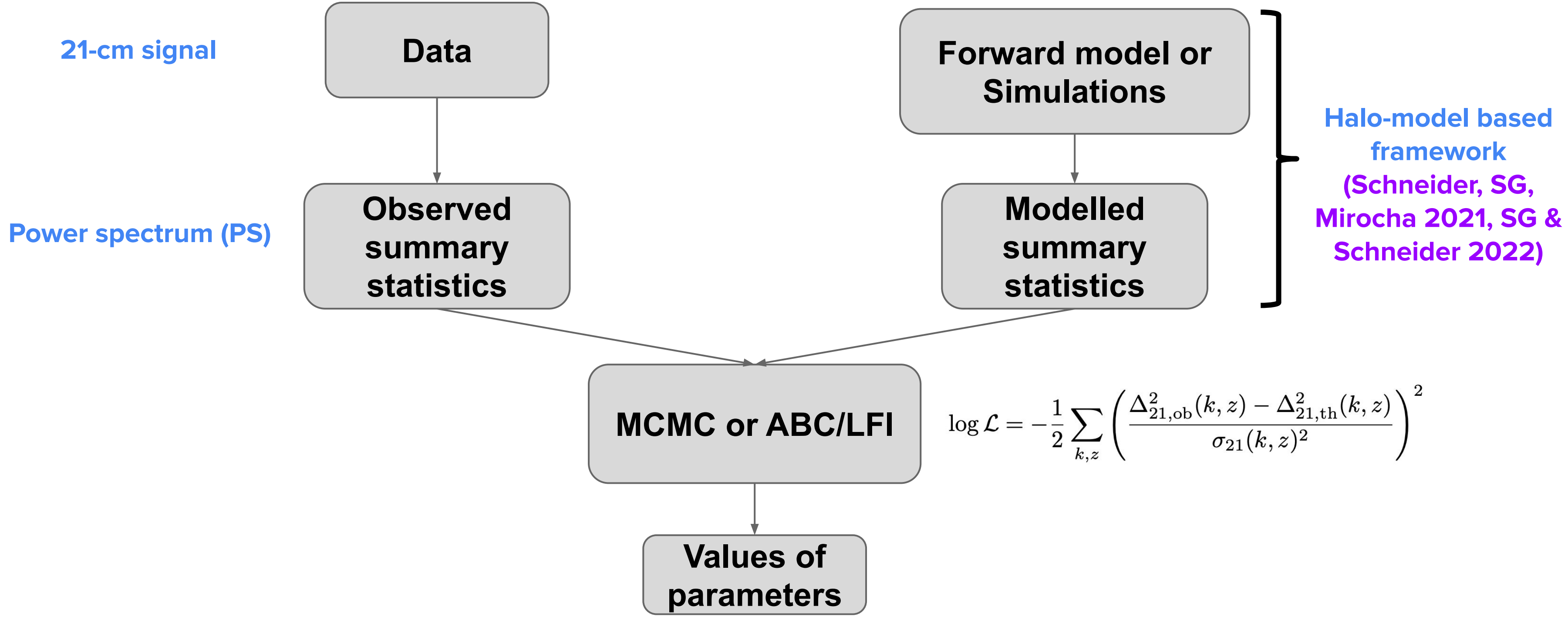


Mock observation at cosmic dawn



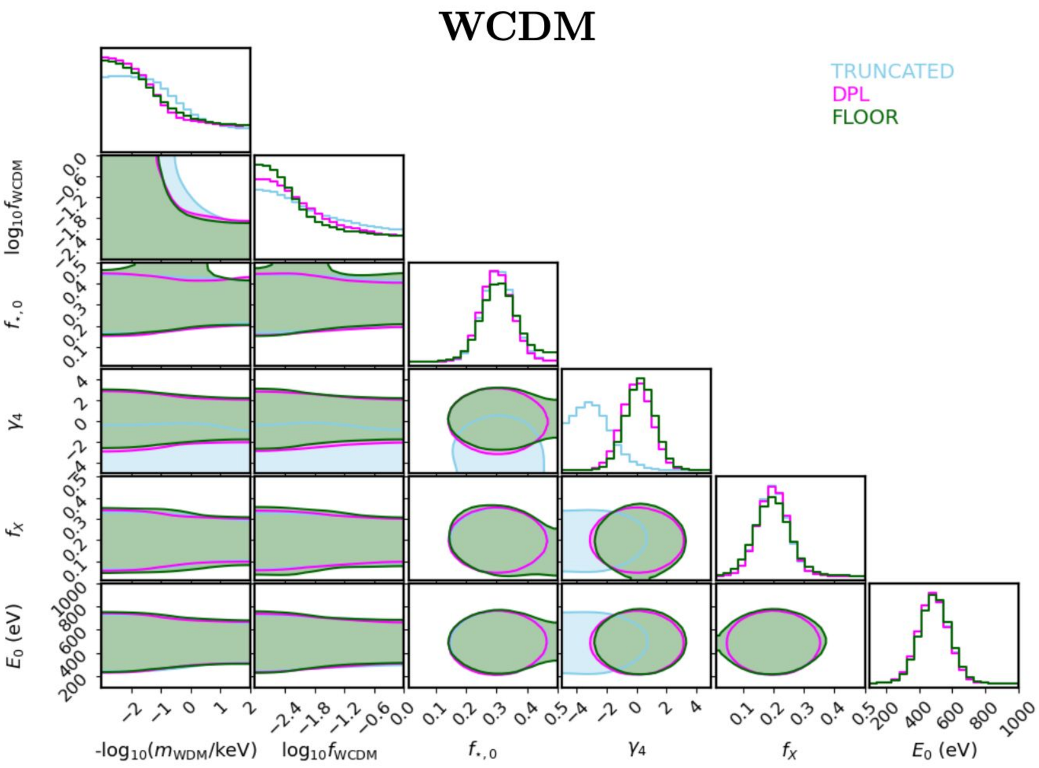
(SG & Schneider 2022)

Inference from 21-cm observations

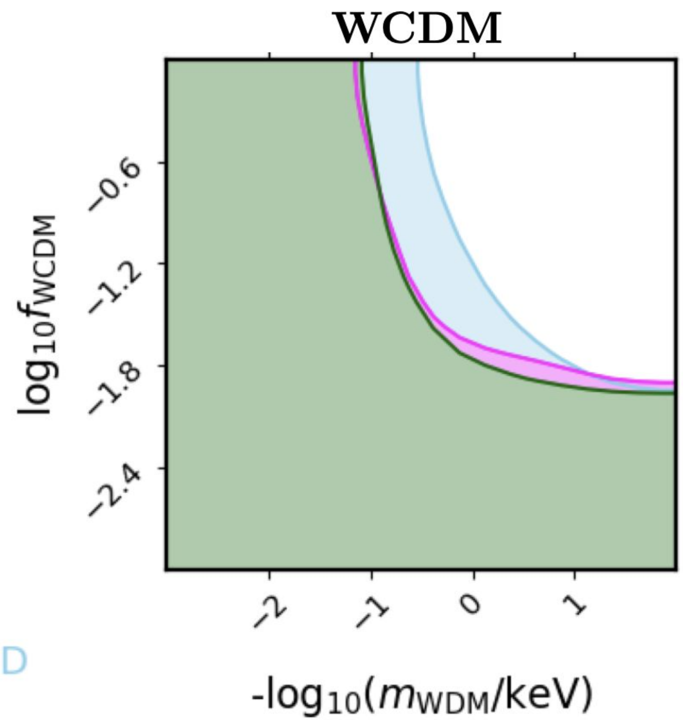


$$\log \mathcal{L} = -\frac{1}{2} \sum_{k,z} \left(\frac{\Delta^2_{21,\mathrm{ob}}(k,z) - \Delta^2_{21,\mathrm{th}}(k,z)}{\sigma_{21}(k,z)^2} \right)^2$$

Corner showing the posterior distribution



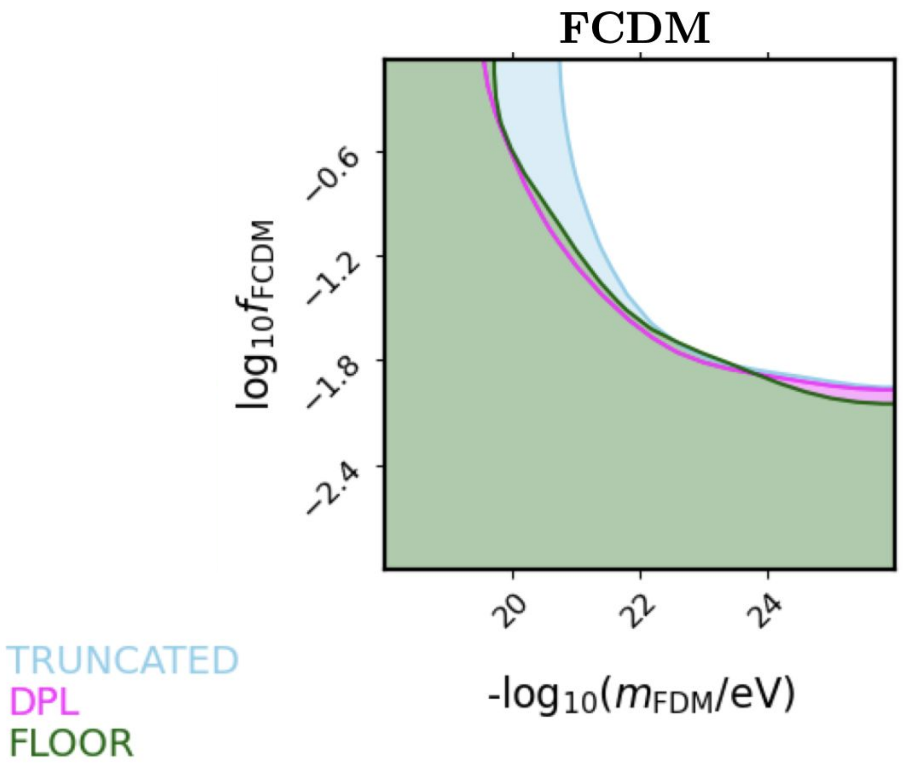
Constraints on cold + warm DM



TRUNCATED
DPL
FLOOR

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

Constraints on cold + fuzzy DM



$$f \sim 1 : m_{\rm FDM} \gtrsim 2 \times 10^{-20}\ \mathrm{eV}\ (\mathrm{FLOOR, DPL}),$$
$$\gtrsim 2 \times 10^{-21}\ \mathrm{eV}\ (\mathrm{TRUNCATED})$$
$$\mathrm{CDM + hot\ relic} : f \lesssim 1\%\ (\mathrm{FLOOR, DPL, TRUNCATED})$$

Summary

- With the current upper limits, we are able to exclude extreme states of the IGM
- Models with excess radio background can achieve very high amplitude and therefore they will be easier to constrain with these upper limits
- 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