Exploring Beyond Standard Cosmological Model during the Epoch of Reionization

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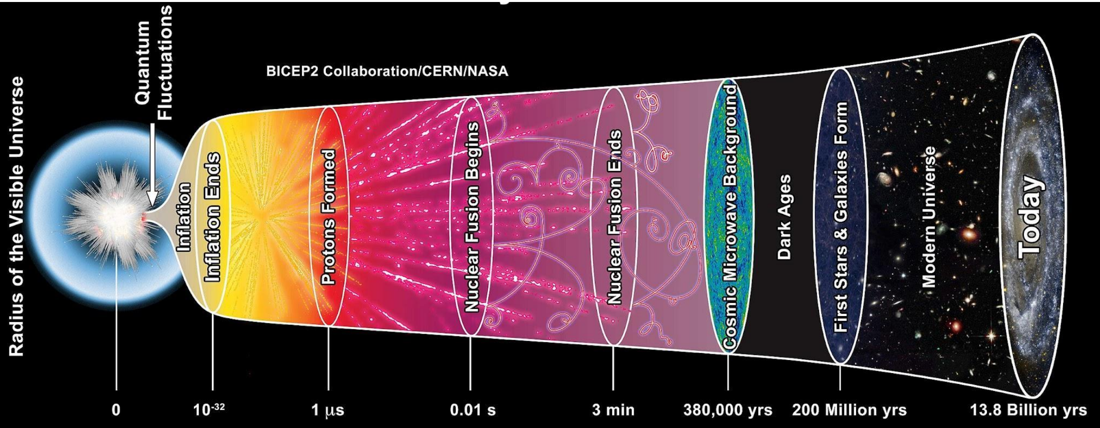
Stockholm University

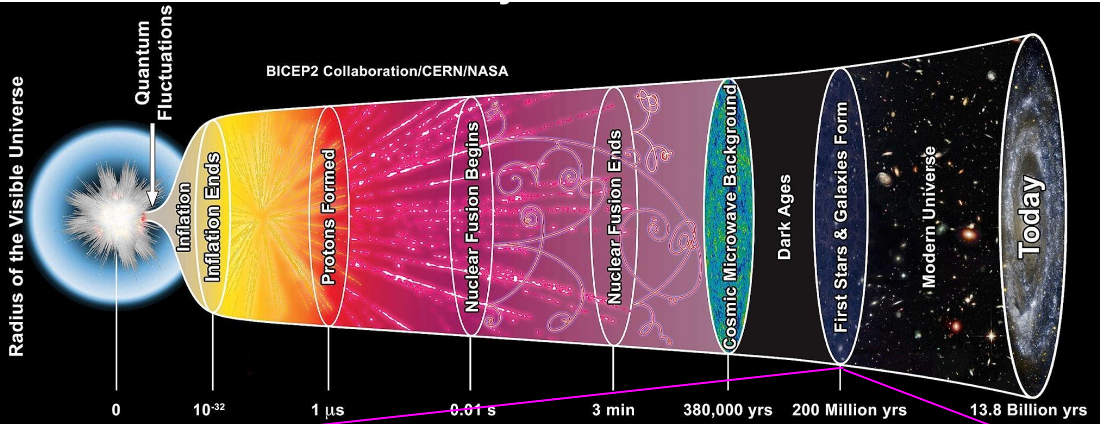
NORDITA

18-22 July 2023

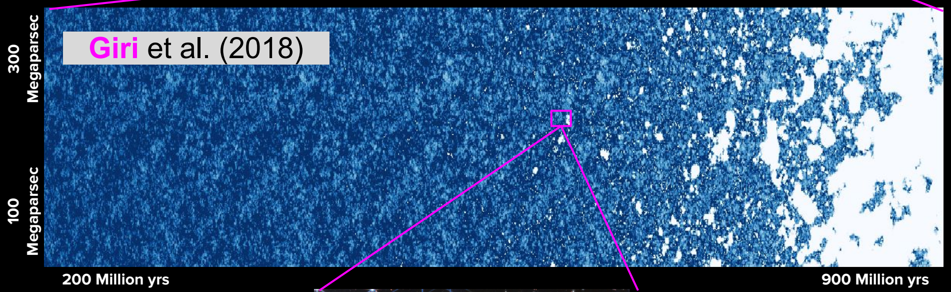
History of our Universe



History of our Universe



Intergalactic neutral hydrogen gas

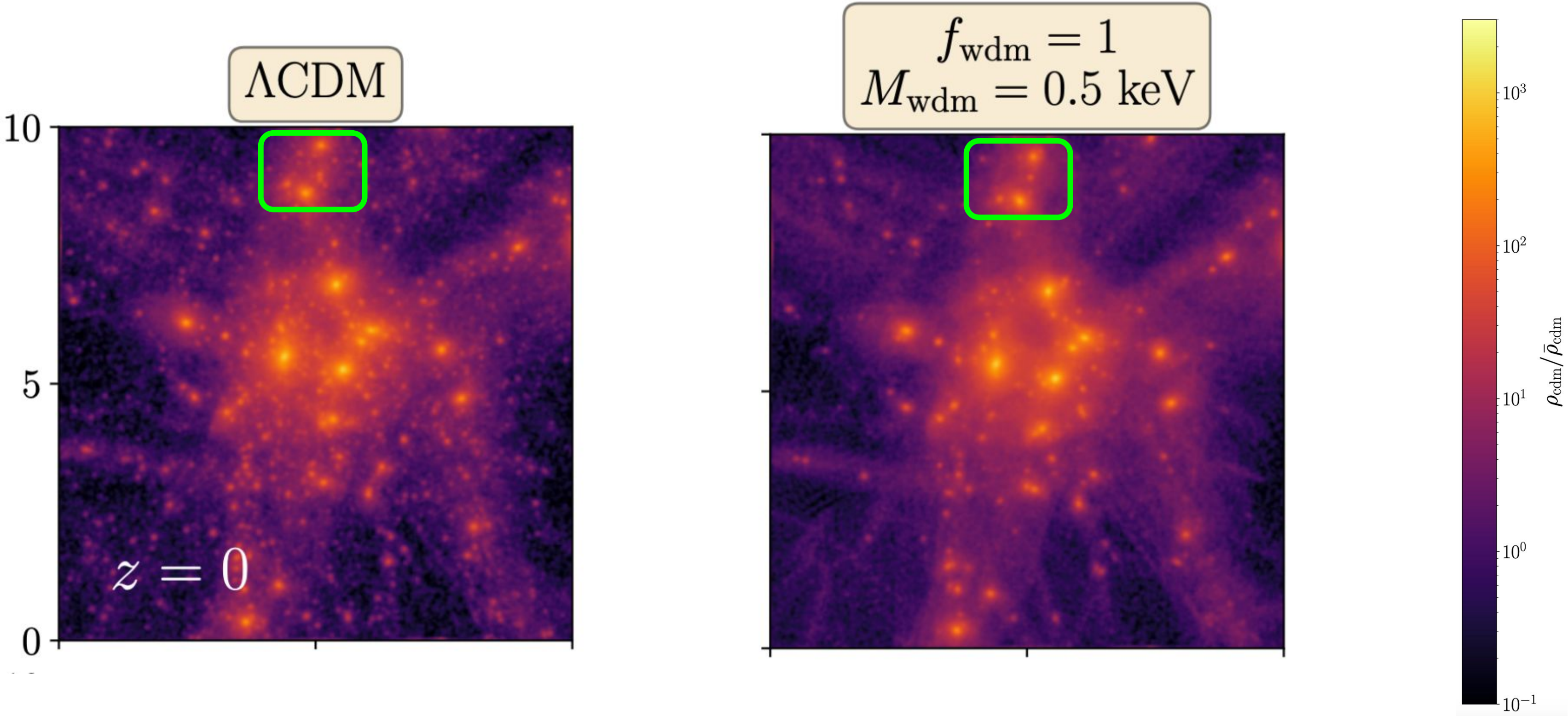


First generation of galaxies

Content

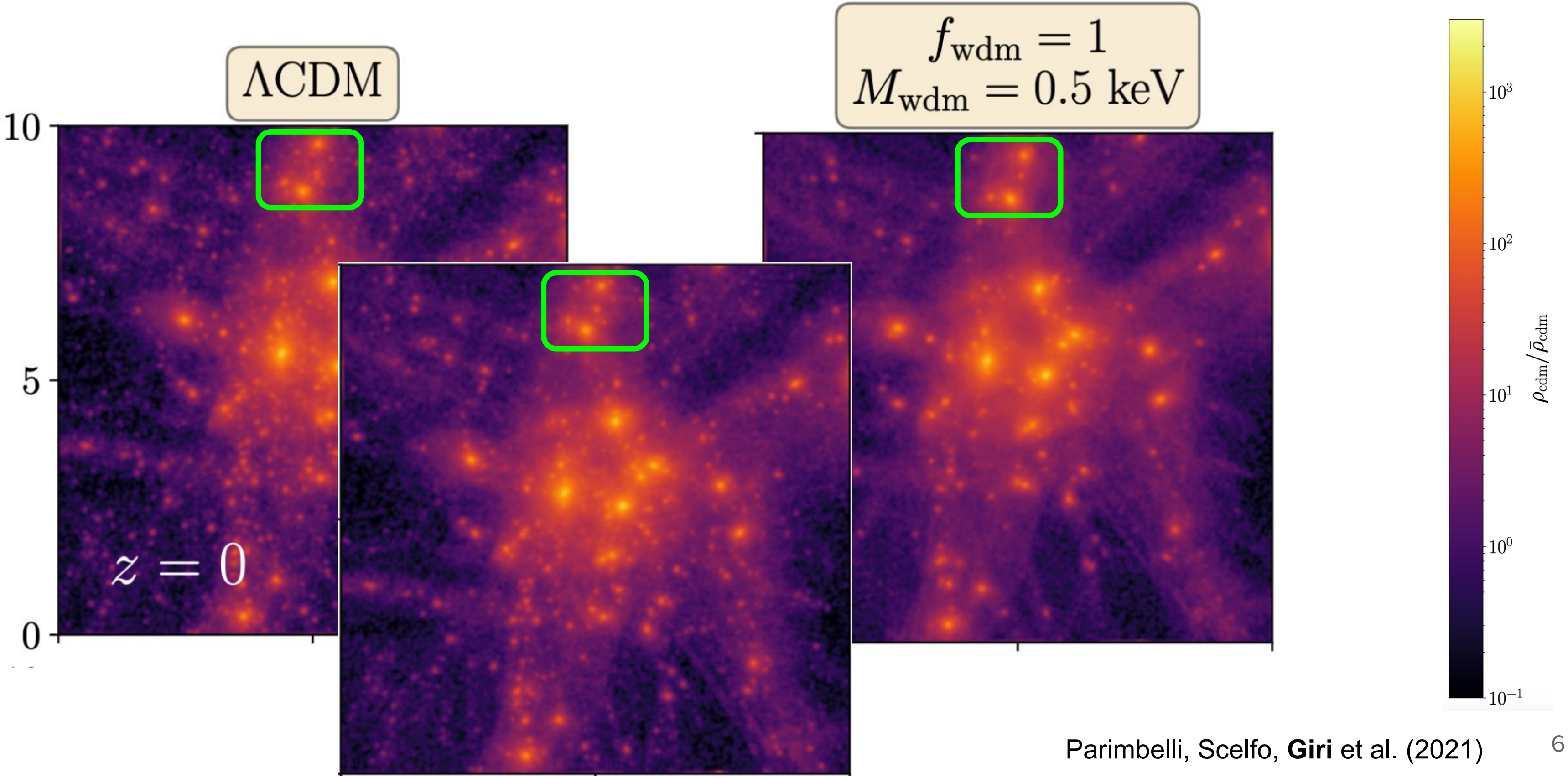
- Implications of non-standard dark matter models on reionization
- Constraints on the nature of dark matter from JWST
- Forecast study for future measurements from SKA
- Constraints on Inflation models

Non-cold dark matter models



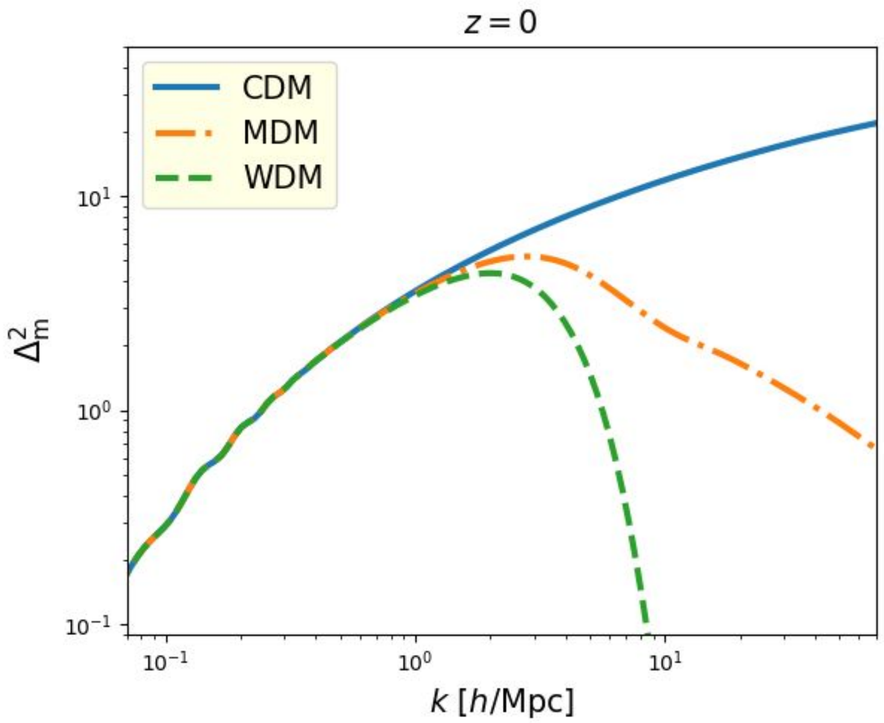
Parimbelli, Scelfo, **Giri** et al. (2021)

Mixture of cold and warm dark matter particles



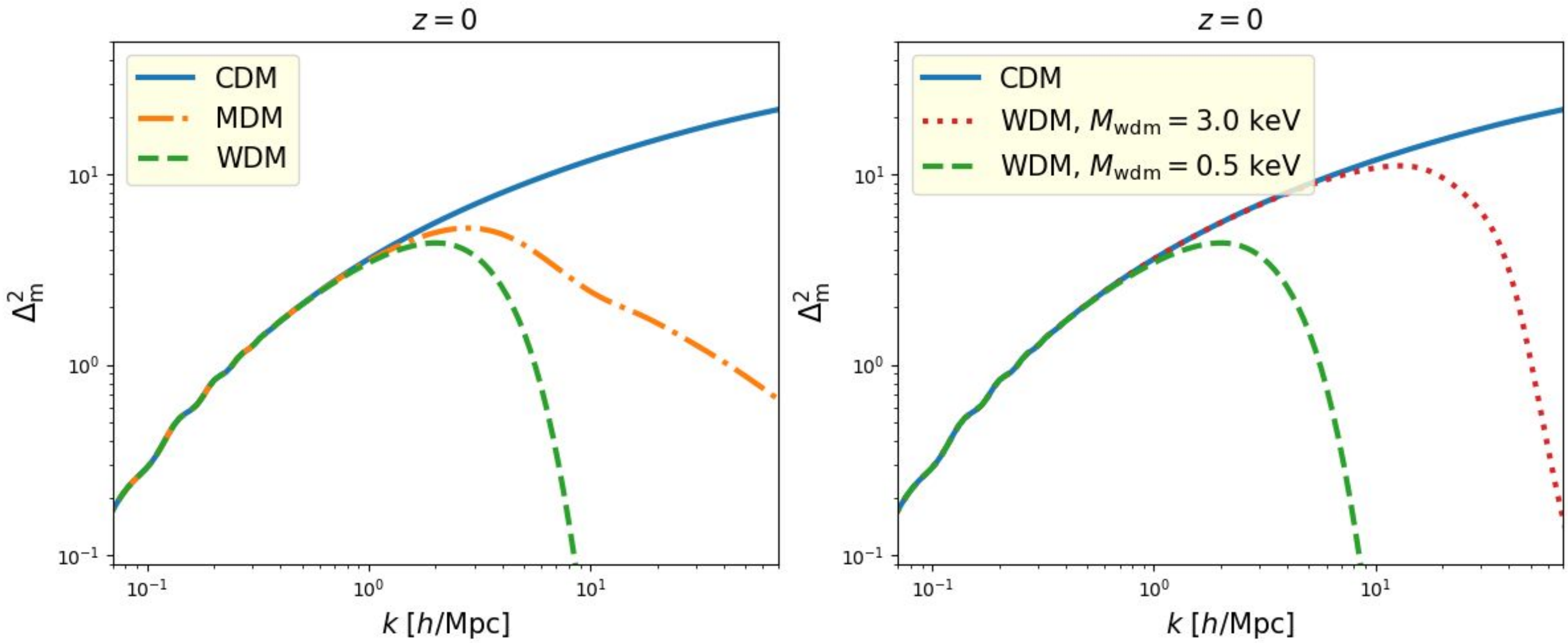
Parimbelli, Scelfo, **Giri** et al. (2021)

Matter power spectrum



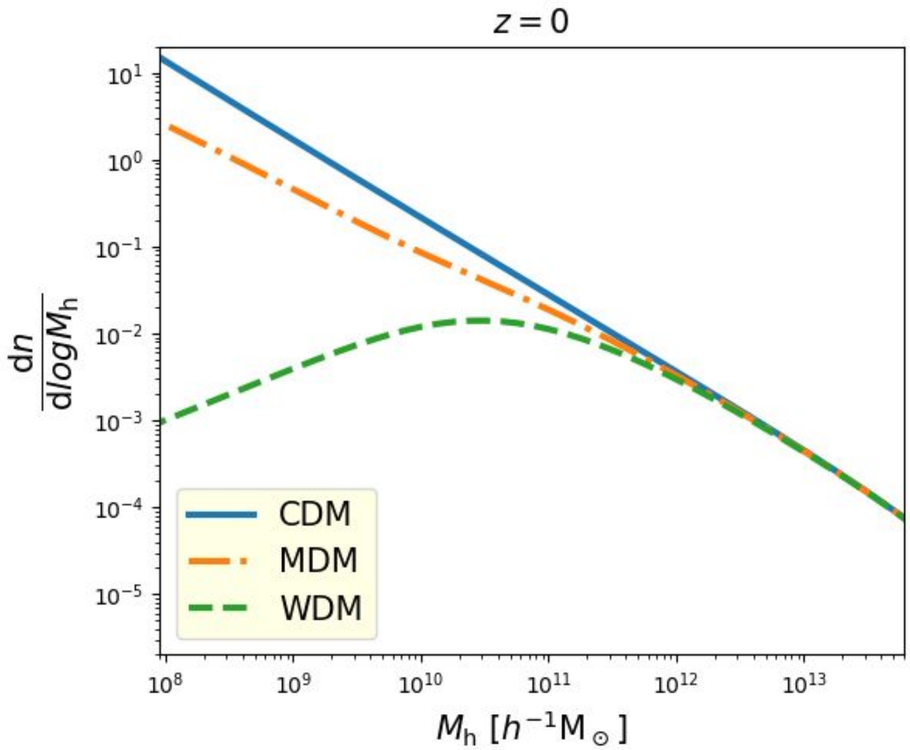
Giri & Schneider (2022)

Dark matter particle mass decides the suppression scale



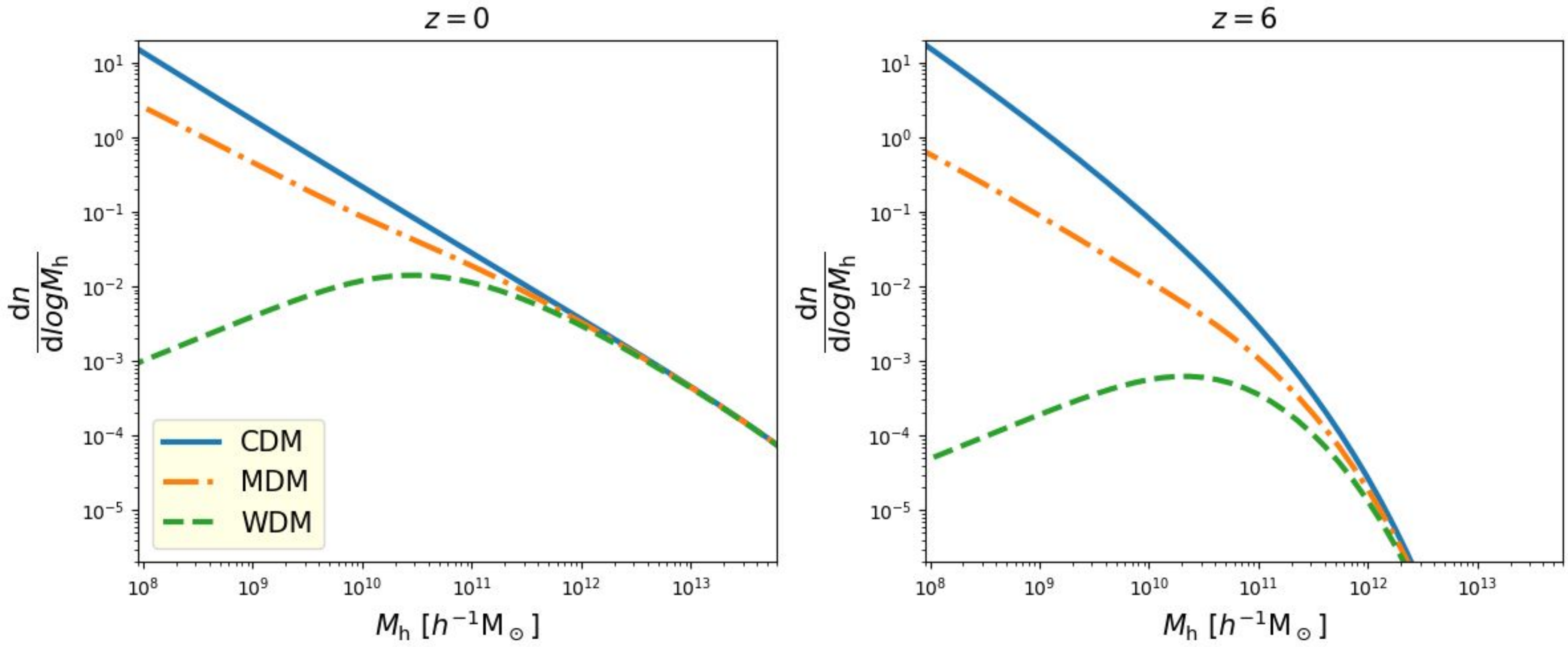
Giri & Schneider (2022)

Halo Mass Function



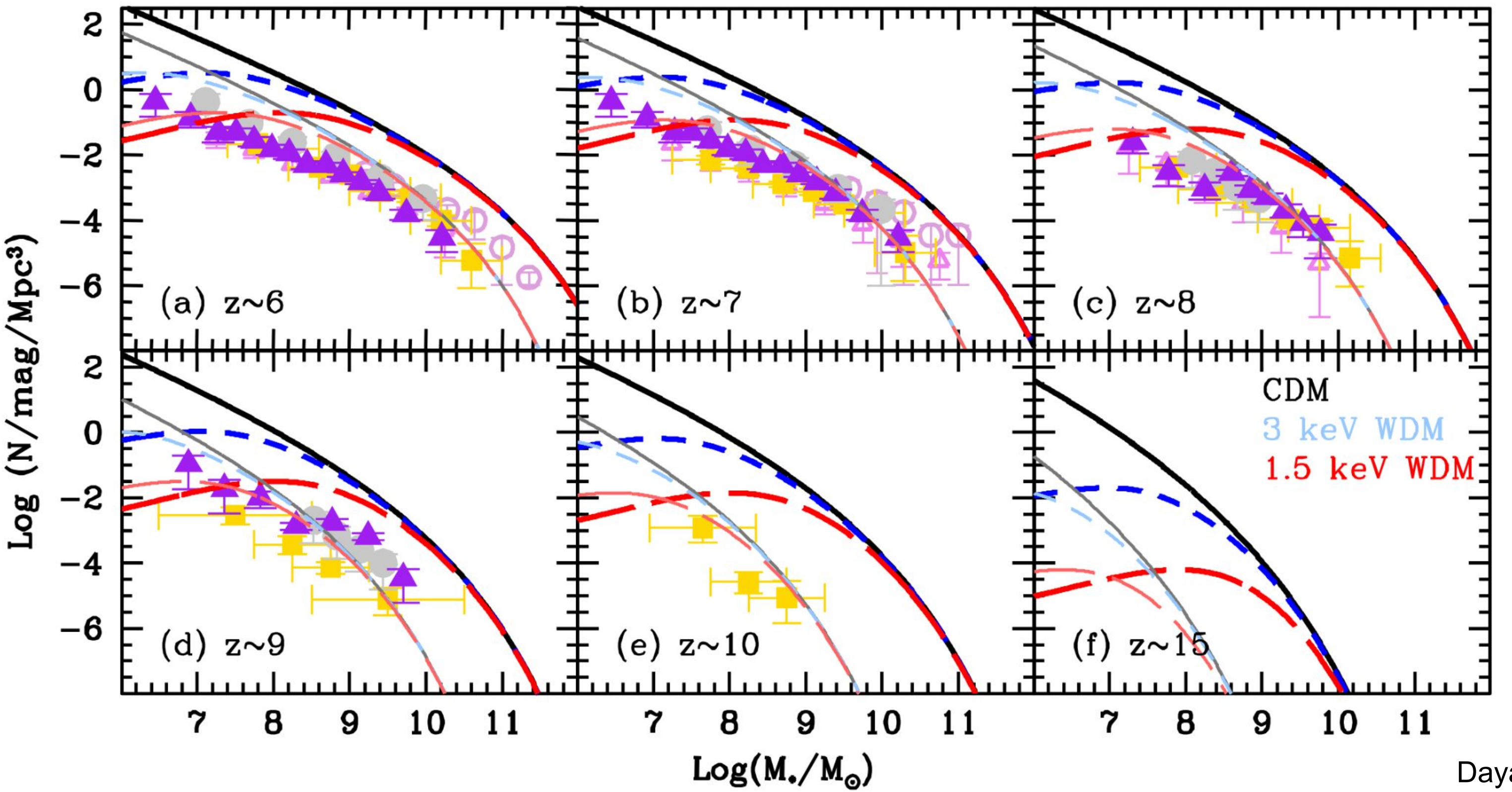
Giri & Schneider (2022)

Differences are more distinct at high redshift



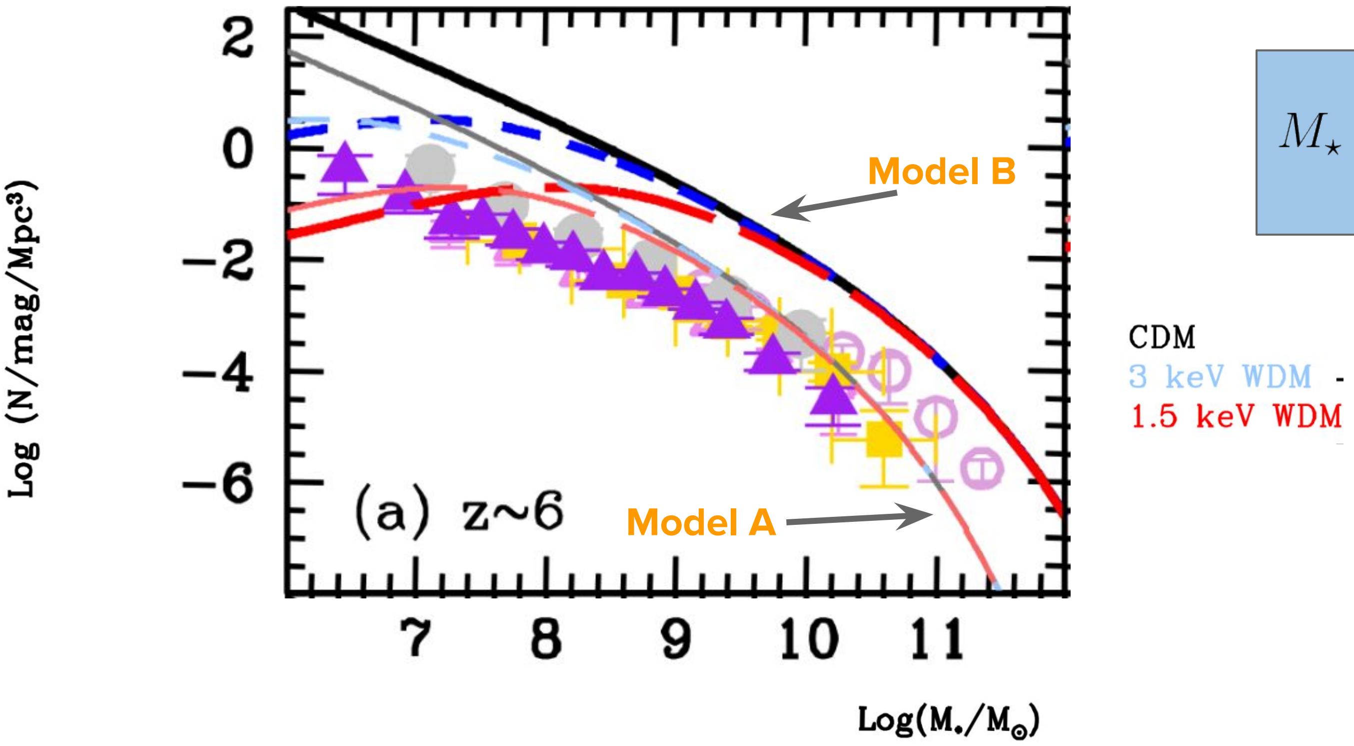
Giri & Schneider (2022)

Testing WDM models with JWST



Dayal & **Giri** (2024)

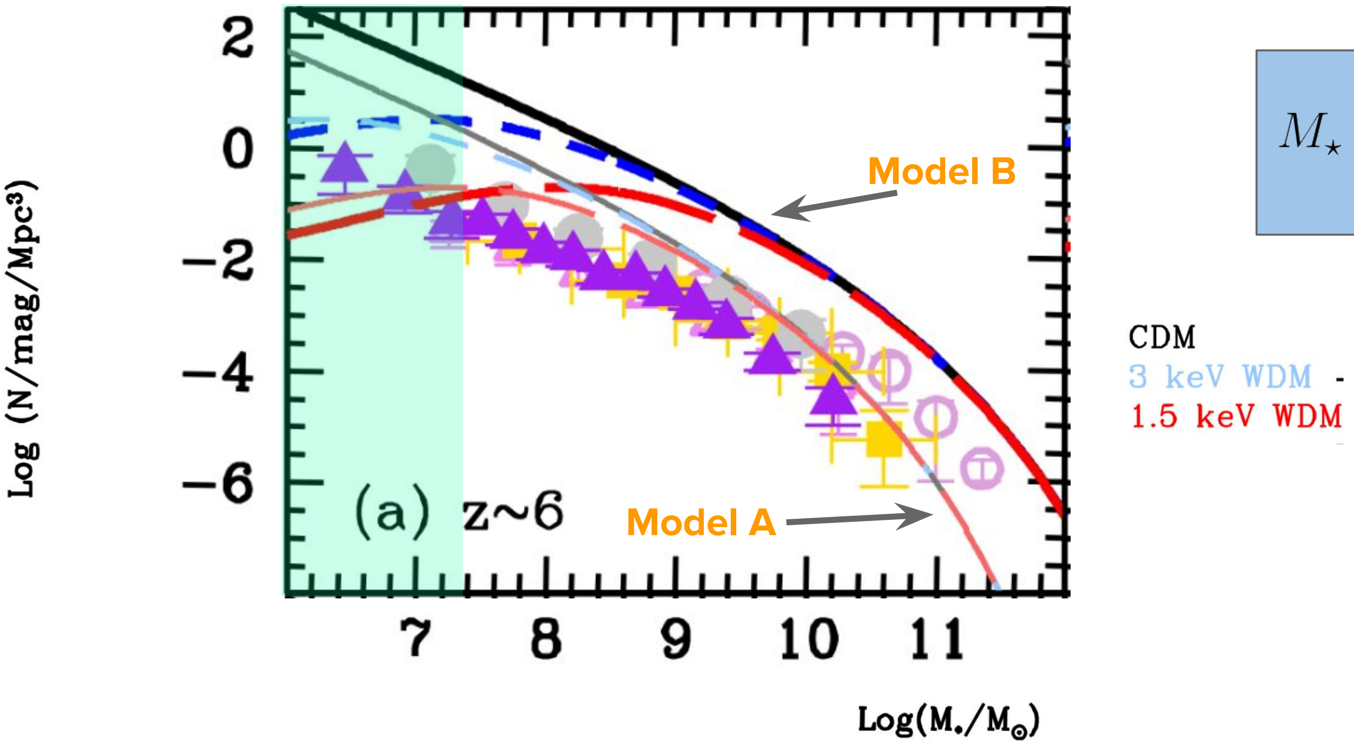
Stellar Mass Function at Redshift 6



$$M_\star = \epsilon_\star(z)\left(\frac{\Omega_{\rm b}}{\Omega_{\rm m}}\right) M_{\rm h}$$

Dayal & **Giri** (2024)

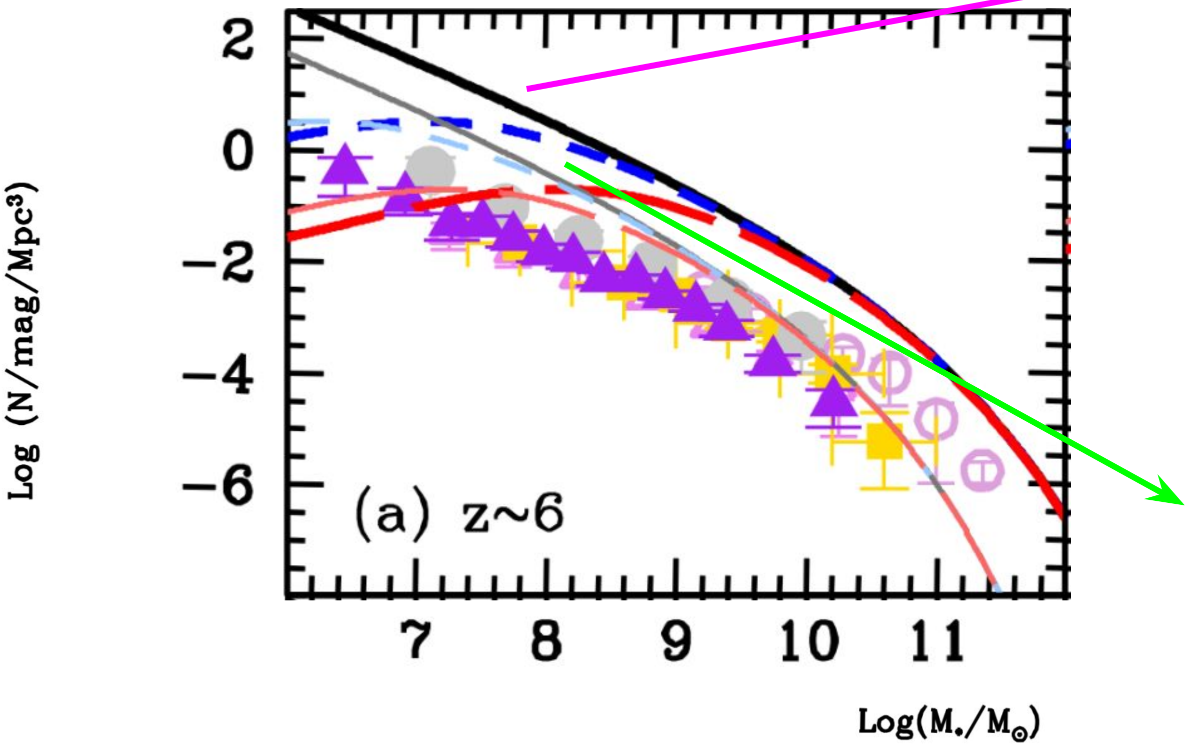
1.5 keV WDM can be ruled out

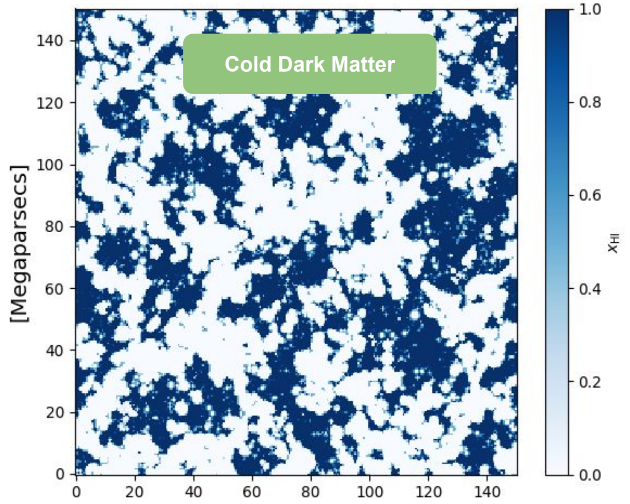


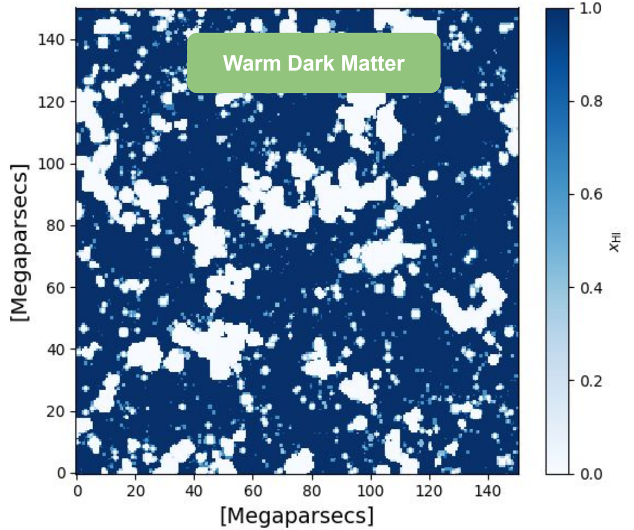
$$M_\star = \epsilon_\star(z)\left(\frac{\Omega_b}{\Omega_m}\right) M_h$$

Dayal & **Giri** (2024)

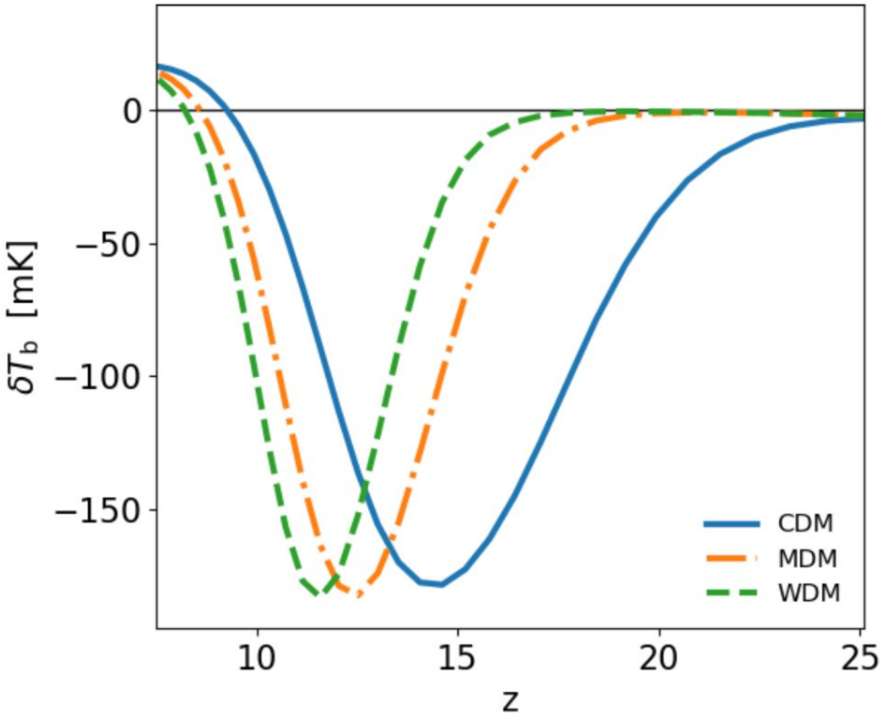
Reionization is delayed in WDM

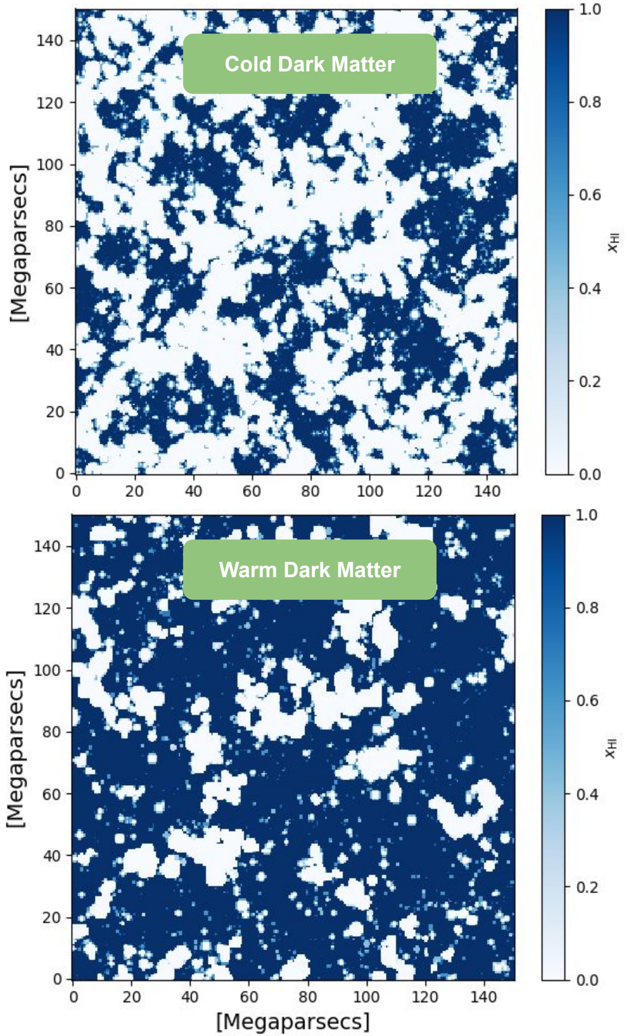






Global 21-cm signal





Giri & Schneider (2022)

One code to run them all

Timothee Schaeffer's Poster

BEoRN

Hydrodynamics + 3D RT
RAMSES
ENZO
ATON

N-body + 3D RT
pyC^{2}RAY
CRASH
LICORICE

N-body + 1D RT
BEARS
GRIZZLY

ZA/2LPT + Excursion Set
21cmFAST
Simfast21
SCRIPT

Analytical
Furlanetto et al. (2004)
HMreio (Schneider, Schaeffer, **Giri** 2023)

One code to run them all

Timothee Schaeffer's Poster

github.com/cosmic-reionization/BEoRN

BEoRN

Hydrodynamics + 3D RT
RAMSES
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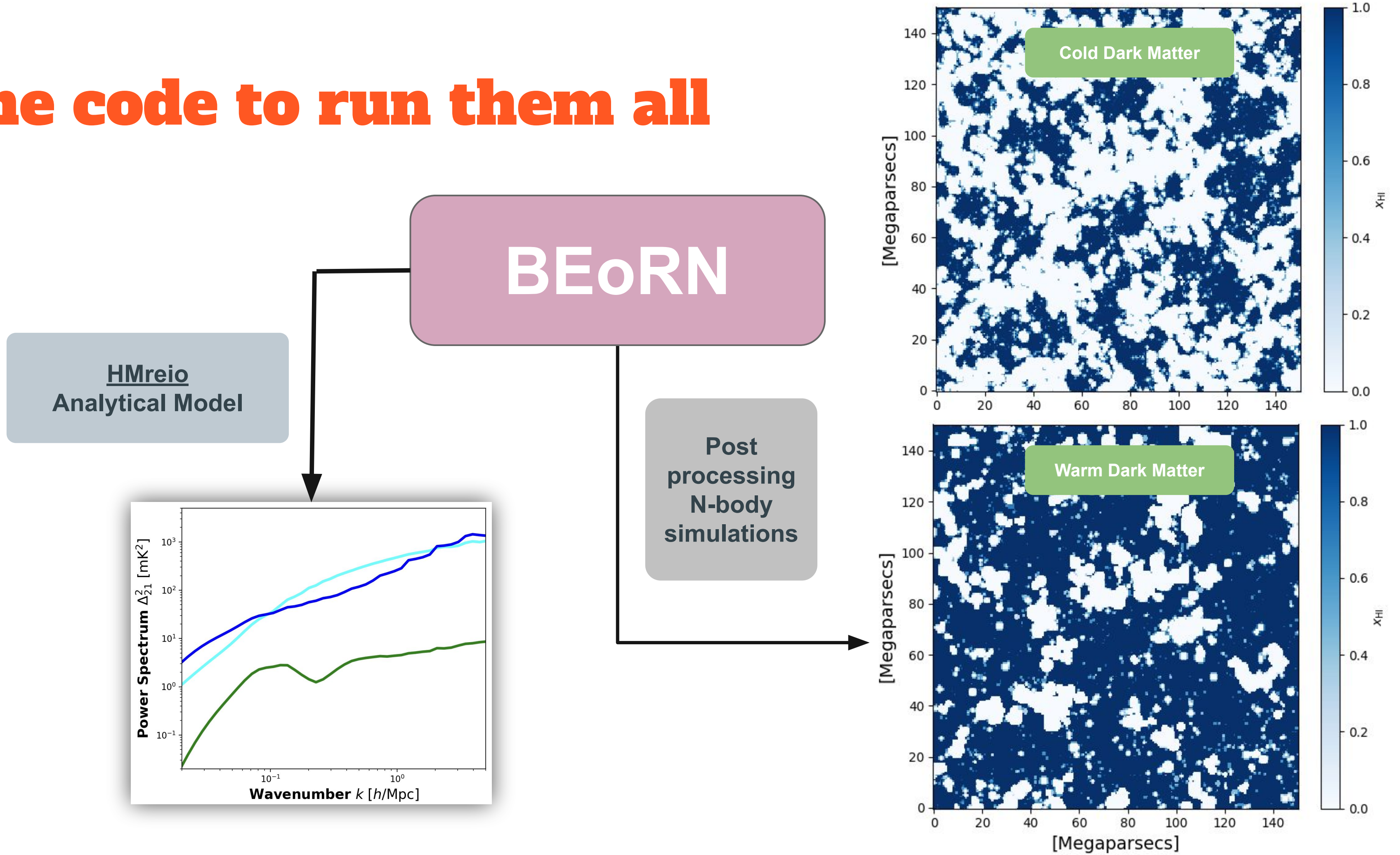
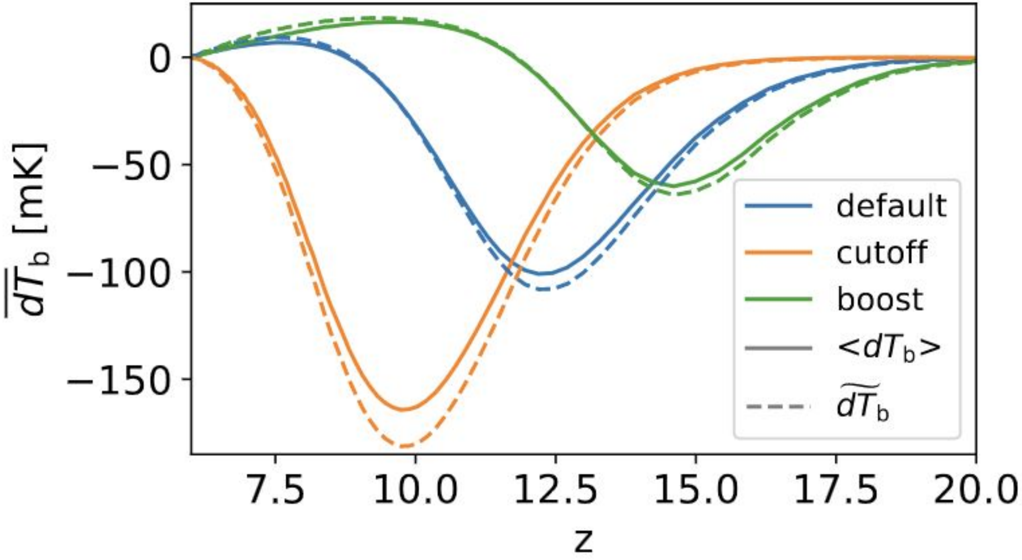
One code to run them all



HMreio: Analytical modelling of Global 21-cm signal

Timothee Schaeffer



$$\widetilde{\delta T_b} = T_0(z)\langle x_{HI}\rangle\langle 1+\delta_b\rangle \frac{x_c + x_\alpha}{1 + x_c + x_\alpha}\left[1 - \frac{T_\gamma(z)}{\langle T_k\rangle}\right]$$

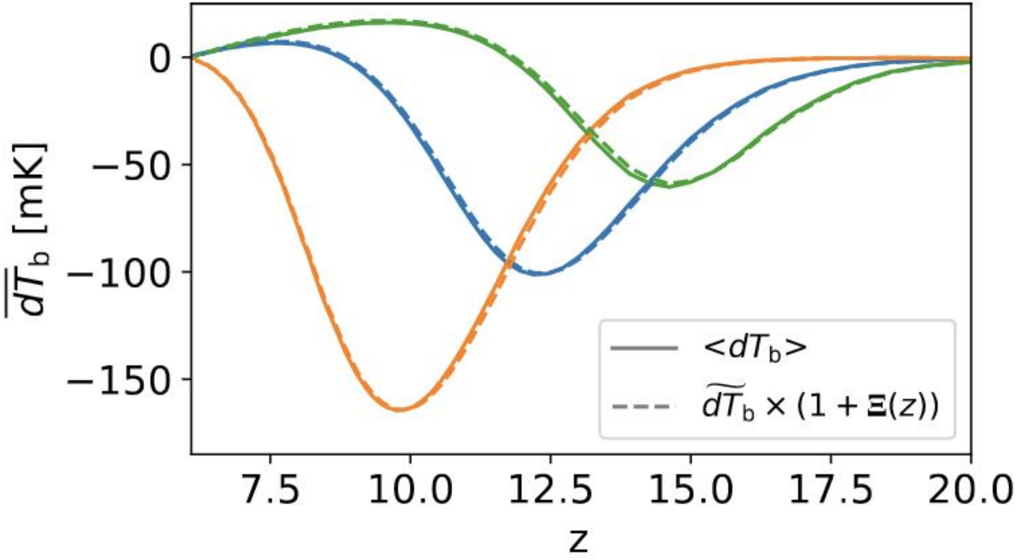
$$\frac{dx_i}{dt} = f_* f_{esc} N_{ion} \bar{n}_b^0 \frac{df_{coll}}{dt}(1 - x_e) - \alpha_A C(z) n_e x_i$$

$$\frac{3}{2}\frac{d}{dt}\left(\frac{k_B T_k n_{tot}}{\mu}\right) = \epsilon_X + \epsilon_{comp} - \mathcal{C},$$

Schaeffer, Schneider & **Giri**
(soon to be submitted)

HMreio: Correction including correlations

Timothee Schaeffer

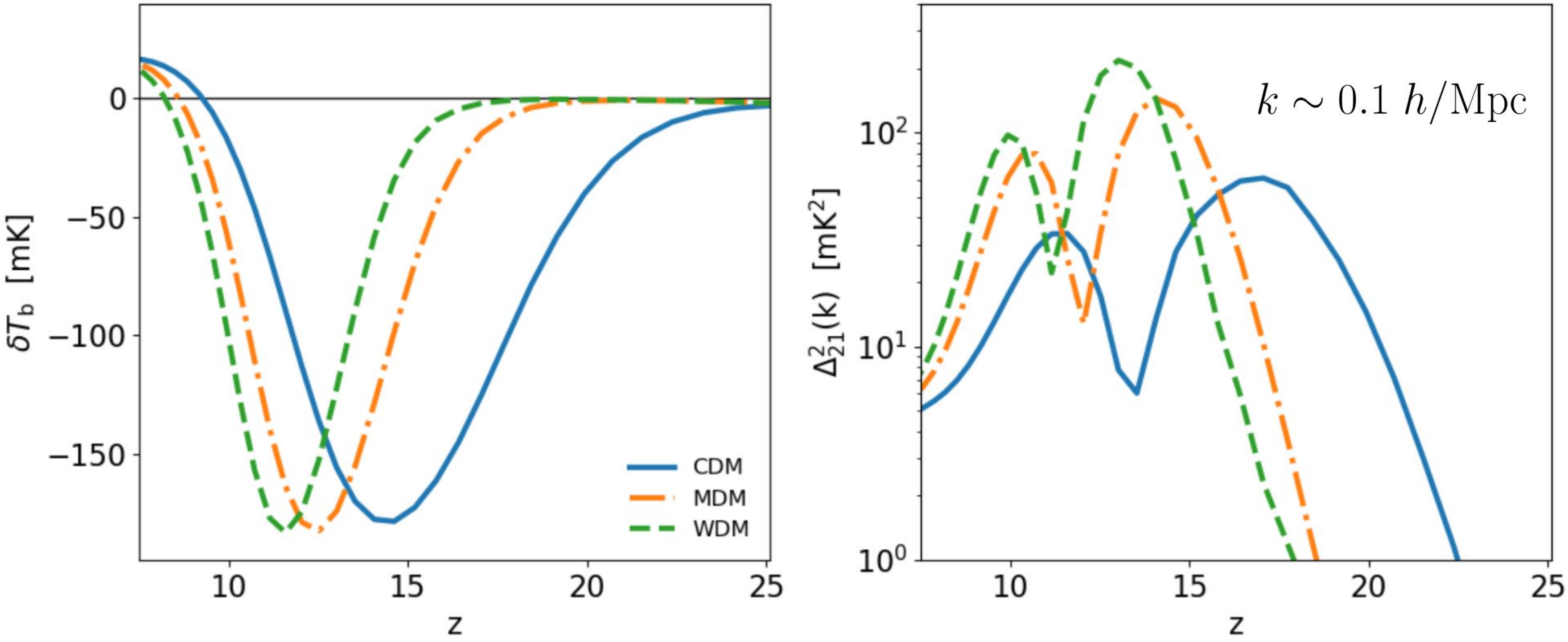


$$\widetilde{\delta T_\mathrm{b}} = T_0(z)\langle x_\mathrm{HI}\rangle\langle 1+\delta_\mathrm{b}\rangle \frac{x_c + x_\alpha}{1 + x_c + x_\alpha}\left[1 - \frac{T_\gamma(z)}{\langle T_\mathrm{k}\rangle}\right]$$

$$\widetilde{\delta T_\mathrm{b}}[1+\Xi(z)] \simeq \widetilde{\delta T_\mathrm{b}}\left(1 + \sum_{\substack{i,j\in\{r,b,T,\alpha\}\\ i\neq j}} \beta_i(z)\beta_j(z)\langle\delta_i\delta_j\rangle\right)$$

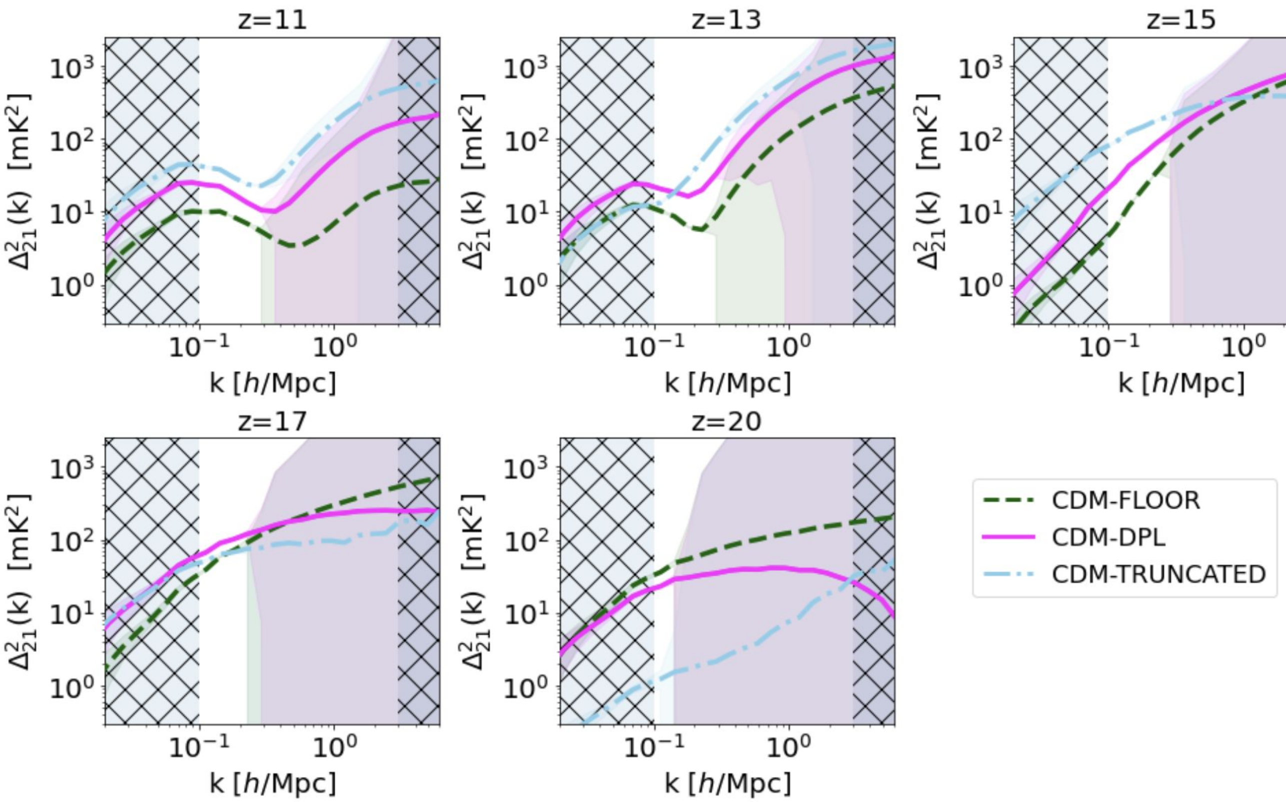
Schaeffer, Schneider & **Giri**
(soon to be submitted)

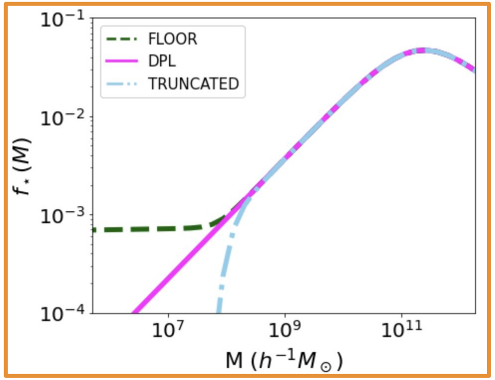
Global 21-cm signal & Power Spectrum



Giri & Schneider (2022)

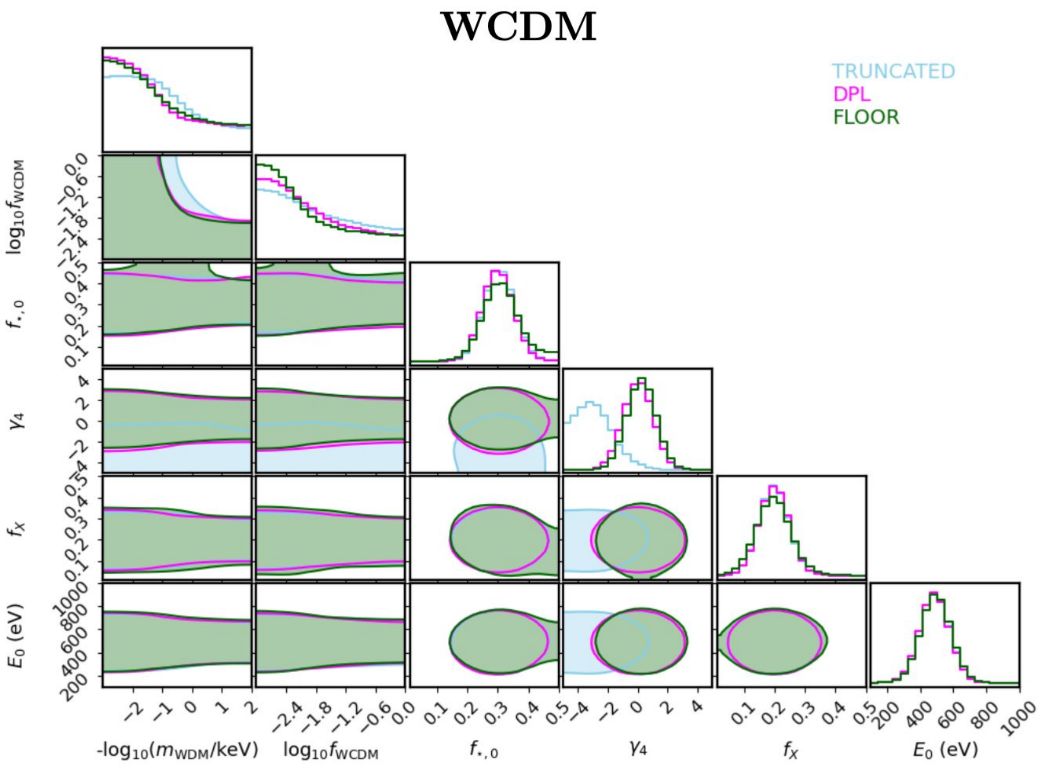
Expected SKA Power Spectra





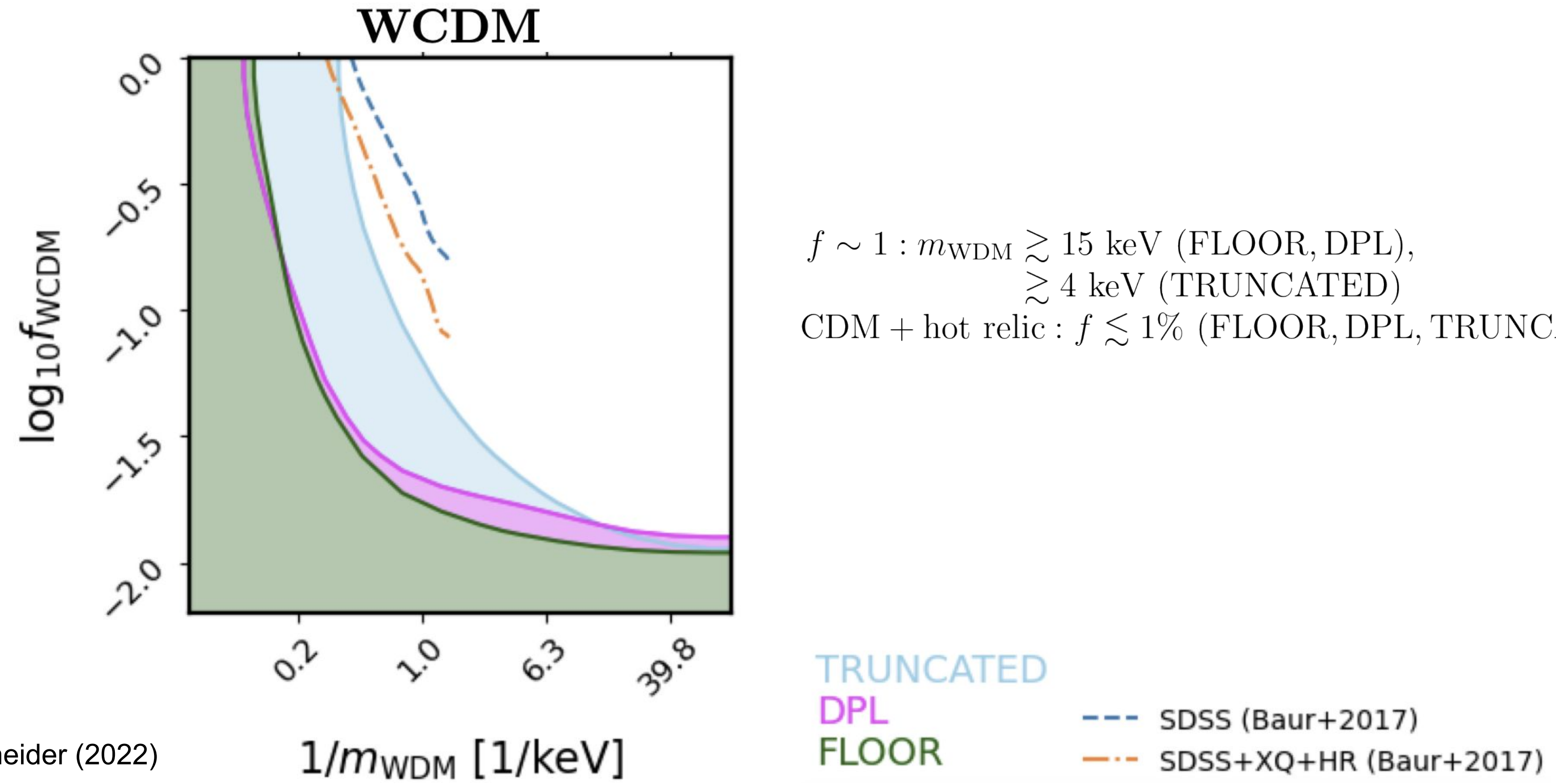
Giri & Schneider (2022)

Forecast study with SKA Power Spectra



Giri & Schneider (2022)

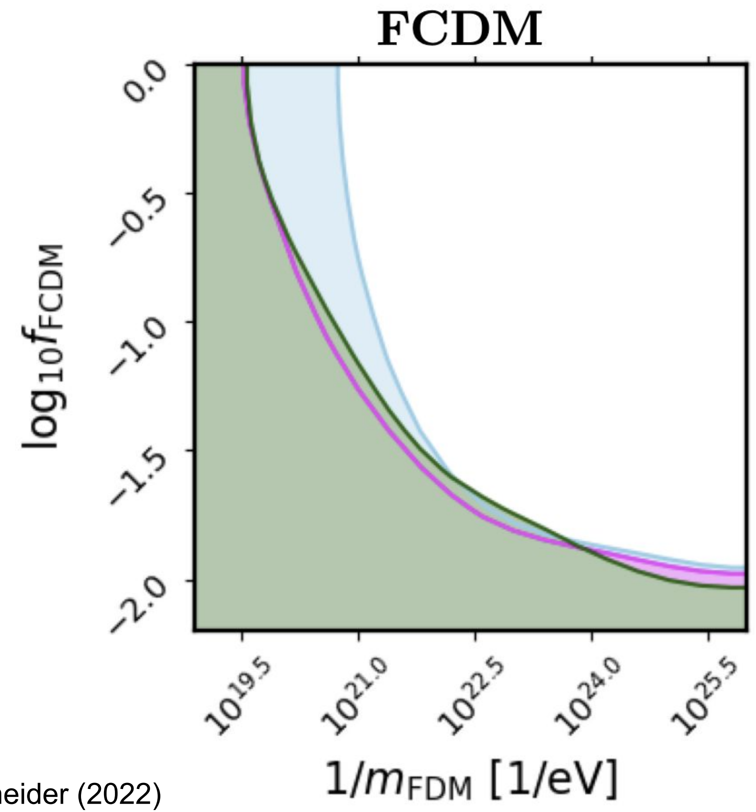
Constraints on warm+cold dark matter (WCDM)



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

Giri & Schneider (2022)

Constraints on fuzzy+cold dark matter (FCDM)

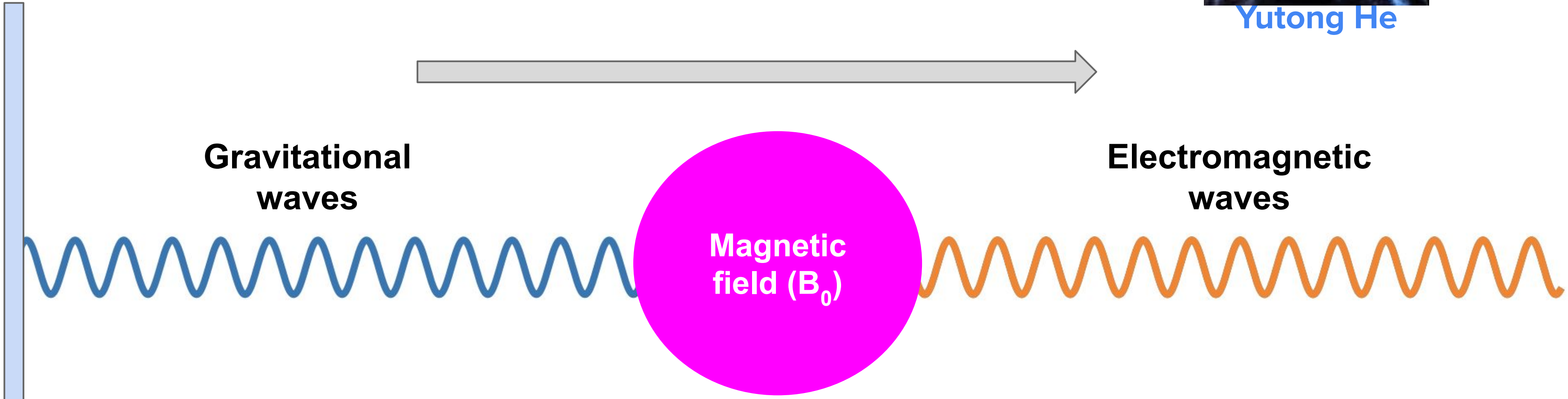


$$f \sim 1 : m_{\rm FDM} \gtrsim 2 \times 10^{-20}\ {\rm eV\ (FLOOR, DPL)},$$
$$\gtrsim 2 \times 10^{-21}\ {\rm eV\ (TRUNCATED)}$$
$${\rm CDM + hot\ relic} : f \lesssim 1\%\ {\rm (FLOOR, DPL, TRUNCATED)}$$

TRUNCATED
DPL
FLOOR

Giri & Schneider (2022)

Primordial Gravitational Wave background



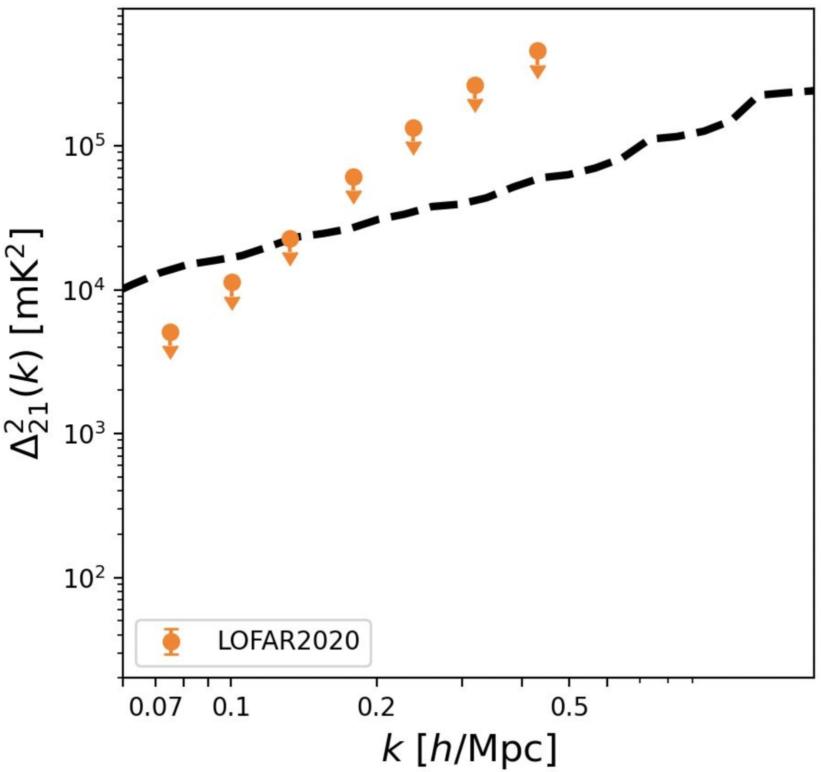
Cosmic Inflation

Conversion probability

$$\mathcal{P} \simeq 6.3 \times 10^{-19} \left(\frac{B_0}{\mathrm{nG}}\right)^2 \left(\frac{\omega_0}{T_0}\right)^2 \left(\frac{\mathrm{Mpc}}{\Delta \ell_0}\right) \left(\frac{\mathcal{I}(z_{\mathrm{ini}})}{10^6}\right)$$

Domcke & Garcia-Cely (2020)

LOFAR 21cm upper limit at z=9.1

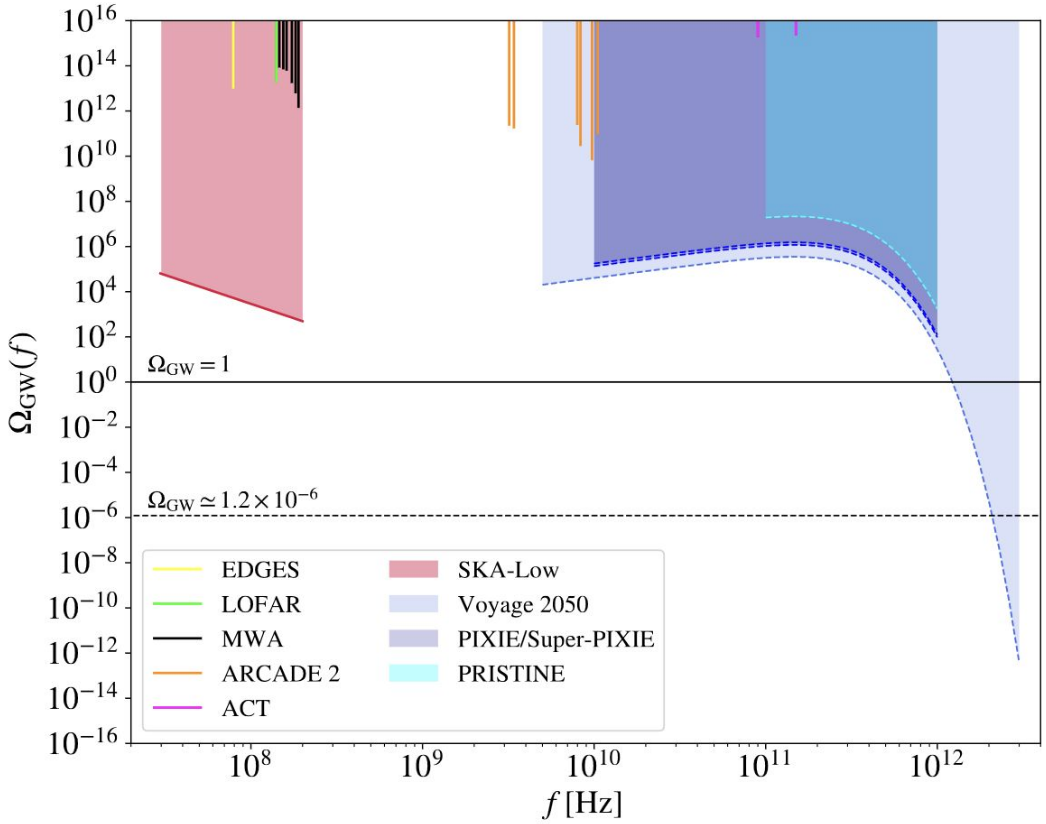


Yutong He

$$\frac{\delta T}{T_{\rm CMB}} = \frac{\pi^4}{15}\left(\frac{T}{\omega}\right)^3 \mathcal{P}\frac{\Omega_{\rm GW}}{\Omega_\gamma},$$

He, **Giri** et al. (2024)

Constraint on primordial GW background



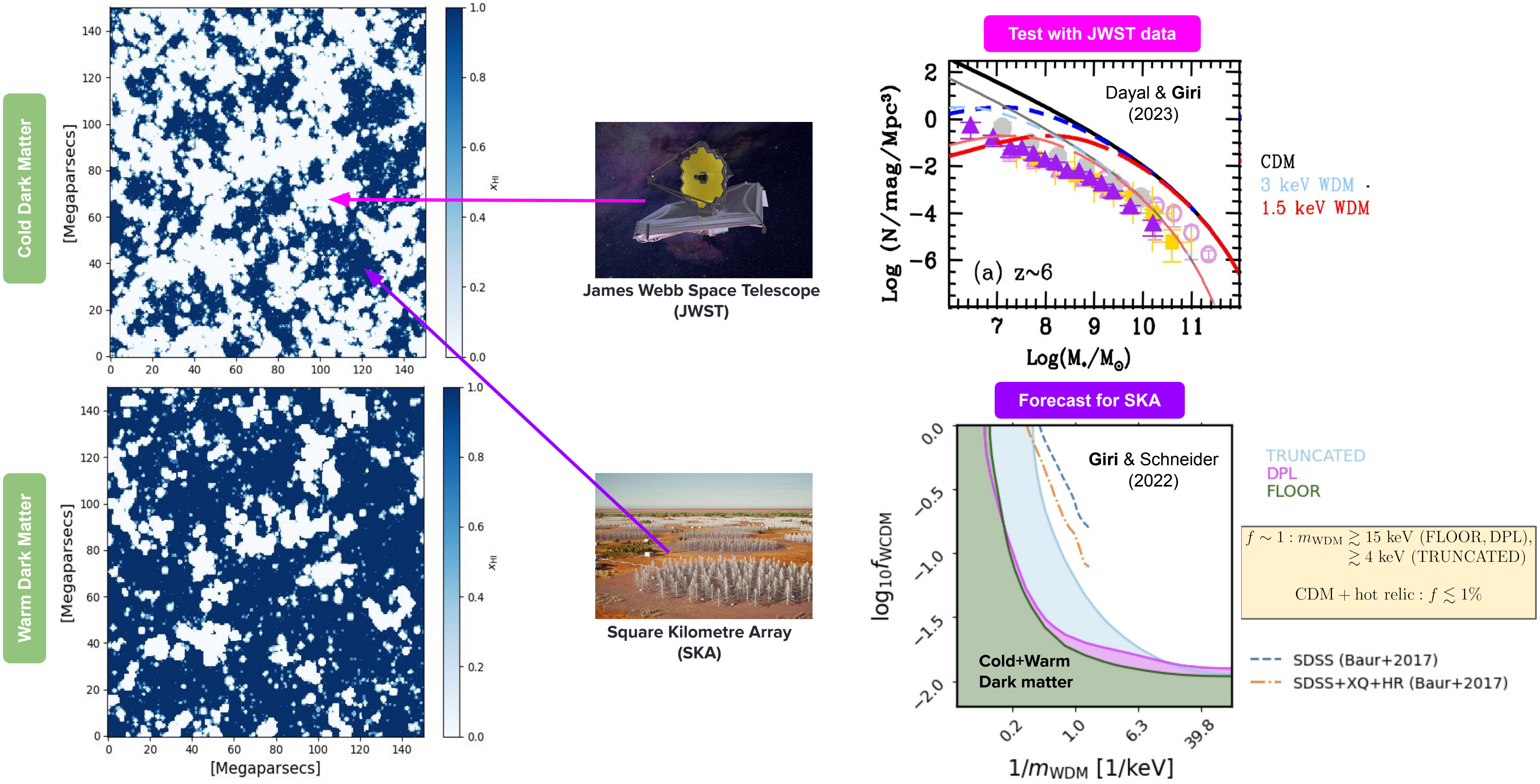
Yutong He

He, **Giri** et al. (2024)

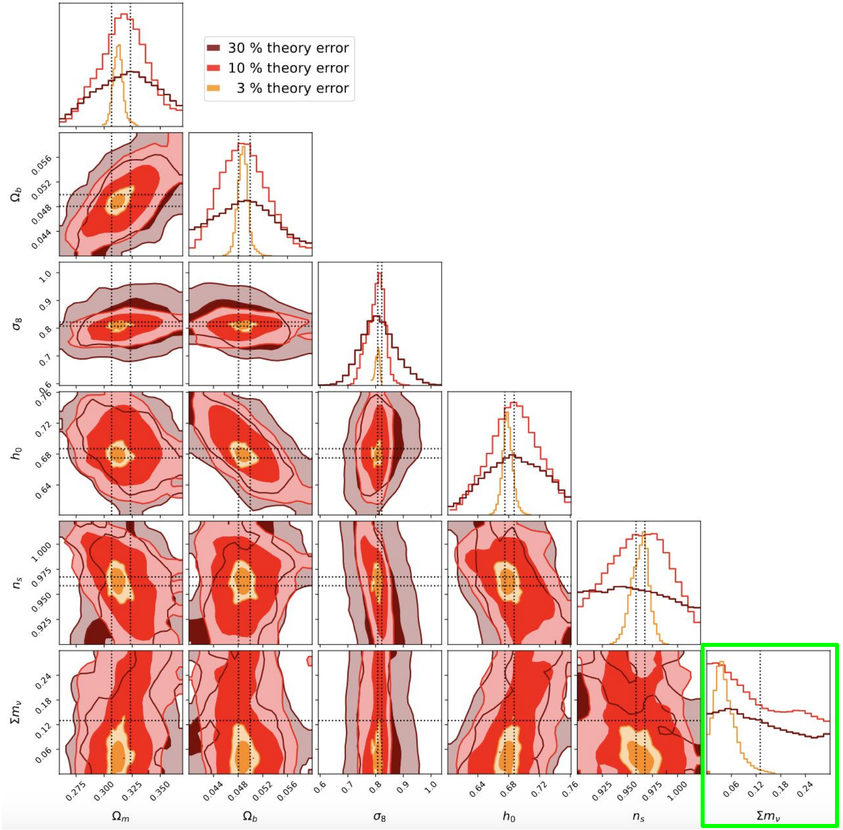
Summary

- Non-cold dark matter models (e.g. WDM & FDM) show **greater distinctions in earlier times**
- **Cosmic reionization is delayed** due to formation of less number of small mass light sources in non-cold dark matter scenarios
- JWST data is already sensitive to rule out extreme dark matter models
    - **M_{WDM}>1.5 keV (current JWST data)**
- Reionization epoch observations can **improve upon the constraints on the dark matter models**
    - **M_{WDM}>4-15 keV (SKA-Low with 1000 hours)**
- We can **constrain primordial gravitational wave background** with the 21-cm signal during reionization

Detecting Beyond Standard Model Cosmology through Epoch of Reionization Observations



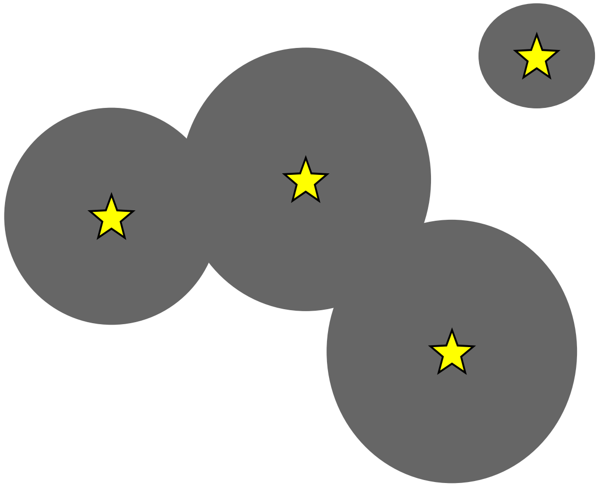
Can we constrain the CDM cosmology?



Timothée Schaeffer’s talk yesterday!

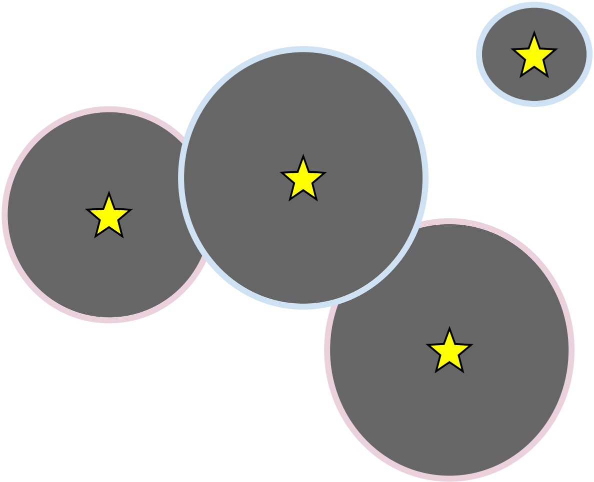
Halo model for bubble distribution

Schneider, SG & Mirocha (2021)



Halo model for bubble distribution

Feng, Cooray & Keating (2017)



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

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

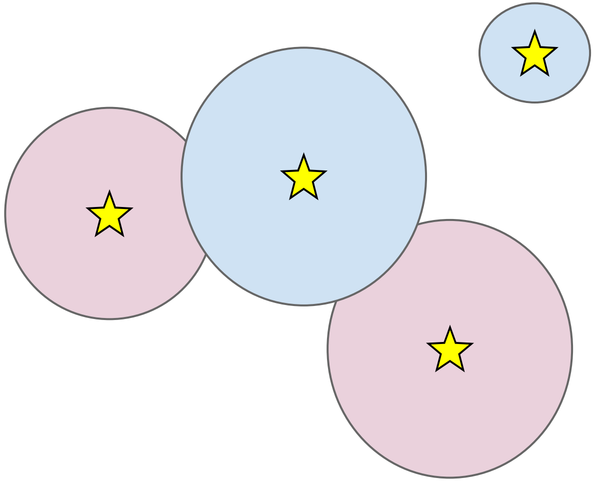
$$P_{XY}(k,z) = P^{1\,\mathrm{h}}_{XY}(k,z) + P^{2\,\mathrm{h}}_{XY}(k,z),$$

Correcting for the bubble overlap

$$P_{\mathrm{xx}}(k) \rightarrow (1 - x_{\mathrm{HII}}^{A})^{2}(1 + k^{B})^{2} P_{\mathrm{xx}}(k)$$

$$P_{\mathrm{x}\delta}(k) \rightarrow (1 - x_{\mathrm{HII}}^{A})(1 + k^{B}) P_{\mathrm{x}\delta}(k)$$

HMreio: Halo model approach for 21-cm signal distribution



Matter distribution

Seljak (2000)

Cooray & Sheth (2002)

...

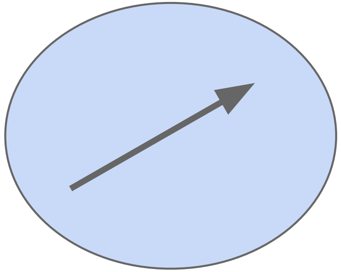
21-cm signal distribution

Schneider, **Giri** & Mirocha (2021)

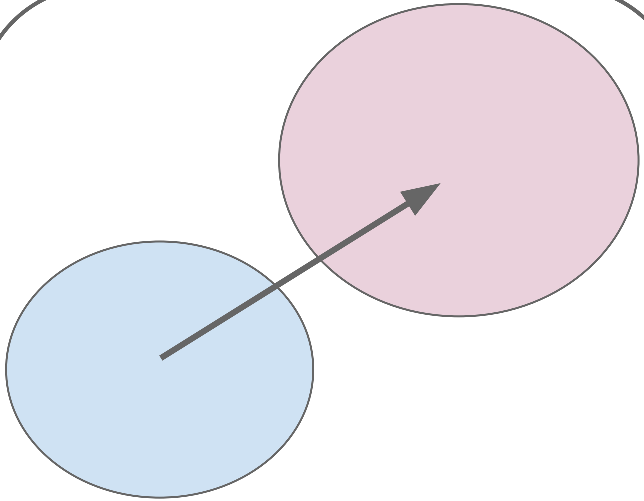
Giri & Schneider (2022)

Schneider, Schaeffer & **Giri** (2023)

HMreio: Halo model approach for 21-cm Power spectrum



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



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

Schneider, **Giri** & Mirocha (2021)

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

Ingredients for the halo model

Linear power spectrum

Halo mass function

Mass accretion

Halo bias

Stellar to halo mass relation

Flux profiles

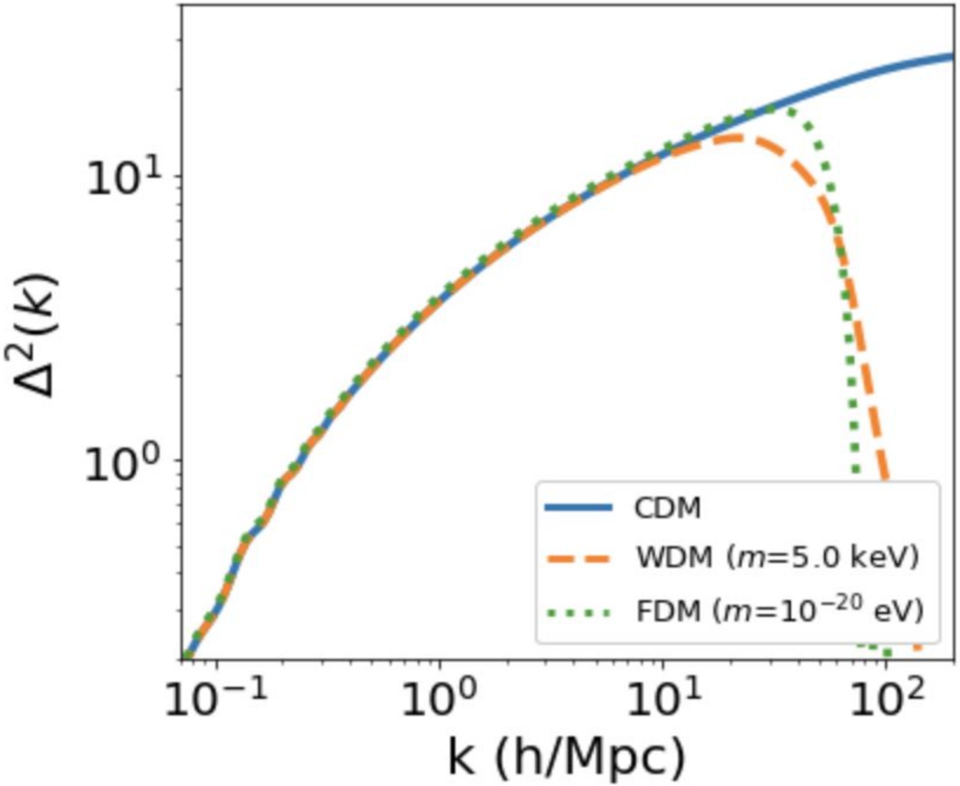
$$P^{1\,\mathrm{h}}_{XY}(k,z) = \frac{\beta_X \beta_Y}{(\bar{\rho} f_{\mathrm{coll}})^2} \int dM \frac{dn}{dM} \tilde{f}_*^2 M^2 |u_X||u_Y|,$$

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

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

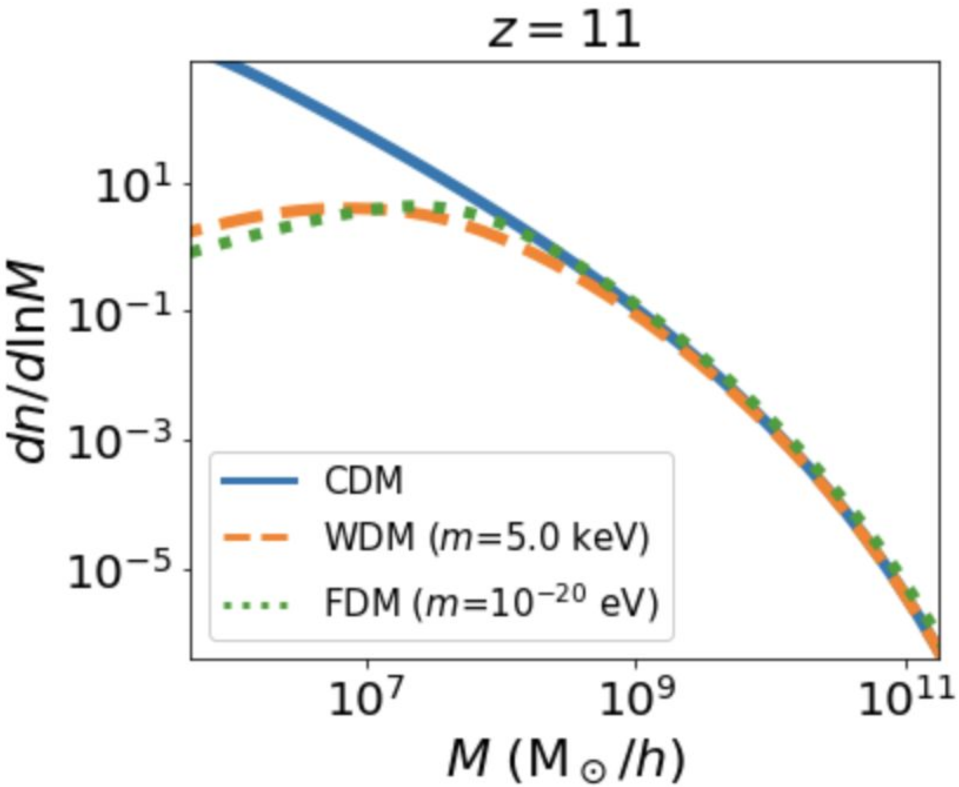
$$\tilde{f}_\star(M) = \frac{1}{M_{\mathrm{ac}}} \int f_\star(M) \dot{M}_{\mathrm{ac}} dt$$

Linear power spectra



z = 0

Halo mass function



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

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

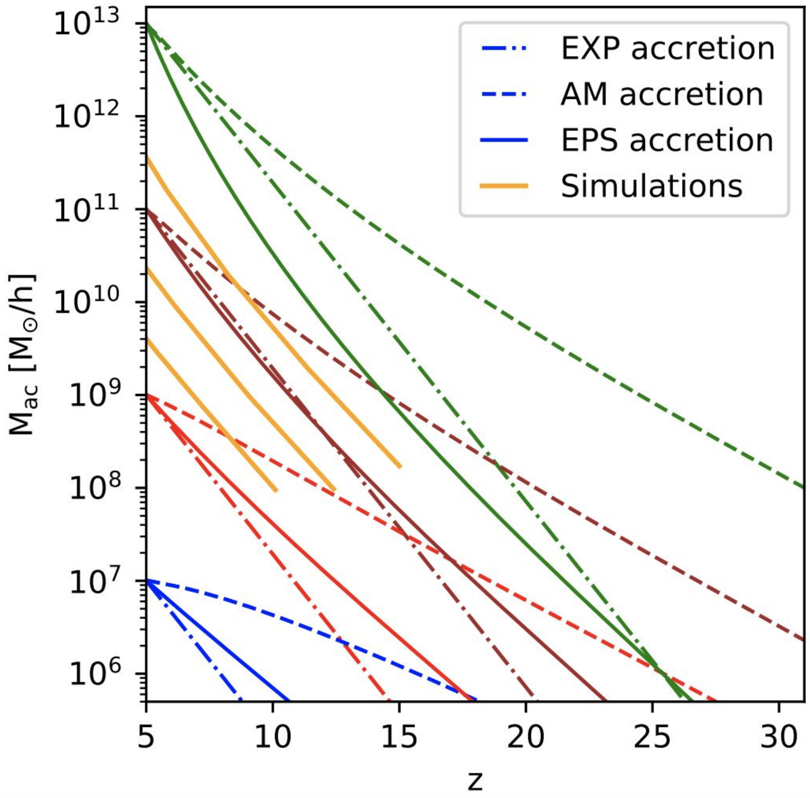
$$f(\nu) = A\sqrt{\frac{2q\nu}{\pi}}(1+\nu^{-p})e^{-q\nu/2}$$

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

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

e.g. Leo+2018

Mass accretion rate

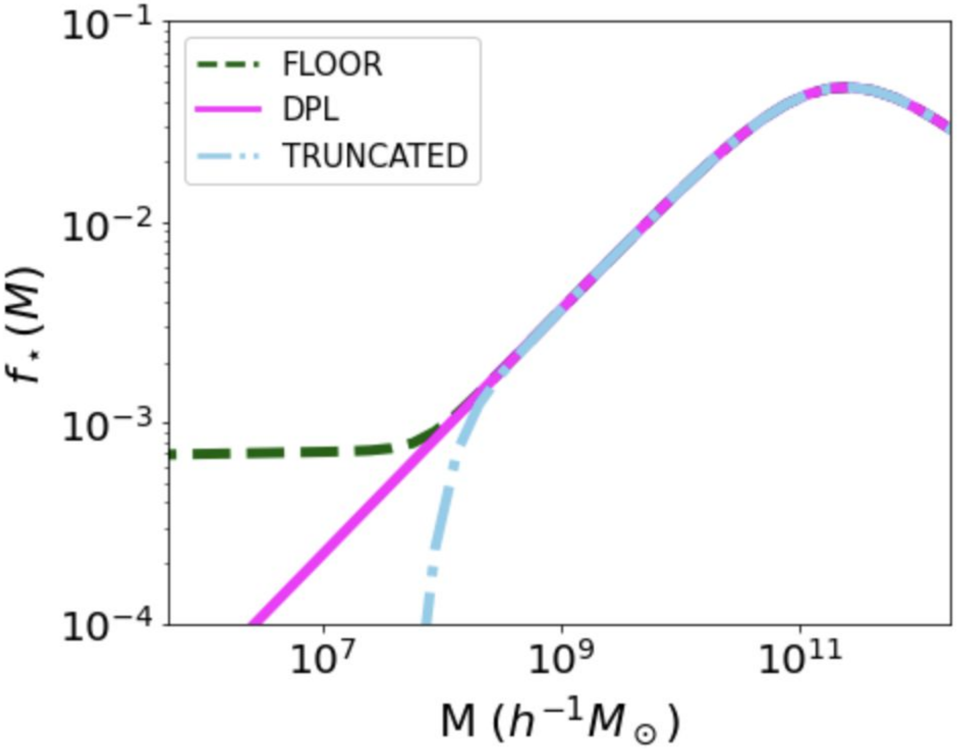


Halo bias

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

e.g. Cooray & Sheth (2002)

Stellar to halo mass relation

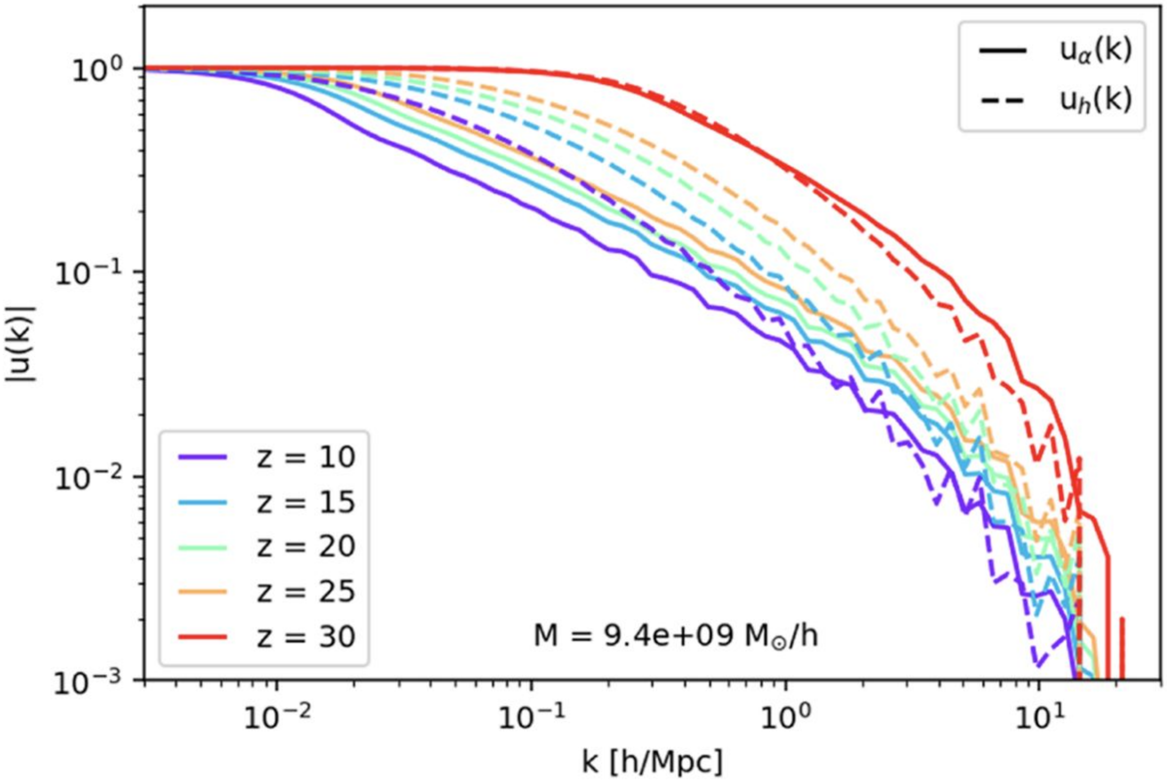


$$f_*(M) = \frac{2(\Omega_b/\Omega_m) f_{*,0}}{(M/M_p)^{\gamma_1} + (M/M_p)^{\gamma_2}} \times S(M)$$

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

(SG & Schneider 2022)

Flux profiles



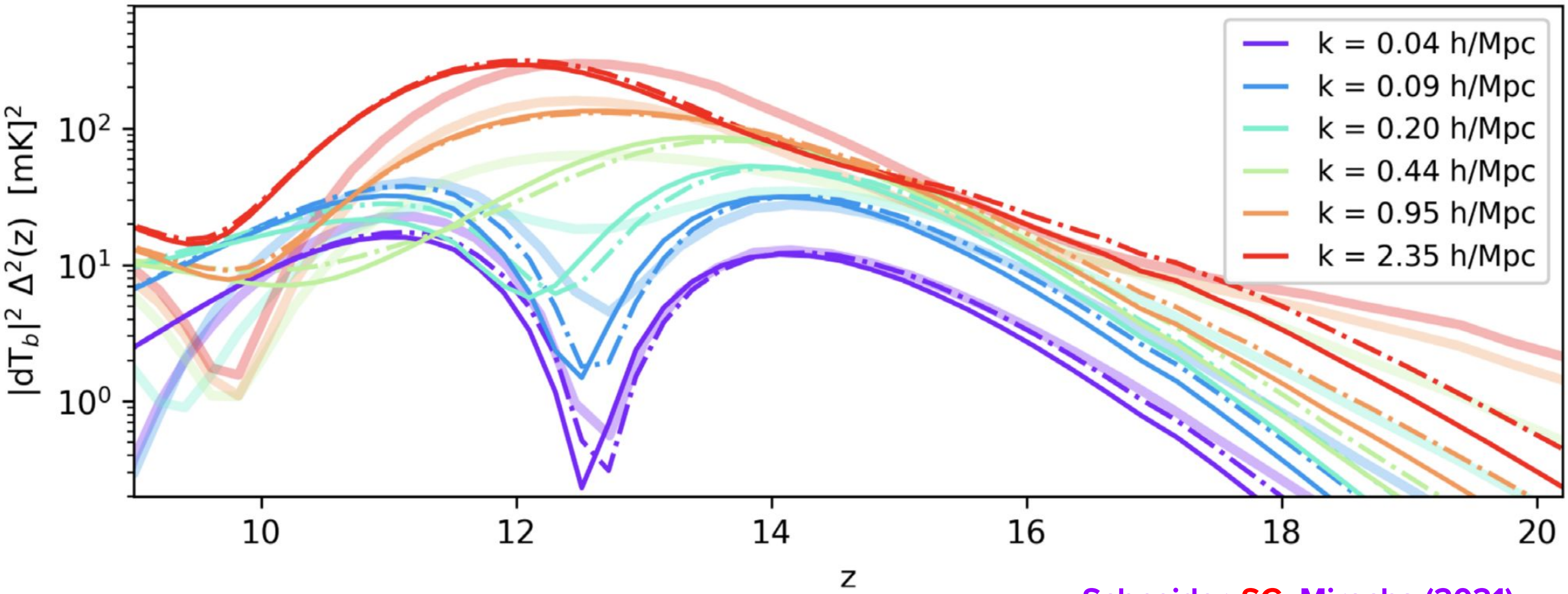
Schneider, SG, Mirocha (2021)

21-cm power spectrum during cosmic dawn

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

Schneider, SG, Mirocha (2021)

Validity of the approach



Schneider, SG, Mirocha (2021)