zhangyao22@mails.tsinghua.edu.cn

清華大學天文系
Department of Astronomy, Tsinghua University

Unveiling the dark matter nature with reionization relics

Yao Zhang

Department of Astronomy, Tsinghua University

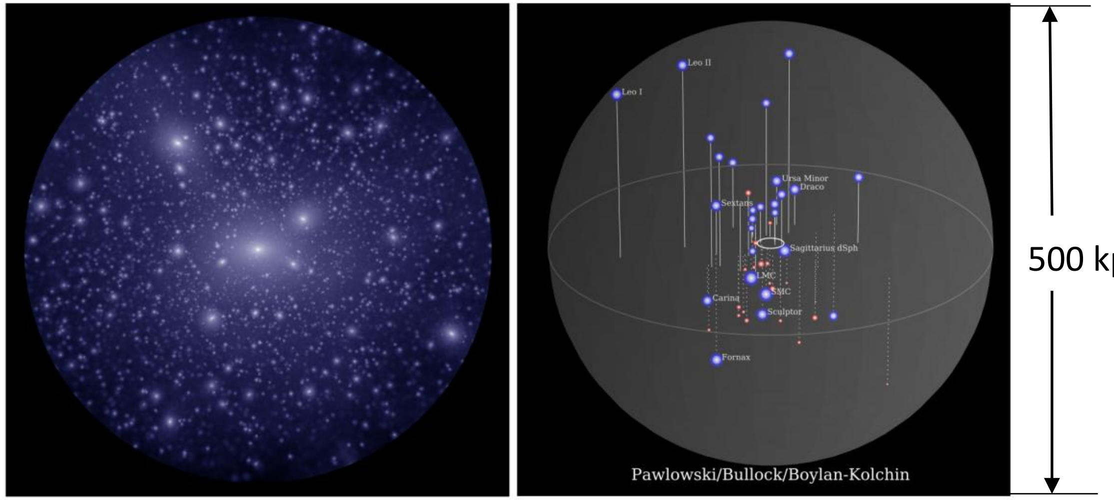
Supervisor: Yi Mao (Tsinghua University)

Collaborators:
Catalina Morales-Gutiérrez (University of Costa Rica),
Paulo Montero-Camacho (Peng Cheng Laboratory),
Heyang Long (The Ohio State University),
Christopher Hirata (The Ohio State University).

21 cm Cosmology Workshop 2024 & Tianlai Collaboration Meeting July 21 - 26, 2024

Small-scale challenges to the CDM model

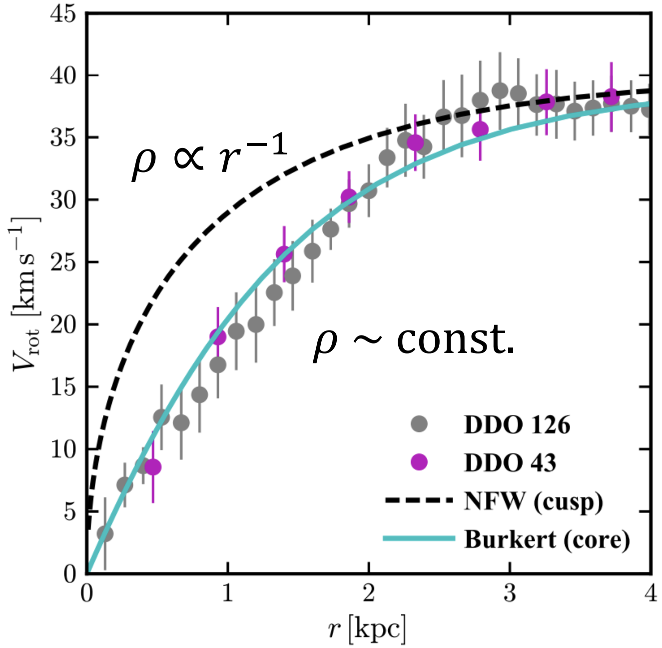
Missing satellites problem



N-body simulation observed satellite galaxies

(Bullock et al. 2017)

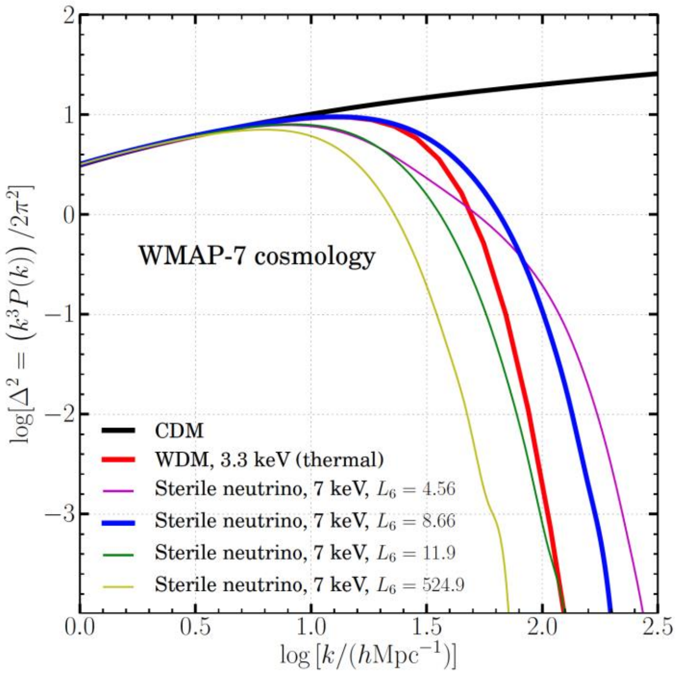
Cusp-core problem



(Bullock et al. 2017)

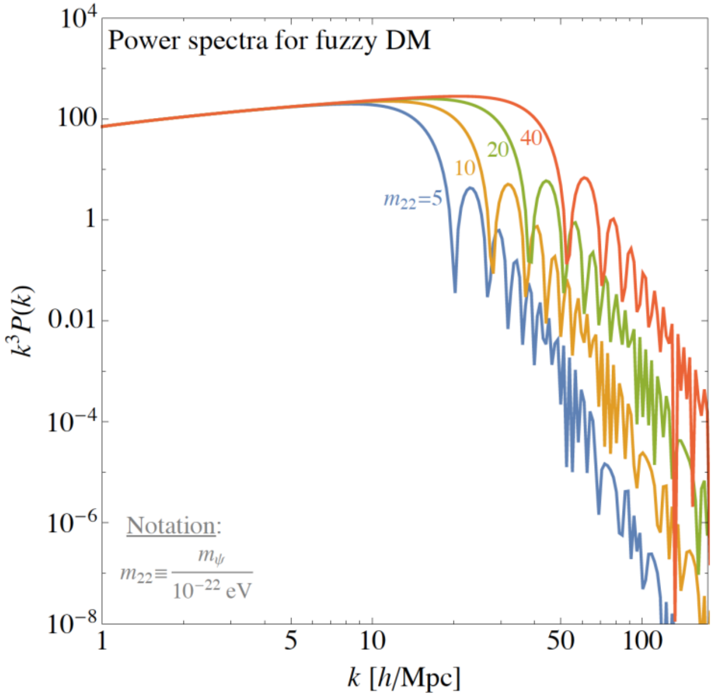
Other DM models: small-scale suppression

Warm Dark Matter



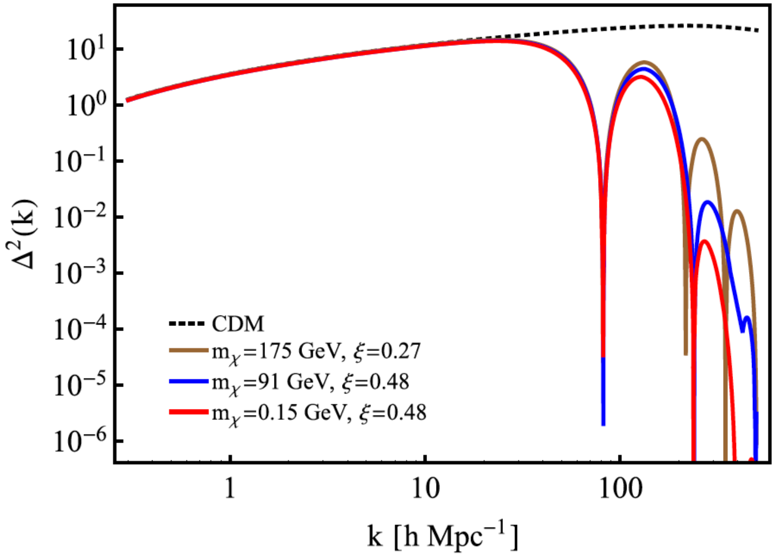
(Bose et al. 2016)

Fuzzy Dark Matter



(Murgia et al. 2017)

Self-interacting Dark Matter

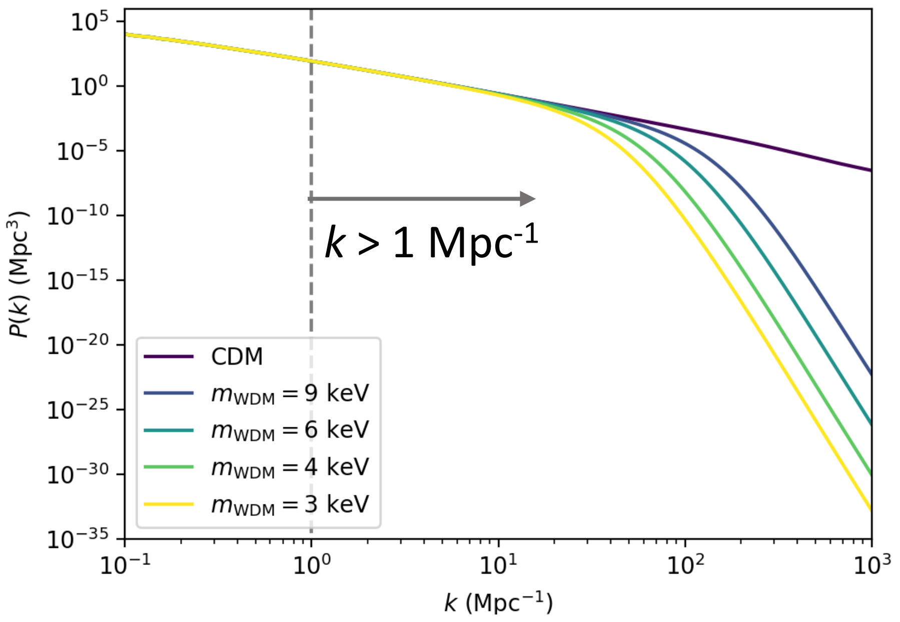


(Hou et al. 2018)

Lyman alpha forest, satellite galaxy population, stellar streams…

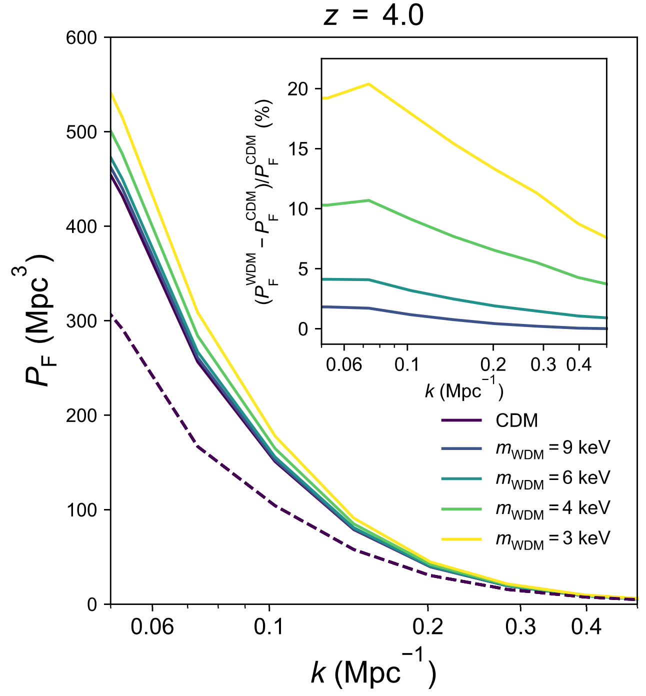
Constrain WDM by large-scale observations

WDM: suppress small-scale structures

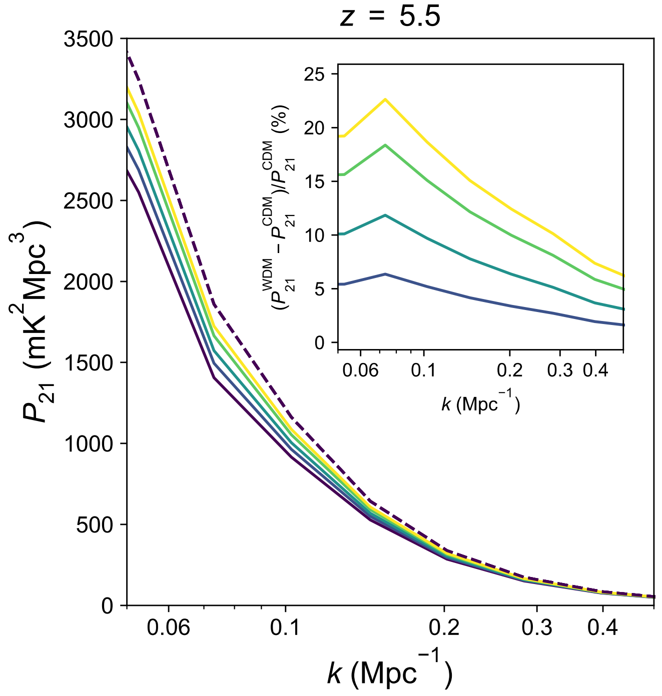


matter power spectrum

Lyα forest power spectrum



21 cm IM power spectrum

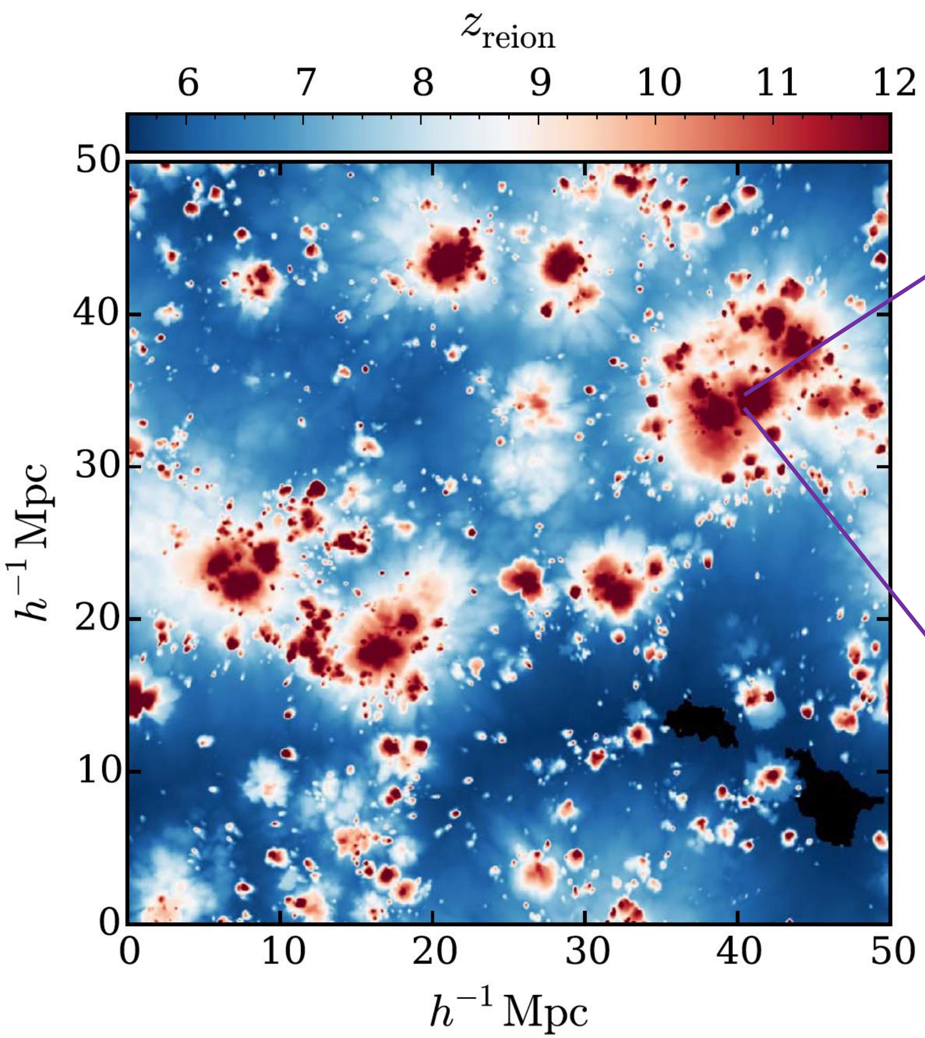


$k \lesssim 0.4$ Mpc^{-1}

How does the small-scale suppression effect of WDM migrate to large scales?

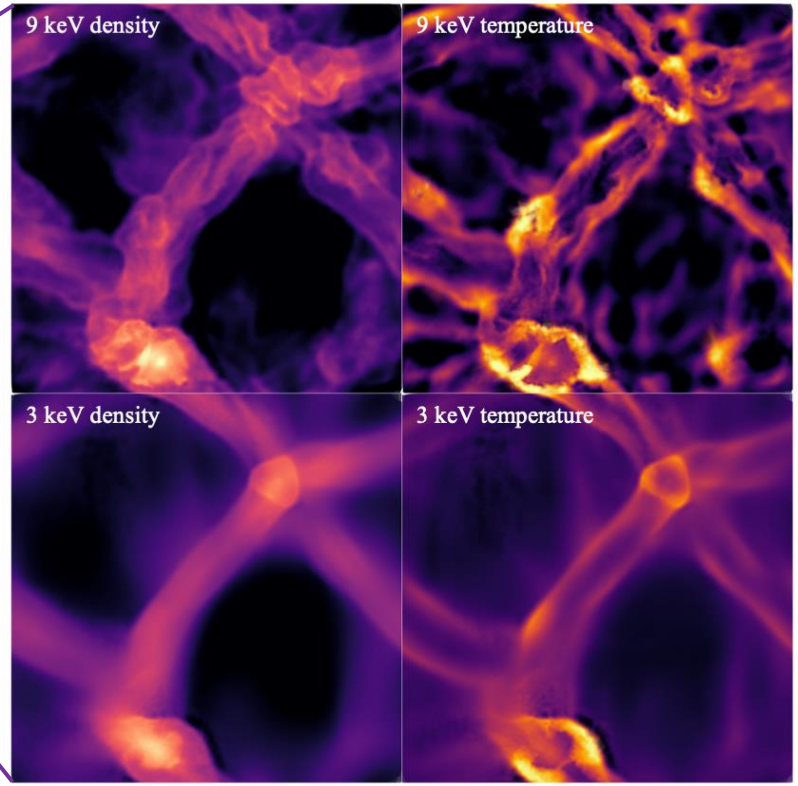
Reionization relics!

Large scale: reionization is inhomogeneous.



(D'Aloisio et al. 2019)

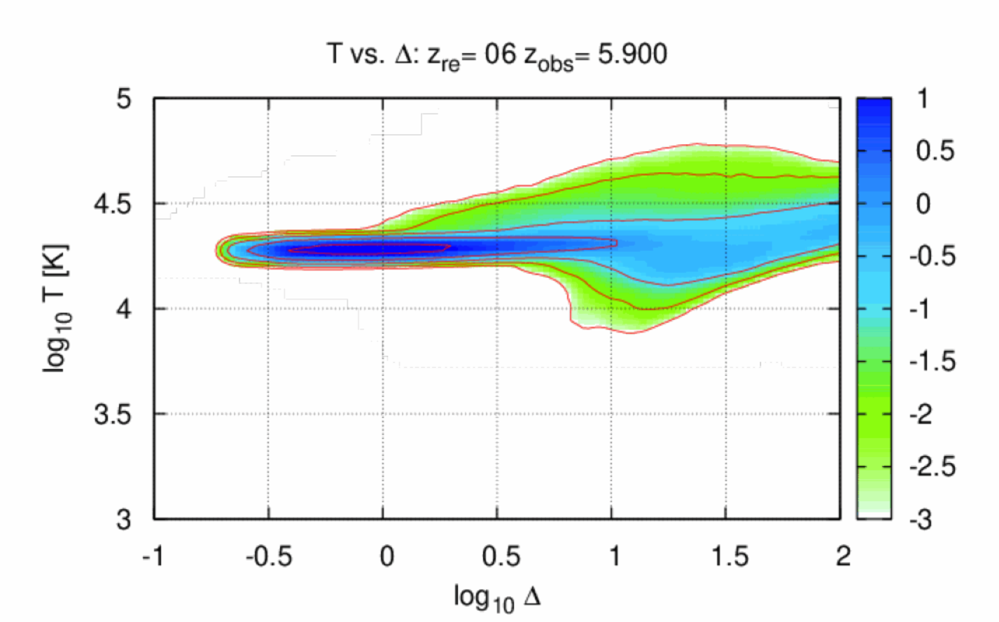
Small scale: post-reionization evolution is sensitive to DM models.



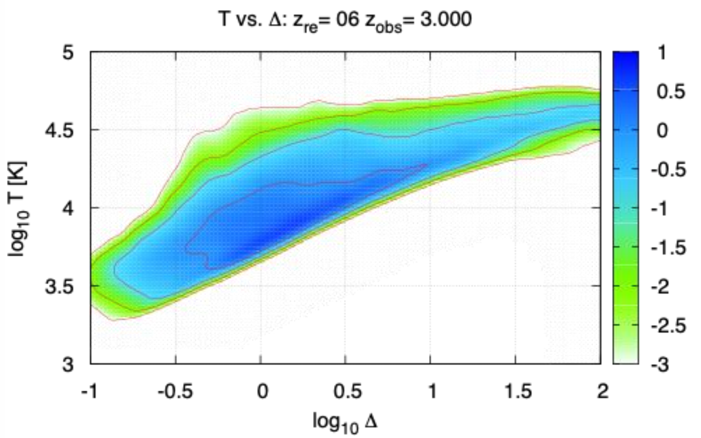
Reionization relic: IGM thermal state

“sensitive” to local z_{re}

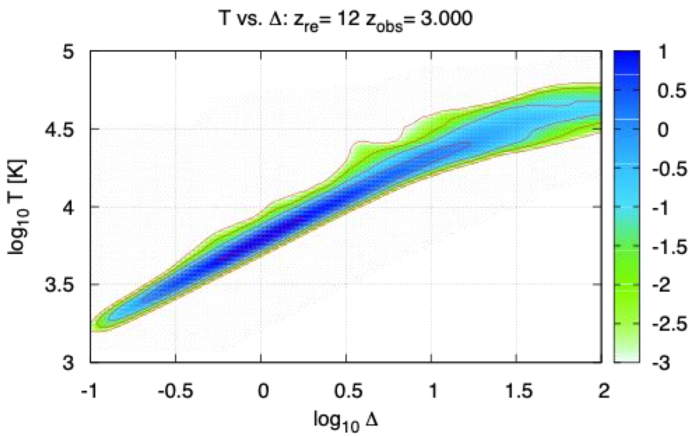
Thermal history of IGM



reionize at z=6



reionize at z=12



The IGM thermal state is sensitive to when IGM reionizes: **thermal relic**

Optical depth $\propto \Delta^2 \alpha_A(T)$

Transparency of IGM is sensitive to z_{re} -> affect **Lyα forest**

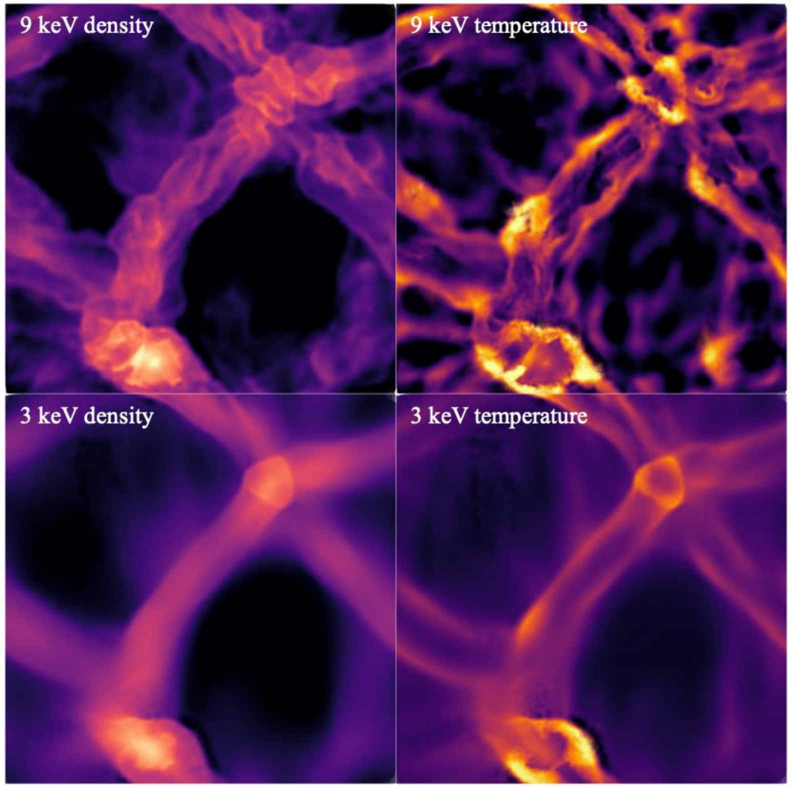
Reionization heats gas to T~2×10^4 K.

Then: adiabatic expansion, photoheating by UV background,

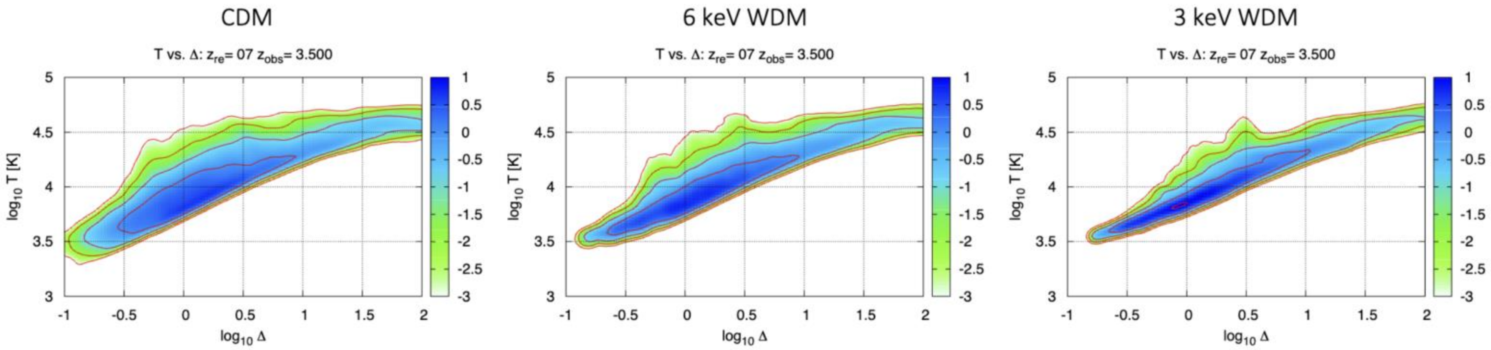
Compton cooling

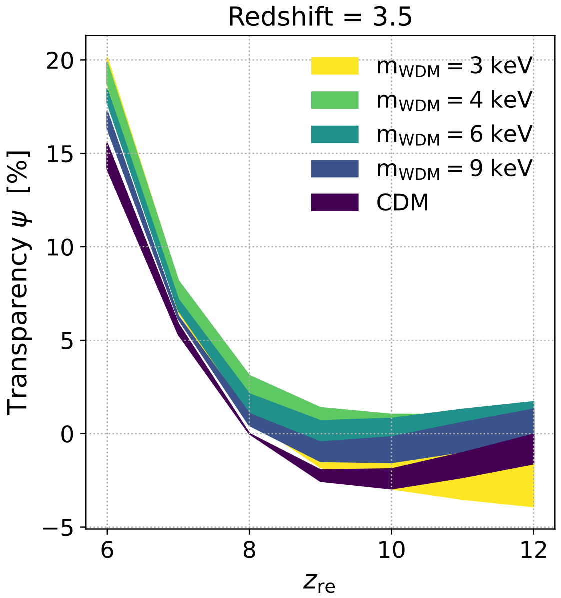
Effects of WDM

Free streaming velocity -> suppress small-scale structures



different thermal history



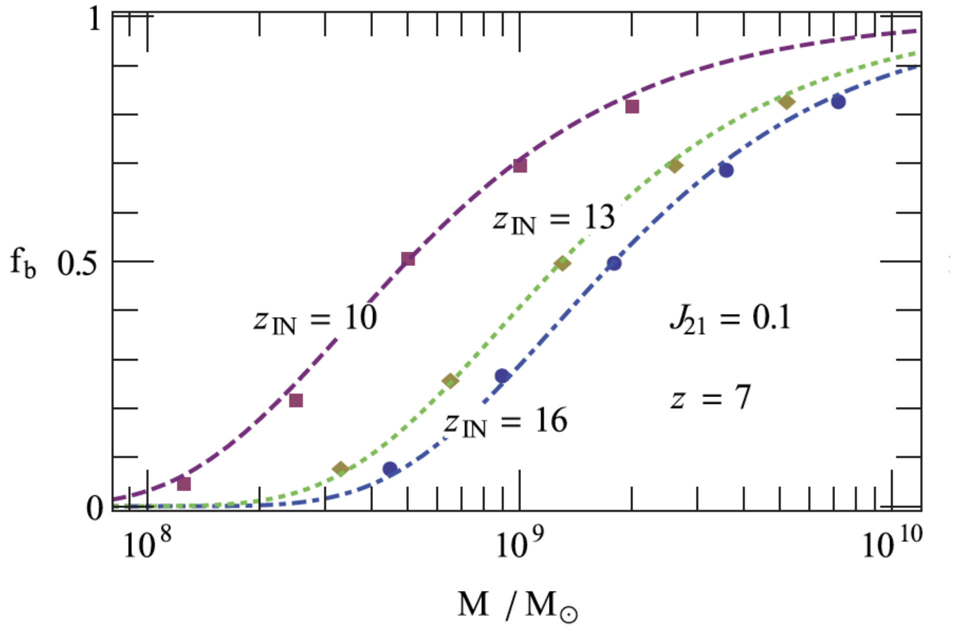


Different transparency - z_{re} relation: distinguishable signal in Lyα forest power spectrum

For lighter WDM, density contrast is smaller, thus dynamical response after reionization is less violent.

Reionization relic: suppress f_b in low-mass halos

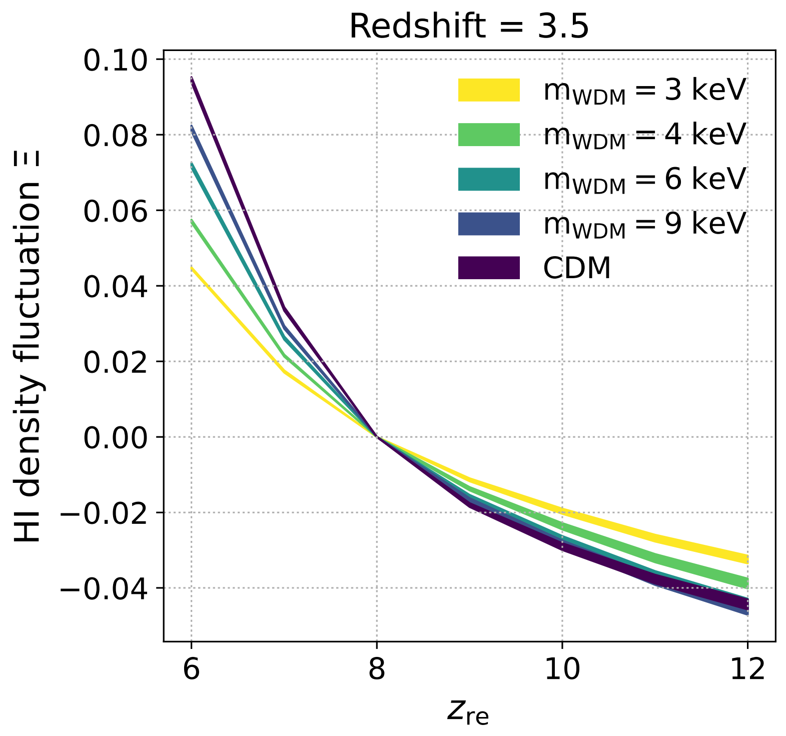
Increased pressure suppresses baryon infalling into low-mass halos.



(Sobacchi & Mesinger, 2013)

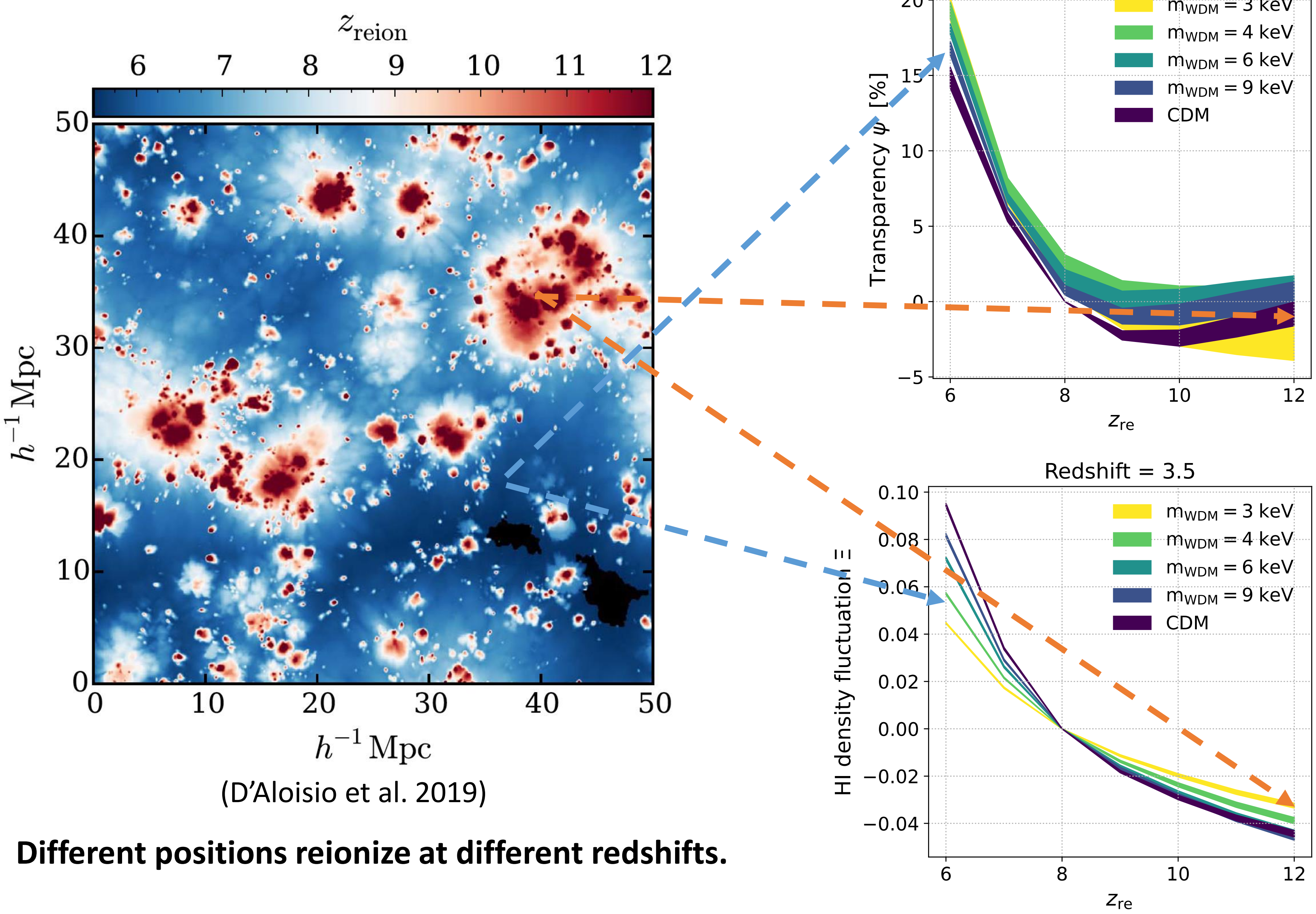
Earlier reionization has stronger suppression effect.

In the **post**-reionization era, 21 cm signal mainly comes from **HI in halos and galaxies.**
Baryon mass in low-mass halos is sensitive to z_{re} ->
affect HI density, and post-reionization **21 cm power spectrum**



In **WDM** models, there are **fewer low-mass halos** to be affected by reionization.

Combine with inhomogeneity



(D'Aloisio et al. 2019)

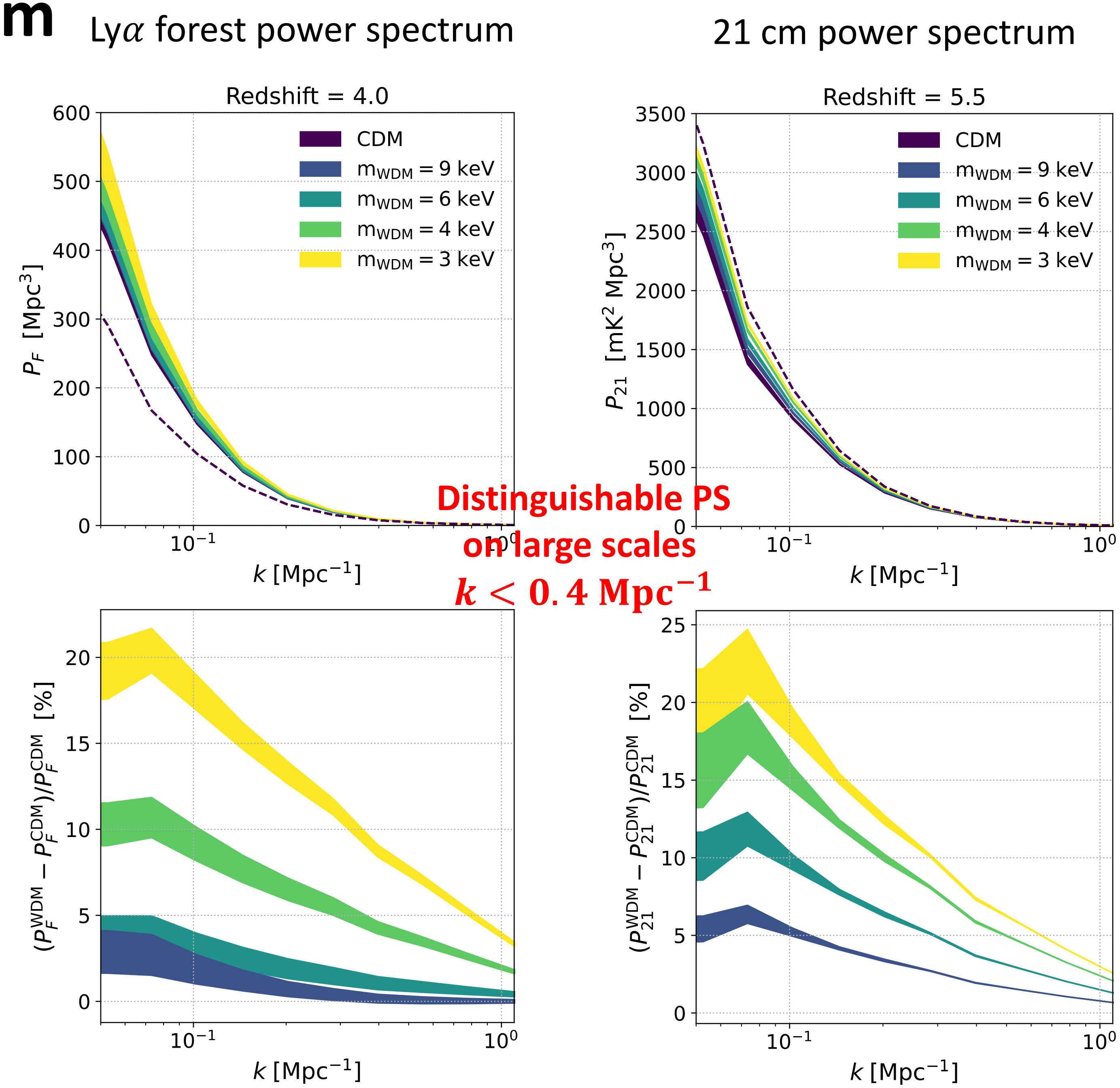
Different positions reionize at different redshifts.

Fluctuations of transparency and HI density on ionized bubble scales

↓

large-scale signals in the power spectrum

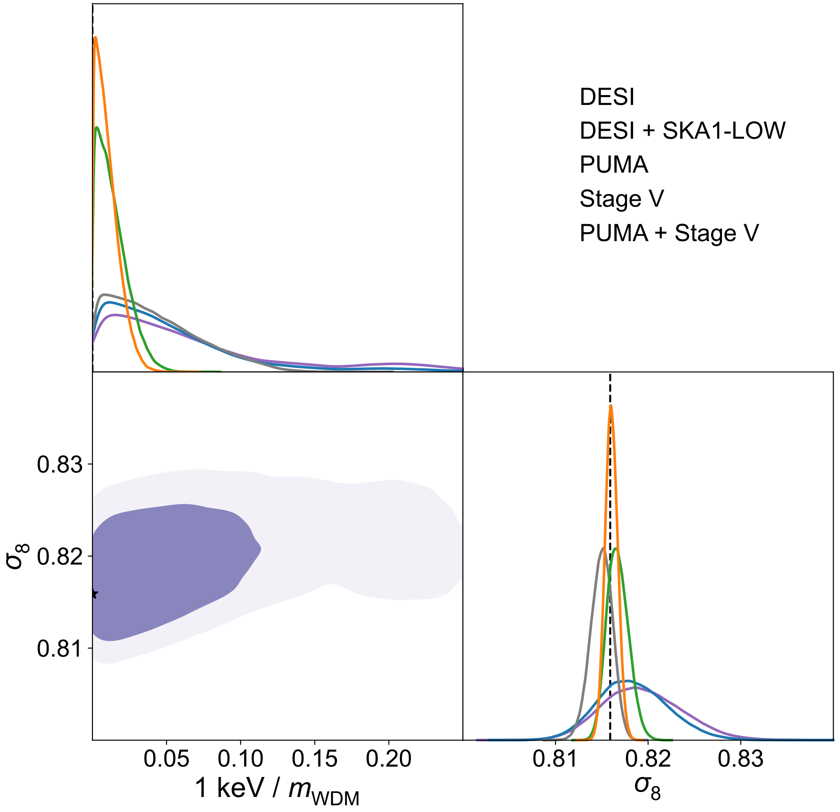
Power spectrum

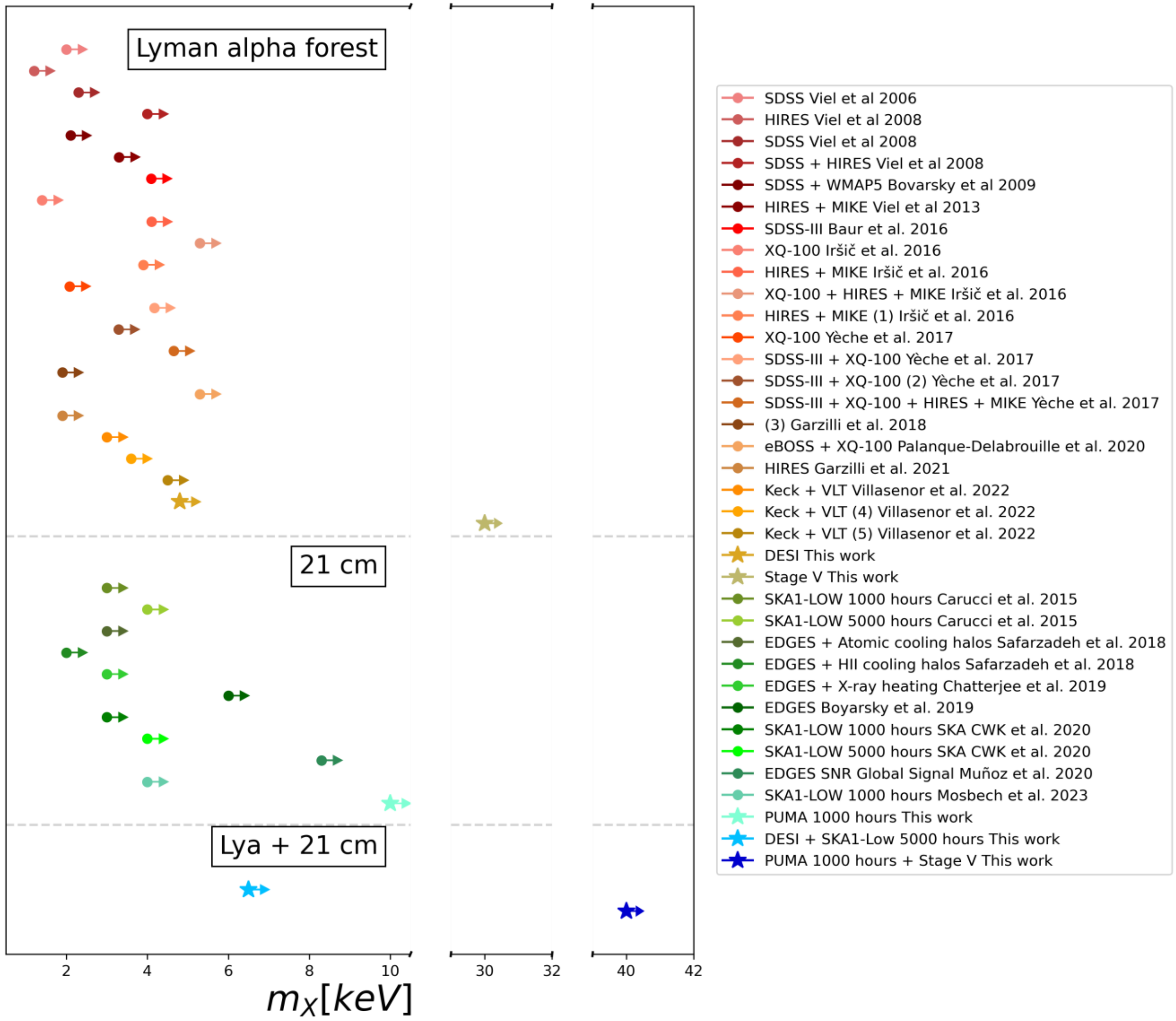


Distinguishable PS on large scales

$\boldsymbol{k < 0.4\ \mathrm{Mpc}^{-1}}$

Forecast: constraint on m_{WDM}





DESI Lyα survey $m_{WDM} > 4.8$ keV

DESI Lyα survey + SKA1-LOW 21 cm IM $m_{WDM} > 6.5$ keV

PUMA 21 cm IM $m_{WDM} > 10$ keV

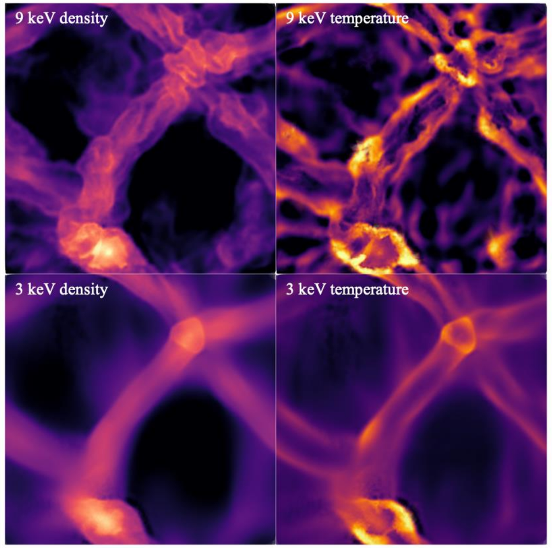
Stage V (e.g. MUST) Lyα surveys $m_{WDM} > 30$ keV

PUMA 21 cm IM + Stage V Lyα surveys $m_{WDM} > 40$ keV

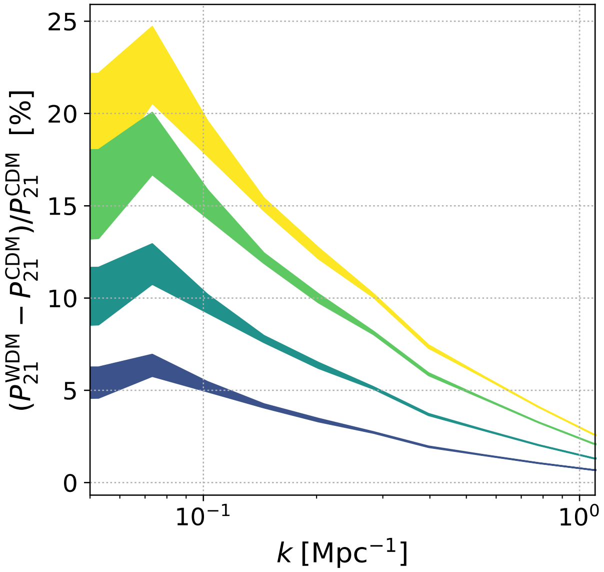
(95% credible intervals)

Summary

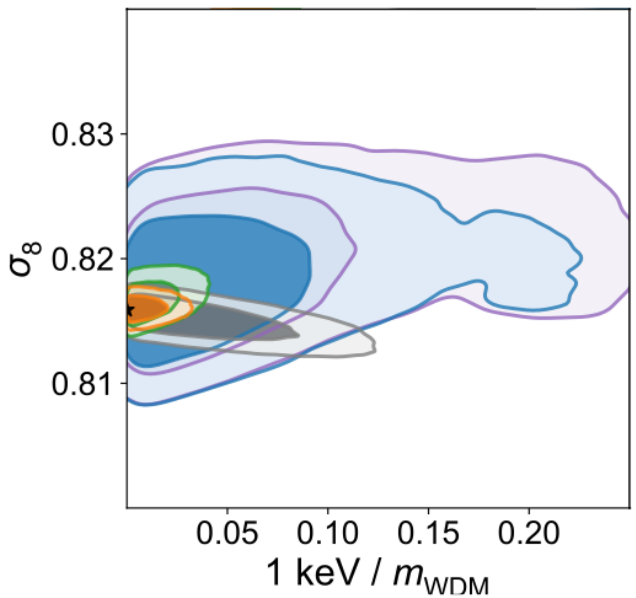
zhangyao22@mails.tsinghua.edu.cn



On small scales, IGM post-reionization evolution is sensitive to DM models.



$P_{\rm F}$ and P_{21} can **differentiate** DM models on k < 0.4 Mpc^{-1}.



Forecast current and future surveys' constraints on $m_{\rm WDM}$.

Not limited to WDM, can be applied to other DM models with small-scale suppression.

Small-scale simulations

$$P_{m,X}(k, z_{obs}) = -\int_{z_{min}}^{z_{max}} \boxed{\frac{\partial X}{\partial z}}(z, z_{obs}) P_{m,x_{\mathrm{HI}}}(k, z) \frac{D_g(z_{obs})}{D_g(z)} dz$$

Small scale: high-resolution hydrodynamical simulation

Modified Gadget-2 box size: 1275 kpc

Particle mass: $9.72\times10^3\, M_\odot$ (DM), $1.81\times10^3\, M_\odot$ (gas)

redshift of reionization: z_{re} = 6, 7, 8, 9, 10, 11, 12

calculate $\psi(z_{re})$ and $\Xi(z_{re})$

Implement WDM: $m_{\mathrm{WDM}} = \{3, 4, 6, 9\}\,\mathrm{keV}$

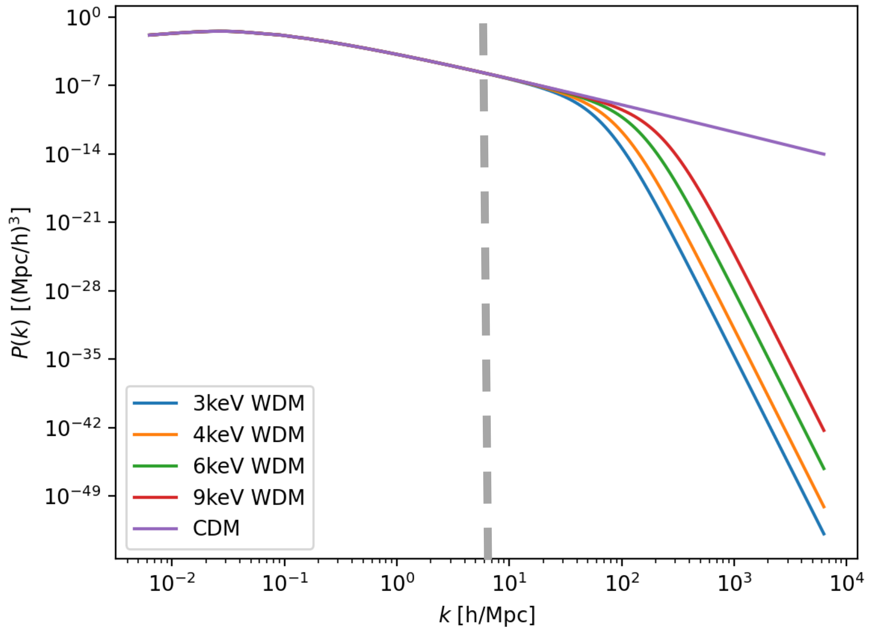
$P_{WDM}(k) = T_{\mathrm{X}}(k)^2 P_{CDM}(k)$ **as initial condition**

transfer function: $T_{\mathrm{X}}(k) = [1 + (\alpha k)^{2\nu}]^{-5/\nu}$ (Bode et al. 2001)

suppression scale: $\alpha = 0.049 \left(\frac{m_{\mathrm{X}}}{1\,\mathrm{keV}}\right)^{-1.11} \left(\frac{\Omega_{\mathrm{X}}}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22} h^{-1}\mathrm{Mpc}$

$\nu = 1.12$ (Viel et al. 2005)

matter power spectrum



Warm dark matter

suppression of small-scale structure

$k > 1\ \mathrm{Mpc}^{-1}$

Large-scale simulations

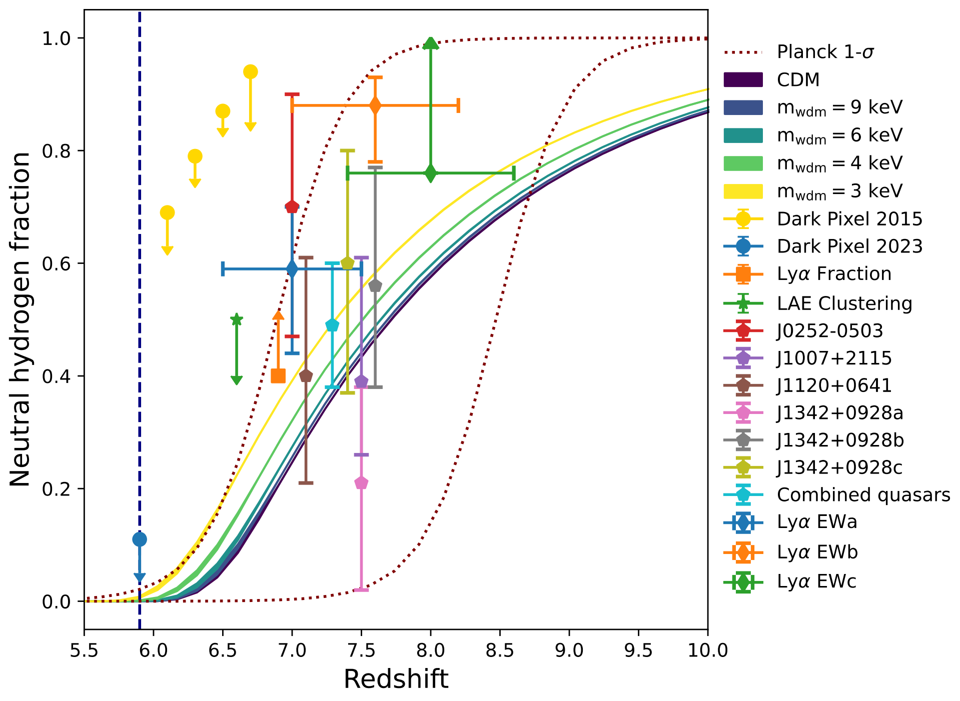
$$P_{m,X}(k, z_{obs}) = -\int_{z_{min}}^{z_{max}} \frac{\partial X}{\partial z}(z, z_{obs}) \boxed{P_{m,x_{\mathrm{HI}}}(k, z)} \frac{D_g(z_{obs})}{D_g(z)} dz$$

Large scale: semi-analytic simulation

21CMFAST box size: 400 Mpc

256^3 HI cells and 768^3 matter density cells

calculate $\boldsymbol{P_{\mathrm{m},x_{\mathrm{HI}}}(z_{re}, k)}$



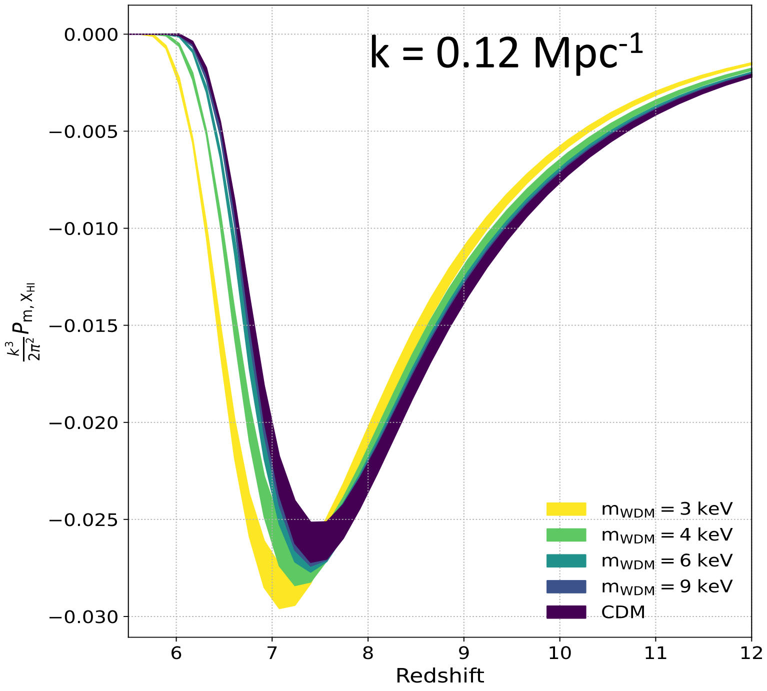
Implement WDM:

transfer function + effective Jeans mass

a new minimum mass that enters the mean collapse fraction

$$M_J \approx 1.5 \times 10^{10} \left(\frac{\Omega_X h^2}{0.15}\right)^{\frac{1}{2}} \left(\frac{m_X}{1\ \mathrm{keV}}\right)^{-4} M_\odot$$

(Sitwell et al. 2014)



Lyα forest power spectrum

Lyα transmission: $\delta_{\rm F} = b_{\rm F}\,(1+\beta_{\rm F}\mu^2)\,\delta_{\rm m} + b_\Gamma\,\psi(z_{\rm re}),$

optical depth: $\tau = \tau_1\,\Delta^2\alpha_A(T)$ $\quad \tau_{\rm eff} = 0.0023(1+z)^{3.65}$ $\quad \psi(z_{\rm re}) = \ln[\tau_1(z_{\rm re})] - \ln[\tau_1(\bar{z}_{\rm re})]$

$$P_F = b_F^2(1+\beta_F\mu^2)^2 P_m + 2b_F b_\Gamma(1+\beta_F\mu^2)P_{m,\psi}$$

$$P_{\rm m,\psi}(z_{\rm obs},k) = -\int_{z_{\rm min}}^{z_{\rm max}} \frac{\partial\psi}{\partial z} P_{\rm m,x_{HI}}(z,k)\frac{D(z_{\rm obs})}{D(z)}{\rm d}z$$

$$P_{\rm Tot}^{\rm CDM}(\boldsymbol{k},z) = P_F^{\rm 3D,CDM}(\boldsymbol{k},z) + P_F^{1D}(k_\parallel,z)P_{\rm w}^{\rm 2D}(z) + P_N^{\rm eff}(z)$$

$$\sigma_\ell^2(z,\boldsymbol{k}) = [P_{\rm Tot}^{\rm CDM}(z,\boldsymbol{k})]^2\frac{4\pi^2}{V_{\rm survey}(z)k^2\Delta k\Delta\mu}$$

$$\mathcal{L} = \exp(-\frac{1}{2}\sum_{\rm bins}(P_\ell(z,\boldsymbol{k}) - P_\ell^{\rm CDM}(z,\boldsymbol{k}))^2/\sigma_\ell^2(z,\boldsymbol{k}))$$

$$P_{\rm w}^{\rm 2D} = \frac{I_2}{I_1^2 L_{\rm q}} \qquad I_1 = \int {\rm d}m\frac{{\rm d}n_{\rm q}}{{\rm d}m}w(m),$$

$$P_{\rm N}^{\rm eff} = \frac{I_3 l_{\rm p}}{I_1^2 L_{\rm q}} \qquad I_2 = \int {\rm d}m\frac{{\rm d}n_{\rm q}}{{\rm d}m}w^2(m), \quad w(m) = \frac{P_{\rm S}/P_{\rm N}(m)}{1+P_{\rm S}/P_{\rm N}(m)}$$

$$I_3 = \int {\rm d}m\frac{{\rm d}n_{\rm q}}{{\rm d}m}\sigma_{\rm N}^2(m)w^2(m)$$

21 cm power spectrum

HI density fluctuation: $\delta_{\rm HI} = (b_{\rm HI} + \mu^2 f)\delta_{\rm m} + \Xi(z_{\rm re},\ z_{\rm obs}\,|\,\overline{z}_{\rm re})$

$$\Xi(z_{\rm re}, z_{\rm obs}\,|\,\overline{z}_{\rm re}) = \ln \frac{\rho_{\rm HI}(z_{\rm re},\ z_{\rm obs})}{\rho_{\rm HI}(\overline{z}_{\rm re},\ z_{\rm obs})}. \quad \rho_{\rm HI}(z_{\rm re},\ z_{\rm obs}) = \int dM_{\rm halo} \frac{dn(M_{\rm halo}, z)}{dM_{\rm halo}} M_{\rm HI}(M_{\rm halo}, z_{\rm obs}, z_{\rm re})$$

$$P_{21} = \overline{T}_{\rm b}^2 b_{\rm HI}^2 (1+\beta_{\rm HI}\mu^2)^2 P_m + 2\overline{T}_{\rm b}^2 b_{\rm HI}(1+\beta_{\rm HI}\mu^2) P_{m,\Xi}$$

$$P_{m,\Xi}(k, z_{\rm obs}) = -\int_{z_{\rm min}}^{z_{\rm max}} {\rm d}z \frac{\partial \Xi}{\partial z}(z, z_{\rm obs}) P_{m,{\rm x}_{\rm HI}}(k, z) \frac{D_g(z_{\rm obs})}{D_g(z)}$$

$$M_{\rm HI}(M_{\rm halo}, z_{\rm obs}, z_{\rm re}) \propto \frac{f_b M_{\rm halo}}{[1 + (2^{1/3}-1) M_F(z_{\rm obs}, z_{\rm re})/M_{\rm halo}]^3} \quad M_F = \tfrac{4}{3}\pi\rho_m\left(\tfrac{\pi}{k_F}\right)^3 \quad M_{\rm hm} := \frac{4\pi}{3}\rho_0\left(\frac{\pi}{k_{\rm hm}}\right)^3$$

$$k_{\rm F}^{-2} = \int_{t_{\rm dec}}^{t} -\frac{4}{3} t_1^{-2/3} t_{\rm dec}^{-1} \frac{\left(t_1^{2/3} - 3t_{\rm dec}^{2/3} + 2t_{\rm dec} t_1^{-1/3}\right)}{\left(t^{2/3} - 3t_{\rm dec}^{2/3} + 2t_{\rm dec} t^{-1/3}\right)} \times \left(-t_{\rm dec} t_1^{-1/3} + t_{\rm dec} t^{-1/3}\right) \left.\frac{c_s^2}{(aH)^2}\right|_{t_1} dt_1. \quad \text{(A6)}$$

$$c_s = \sqrt{\frac{\gamma k_B T_0}{\mu}}$$

$$\frac{n_X(M)}{n_{\rm CDM}(M)} \simeq \left(1 + \left(a\frac{M_{\rm hm}}{M}\right)^b\right)^c$$

$$P_{\rm N}(\boldsymbol{k}, z) = T_{\rm sys}^2(z)\chi^2(z)\lambda(z)\frac{1+z}{H(z)}\left(\frac{\lambda^2(z)}{A_e}\right)^2 \left(\frac{S_{\rm area}}{{\rm FOV}(z)}\right) \times \left(\frac{1}{N_{\rm pol} t_{\rm int} n_{\rm b}(u = k_\perp \chi(z)/2\pi)}\right)$$

Telescope	SKA1-LOW	PUMA
Redshift range	3.5<z<5.5	
Observing time (t_{int})	5000 h	1000 h
Sky coverage (f_{sky})	One pointing (FOV)	0.5
Dish/Station diameter (D_{phys})	40 m	6 m
Maximum baseline (b_{max})	~ 1 km	~ 1.5 km
Number of receivers (N_b)	224 stations	~ 32000
Δz	0.3	0.2
wedge	No	Yes

$$k_{\parallel,\mathrm{min}} = \frac{2\pi}{D_\mathrm{A}(z_\mathrm{max}) - D_\mathrm{A}(z_\mathrm{min})} \quad k_{\perp,\mathrm{min}} = \frac{2\pi D_\mathrm{phys}}{\lambda_\mathrm{obs} D_\mathrm{A}(z)} \quad k_\mathrm{min} = \sqrt{k^2_{\parallel,\mathrm{min}} + k^2_{\perp,\mathrm{min}}}$$

30 k bins in log space from k_{min} to k_{max}=0.4 Mpc^{-1}

wedge: $$\mu_\mathrm{min} = \frac{k_\parallel}{\sqrt{k_\perp^2 + k_\parallel^2}} = \frac{D(z)H(z)/[c(1+z)]}{\sqrt{1+\{D(z)H(z)/[c(1+z)]\}^2}}$$