Imprints of cosmic reionization as a probe of dark matter nature in the post-reionization era

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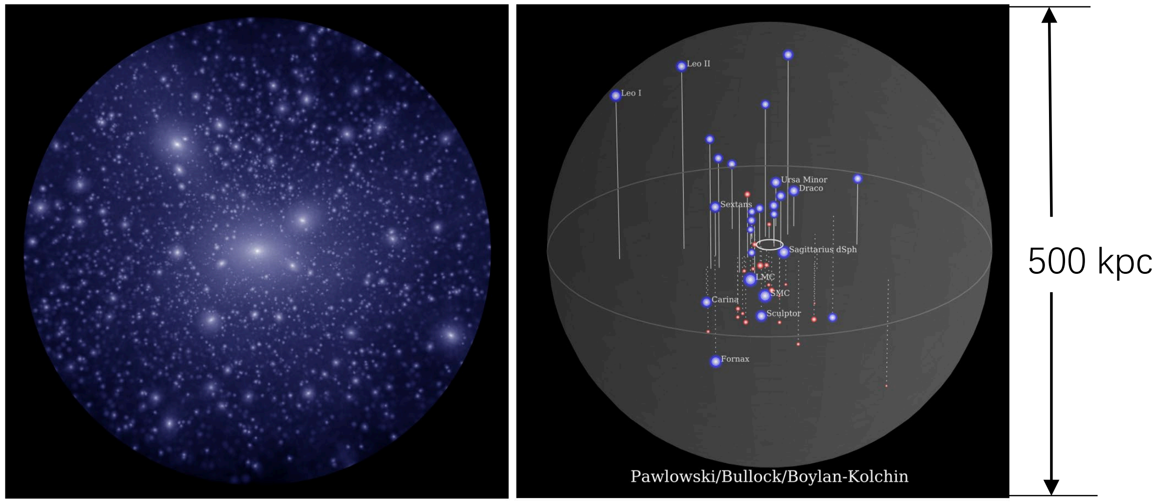
Small-scale challenges to the ΛCDM model

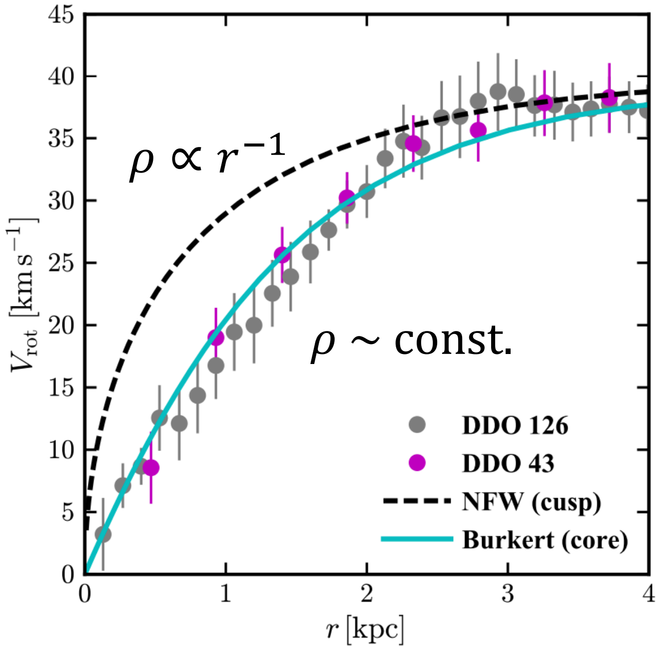
Missing Satellites Problem



N-body simulation observed satellite galaxies

(Bullock et al. 2017)

Cusp-Core Problem



(Bullock et al. 2017)

Other DM models: small-scale suppression

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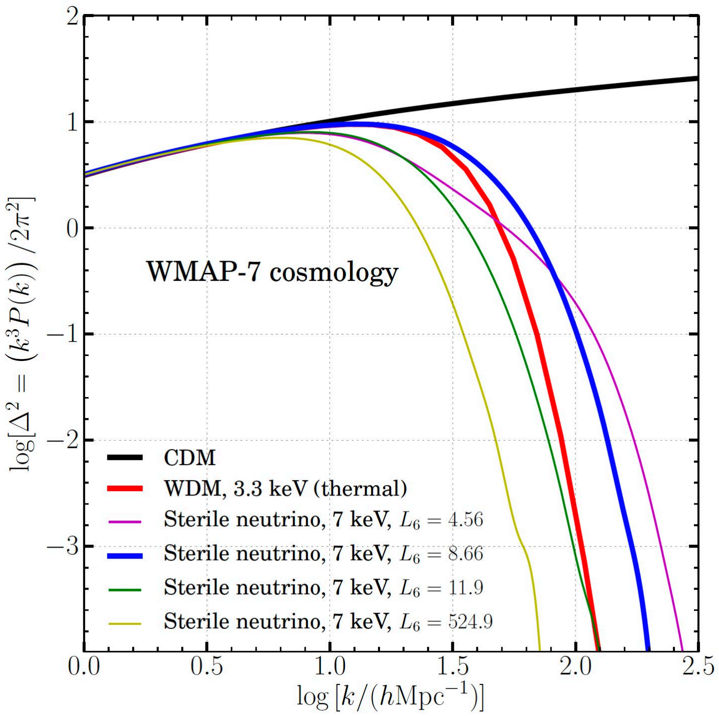
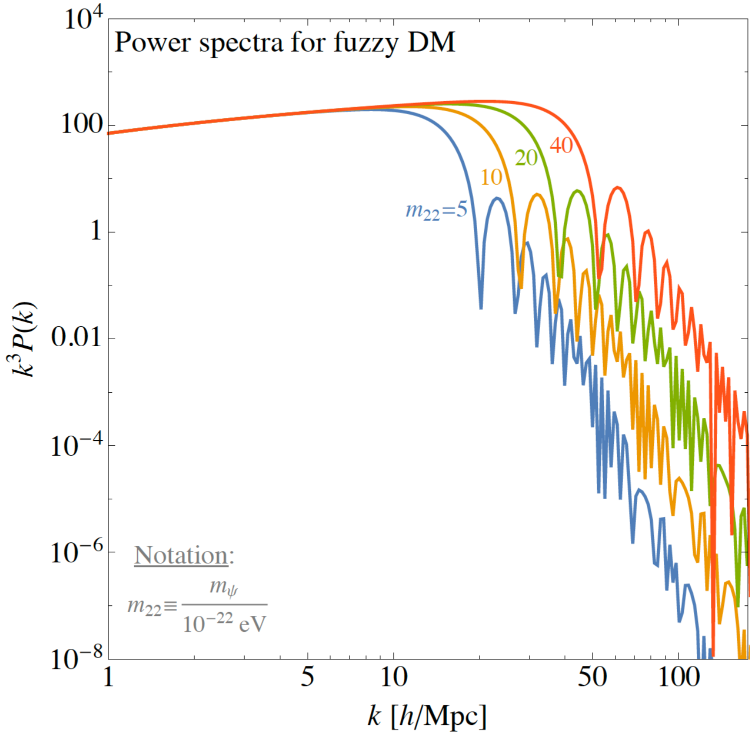
Warm Dark Matter



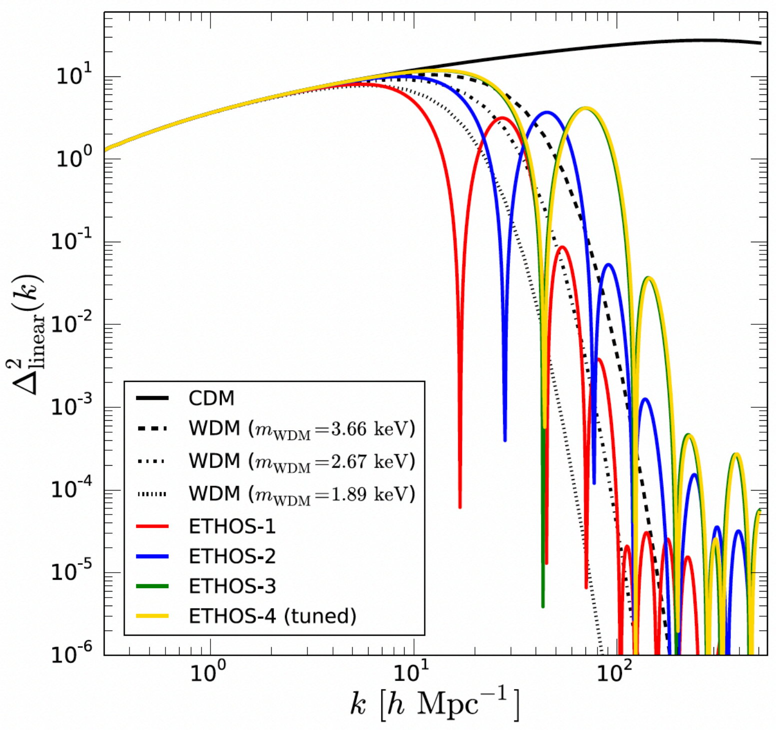
(Bose et al. 2016)

Fuzzy Dark Matter



(Murgia et al. 2017)

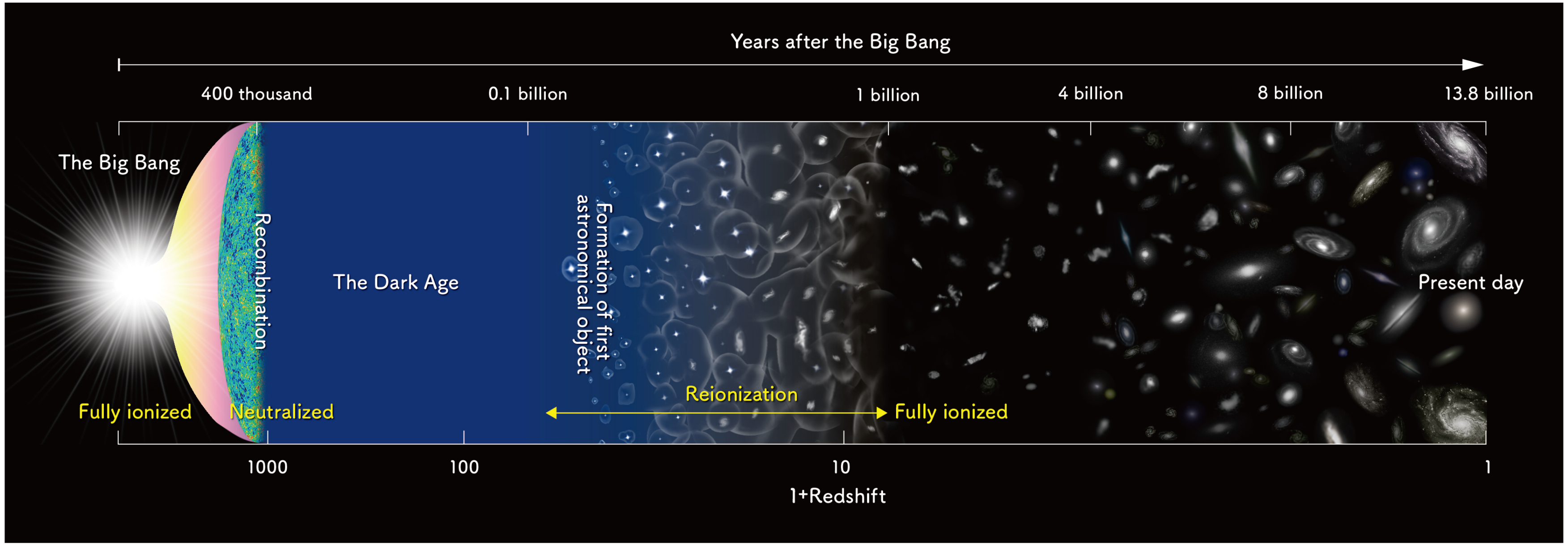
ETHOS



(Vogelsberger et al. 2015)

suppression on small scales: hard to observe

Reionization

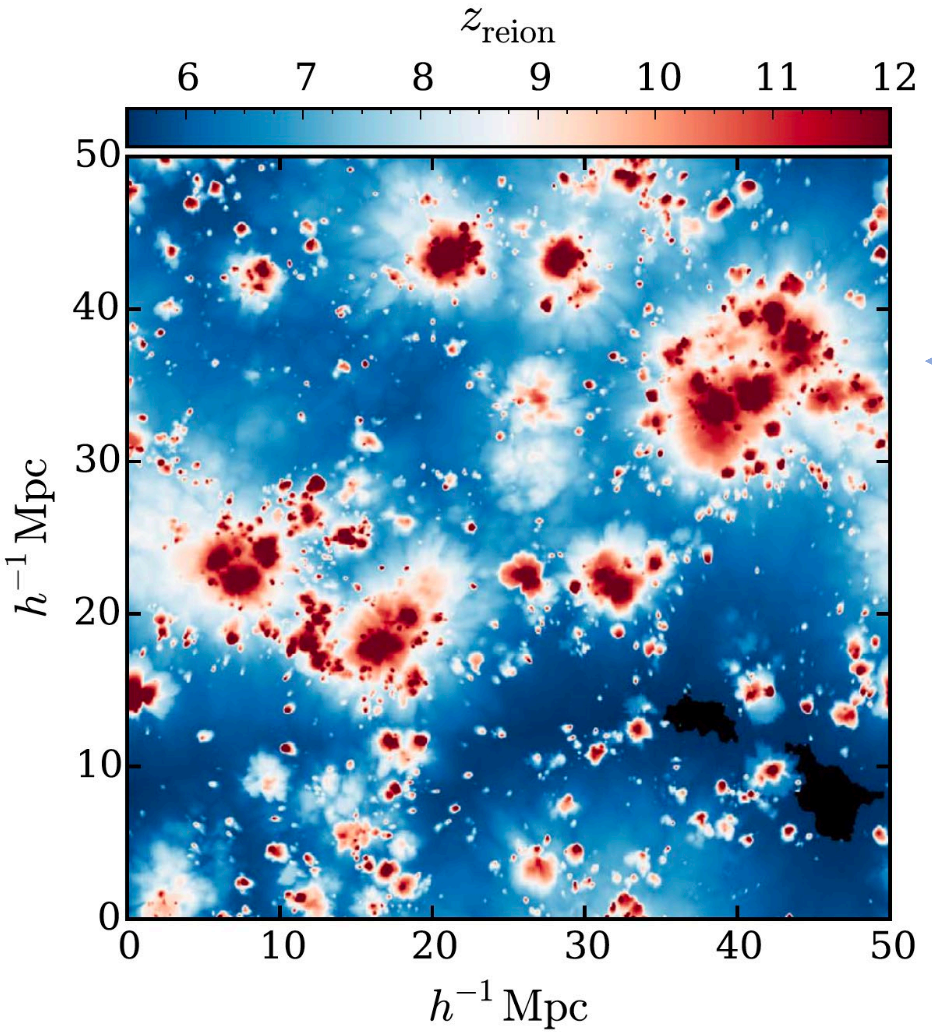


(NAOJ)

H I, He I -> H II, He II

photoionization heating: T of order 10^4 K

Thermal imprints couple to reionization bubble

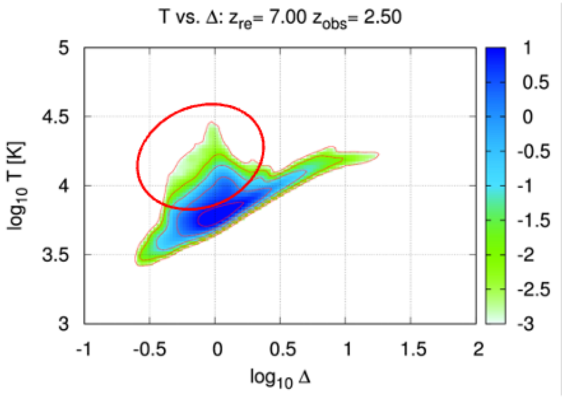


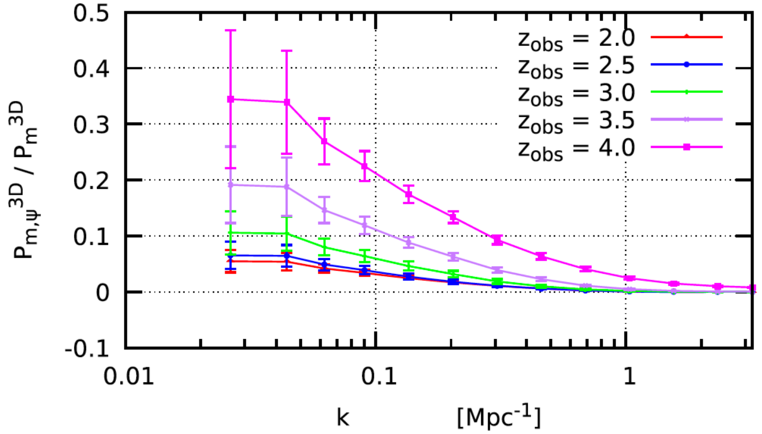
(D'Aloisio et al. 2019)

Different positions reionize at different redshifts.

Small scales: **high-entropy, mean-density gas** (Hirata 2018)
memory: when reionization happens

couple ⟷ bubbles scale

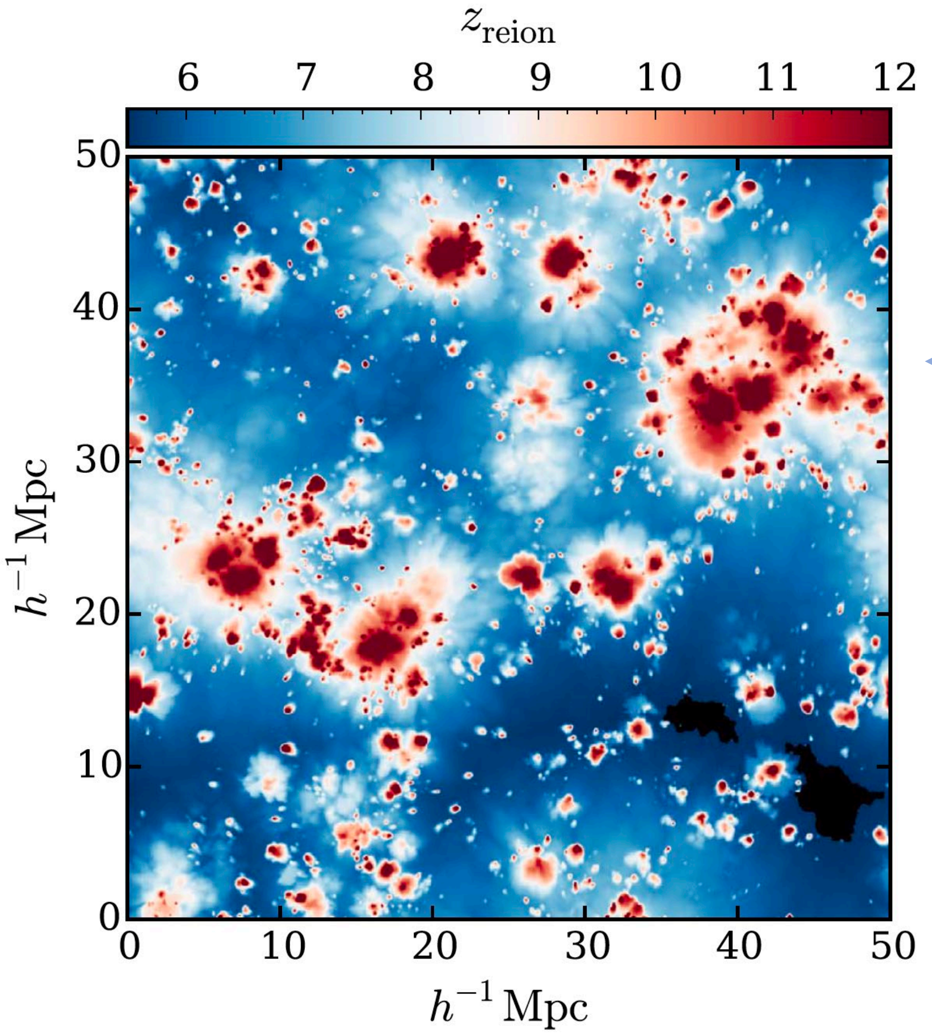




Impact of reionization on Lyα forest power spectrum:
enhancement on large scales

(Montero-Camacho et al. 2019)

Thermal imprints couple to reionization bubble



(D'Aloisio et al. 2019)

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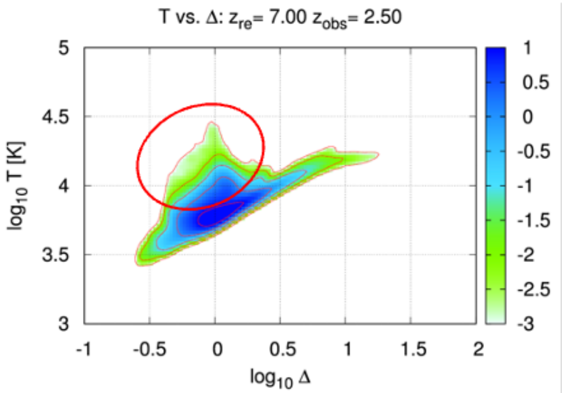

Small-scale suppression:

evolution of IGM

+ process of reionization

Lyα forest 3D power spectrum in WDM model

Thermal relics: form in thermal equilibrium and decouple while being relativistic.
e.g. gravitino

$$P_{\mathrm{F}}^{3D}(k,\mu,z_{\mathrm{obs}}) = b_{\mathrm{F}}^2(1+\beta_{\mathrm{F}}\mu^2)^2 P_{\mathrm{m}}(k,z_{\mathrm{obs}}) + 2b_{\mathrm{F}}b_{\Gamma}(1+\beta_{\mathrm{F}}\mu^2)\, P_{\mathrm{m},\psi}(k,z_{\mathrm{obs}})$$

(Montero-Camacho et al. 2019)

conventional power spectrum — impact of inhomogeneous reionization

$\psi(z_{\mathrm{re}}) = \ln[\tau_1(z_{\mathrm{re}})] - \ln[\tau_1(\bar{z}_{\mathrm{re}})]$ how **transparency** of gas varies with z_{re}

optical depth: $\tau = \tau_1\, \Delta^2 \alpha_A(T)$ **higher $\boldsymbol{\tau_1}$**: gas is more **transparent**

$\langle F\rangle = \langle e^{-\tau}\rangle = \frac{1}{N}\sum_{i=1}^{N}\exp(-\tau_1\Delta_i^2\alpha_A(T_i))$ $\langle F\rangle = \exp(-0.0023a^{-3.65})$ (Kim, Bolton & Viel 2007)

Hybrid method

impact of inhomogeneous reionization: $$P_{\mathrm{m},\psi}(k, z_{\mathrm{obs}}) = -\int_{z_{min}}^{z_{max}} \frac{\partial\psi(z_{\mathrm{obs}}, z_{\mathrm{re}})}{\partial z_{\mathrm{re}}} P_{\mathrm{m},x_{\mathrm{HI}}}(z_{\mathrm{re}}, k) \frac{D(z_{\mathrm{obs}})}{D(z_{\mathrm{re}})} dz_{\mathrm{re}}$$

Small scale: high-resolution hydrodynamical simulation

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, 12 calculate $\psi(z_{re})$

Large scale: semi-analytic model

21CMFAST box size: 400 Mpc

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

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

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

Implement WDM:

transfer function

+

effective Jeans mass

a new minimum mass that enters the mean collapse fraction

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

(Sitwell et al. 2014)

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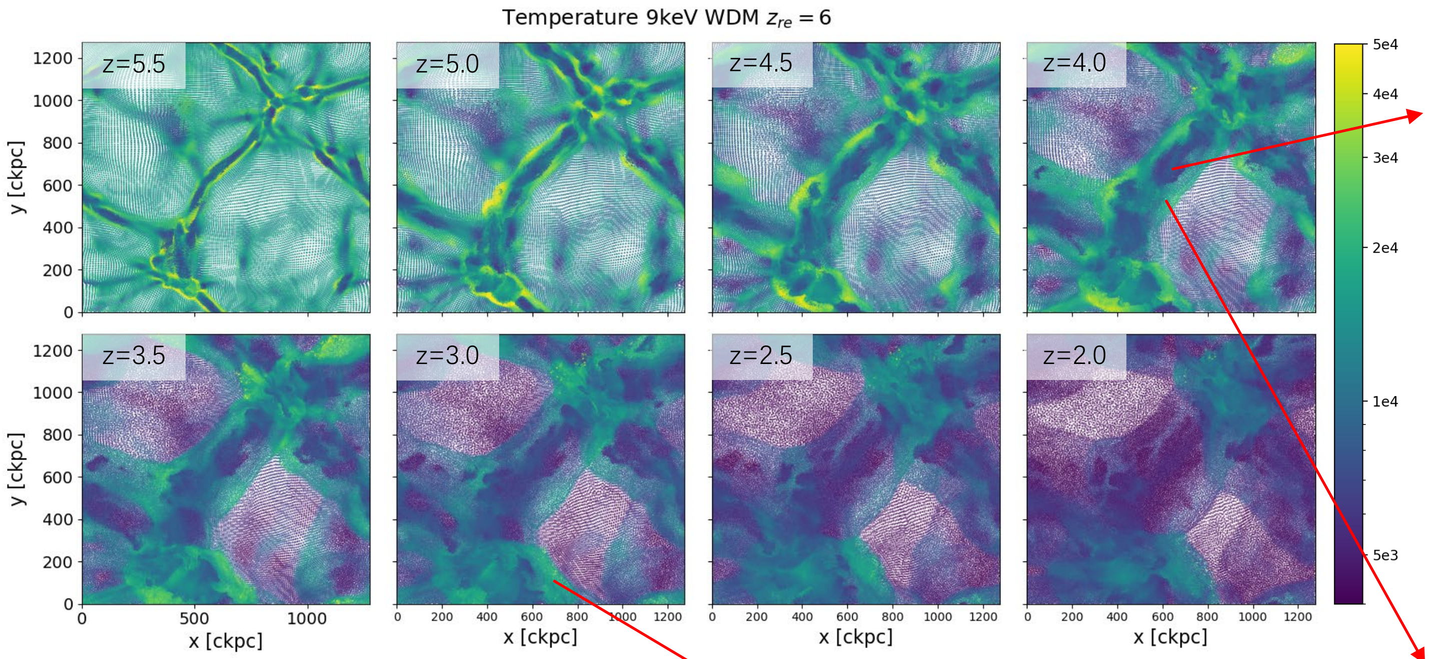
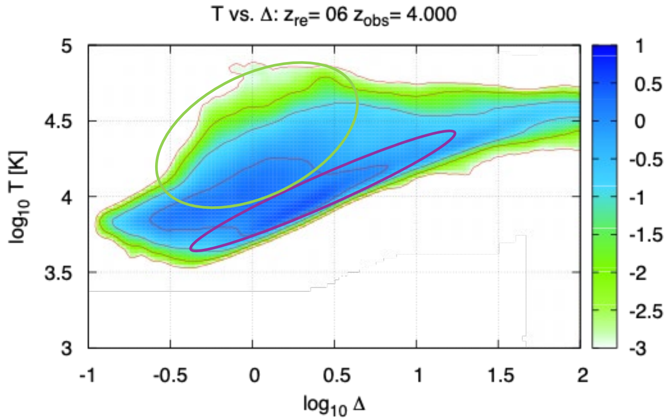
Evolution of gas temperature

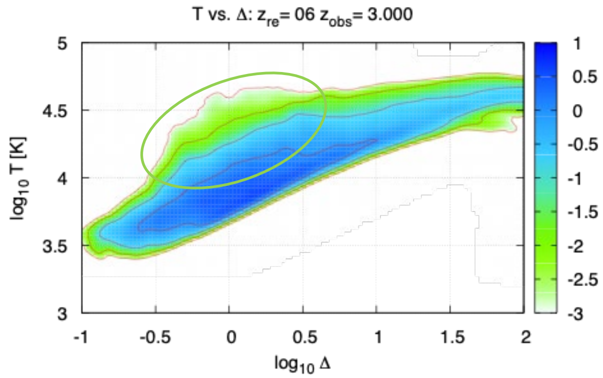


Gas in dense structures (purple):
adiabatic expansion and photoionization heating
-> $T - \Delta$ power-law relation



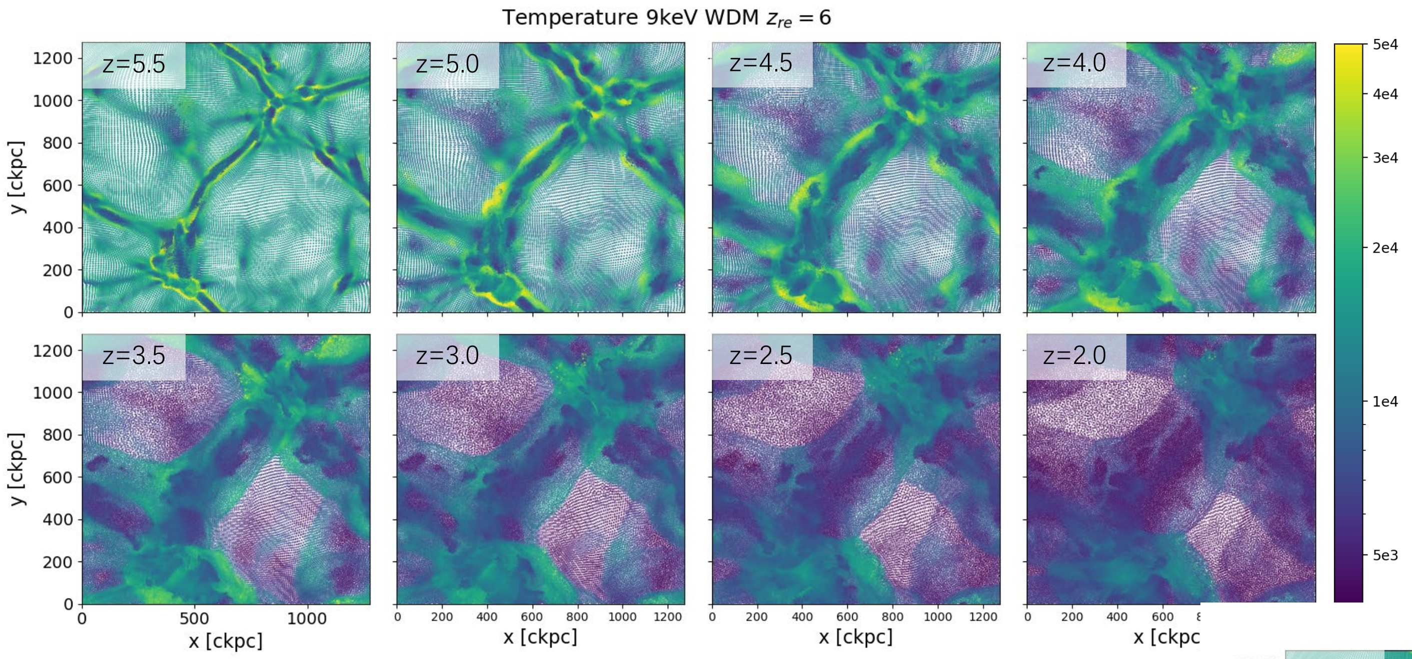
9 keV WDM

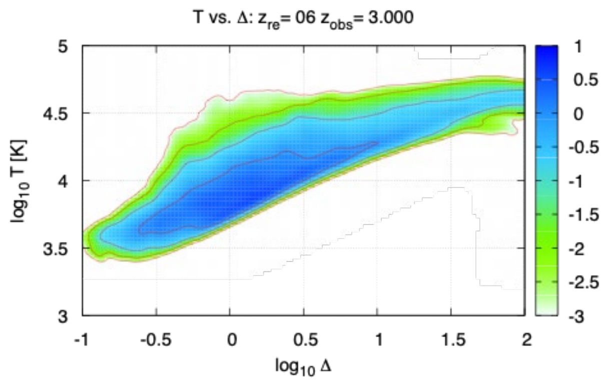
Low and mean density gas around structures:
(yellow and green): compressed and heated



maintain relatively high temperature,
deviate from power-law relation
high-entropy mean-density gas (Hirata, 2018)

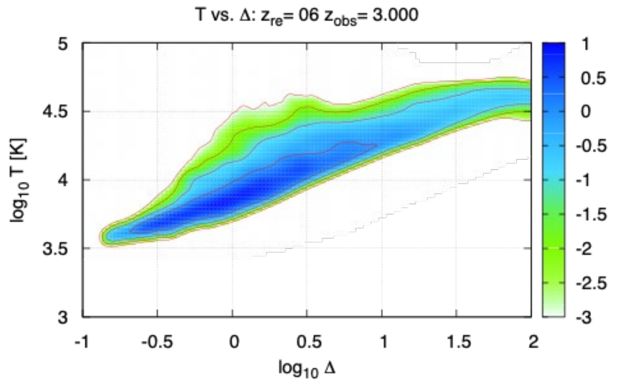
Evolution of gas temperature



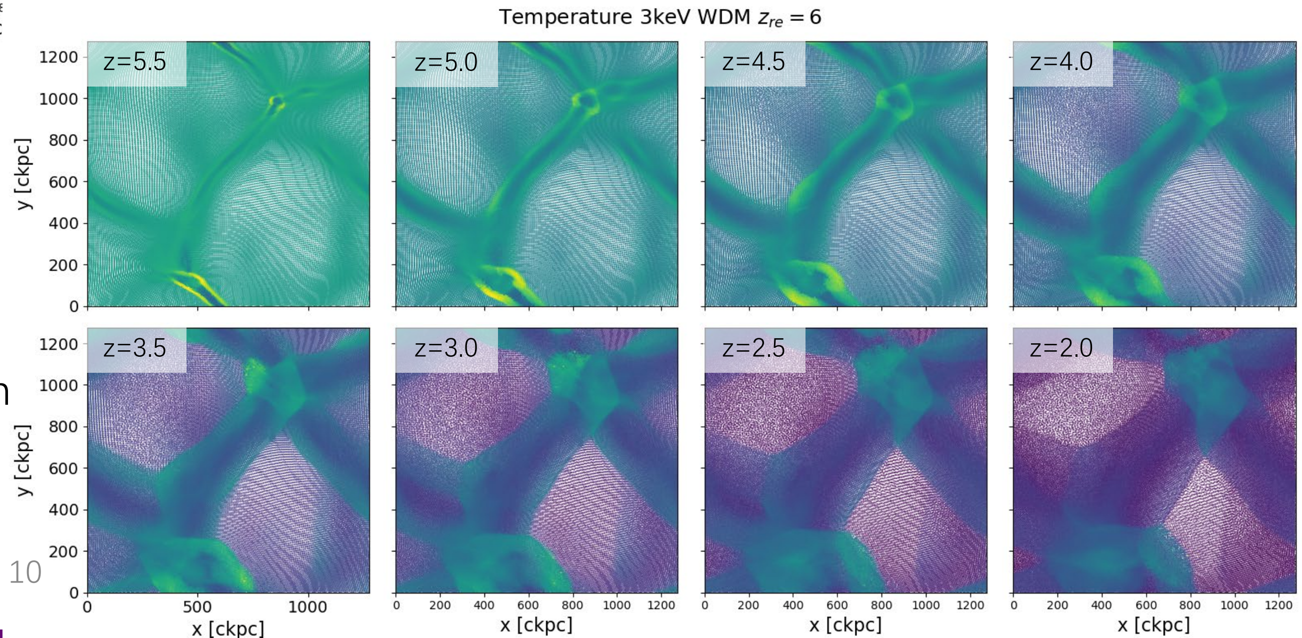


9 keV WDM

Lighter WDM model: expansion of dense gas and compression & heating of low density gas are **less violent**



3 keV WDM
tighter power-law relation



Temperature-density relation

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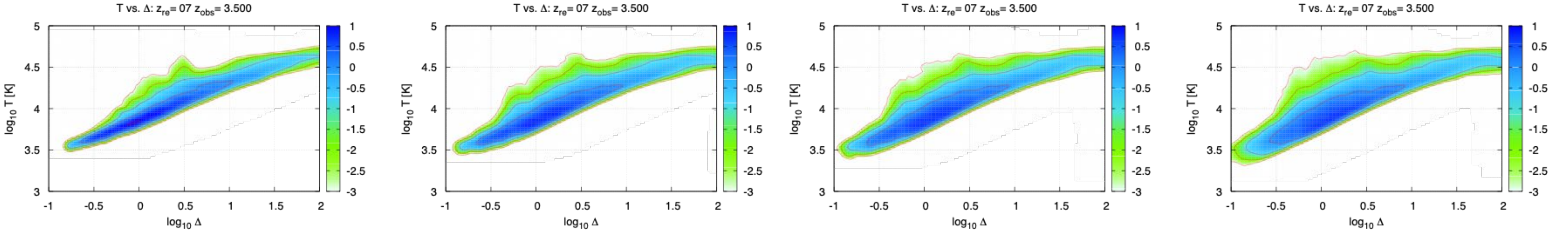
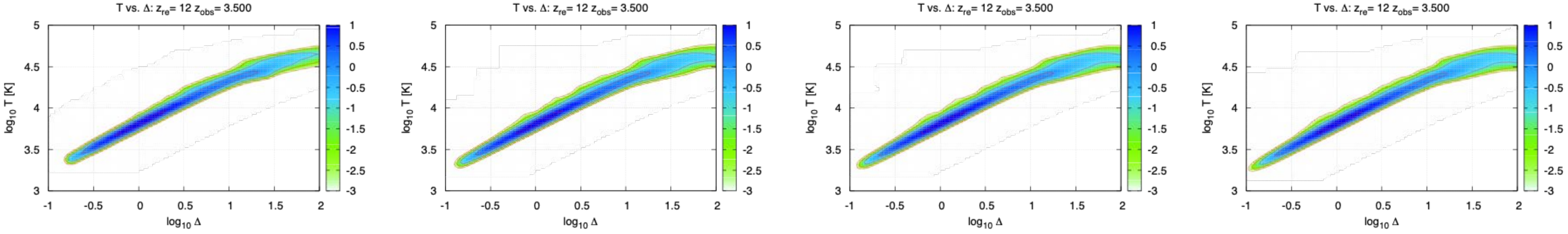
3 keV WDM | 6 keV WDM | 9 keV WDM | CDM



For late reionization ($z_{\rm re} \leq 8$), gas follows a tighter power-law relation in lighter WDM model.

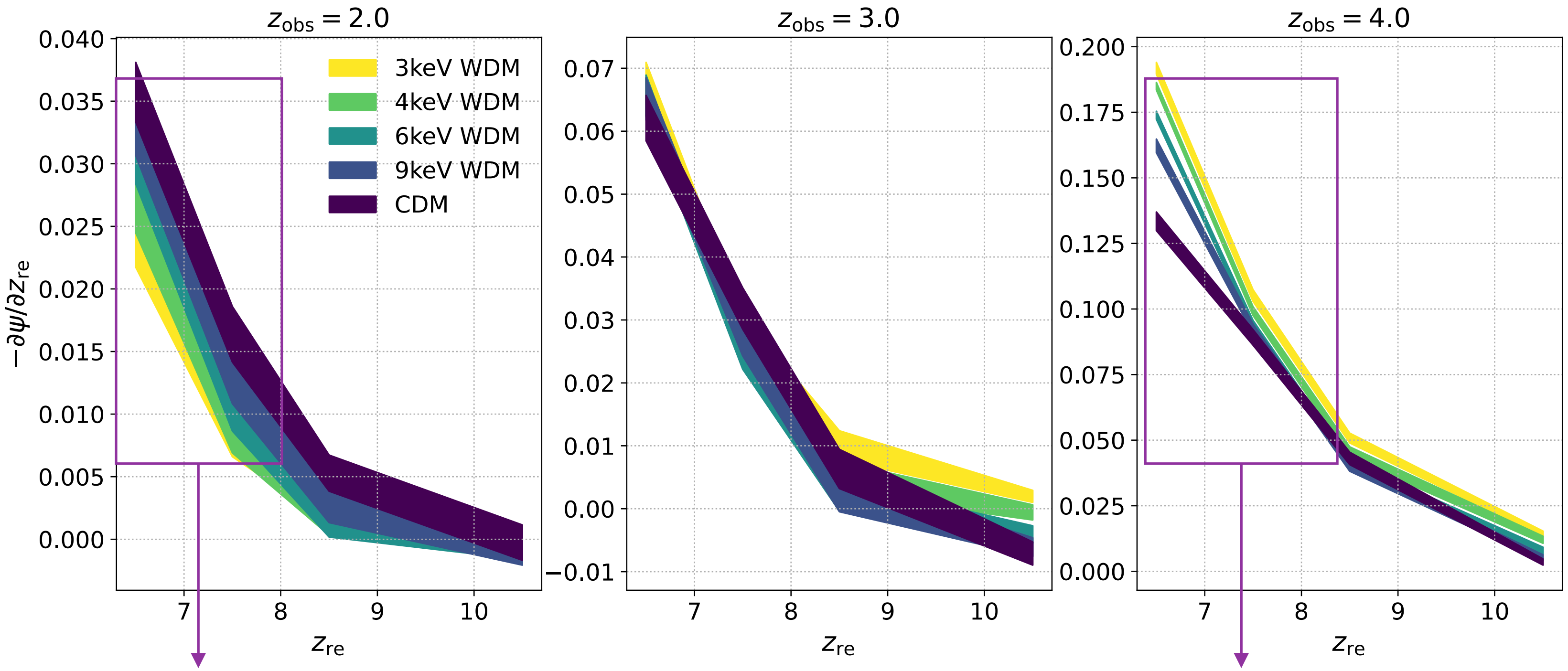


For early reionization: gas has enough time to relax to power-law relation.

Transparency: $\partial\psi(z_{\rm obs}, z_{\rm re})/\,\partial z_{\rm re}$

impact of inhomogeneous reionization: $P_{\rm m,\psi}(k, z_{\rm obs}) = -\int_{z_{min}}^{z_{max}} \frac{\partial\psi(z_{\rm obs}, z_{\rm re})}{\partial z_{\rm re}} P_{{\rm m},x_{\rm HI}}(z_{\rm re}, k)\,\frac{D(z_{\rm obs})}{D(z_{\rm re})}\,dz_{\rm re}$

small scale: thermal imprints



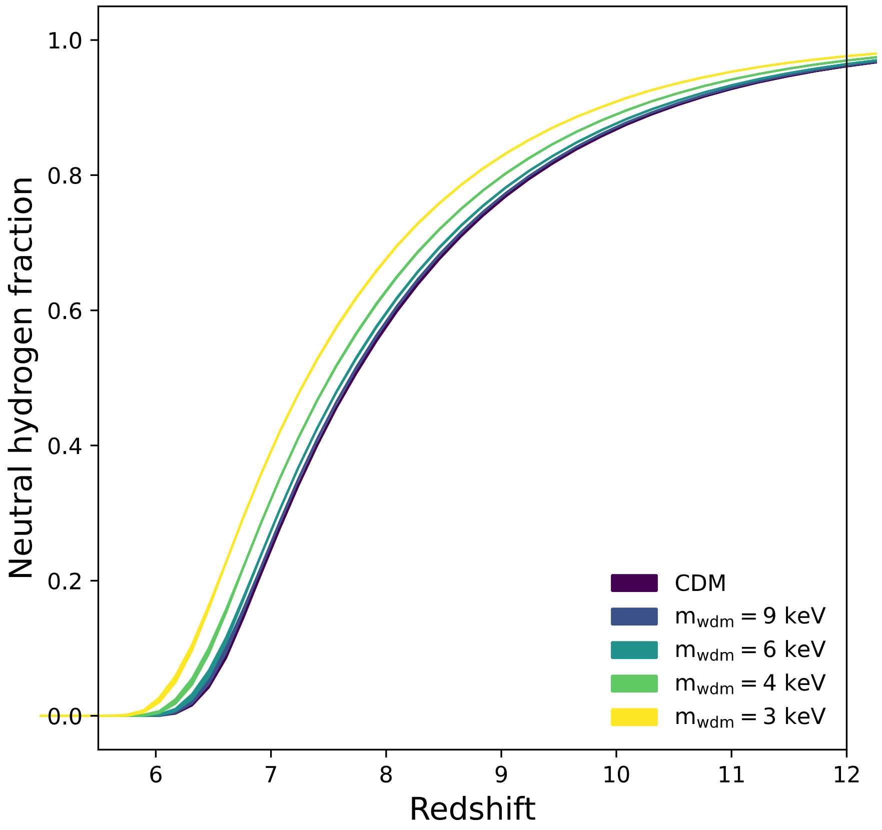
Band: ± standard deviation of 4 realizations

Heavier DM, transparency varies faster. Effect of high-entropy mean-density gas is more prominent.

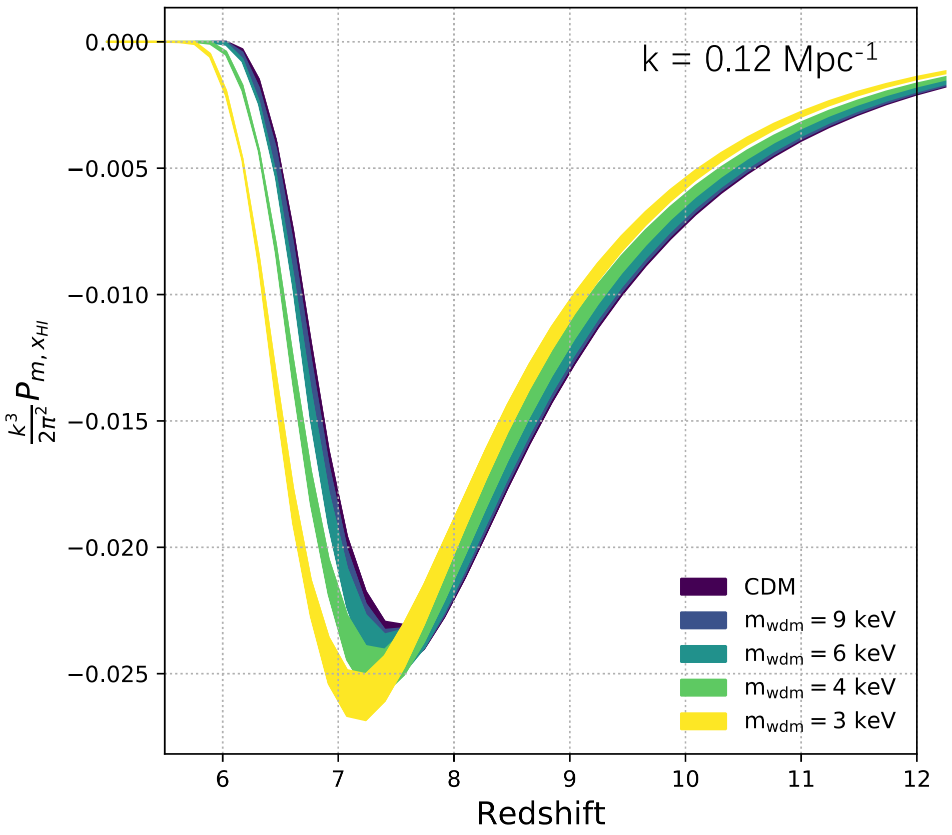
Lighter WDM, transparency varies faster. Cooling is more efficient.

$P_{m,x_{\rm HI}}$: patchy reionization

impact of inhomogeneous reionization: $P_{\rm m,\psi}(k, z_{\rm obs}) = -\int_{z_{min}}^{z_{max}} \frac{\partial\psi(z_{\rm obs}, z_{\rm re})}{\partial z_{\rm re}} P_{{\rm m},x_{\rm HI}}(z_{\rm re}, k) \frac{D(z_{\rm obs})}{D(z_{\rm re})} dz_{\rm re}$



Delay of reionization in WDM



On large scales: enhancement of $P_{m,x_{\rm HI}}$ in WDM

Lyα forest 3D power spectrum

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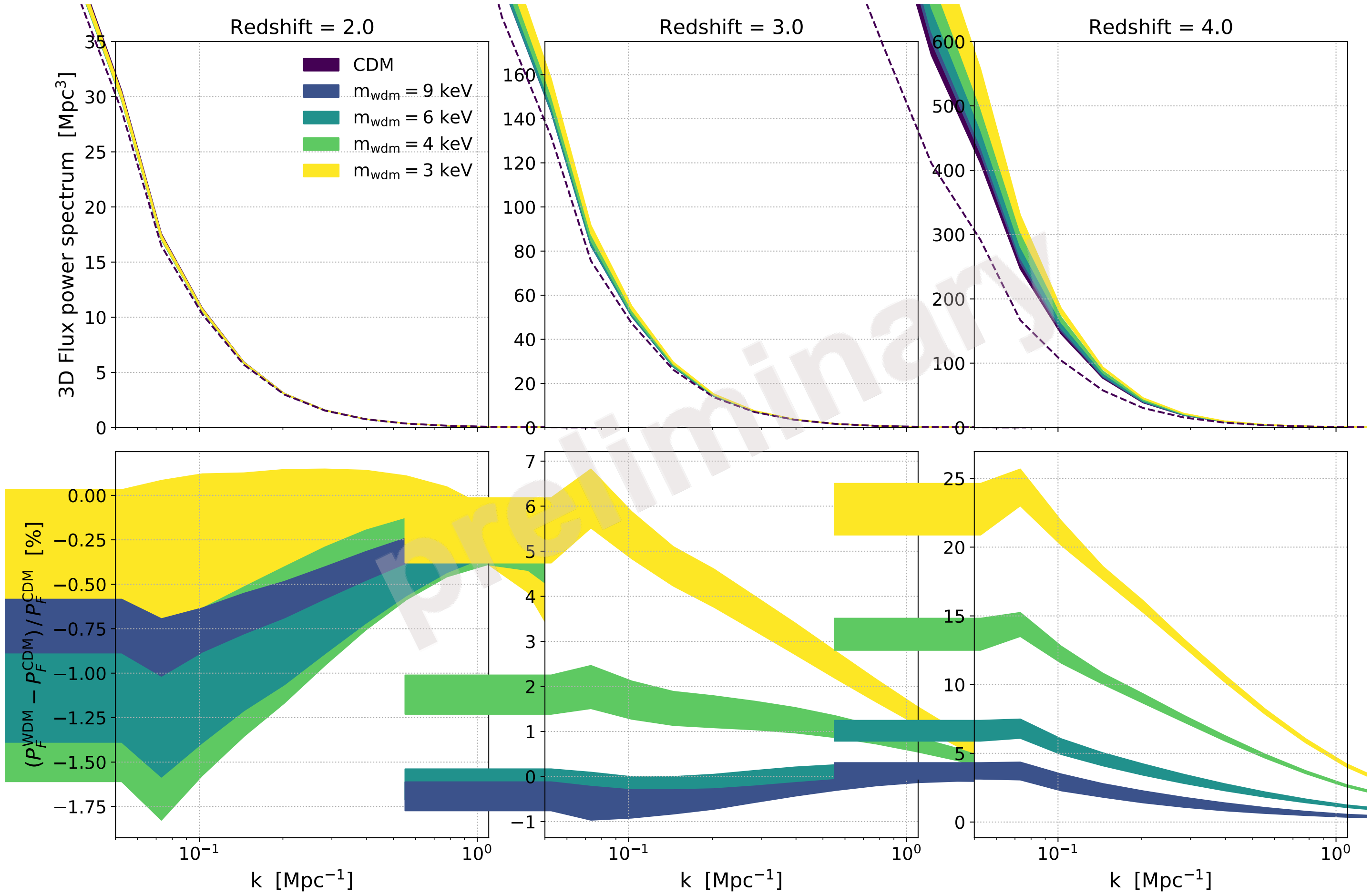
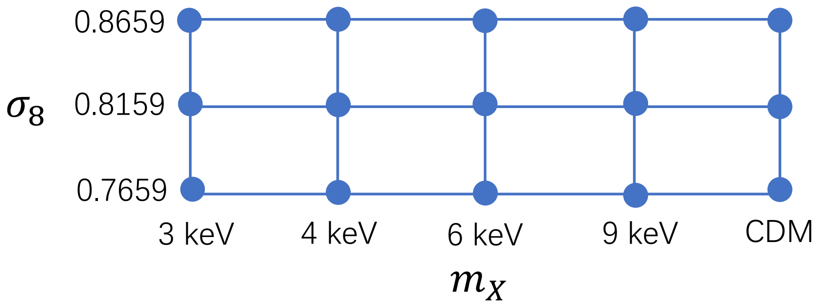
$$P_{\rm F}^{3D} = b_{\rm F}^2(1+\beta_{\rm F}\mu^2)^2 P_{\rm m} + 2b_{\rm F}b_{\Gamma}(1+\beta_{\rm F}\mu^2)\, P_{{\rm m},\psi}$$



Impact of reionization: enhancement of power spectrum

At $z_{obs} \geq 3.0$, the enhancement is larger in lighter WDM.

Forecast: constrain WDM mass by DESI Lyα surveys



MCMC: likelihood function: $\mathcal{L} = \exp[-\frac{1}{2}\sum_{\text{bins}}(P_{\text{F}}^{\text{3D}}(z,\boldsymbol{k}) - P_{\text{F}}^{\text{3D,CDM}}(z,\boldsymbol{k}))^2/\sigma_{\text{F}}^2\,(z,\boldsymbol{k})]$

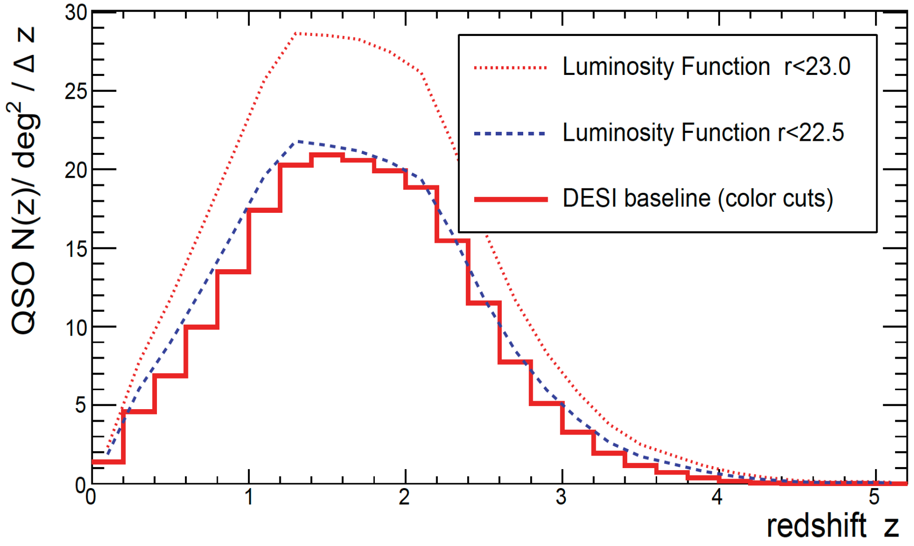
$$\sigma_{\text{F}}^2(z,\boldsymbol{k}) = \frac{[P_{\text{tot}}^{\text{3D,CDM}}(z,\boldsymbol{k})]^2}{N_{\text{mode}}}$$

$$P_{\text{tot}}^{\text{3D,CDM}}(z,\boldsymbol{k}) = P_{\text{F}}^{\text{3D,CDM}}(z,\boldsymbol{k}) + P_{\text{F}}^{\text{1D}}(z,k_{\parallel})P_w^{\text{2D}}(z) + P_N^{\text{eff}}(z)$$

(McDonald & Eisenstein 2007) aliasing term for 2D quasar density

P_w^{2D}: power spectrum of weighted quasar sampling function
P_N^{eff}: weighted pixel noise power

Quasar luminosity function and spectrograph performance of DESI (5 years, 14,000 square degrees)



Expected redshift distribution of the QSO sample (DESI Collaboration 2016)

Forecast: constrain WDM mass by DESI Lyα surveys

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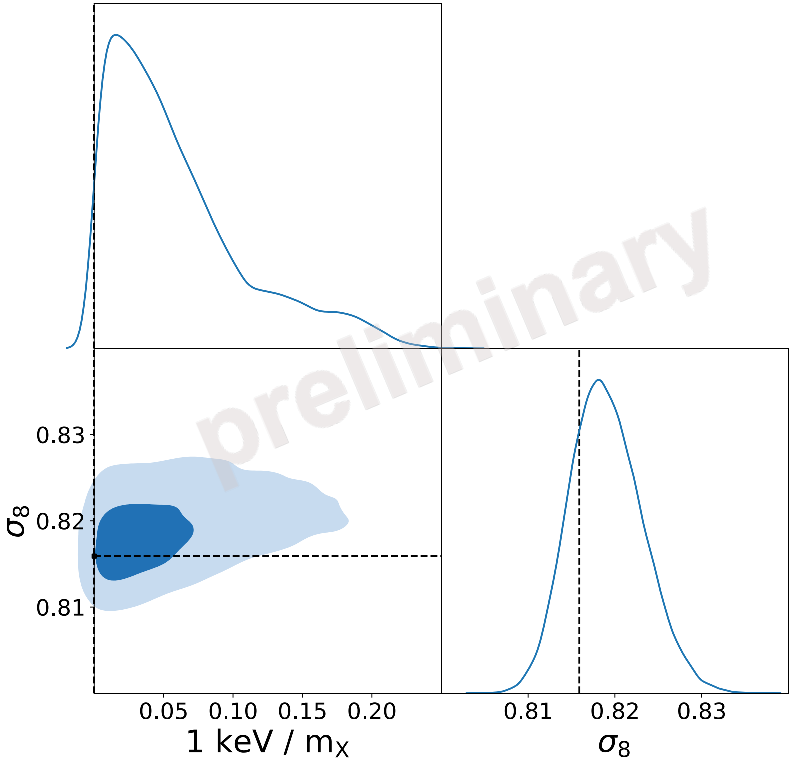
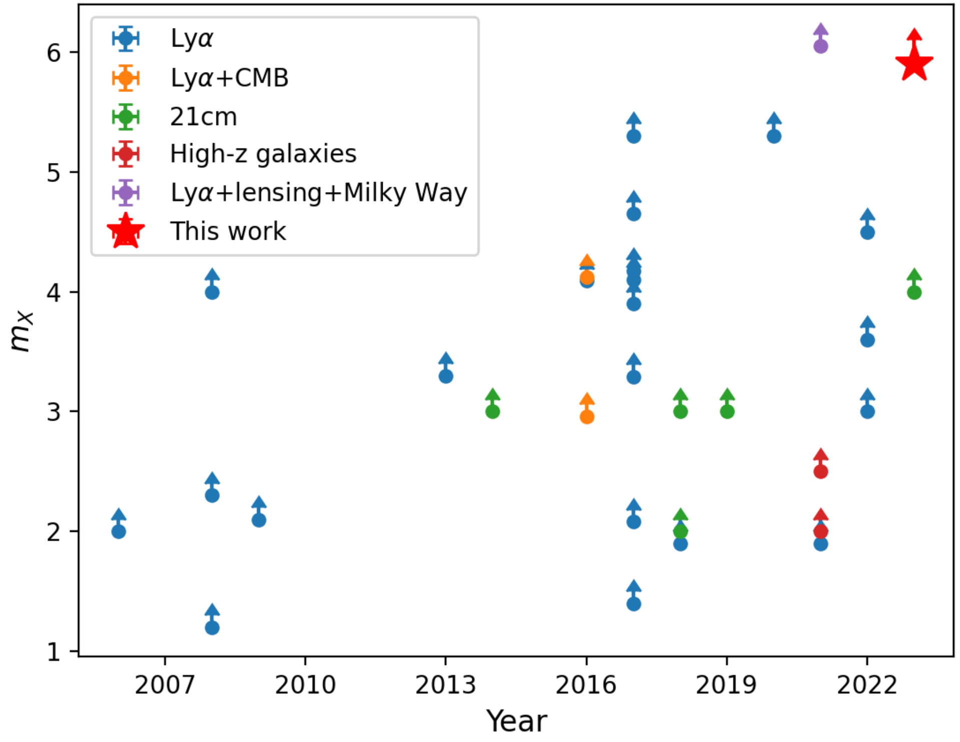


forecast: $\boldsymbol{m_X}$>5.9 keV

$$\sigma_8 = 0.819^{+0.09}_{-0.07}$$

(95% Bayesian credible interval)



Summary

Impact of reionization: $P_{\mathrm{F}}^{3\mathrm{D}} = b_{\mathrm{F}}^2(1+\beta_{\mathrm{F}}\mu^2)^2 P_{\mathrm{m}} + 2b_{\mathrm{F}}b_{\Gamma}(1+\beta_{\mathrm{F}}\mu^2)\,P_{\mathrm{m},\psi}$

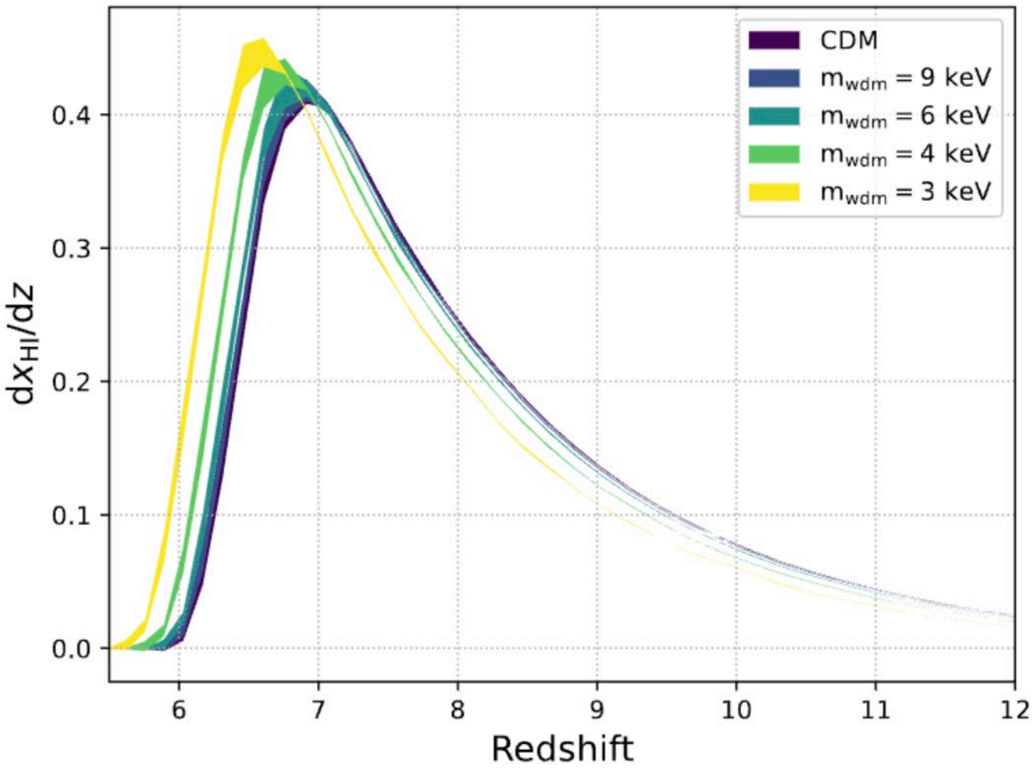
$$P_{\mathrm{m},\psi}(k, z_{\mathrm{obs}}) = -\int_{z_{min}}^{z_{max}} \frac{\partial\psi(z_{\mathrm{obs}}, z_{\mathrm{re}})}{\partial z_{\mathrm{re}}} P_{\mathrm{m},x_{\mathrm{HI}}}(z_{\mathrm{re}}, k) \frac{D(z_{\mathrm{obs}})}{D(z_{\mathrm{re}})} dz_{\mathrm{re}}$$

small scales: thermal imprints — large scales: patchy reionization

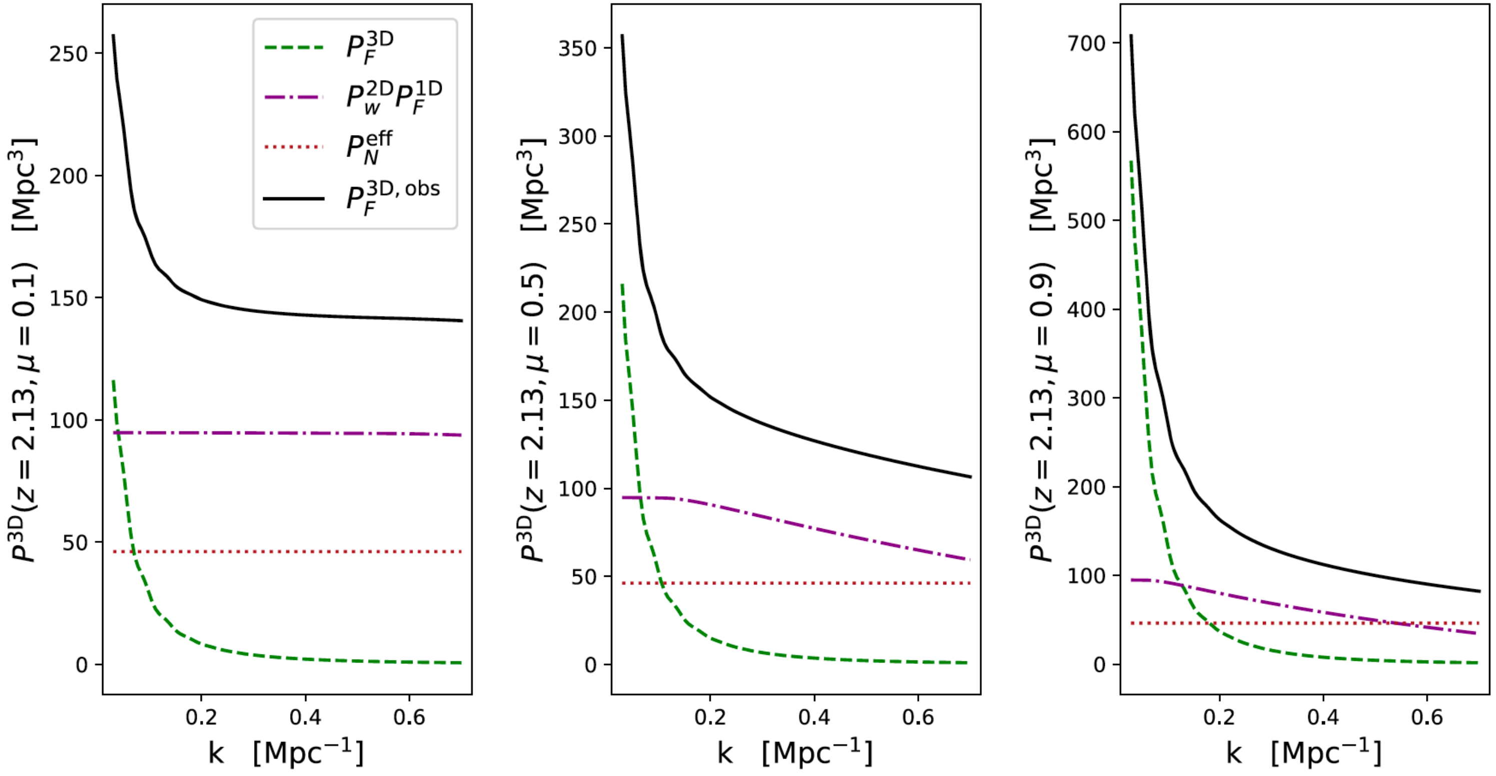
$P_{\mathrm{F}}^{3\mathrm{D}}$ can **differentiate** DM models on k < 1 Mpc^{-1}.

Forecast DESI constraints: $\boldsymbol{m_X > 5.9\ \mathrm{keV}}$ at 95% credible interval

Notes


CDM
m_wdm = 9 keV
m_wdm = 6 keV
m_wdm = 4 keV
m_wdm = 3 keV
dx_HI/dz
0.0
0.1
0.2
0.3
0.4
6
7
8
9
10
11
12
Redshift

Notes



(Montero-Camacho & Mao 2020)

$$P_{\mathrm{w}}^{2\mathrm{D}} = \frac{I_2}{I_1^2 L_{\mathrm{q}}},$$

$$P_{\mathrm{N}}^{\mathrm{eff}} = \frac{I_3 l_{\mathrm{p}}}{I_1^2 L_{\mathrm{q}}},$$

$$I_1 = \int \mathrm{d}m \frac{\mathrm{d}n_{\mathrm{q}}}{\mathrm{d}m} w(m),$$

$$I_2 = \int \mathrm{d}m \frac{\mathrm{d}n_{\mathrm{q}}}{\mathrm{d}m} w^2(m),$$

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

$$w(m) = \frac{P_{\mathrm{S}}/P_{\mathrm{N}}(m)}{1 + P_{\mathrm{S}}/P_{\mathrm{N}}(m)}$$

Notes

Cosmological probe	Constraint	m_X [keV]	Reference
Lyα	Lyα FPS	$\gtrsim 2$	Viel et al. (2006)
	HIRES FPS	$\gtrsim 1.2$	Viel et al. (2008)
	SDSS FPS	$\gtrsim 2.3$	
	SDSS+HIRES FPS	$\gtrsim 4$	
	Lyα FPS	≥ 2.1	Boyarsky et al. (2009)
	Lyα FPS	$\gtrsim 3.3$	Viel et al. (2013)
	SDSS-III FPS	> 4.09	Baur et al. (2016)
	XQ-100 FPS	> 1.4	Iršič et al. (2017)
	HIRES + MIKE FPS	> 4.1	
	XQ-100 + HIRES + MIKE FPS	> 5.3	
	HIRES + MIKE FPS[1.1]	> 3.9	
	XQ-100 FPS	$\gtrsim 2.08$	Yèche et al. (2017)
	SDSS-III + XQ-100 [1.2]	$\gtrsim 3.29$	
	SDSS-III + XQ-100	$\gtrsim 4.17$	
	SDSS-III + XQ-100 + HIRES/MIKE	$\gtrsim 4.65$	
	Lyα FPS[1.3]	$\gtrsim 1.9$	Garzilli et al. (2018)
	eBOSS ($z < 4.5$) + XQ-100 FPS	> 5.3	Palanque-Delabrouille et al. (2020)
	HIRES FPS	≥ 1.9	Garzilli et al. (2021)
	Keck + VLT FPS	> 3.0	Villasenor et al. (2022)
	Keck + VLT FPS best fit[1.4]	> 3.6	
	Keck + VLT FPS + Increased Quasar Sightlines [1.5]	> 4.5	
Lyα + CMB	SDSS-III flux + Planck 2016 + SDSS-III BAO	> 2.96	Baur et al. (2016)
	SDSS-III flux + Planck 2016 + SDSS-III BAO + α_s	> 4.12	
21cm	Atomic cooling haloes + f_*	≥ 3	Sitwell et al. (2014)
	Atomic cooling halos	> 3	Safarzadeh et al. (2018)
	H II cooling halos	> 2	
	EDGES + X-ray heating+ with and without excess radio background	$\gtrsim 3$	Chatterjee et al. (2019)
	EDGES + $f_* = 0.09$	$= 6$	Boyarsky et al. (2019)
	SKA1-LOW	$\gtrsim 4$	Mosbech et al. (2023)
High-z galaxies	UV luminosity function	$\gtrsim 2$	Rudakovskyi et al. (2021)
	JWST Mock data	$\gtrsim 2.5$	
Lyα + lensing + Milky Way	HIRES + MIKE flux, SLACS and DES + SDSS	≥ 6.048	Enzi et al. (2021)

Notes

$$
\begin{aligned}
&(2\pi)^3\delta^{(3)}(\boldsymbol{k}-\boldsymbol{k}')P_{\mathrm{m},\psi}(z_{\mathrm{obs}},k) \\
&= \int_{\mathbb{R}^3} \mathrm{d}^3\boldsymbol{r}' \mathrm{e}^{-\mathrm{i}\boldsymbol{k}'\cdot\boldsymbol{r}'} \langle \tilde{\delta}^*_{\mathrm{m}}(z_{\mathrm{obs}},\boldsymbol{k})\psi(z_{\mathrm{re}}(\boldsymbol{r}'),z_{\mathrm{obs}})\rangle \\
&= -\int_{\mathbb{R}^3} \mathrm{d}^3\boldsymbol{r}' \mathrm{e}^{-\mathrm{i}\boldsymbol{k}'\cdot\boldsymbol{r}'} \int_{z_{\max}}^{z_{\min}} \Big\langle \tilde{\delta}^*_{\mathrm{m}}(z_{\mathrm{obs}},\boldsymbol{k})\frac{\partial\psi(z',z_{\mathrm{obs}})}{\partial z'} \\
&\quad \times \Theta(z'-z_{\mathrm{re}}(\boldsymbol{r}'))\Big\rangle dz' \\
&= -\int_{z_{\min}}^{z_{\max}} \mathrm{d}z' \frac{\partial\psi}{\partial z'}(z',z_{\mathrm{obs}})\langle\tilde{\delta}^*_{\mathrm{m}}(z',\boldsymbol{k})\tilde{x}_{\mathrm{HI}}(z',\boldsymbol{k}')\rangle \frac{D(z_{\mathrm{obs}})}{D(z')}.
\end{aligned}
$$

(Montero-Camacho et al. 2019)