Astroparticle Constraints from Cosmic Reionization and Primordial Galaxy Formation

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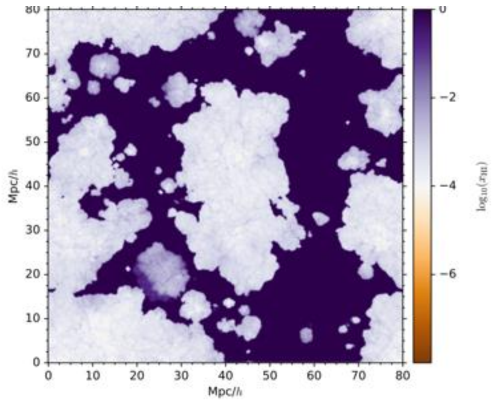
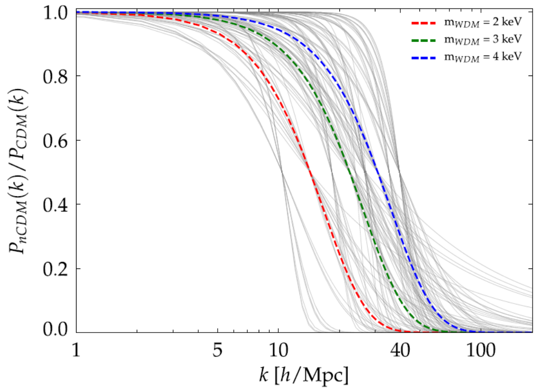
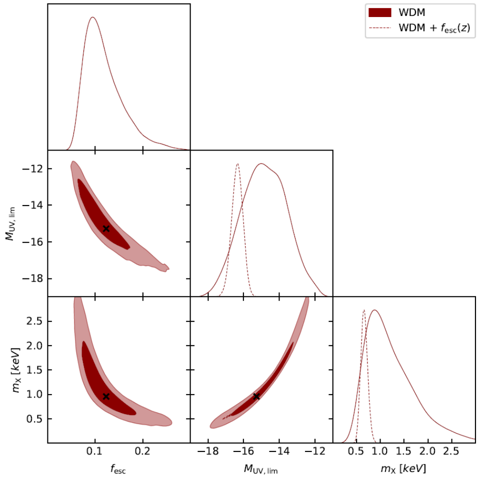
based on Lapi+22, Univ., 8, 476; Gandolfi+22, Univ., 8, 589

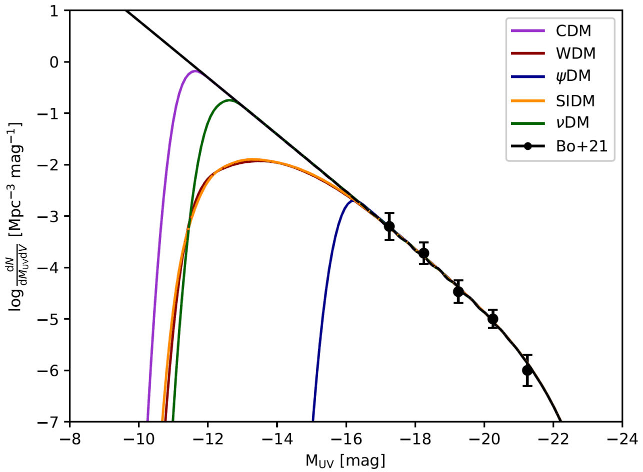
Overview

- Introduction
- Reionization model
- DM scenarios
- Galaxy formation threshold
- Bayesian analysis
- Results
- Summary

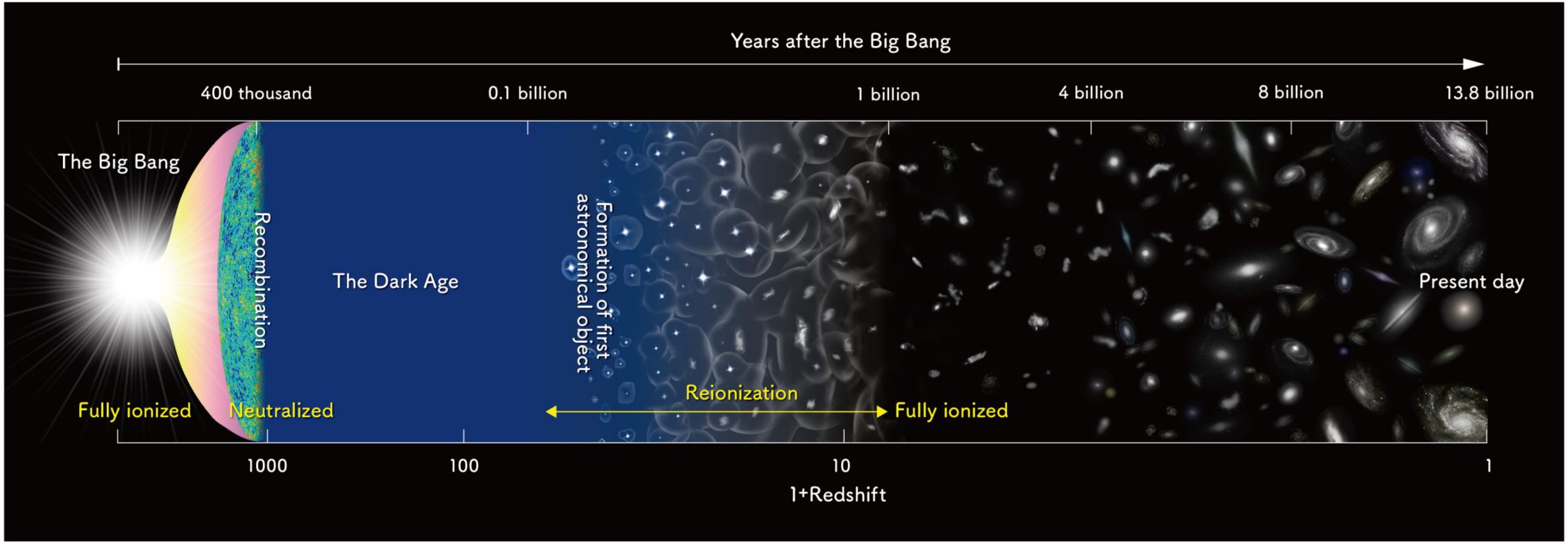






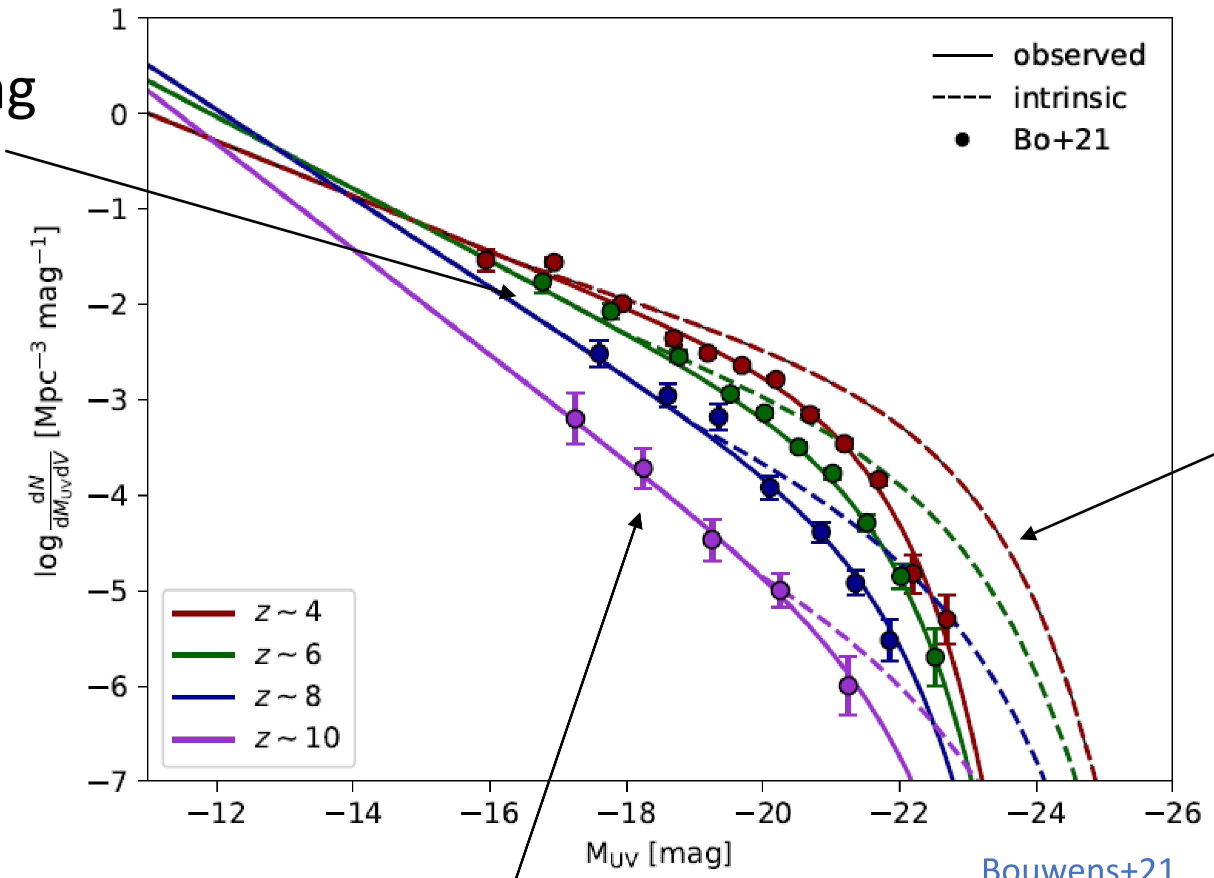


Cosmic Reionization



UV luminosity function

well determined brightward of -16.5 mag For z<10



Bouwens+21

dust corrections only relevant at bright end

Schechter function rendition

$$\frac{\mathrm{d}N}{\mathrm{d}M_{\rm UV}\,\mathrm{d}V} = \phi^{\star}\,\frac{\ln(10)}{2.5}\,10^{-0.4\,(M_{\rm UV}-M^{\star}_{\rm UV})\,(\alpha+1)} \times e^{-10^{-0.4\,(M_{\rm UV}-M^{\star}_{\rm UV})}}$$

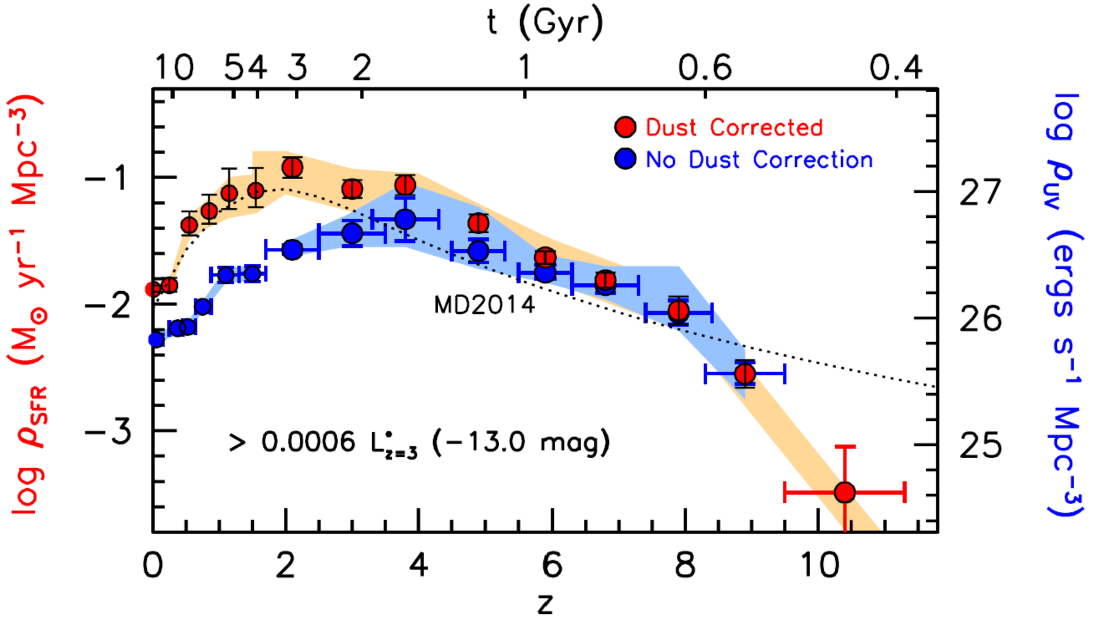
Cosmic ionization rate

limiting magnitude

$$\rho_{\mathrm{SFR}}(z) = \int^{M_{\mathrm{UV}}^{\mathrm{lim}}} \mathrm{d}M_{\mathrm{UV}} \, \frac{\mathrm{d}N}{\mathrm{d}M_{\mathrm{UV}}\,\mathrm{d}V} \, \mathrm{SFR}$$

Chabrier IMF

$$\log \mathrm{SFR}\,[\mathrm{M}_\odot\ \mathrm{year}^{-1}] \approx -0.4\,(M_{\mathrm{UV}} + 18.5)$$



Bouwens+21,+22

$$\dot{N}_{\mathrm{ion}} \approx f_{\mathrm{esc}}\, k_{\mathrm{ion}}\, \rho_{\mathrm{SFR}} + \dot{N}_{\mathrm{ion}}^{\mathrm{AGN}}$$

escape fraction

$$k_{\mathrm{ion}} \approx 4 \times 10^{53}\,\mathrm{s}^{-1}\ \mathrm{M}_\odot^{-1}$$

Chabrier IMF

HII fraction and optical depth

$$\dot{Q}_{\rm HII} = \frac{\dot{N}_{\rm ion}}{\bar{n}_{\rm H}} - \frac{Q_{\rm HII}}{t_{\rm rec}}$$

recombination time

$$t_{\rm rec} \approx 3.2\ {\rm Gyr}\ [(1+z)/7]^{-3}\, C_{\rm HII}^{-1}$$

clumping factor

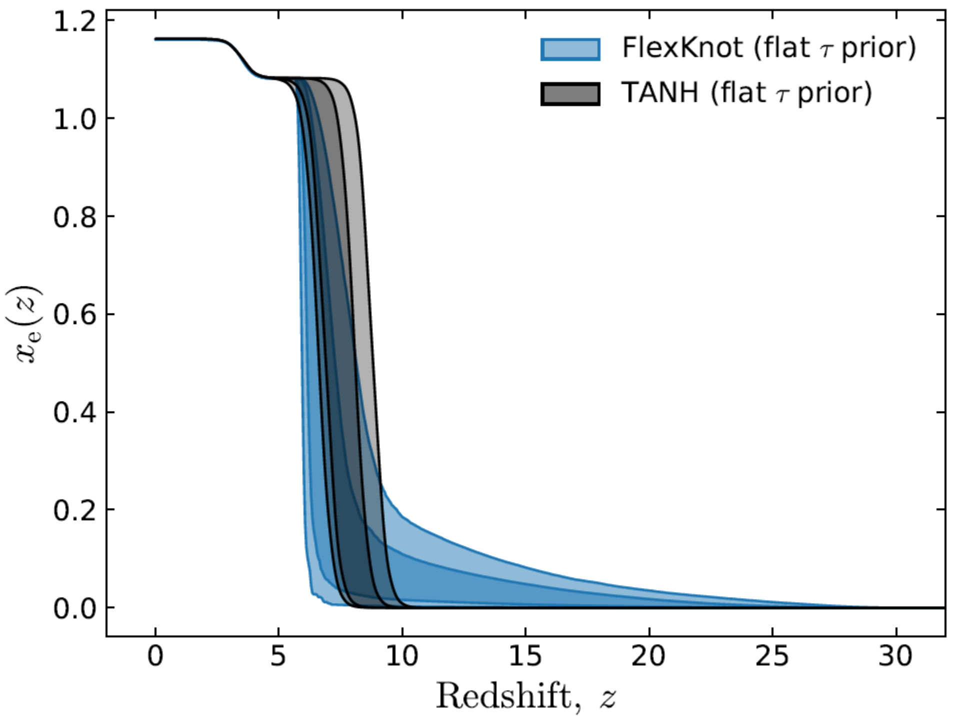
$$C_{\rm HII} \approx \min[1 + 43\, z^{-1.71}, 20]$$

$$\tau_{\rm es}(<z) = c\, \sigma_{\rm T}\, \bar{n}_{\rm H} \int^{z} {\rm d}z'\, f_e\, Q_{\rm HII}(z')(1+z')^2\, H^{-1}(z')$$

free electron number (minorl correction)

Hubble parameter

$$H(z) = H_0\, [\Omega_M\, (1+z)^3 + 1 - \Omega_M]^{1/2}$$



Planck+20 cosmo

DM scenarios

- Warm dark matter (WDM)

thermal relics $m_X \sim O(\text{keV})$
non-negligible free-streaming velocities

- Fuzzy dark matter (ψDM)

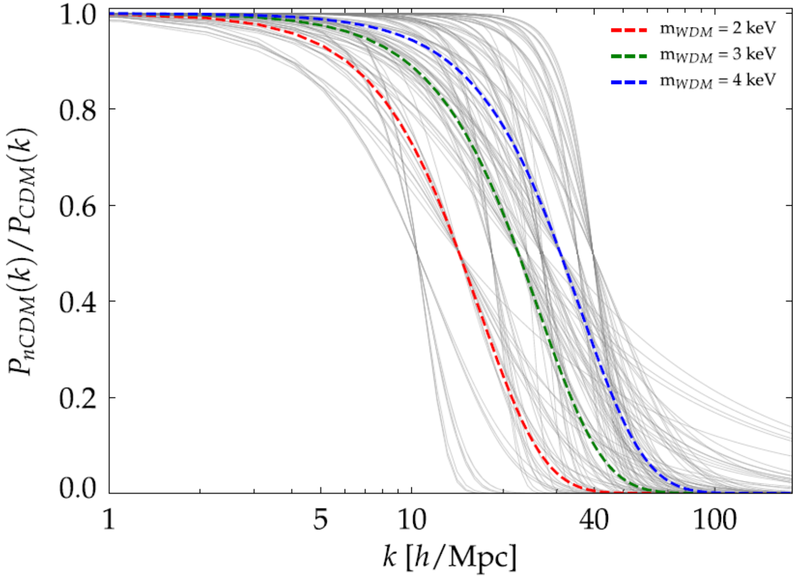
Bose-Einstein condensates of
ultralight axions $m_X \sim O(10^{-22}\ \text{eV})$

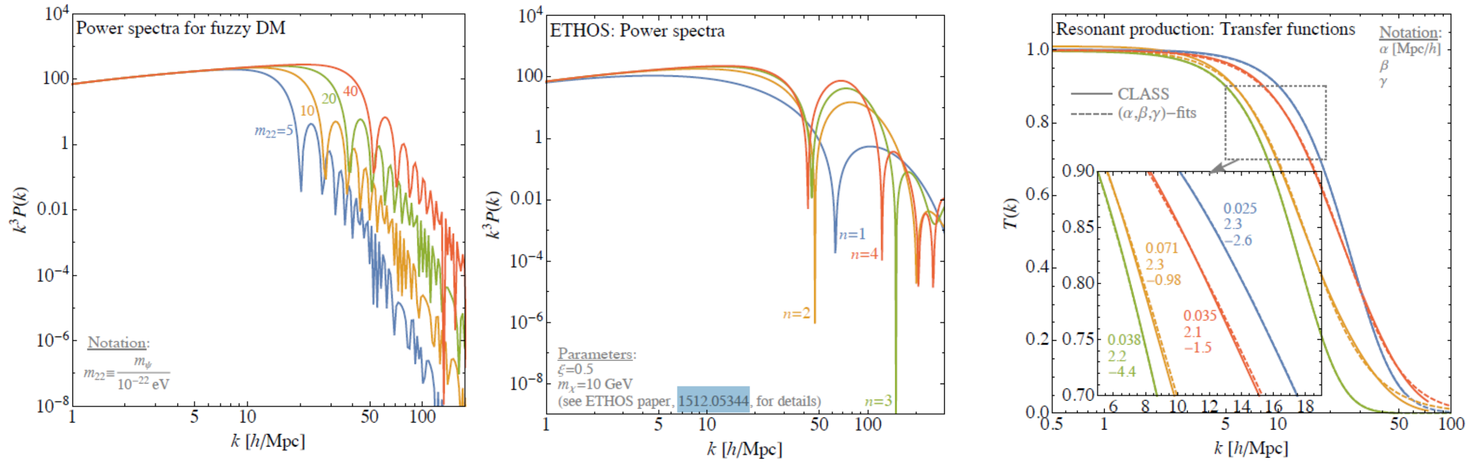
- Self-interacting dark matter (SIDM)

$\sigma_{XX}/m_X \sim 0.1\text{-}1\ \text{cm}^2/\text{g}$ (cf. ETHOS)
kinetic T_X at decoupling

- Sterile Neutrinos (νDM)

non-thermally produced $m_X \sim 7$ keV
and lepton asymmetry L_X (cf. 3.55 X-ray line)





Murgia+18

Halo mass function

Scenario	α	β	γ
WDM	1.0	1.0	1.16
ψDM	1.0	1.1	2.2
SIDM	1.0	1.0	1.34
νDM	2.3	0.8	1

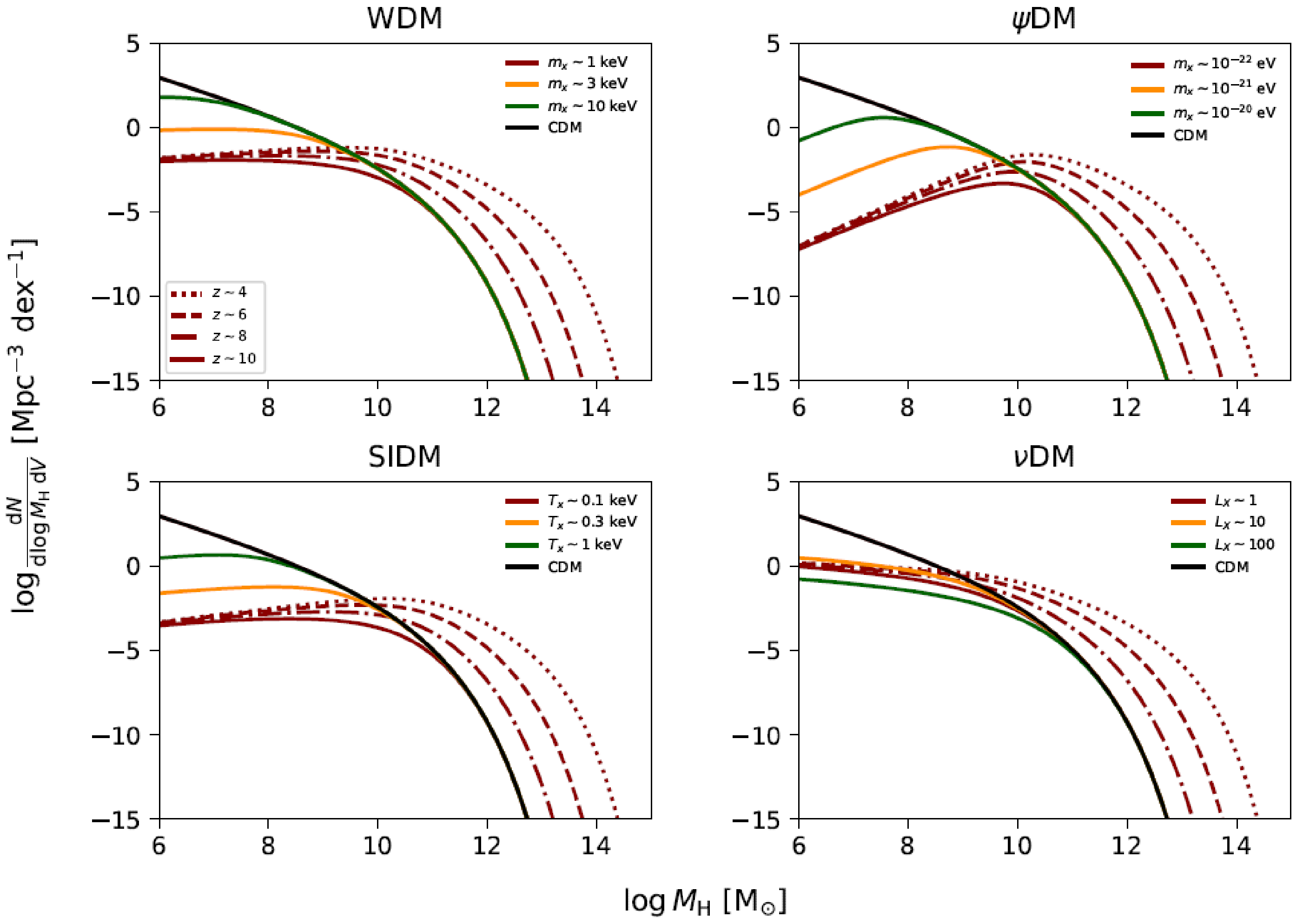
Schneider+12, Schive+16, Huo+18, Lovell+20

$$\frac{\mathrm{d}N_{\mathrm{X}}}{\mathrm{d}M_{\mathrm{H}}\,\mathrm{d}V} = \frac{\mathrm{d}N_{\mathrm{CDM}}}{\mathrm{d}M_{\mathrm{H}}\,\mathrm{d}V}\left[1+\left(\alpha\,\frac{M_{\mathrm{H}}^{\mathrm{cut}}}{M_{\mathrm{H}}}\right)^{\beta}\right]^{-\gamma}$$

Cutoff mass; e.g., for WDM

$$M_{\mathrm{H}}^{\mathrm{cut}} \approx 1.9\times 10^{10}\,\mathrm{M}_{\odot}\,(m_{\mathrm{X}}/\mathrm{keV})^{-3.33}$$

WDM particle mass



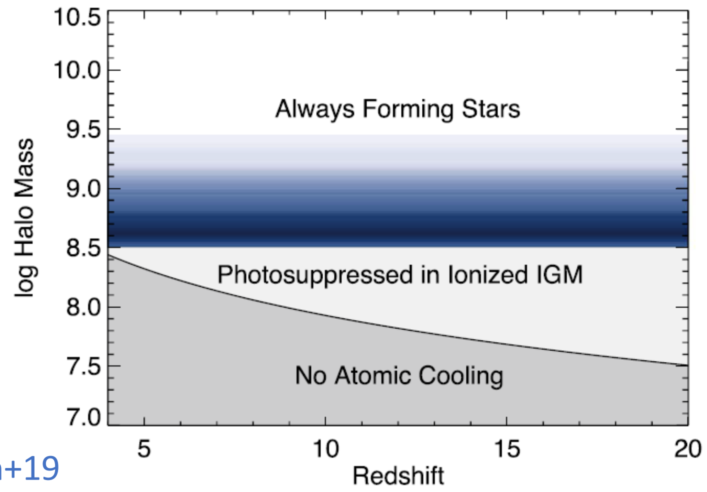
Galaxy formation constraint

$$\int_{M_{\rm H}}^{+\infty} {\rm d}M'_{\rm H}\, \frac{{\rm d}N_X}{{\rm d}M'_{\rm H}\,{\rm d}V}(M'_{\rm H}, z|X) = \int_{-\infty}^{M_{\rm UV}} {\rm d}M'_{\rm UV}\, \frac{{\rm d}N}{{\rm d}M'_{\rm UV}\,{\rm d}V}(M'_{\rm UV}, z)$$

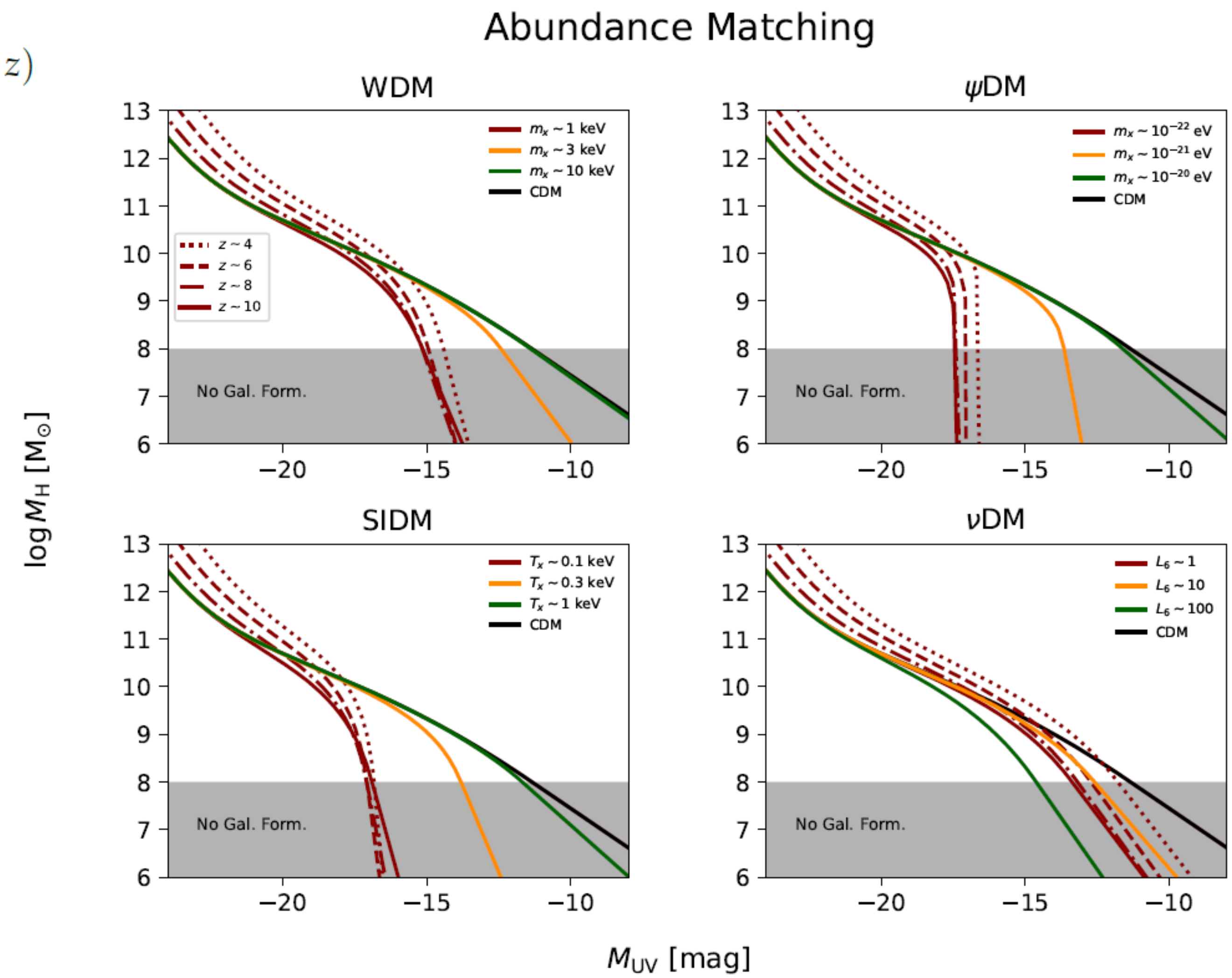
↓

$$M_{\rm H}(M_{\rm UV}^{\rm lim}, z|X) \approx M_{\rm H}^{\rm GF}$$

threshold halo mass for galaxy formation;
e.g., photo-suppression mass



Finkelstein+19



Bayesian analysis

$$\chi_i^2 = \sum_j [\mathcal{M}(z_j,\theta) - \mathcal{D}(z_j)]^2 / \sigma_{\mathcal{D}}^2(z_j)$$

$$\mathcal{L}(\theta) \equiv -\sum_i \chi_i^2(\theta)/2$$

Observable [units]	Redshifts	Values	Errors
$\log \dot{N}_{\rm ion}$ [s^{-1} Mpc^{-3}]			
	{4.0, 4.8}	{50.86, 50.99}	{0.39, 0.39}
	{5.1}	{51.00}	{0.15}
$Q_{\rm HII}$			
	{7.0}	{0.41}	{0.13}
	{7.6}	{0.12}	{0.07}
	{6.6, 6.9, 7.3}	{0.30, 0.50, 0.55}	{0.20, 0.10, 0.25}
	{7.6}	{0.83}	{0.10}
	{7.3}	{0.49}	{0.11}
	{7.1, 7.5}	{0.48, 0.60}	{0.26, 0.22}
	{5.6, 5.9}	{0.04, 0.06} (up.lim.)	{0.05, 0.05}
$\tau_{\rm es}$			
	{∞}	{0.054}	{0.007}

free parameters

$$\theta = \{f_{\rm esc}, M_{\rm UV}^{\rm lim}, m_X\}$$

flat priors

$f_{\rm esc} \in [0,1]$

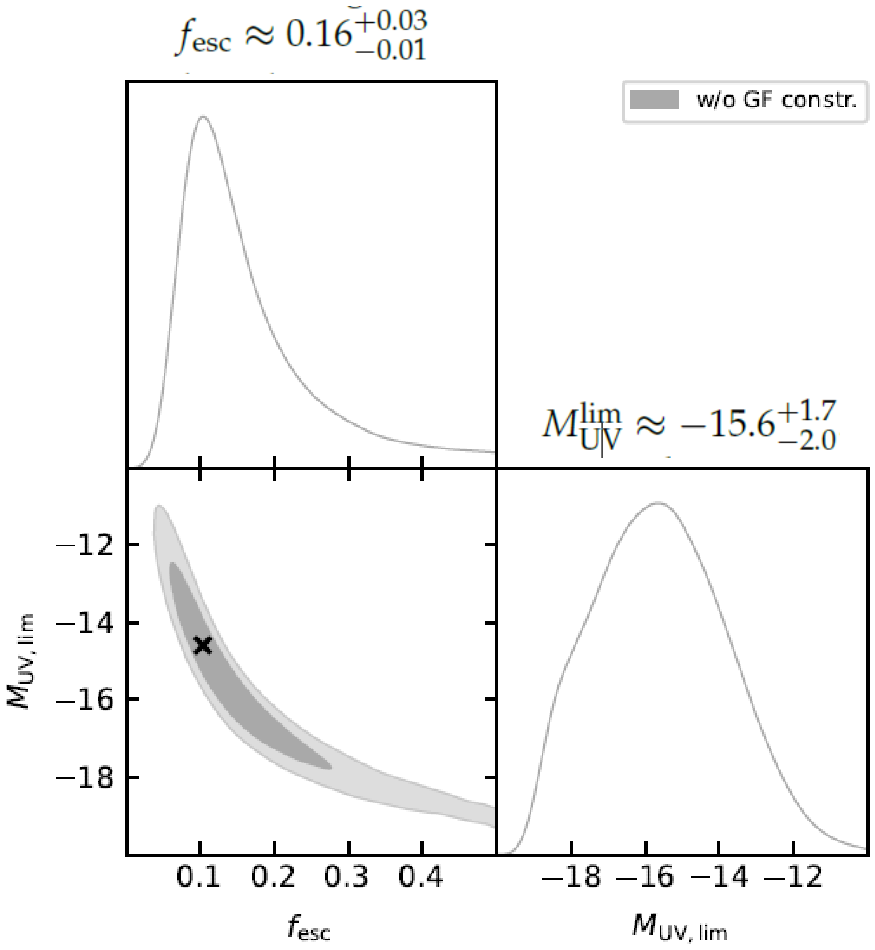
$M_{\rm UV}^{\rm lim} \in [-20,-8]$

$X \in [0,15]$

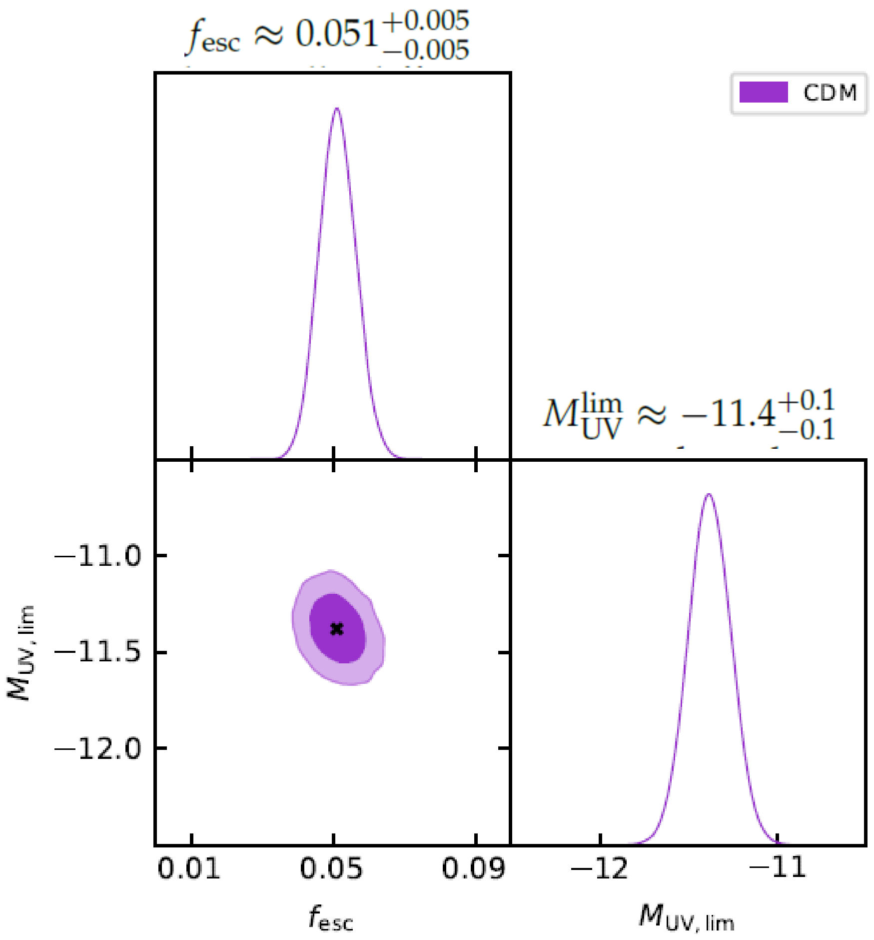
MCMC and dynamic nested sampling of the posterior

$$\mathcal{P}(\theta) \propto \mathcal{L}(\theta)\pi(\theta)$$

Results: CDM

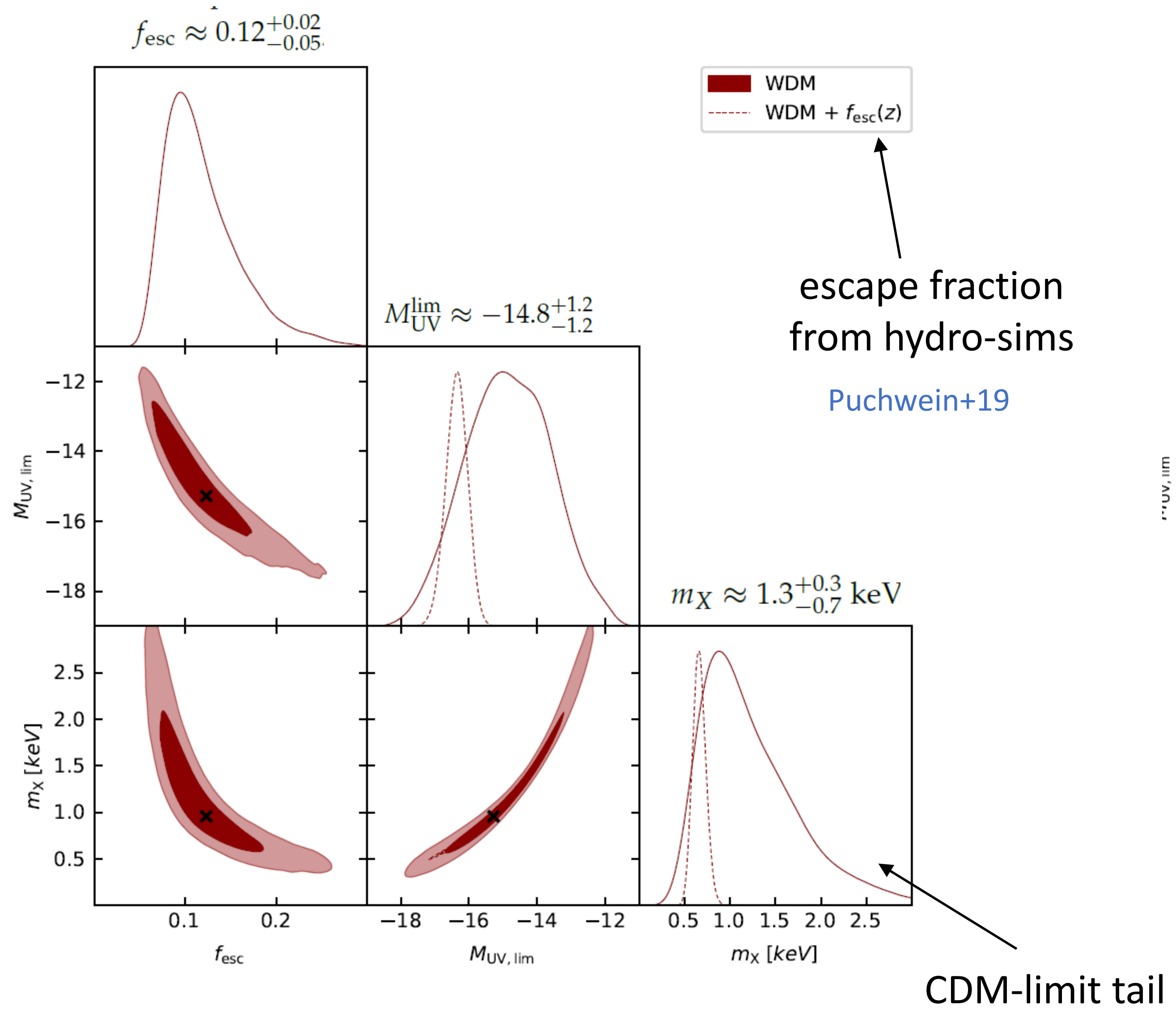


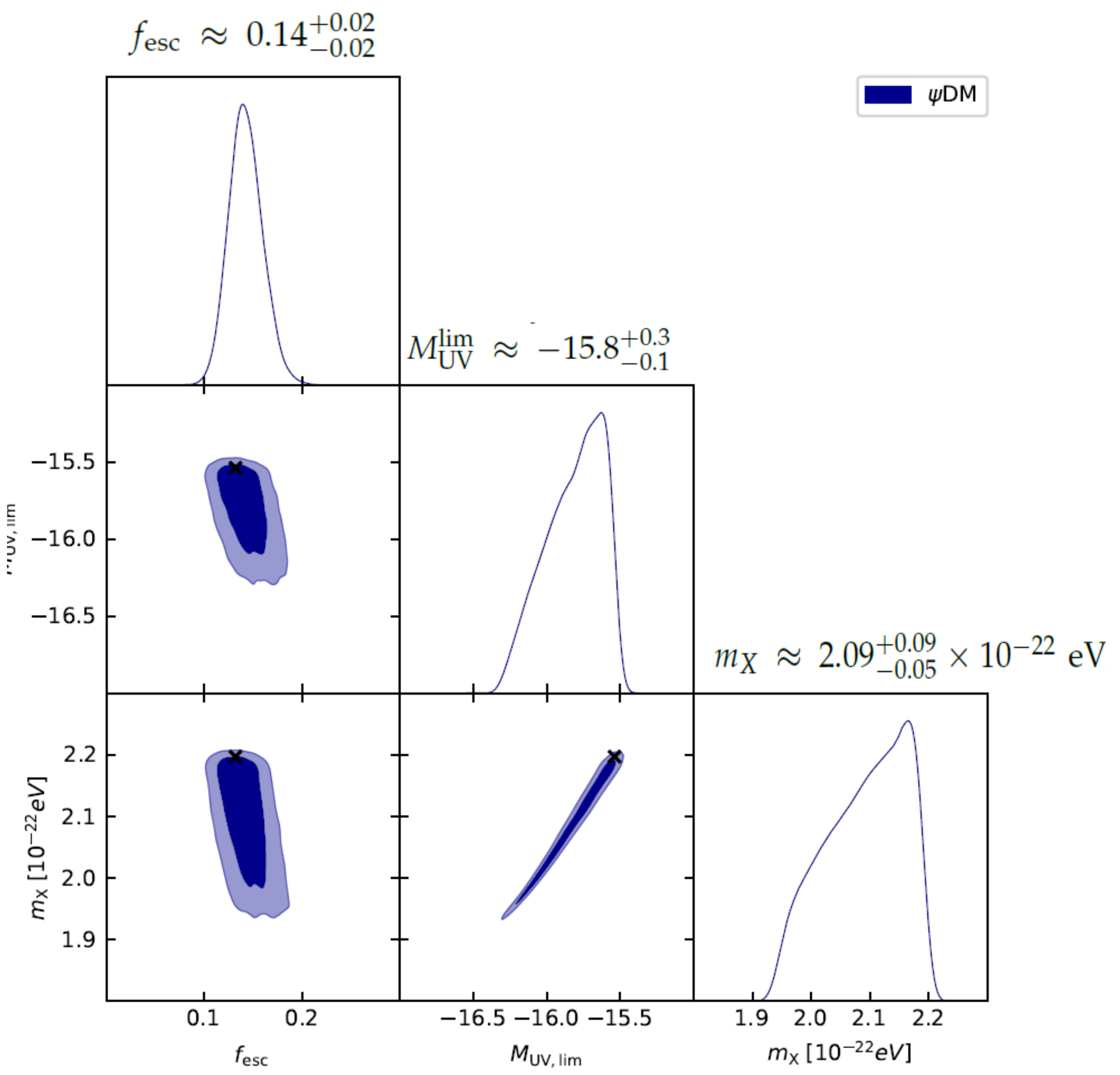
$f_{esc} \approx 0.16^{+0.03}_{-0.01}$
w/o GF constr.
$M_{UV}^{lim} \approx -15.6^{+1.7}_{-2.0}$
$M_{UV,\,lim}$
−12
−14
−16
−18
0.1 0.2 0.3 0.4
f_{esc}
−18 −16 −14 −12
$M_{UV,\,lim}$



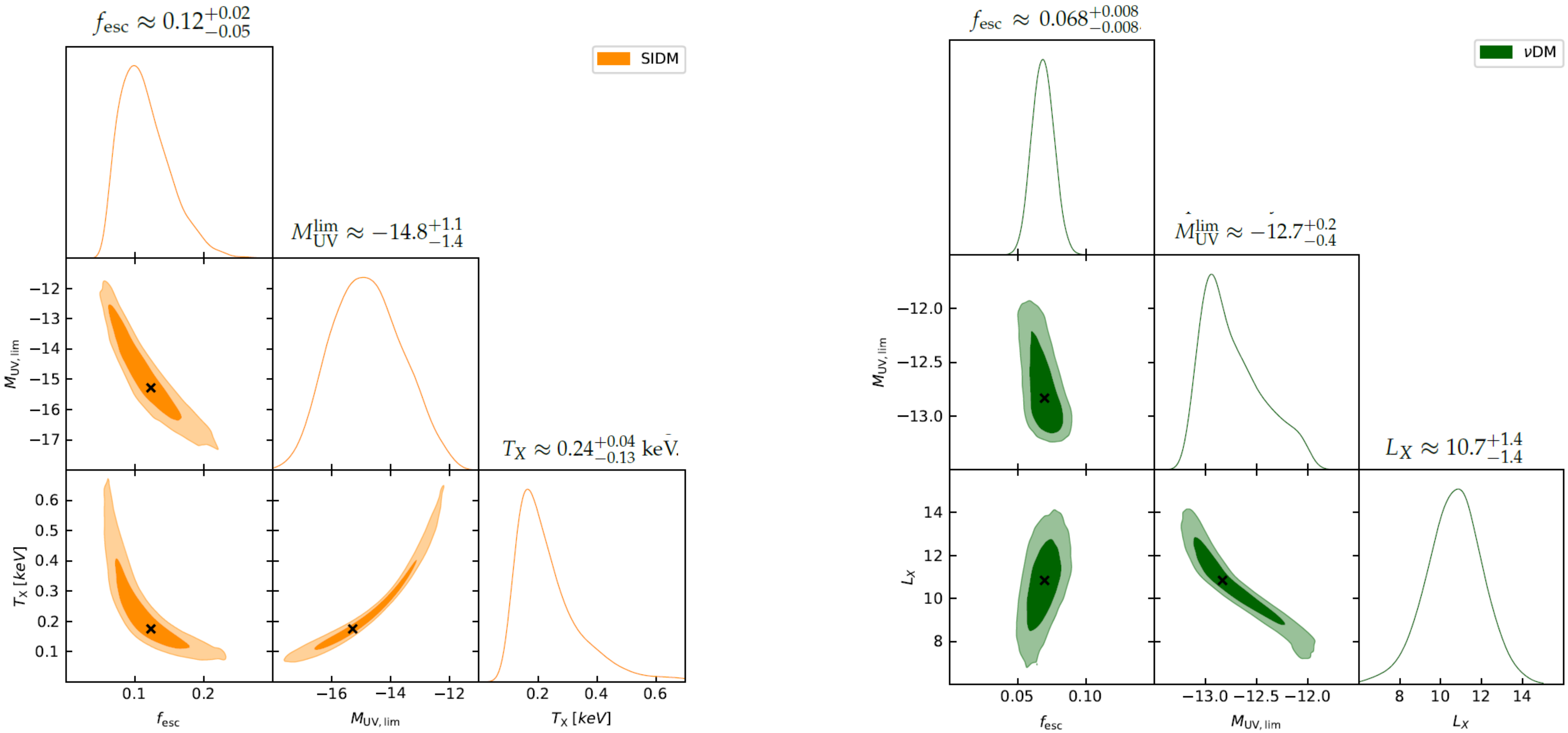
$f_{esc} \approx 0.051^{+0.005}_{-0.005}$
CDM
$M_{UV}^{lim} \approx -11.4^{+0.1}_{-0.1}$
$M_{UV,\,lim}$
−11.0
−11.5
−12.0
0.01 0.05 0.09
f_{esc}
−12 −11
$M_{UV,\,lim}$

Results: WDM and ψDM





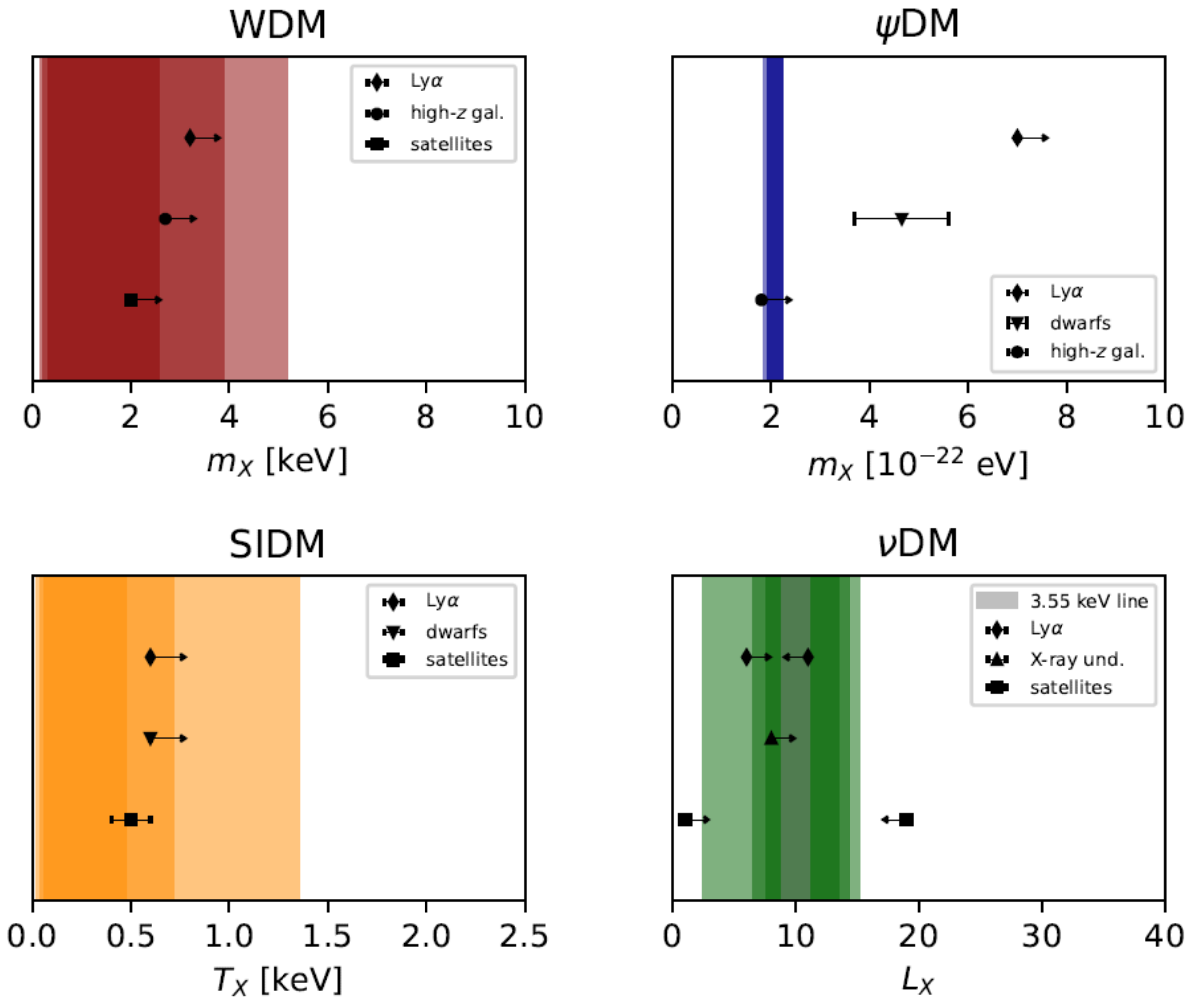
Results: SIDM and νDM



Results: overall

Scenario	$f_{\rm esc}$	$M_{\rm UV,lim}$	X
w/o GF	$0.16^{+0.03}_{-0.01}$	$-15.6^{+1.7}_{-2.0}$	–
CDM	$0.051^{+0.005}_{-0.005}$	$-11.4^{+0.1}_{-0.1}$	–
WDM	$0.12^{+0.02}_{-0.05}$	$-14.8^{+1.2}_{-1.2}$	$1.3^{+0.3}_{-0.7}$
WDM	$f_{\rm esc}(z)$	$-16.4^{+0.3}_{-0.3}$	$0.66^{+0.07}_{-0.08}$
ψDM	$0.14^{+0.02}_{-0.02}$	$-15.8^{+0.3}_{-0.1}$	$2.09^{+0.09}_{-0.05}$
SIDM	$0.12^{+0.02}_{-0.05}$	$-14.8^{+1.1}_{-1.4}$	$0.24^{+0.04}_{-0.13}$
νDM	$0.068^{+0.008}_{-0.008}$	$-12.7^{+0.2}_{-0.4}$	$10.7^{+1.4}_{-1.4}$

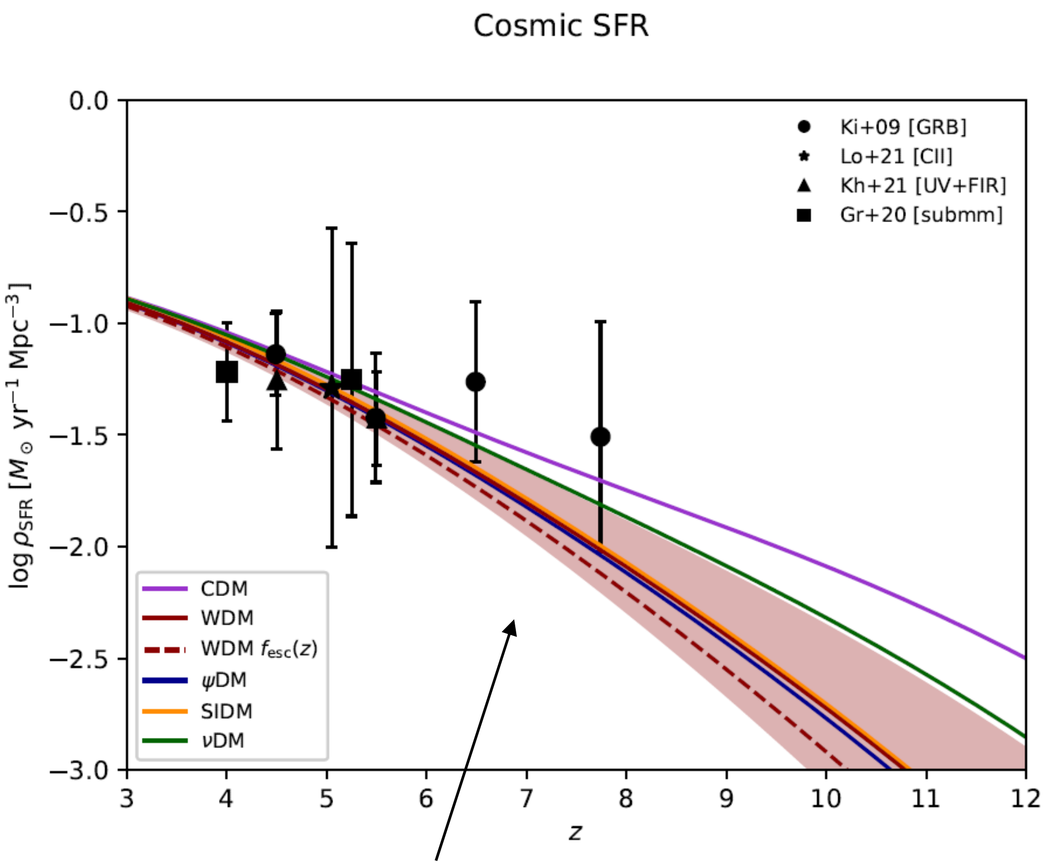
Broad consistency with literature constraints for SIDM and νDM, marginal tension for WDM, strong for ψDM

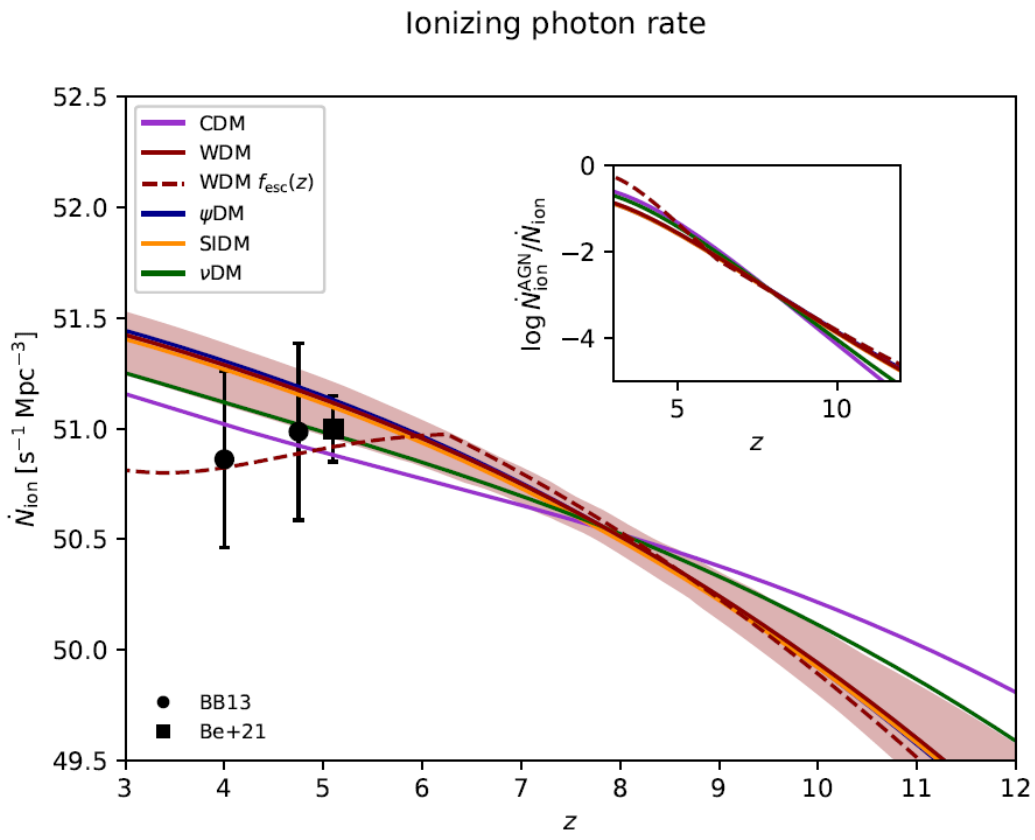


Bayes information criterion:

1. marginal evidence for non-CDM models.
2. no clear preference among alternative CDM scenarios…

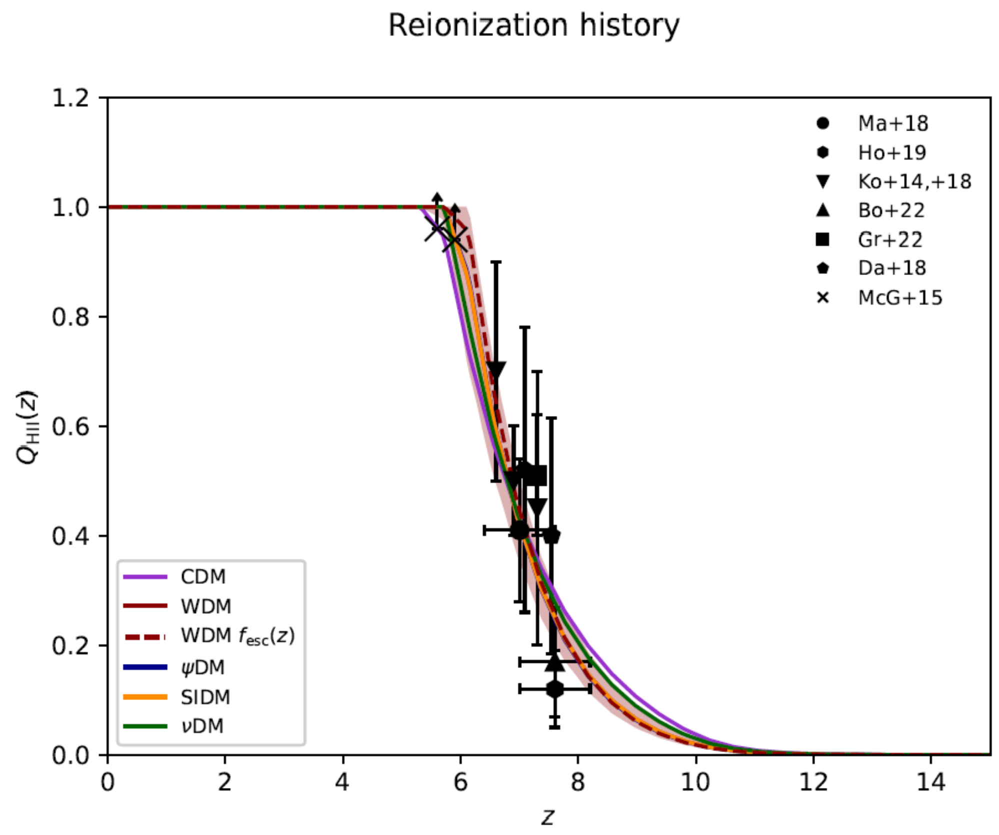
Results: observables

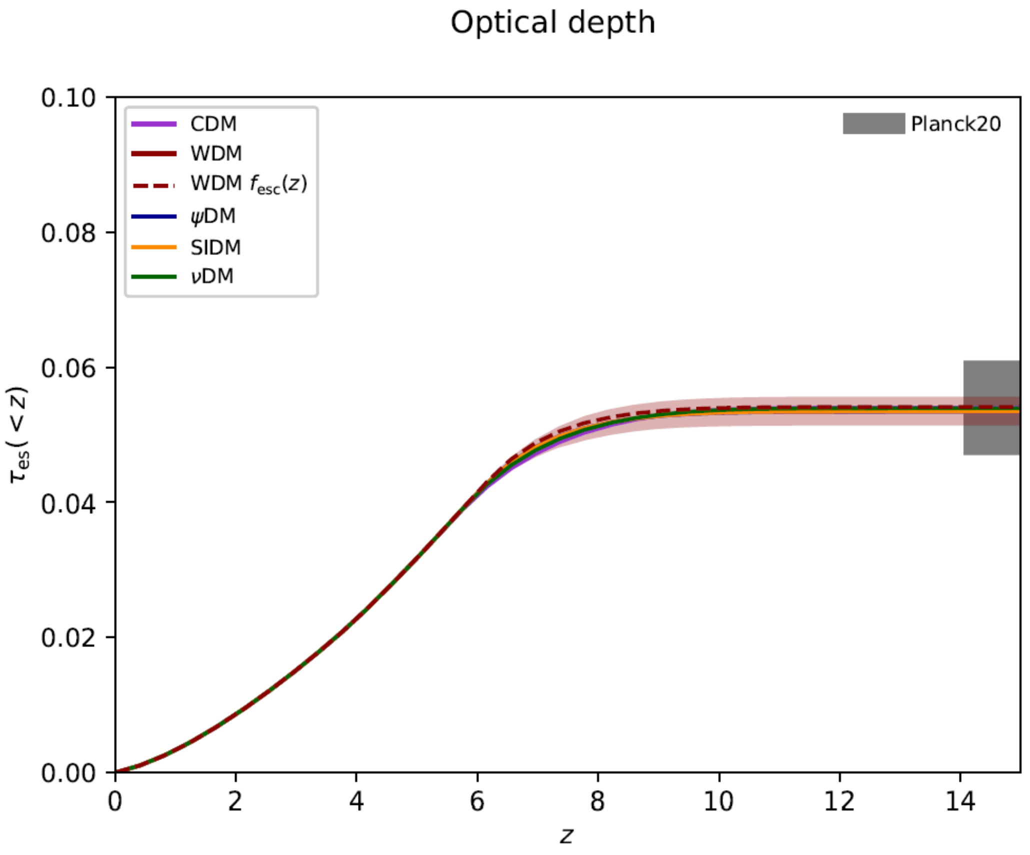




Not fitted upon, but pleasingly consistent with data (cf. Gandolfi+22)

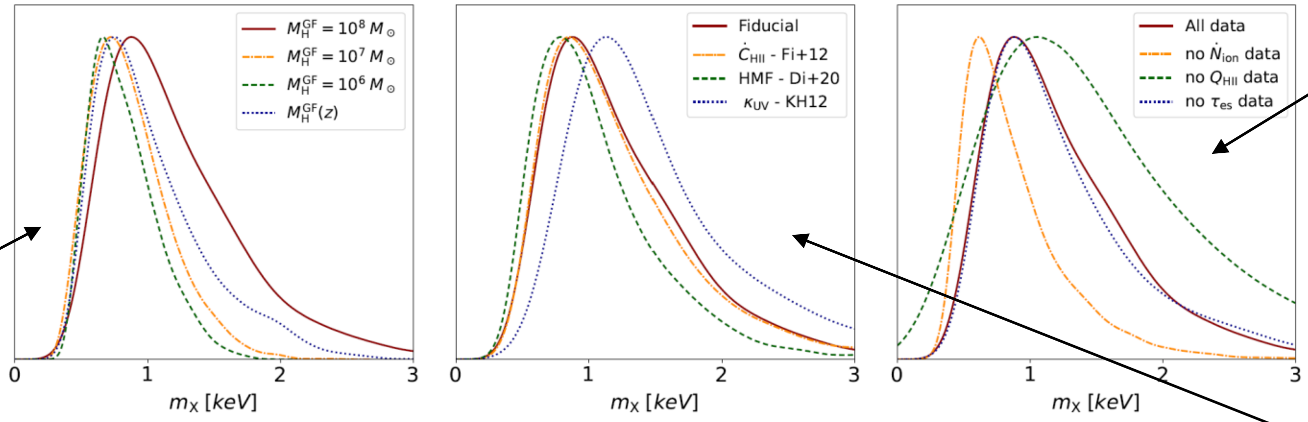
Results: observables





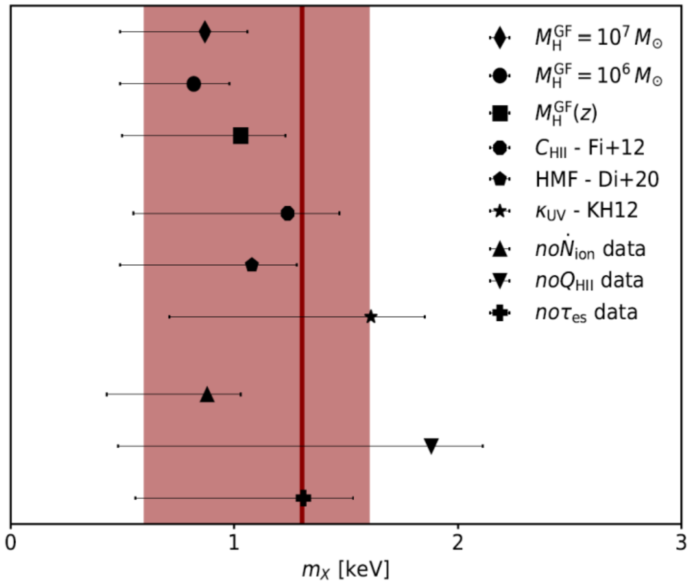
Results: robustness (WDM)

assessing data importance

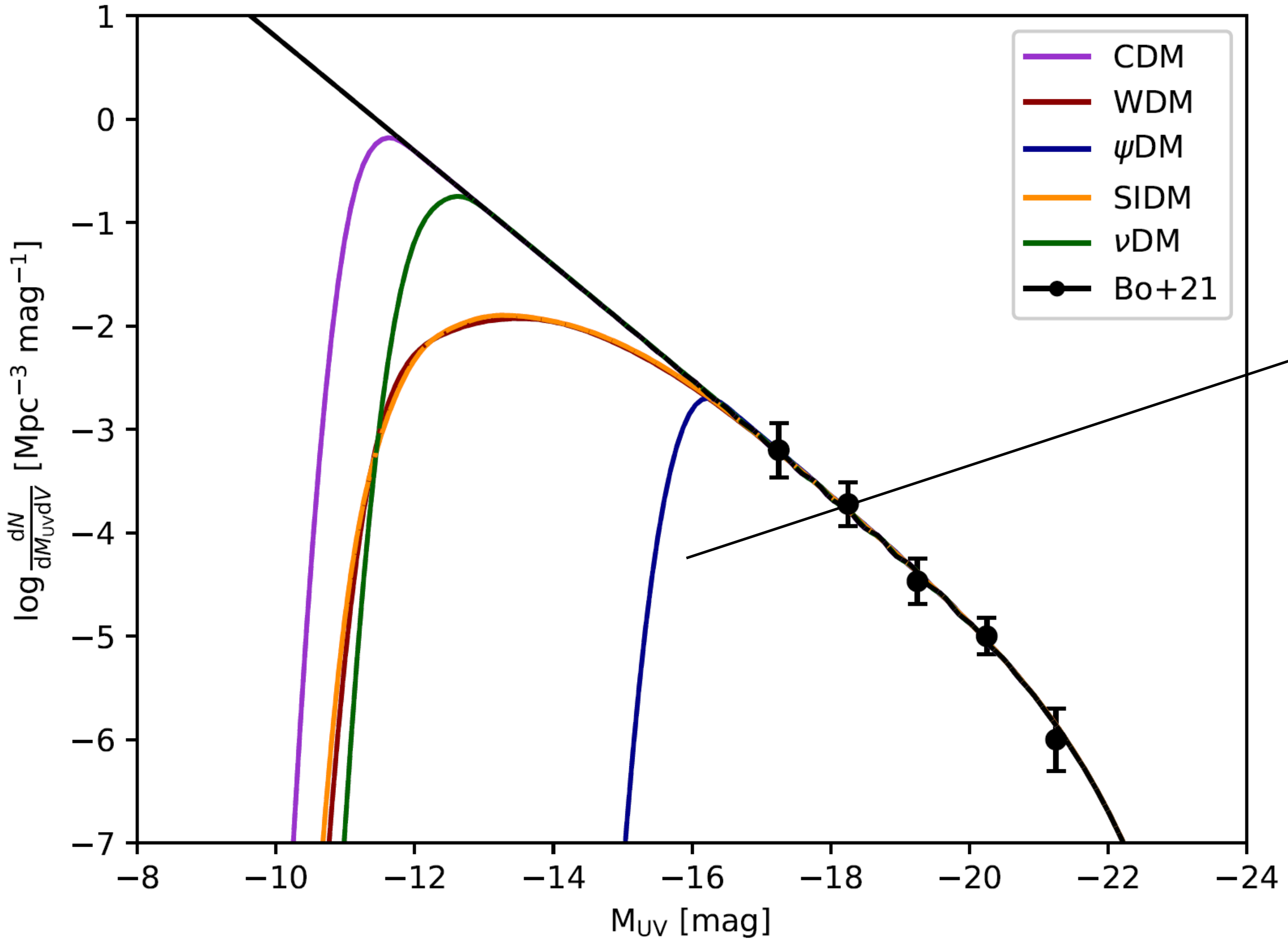


altering GF threshold

changing IMF, clumping,CDM halo MF



Results: predictions for JWST

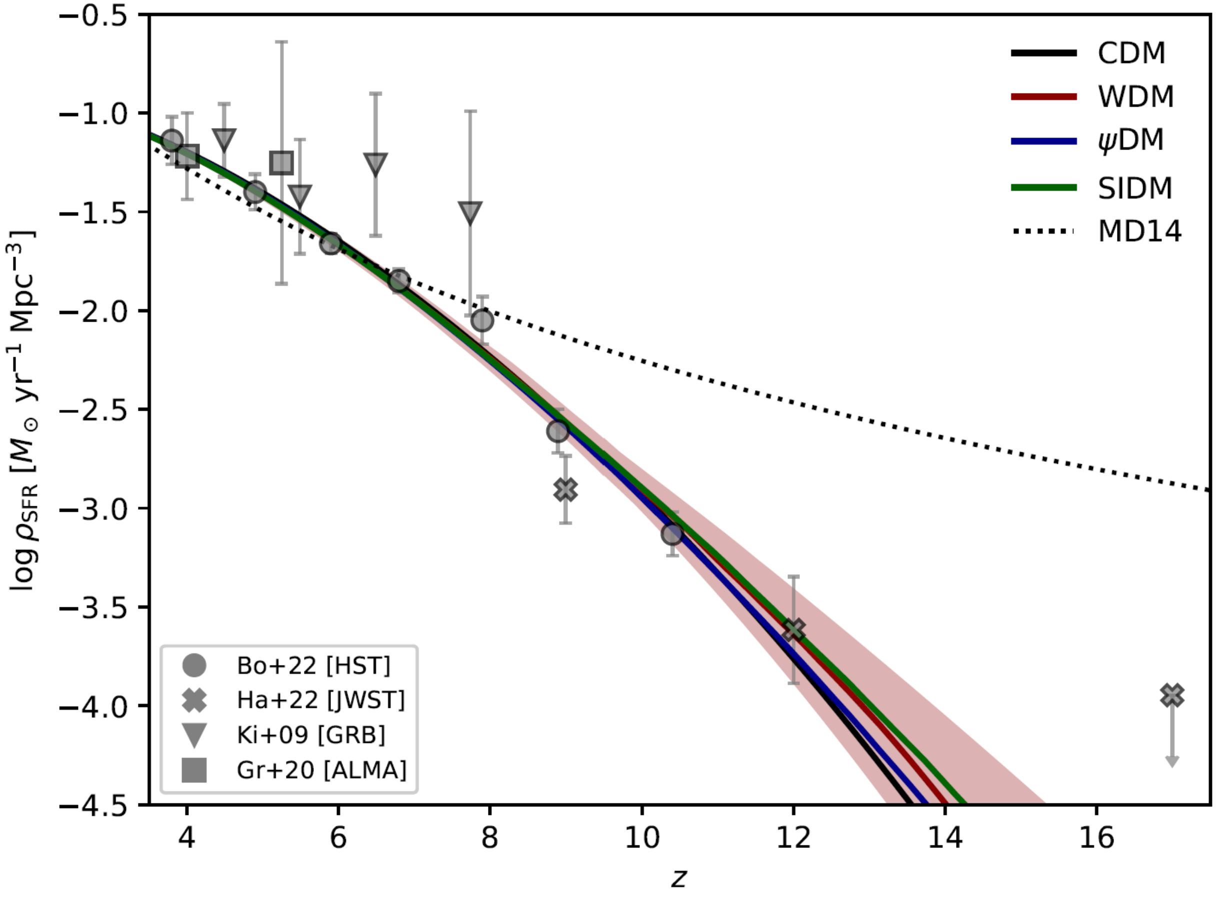


marginally consistent with lensed HST and early JWST data

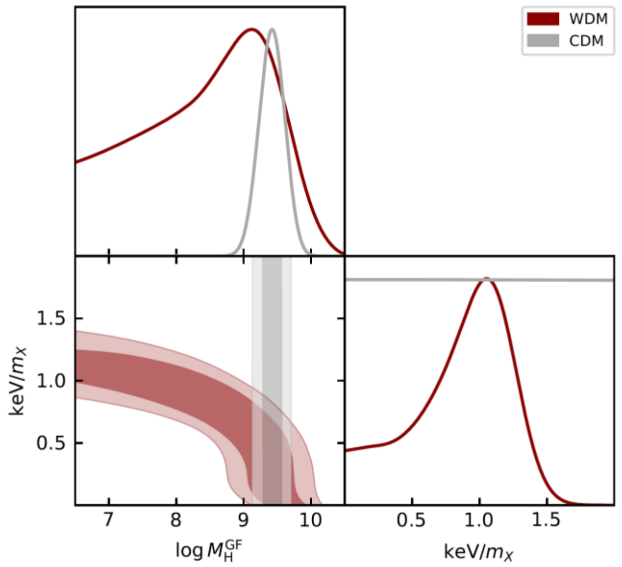
Posterior-based UV LF

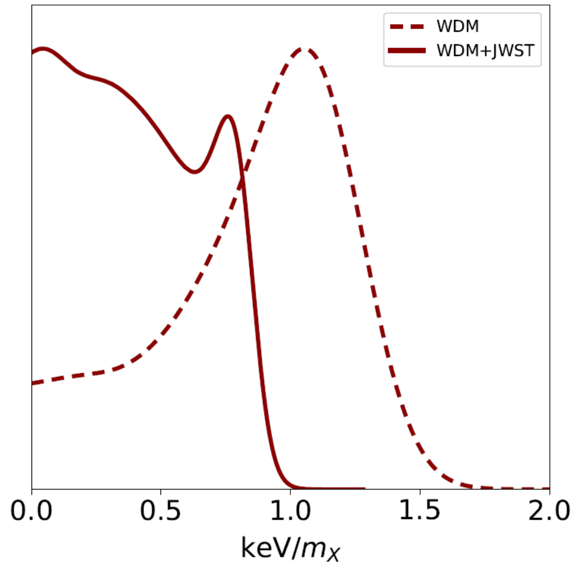
$$\frac{\mathrm{d}N}{\mathrm{d}M_{\mathrm{UV}}\,\mathrm{d}V} = \int \mathrm{d}X\,\mathcal{P}(X)\,\int_{M_{\mathrm{H}}^{\mathrm{GF}}}^{\infty} \mathrm{d}M_{\mathrm{H}}\,\frac{\mathrm{d}N_X}{\mathrm{d}M_{\mathrm{H}}\,\mathrm{d}V}\,\delta_D[M_{\mathrm{UV}} - M_{\mathrm{UV}}(M_{\mathrm{H}}, z|X)]$$

Outlook: cosmic SFR as a probe of DM



Gandolfi+22





Summary

- High redshift data on galaxy luminosity functions and cosmic reionization, analyzed with a simple yet effective empirical model, can provide robust constraints on dark matter scenarios alternative to CDM.

- Relevant astrophysical information on primordial galaxy formation in small halos at high z can be inferred (even for standard CDM).

- Upcoming ultra-faint galaxy surveys in the pre-reionization era via JWST (elucidating a turnover in the luminosity functions) can constitute a robust probe for the nature of dark matter.