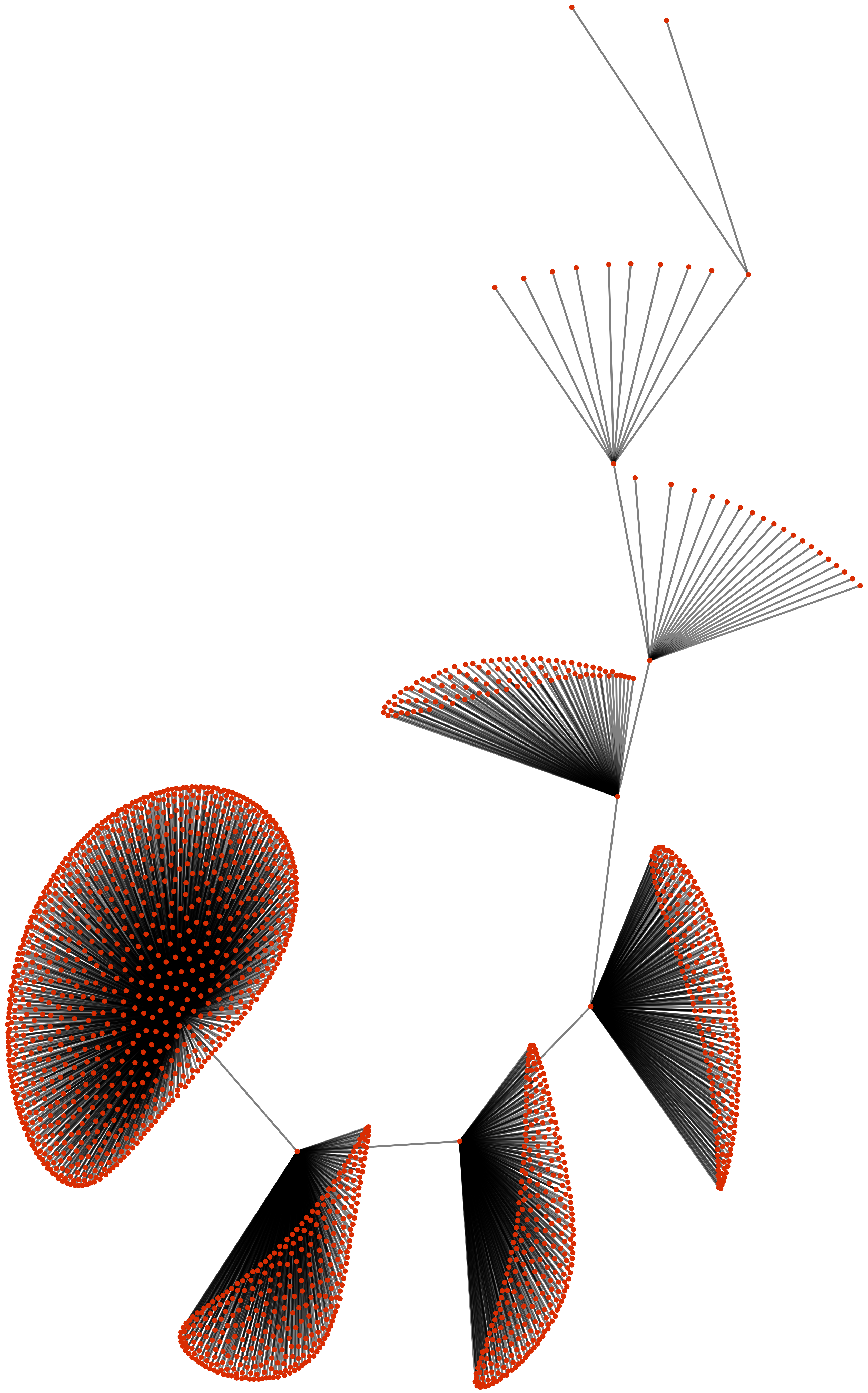

# SMBHs as DM tracers

Juan Urrutia, PhD student at KBFI Tallinn,

COSMOfondue meeting 2025

## Starlight from JWST: Implications for star formation and dark matter models

Juan Urrutia[1,2,⋆], John Ellis[3,4,⋆⋆], Malcolm Fairbairn[3,⋆⋆⋆], and Ville Vaskonen[1,5,6,⋆⋆⋆⋆]

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4 Theoretical Physics Department, CERN, Geneva, Switzerland
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May 16, 2025

**ABSTRACT**

We confront the star formation rate in different dark matter (DM) models with UV luminosity data from JWST up to $z \simeq 25$ and legacy data from HST. We find that a transition from a Salpeter population to top-heavy Pop-III stars is likely at $z \simeq 10$ and that beyond $z = 10-15$ the feedback from supernovae and active galactic nuclei is progressively reduced, so that at $z \simeq 25$ the production of stars is almost free from any feedback. We compare fuzzy and warm DM models that suppress small-scale structures with the CDM paradigm, finding that the fuzzy DM mass $> 4.5 \times 10^{-22}$eV and the warm DM mass $> 1.5$ keV at the 95% CL. The fits of the star formation rate parametrization do not depend strongly on the DM properties within the allowed range. We find no preference over CDM for enhanced matter perturbations associated with axion miniclusters or primordial black holes. The scale of the enhancement of the power spectrum should be $> 27\,\mathrm{Mpc}^{-1}$ at the 95% CL, excluding axion miniclusters produced for $m_a < 7.5 \times 10^{-17}$ eV or heavy primordial black holes that constitute a fraction $f_{\rm PBH} > \max[88 M_\odot/m_{\rm PBH}, 10^{-4}(m_{\rm PBH}/10^4 M_\odot)^{-0.09}]$ of DM.

## JWST SMBH Data Constraints on Fuzzy and Warm Dark Matter

John Ellis,[1,2,*] Malcolm Fairbairn,[1,†] Juan Urrutia,[3,4,‡] and Ville Vaskonen[3,5,6,§]

[1] *King's College London, Strand, London, WC2R 2LS, United Kingdom*
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A semi-analytical model for the evolution of galaxies and supermassive black holes (SMBHs) within the ΛCDM paradigm has been shown to yield BH mass-stellar mass relations that reproduce both the JWST and pre-JWST observations of high-redshift SMBHs. Either fuzzy or warm dark matter (FDM or WDM) would suppress the formation of the smaller galactic halos that play important roles in fits to the high-redshift SMBH data. Our analysis disfavours FDM fields with masses $< 10^{-19}$ eV and WDM particles weighing $< 12.5$ keV, both at the 95% confidence level.

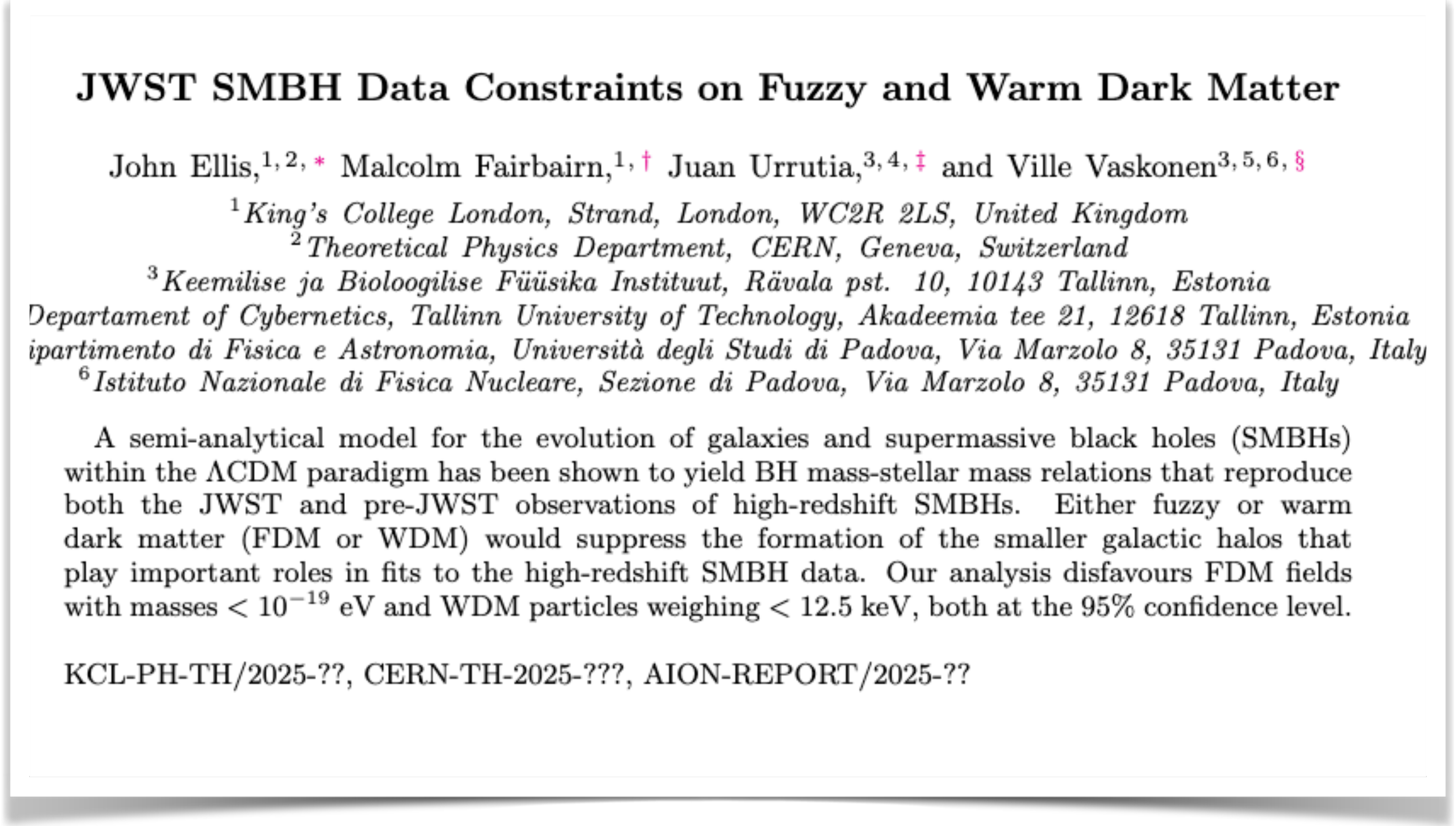
KCL-PH-TH/2025-??, CERN-TH-2025-???, AION-REPORT/2025-??

To appear soon!

To appear soon

# How to test different DM models with GWs

To appear soon



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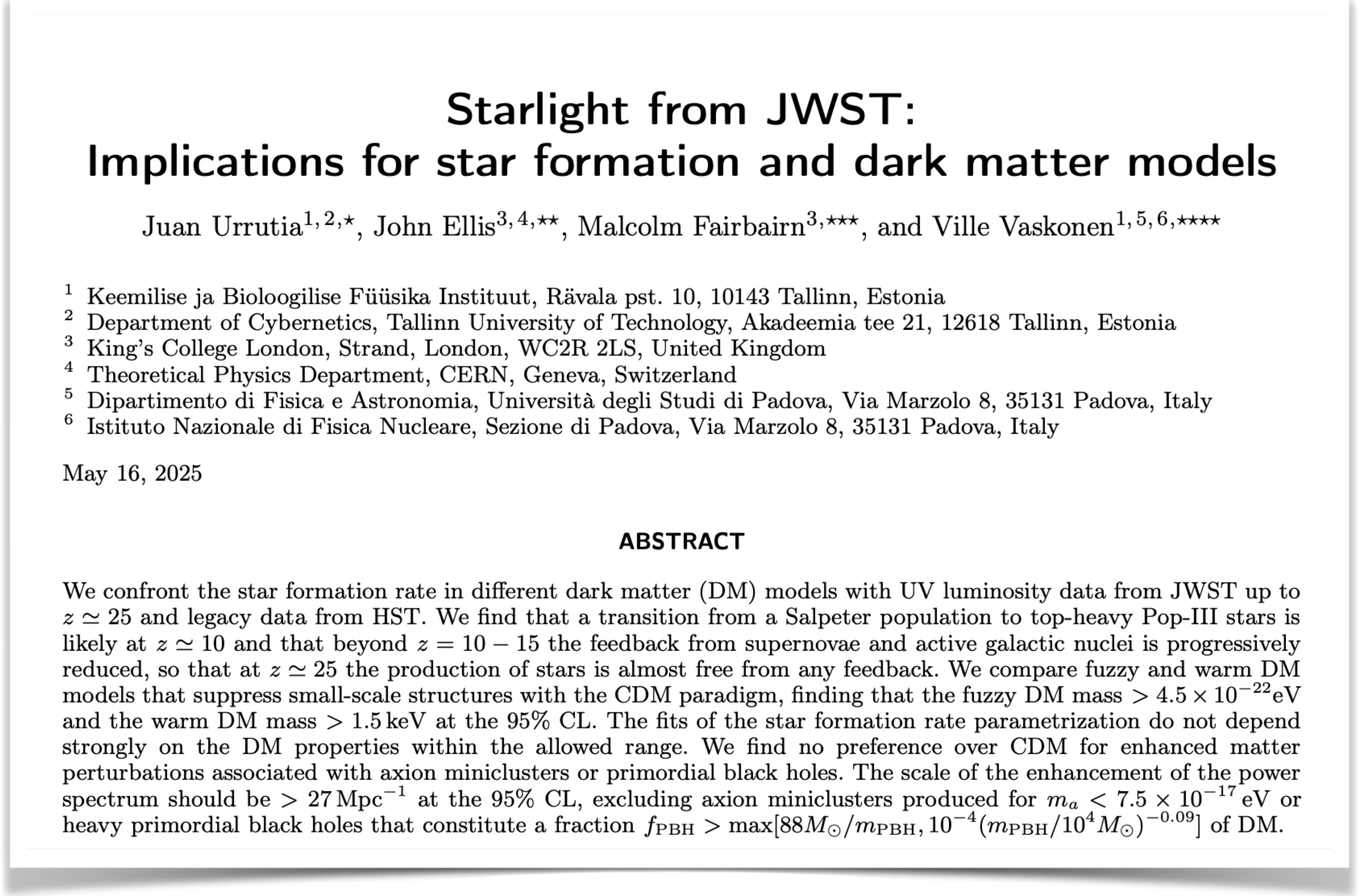
KCL-PH-TH/2025-??, CERN-TH-2025-???, AION-REPORT/2025-??


How SMBH grow



## Starlight from JWST: Implications for star formation and dark matter models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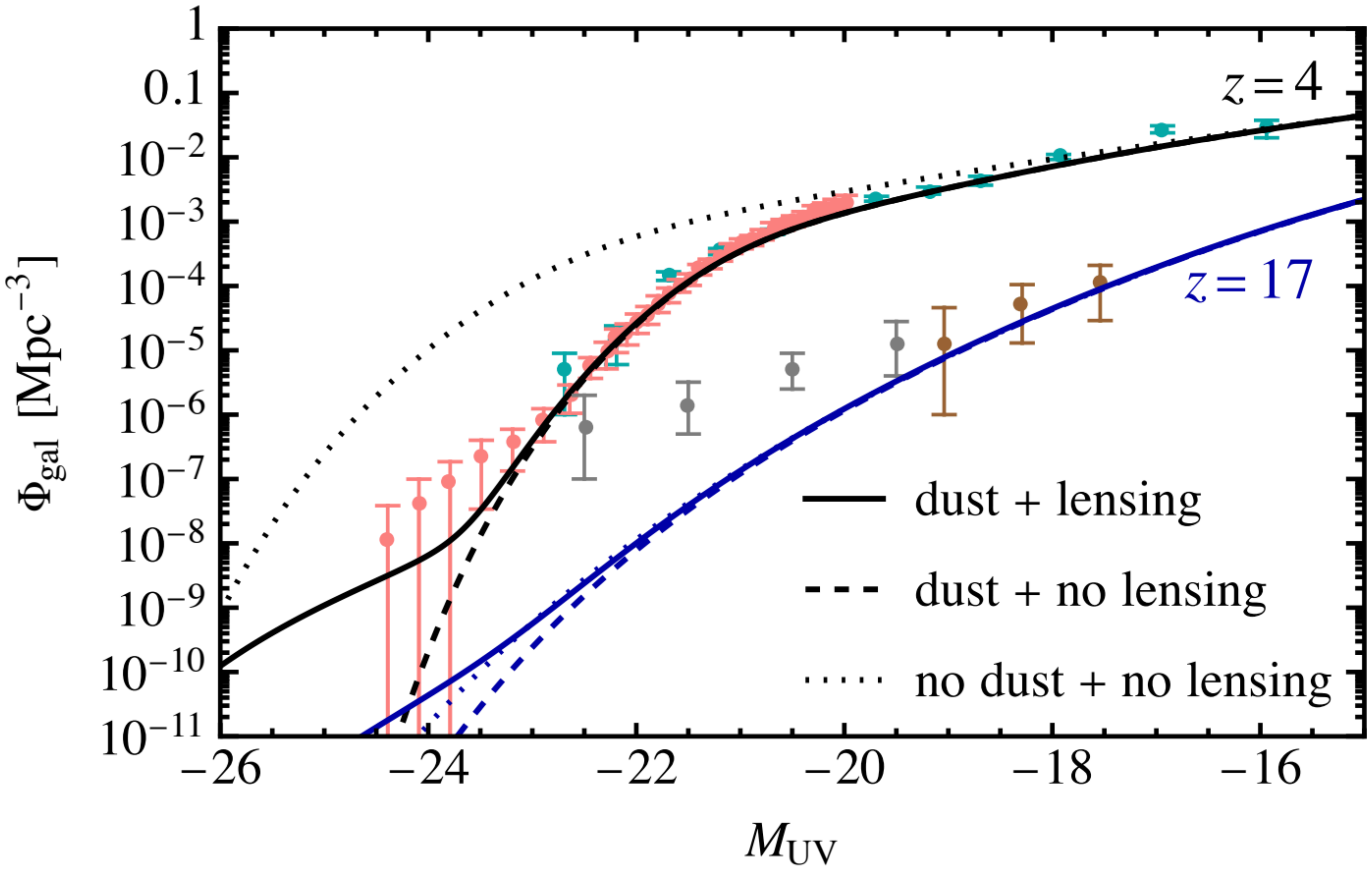
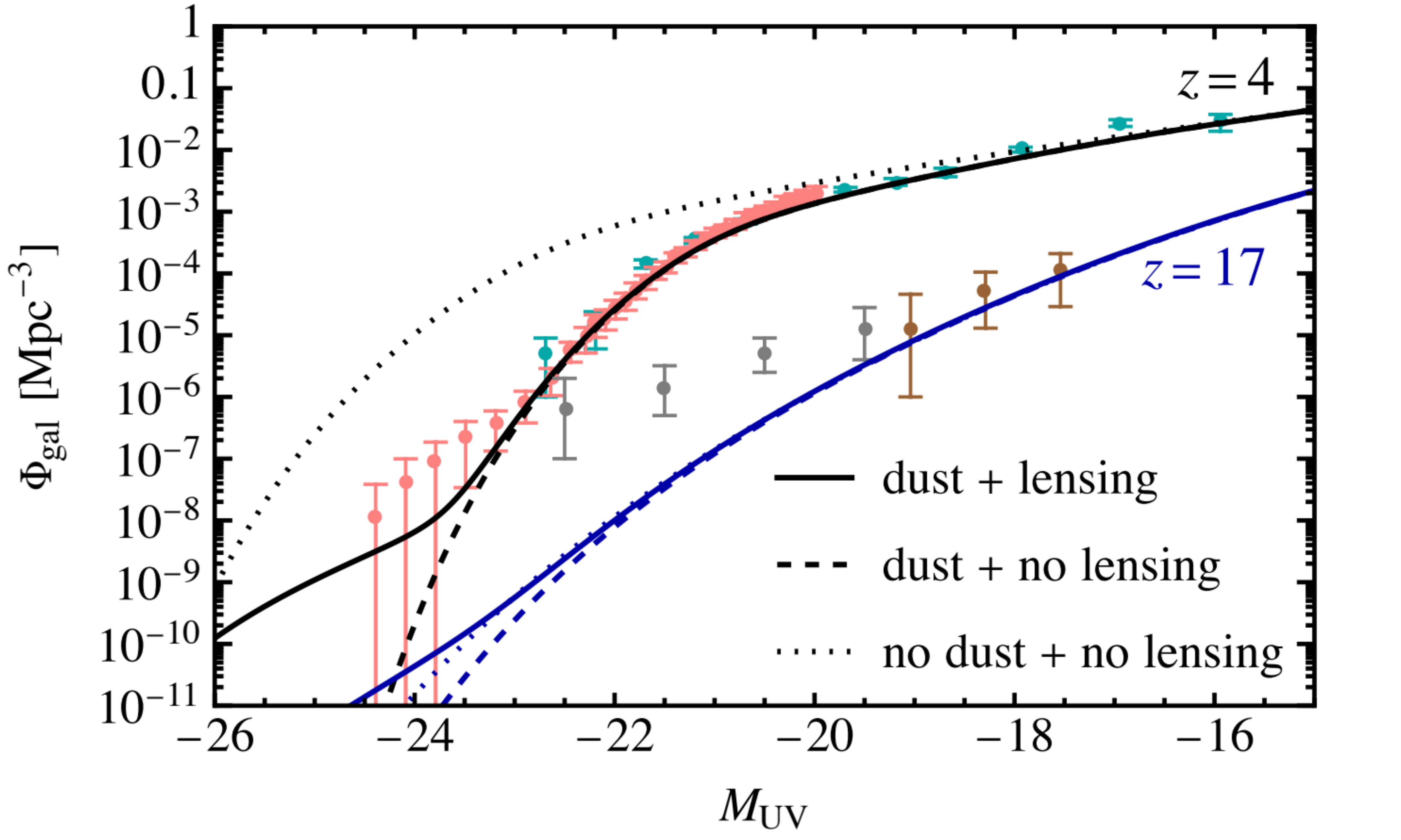
How galaxies work in different DM models

# Exploring the high-z with JWST



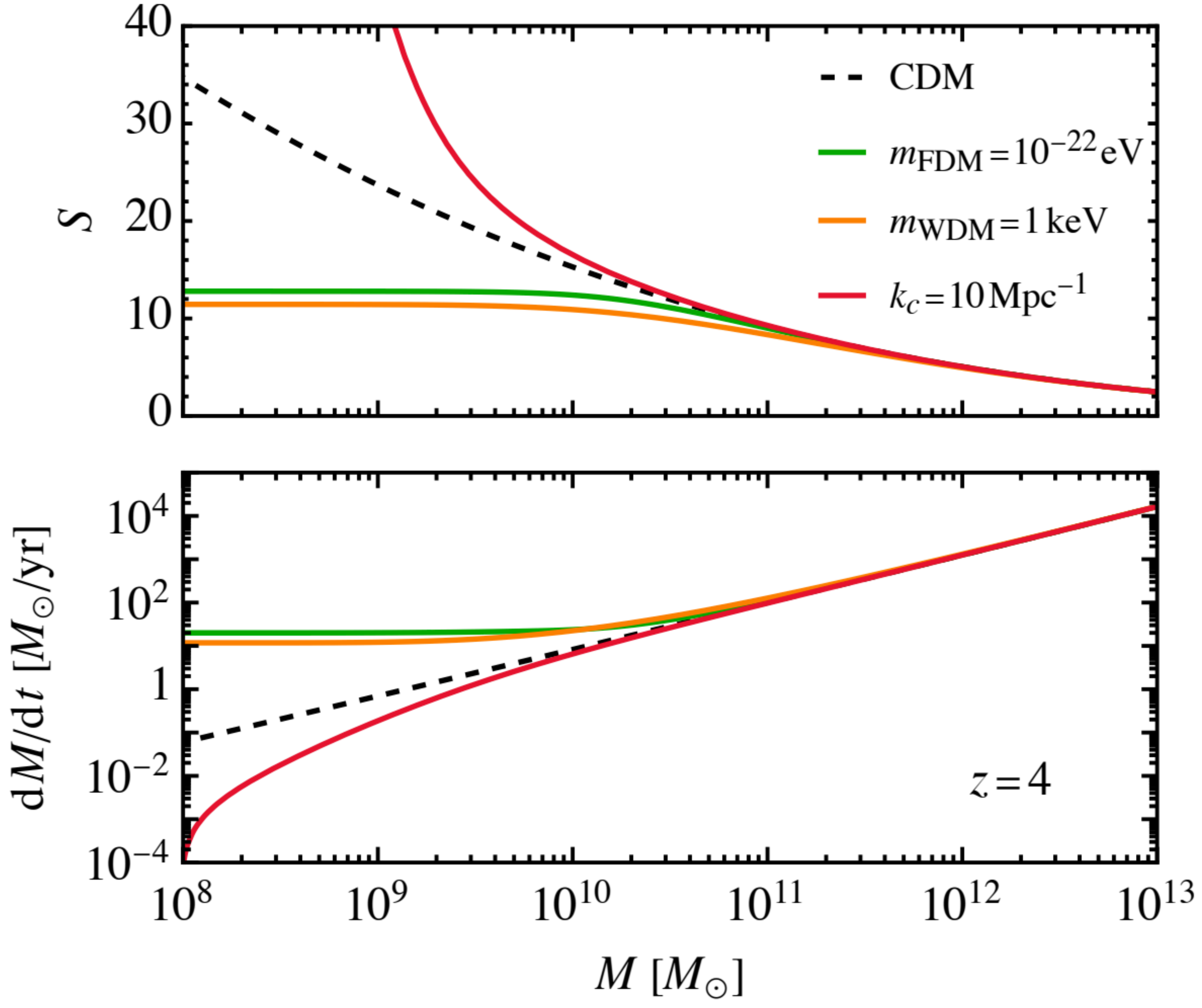

UV is emitted at rest frame, which gets redshifted to the visual. Correct for lensing, and dust attenuation

# Exploring the high-z with JWST

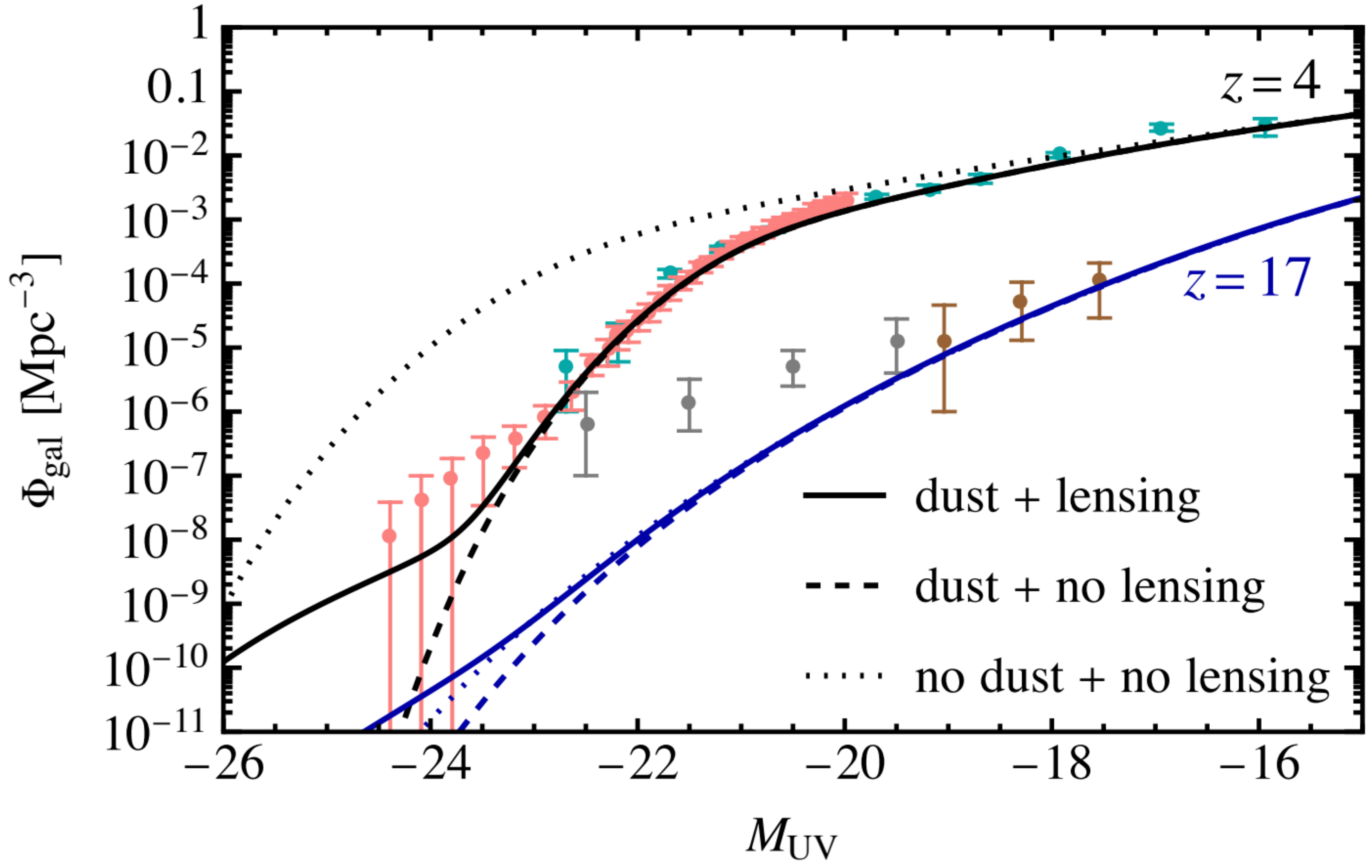



$$f_*(M) = \epsilon \, \frac{\alpha + \beta}{\beta (M/M_c)^{-\alpha} + \alpha (M/M_c)^{\beta}} \, e^{-M_t/M}$$

Star formation is assumed to be proportional to the DM/Baryon accretion



# Exploring the high-z with JWST




The star formation is converted to the magnitude in the UV, a stellar population is needed

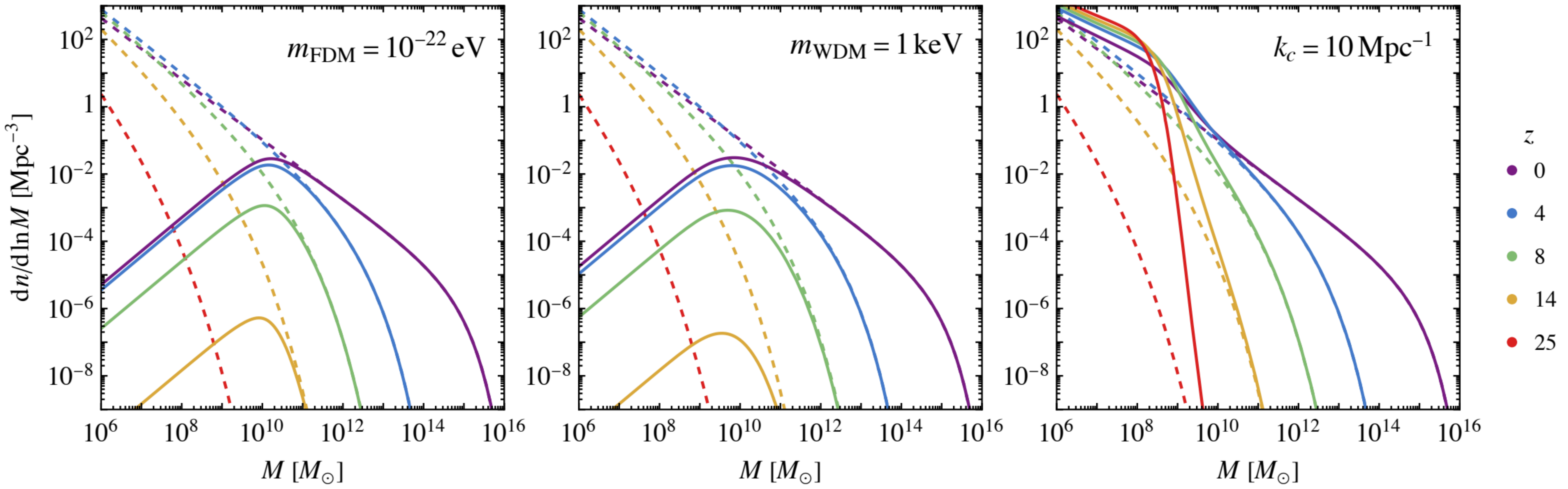
$$\bar{L}_{\rm UV} = \frac{\dot{M}_*}{\kappa_{\rm UV}}$$

$$\log_{10}\left[\frac{L_{\rm UV}}{\rm erg\,s^{-1}}\right] = 0.4\,(51.63 - M_{\rm UV})$$

# Exploring the high-z with JWST

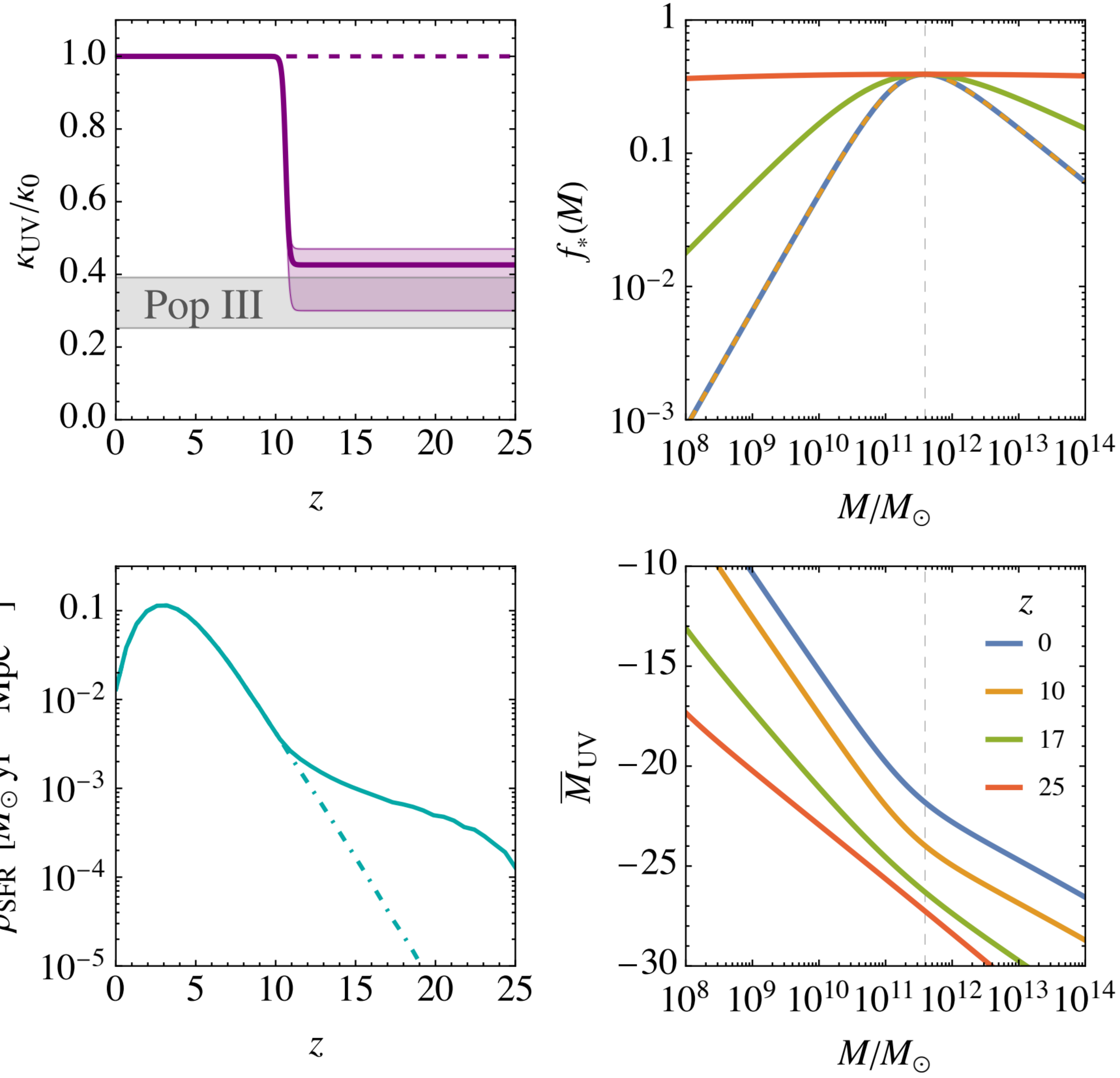
Using the halo mass function, a model for dust attenuation and weak lensing it is possible to compute the UV luminosity function

$$\Phi_{\mathrm{UV}}(L_{\mathrm{obs}}) = \int \mathrm{d}\mu\, \mathrm{d}\ln M\, \frac{\bar{B}}{\mu} \frac{\mathrm{d}P(\mu)}{\mathrm{d}\mu} \frac{\mathrm{d}P(L|M)}{\mathrm{d}L} \frac{\mathrm{d}n}{\mathrm{d}\ln M}$$



$z = 4$
$z = 5$
$z = 6$
$z = 7$
$z = 8$
$z = 9$
$z = 10$
$z = 11$
$z = 12.5$
$z = 14.5$
$z = 17$
$z = 25$
$\Phi_{\rm gal}$ [Mpc$^{-3}$]
$M_{\rm UV}$
0.1
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
−26
−24
−22
−20
−18
−16

# Implications for CDM



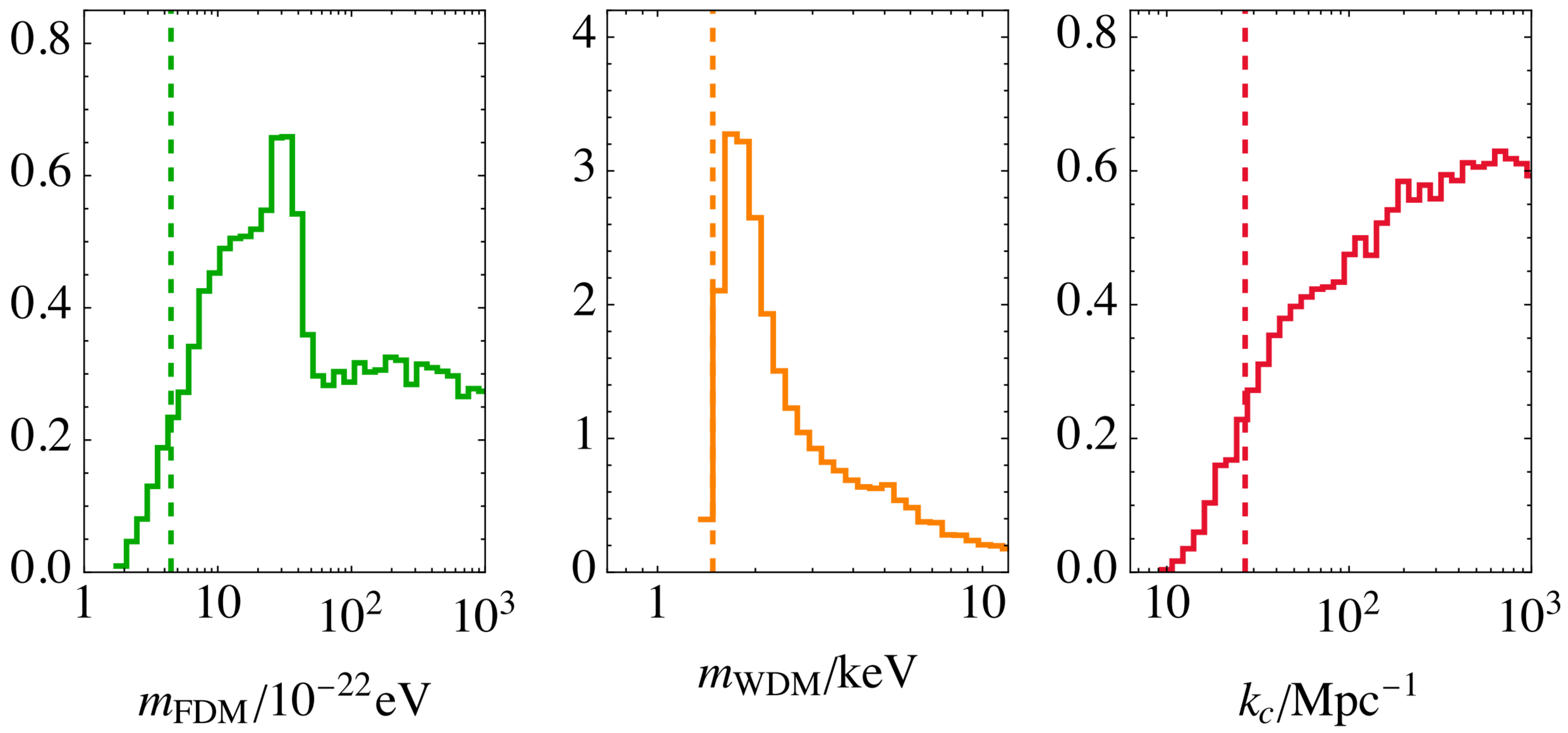

The stellar population changes at $z > 10$, compatible with simulations for Pop-III stars

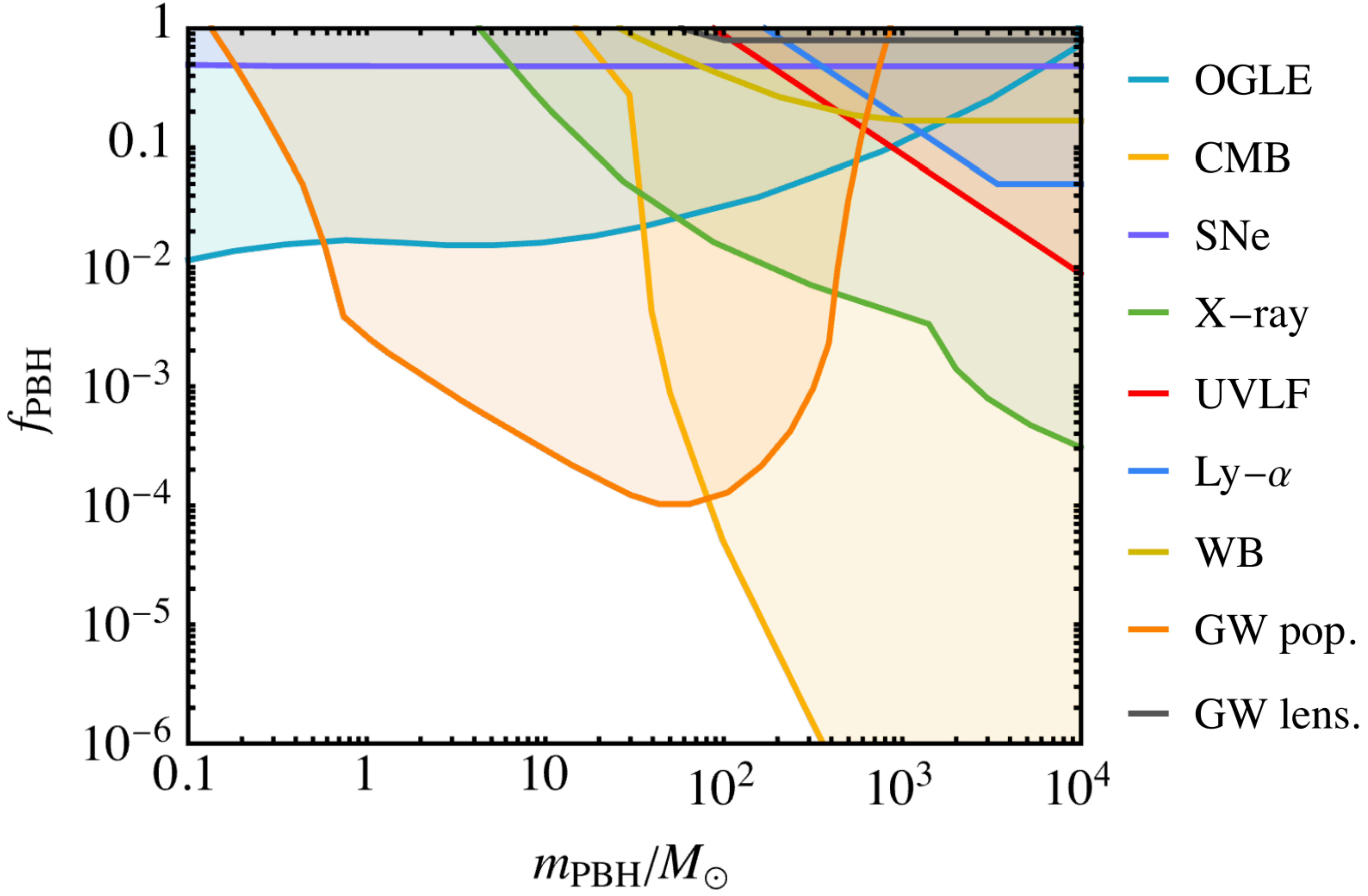
The galactic feedbacks are reduced at $z > 15$

# Implications for DM

Bounds on warm and fuzzy DM, marginally better than those from Hubble due to the uncertainties from JWST

Scenarios with enhanced structure are more constrained






Enhancing the matter power spectrum doesn't help you to explain the overabundance of bright galaxies

# Merger growth of SMBH

SMBH merge differently in different DM models

$$p_{\rm FC}(S, z|S_0, z_0) = A'\left[1 + (a\nu)^{-p}\right]\sqrt{\frac{\nu'}{2\pi}}\,\frac{e^{-\nu'/2}}{S - S_0}\,,$$

$$\nu = \frac{\delta_{\rm sp}(z)^2}{S}\,, \quad \nu' = \frac{(\delta_{\rm ell}(z, S_0) - \delta_{\rm ell}(z_0, S_0))^2}{S - S_0}\,,$$

$$M_J(M, z') + \Delta M_J^{\rm merg.}(M, z, z') = \int_0^M {\rm d}M' M_J(M', z') \times \frac{{\rm d}N}{{\rm d}M'}\,.$$

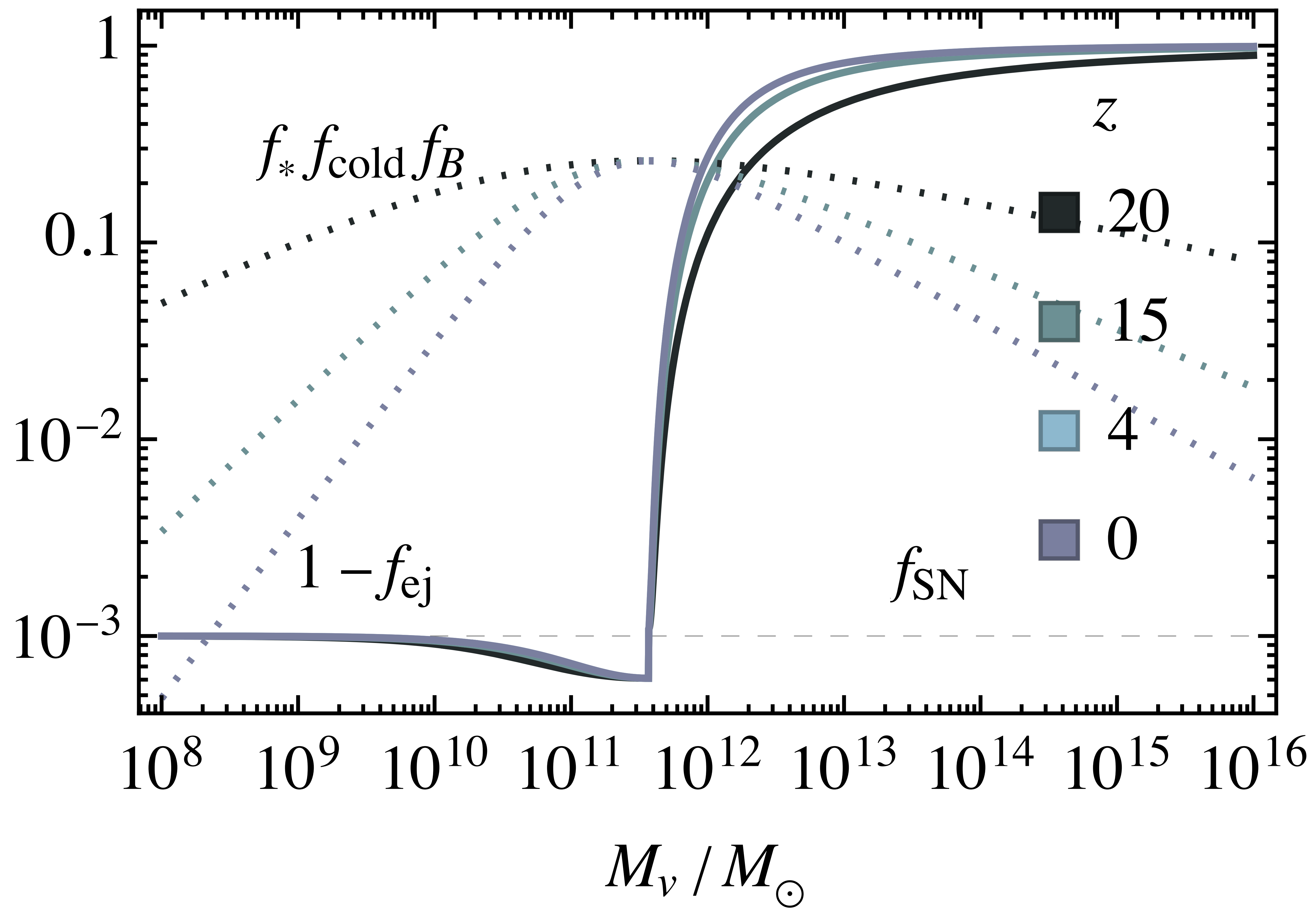
$$\frac{{\rm d}N}{{\rm d}M'} = \frac{{\rm d}S}{{\rm d}M'} p_{\rm FC}(\delta', S'|\delta, S)\,\frac{M}{M'}\,,$$

$$\bar{N}(M, z, z') = \int_0^M {\rm d}M' \frac{{\rm d}N}{{\rm d}M'}\,.$$

DM model changes the halo mass function and the variance of the perturbations $S$

# Accretion growth of SMBH

The galactic feedbacks can be deduced from the star formation




- Star formation in low mass halos is suppressed because SN feedback ejects gas, efficiency cannot be maximal
- In high mass halos, the feedback from the SMBH heats the gas in galaxies

# Complete model

SMBH grow from accreting hot and cold ga

$$f_{\rm ej} \equiv (1-f_*)(1-f_{\rm SN}) \begin{cases} 1\,, & M < M_{\rm c} \\ f_{\rm cold}^2\,, & M \geq M_{\rm c} \end{cases}$$

$$\dot{M}_{\rm BH}^{\rm acc.}(M_{\rm BH}, M) = \min\Big[(1-f_{\rm ej}) f_B (f_1^{\rm acc.}\dot{M} + f_2^{\rm acc.} M),\; f_{\rm Edd.}\dot{M}_{\rm Edd.}(M_{\rm BH})\Big]$$

We consider an efficiency of SMBH mergers

$$\dot{M}_{\rm BH}^{\rm merg.}(M, p_{\rm BH}) = \begin{cases} \dot{M}_{\rm BH}^{\rm merg.}(M) & < 0 \\ p_{\rm BH}\, \dot{M}_{\rm BH}^{\rm merg.}(M) & \geq 0 \end{cases}$$

Stars grow from star formation of cold gas and mergers

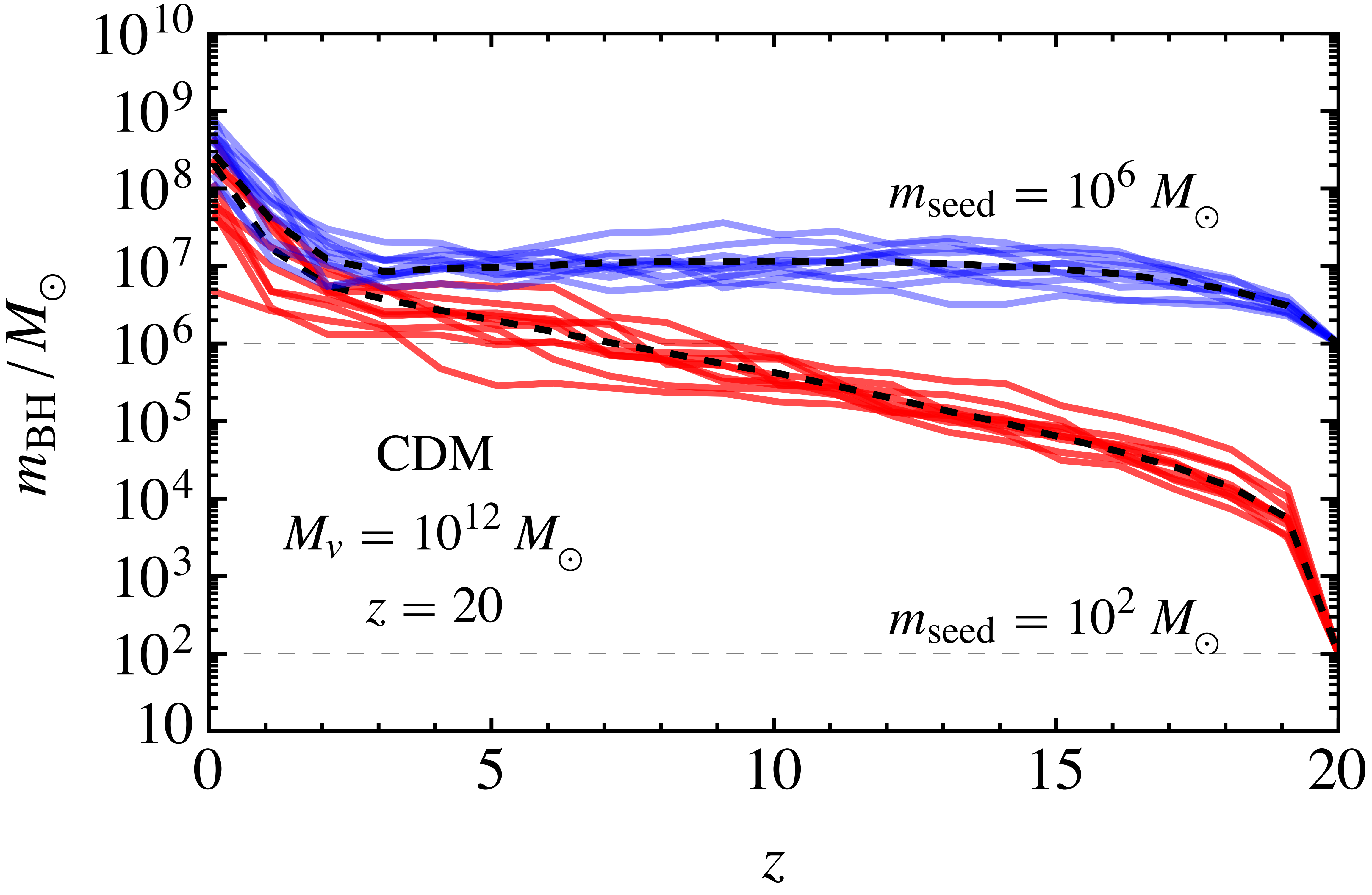
$$f_*(M) = \epsilon\, \frac{\alpha+\beta}{\beta(M/M_c)^{-\alpha} + \alpha(M/M_c)^{\beta}}\, e^{-M_t/M}$$

DM accretion, and feedbacks are fixed for each DM model. We perform the scans over

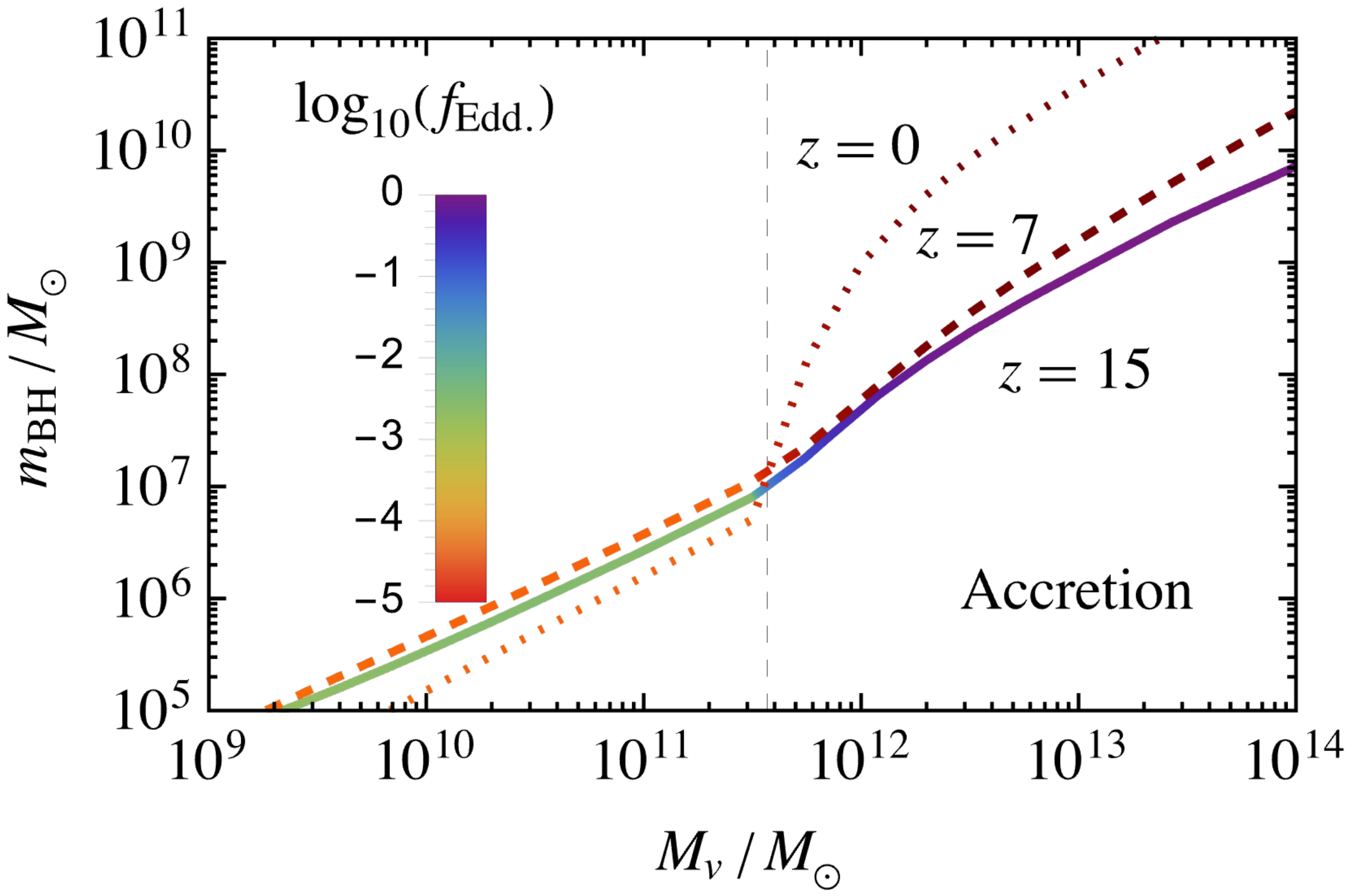
$$(m_{\rm seed}\,, M_{\rm seed}\,, f_{\rm Edd.}\,, f_{\rm SN}\,, m_{\rm DM})$$

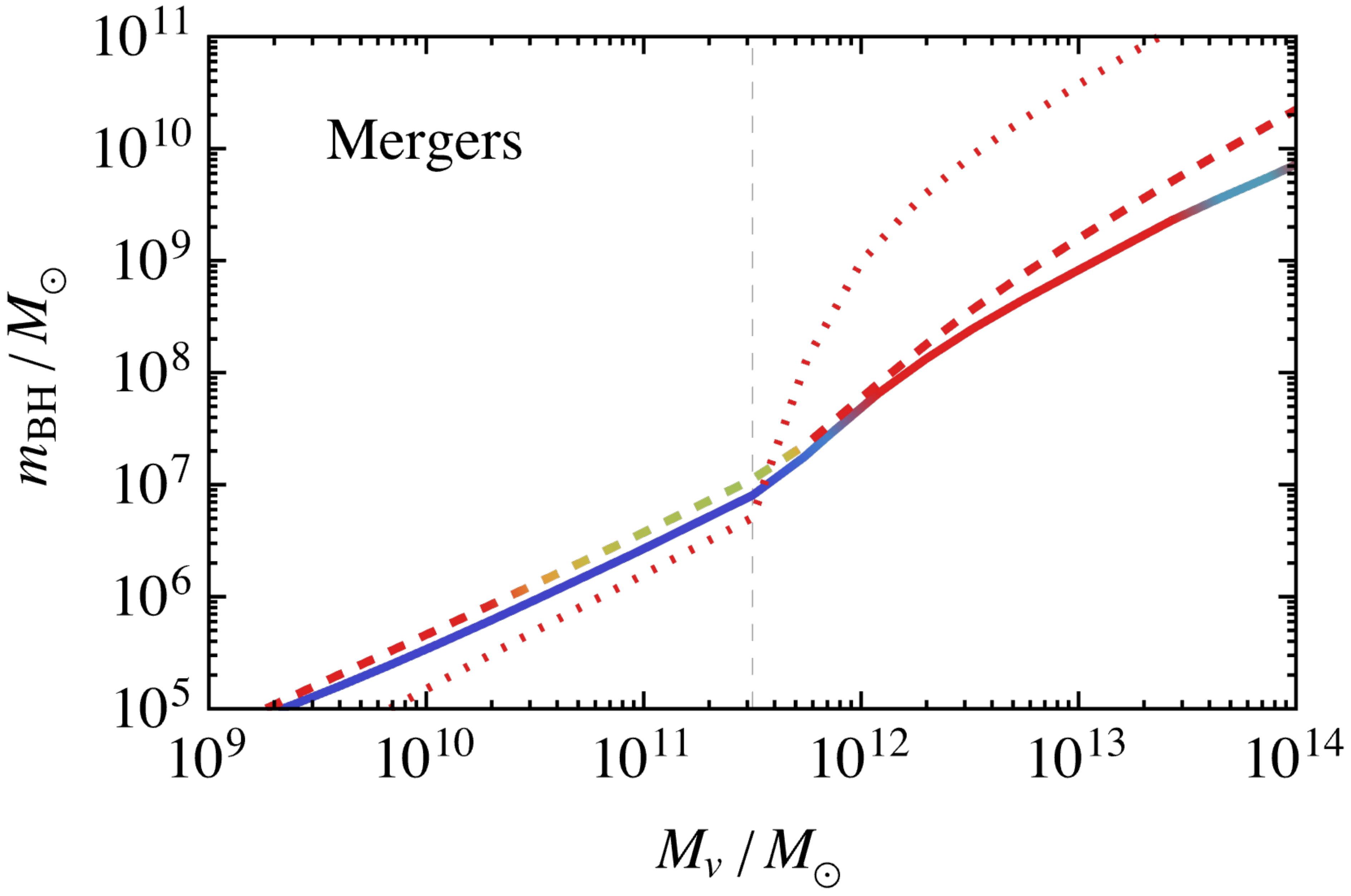
# How SMBH grow

Accretion growth




How a SMBH growths

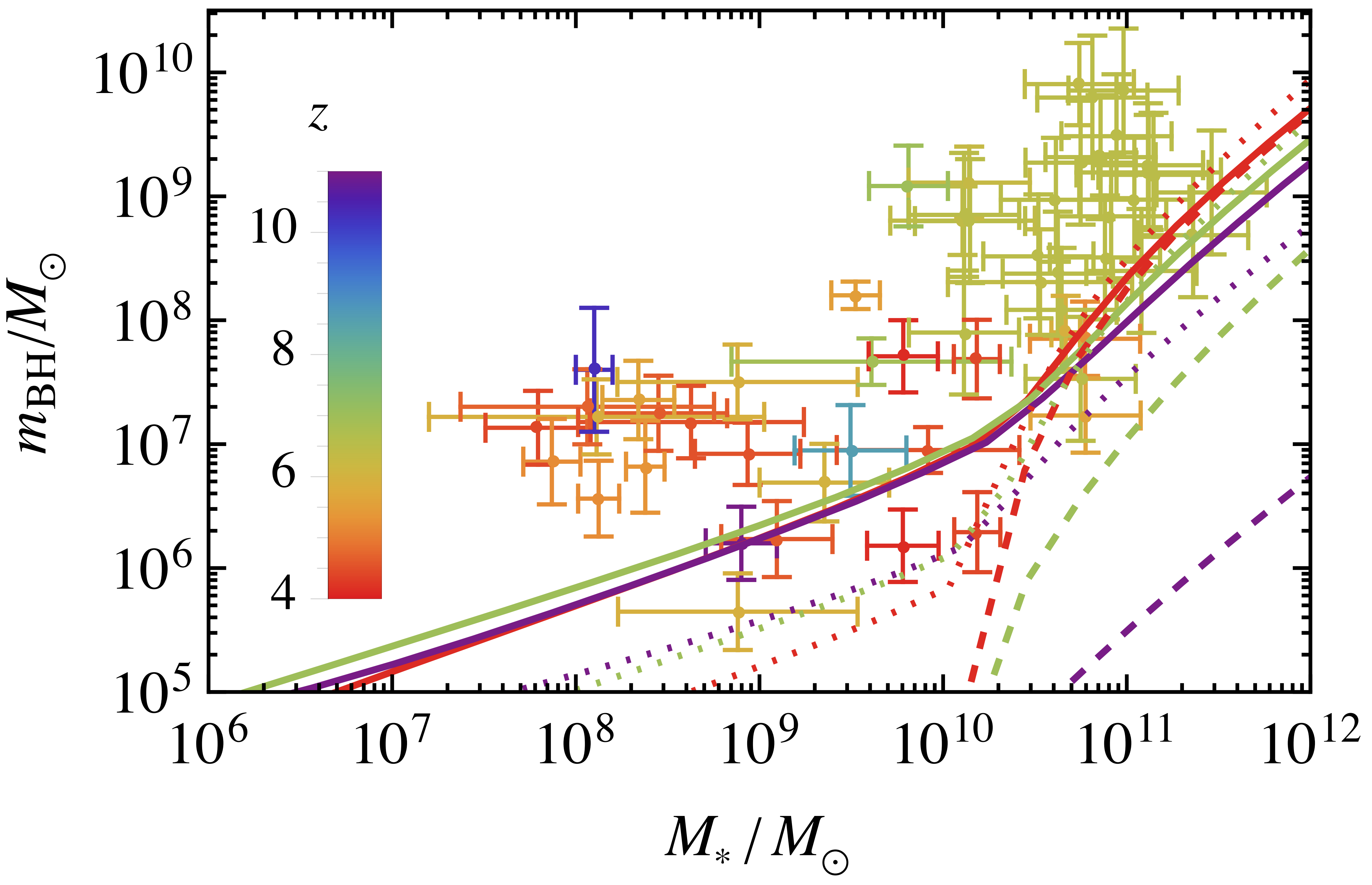


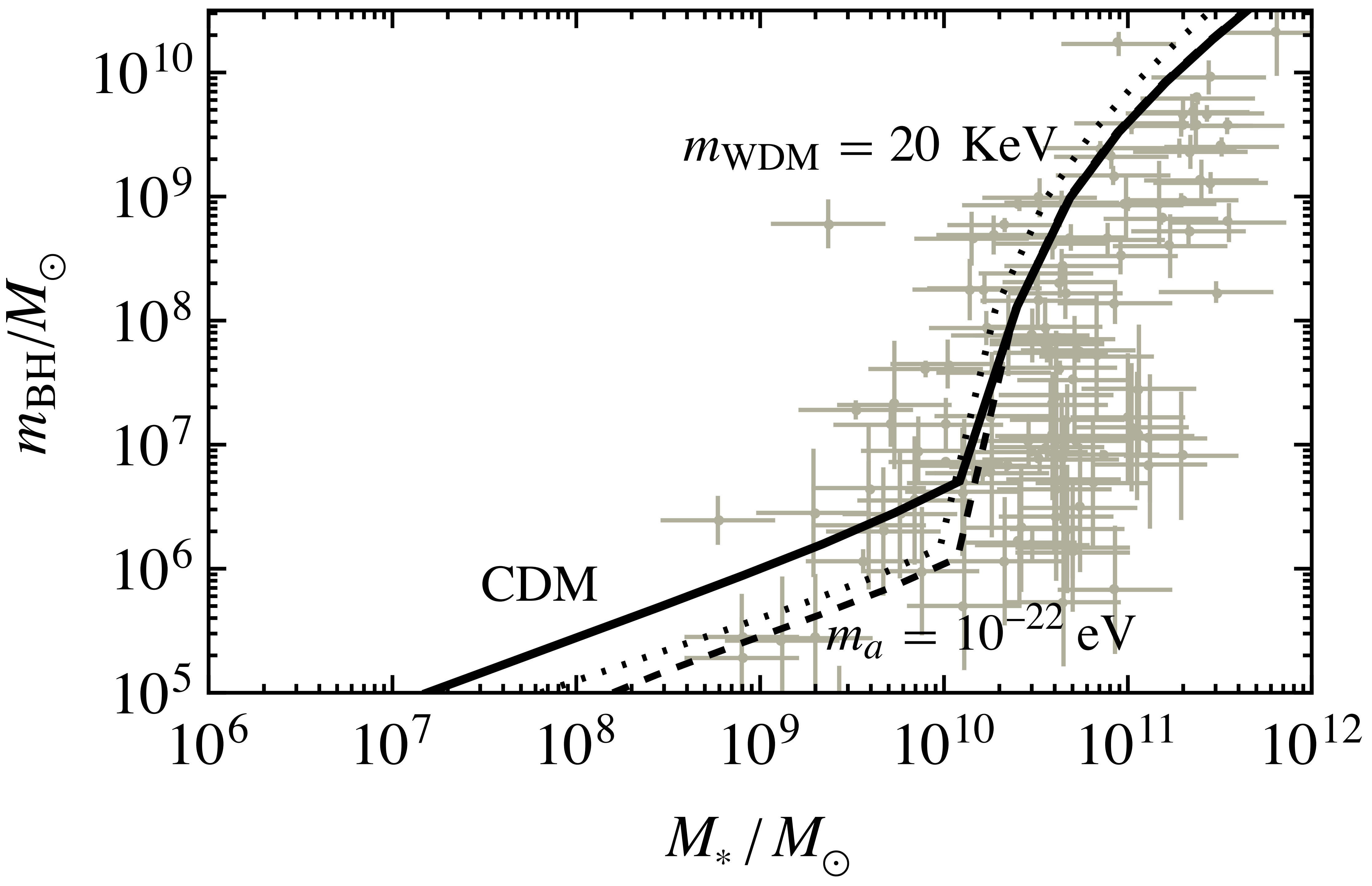

Mergers growth

# How SMBH grow

JWST data, and up to date quasar catalog

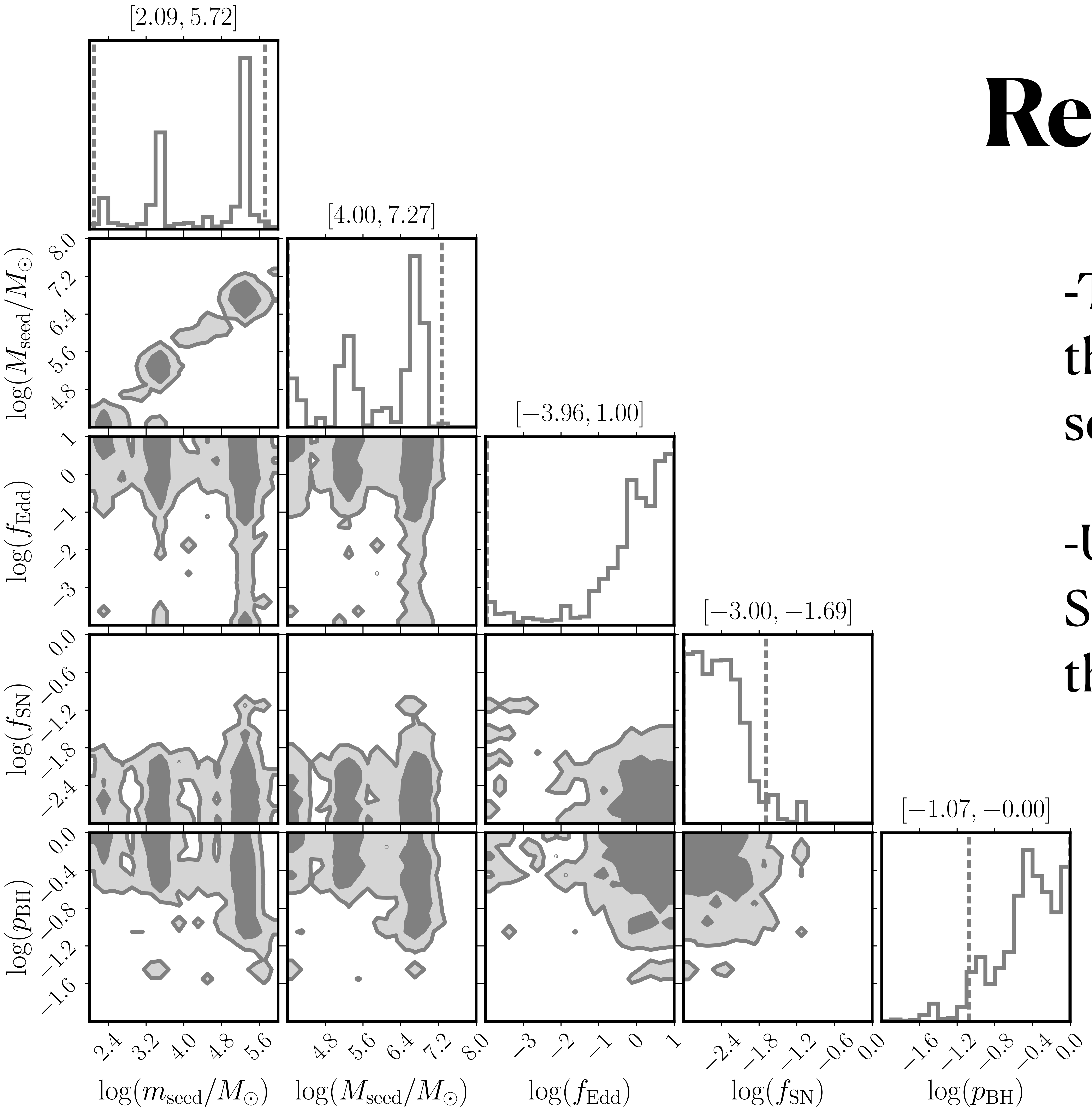



Old low $z$ data




(Heavy seed)

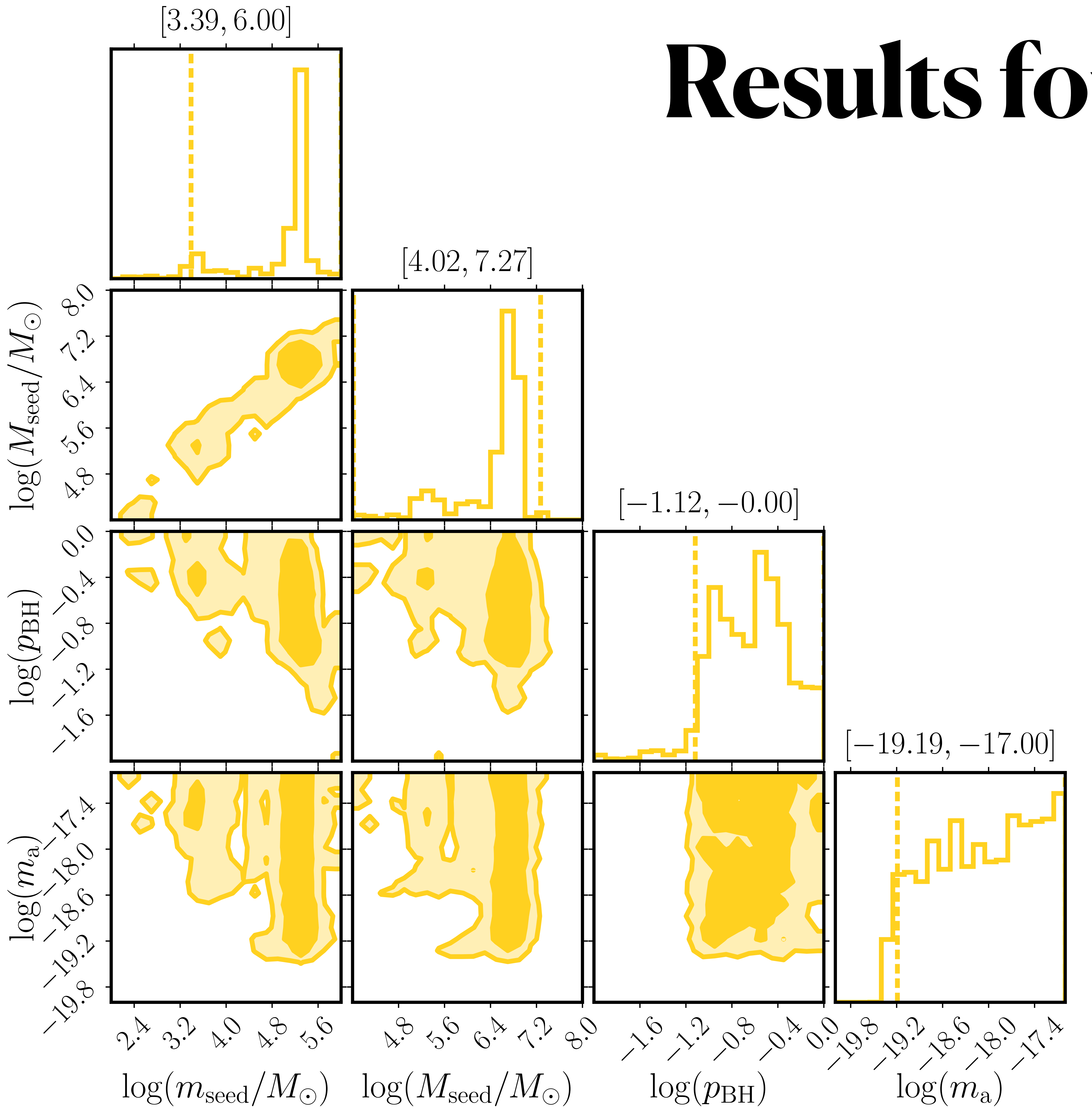
# Results for CDM




-There is a scaling relation between the seed mass of the halo and the seed mass of the black hole

-Upper bound on the inefficiency of SN feedback and a lower bound on the merging efficiency

# Results for FDM



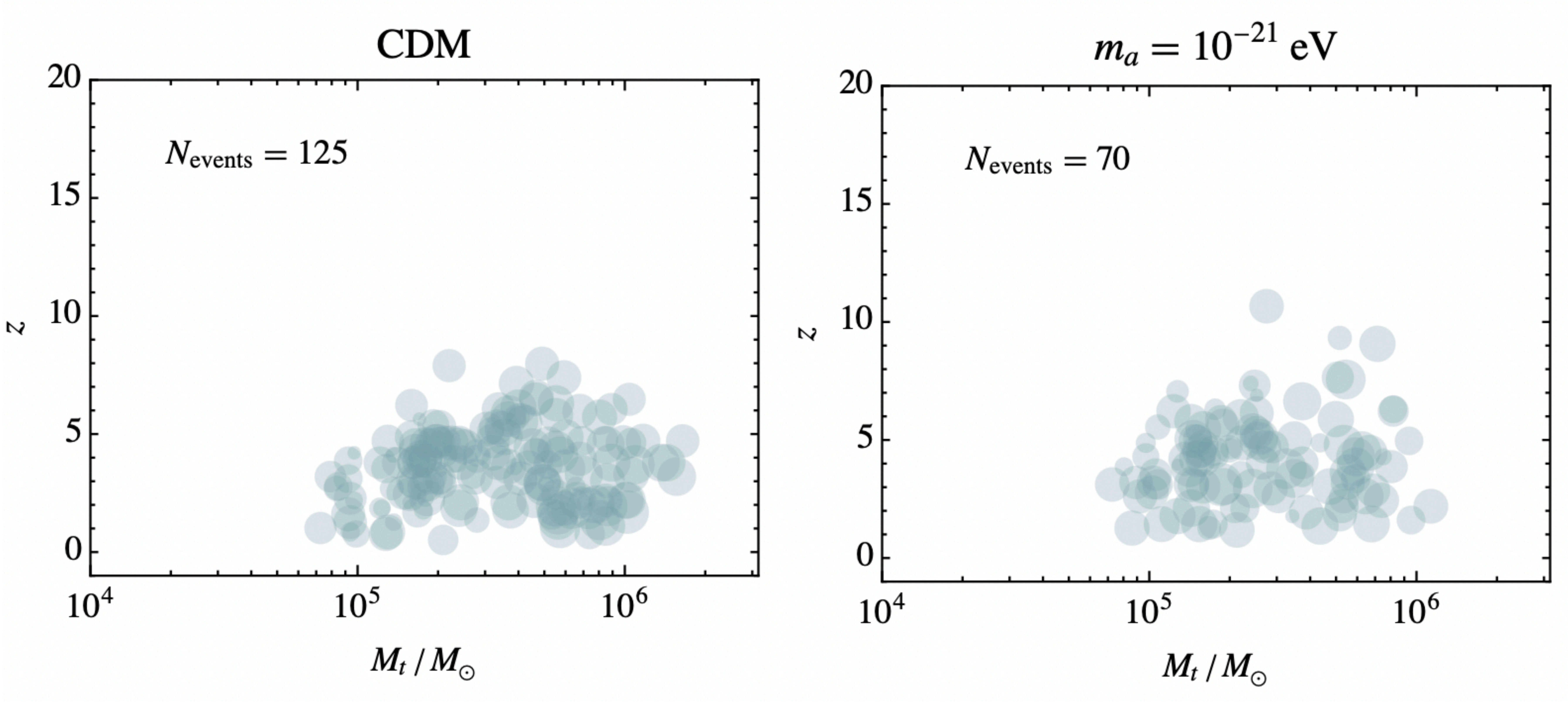

-We have fixed some of the parameters

-For those parameters, the best fit is at the same black hole and seed parameters as CDM

-Very stringent bounds on FDM mass, which are correlated with the seed mass

# LISA events (an example)

We can apply our semi-analytical model and compute the number of detectable events for LISA



# Why are SMBH more powerful discriminators

-Stars are cosmic "snapshots", the UV light is dominated by short-lived high mass stars, the  halos more sensitive to DM are too dim (high redshift, low mass)

-SMBH are long lived objects that carry information from their seeding (which happen at very high redshift and low mass halos) even at intermediate redshifts

-LISA by measuring the origin of the SMBHs is going to put stringent bounds on deviations from CDM. Maybe more powerful than using stars?

# THANKS FOR YOUR TIME