The Epoch of Reionization in Alternative DM models

a view from THESAN-HR simulations

Xuejian (Jacob) Shen

xuejianshen.github.io

Caltech MIT

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Background & Motivations

- Cold Dark Matter (CDM)
  - "Naturalness" candidates from well-motivated BSM theories
    (e.g. WIMPs, hierarchy problem; Axions, strong CP problem)
    + simple structure & production mechanisms
  - Success at large scales

- DM models alternative to the collisionless CDM on astrophysical scales

  WIMPs increasingly constrained
  Small-scale astrophysical anomalies?

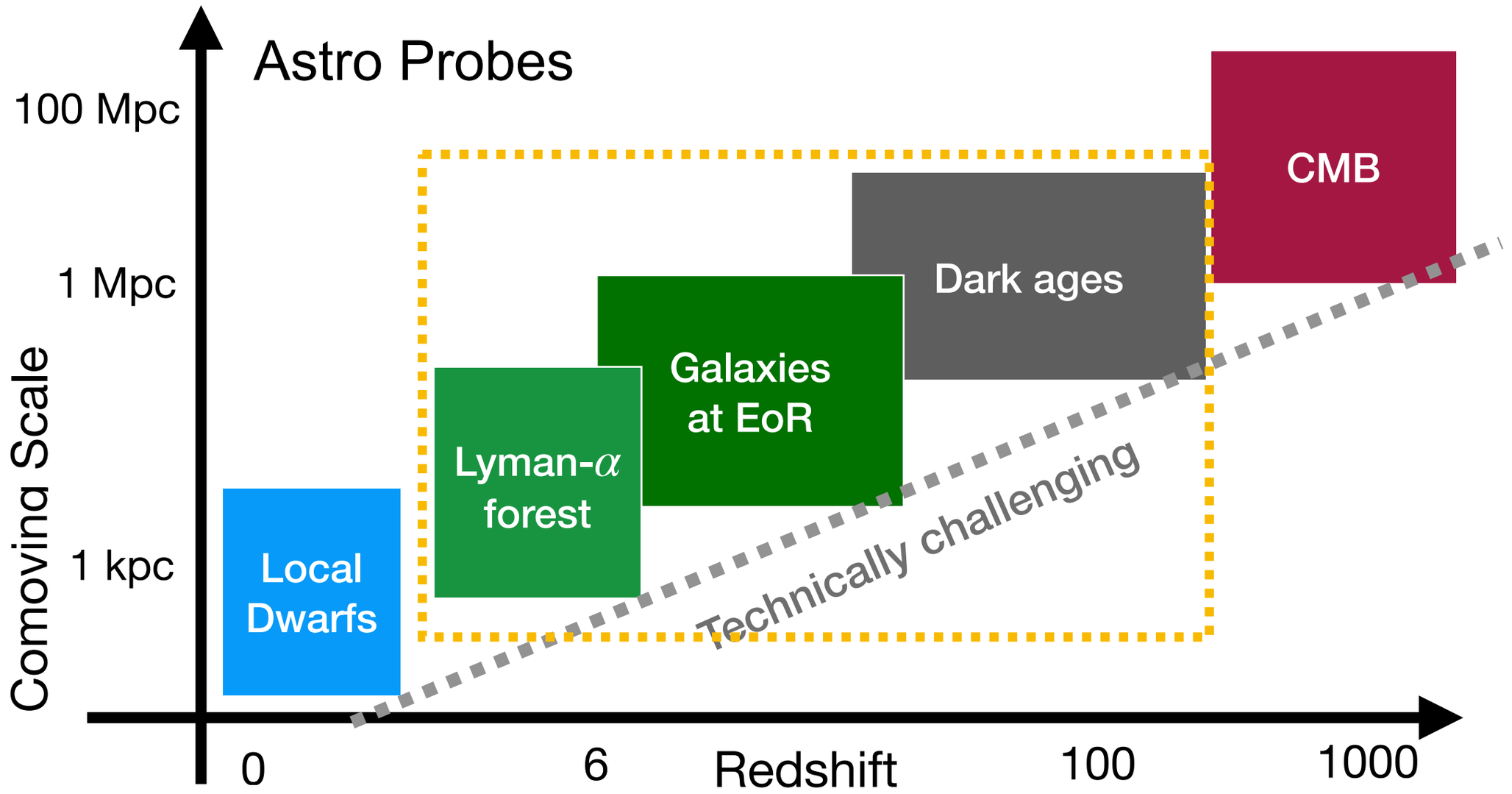
  ⟶ A hidden-sector with rich physics. Deviations from CDM.

- Probes through structural formation
  efficient at constraining a broad class of DM models in a wide theory space
  complementary to direct/indirect detections for e.g. DM self-interactions

Background & Motivations

Baryonic structures in the Epoch of Reionization (EoR)

- reionization is driven by low-mass galaxies (sensitive to DM models that affects small-scale power spectrum, e.g. warm dark matter)
- rich data from next generation imaging surveys (JWST) and 21cm line intensity mapping of the neutral gas from the dark ages to the EoR

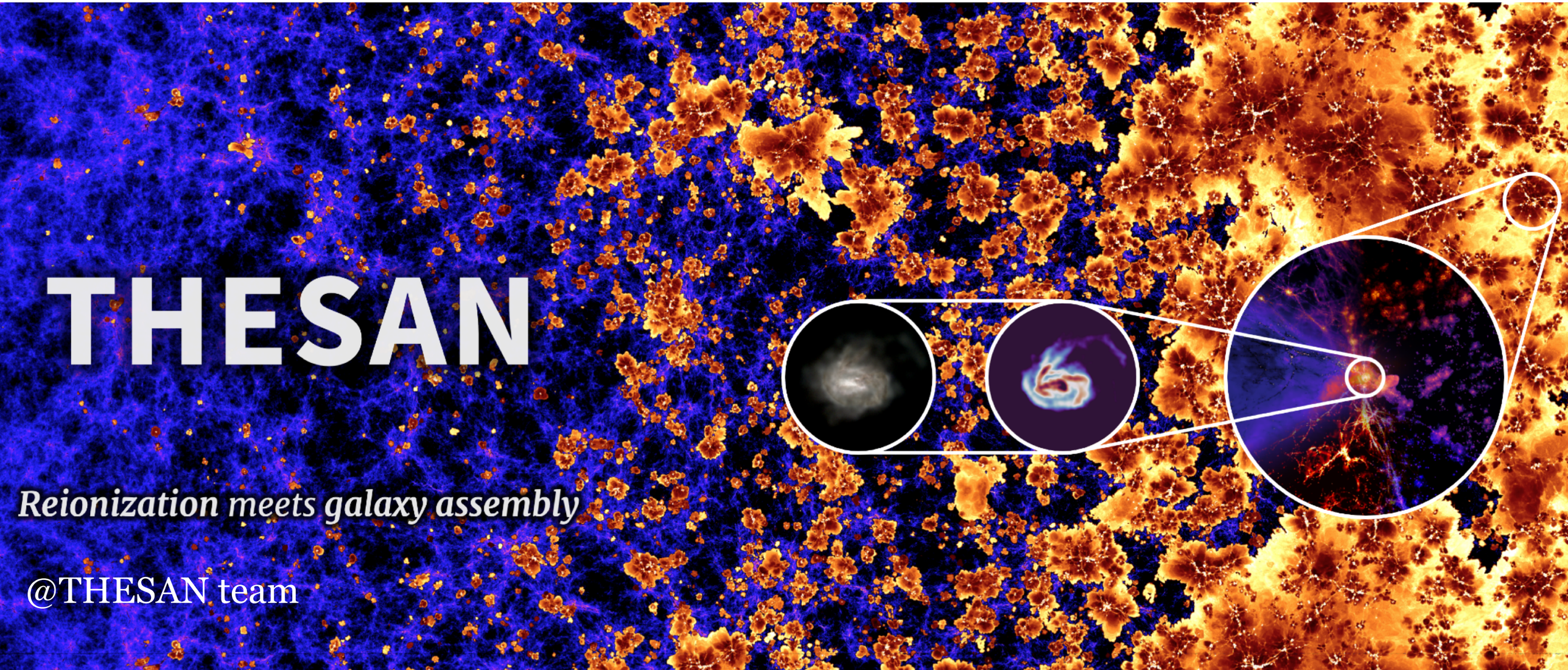


The THESAN project (Kannan+2022; Smith+2022; Garaldi+2022)

— Cosmological Radiation-Hydrodynamic Simulations

- Sourcing & radiative transfer of ionizing photons,
  $E_\gamma \in [13.6, 24.6, 54.4, +\infty]$ eV (using the M1 scheme in AREPO-RT)
- Non-equilibrium thermochemistry

+ IllustrisTNG galaxy formation model (sub-grid star formation & feedback)



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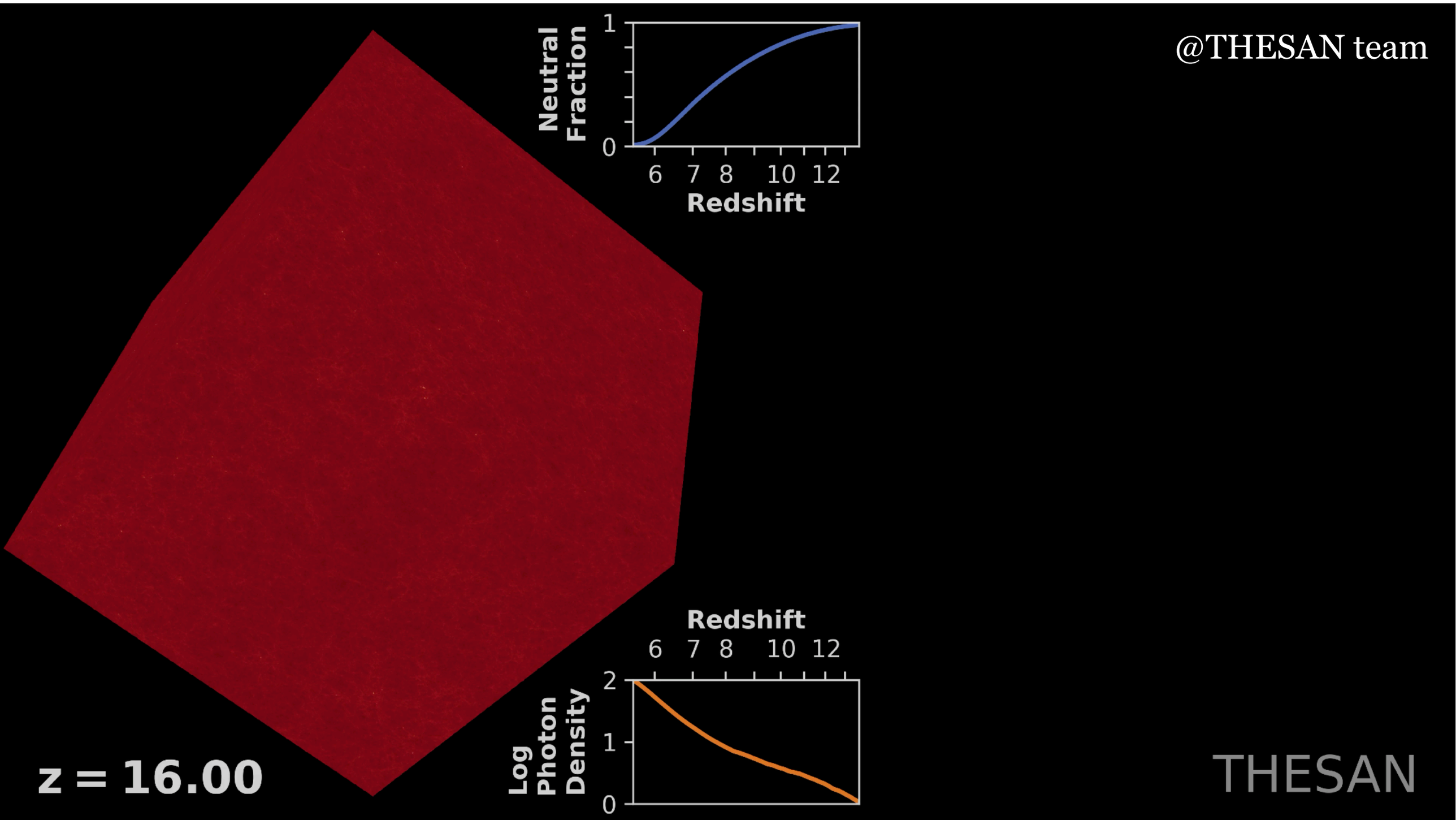
— Cosmological Radiation-Hydrodynamic Simulations

Volume rendering of HI fraction (left) and ionizing radiation field (right)

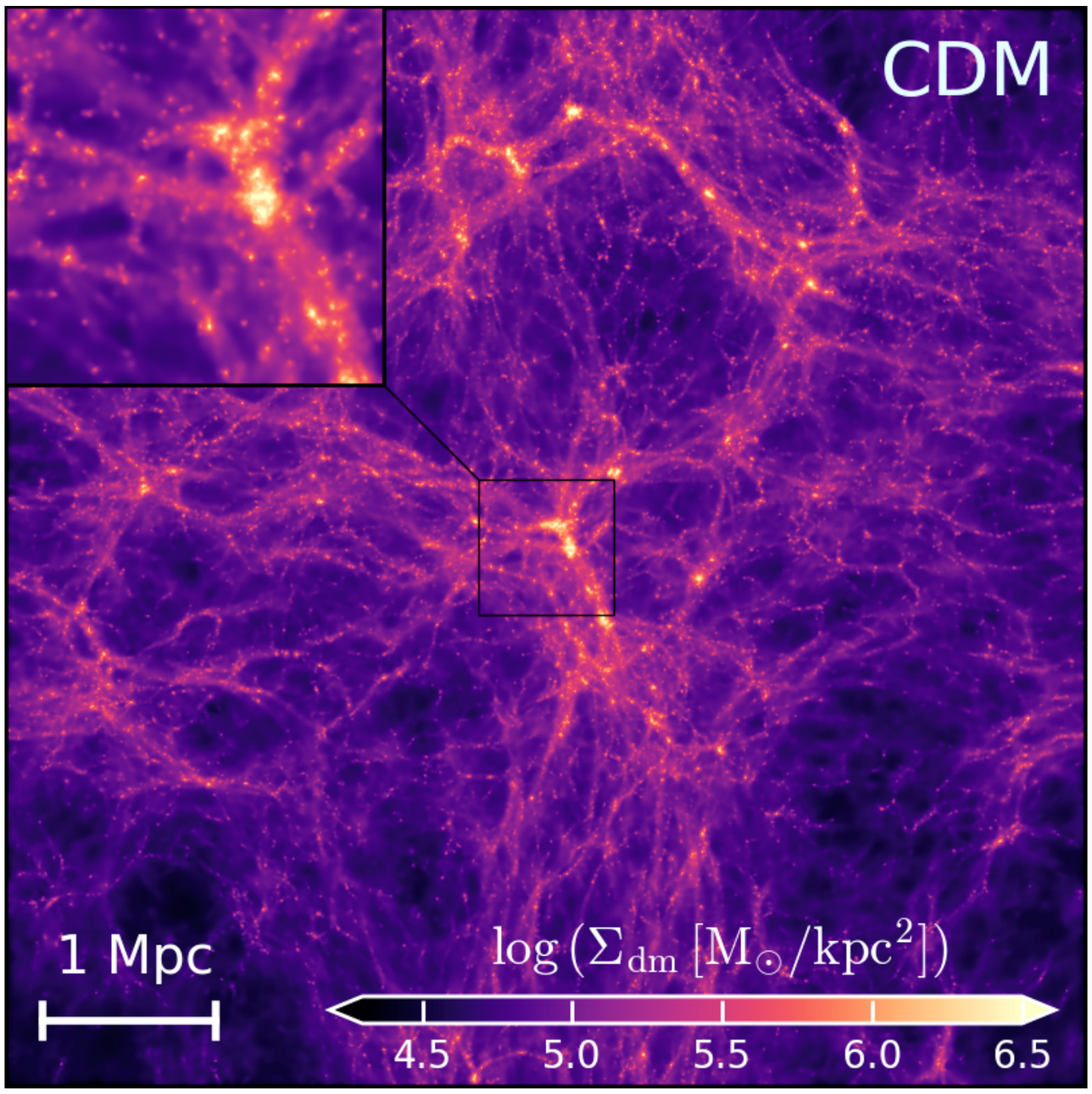


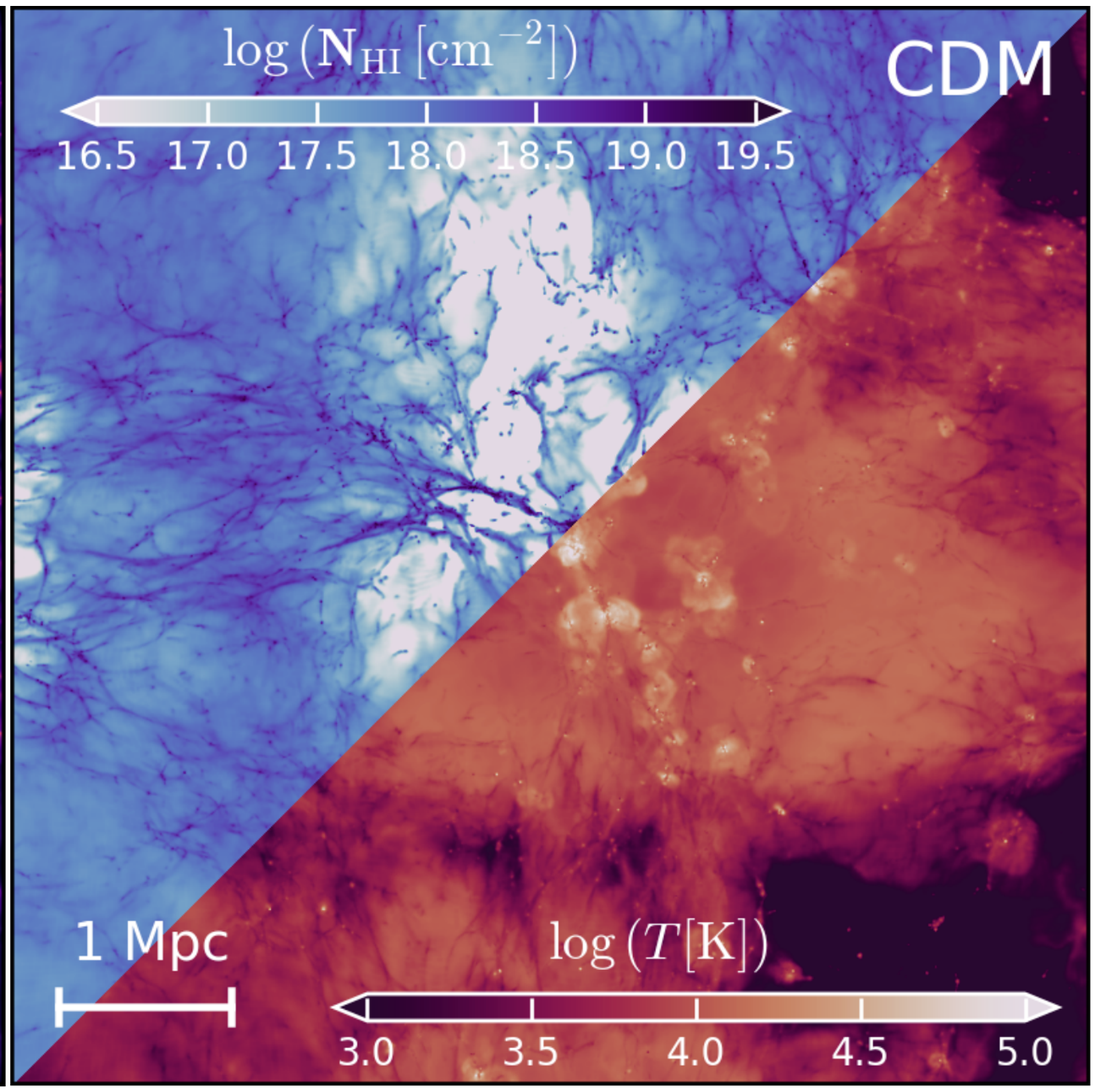
THESAN-HR (Borrow+2022; Shen+2023 in prep)

— A Small-Volume, High-Resolution variant of THESAN

$$L_{\rm box} \sim 4\,{\rm cMpc}/h; \quad \epsilon \sim 85\,{\rm pc}; \quad m_{\rm dm} \sim 4.8 \times 10^5\,{\rm M}_\odot; \quad m_{\rm b} \sim 9 \times 10^4\,{\rm M}_\odot$$

(comparable to e.g. TNG50)





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Exploring DM models alternative to the collisionless CDM

- Warm Dark Matter (WDM)
- Fuzzy Dark Matter (FDM)
- Strong Dark Acoustic Oscillations (sDAO)

Exploring different reionization models

- Radiative transfer on the fly — patchy reionization
- Uniform UV background (UVB) approximation

CDM

DM Surface Density

1 Mpc

$\log(\Sigma_{\rm dm}\,[\mathrm{M}$

4.5 5.0 5.5

Power spectrum

$\Delta^2_{\rm linear}(k)$

$k\,[\mathrm{h/Mpc}]$

CDM

Halo mass function

$\log(\Phi\,[1/\mathrm{cMpc}^3/\mathrm{dex}])$

$100\,m_{\rm dm}$

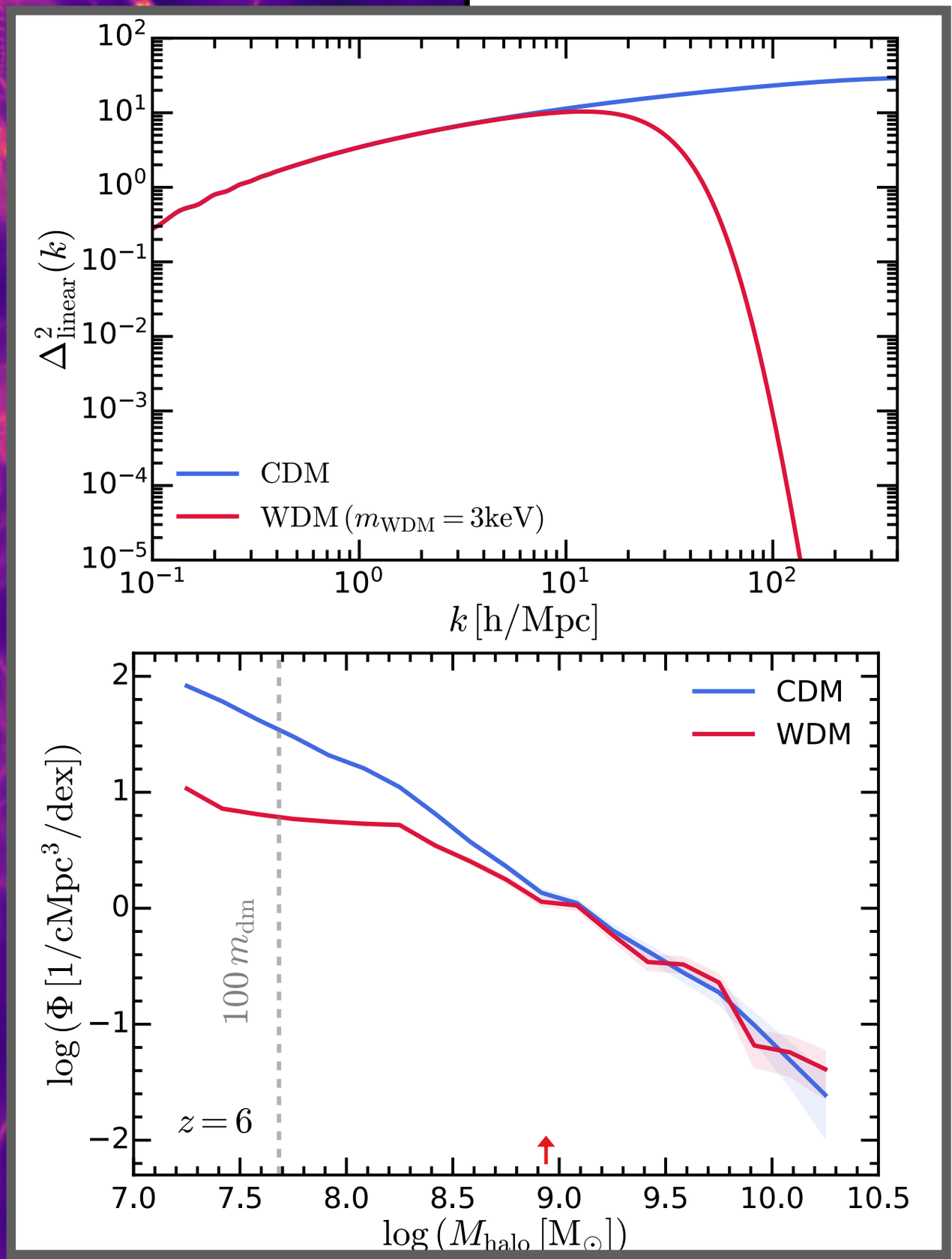
$z = 6$

$\log(M_{\rm halo}\,[\mathrm{M}_\odot])$

WDM

$m_{\rm WDM} = 3\,{\rm keV}$

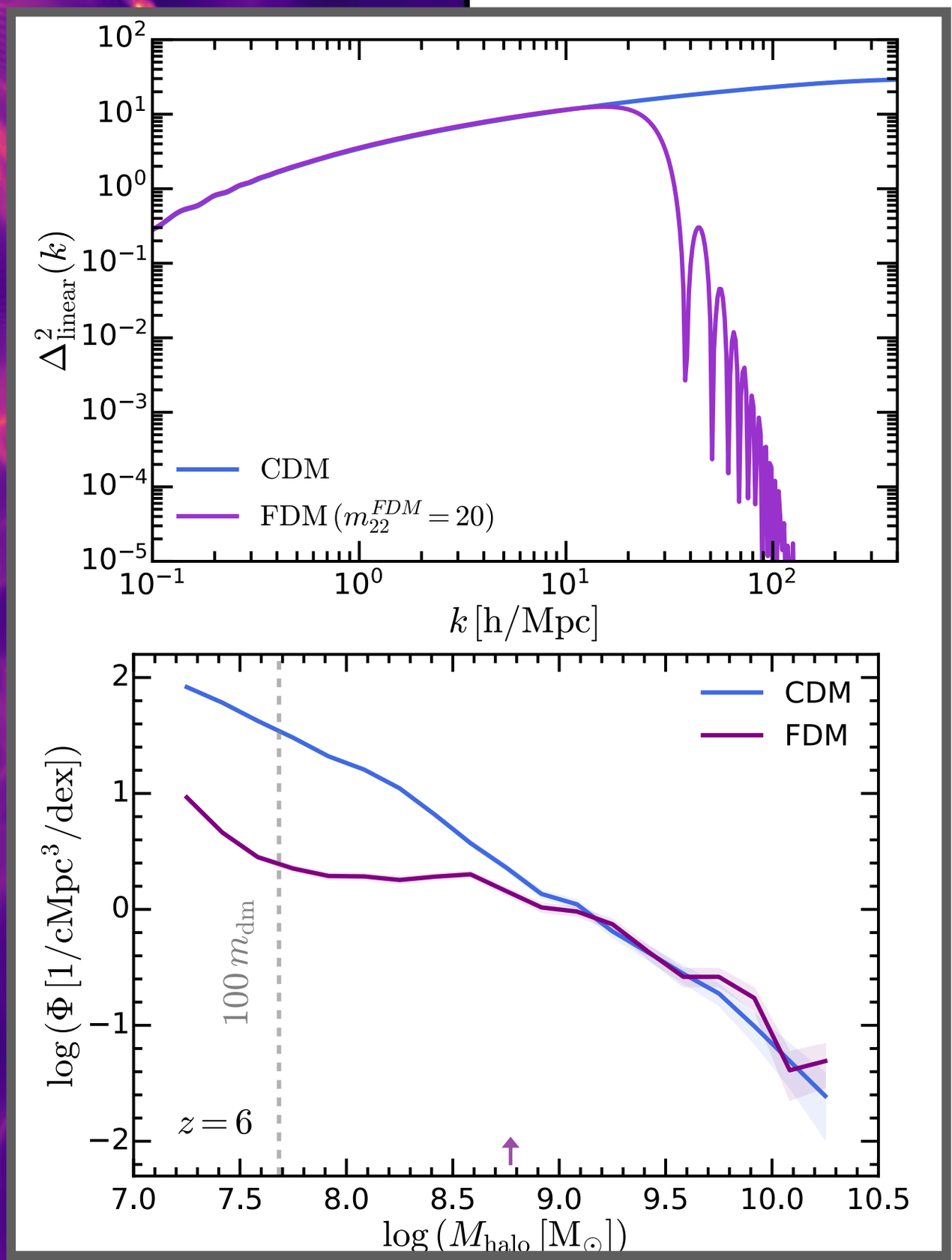
1 Mpc



FDM

$m_{\rm a} = 2 \times 10^{-21}\,{\rm eV}$

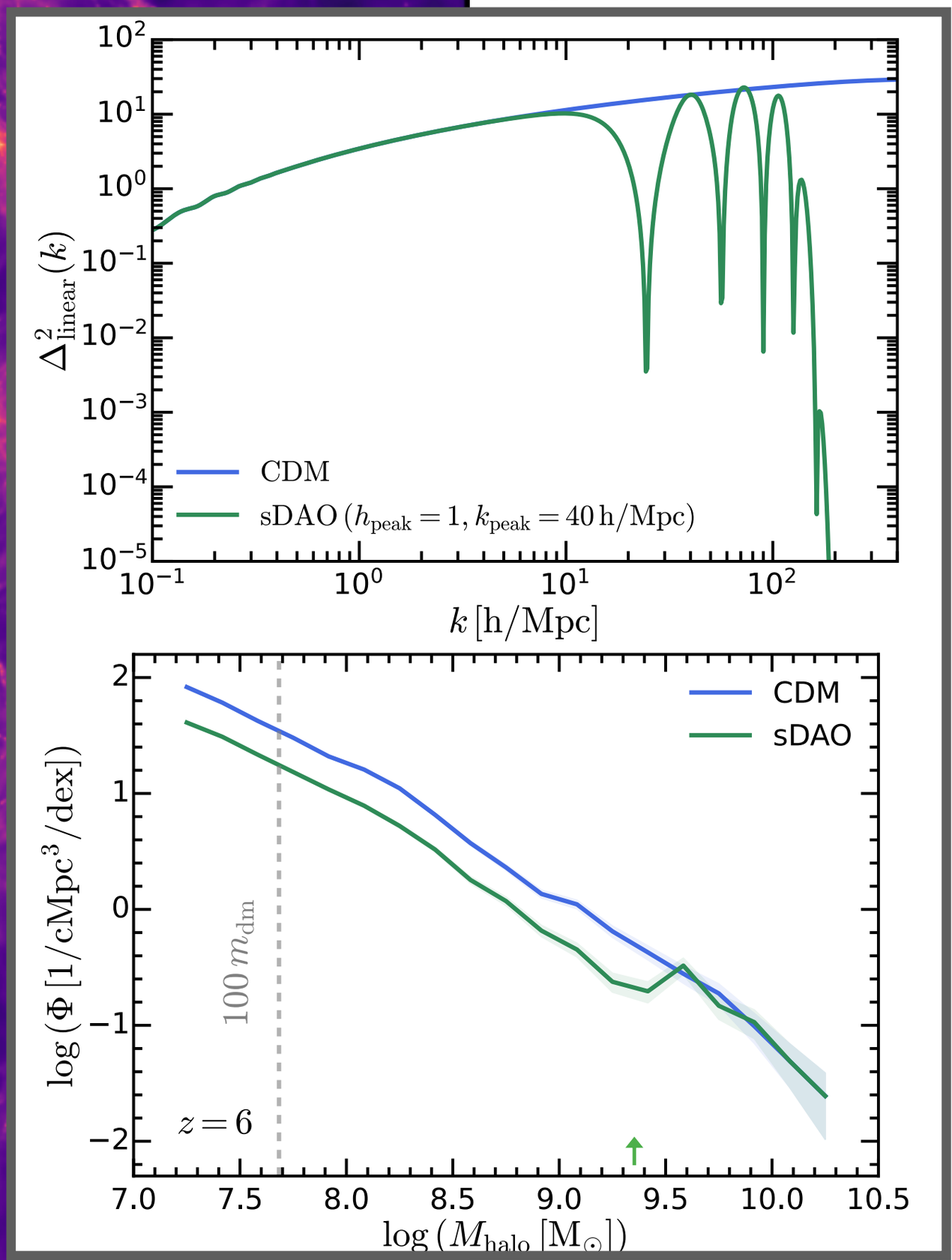
1 Mpc



sDAO

$k_{1/2} \sim 16\,h/\mathrm{Mpc}$

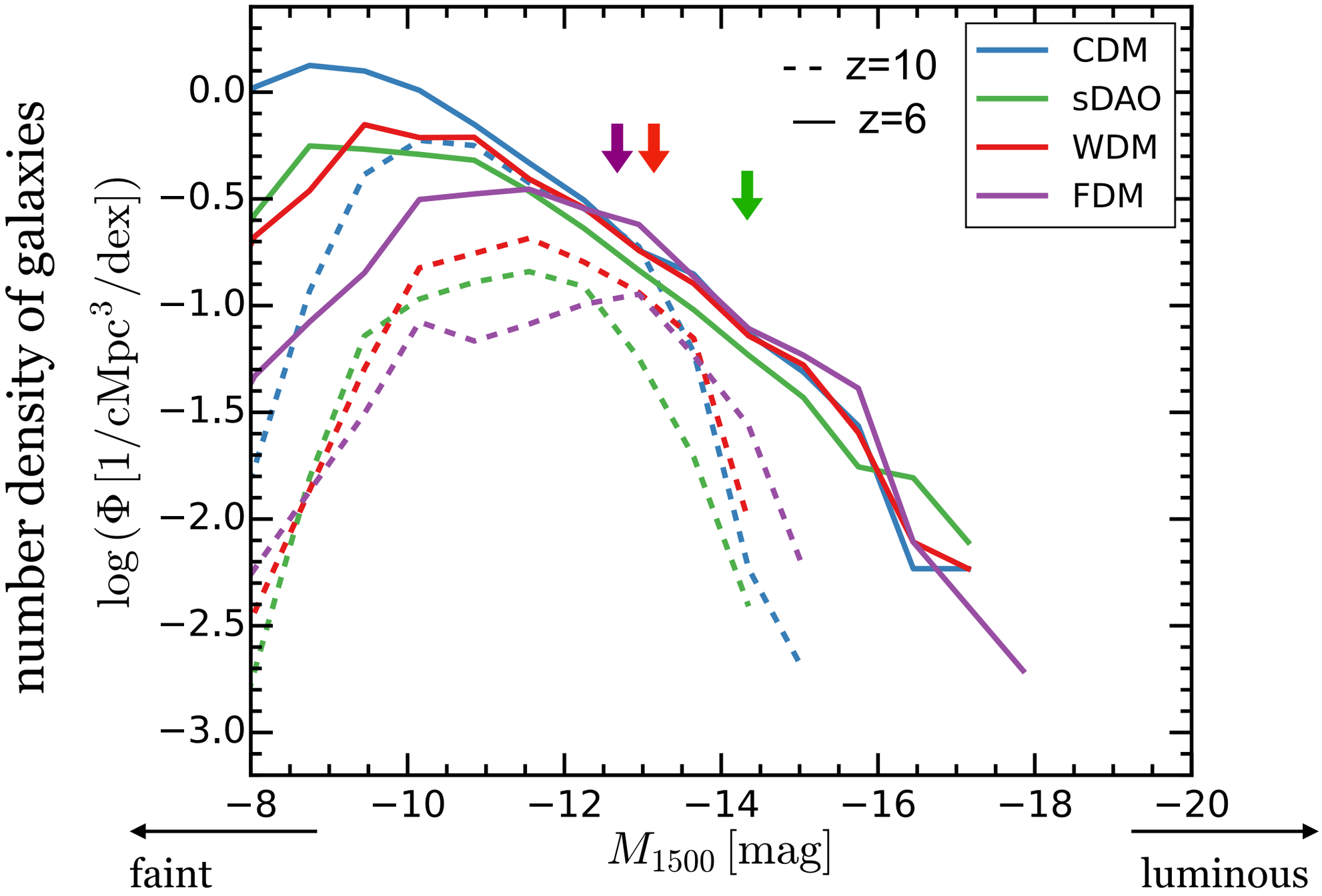
$h_{\mathrm{peak}} = 1$



1 Mpc

Galaxy abundance - UV luminosity functions

- Suppression at faint luminosities ($M_{\rm UV} \gtrsim -14$)
- Signal more prominent at higher redshift



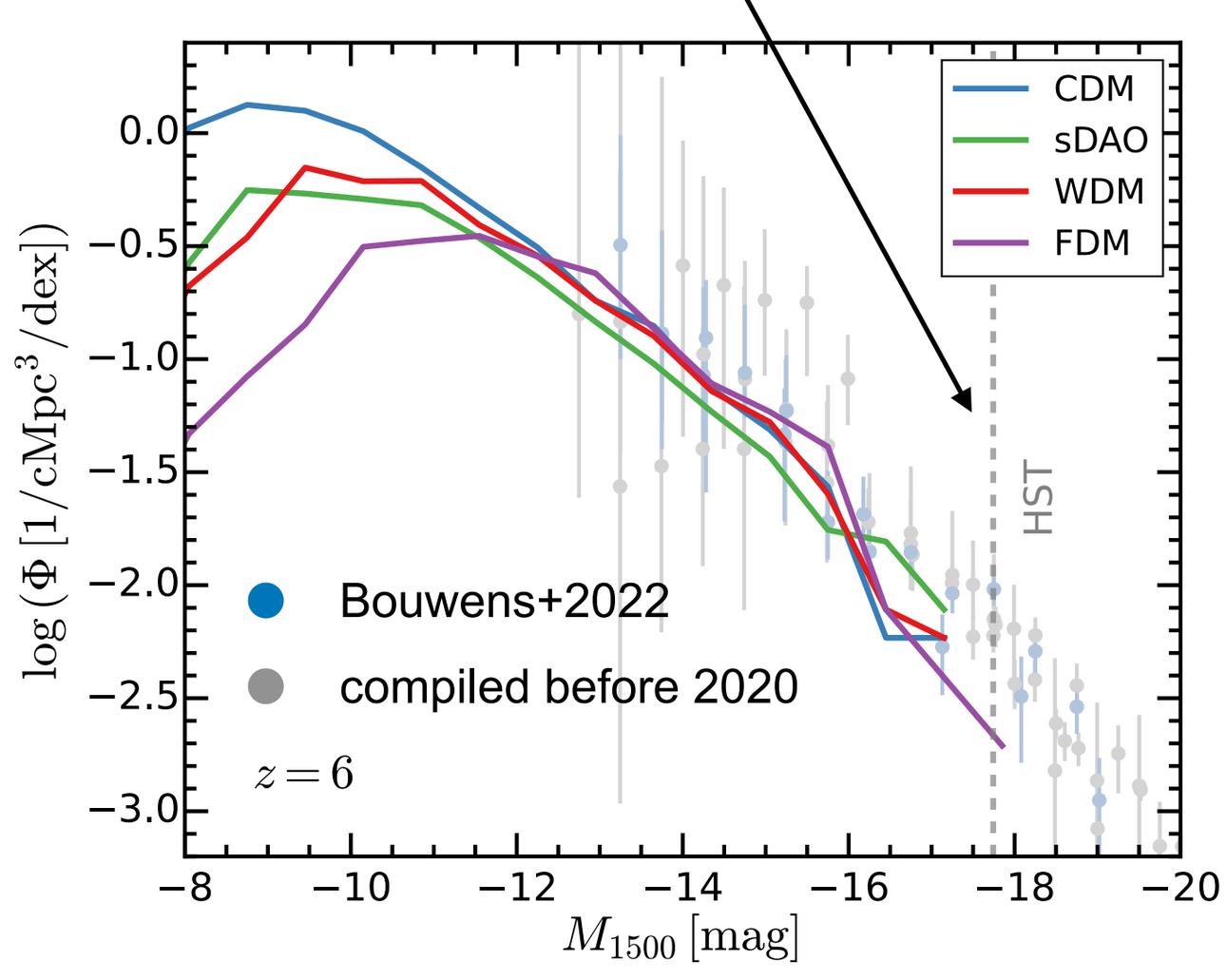
Galaxy abundance - UV luminosity functions

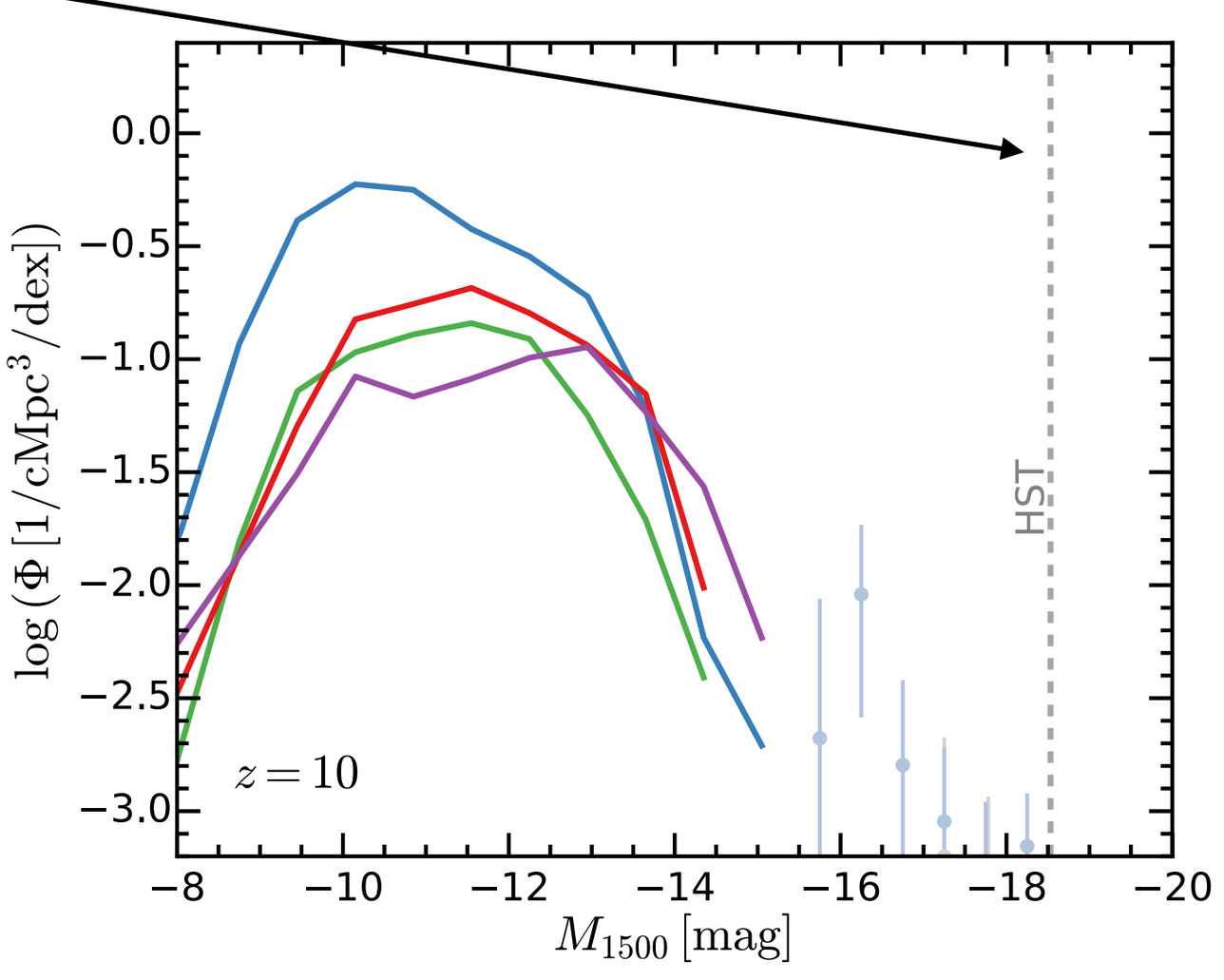
Can we see it?

The Hubble Space Telescope (HST) limit

Plain field limit of HST
(e.g. CANDELS, HUDF)

Lensed fields of HST
(e.g. HFF)





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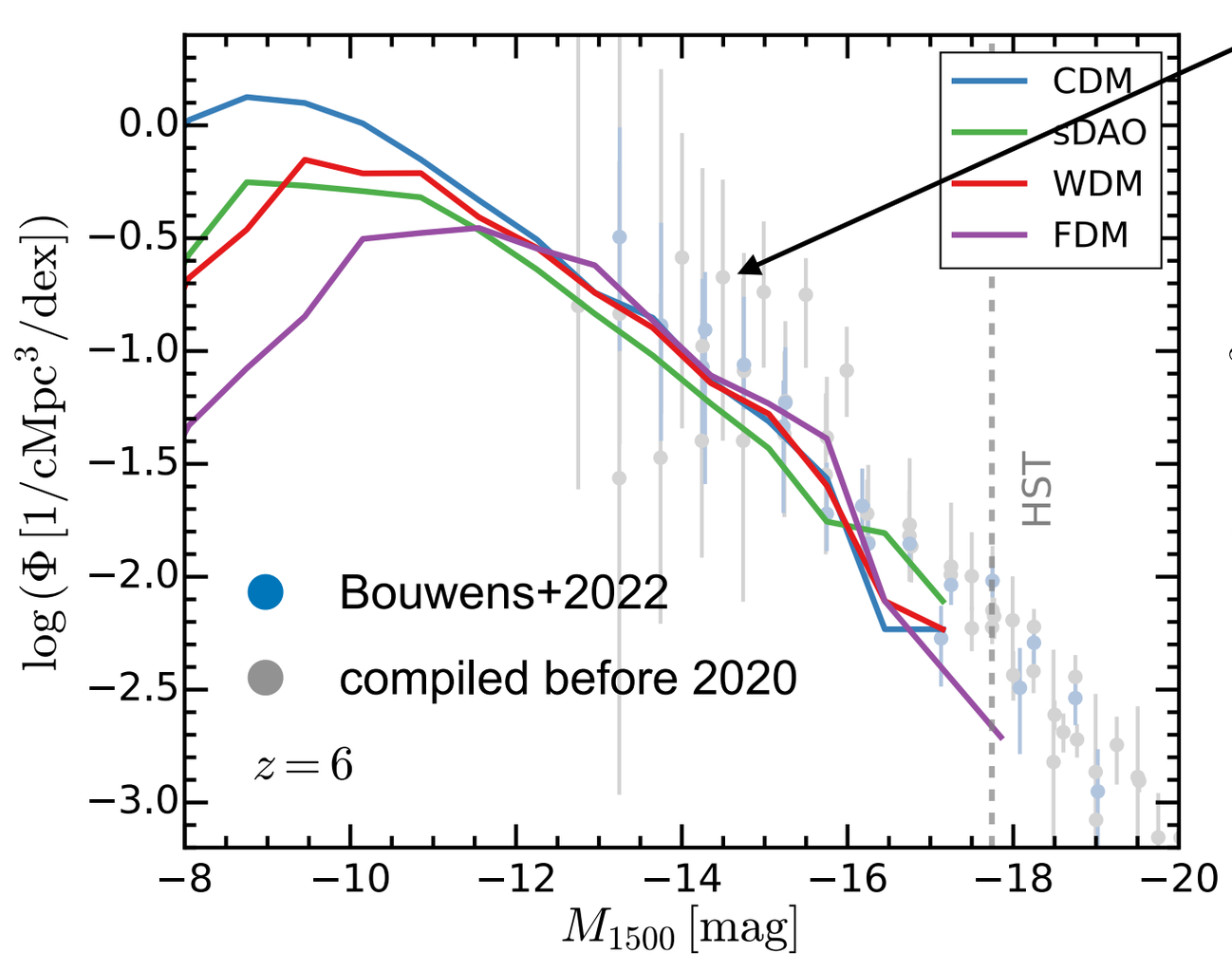
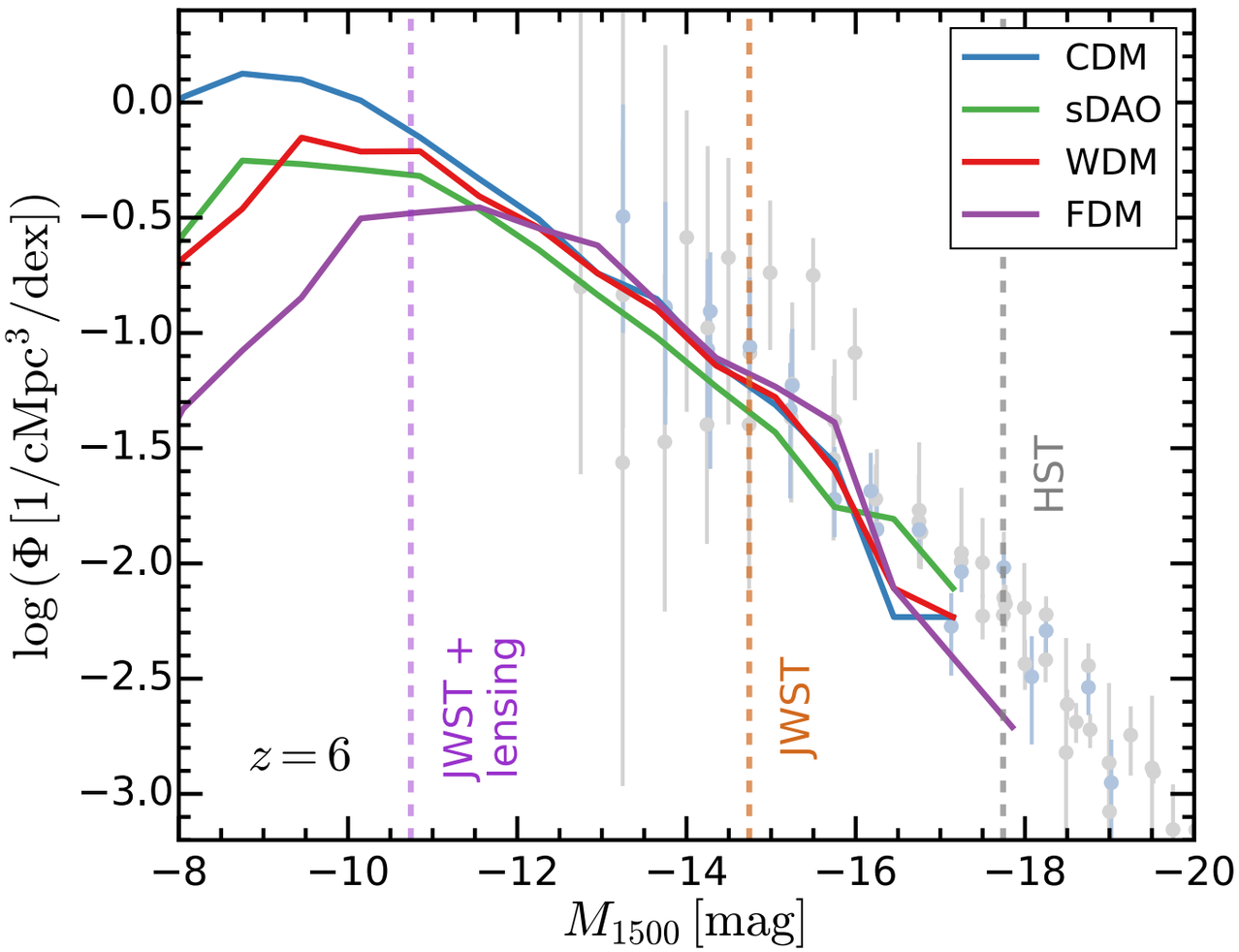
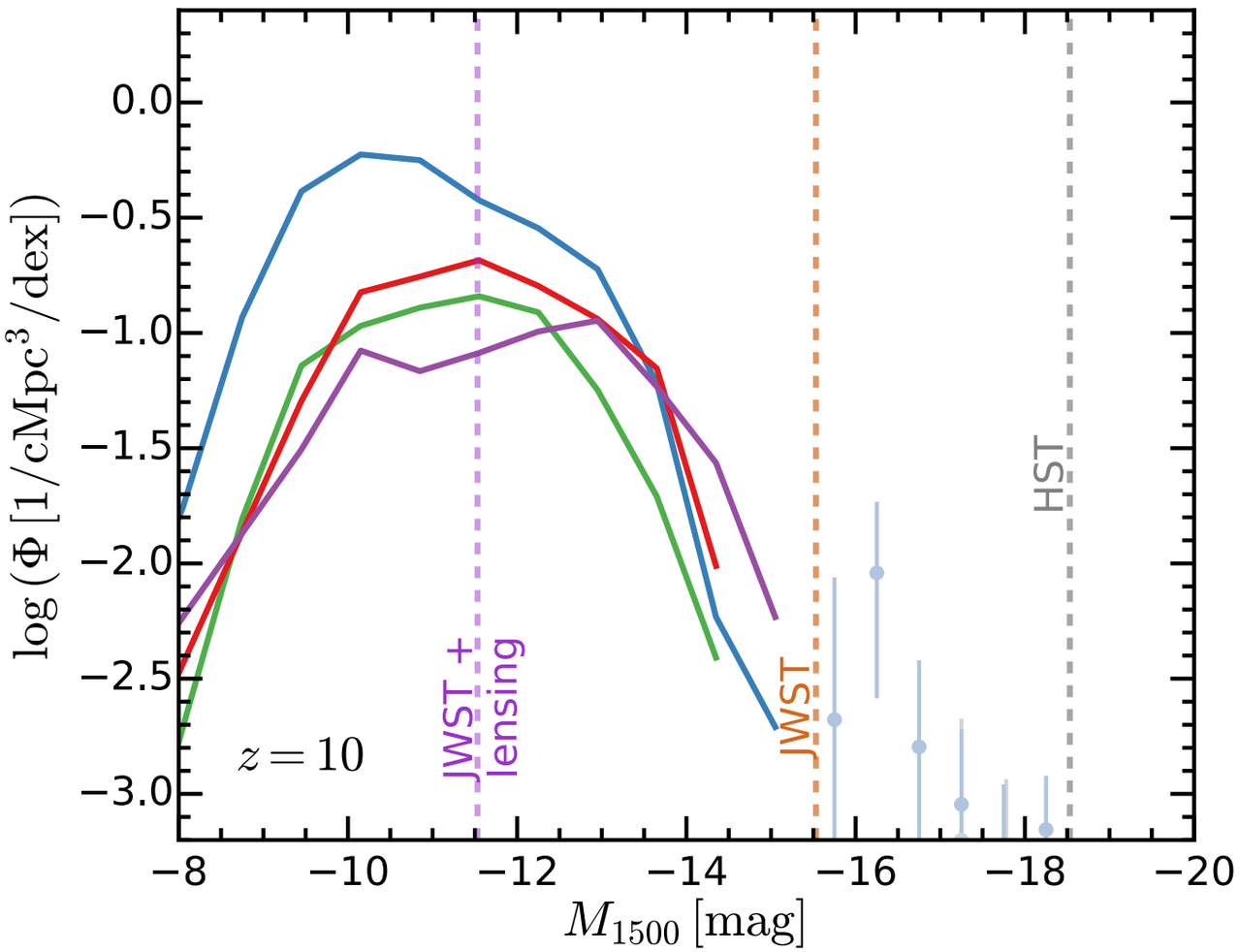


Galaxy abundance - UV luminosity functions

Can we see it?

The James Webb Space Telescope (JWST) limit





Galaxy abundance - UV luminosity functions

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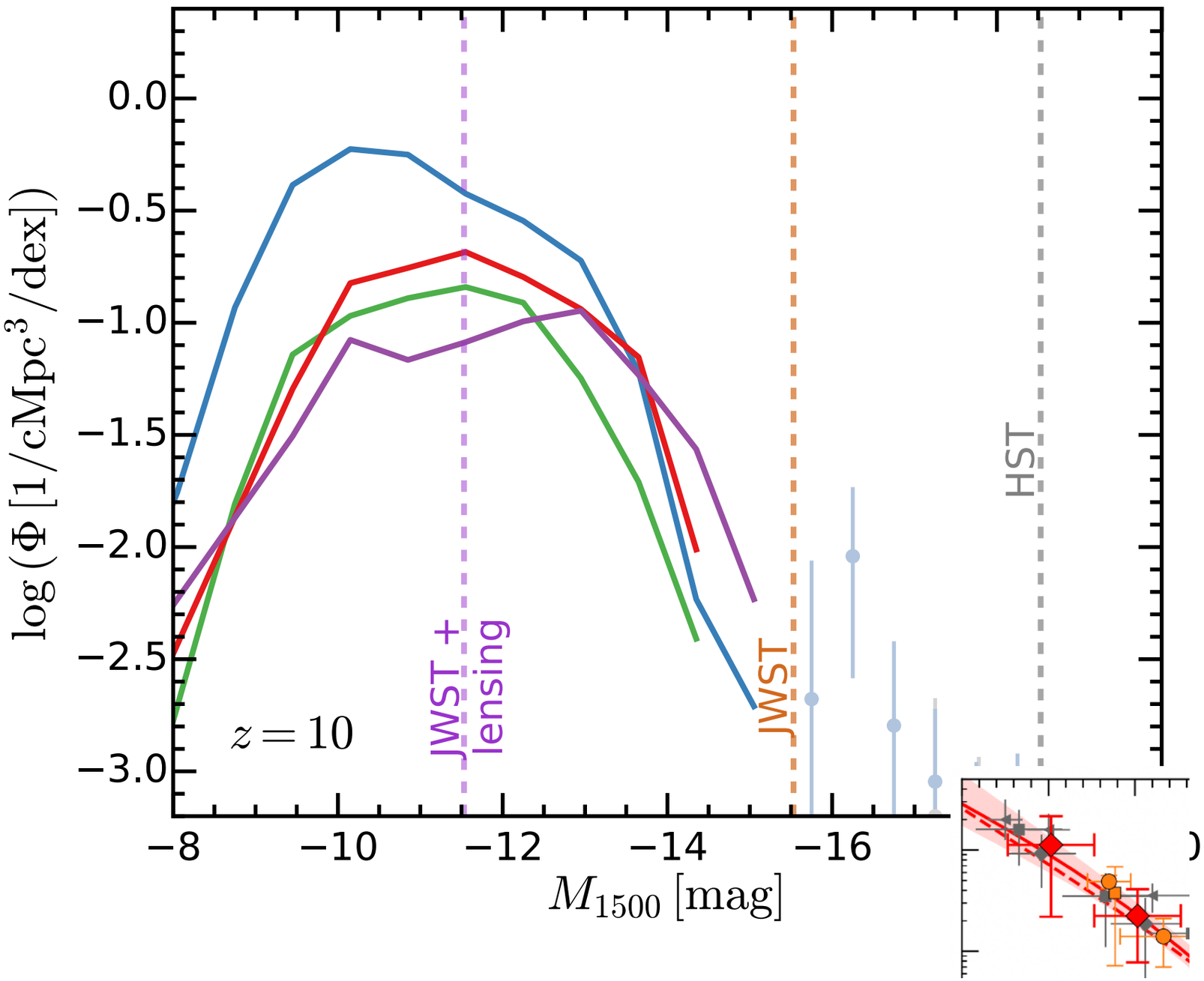


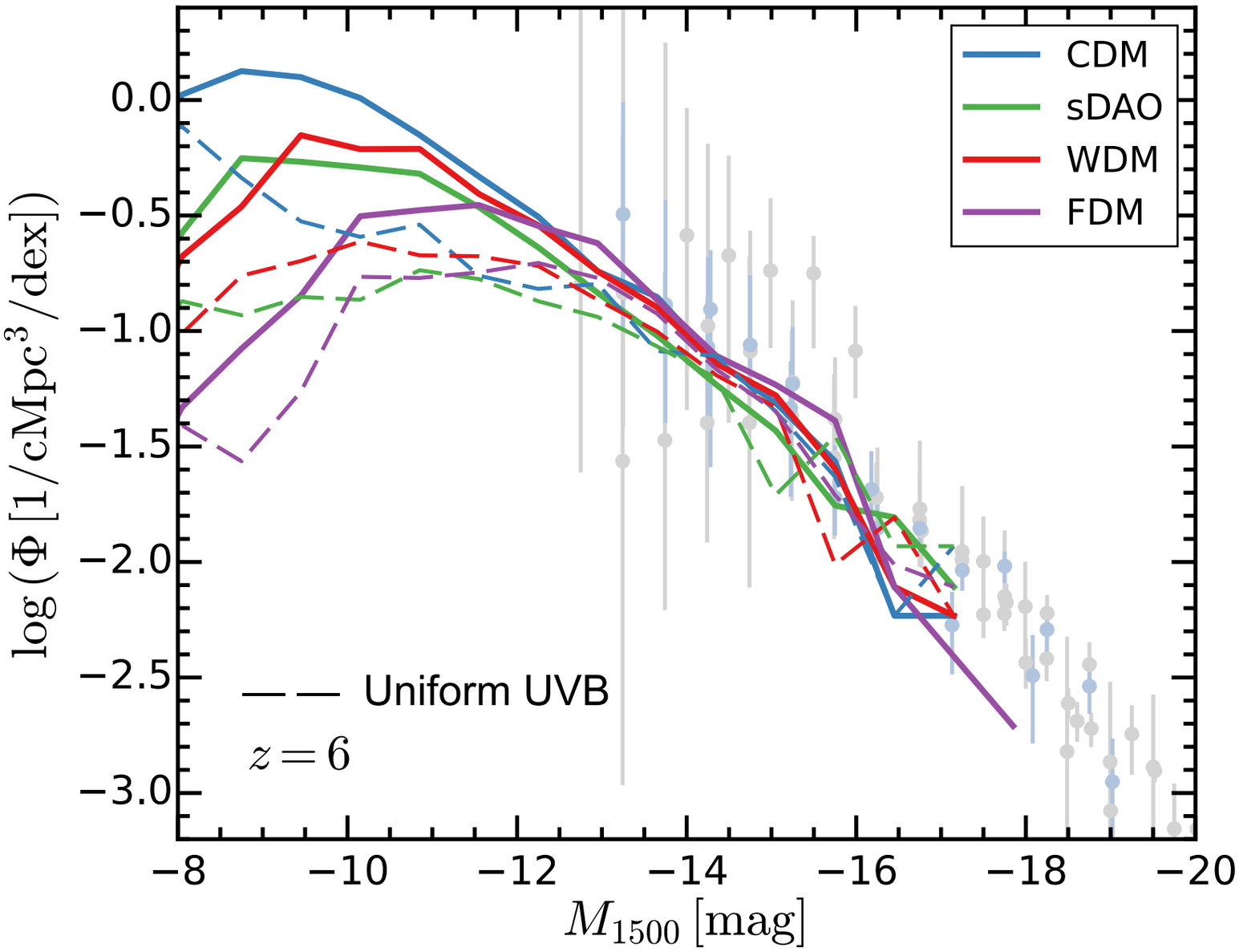
Early JWST data at $z \sim 9$

(Harikane+2022)

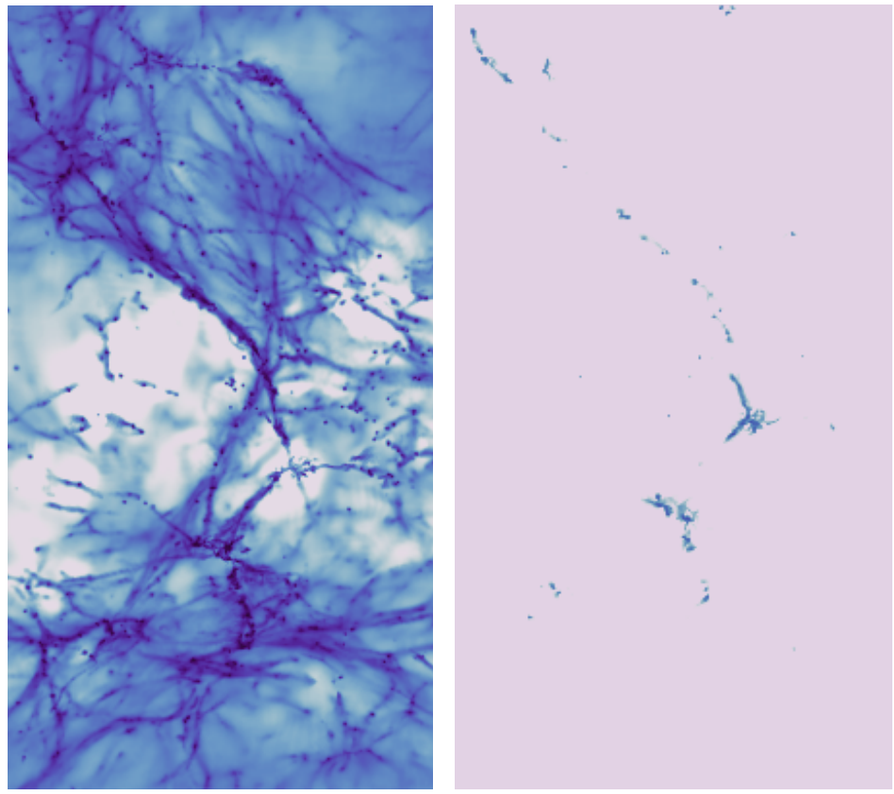
Galaxy abundance - UV luminosity functions

Uncertainties from reionization modeling

- Uniform UV background model will suppress the abundance of faint galaxies ($M_{\rm UV} \gtrsim -13$) after its activation ($z \lesssim 10$)

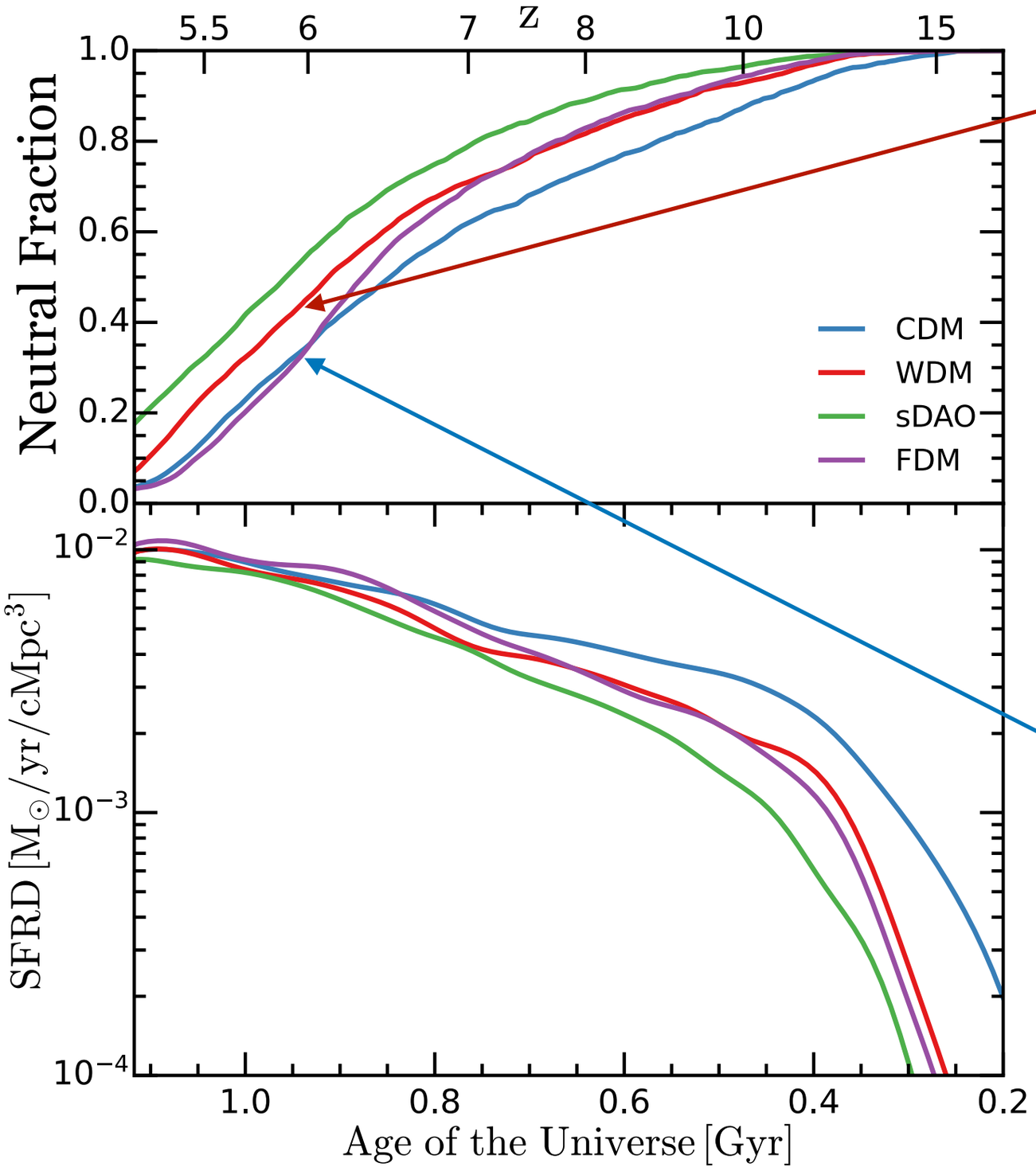


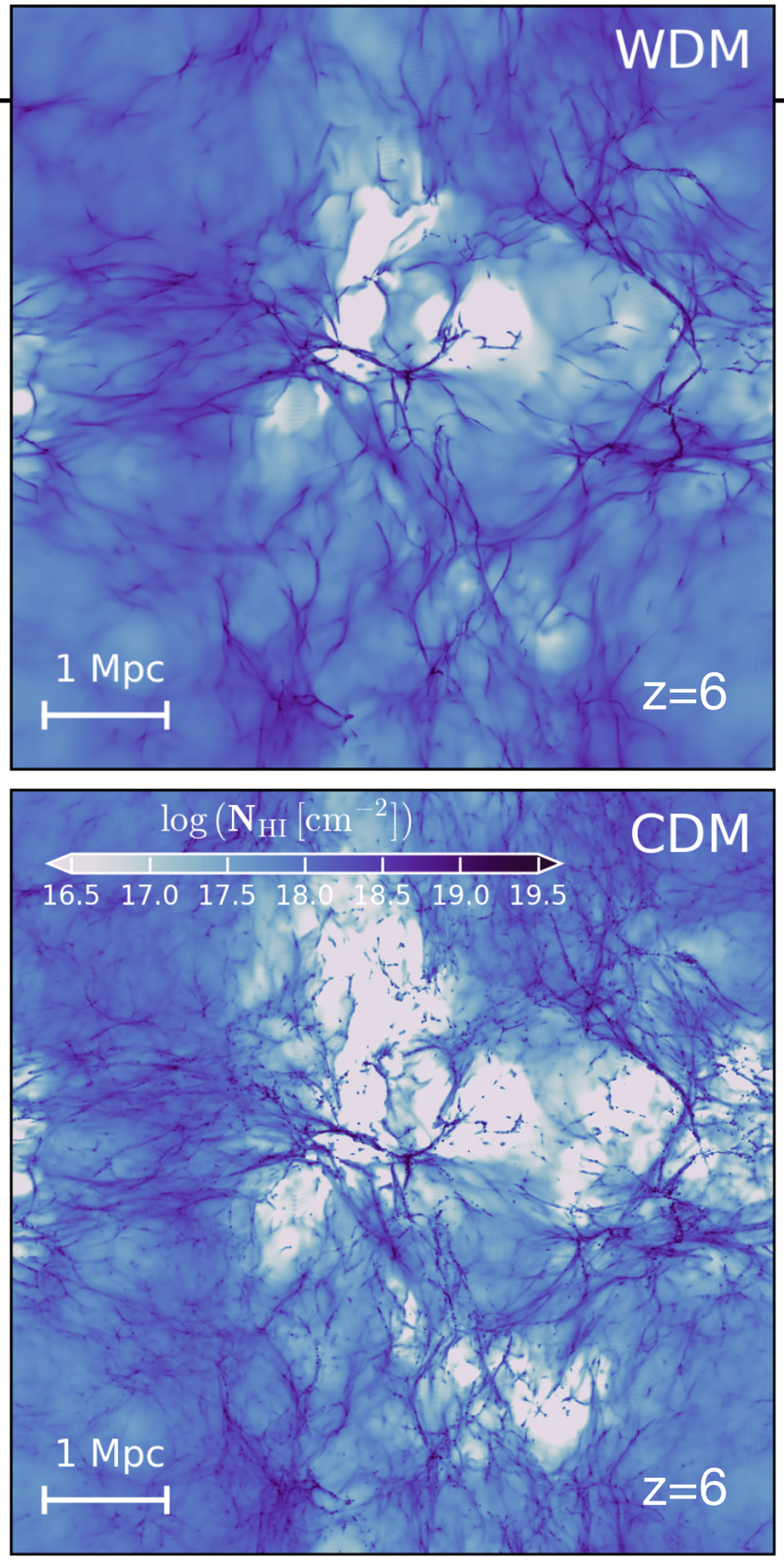
morphology of reionization



Reionization History

- Delayed star formation & reionization



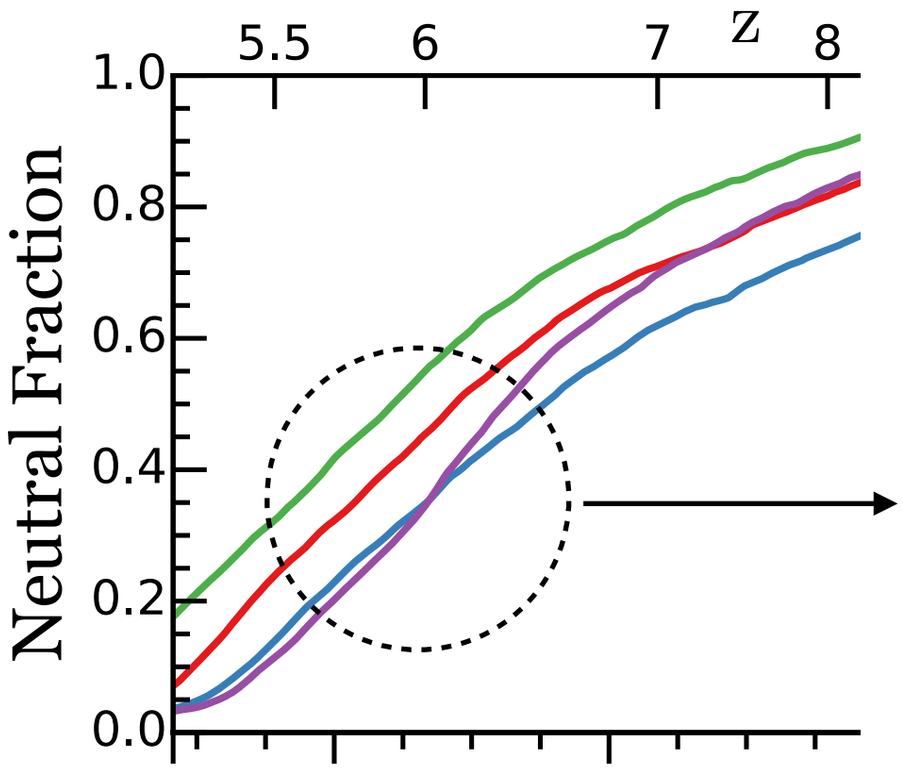


Reionization History

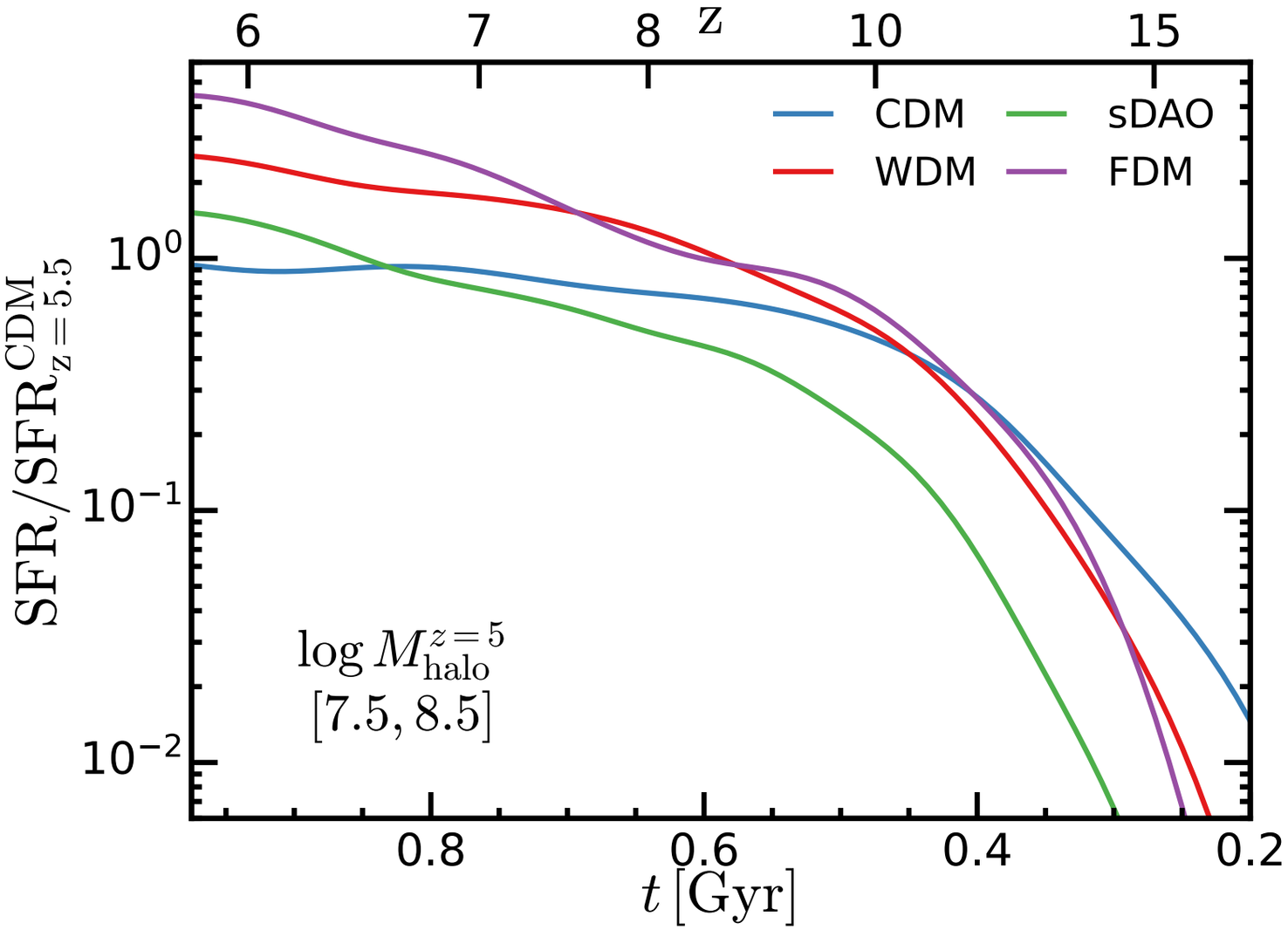
- A positive "feedback" on late-time star formation

  enhanced star formation efficiency and neutral gas abundance in low-mass halos

  $(M_{\rm halo} \lesssim M_{\rm half\,mode})$



"Averaged" star formation history



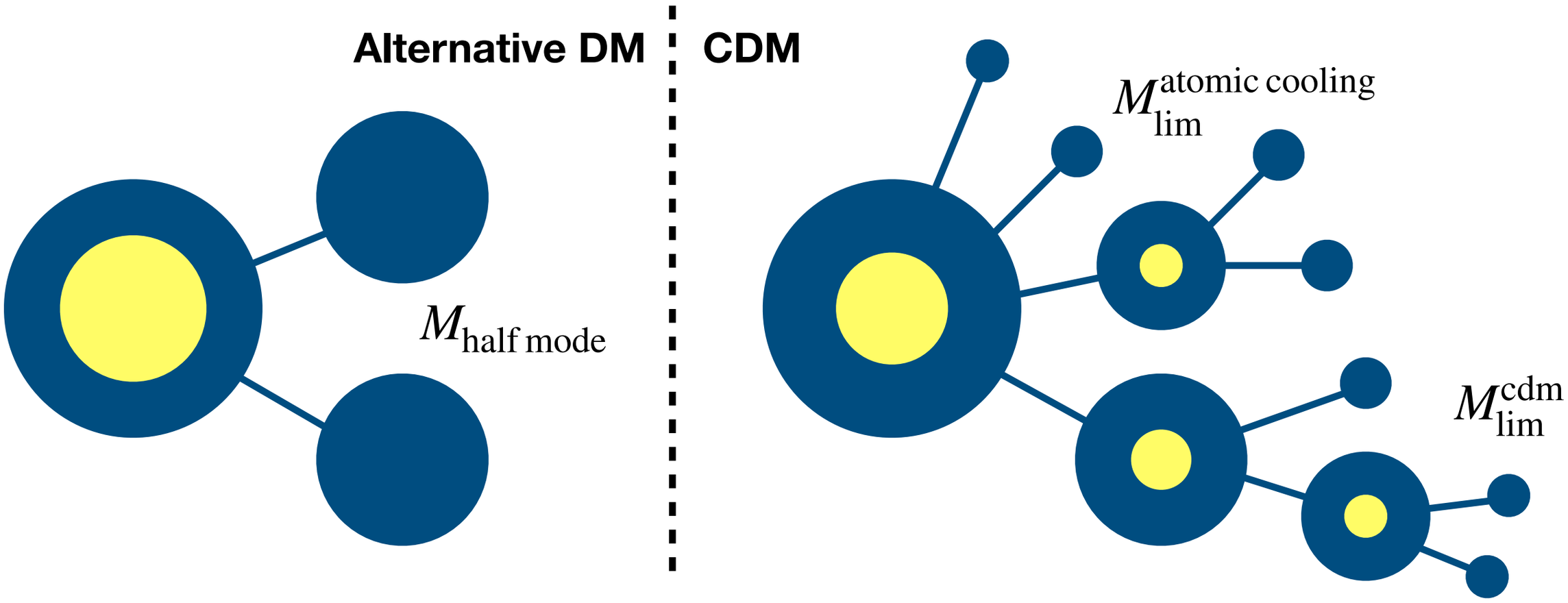
Reionization History

- A positive "feedback" on late-time star formation

  enhanced star formation efficiency and neutral gas abundance in low-mass halos
  $(M_{\rm halo} \lesssim M_{\rm half\,mode})$

  Rooted in the pattern of hierarchical assembly (e.g. Bose+2016; Lovell+2018)

  will not show up for other astrophysical processes that suppress faint galaxy abundance (e.g. stronger supernovae/radiative feedback, early reionization)

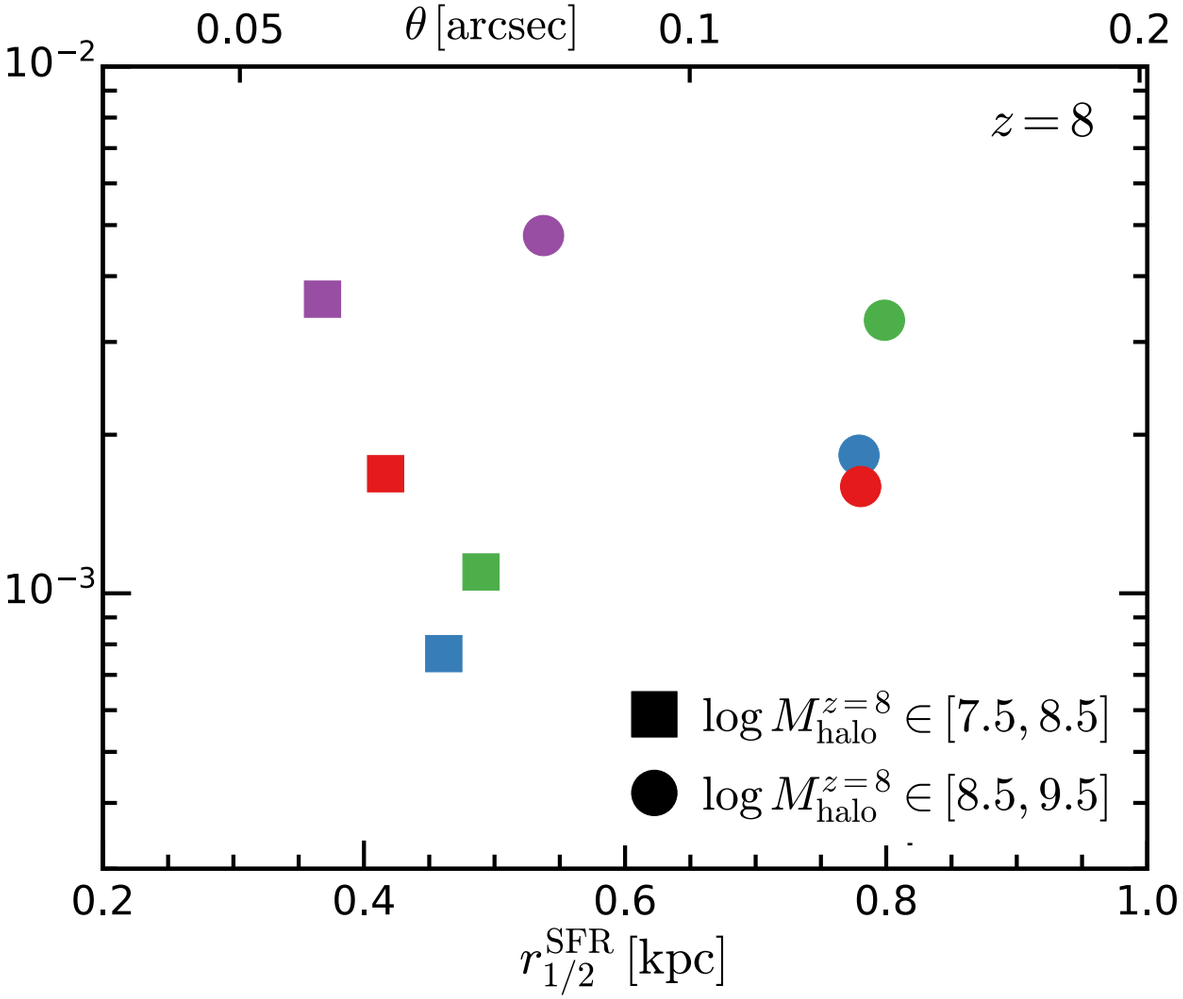


Stellar populations of galaxies in the EoR

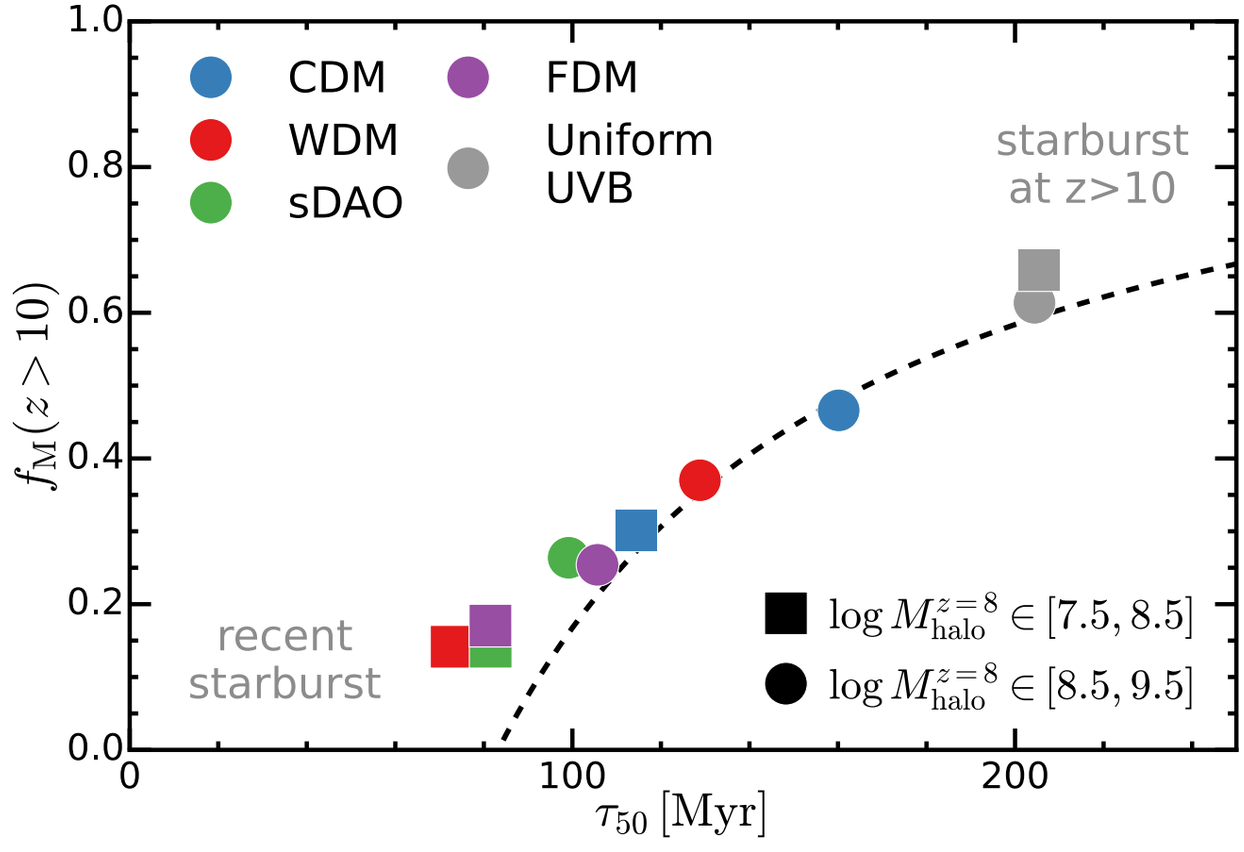
Observational signature associated to the late-time starburst

- younger and more compact stellar population
- steeply-rising star formation history

SFR surface density versus
Half-SFR radius (a proxy for half-light radius in UV)



Fraction of stellar mass formed before z=10 versus
Median stellar age



Take-aways

- THESAN-HR: radiation-hydrodynamical simulations of high-redshift galaxies in CDM, WDM, FDM and sDAO models
- Alternative DM models suppress structure formation at small scales
  - suppress the faint-end UV luminosity function
  - delay cosmic reionization
- Modeling the morphology of reionization matters!
- A "positive feedback", especially in WDM and FDM
  - late-time starbursts
  - younger and more compact stellar populations