Illuminating the Young Universe with FIRE: What drives the evolution of the cosmic star formation rate density?

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Cosmic Dawn at High Latitudes
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FIREbox

FIRE
Feedback In Realistic Environments

Universität Zürich[UZH]

Swiss National Science Foundation

The Cosmic SFR in the Era of JWST

The high-z challenge:

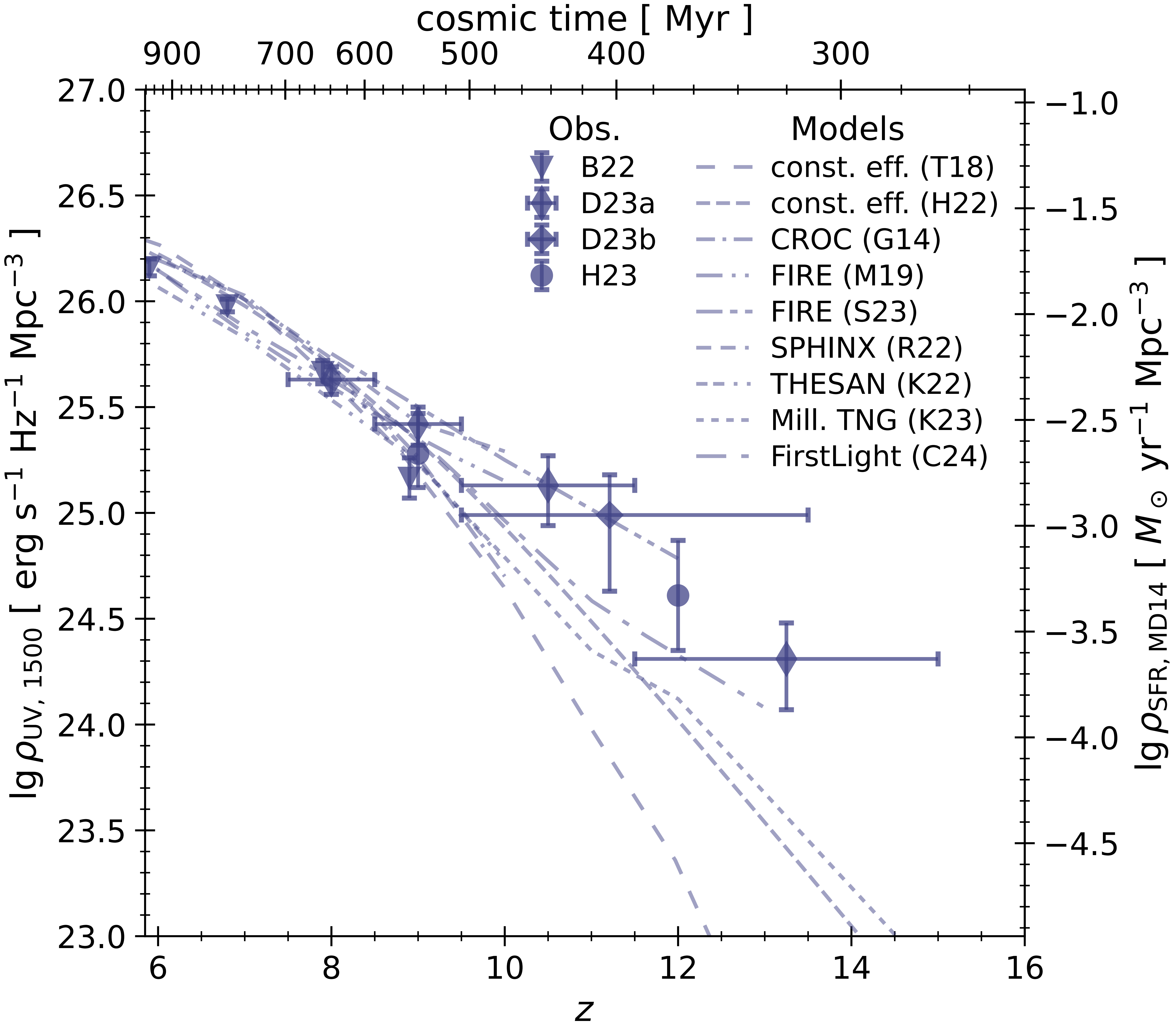
- Many models predict a fast decline of SFR and UV luminosity density at z>10
- Higher than expected SFR and UV luminosity density observed at z>10
  (e.g., Harikane+2023, Donnan+2023a,b, Finkelstein+2023, Bouwens+2023)

Various proposed explanations:

- SF more efficient at higher z
- bursty SF (higher scatter)
- AGN contribution to UV luminosity
- top-heavy IMF

Approach:

- Cosmological simulations (FIREbox^{HR})



What is FIREbox?

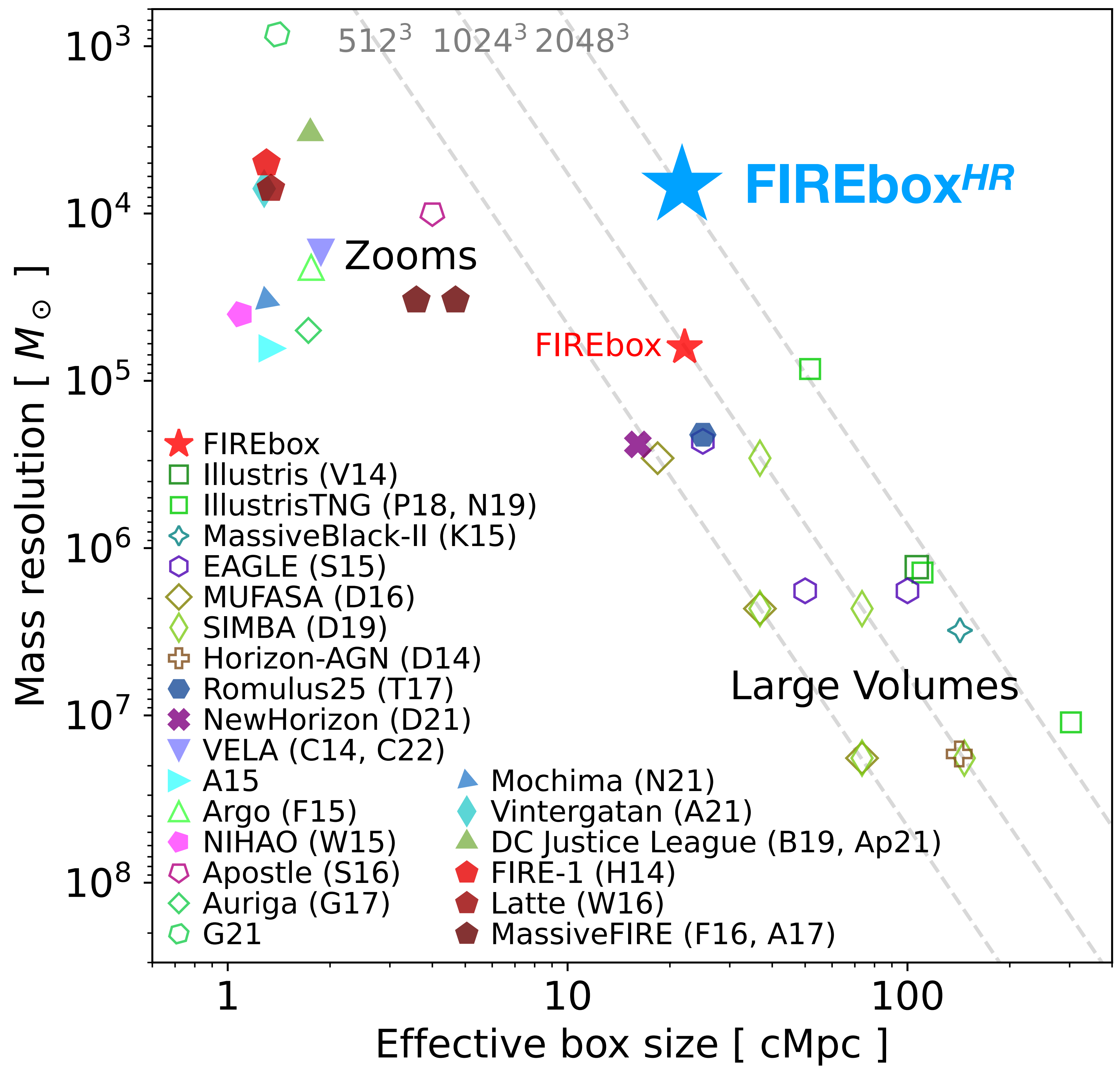
- Part of *Feedback in Realistic Environments* (FIRE) project (Hopkins+2014)
- Suite of cosmological **volume** simulations

FIREbox simulation

- First FIRE cosmological volume simulation (Feldmann+2023, arXiv:2205.15325)
- L=22 cMpc, Planck-15 cosmology
- run to z=0, ~1 billion gas particles, mass resolution $6 \times 10^4\, M_\odot$

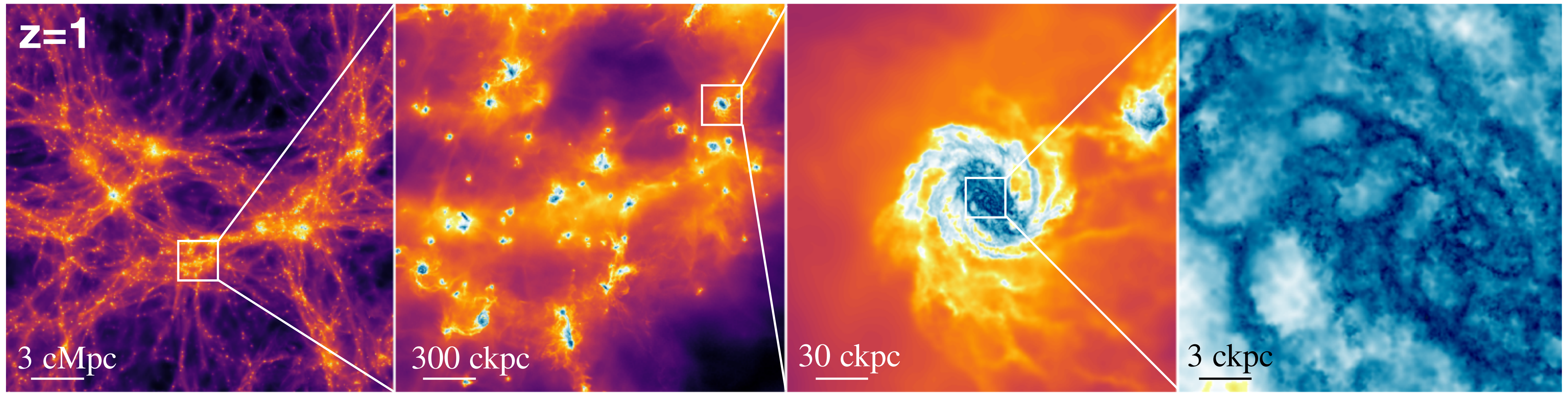
FIREbox^{HR} simulation

- same volume, 8 x more particles, mass resolution $7800\, M_\odot$
- stops at z~6



- Run with **standard** FIRE-2 physics (Hopkins+2018)
  - cooling to 10K
  - SF in dense (>1000 Hcc), self-gravitating gas
  - various channels for stellar feedback
  - cosmic UV background (Faucher-Giguère+2009)
  - no AGN feedback

Validated in numerous previous zoom-in simulations with FIRE-2 physics



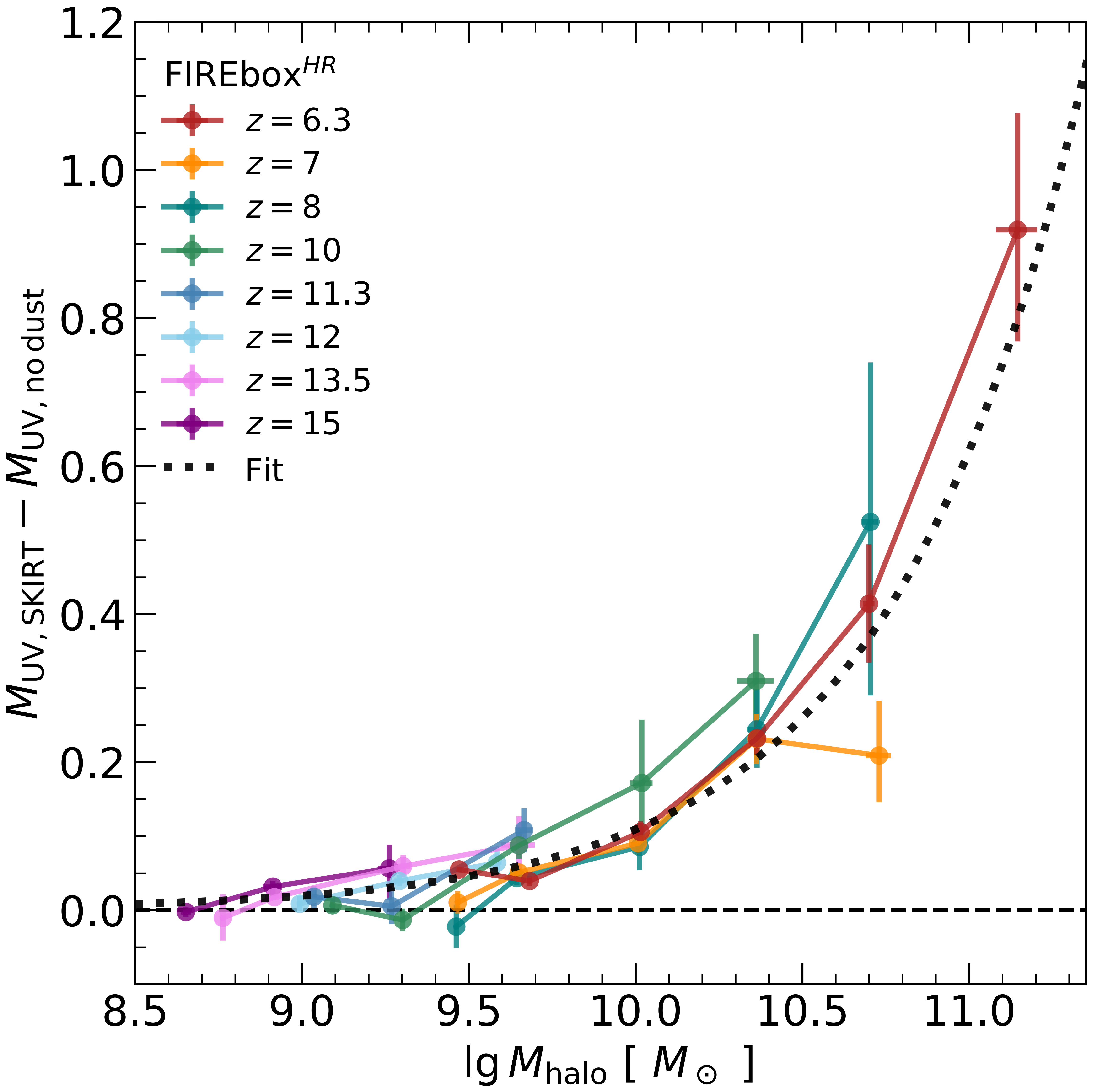
FIREbox (RF+2023)

Analysis

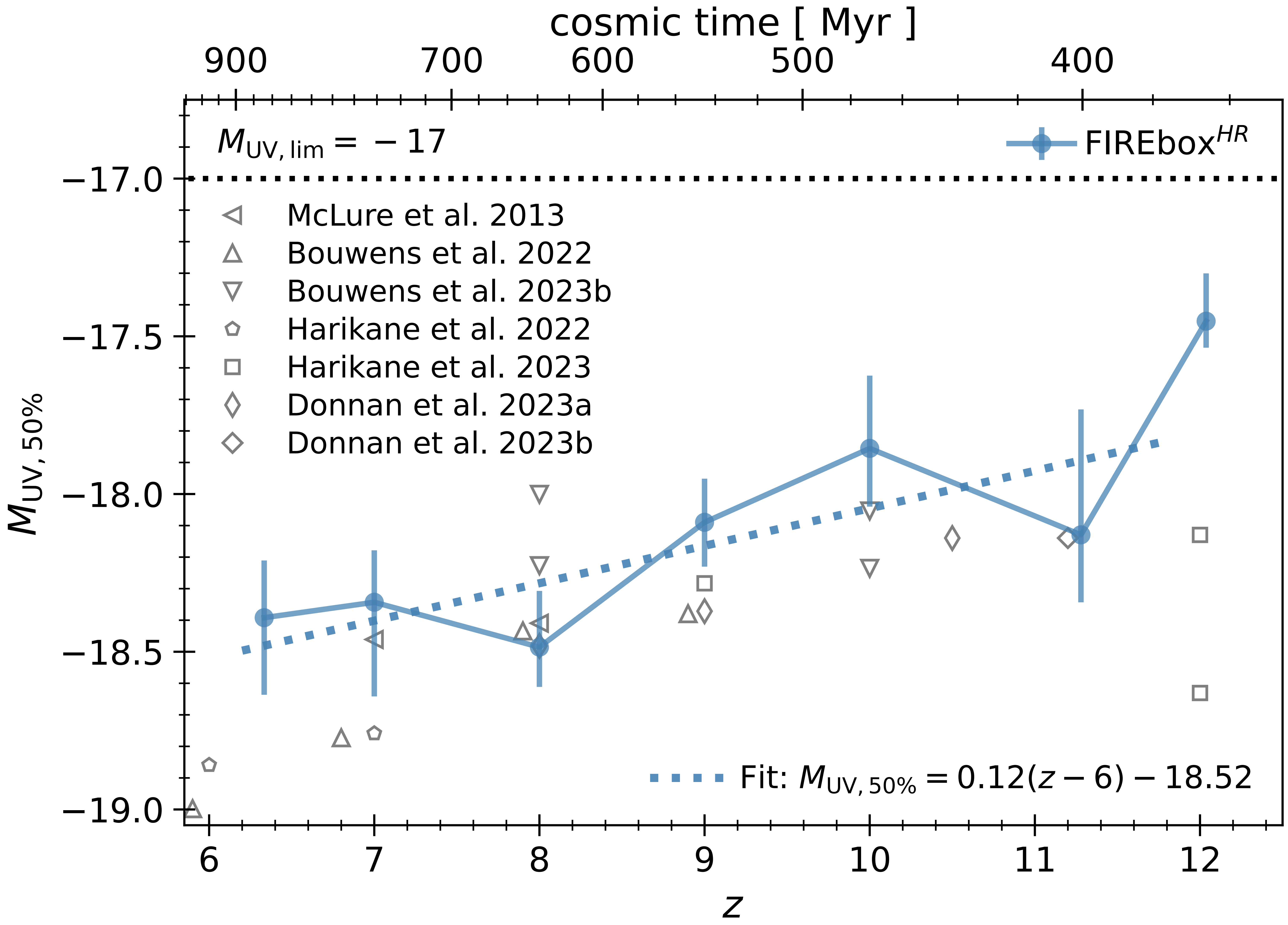
- Amiga Halo Finder for halo properties
  - include halos with $M_{halo} > 10^7 M_\odot$
  - 100k - 500k halos at z~6-12

- Galaxy properties within 3 proper kpc radii

- UV luminosity of galaxies
  - for galaxies in sufficiently massive halos ($\gtrsim 10^9 M_\odot$) with dust radiative transfer code **SKIRT v9** (Camps & Baes 2020)
  - for other galaxies ignore dust contributions

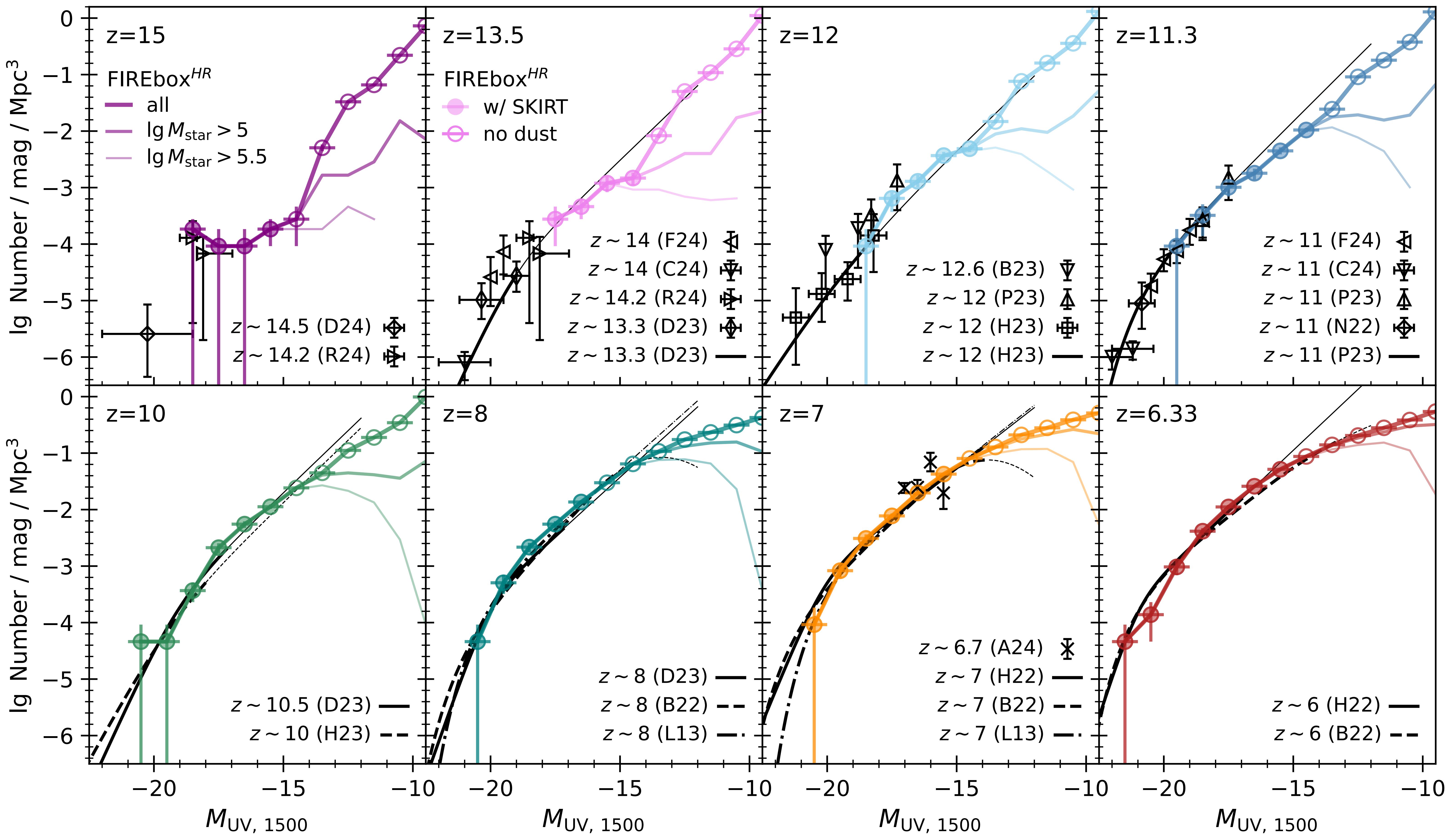


Which galaxies dominate the UV luminosity density at z ~ 6 - 12?



Answer: Moderately faint galaxies (-18.5 < M_{UV} < -17.5), <u>not</u> massive, bright galaxies (M_{UV} < -19)

UV LF in FIREbox^{HR}



before reionization

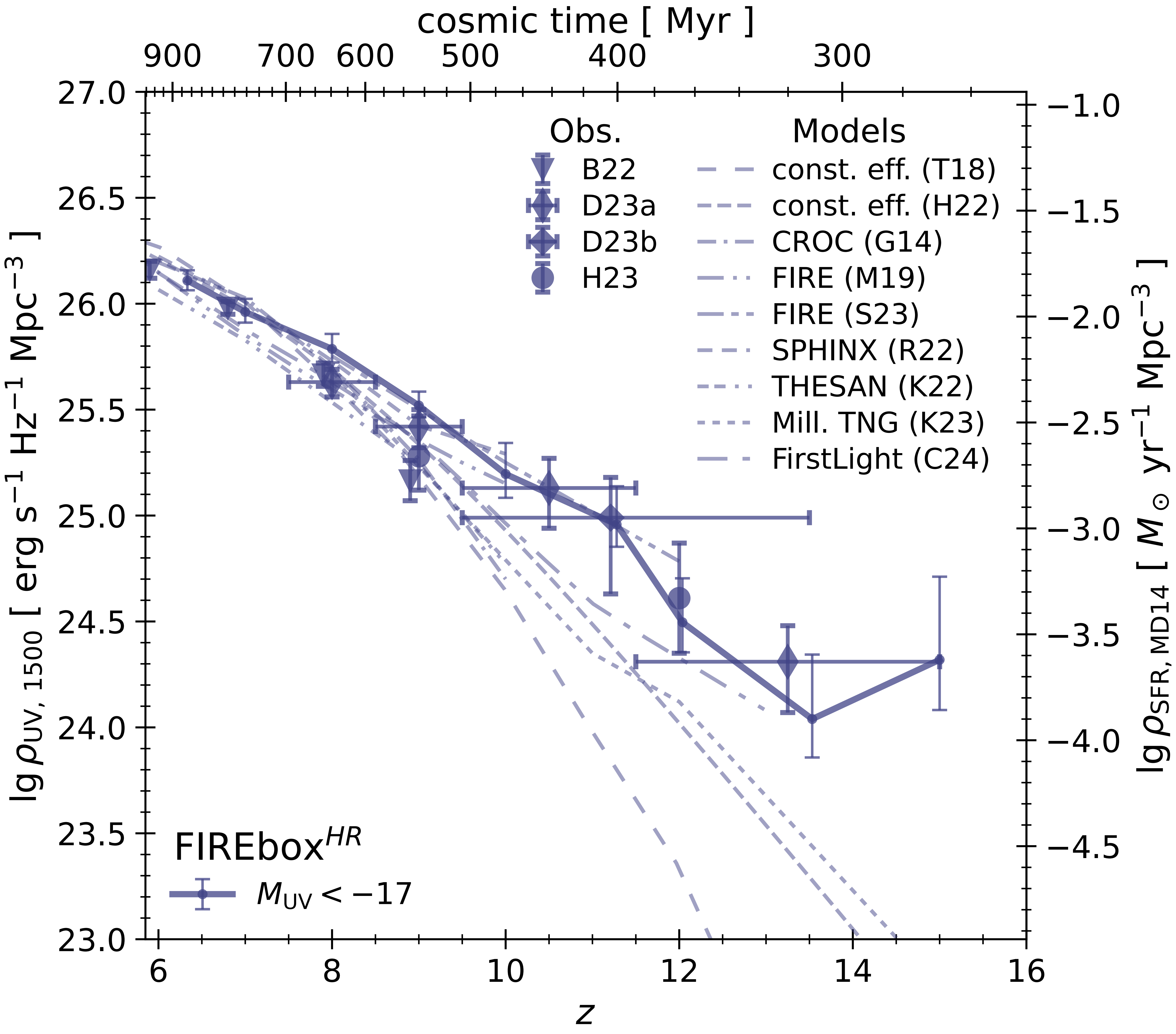
during reionization

- Good agreement with observed UV luminosity function at z~7 – 10
- Deviation from Schechter function at z ≤ 8 for faint magnitudes (M_{UV} > -15)
- Dust attenuation affects only bright end (M_{UV} < -19)
- at z > 10: steeper faint end, contribution from low luminosity (not well resolved) halos

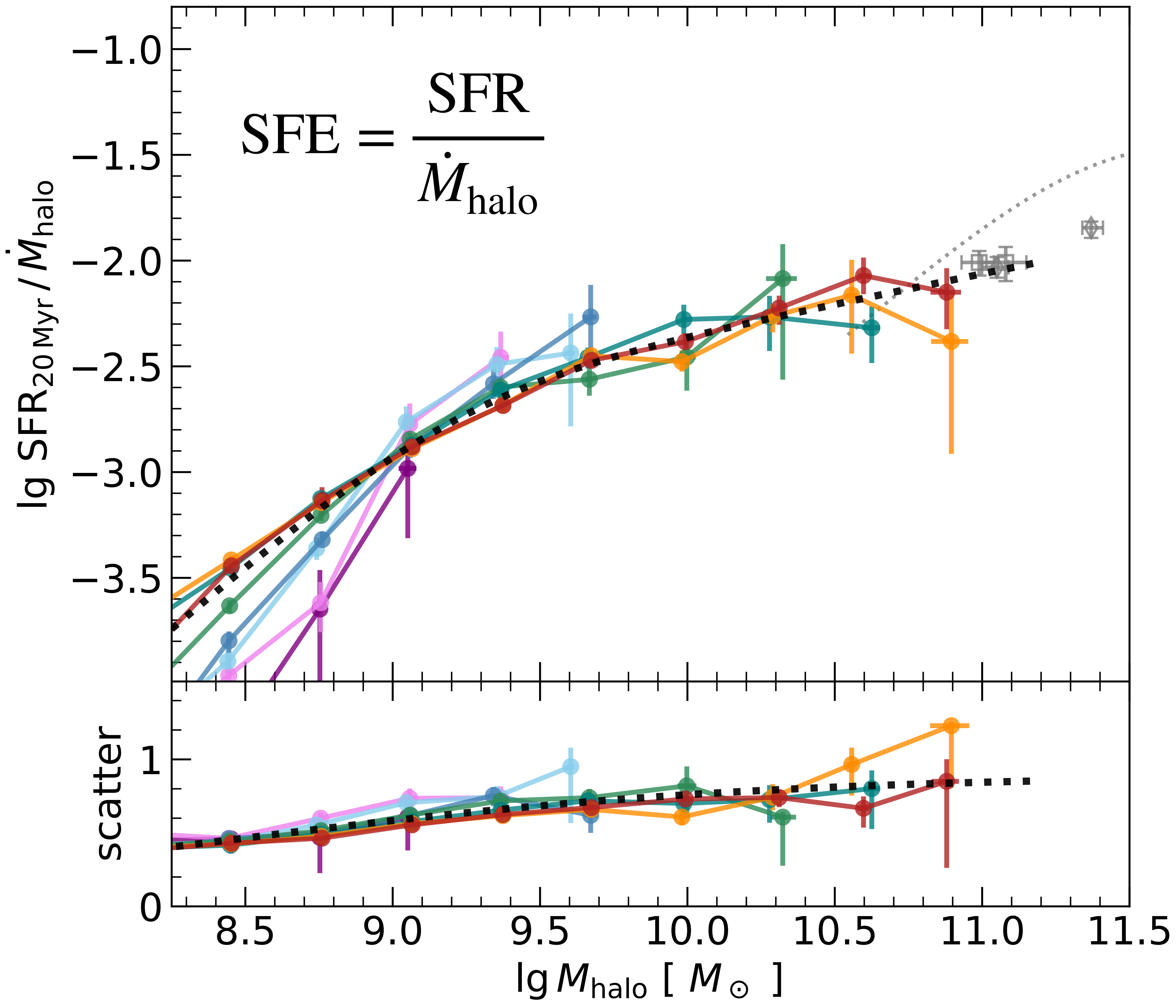
UV luminosity density in FIREbox^{HR}

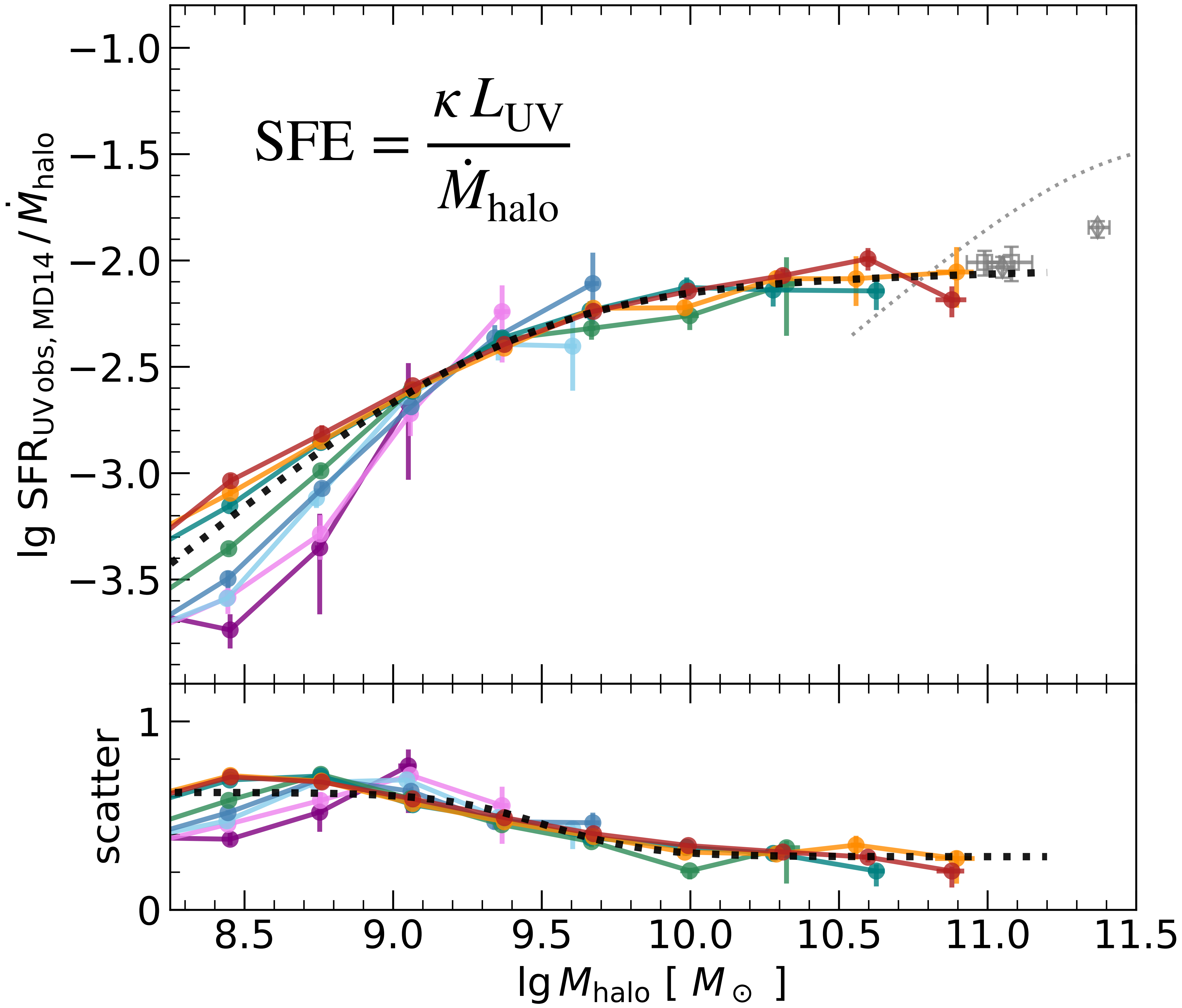
- Observations: Fitted UV Luminosity functions integrated down to M_{UV} = -17
- Simulation: Sum UV luminosity in galaxies with M_{UV} = -17

➜ FIREbox^{HR} reproduces observed UV luminosity density, including the `excess' at z ≥ 10



Star formation efficiency in FIREbox^{HR}





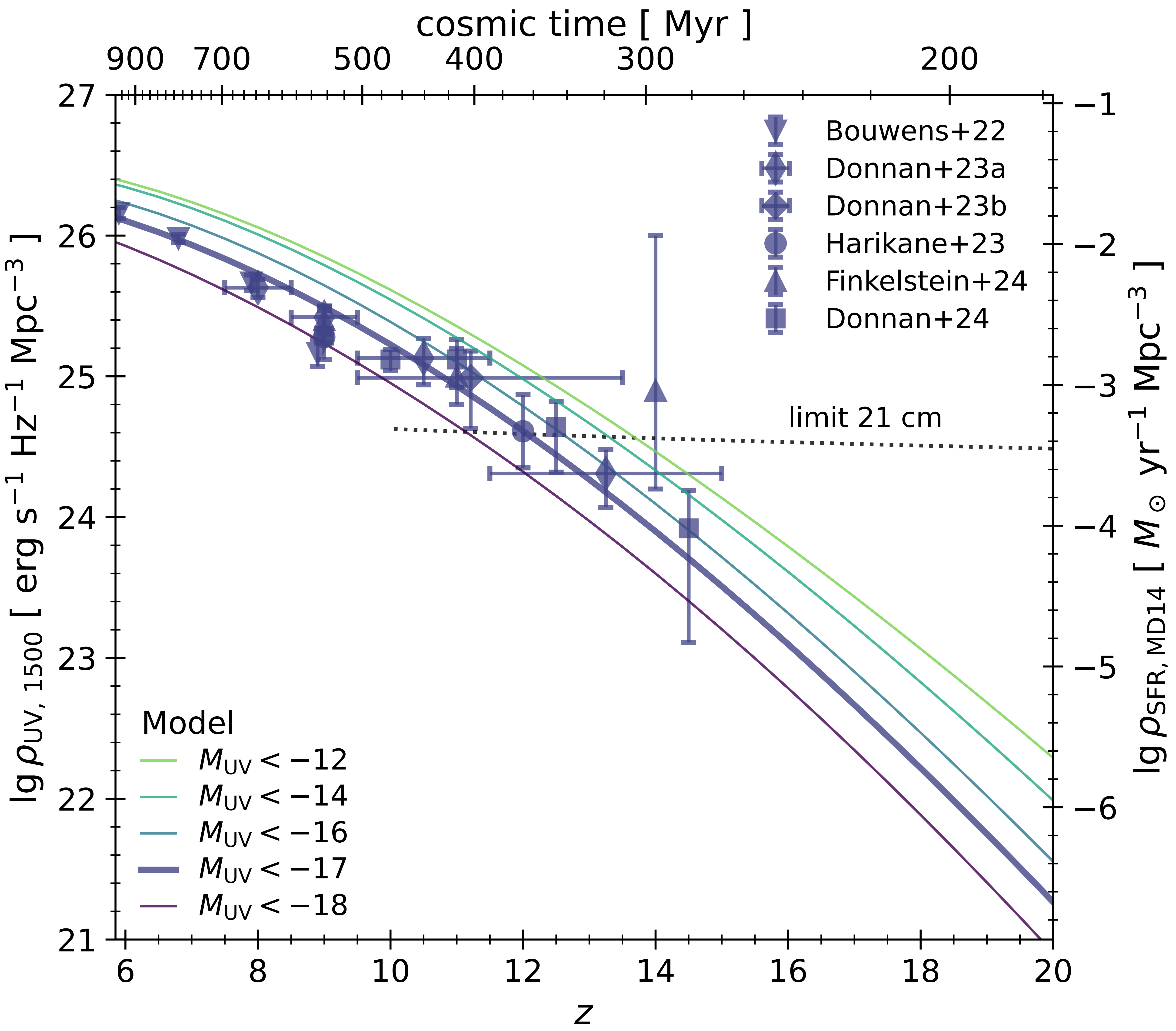
- SFE **redshift-independent** & only weakly halo mass-dependent (for $M_{\mathrm{halo}} \sim 10^9 - 10^{11}\, M_\odot$)
- comparably high SFE for intermediate mass halos that dominate UV luminosity density

Theoretical model

- Assume SFE is lognormal with redshift-independent SFE — halo mass relation from FIREbox*HR* (provides mean and scatter)

$$\rho_{\rm UV}(z) = \frac{1}{\kappa}\int_{-\infty}^{\infty} d\lg M \frac{dn}{d\lg M}\dot{M}\langle \mathcal{S}\rangle_{\rm eff}\,.$$

- Halo number density for any mass and redshift from HMF (Murray+2014), halo accretion rate from Behroozi & Silk 2015



Implications

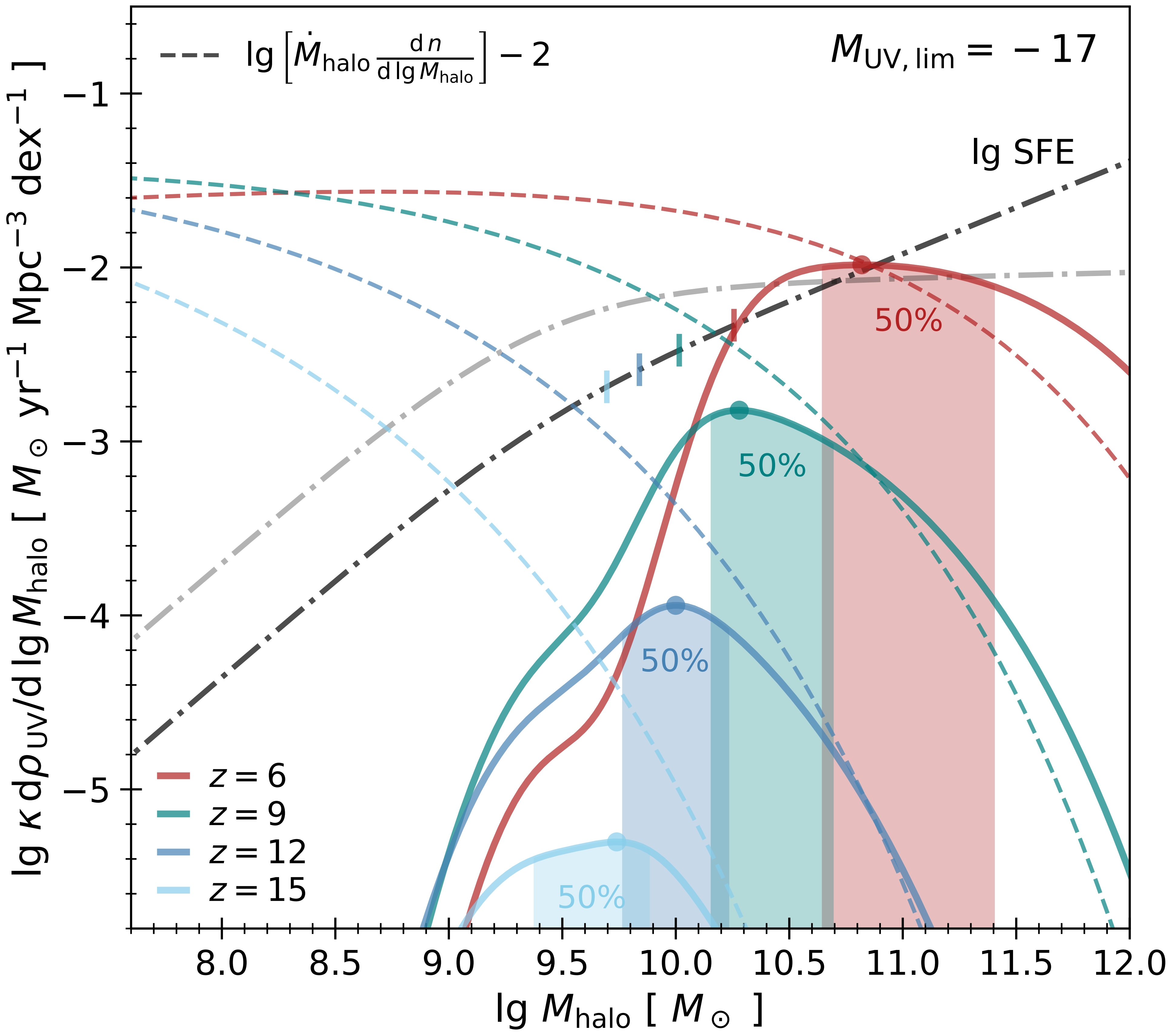
- UV luminosity density does not decline as a power law with redshift, but steeper decline at higher z
- no EDGE like signal from sources with $M_{\rm UV}$<-12
- but ignore Pop III, low mass halos

What drives the high UV luminosity density at z>10?

- Can address this question with the theoretical model

$$\kappa \frac{d\rho_{\mathrm{UV}}}{d\lg M} = \left[\dot{M}\frac{dn}{d\lg M}\right]\langle \mathrm{SFE}\rangle_{\mathrm{eff}}$$

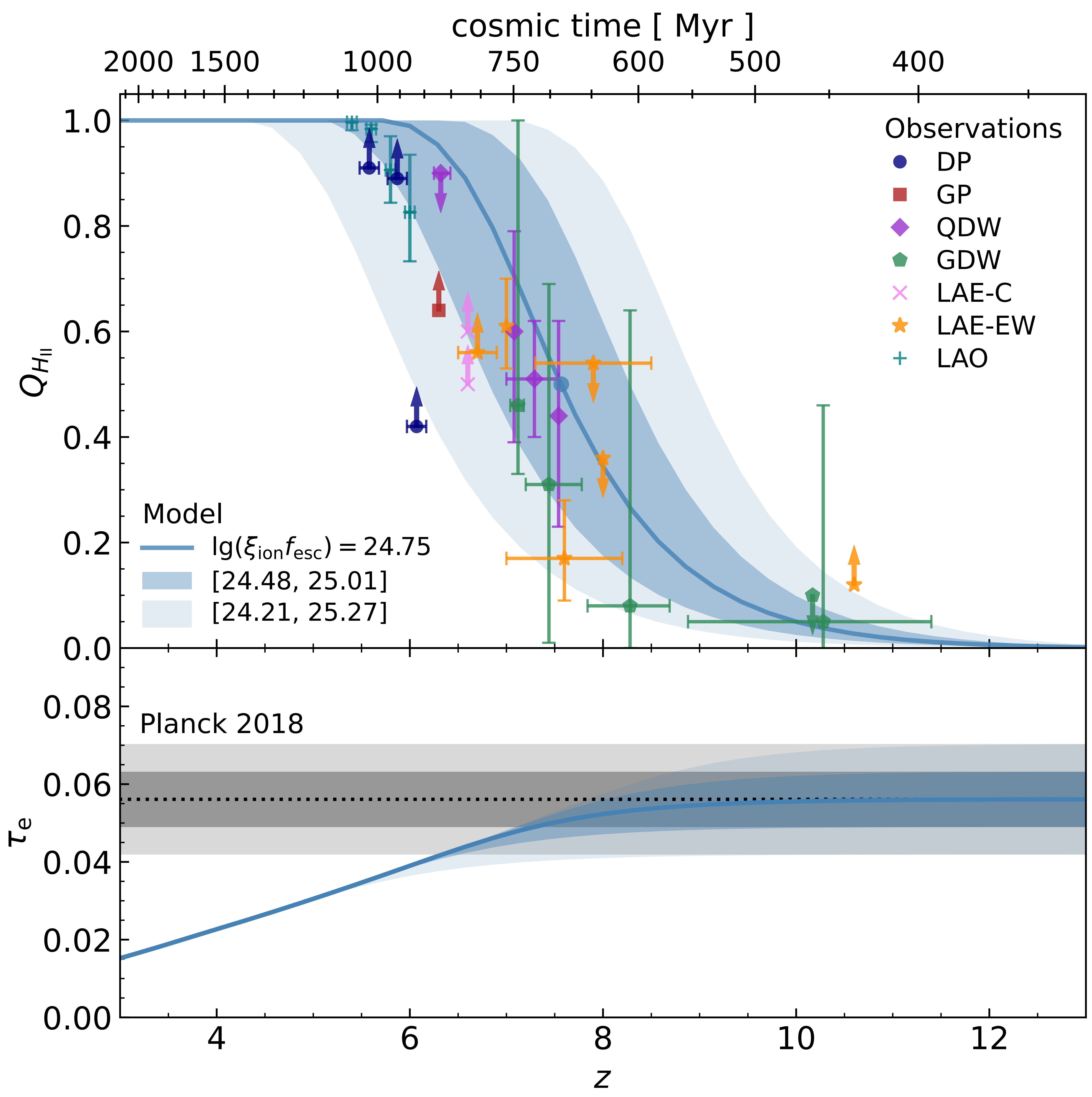
- UV luminosity density dominated by intermediate mass halos ($M_{\mathrm{halo}} \sim 10^9 - 10^{11}\, M_{\odot}$)
- the responsible halo mass range decreases with increasing redshift (b/c SHAR increases and HMF decreases)
- for shallower slope, stronger shift towards lower masses at higher z ➜ higher number density at lower masses partly compensates for decrease of number density at higher z



➜ Increased contribution from more numerous galaxies in lower mass halos at higher z if slope is less steep

Implication for galaxies during re-ionization

- Theoretical model in line with observed reionization history if $\lg(f_{esc}\xi_{ion}[\mathrm{Hz\,erg^{-1}}]) \sim 24.5 - 24.7$
- Re-ionization mid-point $z \sim 6.8 - 7.6$, duration $\Delta z \sim 1.4$ (25-75%), $\Delta z \sim 2.8$ (10-90%).
- Inferred escape fractions are 5-8% (12-20%, 30-50%) if $\lg(\xi_{ion}[\mathrm{Hz\,erg^{-1}}]) \sim 25.8\,(25.4, 25.0)$
- For escape fraction of 20% (Ma+2020), we get $\lg(\xi_{ion}[\mathrm{Hz\,erg^{-1}}]) \sim 25.2 - 25.4$



Summary

- Introduced FIREbox^{HR}: cosmological volume simulation with FIRE-2 physics to z~6 at 7800 $M_\odot$ baryonic resolution
- Simulation results in good agreement with observed UV luminosity density and UV LFs, no tuning to high-z regime

- FIREbox^{HR} predicts (approx.) non-evolving star formation efficiency — halo mass relation
- *No increase in SFE with increasing redshift!*

- Theoretical model based on non-evolving star formation efficiency — halo mass relation from FIREbox^{HR}
- Model suggests origin of high UV luminosity density is additional contributions from galaxies residing in lower mass halos towards higher z

- Ionizing photon production efficiency is $\lg(\xi_{\rm ion}[{\rm Hz\,erg^{-1}}]) \sim 25.2 - 25.4$ if escape fraction is ~20%

See arXiv:2407.02674 for more details! Thank you!