Reionizing the Universe

Ionizing luminosities and photon budget in Cosmic Dawn III

Joe Lewis — Lyman escape 2023
Joe.Lewis@uni-heidelberg.de

STRUCTURES
CLUSTER OF
EXCELLENCE

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Max-Planck-Institut für Astronomie Heidelberg
Max Planck Institute for Astronomy Heidelberg

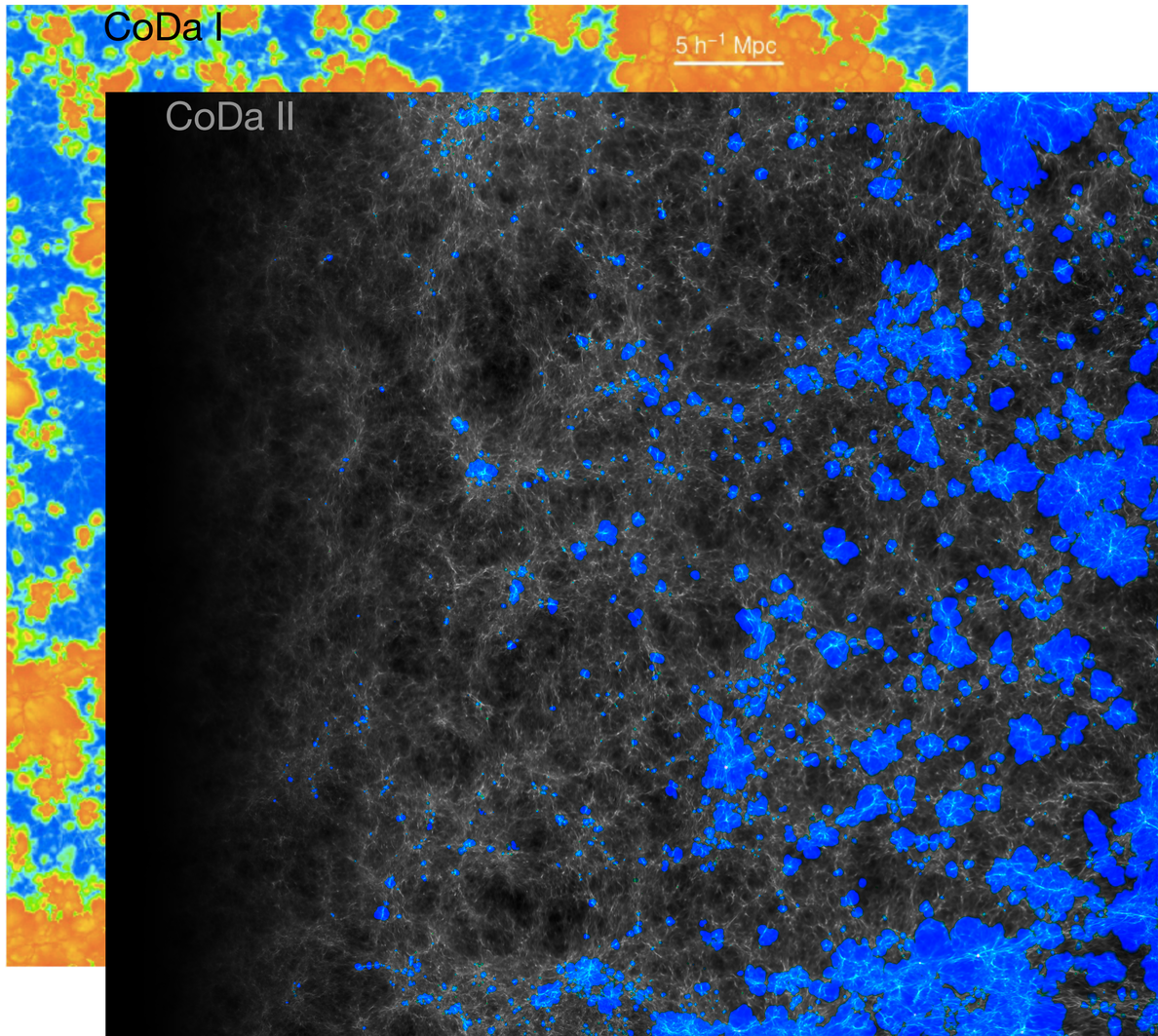
Cosmic Dawn simulations

Simulating cosmic Reionization

- Large (100s Mpc per side) volumes
  - Cosmic variance of sources and voids
- Resolve star forming galaxies (>10^8 $M_\odot$)
- Solve RT of ionizing photons

➡Cosmic Dawn simulations

(Ocvirk+16,20)



RAMSES-CUDATON

A coupled CPU/GPU code

RAMSES-CUDATON

RAMSES

CPUs

- Nbody DM
- Hydro
- SF & FB
- Metals & dust (new!)

CUDATON

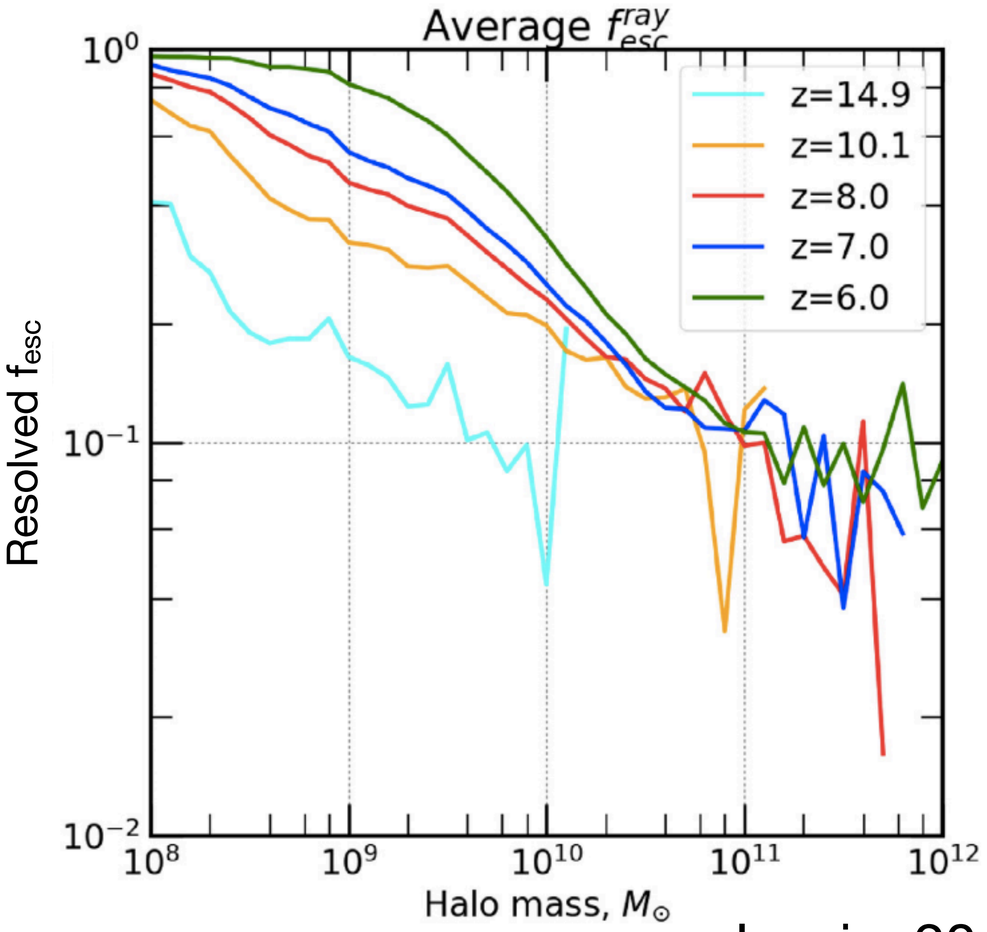
GPUs

- M1 method RT
- H chem, heating & ionisation

Good performance thanks to GPU acceleration… at the cost of AMR (‘just’ need 1000s of GPUs to get right size+resolution!)

Escape fractions in CoDa II

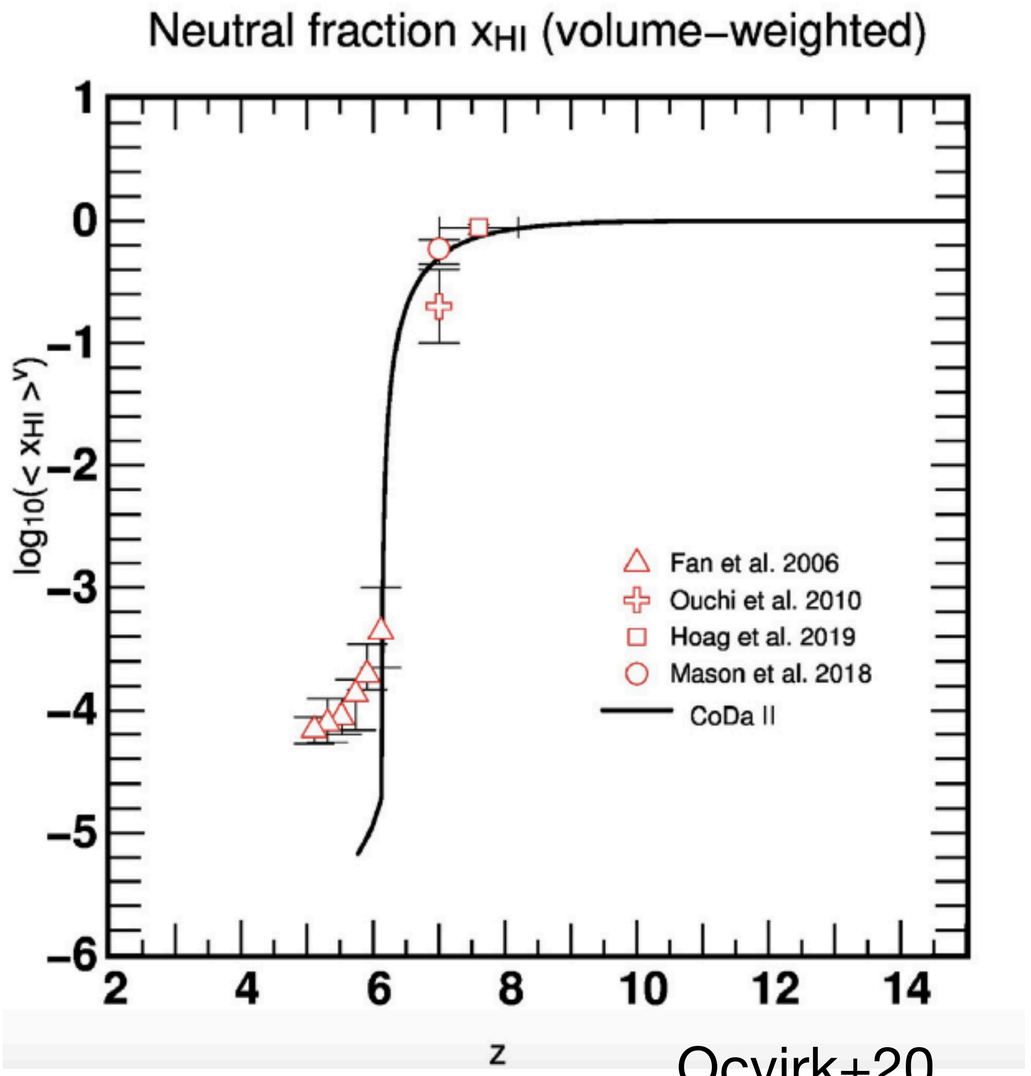
- Fesc decreases with mass
- Increases over time, esp. in low mass haloes
- 5 % escape in high mass haloes (incl. sub grid escape)



Lewis+20

LIMITATIONS OF CODA II

- Most used constraints on IGM ionisation come from spectra of QSO absorption due to the Lyα (e.g. Fan+06)
- CoDa II EoR ends early, fast, and too ionised

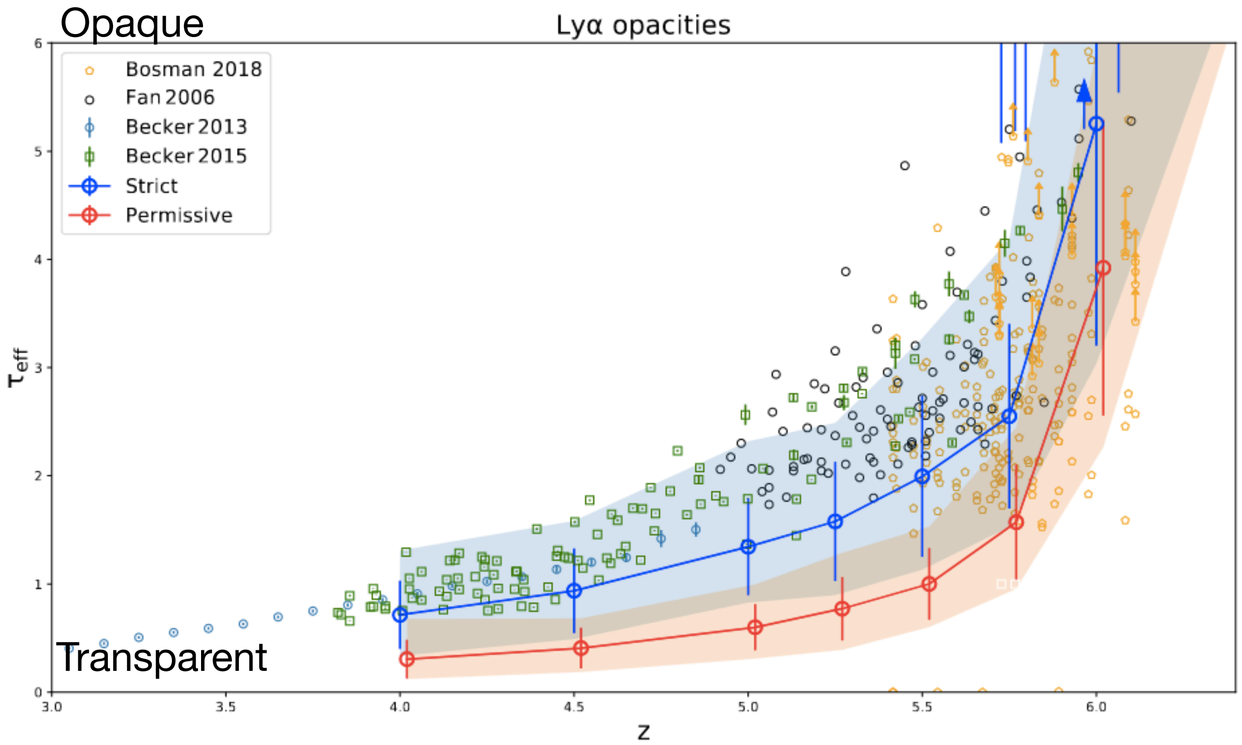


Ocvirk+20

Towards CoDa III…

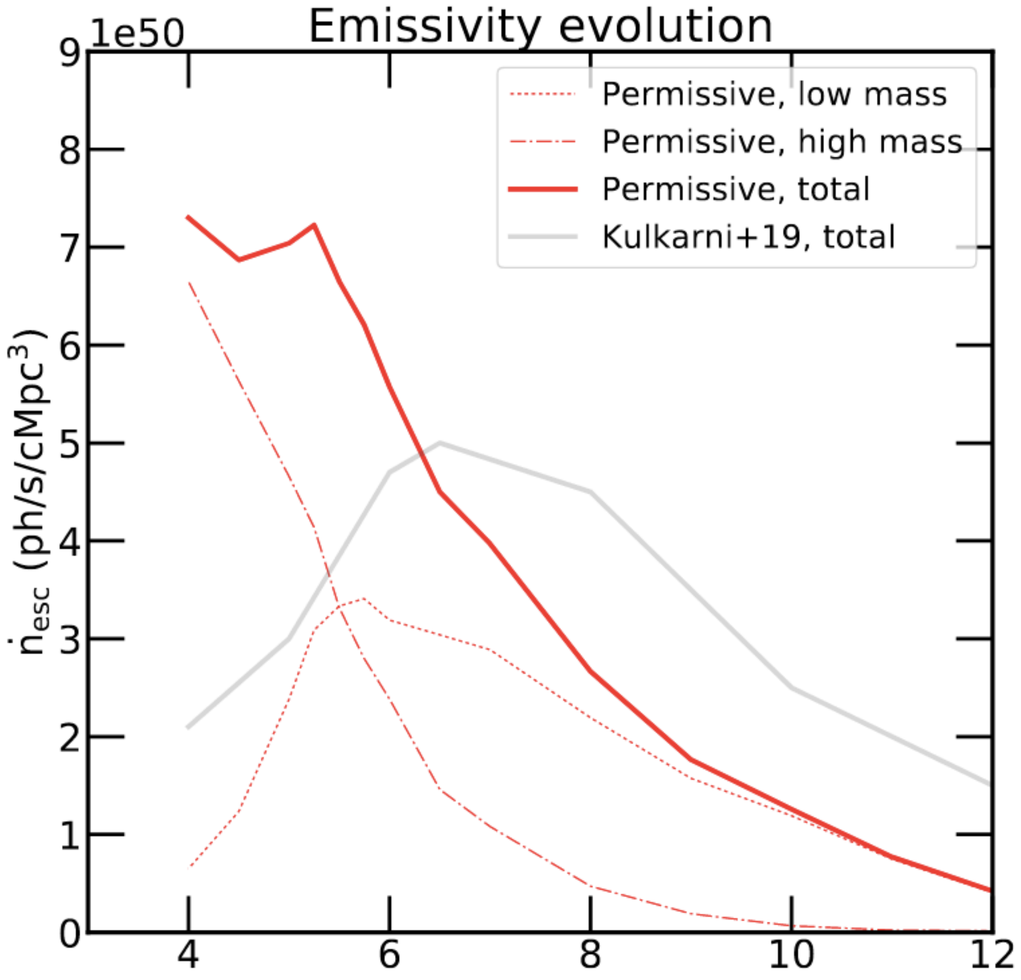
Improved setup

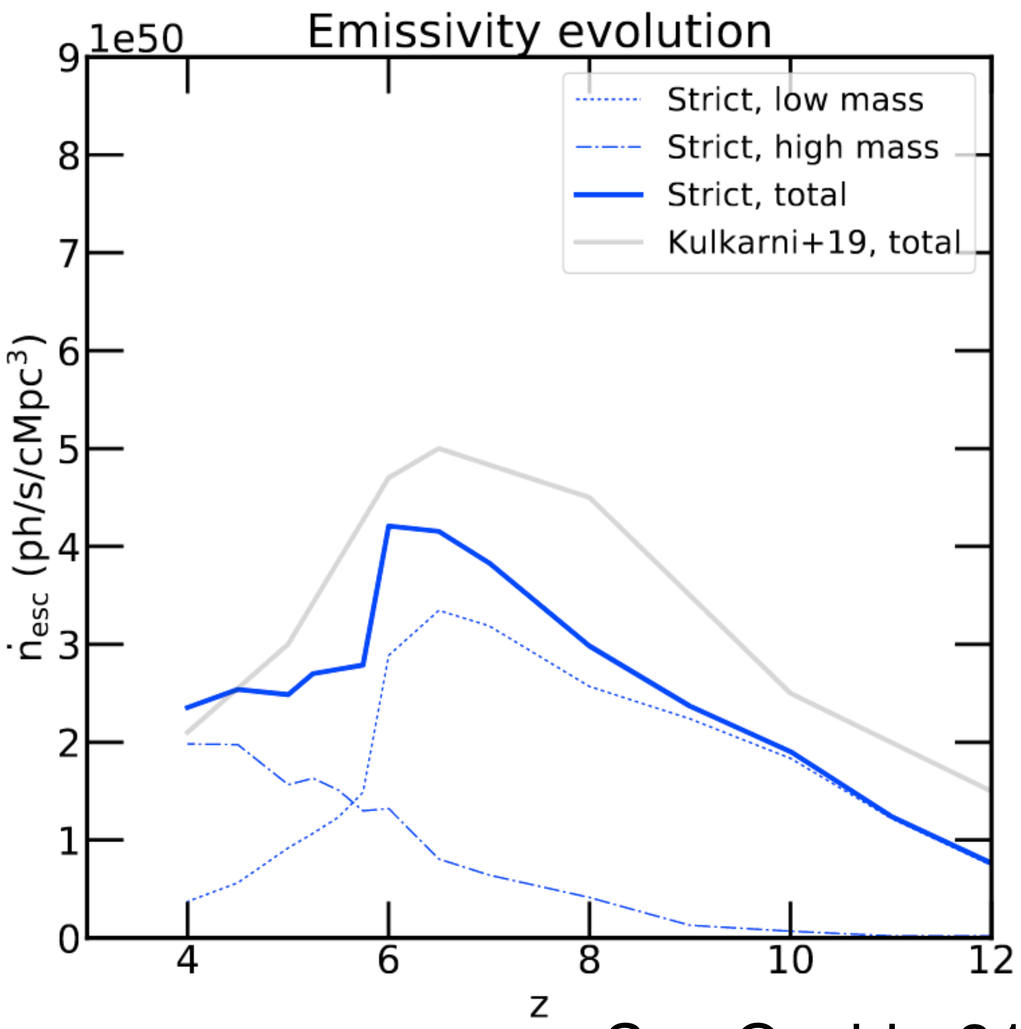
- Adjustments to SF model
- Dust model from Y. Dubois et al.
- Late calibration of Reionization
- Much better agreement wrt IGM constraints



See Ocvirk+21

SF model & total escaping luminosity



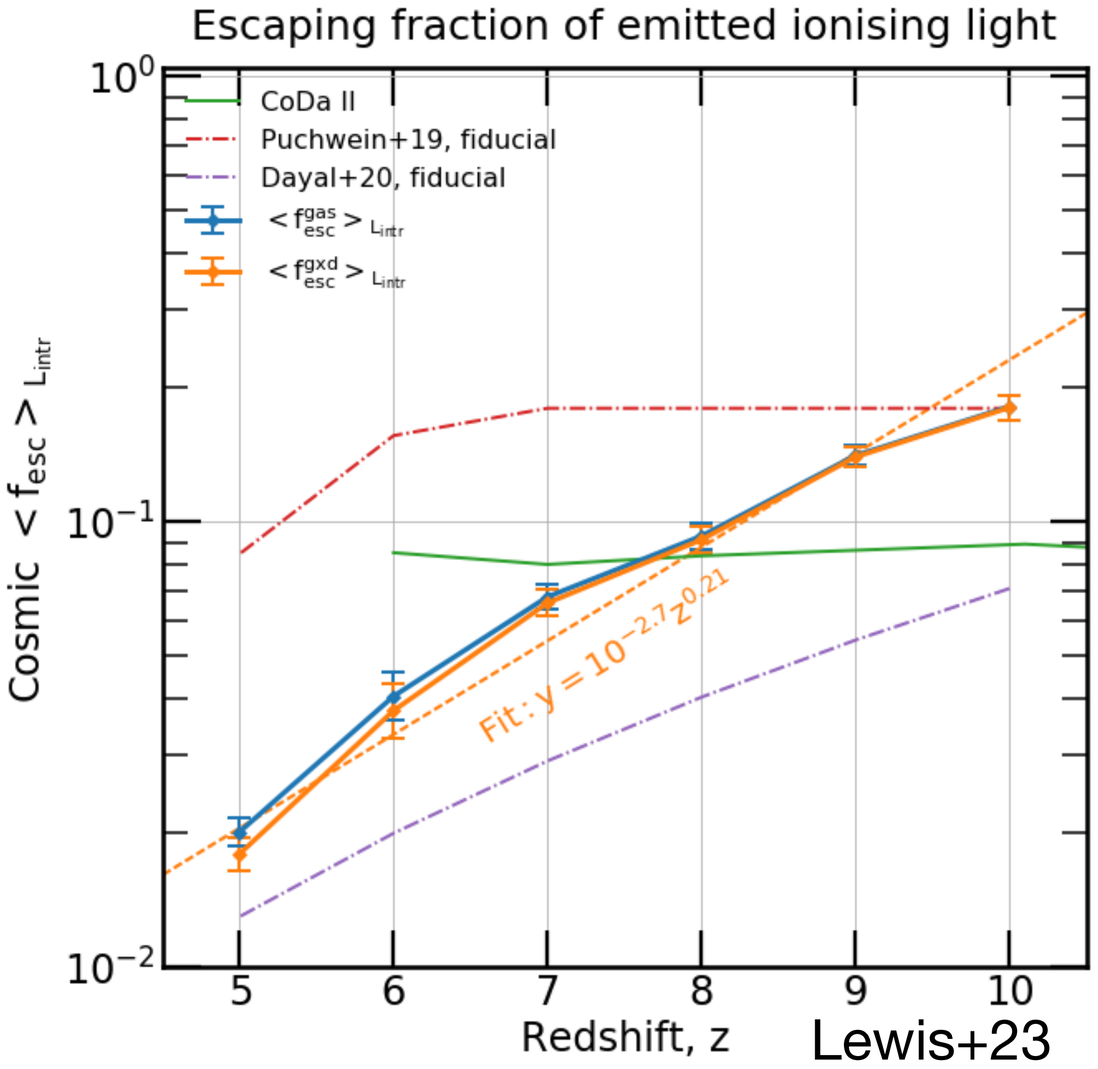


See Ocvirk+21

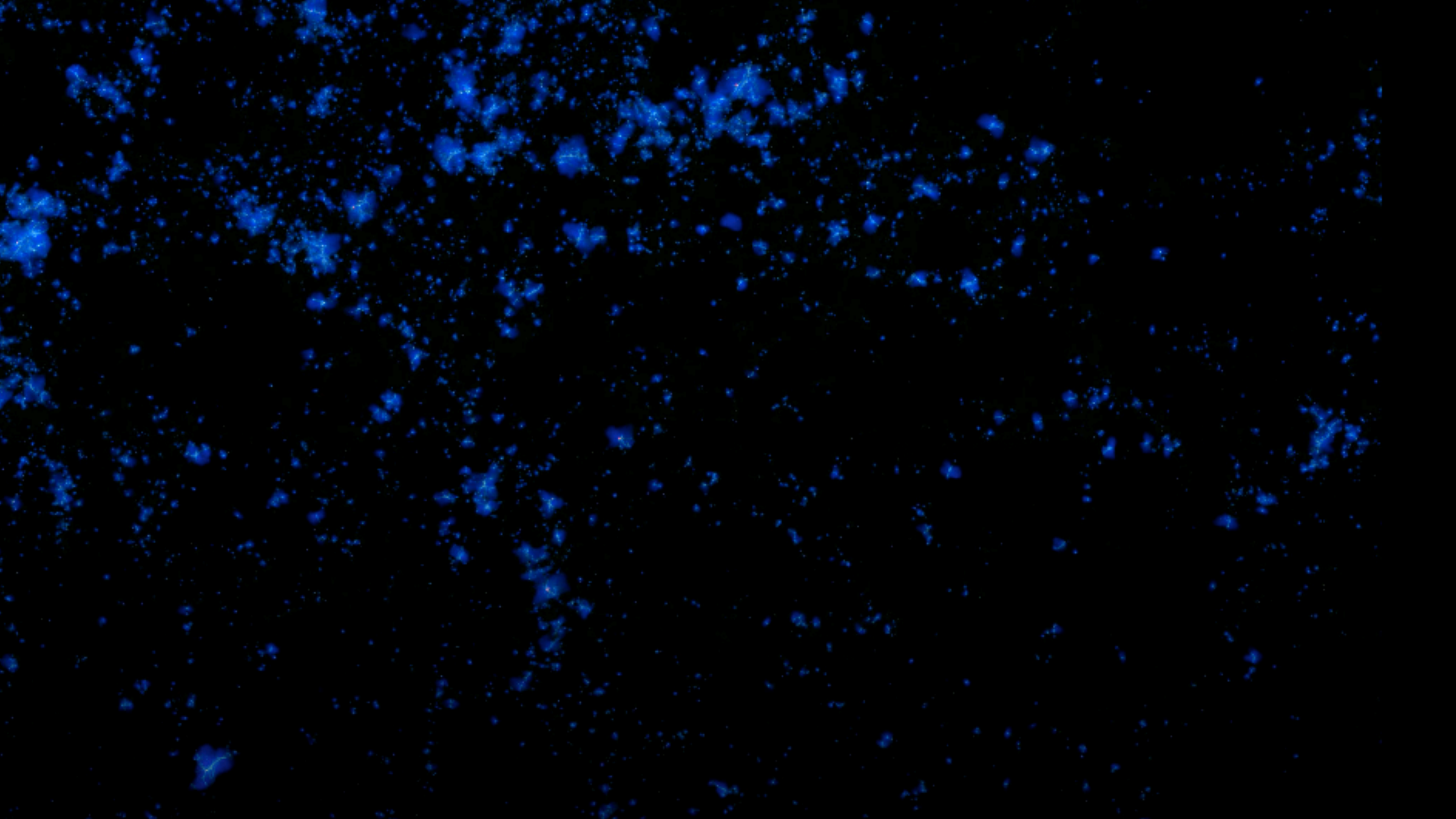
Cosmic escape fraction

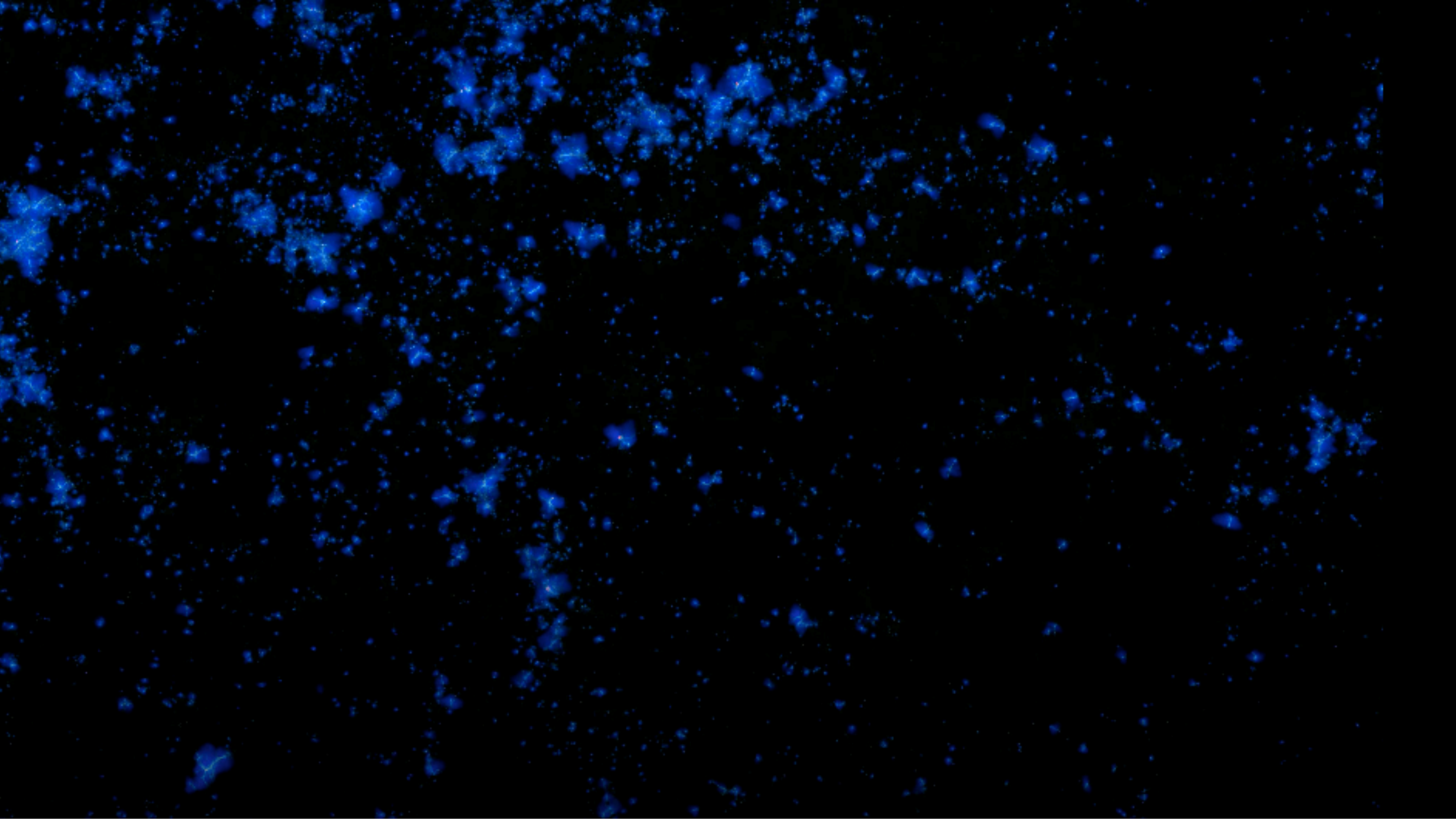
evolution in DUSTiER

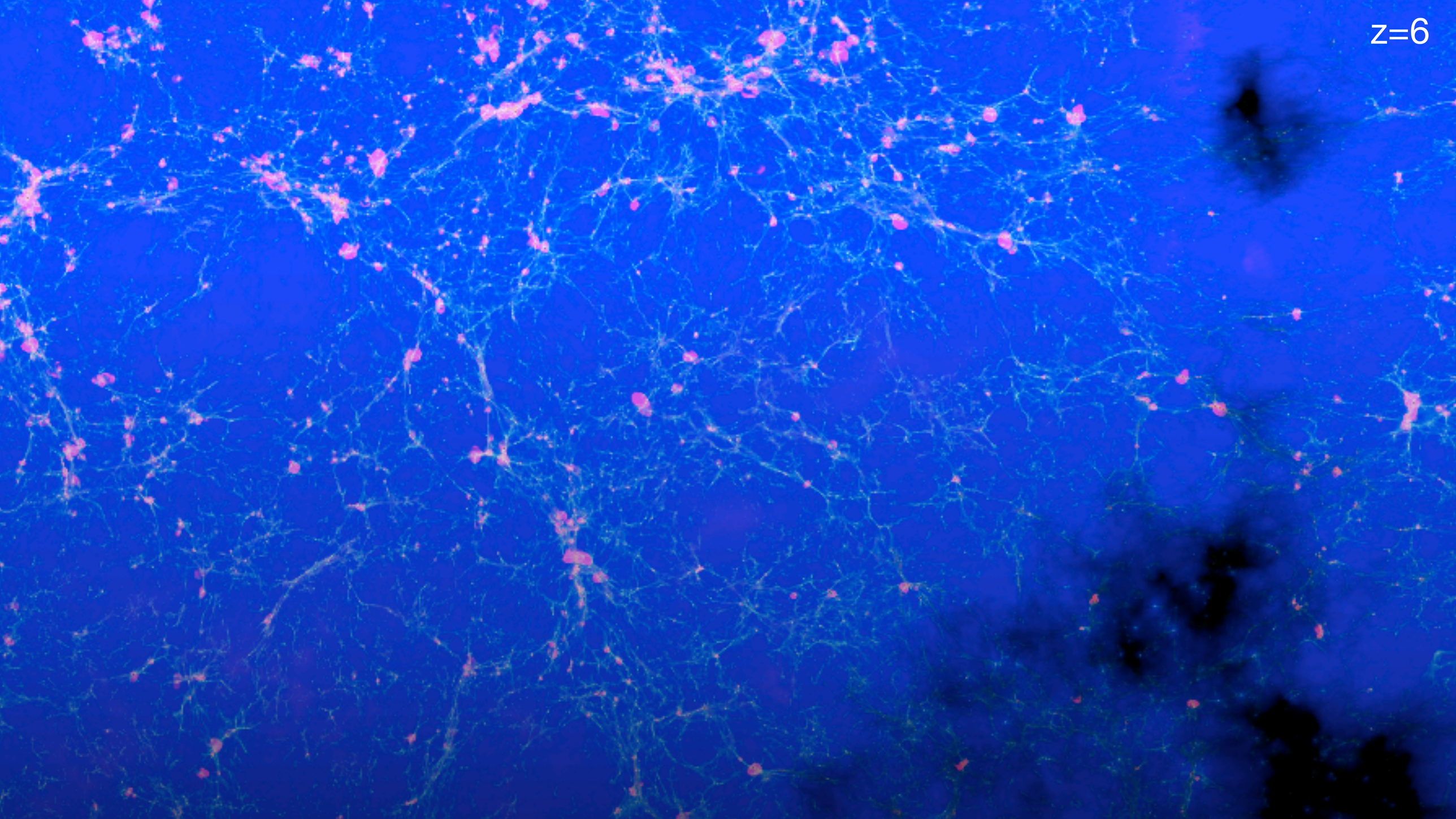
- 20% (z=10) -> 2%(z=5)
- **Lower f_{esc}** in **massive galaxies** + **Suppression** of low mass
- Values between SAM predictions




Introducing…
Cosmic Dawn III






z=6

Cosmic Dawn III

A huge numerical effort

$94^3 \mathrm{Mpc}^3$ box, 8192^3 grid

$$M_{halo} \gtrsim 2 \times 10^7 M_\odot$$

Δx ~ 11.5 kpc comoving (< 2 kpc physical)

zend=4.7

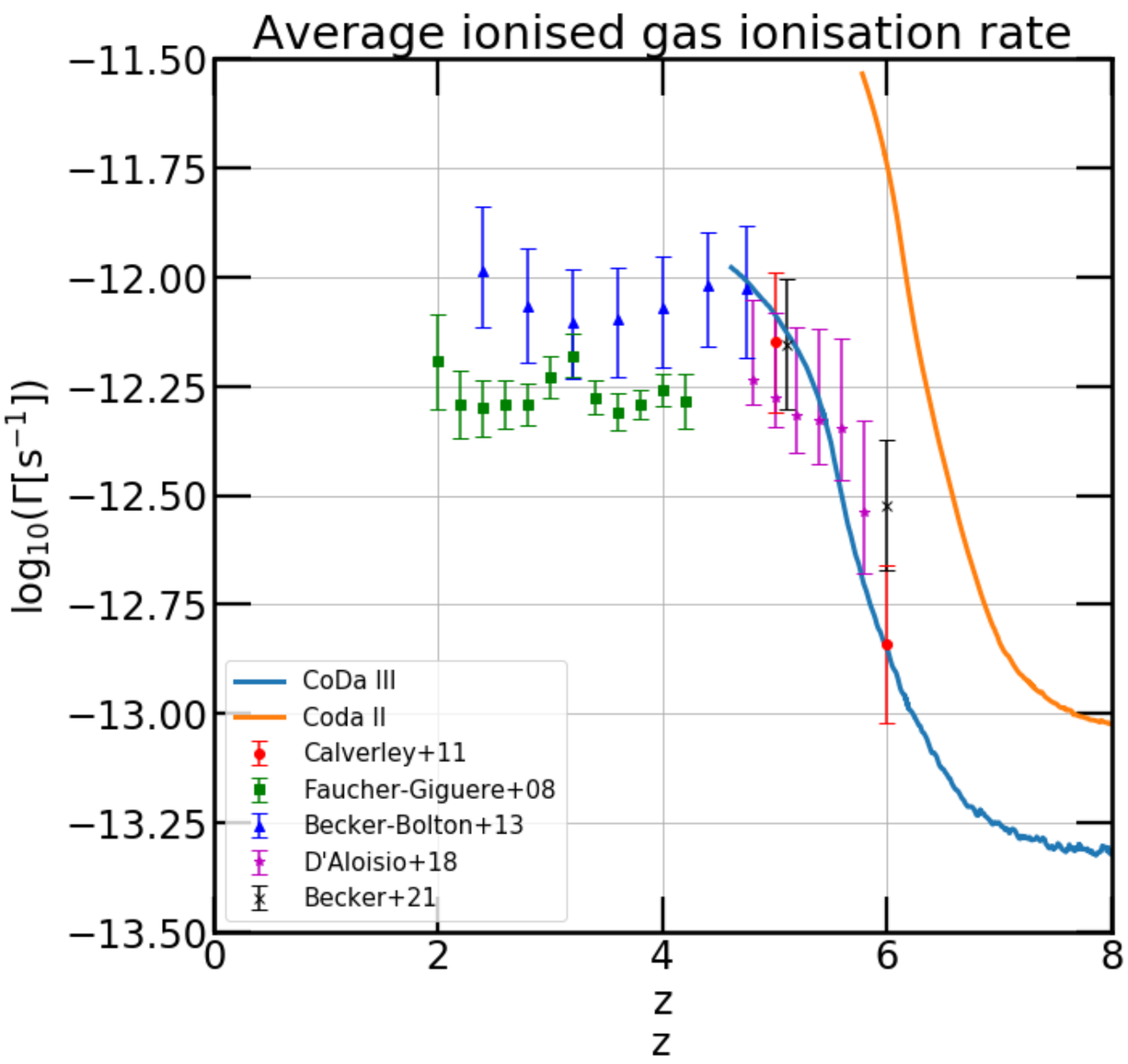
131 072 CPUs & 24 576 GPUs

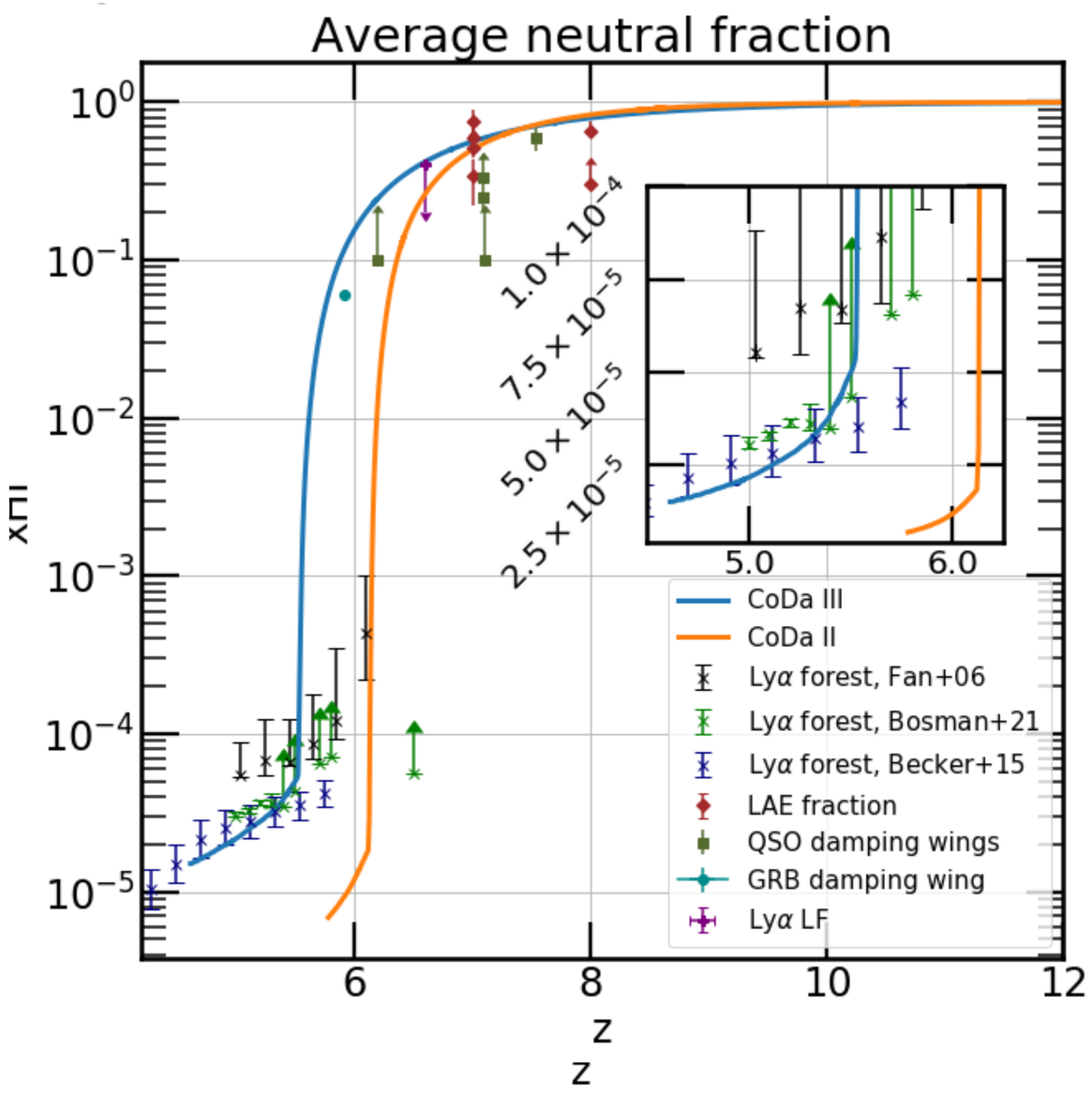
10 days run time

roughly 20PB total

Summit

But does it reionize?

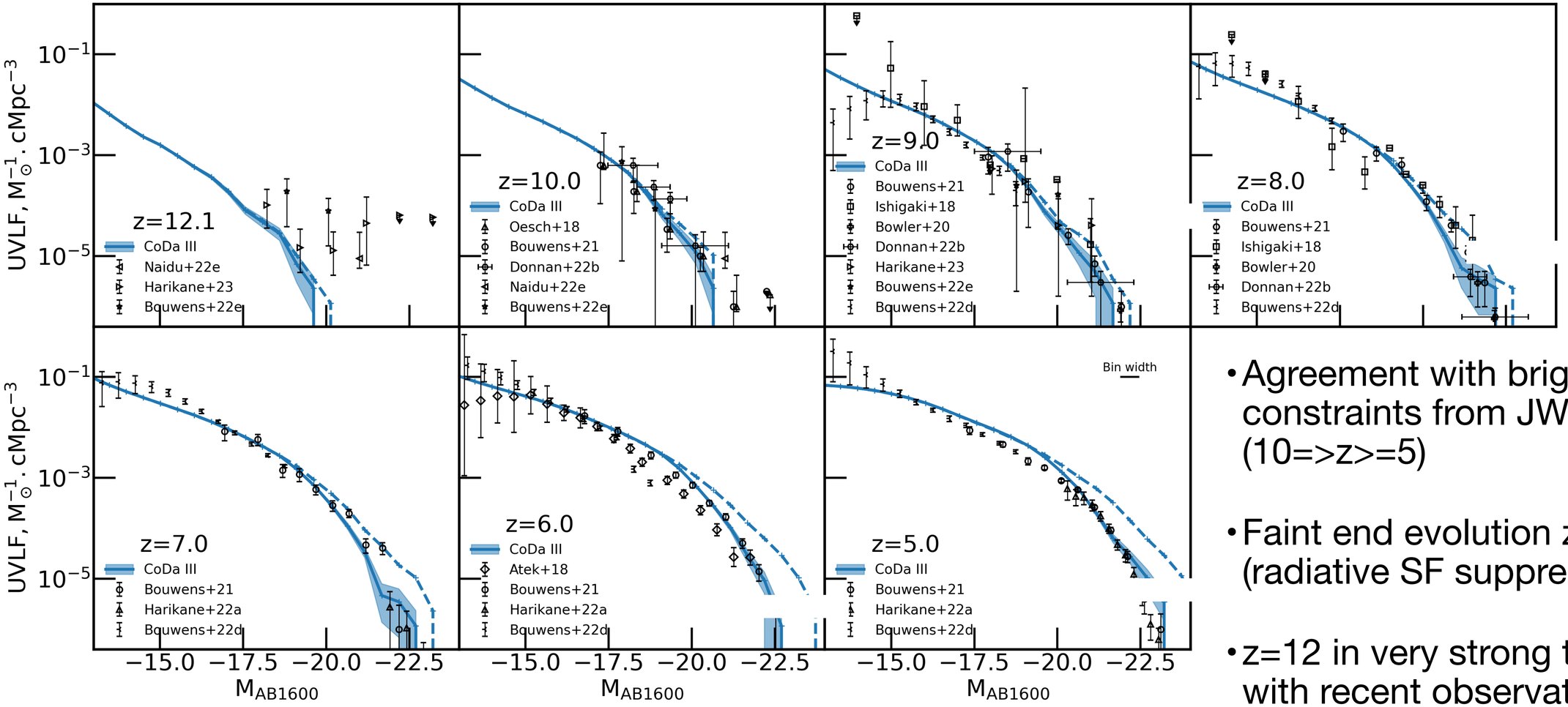




(Very) preliminary CoDa III results

For your eyes only please!

Extinction and UVLF

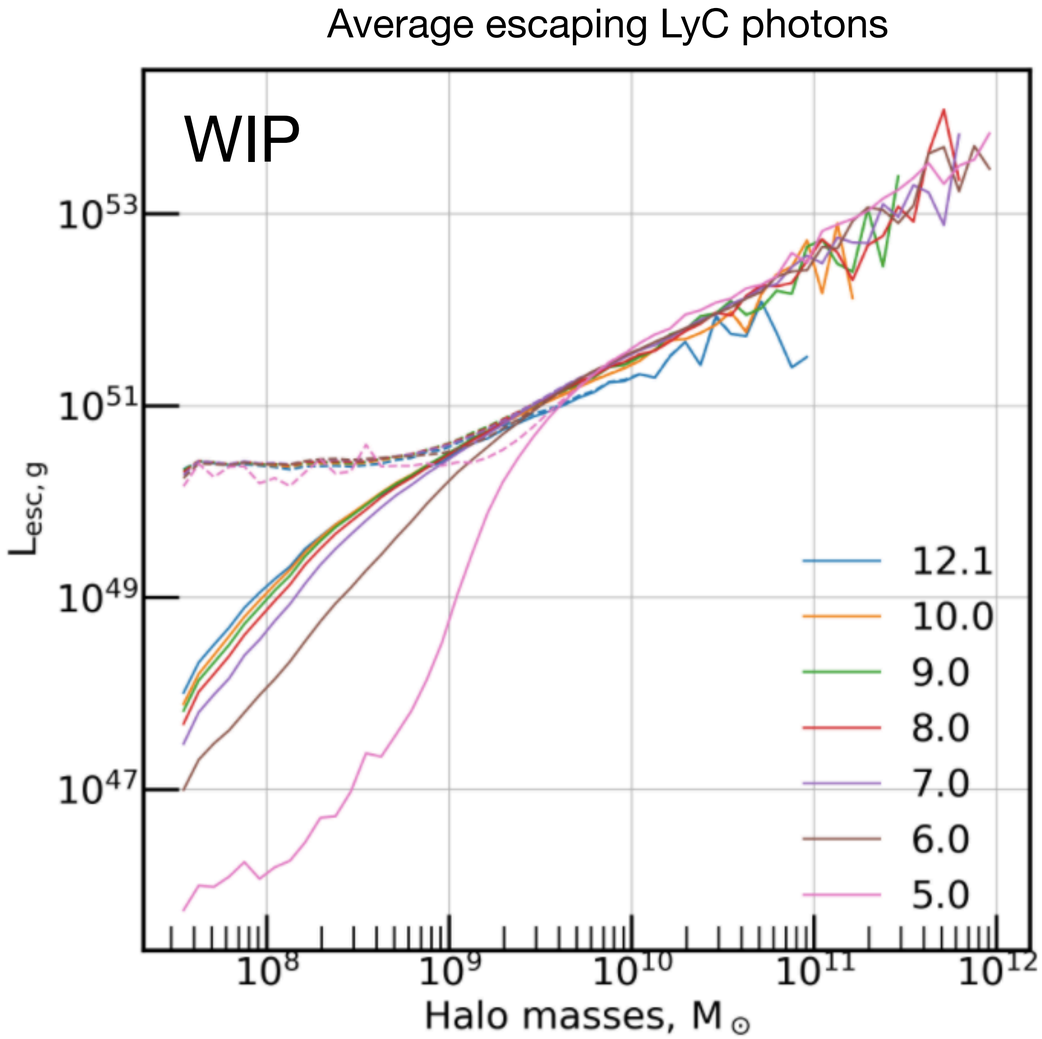


- Agreement with bright end constraints from JWST (10=>z>=5)
- Faint end evolution z<=6 (radiative SF suppression!)
- z=12 in very strong tension with recent observations

Extinction law constrained using UV-slope VS magnitude relation (as in Lewis+23)

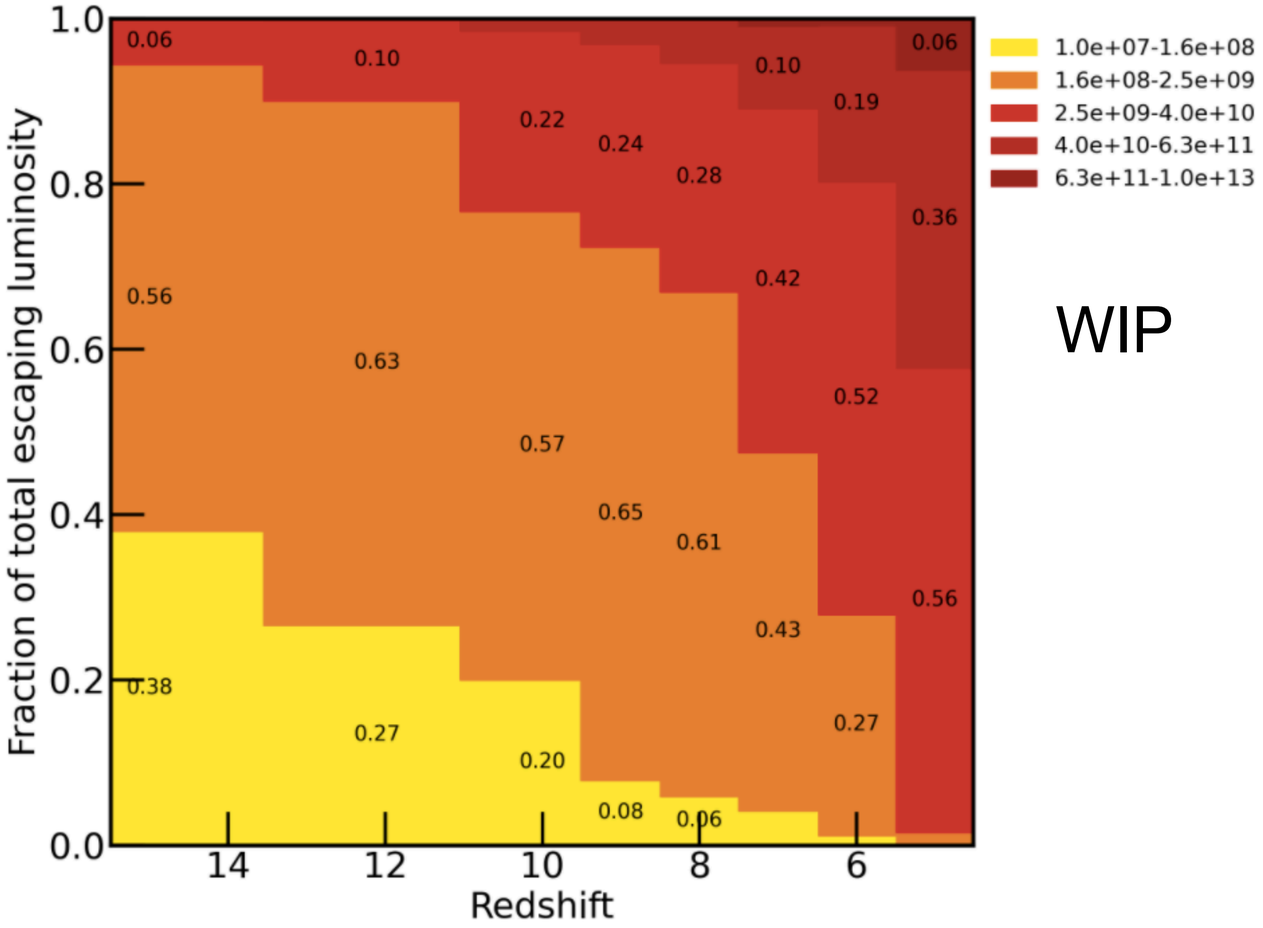
Escaping luminosities

- Escaping luminosity
- L_{esc} increases with mass
- Mean L_{esc} decreases over time in low mass haloes… suppression of SF



Ionising photon budget in CoDa III

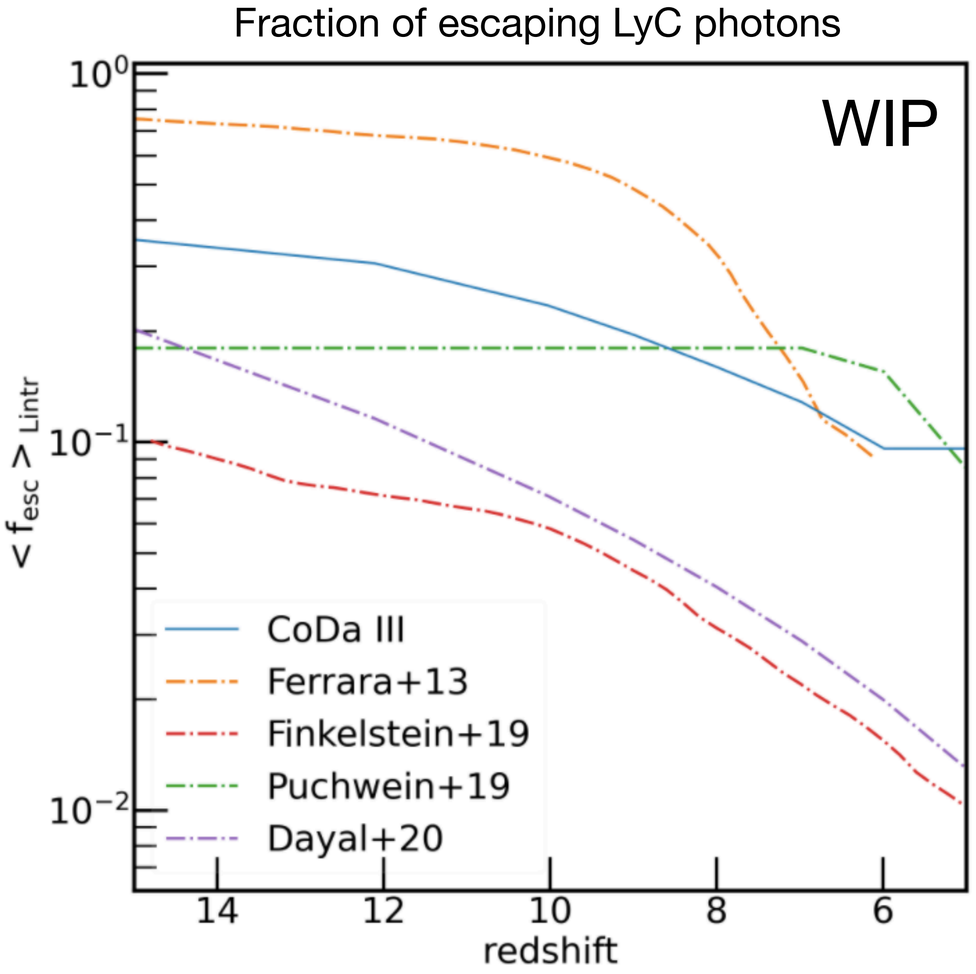
- M_h<2.5e9 $M_\odot$ haloes >=70% of ionizing budget z>=8
  - <2% at z=5!
  - Higher mass haloes take over
- More dynamic than in CoDa II
  - SF suppression



WIP

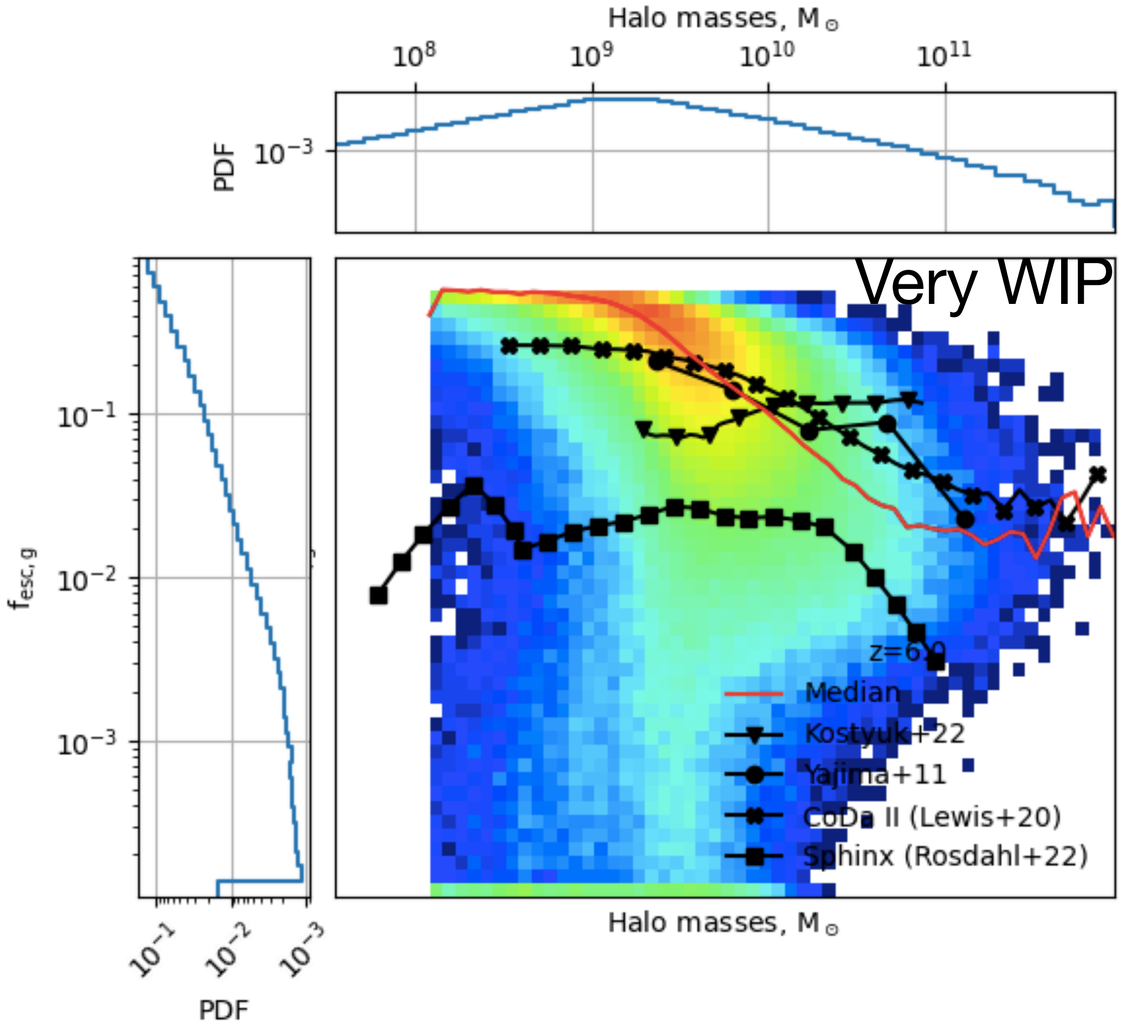
Cosmic escaping fraction

- Decrease from 20% (z=15) to 10% (z=5)
  - Build up of massive low f_{esc} galaxies (% level f_{esc})
  - Suppression of SF in M_h<3e9 $M_\odot$
- Gentler slope than in DUSTiER



Halo mass to f_{esc} relation

- f_{esc} higher in low mass haloes
- slope stronger than in CoDa II
  - … but similar values



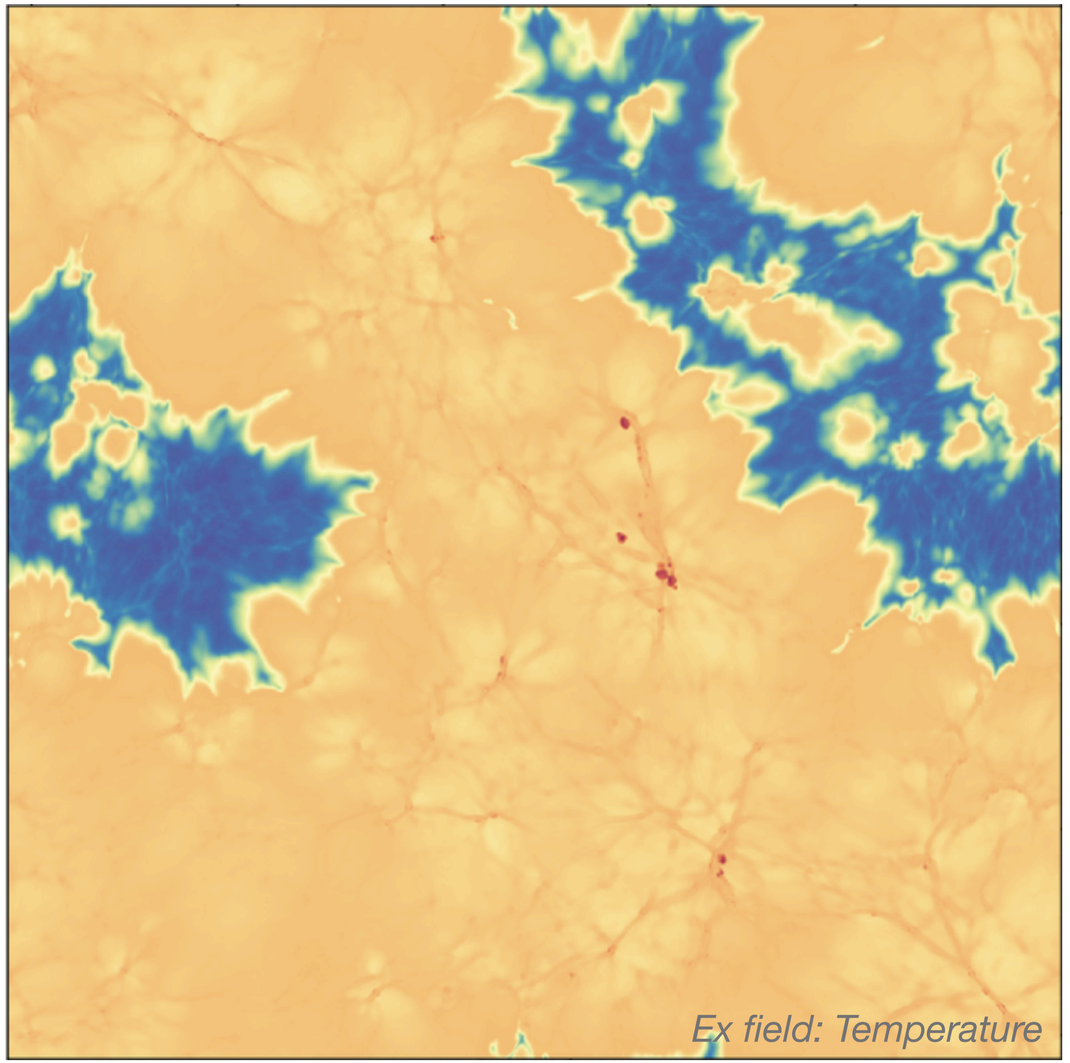
Summary

- Good match to recent constraints on UVLF (z<12… how will this evolve?)
- f_{esc} decreases with halo mass, very high in low mass haloes, a few percent in massive haloes
- Average f_{esc} decreases from 20% to 10% during EoR, due to formation of massive haloes, and SF suppression in low mass haloes
- Strong evolution in drivers of EoR: low masses drive EoR z<8, then overtaken by massive galaxies

Introducing DUSTiER

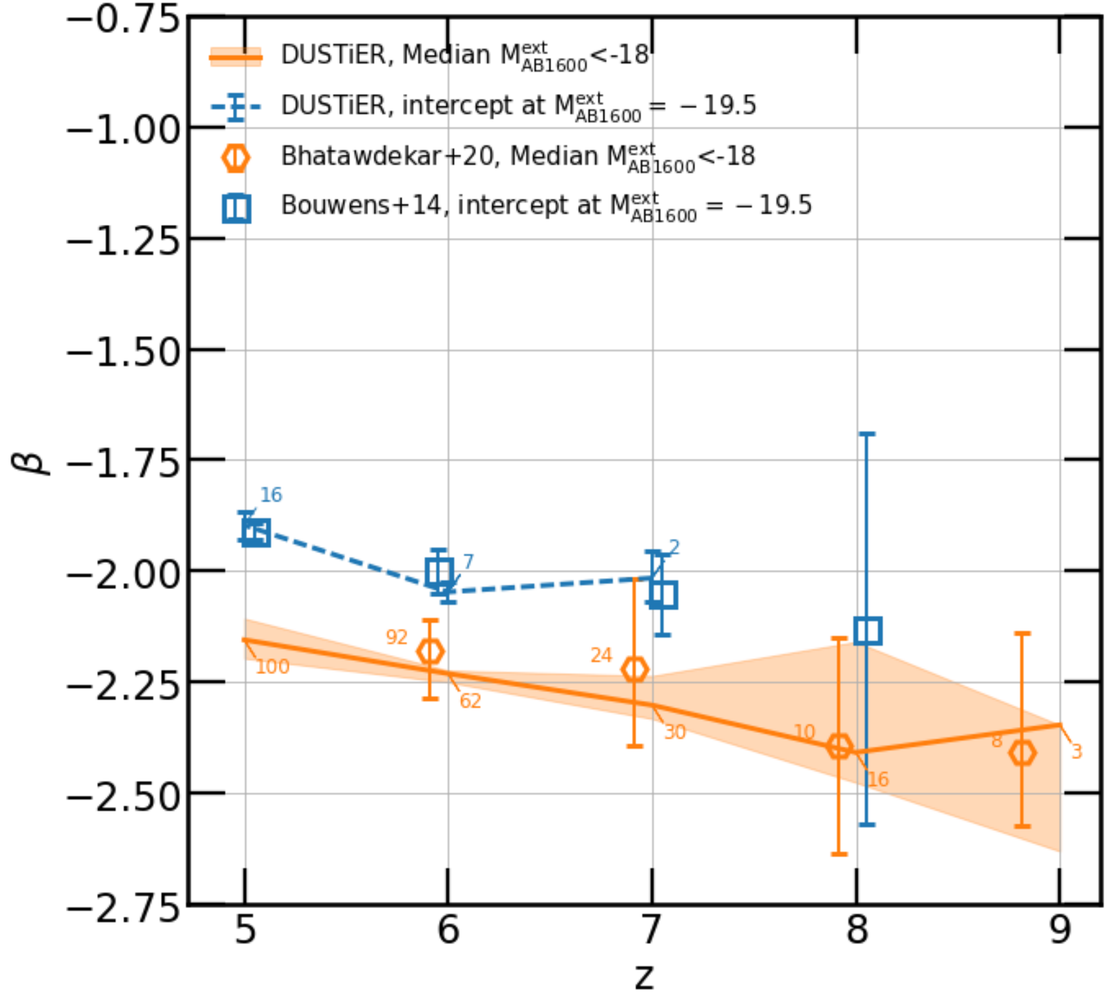
RAMSES-CUDATON, RHD w c=1
16 cMpc/h per side
2048^3 cells (& DM particles)
roughly 1.6 pkpc resolution @ z=6

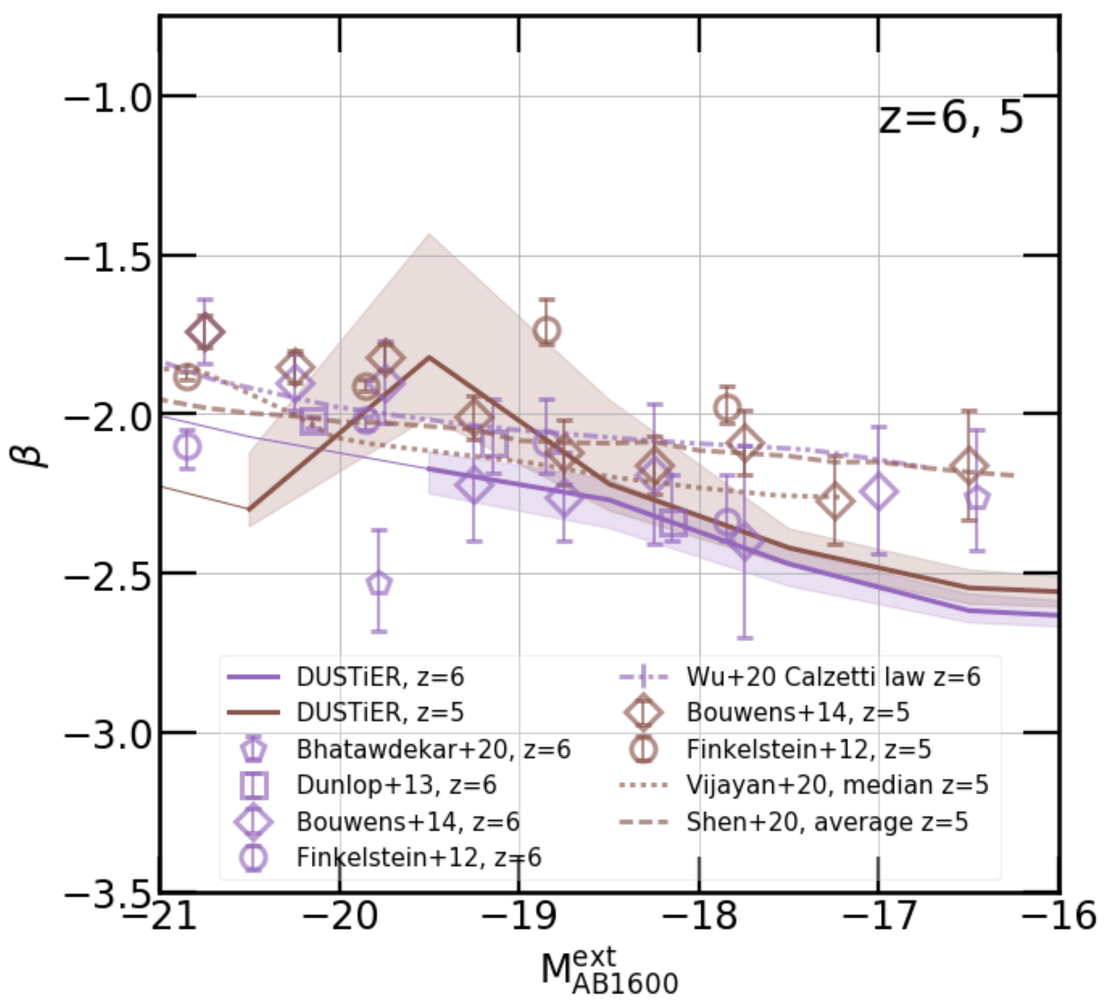
ran on Jean Zay @ IDRIS



See Lewis+23

Ext law and UV slopes





Nitty gritty stuff

For simulators

Setup	
Grid size & Dark matter particle number	8192^3
Box size	94.43 cMpc
Force resolution	
...comoving	11.53 ckpc
...physical (z = 6)	1.65 kpc
Dark matter particle mass	5.09×10^4 $M_\odot$
Average cell gas mass	9.375×10^3 $M_\odot$
Stellar particle mass	11 732 $M_\odot$
Star formation & feedback	
Density threshold for star formation	$50<\rho_{gas}>$
Temperature threshold for star formation	2×10^4 K
Star formation efficiency $\epsilon_\star$	0.03
Massive star lifetime	10 Myr
Supernova energy	10^{51} ergs
Supernova mass fraction, η_{SN}	0.2
Supernova ejecta metal mass fraction	0.05
Radiation	
Stellar ionising emissivity model	BPASS V2.2.1 binary
(from Eldridge & Stanway 2020)	
Stellar particle sub-grid escape fraction, f_{esc}^{sub}	1.0
Effective photon energy	20.28 eV
Effective HI cross-section (at 20.28 eV)	2.493×10^{-22} m^2
Reionization	
CMB electron scattering optical depth, τ_{es} (z = 14)	0.0497
reionization mid-point, $z_{re,\,50\%}$	6.81
reionization complete, $z_{re,\,99.99\%}$	5.53

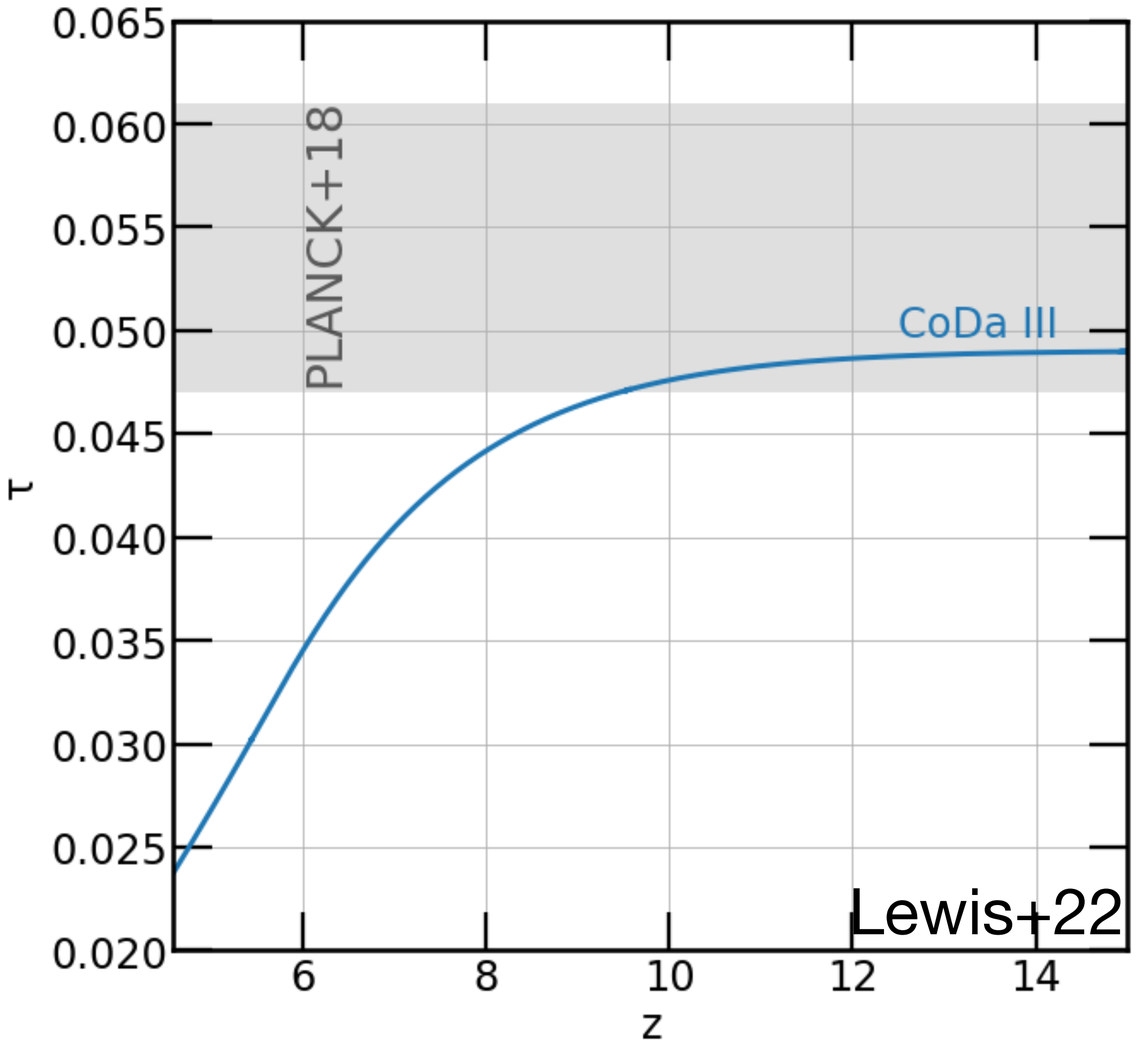
Fixed resolution uni-grid

fof halo finding

Kinetic FB (Dubois+08)
No AGN/AGN FB

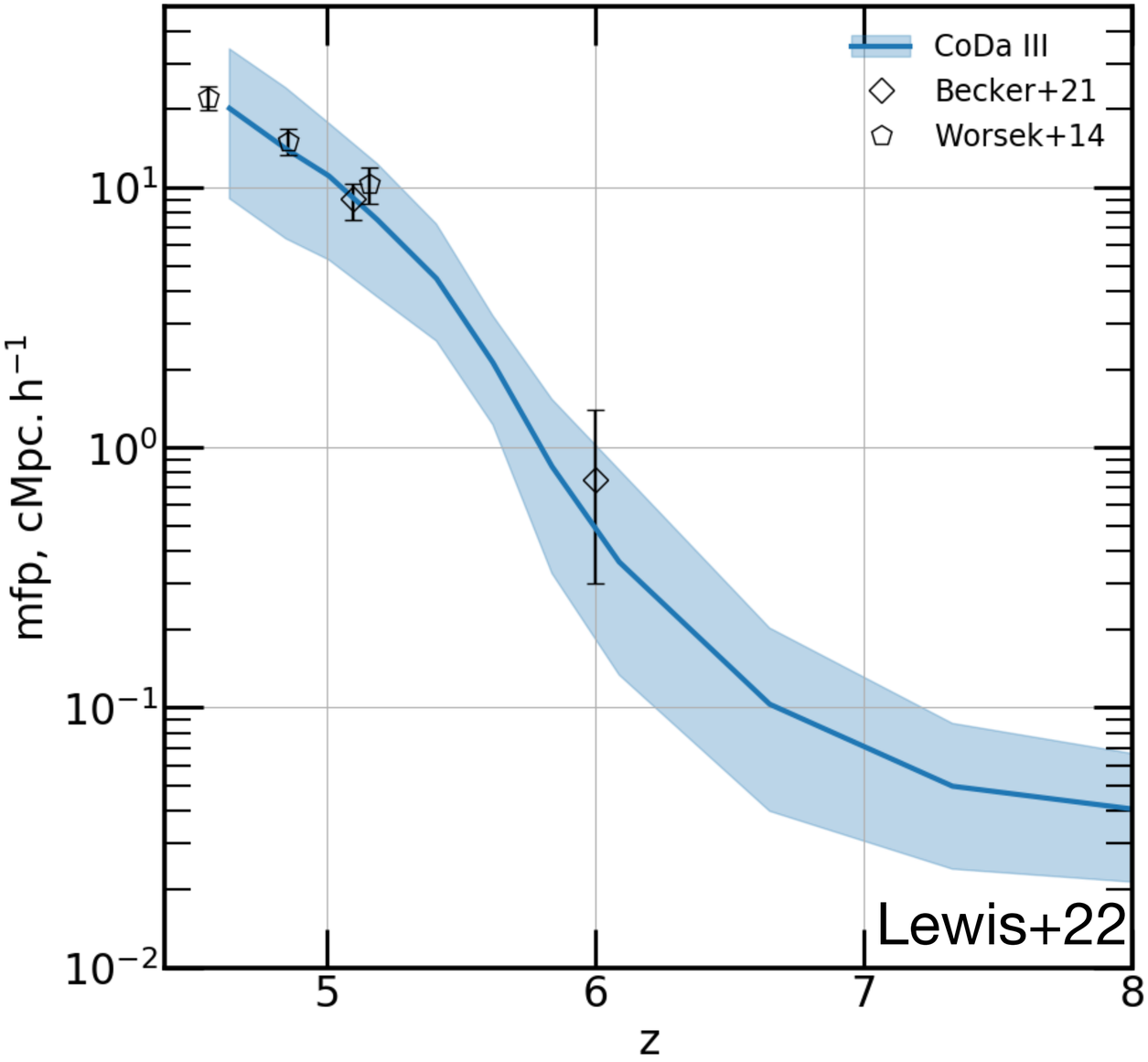
Single frequency M1 RT

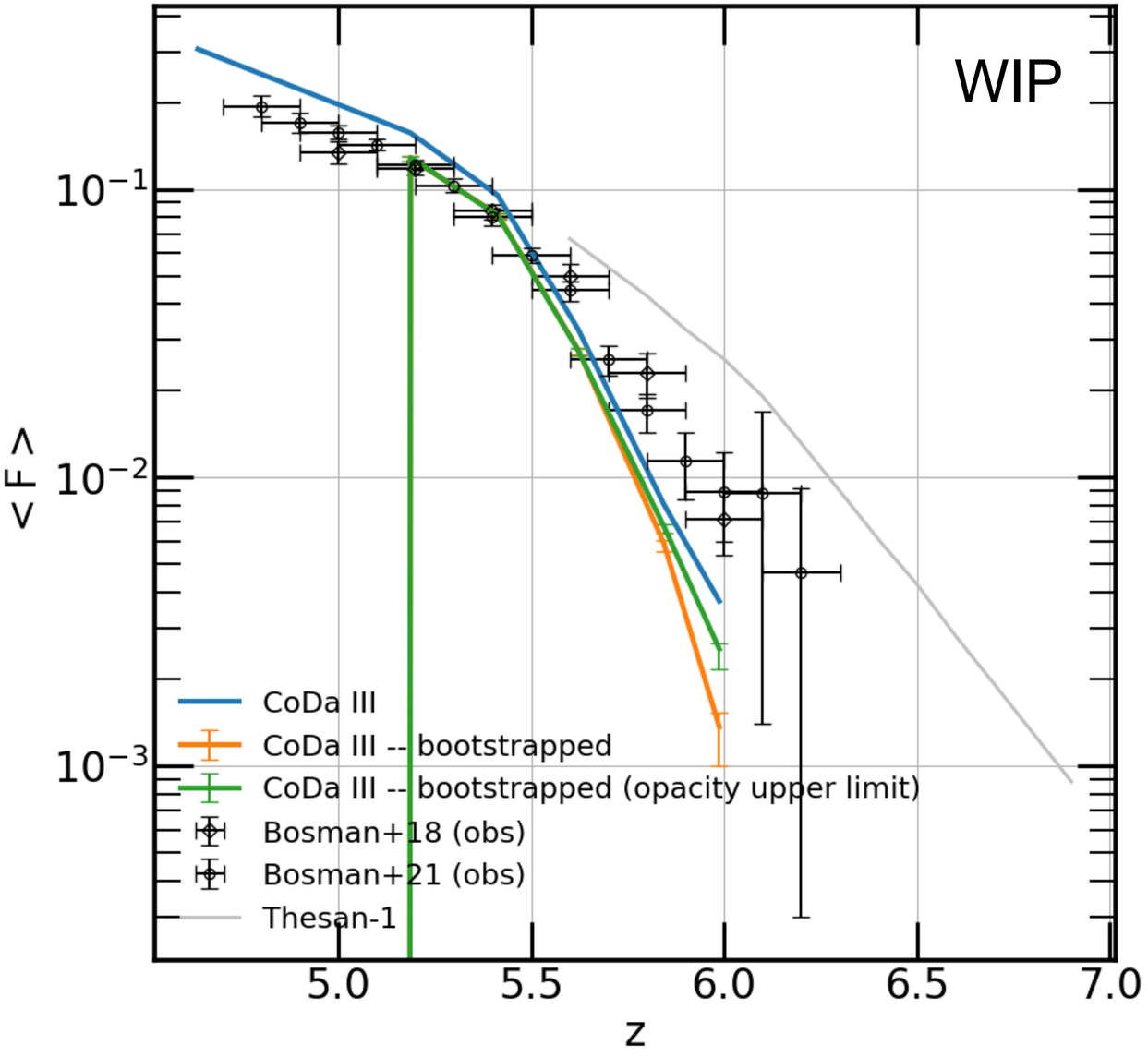
CMB optical depth

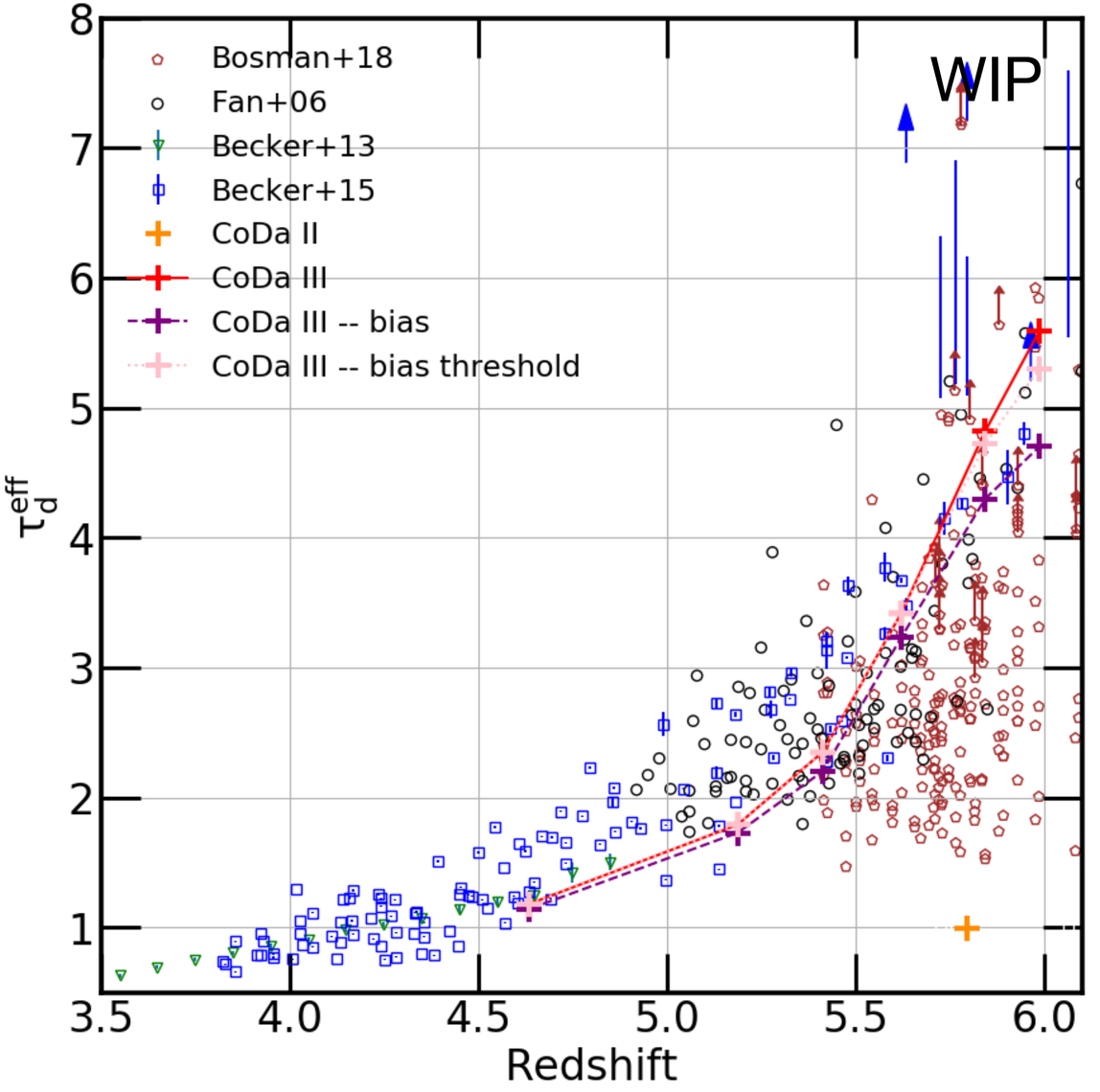


Mean free path
of ionizing photons

- Good match with existing + latests constraints
- Rapid evolution as EoR finishes




WIP
10^{-1}
10^{-2}
10^{-3}
< F >
5.0
5.5
6.0
6.5
7.0
z
CoDa III
CoDa III -- bootstrapped
CoDa III -- bootstrapped (opacity upper limit)
Bosman+18 (obs)
Bosman+21 (obs)
Thesan-1


WIP
Bosman+18
Fan+06
Becker+13
Becker+15
CoDa II
CoDa III
CoDa III -- bias
CoDa III -- bias threshold
τ_d^{eff}
1
2
3
4
5
6
7
8
3.5
4.0
4.5
5.0
5.5
6.0
Redshift