Cosmic Dawn (CoDa) III
Galaxy formation during the Epoch of Reionization
— An update —

P. Ocvirk and Cosmic Dawn collaboration
https://coda-simulation.github.io/
Observatoire astronomique de Strasbourg
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Cosmic Dawn Collaborators

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- **J. Lewis** (Zentrum für Astronomie, Heidelberg)
- **J. Sorce** (ICs, **CLUES,** CRISTAL Lille)
- **L. Keating** (Univ. Edinburgh)
- **R. Teyssier**, (Princeton) (code + sci. exp.)
- **Y. Dubois** (IAP) (SN feedback, dust model)
- **F. Roy, Y. Rasera** (Observatoire de Paris) (large scale deployment, pfof)
- **M. Gronke** (MPA Garching) (sci exp)
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- **S. Gottloeber** (Leibniz Institute for Astrophysics, Potsdam) (ICs + sci. exp., **CLUES**)
- **G. Yepes**, A. Knebe (Universidad Autonoma de Madrid) (ICs + sci. exp., **CLUES**)
- **Y. Hoffmann** (Hebrew University of Jerusalem) (ICs, **CLUES**)

Dark ages / EoR open questions

- When did dark ages / reionization start / finish?
- Ionising sources? Galaxies (high/low mass?) / BHs (stellar / supermassive)
- Ionising UV Escape fraction? Impact of dust?
- Radiative feedback on early galaxies? mass limit for star formation?
- Impact on reionization history?

Addressing these questions numerically is extremely challenging:

- **COUPLED** radiation hydrodynamics galaxy formation code, costly
- High mass resolution (to account for all sources down to at least $10^8\ M_\odot$ haloes)
- Large volume (bright-end galaxy MF, galaxy clusters) => L~ 100 Mpc

=> **COSMIC DAWN SIMULATIONS**

I - Fully coupled Radiation-hydro with RAMSES-CUDATON (Ocvirk+2016)

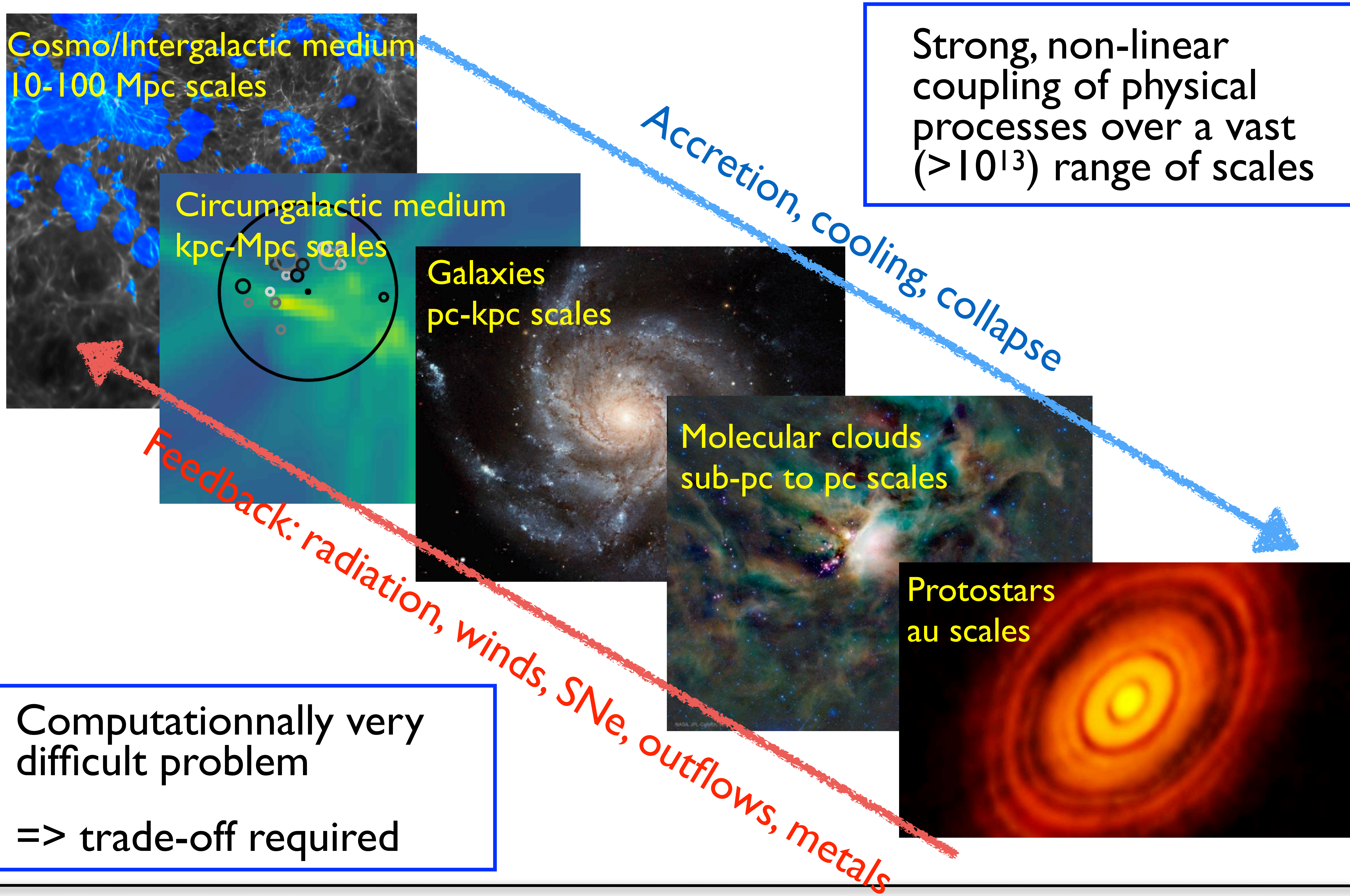
- **RAMSES** (Teyssier 2002): **CPU**
  - gravity (PM) + hydrodynamics
  - star formation + SN thermal + kinetic feedback
  - chemical enrichment, dust production + destruction (Lewis+2022)

↑ T, x_{HI}

↓ T, ρ_{HI}, stars, ρ_{dust}

- **ATON** (Aubert 2008): UV Radiative Transfer,
  - photon propagation, H ionization
  - H Photo-heating + cooling
  - dust absorption

II - The tyranny of scales



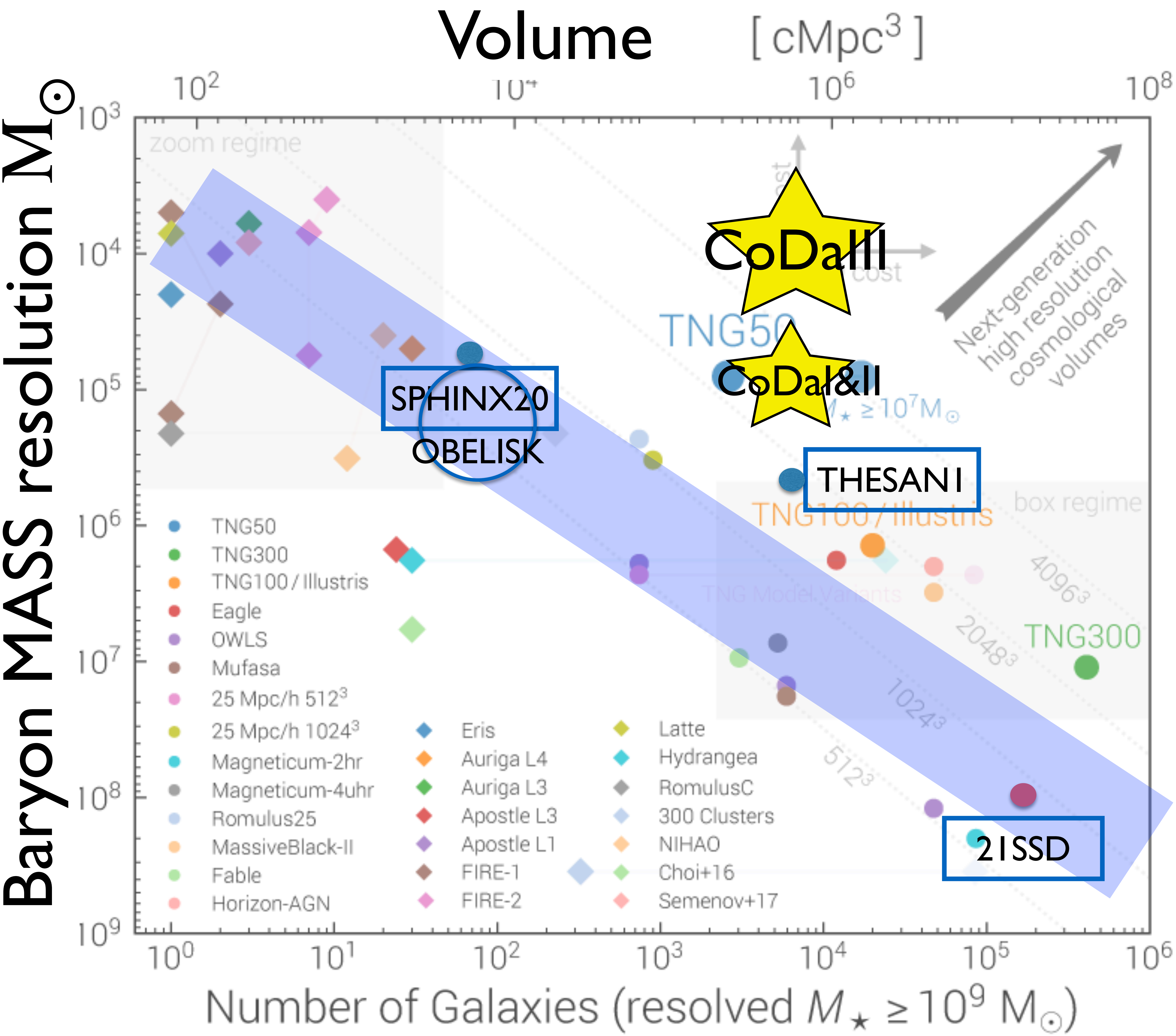
Strong, non-linear coupling of physical processes over a vast ($>10^{13}$) range of scales

Computationally very difficult problem

=> trade-off required

(Inspired from J. Rosdahl's slide)

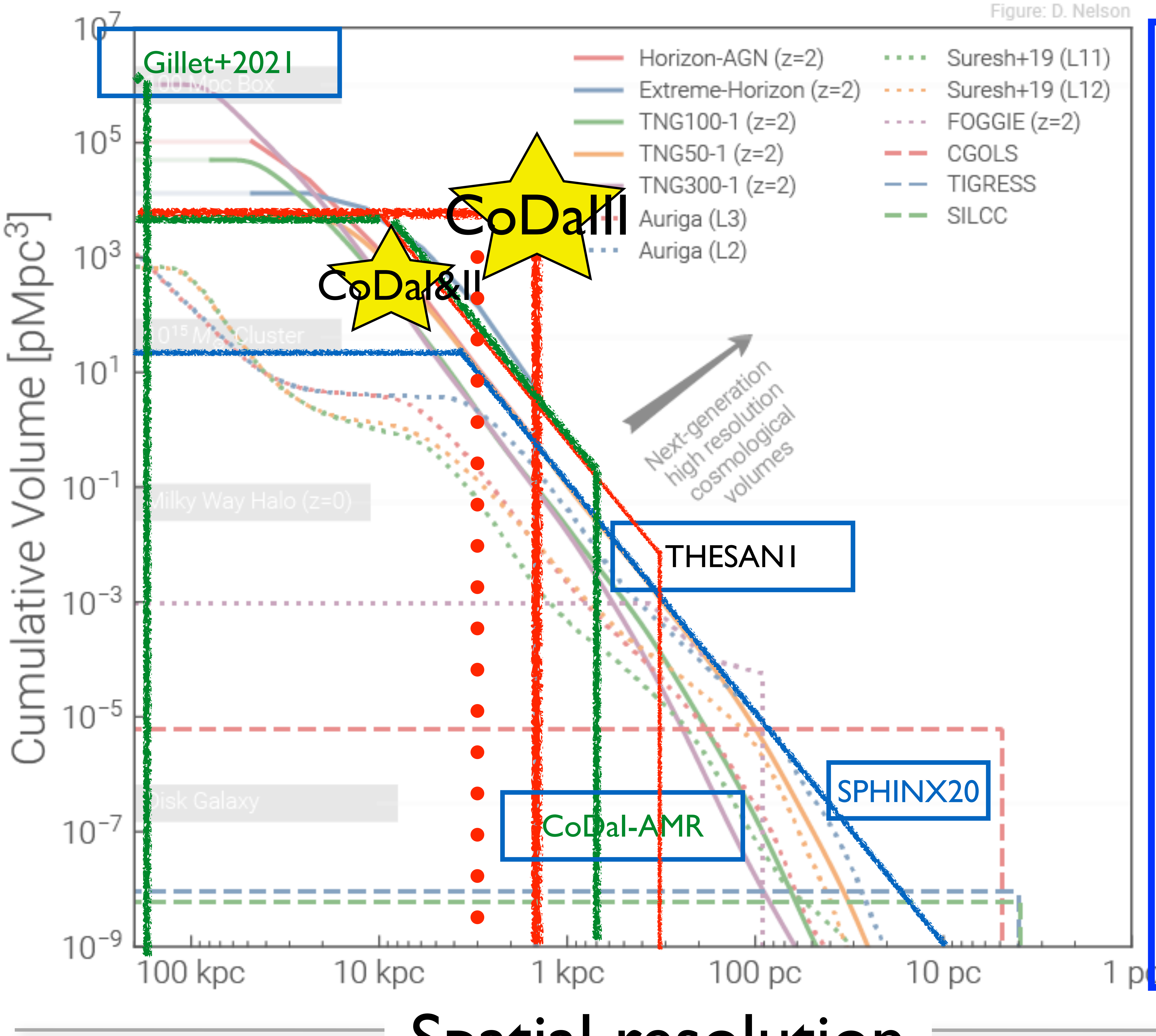
The "main sequence" of galaxy formation simulations



- trade-off between size and resolution
- highlighted = recent EoR, fully coupled Radiation-hydrodynamical sims
- Cosmic Dawn sims stands out due to:
  - raw power
  - GPU optimization
- Intermediate resolution:
  - Large volume
  - ~coarse description of low mass haloes

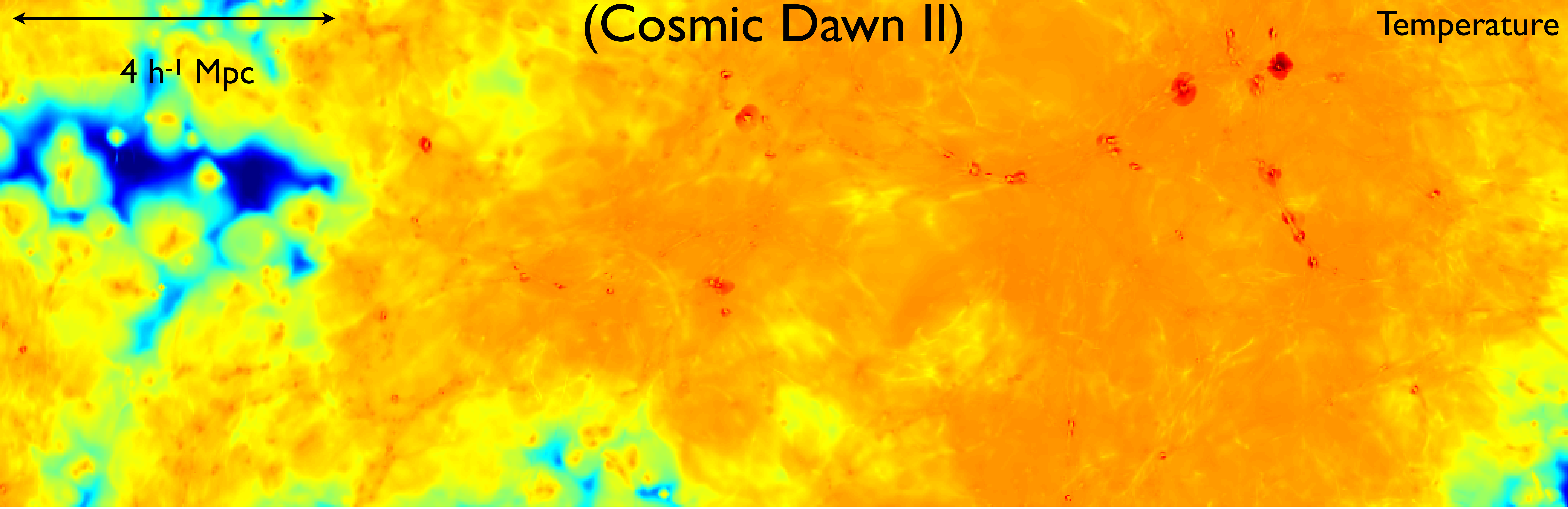
(plot from tng-project.org)

The “main sequence” of galaxy formation simulations



- EoR sims footprints are shown for z=6
- trade-off between size and resolution
- inclined tracks = AMR/SPH sims
- AMR/SPH sims can reach very high res
- but use a reduced speed of light c=0.2-0.02
- Again, CoDa sims stands out as very large, intermediate resolution, fixed grid sims.

(plot from tng-project.org)



Galaxy populations LFs & rad. FeedBack

Photon budget of galaxies

21cm

Reionization history of galaxies/pairs/LG

IGM transmission ($Ly\alpha$, LyC)

Ocvirk 2016,2020, Dawoodbhoy 2018, 2023, Lewis 2020, Aubert 2018, Sorce 2022, Gronke 2020, Park 2021,Park 2022, Lewis 2022, Gillet 2021, Conaboy+2023(in prep.)

II - Cosmic Dawn III setup

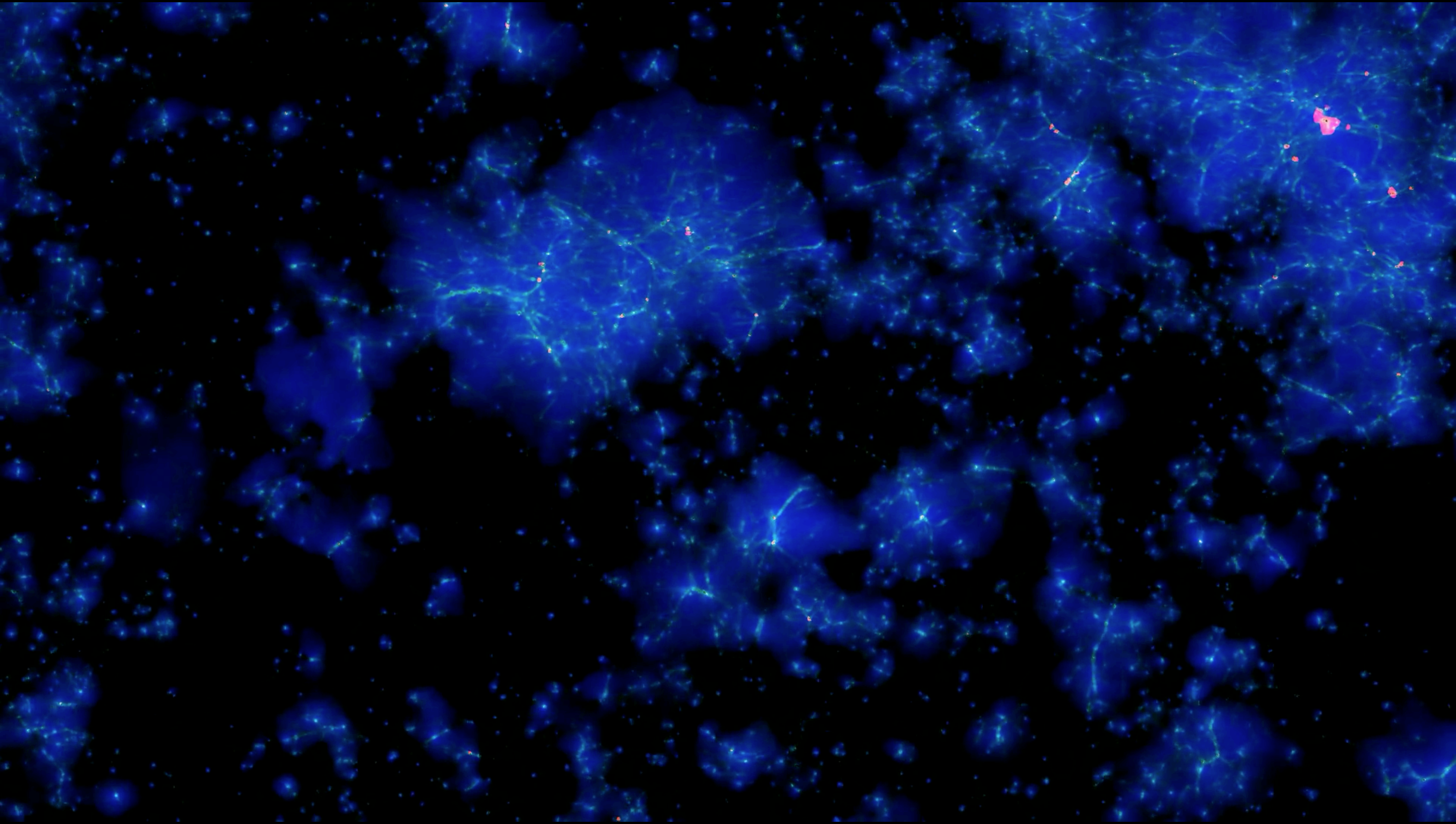
Run parameters					
Domain	Box size (h^{-3} $cMpc^3$)	64^3	Ionizing radiation	Emissivity (ph/s/)	BPASSv2.2.1
	Grid size	8192^3		Lifetime (Myr)	
	Cell size dx(z=6)	1.65 pkpc		sub-grid f_{esc}	**1**
Mass resolution (M_{sun})	DM particle mass	5×10^4	Setup	Computer	Summit
	Stellar particle mass	$\sim 10^4$		Number of nodes	4096
	Minimum halo mass	3.10^7		Number of CPUs	131 072
Star formation	Density threshold (rho/rho_average)	50		Number of GPUs	24 576
	Efficiency	0.03		Total data	20 PetaBytes
	Temperature threshold	2×10^4 K		End redshift	4.6

- Main improvement in spatial and mass resolution (x2 and x8)
  - => improved description of galaxies and sinks
- > 1 trillion particles+cells
- Huge parallelism
- Updated physics: BPASS, metals & dust (Lewis+ 2022), SF T threshold

Summit

Oak Ridge Leadership Computing Facility

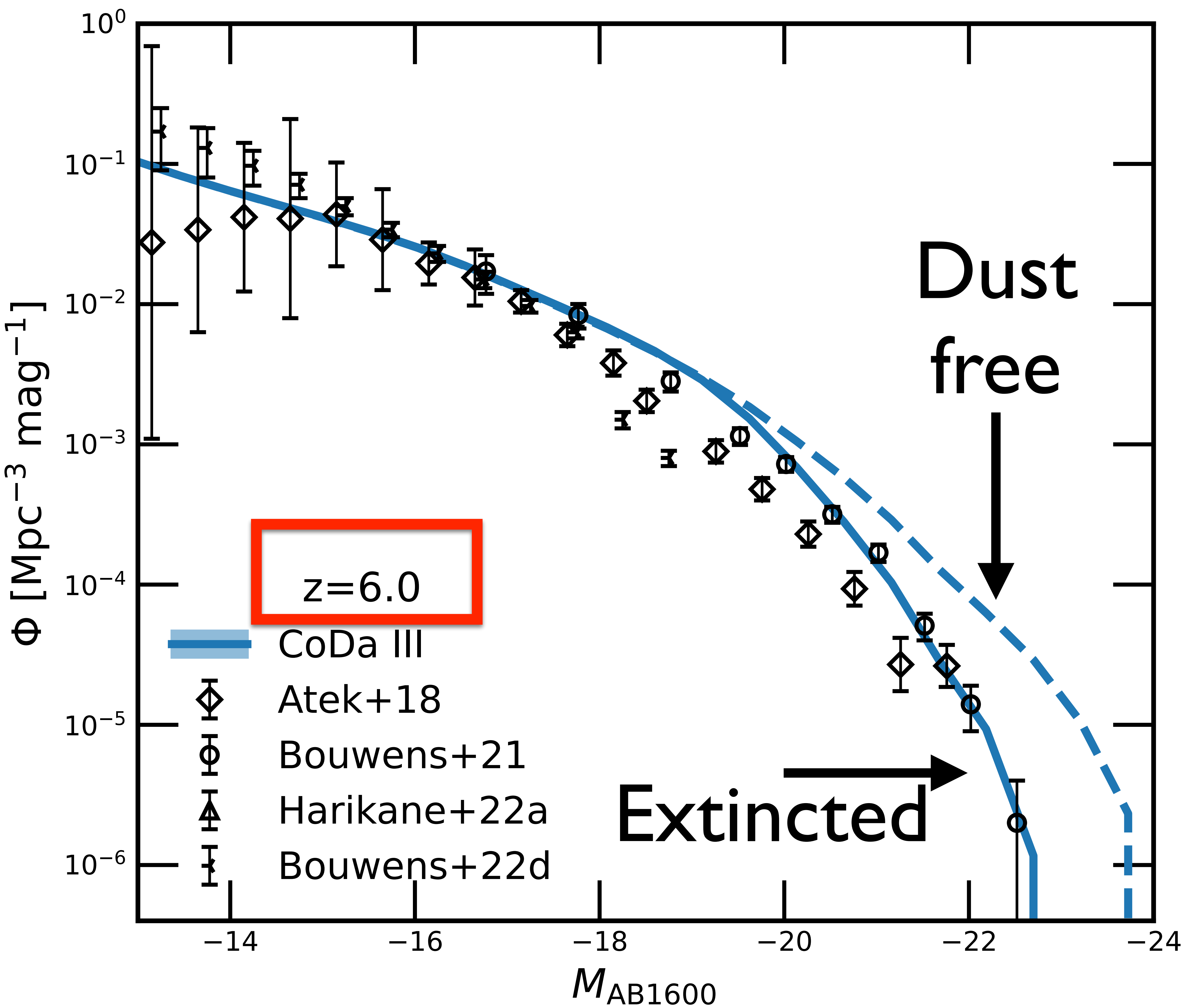
https://coda-simulation.github.io/



Cosmic Dawn III - 16/h cMpc sub-region

Cosmic Dawn III - 16/h cMpc sub-region

CoDa III luminosity functions

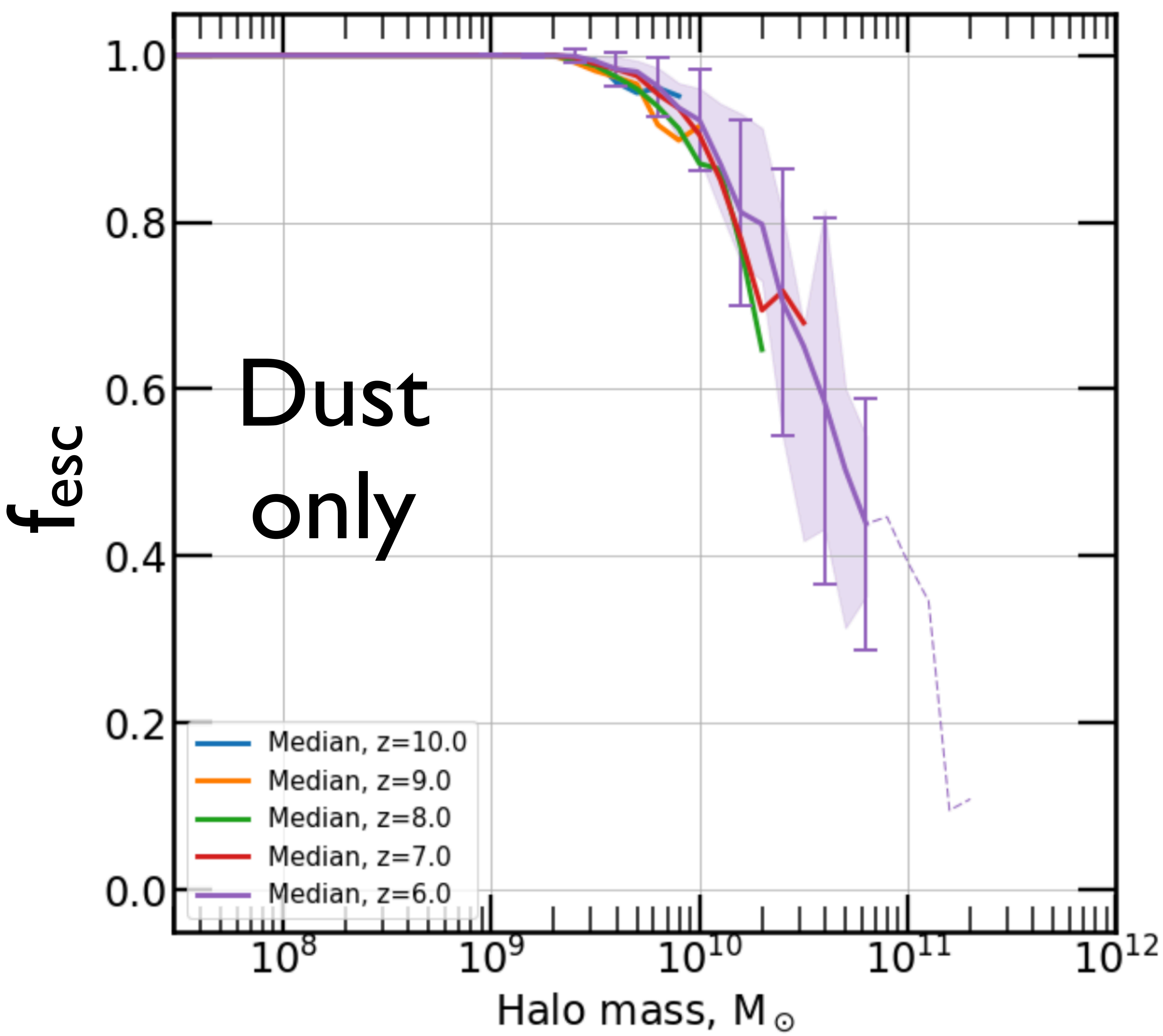


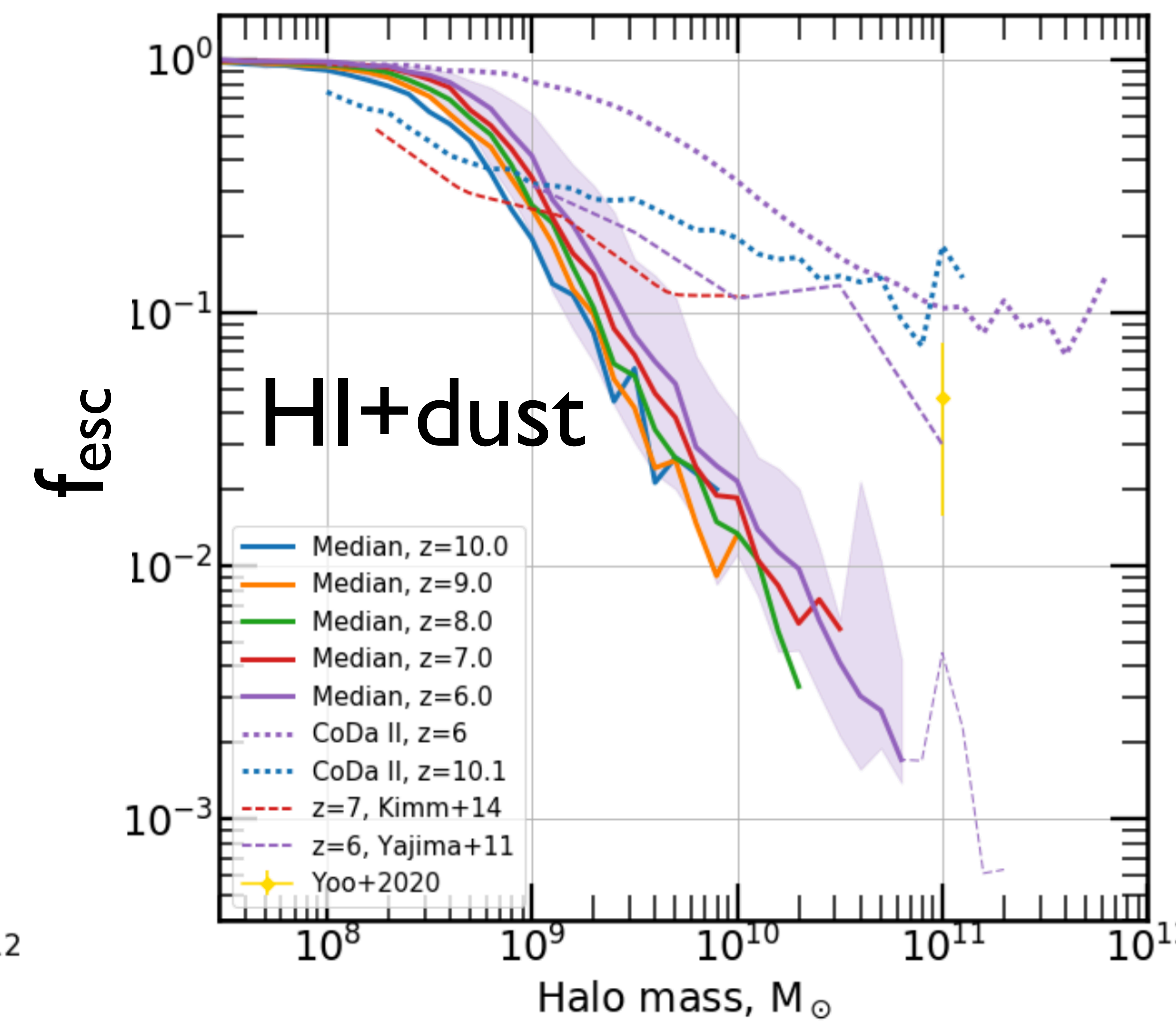
Lewis et al. 2024, in prep.

- Dust affects galaxies brighter than -19
- Dust crucial to reconcile bright-end UVLF (prevents overshooting as in CoDaII)
- Slight overproduction in -18,-20 range?
- Dust is important at all redshifts
- Fair agreement with pre-JWST observed LFs
- No agreement on highest z JWST detections
- Even dust-free galaxies do not match z>=12 JWST

Ionizing escape fractions and dust

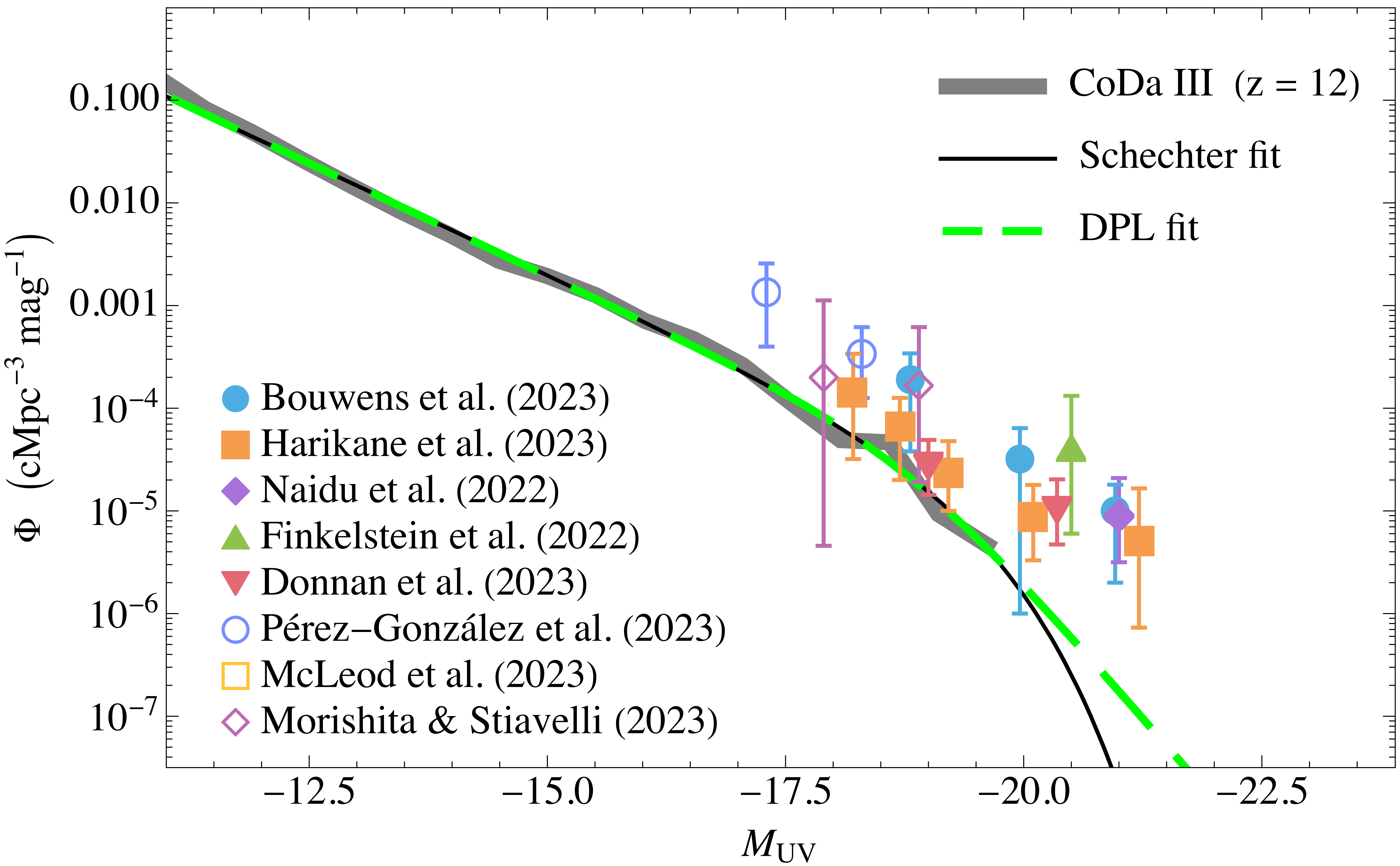
Lewis, Ocvirk et al. 2023
From DUSTiER = Cosmic Dawn III calibration sim





- Escape fraction decreases with increasing halo mass
- Absorption from dust becomes important for M= a few times $10^{10} M_\odot$
- At such masses the HI fesc is already very low => HI absorption dominates

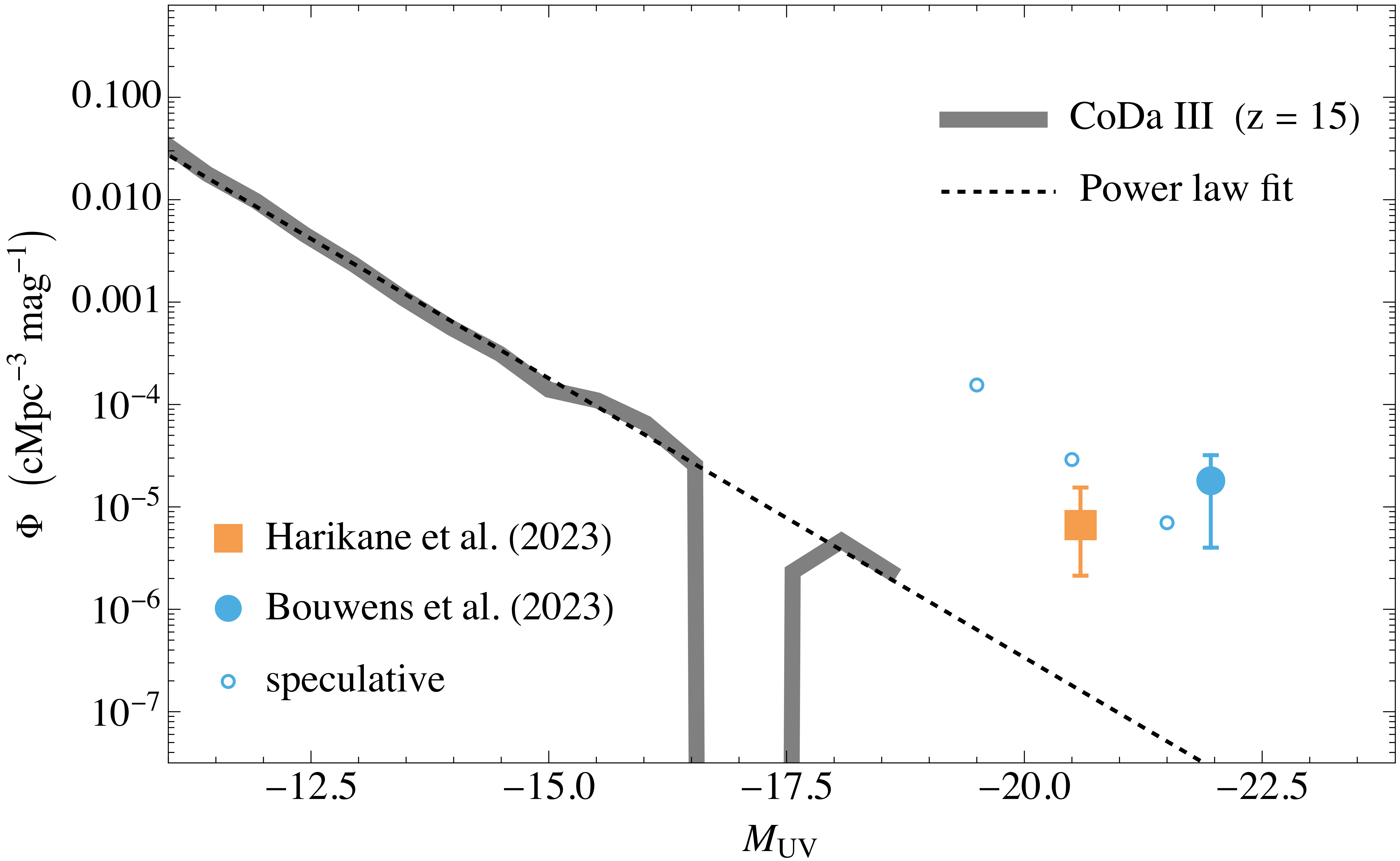
CoDa III LFs + literature update



- Due to redshift errors, JWST high-z LFs have been very uncertain
- Litterature follow-up by T. Dawoodbhoy.
- => mild tension at z=10-12

courtesy T. Dawoodbhoy

CoDa III LFs + literature update

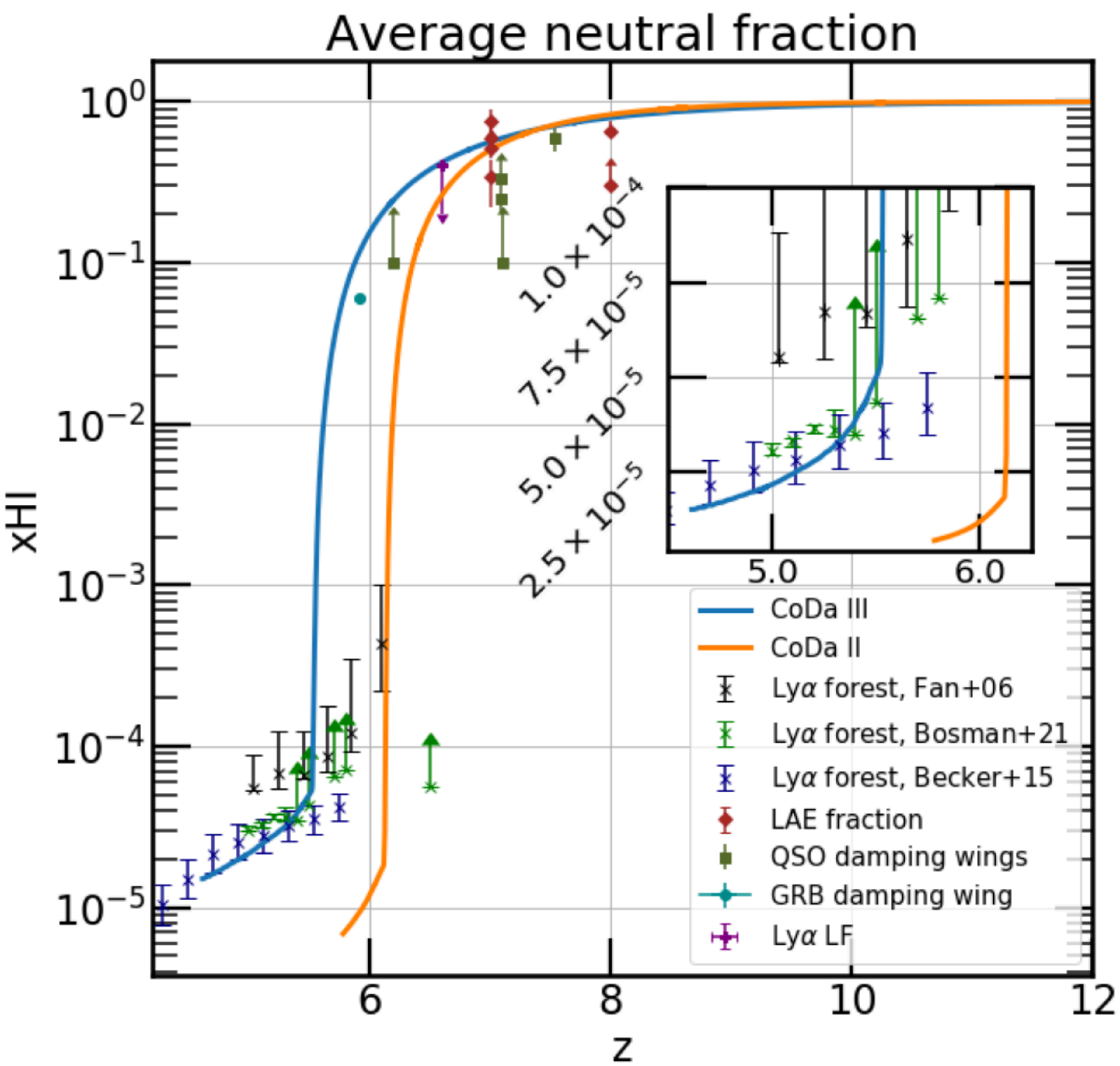


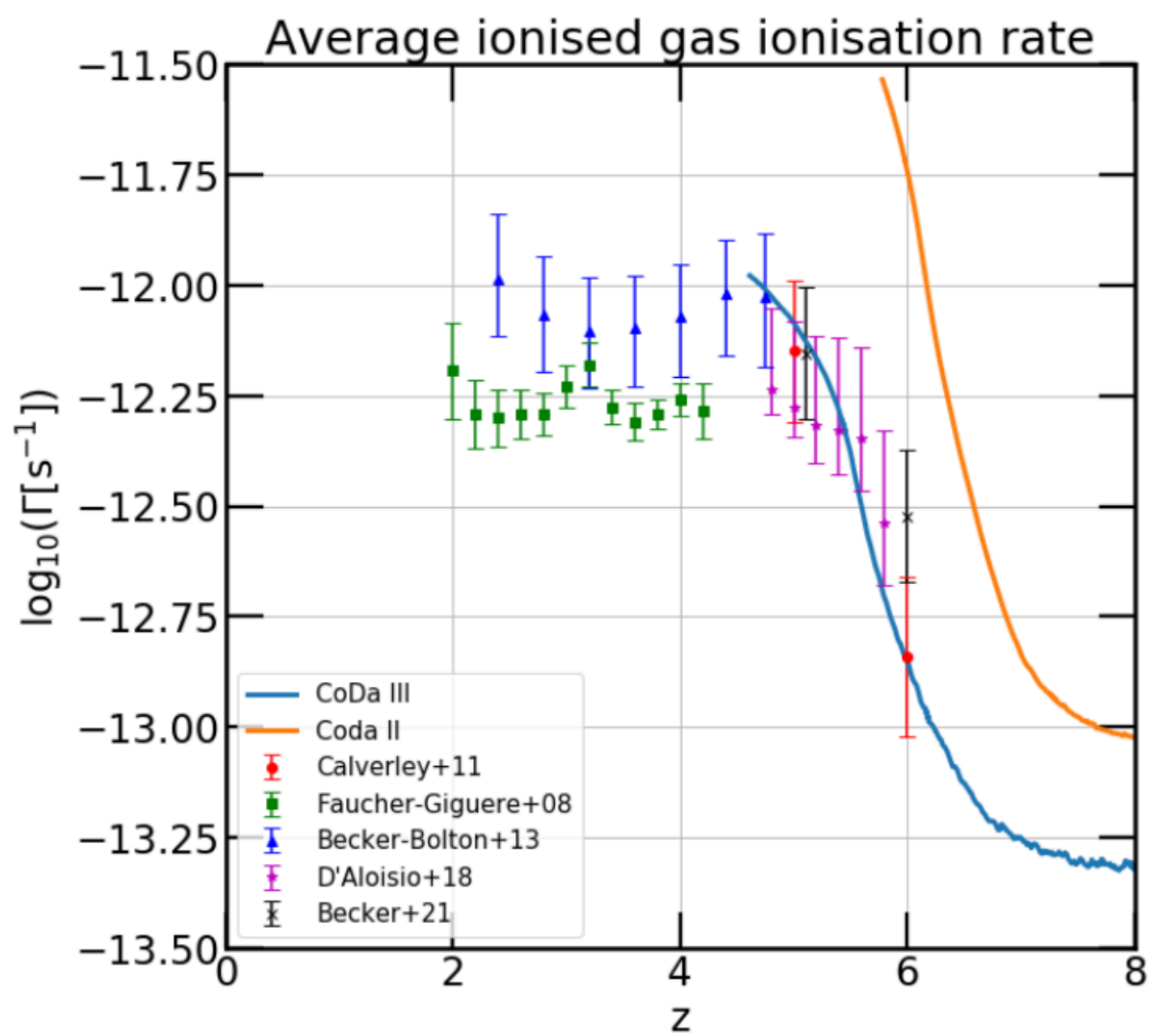
- Due to redshift errors, JWST high-z LFs have been very uncertain
- Litterature follow-up by T. Dawoodbhoy.
- => less tension at z=10-12, but tension at z=15 remains

courtesy T. Dawoodbhoy

Cosmic Dawn III - State of the IGM

Lewis et al. 2022

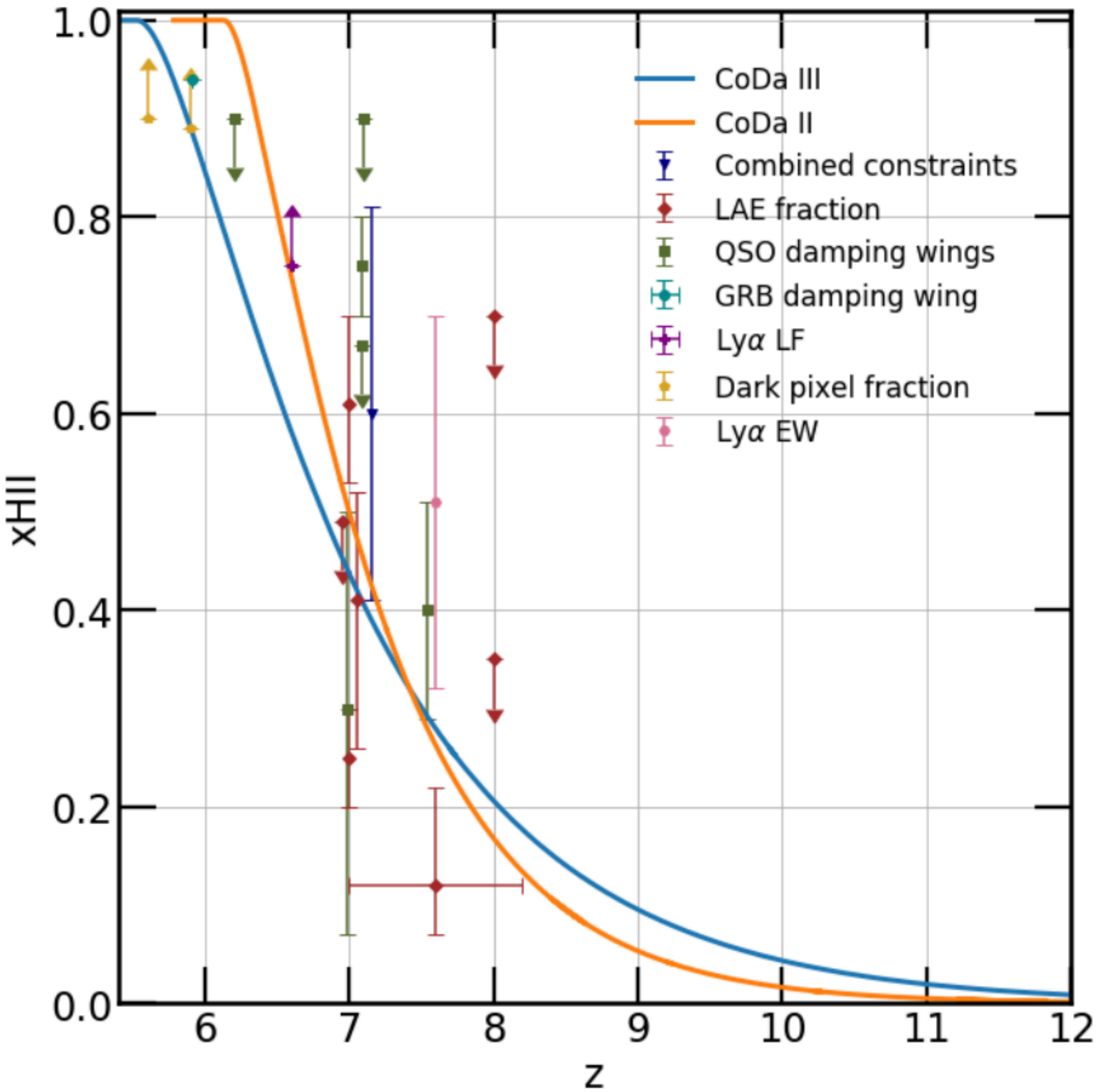


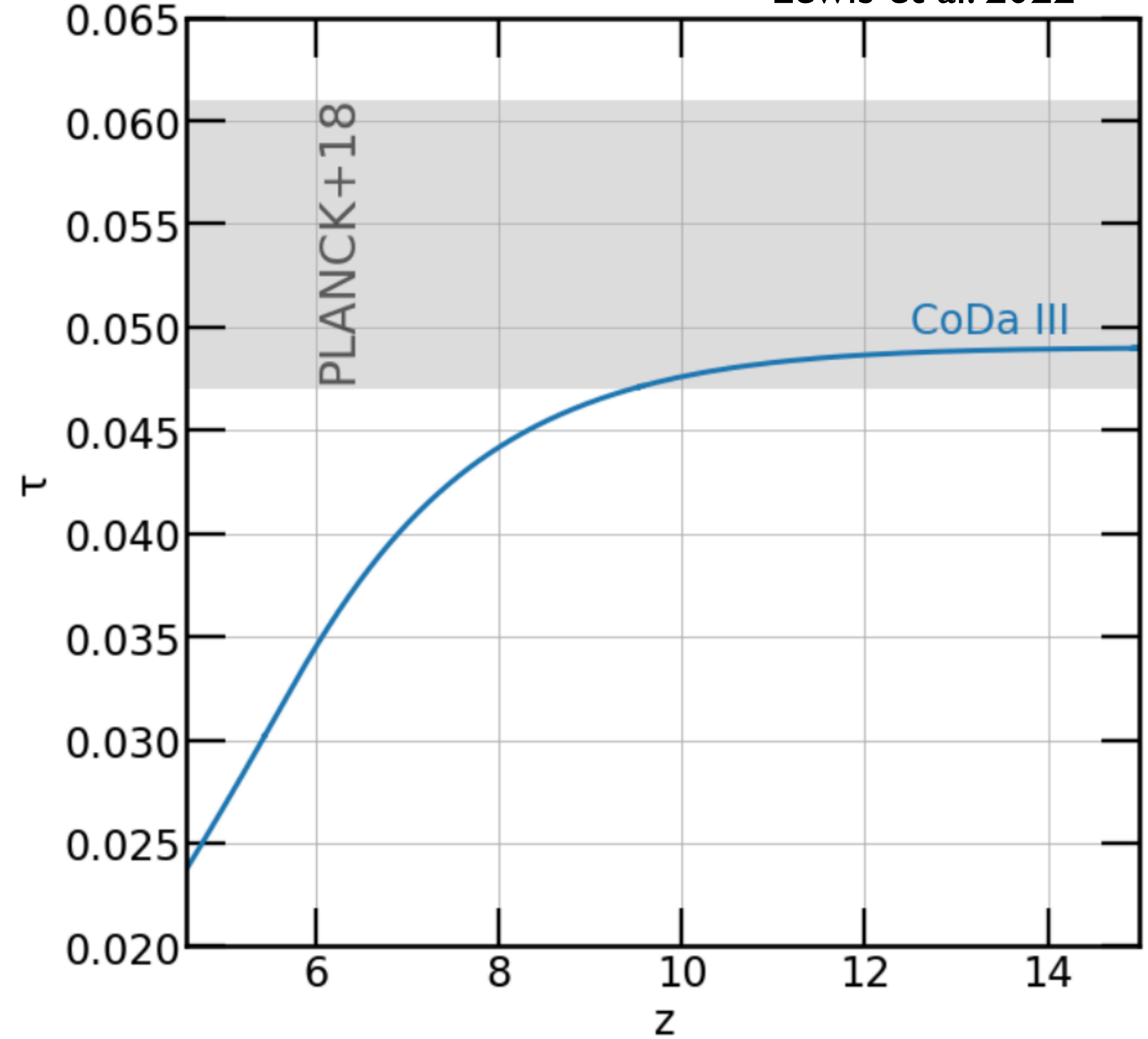


- CoDa II run failed hard in neutral fraction evolution and ionization rate
- CoDa III gives much better agreement. (also in mfp) Why?
- Observational estimates have been revised, but thats not all

Cosmic Dawn III reionization history

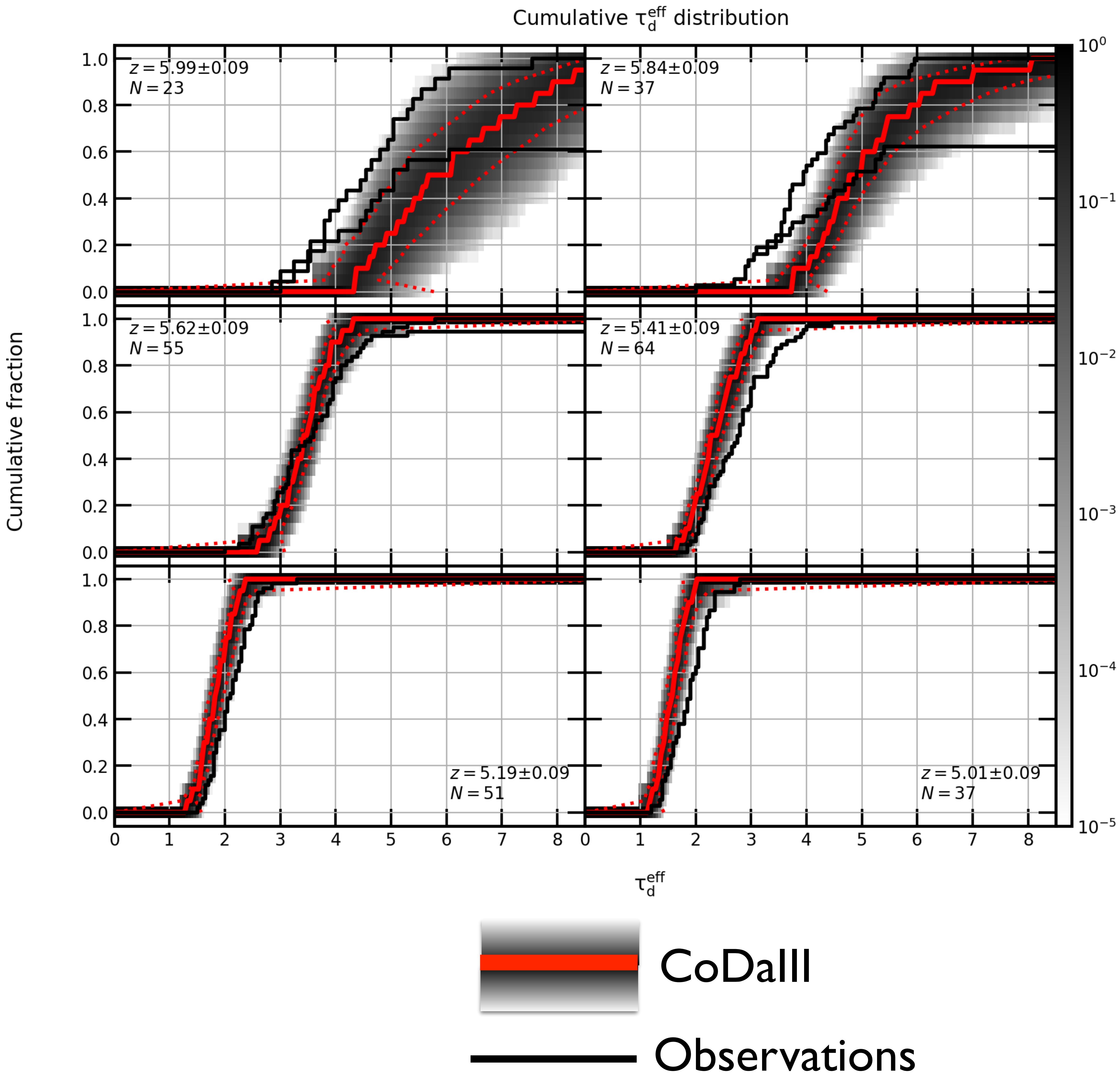
Lewis et al. 2022





- Reionization history fully compatible with current observational constraints
- Reionization finishes at z=5.5 (vs 6.1 in Cosmic Dawn II)
- Despite late reionization, good agreement with Planck electron-scattering τ

CoDa III: Lyman alpha opacities PDF



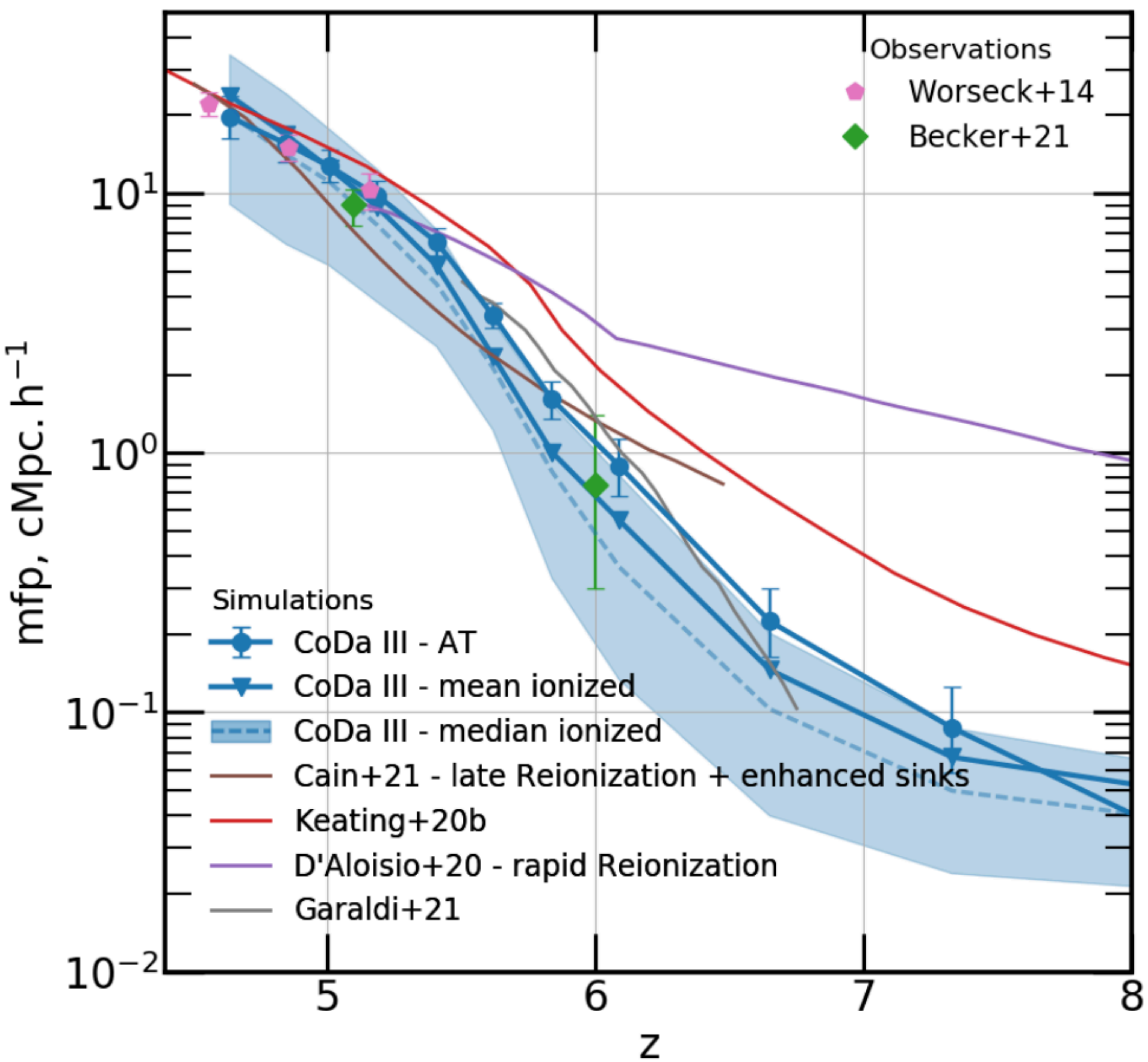
Lewis et al. 2024, in prep.

Overall much better agreement than CoDaII

- z=6: slightly too opaque
- z=5: slightly too transparent
- => Likely consistent with small xHI(z) offset?
- Other possible causes:
  - => small box effect?
  - => Missing ionising rate fluctuations?

CoDa III: The ionizing mean free path

Lewis+2022



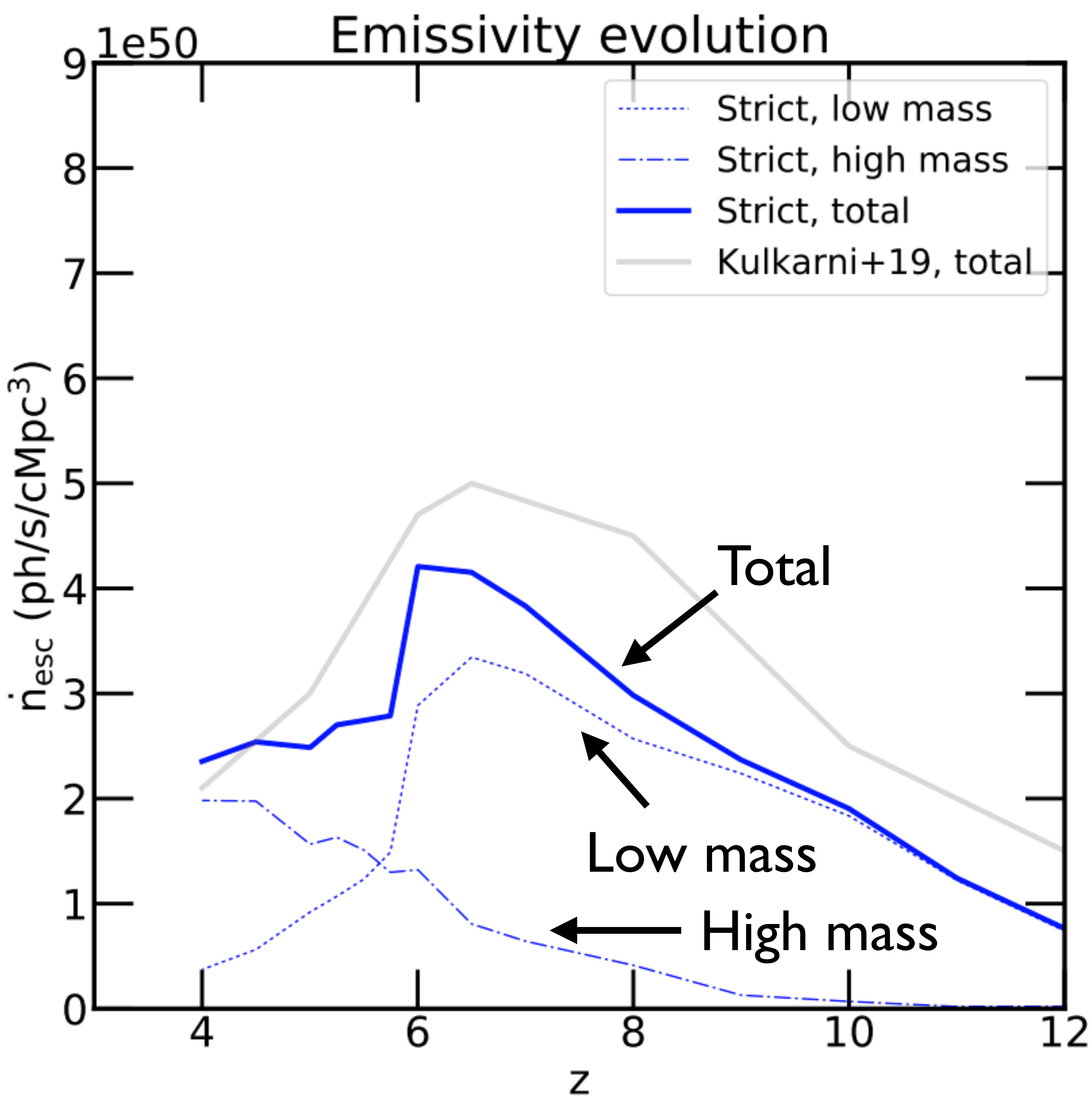
Becker 2021 mfp significantly below models at the time.

But very good agreement with CoDa III.

Very strong evolution with z, different estimates:

- AT: Average Transmission
- Neutral mode not observable
- => Mean/median ionized mode
- shaded: 25-75 percentile

The rise and fall of cosmic emissivity



Ocvirk et al. 2021

8 h^{-1}Mpc CoDa III **calibration**

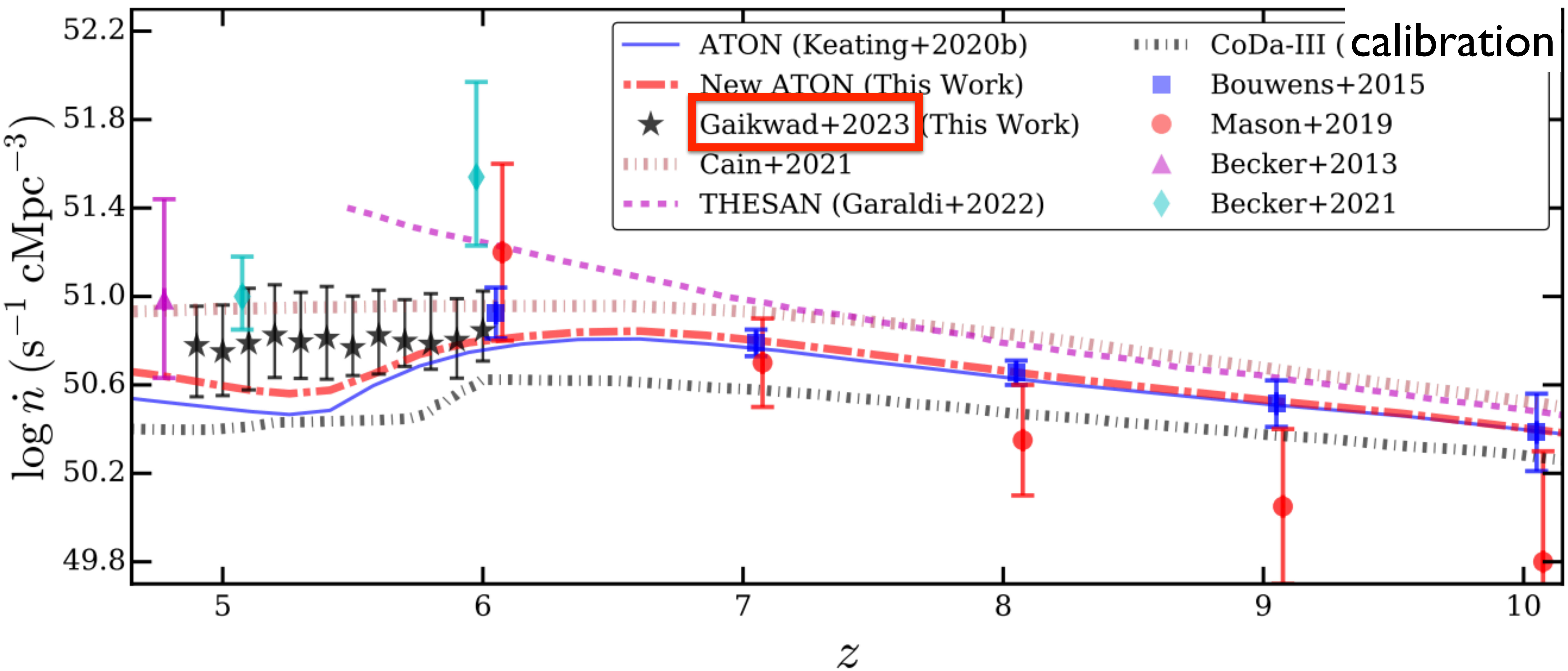
Drop at z>6 occurs naturally in Cosmic Dawn III as:

- Low mass (2×10^9 $M_\odot$) haloes:
  - have high f_{esc}
  - => drive reionization at z>6
  - are radiatively suppressed
- High mass haloes:
  - have low f_{esc}
  - have slow build-up
  - => can not compensate

$T<T_{sf} = 2\times10^4$K for star formation is key to obtain this behaviour

Sharp drop = small box effect?

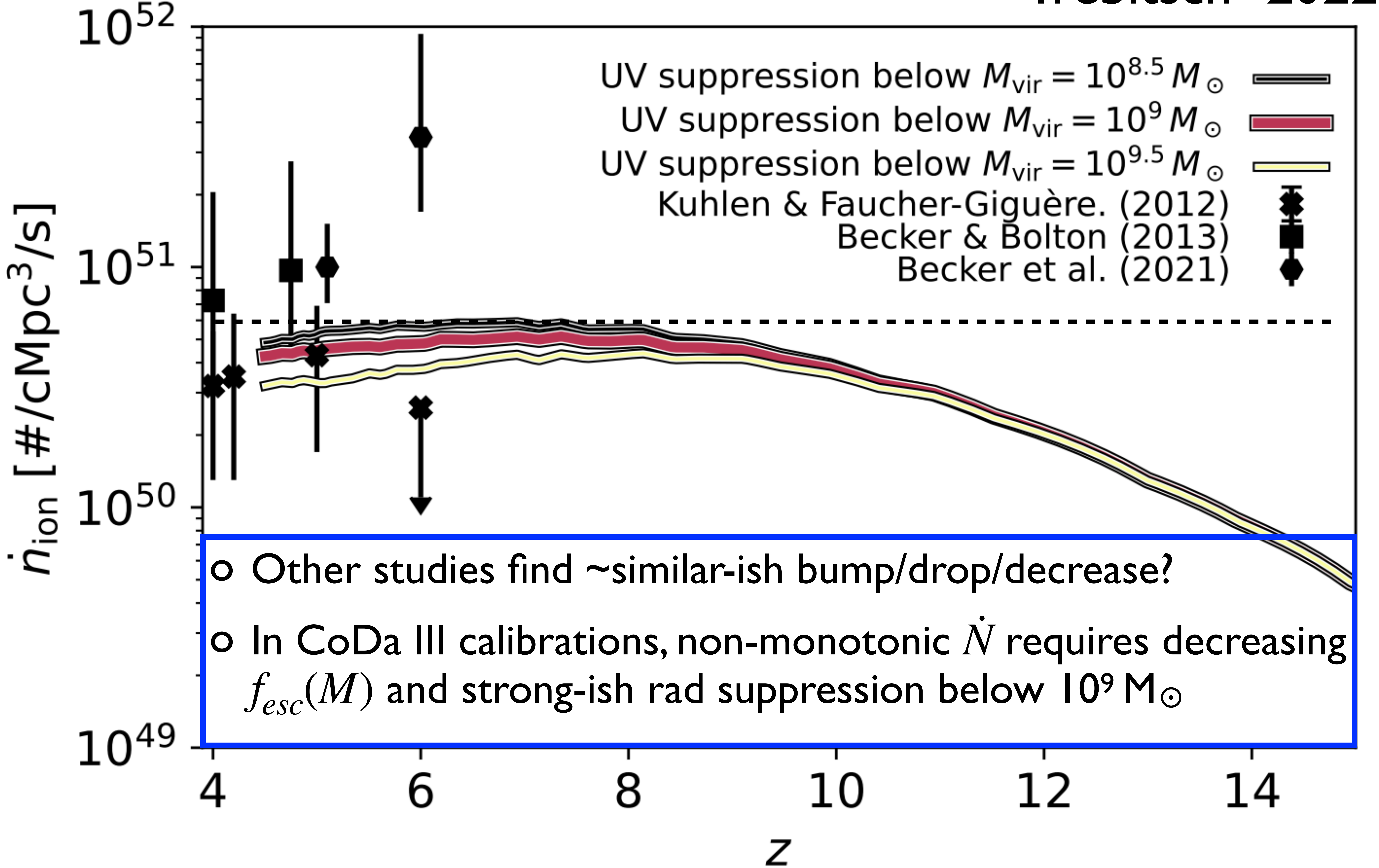
Cosmic ionizing emissivity



- Other studies find ~similar-ish bump/drop?
- In CoDa III calibrations, non-monotonic $\dot{N}$ requires decreasing $f_{esc}(M)$ and strong-ish rad suppression below 10^9 $M_\odot$

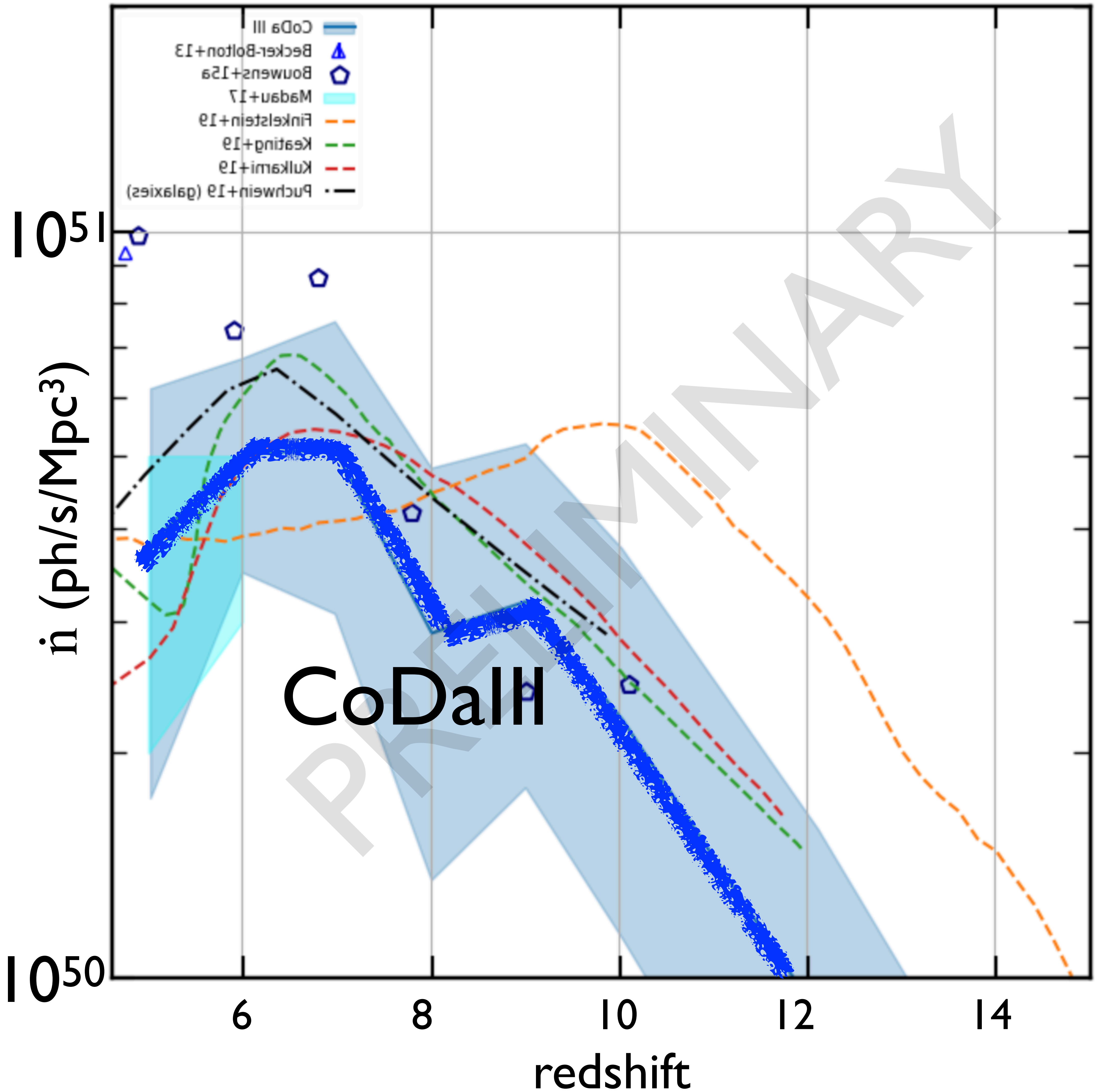
Cosmic ionizing emissivity

Trebitsch+2022



- Other studies find ~similar-ish bump/drop/decrease?
- In CoDa III calibrations, non-monotonic $\dot{N}$ requires decreasing $f_{esc}(M)$ and strong-ish rad suppression below $10^9\,M_\odot$

The rise and fall of cosmic emissivity



Ocvirk+Lewis et al. 2024 in prep.
64 h^{-1}Mpc CoDa III full box

Drop at z>6 occurs naturally in Cosmic Dawn III as:

- Drop at z=6 confirmed in Cosmic Dawn III full box (~100Mpc)^3
- Large variance
- Drop still visible despite larger volume and patchy reionization
- compatible with semi-analytical literature

Summary

- **Cosmic Dawn III** simulation is the largest fully coupled Radiation-Hydrodynamics EoR galaxy formation simulation ever made.
- Good match with galactic and IGM observables, pre-JWST Luminosity functions, reionization history, τ, Hydrogen ionizing rate, LyC mean free path, and now also neutral fraction at z<6.
- Dust has a strong impact on LF but not necessarily on escape fractions
- 'Vanilla' high-z galaxy pop, tension with JWST at z>10
- bump/drop/break in cosmic ionising emissivity $\dot{N}$ persists in full box
  - Potentially linked to rad suppression and $f_{esc}(M)$ (in CoDa sims)
  - but not only…
- Can we test rad suppression ? requires reaching M_{AB1600}=-11 at z=6-5

- Coming up: revisiting photon budget, escape mechanism, Tr(R) (cf. Kashino)
- work in progress: new methods for RT, beyond M1

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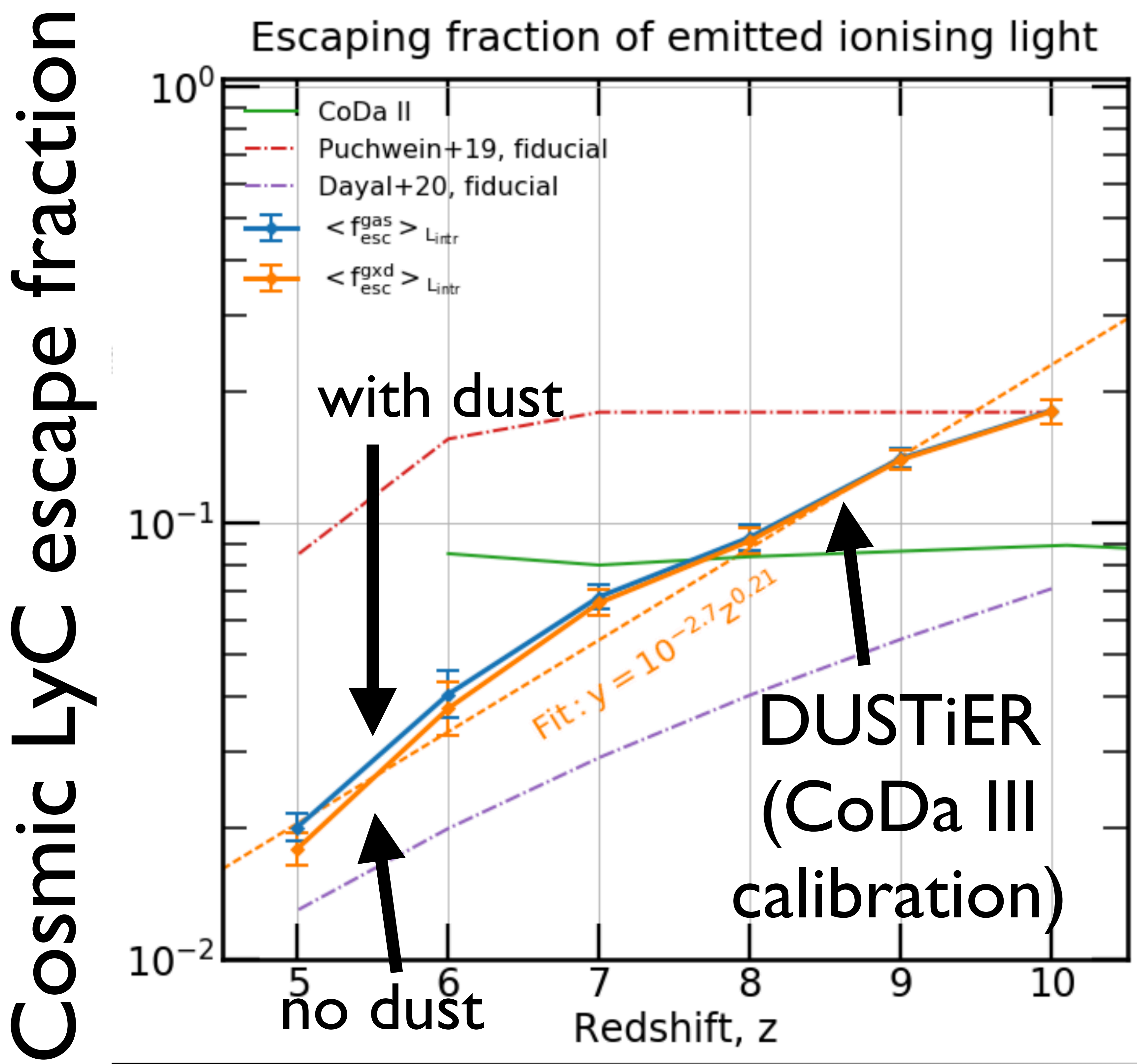
The bump/drop/break in $\dot{N}$: alternatives

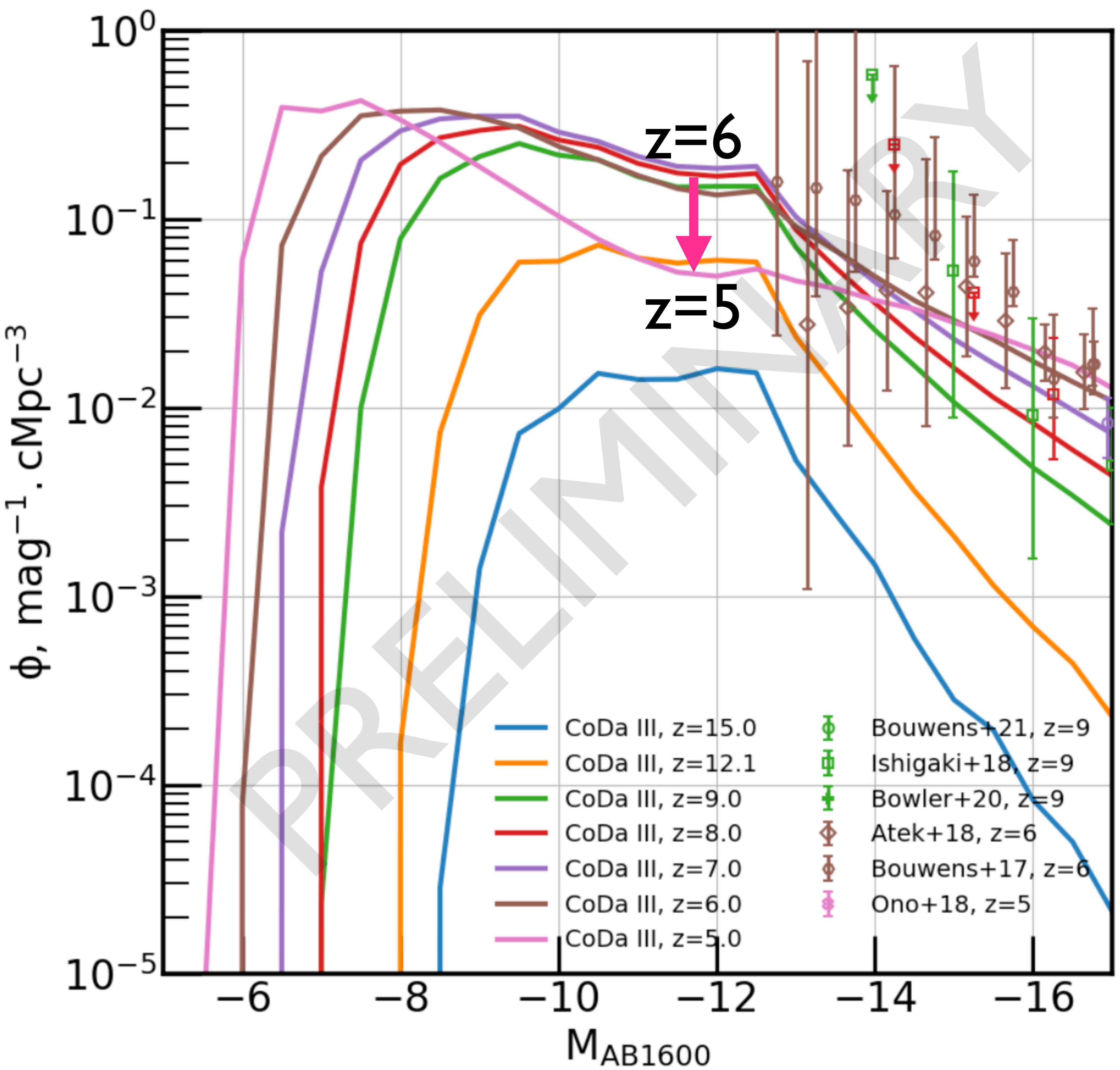
- Suppression mass is poorly constrained, but many other aspects of high-z universe modelling are uncertain:
  - high-z IMF / PopIII properties and transition to PopII?
  - Missing IGM structure? (clumping, Cain et al. 2021)
  - **Impact of dust?** (see below, DUSTiER, Lewis et al 2023)



- average f_{esc} weighted by L_{intr}
- Decreases with z driven by:
  - suppression of high f_{esc} galaxies (low mass)
  - High mass haloes with low f_{esc} increasingly dominating star formation budget (=> L_{intr})
- Accounting for dust absorption makes little difference

Smoking gun for rad. suppression a - high z (requires JWST)

Faint-end UV Luminosity Function
Cosmic Dawn III

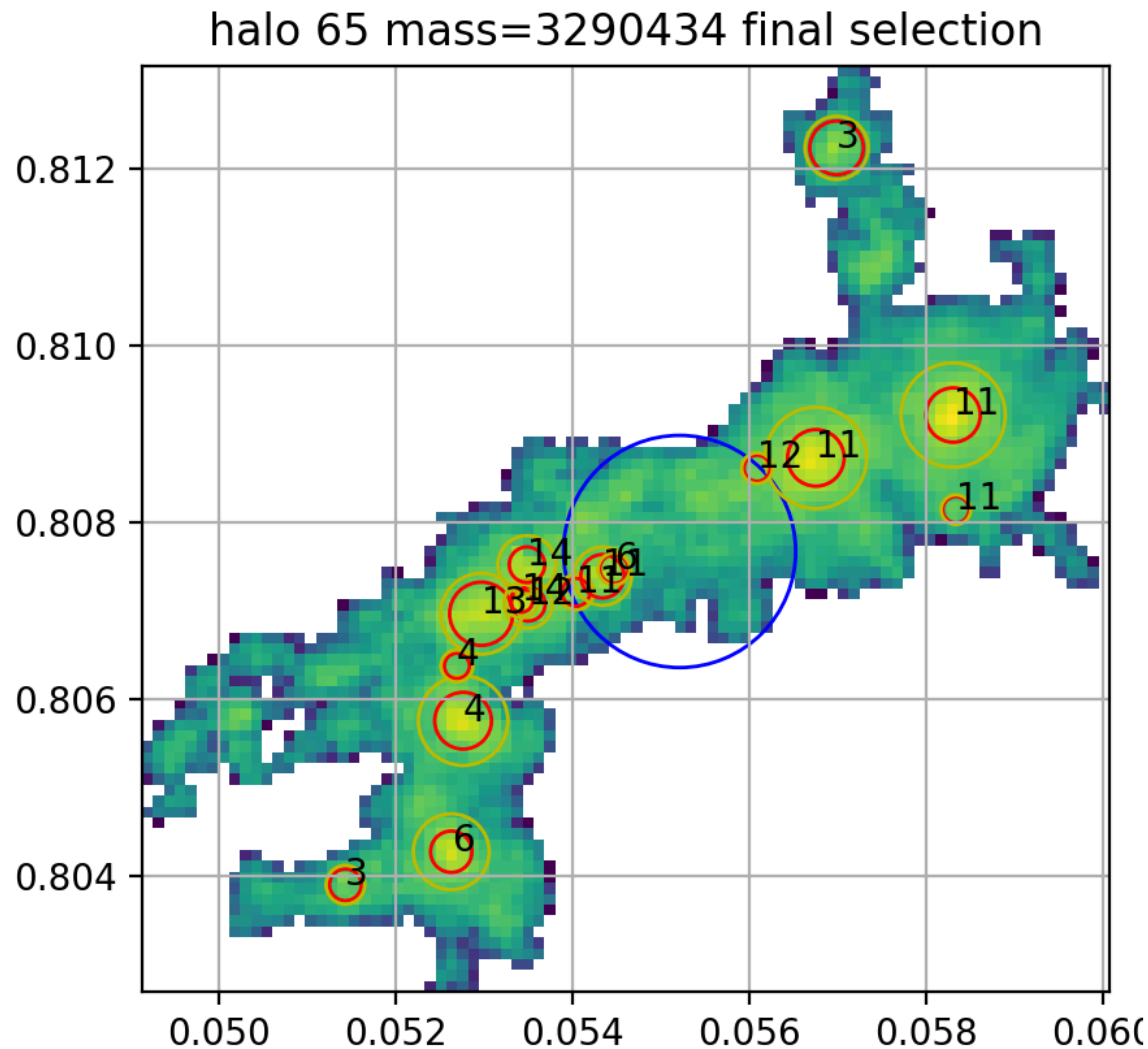


- Rad suppression causes drop in high-z faint-end LF
- Very large obs. uncertainties due to cluster mass model
- JWST should improve thanks to getting redshifts in these fields
- => How much the error bars will shrink?
- => How robust is our prediction to changes in:
  - Physics: source model (hardness), B fields, baryon drift, …
  - Numerics: dx, RT method

Work in progress

- segmentation / halo finding overhaul
- New methods for radiative transfer

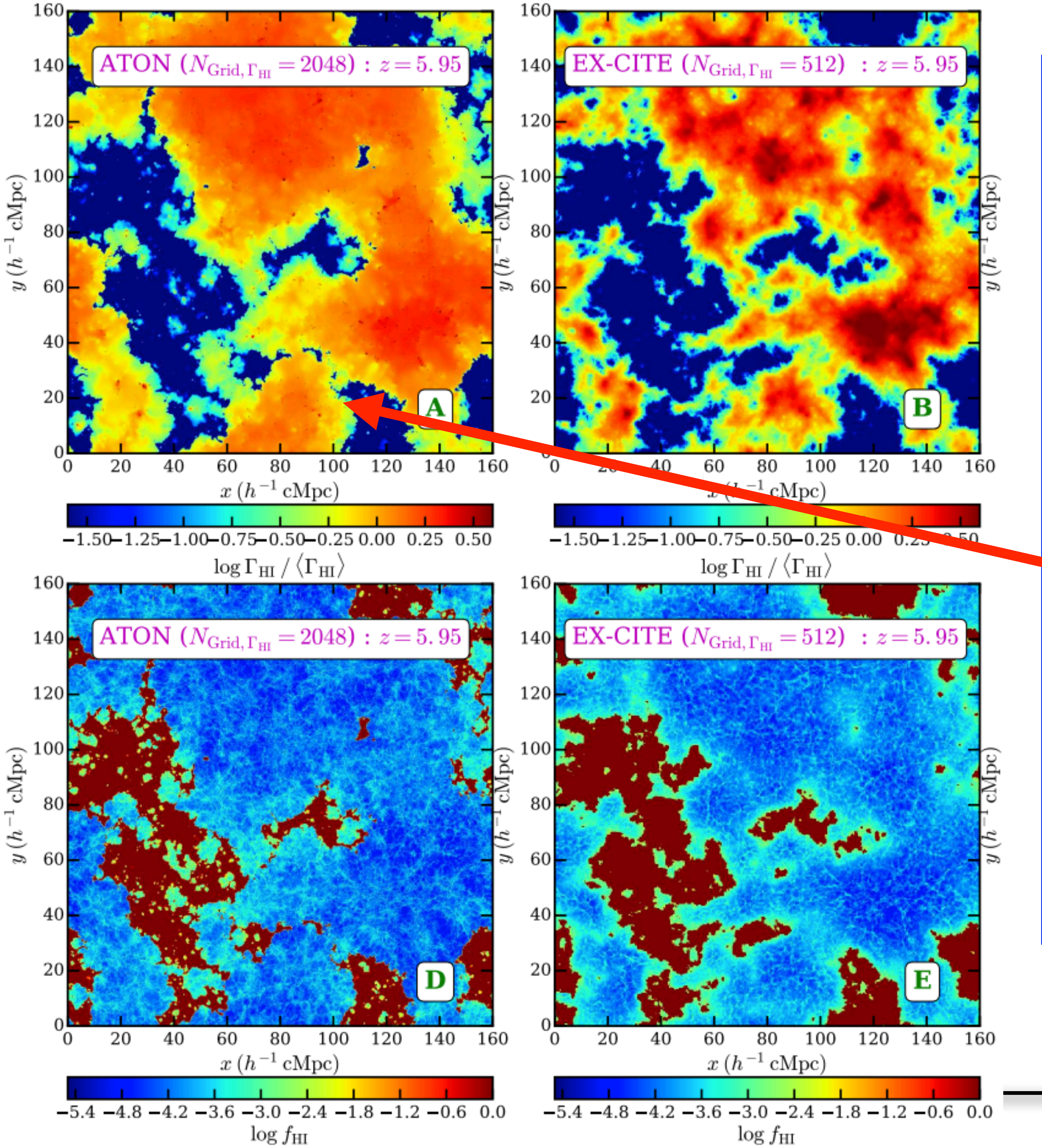
Segmentation / structure detection in very large simulations



Very bad for any galactic properties beyond M* (e.g. fesc)

- Halo detection / catalog is a significant fraction of a simulation compute budget
- With CoDaIII (8192^3) we tried:
  - PHEW => OOM
  - ROCKSTAR => OOM
  - pfof (Roy & Rasera) => runs but stripped down (vxyz)
- Main drawback: overlinking: one fof structure can contain many haloes
- => need to postprocess fof structures with rockstar, SoD/HaloMaker, in progress

Accuracy of radiative transfer methods in reio simulations?

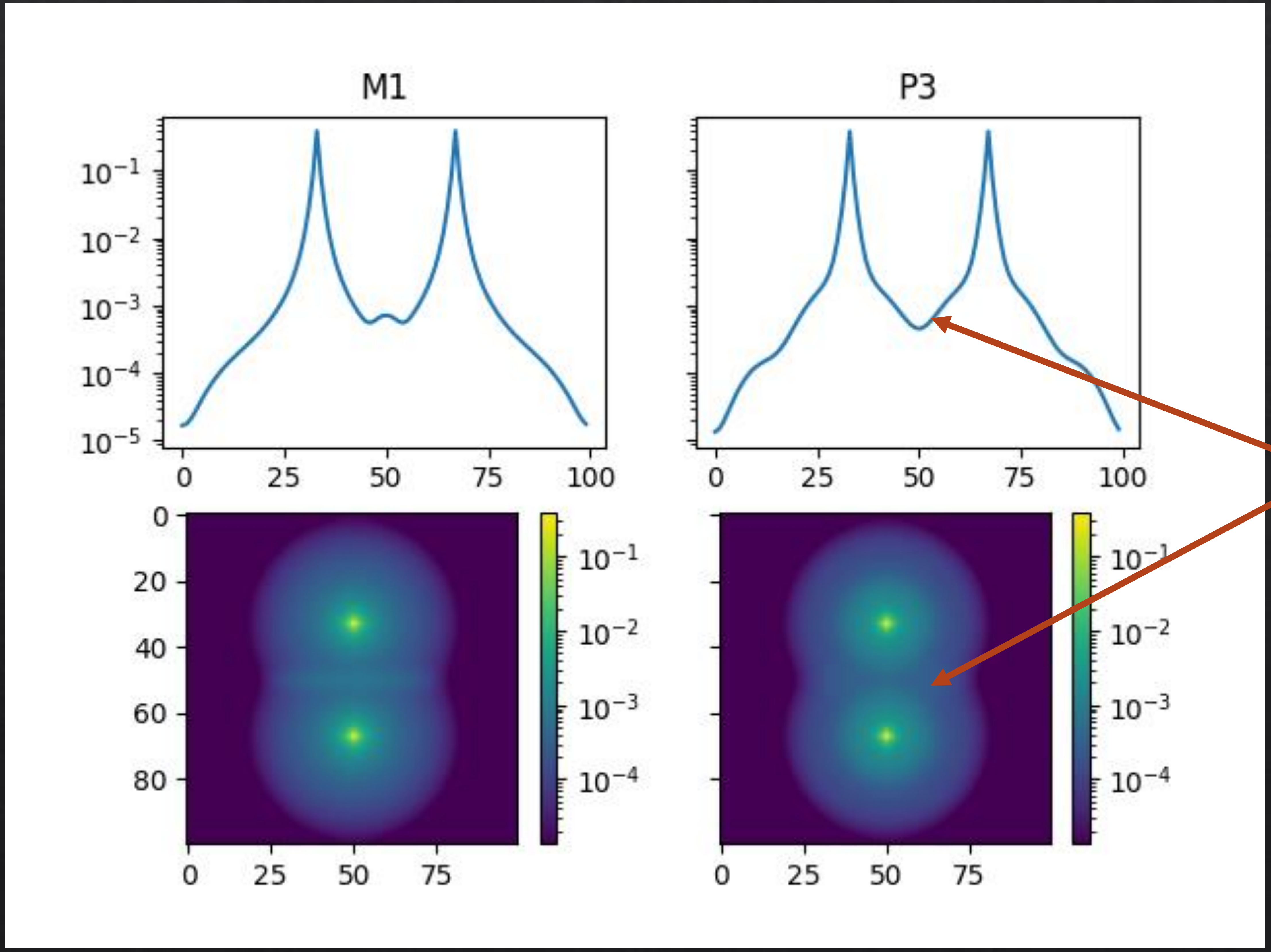


- Most galaxy formation sims use M1 for RT. in M1 photons are collisional ! => artefacts
  - pseudo-sources in crossing beams
  - Dark rings around sources
  - Missing small scale power in radiation fields (overly smooth)
  - over-ionized absorbers
  - … (Wu et al. 2021)
  - Gaikwad+ 2023

Towards new methods for radiative transfer in astro sims

M1 vs Pn: Continuous regime

Continuous response comparison profiles of 3D M1 and P3



- Single wave front for both models
- Same amplitude for both models
- Same integral for both models
- No pseudo source for P3
- Slight oscillation for P3
- No negative energy for P3

The Pn model

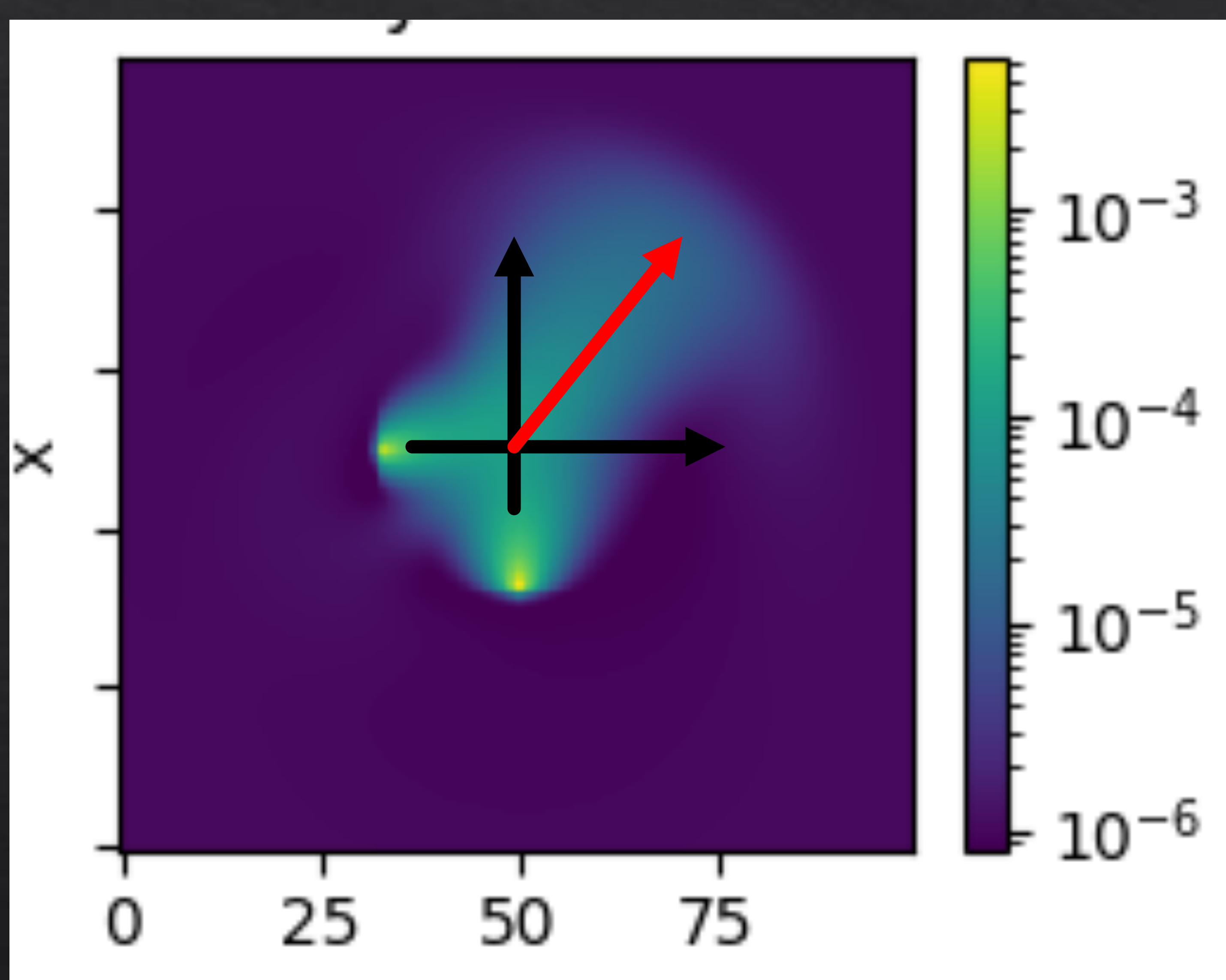
courtesy Mei Palanque, 2nd year PhD

Towards new methods for radiative transfer in astro sims

The Beam Problem

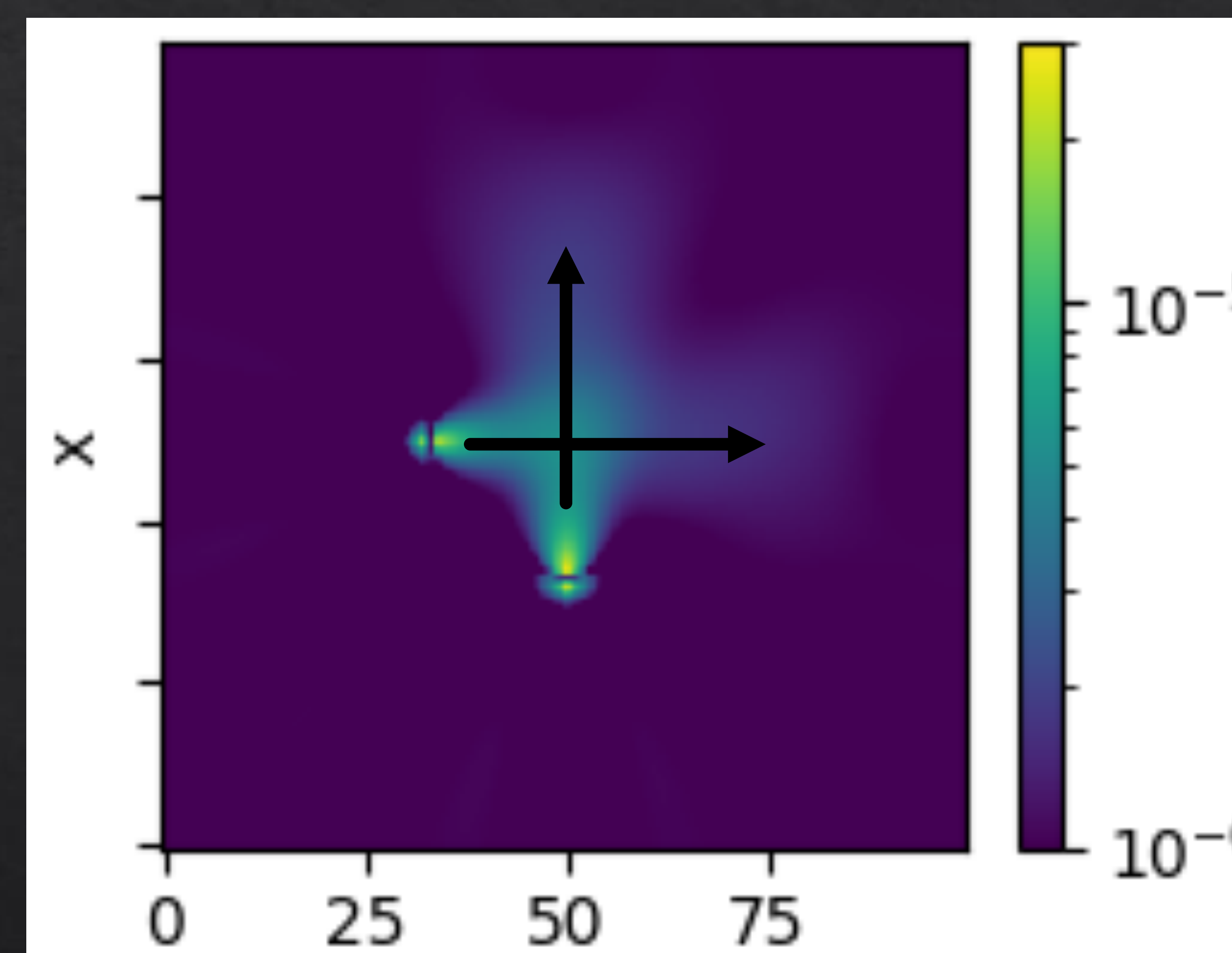
The Pn model

What we see vs what we expect



Simulation of two non isotropic continuous sources using the M1 model

Crossing of beams



Simulation of two non isotropic continuous sources using the P9 model (norm), cut below 1e-6

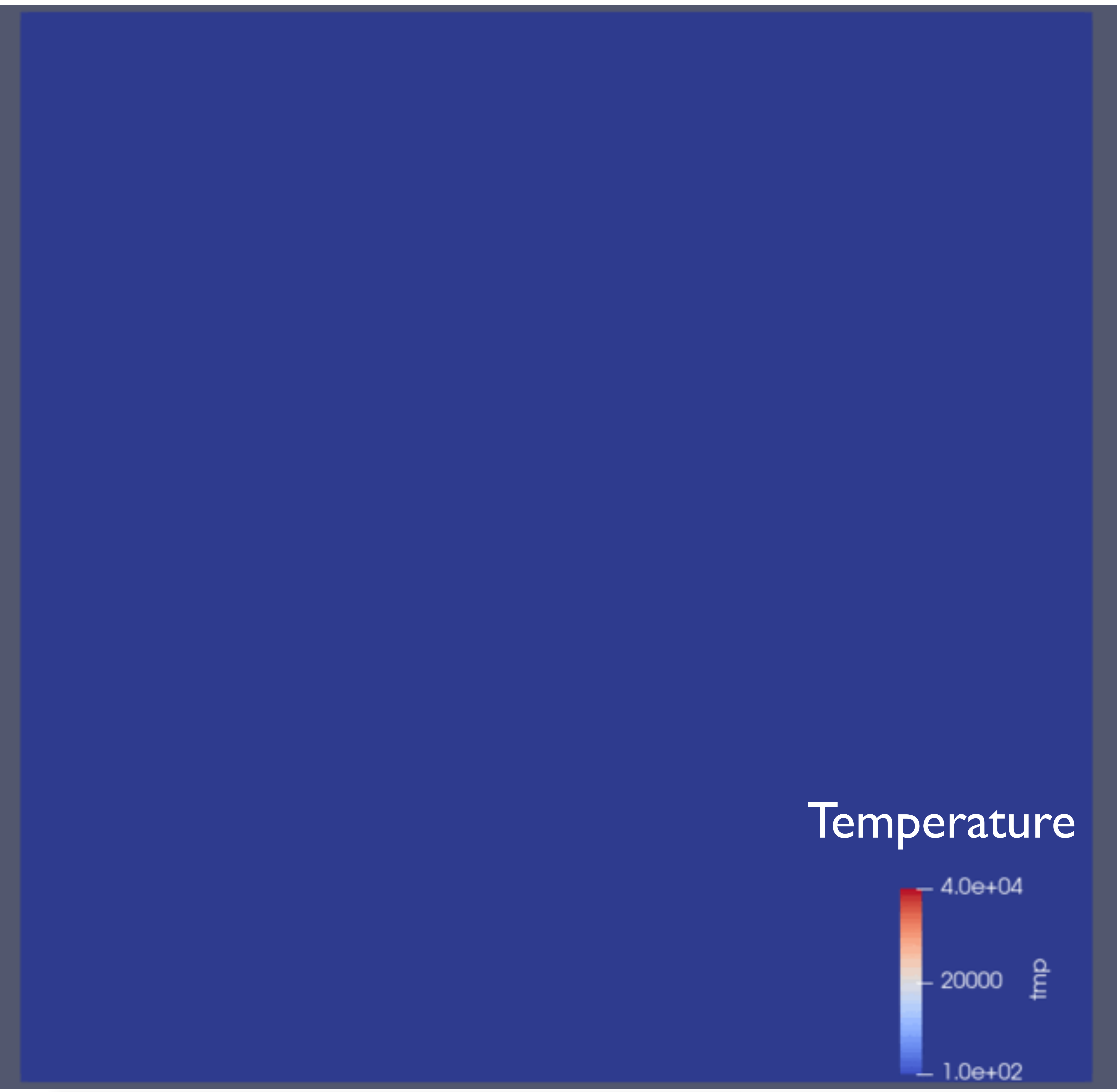
=> Can correct M1 issue, but at higher degree

M1: 4 moments (E,Fxyz)

P9: $(9+1)^2$ moments

courtesy Mei Palanque, 2nd year PhD

Towards new methods for radiative transfer in astro sims



- P_9 cost = 25 times M1
- =>GPU optimization:
- On top of RKMS: Reduced Kinetic Model Solver
- Collaboration with P. Gerhard (maths Strasbourg)
- Implemented chemistry into RKMS + dim/adim of fields
- OpenCL:
  - more general than CUDA (i.e. not limited to NVIDIA)
- <= Stromgren sphere with P9 RKMS

courtesy Mei Palanque, 2nd year PhD

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- 'Vanilla' high-z galaxy pop, tension with JWST at z>10
- bump/drop/break in cosmic ionising emissivity $\dot{N}$ required?
  - Potentially linked to rad suppression and $f_{esc}(M)$ (in CoDa sims)
  - but not only…
- Can we test rad suppression ? requires reaching M_{AB1600}=-11 at z=6-5

- Coming up: revisiting photon budget, escape mechanism, Tr(R) (cf. Daichi)
- work in progress: new methods for RT, beyond M1

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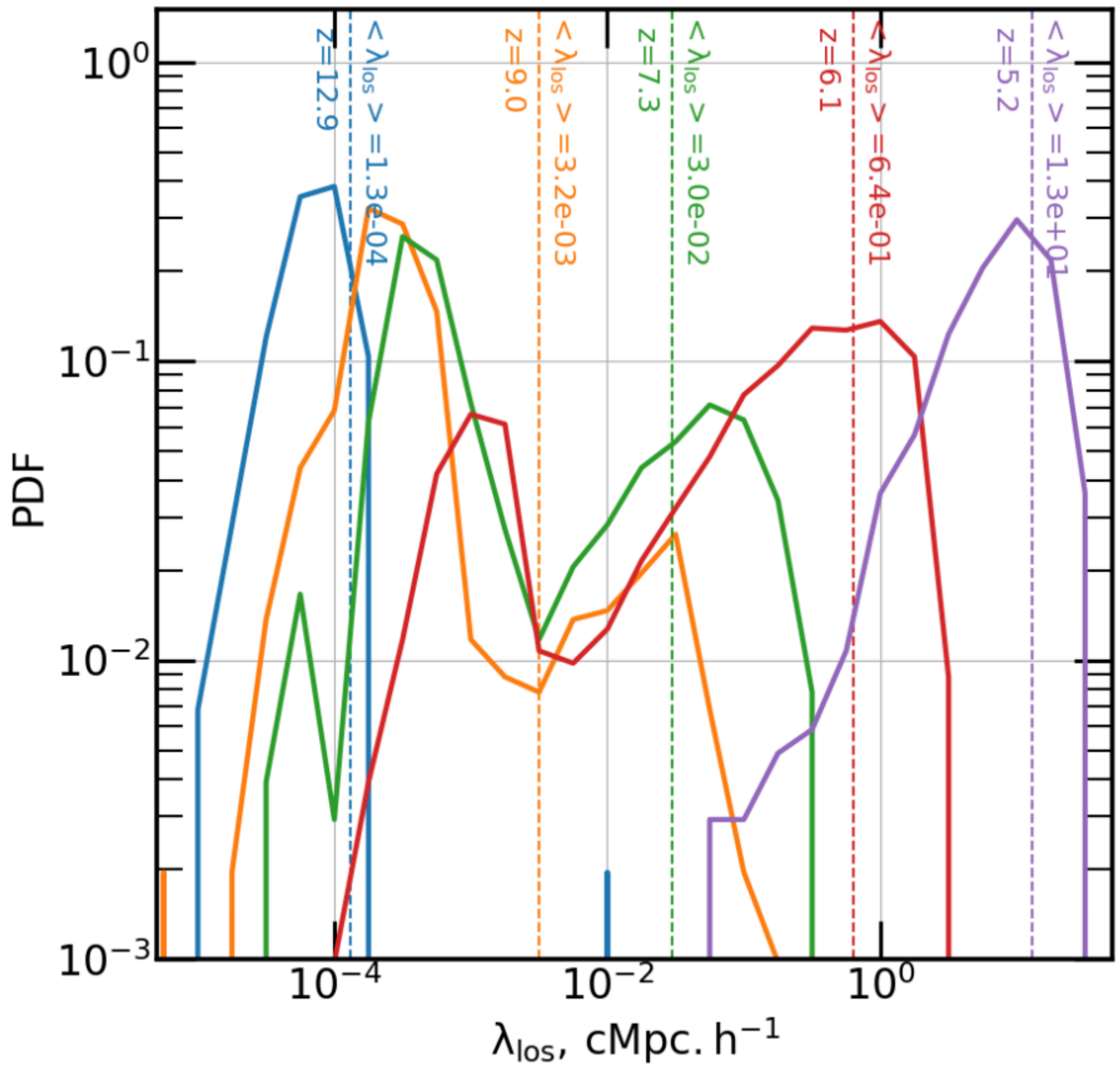
CoDa III: The ionizing mean free path

Lewis+2022

Neutral | Ionized



Ionizing Mean free path

Mean free path at 912 Å measured along 4096 LoSs

- Strong evolution with z
- Unimodal vs bimodal
- Bimodality reflects coexistence of neutral vs ionized regions
- method of averaging affects the estimate

Summary

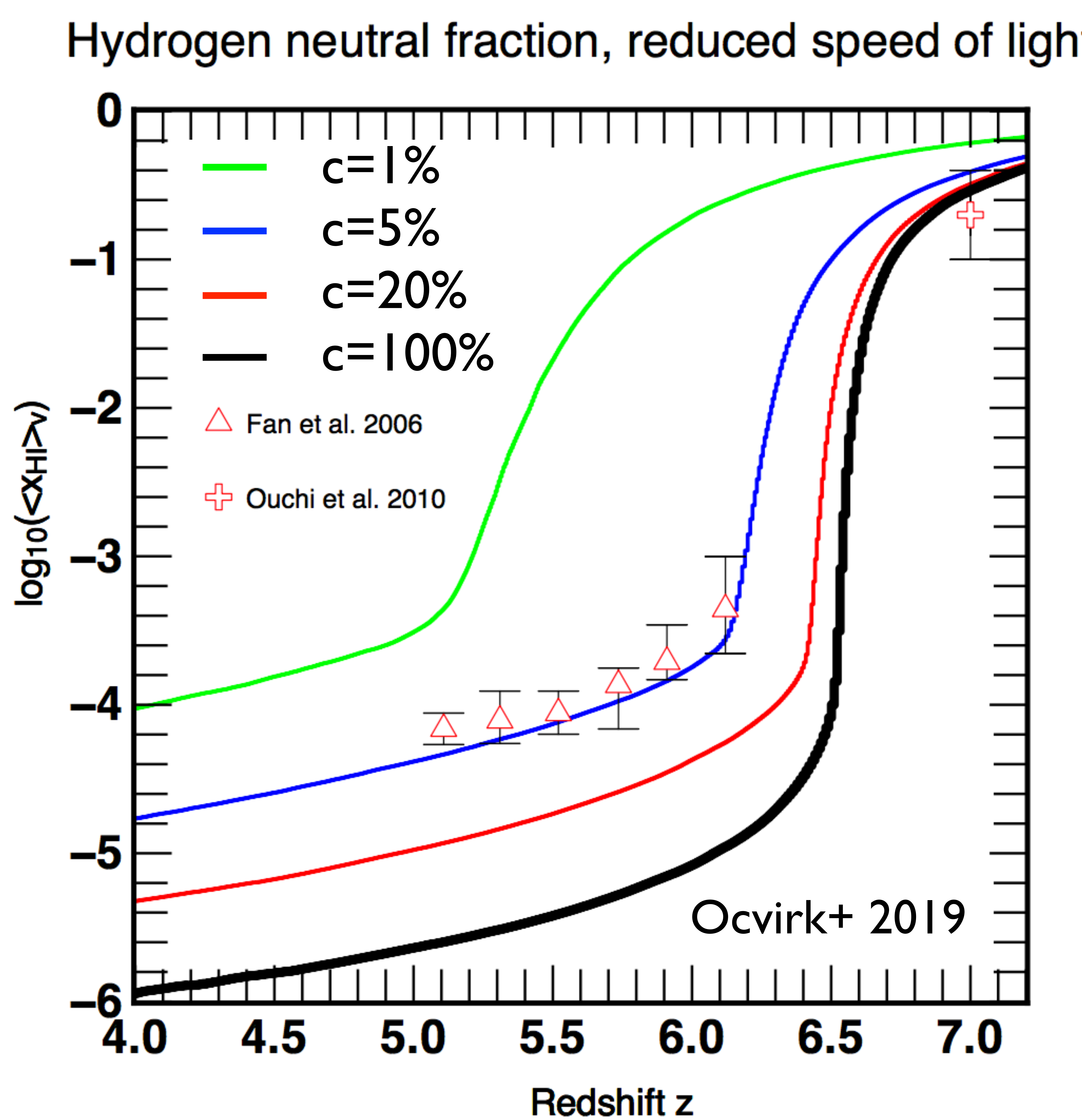
- **Cosmic Dawn III** simulation is the largest fully coupled Radiation-Hydrodynamics EoR galaxy formation simulation ever made.
- Good match with currently available observables, pre-JWST Luminosity functions, reionization history, τ, Hydrogen ionizing rate, LyC mean free path, and now also neutral fraction at z<6.
- 'Vanilla' high-z galaxy pop (as compared to e.g. JWST)
- Newfound agreement in x_{HI} involves late z_{rei}=5.5 and non-monotonic cosmic ionising emissivity $\dot{N}$ (bump/drop/break?)
  - Potentially linked to rad suppression and $f_{esc}(M)$ (in CoDa sims)
  - but not only…
- Rad suppression can be tested: M_{AB1600}=-11 at z=6-5 or at z=0 with LSST

- Work in progress on lots of topics
- Interested in using CoDaIII data? => pierre.ocvirk@astro.unistra.fr

The average neutral fraction and the speed of light

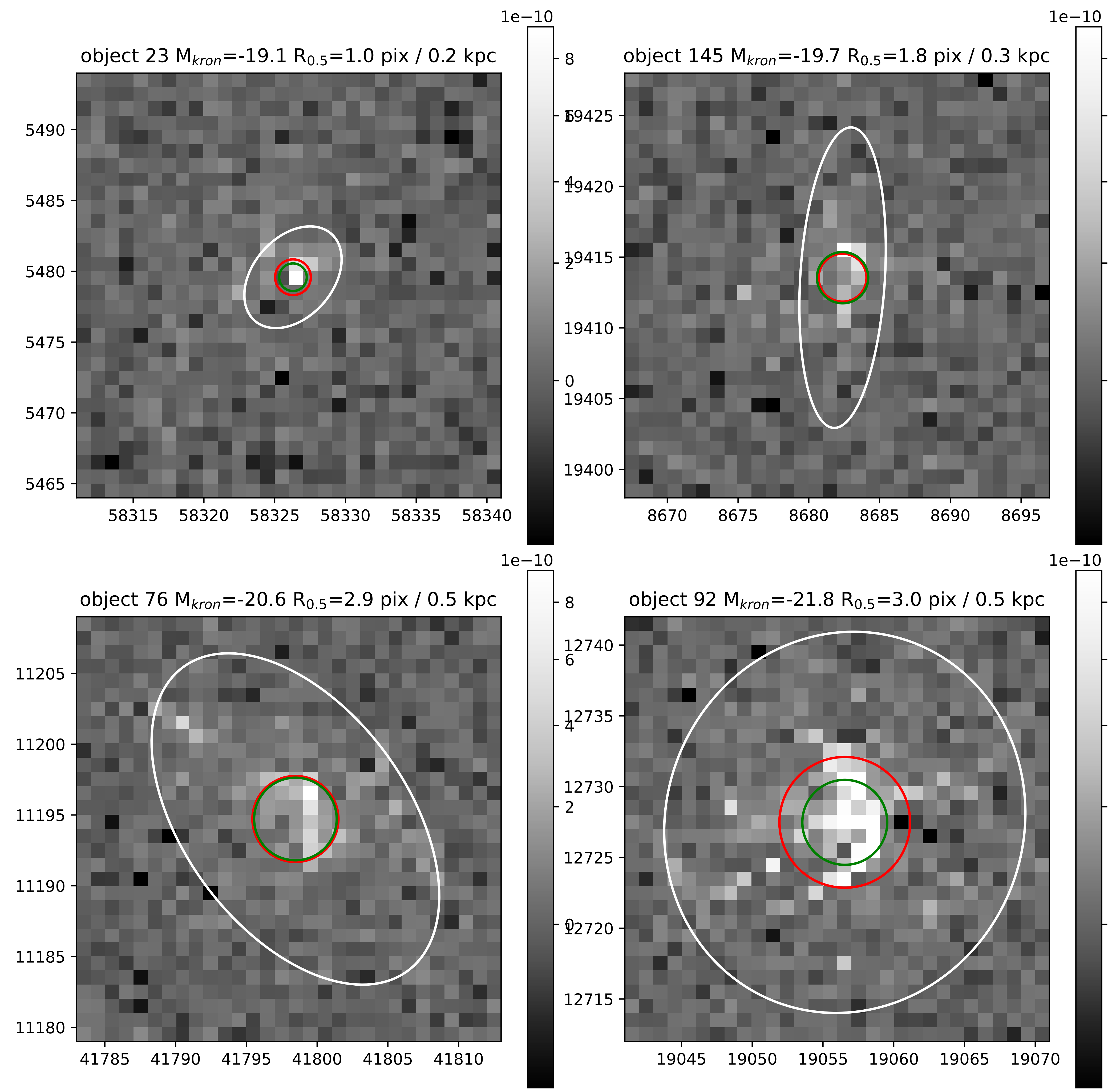
- Reduced speed of light approximation (RSL):
  - Code much faster
  - Easy to implement
- Impact on results?
- RAMSES-CUDATON uses c=1 thanks to GPU
- => good testbed for RSL

- Reducing the speed of light increases x_{HI}
- **The good agreement at c=5% vanishes for c=1**

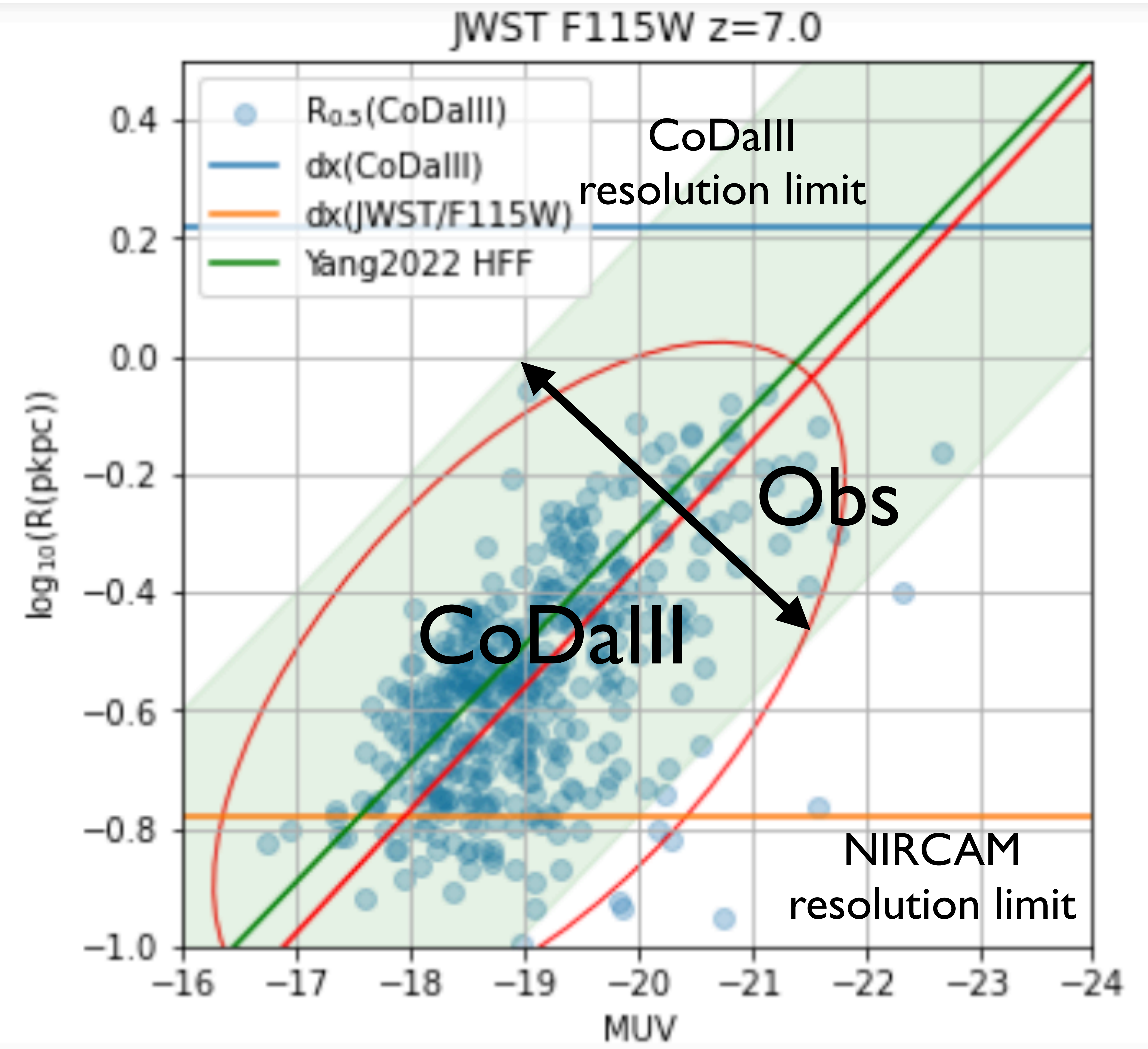


“Observing” Cosmic Dawn III galaxies with JWST

- At z=7, 1500 Angstrom falls into NIRCAM/F115W filter (0.031 arcsec)
- Make stellar flux map at JWST resolution at z=7
- (convolve with JWST PSF)
- Add noise, sigma=0.04 nJy per pixel
- Detect sources with python photutils, threshold=3*sigma
- (Deblend)
- UVLF? M-R relation?



Size-luminosity relation at z=7



- Half-light radius vs MAB_{1500}
- Almost perfect agreement with observations (Yang2022)???
- Considering measured sizes are 3-10 times smaller than CoDa III force resolution
- => To do:
  - convolve with PSF
  - deblend
  - perform Sersic fitting to get effective radius

Key results summary

- **Cosmic Dawn III** simulation is the largest fully coupled Radiation-Hydrodynamics EoR galaxy formation simulation ever made.
- Good match with currently available observables, Luminosity functions, reionization history, τ, Hydrogen ionizing rate, and now also neutral fraction at z<6.
- Newfound agreement involves a drop in cosmic ionising emissivity

- **DUSTiER**'s UV LFs, slopes and evolution compatible with observations
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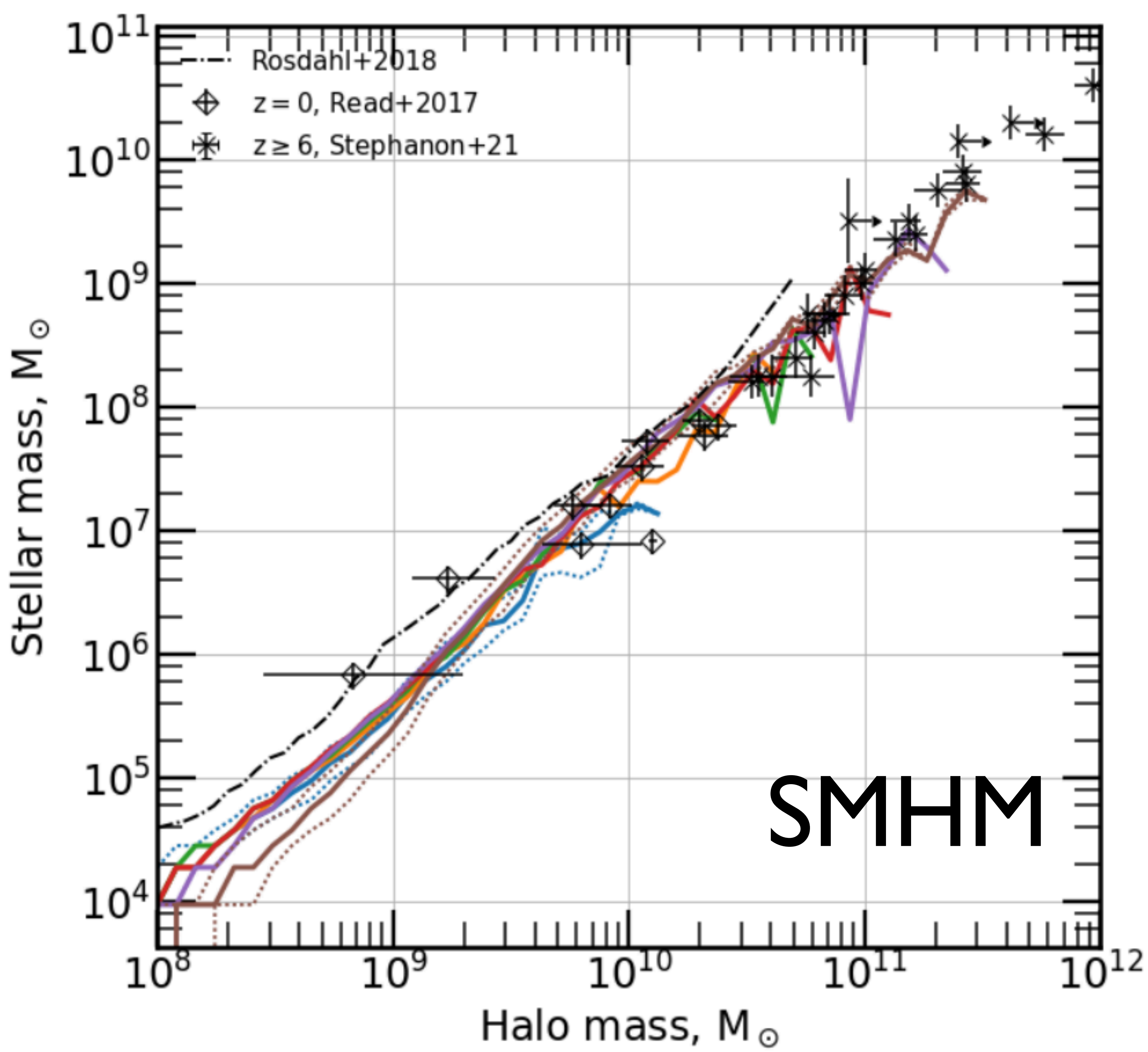
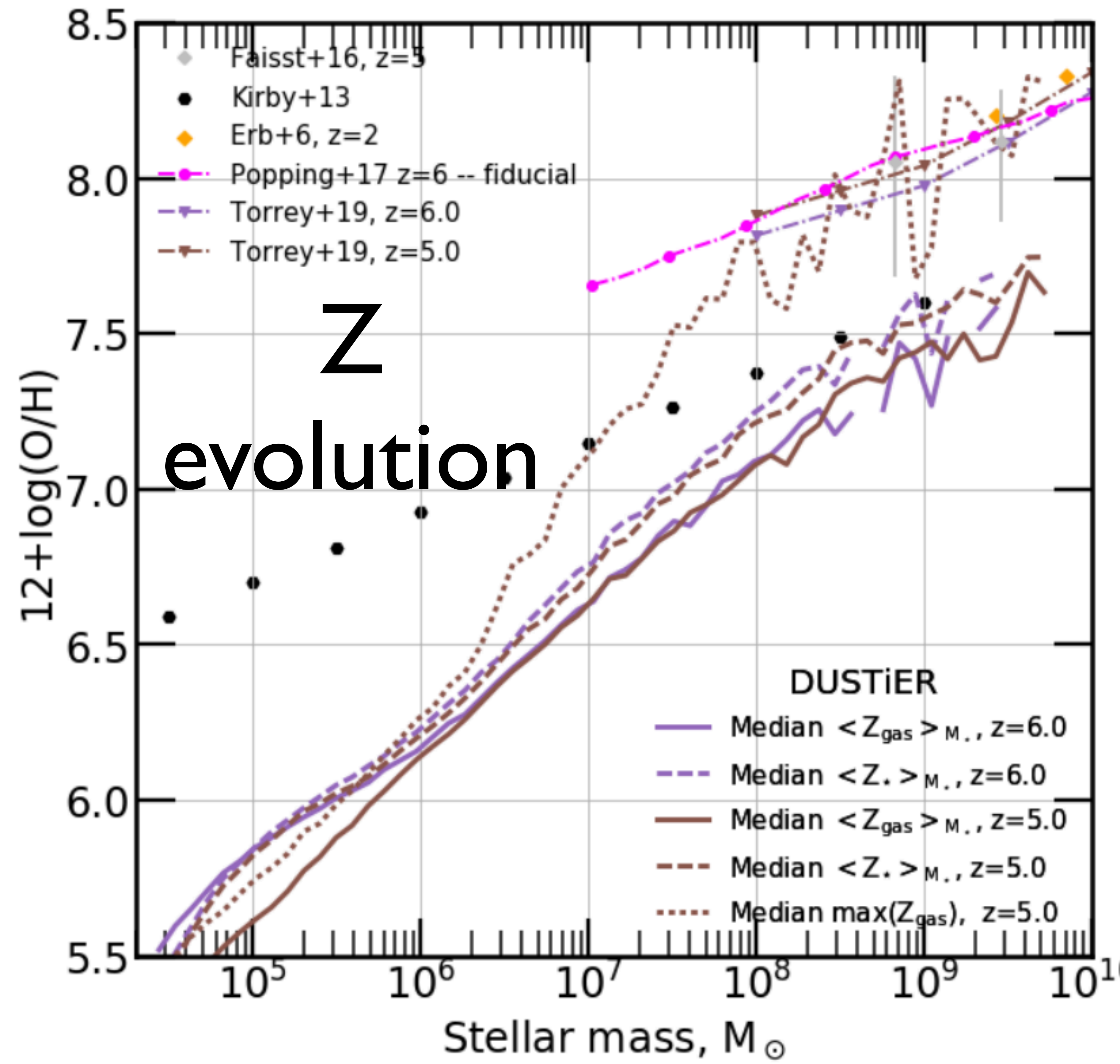
- Interested in using the data? Get in touch! pierre.ocvirk@astro.unistra.fr

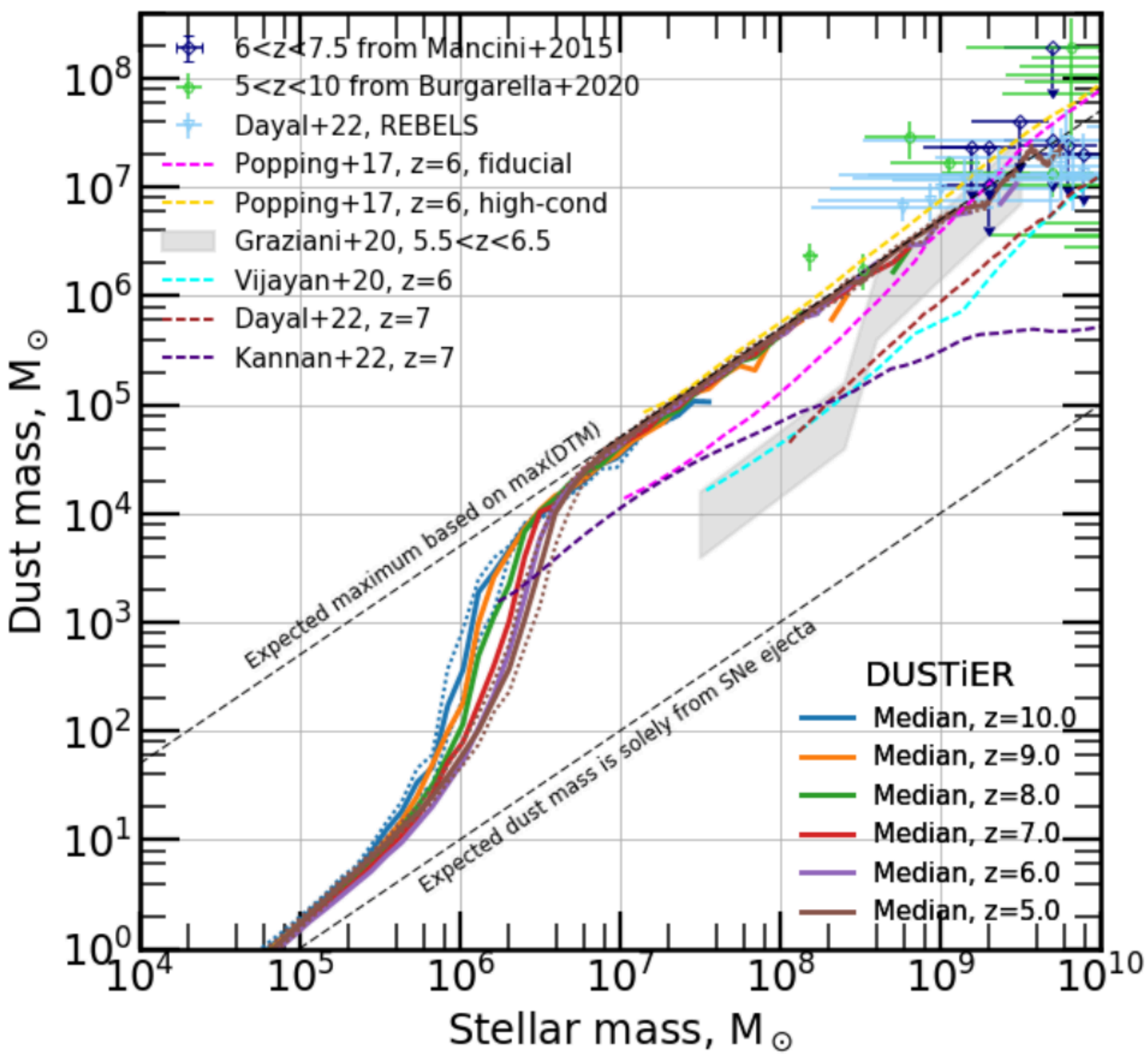
DUSTiER: Dust in the Epoch of Reionization (Lewis+ 2023)





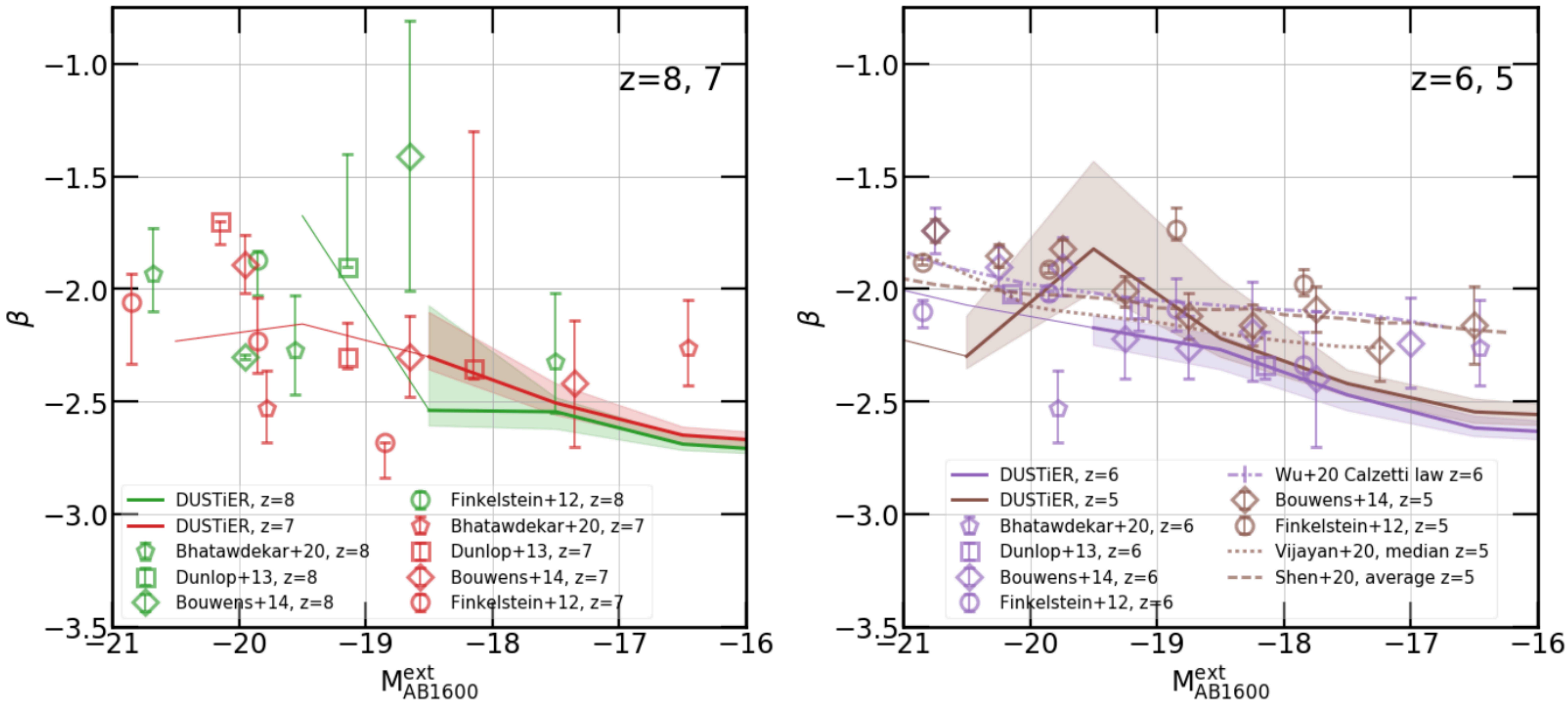
- **16 h^{-1} Mpc calibration run of Cosmic Dawn III, identical physics**
- SMHM and Mass-Z already in place at z=6 almost no evolution of Z(M) with redshift
- Metallicity slightly low compared to observational constraints

DUSTiER: dust vs stellar mass



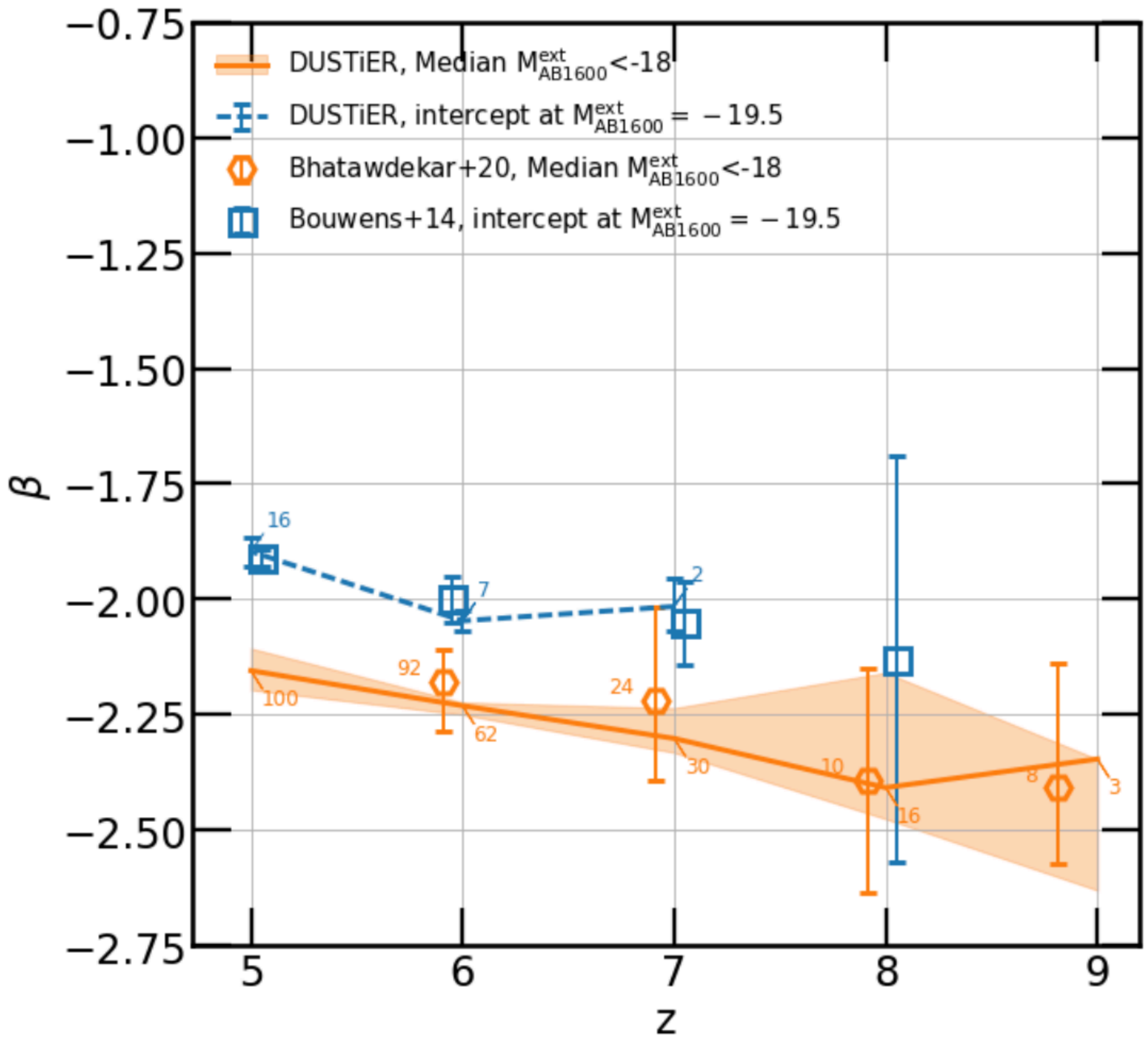
- Dust model calibrations
- not trivial
- Obs. constraints at $>10^8 M_\odot$
- good match at massive end
- No constraints at lower mass
- Saturated behaviour due to:
  - fairly low dust condensation from SN
  - fast increase through grain growth
  - inefficient destruction

DUSTiER: UV slopes



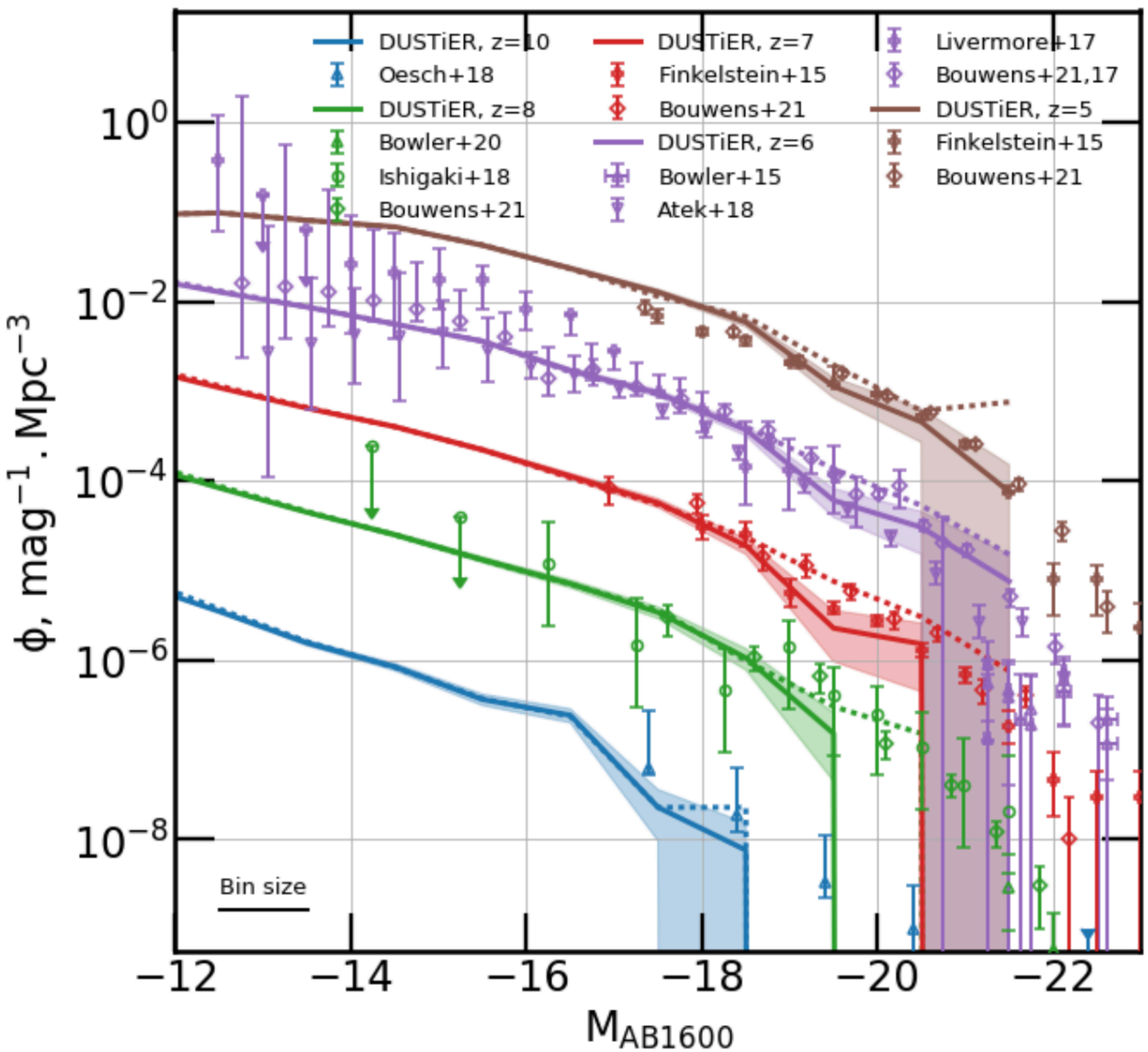
- Uses LMC extinction curve (Draine & Li 2001)
- Fair match to observations at M<-18, bright galaxies tend to be redder
- Faint end too blue but missing nebular continuum ($\Delta\beta = 0.1 - 0.3$)

DUSTiER: UV slope evolution



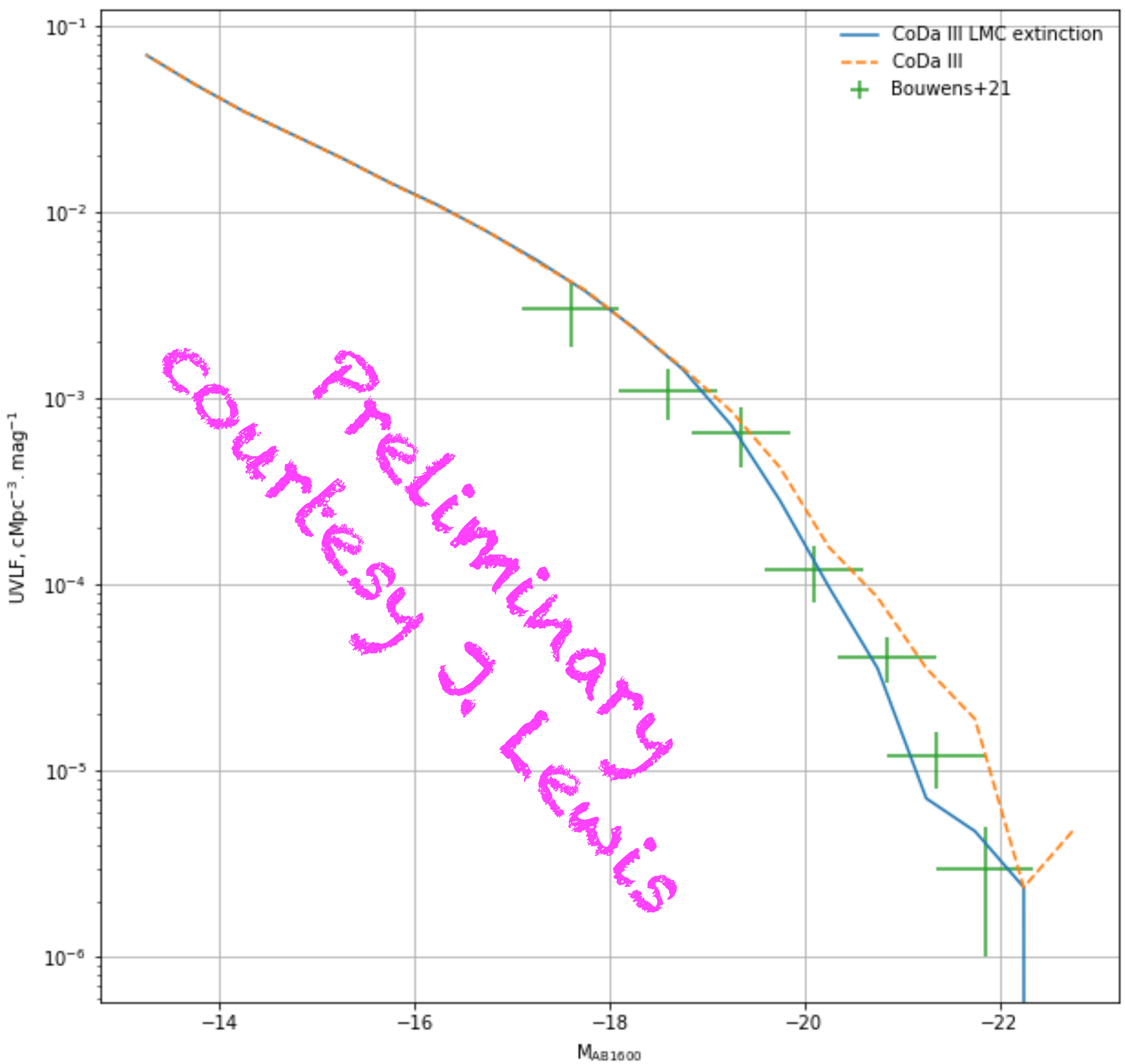
- Different ways of evaluating average slope:
  - Bouwens: intercept
  - Bhatawdekar, median of bright-ish M_{AB1600}<-18 galaxies
- CoDa III: slow but steady evolution
- Suprisingly, CoDa III matches well both methods

DUSTiER: Impact of dust on UV galaxy luminosity functions



- Dust affects the UV LF at ALL redshifts
- Mostly for M_{AB1600}<-18
- Prevents overshooting at bright end (CoDa II)
- => reconciles predictions with observations
- Fair agreement with pre-JWST observed LFs
- Full Cosmic Dawn III analysis ongoing

CoDaIII: Impact of dust on UV galaxy luminosity functions, z=8



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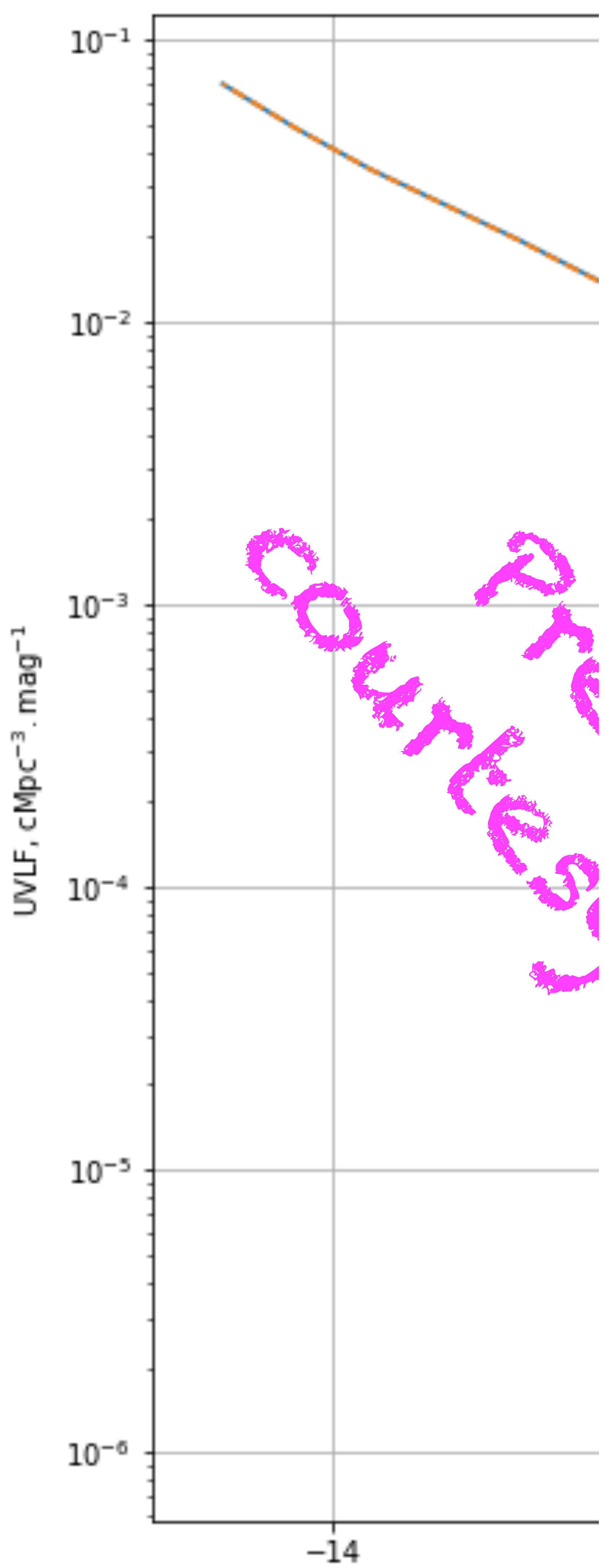

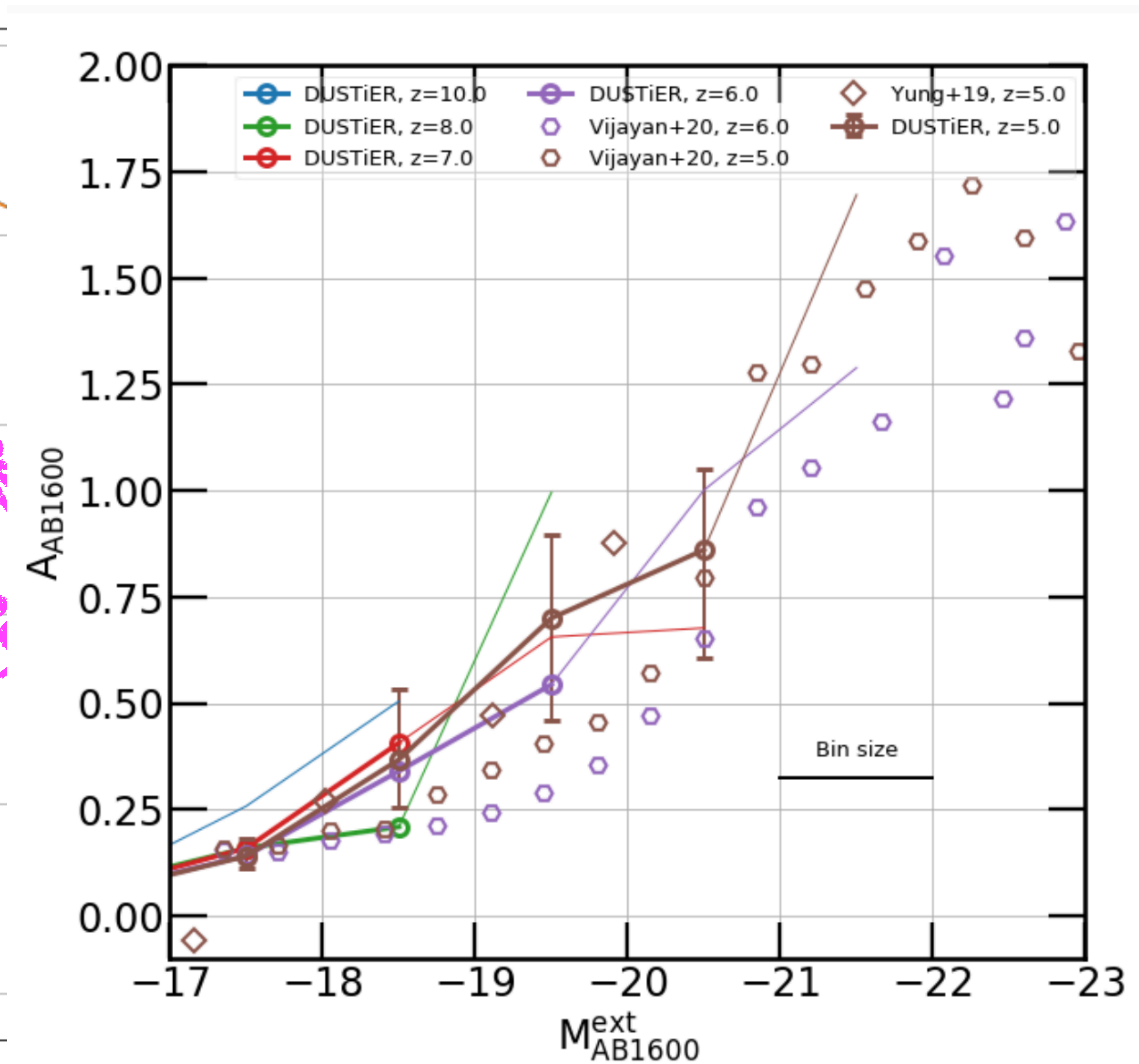

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MAB1600<-18

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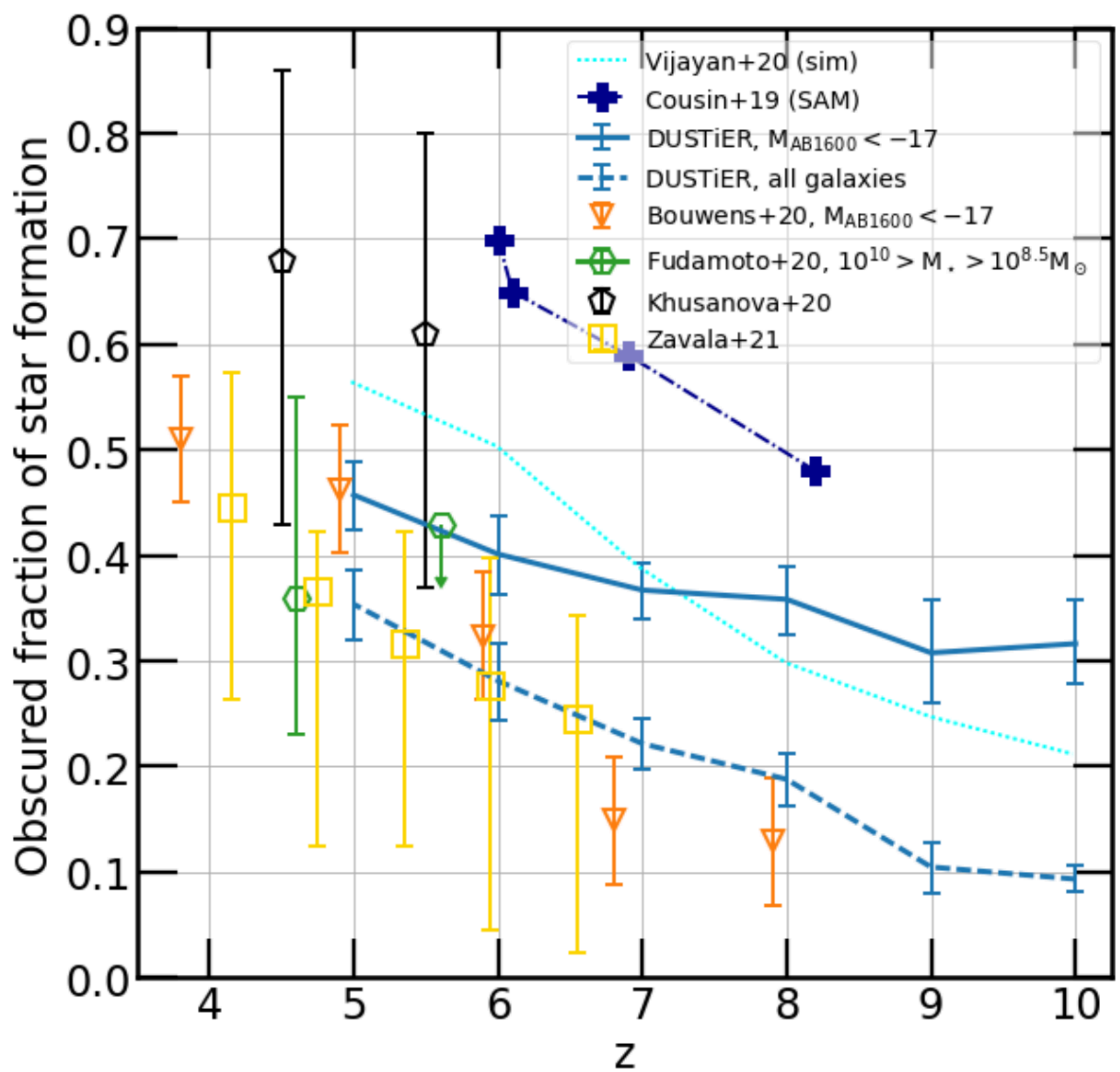
: Dawn III
going

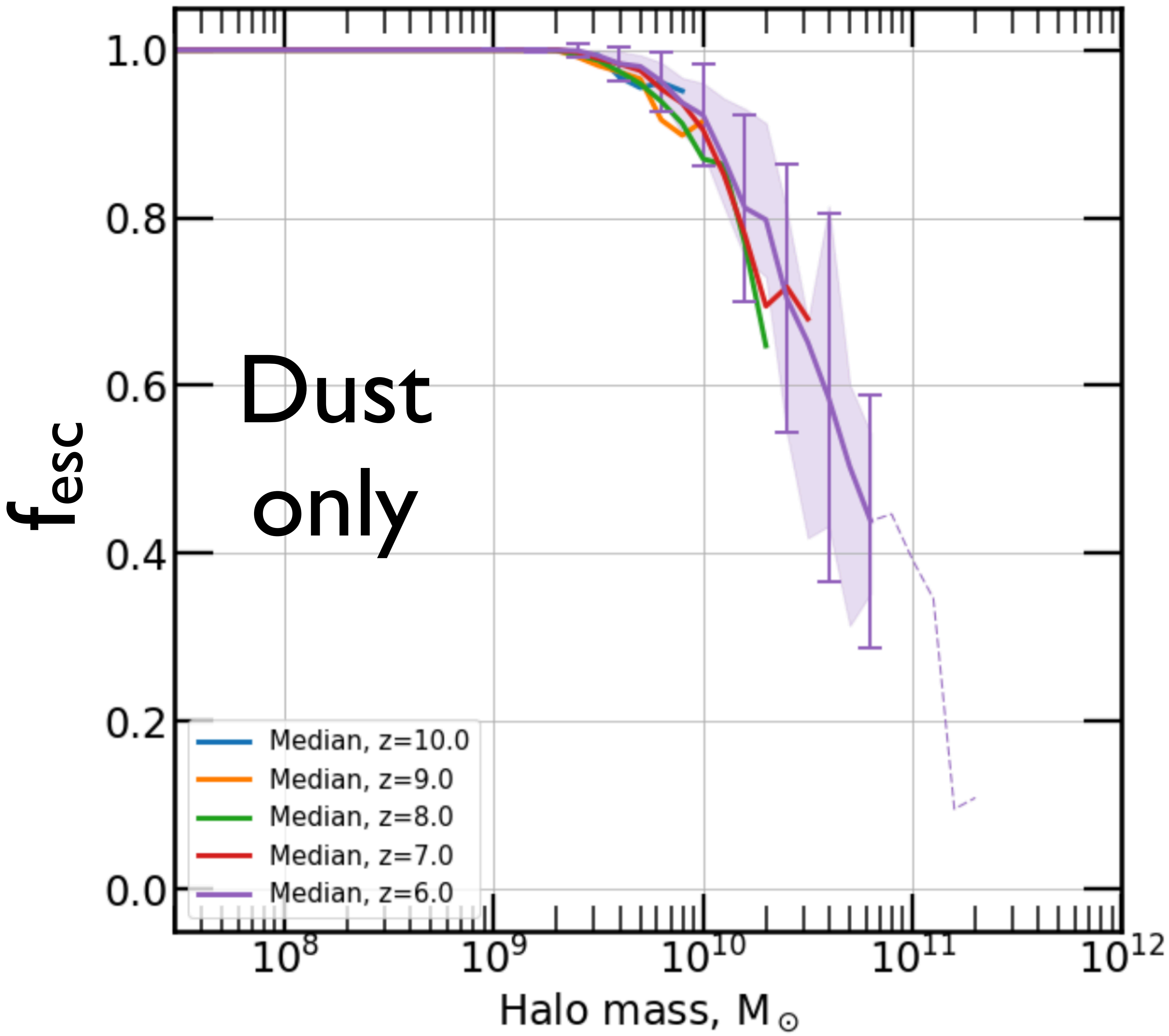
DUSTiER: Fraction of obscured star formation

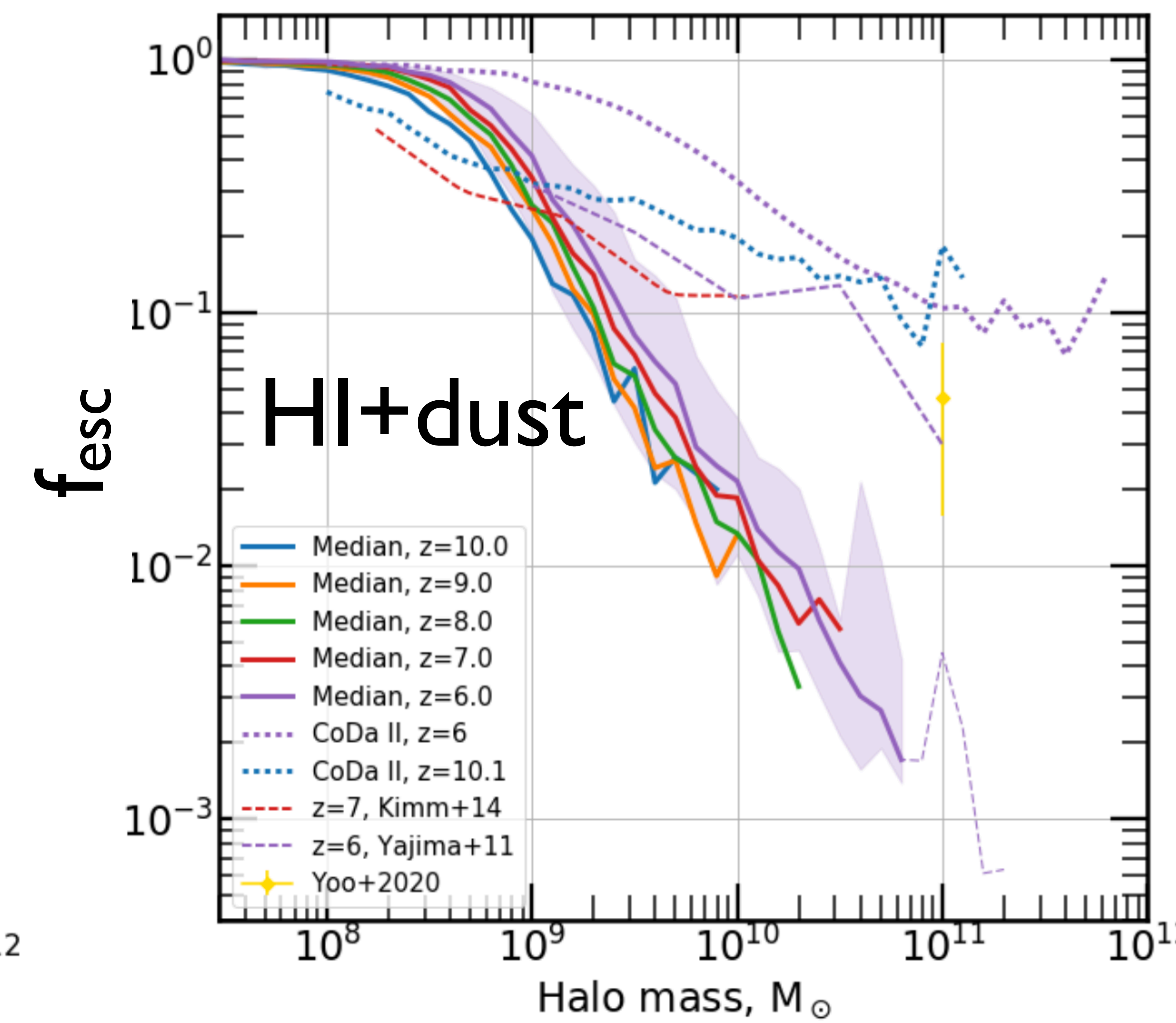


- Obtained as f= L^{ext}/L^{int}
- f increases with time
- driven by dust build-up
- => strong dependence on sample selection
- (=>) large dispersion in observational estimates
- rough match at z=5-6

Ionizing escape fractions and dust

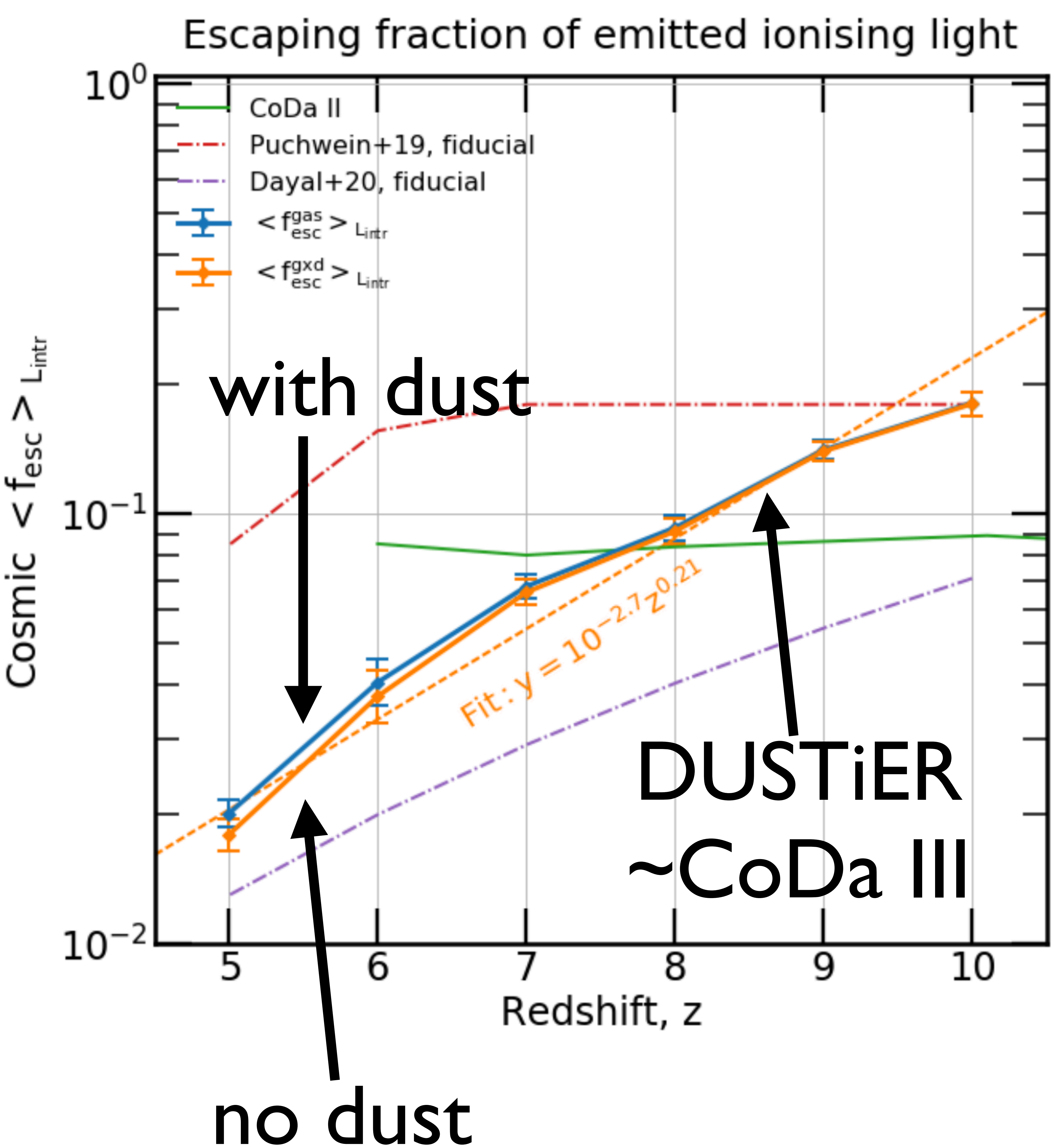
Lewis, Ocvirk et al. 2023
From DUSTiER = Cosmic Dawn III calibration sim





- Escape fraction decreases with increasing halo mass
- Absorption from dust becomes important for M= a few times $10^{10} M_\odot$
- At such masses the HI fesc is already very low => HI absorption dominates

Impat of dust on cosmic ionizing escape fraction



- DUSTiER: DUST in the Epoch of Reionization (Lewis+2023)
- average f_{esc} weighted by L_{intr}
- Decreases with z driven by:
  - suppression of high f_{esc} galaxies (low mass)
  - High mass haloes with low f_{esc} increasingly dominating star formation budget (=> L_{intr})
- Accounting for dust absorption makes little difference

Key results summary

- **Cosmic Dawn III** simulation is the largest fully coupled Radiation-Hydrodynamics EoR galaxy formation simulation ever made.
- Good match with currently available observables, Luminosity functions, reionization history, τ, Hydrogen ionizing rate, and now also neutral fraction at z<6.
- Newfound agreement involves a drop in cosmic ionising emissivity

- **DUSTiER**'s UV LFs, slopes and evolution compatible with observations
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