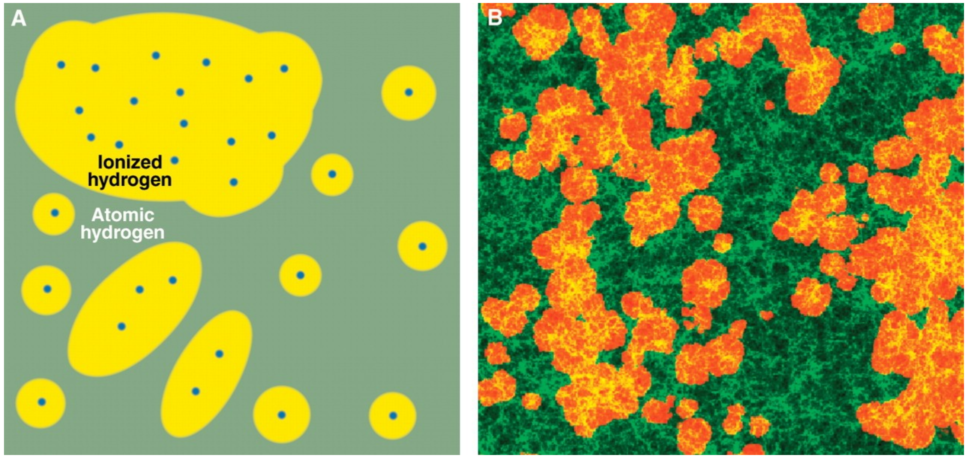
Simulating Cosmic Reionization with high-dynamic range

Ilian Iliev
University of Sussex

Drivers of Cosmic Reionization: sources and sinks

- On large scales EoR is driven by a complex interplay of radiation sources and sinks.
- Sources:
  - Stars
  - QSOs
  - More exotic? (decaying DM,...)
- Sinks
  - Neutral patches
  - Recombinations in ionized gas
  - Absorbers (LLS, DLA)



(Barkana 2006, Iliev et al. 2006)

Some unique features/challenges:

- vast range of scales
- some unique physics (e.g. Pop III)
- radiative transfer required

What are the simulation challenges?

- **Ingredients** **Scales**

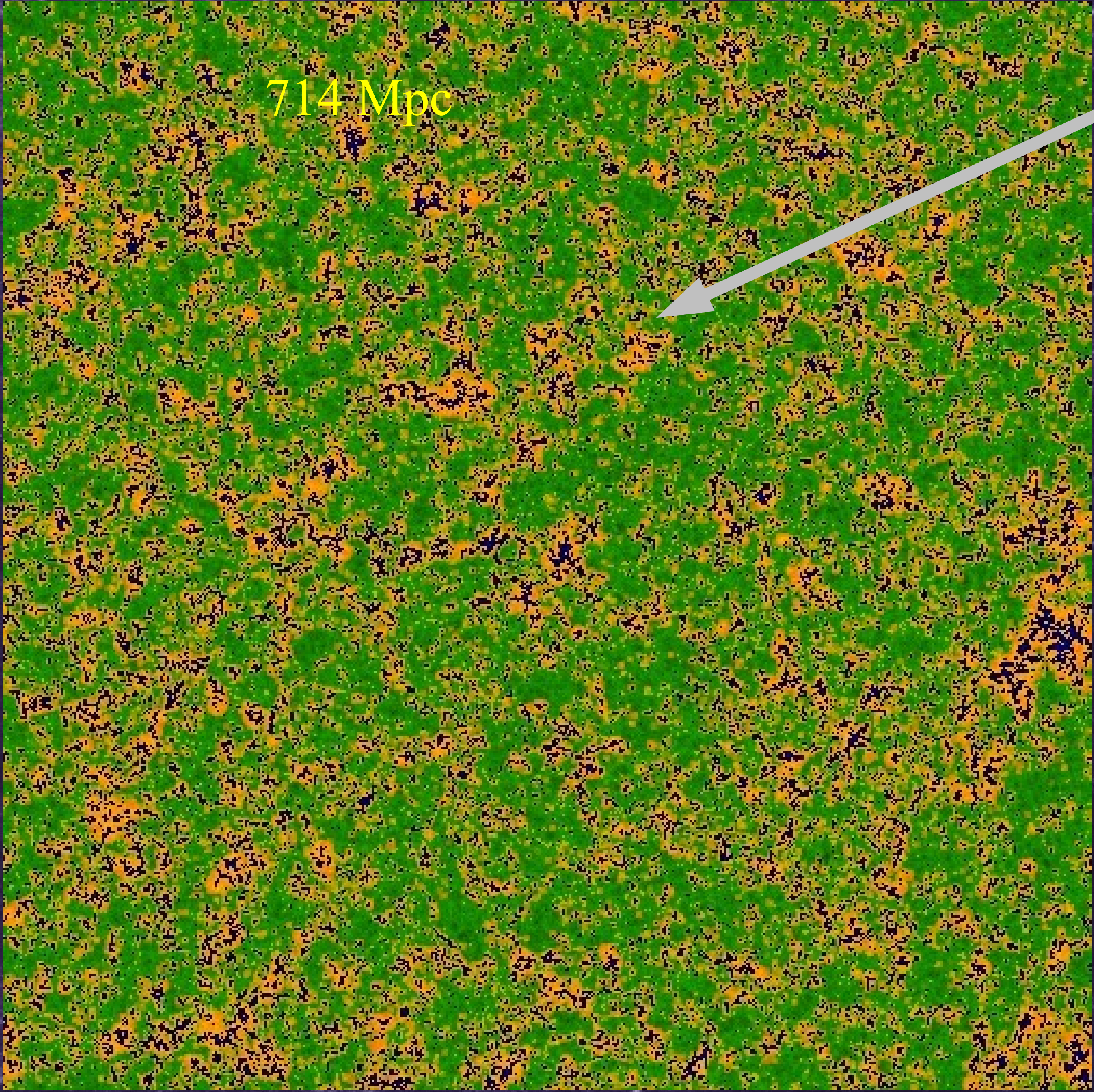
Gravity
Hydrodynamics → $\mathcal{O}$(kpc)– $\mathcal{O}$(Gpc)
Radiation

Black holes } $\mathcal{O}$(AU)
Star formation
Supernovae } $\mathcal{O}$(pc) – $\mathcal{O}$(100 pc)
Stellar ejecta
. . .

i.e. need huge dynamic range, impossible for now

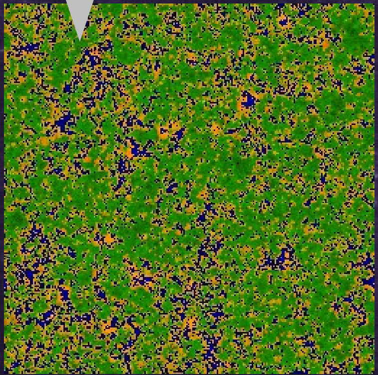
Slide credit: E. Garaldi

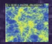
Scales of Cosmic Reionization



Large-scale EoR simulations for LOFAR/SKA ~700 Mpc, 5x5 deg

Intermediate scales (~100 Mpc; e.g. CoDa, Thesan, ...)





Zoom hydro sims (few Mpc or less)

Radiation is critical ingredient during EoR

The radiation transport equation: propagation of light intensity

Peebles 1971, Gnedin&Ostriker 1997, Abel et al. 1999, Gnedin&Madau 2022

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \frac{\mathbf{n}}{a}\cdot\frac{\partial I_\nu}{\partial \mathbf{x}} - \frac{H(t)}{c}\left(\nu\frac{\partial I_\nu}{\partial \nu} - 3I_\nu\right) = -\kappa_\nu I_\nu + S_\nu$$

7 independent variables: position, time, frequency, light ray direction

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Conservation of Photons

Cosmological redshift+dilution

Sinks

Sources

7 independent variables: position, time, frequency, light ray direction

Gas heating and cooling

- Radiation needs to be solved together with the thermal evolution

$$\frac{dT}{dt} = -2HT + \frac{2T}{3\Delta}\frac{d\Delta}{dt} + \frac{T}{\mu}\frac{d\mu}{dt} + \frac{2\mu}{3k_B n}(\mathcal{H} - \Lambda)$$

$$H_i = 4\pi \int_{\nu_i}^{\infty} \frac{J_\nu}{h\nu}(h\nu - h\nu_i)\,\sigma_i d\nu$$

- and gas chemistry

$$\frac{dx_{\mathrm{HI}}}{dt} = -x_{\mathrm{HI}}\Gamma_{\mathrm{HI}} + n_e x_{\mathrm{HII}}\alpha^{A}_{\mathrm{HII}}$$

How to treat the transfer of ionizing radiation?

- Approach 1: (mostly) ignore it

Starting from certain ‘reionization’ redshift, apply a spatially-uniform, time-evolving UVBG to each resolution element.

Needs empirical corrections for self-shielded regions
Does not capture reionization topology
Essentially costless (in terms of RT)
Could be OK for low-z and locally within ionized regions at high-z

Used by, e.g.:
low-z sims (IllustrisTNG, NewHorizon, FIRE)
FirstLight (Ceverino et al. 2017)
FLARES (Lovell et al. 2021, Vijayan et al. 2021)
CHIPS (Villasenor et al. 2021)

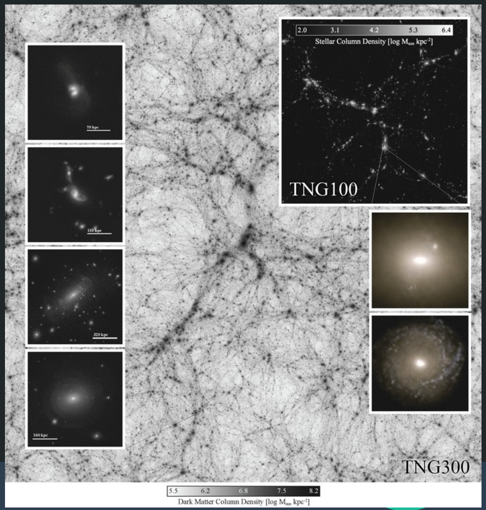

Image: TNG collaboration

How to treat the transfer of ionizing radiation?

- Approach 2: semi-numerical

Infer the distribution of HII regions from the initial conditions using excursion set, halo abundance matching, or similar.

Cons:
Fails at scales ≲ Mpc
Issues at ionized bubbles overlap
Typically not photon-conserving
Limited verification

Pros:
Quite cheap, relatively easy to use
Quickly explore parameter space
Easily simulate 100Mpc-Gpc box

Used by, e.g.

21cmFAST (Mesinger et al. 2011)
21cmSPACE (Fialkov et al. 2012)
AMBER (Trac et al. 2022)
BEORN (Schaeffer et al. 2023)

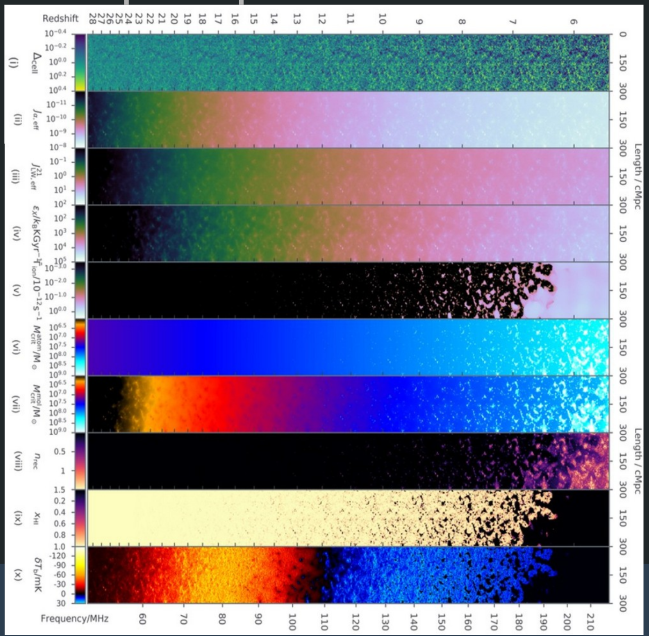

Image credit: A. Mesinger

How to treat the transfer of ionizing radiation?

- Approach 3: N-body+SAM+simplified RT

Use DM density from N-body simulations + a semi-analytical model built for reionization-era galaxies + approximate RT (e.g. spherical HII regions).

Cons:	Pros:
RT is approximate at best	Fast
baryon physics is approximate	Easily model $\mathcal{O}$(100 Mpc) volumes

Used by, e.g.

GRIZZLY (Ghara et al. 2015, 2018, *no SAM*)

DRAGONS (Poole et al. 2016, Angel et al. 2016, Mutch et al. 2016)

ASTRAEUS (Hutter et al. 2021)

How to treat the transfer of ionizing radiation?

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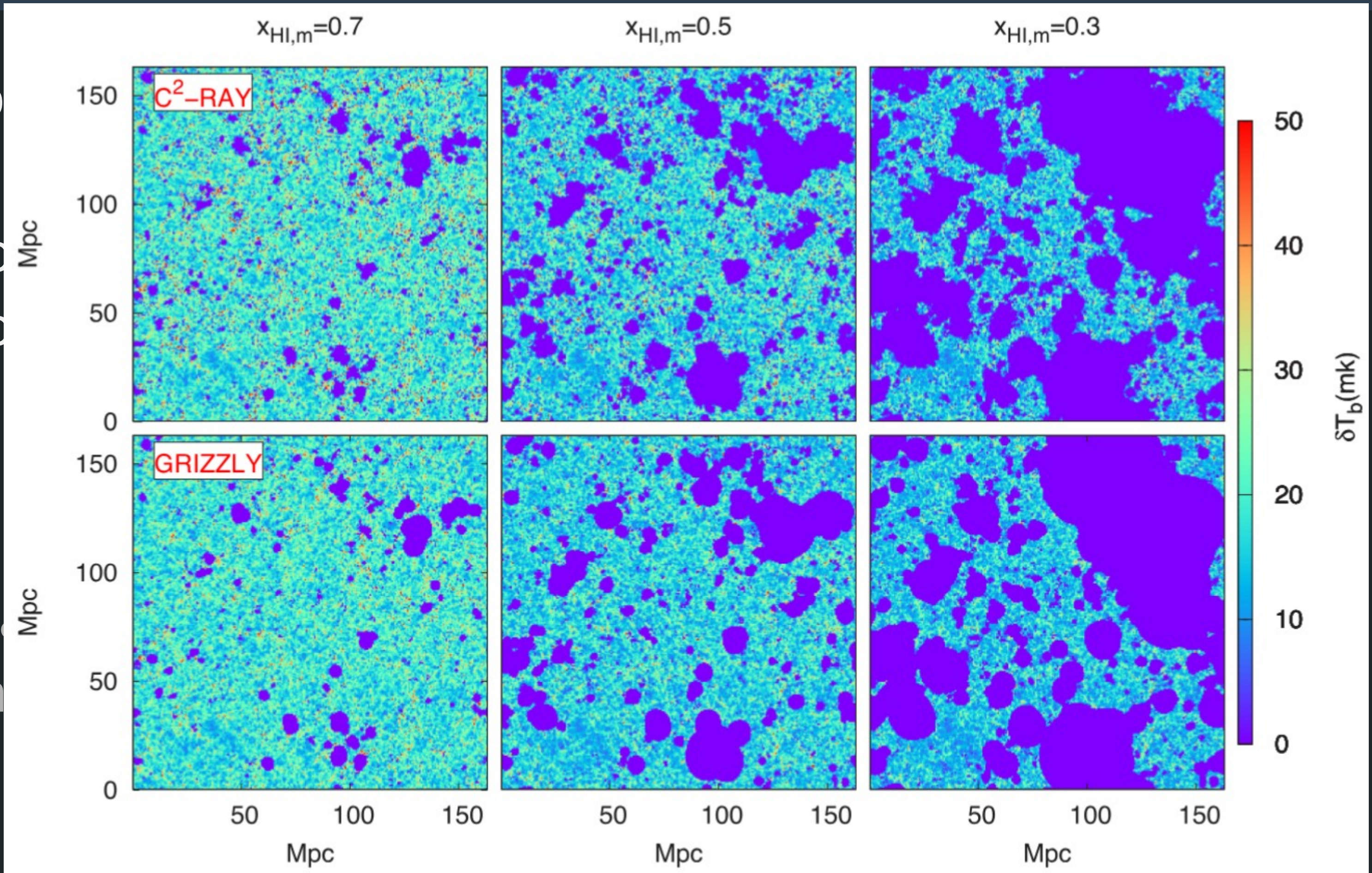

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ASTRAEUS (Hutter et al. 2021)

How to treat the transfer of ionizing radiation?

- Approach 4: N-body/hydro+full RT

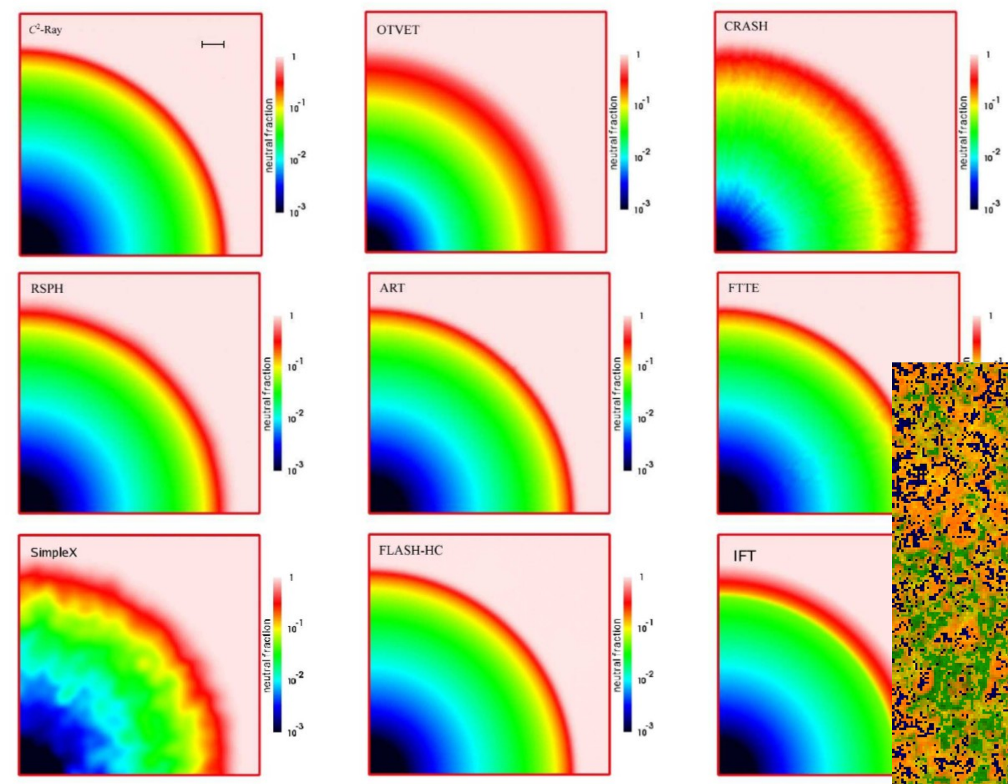
Run cosmological structure formation simulations without RT, and include radiation by post-processing the outputs.

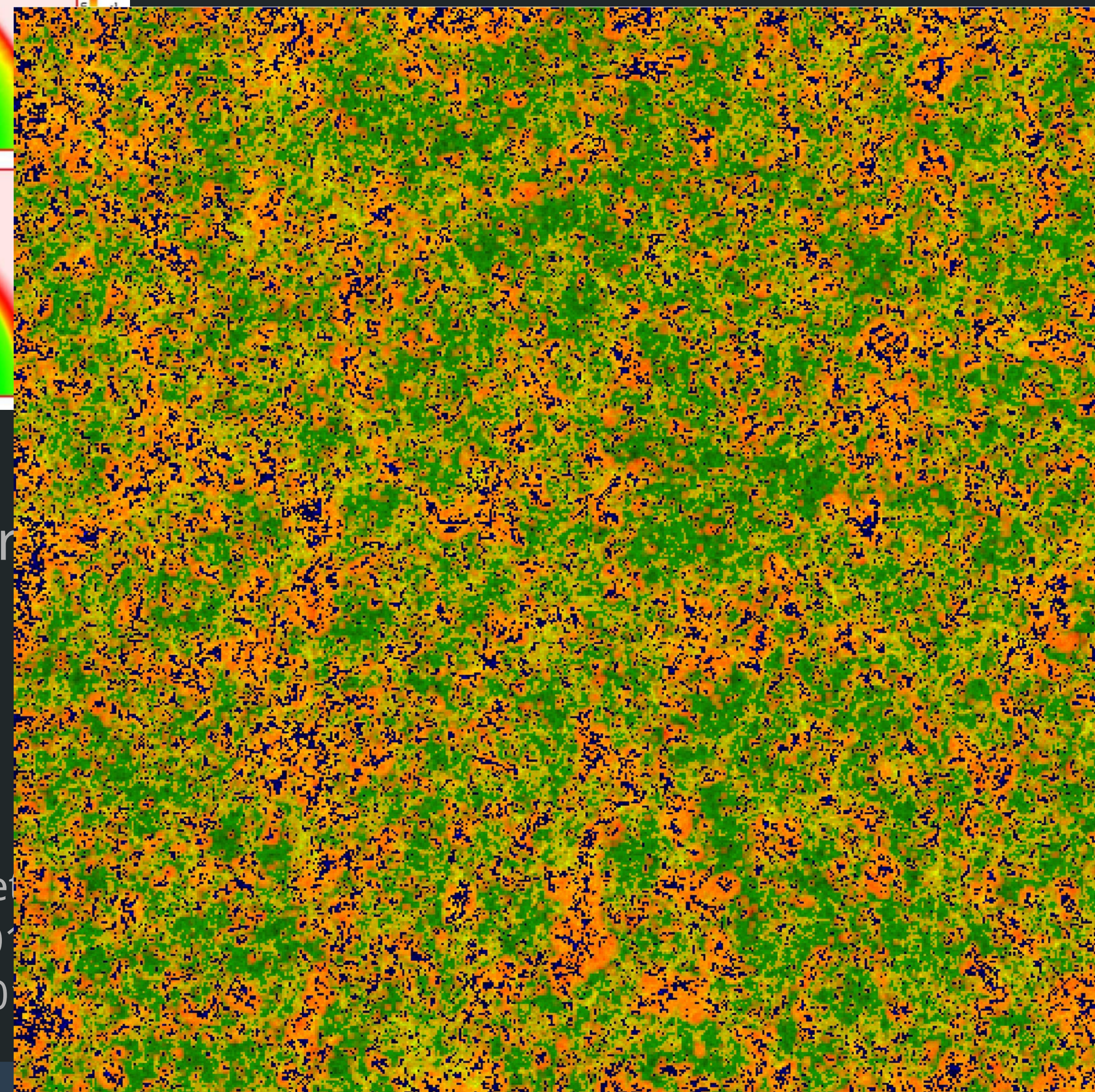
Cons:
No detailed radiative feedback
Galaxy modelling (often) approx.

Pros:
Can do large vol. (hundreds of Mpc)
Resolve ACHs in large volume
Proper RT
Faster then full hydro-RT
Extensively tested and verified

Used by, e.g.
C2-RAY/pyC2Ray simulations (e.g. Iliev et al. 2006, Mellema et al. 2006, Bianco & Hirling 2024)
ATON simulations (e.g. Chardin et al. 2017, Kulkarni et al. 2019, Keating et al. 2020)
CRASH simulations (e.g. Ciardi et al. 2001, Eide et al. 2018,2020, Ma et al. 2022)

nsfer of ionizing on?





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Used by, e.g.

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ATON simulations (e.g. Chardin et al. 20

CRASH simulations (e.g. Ciardi et al. 200

How to treat the transfer of ionizing radiation?

- Approach 5: Hydro + approximate RT

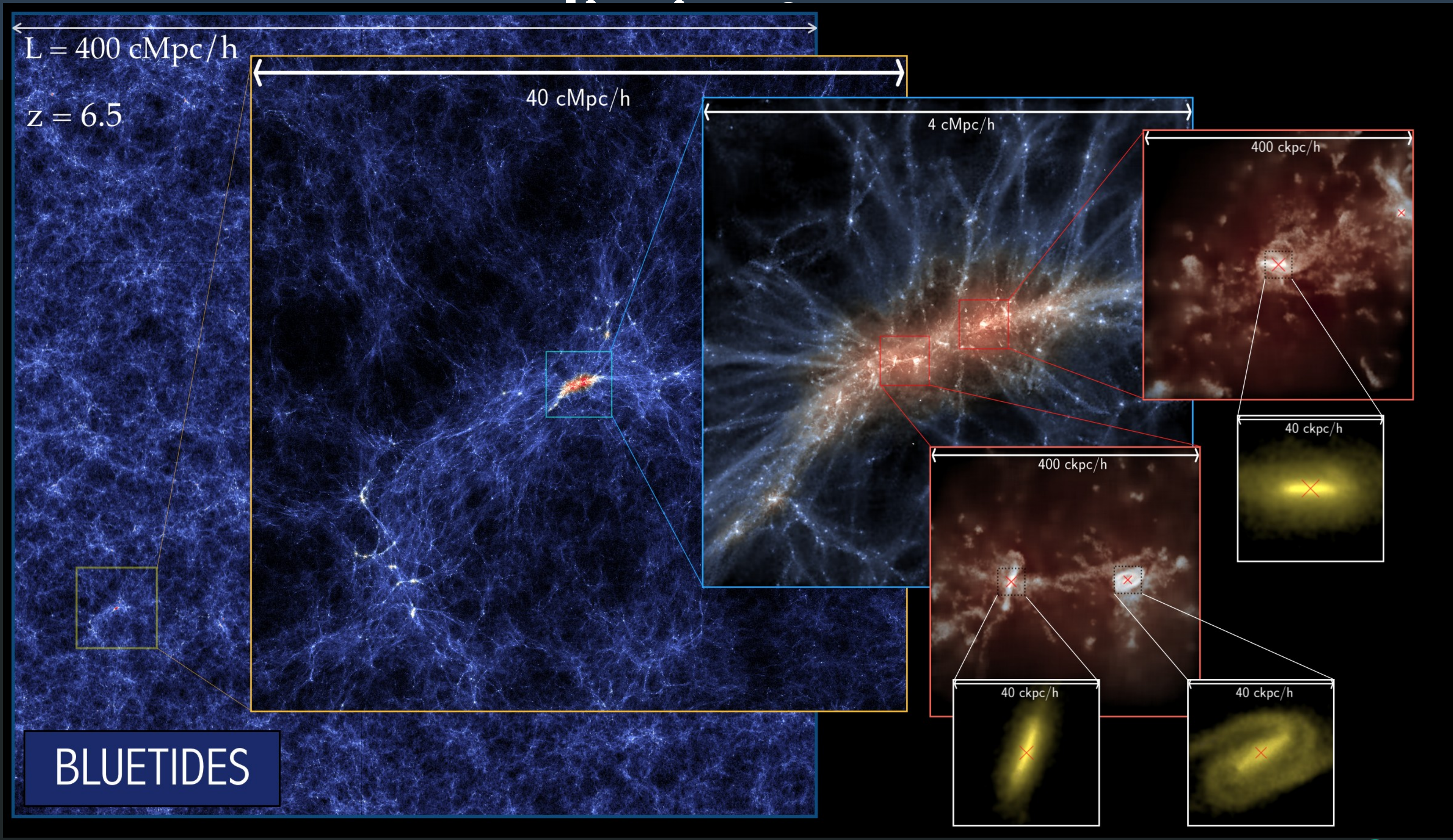
Run hydrodynamical simulations without RT, and include radiation by post-processing its outputs.

Cons:
RT effects are only approximated

Pros:
Little extra cost over pure hydro.

Used by, e.g.
BlueTides (Huang et al. 2018)
ASTRID, ASTRID-ES, PRIYA (Bird et al. 2022,2023, Davies et al. 2023)
Sherwood-Relics (Puchwein et al. 2022)

How to treat the transfer of ionizing



How to treat the transfer of ionizing radiation?

- Approach 6: Full radiative hydrodynamics

Solve the fully-coupled RHD equations, following DM, gas, radiation, galaxy formation, ...

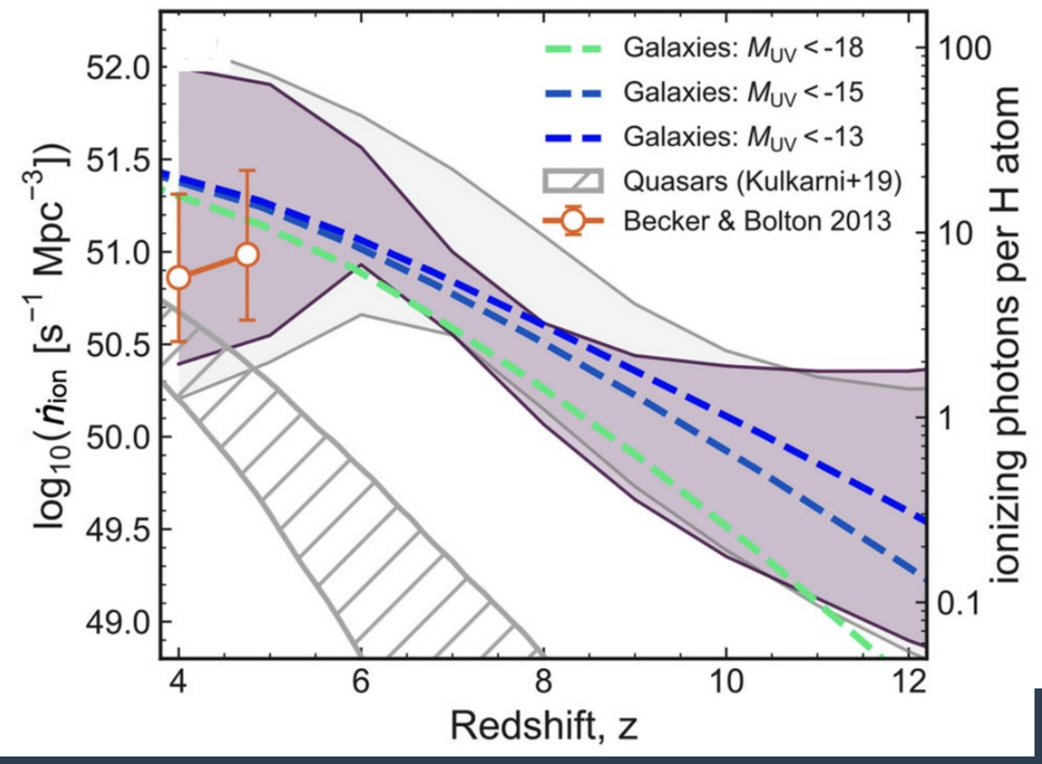
Cons:
Computationally very expensive
→ only few runs affordable
Volumes not large enough for 21-cm

Pros:
The closest to the real Universe
Can be used as benchmark/subgrid for more approximate methods.

Used by, e.g.
CROCs (Gnedin 2014); TechnicolorDawn (Finlator et al. 2018);
Renaissance (Xu et al. 2016); Obelisk (Trebitsch et al. 2021,2023);
AURORA (Pawlik et al. 2017); SPHINX (Rosdahl et al. 2018,2022);
CoDa I/II/III (Ocvirk et al. 2016, 2020, Lewis et al. 2022);
Thesan (Kannan et al. 2022, Garaldi et al. 2022, Smith et al. 2022);

Basic observational constraints

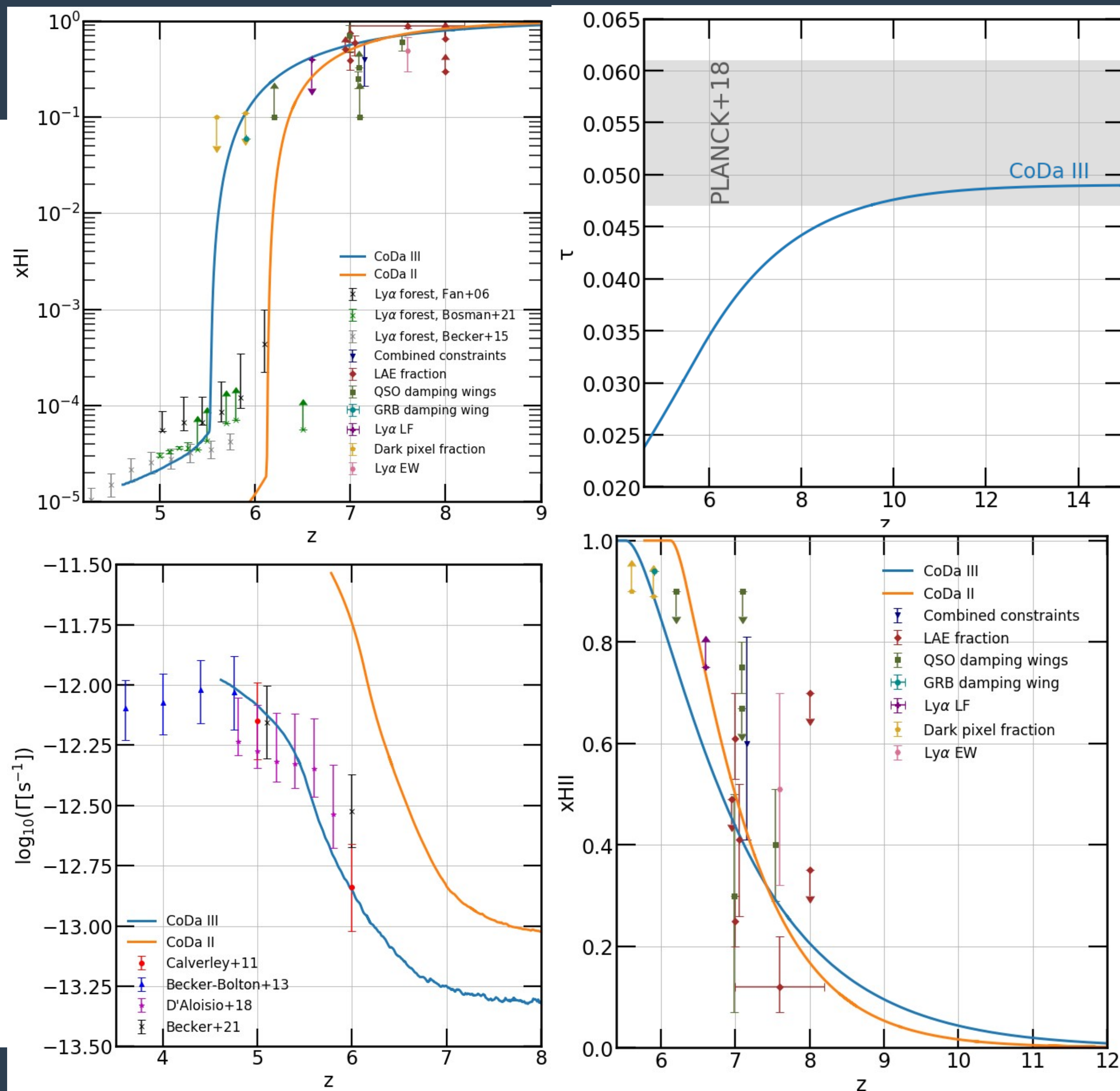
- Integrated electron scattering optical depth τ = 0.054 ± 0.007 (Aghanim et al. 2018; Planck collaboration)
- Reionization is still ongoing at z~7 (Ota et al. 2010; Pentericci et al. 2011; Mason et al. 2018)
- and (possibly) ends by z~5.5 – 6 (Eilers et al. 2018, Yang et al. 2020, Bosman et al. 2021)
- driven by galaxies (Chardin et al. 2017, Garaldi et al. 2019a, Mason et al. 2019, Trebitsch et al. 2021)



Mason et al. (2019b)

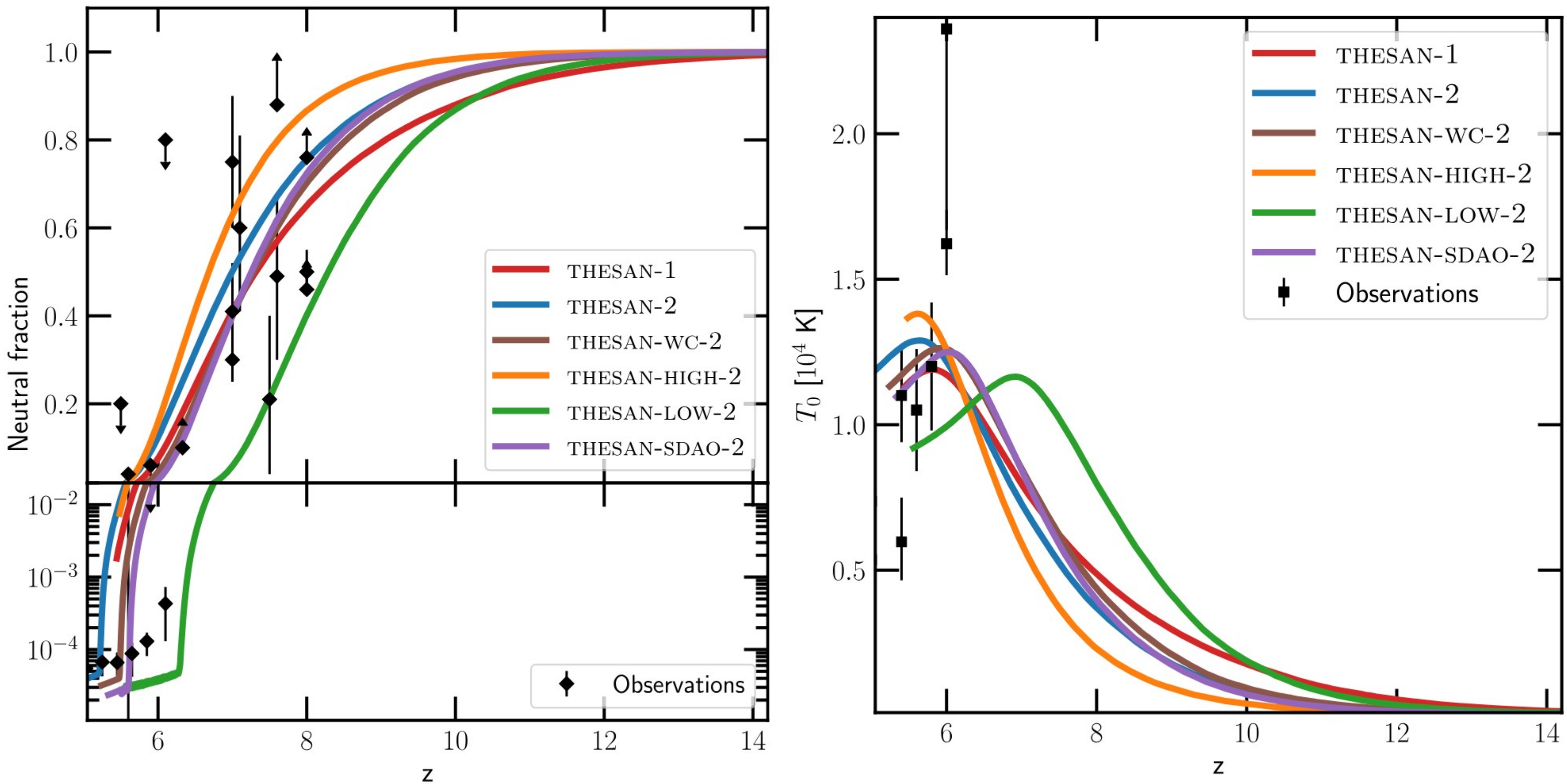
Cosmic Dawn III: calibration

(Lewis et al. 2022, MNRAS, 516, 3389)



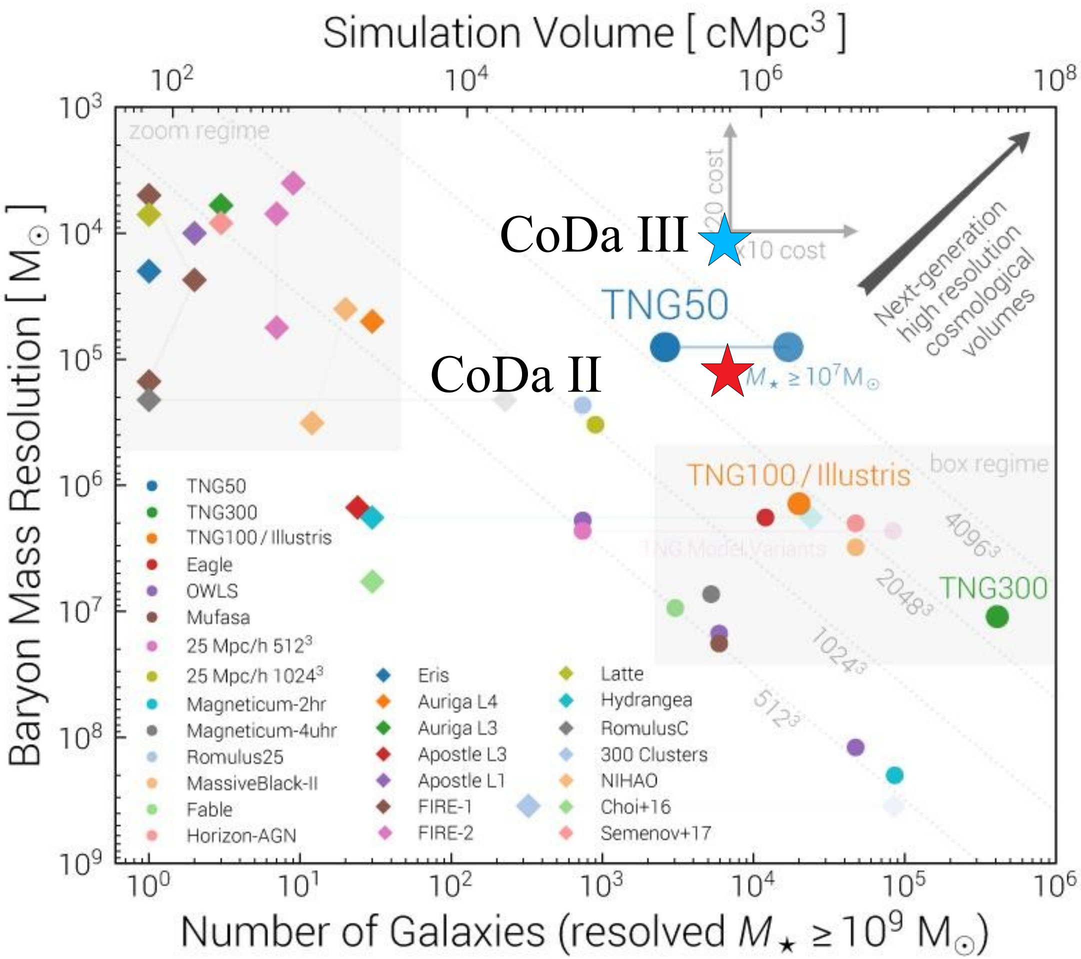
Thesan: calibration

(Kannan et al. 2022)



Cosmic Dawn suite

(Ocvirk et al. 2020; 2022; Lewis et al. 2022)



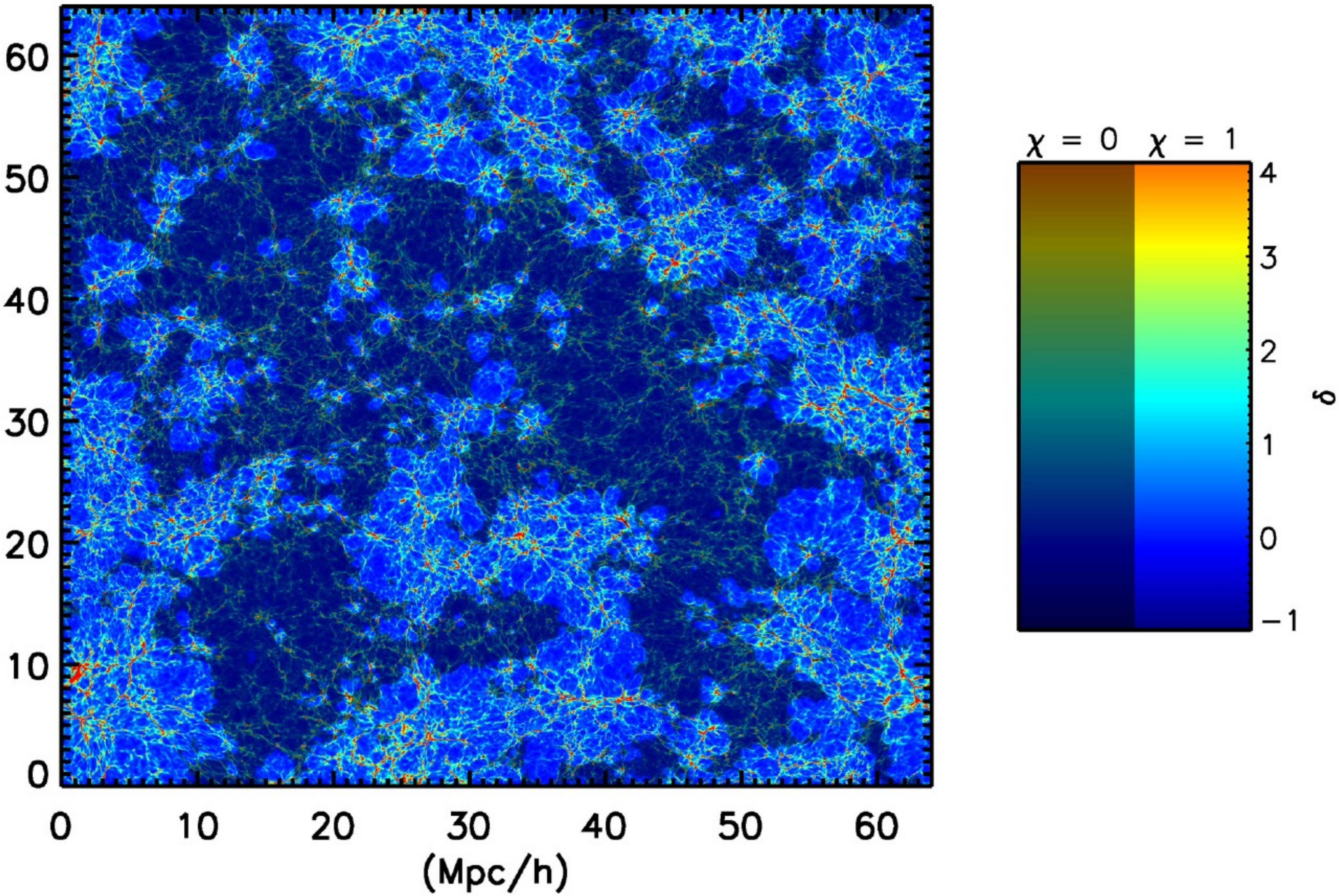
Source: Illustris website, modified here

- 131,072 CPUs, 24,576 GPUs
- 64 h^{-1} Mpc box(~94Mpc), 8,192^3 grid
- min Mhalo ~2 x 10^7 M_solar
- Δx ~ 11 kpc comoving

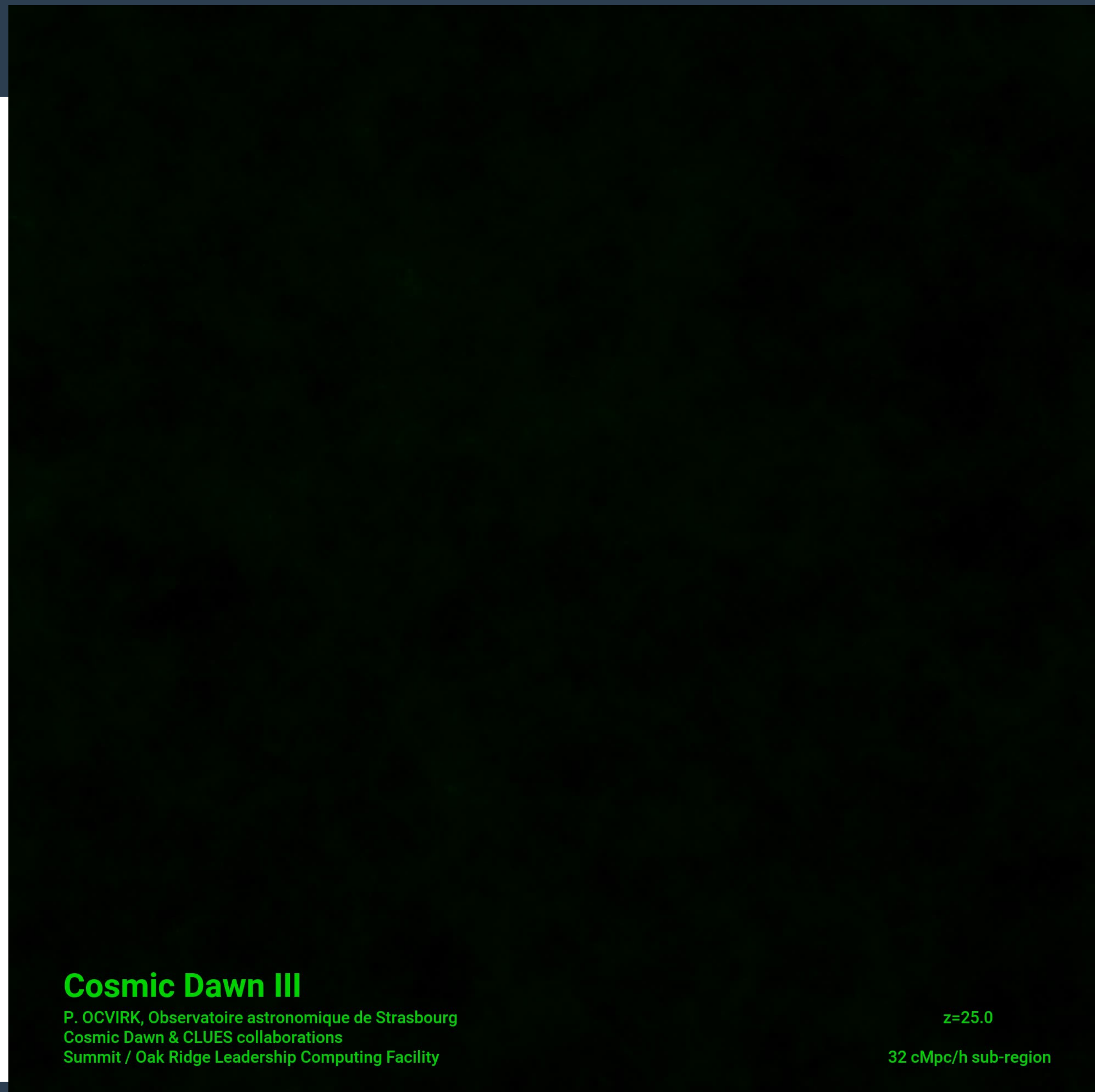
- 10 days runtime on Summit
- 20 PB data

Cosmic Dawn II: patchiness

(Taha et al. 2018)

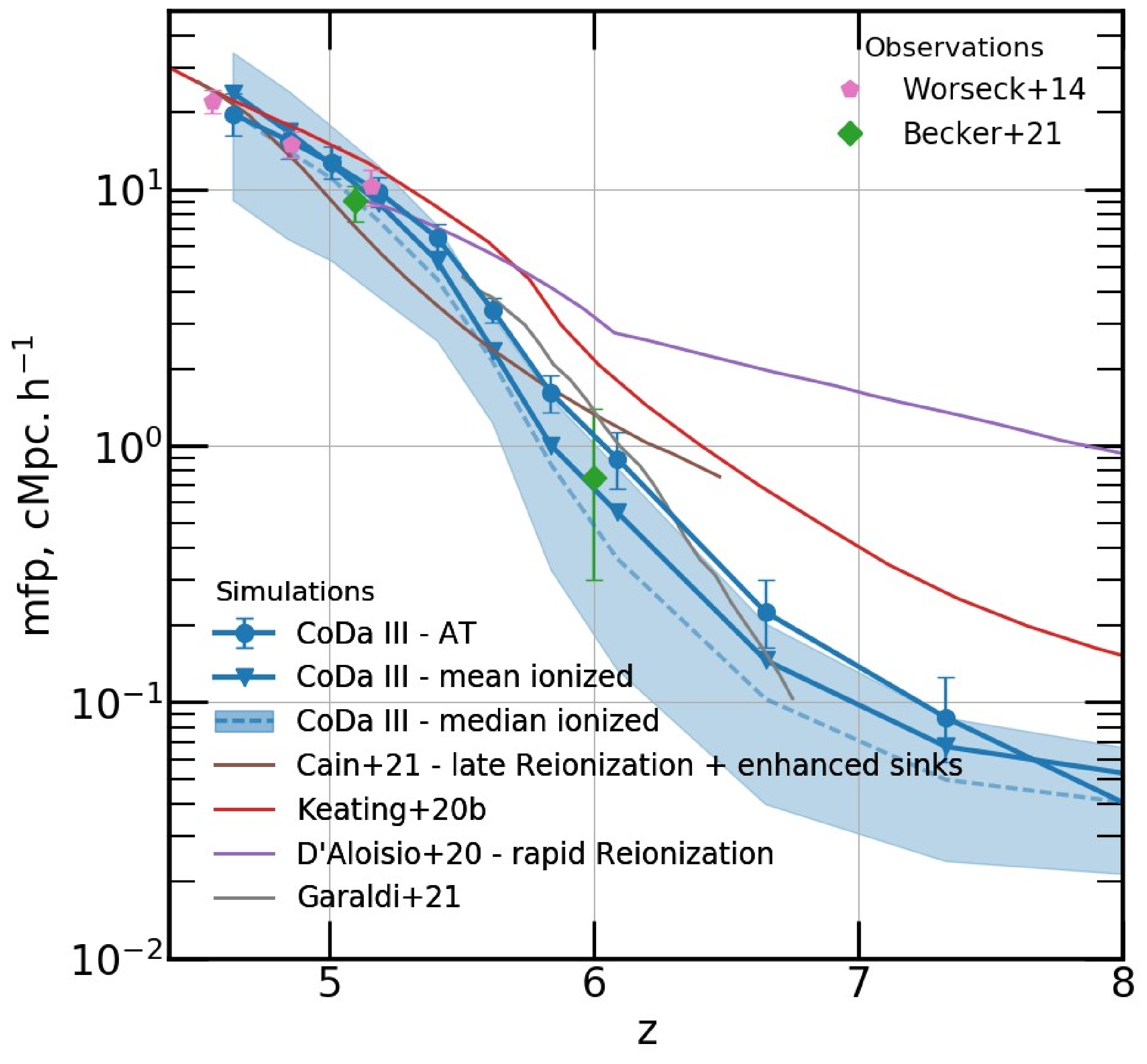


Cosmic Dawn III



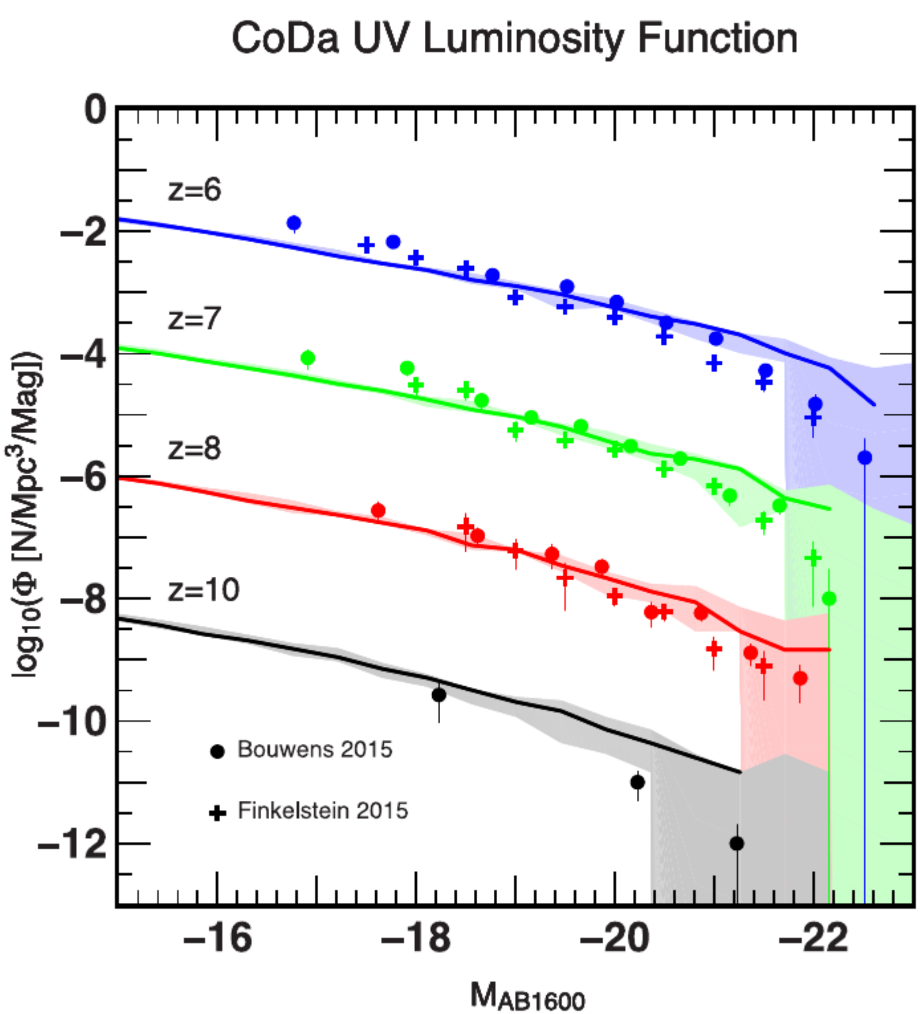
Cosmic Dawn III: mean free paths

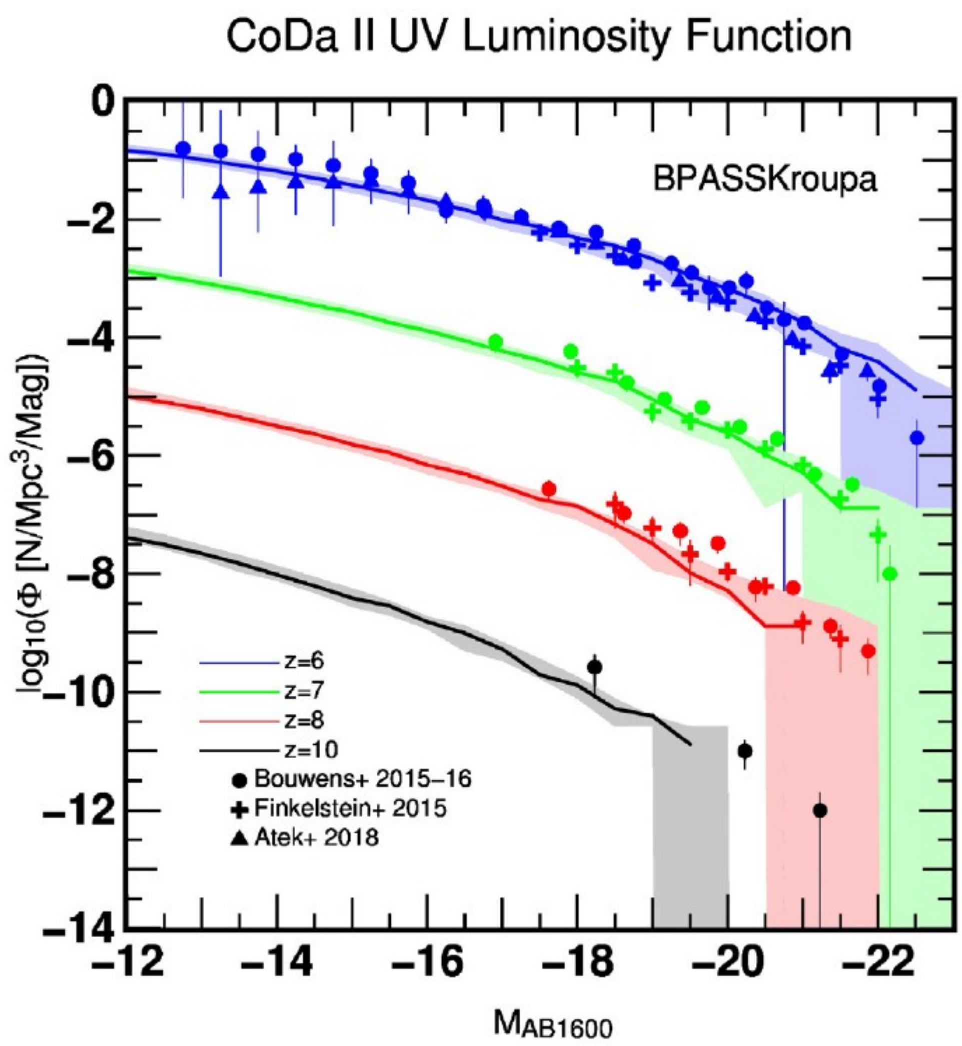
(Lewis et al. 2022)



UV luminosity functions

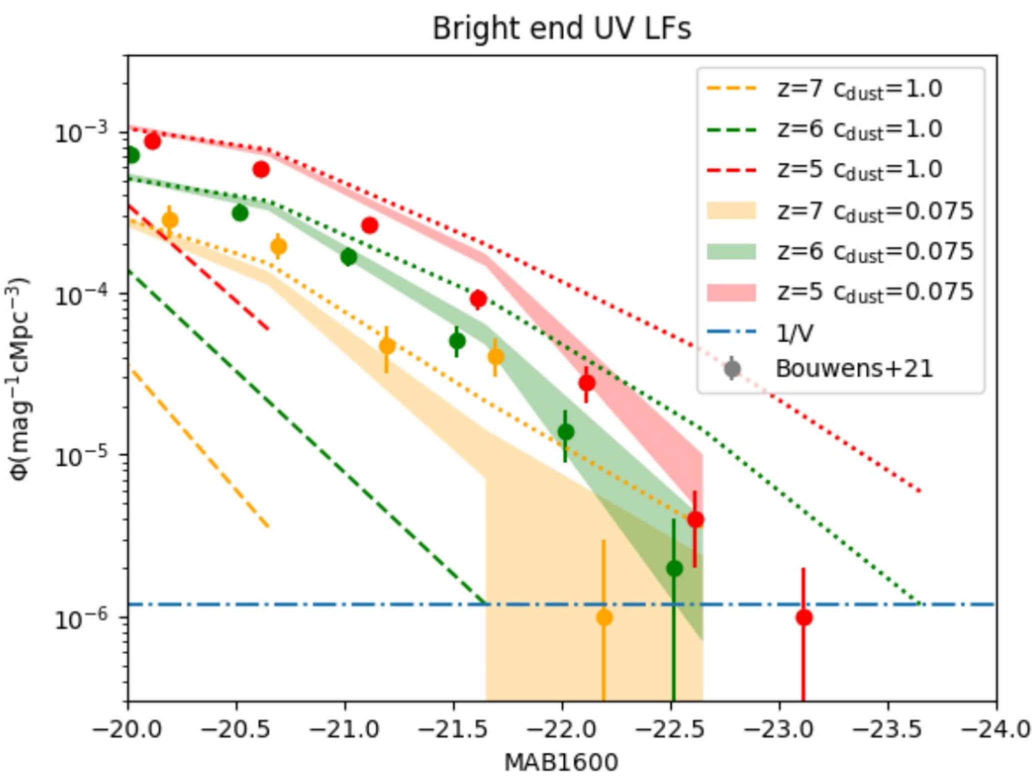
(Ocvirk et al. 2018, 2020)

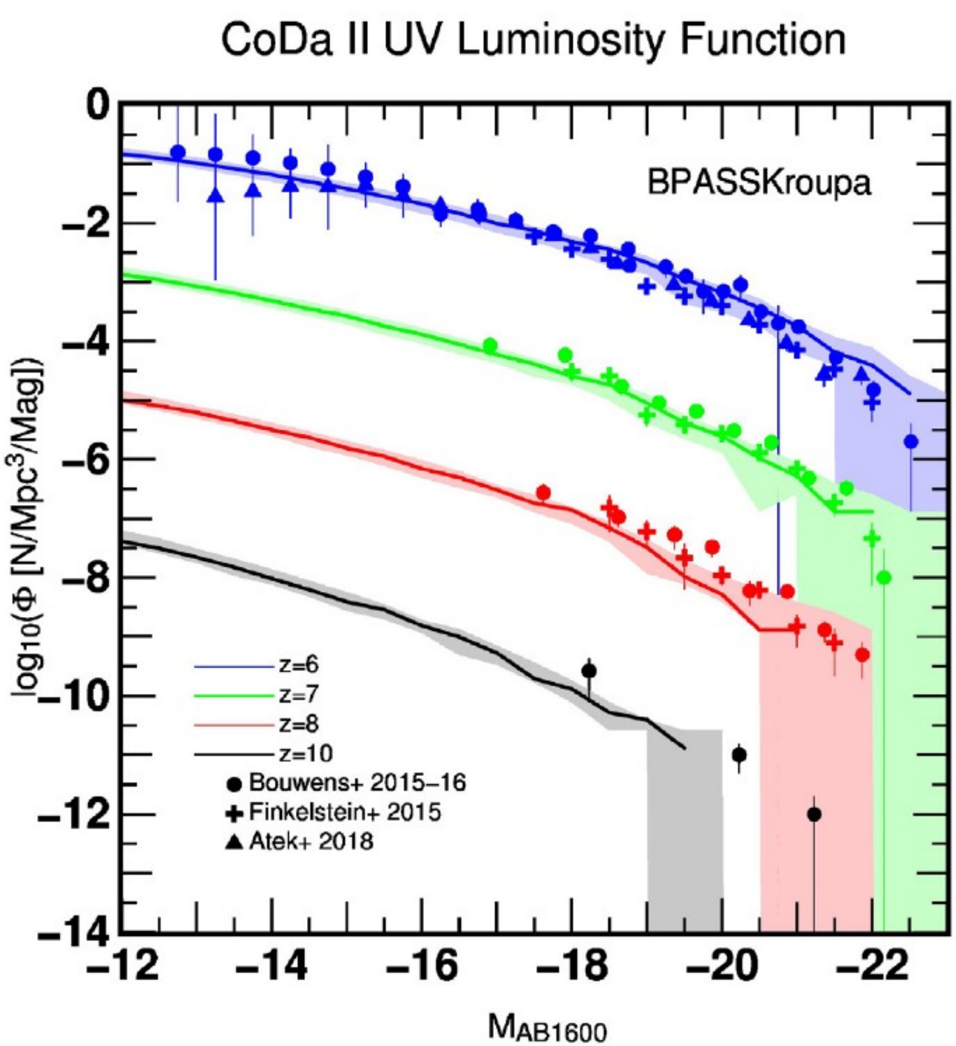




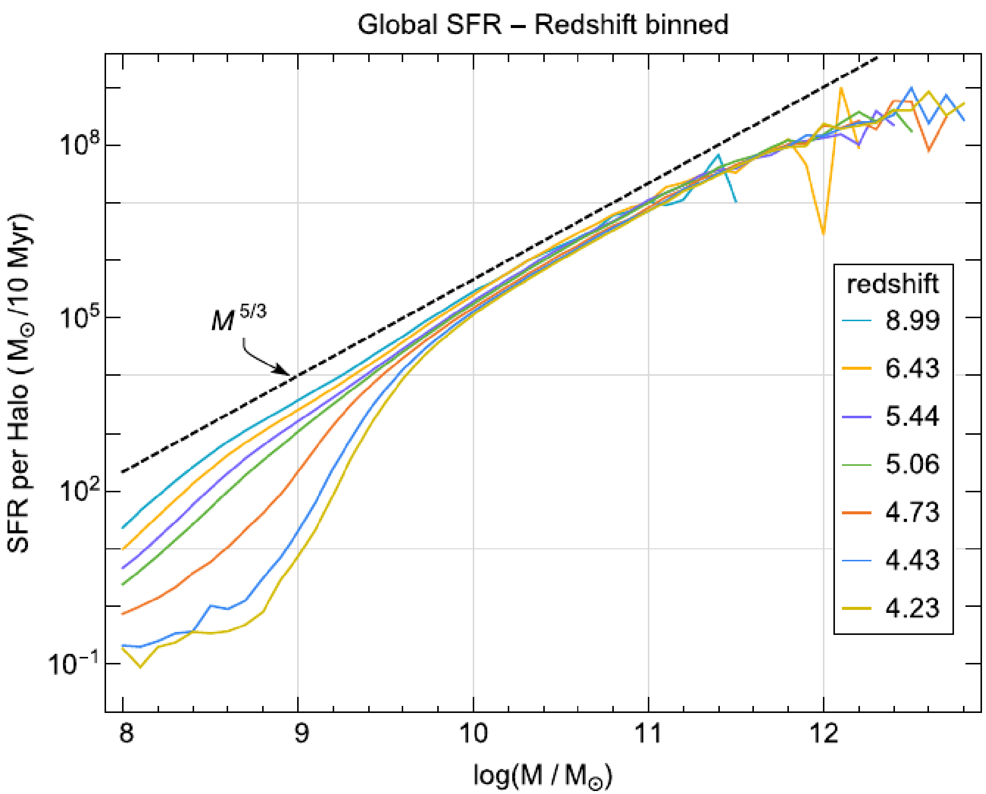
UV luminosity functions
(Ocvirk et al. 2018, 2020, 2025)

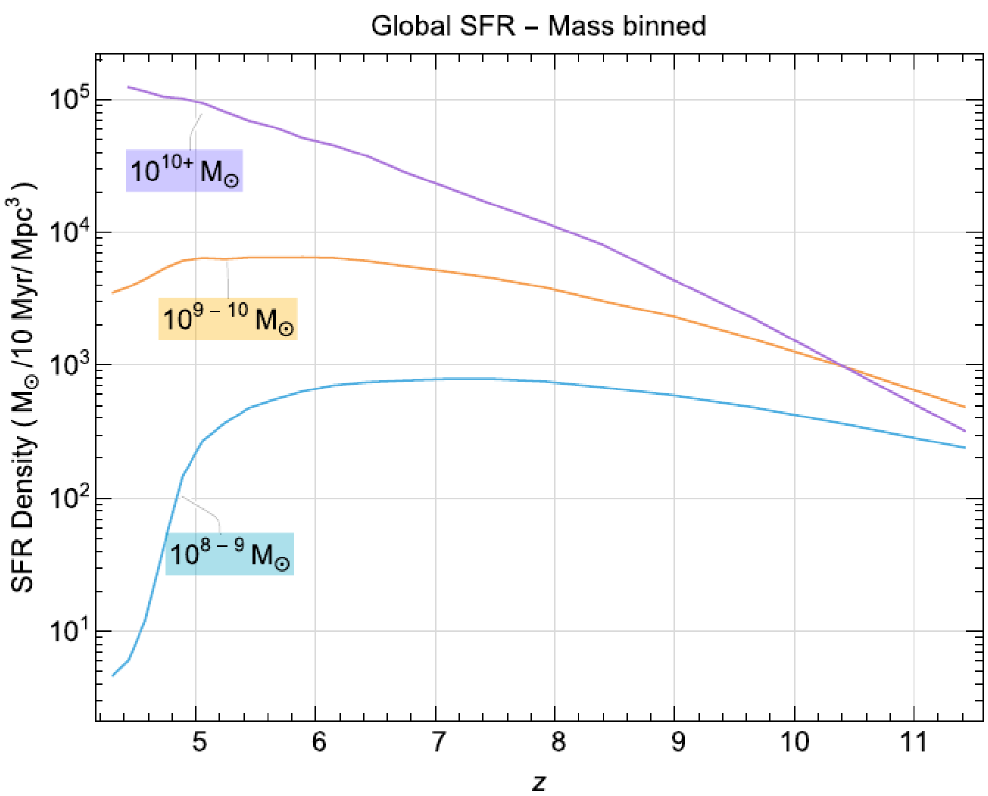
Cosmic Dawn III (incl. dust effects)





Reionization feedback: SFR density (Taha et al. 2018)

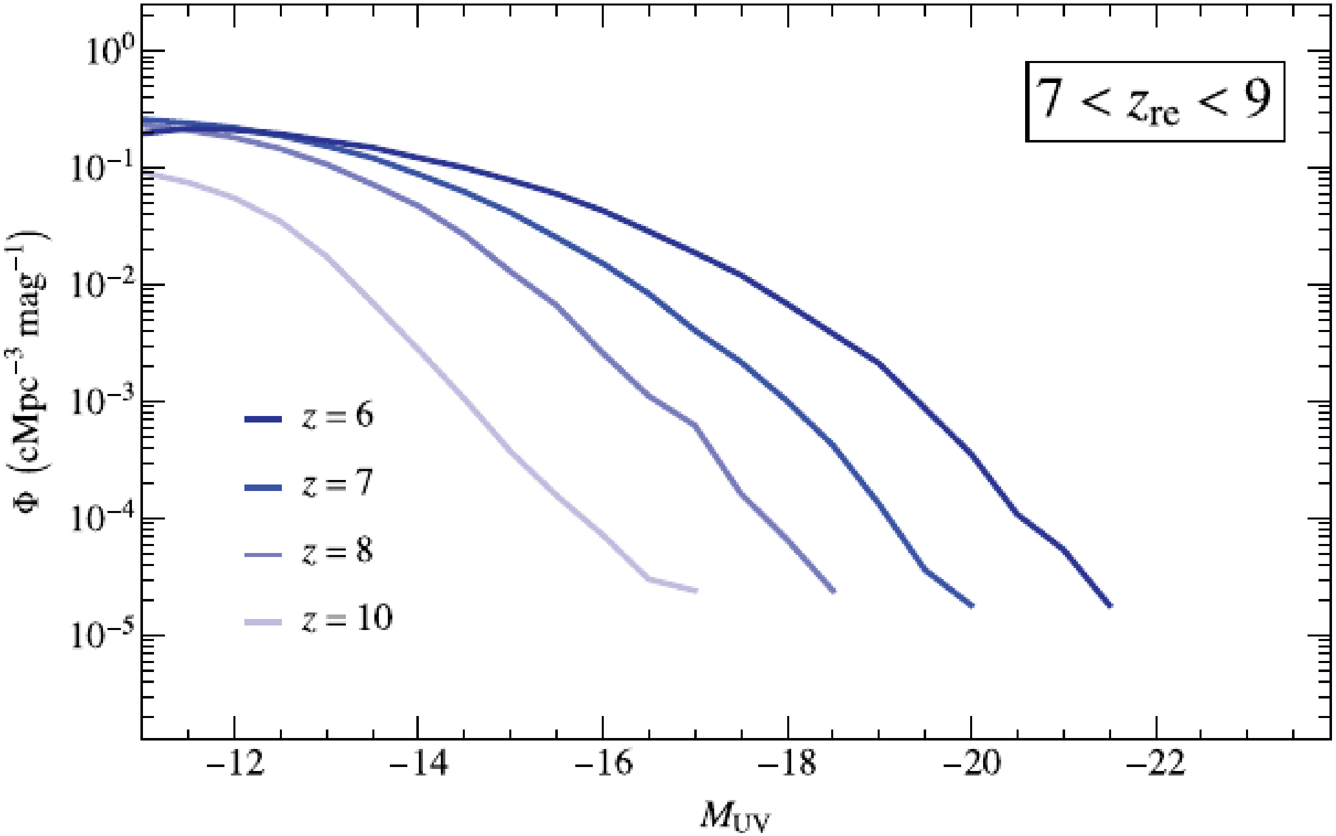




Inhomogoneous UVLF during EoR

(Dawoodboy et al. 2023)

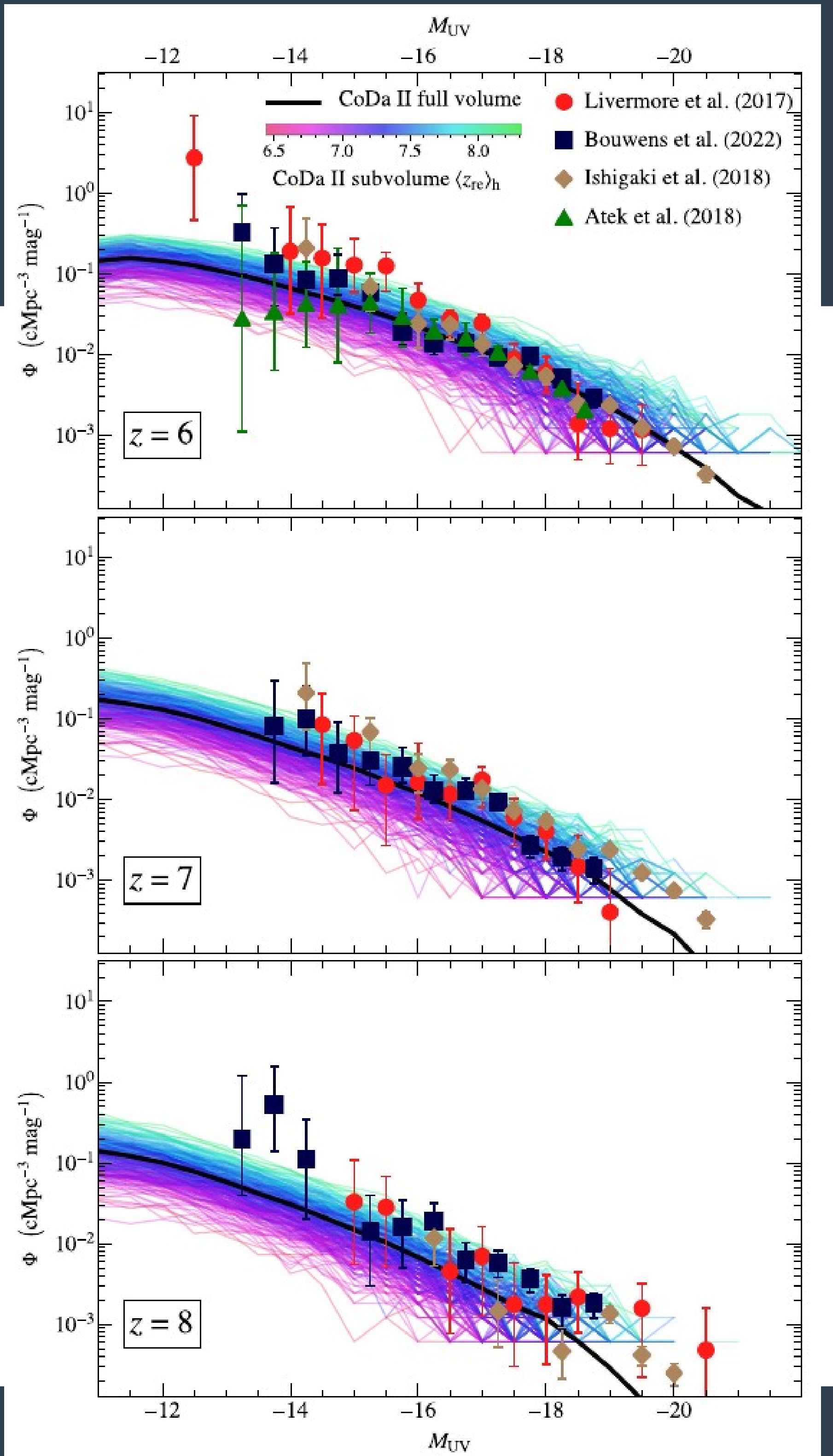
- UVLF for intermediate-reionization regions changes shape over time
- Faint end much flatter at z~6



Inhomogoneous UVLF during EoR

(Dawoodboy et al. 2023)

- Observations generally have quite small volumes and low statistcs (rapidly changing with JWST)
- Reasonable agreement with simulated UVLF at all redshifts
- Significant cosmic variance effects, particularly for lensing observations



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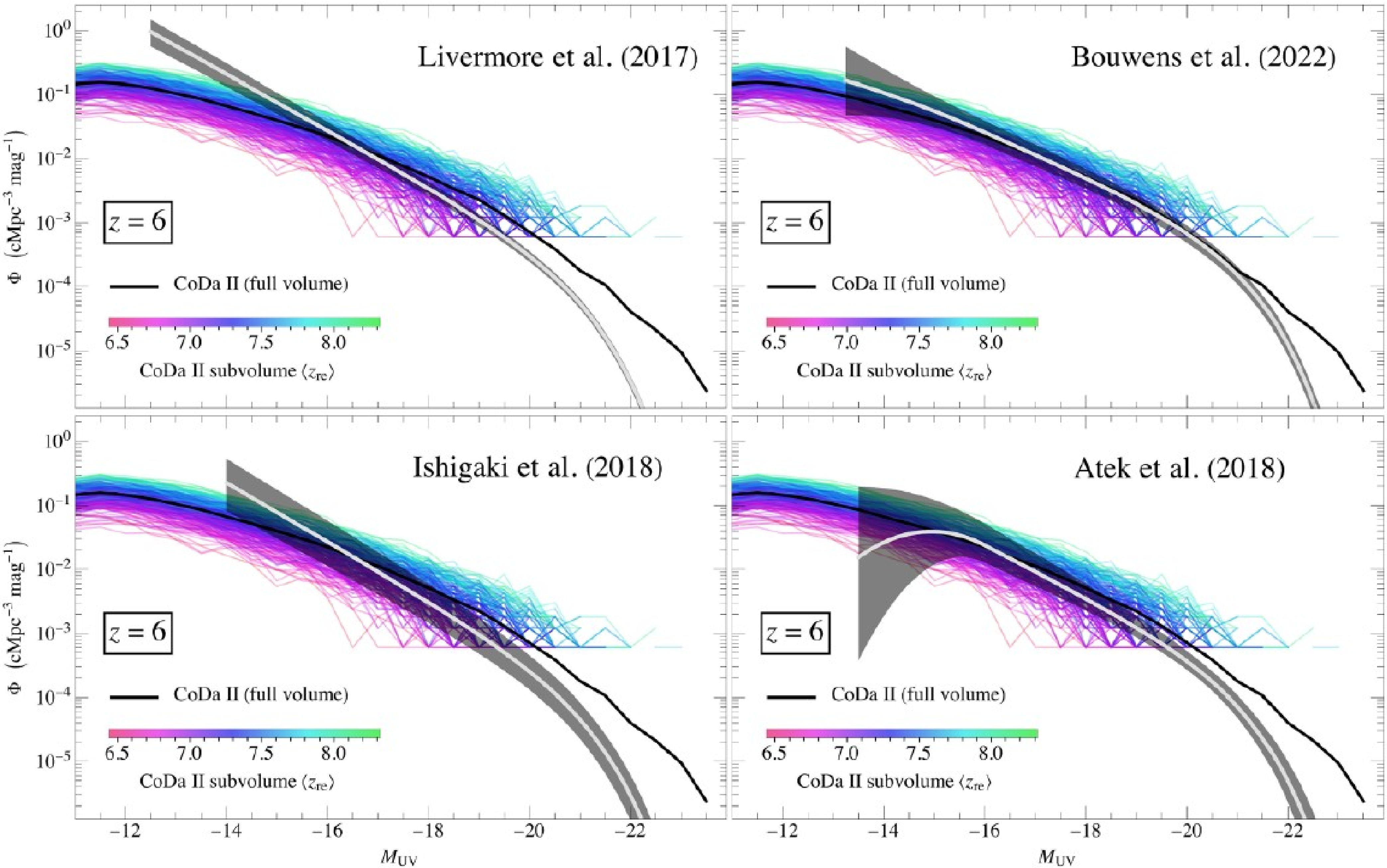
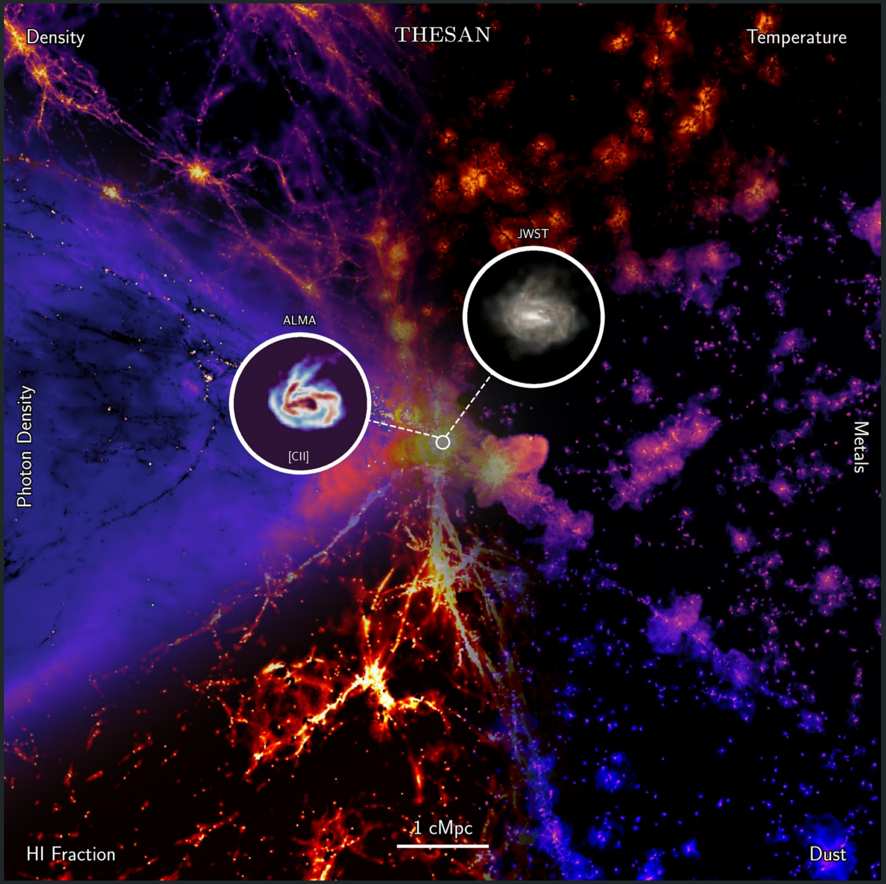


Thesan suite

Large cosmological RMHD simulations (AREPO code), public data available

- **Rich physics**
  - Illustris-TNG galaxy formation model
  - radiation from stars, binaries and BH
  - cosmic dust
  - → A single free parameter at high-z
- **Advanced numerics**
  - variance-suppressed ICs
  - physical (f_{esc}, DM) and numerical variations
- **Ongoing development:**
  - THESANZOOM: zoom-in with accurate ISM, parent-box RT and improved dust model
  - THESANVARIANT: multi-object zoom
  - THESANXL: A low-res. Thesan over (400 Mpc)^3



Garaldi et al., 2022; Kannan, **EG** et al. 2022, Smith, **EG**, et al. 2022, **Garaldi** et al. in prep.

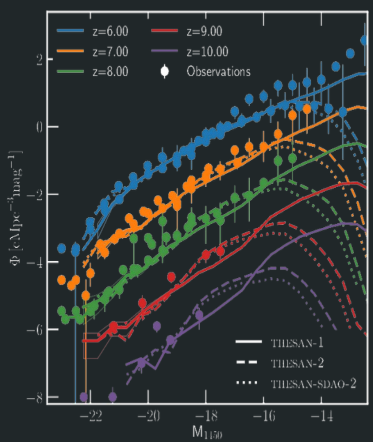
- **An important tool to study the EoR-galaxy connection**

Slide credit: E. Garaldi

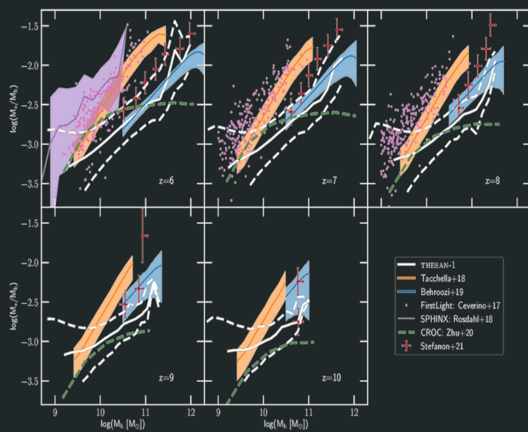
Thesan successes and failures

Garaldi et. al. 2022 | Kannan, EG et al., 2022 | Garaldi et. al, in prep.

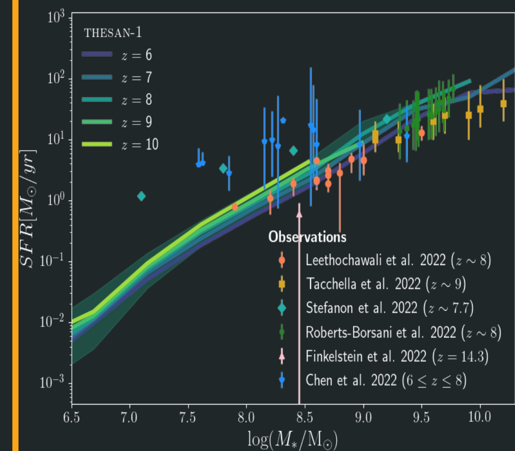
UV LUMINOSITY FUNCTION



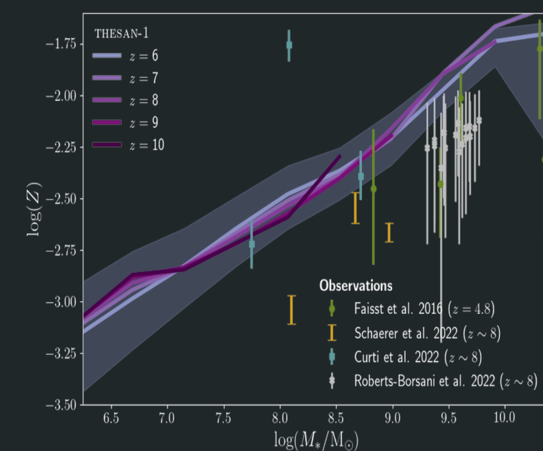
STELLAR-TO-HALO MASS RELATION



GALAXY MAIN SEQUENCE

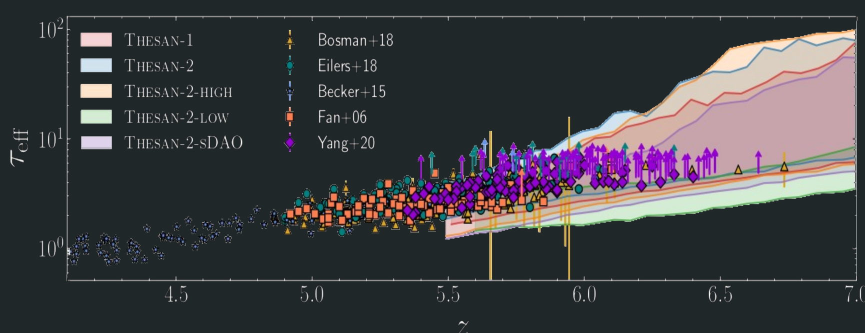


(STELLAR) MASS – (GAS) METALLICITY RELATION

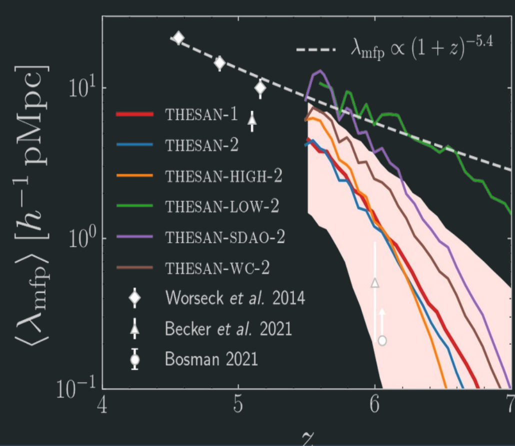


JWST OBSERVATIONS

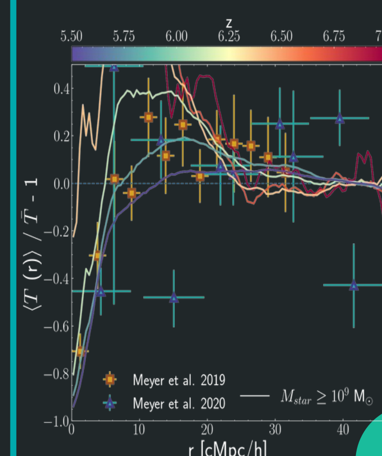
LYA OPTICAL DEPTH EVOLUTION



MEAN FREE PATH OF IONIZING PHOTONS



GALAXY PROXIMITY EFFECT ON LYA FLUX

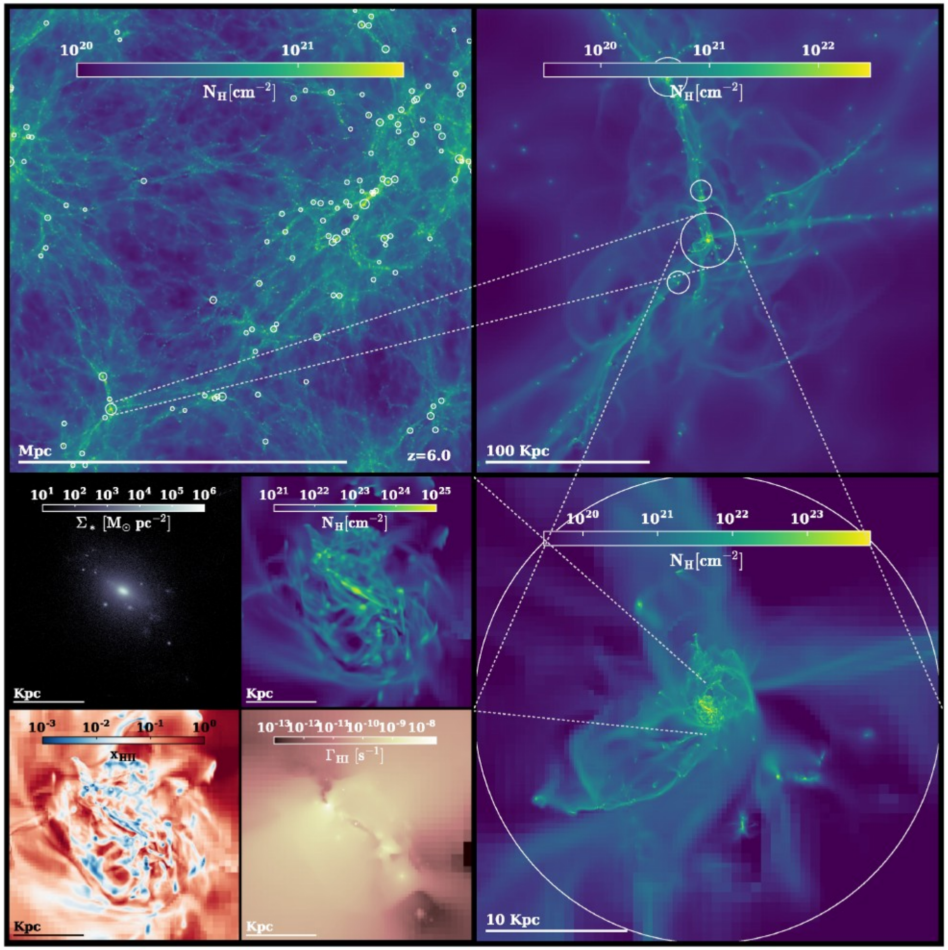


galaxy main sequence
mass-metallicity relation
lya transmission peaks properties
metal lines luminosity vs. sfr
Line Intensity Mapping predictions
…

Slide credit: E. Garaldi

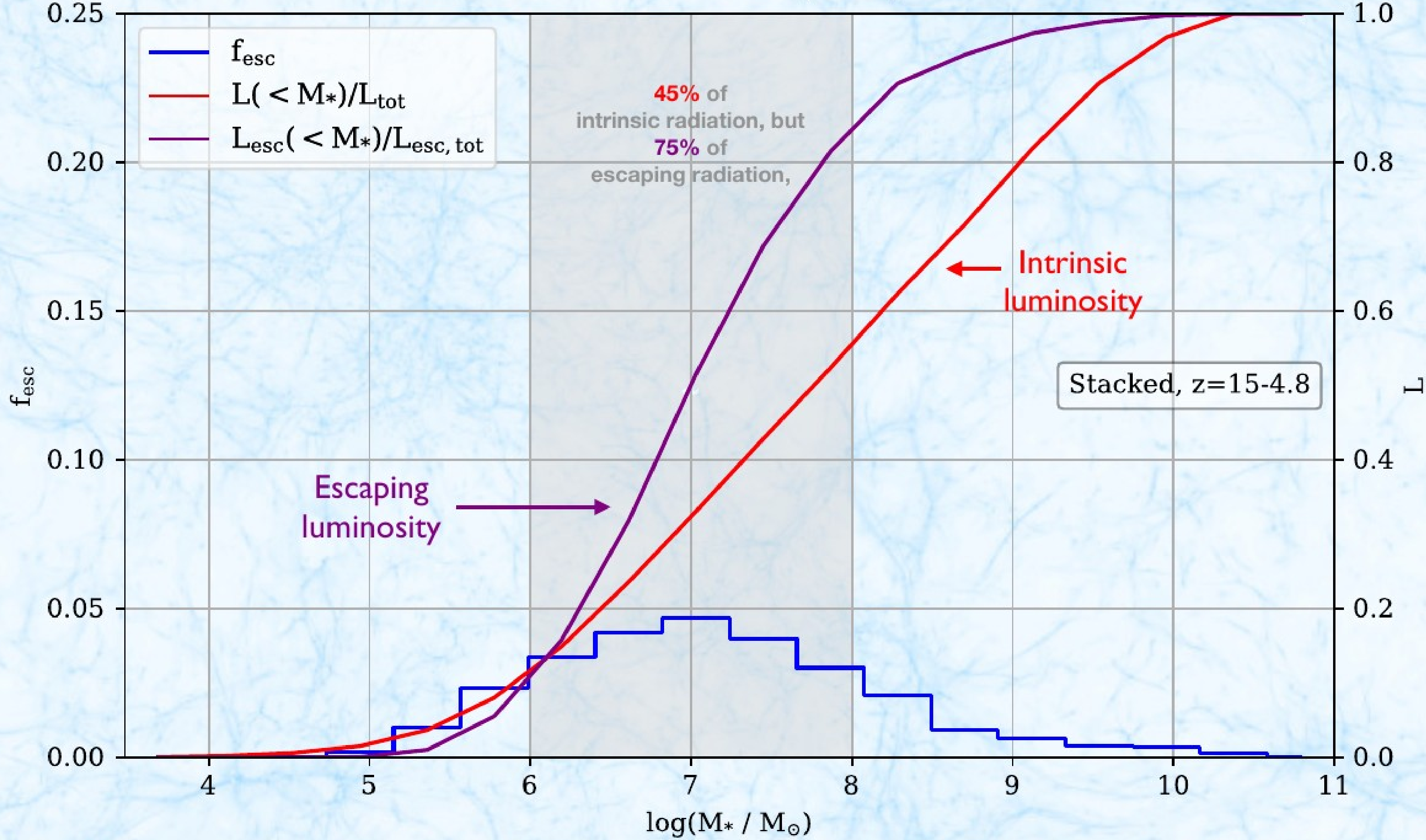
SPHINX (Rosdahl 2018, 2022)

- Suite of Ramses-RT (AMR) simulations
- Relatively small volumes (10-20 cMpc)
- High (local) resolution
- Some publicly available data



Correlation of f_{esc} with galaxy mass

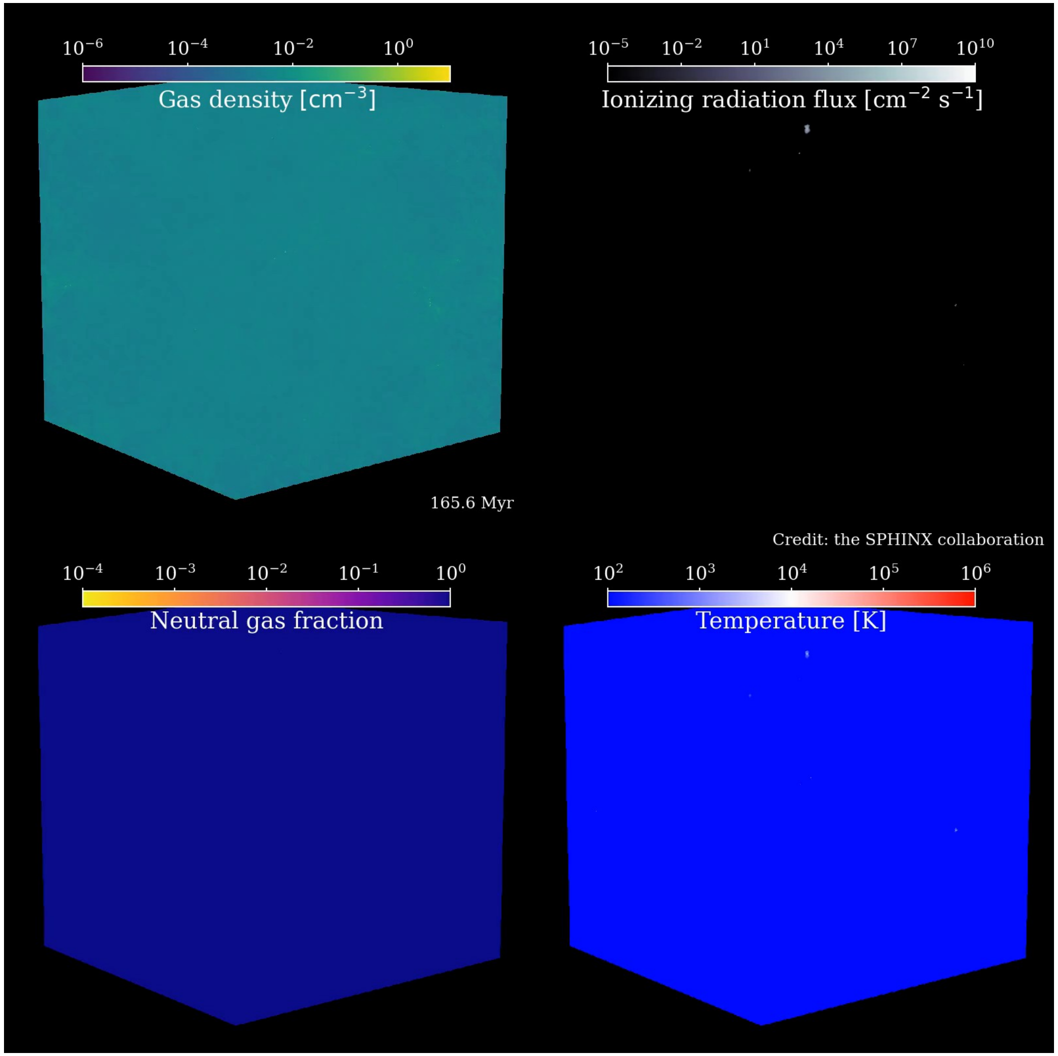
From Rosdahl et al. (2022)



- f_{esc} is luminosity-weighted
- Red/purple: fraction of emitted/escaped photons for galaxies $<M_*$
- Small f_{esc} at high and low masses due to low SN feedback efficiency

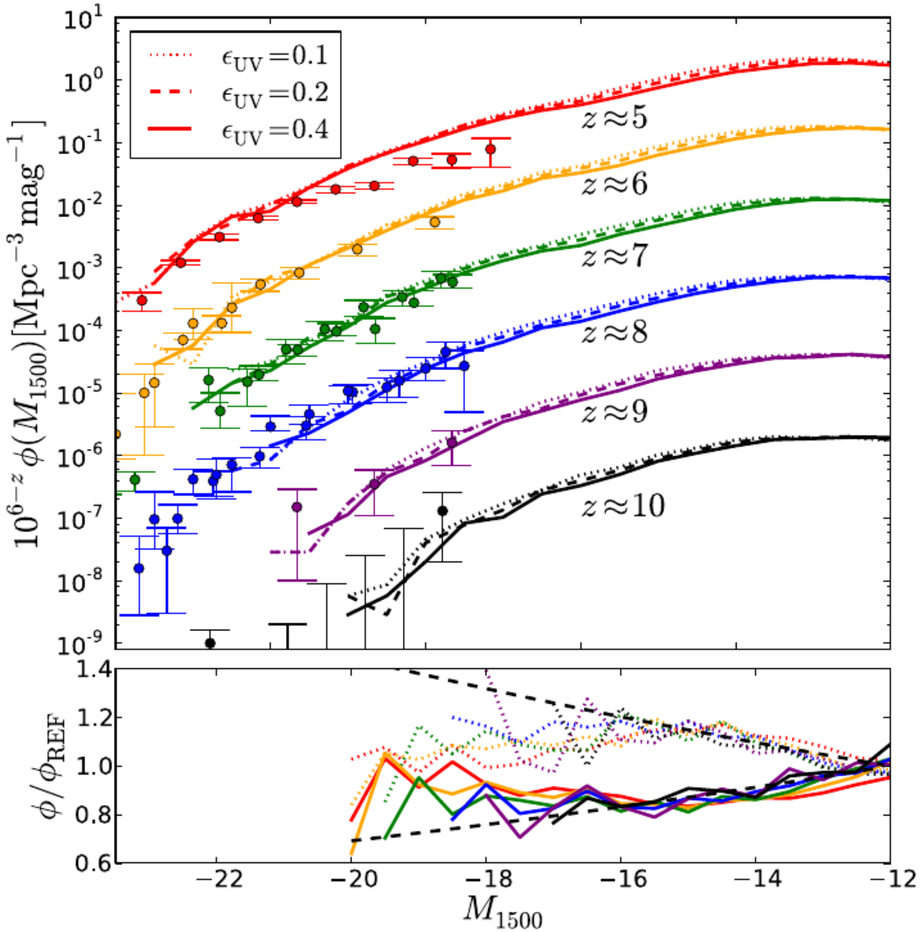
Slide credit: J. Rosdahl

SPHINX (Rosdahl 2018, 2022)



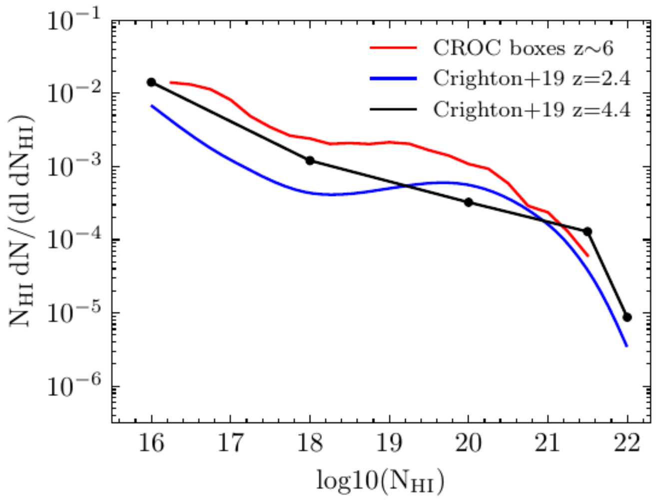
Cosmic Reionization on Computers (CROCs) suite (Gnedin and Kaurov 2014)

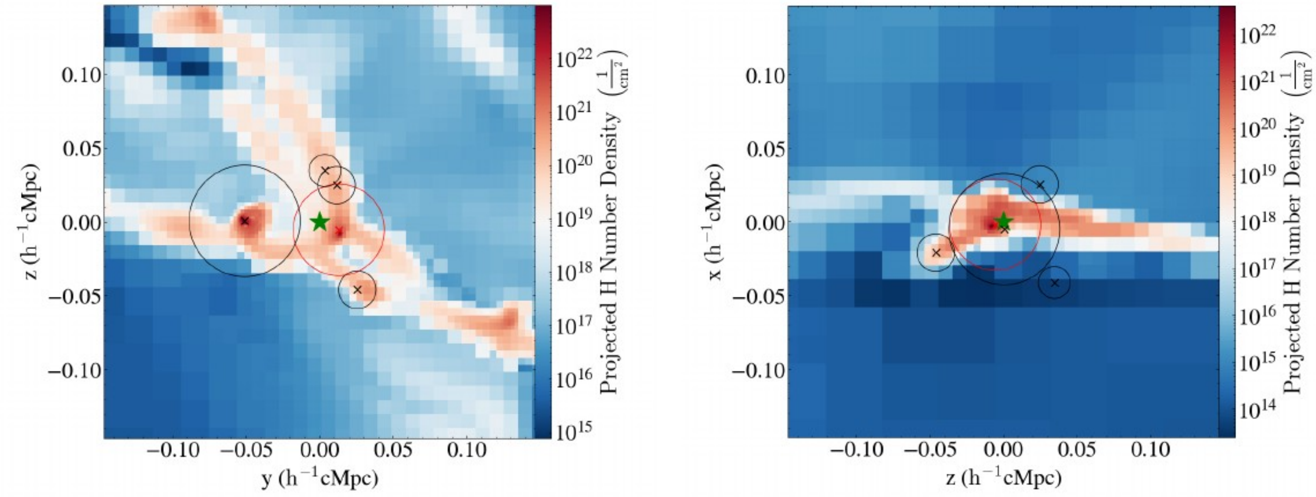
- Large suite of simulations over range of medium-size volumes (20-80 cMpc)
- Using ART (AMR) cosmological code
- Well calibrated to observations



Cosmic Reionization on Computers (CROCs) (Fan et al. 2022, ArXiv/2212.07033)

- Able to simulate realistic LLS in cosmological volumes
- Important for modelling the photon sinks and mean free path

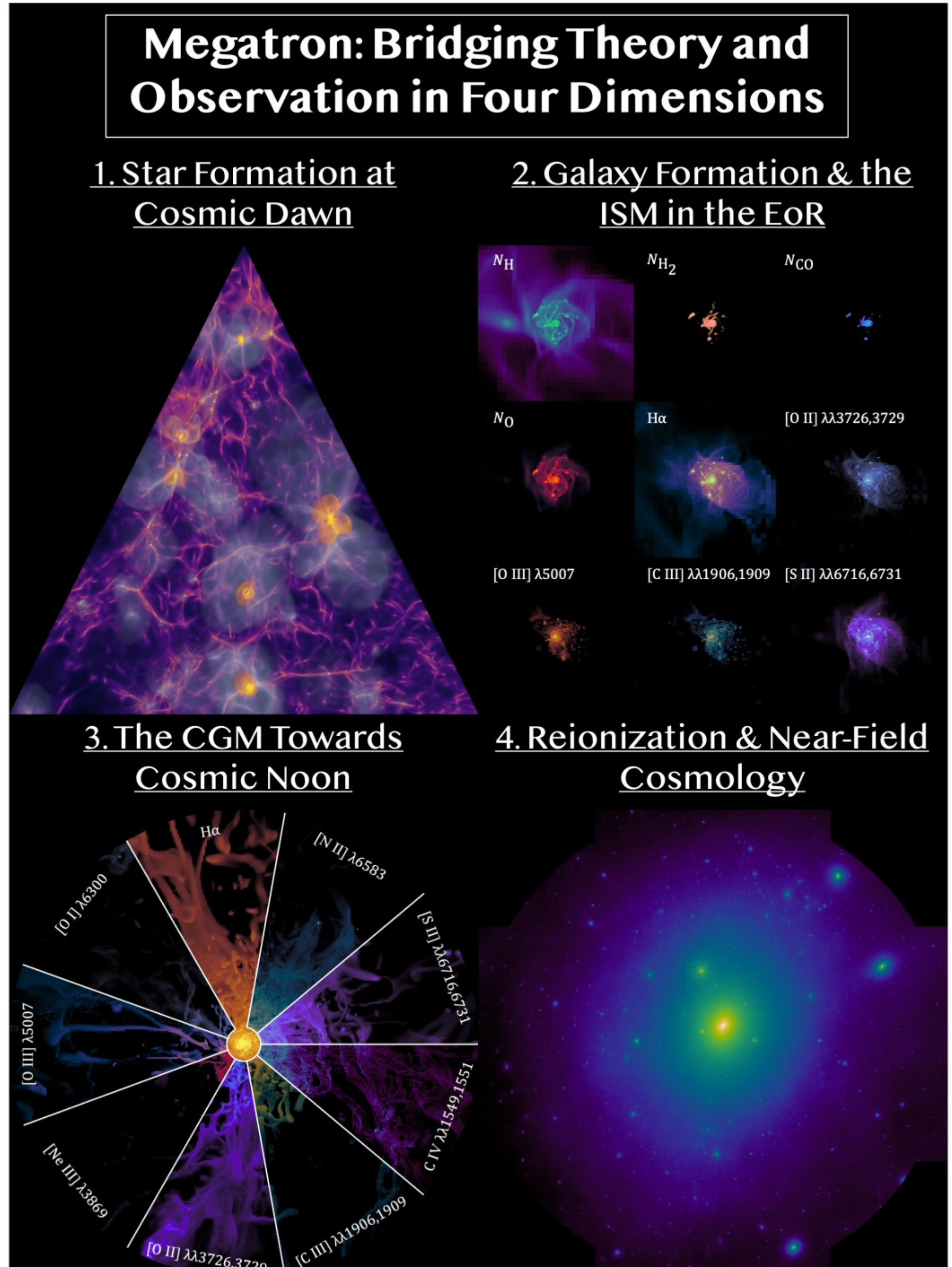




Megatron
(Katz et al. 2025)

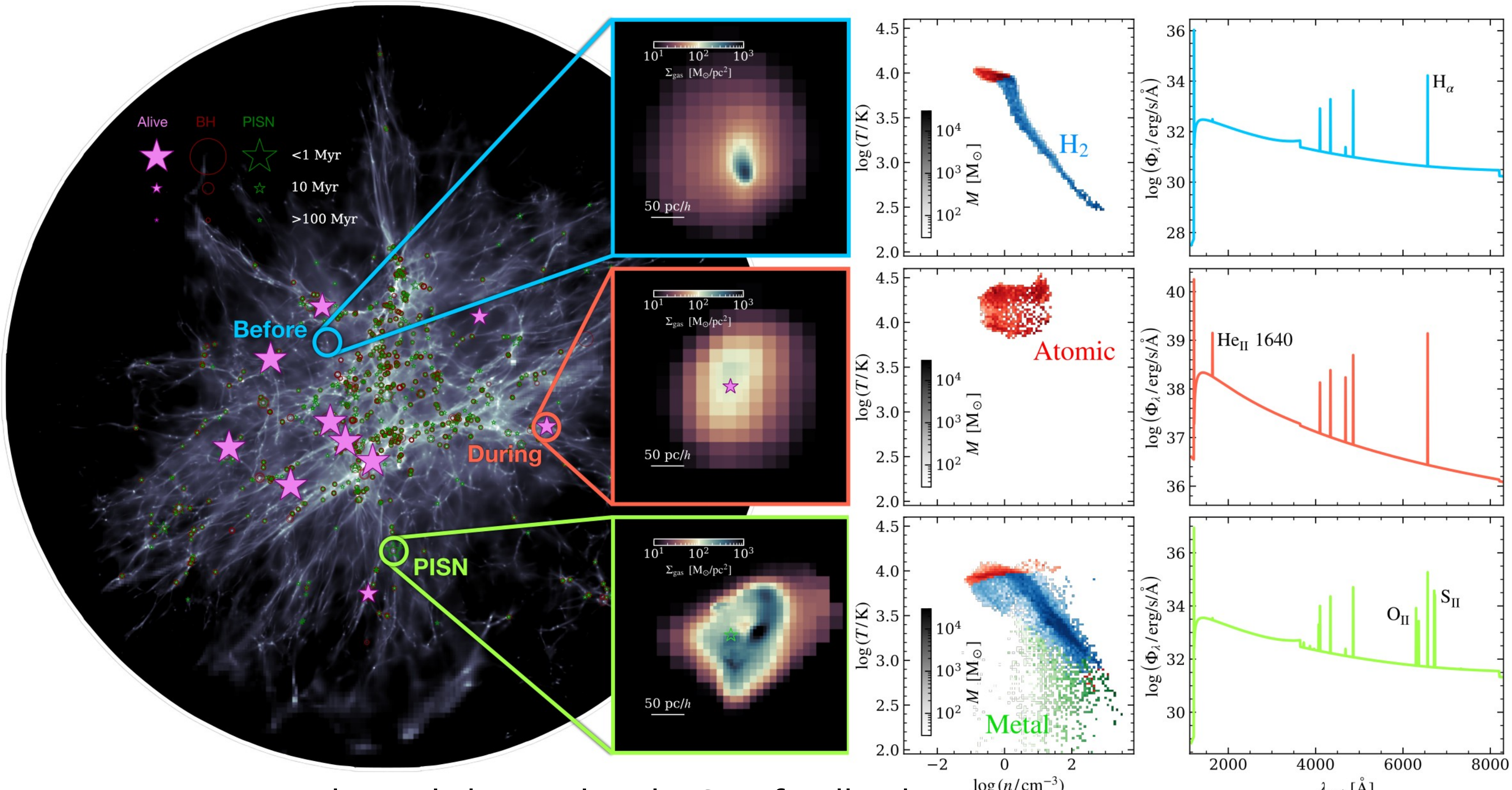
- Hydro+full RT AMR simulations
- Modified version of Ramses-RT with an extended chemistry network
- 4 SF models + Sne/Hne
- PopIII+PopII evolution

- Modelling evolution of an isolated MW-like (at z=0) halo from 50 Mpc/h volume
- Lagrangean region ~18 Mpc/h
- ICs modified to get more JWST galaxies
- Large number of (small) galaxies
- Full metallicity evolution
- Detailed spectra produced



Megatron: Pop III stars

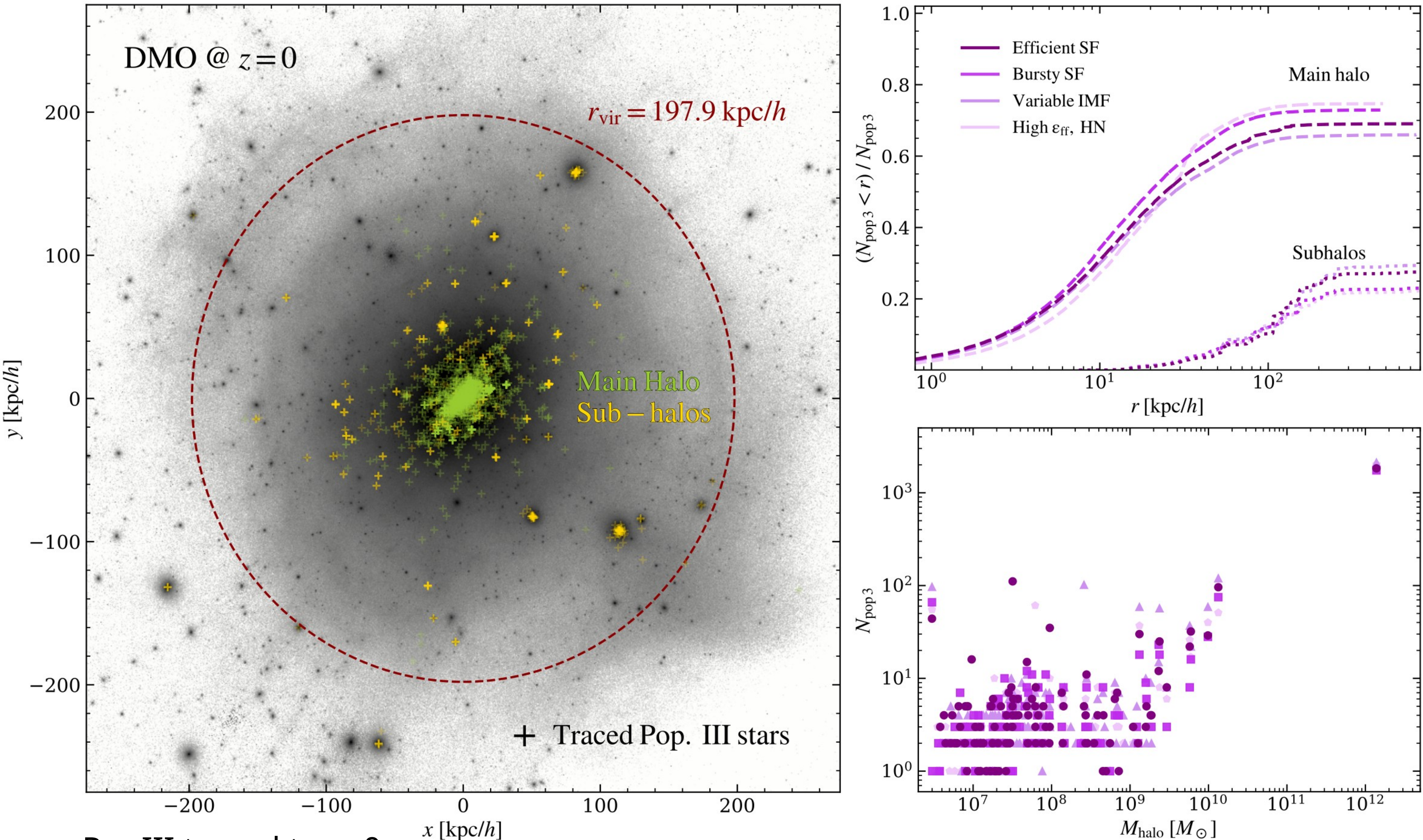
(A. Storck et al. 2025)



PopIII suppressed mostly by LW, less by SNe feedback

Megatron: tracing Pop III stars to z=0

(A. Storck et al. 2025)



PopIII traced to z=0

SEEDZ suite
Prole et al. 2026)

- Simulations focused on black hole evolution and feedback
- Bondi BH accretion model
- Very high spatial resoltion (moving mesh)
- No RT, SNe+X-ray feedback

- BH feedback depends on BH mass and halo, but typically disrupts the halo, even for weak assumed feedback
- JWST data suggests weaker BH feedback than typically assumed. After initial quenching the gas reservoir restores
- Useful for (subgrid) modelling of BH in larger volumes