The Cosmic Dawn (CoDa) Project: Simulating Reionization and Galaxy Formation

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Collaborators in this work include:

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(1)U Texas at Austin (2)U Sussex (7)U Strasbourg (8) U Zurich (9) U Madrid (10) AIP Potsdam (13) Hebrew U (15)U Washington (16) U Lyons

"CoSyne: Cosmological Synergies in the Upcoming Decade"
Institut d'Astrophysique, Paris, December 11, 2019

The Cosmic Dawn (CoDa) Project: Simulating Reionization and Galax Formation

Cosmic Dawn: Fully-Coupled Radiation-Hydro Simulations of Reionization and Galaxy Formation

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"CoSyne: Cosmological Synergies in the Upcoming Decade"

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Introducing the CoDa (COSMIC DAWN) Simulations

- Largest fully-coupled rad-hydro reionization simulations to-date, *global* and *local*

- *Volume large enough* to simulate global reionization; *resolution high enough* to follow all atomic-cooling halos (>10^8 M_solar), including MW/M31 dwarf satellites.

- 3 EOR Simulations of L > 90 Mpc boxes, from **CLUES** Constrained Realization I.C.'s
  -- **CoDa I** and **CoDa II :**

RAMSES-CUDATON simulations (uniform grid): hybrid CPU-GPU code

- Grid size = $(4096)^3$ cells, Δx ~ 20 cKpc < 3 Kpc's ; N-body particles = $(4096)^3$ ~ 69 billion
- Minimum halo mass ~ 10^8 M_solar ~300 particles

Ocvirk, Gillet, **Shapiro**, Aubert, Iliev, Teyssier, Yepes, Choi, Park, D'Aloisio, Sullivan, Gottloeber, Hoffman, Stranex, Knebe 2016, MNRAS, 463,1462 (**arXiv:1511.00011**) **(CoDa I**)

Ocvirk, Aubert, Sorce, **Shapiro**, Deparis, Dawoodbhoy, Lewis, Teyssier, Yepes, Gottloeber, Ahn, Iliev, Hoffman, 2019, MNRAS, submitted (**arXiv:1811.11192) (CoDa II**)

-- **CoDa I – AMR :**

EMMA simulation (Adaptive Mesh Refined): hybrid CPU-GPU code

- AMR resolution = $(16,384)^3$ cells (fully-refined) ➔Δx ~ 5 cKpc ➔ ~ 500 pc
- N-body particles = $(2048)^3$ ~ 8.6 billion
- Minimum halo mass ~ 10^8 M_solar ~ 36 particles

Aubert, Deparis, Ocvirk, **Shapiro**, Iliev, Yepes, Gottloeber, Hoffman, Teyssier 2018, ApJL , 856, L22 (**arXiv:1802.01613**) (**CoDa I - AMR**)

Simulating Galaxy Formation and Reionization of the Local Universe with Fully-Coupled Radiation-Hydro: CoDa II

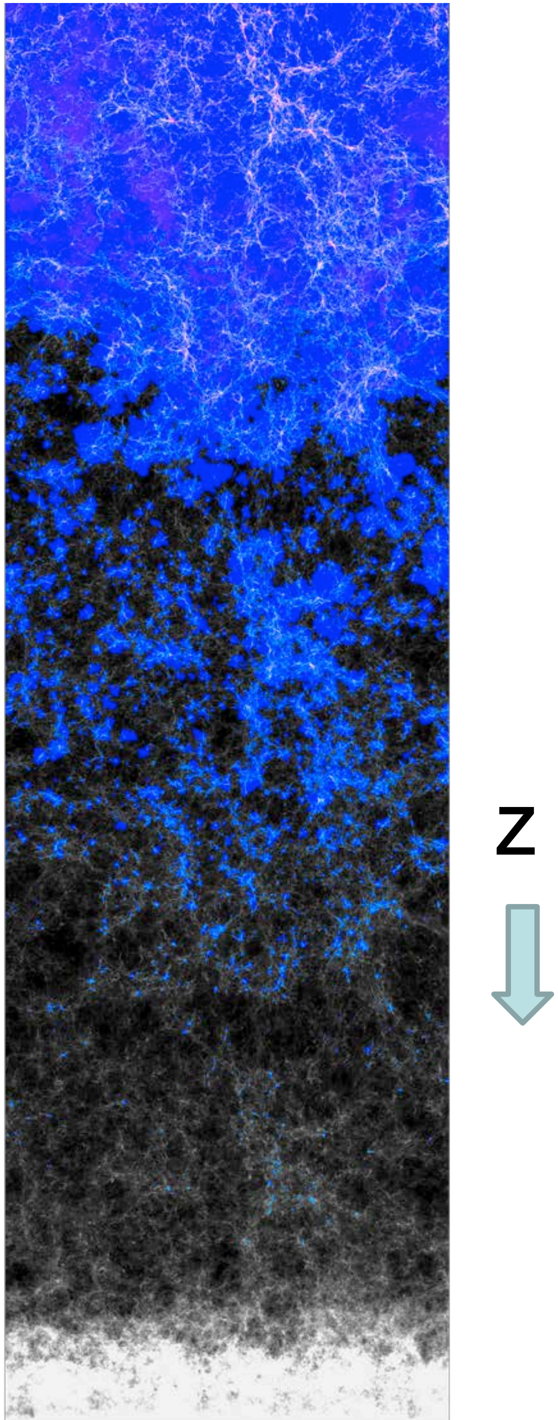
Ocvirk, Aubert, Sorce, Shapiro, Deparis, Dawoodbhoy, Lewis, Teyssier, Yepes, Gottloeber, Ahn, Iliev, Hoffman 2019, MNRAS submitted (arXiv: 1811.11192)

RAMSES-CUDATON simulation

- Box size = 94 cMpc
- Grid size = $(4096)^3$ cells, $\Delta x \sim 20$ cKpc < 3 Kpc
- N-body particles = $(4096)^3 \sim 69$ billion
- Minimum halo mass ~ 10^8 M_solar ~300 particles
- Newer CLUEs initial conditions

TITAN Supercomputer requirements

- # CPU cores (+ # GPUs) = 65536 (+ 16384)
- runtime ~ 6 days



CoDa II

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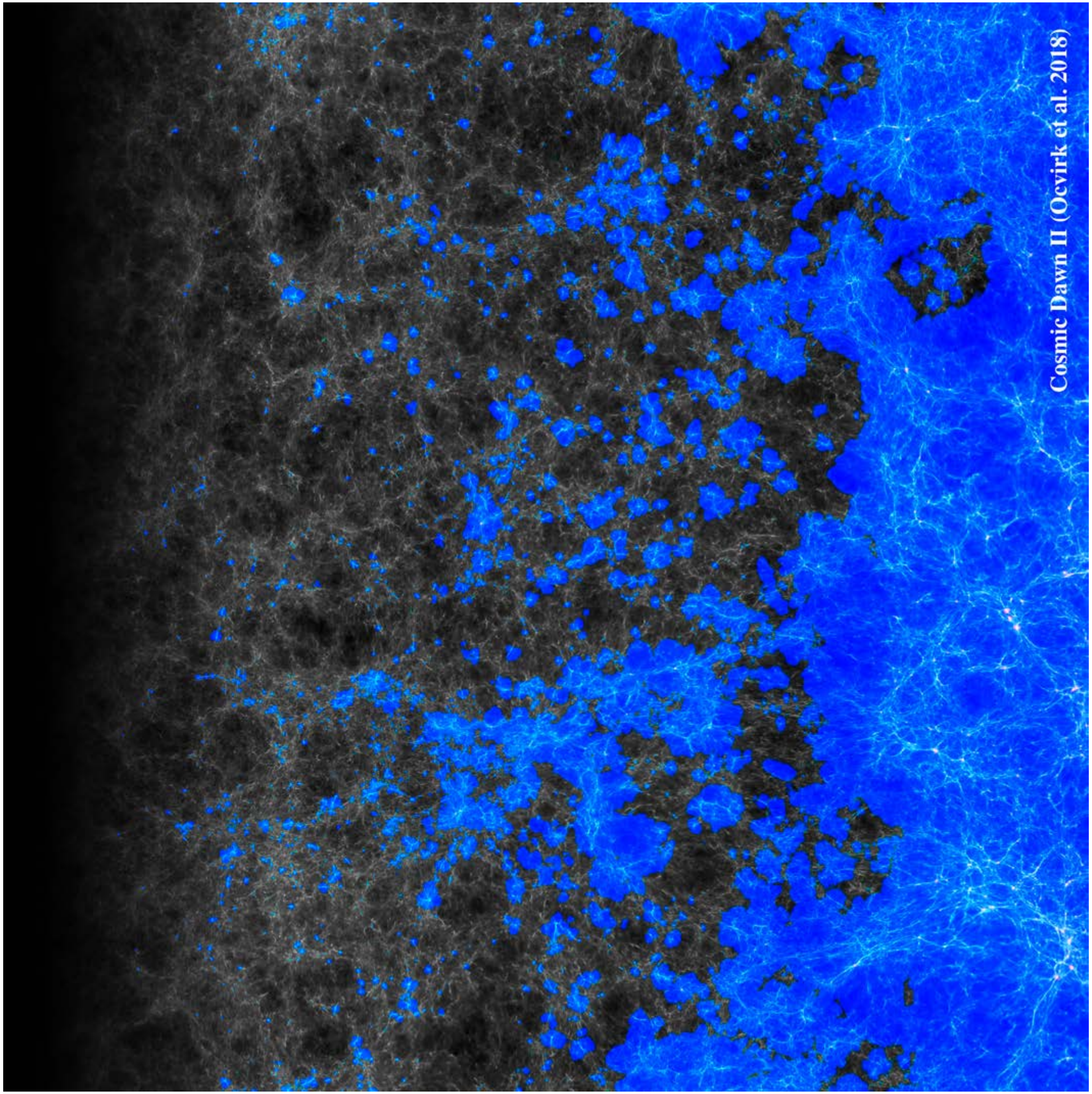
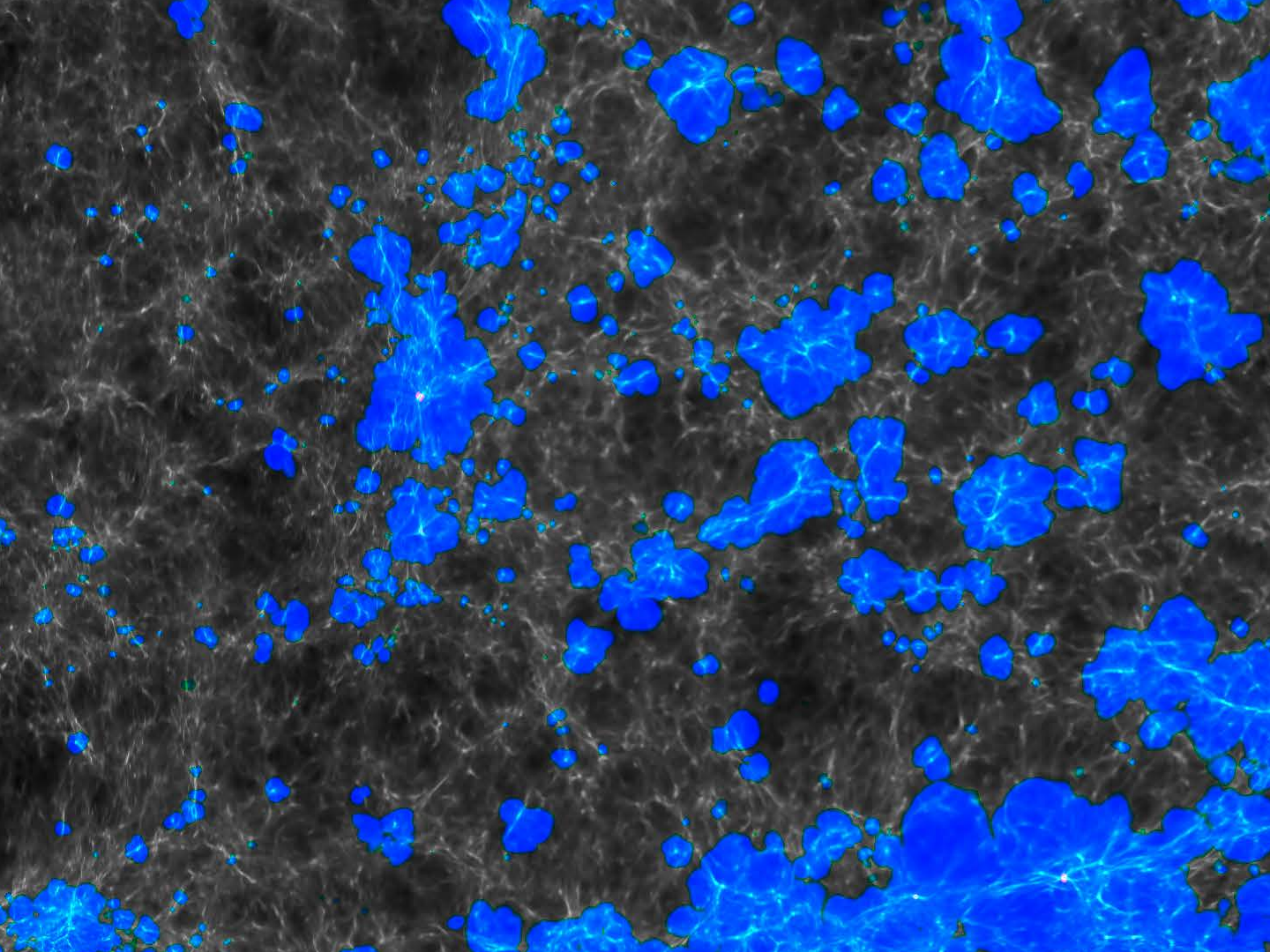
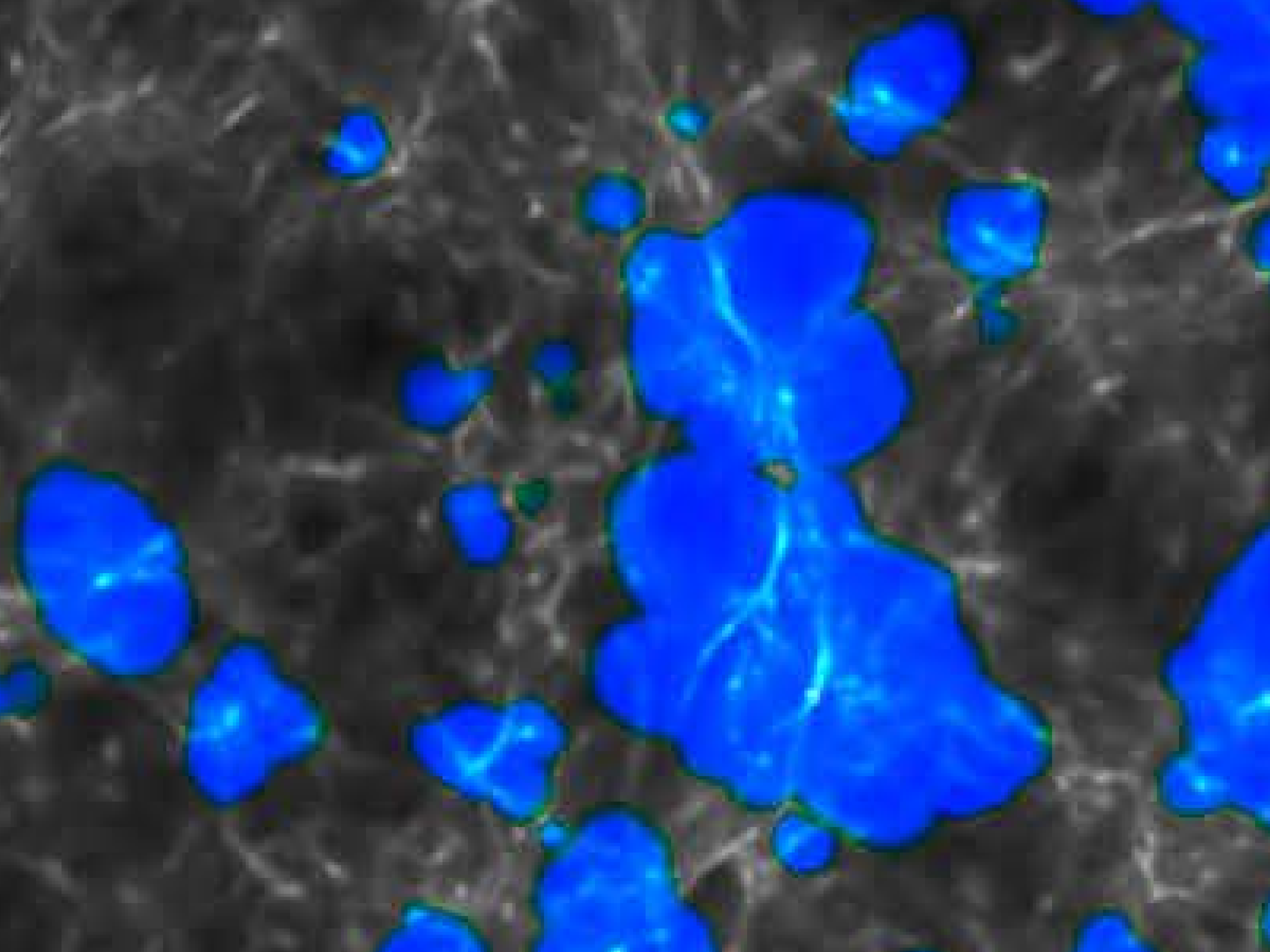


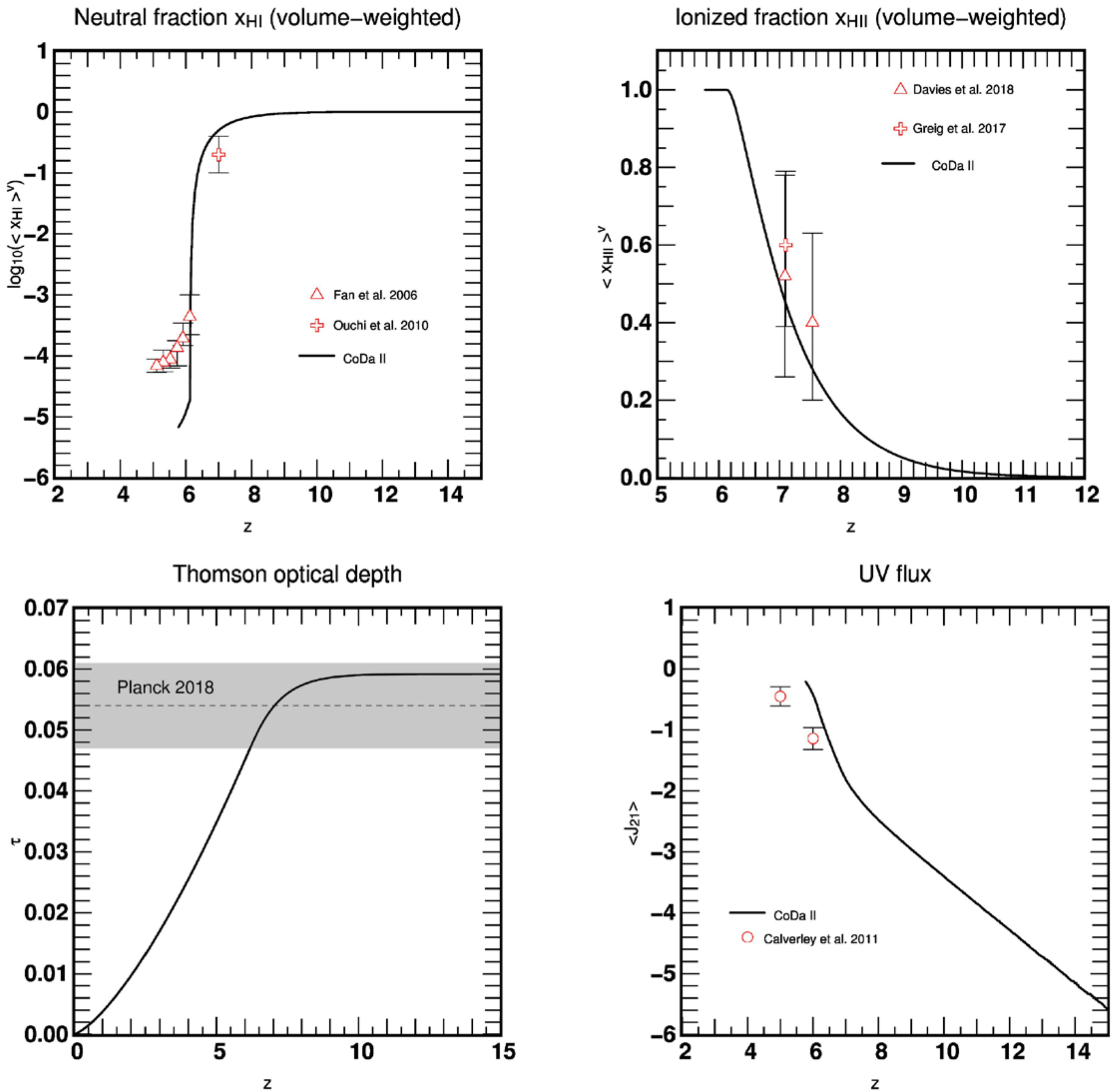
Z





CODA II

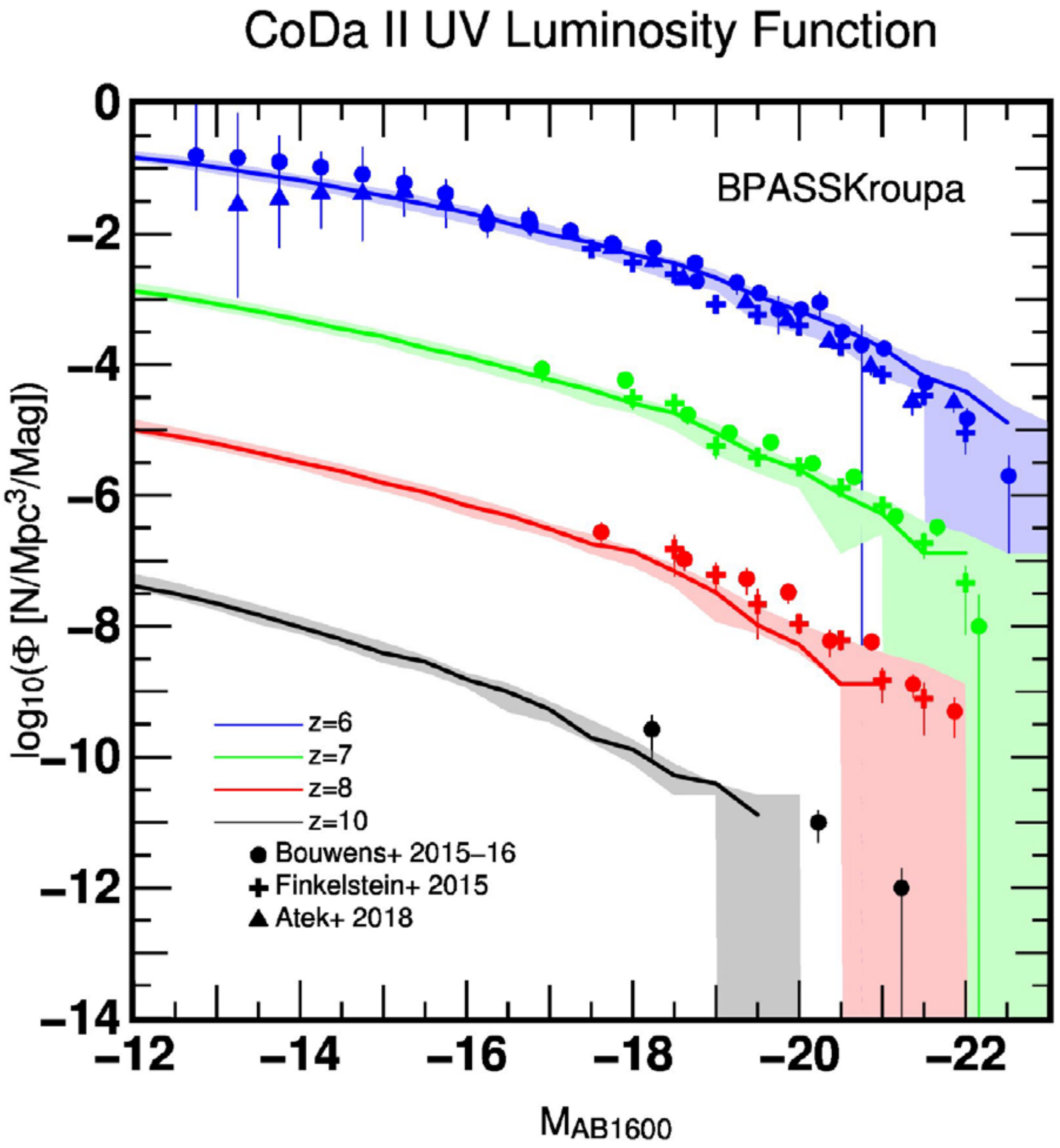
- Star formation efficiencies calibrated so reionization ends early enough:
  $z_{rei} > 6$
- Good agreement with observable constraints
- Post-reionization neutral fraction (UV background) a bit low (high), respectively
  ➔ gas clumping missing at small scales?



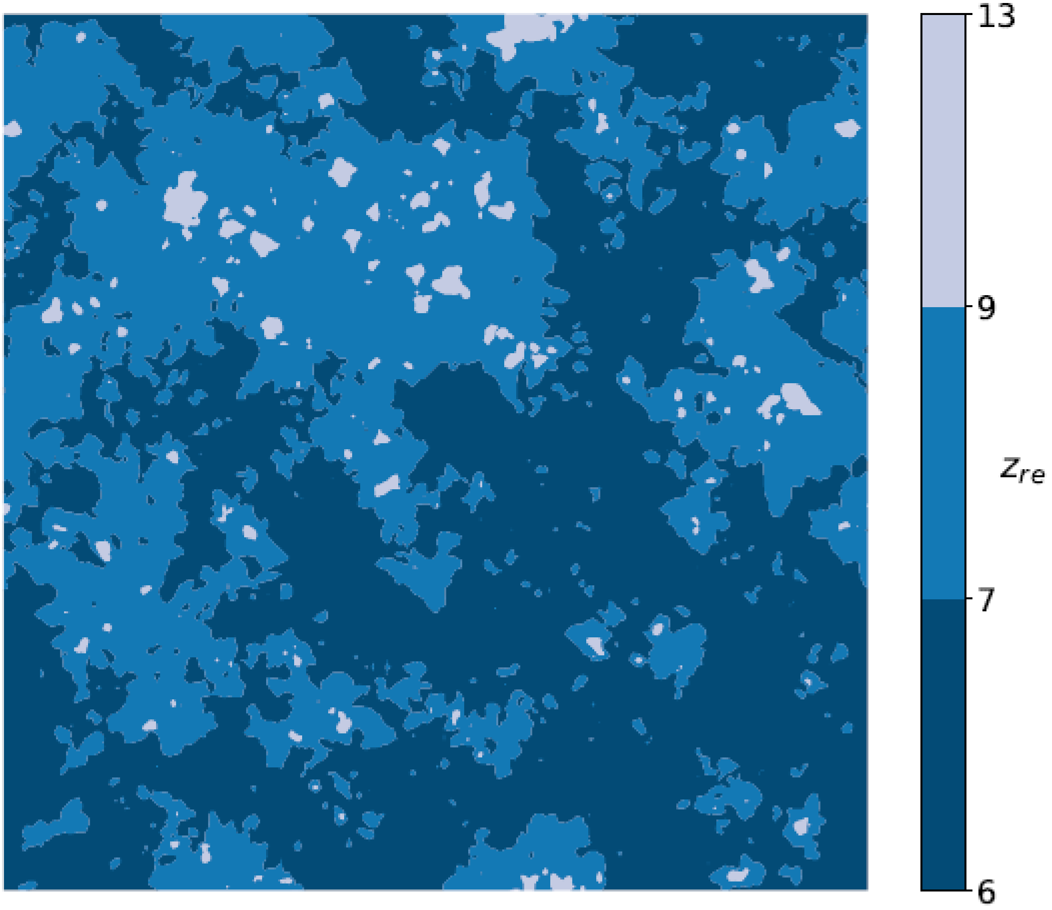
UV Luminosity Function vs. Galaxy Observations from Bouwens + (2015), (2016), Finkelstein + (2015), Atek + (2018)

CODA II

- Shaded areas and thick lines show the envelope and median of the LFs of 5 independent, rectangular subvolumes, each 1/5 full box volume, similar to CANDELS-DEEP volume at z = 6
- M_{AB1600} magnitudes computed using BPASS Z = 0.001 binary population model (no dust) for each halo star particle, evolved since its birth-time, scaled to deliver the same ionizing photons released per 10 Myr

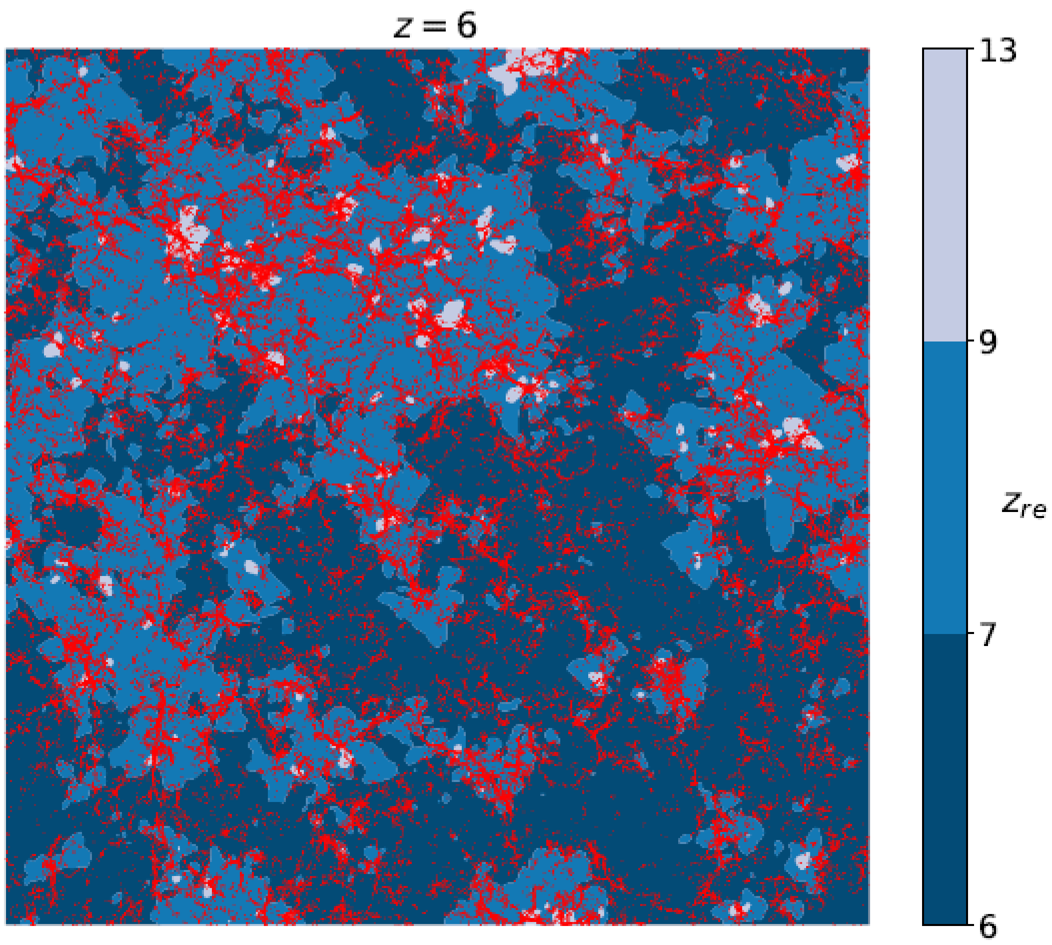


The Inhomogeneous UV Luminosity Function of High-Redshift Galaxies



Reionization was inhomogeneous in time and space

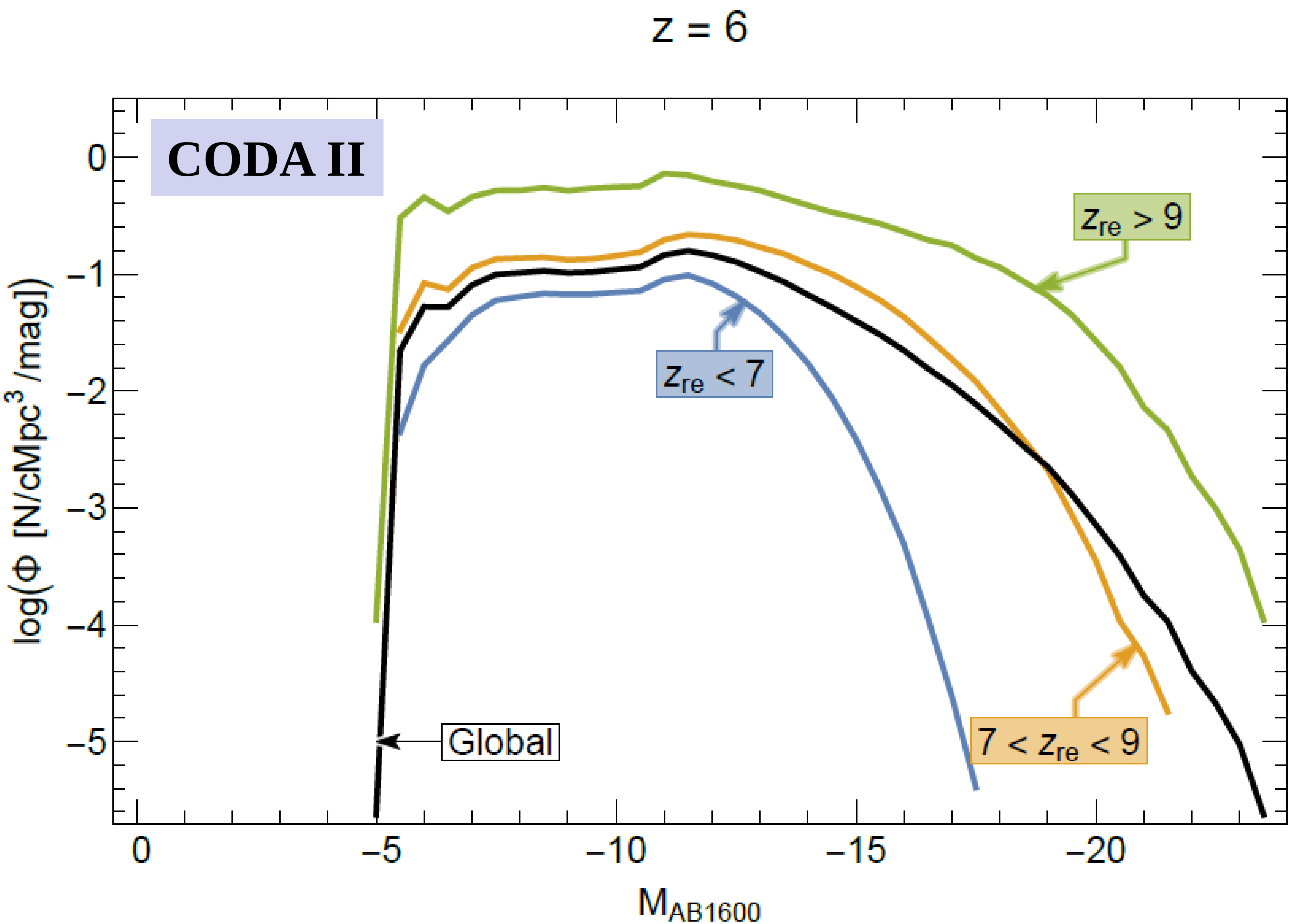
The Inhomogeneous UV Luminosity Function of High-Redshift Galaxies



Galaxies at
$z = 6$
superposed
on reionization
redshift map

- Halo clustering correlates with reionization redshift ➔ So must the high-redshift galaxy UV Luminosity Function!

The UV Luminosity Function of High-Redshift Galaxies is Inhomogeneous!



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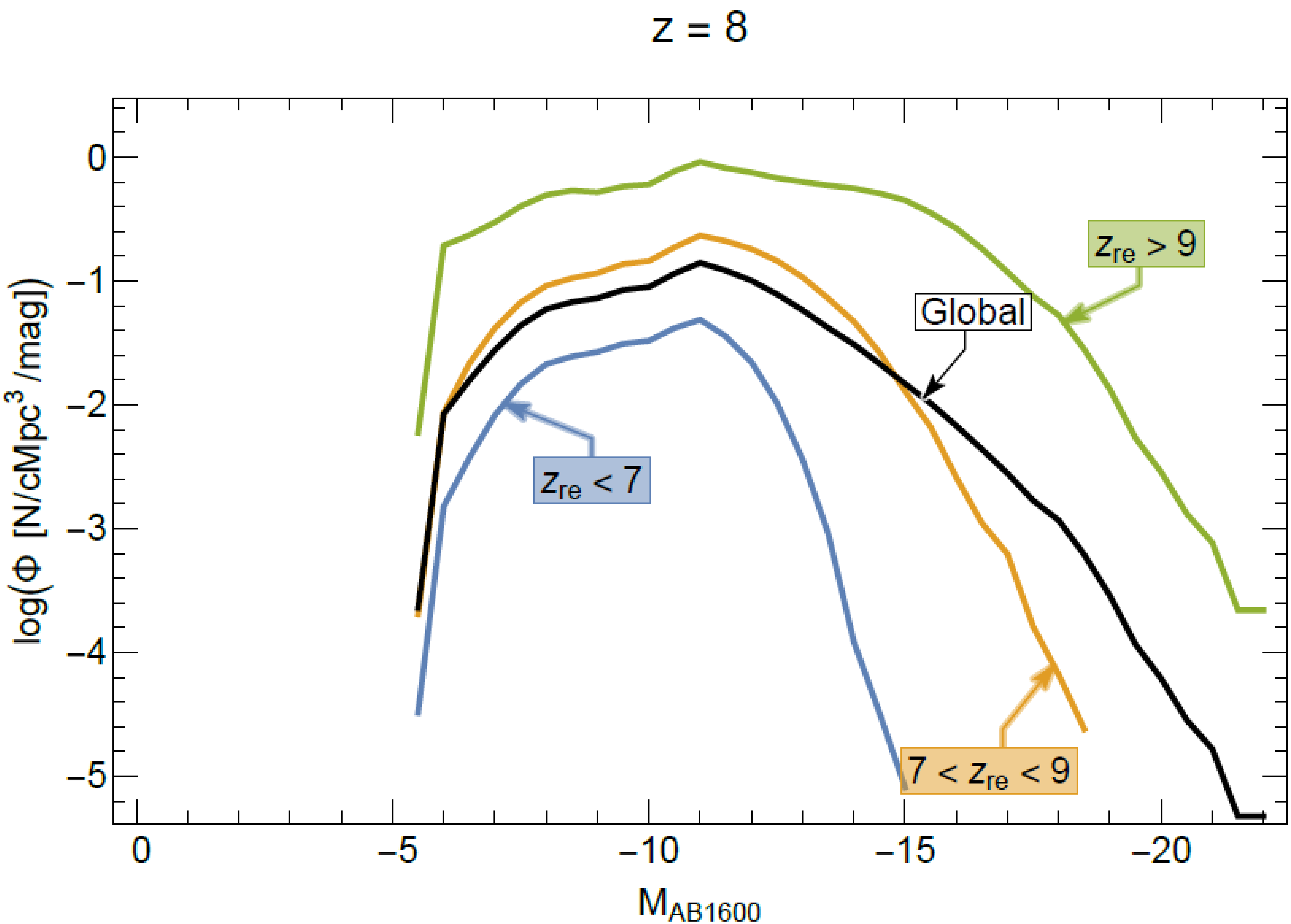

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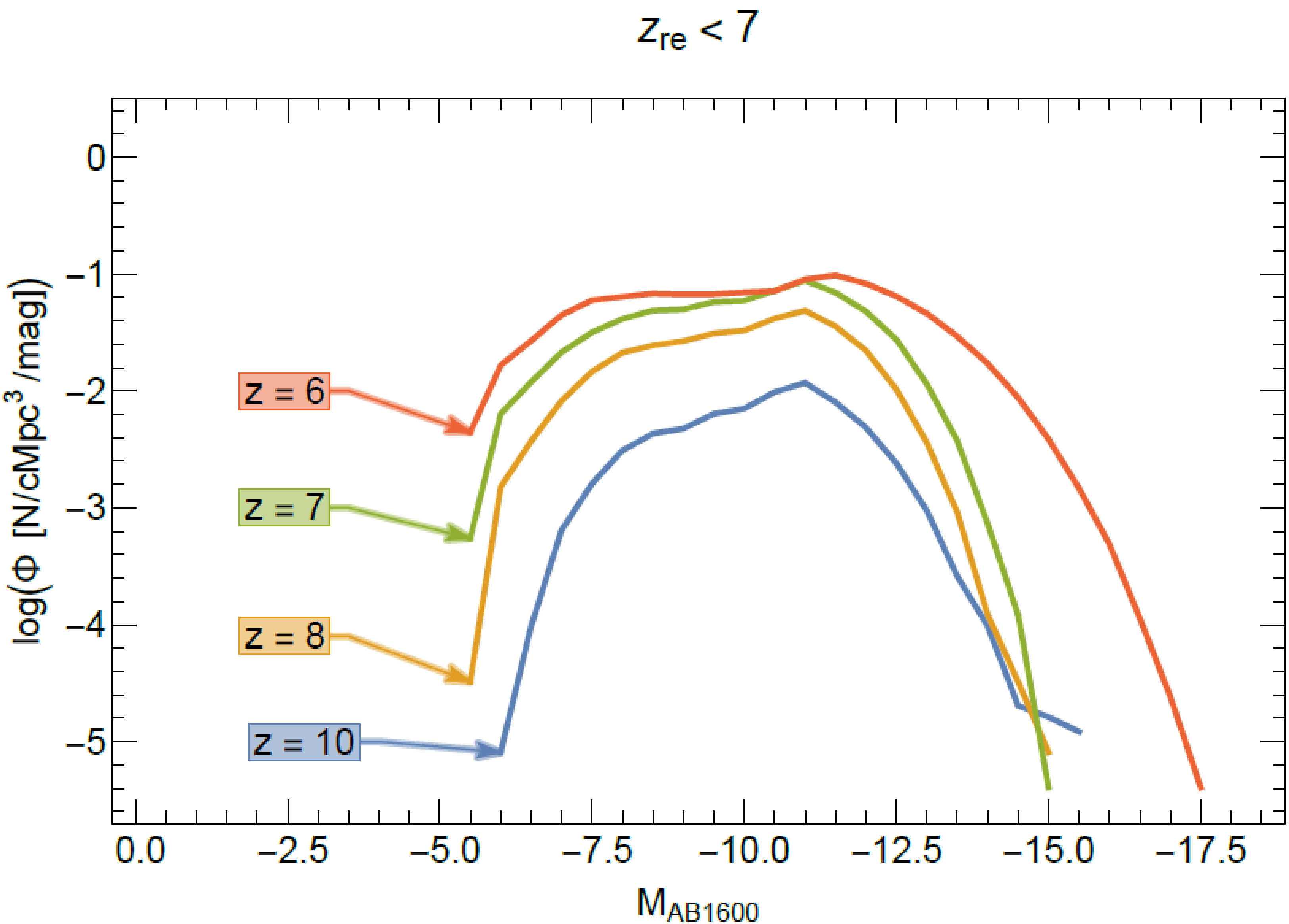

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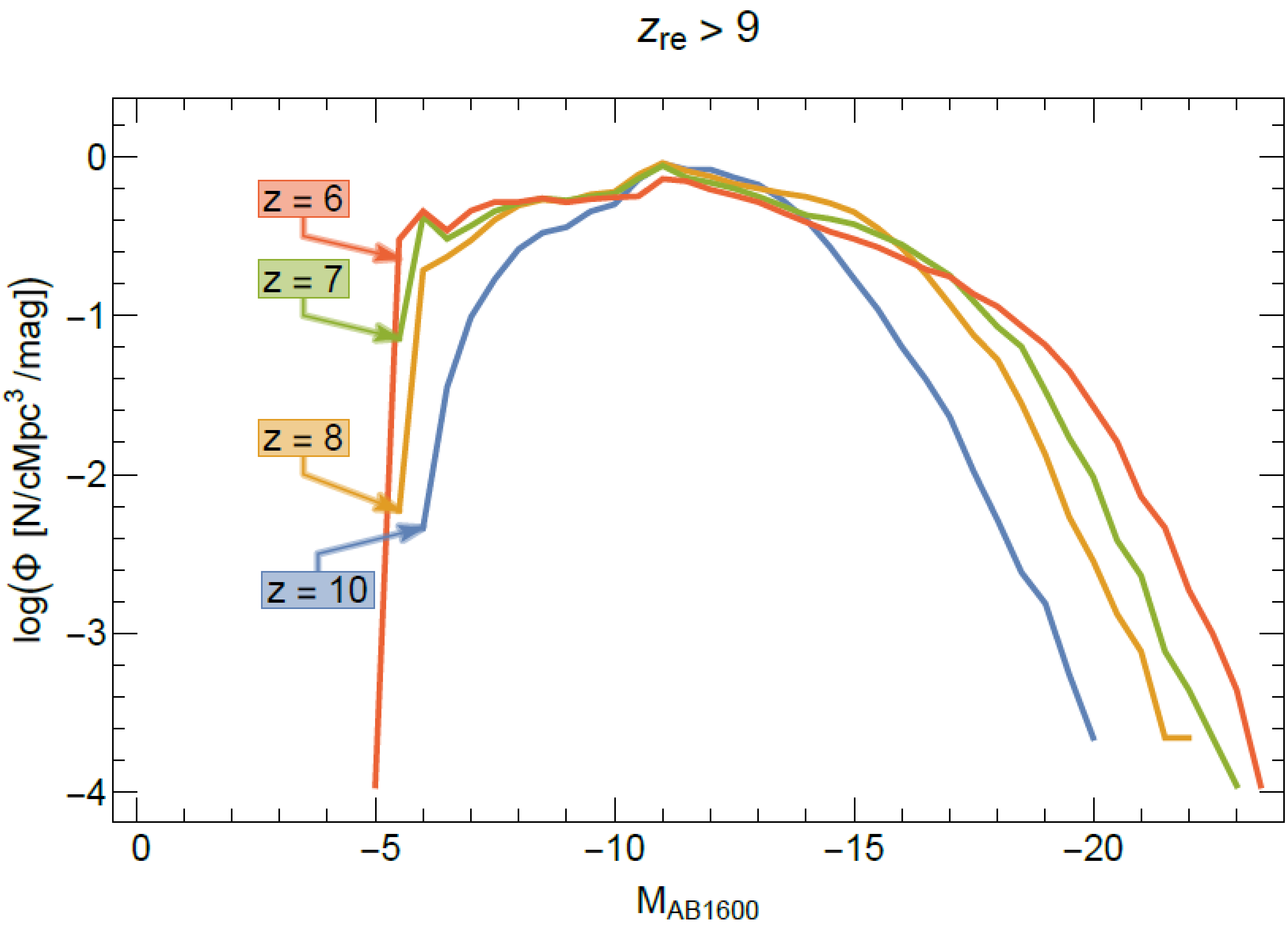

Q: Why is the UV LF of galaxies inhomogeneous during the EOR?

A:

1. (SFR depends upon halo mass)
   +
   (halo mass function is inhomogeneous)

2. (SFR depends upon halo mass)
   +
   (reionization suppresses SFR in low-mass halos)
   +
   (reionization is inhomogeneous)

3. (SFR in ALL halos depends upon local reionization redshift)
   +
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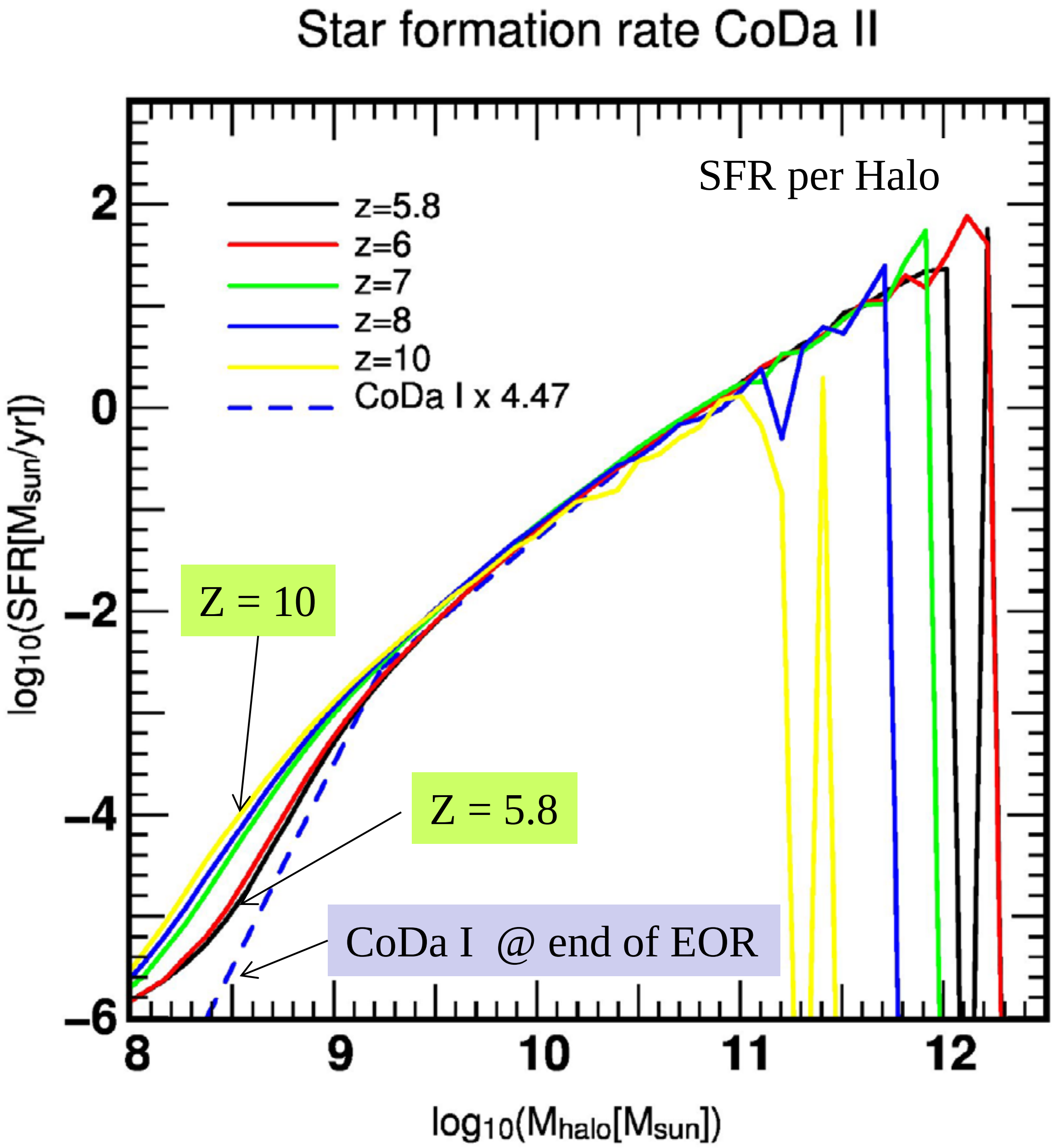
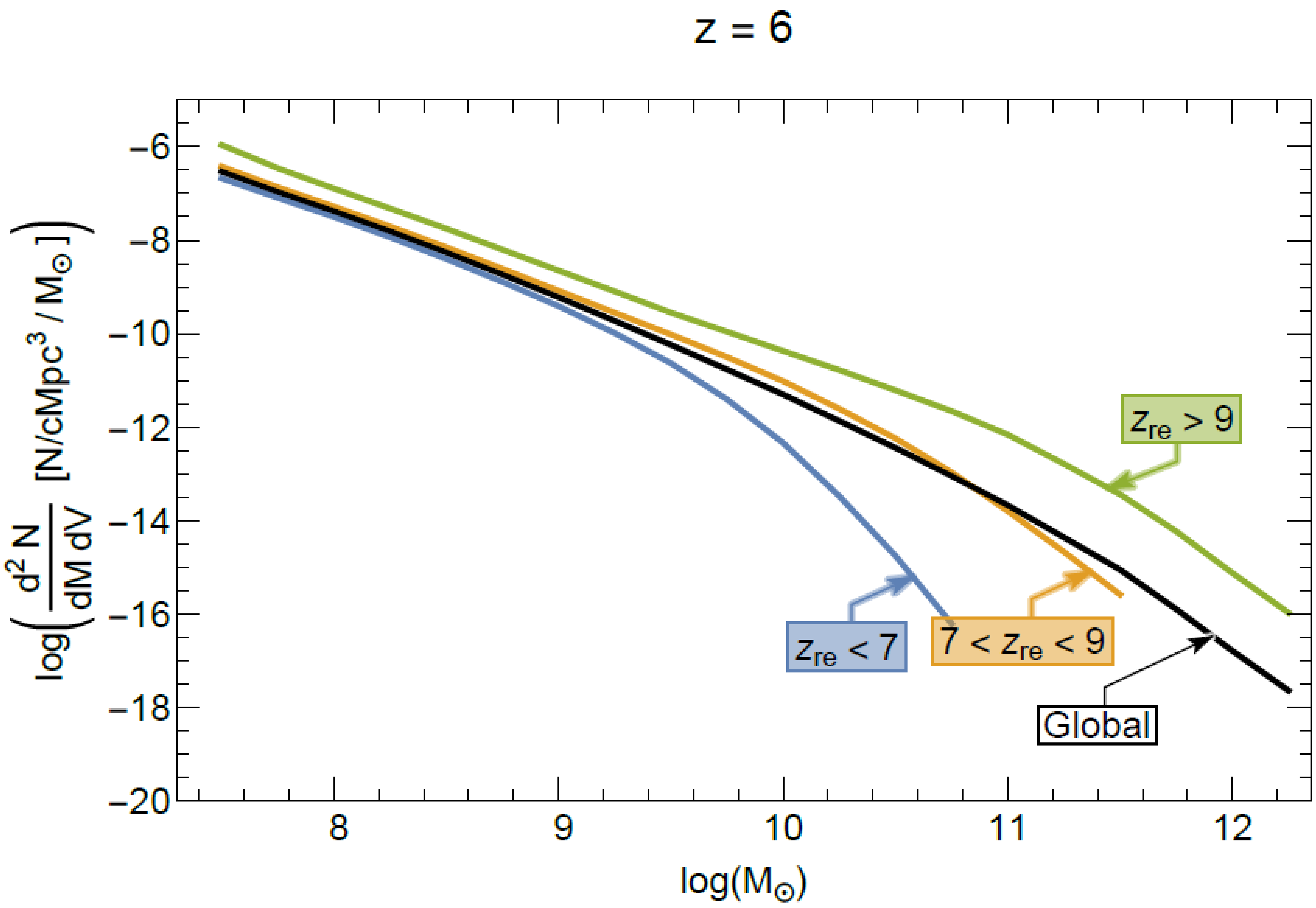
CODA II

➢ Star formation rate (SFR) was higher in higher-mass haloes even **before** the low-mass haloes were suppressed by reionization



- SFR $\propto M^{\alpha}$, $\alpha \sim 1.4$ for $M > 10^{10}$ solar masses, steepening below $M \sim 10^{9}$, but then drops sharply below $M \sim 3 \times 10^{9}$ toward EOR end

The Inhomogeneous Halo Mass Function of High-Redshift Galaxies



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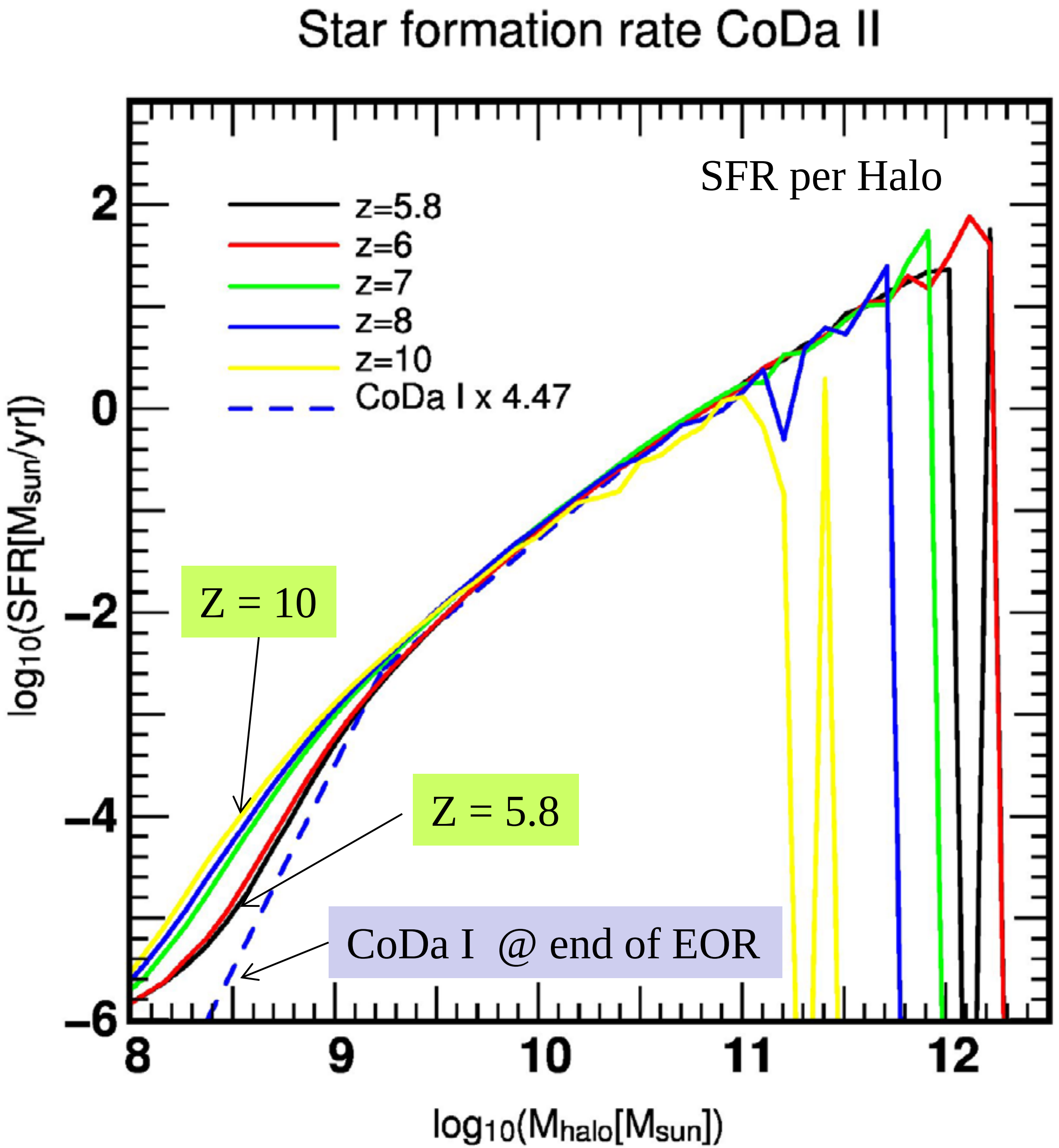
CODA II

- Star formation rate (SFR) was higher in higher-mass haloes even **before** the low-mass haloes were suppressed by reionization

- Reionization suppresses star formation rate in dwarf galaxies, for $M < 10^9$ solar masses



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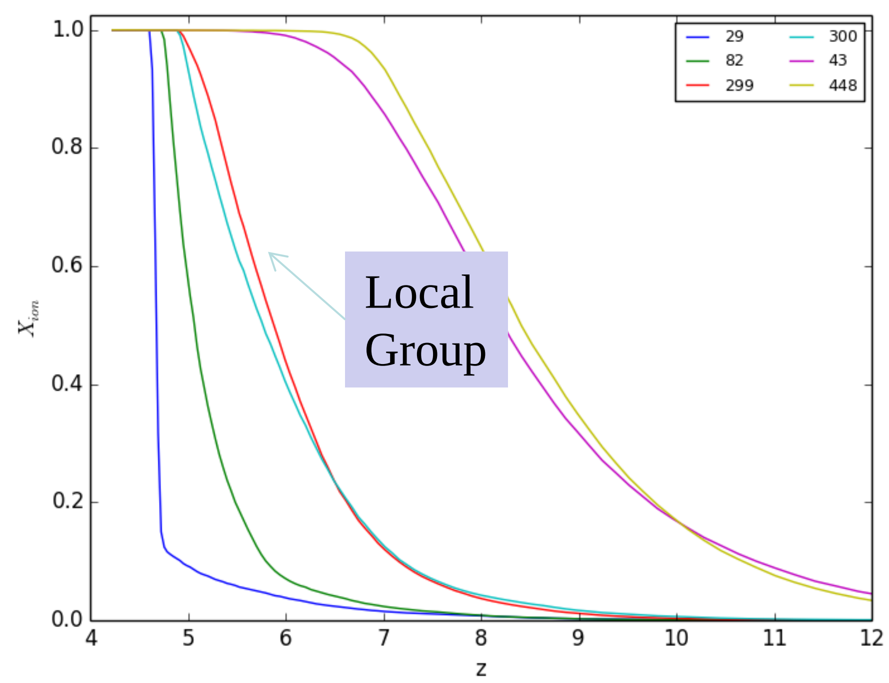
Suppression of Star Formation in Low-Mass Galaxies Caused by the Reionization of their Local Patch

Dawoodbhoy, **Shapiro**, Ocvirk, Aubert, Gillet, Choi, Iliev, Teyssier, Yepes, Knebe, Gottloeber, D'Aloisio, Park, Hoffman 2018, MNRAS, 480, 1740 (**arXiv:1805.05358**)

Local Reionization:
There Goes the Neighborhood!

- **Reionization history was different in different locations ➔** each point in space had its own redshift of local reionization, $z_{re}(\mathbf{x})$

- From CoDa I, we computed local reionization redshift field $z_{re}(\mathbf{x})$, by smoothing underlying 4096^3 cells to 256^3 cells, 0.357 cMpc on a side. Each halo was assigned the value of z_{re} for its location.



Zoom-In $(4\ h^{-1}\ \mathrm{cMpc})^3$ Subvolumes = (full simulation volume/4096)

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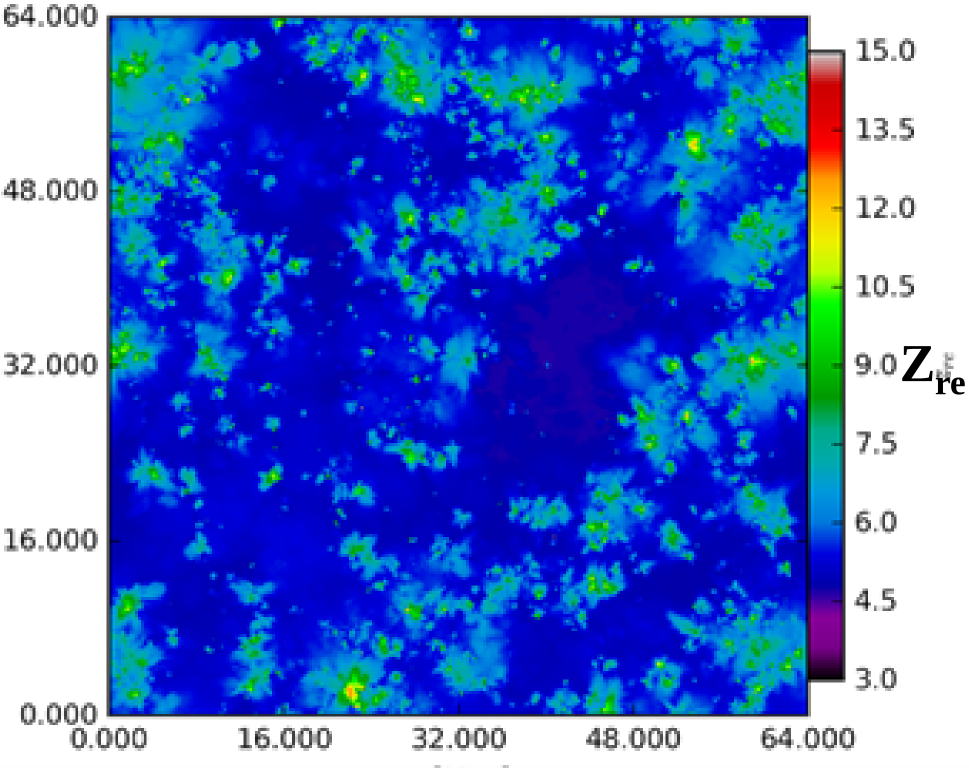
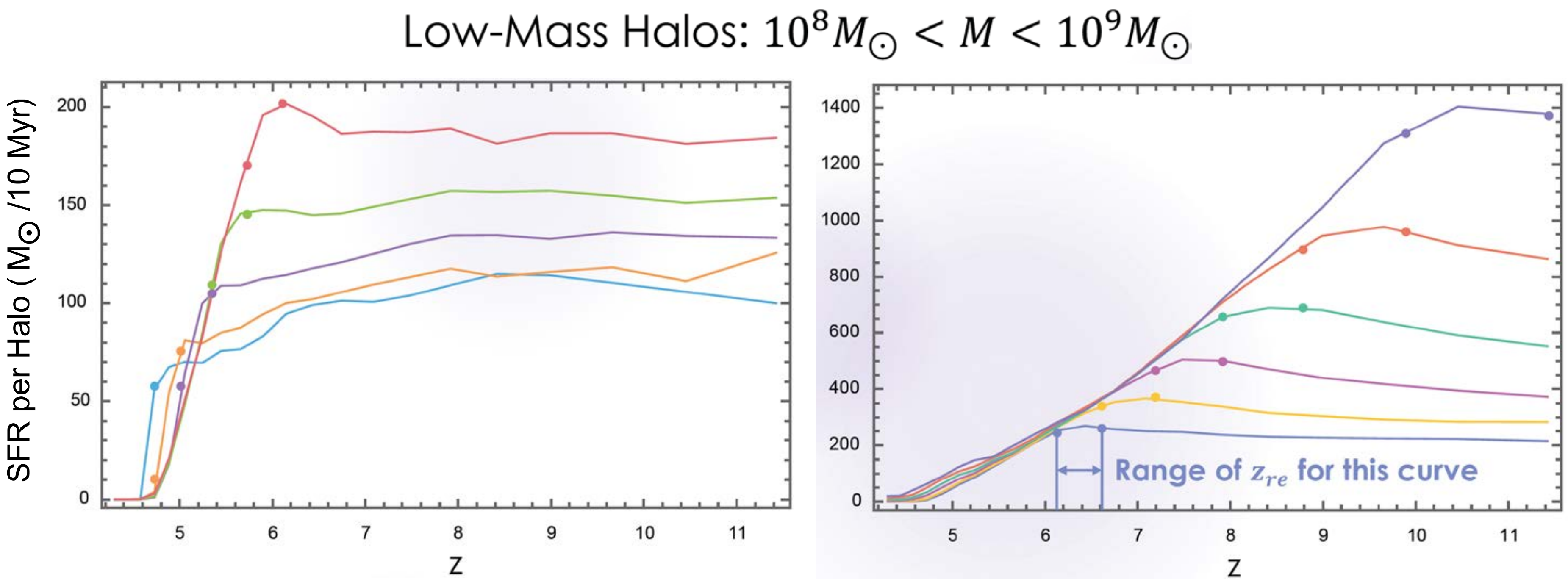
- Local reionization redshift field resembles underlying cosmic web of dark matter, galaxies and IGM: density peaks reionized first, while voids and underdense regions reionized last and occupy the most volume.

Local Reionization Redshift Field



Local Reionization and Suppression of the SFR

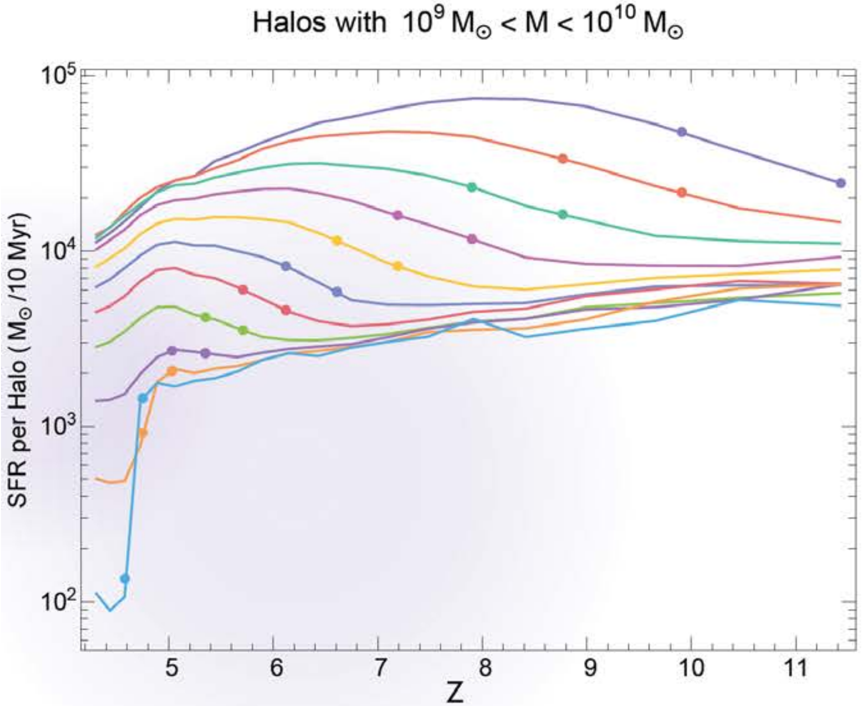
- The globally-averaged suppression of SFR per halo in low-mass halos is actually the superposition of different ***local*** reionization and suppression histories.
- Grouping halos of different mass in bins of local reionization redshift z_{re} shows: **suppression of low-mass halos follows their *local* reionization**!



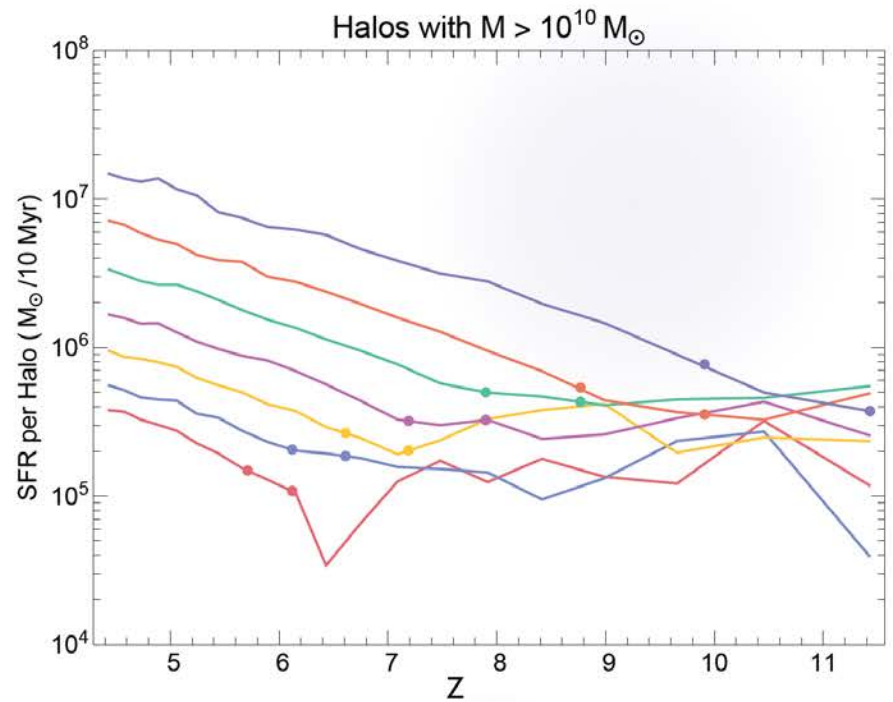
SFR per halo vs. redshift for low-mass haloes, 10^{8-9} $M_\odot$, for different z_{re}: 2 dots on each curve indicate range of z_{re} for each bin.

Local Reionization and Suppression of the SFR

- Haloes of intermediate mass, $10^{9-10}\ M_\odot$, show suppression, too, but weaker and with a delayed turn-over.
- High-mass haloes, above $10^{10}\ M_\odot$, show increasing mass-bin-averaged SFRs per halo, with no suppression turn-over.



Weaker and delayed suppression



No suppression

SFR per halo vs. redshift for haloes of intermediate-mass ($10^{9-10}\ M_\odot$) and high-mass ($> 10^{10}\ M_\odot$), for different z_{re}: 2 dots on each curve indicate range of z_{re} for each bin (left = intermediate-mass, right = high-mass).

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A:

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   +

   (halo mass function is inhomogeneous)

2. **(SFR depends upon halo mass)**

   +

   (reionization suppresses SFR in low-mass halos)

   +

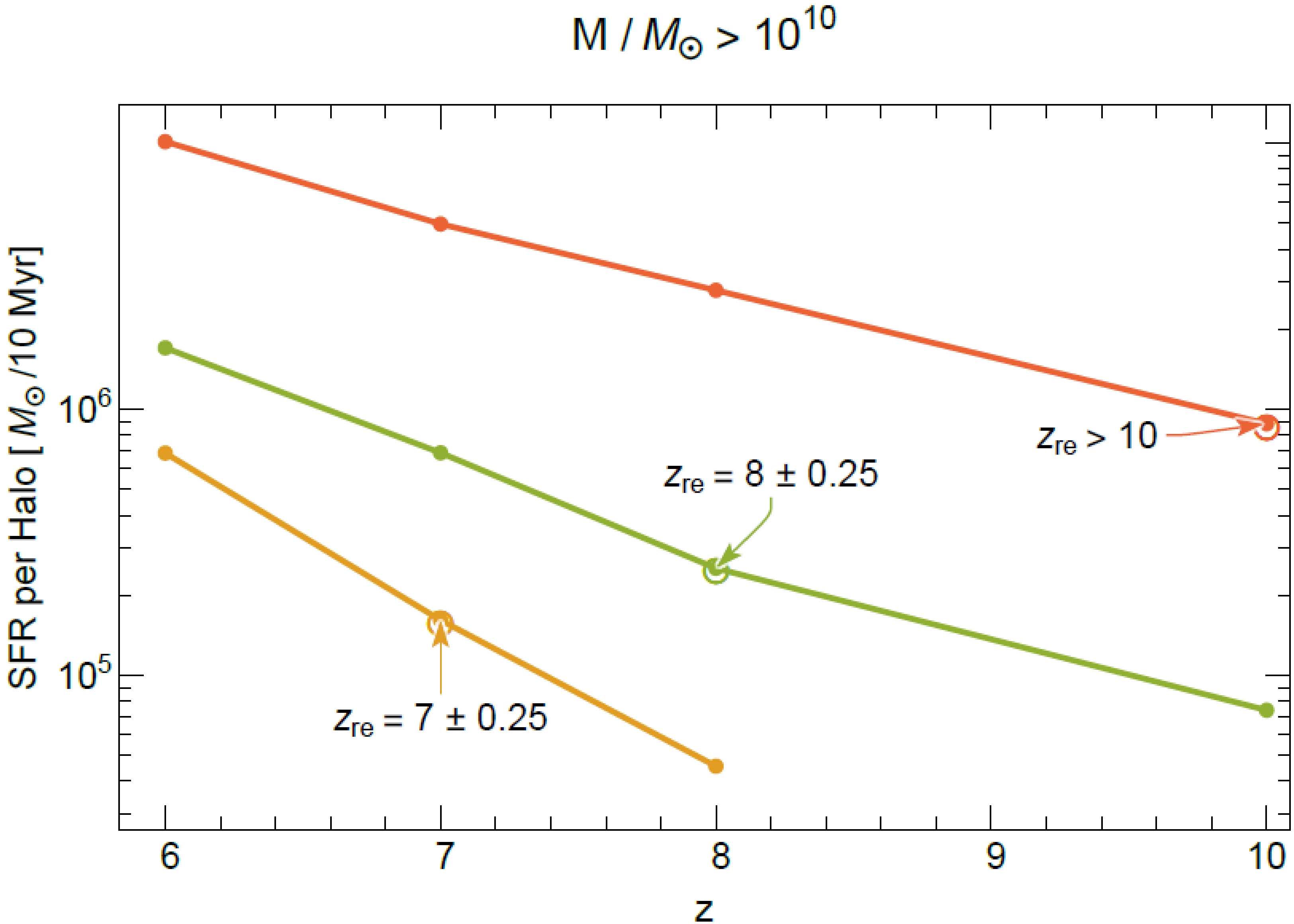
   (reionization is inhomogeneous)

3. **(SFR in ALL halos depends upon local reionization redshift)**

   +

   (reionization is inhomogeneous)

CoDa II SFR in high-mass halos unsuppressed following local reionization ➔ it just keeps rising

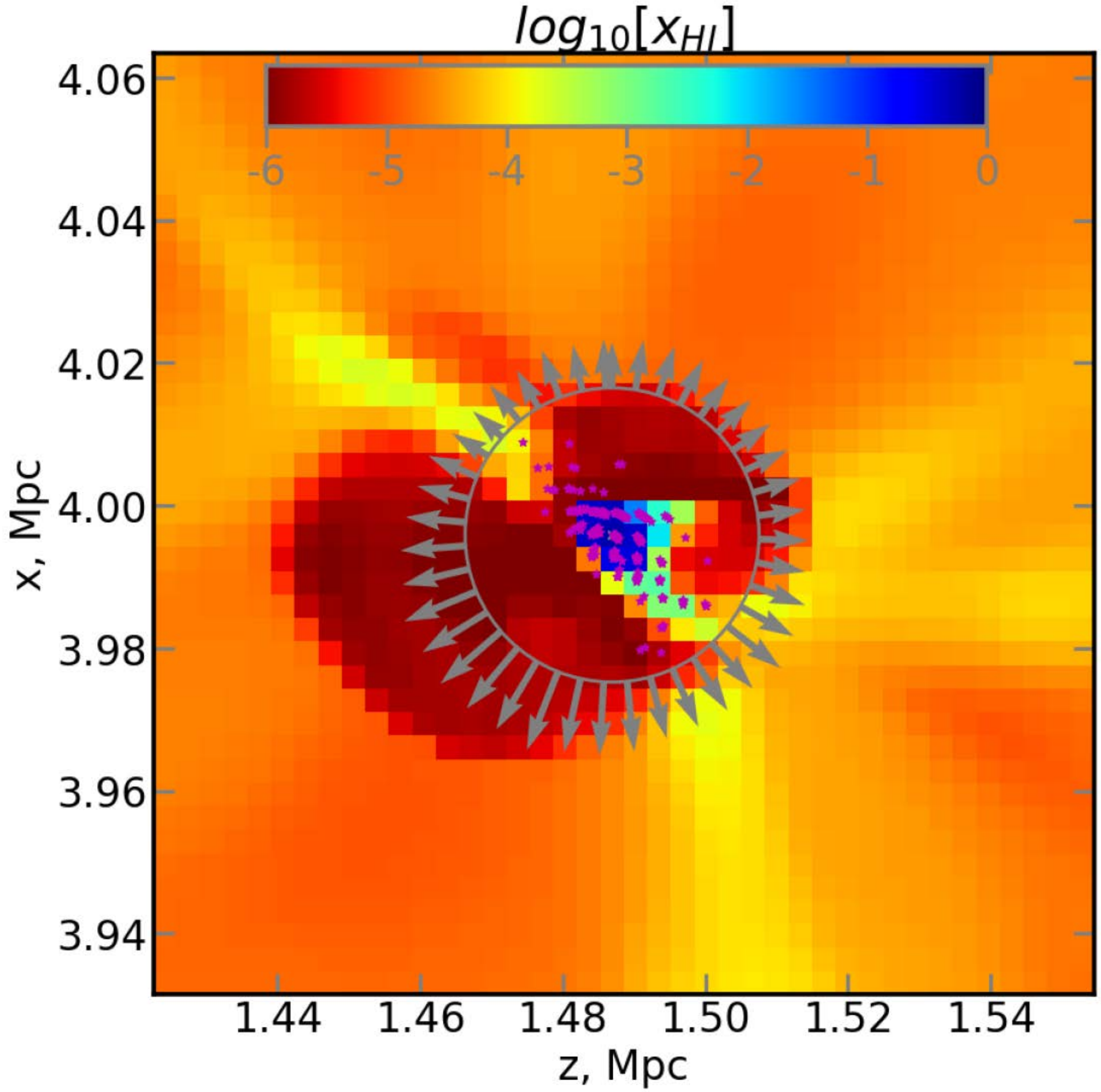


CoDa II: Galaxy Escape Fractions and the Ionizing Photon Budget

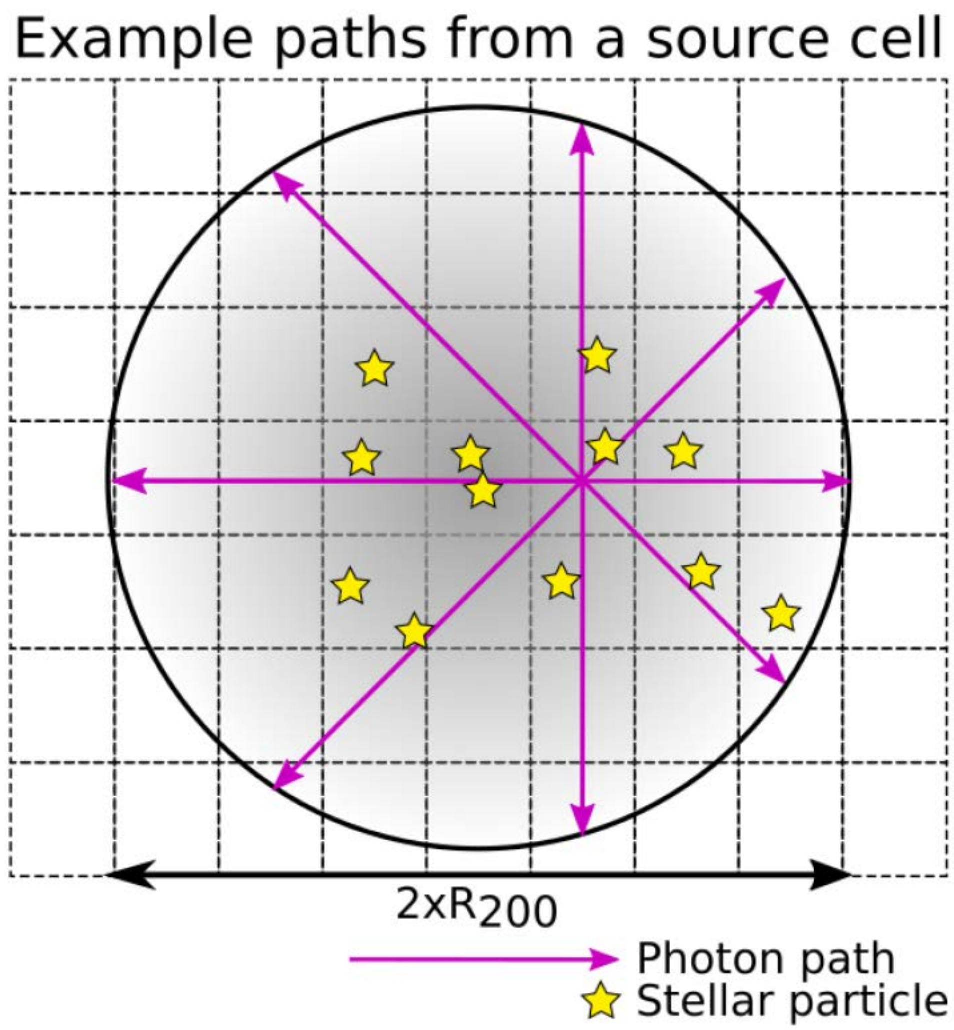
Lewis, Ocvirk, Shapiro, Aubert, et al 2019, to be submitted

Zoom-in on a single halo at z = 6 with $M \sim 10^{10}\ M_{solar}$

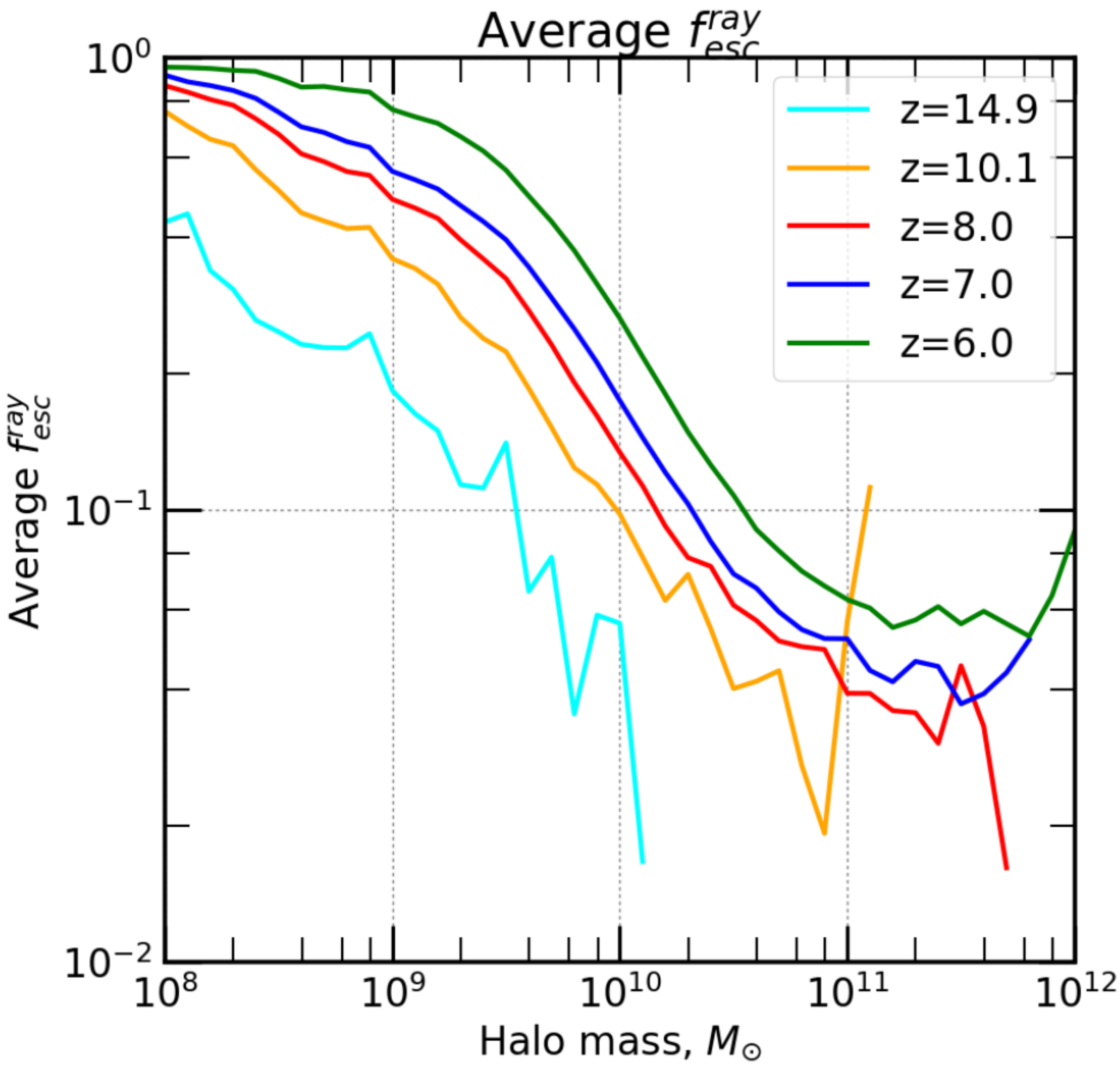
- Pink symbols are young star particles
- Circle is virial radius r_200
- Circle is region from which we compute f_esc by ray-tracing
- Arrows show the escaping ionizing radiation flux

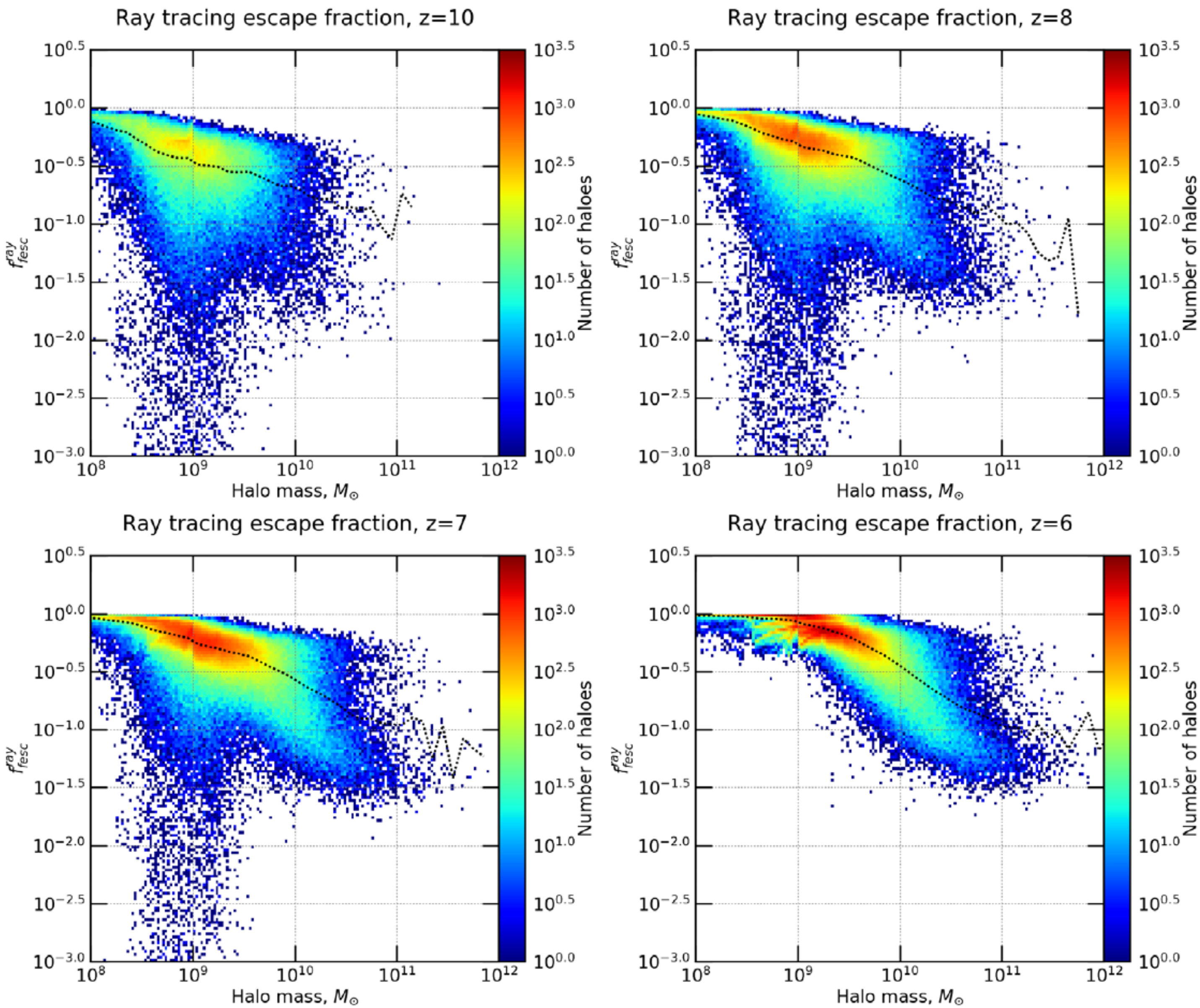


f_esc: ray-tracing starlight from each halo cell



- f_{esc} is higher for low-mass halos, decreasing with halo mass
- f_{esc} for a given M_{halo} increases over time during the EOR



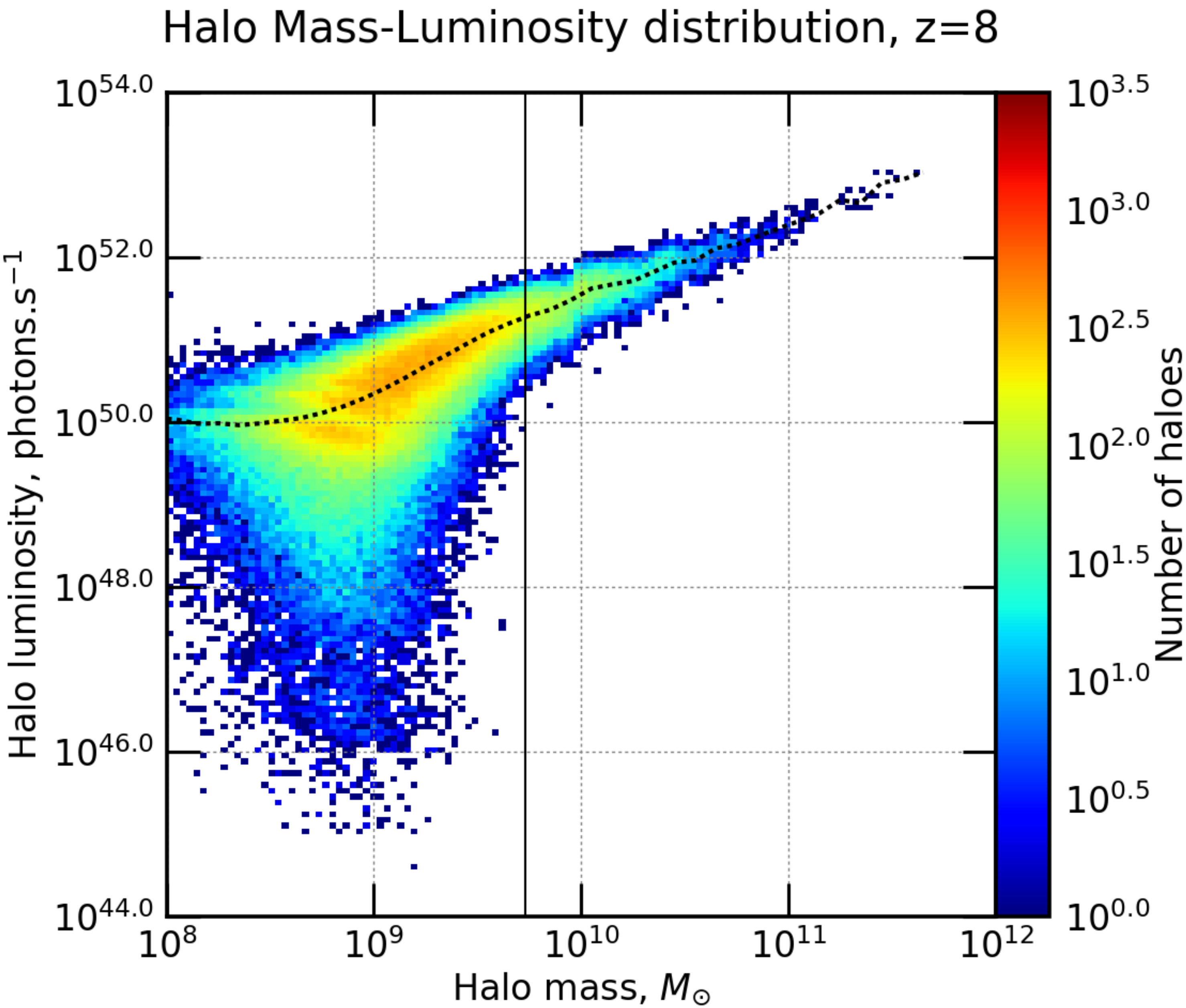


- There is a significant scatter in f_{esc} about the mean relationship vs. halo mass at the same redshift, greater at low mass

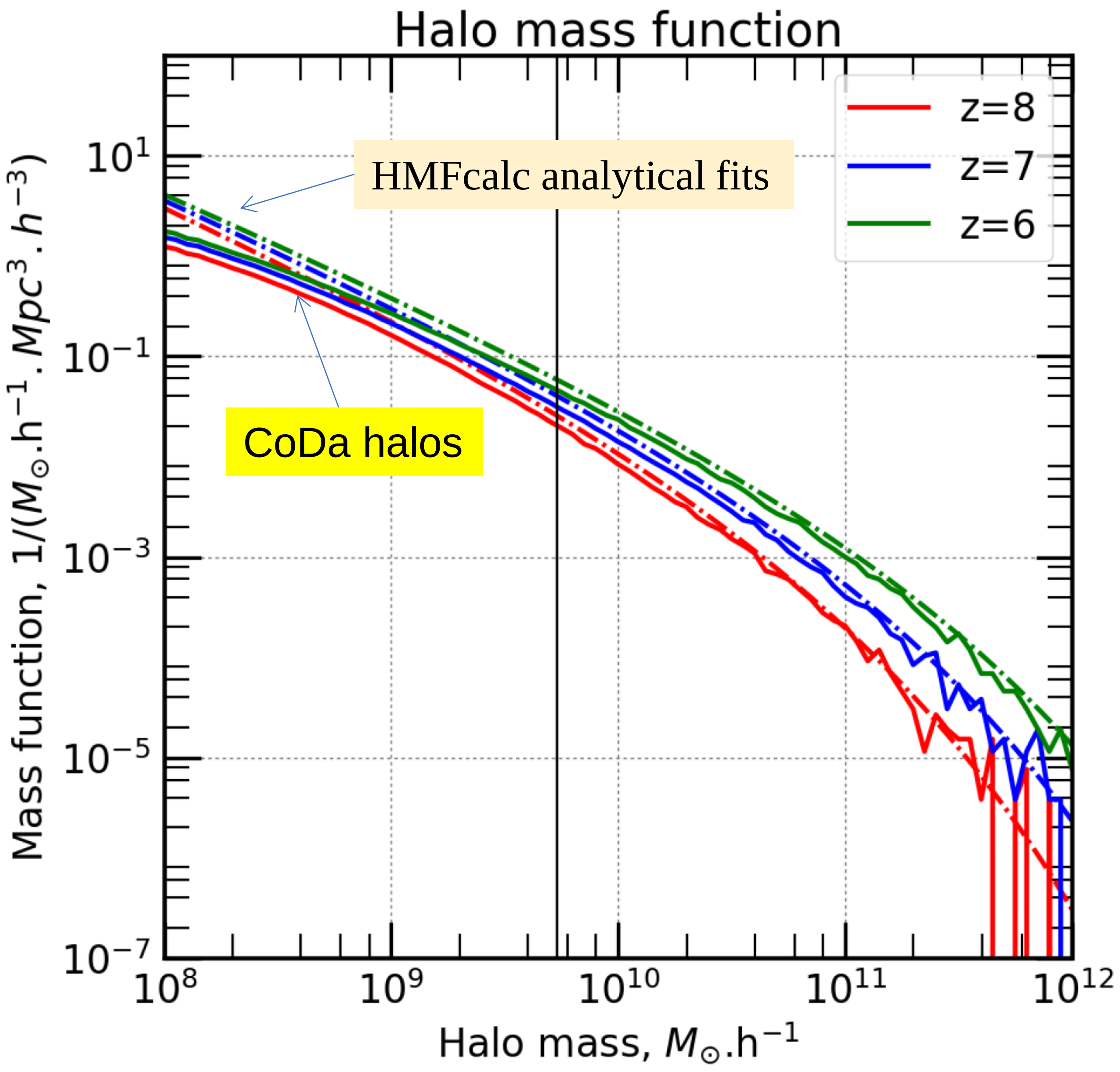
- Ionizing photon luminosity per halo depends on

  f_{esc} X SFR

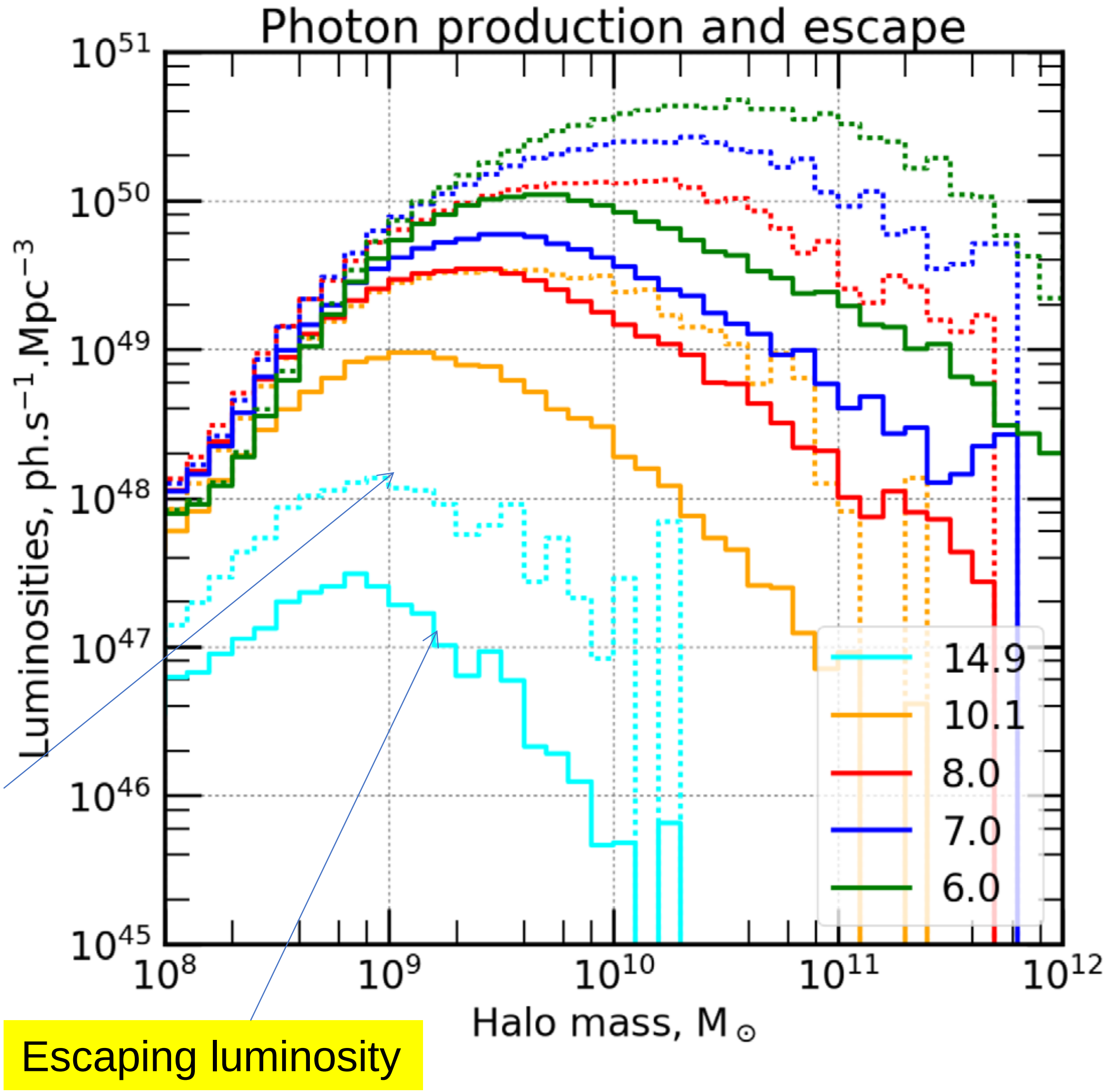
- Higher f_{esc}'s at low mass offset higher SFR's at higher mass



- The contribution of halos of different mass to the total ionizing photon emissivity of galaxies during the EOR also depends on the halo mass function.



- The halo mass range that dominates the total rate of photon release is *lower* than the mass range that dominates the total SFR density, since f_{esc} is lower for higher-mass halos.

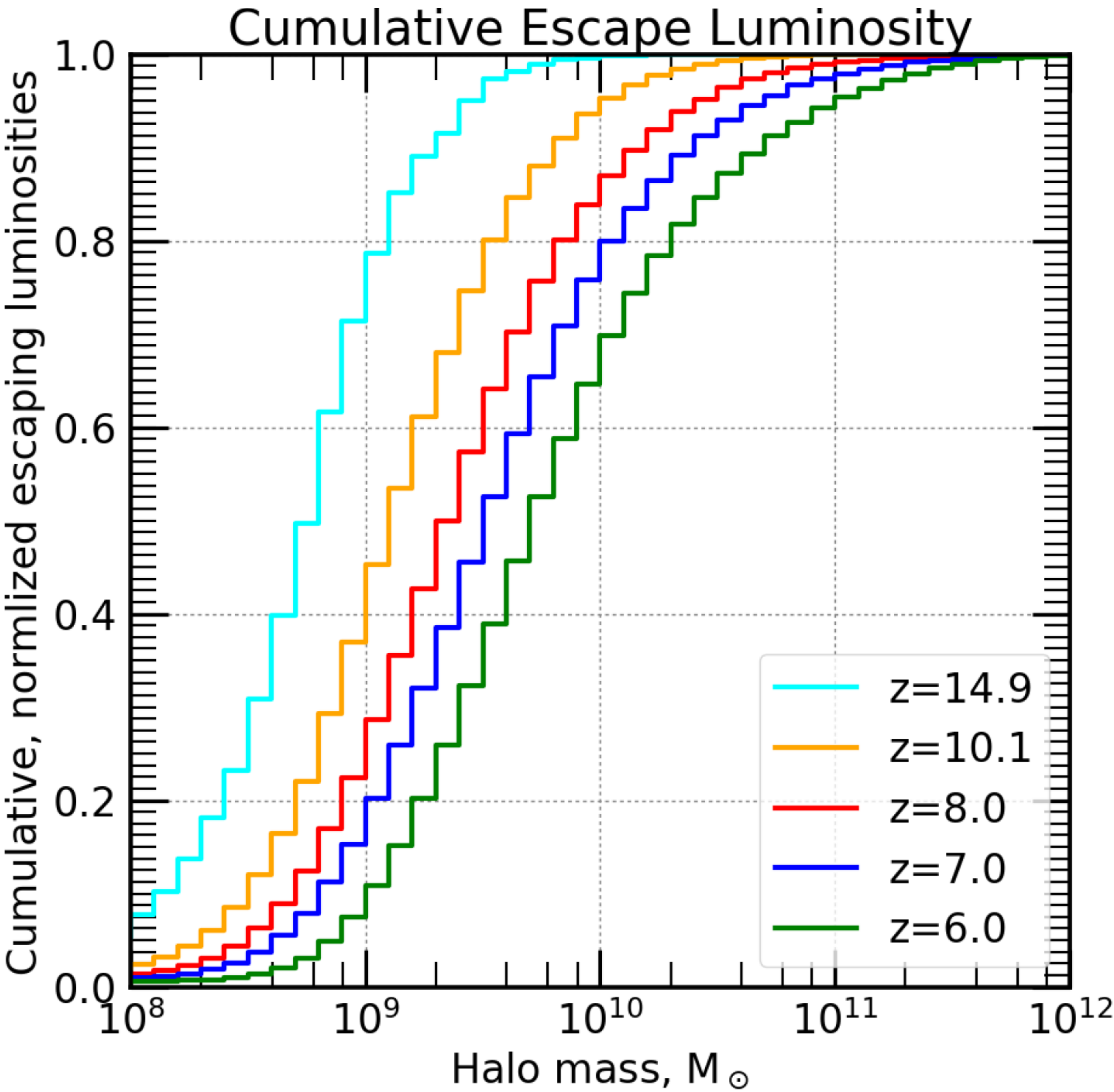


- When $\langle x_{H\,II} \rangle$ = 0.5

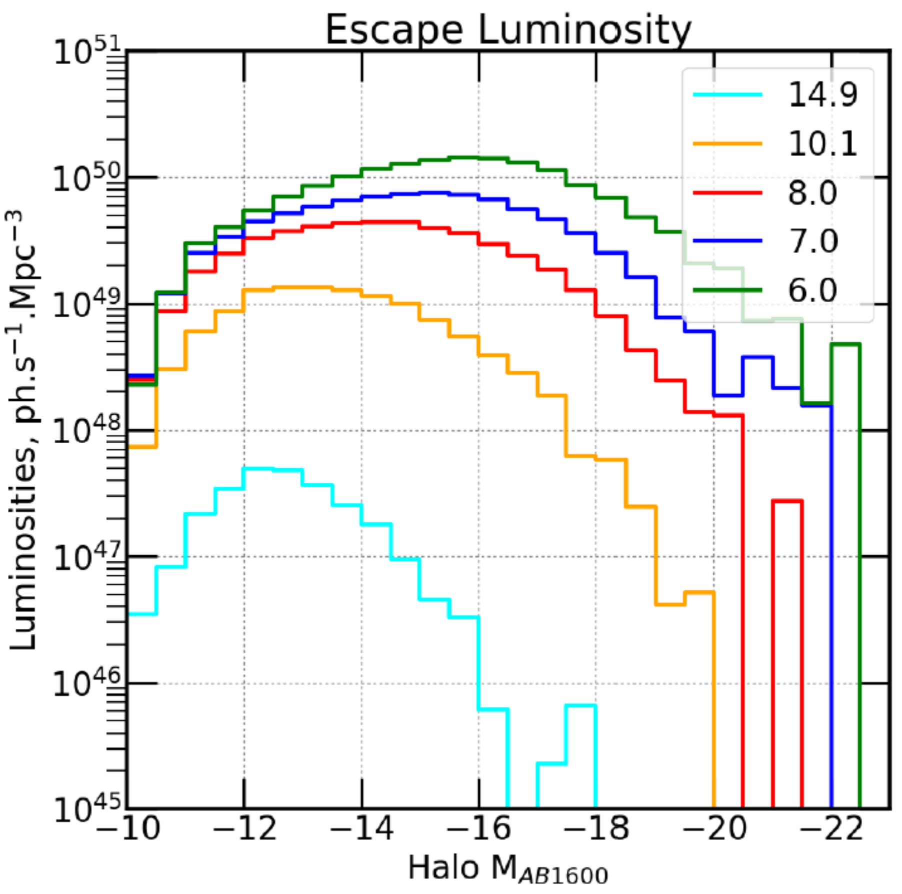
  at z ~ 7, ~ 80% of ionizing photons released come from halos between 10^9 and 4 X 10^{10} M_{solar}

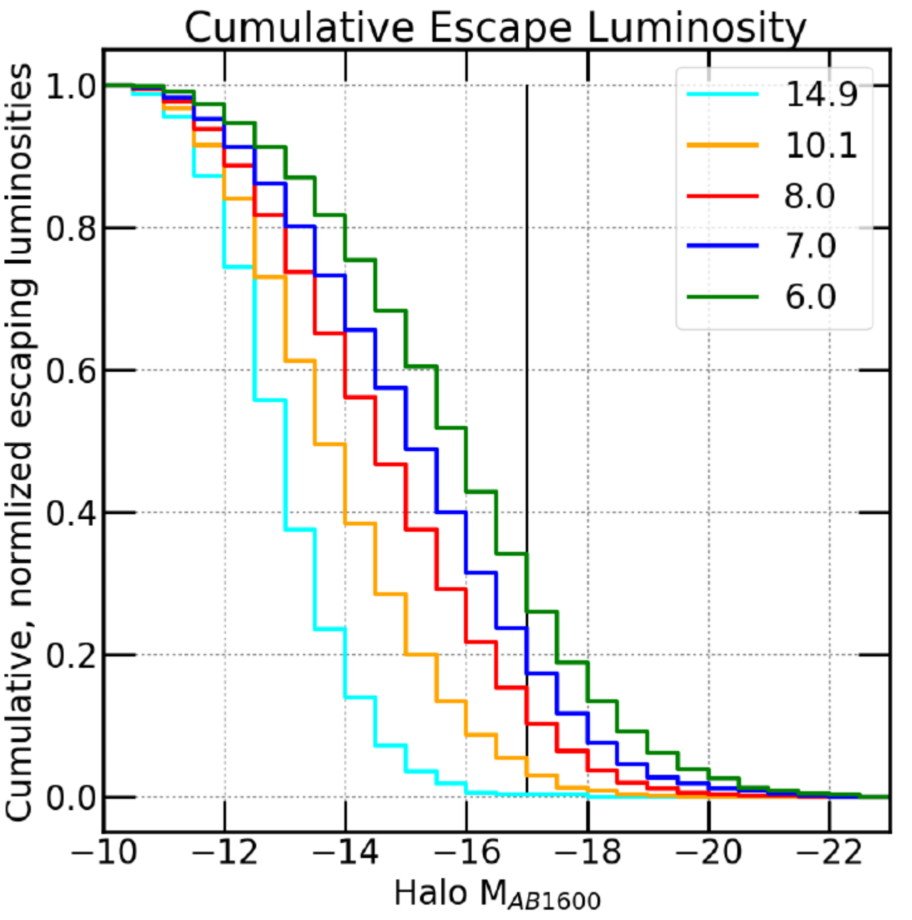
- When $\langle x_{H\,II} \rangle$ = 0.1

  at z ~ 8.5, ~ 80% come from M < ~ 5 X 10^9 M_{solar}



Which galaxies in the UV luminosity function dominate reionization?





- **Galaxies with M_{AB1600} between -13 and -18 dominate reionization at z = 6 - 8**

- **Deep surveys in cluster fields (e.g. Bouwens + 2017; Atek + 2018) may soon detect galaxies responsible for > 80% of reionization photons at z = 6 - 8**