Simulating the Cosmic Dawn and Epoch of Reionization at all scales

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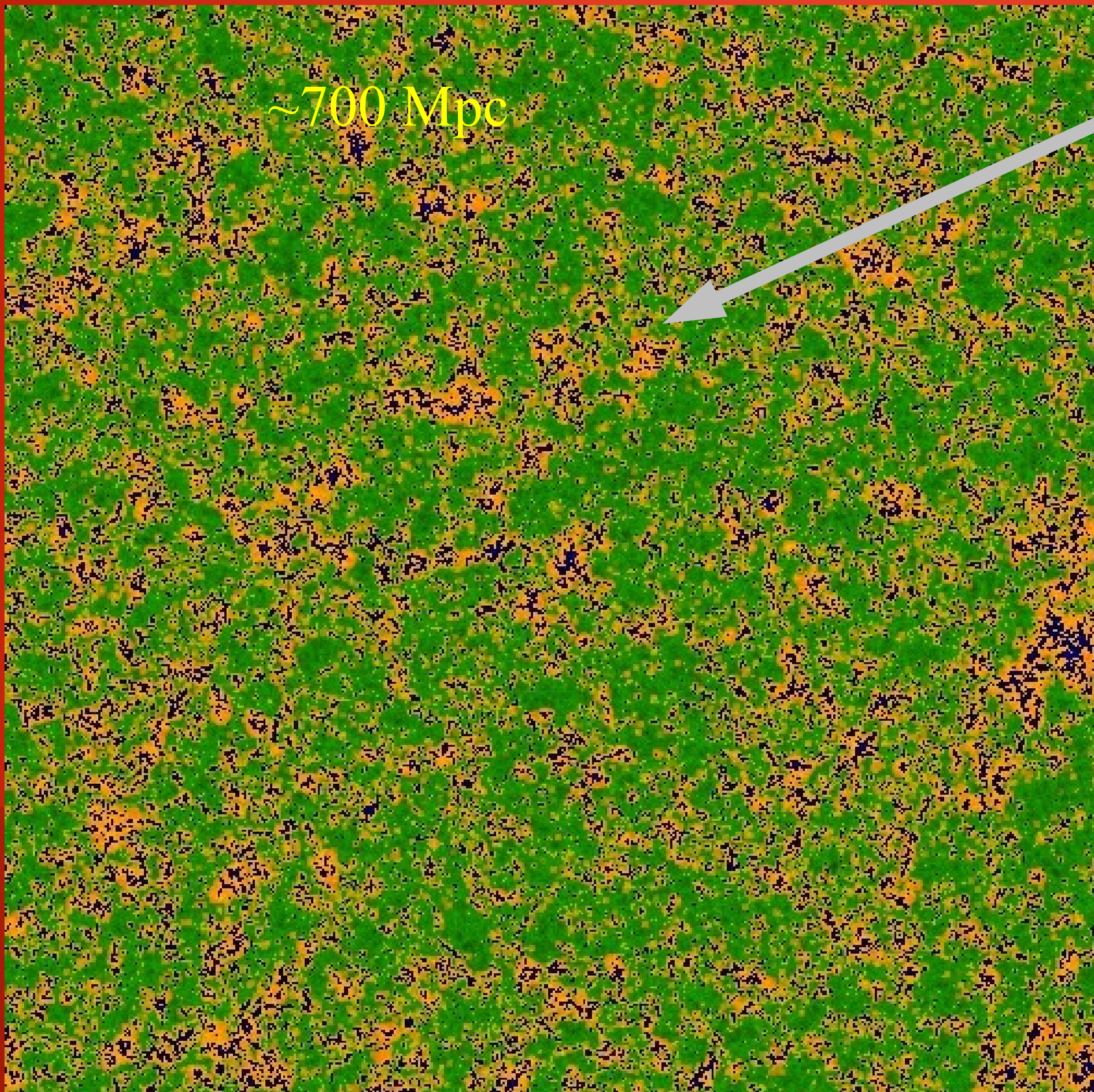
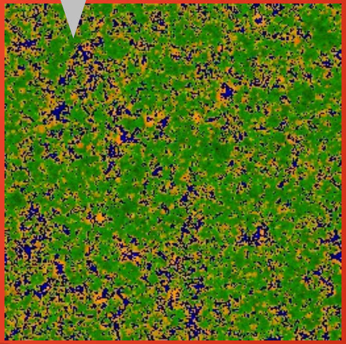
HPC projects: (INCITE) Cosmic Dawn; (JSC) Hestiaeor, LGreion; (PRACE) Multi-scale reionization, PRACE4LOFAR, LocalUniverse, subgridEoR, subgridEoRevol

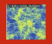
Multi-scale reionization



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

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



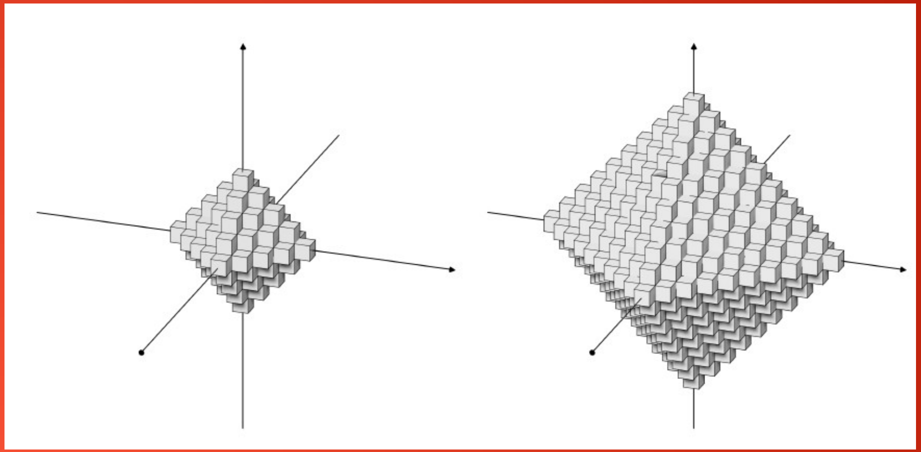


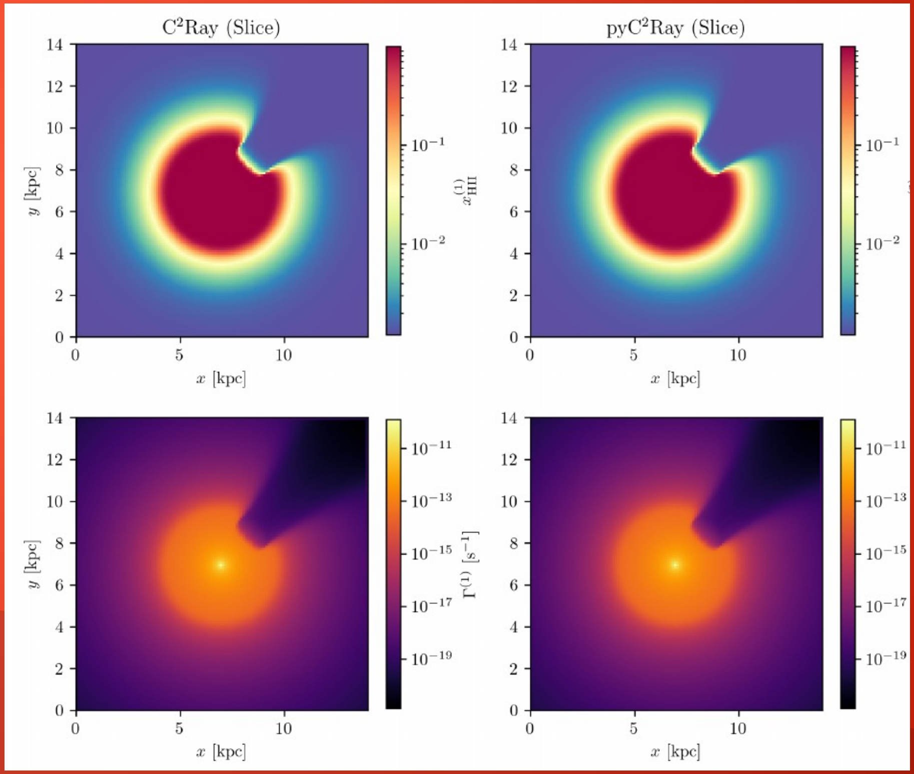
Zoom hydro sims
(few Mpc or less in zoom)

pyC^2-Ray code

(Hirling et al., 2023, arXiv:2311.01492 in press in Astronomy and Computing)

- Based on C^2-Ray code (Mellema 2006)
- Ray-tracing now done on GPUs using a novel approach (ASORA)
- Code now using Python interface, with CUDA and Fortran called for computationally-intensive calls
- Extensively tested
- About 100x cheaper to run than original CPU version

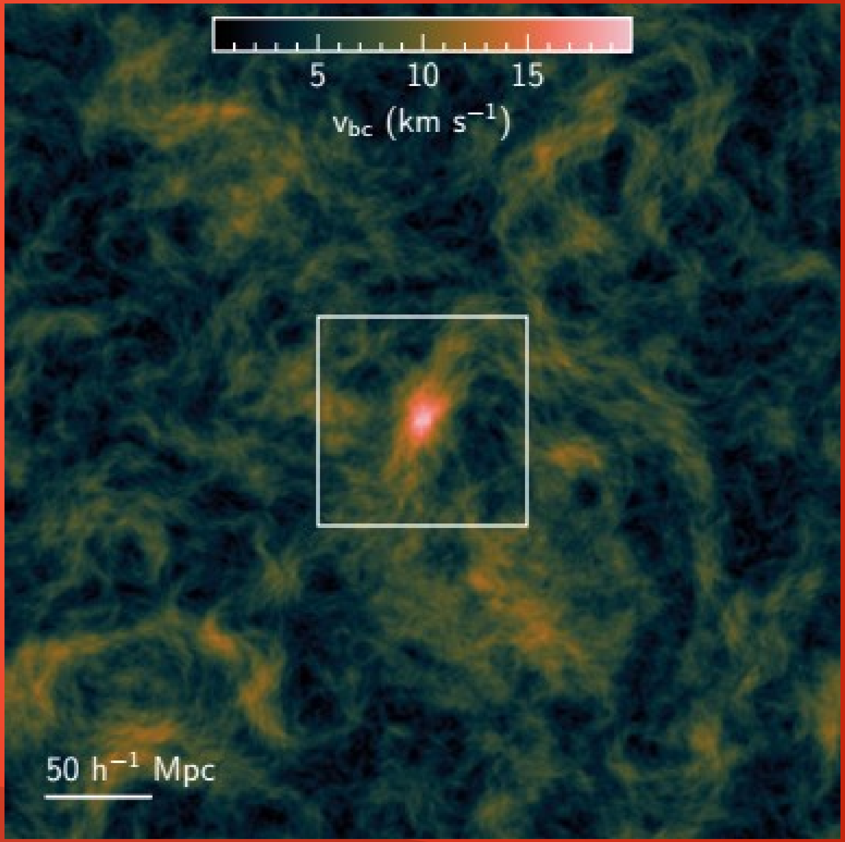




Baryon-dark matter drift velocities in zoomed simulations

(Conaboy et al., 2023, MNRAS, 525, 5479)

- Relative velocity between baryons and CDM at recombination is roughly 30km/s (Tseliakovich & Hirata, 2010)
- Sound speed drops from relativistic (≈c/√3) to thermal velocities of hydrogen atoms (≈2×10^{-5} c)
- Supersonic → Suppression of power on small scales
- Previously considered in small volumes (easier to do, since vbc is coherent on small scales)
- Aim: implementation in large cosmological volumes, in proper cosmological context

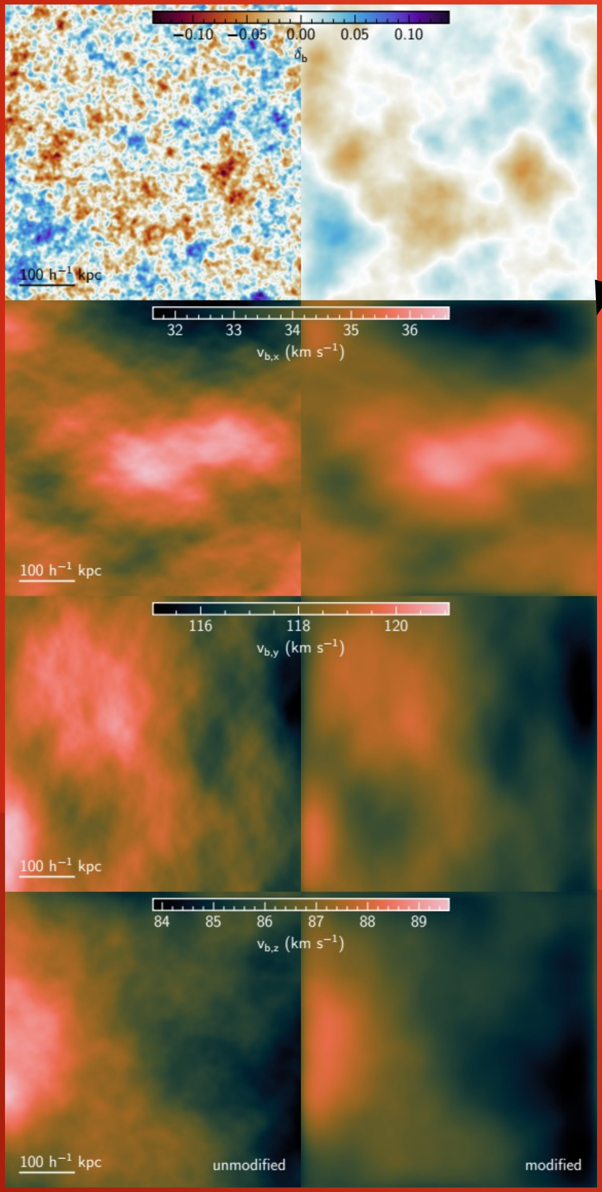


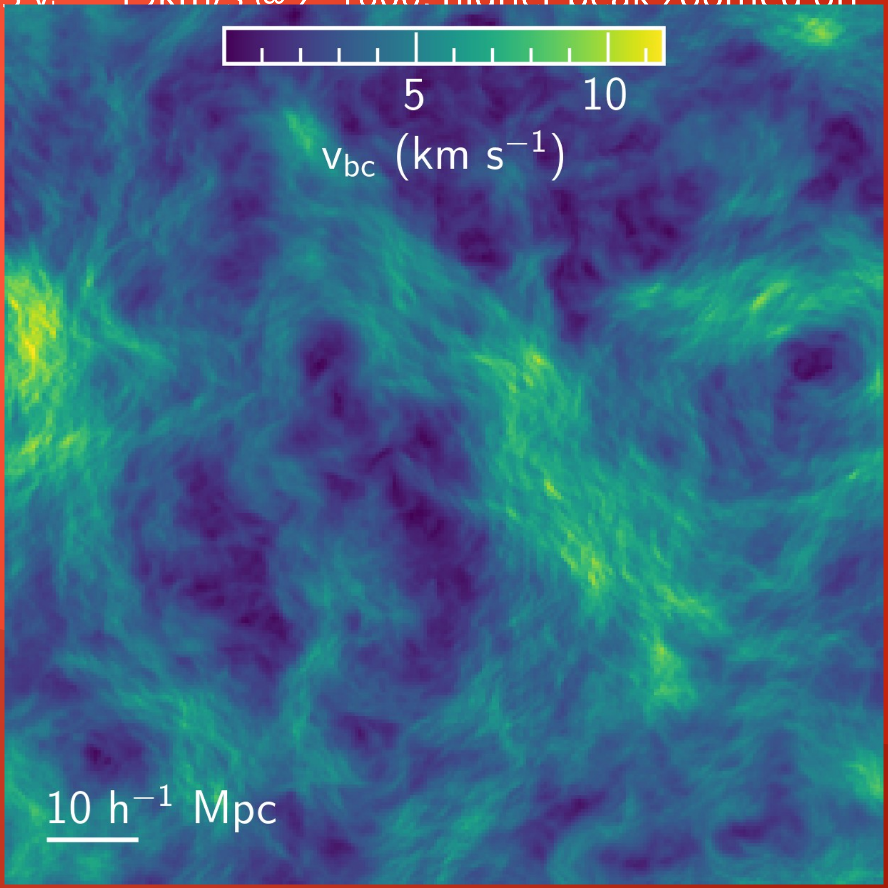
$v_{bc} = |v_b - v_c|$ field in the full 400 h^{-1} Mpc initial conditions at $z_{ini} = 200$

Initial Conditions (z = 200)

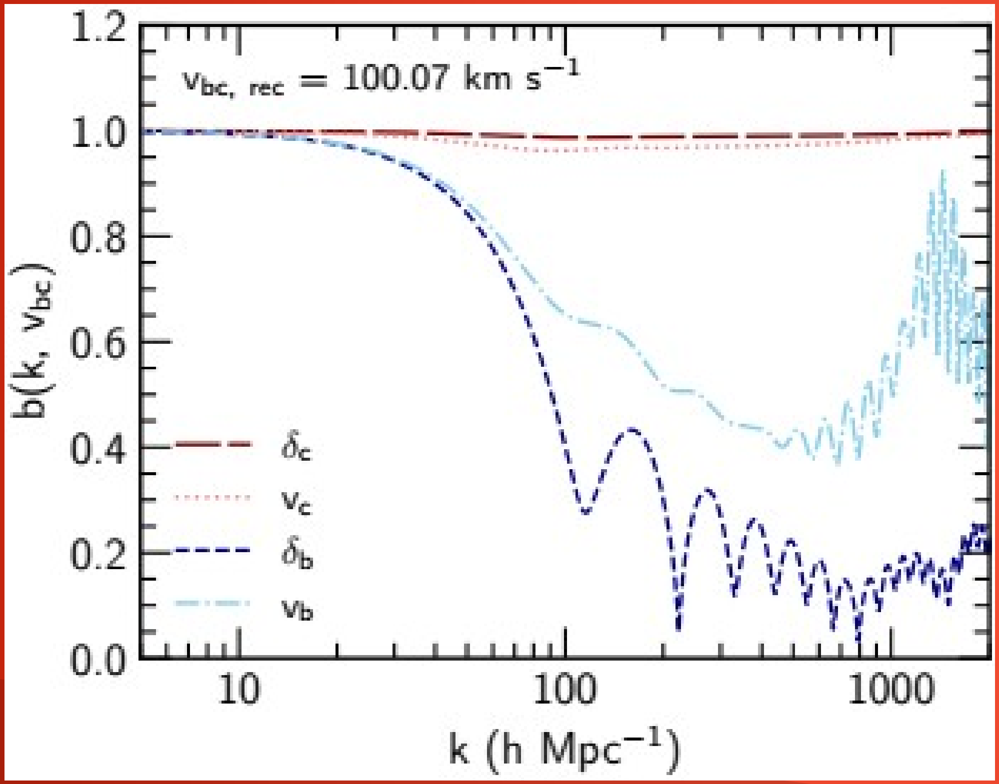
(Conaboy et al., 2023, MNRAS, 525, 5479)

- Local modulation of Power Spectrum
- Compute bias b(k, vbc) = P(k, vbc)/P(k, vbc=0)
- Convolve bias into locally coherent regions
- RMS v_{bc} = 19km/s @ z=1000, higher peak zoomed on

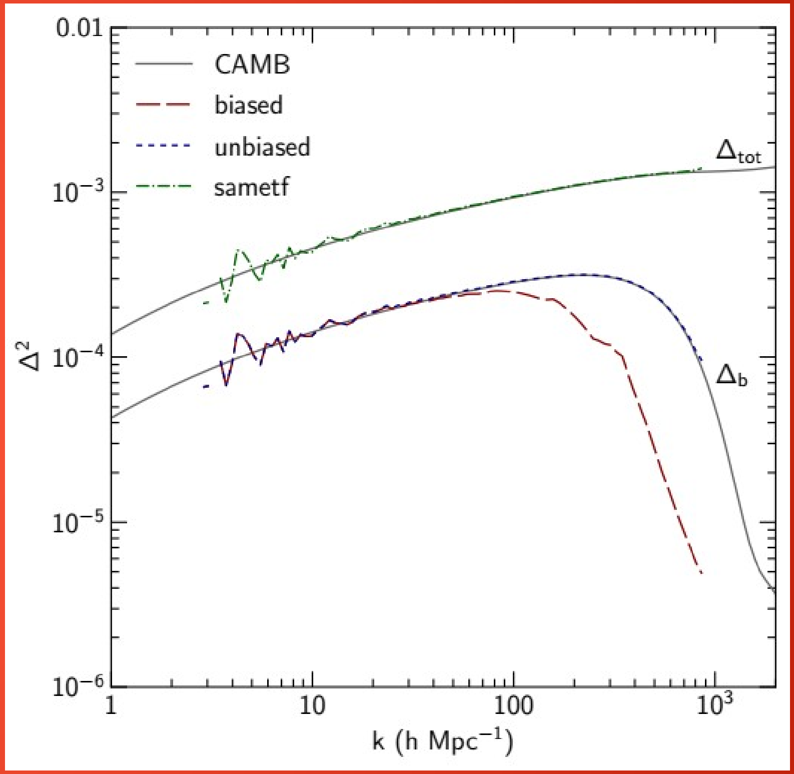




Supersonic Drift Velocities: bias and power spectra
(Conaboy et al., 2023, MNRAS, 525, 5479)



Bias factors

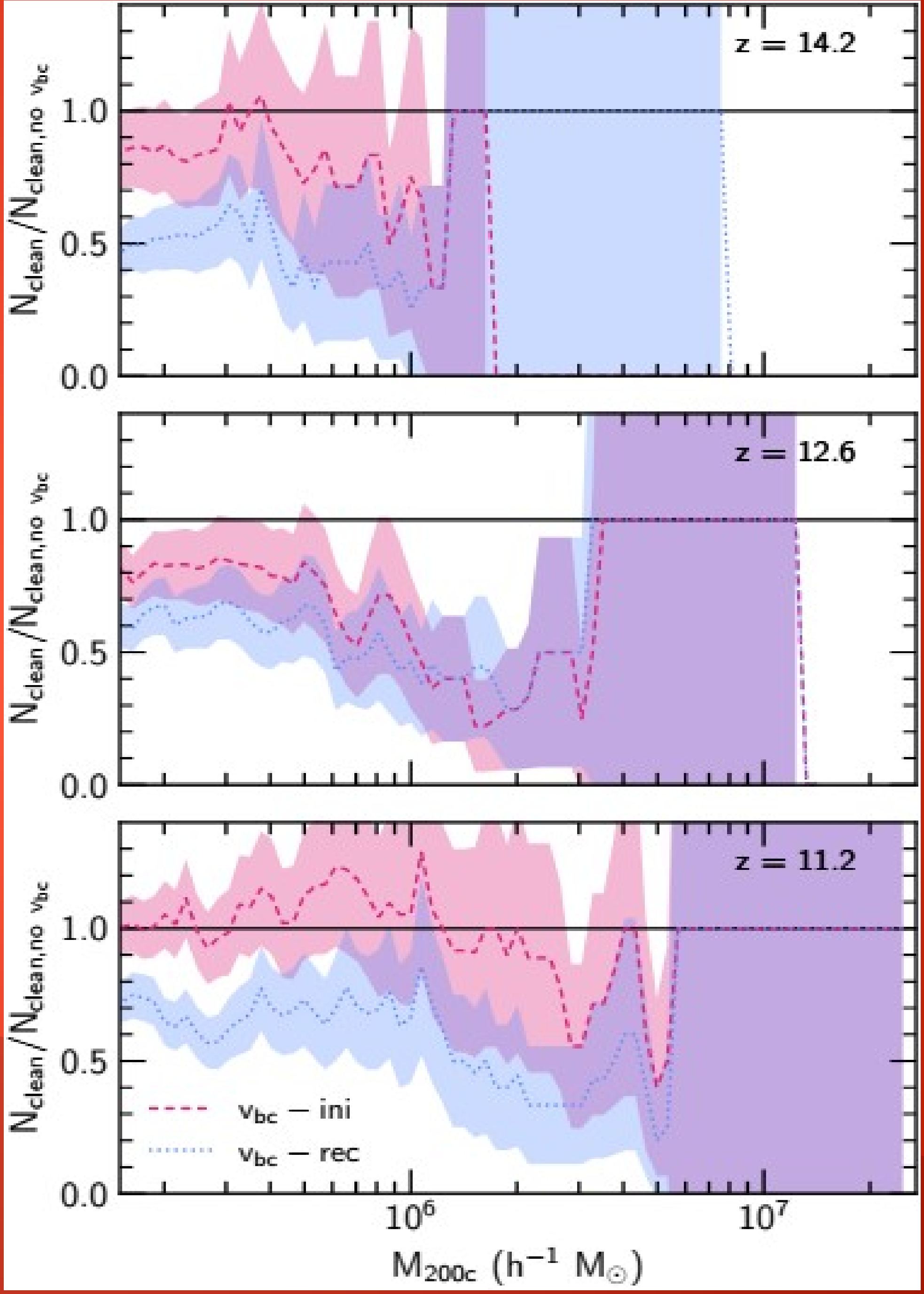


Power spectra

Effect on the halo mass functions

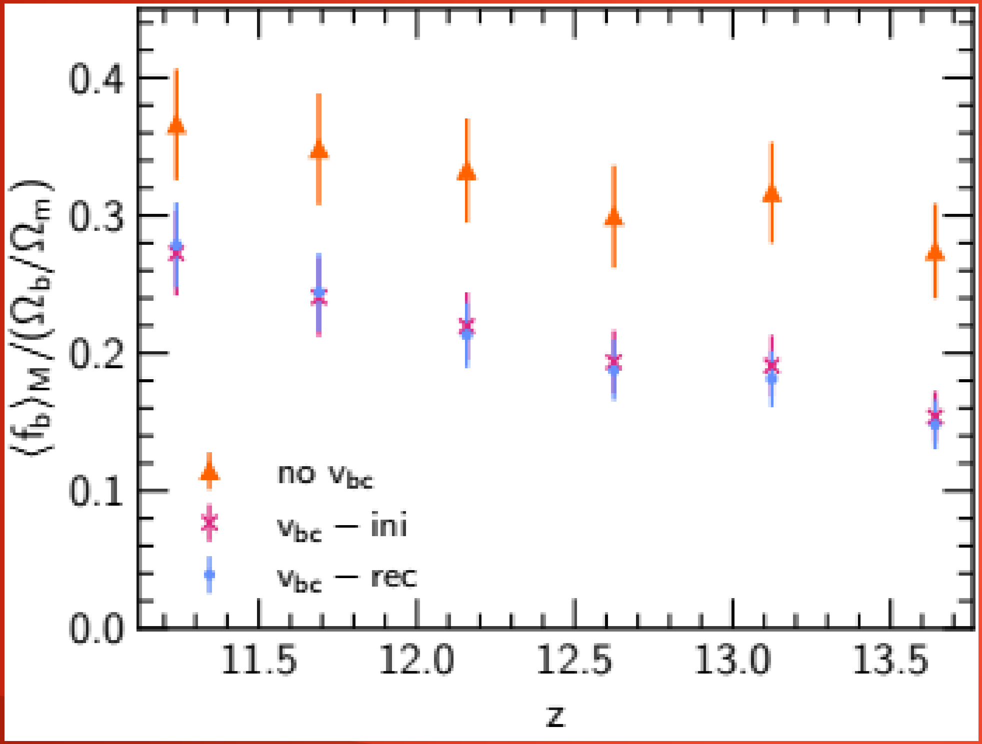
(Conaboy et al., 2023, MNRAS, 525, 5479)

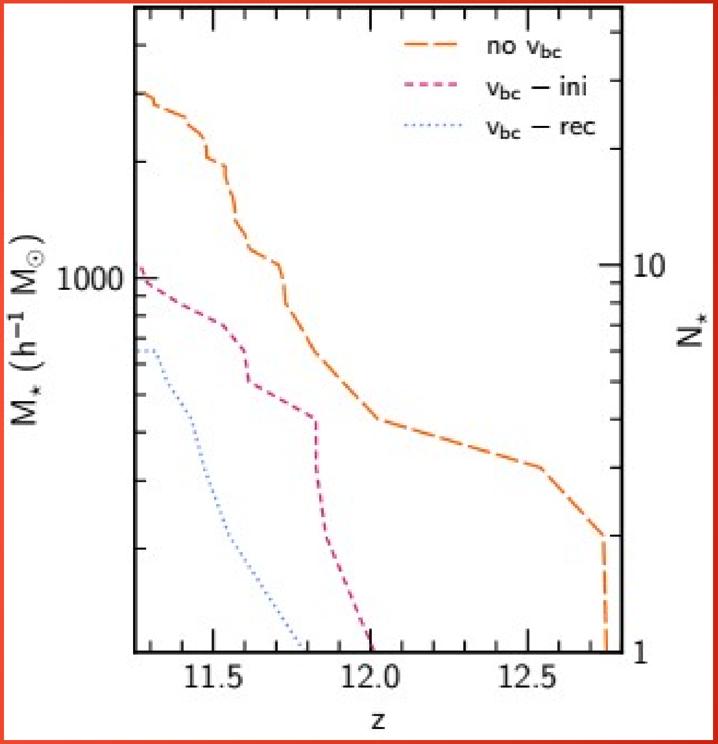
- 3 cases compared:
  - no vbc
  - vbc-ini — vbc in ICs
  - vbc-rec — vbc + bias
- Partial account for vbc (weakly) suppresses halo formation
- Full vbc effect massively suppresses low-mass halos



Supersonic Drift Velocities: baryon fractions and star formation

(Conaboy et al., 2023, MNRAS, 525, 5479)





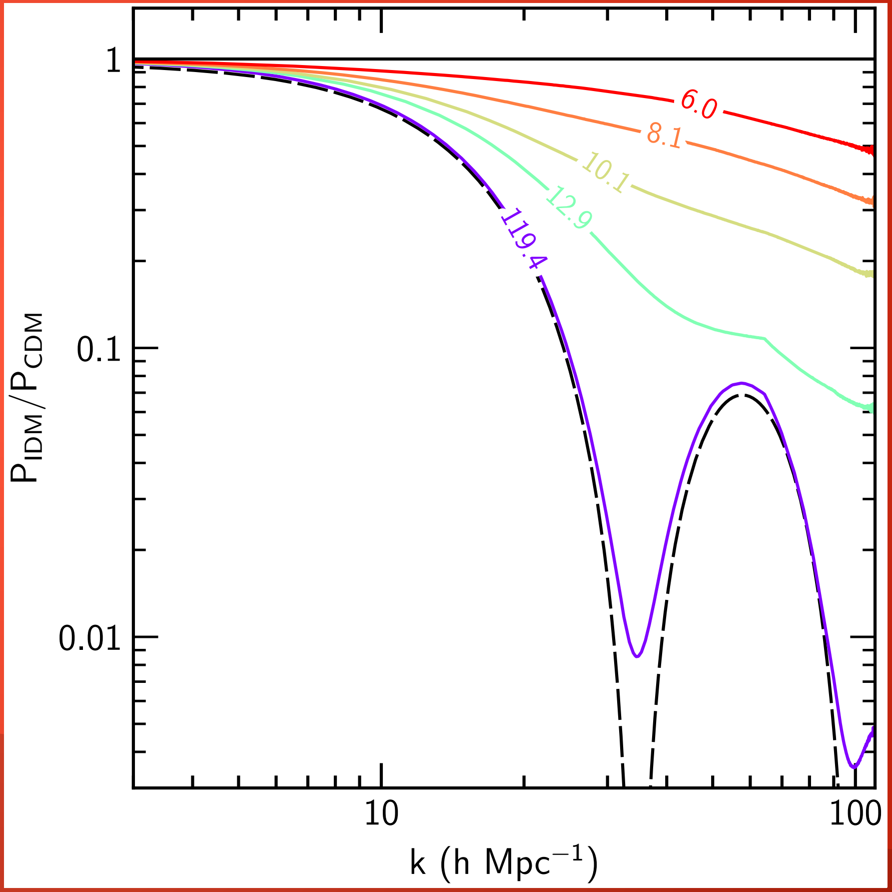
vbc suppresses the baryon fraction in halos by 30-50% (redshift-dependent) compared to no vbc. Little difference between vbc cases.

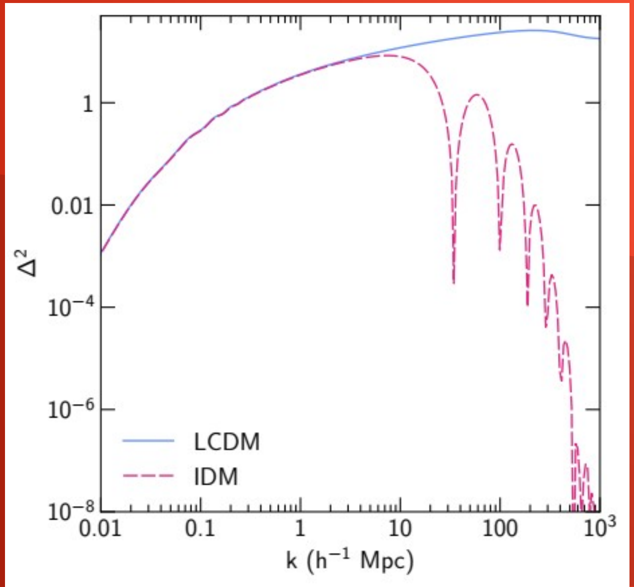
Many fewer stars are formed in vbc cases. Stronger effect with full vbc.

Interacting DM: effect on early structures and reionzation

(Schwandt, Conaboy, Iliev, Yepes, et al. in prep.)

- Certain types of DM interact with radiation, resulting in suppression of power on small scales (Boehm, et al. 2014)
- EoR and early structures can provide interesting constraints on such DM models





Interacting DM: effect on early structures

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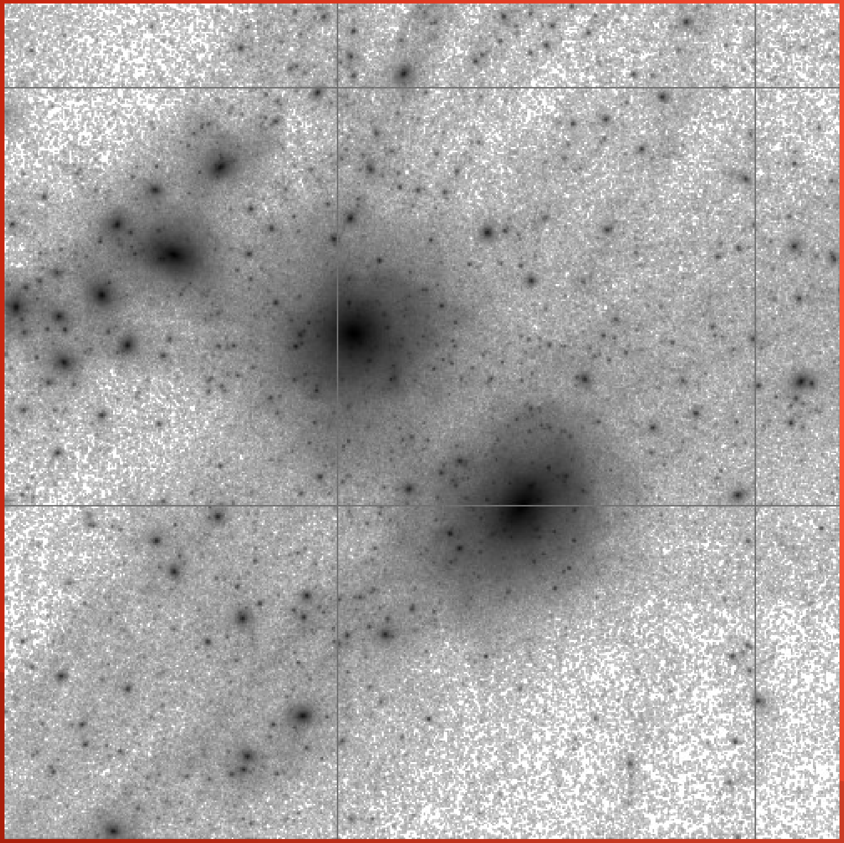
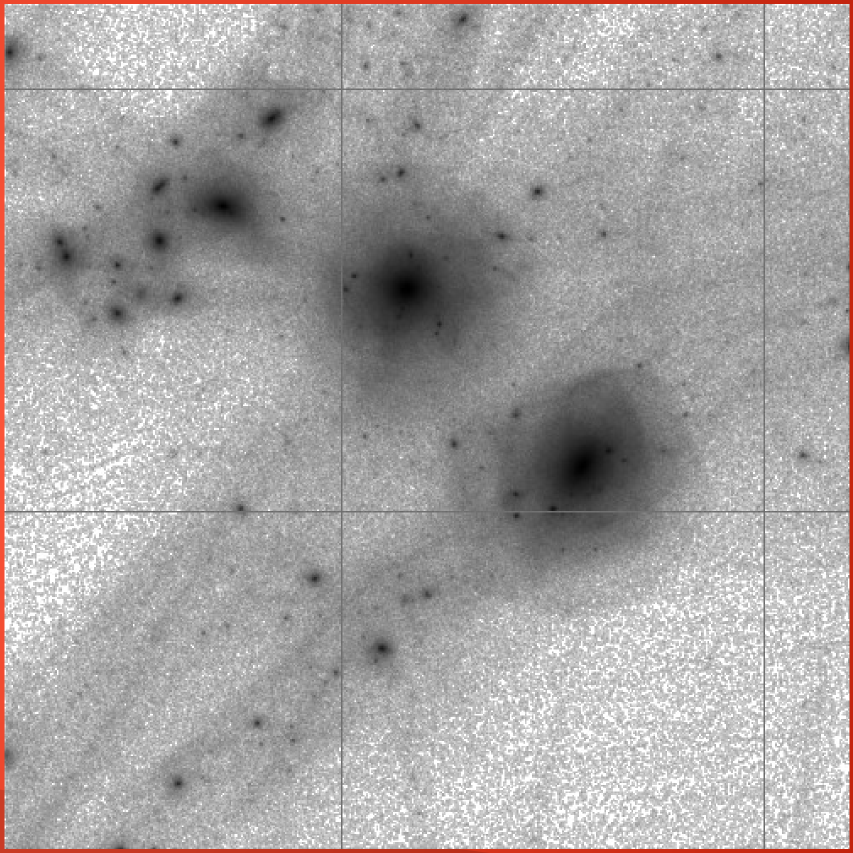


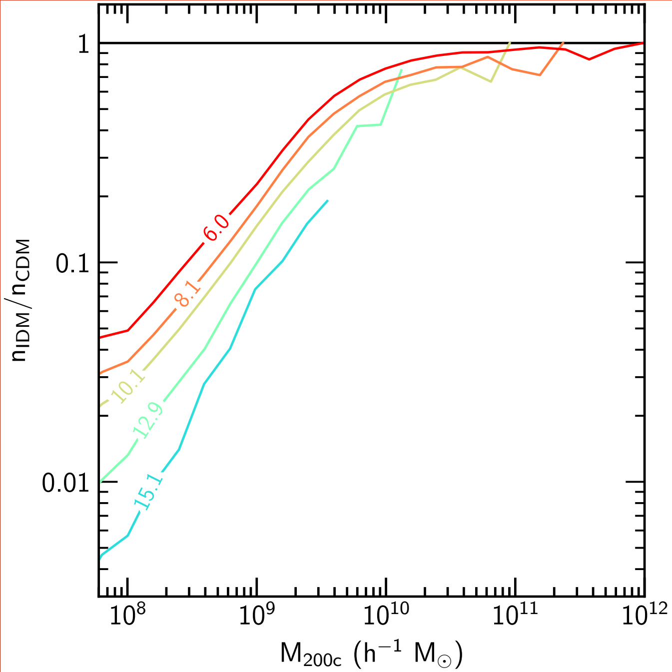


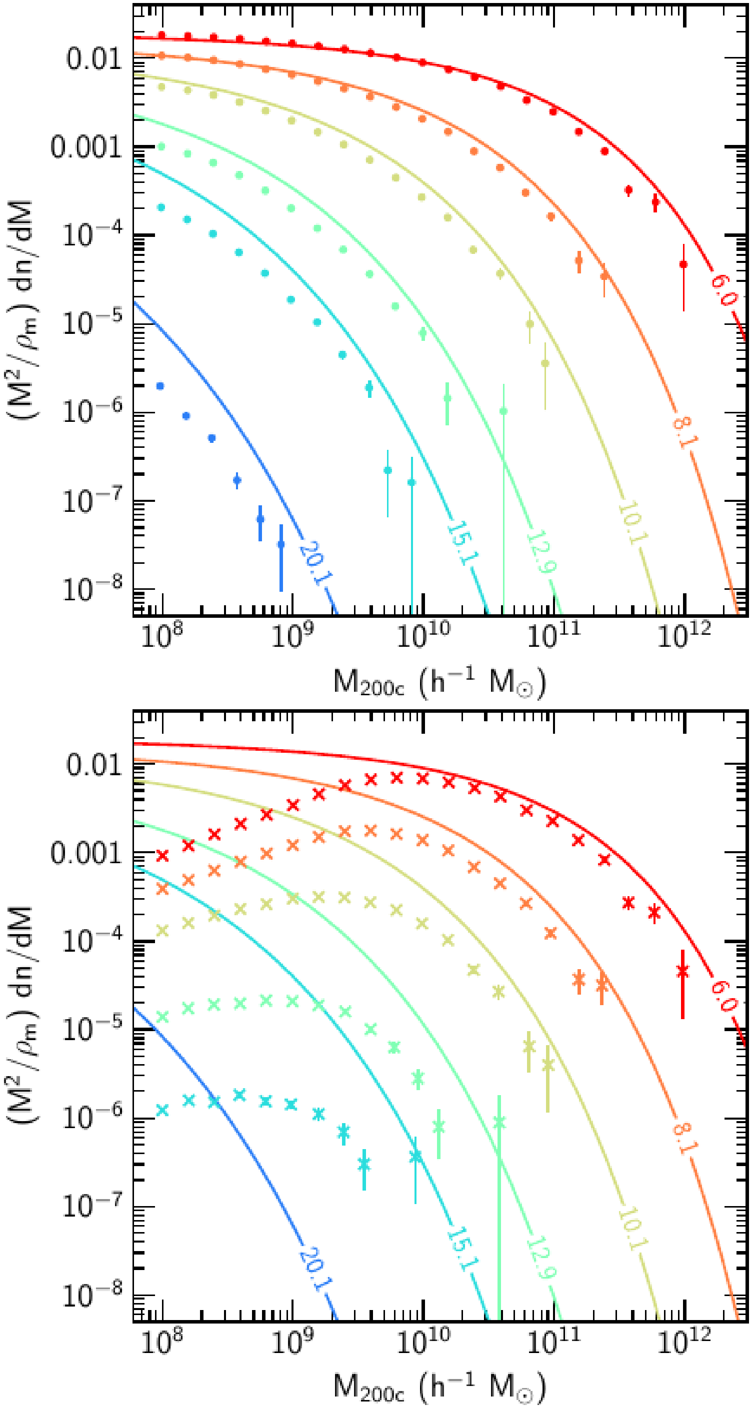
Certain types of DM interact with radiation in the primordial Universe, resulting in suppression of small structures.

Interacting DM: halo mass function

(Schwandt, Conaboy, Iliev, Yepes, et al. in prep.)

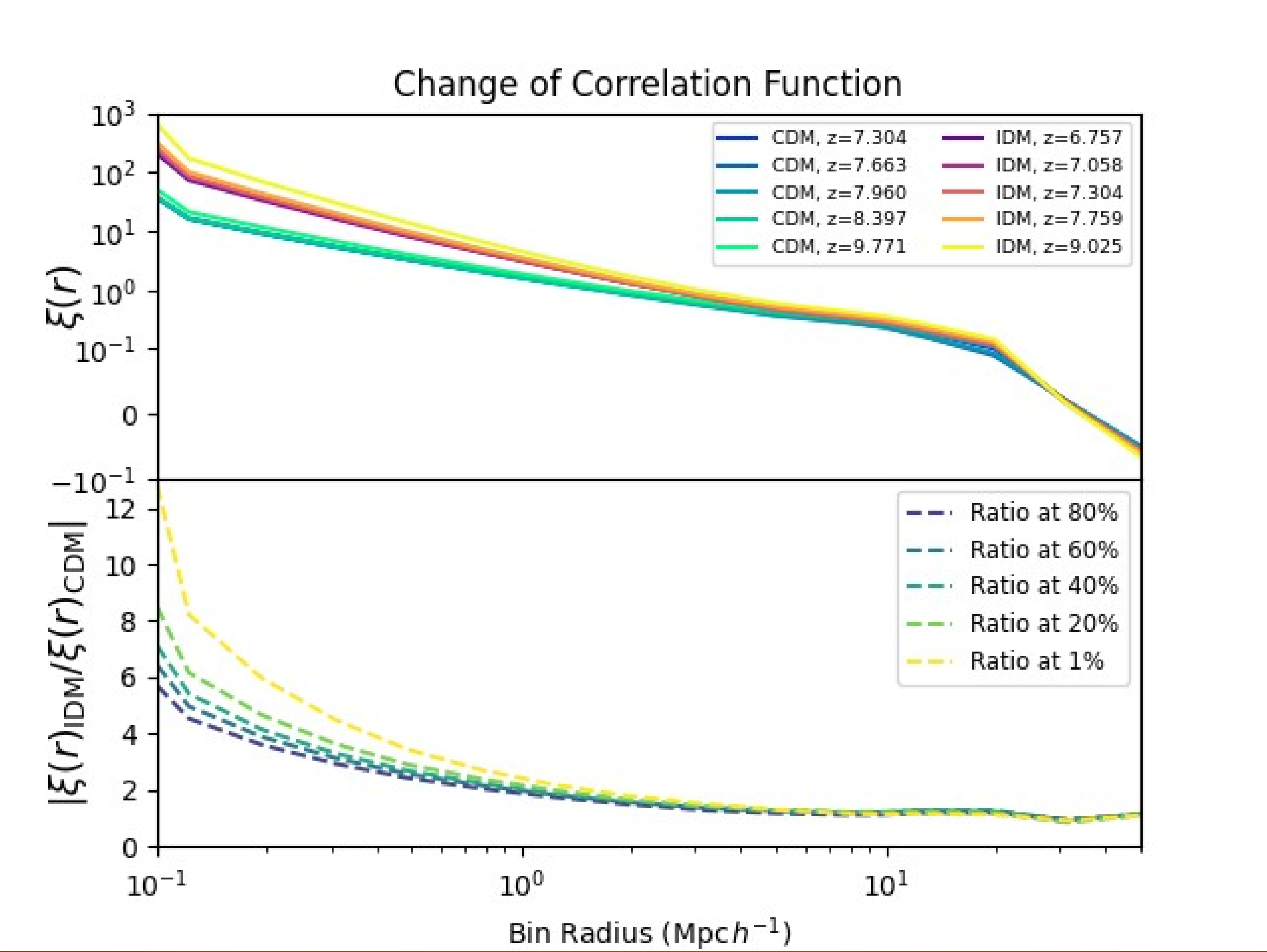
- IDM models yield significant suppression of the low-mass halos, likely main drivers of reionization
- No effect on massive halos
- Watson (2012) HMF shown for reference





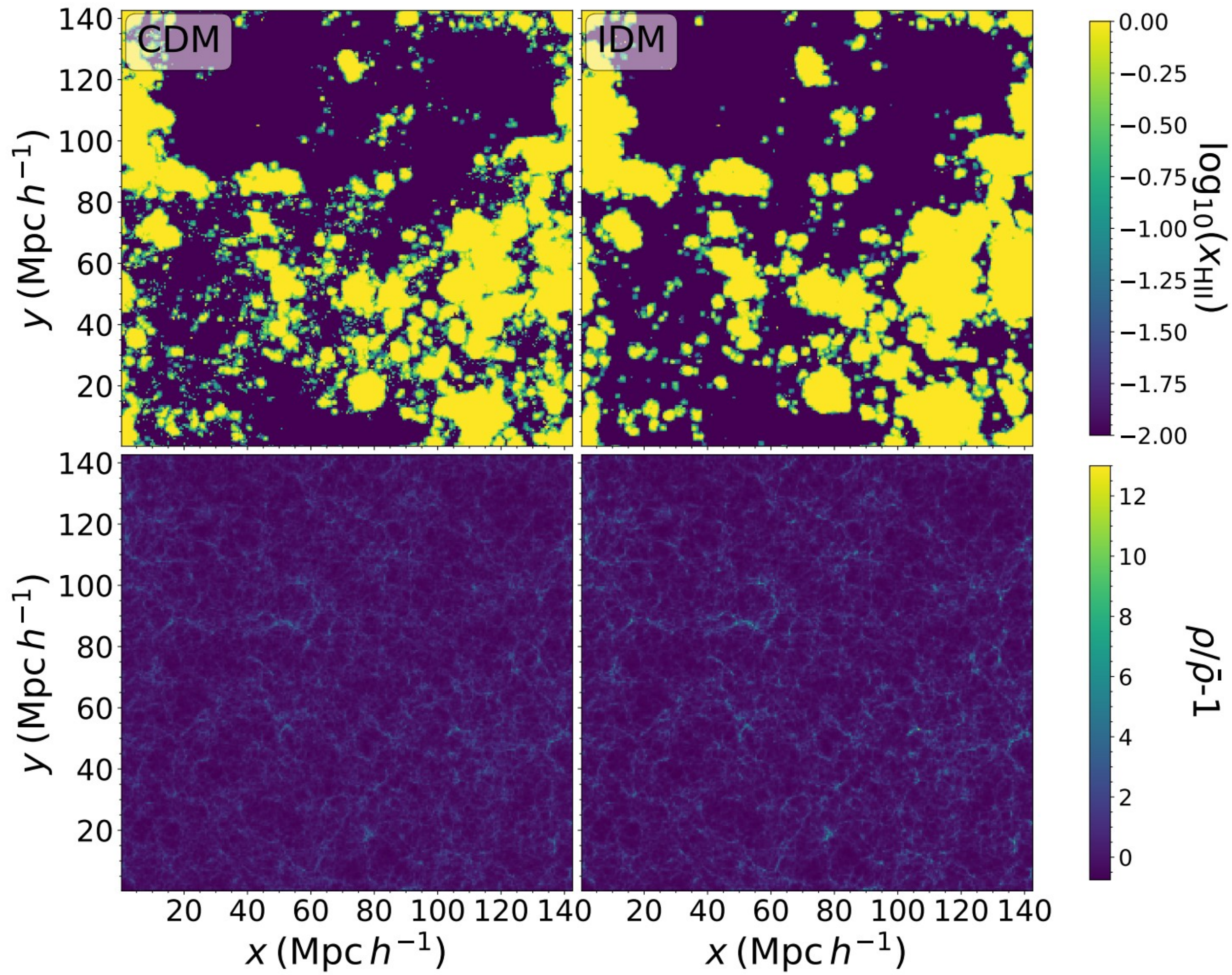
Halo 2-pt correlation functions

(Schwandt, Conaboy, Iliev, Yepes, et al. in prep.)



IDM vs CDM: reionization morphology

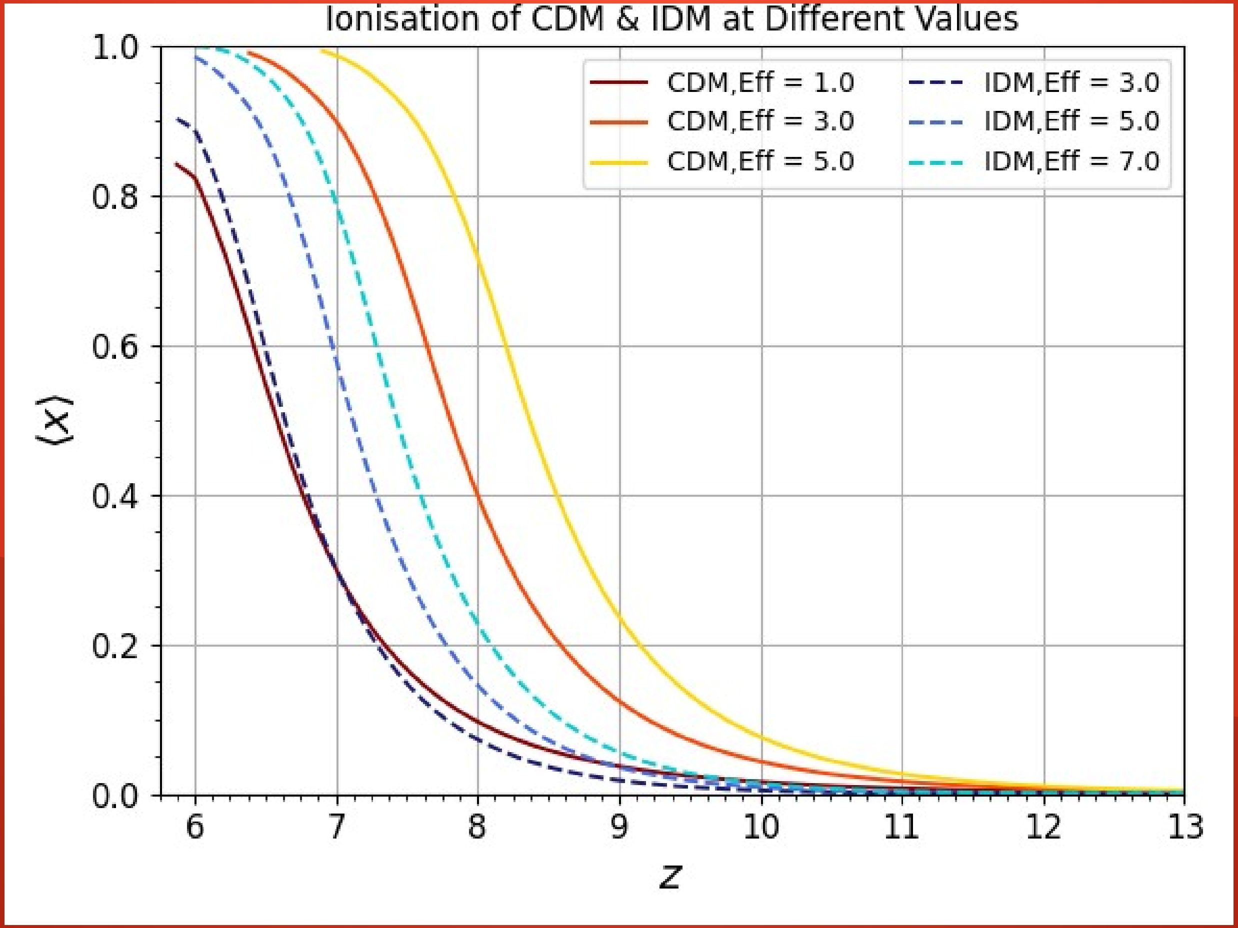
(Schwandt, Conaboy, Iliev, Yepes, et al. in prep.)



IDM vs CDM: reionization history

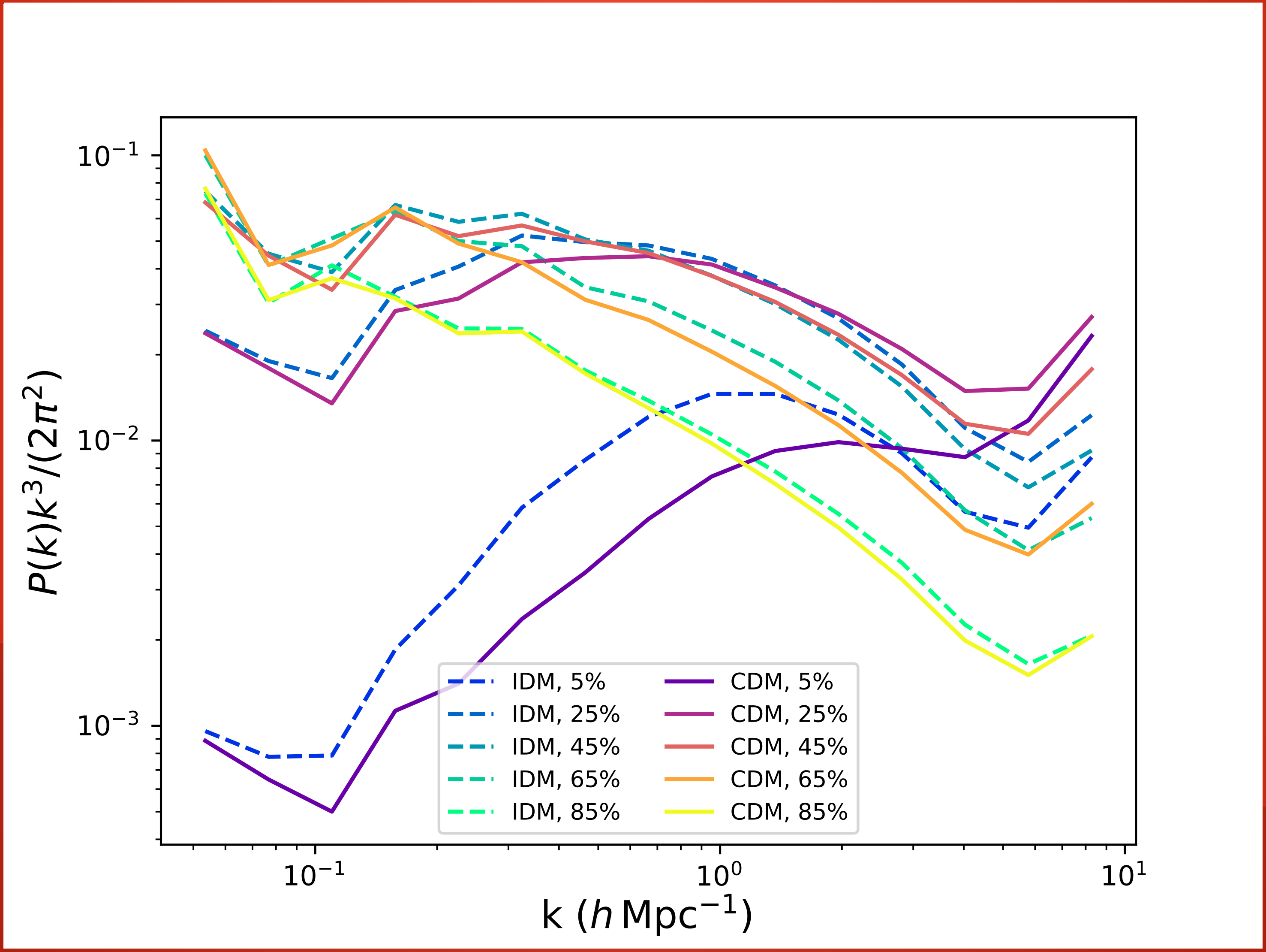
(Schwandt, Conaboy, Iliev, Yepes, et al. in prep.)

- Reionization in IDM models starts later and initially proceeds slowly due to lack of low-mass halos, speeding up later



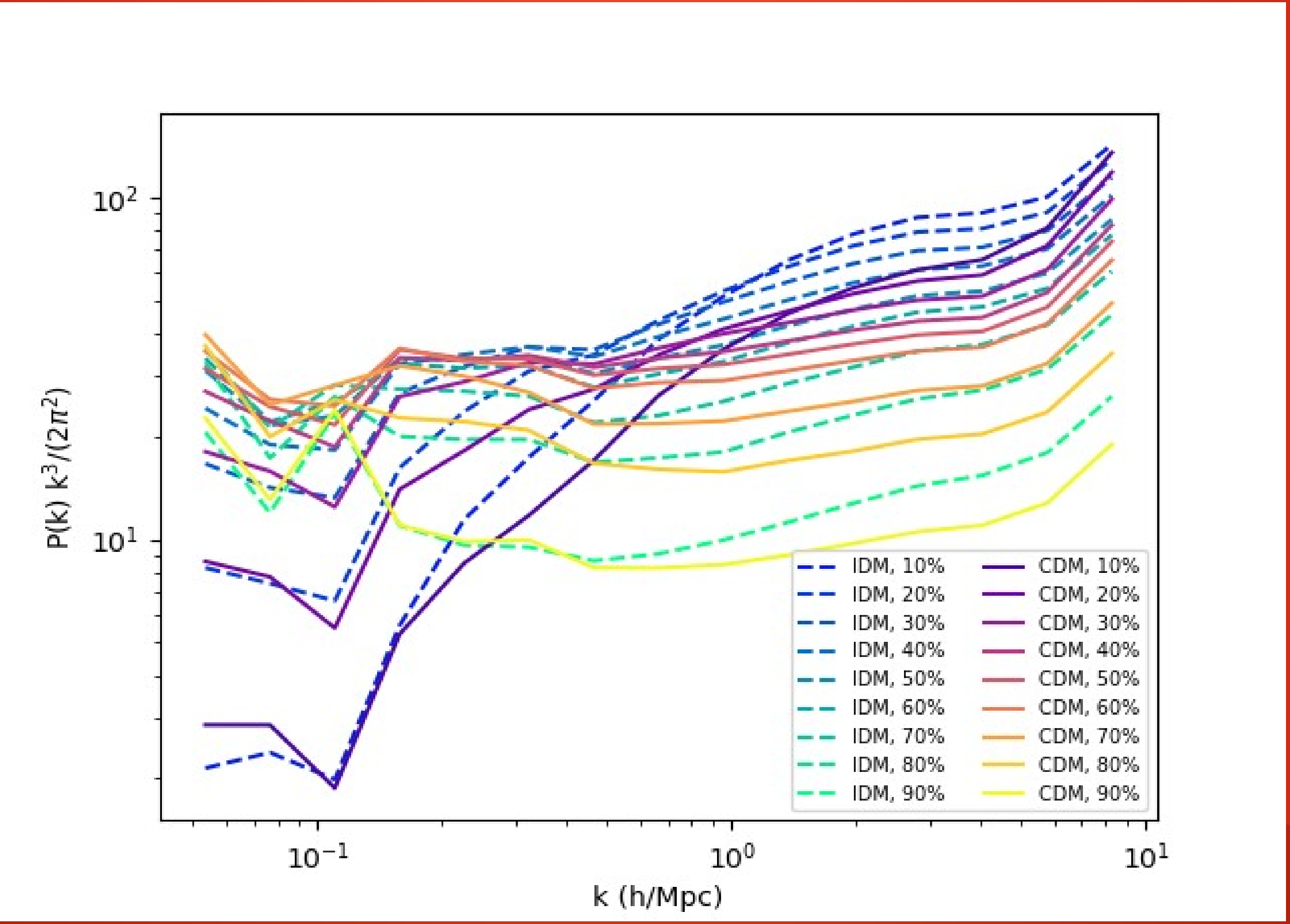
IDM vs CDM: HII power spectra

(Schwandt, Conaboy, Iliev, Yepes, et al. in prep.)



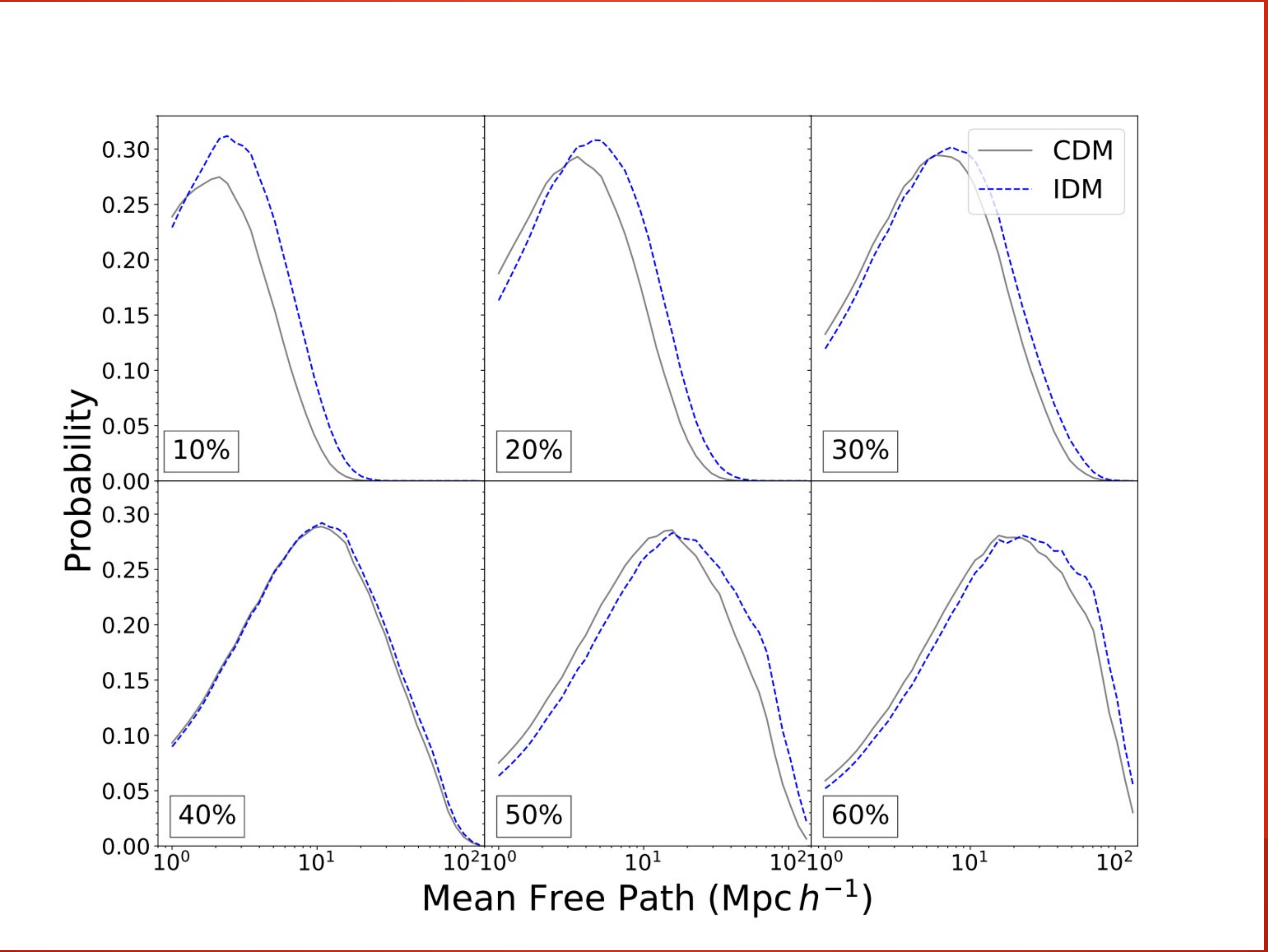
IDM vs CDM: 21-cm power spectra

(Schwandt, Conaboy, Iliev, Yepes, et al. in prep.)



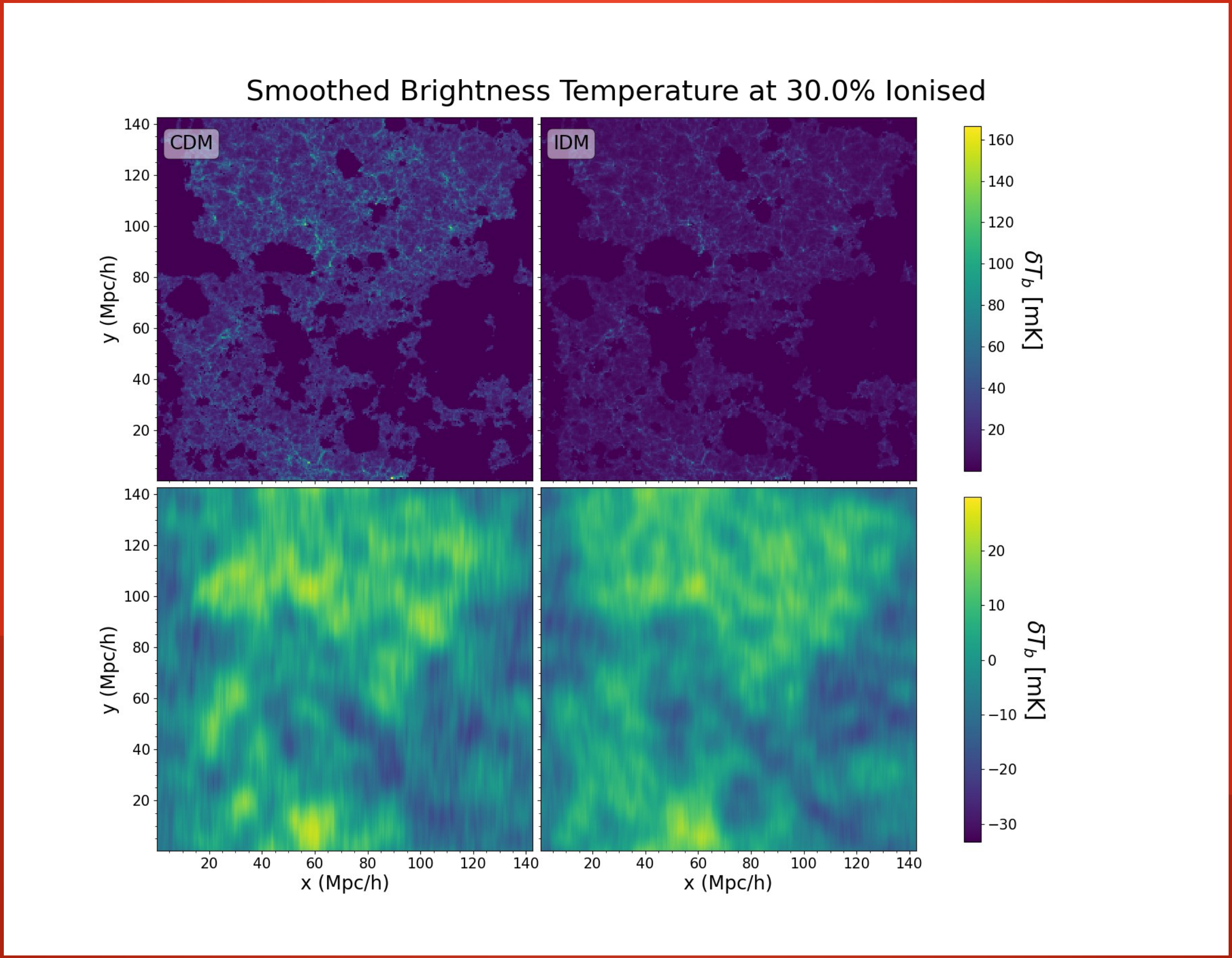
CDM vs IDM: MFP bubble sizes

(Schwandt, Conaboy, Iliev, Yepes, et al. in prep.)



Detectability with SKA

(Schwandt, Conaboy, Iliev, Yepes, et al. in prep.)



Reionization in the Hestia suite

(Conaboy, Iliev, Attard, Libeskind, et al., in prep.,)

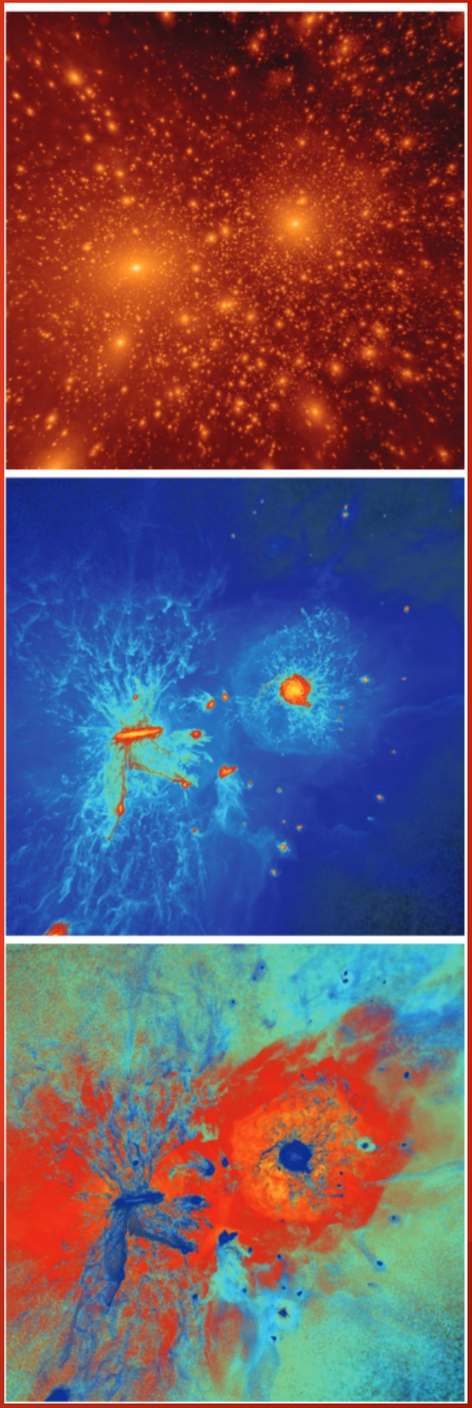
- Hestia suite of simulations is large set of constrained zoom simulations of the local neighbourhood (Libeskind et al, 2020)
- This project aims to re-simulate Hestia ICs with full radiative hydrodynamics to understand EoR effects on the local structures.
- Running on JSC (Juelich).

HESTIA

(HIGH-RESOLUTION ENVIRONMENTAL SIMULATIONS OF THE IMMEDIATE AREA)

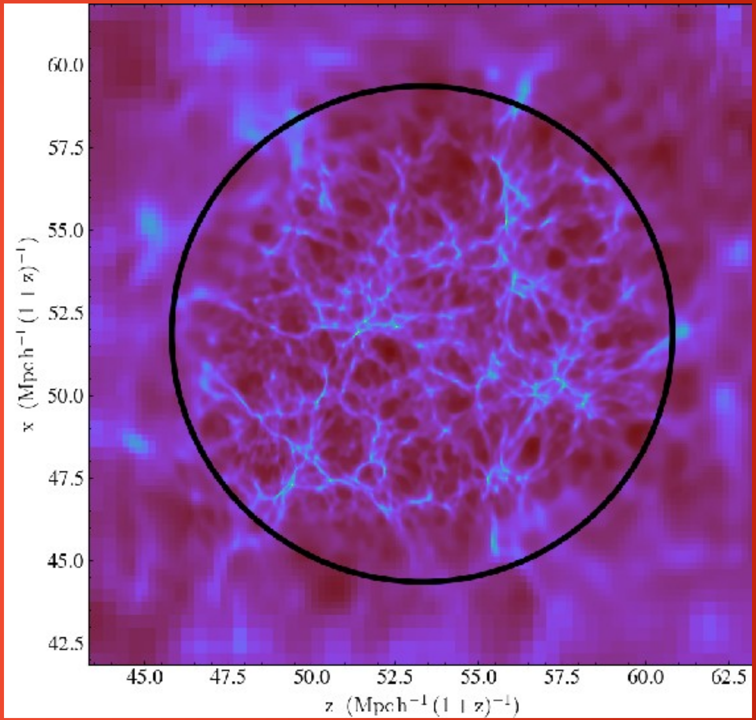
- Constrained zoom simulation run using AREPO
- Uses CLUES ICs constrained with cosmicFlows-2 (Tully et al. 2013)
- Baryonic physics the AURIGA galaxy formation model (includes gas cooling through primordial and metal cooling) (Grand et al. 2017)
- Reionization is modelled using a spatially uniform UV background

Libeskind et al. (2020)



HESTIA-RT

- Suite of 6 zoom-simulations with base resolution of 256^3
- 2 DMO simulations (4096^3 and 16384^3 effective resolution)
- 2 HYDRO simulations
  - 4096^3 effective resolution
  - One with Mechanical Feedback
  - One with Kinetic Feedback
- 2 RHD simulations
  - 4096^3 effective resolution
  - One with Mechanical Feedback
  - One with Kinetic Feedback

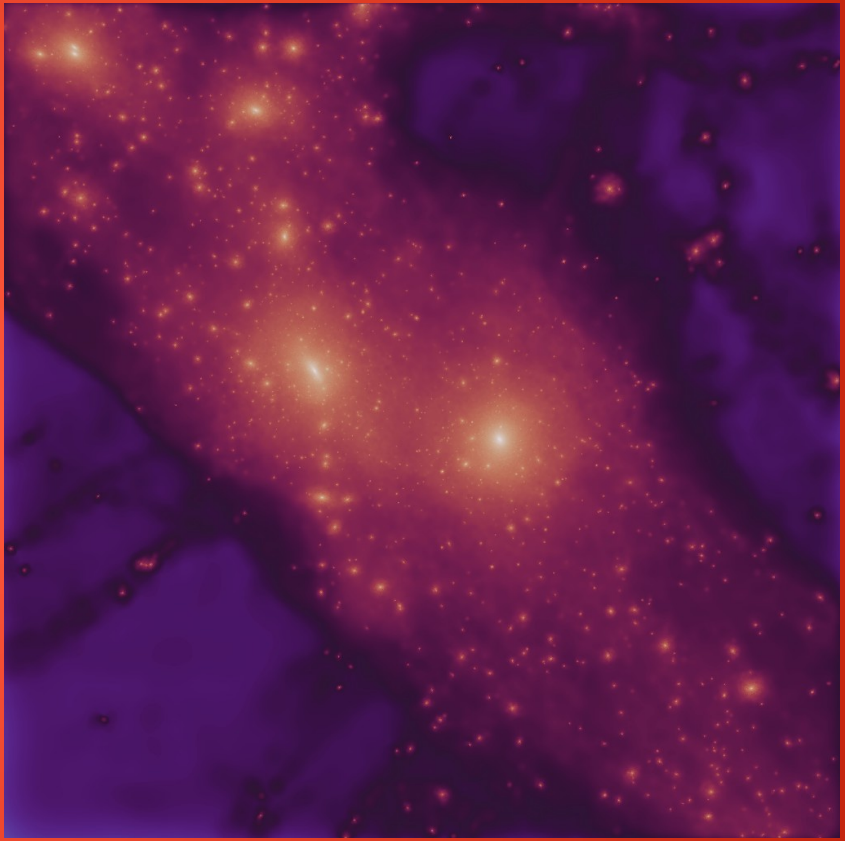


Projected DM density of DMO-16384 run at z = 0 centered on LG

Recasting and checking Ics

(Conaboy, Iliev, Attard, Libeskind et al., in prep.)

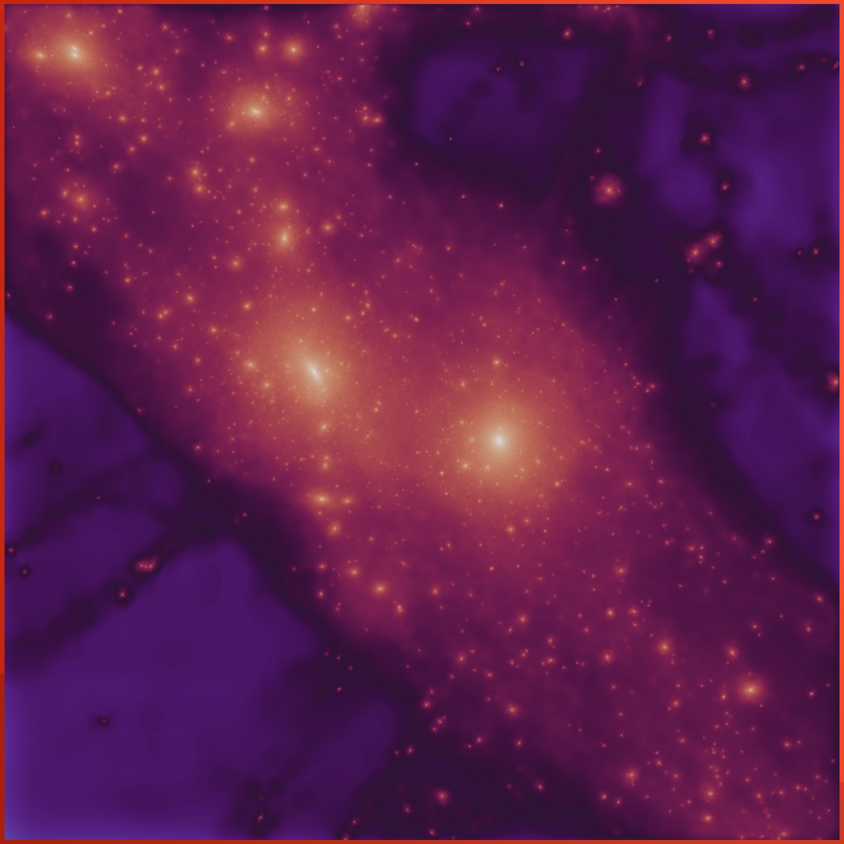
- Original simulations ran with AREPO (moving mesh).
- Constrained ICs were re-cast in Ramses-compatible format: constrained modes+Giningagap for adding small scales
- N-body zooms ran to z=0 and reproduce LG very well



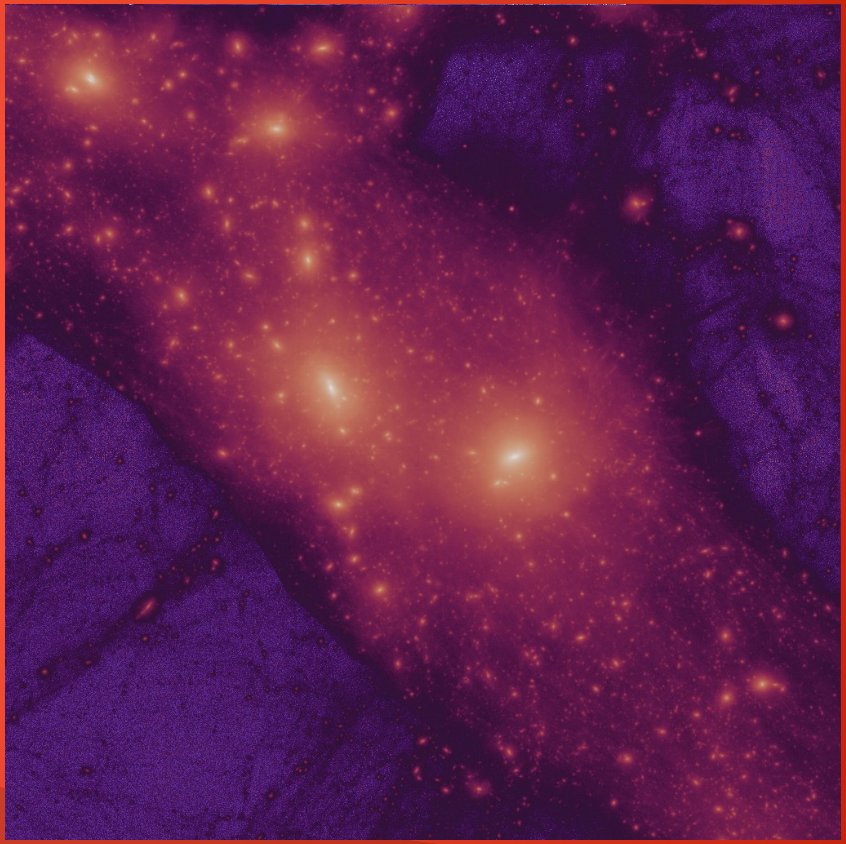
Effective resolution	$\Delta d_{\rm sep}$ (%)	$\Delta M_{\rm M31}$ (%)	$\Delta M_{\rm MW}$ (%)
4096^3	-22.20	-2.61	-3.26
16384^3*	-21.48	0.06	-2.41

Effect of resolution

(Conaboy, Iliev, Attard, Libeskind et al., in prep.)



4096^3 effective in zoom

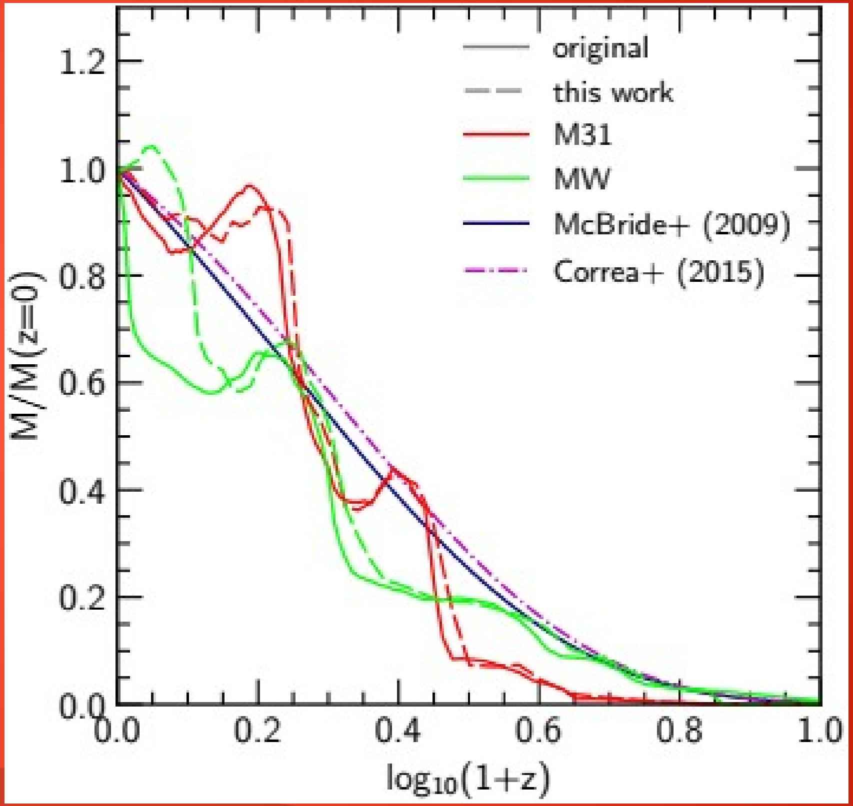


16384^3

Mass accretion history of LG

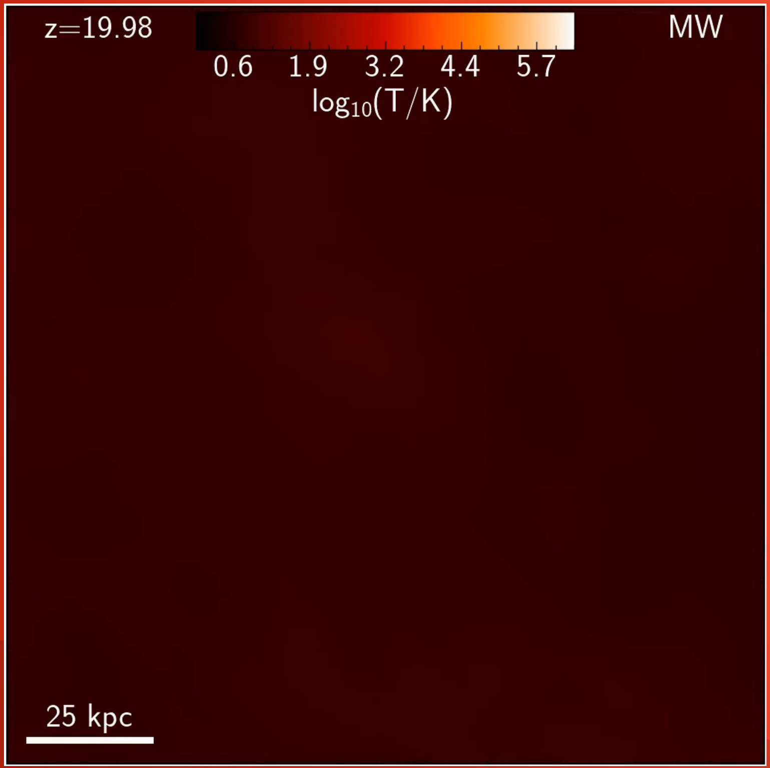
(Conaboy, Iliev, Attard, Libeskind et al., in prep.)

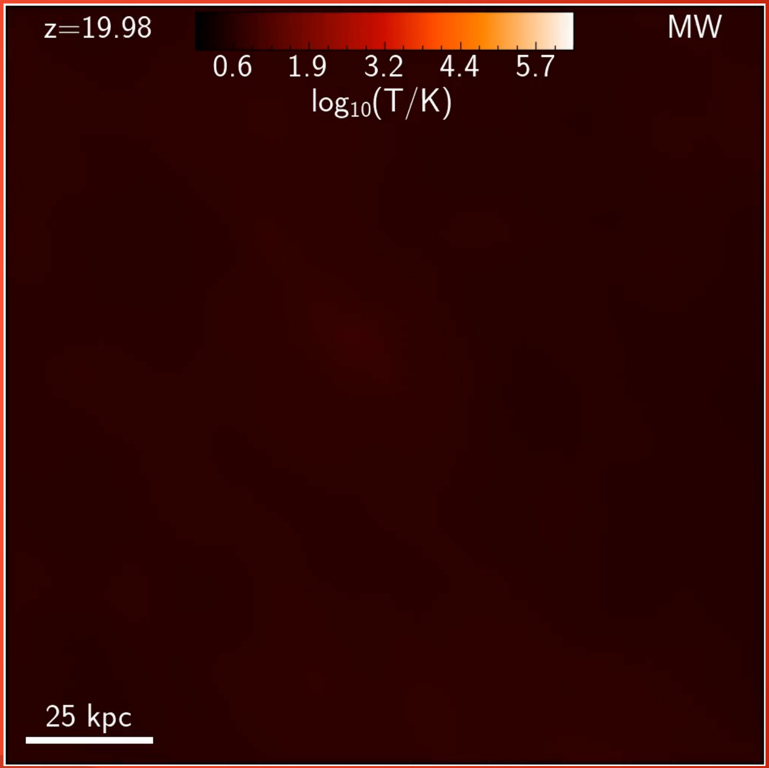
- Mass growth is very similar to original Hestia.
- Some interesting differences at late times
- Reionization history and effect on satellites: in progress



Reionization in Hestia: effect of RT

(Conaboy, Iliev, Attard, Libeskind et al., in prep.)





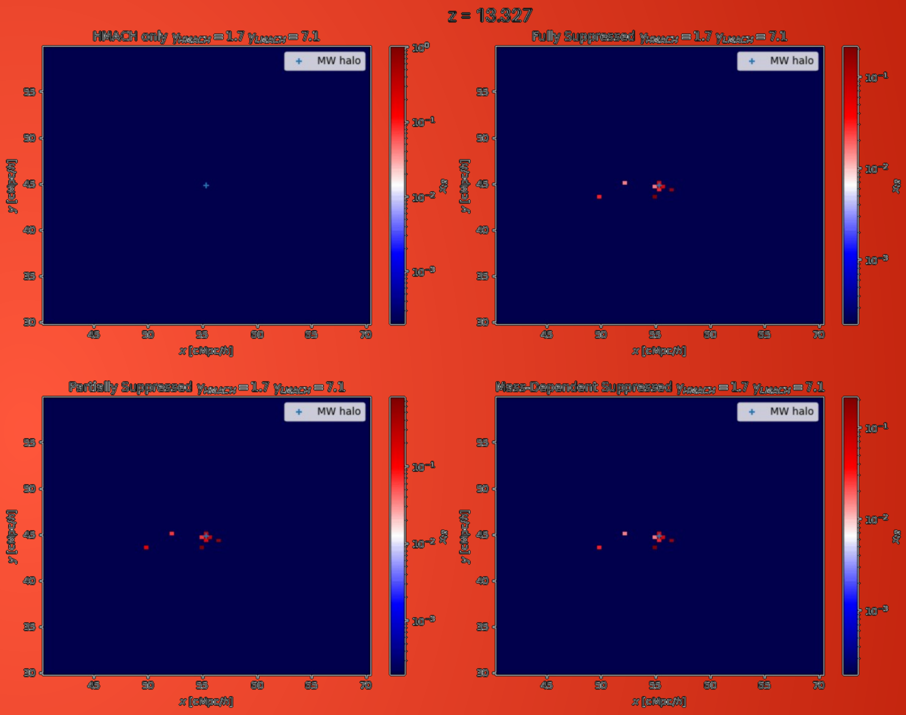
Hydro only

Hydro+RT

PYC2RAY – SOURCE MODELS

(Attard, Iliev, Conaboy, Libeskind et al., in prep.)

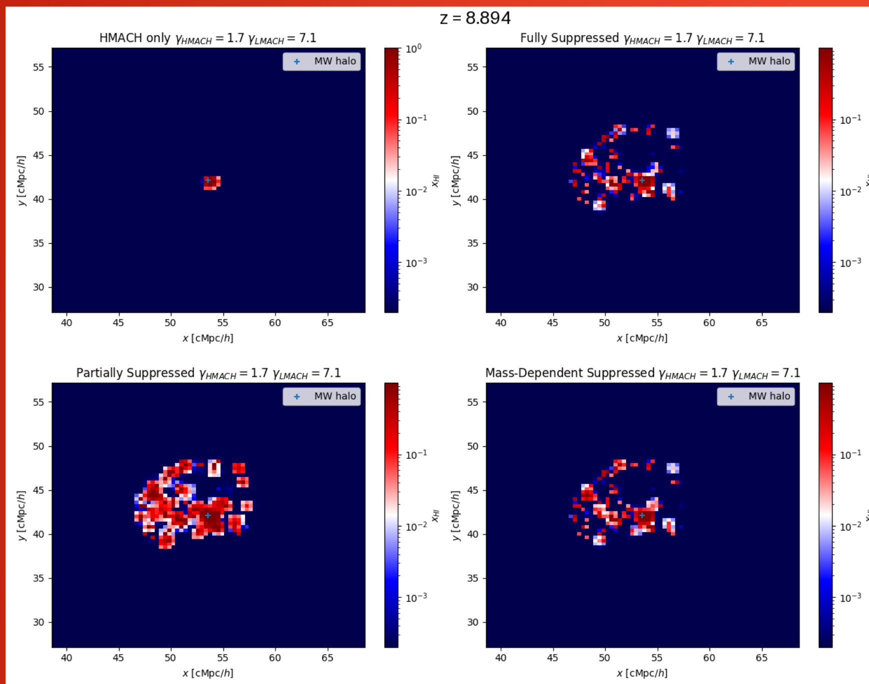
- Implementation of four different source models (based on Dixon et al. 2016):
  - HMACHs only
  - Fully Suppressed LMACH
  - Partially Suppressed LMACHs
  - Mass Dependent LMACH suppression:
    - Most realistic option
    - Suppression follows:

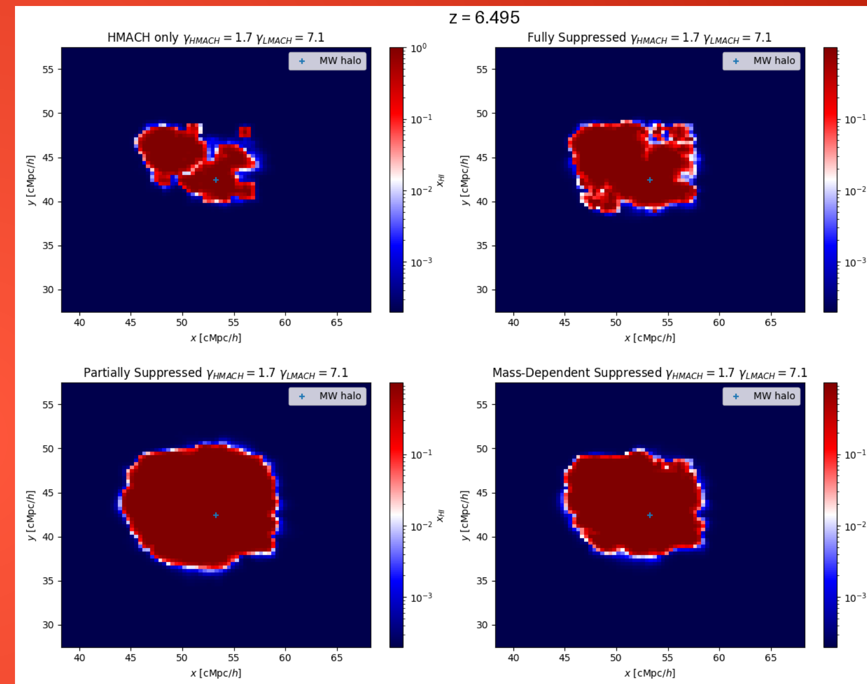


$$g_\gamma = g_{\gamma,\mathrm{HMACH}} \times \left[\frac{M_{\mathrm{halo}}}{9 \times 10^8\, \mathrm{M}_\odot} - \frac{1}{9} \right]$$

IMPLEMENTED SOURCE MODELS TO HESTIA-RT

(Attard, Iliev, Conaboy, Libeskind et al., in prep.)





Summary

- Reionization is inherently multi-scale — pc to 100s of Mpc.
- Baryon-dark matter relative drift velocities are now (for first time) implemented in very large volume zoom simulations.
- The relative drift velocities stronglly influence the halo mass function, baryon content and star formation in halos, especially at lower masses
- EoR signals could be useful for learning about nature of dark matter.
- Local Group data offers a wealth of information about reionization and early galaxy formation