Contribution of the Smallest Galaxies to Reionization: A Qualitatively Different Picture

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Tale of Two Simulations

The Renaissance Simulations

Statistical properties of the first galaxies in ~200 Mpc^3 survey volumes

$10^6 < M_h/M_{sol} < 10^{10}$

$10^3 < M_*/M_{sol} < 10^8$

$20 > z > 7.5$

100 Million core-hrs

Enzo AMR

$\dot{n}_{\mathrm{ion,esc}}$

$f_{sf}(M_h)$

Reionization Simulation

Fully coupled RHD cosmological simulation with dynamic sources

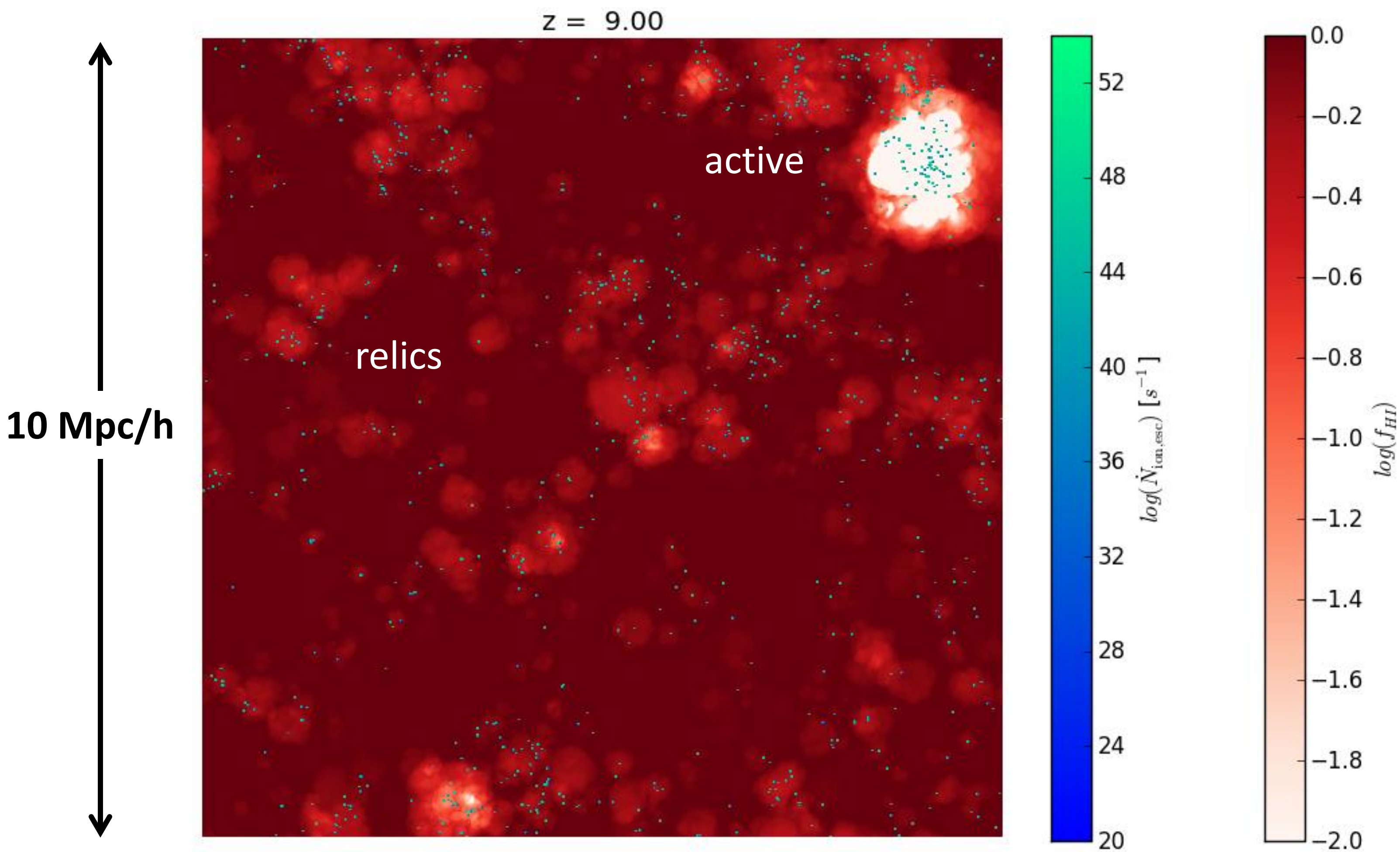
$10^7 < M_h/M_{sol} < 10^{10}$

$20 > z > 5$

0.5 Million core-hrs

Enzo uniform grid

Early reionization is dominated by episodic star formation in low mass halos, resulting in an earlier onset and abundant relic HII regions



1152^3

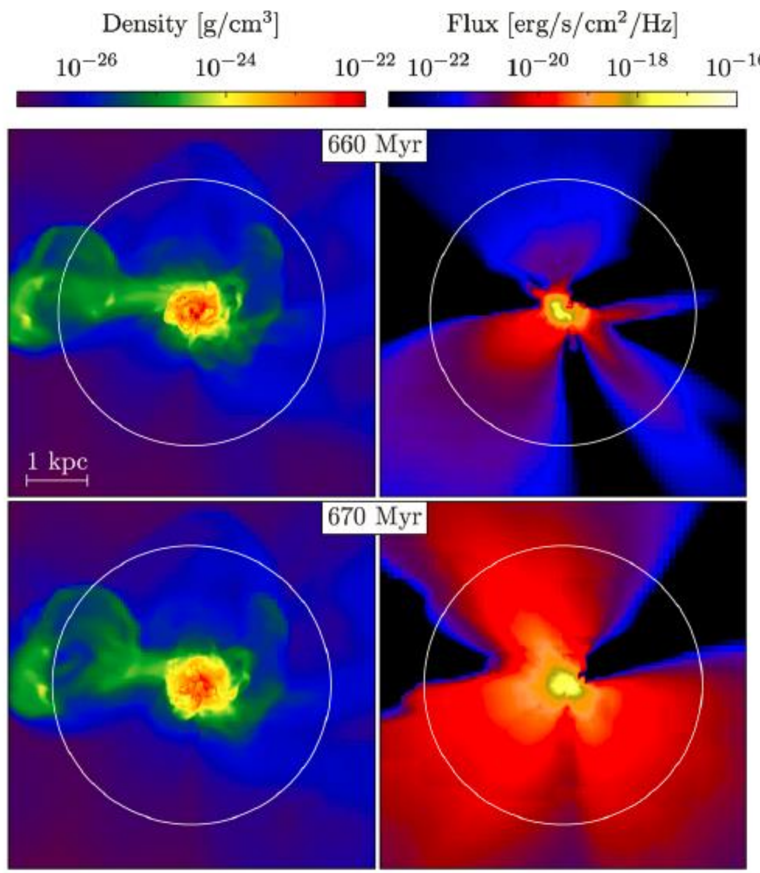
M. Norman, Aspen EoR 2016

Norman et al., in prep

Theoretical Motivation

Birth of a Galaxy III, Wise et al. (2014)

- Wise et al. (2014) showed that *metal-cooling halos** with $10^7 < M_h/M_{sol} < 10^{8.5}$ contribute up to ~30% of the ionizing flux during reionization due to their:
  - high space density
  - high ionizing escape fractions
  - not insignificant star formation rates
- Shortcoming: small sample size (32)

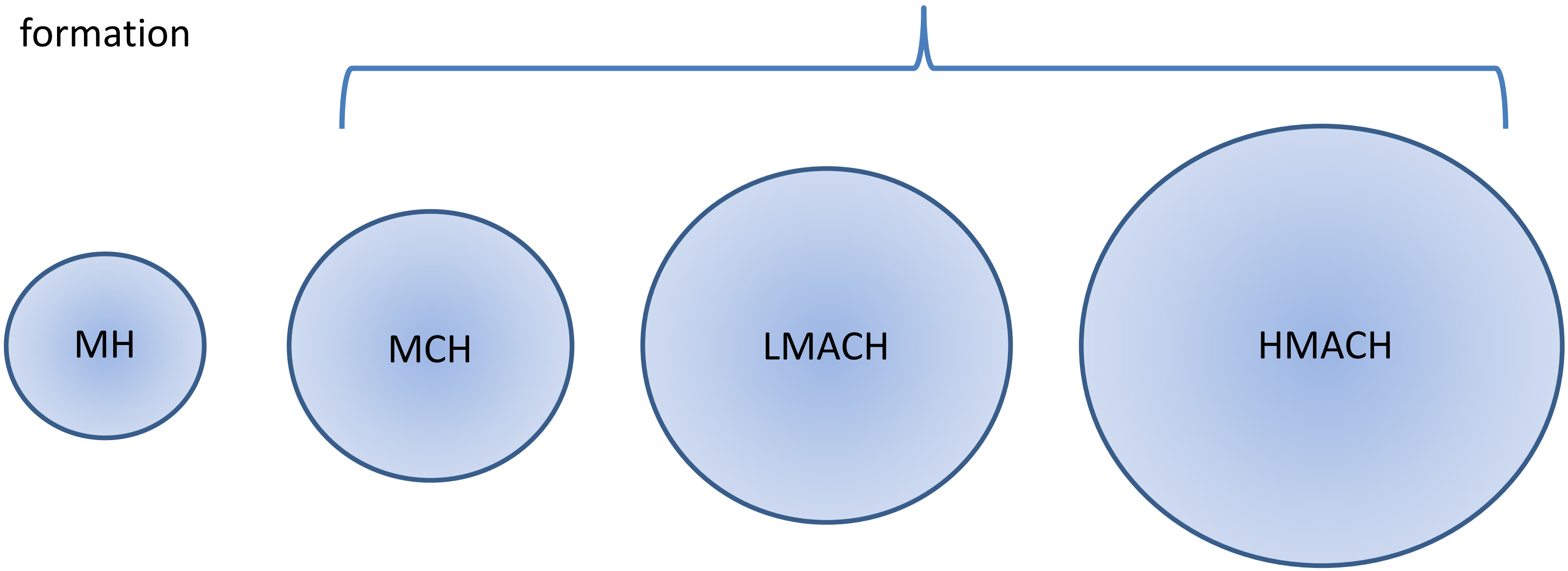


**low mass halos enriched by prior Pop III/Pop II SNe which cool via metal fine structure lines*

Halos with Ionizing Sources

Pop III
star
formation

Metal-enriched star formation



Pop III
minihalos
10^{5-7} Msol

Metal cooling
halos
10^{7-8} Msol

Atomic
cooling
halos
10^{8-9} Msol

Atomic
cooling
halos
$>10^{9}$ Msol

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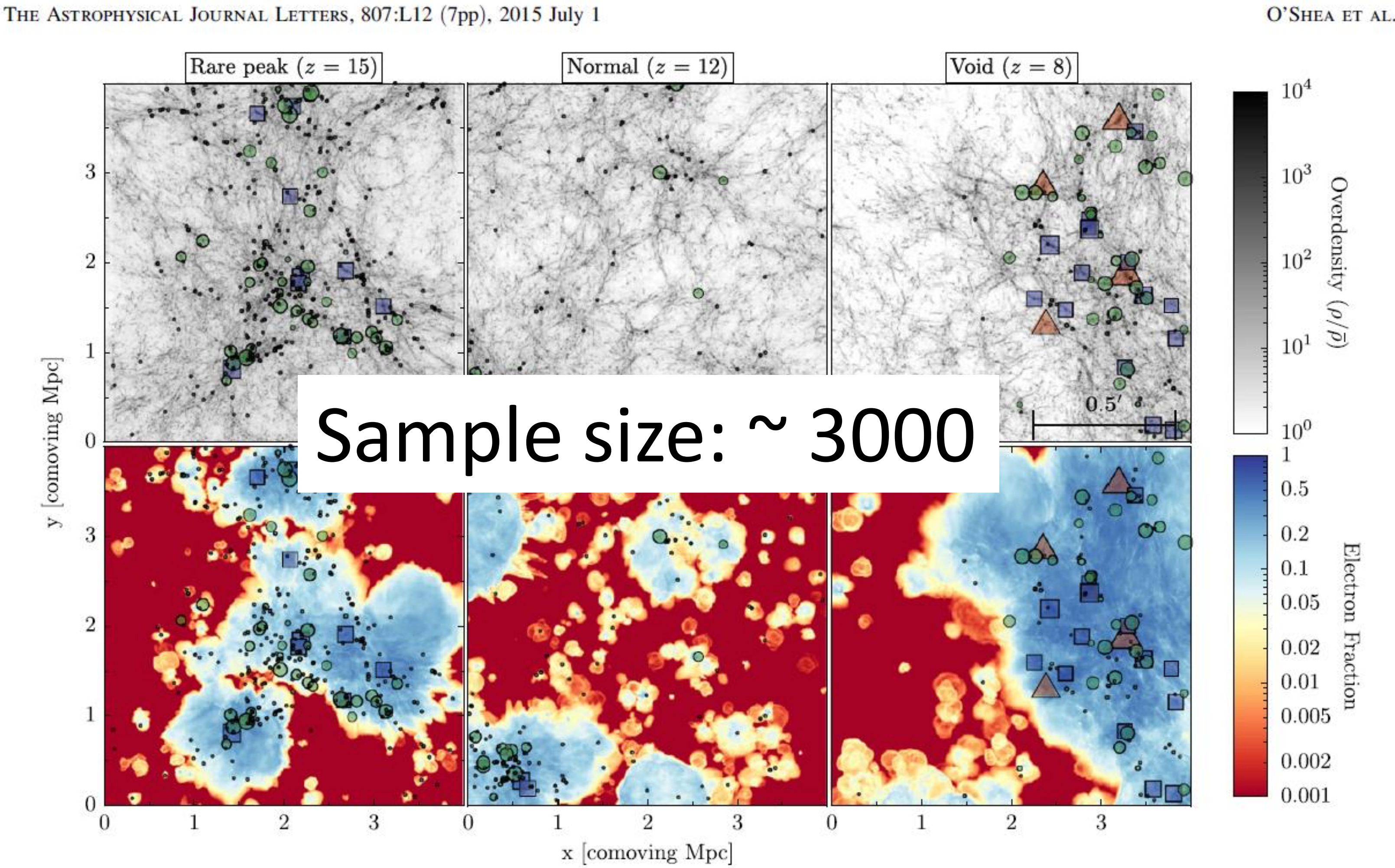
Renaissance Simulations

AMR Radiation Hydrodynamic Cosmology Simulations on Blue Waters Sustained Petascale Supercomputer



Sample size: ~ 3000

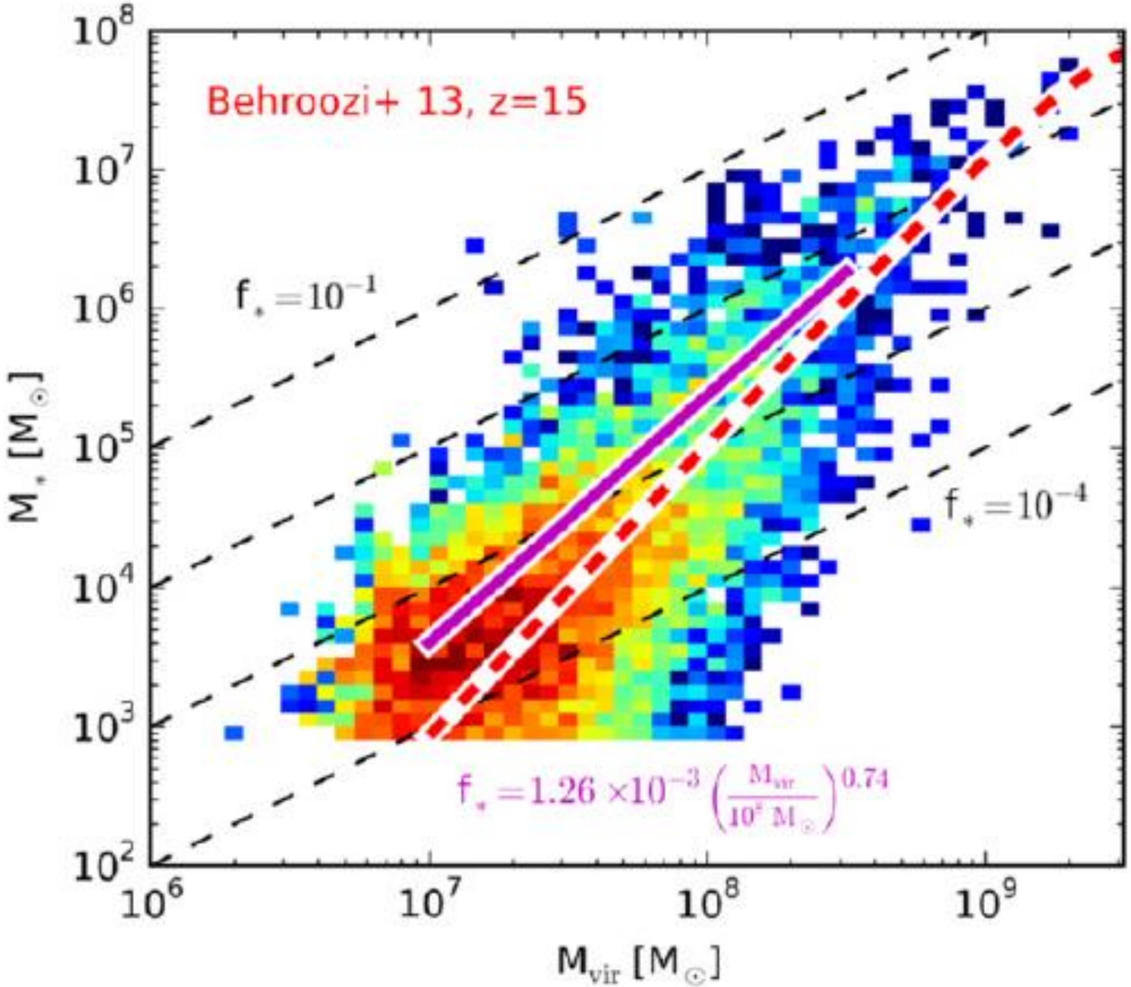
O'Shea et al. (2015)

Renaissance Simulations Publications

Reference	Topic
Xu et al. (2013)	Pop III stars and remnants
Xu et al. (2014)	X-ray feedback from Pop III black holes
Chen et al. (2014)	Scaling relations for SAMs
Ahn et al. (2015)	21 cm signal from X-ray preheating
O'Shea et al. (2015)	UV luminosity function
Xu et al. (2016a, submitted)	Late Pop III star formation
Xu et al. (2016b, in prep)	Galaxy properties and escape fractions
Xu et al. (2016c, in prep)	X-ray background from Pop III stars

Stellar Mass vs. Halo Mass

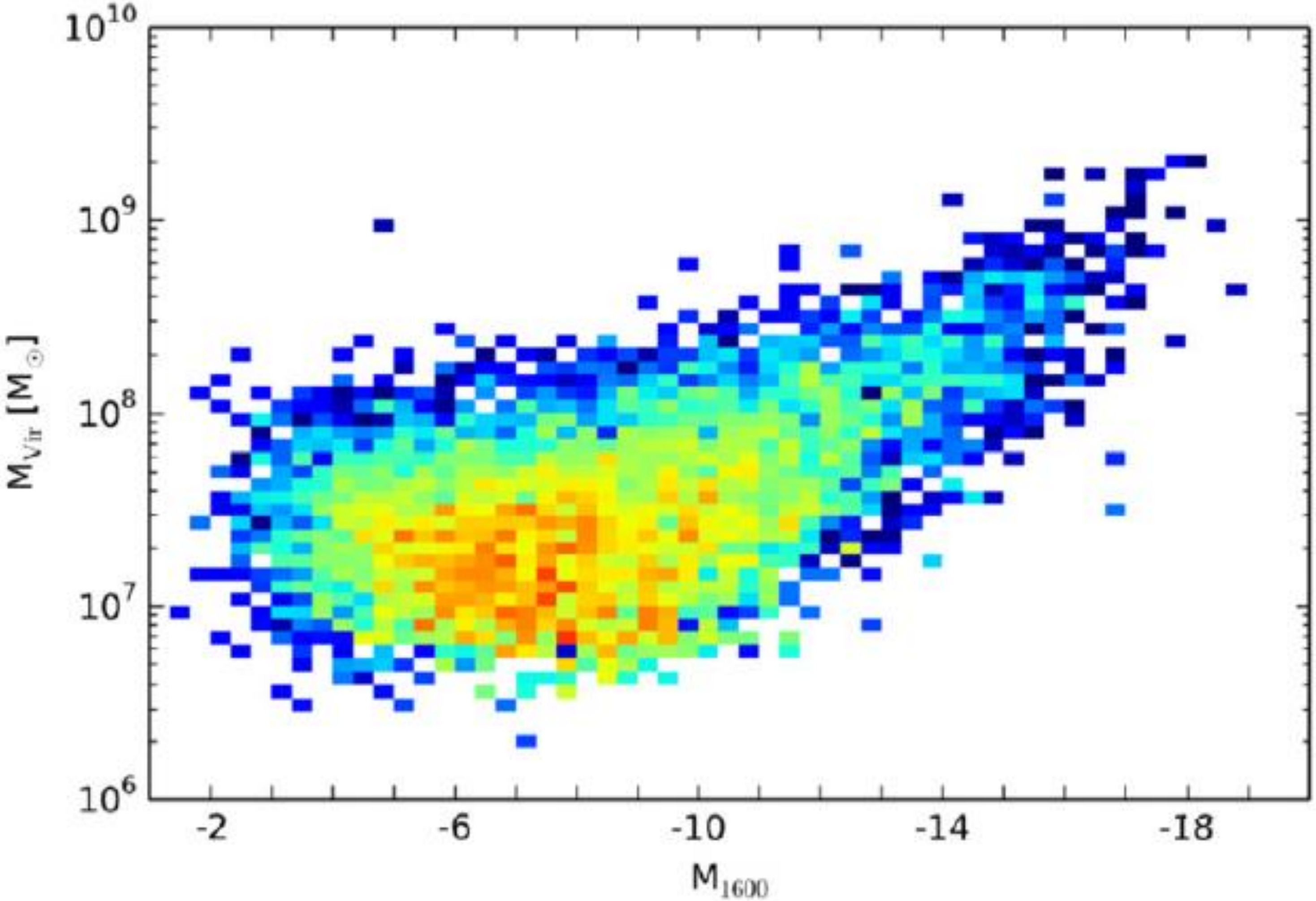
Sample size: ~3000



All halos at final redshift

O'Shea et al. (2015)

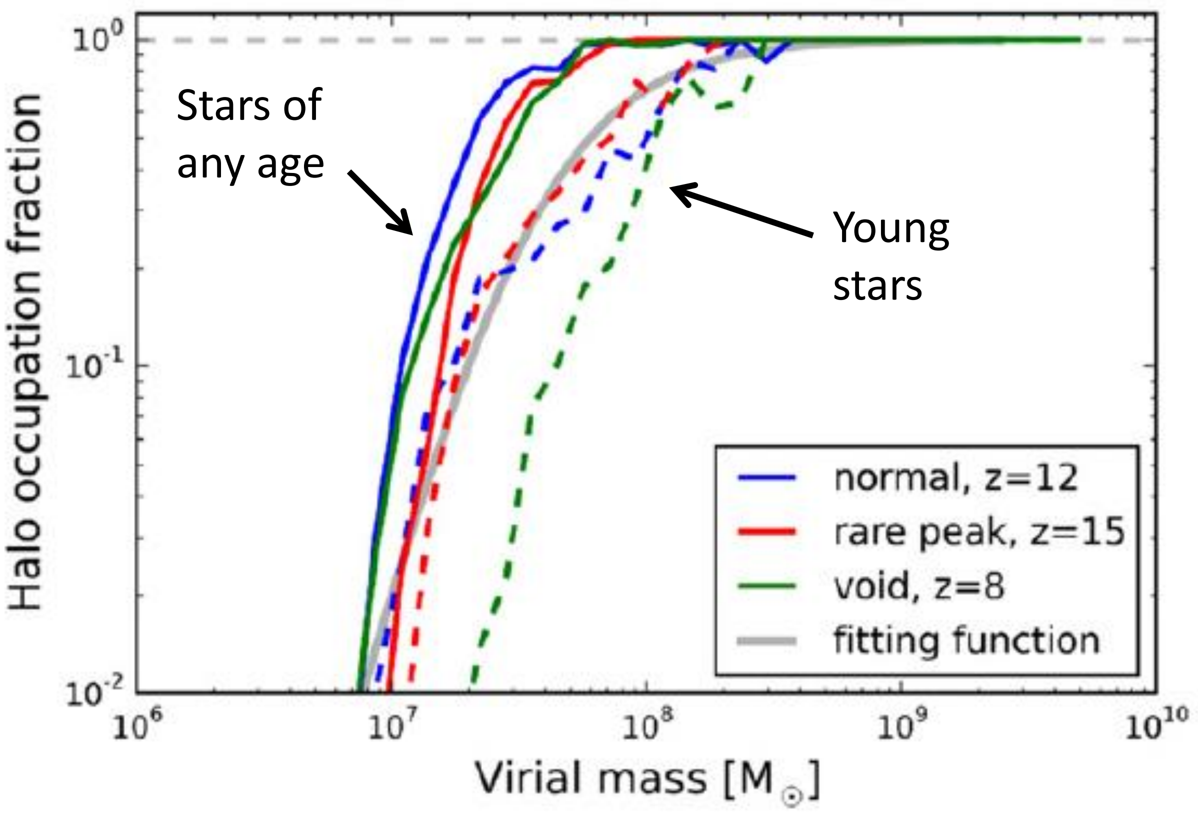
M_{1600} vs. Halo Mass



All halos at final redshift

O'Shea et al. (2015)

Not all halos form stars, and those that do form them episodically



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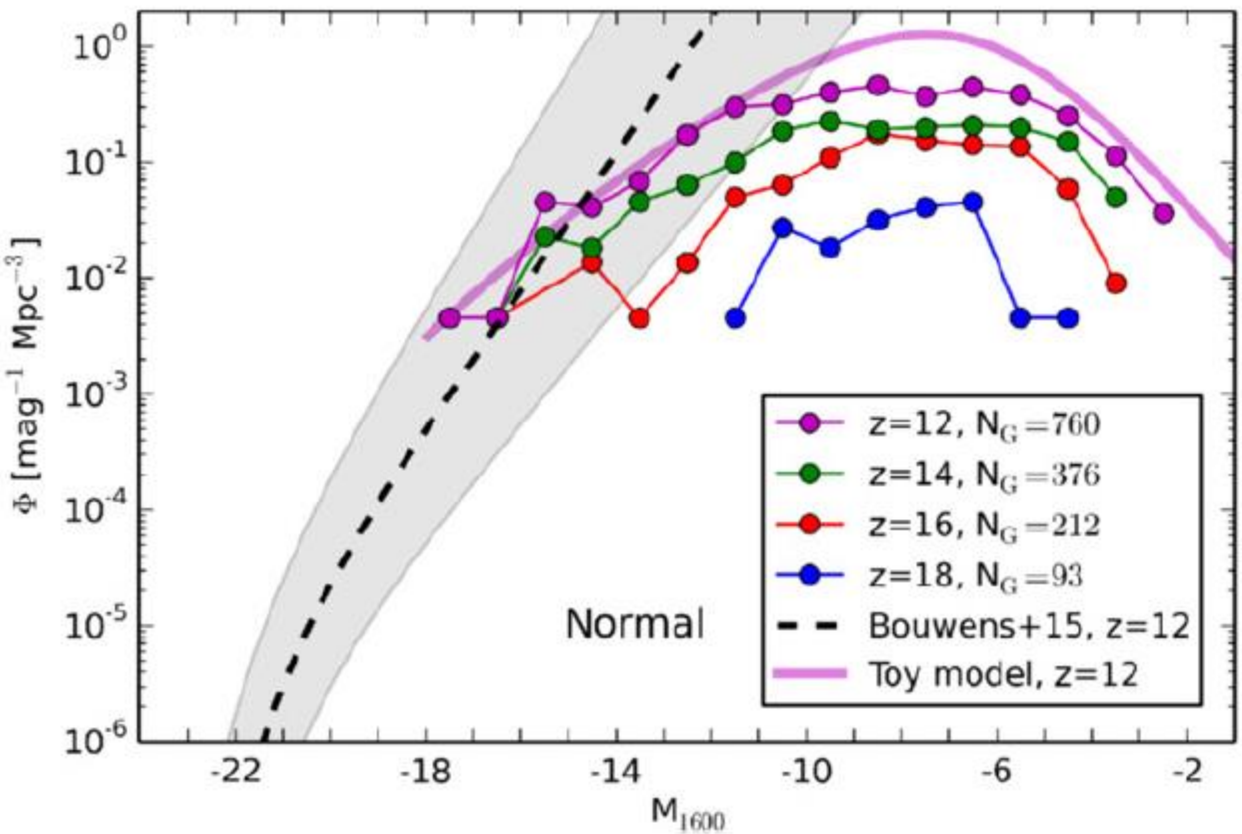
O'Shea et al. (2015)

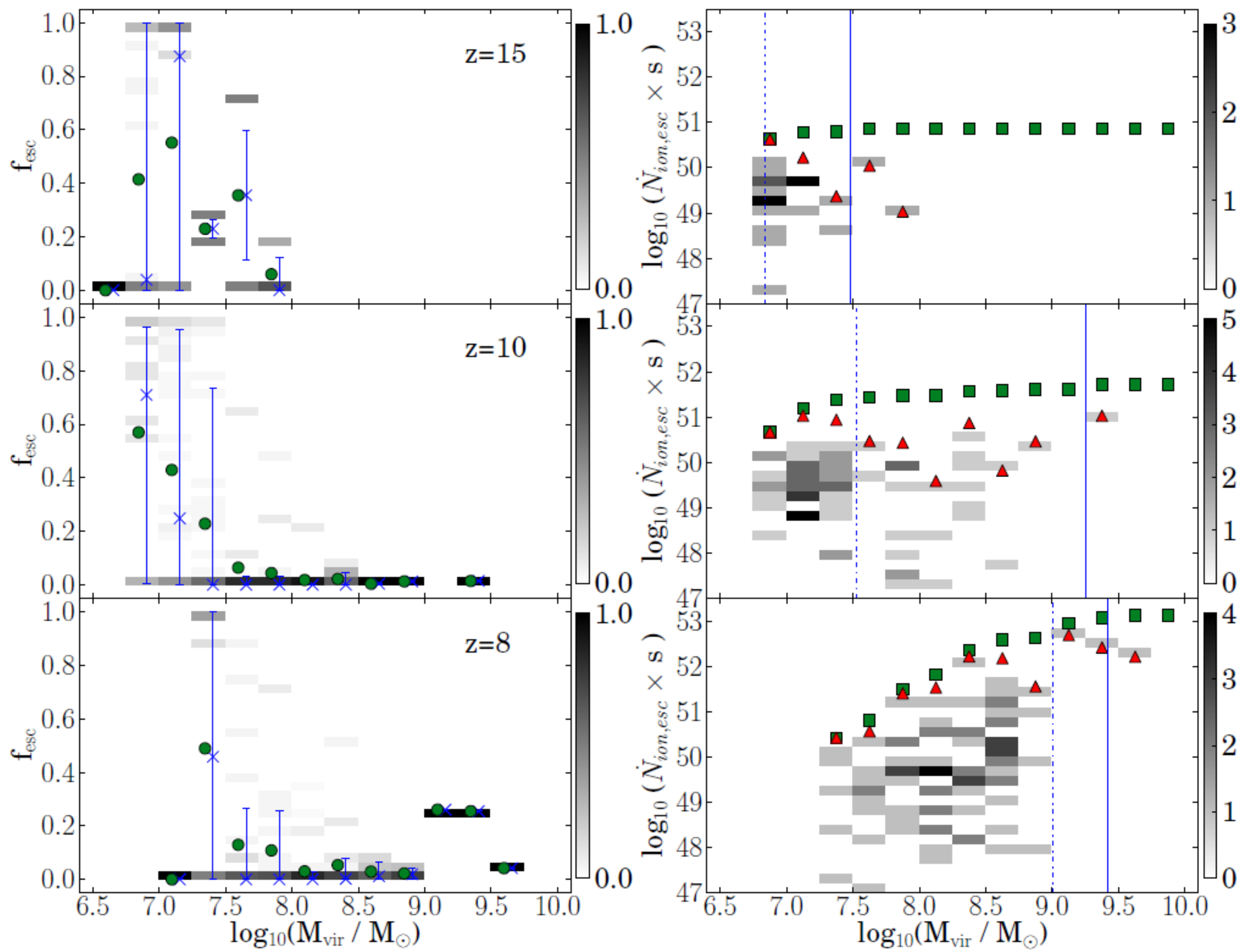
The UV luminosity function flattens



O'Shea et al. (2015)

Lower mass halos have higher escape fractions

FIRST GALAXY PROPERTIES AND UV ESCAPE FRACTIONS



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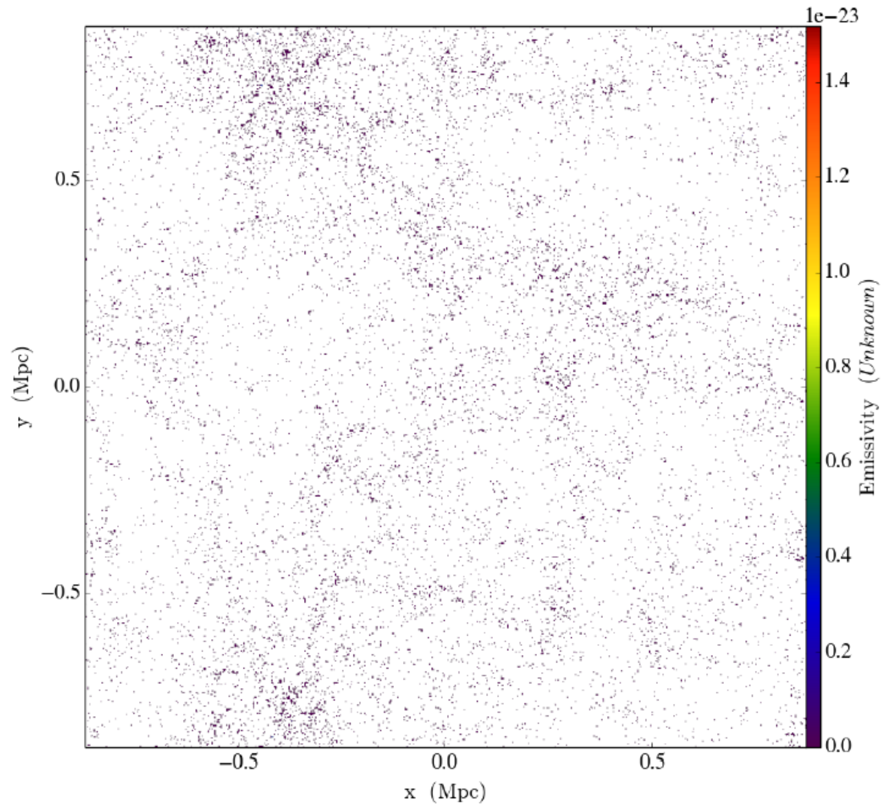
Xu et al. in prep.

Fully Coupled Cosmological RHD Simulation with Calibrated Sources

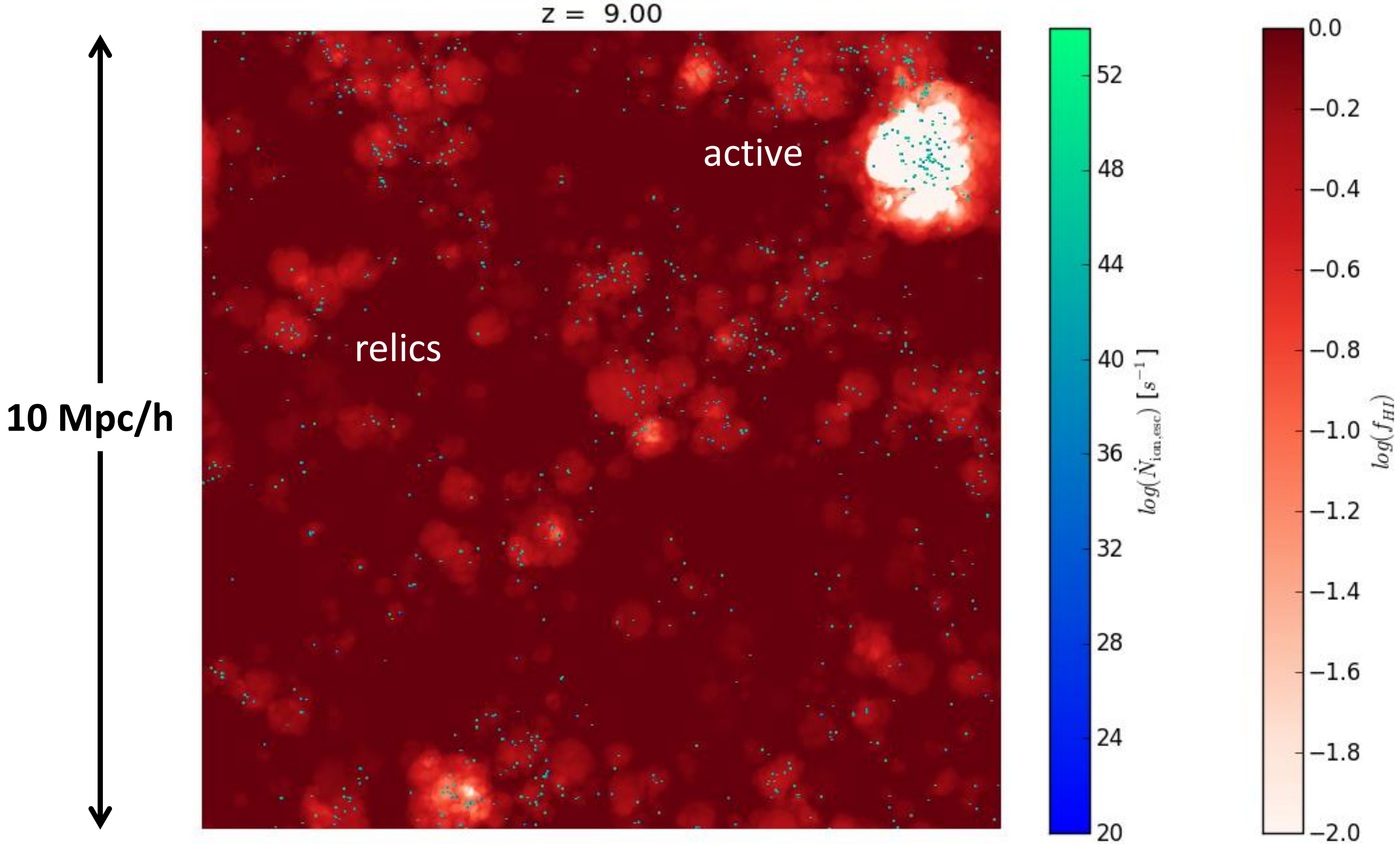
- 10 Mpc/h box
- 1152^3 particles/cells
  - m_{dm}=6.96 x 10^4 M_{sol}
  - HMF complete to M_h~10^7 M_{sol}
- Inline halo finding to source ionizing emissivity field
  - Probabilistic model for assigning emissivity to a halo derived from *Renaissance Simulations*
- Flux limited diffusion radiation transport coupled to multispecies hydro+Nbody (Norman+2015)

z=10



Norman et al., in prep

Early reionization is dominated by episodic star formation in low mass halos, resulting in an earlier onset and abundant relic HII regions



1152^3

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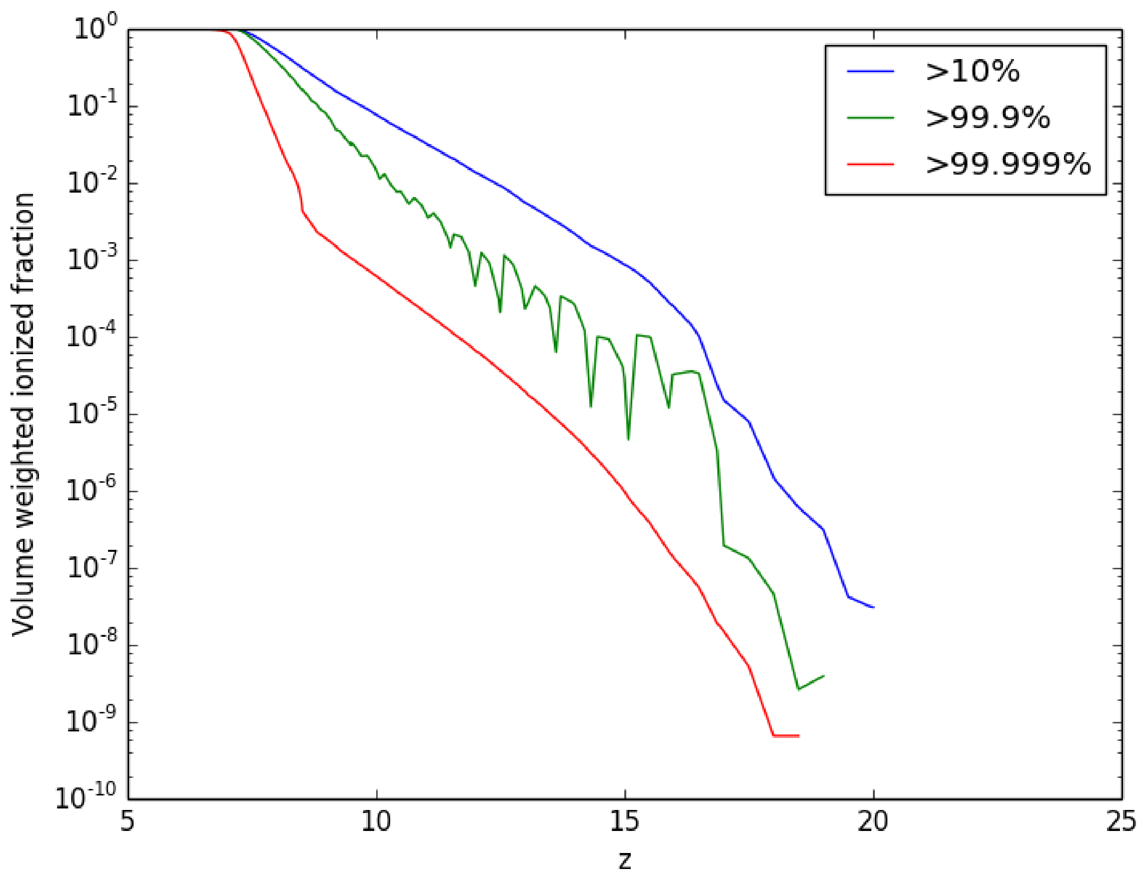
Norman et al., in prep

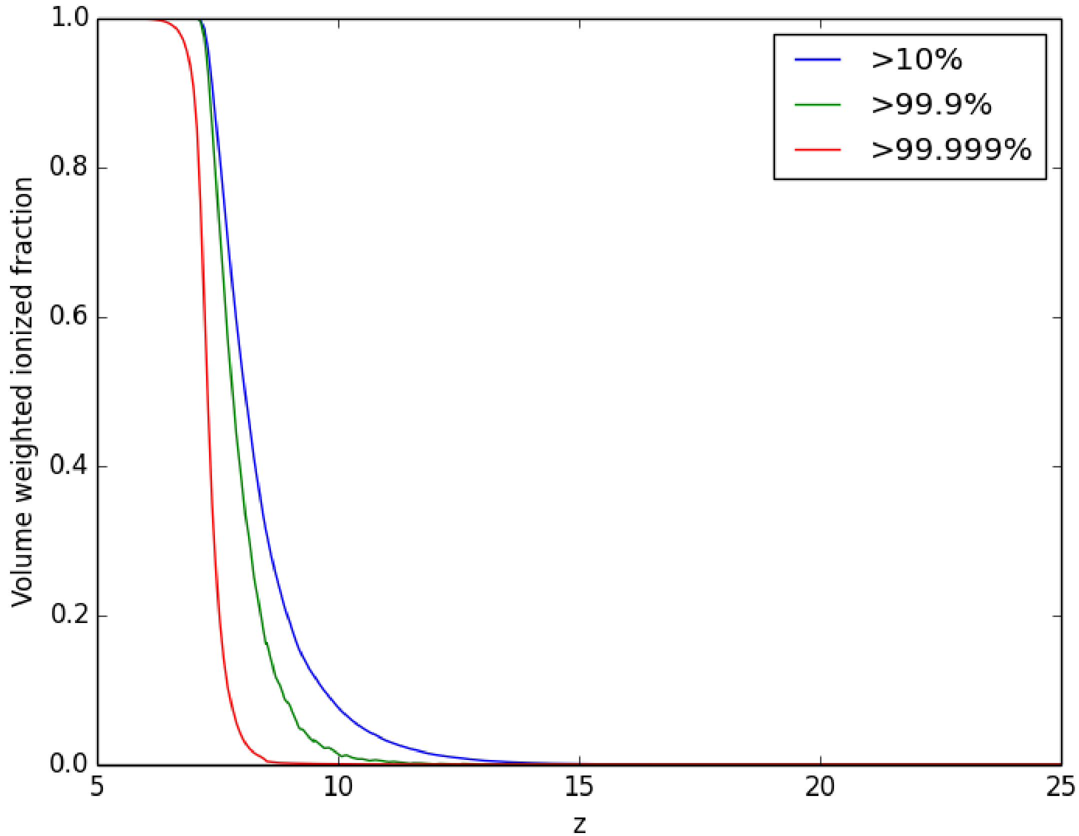
More than 10% of the volume is ionized above f_i=0.1 by z=10



All of the volume is ionized above f_i=0.999 by z=7.1

Norman et al., in prep

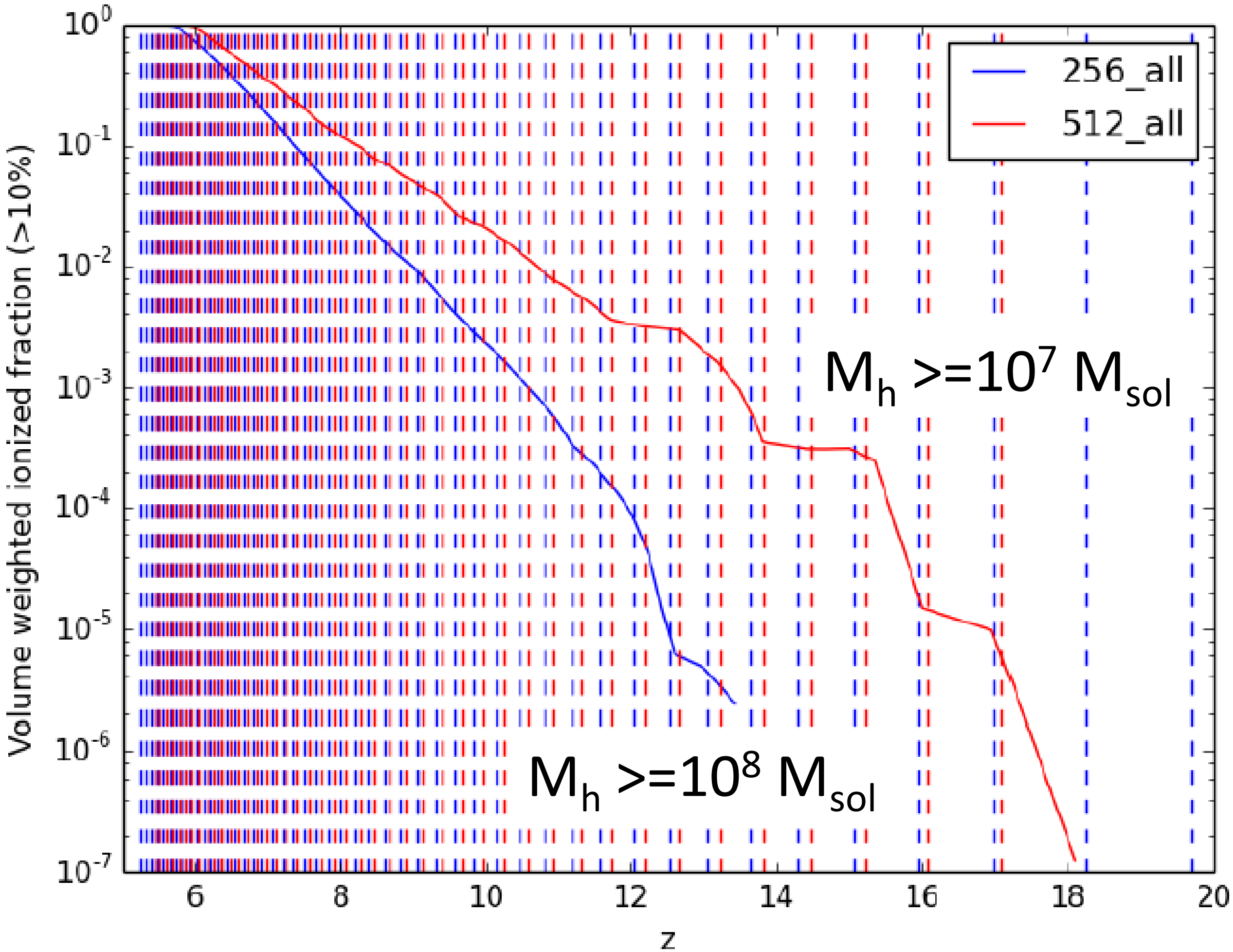
More than 10% of the volume is ionized above f_i=0.1 by z=10



All of the volume is ionized above f_i=0.999 by z=7.1

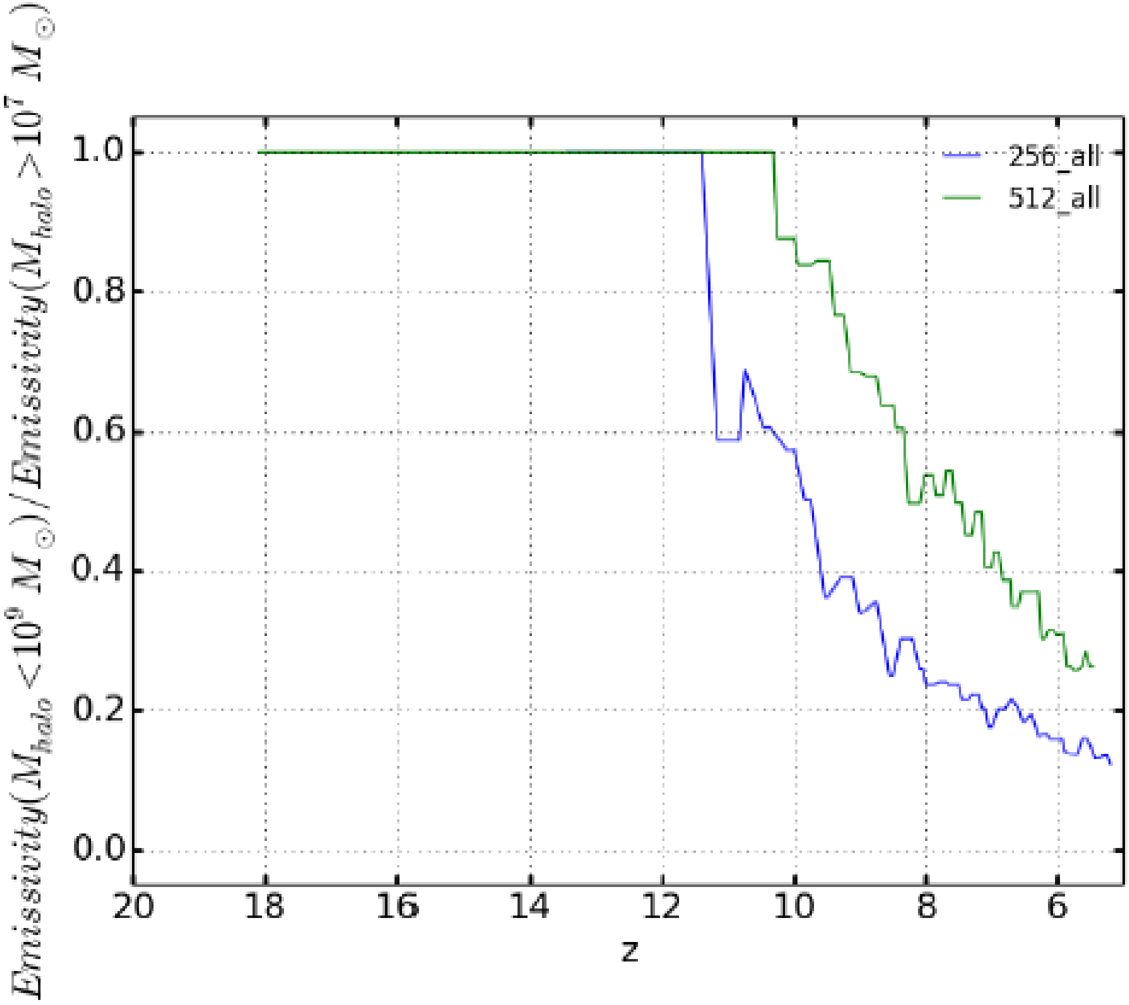
Norman et al., in prep

Contribution of halos btw. 10^7 and 10^8 M_{sol}: resolution study



Norman et al., in prep

Fraction of emissivity coming from halos below 10^9 M_{sol}



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Norman et al., in prep

Conclusions

- Low mass halos ($10^7 < M_h/M_{sol} < 10^8$) enriched by SNe from earlier star formation (Pop III and II) contribute significantly to *earliest phases of reionization* due to their
  - High number density
  - High ionizing escape fractions
  - Modest but non-zero star formation rates
- Bursty nature of star formation in such halos introduces a *stochastic nature* to early reionization
- *Late stages of reionization* are dominated by more massive halos which form stars continuously
- We have carried out a fully-coupled RHD simulation of reionization in a small volume which achieves overlap at z=7.1 and a tau(es)=0.069 with source luminosities and ionizing escape fractions measured from the *Renaissance Simulations*

Pop III metals may be more important that Pop III photons

Renaissance Simulations Fact Sheet

Configuration	
L_periodic (cMpc)	40
L_refined (cMpc)	6.6
N_p (effective)	4096^3
m_p (solar mass)	2.9×10^4
AMR levels	12
Δx min (pc)	19/(1+z)
z_init	99

Simulations	
Runs	7
Core-hrs	~100 M
Data (TB)	~70

Physics	
Cosmology	WMAP7
ICs	MUSIC
Code	ENZO
gas dynamics	9-species primord. 2 metal fields
Chemistry/cooling	9-species noneq. metal line
Radiative transfer	EUV, LW
Lyman-Werner bkgd	Yes
Pop III SF+FB	Wise+ 2012b
Pop II SF+FB	Wise+ 2012b

Star Formation Prescriptions

Wise et al. (2012a,b; 2014)

Pop III	[Z/H] <= -4
Particle	Individual Pop III star
Mass	IMF w/M_{char}=40 M_{sol}
thresholds	$f_{H2}>5\times10^{-4}$, $\delta_b>5\times10^5$, div(V)<0
Star properties	Schaerer (2002)
SN yields	Heger & Woosley (2003)

Pop III IMF

$$f(\log M)dM = M^{-1.3}\exp\left[-\left(\frac{M_{\rm char}}{M}\right)^{1.6}\right]dM$$

Metal-enriched	[Z/H] > -4
Particle	Molecular cloud/star cluster
Mass	> 1000 M_{sol}
thresholds	T<1000K, $\delta_b>5\times10^5$ div(V)<0
SF efficiency	0.07 f_{cold} inside MC radius
Radiative FB	6000 γ/baryon over 20 Myr
SN FB	6.8×10^{48} erg/s/Msol after 4 Myr
Mass recycling & enrichment	$\Delta m_{\rm ej} = \frac{0.25\,\Delta t\,M_\star}{t_0 - 4\,{\rm Myr}}$ $y = 0.005$

FLD versus MORAY

The Astrophysical Journal Supplement Series, 216:16 (24pp), 2015 January

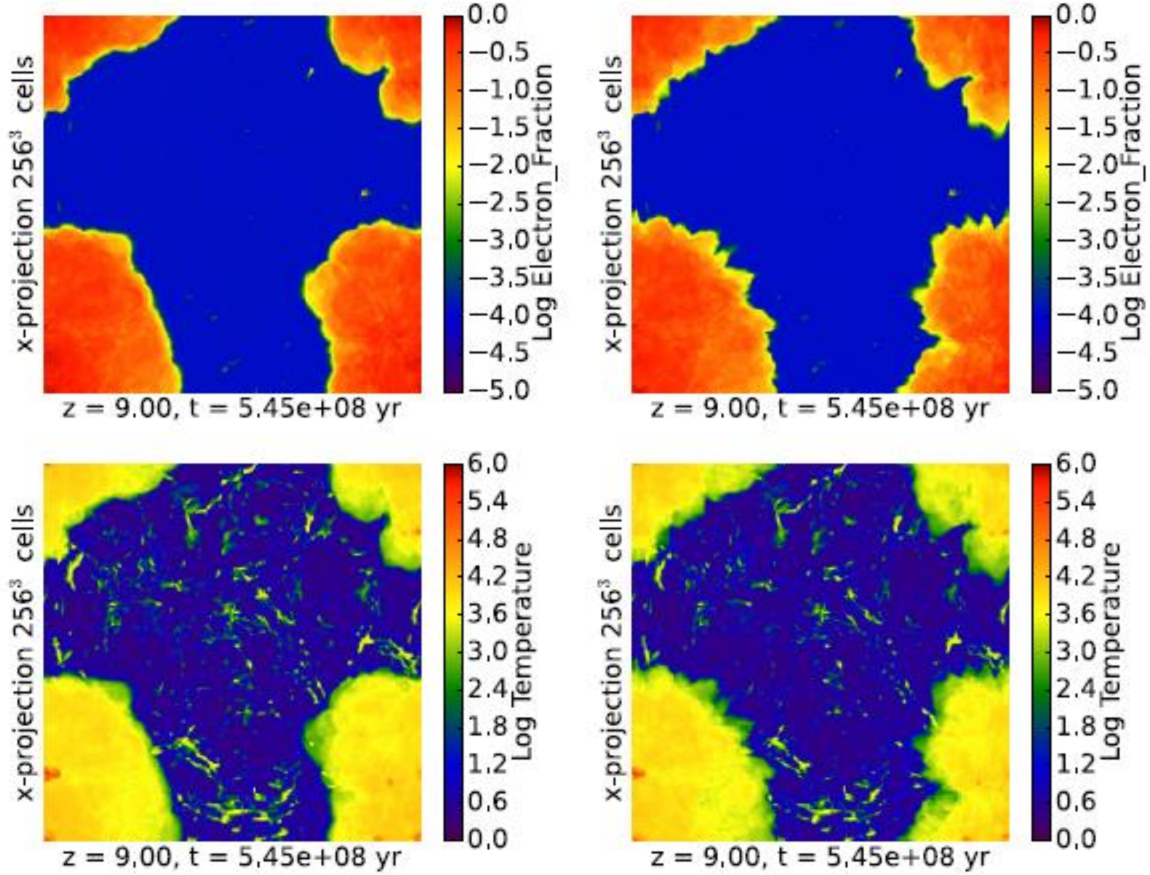
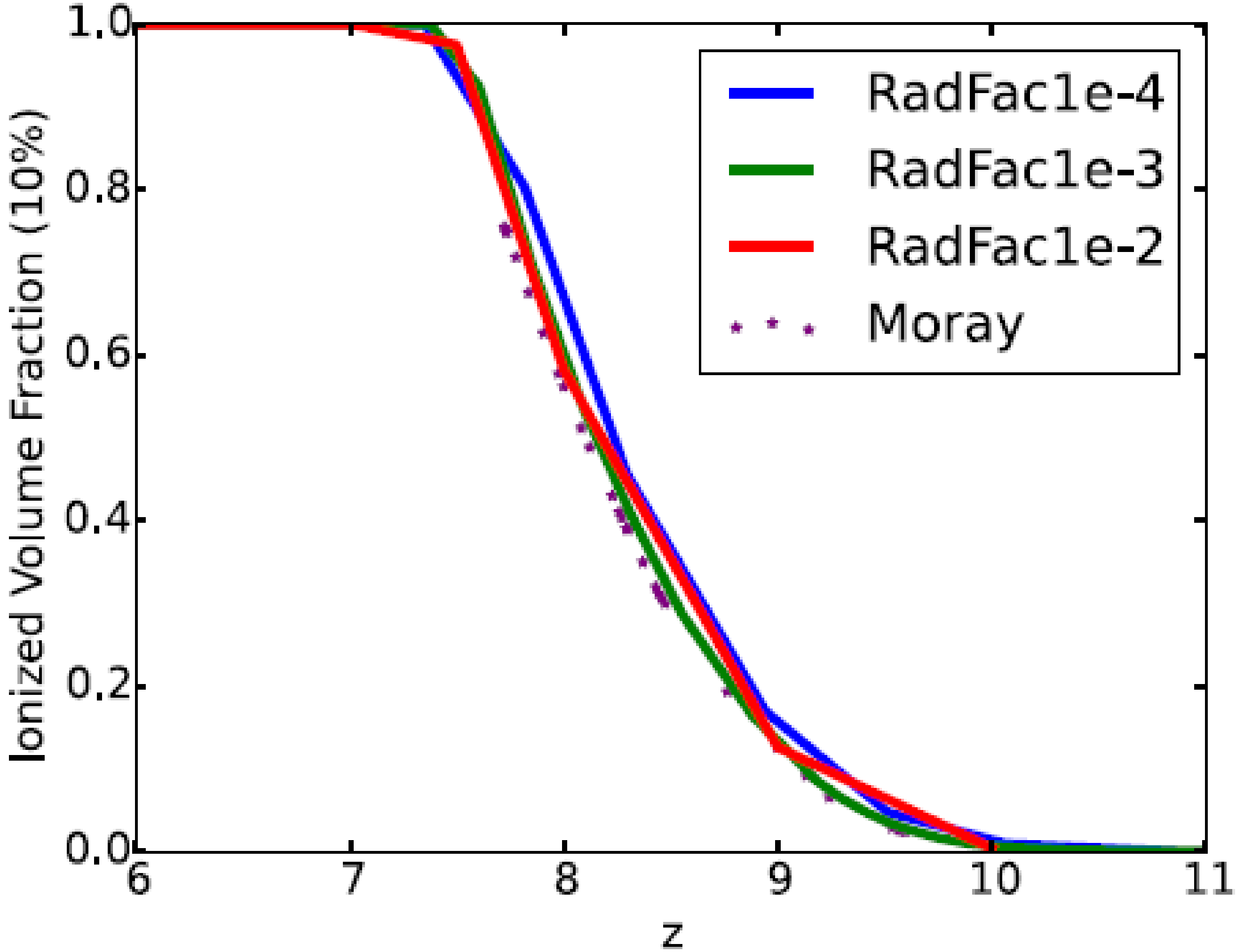


Figure 18. Same as Figure 17 except for $z = 9$.

Norman et al. (2015)

FLD versus MORAY



Norman et al. (2015)