Propelling Reionization with the Faintest Galaxies

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Motivating Questions

- What were the properties of the first galaxies?
- Which were the main sources of reionization?
- What fraction of ionizing photons escape from the first galaxies into the intergalactic medium?
- How many first galaxies will the HST Frontier Fields and JWST detect?
- How did the first stars affect early galaxy formation?
- How are the first galaxies connected to local dwarf galaxies?
- What is the origin of the observed metallicity floors in the Milky Way halo, dwarf galaxies, and damped Lyman-α absorbers?

Simulation Details

- Enzo: Adaptive Mesh Refinement (AMR)
- +Moray: Radiation Hydrodynamics

"Birth of a Galaxy" – 300 Pop III stars & 32 Galaxies

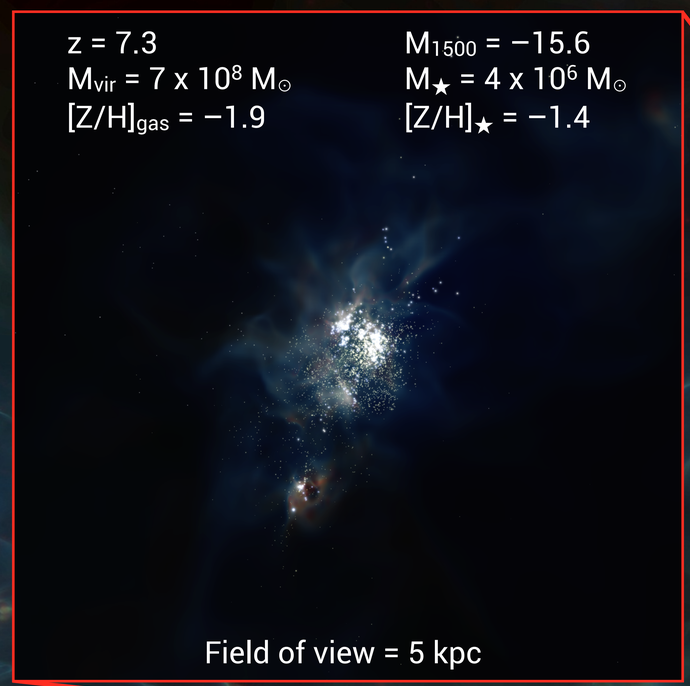
Small-box (1 Mpc)^3, ultra-high resolution (~0.1 pc), multiple physics models
Wise et al. (2012a,b), Wise et al. (2014)

- Distinct star formation and feedback modes for Population III and metal-enriched stars, modeled as single stars and stellar clusters, respectively.
- Non-equilibrium H, He, H_2 chemistry
- Metallicity-dependent radiative cooling rates
- Radiative feedback from Population III and young metal-enriched stars
- Pair-instability and Type II supernova (thermal and chemical) feedback
- Radiation pressure from Lyman continuum photons
- Pop III characteristic mass of 100 $M_\odot$

"Renaissance Simulation" – 35,000 Pop III stars & 3,000 Galaxies

Survey volume (40 Mpc)^3, high resolution (~1 pc), three zoom-in regions
Xu et al. (2013, 2014), Chen et al. (2014), Ahn et al. (2014)

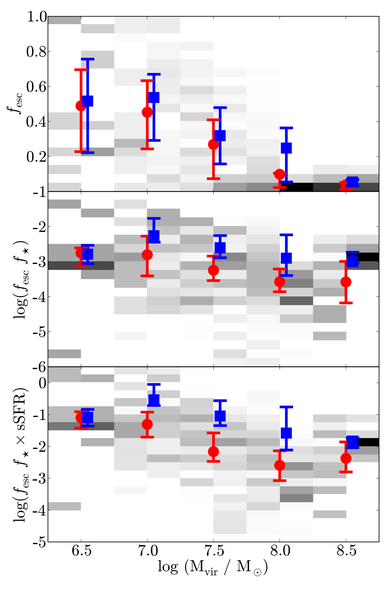
- Zoom-in regions focusing on an overdense region (∂ ~ 3), normal region (∂ ~ 1), and void (∂ ~ 0.5) region.
- Uses the most physical model of the "Birth of a Galaxy" simulations but with a Pop III characteristic mass of 40 $M_\odot$
- Over 20 million core-hours on NCSA's Blue Waters



Main Results

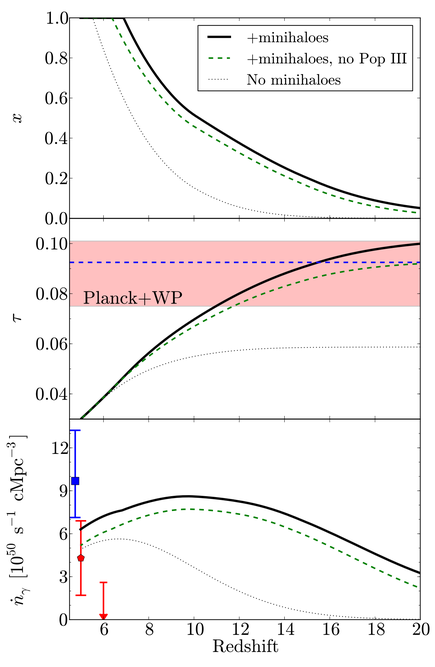
- Galaxies below the atomic cooling limit provide nearly 30% of the ionizing budget with a UV escape fraction of ~50%.
- Galaxies can form in halos with masses as small as 3 x 10^6 $M_\odot$ and stellar masses <10^4 $M_\odot$, only to have further star formation suppressed by internal and external radiative feedback.
- The galaxy luminosity function prior to reionization flattens at M_{UV} > −14.
- X-ray heating from highly-clustered regions of first galaxies may be detectable by SKA.

UV Escape Fraction



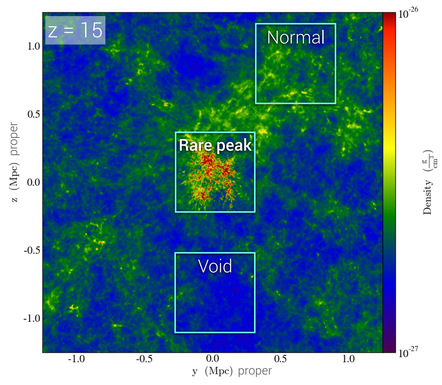
- The fraction f_{esc} of ionizing radiation escaping into the IGM is critical to constrain for reionization models.
- Galaxies can form in halos that only radiatively cool from H_2 and metal-line transitions (T_{vir} < 10^4 K).
- Halos with M_{vir} < 3 x 10^7 $M_\odot$ ($M_\star$ < 10^4 $M_\odot$) have f_{esc} ~ 50% and decrease in larger halos to 5-10%.
- Radiative and supernova feedback create low-density and ionized channels in which photons can easily escape.

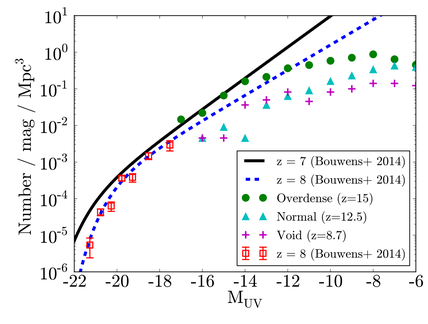
Contribution to Reionization

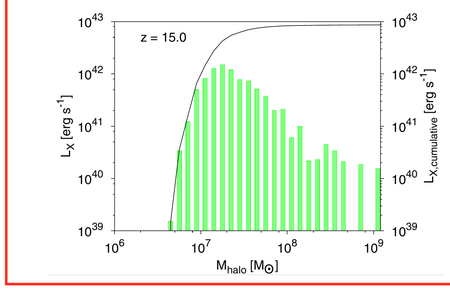


- The faintest galaxies in minihalos provide **~75%** ionizing photon budget at z = 15, resulting in an extended reionization history.
- In models without minihalos, the ionization fraction x ~ 0.1 at **z = 10**, compared to **0.5** when considering the faintest galaxies ($M_\star$ < 10^4 $M_\odot$) that form in our simulations.
- Matches **both** constraints from the WMAP Thomson scattering optical depth and the inferred UV background at z = 4-6.

"Renaissance Simulation" Results





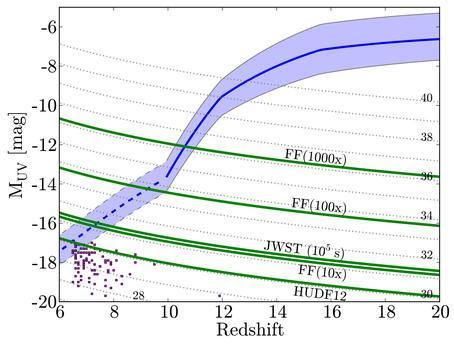


- Each zoom-in region (~6 comoving Mpc) is roughly a field of view for JWST/NIRCam.
- Halos below the atomic cooling limit (T_{vir} = 10^4 K) have a stellar mass–halo mass relationship of

$$\log M_\star = 3.5 + 1.3 \log(M_{vir} / 10^7\ M_\odot)$$

- The faint-end of the galaxy luminosity maintains a power-law before flattening at M_{UV} > −14.
- A non-monotonic relationship between metallicity and halo mass exist for the smallest galaxies, originating from pre-enrichment from Population III stars.
- A few halos above the atomic cooling limit are still chemically pristine and are candidates for the direct collapse scenario for massive black hole seed formation.
- Halos with masses 10^9 $M_\odot$ have 50 Population III stellar remnants on average, which has implications for the existence of high-mass X-ray binaries and intermediate-mass black holes.
- X-rays just below 1 keV from such objects are the most efficient in heating the surrounding IGM to over 100 K at z = 10 and some high-density regions up to 10^4 K.
- A combination of absorption and emission from a biased region (θ ~ 10') may be detected by SKA after a 1000-hr integration.

Observability



- The shaded region shows the absolute UV magnitude at 1500 Å for a typical galaxy contributing to reionization.
- The squares show galaxies detected in the HUDF12 campaign (McLure et al. 2012).
- The green lines show the sensitivity limits for HUDF12, the Frontier Fields, and JWST.
- These efforts will detect typical galaxies out to z = 8-10, whereas the bulk of the ionizing photons originate from fainter galaxies.

Also, see posters and talks by

Daegene Koh, Monday, #143.04
Kirk Barrow, Monday, #143.58
Qi Ge, Wednesday, #347.11
Chao Shi, Wednesday, #347.12
Ayçin Aykutalp, Wednesday, #305.06

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WHERE DISCOVERIES BEGIN
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