A Simulated Census of the First Galaxies

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Outline

- Radiation hydrodynamics simulations of the First Stars and Galaxies ($z \geq 7$)
  - "Birth of a Galaxy" simulation (30 galaxies; boxsize = 1 Mpc)
    - Star formation histories, galaxy properties, reionization, and luminosity functions
    - Wise et al. (2012ab, 2014)
  - "Renaissance" simulation (3000 galaxies; boxsize = 40 Mpc)
    - Remnants from the first stars, galaxy properties, luminosity functions – investigated in three zoom-in different environments
    - Xu et al. (2013, 2014); Chen et al. (2014); Ahn et al. (2015); O'Shea et al. (2015)
Observations in Local Dwarfs
Z-L Relation & Metallicity Distribution Functions

- In the least luminous galaxies, there exists some enrichment.
  - Where do these metals originate?
  - Were the protogalactic clouds pre-enriched by Population III stars?
  - What fraction of metals originate from internal star formation?
- Can we use these observations to constrain theories and simulations of dwarf galaxy formation at high-z?

Kirby+ (2011)
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Aoki+ (2014)
THE BIRTH OF A GALAXY
Numerical Approach
Cosmological Simulations – Enzo

- Requirements:
  - Follows the high-$z$ formation of a galaxy in a $\sim 10^9 \, M_\odot$ halo ($M_★ \sim 10^6-7 \, M_\odot$)
  - Resolves the smallest (Pop III) star-forming mini-haloes ($M \sim 10^5 \, M_\odot$)
  - Accurate model of star formation and feedback – smaller halos are more susceptible to feedback effects.

- Approaches:
  - Small-scale box (1 comoving Mpc$^3$); 2000 $M_\odot$ DM resolution
  - Adaptive mesh refinement (AMR) – 1 comoving pc maximal resolution
  - Distinct modes of Population II and III star formation and feedback
  - Radiative and supernovae feedback from both populations

Wise et al. (2012ab, 2014)
Pre-reionization dwarf galaxy properties
Radiative cooling agents

Wise et al. (2014)
FoV = 150 comoving kpc
$M_{\text{tot}}(z=7) = 10^9 \, M_\odot$
- Most massive halo \((10^9 M_\odot)\) at \(z = 7\)
- Undergoing a major merger
- Bi-modal metallicity distribution function
- 2\% of stars with \([Z/H] < -3\)
- Induced SF makes less metal-poor stars formed near SN blastwaves
First galaxy properties

- H2-cooling (inefficient SF)
- Lyα-cooling (efficient SF)

Wise et al. (2014)
UV escape fractions

- Red: non-weighted mean
- Blue: luminosity-weighted mean
- Halos with $M \leq 10^8 \, M_\odot$ contribute the most to the ionizing photon budget at $z > 12$.
  - High escape fractions
  - Able to form stars even without atomic cooling, i.e. $T < 10^4 \, K$.
- Escape fractions are highly variable.
“Renaissance” simulations
The First Galaxies
Renaissance Simulations

• Follow three regions (“rare peak”, mean, void) until $z \sim 10$.
  • 40 comoving Mpc box, 5 comoving Mpc zoom-in region
• At $z = 15$ in the rare peak region, there are
  • Three $>10^9 \, M_\odot$ DM halos; $>13,000$ Pop III stars
  • $\sim 3 \times 10^8 \, M_\odot$ of Pop II stars in $\sim 1,000$ dwarf galaxies

Xu, JW, Norman (2013)
Xu et al. (2014)
Chen, JW, et al. (2014)
Ahn et al. (2015)
$z = 15$

- **Normal**
- **Rare peak**
- **Void**

Density ($\frac{\rho}{\rho_c}$)
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Overdense “Rare Peak” Region

Projected Density
(scale: $3 \times 10^{-28} - 3 \times 10^{-24} \text{ g/cm}^3$)

Projected Temperature
(scale: $10^3 - 3 \times 10^4 \text{ K}$)

Xu, Wise, Norman (2013)
Xu et al. (2014)
Chen et al. (2014)
Ahn et al. (2015)
O’Shea et al. (2015)
The First Galaxies
High-z Galaxy Luminosity Functions

- Flattening at \( M_{UV} \approx -14 \)
- **Magenta** line: Can be matched with a “galaxy occupation fraction”
- FF = Unlensed Frontier Fields
- H = Hubble XDF
- J = JWST 10^5 s ultra-deep field
- Jx10 = 10x magnification

Observed at \( z=8 \) (e.g. Bouwens+ 2015; Finkelstein+ 2014)
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High-z Galaxy Environments

Detection by
Red: HUDF
Blue: JWST Ultra-deep
Green: JWST + 10x mag.

Summary

- Halos below the atomic cooling limit ($T_{\text{vir}} = 10^4$ K) can cool through metal-line transitions and form stars inefficiently.

- These low-mass halos can have high UV escape fractions up to 50%.

- Escape fractions are highly variable in time and angle and are correlated with SFR with some delay.

- UV Galaxy luminosity functions flatten at $M_{1600} \gtrapprox -14$ because not all low-mass halos host new star formation.

- Its normalization can vary up to an order of magnitude from cosmic variance.