Formation of the first galaxies

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Overview

- Initial conditions
- Protogalaxies
- Assembly of the first galaxies

Initial conditions

Background cosmology

- Lambda Cold Dark Matter (ΛCDM) model

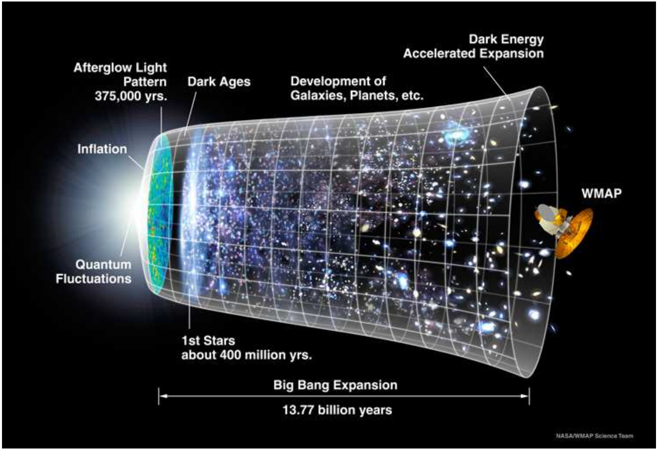

Figure 1: Cosmic timeline (Source: NASA/WMAP Science Team)

Initial conditions

Background cosmology

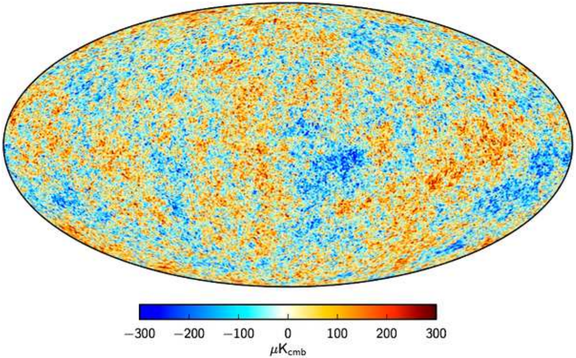

Figure 2: Cosmic microwave background (CMB)
(Source: WMAP/PLANCK Collaboration)

Initial conditions

Growth of fluctuations

- Density fluctuations = seeds for galaxies
- Linear growth of contrast in perturbation theory:

$$\rho(t, \mathbf{x}) = \langle \rho(t) \rangle \big(1 + \delta(t, \mathbf{x})\big)$$
$$\ddot{\delta}(t) + 2H(t)\dot{\delta}(t) = 4\pi G \langle \rho(t) \rangle \delta(t, \mathbf{x}).$$

Early protogalaxies

Dark matter halos

- Non-linear regime: Collapse under own gravity
- Virialization at $t \sim 2t_{\mathrm{ta}}$
- Cosmic web structure

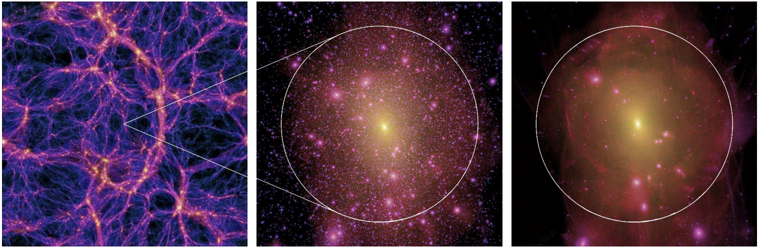

Figure 3:
Left: Simulated DM density in a $(137\mathrm{Mpc})^2$ frame at $z = 0$.
Middle/Right: Zoom-in on halo for CDM and WDM (circle: $r_{50} \sim 1\mathrm{Mpc}$)
(Source: Aquarius/Springel et al., Lovell et al.)

Early protogalaxies

Dark matter halos

- Halo potential wells bind primordial gas
- Halos/gas clouds grow by accretion and merging
- They are the sites of galaxy formation
  - But: Suppression of baryonic structure below Jeans scale:

$$\lambda_J \sim c_s/\sqrt{G\rho_\mathrm{b}}$$

  - $\hat{=}$ Suppression below Jeans mass:

$$M_\mathrm{J}(z) = \frac{4\pi}{3}\left(\frac{\lambda_\mathrm{J}}{2}\right)^3 \rho_\mathrm{b}(z).$$

  - First baryonic structures with $M > M_\mathrm{J}$: "minihalos" at $z \sim 20 - 30$
  - Formation of Pop. III stars in halos with $M \sim 10^6 M_\odot$

Early protogalaxies

Evolution of primordial gas

- Gas evolution more complex:
  - Gravity
  - Hydrodynamics
  - Radiative processes
  - Chemical reactions
- Full details not understood yet
- Tentative picture from simulations & semi-analytical models

Early protogalaxies

Accretion and shock-heating

- Two (co-existing) modes of accretion:
- Hot mode (High mass halos $M \gtrsim 10^{10} M_{\odot}$)
  - Gas shock-heated to the virial temperature:

$$\frac{3}{2} k_{\mathrm{B}} T_{\mathsf{vir}} \sim \frac{G M_{\mathsf{vir}} \mu m_{\mathrm{H}}}{R_{\mathsf{vir}}}$$

  - approximately confirmed by hydrodynamical simulations
- Cold mode (Low mass halos)
  - Cooling time short: $t_{\mathrm{cool}} \ll t_{\mathrm{dynamical}}$
  - Pressure support removed $\rightarrow$ Virial shock unstable
  - Gas falls ballistically to center, radiates at lower T

Early protogalaxies

Accretion and shock-heating

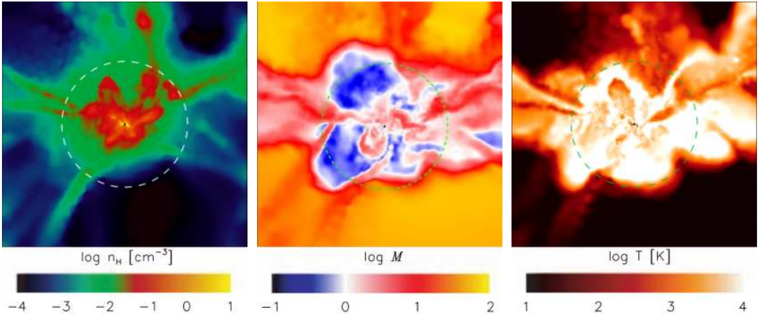

Figure 4: Accretion on simulated galaxy at $z \gtrsim 10$ (circle: r_{vir}).
Left: Hydrogen number density n_H
Middle: Mach number M
Right: Gas temperature T.
(Source: Greif et al.)

Early protogalaxies

Gas cooling

- Required for star formation
- Responsible for disc formation
- Cooling processes:
  - $T_{\text{vir}} \lesssim 10^7\mathrm{K}$: Line cooling: Decay of atomic/molecular energy quantum states excited by collisions;
  - $T_{\text{vir}} \gtrsim 10^7\mathrm{K}$: Bremsstrahlung;
  - $z \gtrsim 10$: Inverse Compton scattering between ions and CMB photons.

Early protogalaxies

Gas cooling

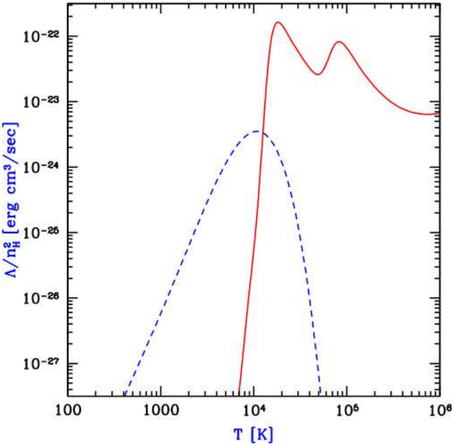

Figure 5: Red: Cooling rate for atomic gas.
Blue: Additional contribution of molecular cooling.
(Source: Loeb)

Early protogalaxies

Gas cooling

- Cooling inefficient at high redshifts:
- $T_{\text{vir}} \ll 10^4\mathrm{K}$ insufficient to excite primordial atoms
- Cooling relied on rare $\mathrm{H_2}$ formed by:

$$\mathrm{H} + \mathrm{e}^- \rightarrow \mathrm{H}^- + h\nu$$
$$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H_2} + \mathrm{e}^-$$

Early protogalaxies

Feedback and (re-)heating

- Early star formation self-regulated:
  - Ionizing + H_2-dissociating UV background radiation (Lyman-Werner feedback)
  - Contribution by SN and AGN feedback
  - Low mass early halos couldn't retain reheated gas
- However: Ionization stimulates H_2 production
- Transition between stellar generation driven by chemical feedback

Early protogalaxies

Feedback and (re-)heating

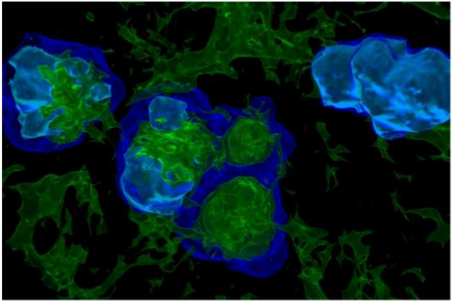

Figure 6: Radiative feedback around simulated forming Pop. III stars.
Blue: Ionized bubbles
Green: Molecule abundance
(Source: Johnson et al./TACC)

Assembly of the first galaxies

Defining characteristics

- Many star system embedded in dark halo
- Star formation survives feedback

Assembly of the first galaxies

Atomic cooling halos

- Mass scale for ongoing star formation = ?
- Promising candidate: Atomic cooling halos:

$$\begin{aligned} M &\sim 10^7 M_\odot \\ T_{\mathsf{vir}} &\sim 10^4 \mathrm{K} \\ z &\sim 10 - 15 \end{aligned}$$

Assembly of the first galaxies

Atomic cooling halos

- Partial ionization stimulates $\mathrm{H_2}$ and HD production:

$$\mathrm{H} + \mathrm{e}^- \rightarrow \mathrm{H}^- + h\nu$$
$$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H_2} + \mathrm{e}^-$$
$$\mathrm{D}^+ + \mathrm{H_2} \rightarrow \mathrm{HD} + \mathrm{H}^+$$

- Enhanced cooling down to $T_{\mathrm{CMB}} = 2.7(1+z)$ for $X_{\mathrm{HD}} \gtrsim 10^{-6}$

Assembly of the first galaxies

Star formation history

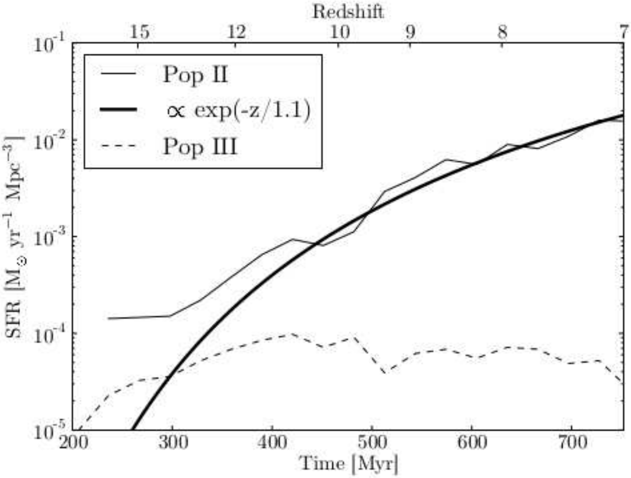

Figure 7: Cosmic SFR for Pop. II (solid) and Pop. III (dashed) (Source: Wise et al.)

Assembly of the first galaxies

The role of mergers

- Merger history has important influence on galaxy formation:

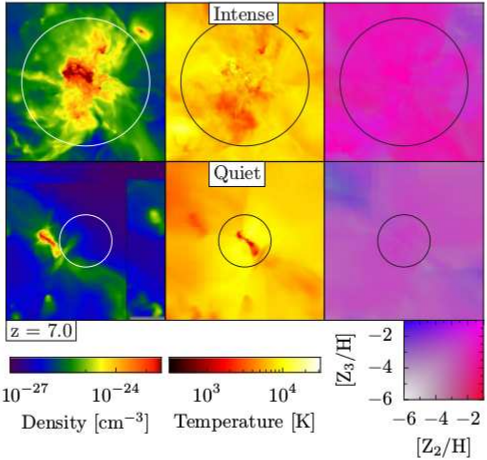

Figure 8: Comparison of quantities with and without major merger series between $z = 10$ and $z = 7$. Circle: $r_{200} \sim 4\text{kpc}$. (Source: Wise et al.)

Summary

- Stars & galaxies form in dark halos
- Cooling was inefficient at early times
- Radiative and mechanical feedback dissolves dark minihalos
- First galaxies assembled in atomic cooling halos