Galaxy Formation: Introduction

Galaxy Formation

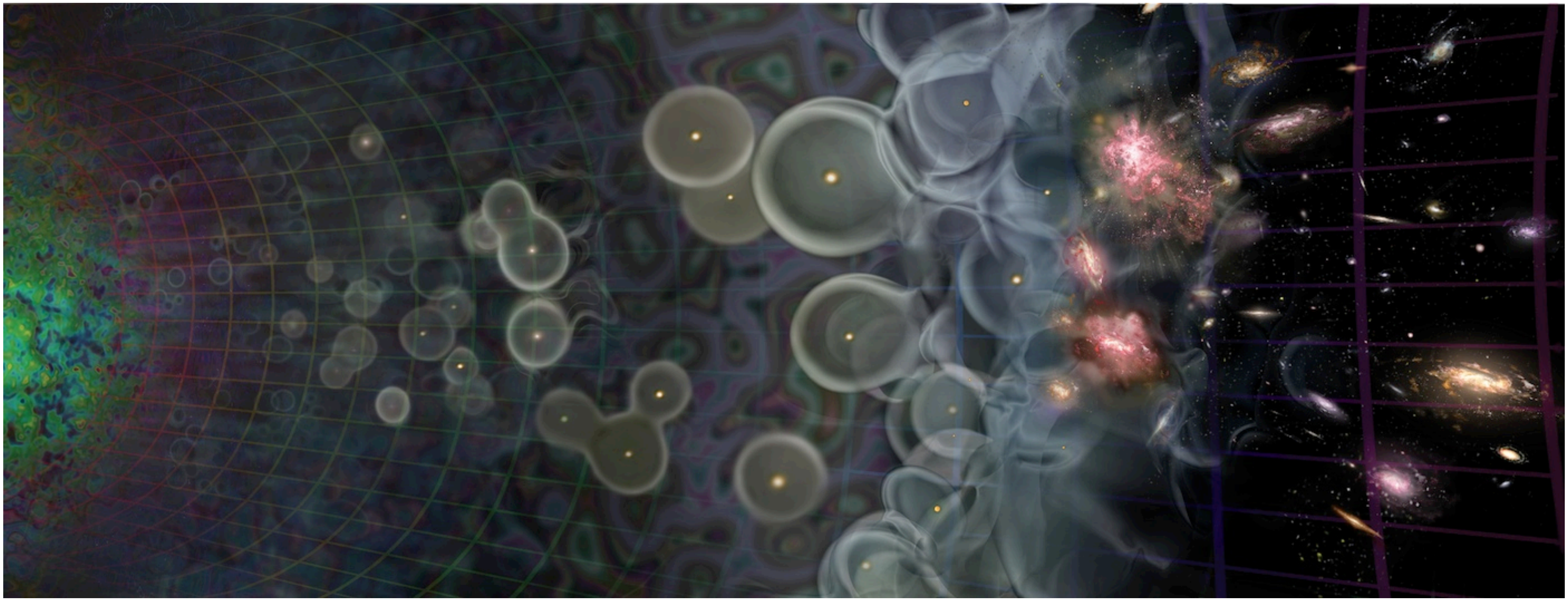
- The early stages of galaxy evolution - but there is no clear-cut boundary, and it also has two principal aspects: assembly of the mass, and conversion of gas into stars
- Must be related to large-scale (hierarchical) structure formation, plus the dissipative processes - it is a very messy process, much more complicated than LSS formation and growth
- Probably closely related to the formation of the massive central black holes as well
- Generally, we think of massive galaxy formation at high redshifts ($z \sim 3$ - 10, say); dwarfs may be still forming now
- Observations have found populations of what must be young galaxies (ages < 1 Gyr), ostensibly progenitors of large galaxies today, at $z \sim 5$ - 7
- The frontier is now at $z \sim 7$ - 20, the so-called Reionization Era

A General Outline

- The smallest scale density fluctuations keep collapsing, with baryons falling into the potential wells dominated by the dark matter, achieving high densties through cooling
  - This process starts right after the recombination at $z \sim 1100$
- Once the gas densities are high enough, star formation ignites
  - This probably happens around $z \sim 20$ - 30
  - By $z \sim 6$, UV radiation from young galaxies reionizes the unverse
- These protogalactic fragments keep merging, forming larger objects in a hierarchical fashion ever since then
- Star formation enriches the gas, and some of it is expelled in the intergalactic medium, while more gas keeps falling in
- If a central massive black hole forms, the energy release from accretion can also create a considerable feedback on the young host galaxy

An Outline of the Early Cosmic History

(illustration from Avi Loeb)



Recombination: Release of the CMBR

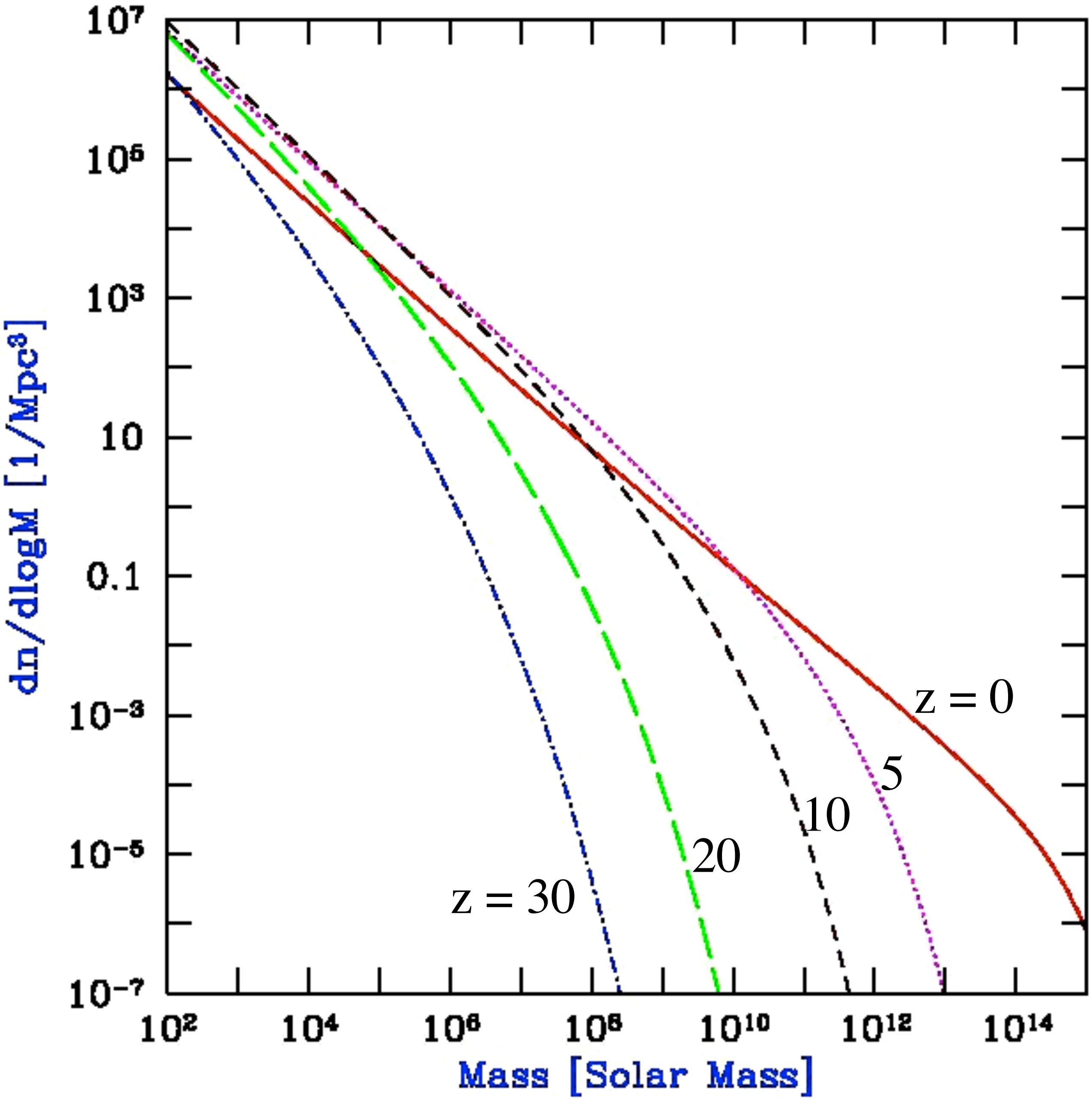
Dark Ages: Collapse of Density Fluctuations

Reionization Era: The Cosmic Renaissance

Galaxy evolution begins

The Evolving Dark Halo Mass Function

(Press-Schechter)



Barkana & Loeb

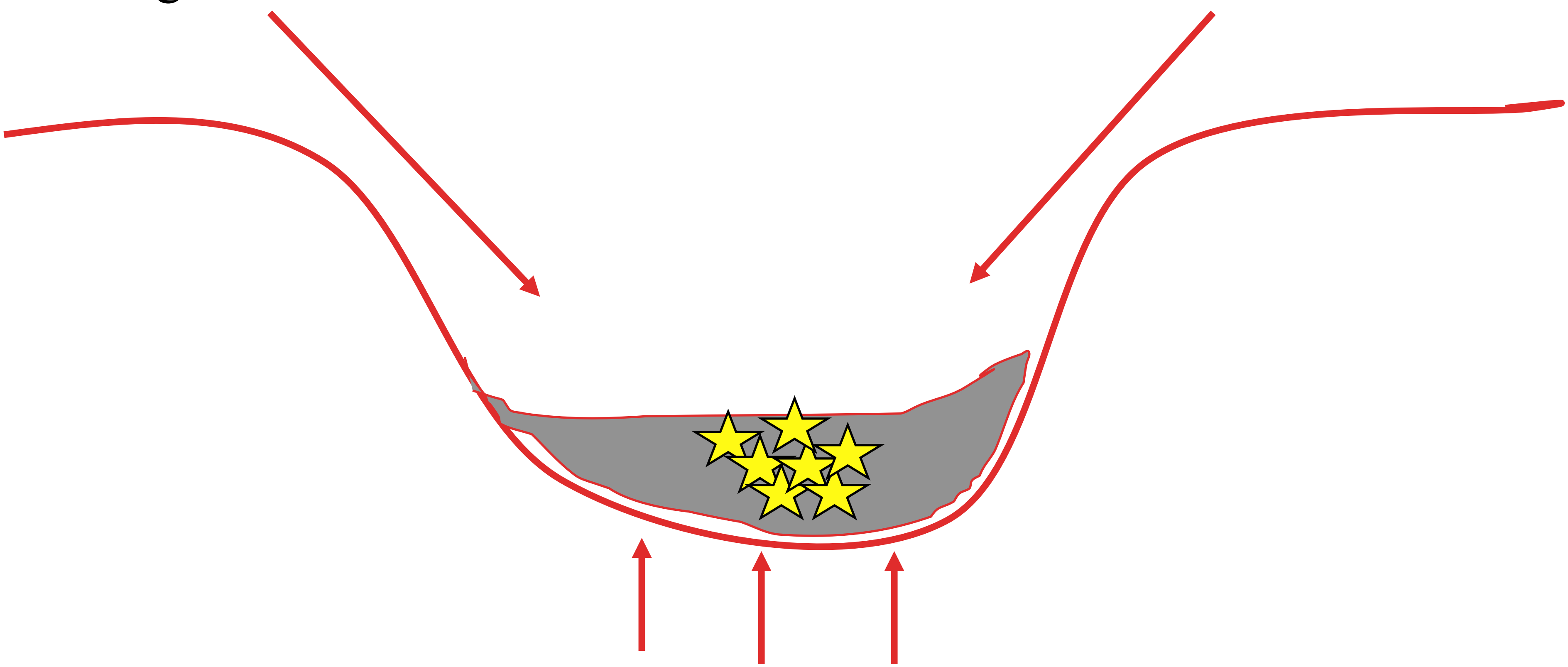
Physical Processes of Galaxy Formation

- Galaxy formation is actually ***a much messier problem than structure formation.*** In addition to gravity and build-up of host dark halos (fairly well understood) we need to add:
  - Shock heating of gas
  - Cooling of gas into dark halos
  - Formation of stars (also not a well understood process!) from the cold gas
  - The evolution of the resulting stellar population
  - Feedback processes generated by the ejection of mass and energy from evolving stars
  - Production and mixing of heavy elements (chemical evolution)
  - Effects of dust obscuration
  - Formation of black holes at galaxy centers and effects of AGN emission, jets, etc.

  … etc., etc., etc.

Recipe for Galaxy Formation

Gas flows from
intergalactic medium



Potential well formed by gravity of (primarily) dark matter

What is a Protogalaxy?

Not a very well defined answer; some possibilities:

- Galaxy in the first X % or Y yrs of its life (X=?, Y=?)
- Galaxy which has formed X % of its stars (X=?)
- Galaxy which has assembled X% of its final mass (X=?)
- Initial density fluctuation which has not formed any stars yet
- Galaxy at a very high redshift $z > Z$ (Z=?)

… etc., etc.

- Generally we think of the progenitors of massive galaxies today, roughly in the first Gigayear of their life, i.e., at $z > 5$ish
- We certainly expect vigorous star formation to be occuring, and therefore a luminous object

Energy Release From Forming Galaxies

Galaxies collapse and cool. The release of the binding energy is:

$$|E_{bind,gal}| \simeq M_{cool} \langle V_{3d}^2 \rangle \simeq$$

$$\simeq 1.2 \times 10^{59} \mathrm{erg} \times (M_{cool}/10^{11} M_\odot)\ (V_{3d}/250 \mathrm{km\ s^{-1}})^2$$

where M_{cool} is the total mass which can cool radiatively

Binding energy was also released by collapsing protostars, and is of a comparable magnitude:

$$|E_{bind,\star}| \simeq G\ M_{\Sigma\star} \langle M_\star \rangle / \langle R_\star \rangle \simeq$$

$$\simeq 4 \times 10^{58} \mathrm{erg} \times (M_{\Sigma\star}/10^{10} M_\odot)\ (\langle M_\star \rangle / M_\odot)\ (R_\odot / \langle R_\star \rangle)$$

where $M_{\Sigma\star}$ is the total mass converted to stars in the PG phase, $\langle M_\star \rangle$ is the average star mass, and $\langle R_\star \rangle$ is the average star radius.

Energy Release From Forming Galaxies

Probably the most important energy source in PGs was the nuclear burning in initial starbursts:

$$E_{nuc} \simeq \epsilon \, M_{\Sigma\star} \, c^2 \, \Delta X \simeq 10^{60}\mathrm{erg} \, (\epsilon/0.001) \, (M_{\Sigma\star}/10^{10} M_\odot) \, (\Delta X/0.05)$$

where $M_{\Sigma\star}$ is the total mass burned in stars in the PG phase, $\epsilon \simeq 1 \ \mathrm{Mev}/m_p c^2 \simeq 0.001$ is the average net efficiency of nuclear reactions in stars, and $\Delta X \simeq \Delta Z + \Delta Y \simeq 0.05$ is the fraction of the hydrogen converted to helium and metals.

Note: the mean metallicity of old stellar populations is ~ Solar, i.e., about 1.7% by mass; and you get ~ 3-5 g of He (ΔY) for each 1 g of metals (ΔZ) produced in stellar burning

Finally, early active galactic nuclei may have been important contributors to the energy budget in at least some, and possibly all PGs. Their energy release could have rivaled other mechanisms. Taking a rough guess for the average luminosity $\langle L_{bol} \rangle$ and the duration of the active episode Δt:

$$E_{AGN} \sim \langle L_{bol} \rangle \, \Delta t \simeq 1.2 \times 10^{60}\mathrm{erg} \, (\langle L_{bol} \rangle/10^{10} L_\odot) \, (\Delta t/10^8 \mathrm{yr})$$

Next:

Galaxy Formation: Observations