The first galaxies

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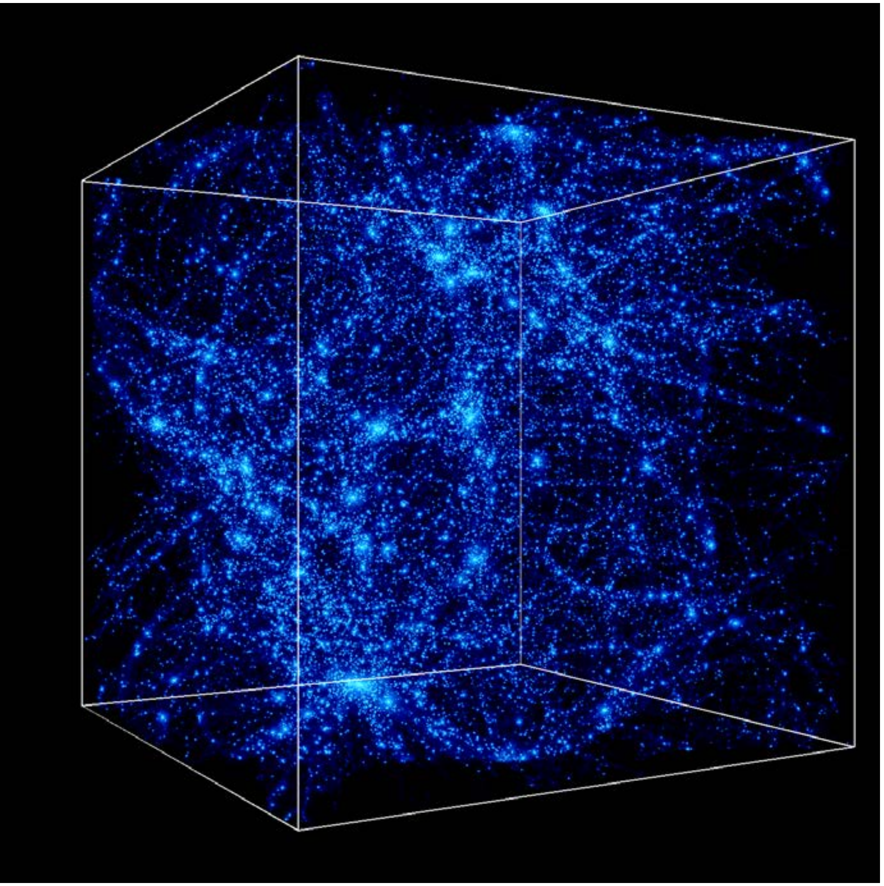
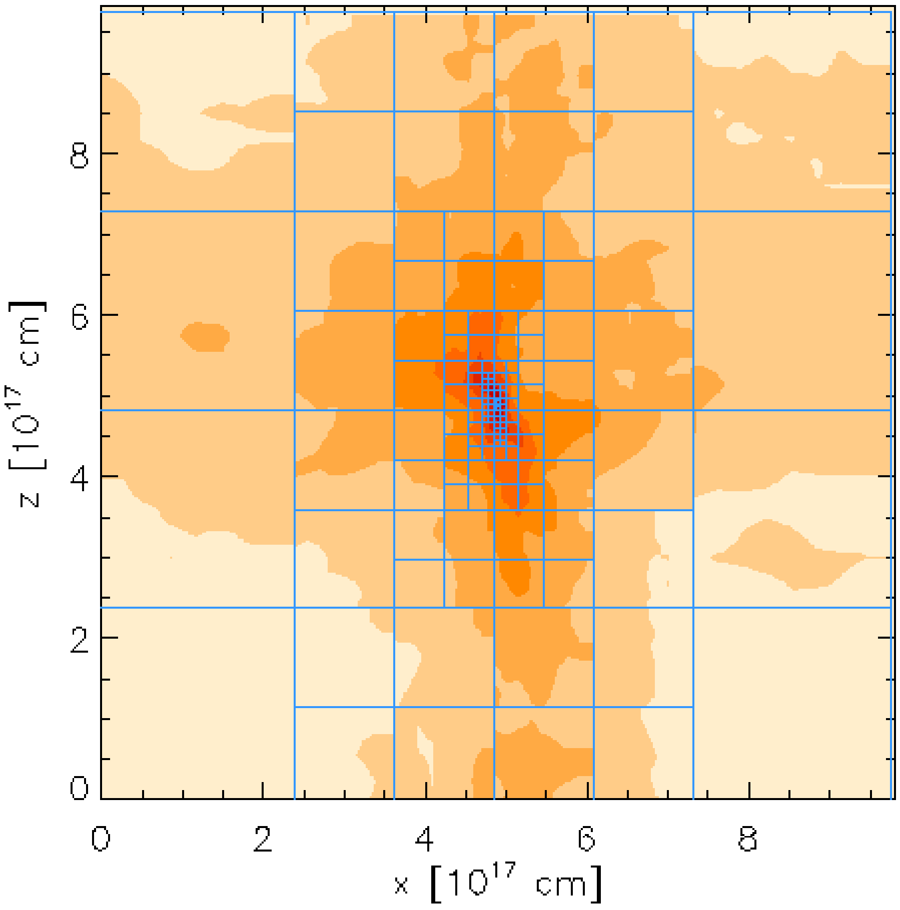
How do we study the formation of galaxies? With numerical simulations





Numerical techniques are borrowed from aerospace engineering and well tested

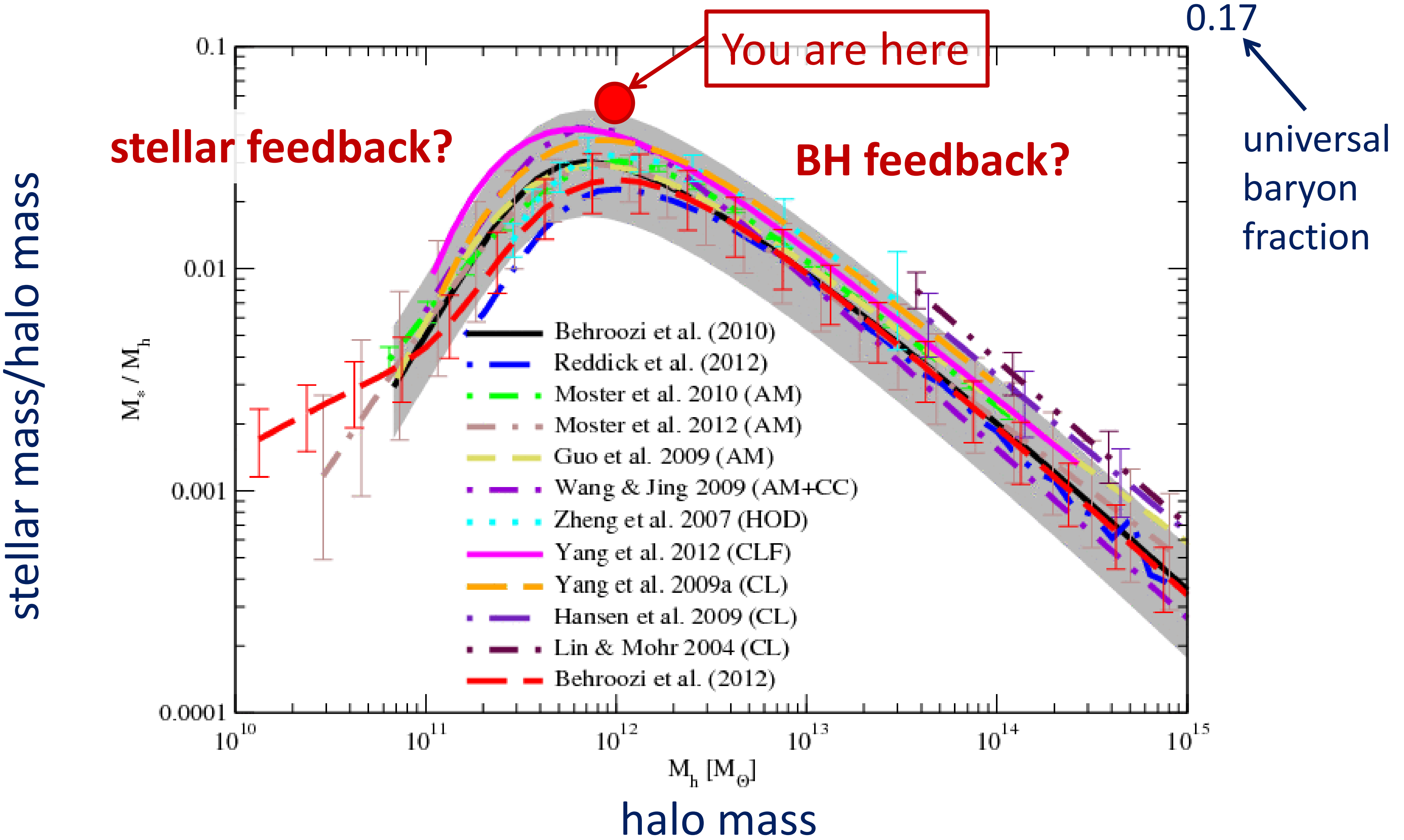
Ingredients of galaxy formation simulations

Green is good (understood)

Red is bad (not understood)

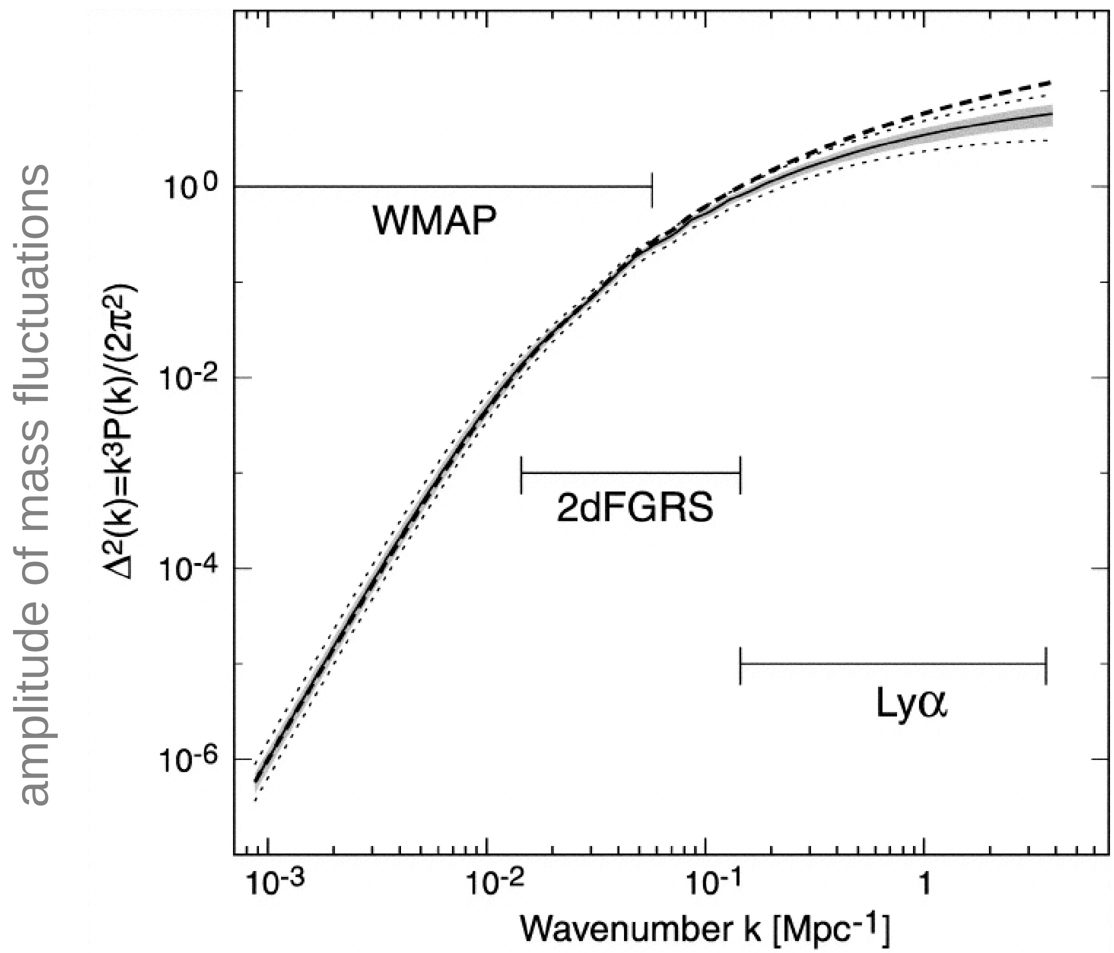
- *CDM model:* provides well-motivated initial conditions
- *dark matter:* dominates gravitationally on scales > kpc, shapes skeleton of the large-scale structure and galaxy potential wells, in which baryonic drama of galaxy formation plays out
- *radiative cooling:* shocks and UV radiation heat the baryons, but dissipative particle collisions allow baryonic matter to radiate away its thermal energy and sink to the center of the potential well, where it can reach high enough density required for star formation
- *star formation:* although we do not yet have a complete understanding of star formation, empirically we know that stars form in densest, molecular regions of the interstellar medium
- *stellar feedback:* newly born stars inject energy and metals released during thermonuclear burning back to the interstellar medium and thus regulate formation of future stars

Matching numbers of halos and galaxies indicates that star formation is inefficient, especially at low and high masses



Behroozi et al. 2012

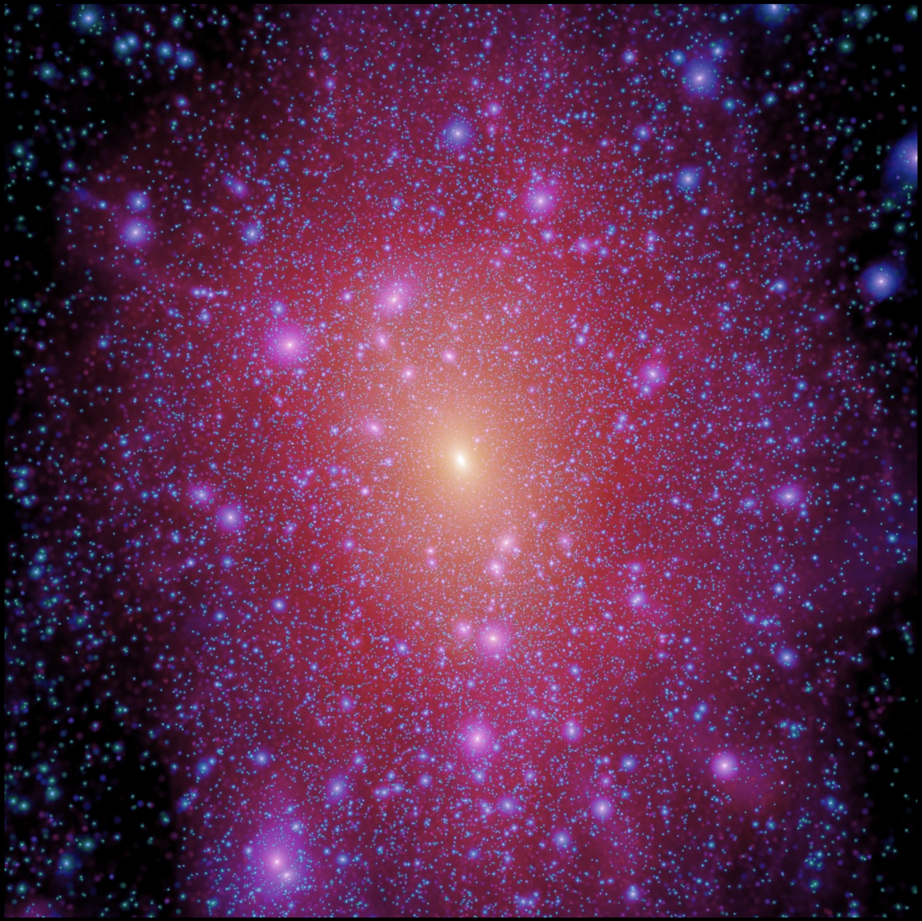
Stronger (measured) primordial fluctuations on small scales determine that low-mass *halos* form before high-mass *halos*

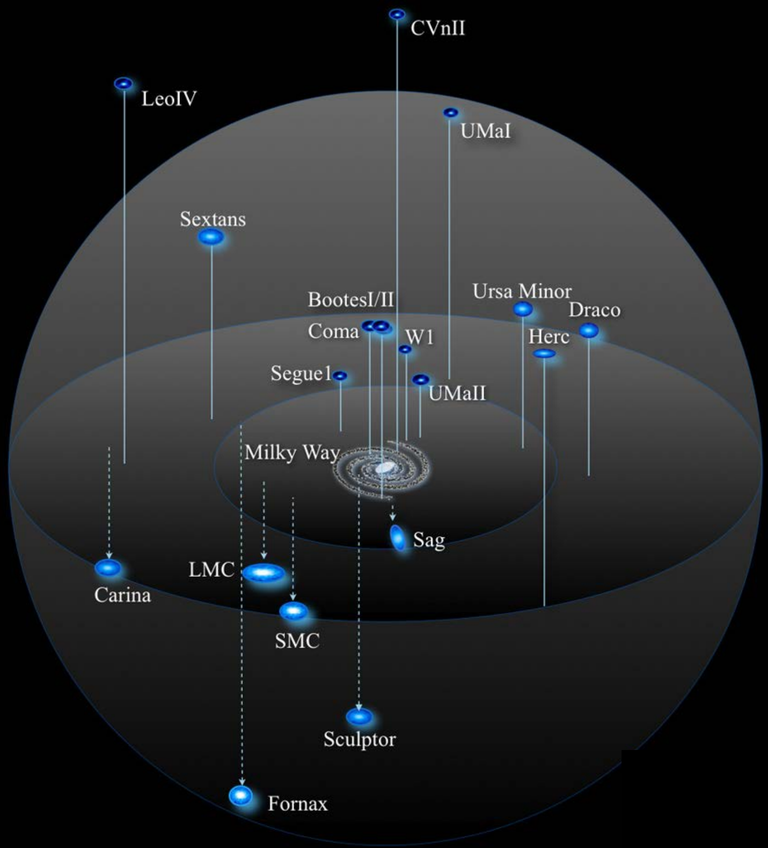


small scales →

Missing Satellite Galaxies

Klypin et al. 1999, Moore et al. 1999





>10^5 identified subhalos

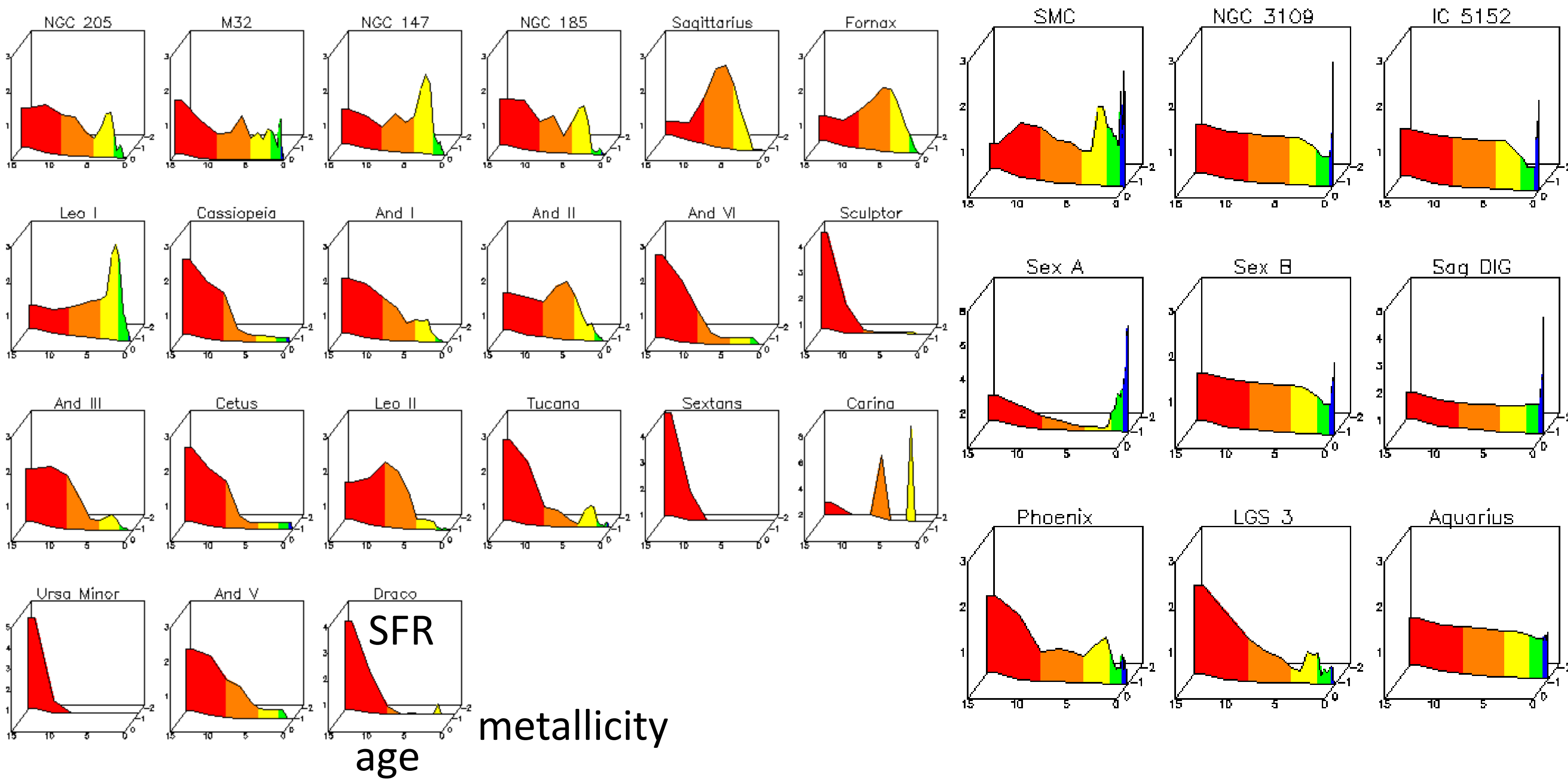
25 satellite galaxies $(L_V > 10^5 L_\odot)$

Aquarius simulation

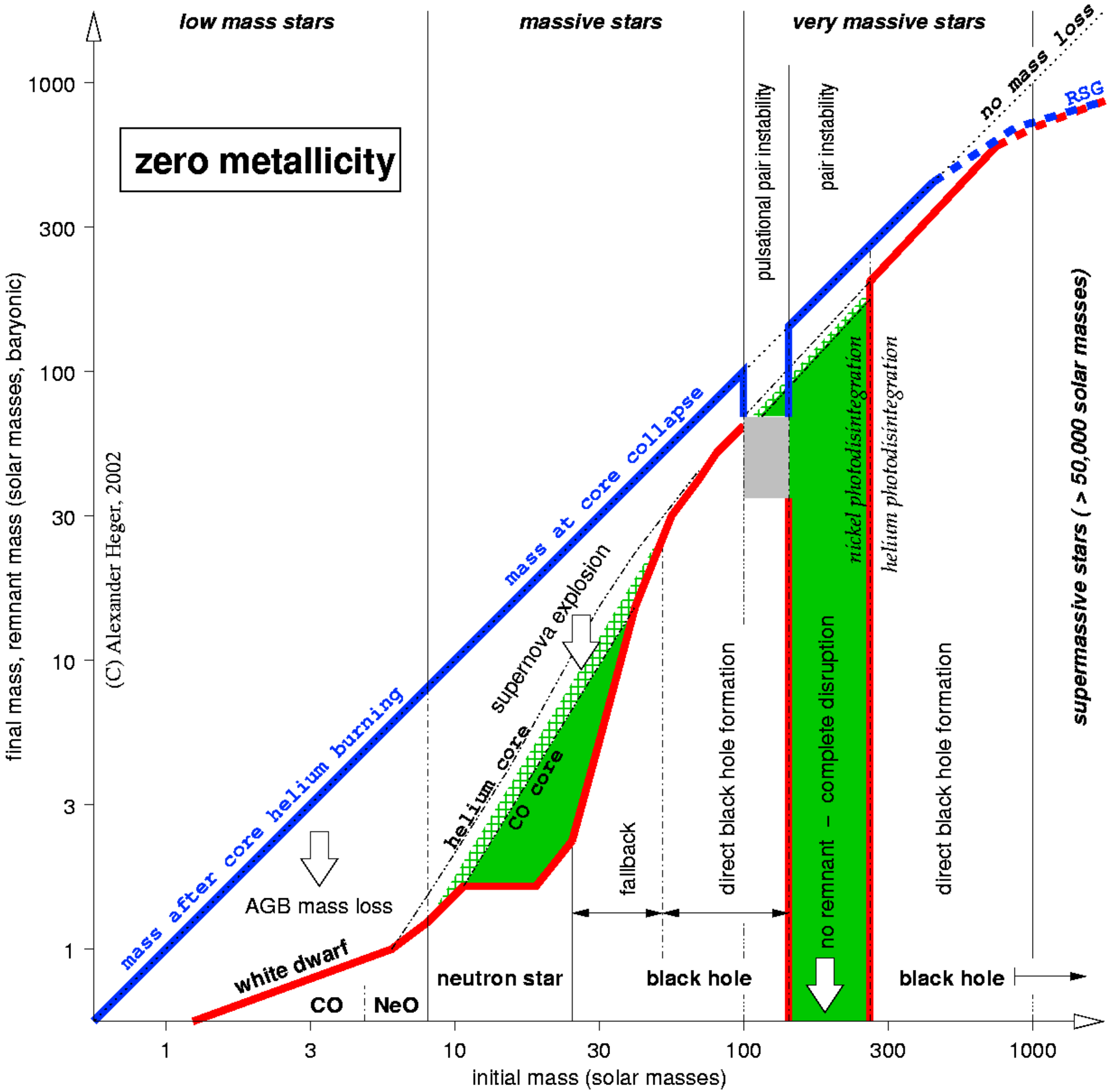
All real dwarf galaxies had early star formation and metal enrichment

(from HST CMDs: Dolphin et al. 2005, Holtzman et al. 2006)

What were the first stars that seeded heavy elements?

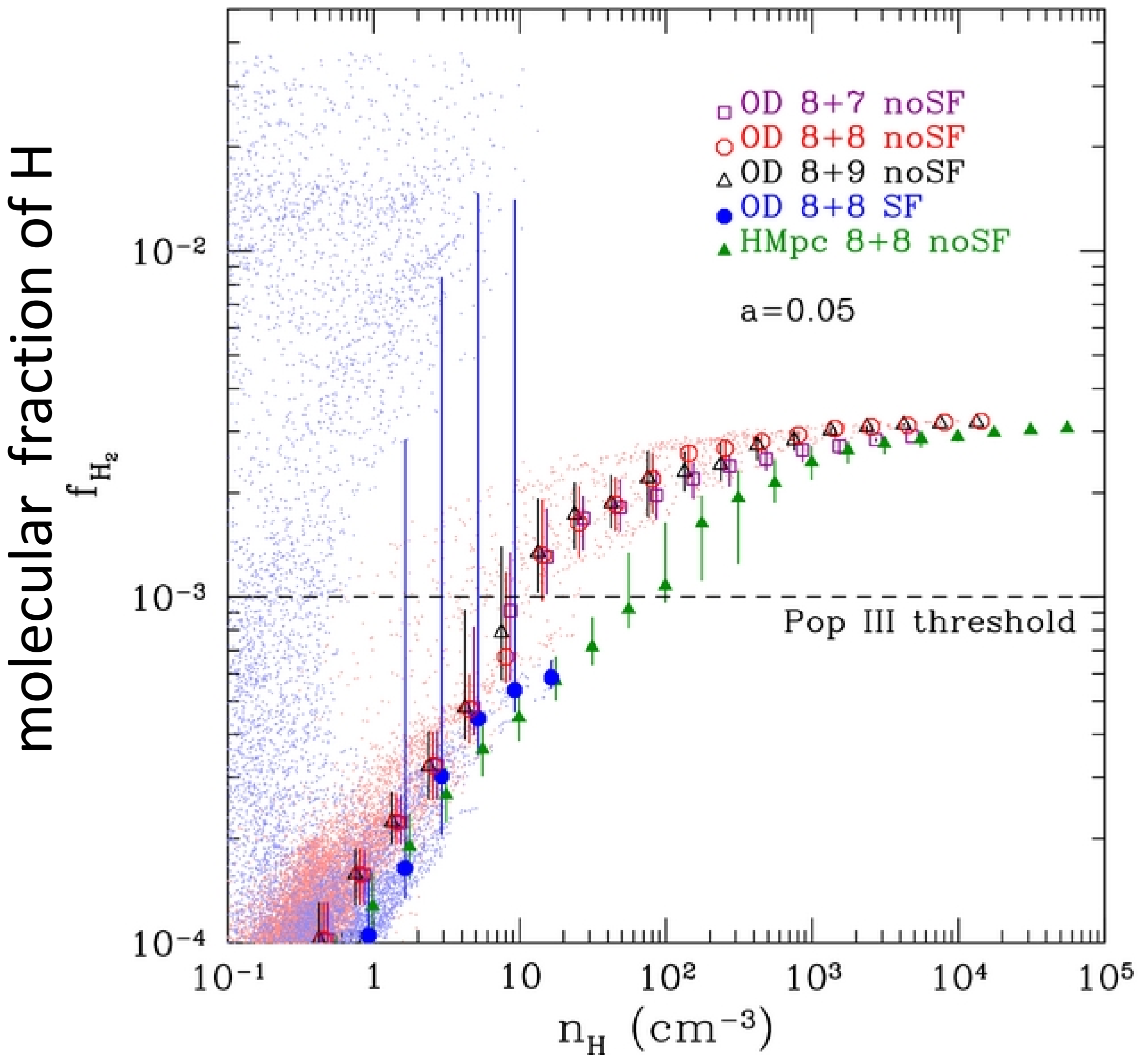


First stars were *probably* more massive than normal stars



because without heavy elements (metals) cosmic gas is warmer when it collapses to a star (no metal line transitions)

Metal-free stars form because gas cools by molecular H_2 transitions



form a star when:

[M/H] < -3.5

$f(H_2) > 10^{-3}$

$n_H > 10^4$ cm^{-3}

→ collapse within 2 Myr

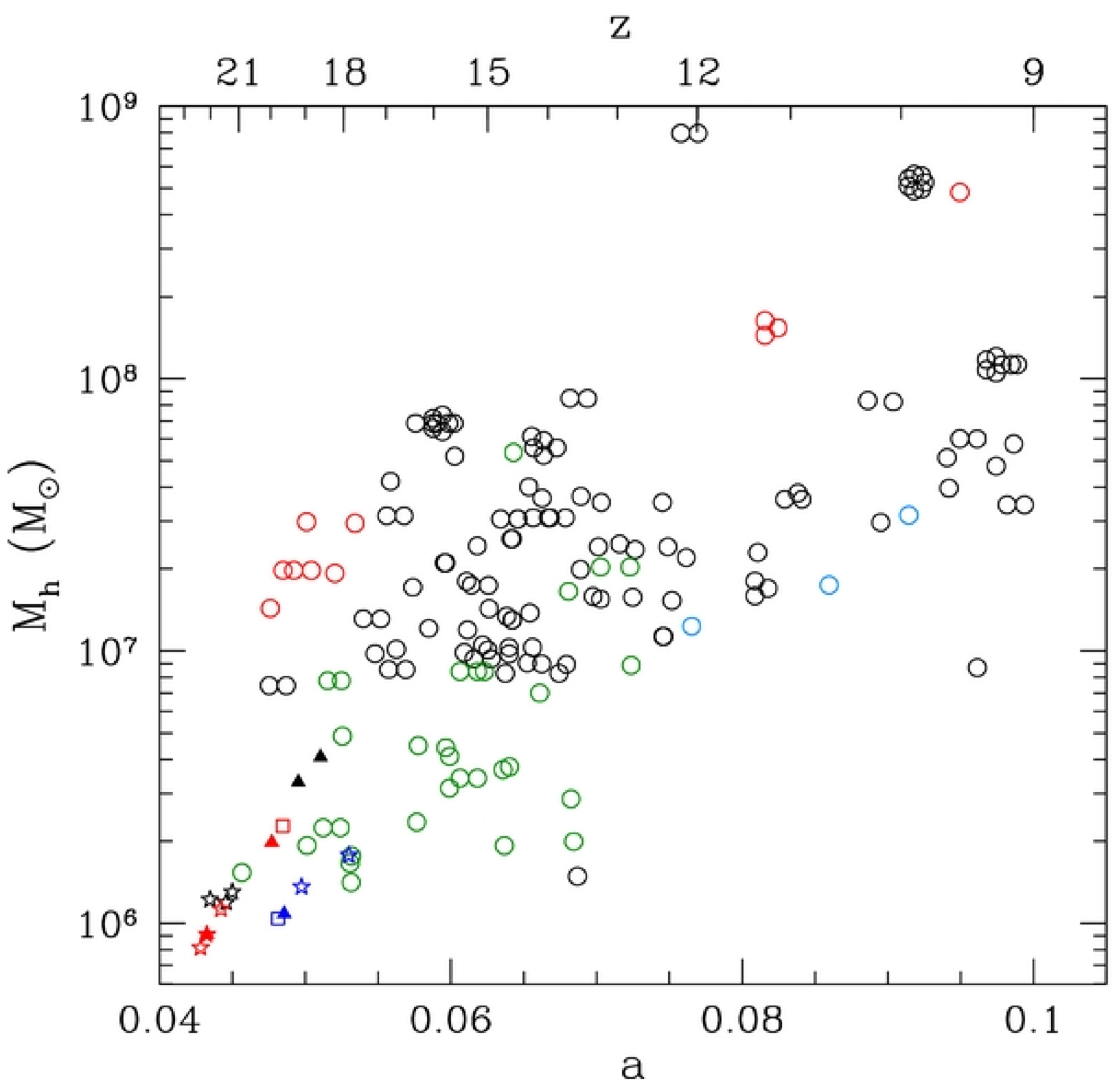
two choices for stellar mass

$M_* = 100$ or $170\ M_\odot$

to study maximum feedback effects

Muratov, OG et al. (2013)

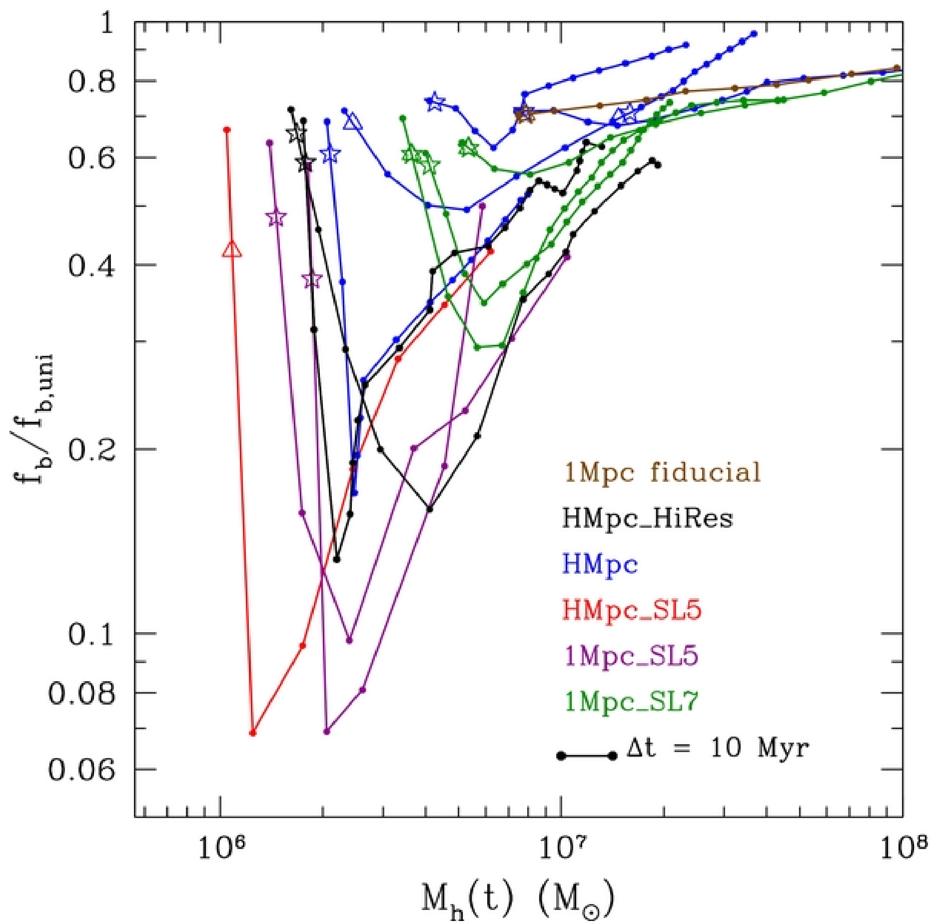
Star formation begins in very small halos… ~10^6 $M_\odot$



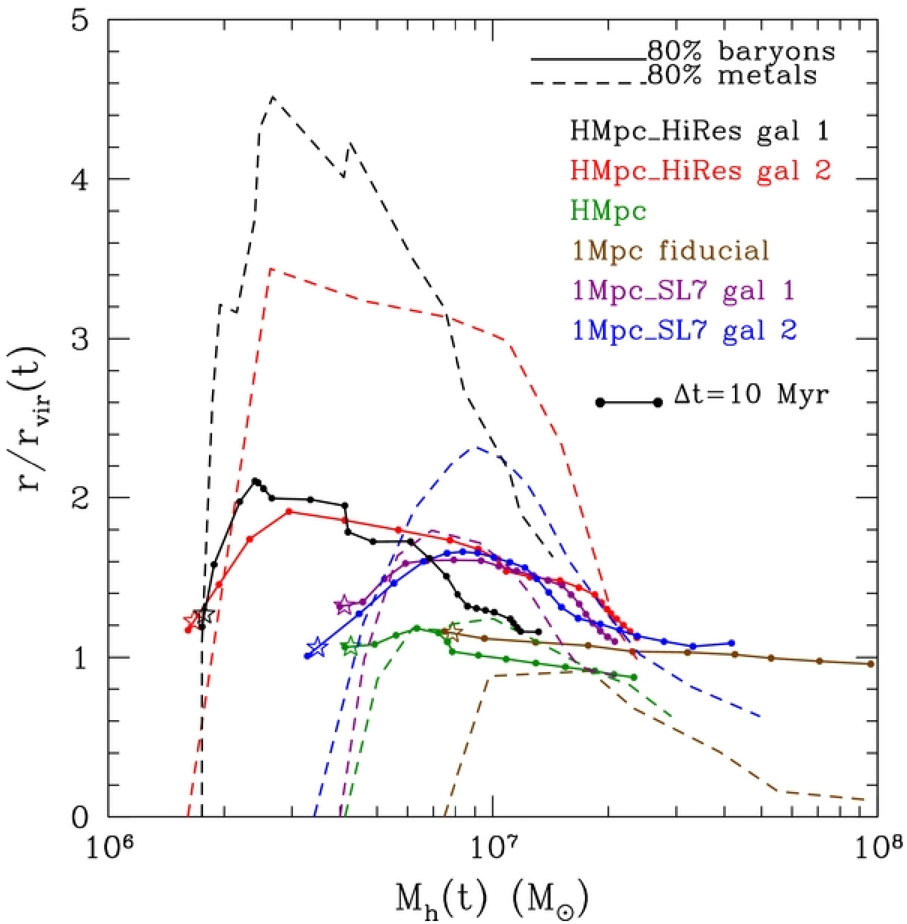
each point is a Pop III star, vs. galaxy mass where it formed and time when it formed

Feedback of first stars is strong but dependent on halo mass

much less efficient when $M_h > 10^7\ M_\odot$

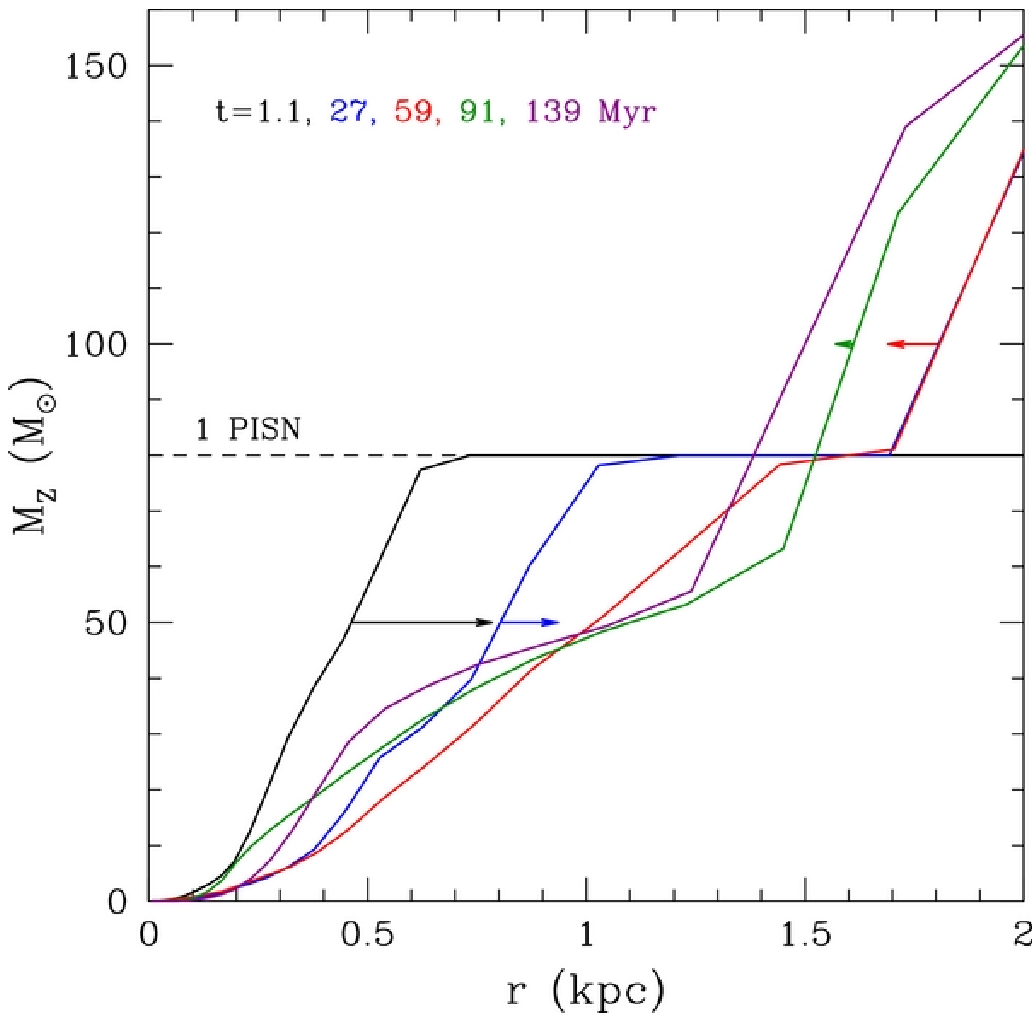


Baryon fraction within virial radius vs. galaxy mass over time



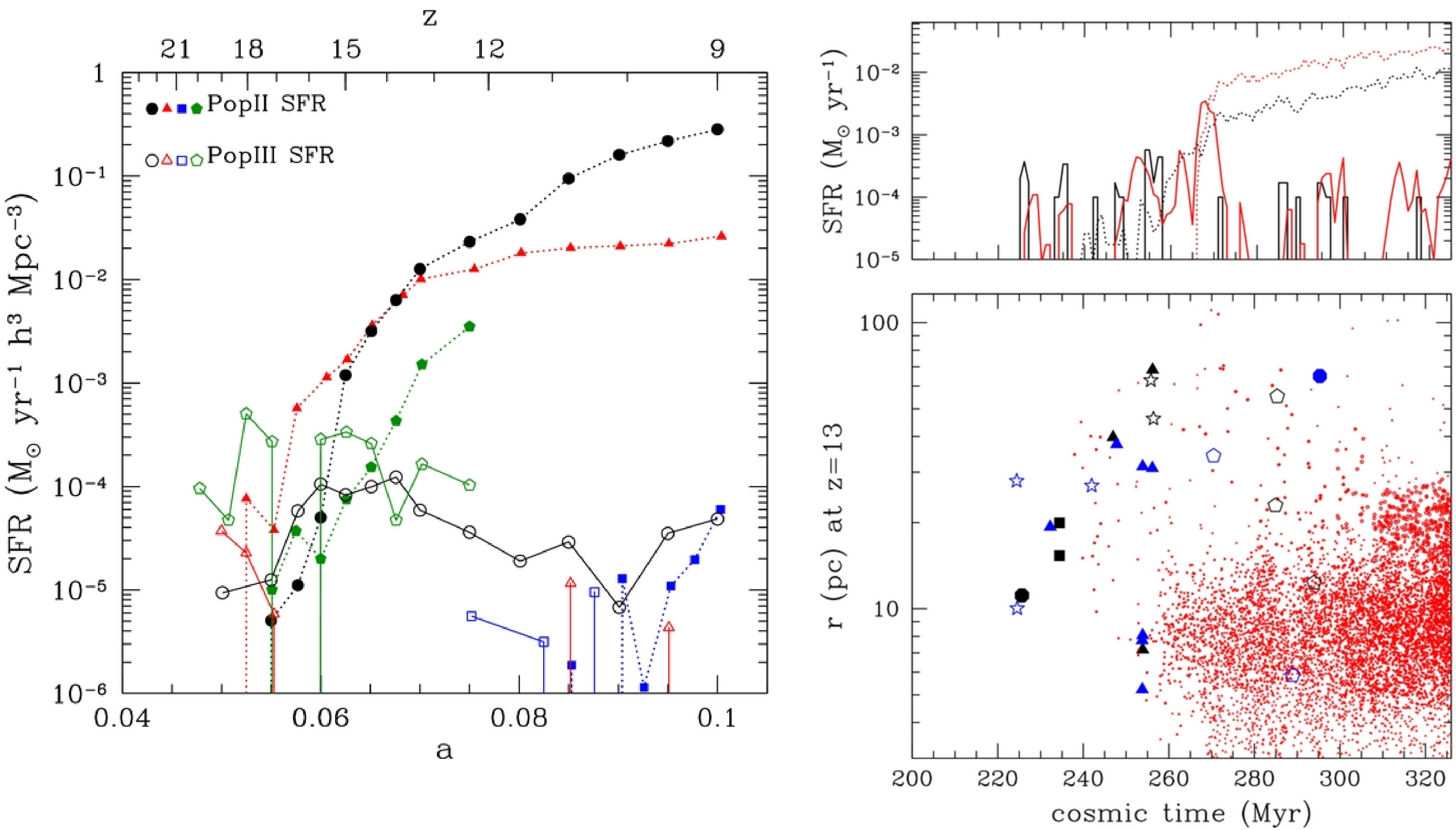
Radius containing fixed baryon fraction, and metal mass

Infall of fresh gas overturns expanding gas and metals



First SN shell extends to ~0.8 kpc in 40 Myr, second SN shell to > 1 kpc in 80 Myr but by 120 Myr the enriched gas is overturned by infalling pristine gas

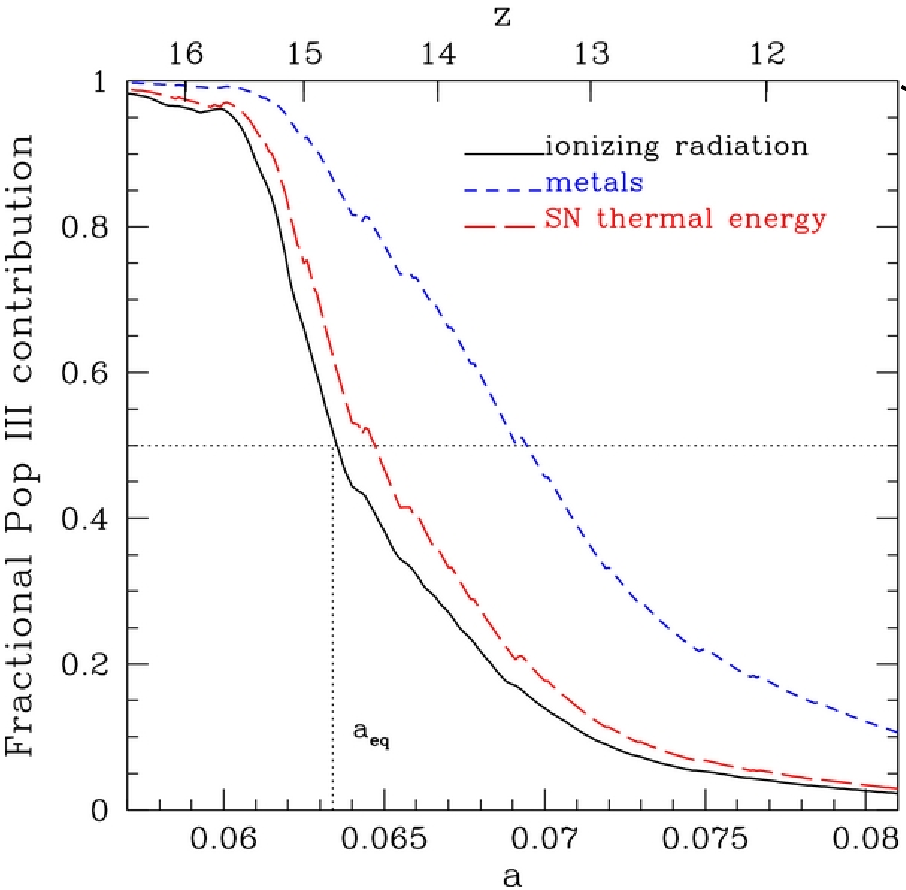
Enriched gas allows fast Pop II (normal) star formation

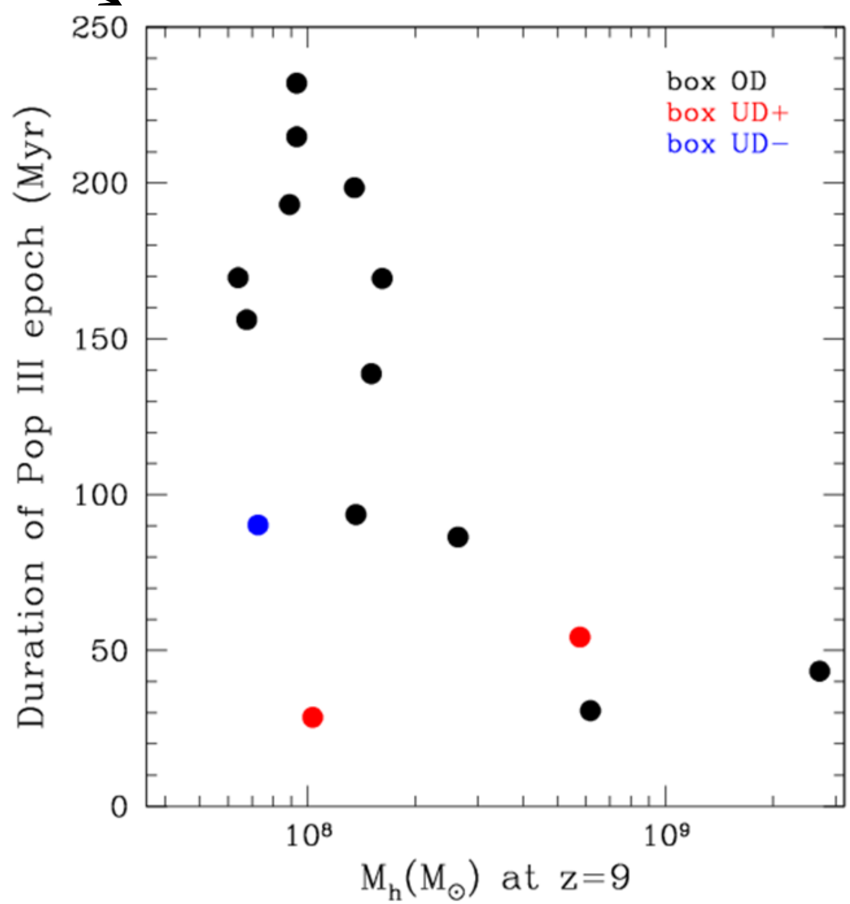


Pop II star formation overtakes Pop III in ~100 Myr

(blue/black symbols = Pop III, red points = Pop II)

From Pop III to Pop II





The duration of Pop III era is less than 200 Myr in a given galaxy

Summary

- First stars begin forming at $z \approx 20$ in halos $\sim 10^6\ M_\odot$
- Could be very massive and produce ultrahigh energy phenomena
- Their explosions push gas and metals out of their galaxies
- But after 50 – 200 Myr the metals rain back on the galaxies, allowing normal (Pop II) star formation
- Metal-free (Pop III) phase lasts longer in smaller halos
- Last metal-free stars may continue forming in low-density regions of the universe until $z \approx 6$, when cosmic hydrogen is reionized and all star formation in small halos ends