The transition from Pop III to Pop II star formation in the first galaxies

(and what happens after that)

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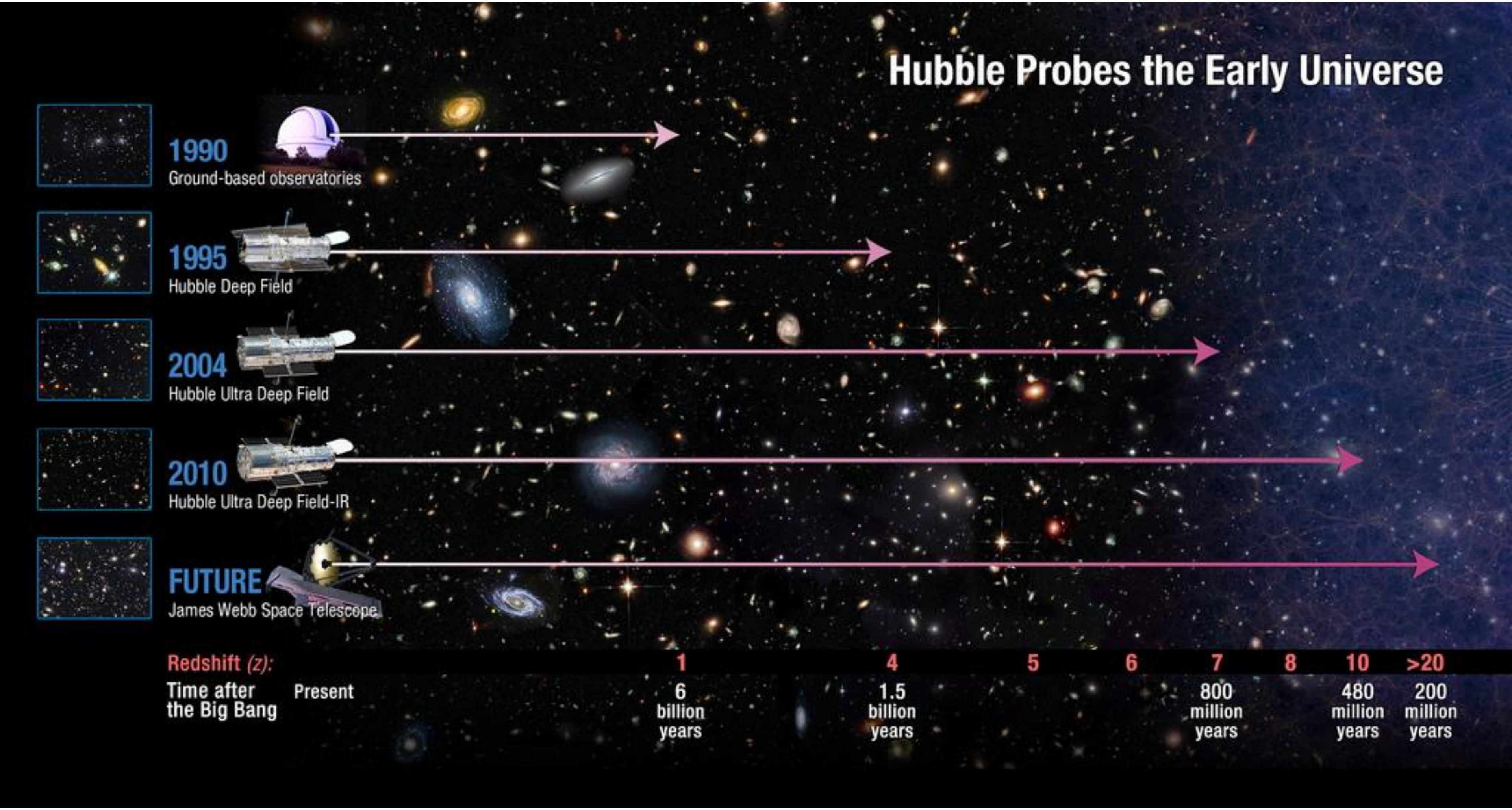
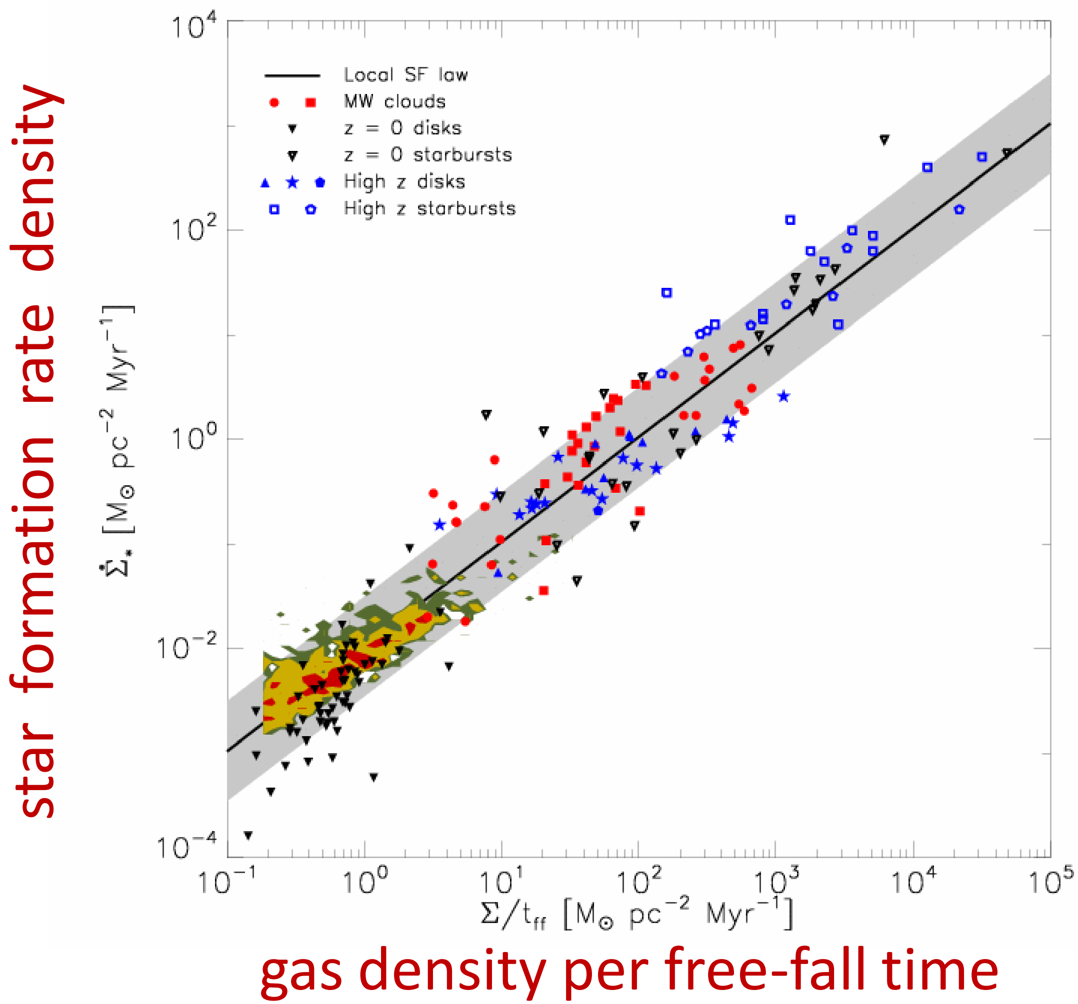
Current Frontier:

Can we model the first galaxies based on observations of later galaxies?



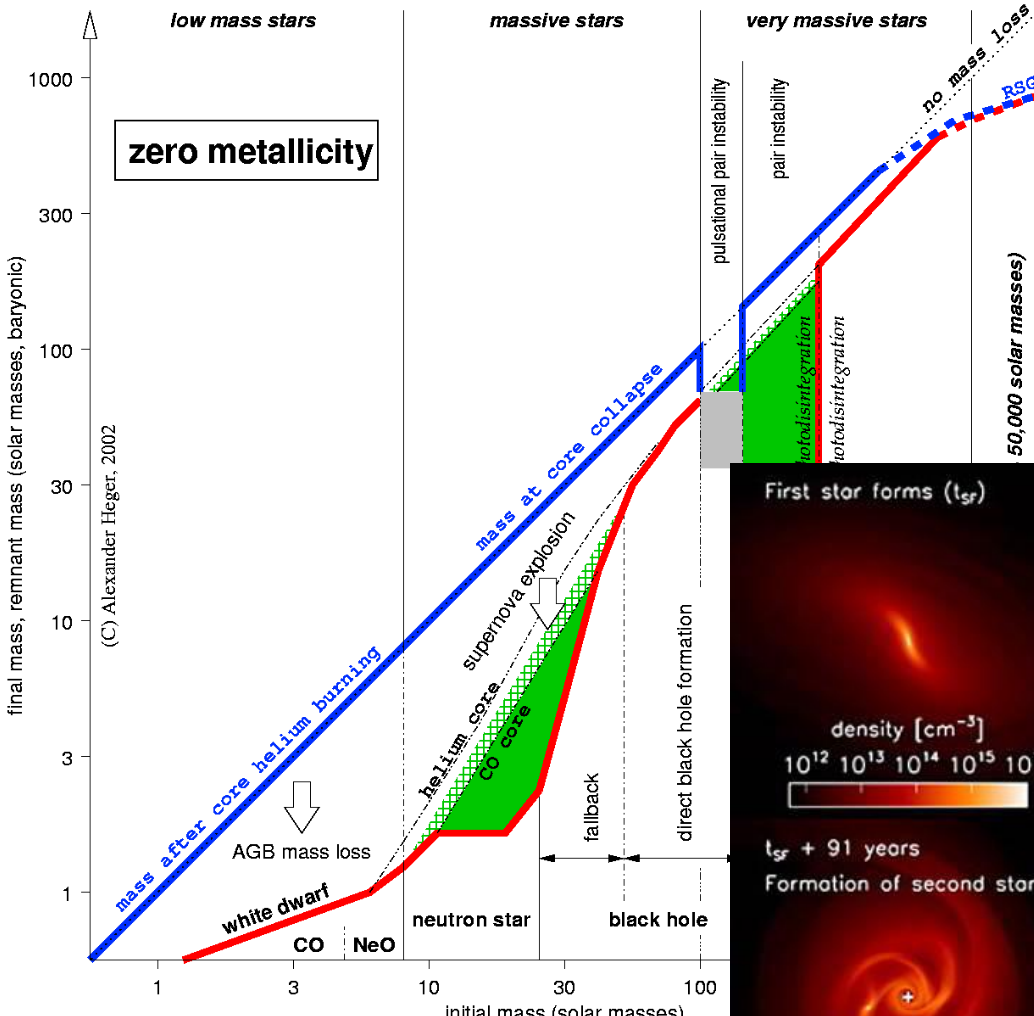
In normal galaxies at low and high redshift
global efficiency of star formation is fairly constant: $\varepsilon_{SF} \approx 0.01$

How far in redshift can we extrapolate?



Krumholz et al. 2011

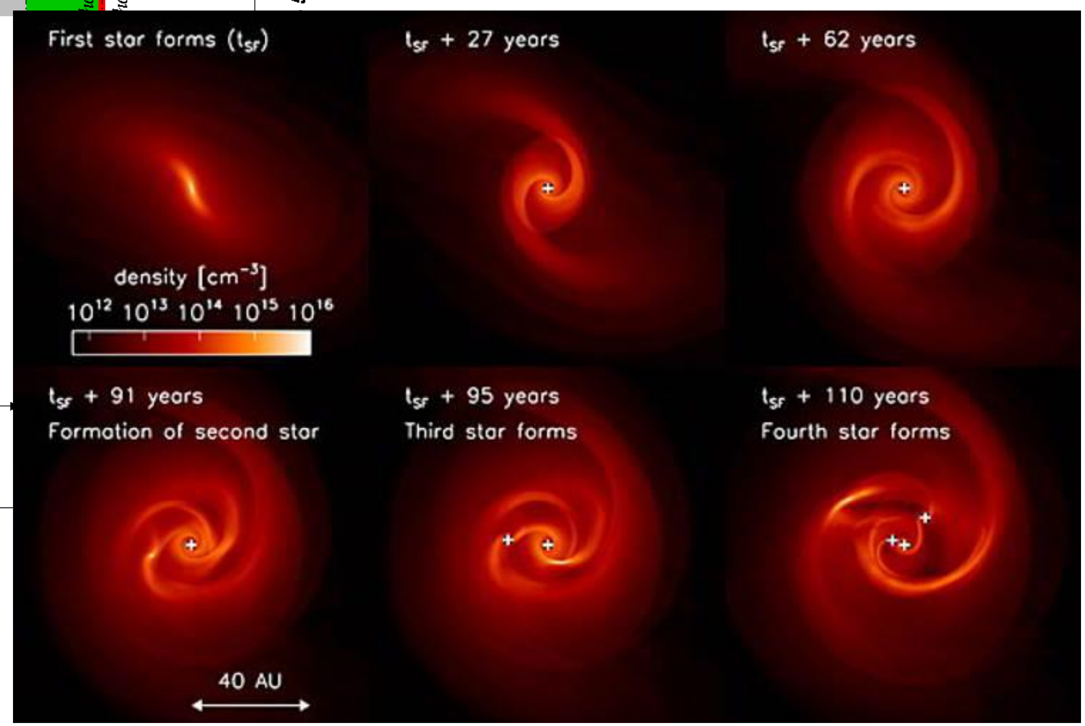
First Stars: probably more massive than normal…



Talks this afternoon by Naoki Yoshida and John Wise

or not…

does it matter?



Clark et al. (2011)

Cosmological simulations with run-time treatment of H_2 chemistry and radiative transfer

- Adaptive Refinement Tree hydro AMR code (Kravtsov 1999)
- star formation in molecular gas, supernovae feedback (thermal) and metal enrichment, stellar mass loss
- radiative cooling and heating: Compton, UV background, density and metallicity dependent net cooling/heating equilibrium rates taking into account atomic line and molecular processes
- 3D radiative transfer using the Optically Thin Eddington Tensor approximation (N. Gnedin & Abel 2001)
- H2 formation on dust grains/destruction by UV with a model for approximate H2 self-shielding and shielding by dust, assuming dust-to-gas ratio scales linearly with metallicity of the gas (N. Gnedin & Kravtsov 2010,2011)

$$\frac{\partial n_j}{\partial t} + 3Hn_j + \frac{1}{a}\mathrm{div}_x(n_j\vec{v}) = \dot{\mathcal{I}}_j + \dot{\mathcal{M}}_j + \dot{\mathcal{D}}_j,$$

Ionization by cosmic and local interstellar UV flux

atomic and molecular chemistry

dust chemistry

Tracking abundance of species of H, He, and H_2

$$
\begin{cases}
\dot{\mathcal{I}}_{\rm HI} &= -n_{\rm HI}\Gamma_{\rm HI} - C_{\rm HI}n_e n_{\rm HI} + R_{\rm HII}n_e n_{\rm HII},\\
\dot{\mathcal{I}}_{\rm HII} &= -R_{\rm HII}n_e n_{\rm HII} + n_{\rm HI}\Gamma_{\rm HI} + C_{\rm HI}n_e n_{\rm HI},\\
\dot{\mathcal{I}}_{\rm HeI} &= -n_{\rm HeI}\Gamma_{\rm HeI} - C_{\rm HeI}n_e n_{\rm HeI} + (D_{\rm HeII} + R_{\rm HeII})n_e n_{\rm HeII},\\
\dot{\mathcal{I}}_{\rm HeII} &= -n_{\rm HeII}\Gamma_{\rm HeII} - (D_{\rm HeII} + R_{\rm HeII})n_e n_{\rm HeII} - C_{\rm HeII}n_e n_{\rm HeII} + n_{\rm HeI}\Gamma_{\rm HeI} + C_{\rm HeI}n_e n_{\rm HeI} + R_{\rm HeIII}n_e n_{\rm HeIII},\\
\dot{\mathcal{I}}_{\rm HeIII} &= -R_{\rm HeIII}n_e n_{\rm HeIII} + n_{\rm HeII}\Gamma_{\rm HeII} + C_{\rm HeII}n_e n_{\rm HeII},\\
\dot{\mathcal{I}}_{\rm H_2} &= \dot{\mathcal{I}}_{\rm H^-} = \dot{\mathcal{I}}_{\rm H_2^+} = 0.
\end{cases}
$$

$$
\begin{cases}
n_{\rm H^-} &= \dfrac{k_1 n_e n_{\rm HI} + k_{23} n_e n_{\rm H_2}}{\Gamma_A + k_2 n_{\rm HI} + k_5 n_{\rm HII} + k_{14} n_e + k_{15} n_{\rm HI} + k_{16} n_{\rm HII} + k_{28} n_{\rm HeII} + k_{29} n_{\rm HeI}},\\
n_{\rm H_2^+} &= \dfrac{\Gamma_D n_{\rm H_2} + k_3 n_{\rm HI} n_{\rm HII} + k_7 n_{\rm H_2} n_{\rm HII} + k_{16} n_{\rm HII} n_{\rm H^-} + k_{25} n_{\rm H_2} n_{\rm HeII}}{\Gamma_B + \Gamma_C + k_4 n_{\rm HI} + k_6 n_e},\\
\dot{\mathcal{M}}_{\rm HI} &= \Gamma_A n_{\rm H^-} + \Gamma_B n_{\rm H_2^+} + 2\Gamma_E n_{\rm H_2} + 2\Gamma_{LW} n_{\rm H_2} - k_1 n_e n_{\rm HI} - k_2 n_{\rm H^-} n_{\rm HI} - k_3 n_{\rm HII} n_{\rm HI} - k_4 n_{\rm H_2^+} n_{\rm HI} -\\
&\quad k_{26} n_{\rm HeII} n_{\rm HI} - 2k_{30} n_{\rm HI}^3 - 2k_{31} n_{\rm HI}^2 n_{\rm H_2} - 2k_{32} n_{\rm HI}^2 n_{\rm HeI} + 2k_5 n_{\rm HII} n_{\rm H^-} + 2k_6 n_e n_{\rm H_2^+} + k_7 n_{\rm H_2} n_{\rm HII} +\\
&\quad 2k_8 n_e n_{\rm H_2} + 2k_9 n_{\rm HI} n_{\rm H_2} + 2k_{10} n_{\rm H_2} n_{\rm H_2} + 2k_{11} n_{\rm HeI} n_{\rm H_2} + k_{14} n_e n_{\rm H^-} + k_{15} n_{\rm HI} n_{\rm H^-} +\\
&\quad k_{23} n_e n_{\rm H_2} + k_{24} n_{\rm HeII} n_{\rm H_2} + k_{27} n_{\rm HeI} n_{\rm HII} + k_{28} n_{\rm HeII} n_{\rm H^-} + k_{29} n_{\rm HeI} n_{\rm H^-},\\
\dot{\mathcal{M}}_{\rm HII} &= \Gamma_B n_{\rm H_2^+} + 2\Gamma_C n_{\rm H_2^+} - k_3 n_{\rm HI} n_{\rm HII} - k_5 n_{\rm H^-} n_{\rm HII} - k_7 n_{\rm H_2} n_{\rm HII} - k_{16} n_{\rm H^-} n_{\rm HII} - k_{27} n_{\rm HeI} n_{\rm HII} + k_4 n_{\rm H_2^+} n_{\rm HI} +\\
&\quad k_{24} n_{\rm HeII} n_{\rm H_2} + k_{26} n_{\rm HI} n_{\rm HeII},\\
\dot{\mathcal{M}}_{\rm HeI} &= -k_{27} n_{\rm HII} n_{\rm HeI} - k_{29} n_{\rm H^-} n_{\rm HeI} + k_{24} n_{\rm HeII} n_{\rm H_2} + k_{25} n_{\rm HeII} n_{\rm H_2} + k_{26} n_{\rm HeII} n_{\rm HI} + k_{28} n_{\rm HeII} n_{\rm H^-},\\
\dot{\mathcal{M}}_{\rm HeII} &= -k_{24} n_{\rm H_2} n_{\rm HeII} - k_{25} n_{\rm H_2} n_{\rm HeII} - k_{26} n_{\rm HI} n_{\rm HeII} - k_{28} n_{\rm H^-} n_{\rm HeII} + k_{27} n_{\rm HII} n_{\rm HeI} + k_{29} n_{\rm H^-} n_{\rm HeI},\\
\dot{\mathcal{M}}_{\rm HeIII} &= 0,\\
\dot{\mathcal{M}}_{\rm H_2} &= -\Gamma_D n_{\rm H_2} - \Gamma_E n_{\rm H_2} - \Gamma_{LW} n_{\rm H_2} - k_7 n_{\rm H_2} n_{\rm HII} - k_8 n_e n_{\rm H_2} - k_9 n_{\rm HI} n_{\rm H_2} - k_{10} n_{\rm H_2} n_{\rm H_2} - k_{11} n_{\rm HeI} n_{\rm H_2} -\\
&\quad k_{23} n_e n_{\rm H_2} - k_{24} n_{\rm HeII} n_{\rm H_2} - k_{25} n_{\rm HeII} n_{\rm H_2} + k_2 n_{\rm H^-} n_{\rm HI} + k_4 n_{\rm H_2^+} n_{\rm HI} + k_{30} n_{\rm HI}^3 +\\
&\quad k_{31} n_{\rm HI}^2 n_{\rm H_2} + k_{32} n_{\rm HI}^2 n_{\rm HeI}.
\end{cases}
$$

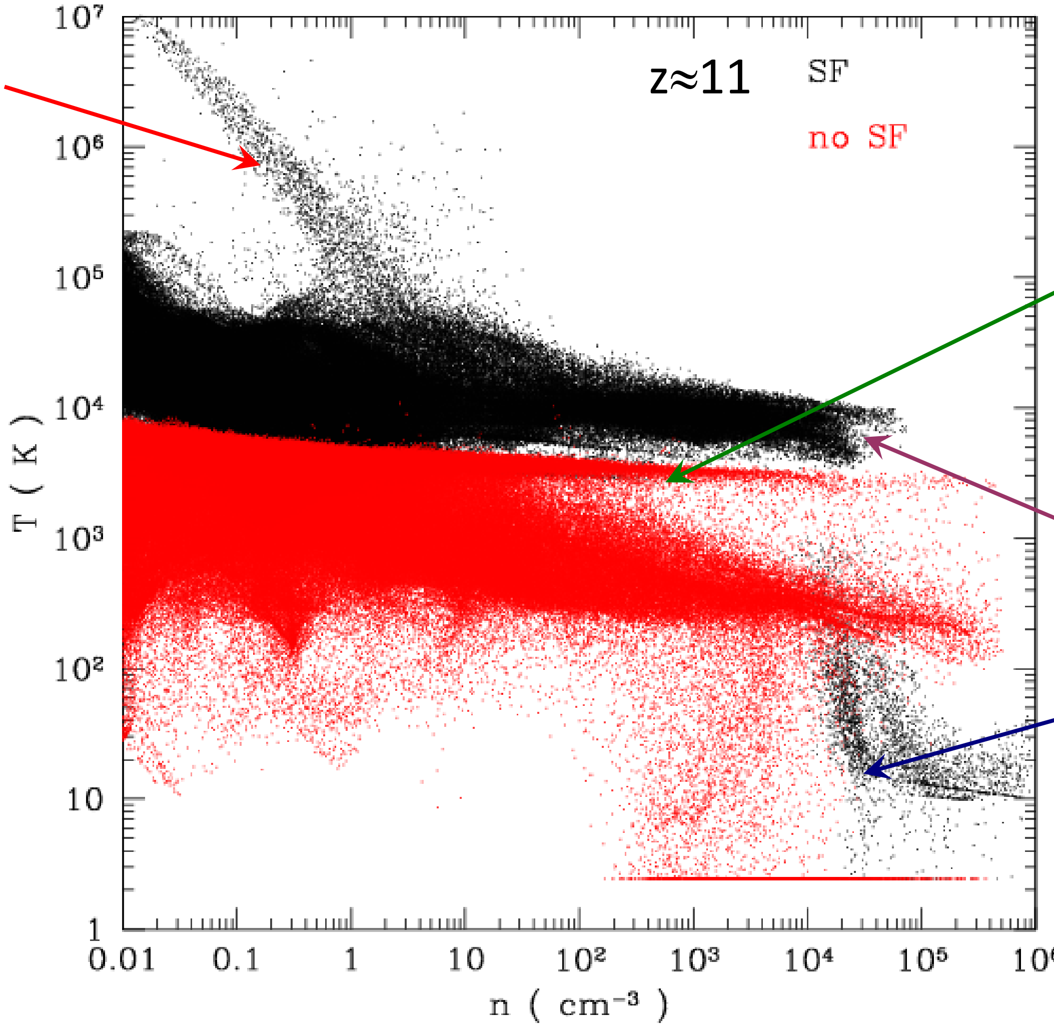
$$
\begin{cases}
\dot{\mathcal{D}}_{\rm H_2} &= D_{\rm MW} R_0 C_\rho n_{\rm HI}(n_{\rm HI} + 2n_{\rm H_2}),\\
\dot{\mathcal{D}}_{\rm HI} &= -2\dot{\mathcal{D}}_{\rm H_2},\\
\dot{\mathcal{D}}_{\rm HII} &= \dot{\mathcal{D}}_{\rm HeI} = \dot{\mathcal{D}}_{\rm HeII} = \dot{\mathcal{D}}_{\rm HeIII} = \dot{\mathcal{D}}_{\rm H^-} = \dot{\mathcal{D}}_{\rm H_2^+} = 0,
\end{cases}
$$

$$
\begin{cases}
\Gamma_A &= S_D \Gamma_A^{\rm RT} \quad [{\rm H^-} + \gamma \rightarrow {\rm HI} + e],\\
\Gamma_B &= S_D \Gamma_B^{\rm RT} \quad [{\rm H_2^+} + \gamma \rightarrow {\rm HI} + {\rm HII}],\\
\Gamma_C &= S_D \Gamma_C^{\rm RT} \quad [{\rm H_2^+} + \gamma \rightarrow 2{\rm HII} + e],\\
\Gamma_D &= S_D S_{\rm H_2} \Gamma_D^{\rm RT} \quad [{\rm H_2} + \gamma \rightarrow {\rm H_2^+} + e],\\
\Gamma_E &= S_D S_{\rm H_2} \Gamma_E^{\rm RT} \quad [{\rm H_2} + \gamma \rightarrow 2{\rm HI}\ \ (h\nu > 13.6\,{\rm eV})],\\
\Gamma_{LW} &= S_D S_{\rm H_2} \Gamma_{LW}^{\rm RT} \quad [{\rm H_2} + \gamma \rightarrow 2{\rm HI}\ \ (\text{Lyman-Werner band})].
\end{cases}
$$

$$
S_D = e^{-D_{\rm MW}\sigma_0 (n_{\rm HI} + 2n_{\rm H_2}) L_{\rm Sob}}
$$

$$
S_{\rm H_2} = \begin{cases} 1, & \text{for } N_{\rm H_2} < 10^{14}\,{\rm cm^{-2}},\\ (N_{\rm H_2}/10^{14}\,{\rm cm^{-2}})^{-3/4}, & \text{for } N_{\rm H_2} > 10^{14}\,{\rm cm^{-2}}, \end{cases}
$$

Simulations reproduce all main phases of the galactic ISM. Star formation takes place only in molecular gas.



hot, low-density gas heated by shocks and SNe

warm atomic gas (formerly known as "cold" phase)

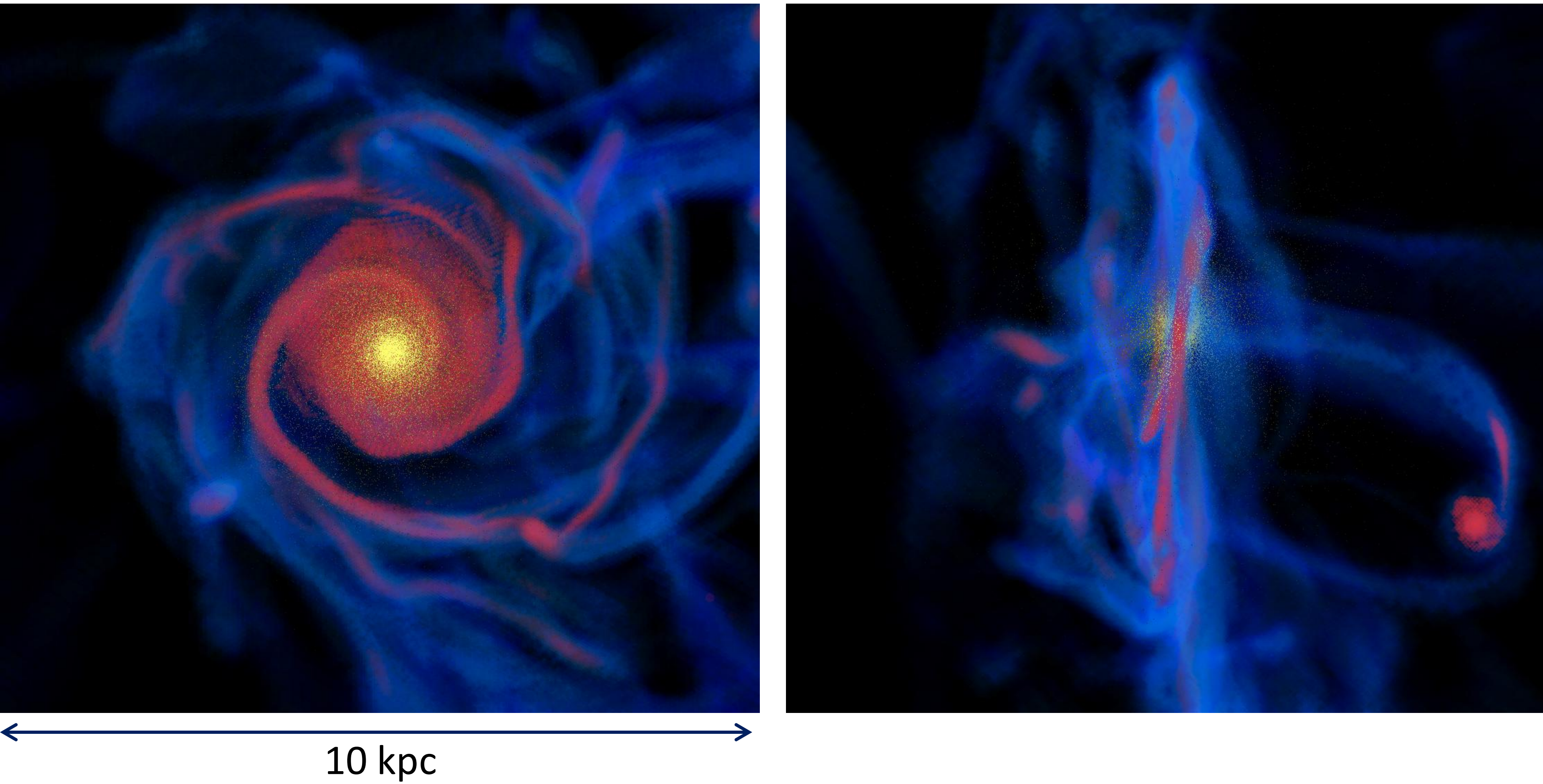
HII regions

cold molecular gas

Muratov et al. (2012, in prep.)

All molecular gas is in thin disks, including satellites

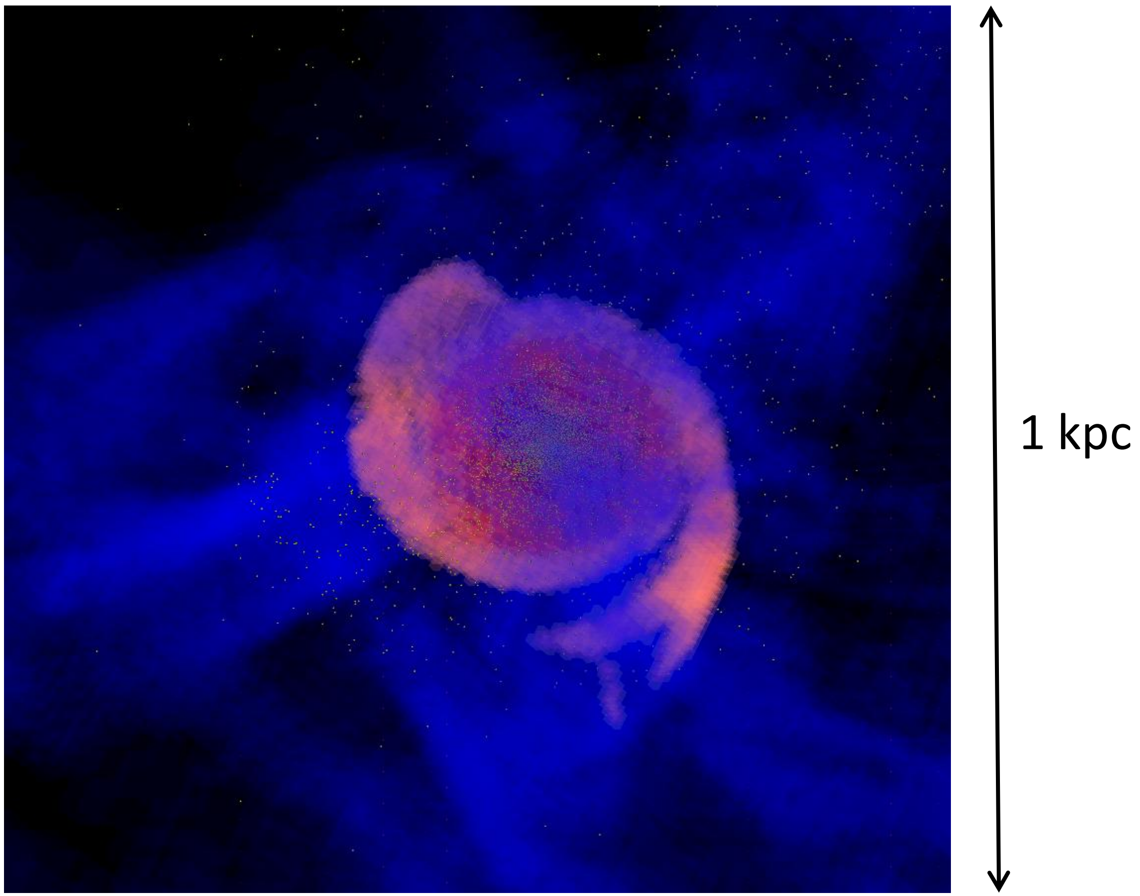
Most of the gas is atomic and is not participating in star formation



Disk galaxy at $z=3$: stars, molecular gas, atomic gas

Zemp, O. Gnedin, N. Gnedin, Kravtsov (2012)

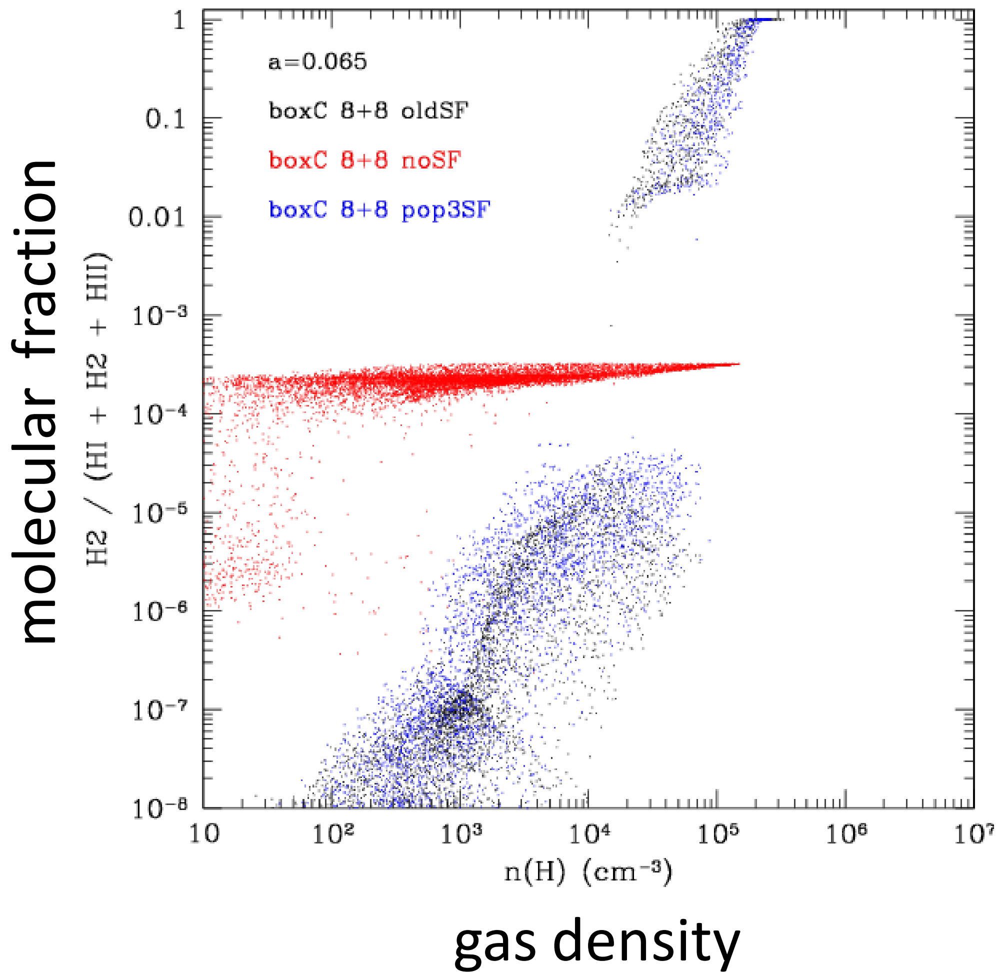
Most of the gas is atomic and is not participating in star formation



Dwarf galaxy at z=7: stars, molecular gas, atomic gas

(Muratov et al. 2012, in prep.)

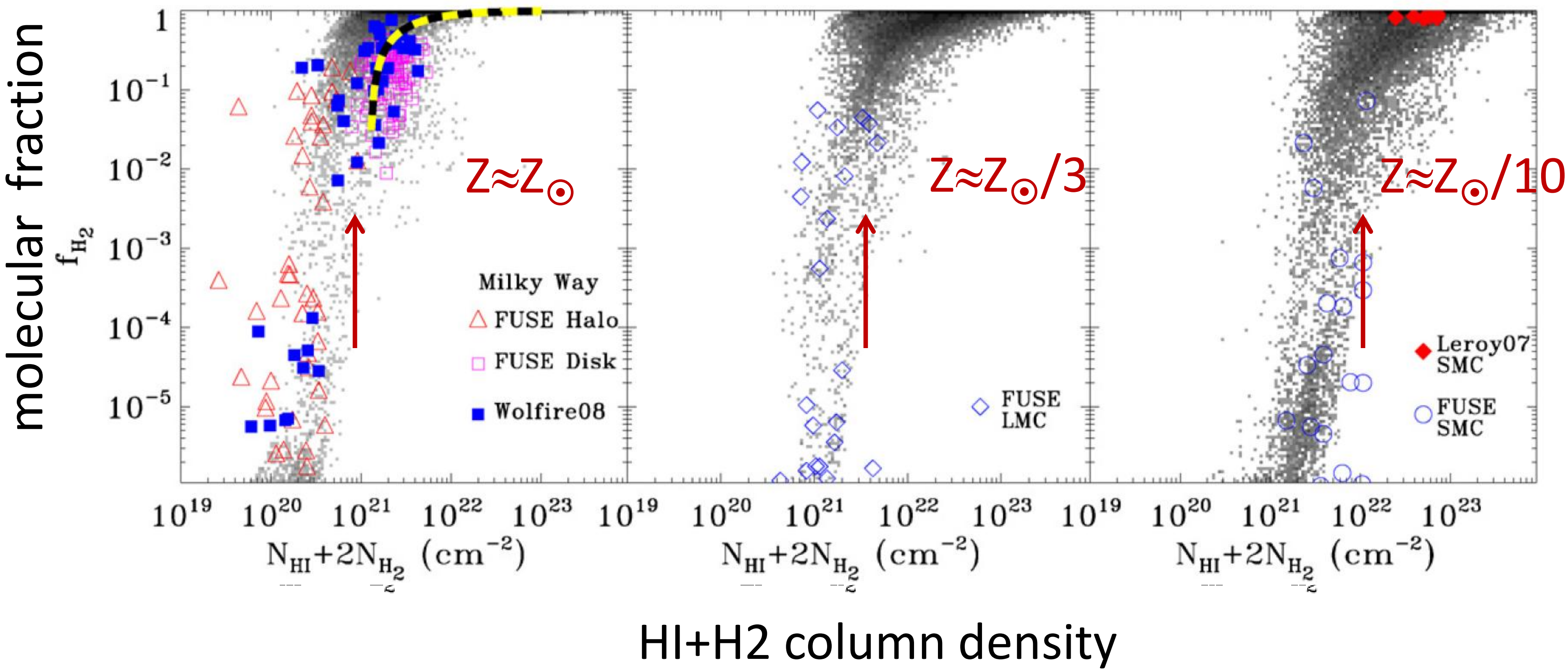
Star formation in molecular gas selects only very-high density regions



But the first (metal-free) stars are a problem…

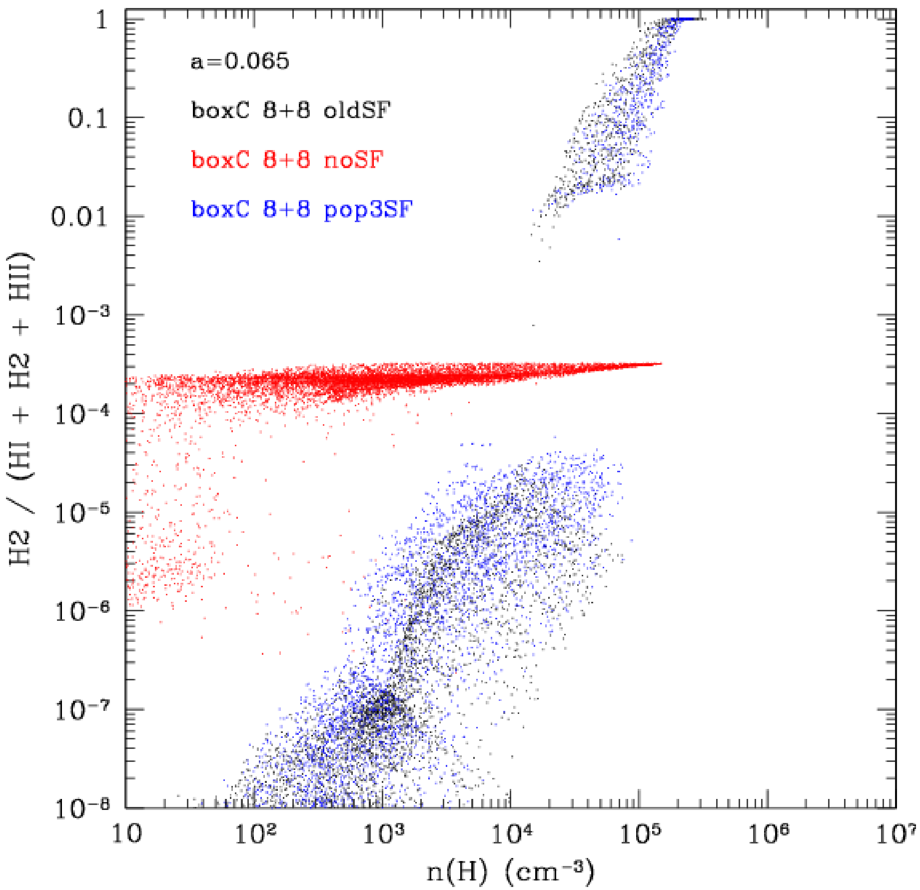
Transition from atomic to molecular gas depends on the metallicity: $n_H \propto Z^{-1}$

(model is trained to reproduce the trend in MW, LMC, and SMC)



N. Gnedin, Tassis, Kravtsov (2009) N. Gnedin & Kravtsov (2010)

Pop III star formation



Muratov et al. (2012, in prep)

Pop III star formation is controlled by H- cooling.

<u>*Simple recipe*</u>:

[M/H] < -3.5

$f(H_2) > 10^{-4}$

$n_H > 5000$ cm^{-3}

collapse within 4 Myr

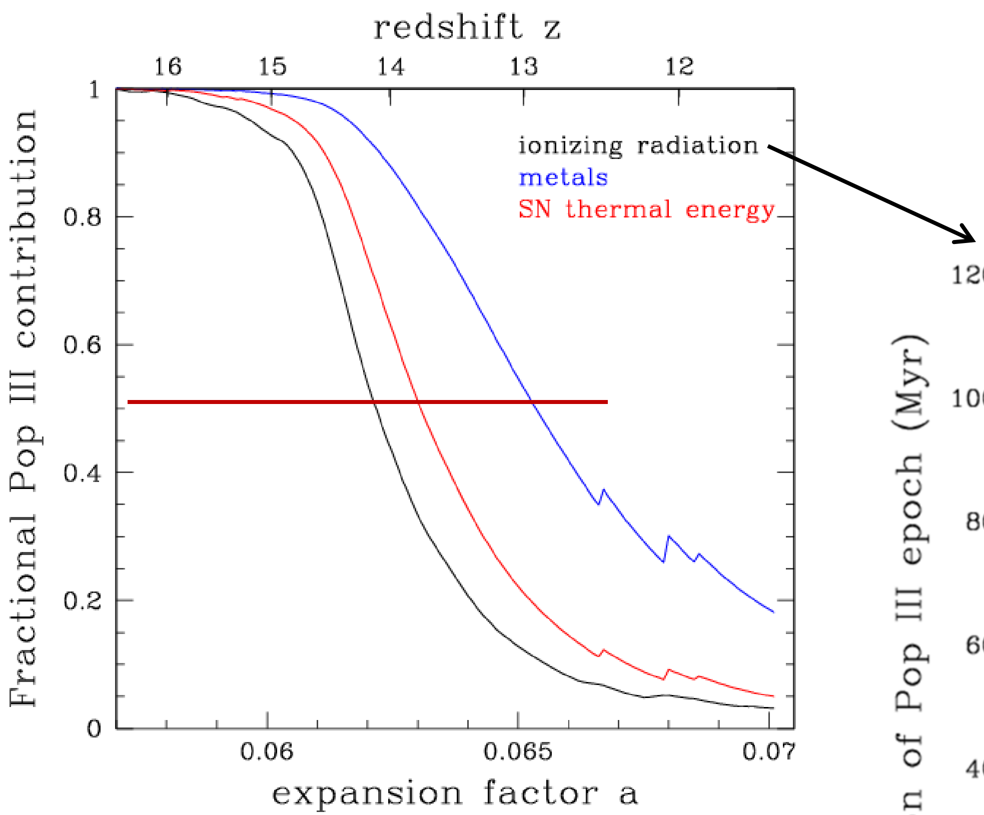
(based on Abel et al. 2002)

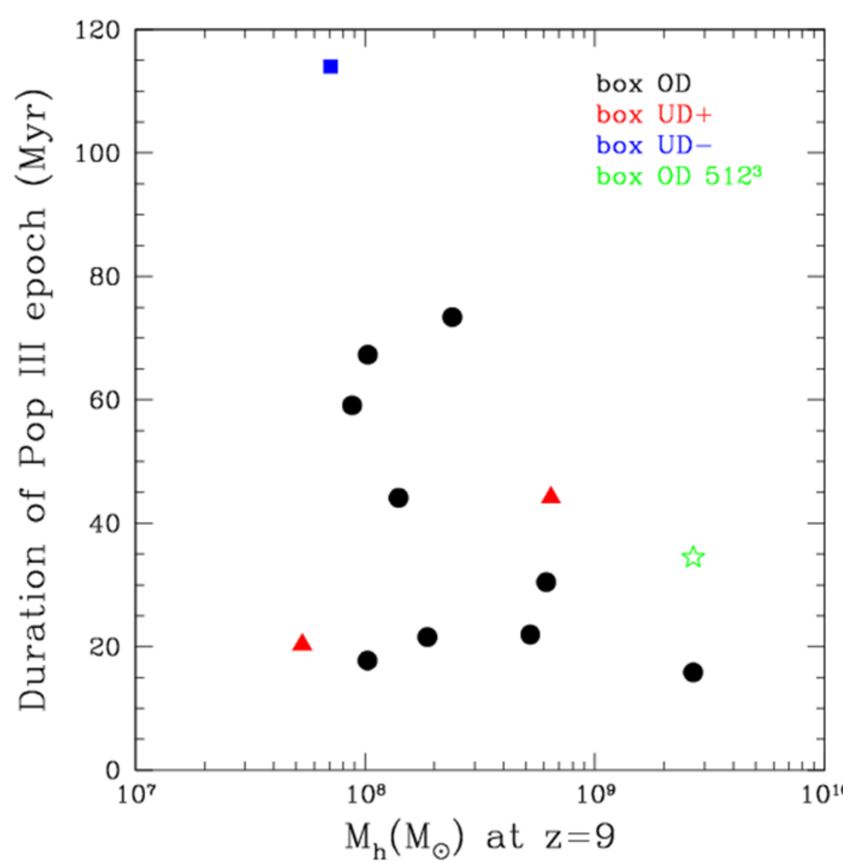
only two choices for stellar mass

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

to study maximum feedback effect

From Pop III to Pop II

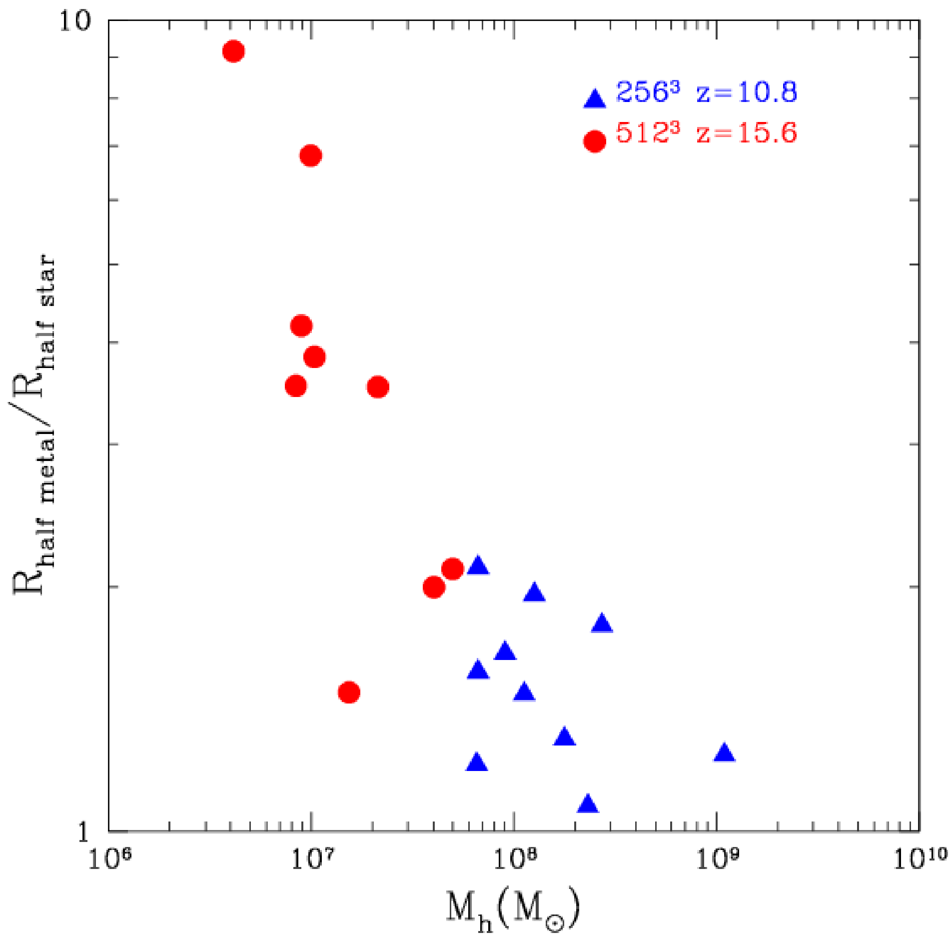




The duration of Pop III era is less than 100 Myr in a given galaxy

Metals spread from the immediate star formation regions, but not too far in massive galaxies

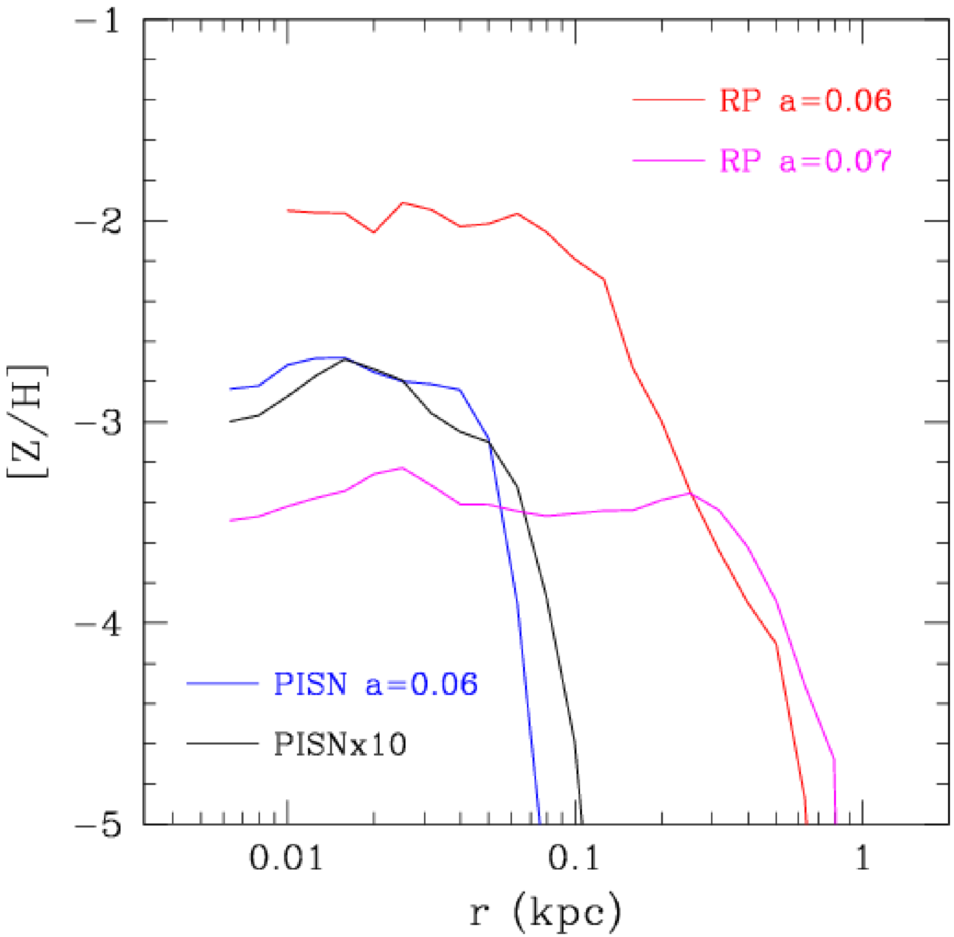
half-mass radius of metals / half-mass radius of stars



halo mass

New feedback effect: radiation pressure of massive stars

Metals spread much further



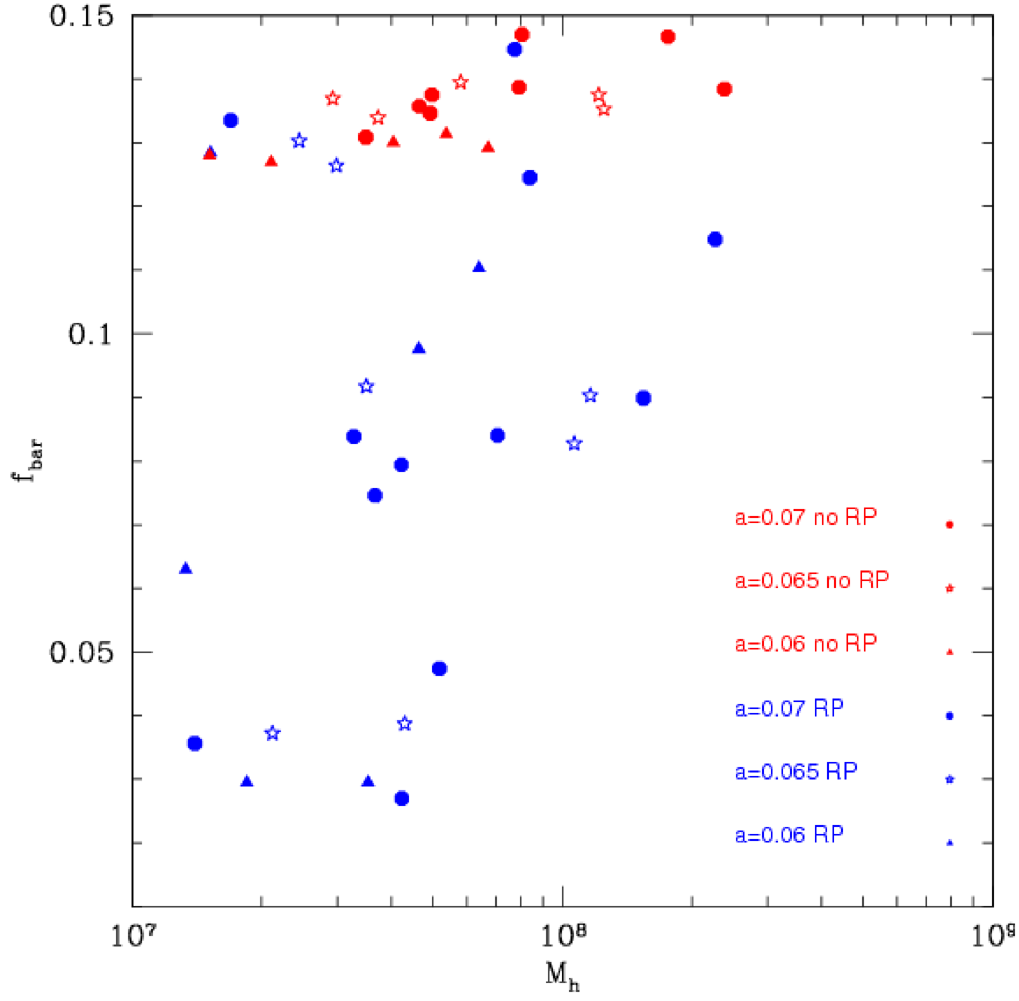
$L_{rad}/c/area$

spread over 27 cells around a massive star for ~ 3 Myr

pushes the gas much further and reduces the central density

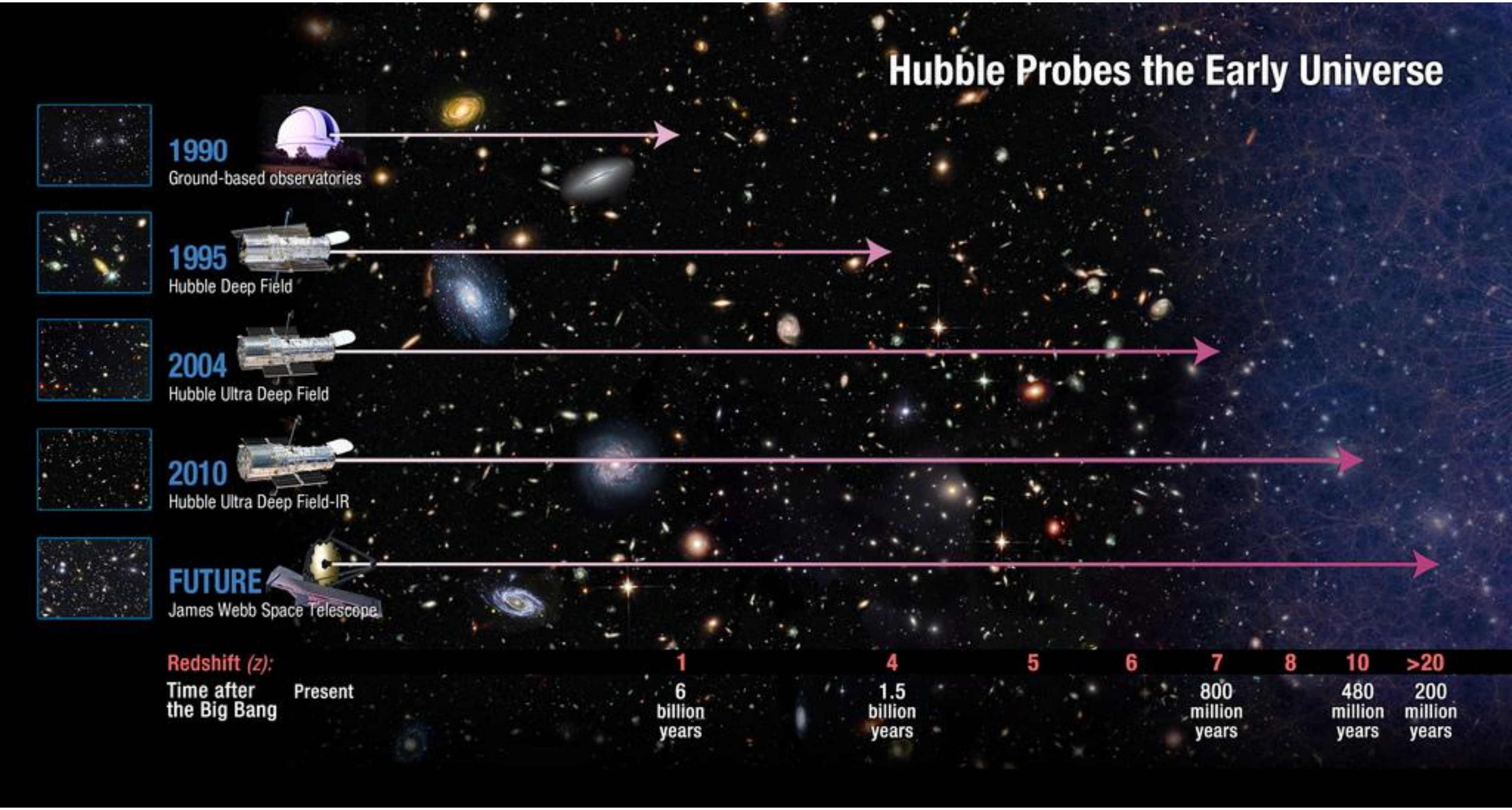
Muratov et al. (2012, in prep)

Baryon fraction of halos can be significantly reduced by radiation pressure



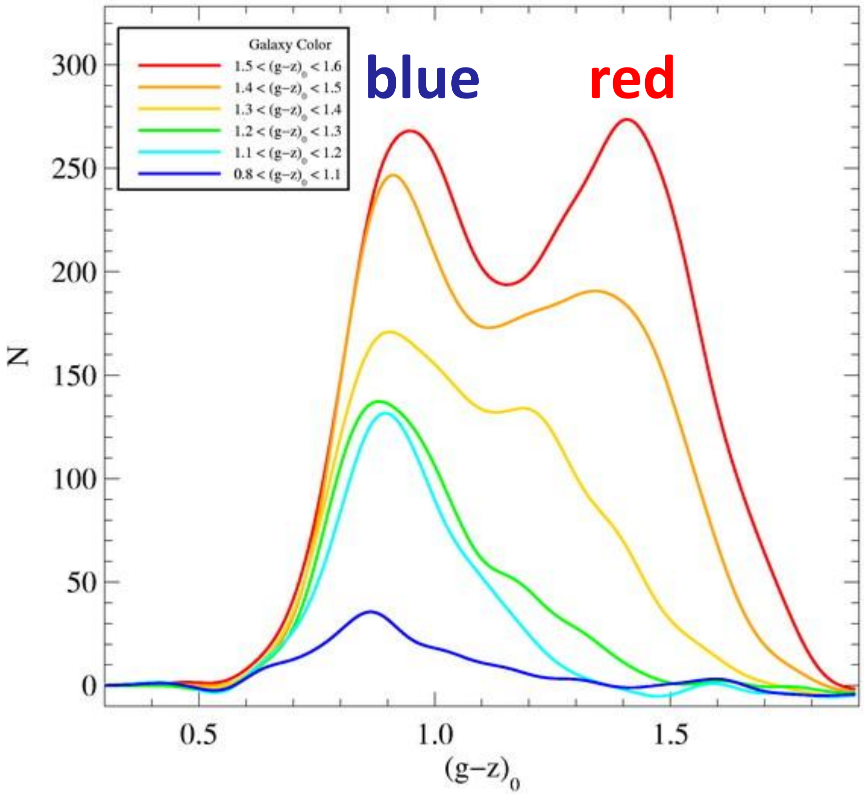
Another Frontier:

Globular clusters are unique and important tracers of early star formation in galaxies

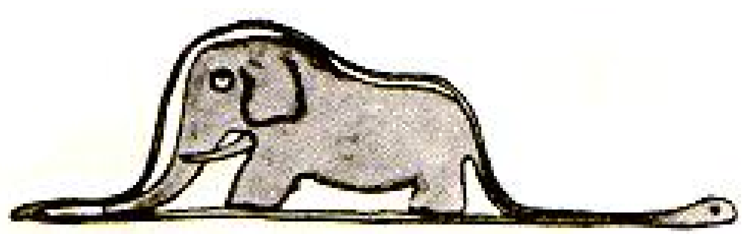


Metallicity distribution encodes the conditions of the galactic ISM at the time of cluster formation

- Bimodality of color and metallicity in most galaxies
- Usual interpretation: red clusters are associated with host galaxy, blue clusters formed somehow independently



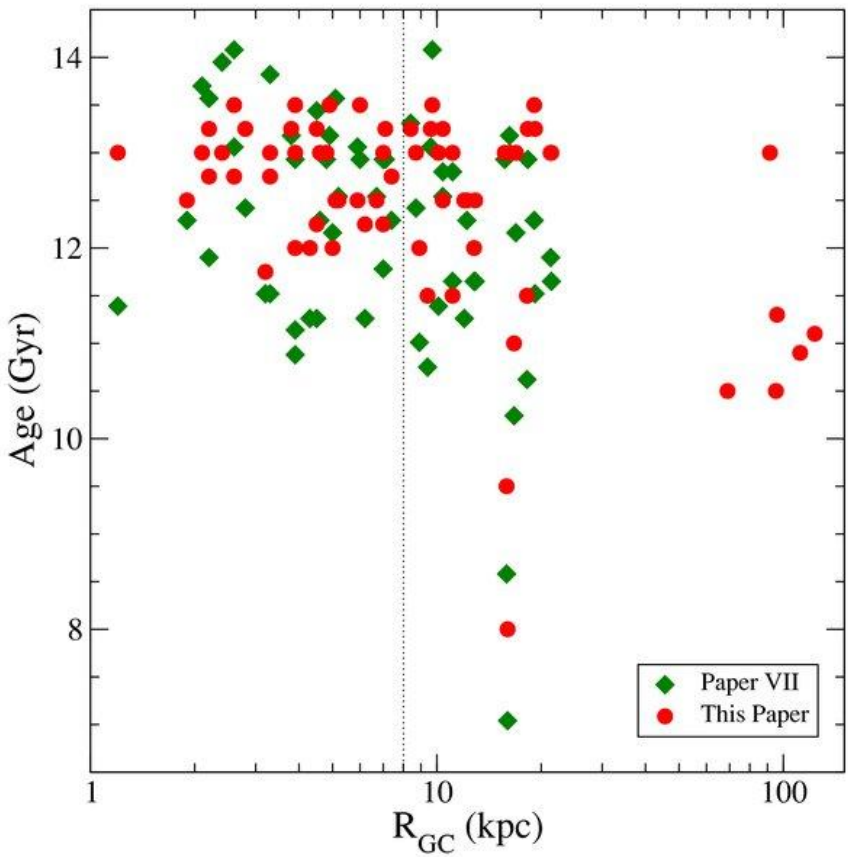
Understanding the origin of the metallicity distribution is key to reconstructing the epoch of most active star formation in galaxies

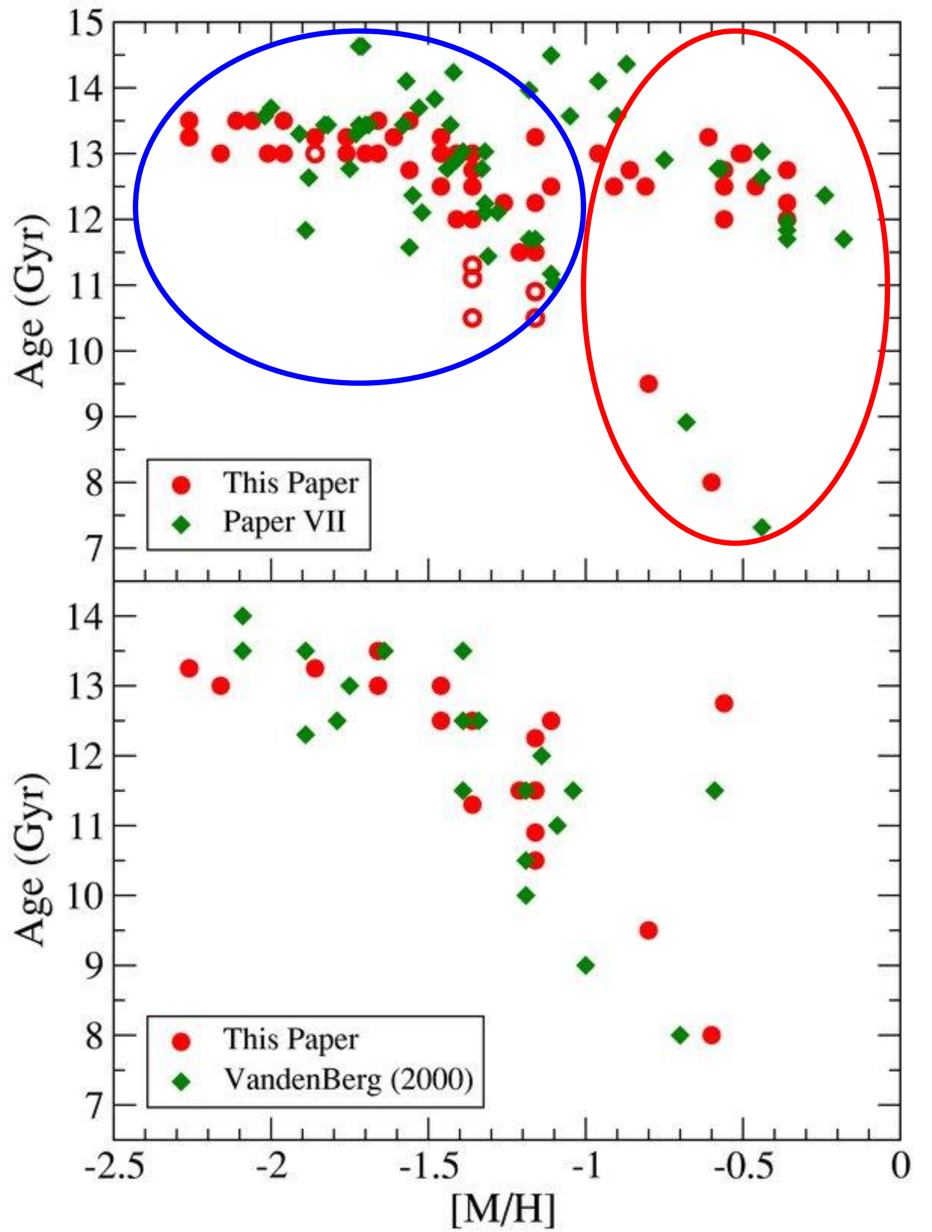


Peng et al. (2006) – ACS Virgo Cluster Survey

Galactic globular clusters have a spread of ages and not too low metallicity – must form over an extended period

age spread increases with metallicity and distance from the Galactic center

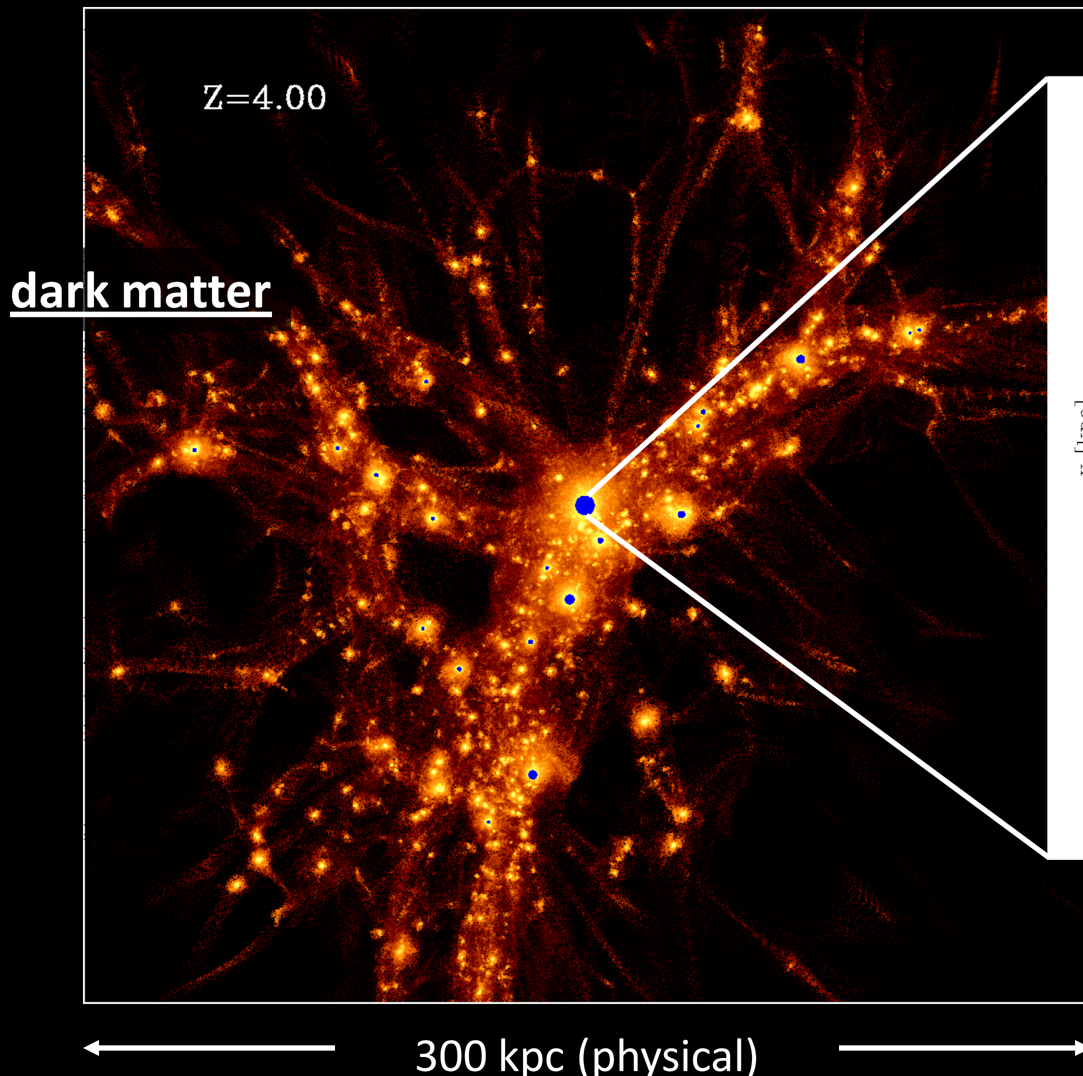


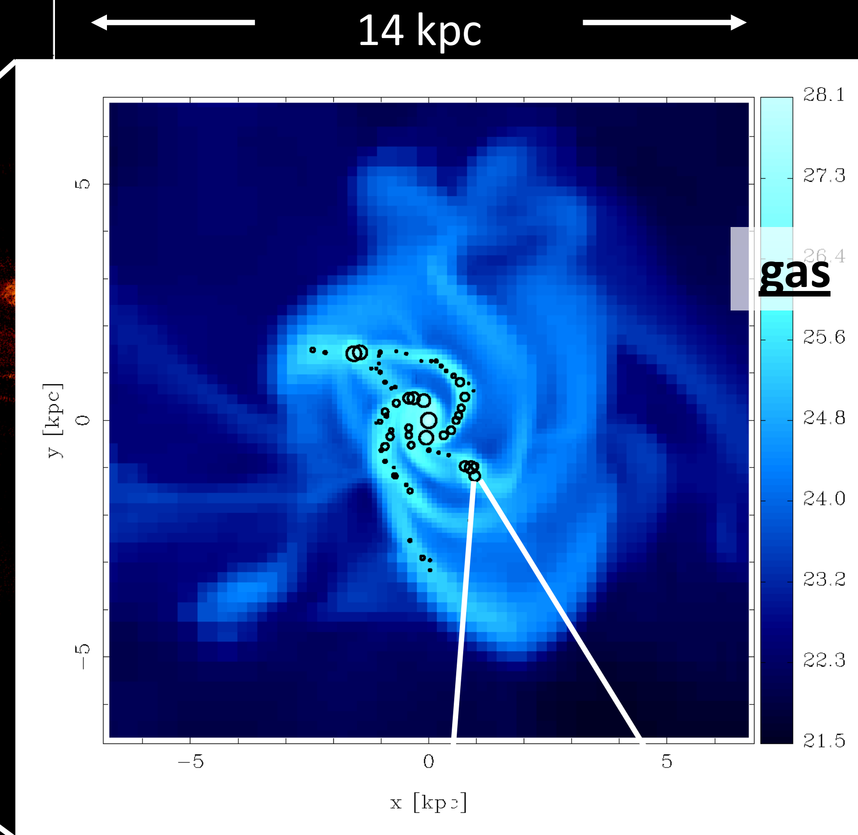


Dotter et al. (2010)

Marín-Franch et al. (2009)

Such *dense and massive* molecular clouds are now resolved by hydrodynamic cosmological simulations with adaptive mesh refinement

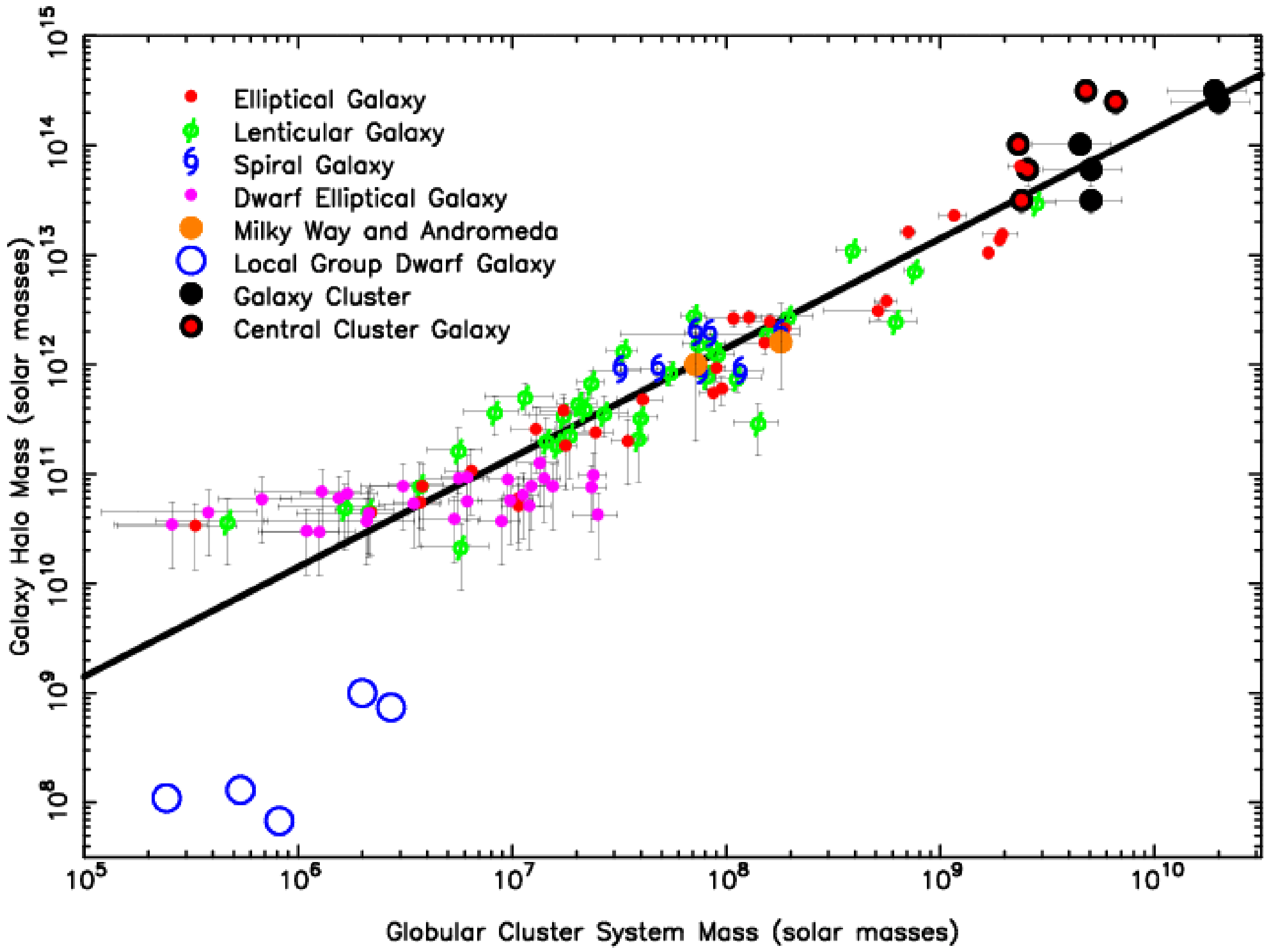




A. Kravtsov & OG (2005): power-law mass function

$M_{GC} \approx 10^{-4} M_{host}$

Recent observations confirm that the globular cluster formation efficiency is similar in galaxies of (almost) all type and environment



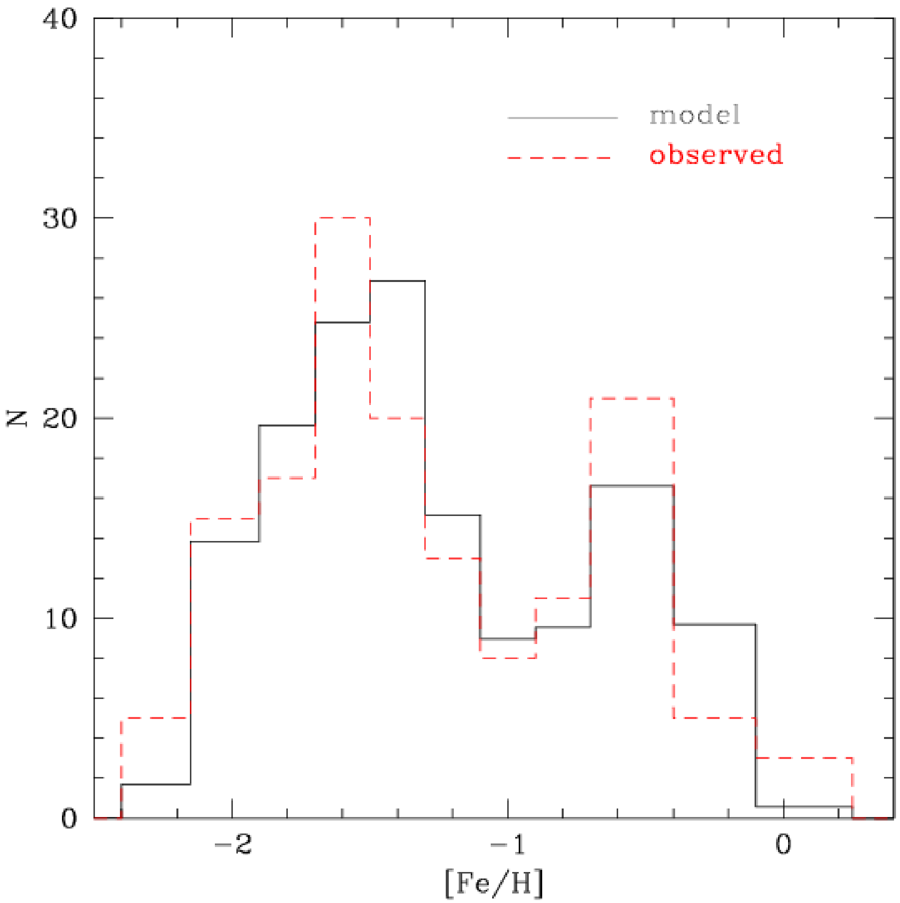
Spitler & Forbes (2009)

$$M_{GC} \approx 10^{-4} M_{host}$$

Can a single formation mechanism produce bimodality? Yes

Model: GC formation is triggered by gas-rich mergers

(only needed to form GCs before the bulk of field stars)



begin with cosmological simulations of halo formation

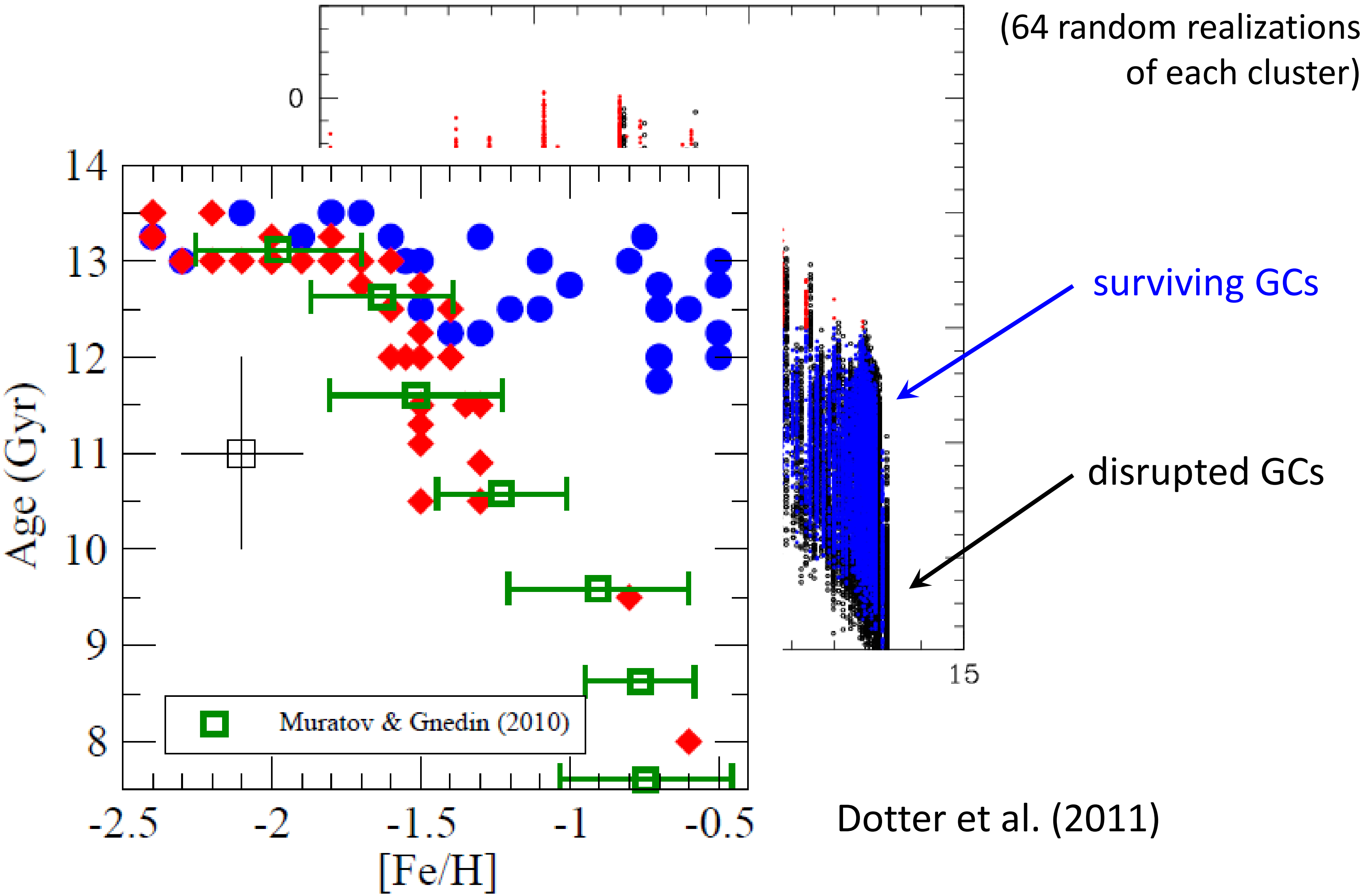
supplement halos with cold gas mass based on observations

use M_{GC} - M_{gas} relation from hydro simulations

metallicity from observed M_*-Z relation for host galaxies, include evolution with time

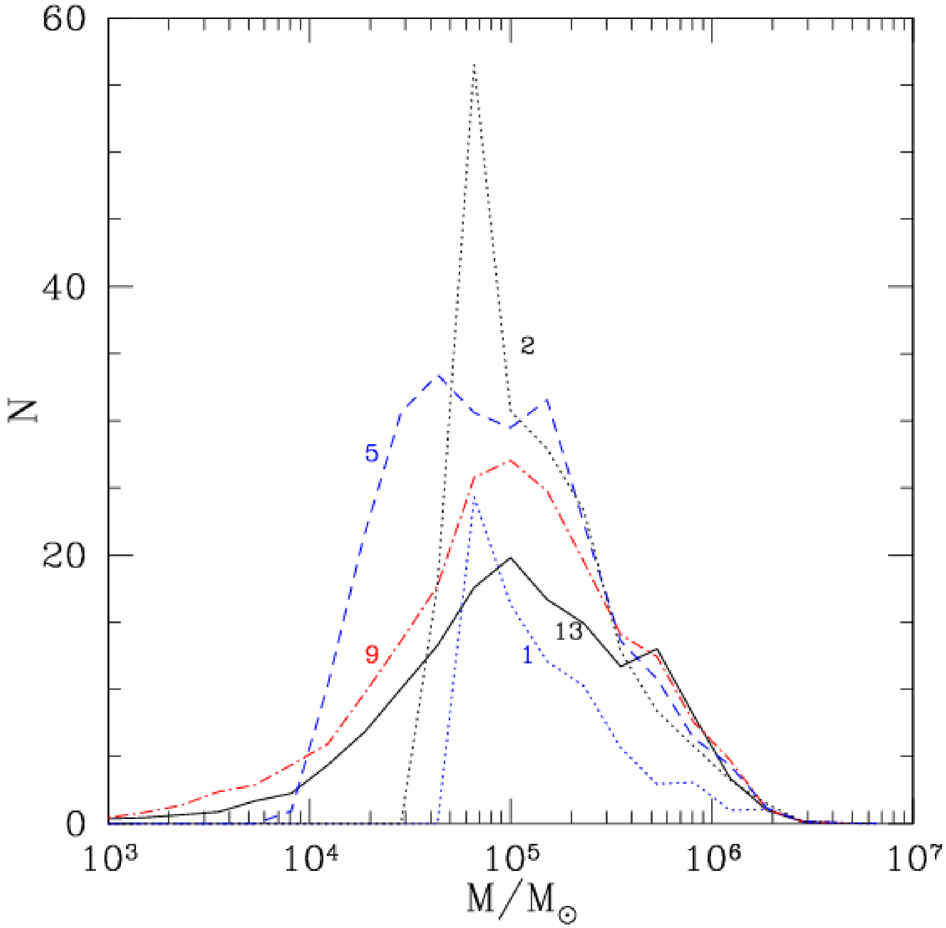
Muratov & OG (2010)

The number of massive mergers declines with cosmic time, results in a spread of cluster ages of several Gyr



Dotter et al. (2011)

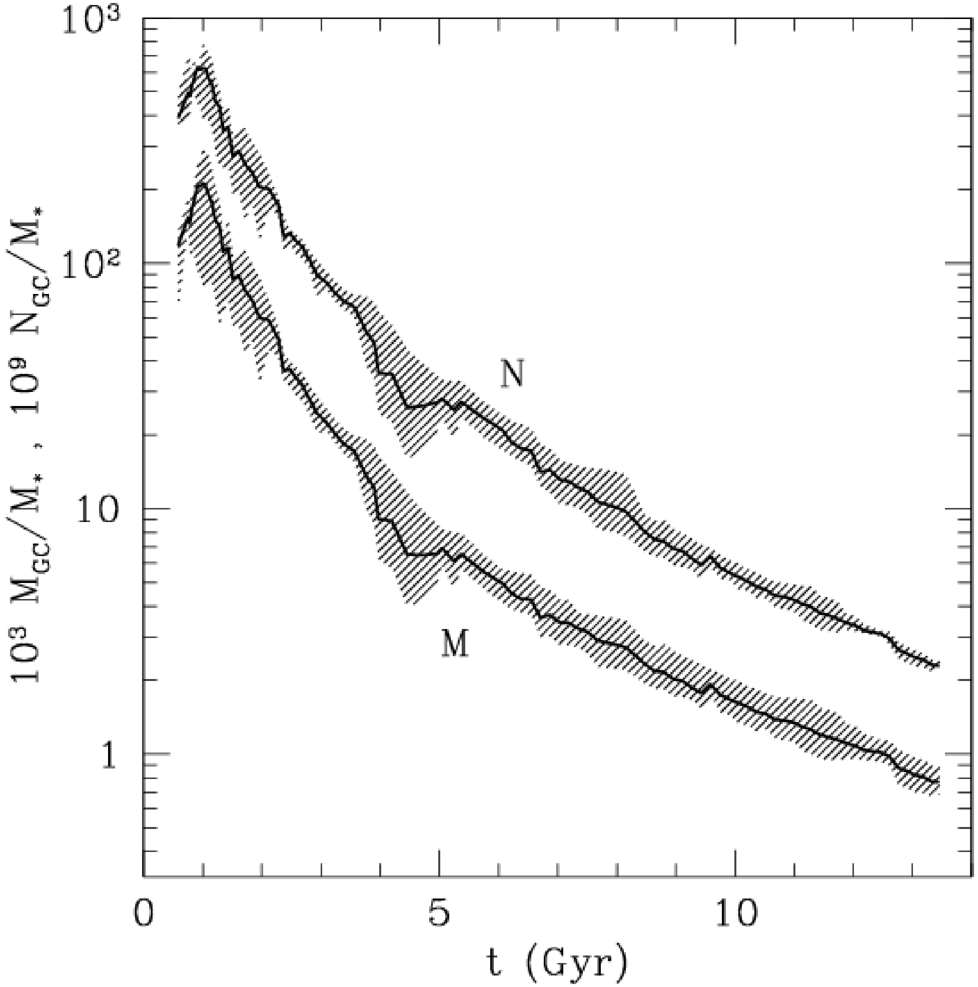
Evolution of the cluster mass function: competition between formation and disruption



Dynamical disruption is partly responsible for bimodality: it removes low-mass clusters

Only massive clusters survive, therefore need to follow only mergers of massive protogalaxies.

They are rare at low redshift.



Globular clusters were a much more dominant component of galactic star formation at $z>3$ than in the last 10 Gyr.

Now they are important to us because they preserve the chemical signature of the early star formation in the universe.

Summary

- Epoch of Pop III star dominance is short-lived *(less than 100 Myr in a given galaxy)*
- Transport of metals into IGM is still model-dependent *(some key physics may be missing)*
- Globular clusters mark the episodes of most active star formation in galaxies
- Early galaxies may have up to ~20% of stars forming in massive clusters