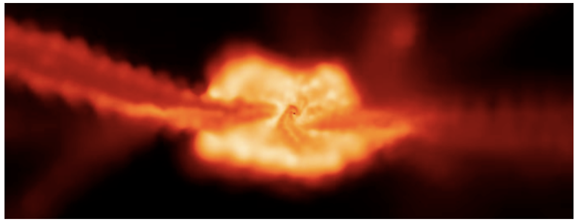


The First Stars and Galaxies: Challenges for the Next Decade
March 8-11, 2010
Austin, Texas

The Pop III/II Transition

Raffaella Schneider

INAF/Osservatorio Astrofisico di Arcetri

What are the minimal conditions for the formation of the first low-mass long-lived stars?

cooling by metals fine-structure lines

Omukai (2000); Bromm et al. (2001); Schneider et al. (2002); Bromm & Loeb (2003); Santoro & Shull (2006); Jappsen et al. (2007); Smith, Sigurdsson & Abel (2008); Jappsen et al. (2009); Hocuk & Spaans (2010)

cooling by dust grains thermal emission

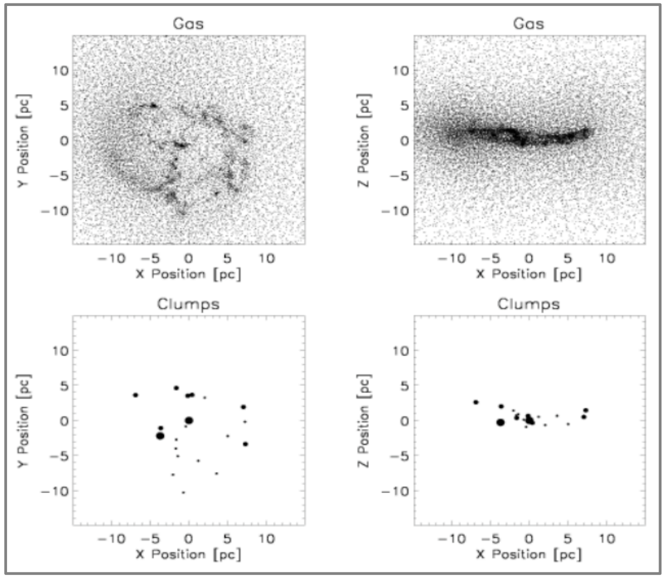
Schneider et al. (2003), (2006); Omukai et al. (2005); Tsuribe & Omukai (2006); Clark, Glover & Klessen (2008)

the role of metals

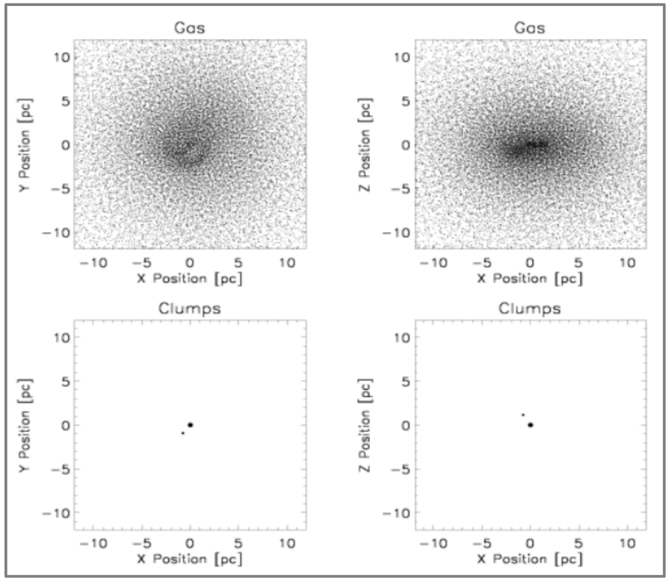
★ Bromm, Ferrara, Coppi & Larson (2001)

SPH simulation isolated halo with $M_{halo} = 2\times10^6\ M_{sun}$ at $z = 30$ no H_2 and only metal-line cooling (C, N, O, Fe, S, Si)

Run A: $Z = 10^{-3}\ Z_{sun}$



Run B: $Z = 10^{-4}\ Z_{sun}$



$t_{cool} \approx t_{ff}$

onset of vigorous fragmentation at
$Z_{cr} \approx 5 \times 10^{-4}\ Z_{sun}$

$t_{cool} > t_{ff}$

$n \approx 10^{2.5}\ cm^{-3}$ $T \approx 5000$ K

$$\Lambda(Z) \simeq 3 \times 10^{-30} \mathrm{erg\ cm^{-3}\ s^{-1}} \left(\frac{Z}{10^{-4} Z_\odot}\right) \left(\frac{n_H}{1\mathrm{cm}^{-3}}\right)^2 = \Gamma_{ad} \simeq 10^{-24} \mathrm{erg\ cm^{-3}\ s^{-1}} \left(\frac{T}{5000\mathrm{K}}\right) \left(\frac{n_H}{300\mathrm{cm}^{-3}}\right)^{3/2}$$

cooling rate compressional heating rate

Distinguishing between different coolants

$$[A/H] = \log_{10}(N_A/N_H) - \log_{10}(N_A/N_H)_\odot$$

★ Bromm & Loeb (2003)

one-zone model CII (158 μm) and OI (63, 145 μm) line cooling

initial conditions: T_c=200 K n_c=10^4cm^{-3}

$$\underbrace{\Lambda_{CII,OI}(n_c, T_c)}_{\text{cooling rate}} > \underbrace{1.5\, n_c\, KT_c/t_{ff}}_{\text{compressional heating rate}}$$

$[C/H]_{crit} \cong -3.5 \pm 0.1$ $[O/H]_{crit} \cong -3.02 \pm 0.2$

★ Santoro & Shull (2006)

CII (158 μm), OI (63, 145 μm), SiII (35 μm), FeII(26, 35 μm) line cooling

$[C/H]_{crit} \cong -3.48$ $[O/H]_{crit} \cong -3.78$

$[Si/H]_{crit} \cong -3.54$ $[Fe/H]_{crit} \cong -3.52$

Fragment masses: $$M_J = (700\, M_\odot)\left(\frac{T_{frag}}{200\ K}\right)^{3/2}\left(\frac{n_H}{10^4\ cm^{-3}}\right)^{-1/2}$$

$M_{J,C} \cong 1000\, M_{sun}$ $M_{J,O} \cong 90\, M_{sun}$

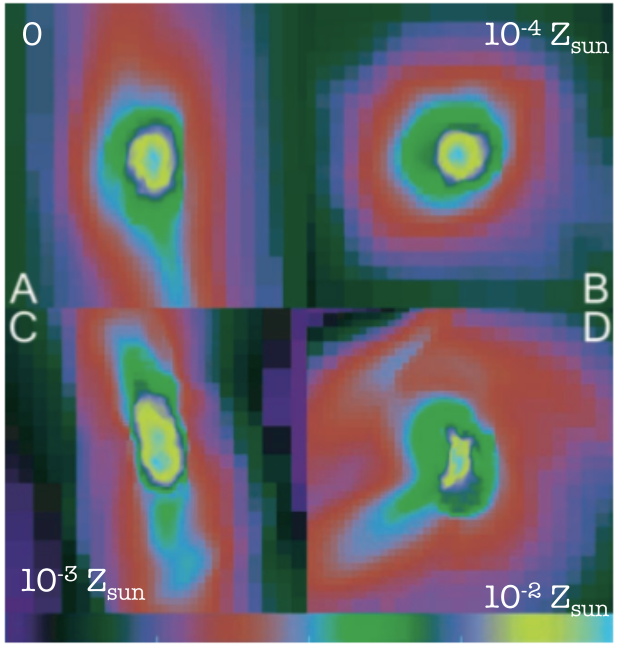
$M_{J,Si} \cong 130\, M_{sun}$ $M_{J,Fe} \cong 50\, M_{sun}$

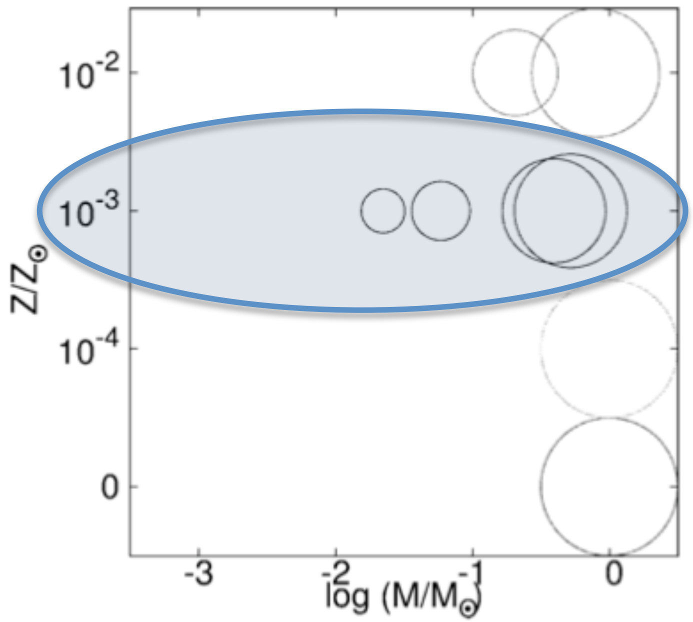
Numerical simulations with H_2 and metal line cooling

★ Smith & Sigurdsson (2007)

3D AMR simulation   cosmological initial conditions 5×10^5 Msun halo at z = 18

No UV background is assumed: cooling from H2, CI (370μm, 610μm), OI, SiII, FeII and SI (25 μm)





multiple clump formation when $10^{-4}\,Z_{sun} < Z_{cr} \leq 10^{-3}\,Z_{sun}$

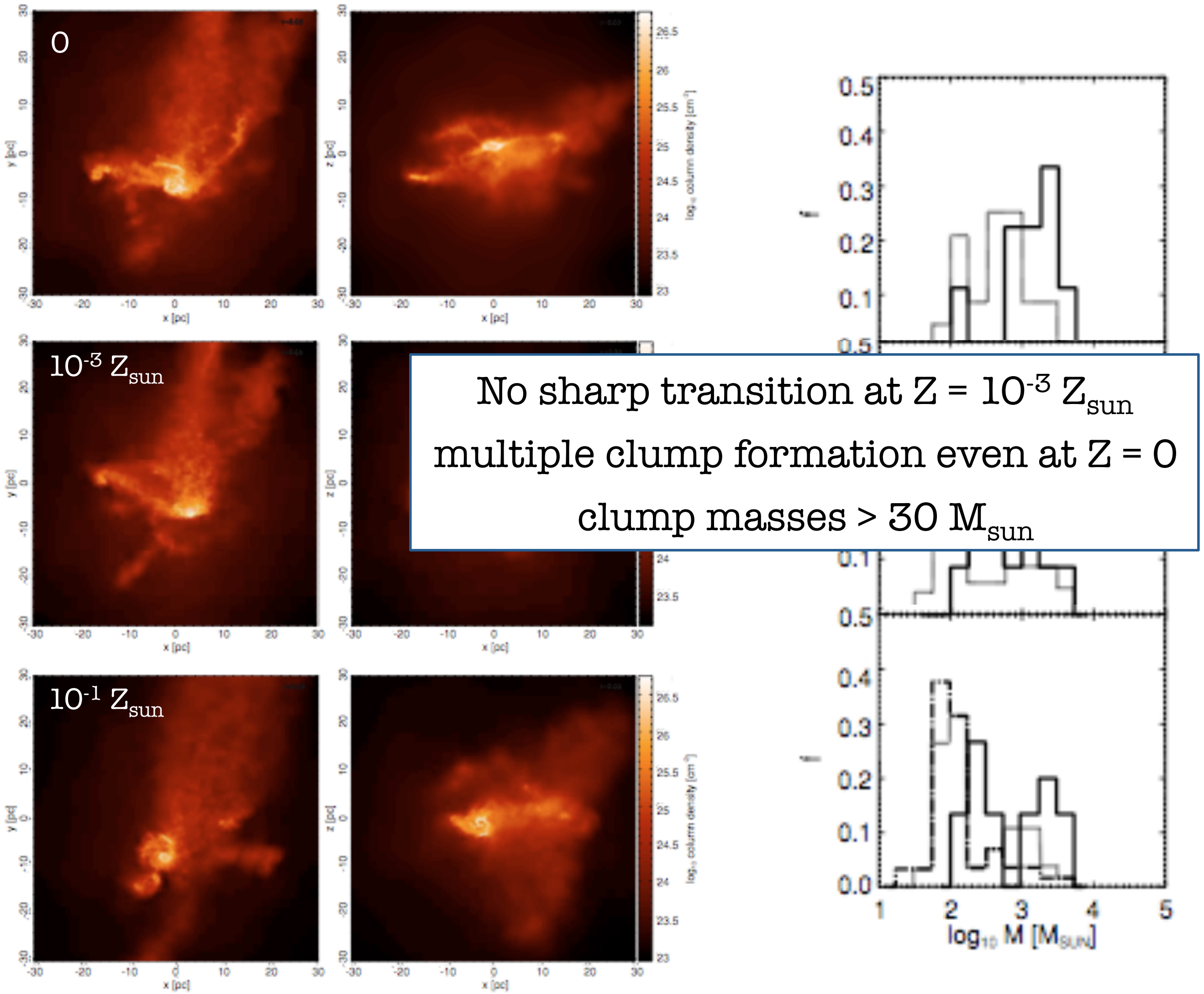
is this enough to mark a shift from the primordial to a modern IMF?

dependence on the initial conditions

★ Jappsen et al. (2007; 2009a; 2009b)

3D SPH simulation   molecular and atomic fine structure line cooling

(1) Cold initial conditions: isolated halo with $M_{halo} = 2\text{x}10^6\ M_{sun}$ at z = 30 (same as in Bromm et al. 2001)



No sharp transition at $Z = 10^{-3}\ Z_{sun}$

multiple clump formation even at Z = 0

clump masses > 30 M_{sun}

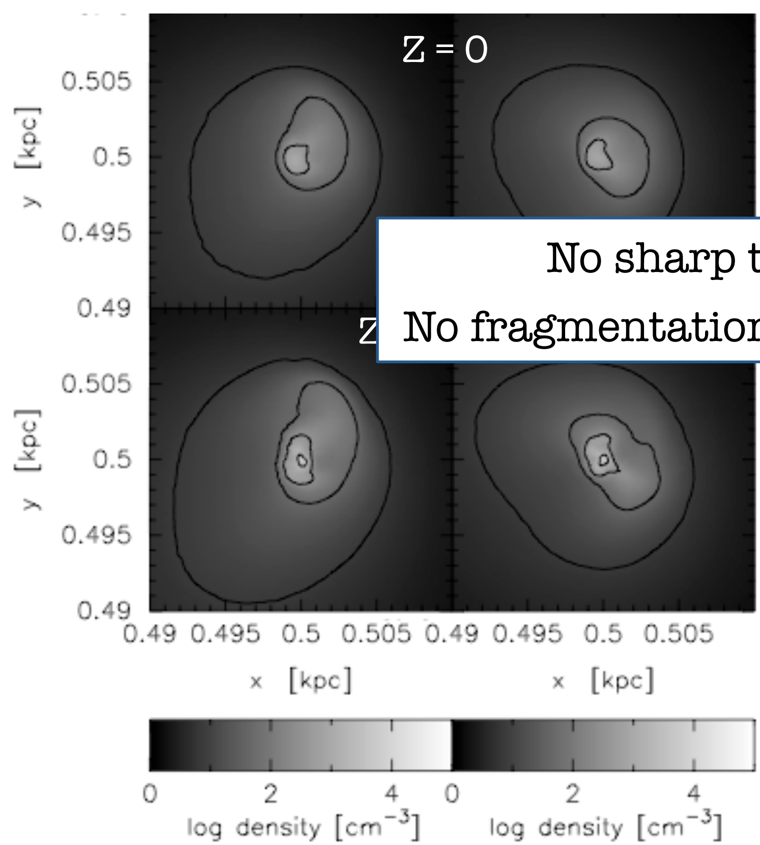
dependence on the initial conditions

★ Jappsen et al. (2007; 2009a; 2009b)

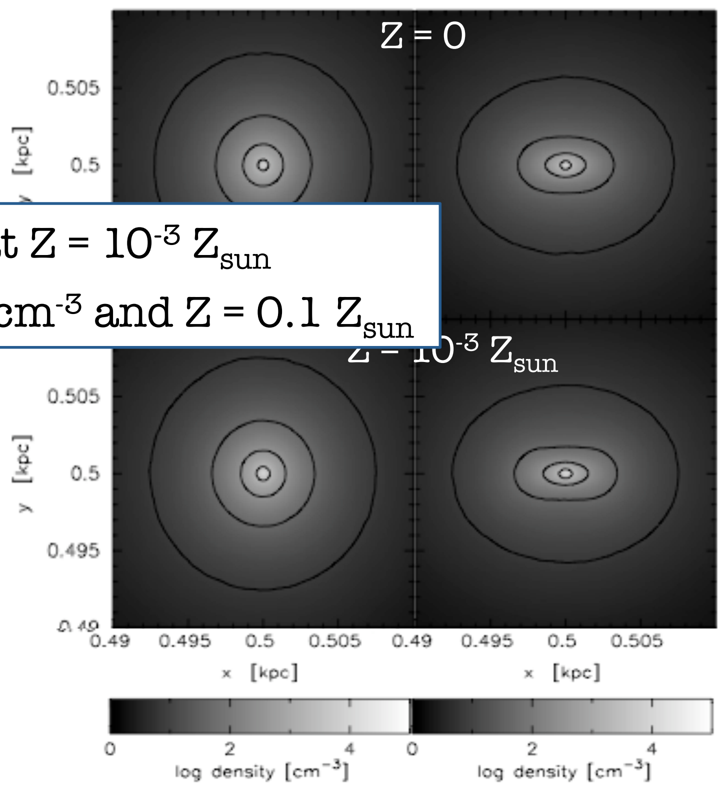
3D SPH simulation   molecular and atomic fine structure line cooling

(2) Warm initial conditions: isolated halo with $M_{halo} = 7.8 \times 10^5 M_{sun}$ at $z = 25$ in a fossil HII region

turbulence



rotation



No sharp transition at $Z = 10^{-3} Z_{sun}$

No fragmentation up to 10^5 cm^{-3} and $Z = 0.1 Z_{sun}$

What are the minimal conditions for the formation of the first low-mass long-lived stars?

cooling by metals fine-structure lines

Omukai (2000); Bromm et al. (2001); Schneider et al. (2002); Bromm & Loeb (2003); Santoro & Shull (2006); Jappsen et al. (2007); Smith, Sigurdsson & Abel (2008); Jappsen et al. (2009); Hocuk & Spaans (2010)

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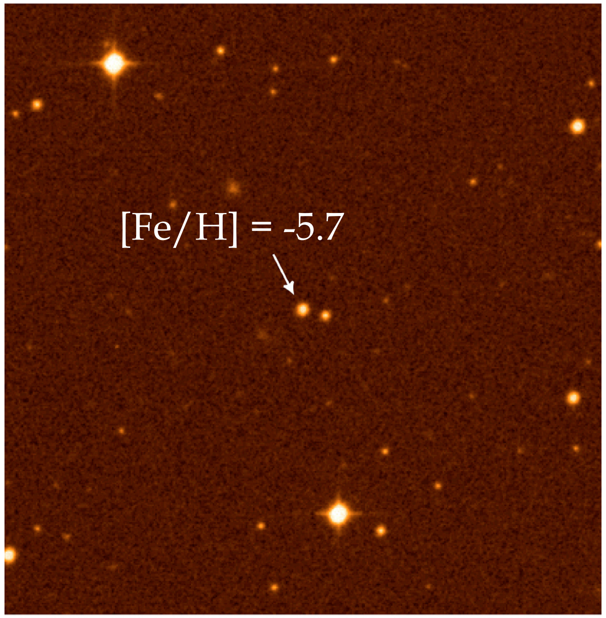
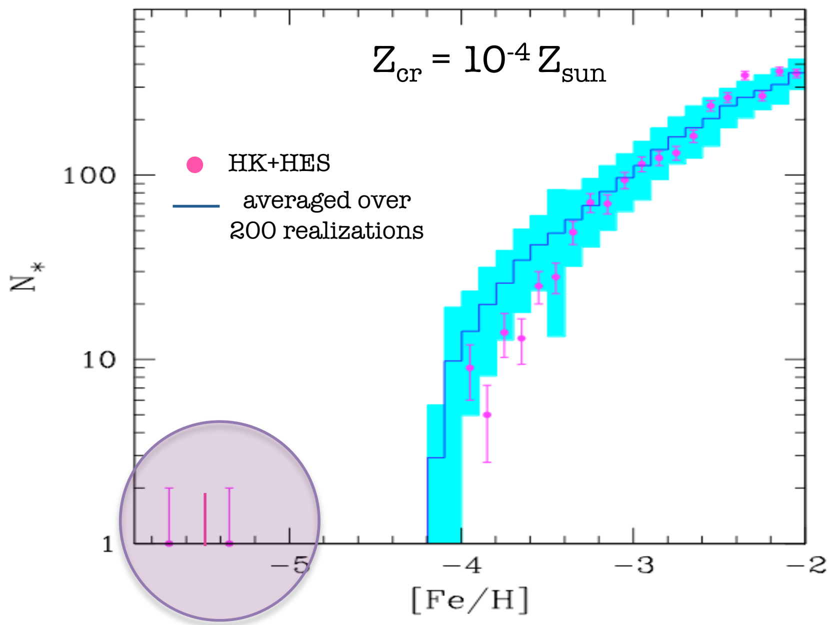


Christlieb et al 2002,2004, 2008

Metallicity Distribution Function

HK+HES sample (2756 stars [Fe/H] < -2)



Salvadori, Schneider & Ferrara (2007)

Nature **422** (2003), 869–871 (issue 24 April)

LOW-MASS RELICS OF EARLY STAR FORMATION

R. Schneider * †, A. Ferrara ‡, R. Salvaterra‡, K. Omukai § and V. Bromm ¶

the role of dust grains

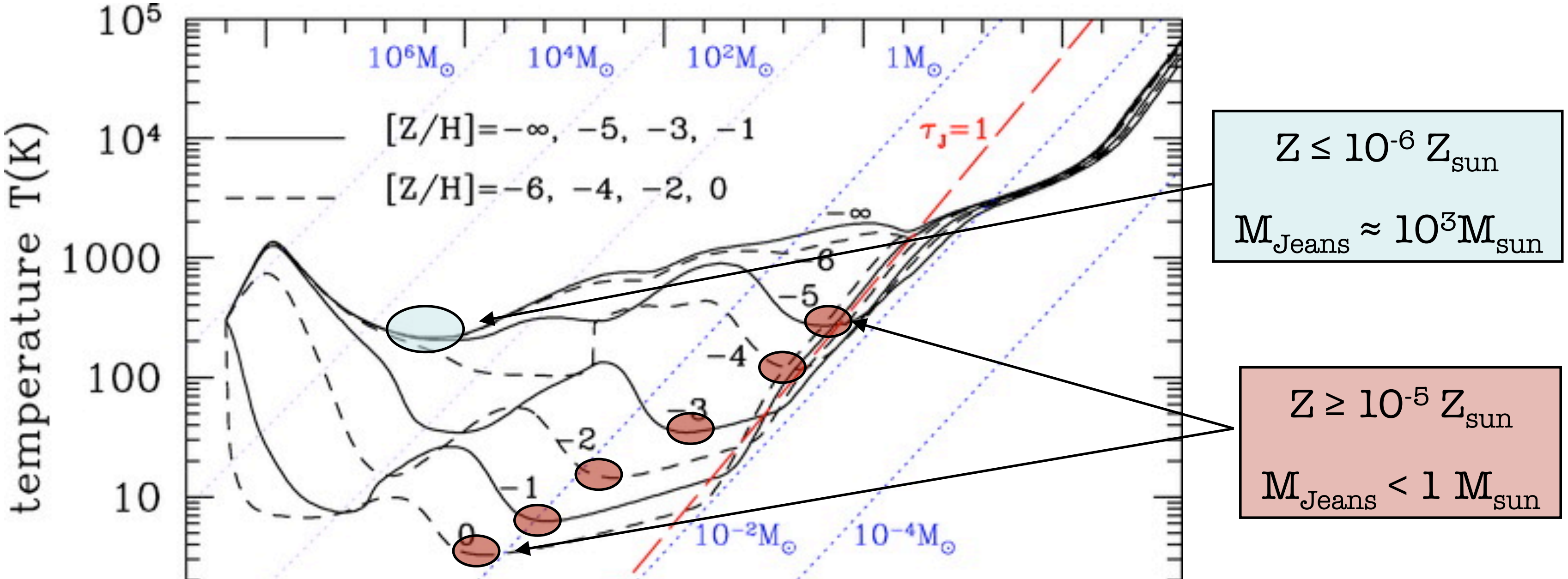
★ Schneider et al. (2002; 2003; 2006), Omukai et al. (2005)

One-zone model with simplified dynamics but detailed chemical and thermal evolution (478 reactions for 50 species)

Molecular cooling (H_2, HD, H_2O, OH) metal line cooling (CI, CII, OI)

Dust grains (H_2 formation, cooling via thermal emission)

solar composition, present-day dust properties ($M_{dust}/M_{met} \cong 0.47$)

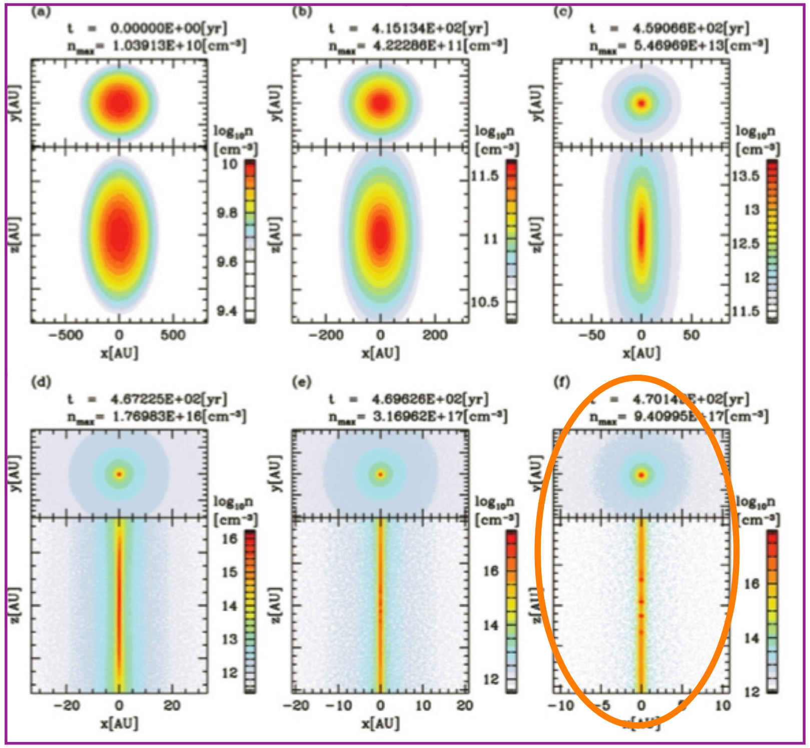


SHARP TRANSITION IN FRAGMENTATION SCALES
for $10^{-6}\,Z_{sun} < Z_{cr} \leq 10^{-4}\,Z_{sun}$

simulations of dust-induced fragmentation

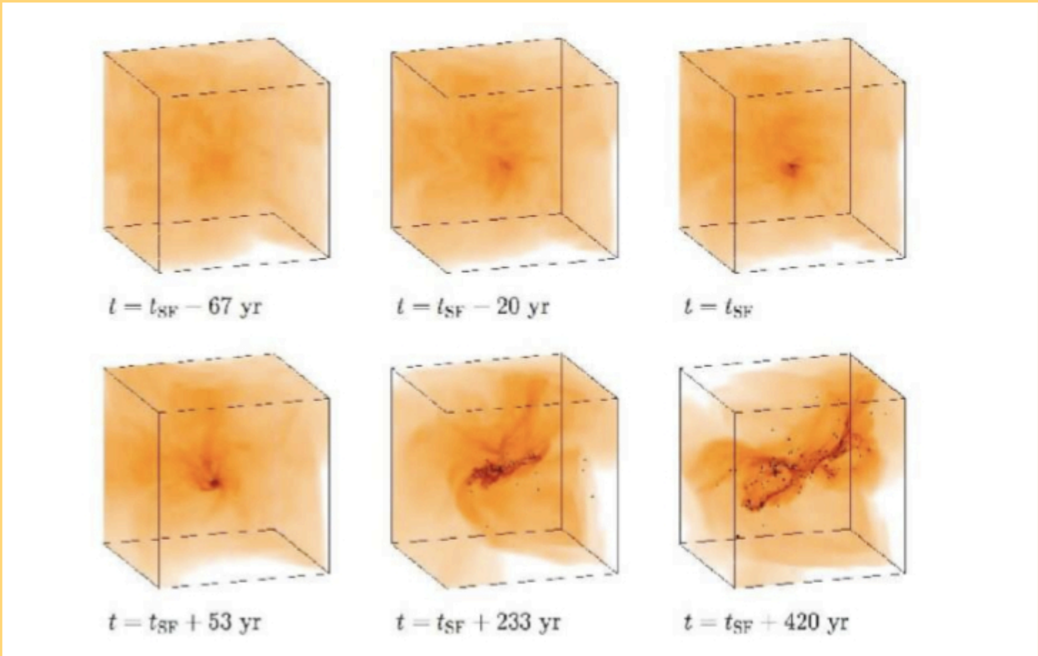
★ Tsuribe & Omukai (2006)

$Z=10^{-5}\ Z_{sun}\quad \varepsilon=2$



★ Clark, Glover & Klessen (2008)

$Z = 10^{-5}\ Z_{sun}$ cloud including the effect of rotation

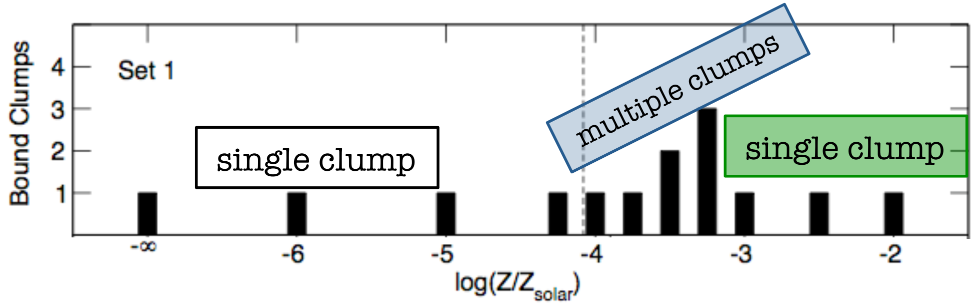


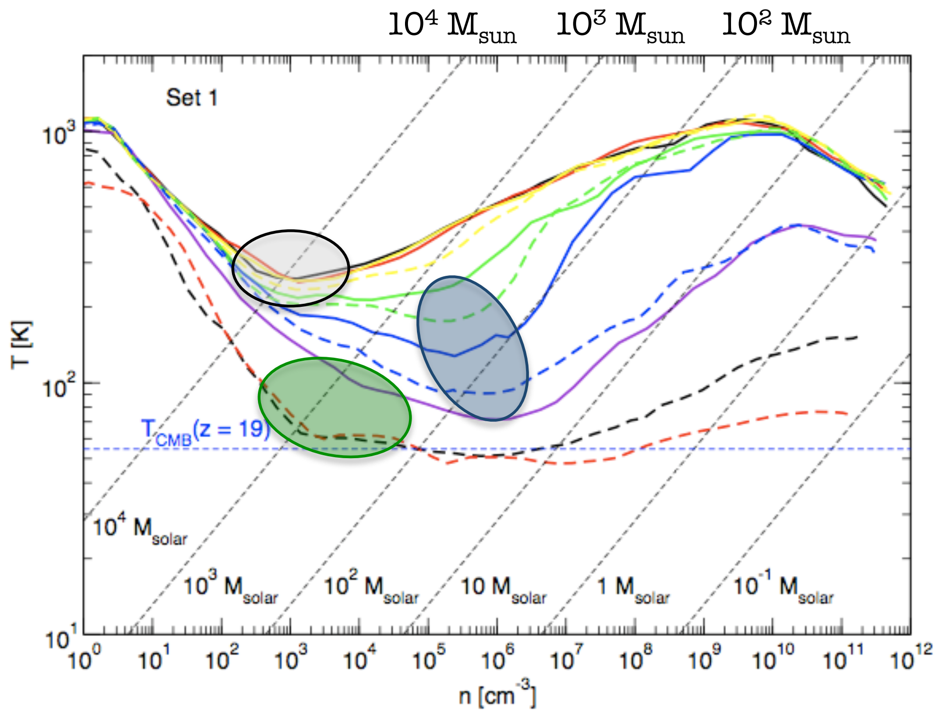
formation of a cluster of stars with $M_{ch} \sim 1\ M_{sun}$

at $Z_{cr} = 10^{-5}\ Z_{sun}$

simulating the collapse in the presence of the CMB field

- ★ Smith et al. (2008)
- ★ Jappsen et al. (2009a,b)

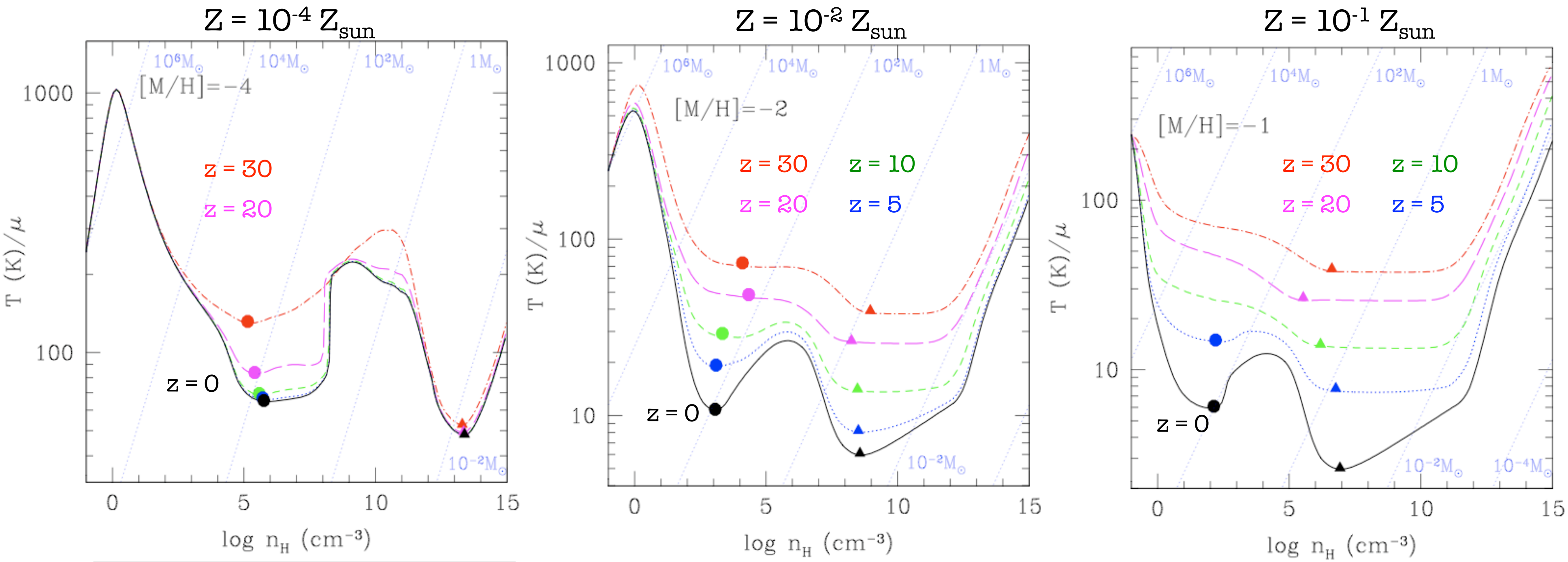




CMB inhibits fragmentation at high metallicities

thermal evolution with metals, dust & the CMB

★ Schneider & Omukai (2010)

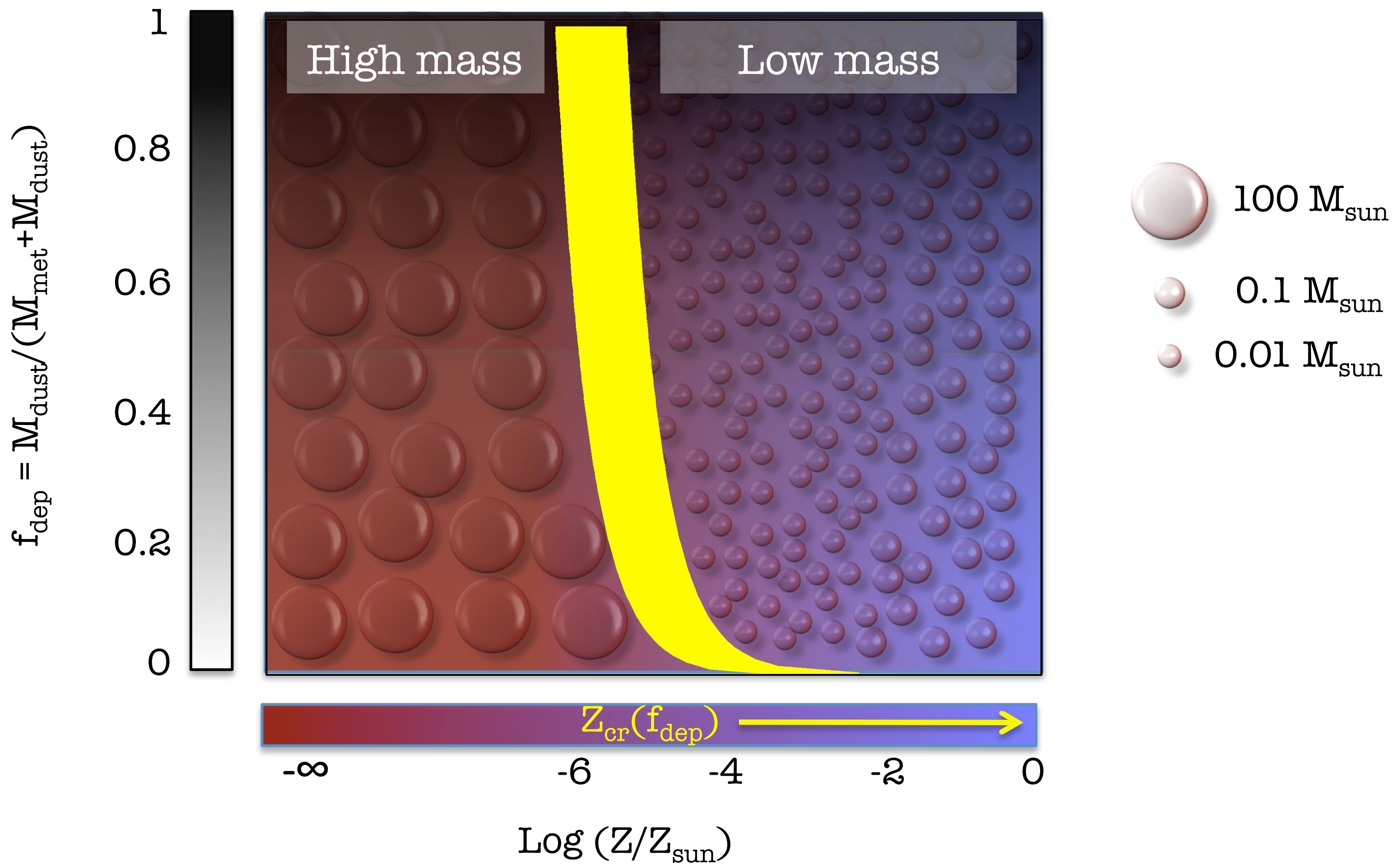


the increase in T_{dust} lowers the efficiency of H_2 formation dust induced fragmentation is not affected

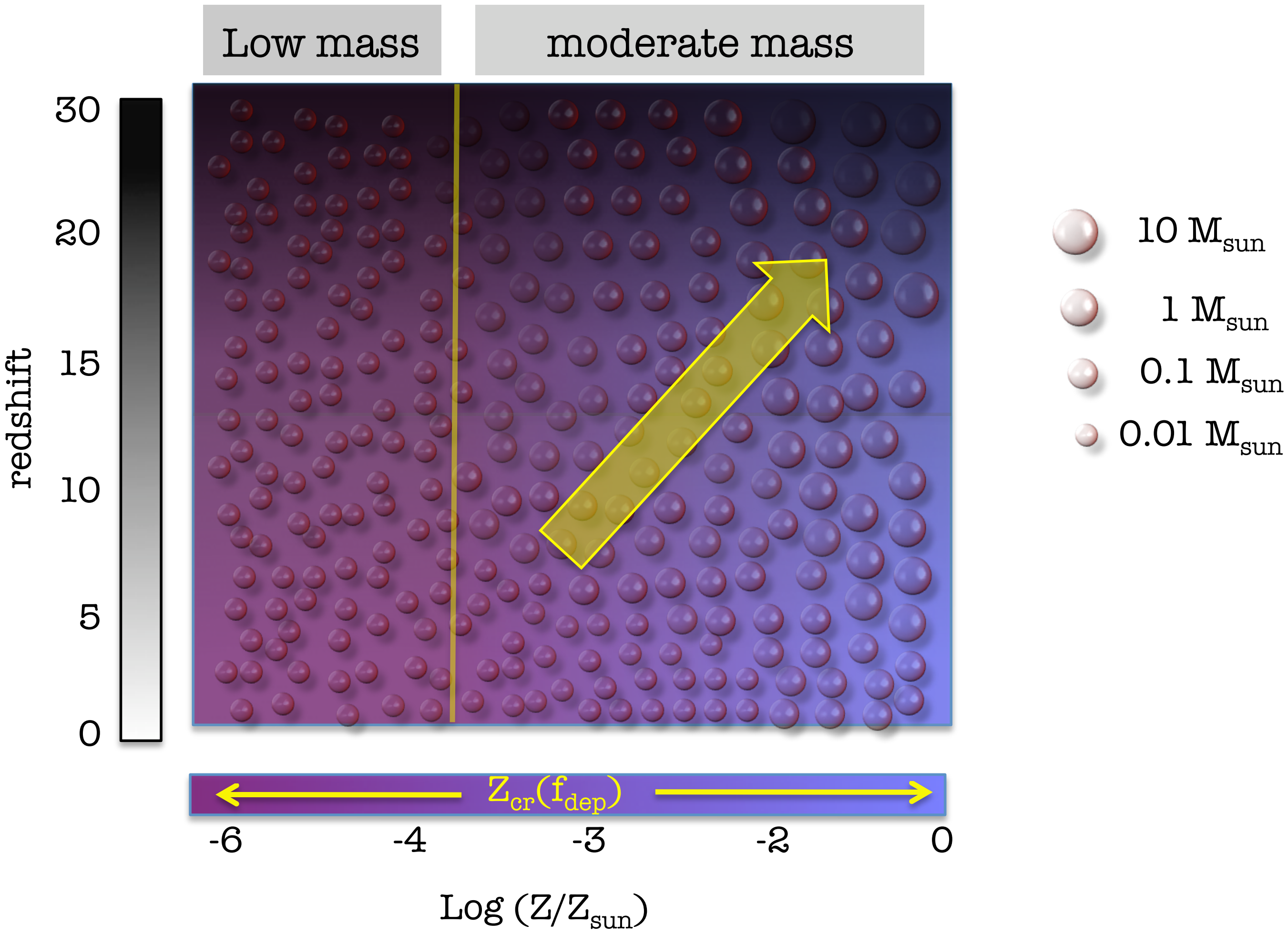
$T_{gas} \approx T_{dust} \approx T_{CMB}$ thermal evolution is affected at all densities

at the highest Z and z the 2 fragmentation epochs merge

minimal conditions for the first low mass star formation

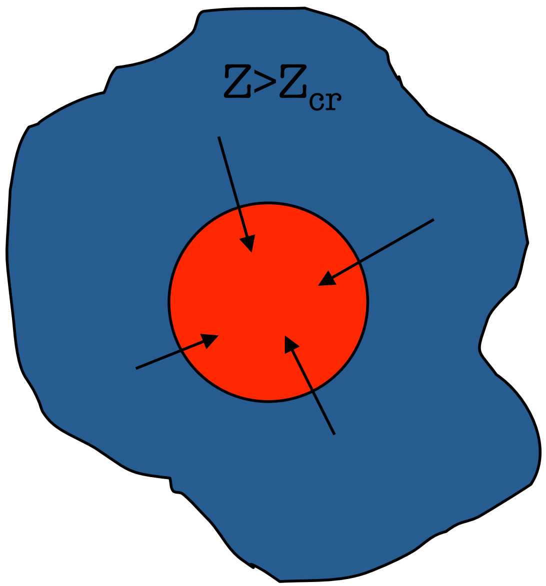


minimal conditions for the first low mass star formation

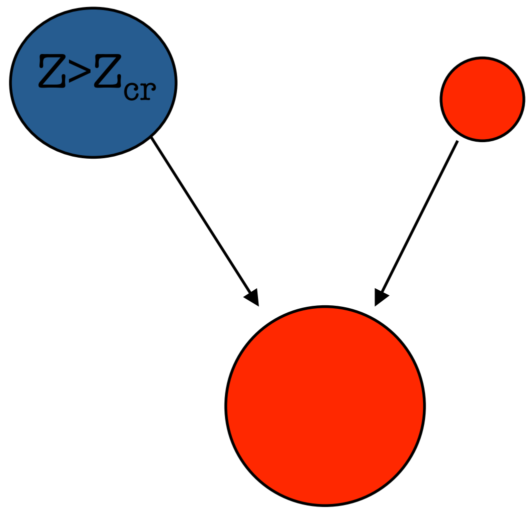


chemical feedback

Pop III stars can form at late epochs if pockets of $Z < Z_{cr}$ gas are present



(i) transport of metals by outflows



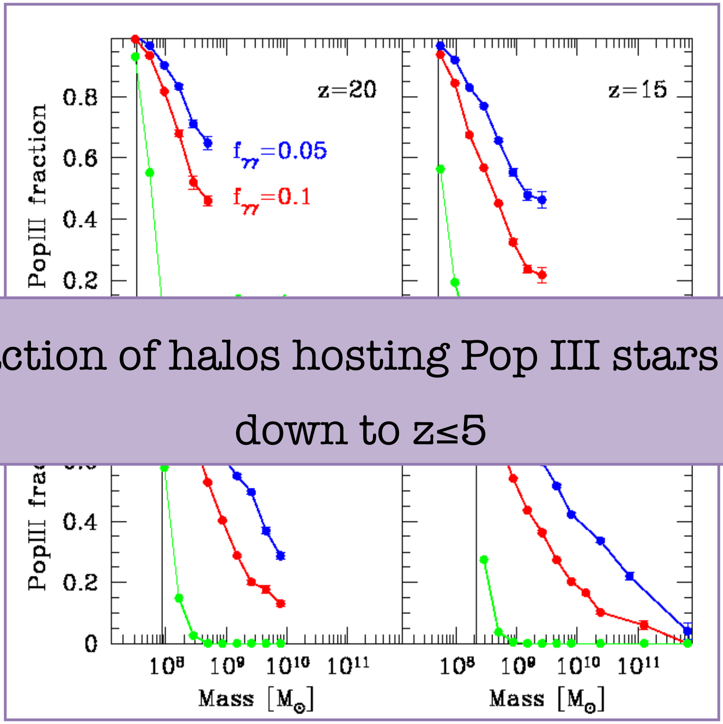
(ii) genetic propagation

chemical feedback

★ semi-analytic studies

(Scannapieco et al. 2003; MacKey et al. 2003; Schneider et al. 2005; Furlanetto & Loeb 2005; Grief & Bromm 2006; Whythe & Cen 2007; Trenti & Stiavelli 2009)

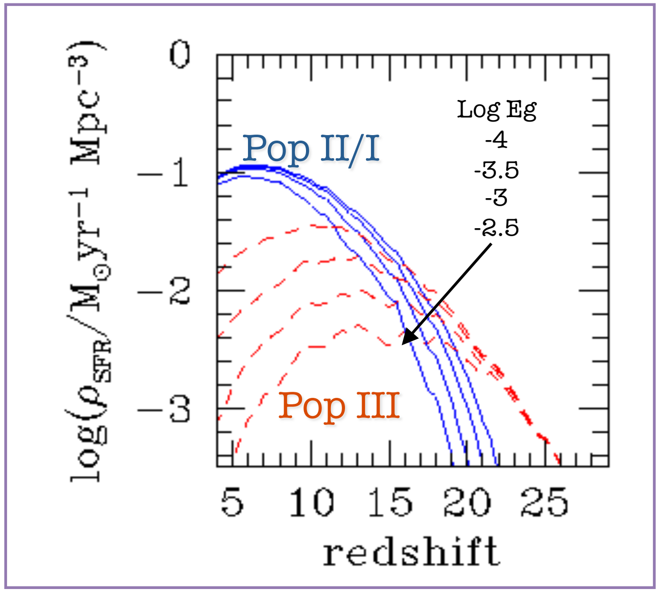
Schneider, Salvaterra, Ferrara & Ciardi (2005)



fraction of halos hosting Pop III stars ≠ 0

down to z≤5

Scannapieco, Schneider & Ferrara (2003)



Pop III to Pop II/I transition is extended in time

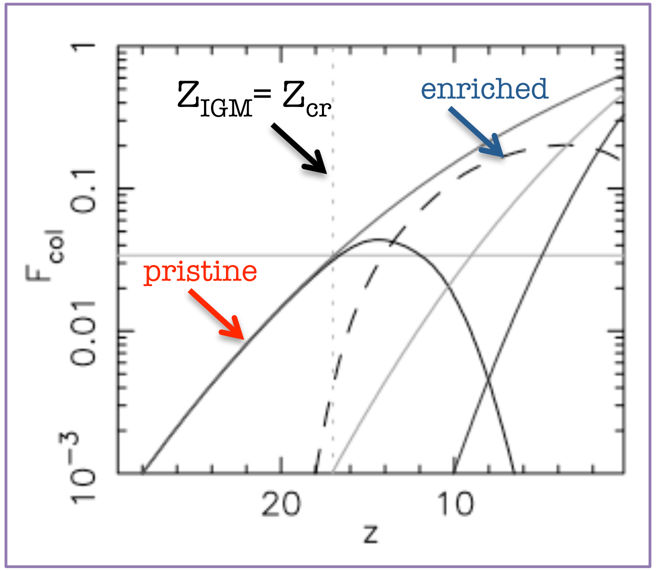
PopIII stars contribute to SFR at z < 10

chemical feedback

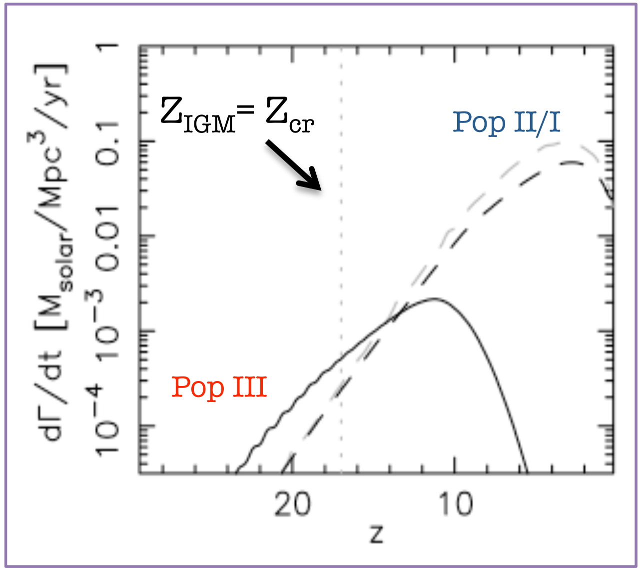
★ semi-analytic studies

(Scannapieco et al. 2003; MacKey et al. 2003; Schneider et al. 2005; Furlanetto & Loeb 2005; Grief & Bromm 2006; Whythe & Cen 2007; Trenti & Stiavelli 2009)

Collapsed fraction



Star formation rate



Whythe & Cen (2007)

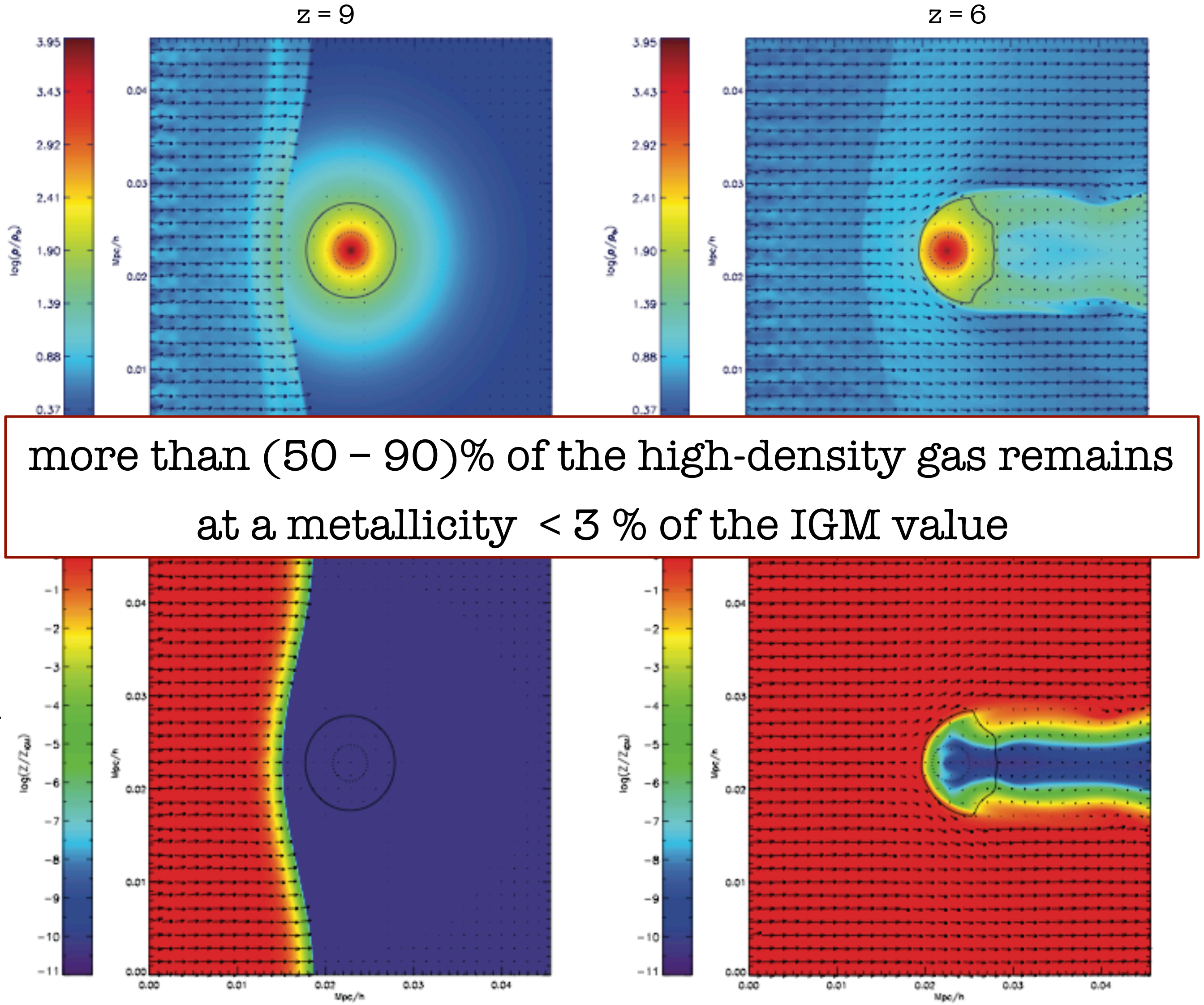
mini-halos as repositories of pristine gas

Cen & Riquelme (2008)

10 km/s metal enriched shock encompassing a $10^7\ M_{sun}$ virialized halo

density

metallicity

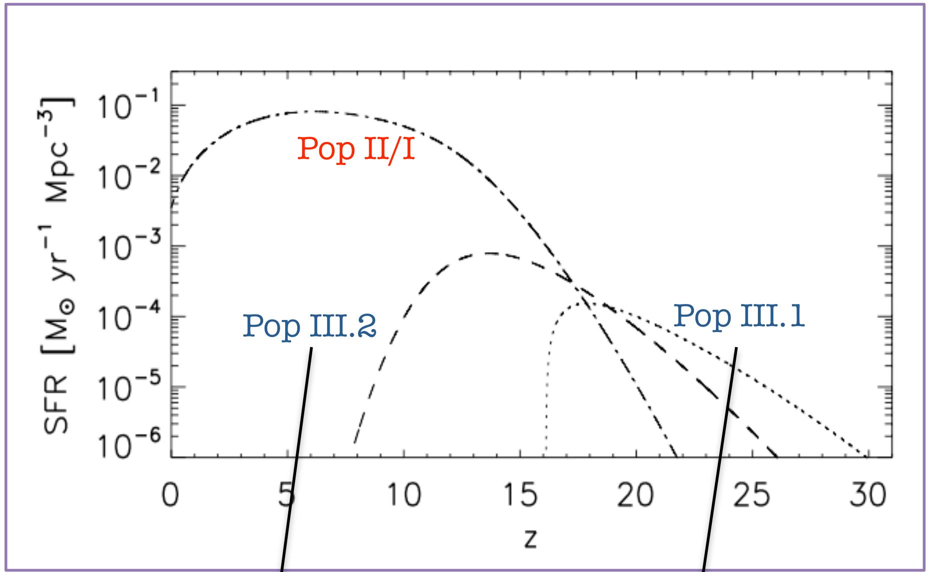


more than (50 – 90)% of the high-density gas remains at a metallicity < 3 % of the IGM value

two populations of metal-free stars

Press-Schechter like formalism combined with analytic recipes for chemical and radiative feedback

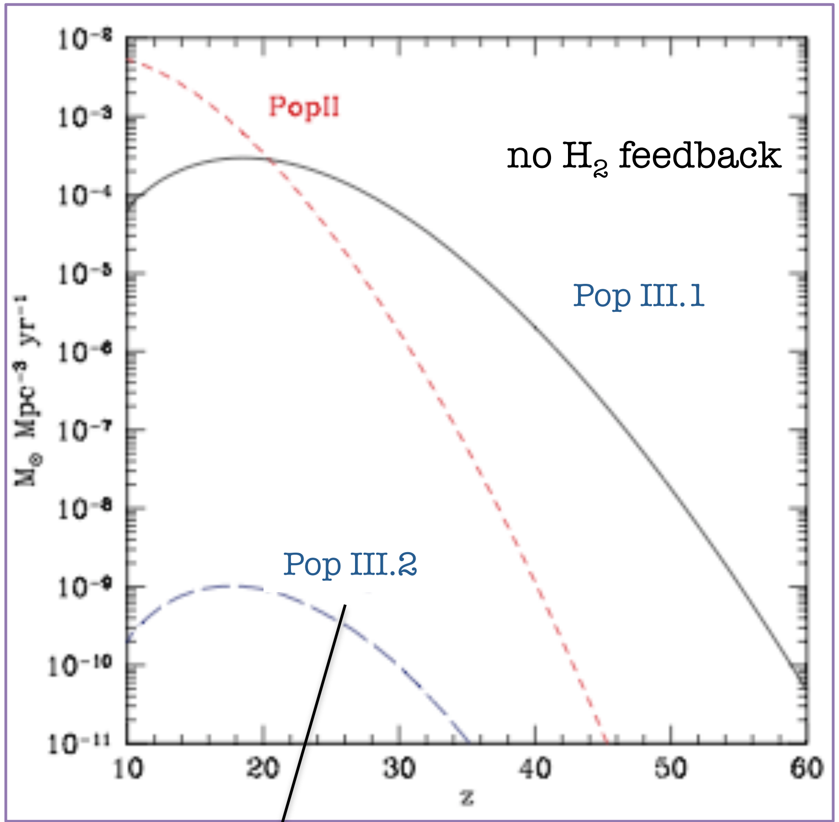
Grief & Bromm (2006)



in Ly α -cooling halos
killed by chemical fdbk
due to GALACTIC OUTFLOWS

in H_2-cooling halos
killed by LW-background

Trenti & Stiavelli (2009)



in Ly α -cooling halos
killed by chemical fdbk
due to SELF-ENRICHMENT

two populations of metal-free stars

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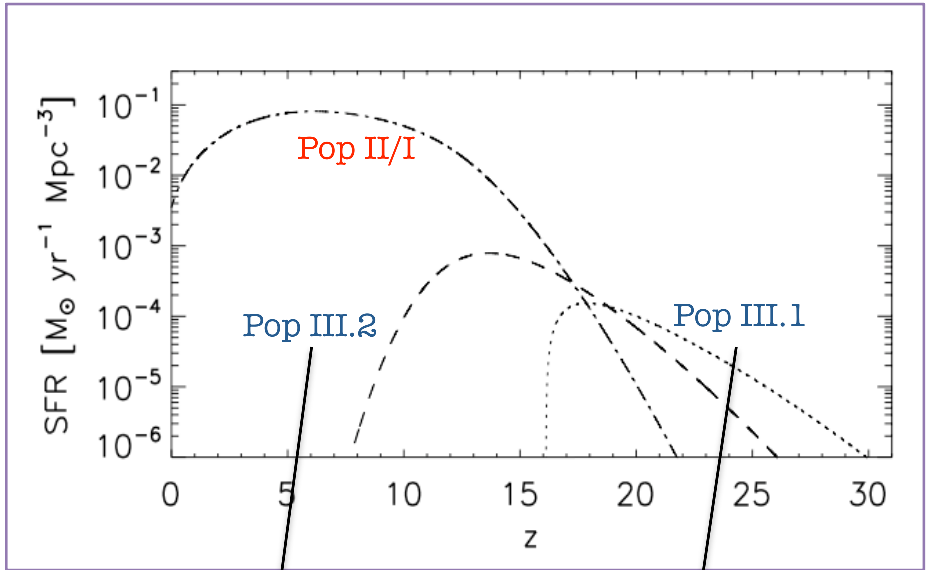

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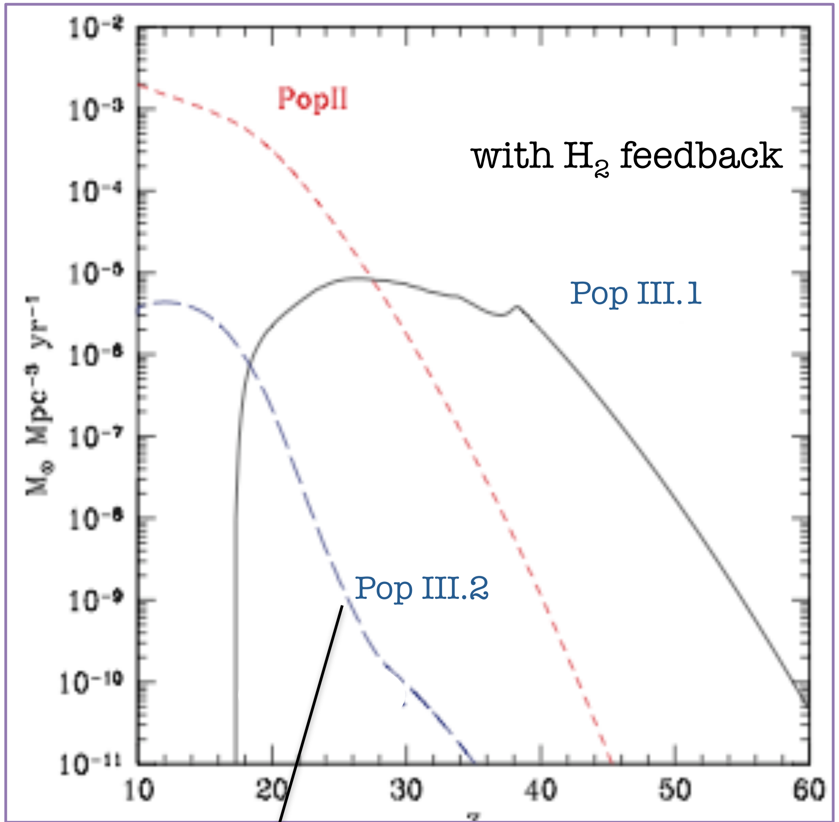


in Ly α -cooling halos
killed by chemical fdbk
due to SELF-ENRICHMENT

The Pop III/II transition on cosmic scales

★ <u>numerical studies</u>

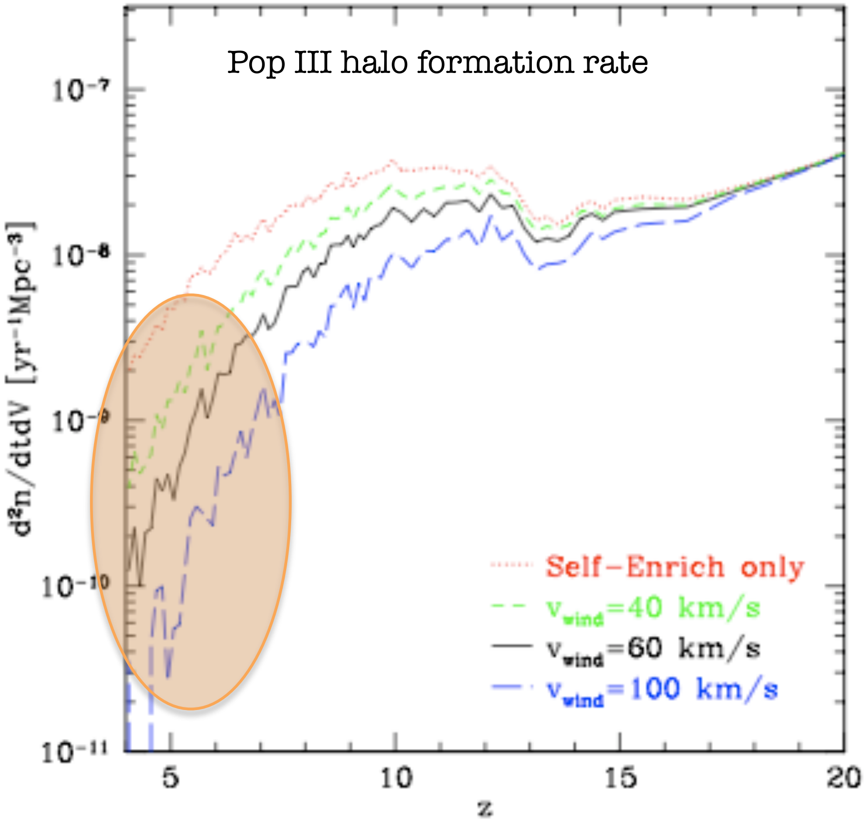
SPH SIMULATION (metallicity-dependent IMF)

Tornatore, Ferrara & Schneider (2007)

HYBRID CODES dark matter simulation+semi-analytic gas physics

Trac & Cen (2007) Trenti, Stiavelli & Shull (2009)

Trenti, Stiavelli & Shull (2009)



numerical simulations

★ Tornatore, Ferrara & Schneider (2007)

GADGET-2 with improved treatment of chemical enrichment (Tornatore et al 2007)

metallicity-dependent stellar IMF

$Z > Z_{cr}$ Salpeter IMF $0.1 < M/M_{sun} < 100$
$y = y(Z)$ $\varepsilon = 3.4\ 10^{15}$ erg/gr Woosley & Weaver 1995

$Z < Z_{cr}$ Salpeter IMF $100 < M/M_{sun} < 500$
$y = 0.183$ $\varepsilon = 3.5\ 10^{16}$ erg/gr Heger & Woosley 2002

Reference run:

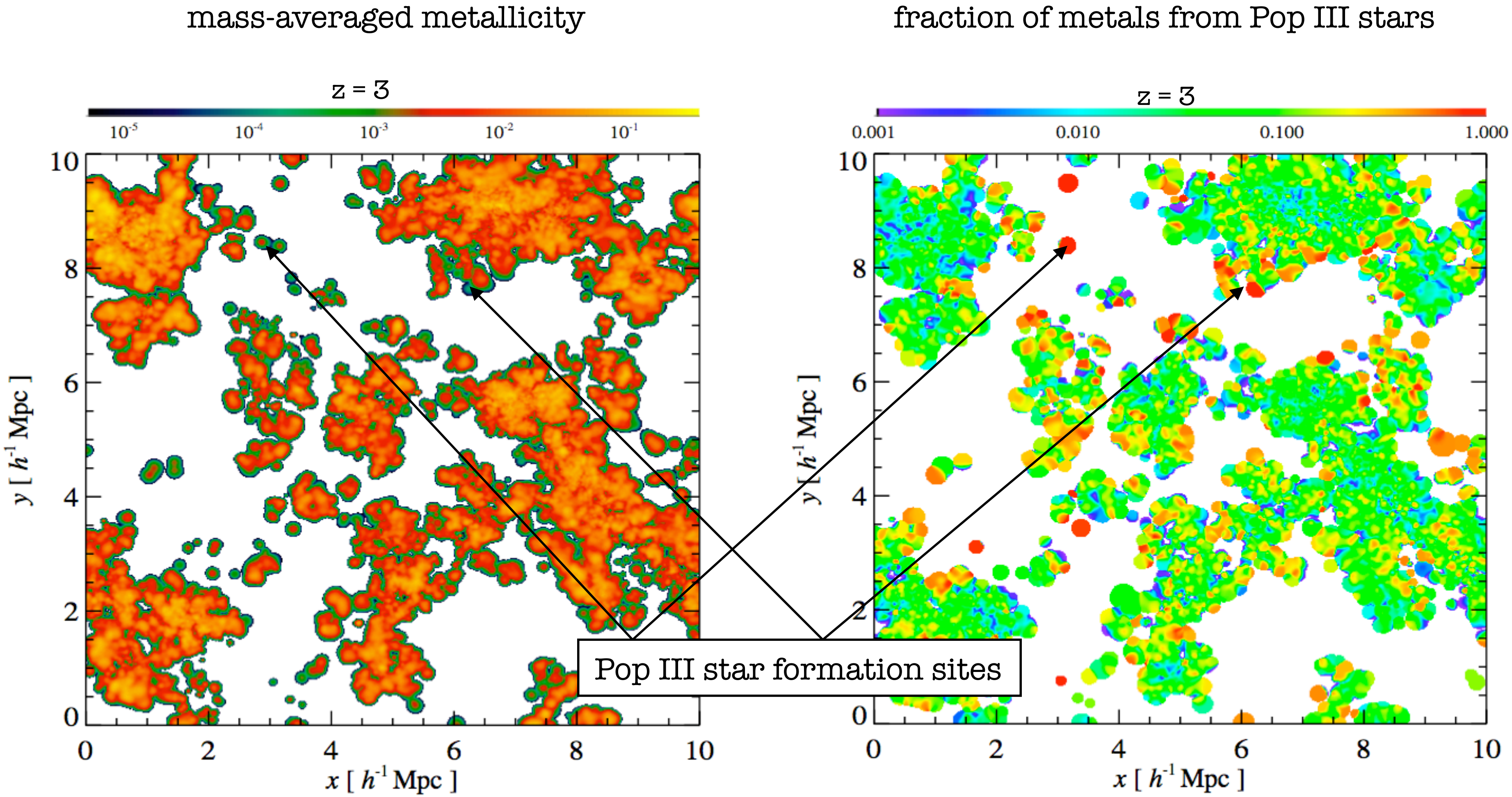
$Z_{cr} = 10^{-4}\ Z_{sun}$

$L_{box} = 10 h^{-1}$ Mpc $N_p = 2 \times 256^3$ $M_p = 3.6\ 10^6\ h^{-1}\ M_{sun}$

2 additional runs: $L_{box} = 5\ h^{-1}$ Mpc $N_p = 2\text{x}256^3$ $M_p = 4.5\ 10^5\ h^{-1}\ M_{sun}$
$5\ h^{-1}$ Mpc $N_p = 2\text{x}128^3$ $M_p = 3.6\ 10^6\ h^{-1}\ M_{sun}$

spatial distribution of metals

★ Tornatore, Ferrara & Schneider (2007)

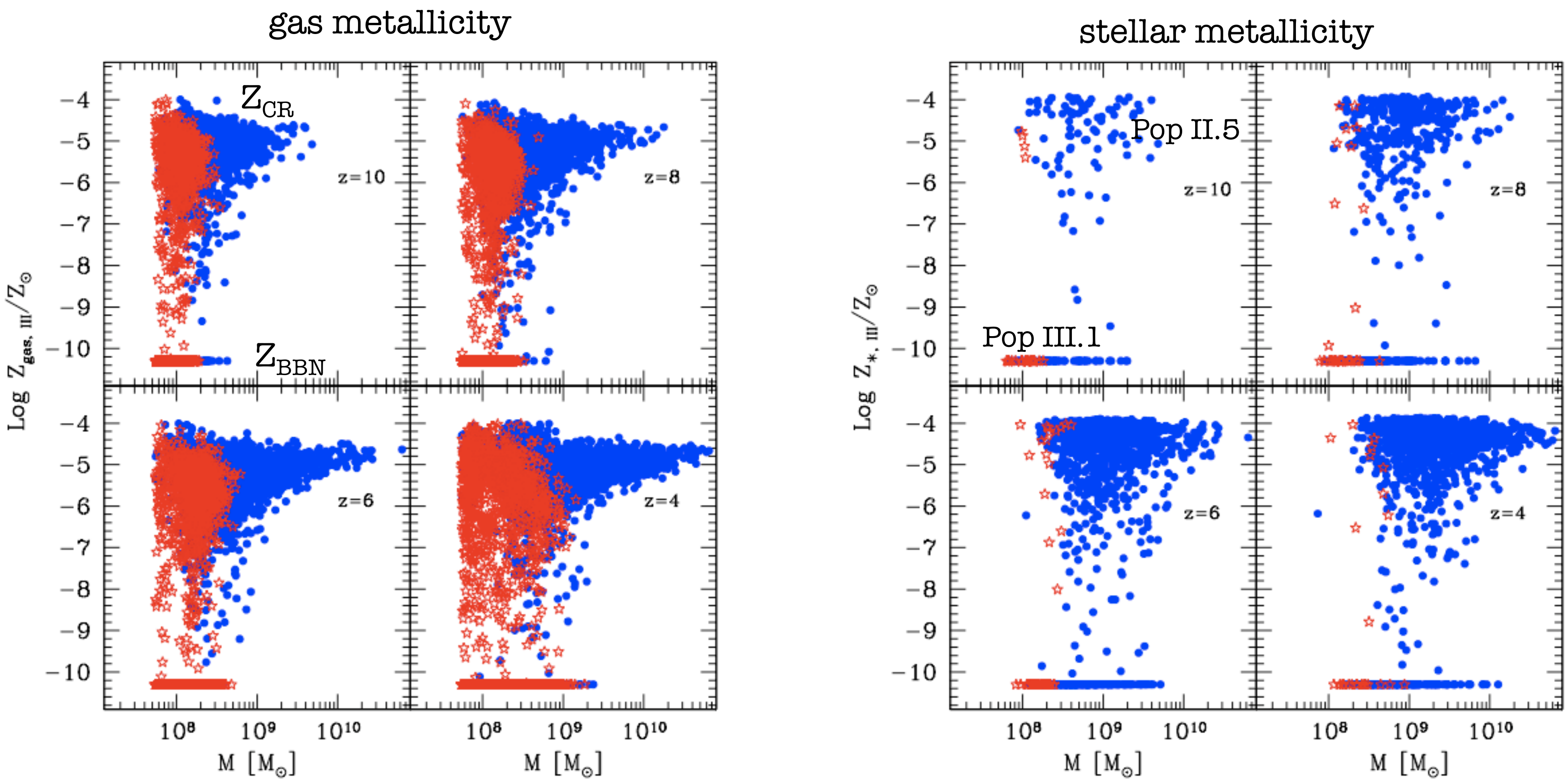


Pop III stars appear to be hidden in the outskirts of collapsing structures

A fraction of observable z>3 objects may be powered by radiative (LAEs, LBGs) or mechanical (PISN) input of Pop III stars

properties of Pop III star forming sites

- ☆ pure halos: only $Z < Z_{cr}$ gas/stars
- ● mixed halos: both $Z < Z_{cr}$ and $Z > Z_{cr}$ gas/stars

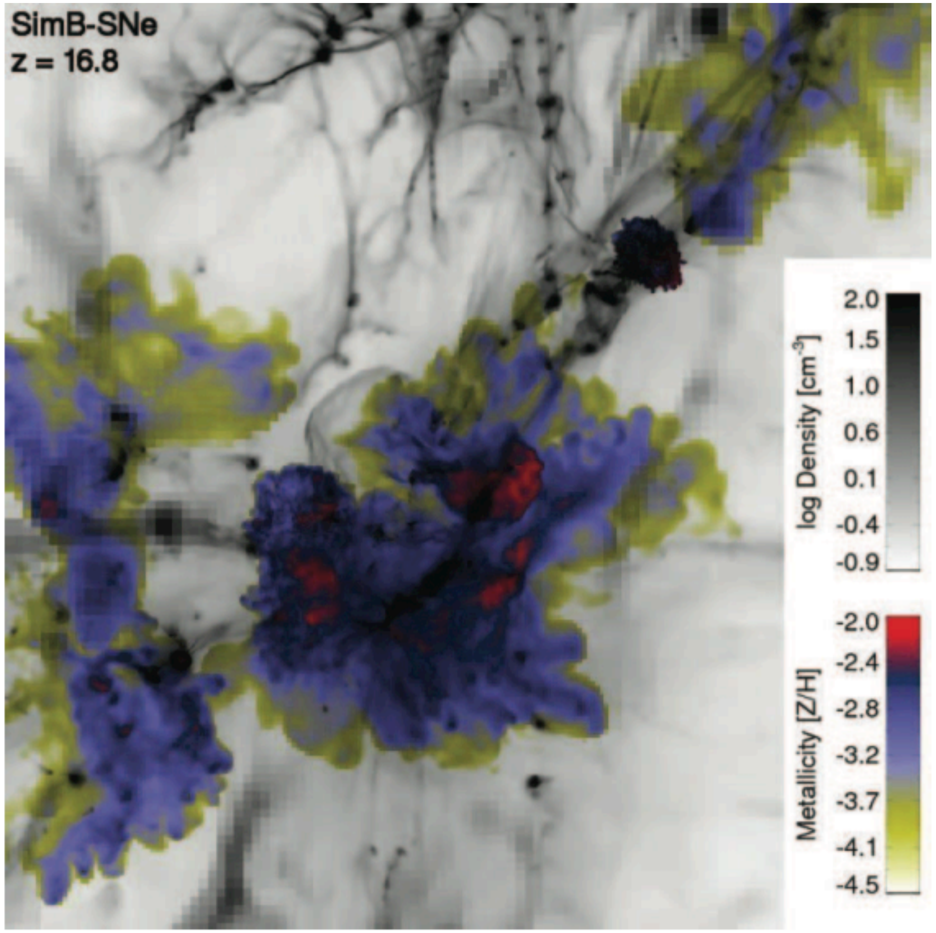


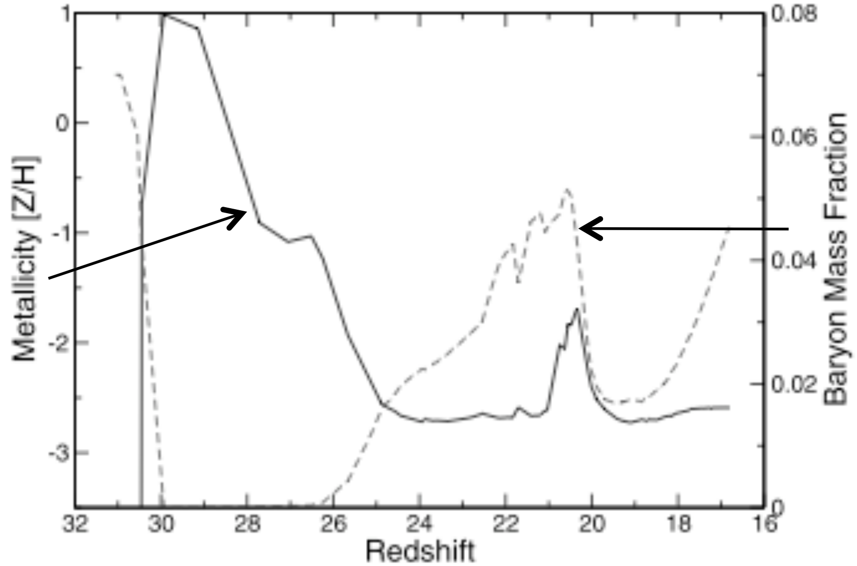
Schneider et al. in prep

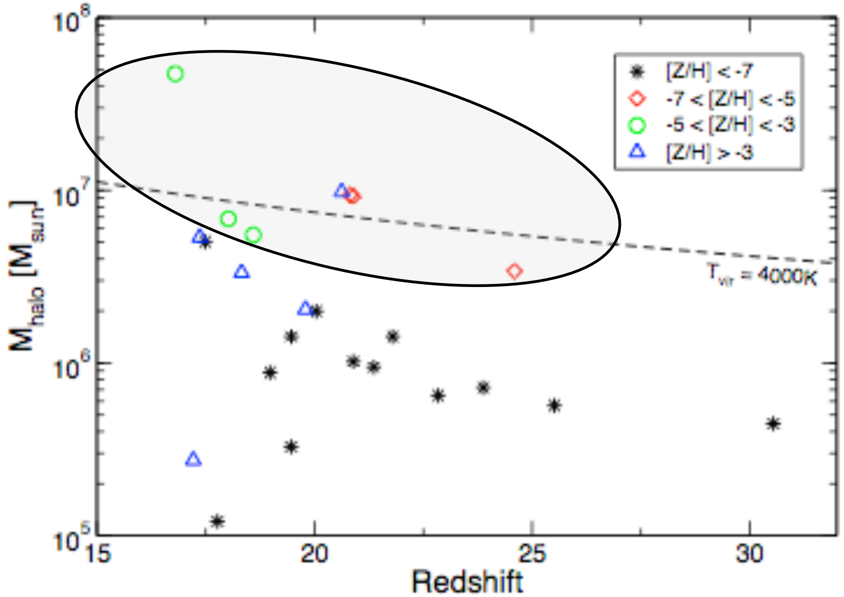
resolving the first protogalaxies

Ricotti, Gnedin & Shull (2002, 2008); Wise & Abel (2007, 2008); Whalen et al. (2008); Greif et al. (2008, 2010)

Wise & Abel (2008)







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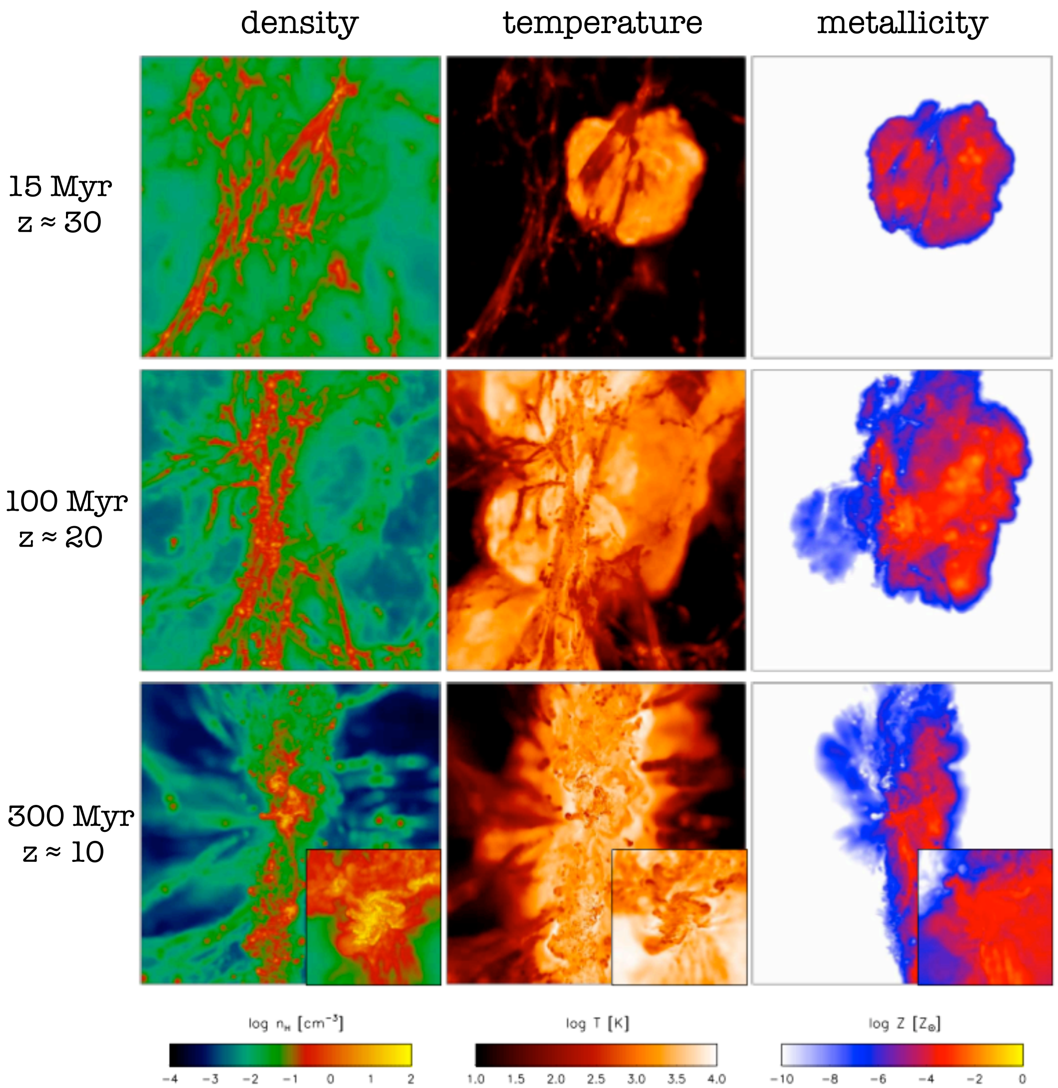
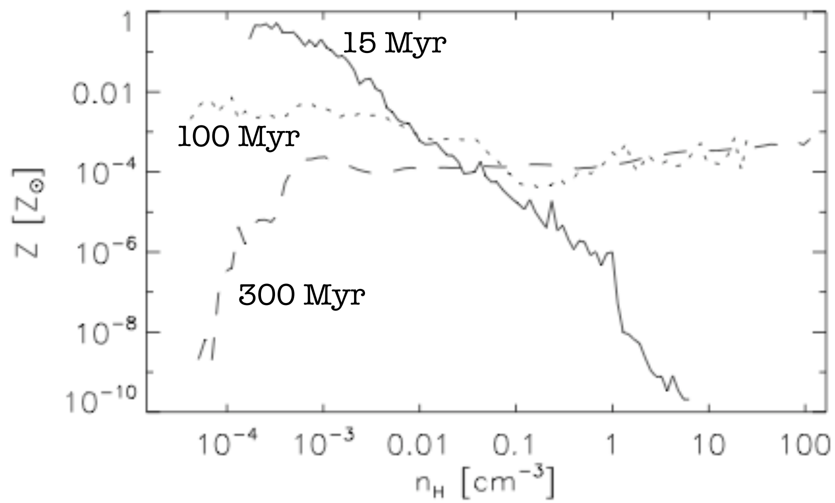
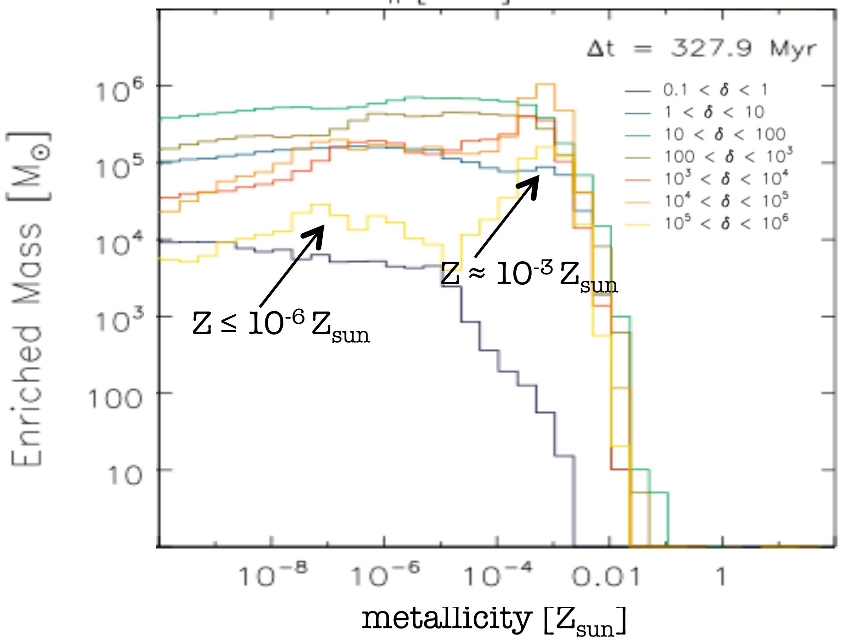
Greif, Glover, Bromm & Klessen (2010)



average metallicity





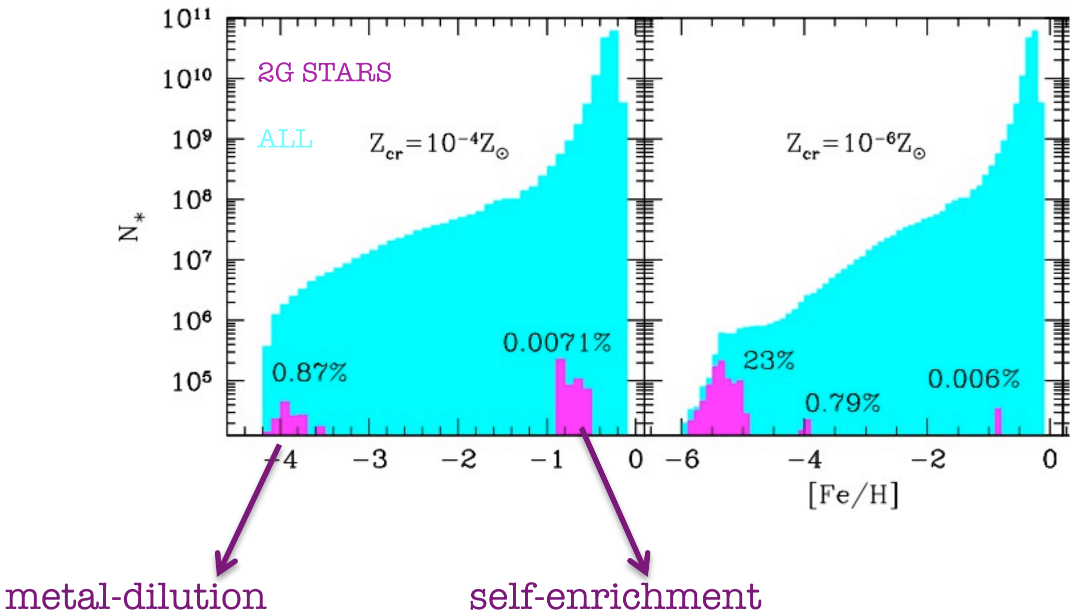
Observational searches in the Local Universe: stellar archaeology

GAMETE (GAlavy MErger Tree & Evolution)

Salvadori, Schneider & Ferrara (2007)

Metallicity Distribution Function of Halo stars

statistics of second-generation (2G) stars: enriched by yields of PopIII SN



Beers & Christlieb (2006) sample

1150 stars with -4 < [Fe/H] < -2.5

Z_{cr}/Z_{sun}	Number of 2G stars
10^{-4}	1.3
10^{-6}	0.3
0	6×10^{-2}

conclusions

- minimal conditions for the first low-mass stars may require dust-cooling:

$$Z_{cr}(f_{dep}) = 10^{-5\pm1}\ Z_{sun}$$

- metal lines-cooling lead to ent masses of few x10 M_{sun}

- if $10^{-6}Z_{sun} \le Z_{cr}(f_{dep}) \le 10^{-4}$ ow-mass stars can form at any z;

at higher $Z_{cr}(f_{dep})$ the effect o CMB is important: 10s M_{sun} stars at $z > 15$

- dust is observed to be pres z ≈ 6: supernovae as dust factories

- on cosmic scales: the Pop I ransition is NOT sharp in time!

inhomogeneous metal enric t and the resistance of mini-halos to metal-enriched shocks lead to a lon of Pop III star formation

- proto-galaxies at z =10 are y to be already partially enriched:

Pop III and Pop II stars co-ex g