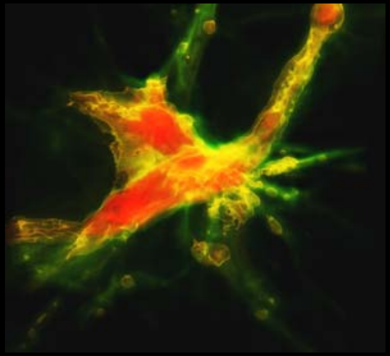
Connecting the first galaxies with local dwarf systems

(arXiv:1702.07355)



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Quantifying and Understanding the Galaxy—Halo Connection
May. 18, 2017

Overview

- Motivation: understanding the nature and formation of low-mass dwarf galaxy by tracing their evolution from the era of the first generation of stars down to z=0.

  Ultra faint dwarfs (UFDs)

  metal-poor ([Fe/H]<-2),
  low stellar mass ($M_{star}<10^5 M_{\odot}$),
  old ages (> 10 Gyr),
  large M/L ratios (M/L > 100).

- Method : cosmological hydrodynamic zoom-in simulations.

- Goal : provide theoretical understanding of chemical abundances of stellar populations in UFDs, including the contribution from the first stars, in the full cosmological settings.

Recent dwarf galaxy formation

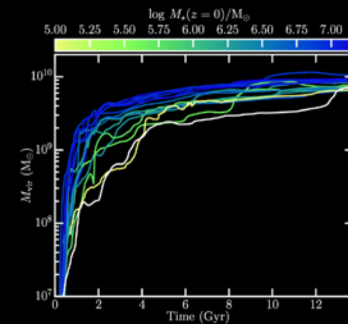
Stellar mass

10^7 M$_\odot$

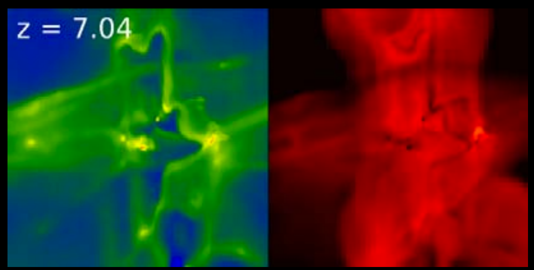
10^6 M$_\odot$

10^5 M$_\odot$

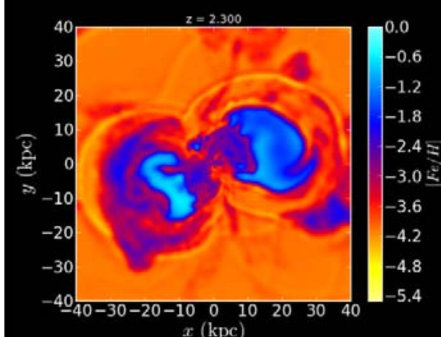
10^4 M$_\odot$

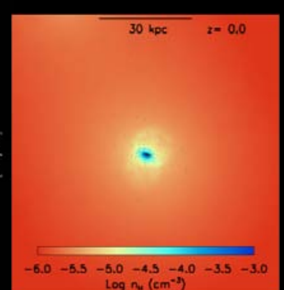


Fitts et al. (2016)
FIRE,
Res. : 500 M$_\odot$ (gas), ~2500 M$_\odot$ (DM)



Simpson et al. (2013)
ENZO, Res. : 500 M$_\odot$ (gas), ~2000 M$_\odot$ (DM)





Wheeler et al. (2015), Onorbe et al. (2015)
FIRE , Res. : 125-500 M$_\odot$ (gas), ~700-2000 M$_\odot$ (DM)

Jeon et al. (2017)
Gadget , Res. : 500 M$_\odot$ (gas), ~500 M$_\odot$ (DM)

10^9 M$_\odot$ 10^{10} M$_\odot$ Halo mass

From first stars to local dwarfs

First stars (Pop III stars)

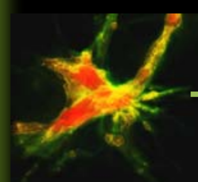
at z>15, primordial gas in minihaloes (M_{vir} =$10^{5\text{-}6}$ $M_{\odot}$)

Second gen. of stars (Pop II stars)

Pop II stars could contain chemical signatures of Pop III stars.
Low-mass Pop II stars survive until today – we observe those.

First galaxies

at z~15, $M_{vir} < 10^{8\text{-}9}$ $M_{\odot}$



Fossil galaxies?

No or a little additional star formation

Dwarf galaxies could preserve chemical signatures of early stars.

First stars & Galaxies (t_H ~ a few 100 Myr)

Reionization (t_H ~ 1 Gyr)

Today z=0

Simulation detail

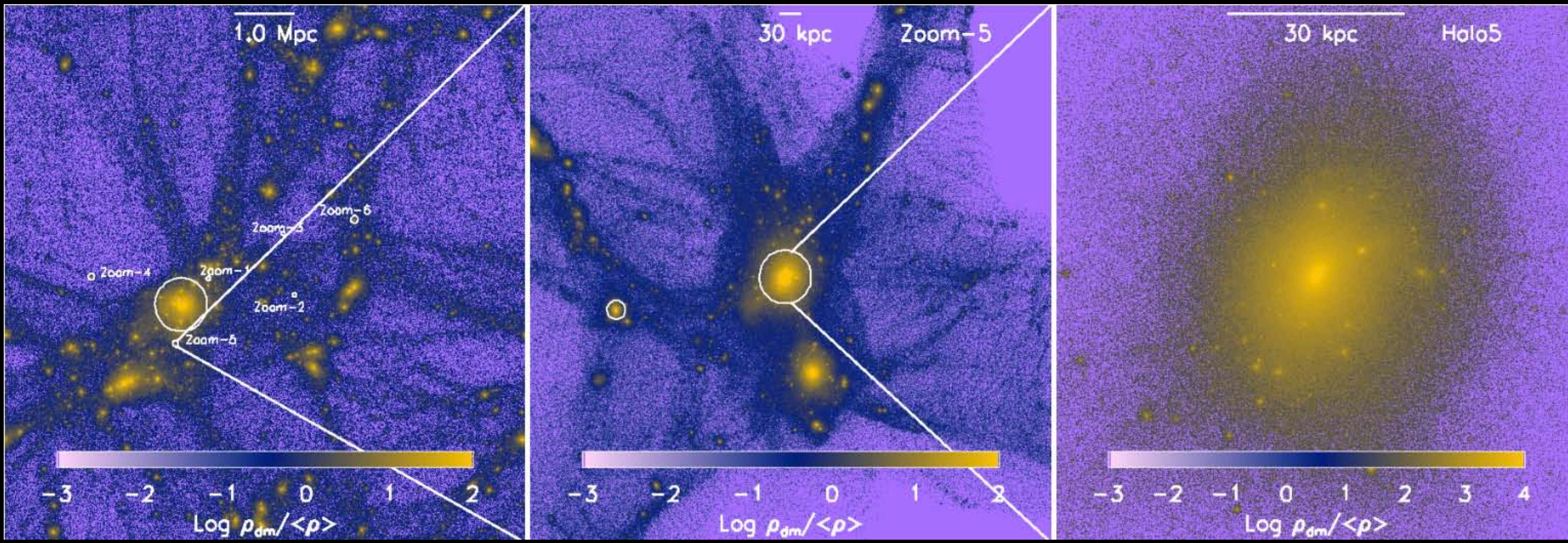
- Modified version of Gadget-3 (OWLS)
- Resolution : 500 $M_\odot$ (gas), ~2000 $M_\odot$ (DM)

- Star formation :
  - Schmidt law
  - Density threshold of n_H = 100 cm^{-3}, critical metallicity $Z_{crit} = 10^{-5.5} Z_\odot$ (PopII/I)
  - Pop III : top-heavy IMF, [10, 100] $M_\odot$
  - Pop II/I : Chabrier IMF, [0.1, 100] $M_\odot$

- SNe feedback : thermal energy
- Non-equilibrium cooling, UV photoheating (Haardt & Madau 2011), reionization (z=7-6), self-shielding of the dense gas

- SNe yield : C, O, Mg, Ne, Si, Iron (Wiersma et al . 2009)
  PopIII Pair-instability SNe (PISNe) : Heger & Woosely (2002)
  PopIII Core-collapse SNe (CCSNe) : Heger & Woosely (2010)
  PopII : Portinari (1998)
- Metal mixing : diffusion method, diffusion coefficient (Greif et al. 2009)

Simulated Dwarfs



Characteristics of the simulated UFD analogs at $z = 0$.

Halo	M_{vir}	r_v	M_*	D_h	f_b	$r^*_{1/2}$	[Fe/H]	[α/Fe]	σ_*	SF_{trun}
Unit	[$10^9\ M_\odot$]	[kpc]	[$10^4\ M_\odot$]	[Mpc]	[%]	[pc]	-	-	[kms^{-1}]	-
halo1	1.53	23.7	4.3	0.6	0.08	345	-2.63	0.52	6.4	Yes
halo2	1.53	23.5	3.8	2.0	0.07	320	-2.25	0.44	6.0	Yes
halo3	1.60	23.9	8.2	2.1	0.1	296	-2.28	0.52	6.7	Yes
halo4	2.21	26.6	13.0	1.9	0.96	513	-2.45	0.54	11.2	No
halo5	3.15	29.9	20.0	0.9	0.05	479	-2.27	0.53	9.9	No
halo6	3.95	32.1	88.6	3.7	0.1	438	-1.23	0.47	11.6	No

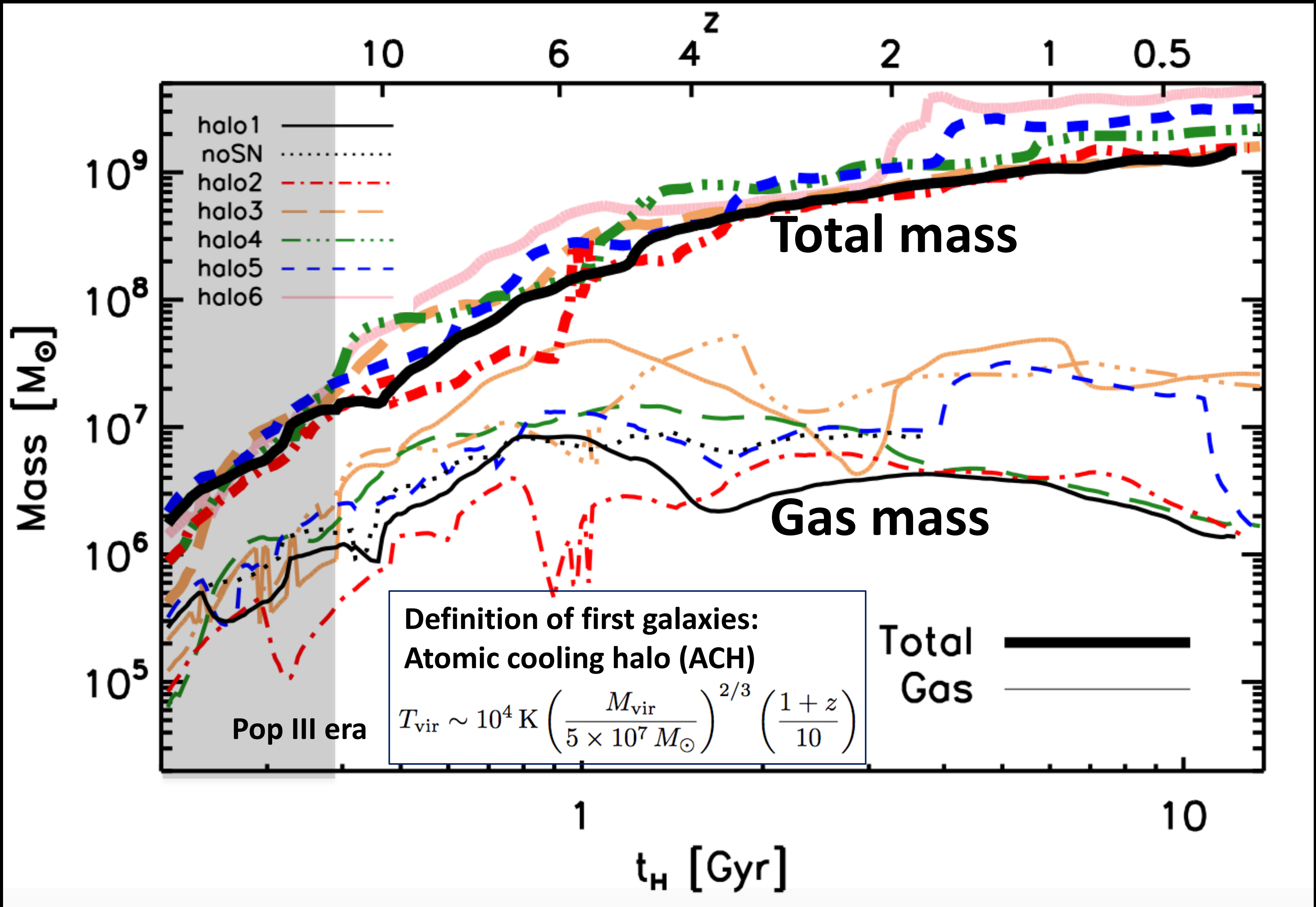
DM

Gas Density

Temp.

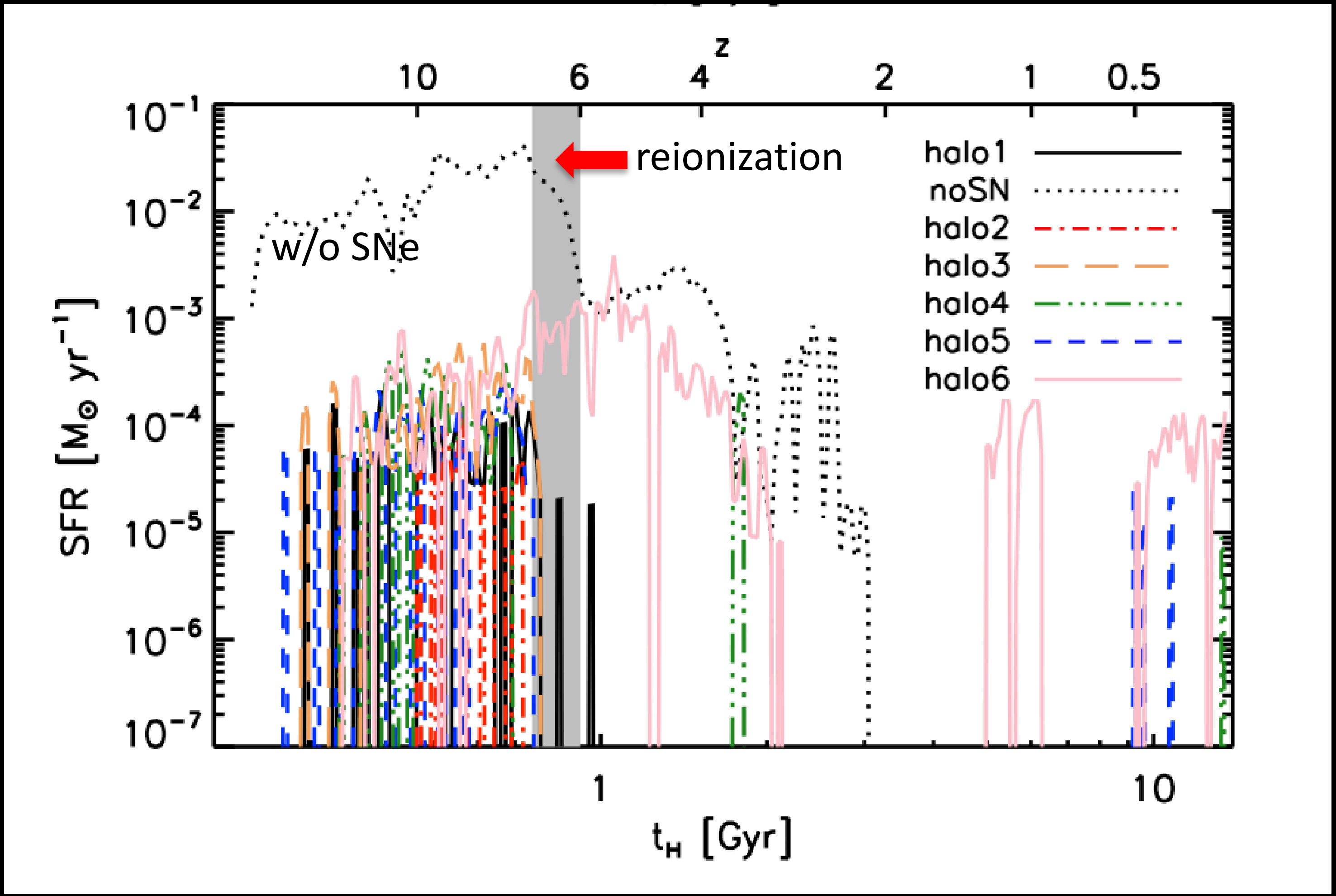
Metals

Mass Growth



z
10
6
4
2
1
0.5
halo1
noSN
halo2
halo3
halo4
halo5
halo6
Total mass
Gas mass
Mass [M⊙]
10⁹
10⁸
10⁷
10⁶
10⁵
Pop III era
Definition of first galaxies:
Atomic cooling halo (ACH)
$T_{\rm vir} \sim 10^4\,{\rm K}\left(\frac{M_{\rm vir}}{5\times10^7\,M_\odot}\right)^{2/3}\left(\frac{1+z}{10}\right)$
Total
Gas
1
10
t_H [Gyr]

Truncated star formation haloes by reionization

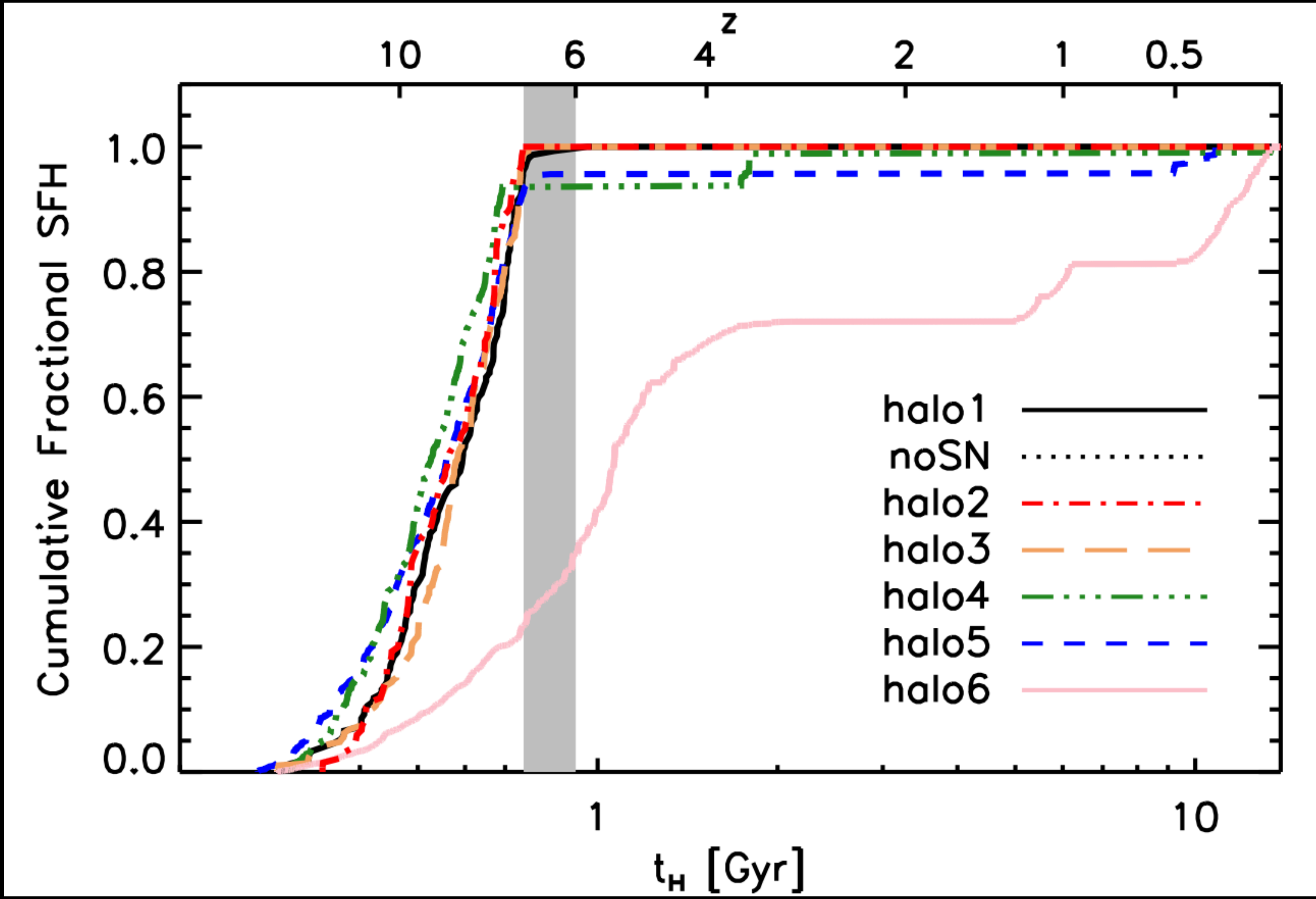


(M_{vir}=1.5 x 10^9 $M_\odot$)

(M_{vir}= 4 x 10^9 $M_\odot$)

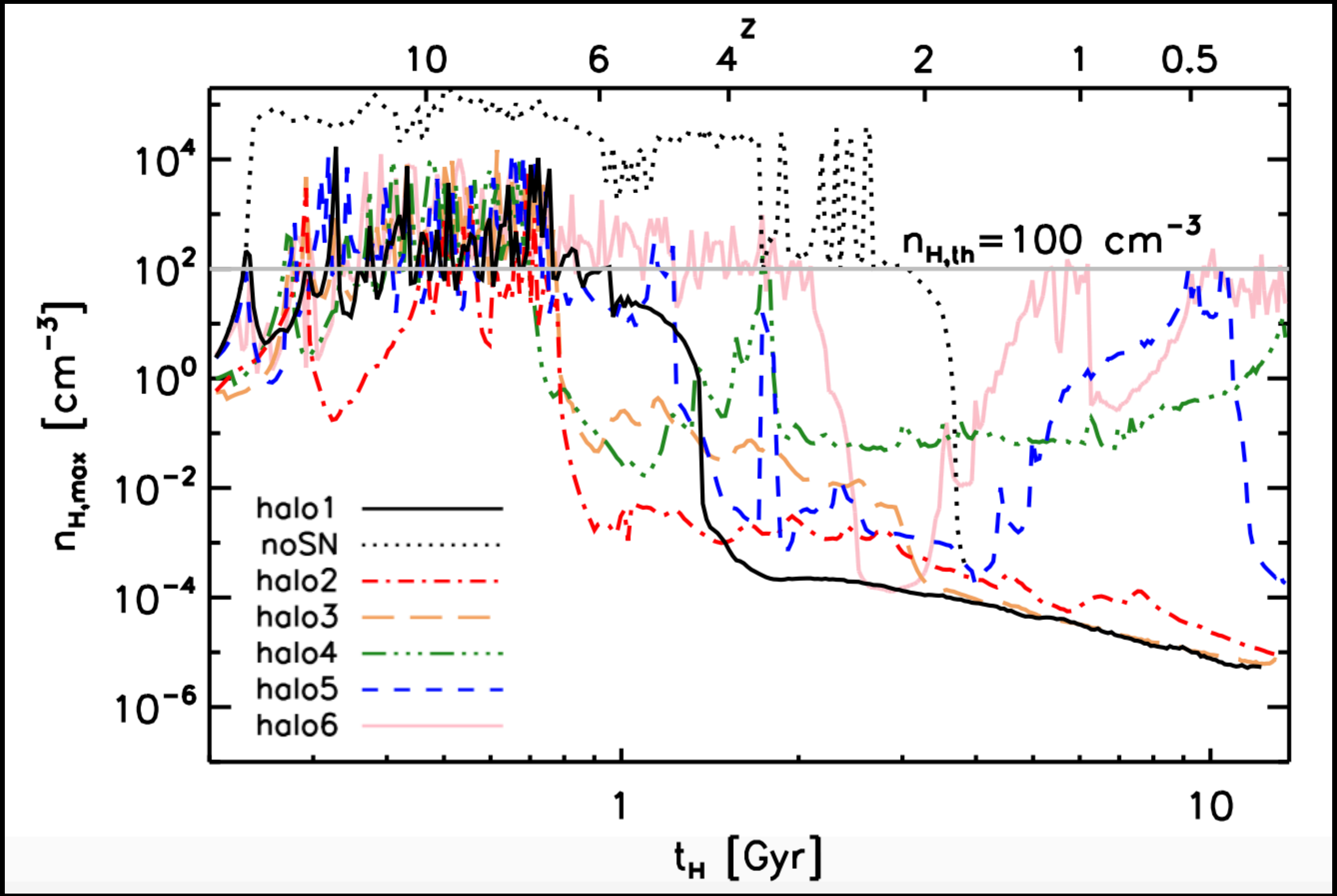
- Quenching of star formation by reionization in low-mass galaxies (Halo1,2,3: $M_h < 2x10^9$ $M_\odot$)

Star formation history



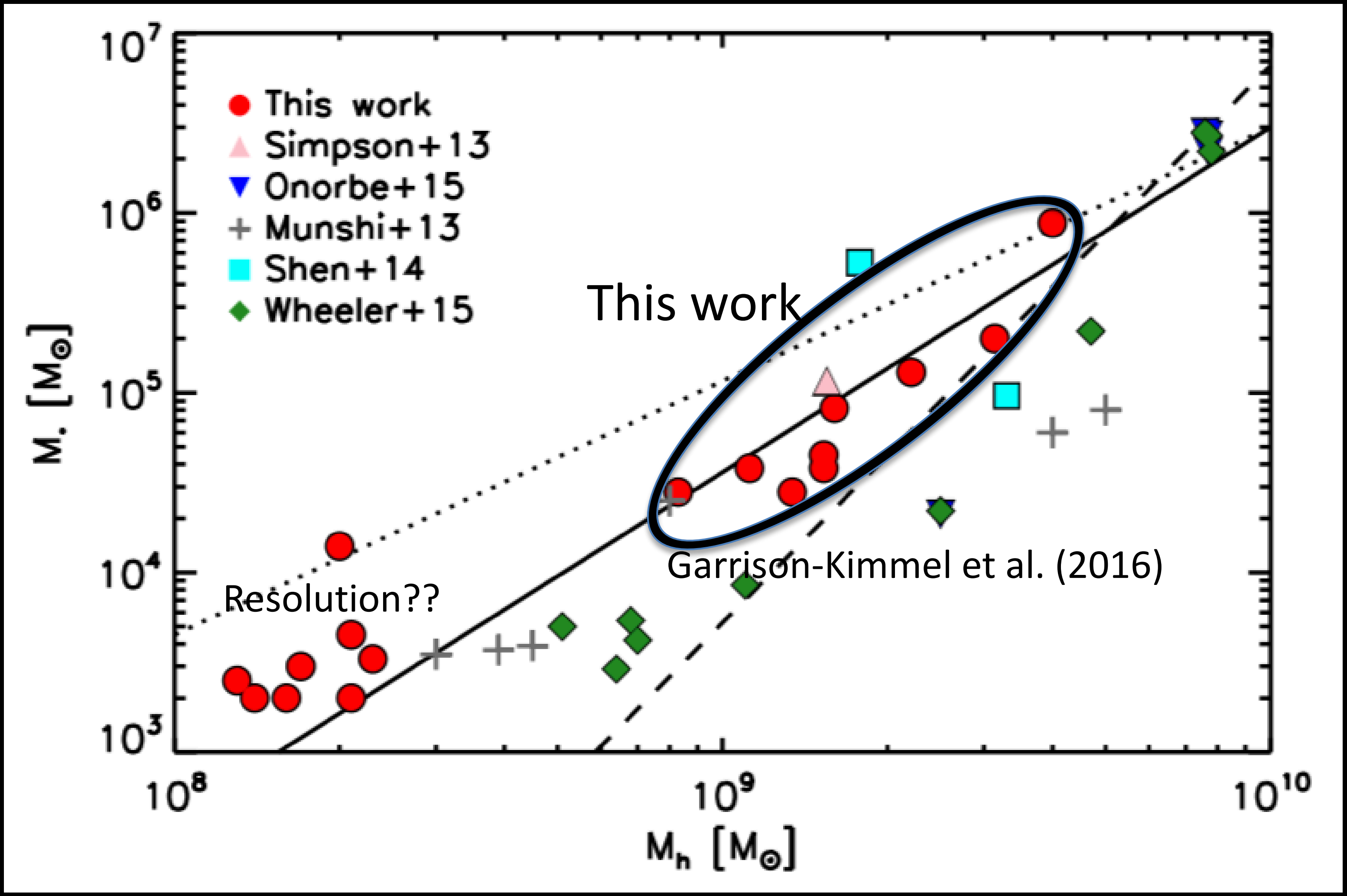
More than 90% of stars were formed prior to reionization in all runs except the most massive halo case ($M_{vir} = 4 \times 10^9 M_{\odot}$).

Gas property

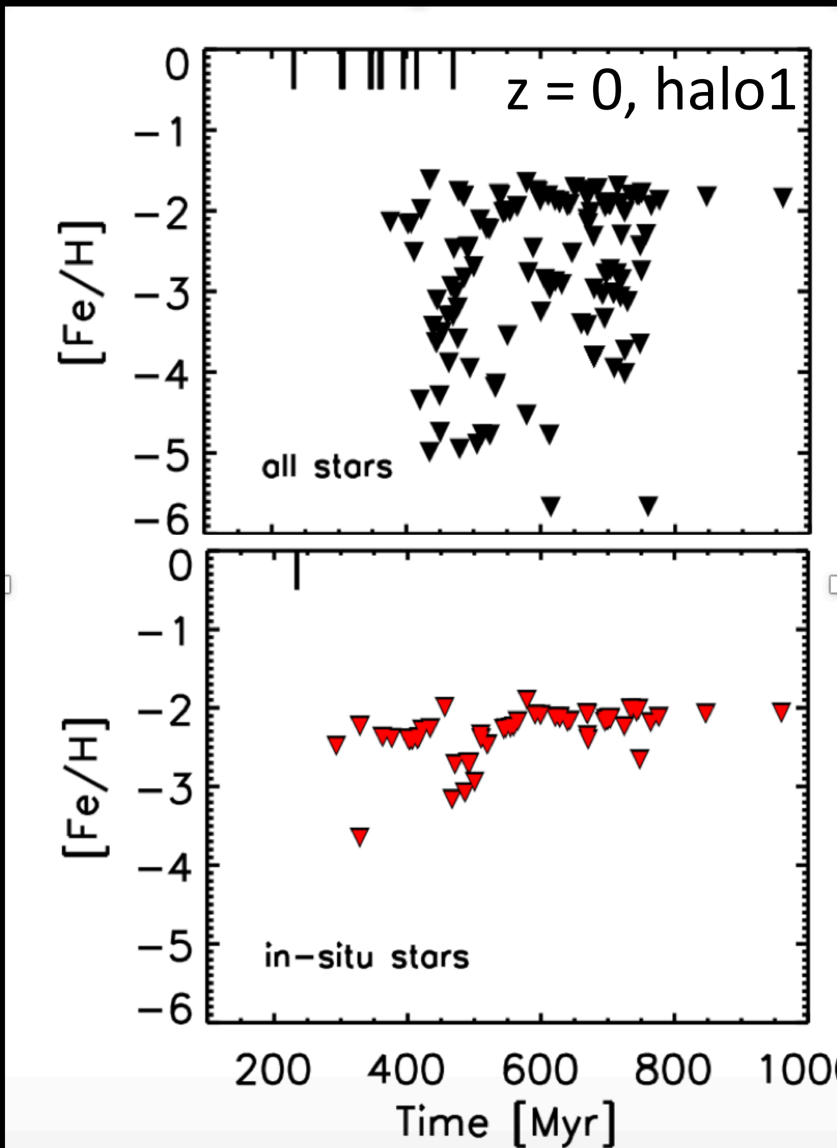


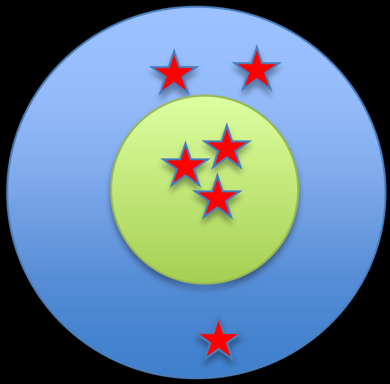
- Low-mass galaxies ($M_h < 2x10^9\ M_\odot$) : $n_H = 10^{-5}\ cm^{-3}$, mostly ionized gas.
- Most massive galaxy, halo6 : $n_H > 10\ cm^{-3}$, gas-rich ($3x10^7\ M_\odot$, ionized fraction of 54% - similar to field dwarfs - Leo P, Leo T.

Halo-to-stellar mass relation



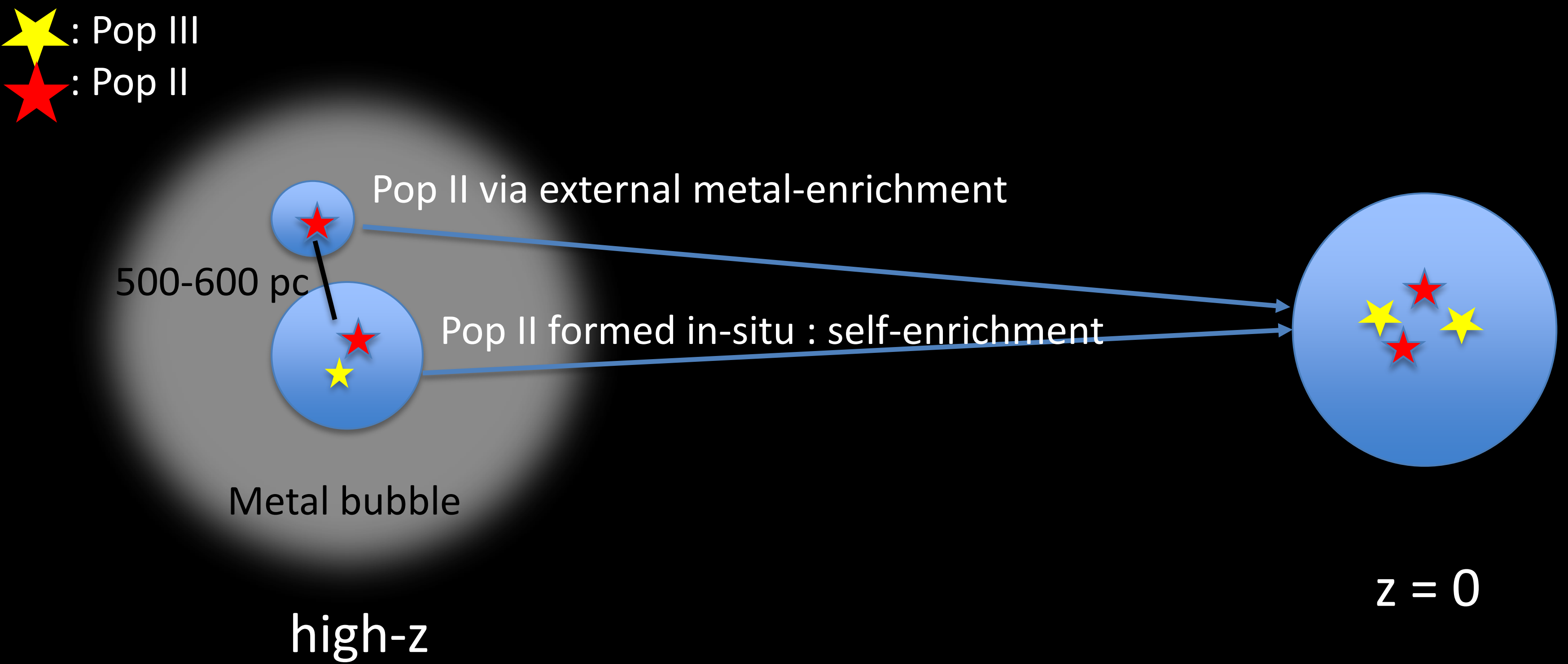
Presence of metal-poor stars





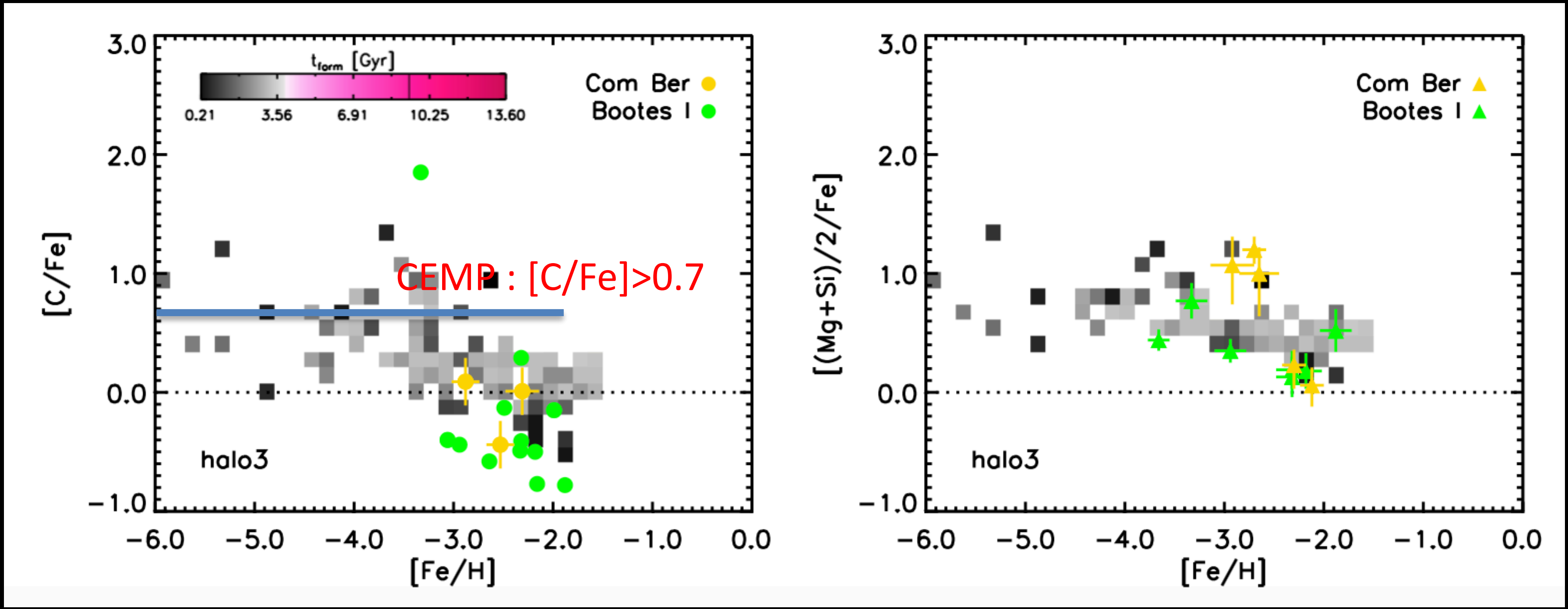
Low metallicity stars were formed in minihalos at high-z via external metal-enrichment.

Internal vs. external enrichment



Metal poor stars, [Fe/H<-3], were mainly formed via external metal enrichment.

Observational calibration: stellar abundances
(Halo3: $M_{star}=2\times10^3\ M_\odot$)



Carbon

- Carbon enhanced metal poor stars (CEMPs) were formed under the influence of Pop III stars.
- CEMPs – Pop III SNe
- Carbon-normal – self-enrichment via Pop II SNe.

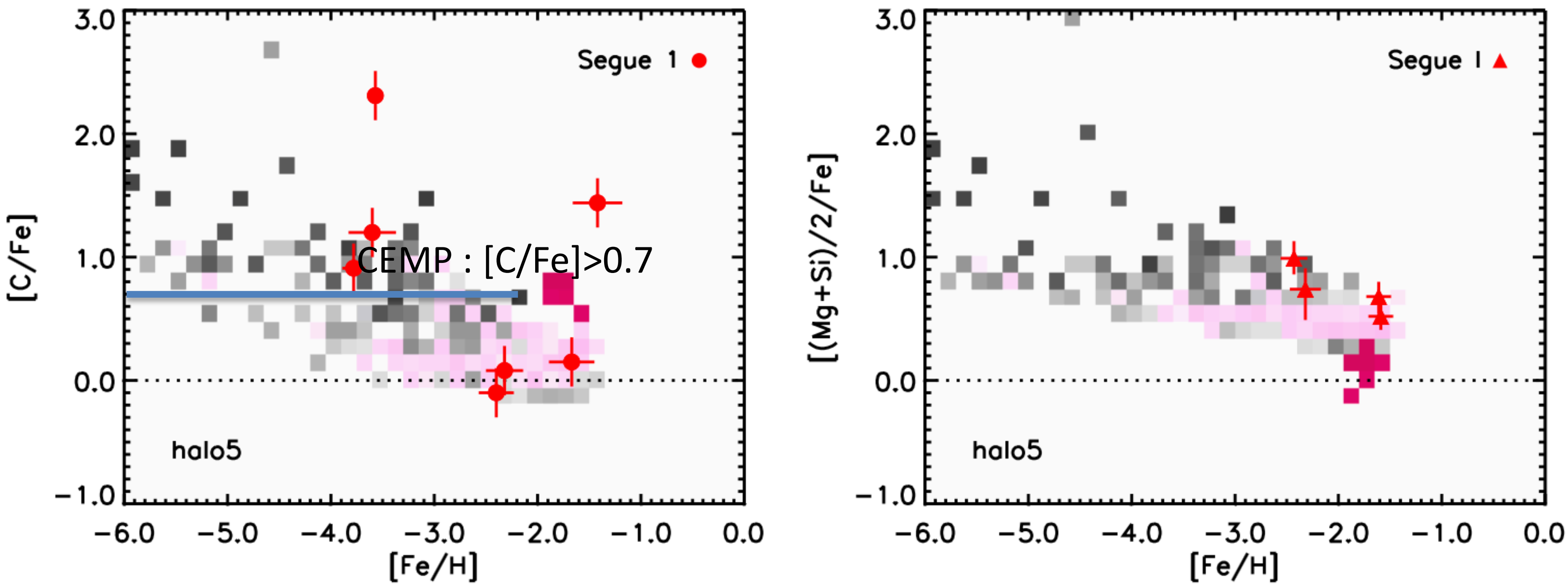
Alpha-elements

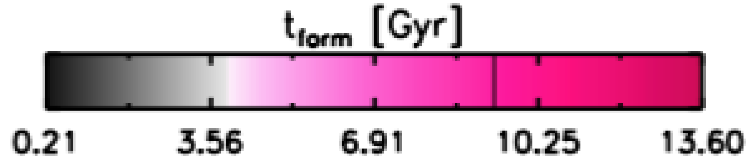
Alpha-elements are enhanced, meaning that they were mainly enriched by Type II SNe from PopIII and PopII stars: an indicator of short duration of star formation.

Stellar abundances (Halo5: M_{star}=2x10^5 $M_{\odot}$)

Carbon

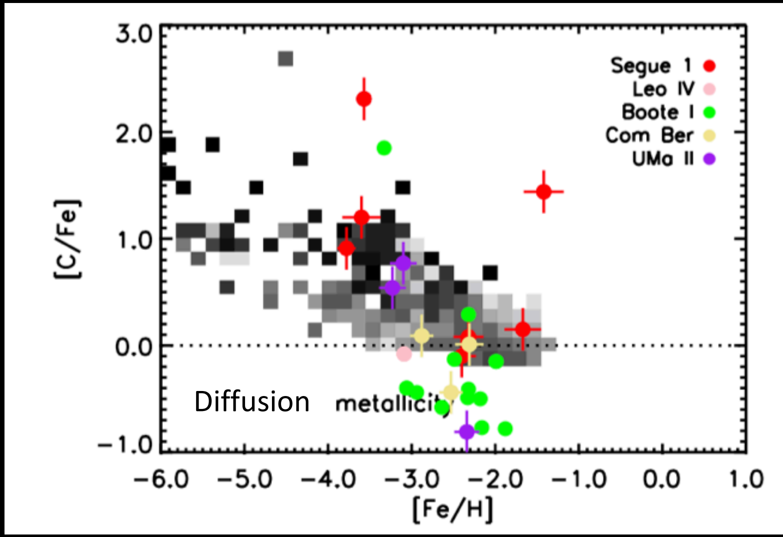
Alpha-elements



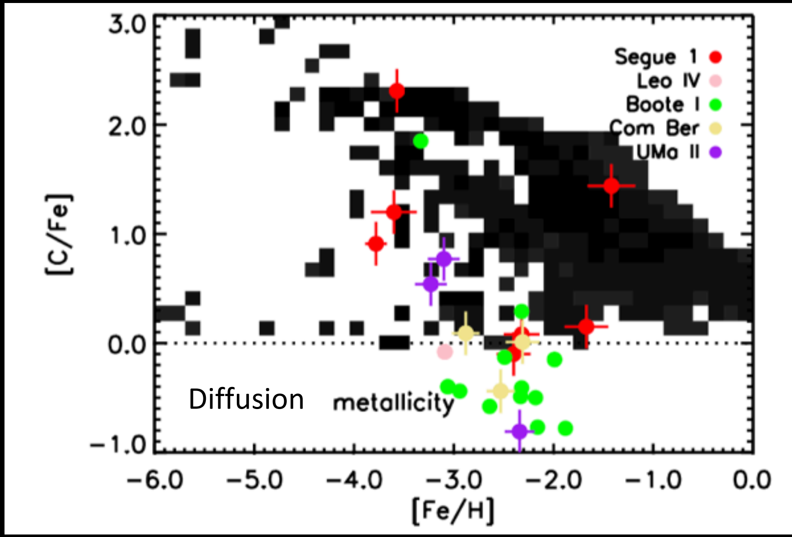


It is not easy to match observations

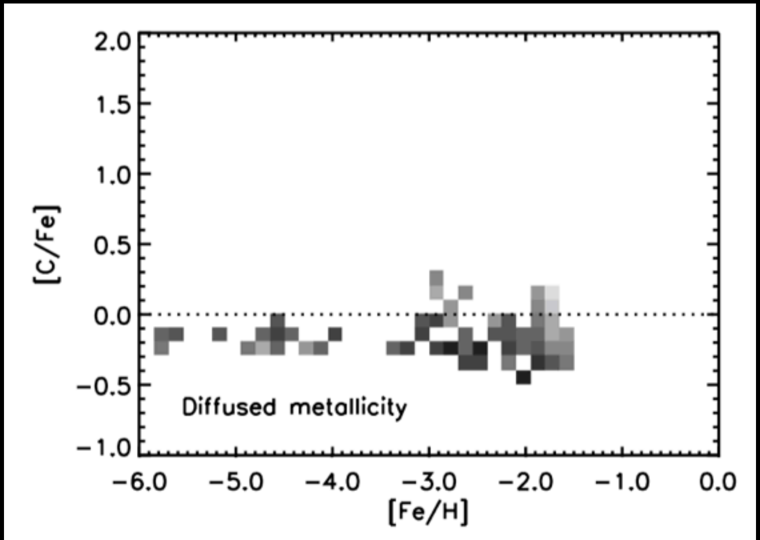
Diffusion metallicity



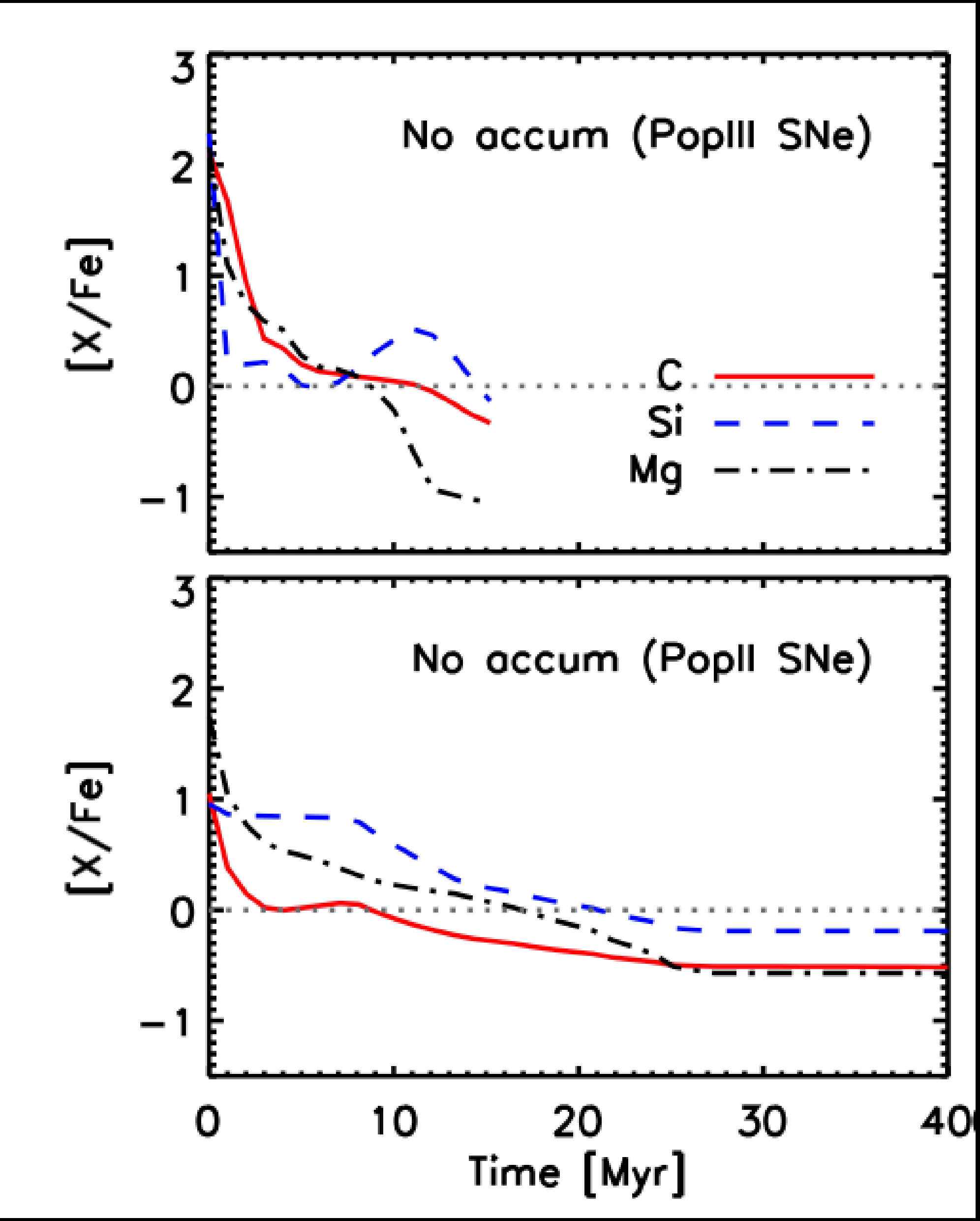
No supernovae feedback



No Population III Stars



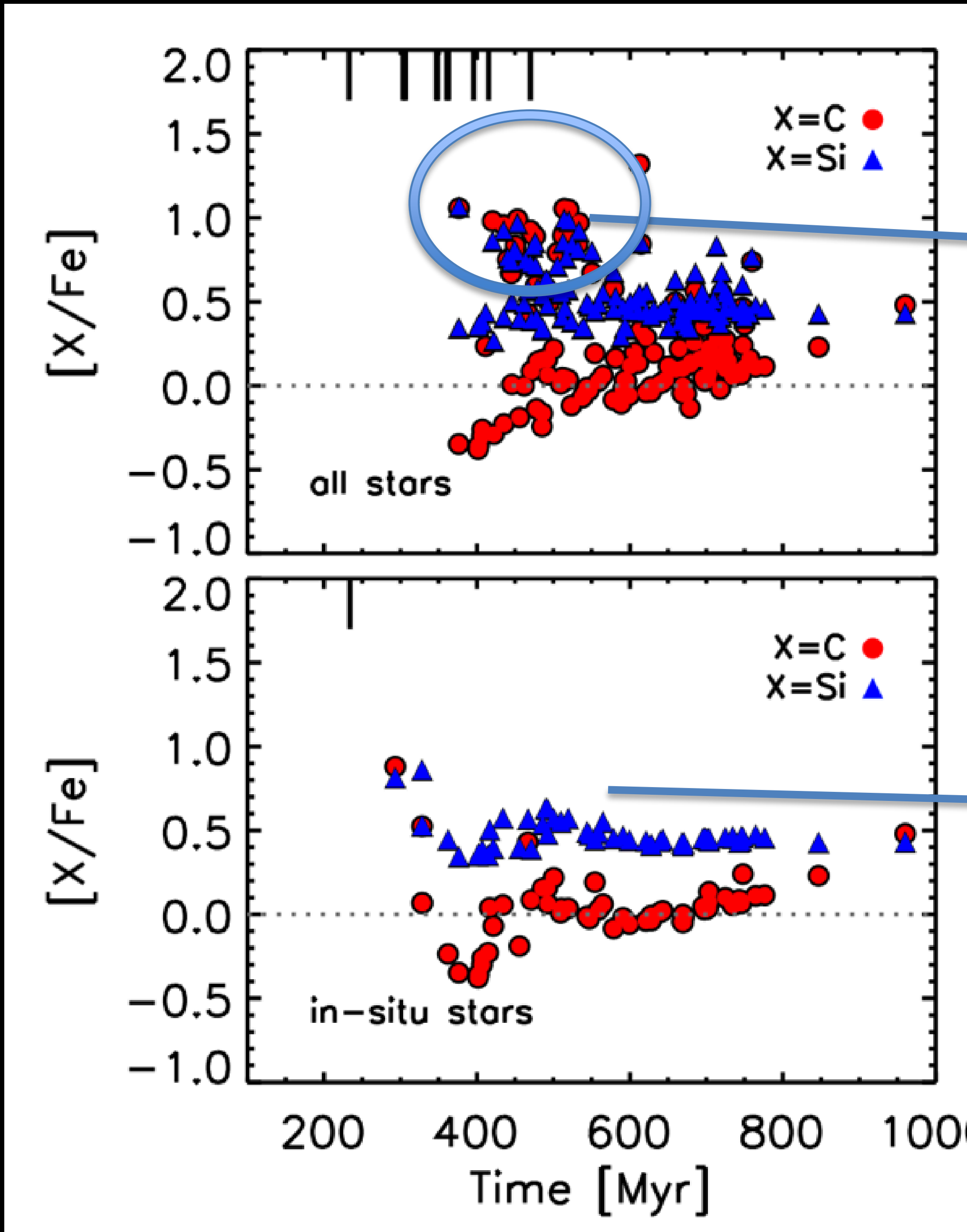
How do we distinguish Pop III signatures?



General yield trends:

Pop III yield:
[C/Fe] ratio is similar or larger than [alpha/Fe].

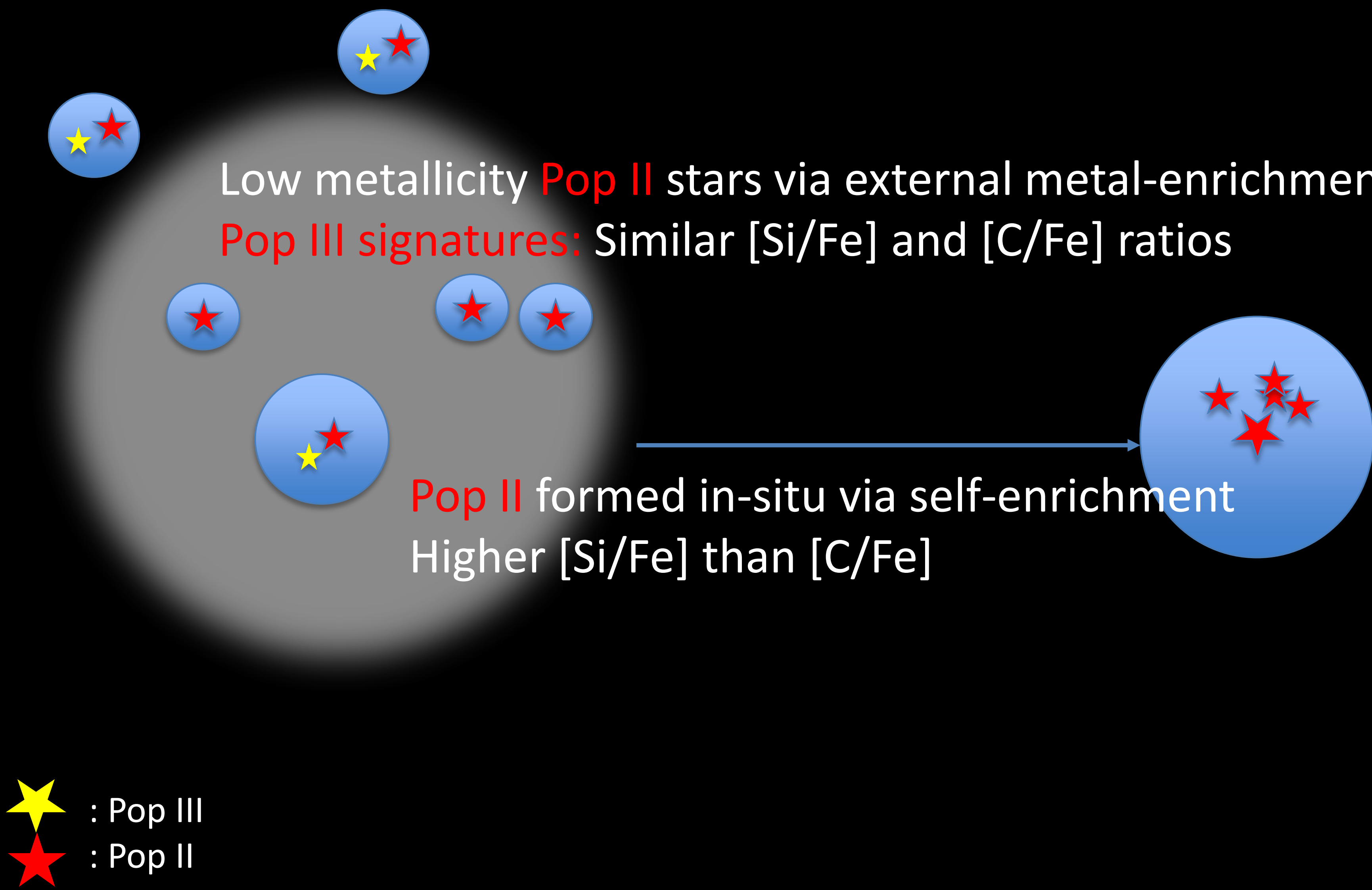
Pop II yield:
opposite trend for Pop II SNe yields:
Higher [alpha/Fe] than [C/Fe] ratios.



Similar [Si/Fe] and [C/Fe] ratios.
-> Pop III signatures.

higher [Si/Fe] than [C/Fe] ratios.
Self-enrichment.
-> Pop II signatures

Assembly of dwarf galaxies



UFD analogs and the observed UFDs.

SUMMARY OF COMPARISON BETWEEN THE SIMULATED UFD ANALOGS AND THE OBSERVED UFDS.

UFDs	$M_*[M_\odot]$	Analogs	Similar properties
Segue I	1.0×10^3	HALO5	[α/Fe], [C/Fe], $[Fe/H]_{max}$
Com Ber	3.7×10^3	HALO3	[α/Fe], [C/Fe]
UMa II	4.1×10^3	HALO6	[α/Fe], $[Fe/H]_{max}$
CVn II	7.9×10^3	HALO2	[α/Fe]
Leo IV	1.0×10^4	HALO4	[α/Fe], [C/Fe], $[Fe/H]_{max}$
UMa I	1.4×10^4	NONE	-
Bootes I	2.9×10^4	HALO3	[α/Fe], [C/Fe], $[Fe/H]_{max}$
Hercules	3.7×10^4	HALO2	[α/Fe], [C/Fe], $[Fe/H]_{max}$

Need further zoom-in simulations with the MW environmental effects..

Summary:

- We confirm that in local dwarf galaxies reionization, in combination with supernova feedback, did play a critical role in suppressing star formation.

- The effectiveness of reionization in preventing star formation strongly depends on halo mass.

- Population III stars and the associated external metal-enrichment is important in producing low-metallicity stars ([Fe/H]<-4), and for the origin of CEMPs.

- We can reproduce CEMPs and enhanced alpha elements, consistent with observations of UFDs.

- Pop III and Pop II signatures can be distinguishable based on the distinct yield trends.

- These predictions can be probed with upcoming deep observations of metal-poor stars.

Thanks!