Stellar Archaeology as a Time Machine to the First Stars

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Connecting the first galaxies with ultra faint dwarfs in the Local Group

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From first stars to local dwarfs

First stars (Pop III stars, >100 $M_\odot$)

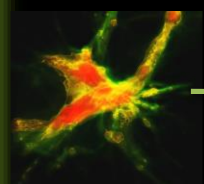
at z>15, primordial gas in minihaloes ($M_{vir} = 10^{5\text{-}6}\ M_\odot$)

Second gen. of stars (Pop II stars, ~ 1 $M_\odot$)

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

First galaxies

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



Fossil galaxies?

No or a little additional star formation
Dwarf galaxies could preserve chemical signatures of early stars.

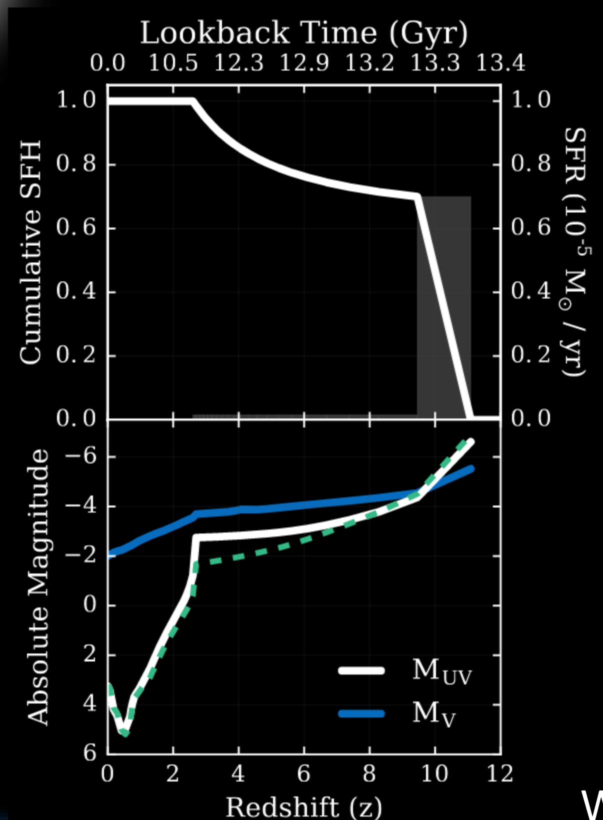
First stars & Galaxies
(t_H ~ a few 100 Myr)

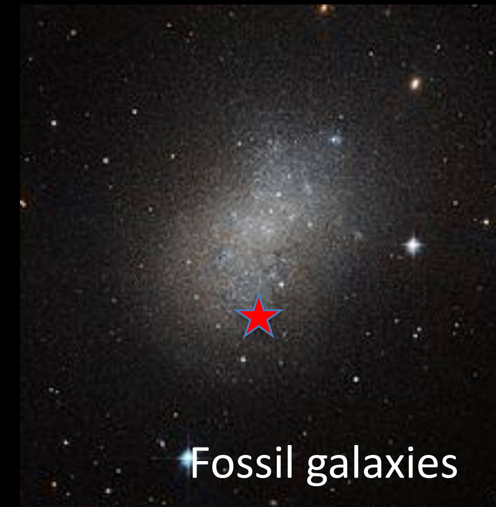
Reionization
(t_H ~ 1 Gyr)

Today z=0

Dwarf galaxies as a time machine
Stellar Archaeology

No/a little star formation for ~ 13 Gyr





Ultra faint dwarf galaxies (UFDs) from > 70% of stars at high-z.

- Reionization
- Supernova feedback
- Environmental effect

: see Eline Tolstoy's talk

Weisz et al. 2017

Today z=0

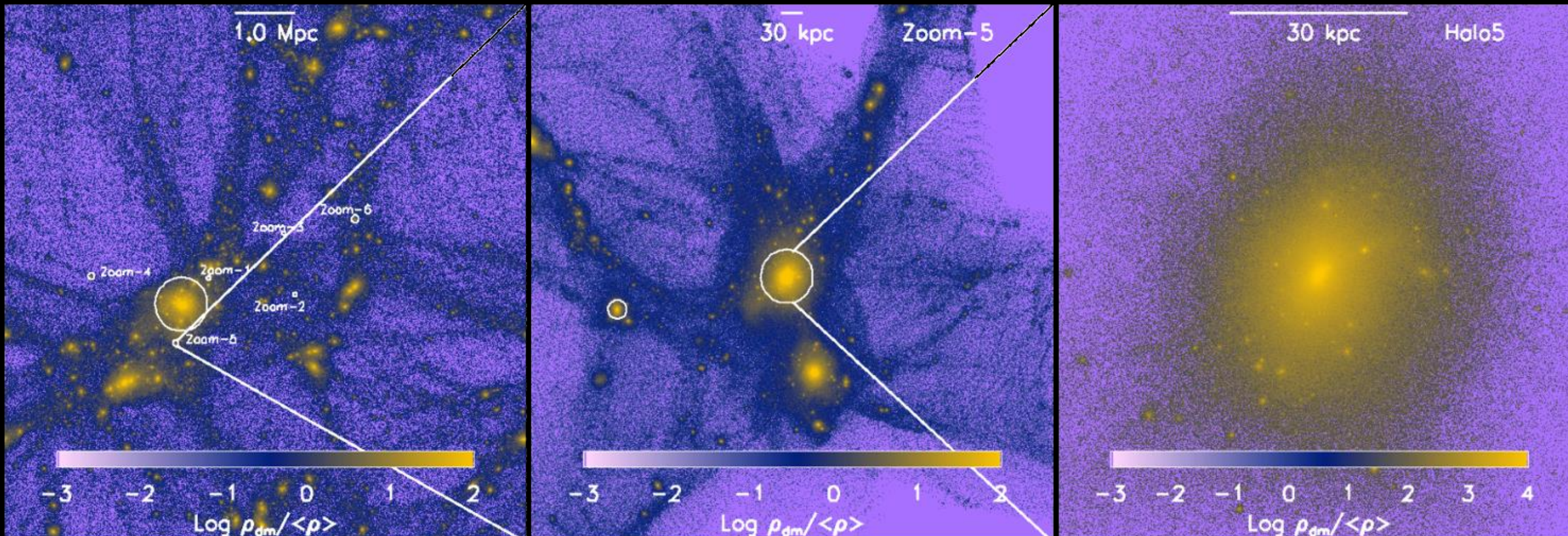
Key Questions

(1) Which physical processes played an important role in determining star formation histories (SFHs) in UFDs?

(2) Can we reproduce the chemical abundances of observed UFDs from cosmological simulations?

(3) What will be the mass scale of the galaxies that show ‘pure’ signatures of Pop III stars?

Simulated Dwarfs



CHARACTERISTICS OF THE SIMULATED UFD ANALOGS AT $z = 0$.

Halo	$M_{\rm vir}$	$r_{\rm v}$	M_*	$D_{\rm h}$	$f_{\rm b}$	$r^*_{1/2}$	[Fe/H]	[α/Fe]	σ_*	$\rm SF_{trun}$
Unit	[$10^9\ M_\odot$]	[kpc]	[$10^4\ M_\odot$]	[Mpc]	[%]	[pc]	-	-	[$\rm km s^{-1}$]	-
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

(Jeon, Besla & Bromm, 2017)

Simulation detail

- Gadget-3
- 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, 150] $M_{\odot}$
  - Pop II/I : Chabrier IMF, [0.1, 100] $M_{\odot}$

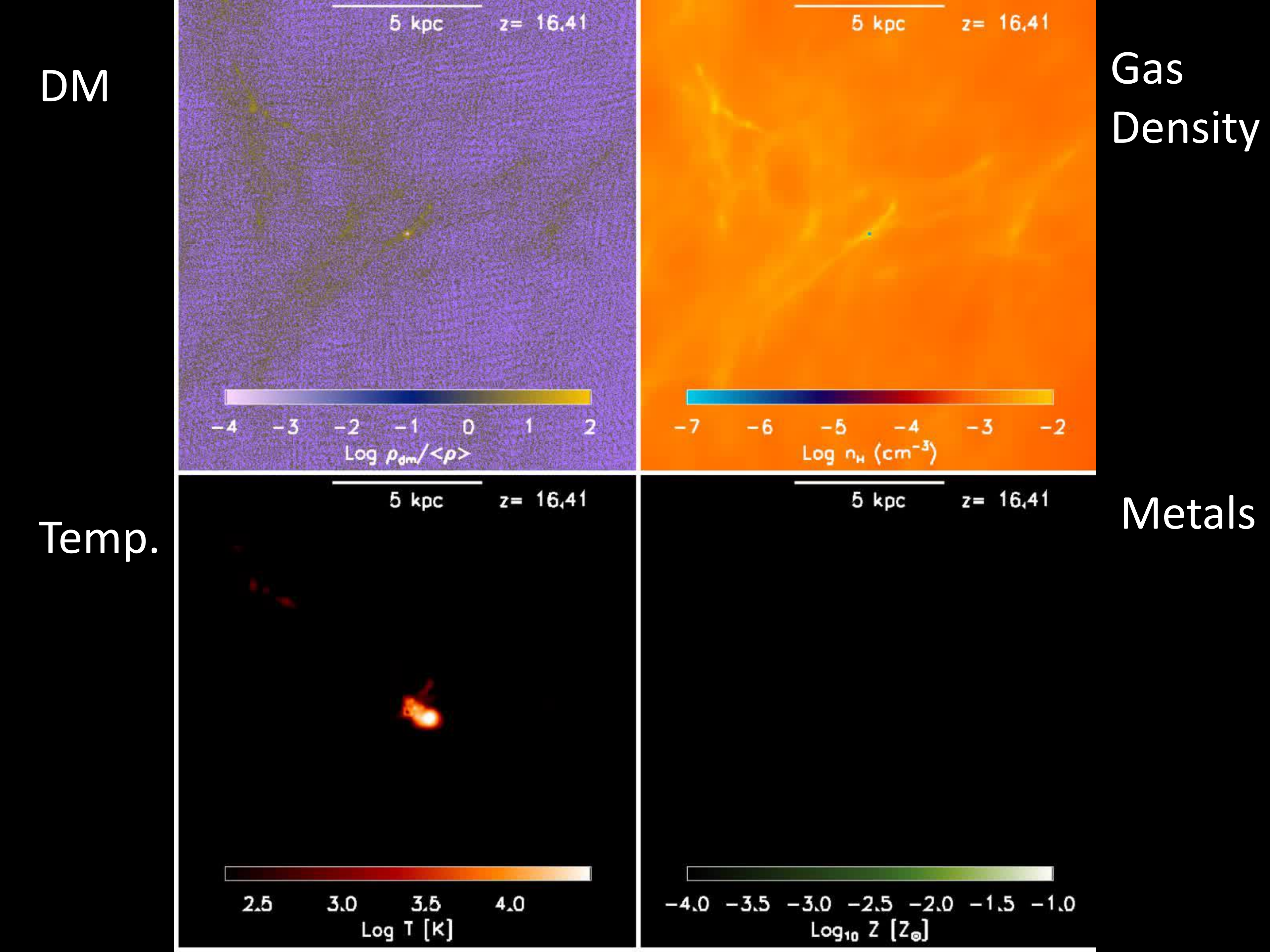
- SNe feedback : thermal energy
- Non-equilibrium cooling, UV photoheating (Haardt & Madau 2011),
- reionization (z=7-6),
- self-shielding of the dense gas

- SNe yield : C, O, Mg, Ne, Si, Iron (Wiersma et al. 2009)

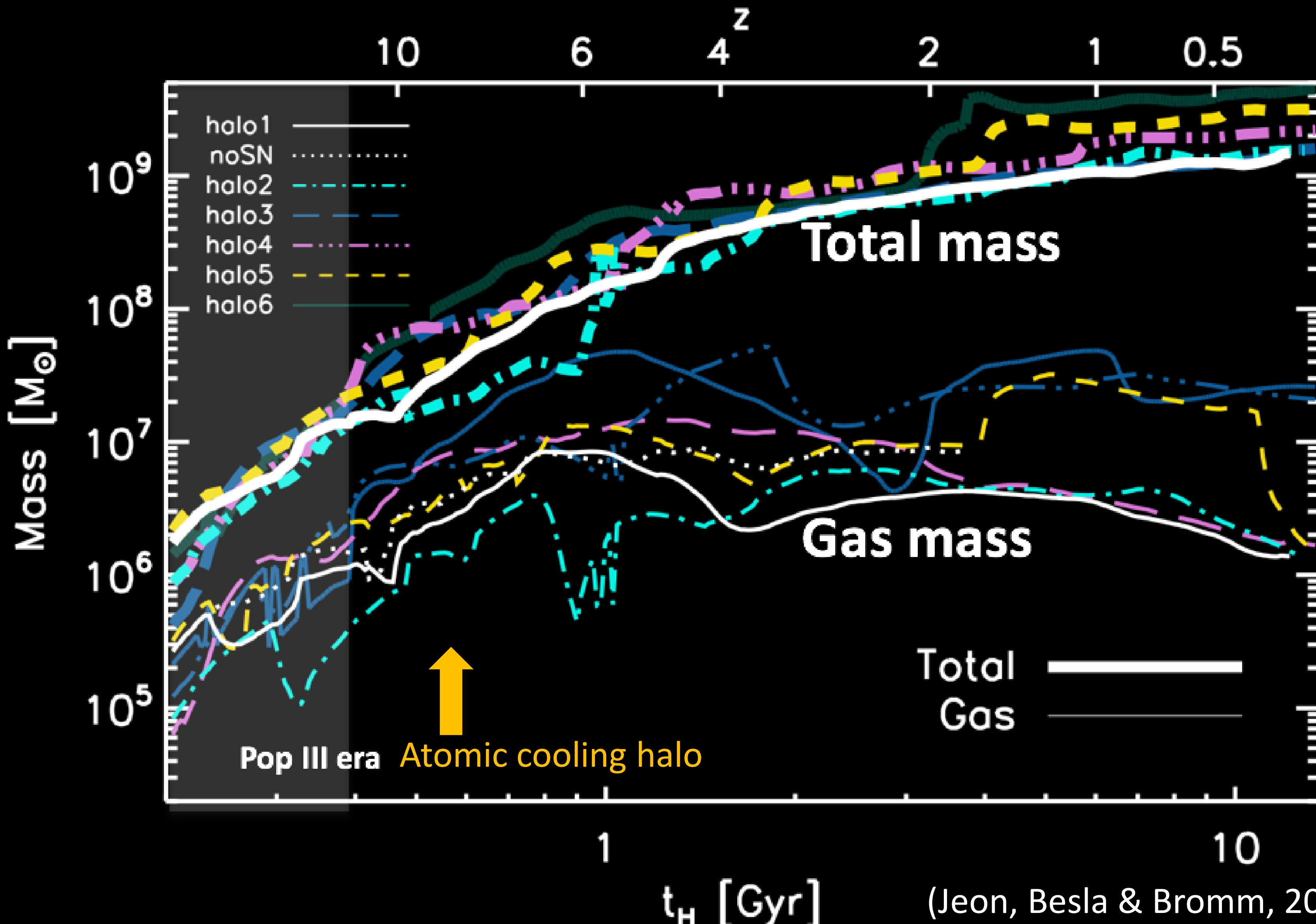
  PopIII Pair-instability SNe (PISNe) : Heger & Woosely (2002)

  PopIII Core-collapse SNe (CCSNe) : Heger & Woosely (2010)

  PopII : Marigo (2001), Portinari (1998), Thielemann et al. 2003)
- Metal mixing : diffusion method, diffusion coefficient D~ rho x velocity x l (Greif et al. 2009)

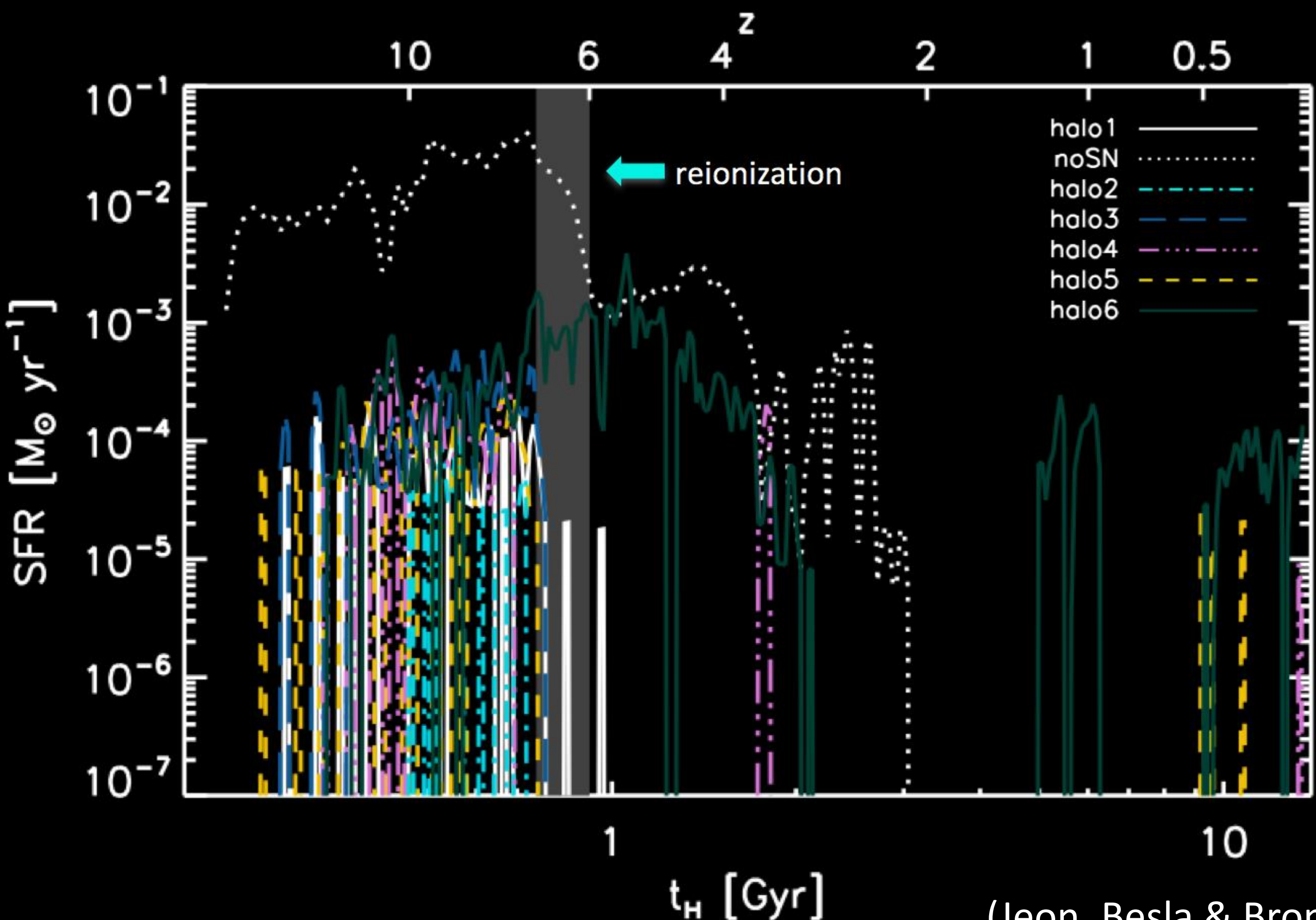

DM
Gas Density
Temp.
Metals
5 kpc
z= 16.41
−4 −3 −2 −1 0 1 2
Log $\rho_{dm}/<\rho>$
−7 −6 −5 −4 −3 −2
Log n_H (cm^{-3})
2.5 3.0 3.5 4.0
Log T [K]
−4.0 −3.5 −3.0 −2.5 −2.0 −1.5 −1.0
Log_{10} Z [$Z_{\odot}$]

Mass Growth



(Jeon, Besla & Bromm, 2017)

Truncated star formation haloes by reionization



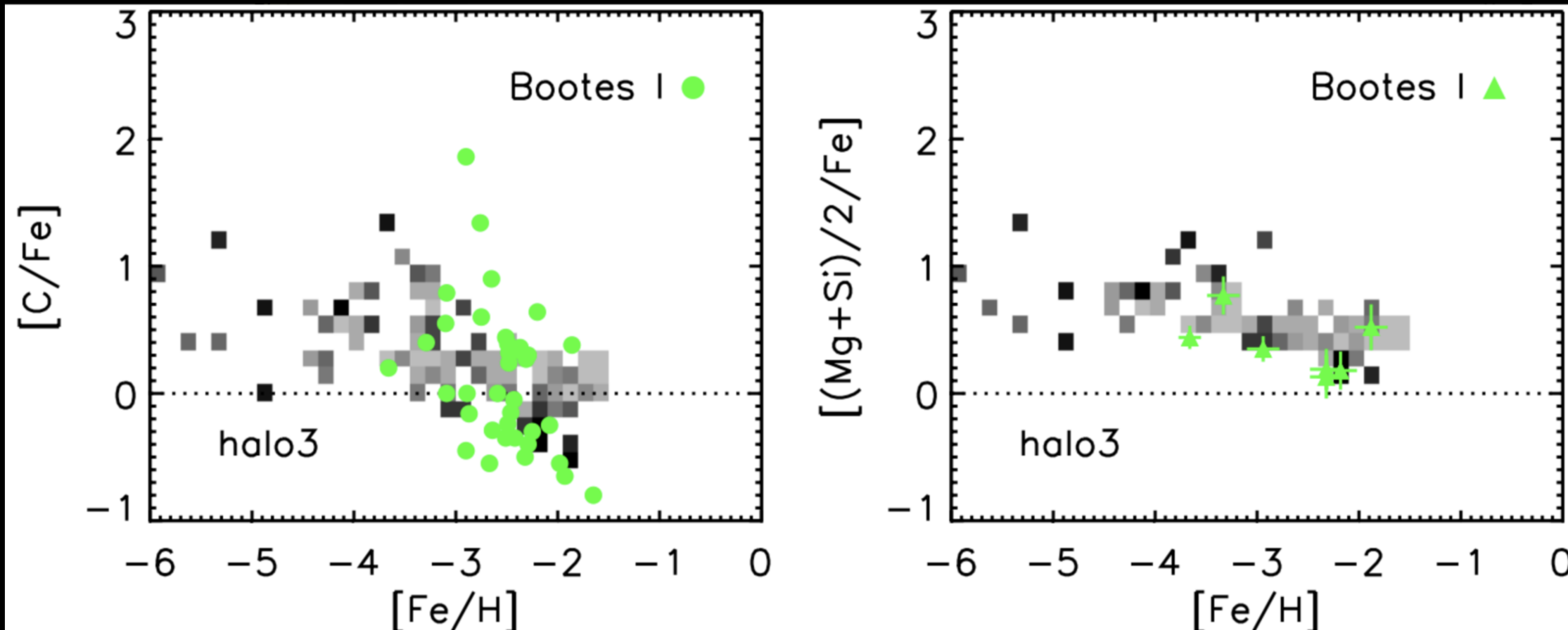
(Jeon, Besla & Bromm, 2017)

Quenching of SF by reionization and SNe in low-mass galaxies ($M_h < 2\text{x}10^9$ $M_\odot$)
Continuous SF in galaxies ($M_h > 3\text{-}4 \text{ x } 10^9$ $M_\odot$, $M_{HI}\sim10^5$ $M_\odot$; Leo P, Leo T)

Stellar abundances: signatures of PopIII

Carbon

Alpha-elements



- <u>CEMPs – Pop III SNe - external metal enrichment</u>
- <u>Carbon-normal – self-enrichment via Pop II SNe.</u>

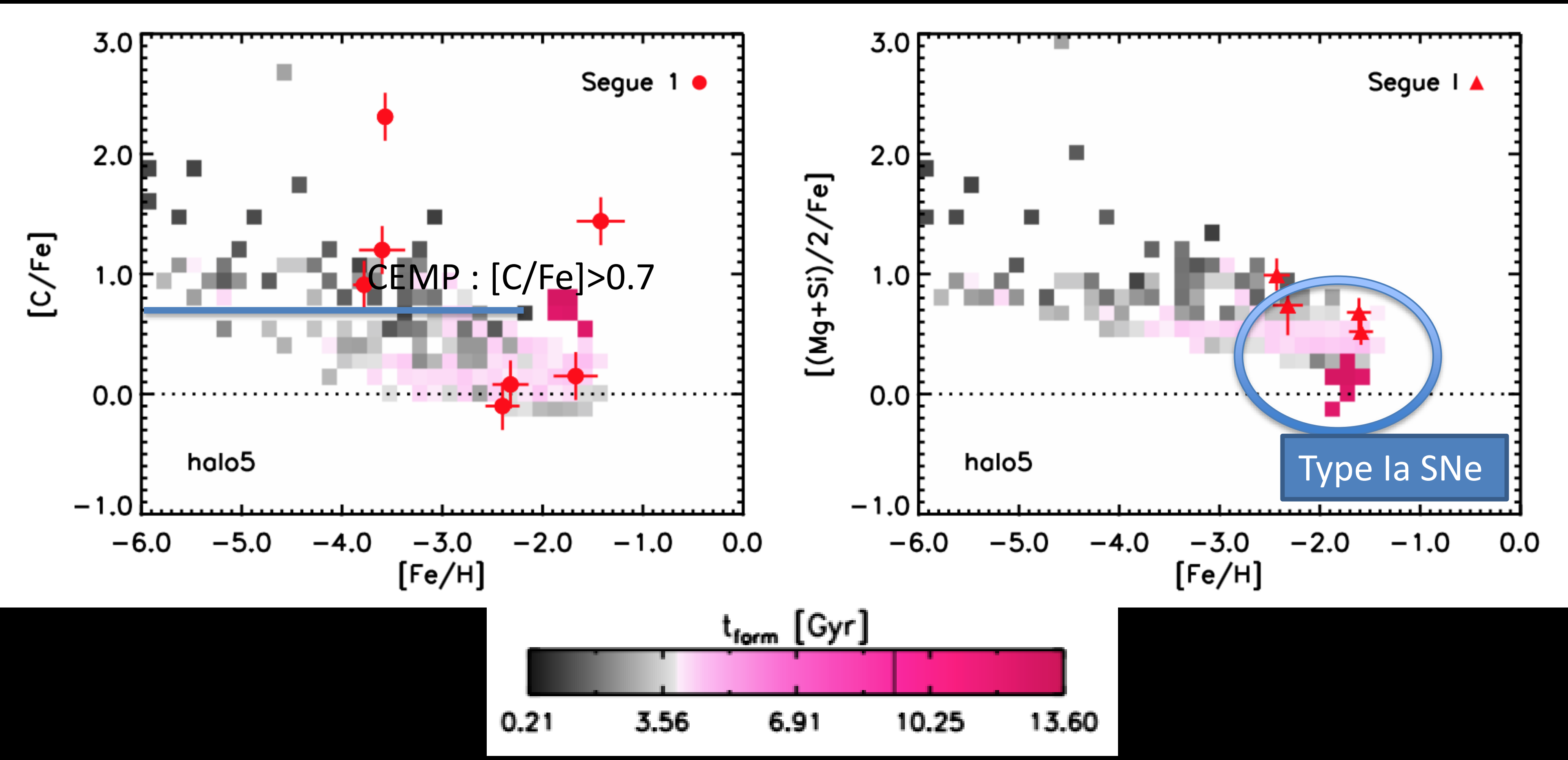
- Alpha-elements are enhanced, meaning that they were mainly enriched by Type II SNe from PopIII and PopII stars.

(Jeon, Besla & Bromm, 2017)

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

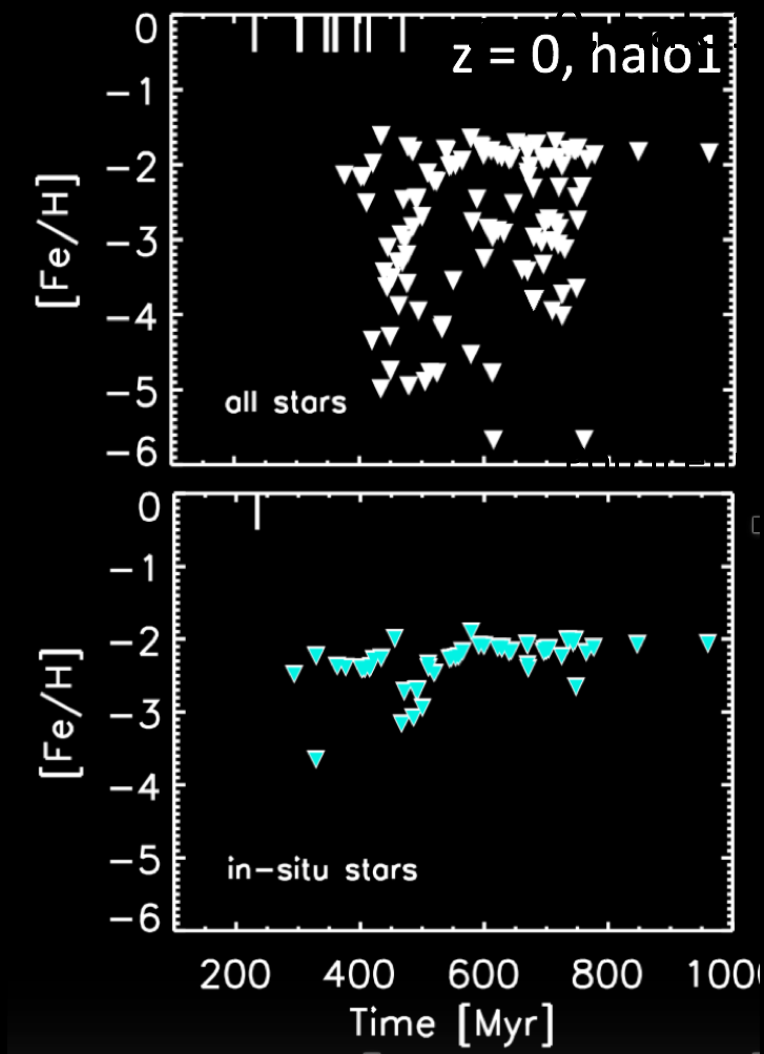
Carbon

Alpha-elements

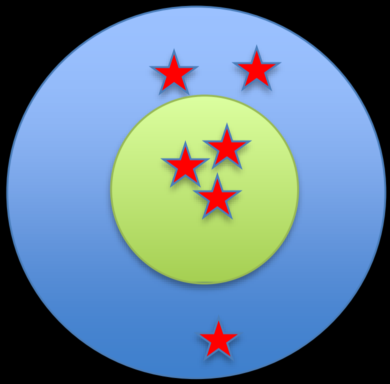


(Jeon, Besla & Bromm, 2017)

Presence of metal-poor stars



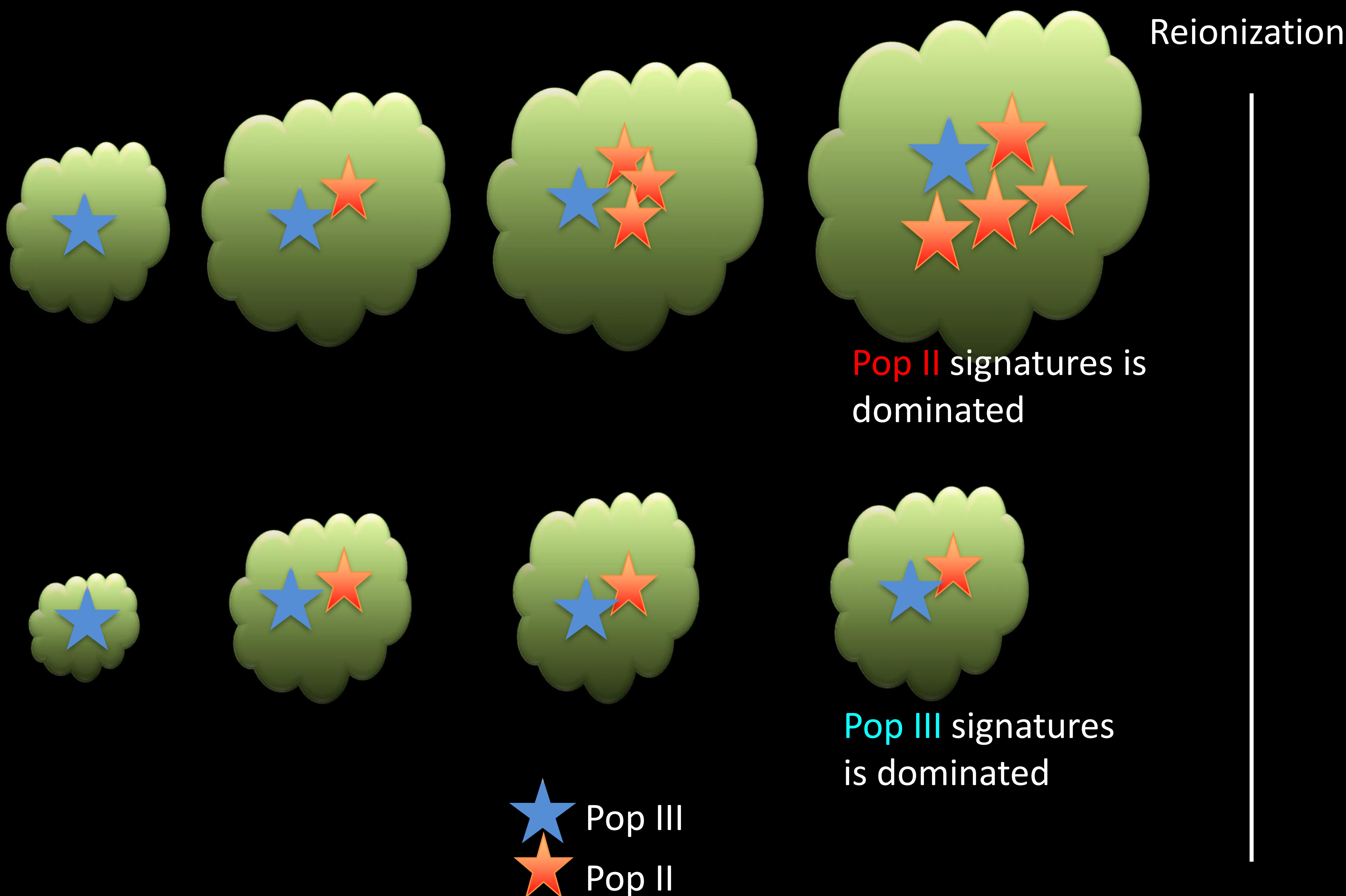
(Jeon, Besla & Bromm, 2017)



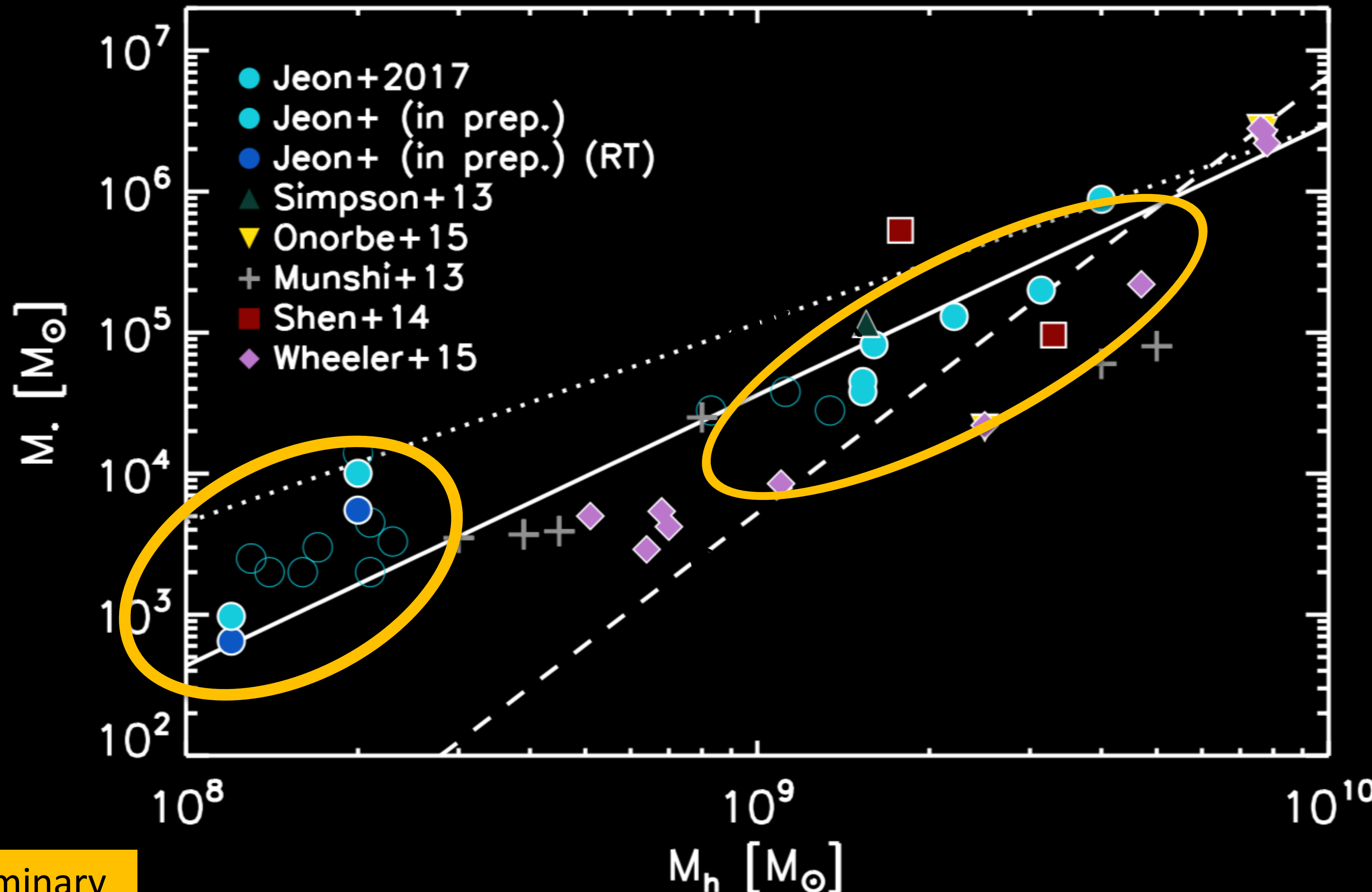
Low metallicity stars were formed in minihalos at high-z via external metal-enrichment.

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

Multiple vs. mono enrichment



Do we need smaller galaxies?

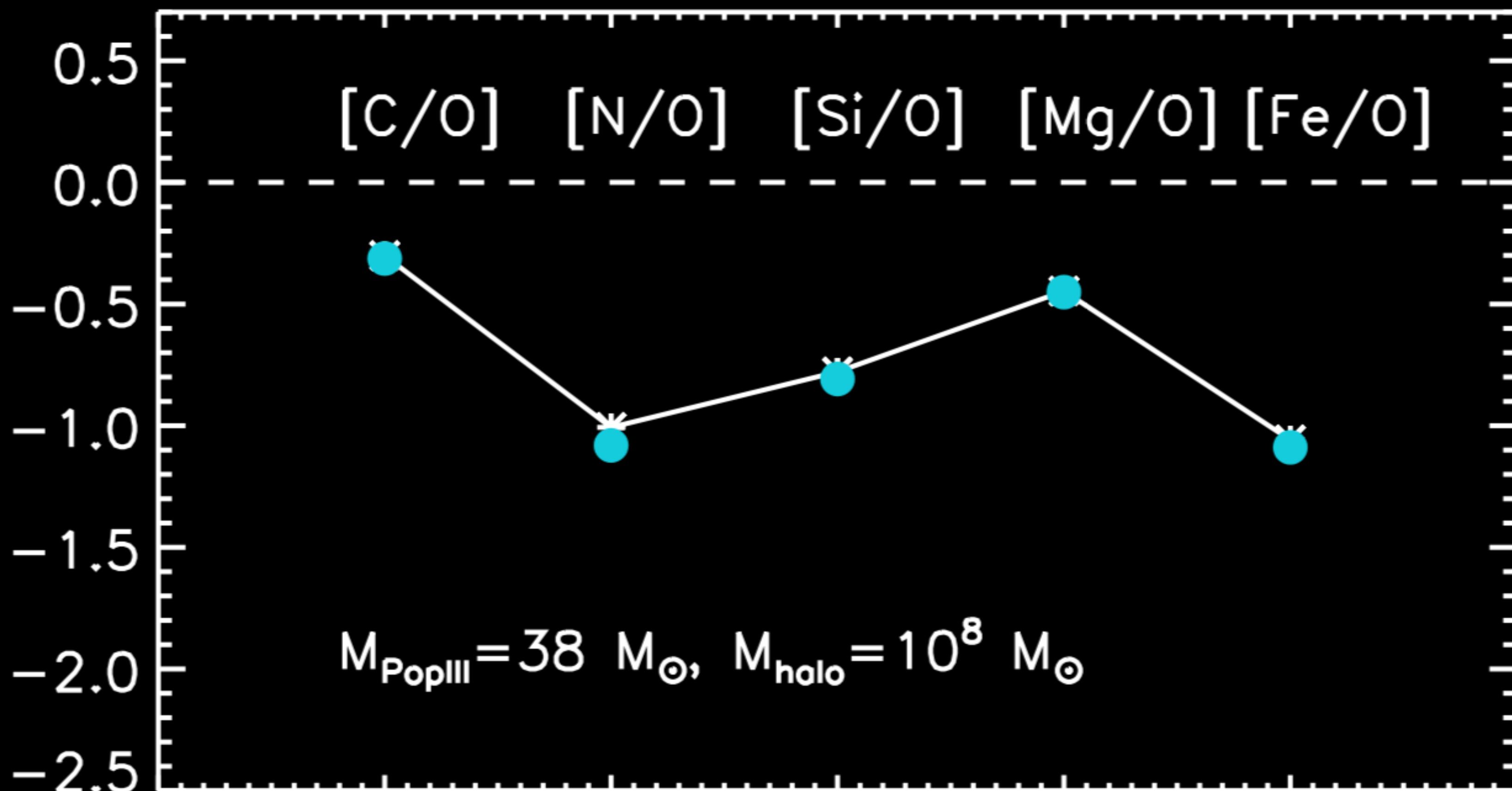


Preliminary

M_{gas} ~ 63 $M_\odot$, M_{DM} ~ 260 $M_\odot$,
with/without photoionization heating (RT)

(Jeon, Besla & Bromm, 2017, Jeon et al.,in prep.)

Abundance from a single Pop III SN



Jeon et al. (in prep.)

- $M_{halo} \sim 10^9\ M_\odot$ (z=0) , multiple metal enrichment
- $M_{halo} \sim 10^8\ M_\odot$ (z=0), maybe a mono enrichment is possible.

The other probe of first stars

Metal poor <u>stars</u>

[Fe/H] < -2

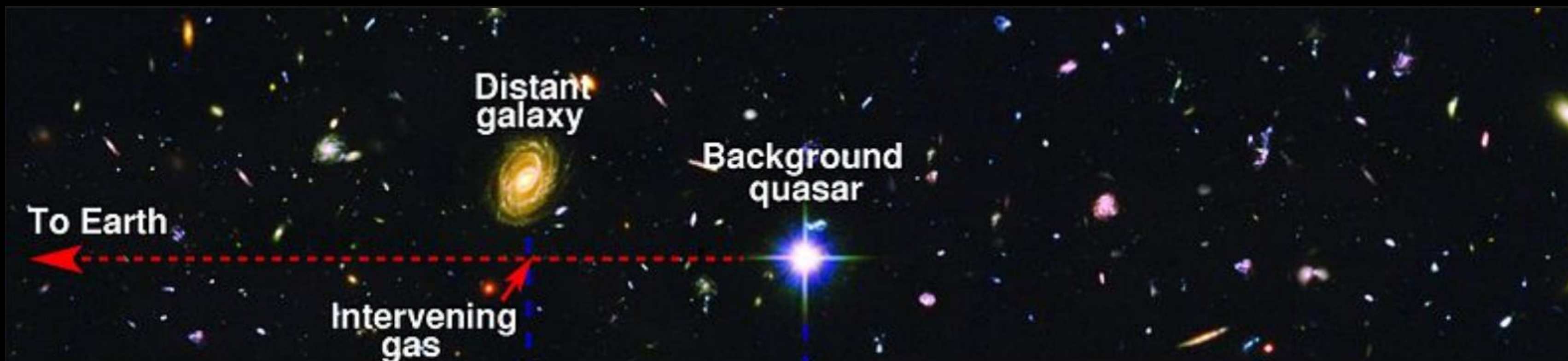
at z=0

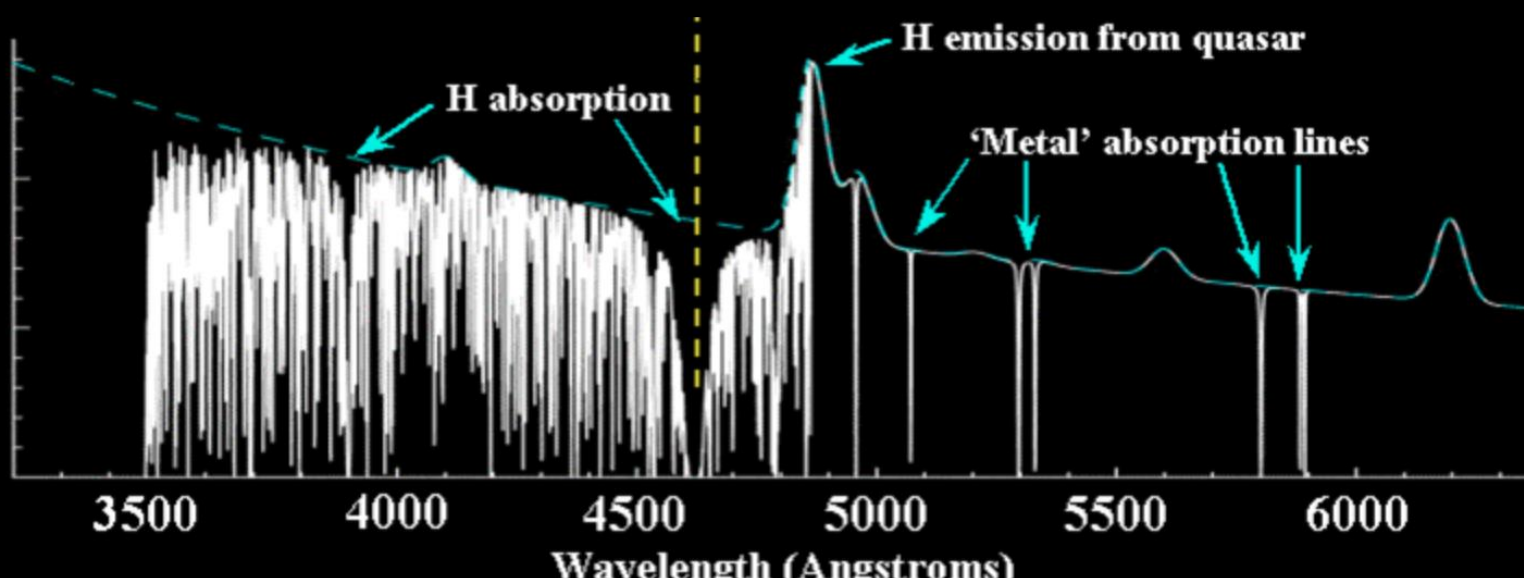
Metal poor <u>gas</u>

[Fe/H] < -2

at z=0 - 4

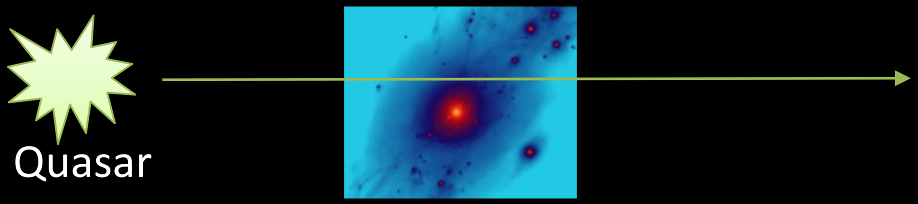
Damped Lyman alpha system (DLAs)



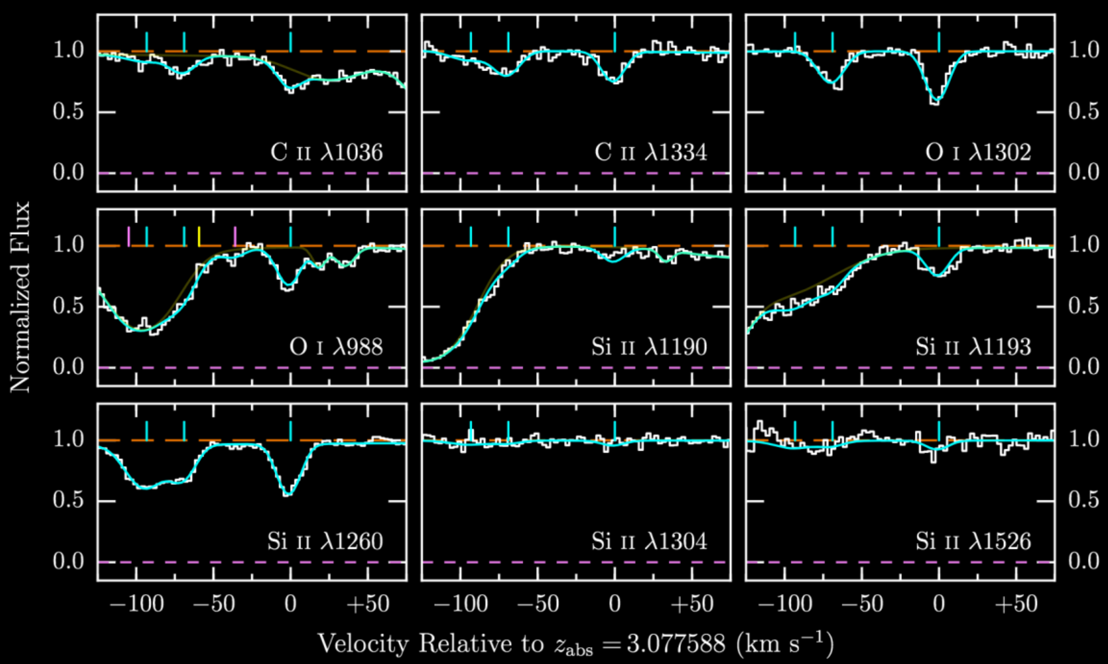


Gas with neutral hydrogen column density of $N_{HI} \sim 10^{20.3}$ cm^{-2}

Metal-poor DLAs as another probe of first stars



neutral gas enriched by Pop III stars



[Fe/H] ~ -3 at z=3, N_{HI}~10^{21} cm^{-2} (Cooke et al. 2017)

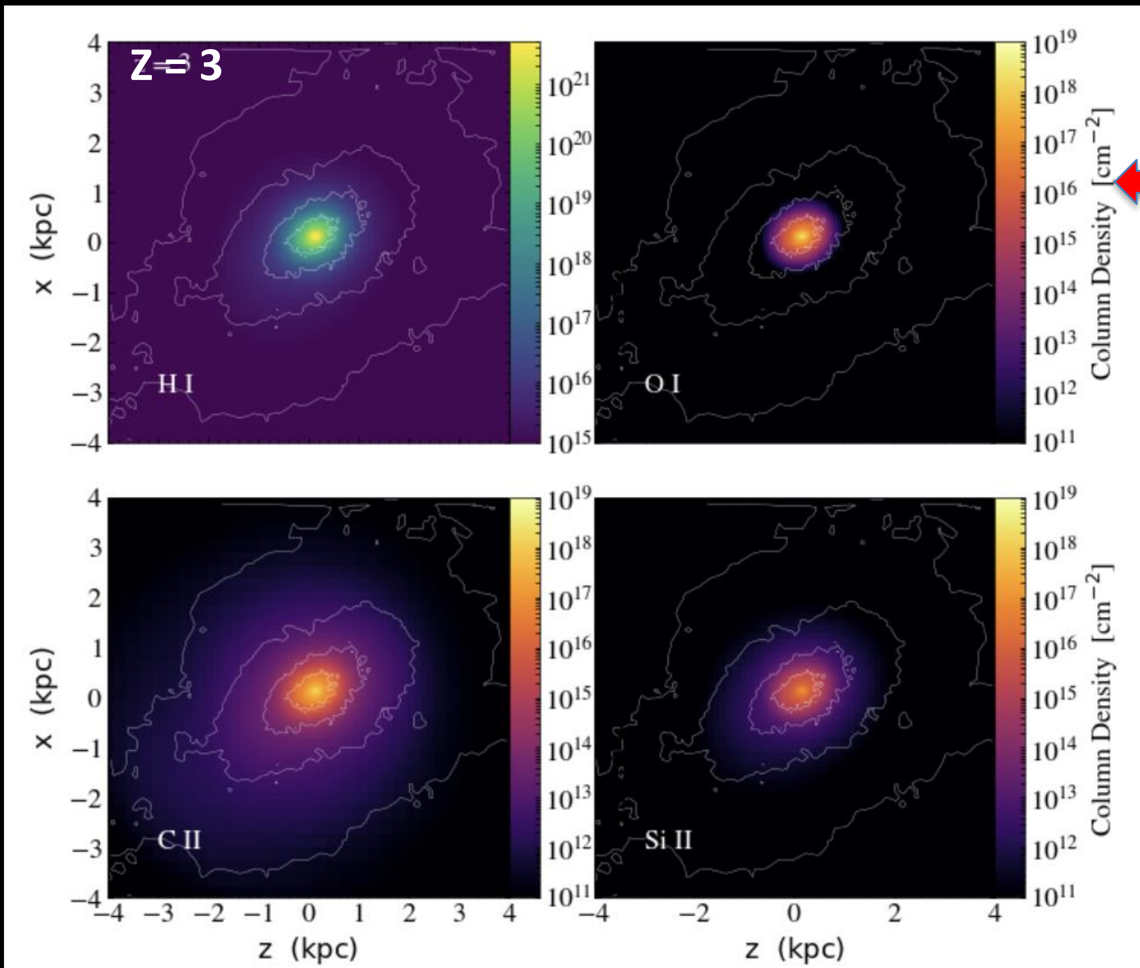
"Gas polluted by metals from 20.5 $M_{\odot}$ Pop III star?"

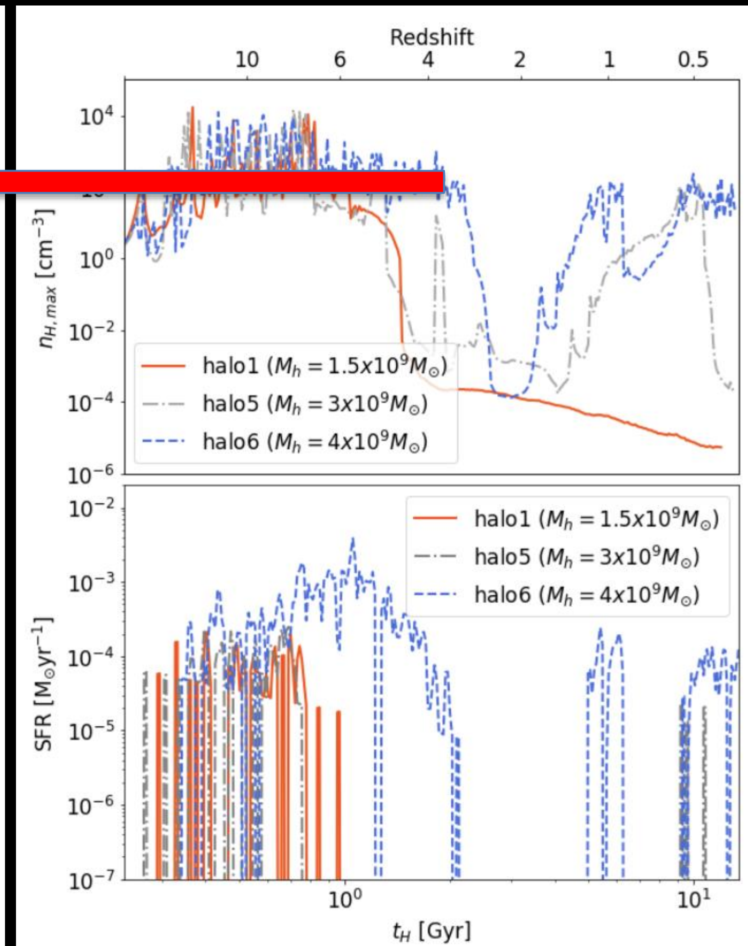
The origin of the DLA.

Q: Can the progenitors of local, gas-rich dwarf galaxies possibly be detected as DLA systems over cosmic time?

Q: Is it the gas at z=3 that could contain the signatures of Pop III?

Neutral gas in dwarfs

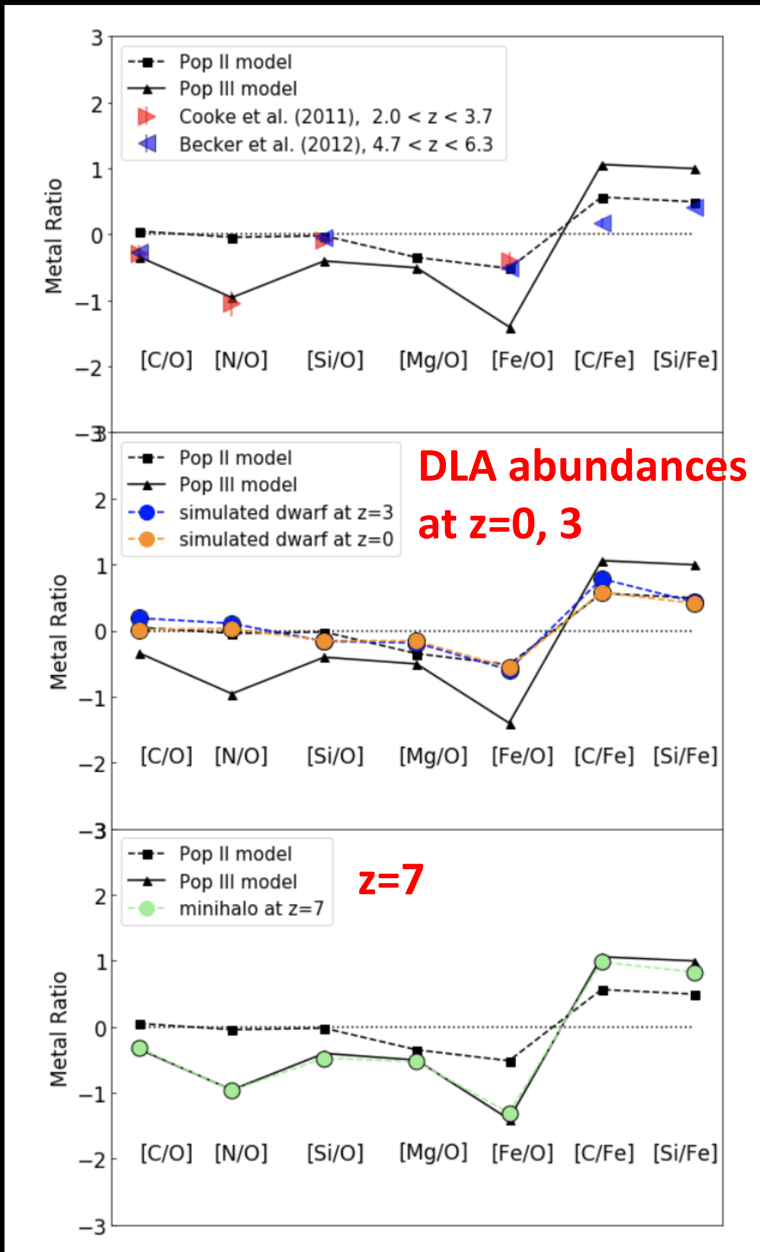




Jeon, Besla & Bromm, 2018 (submitted)

- Gas-rich dwarf
- M_{HI}~10^5 $M_\odot$ (similar to field dwarfs - Leo P, Leo T.)

Can do dwarfs contain Pop III DLAs?



- The progenitors of local dwarfs are expected to be seen for most of their evolution as DLAs that are contaminated by Pop II stars.
- Pop III DLA could exist at high-z (z > 7).

UFDs → No neutral gas at z=3

Gas-rich dwarfs → Too metal-enriched at z=3

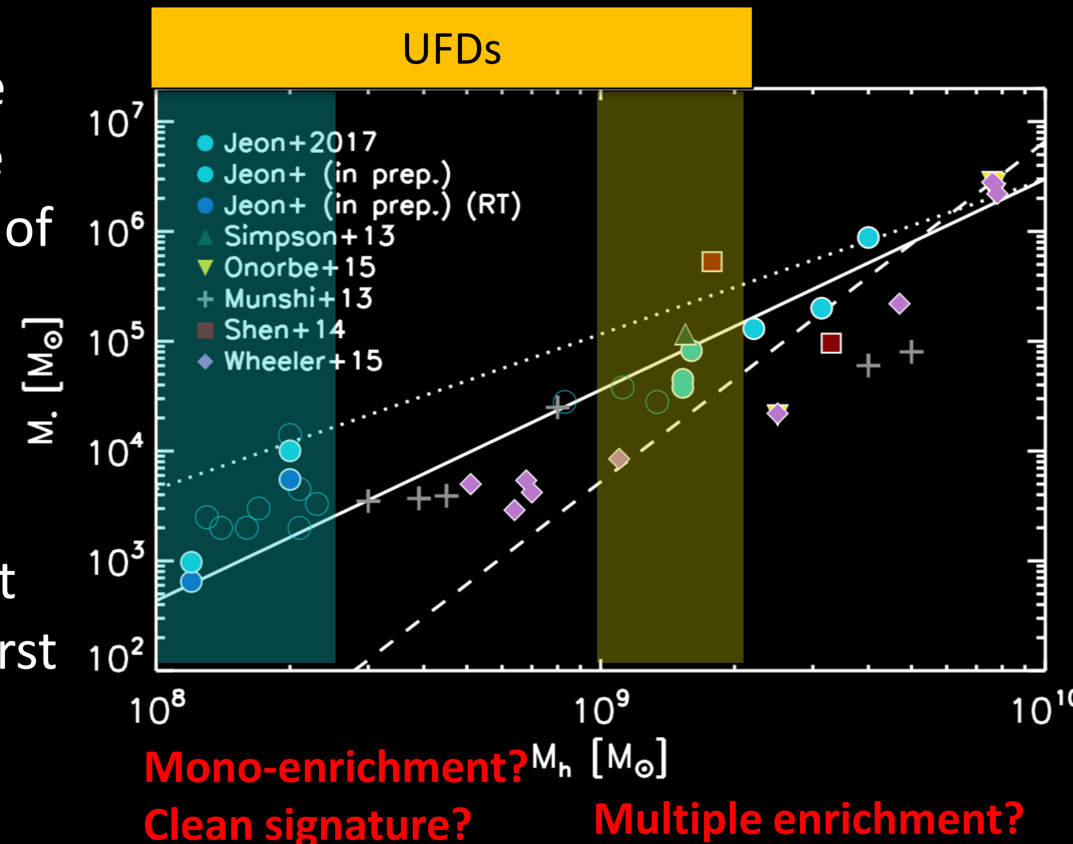
- Extremely metal poor DLA ([Fe/H] ~ -3 at z=3, N_{HI}~10^{21} cm^{-2}) is hard explain in the context of dwarf galaxy assembly.
- Rather metal-poor DLAs are likely to be located at the outskirts of massive galaxies.

Jeon, Besla & Bromm, 2018 (submitted)

Summary

It is important to understand the nature of metal-poor stars in the context of the assembly process of dwarf galaxies.

UFDs : one of the best places to look for the metal poor stars that hold clues to the nature of the first generating of stars.



- Our simulations show that
  - reionization and supernova feedback played an important role in suppressing star formation in UFDs.
  - pop III stars and the external metal-enrichment is important in producing low-metallicity stars ([Fe/H]<-4), and for the origin of CEMPs.

Thank you!