The 8th KIAS Workshop on Cosmology and Structure Formation

Nov. 8, 2018

The formation of dwarf galaxies from high-z to the local Universe

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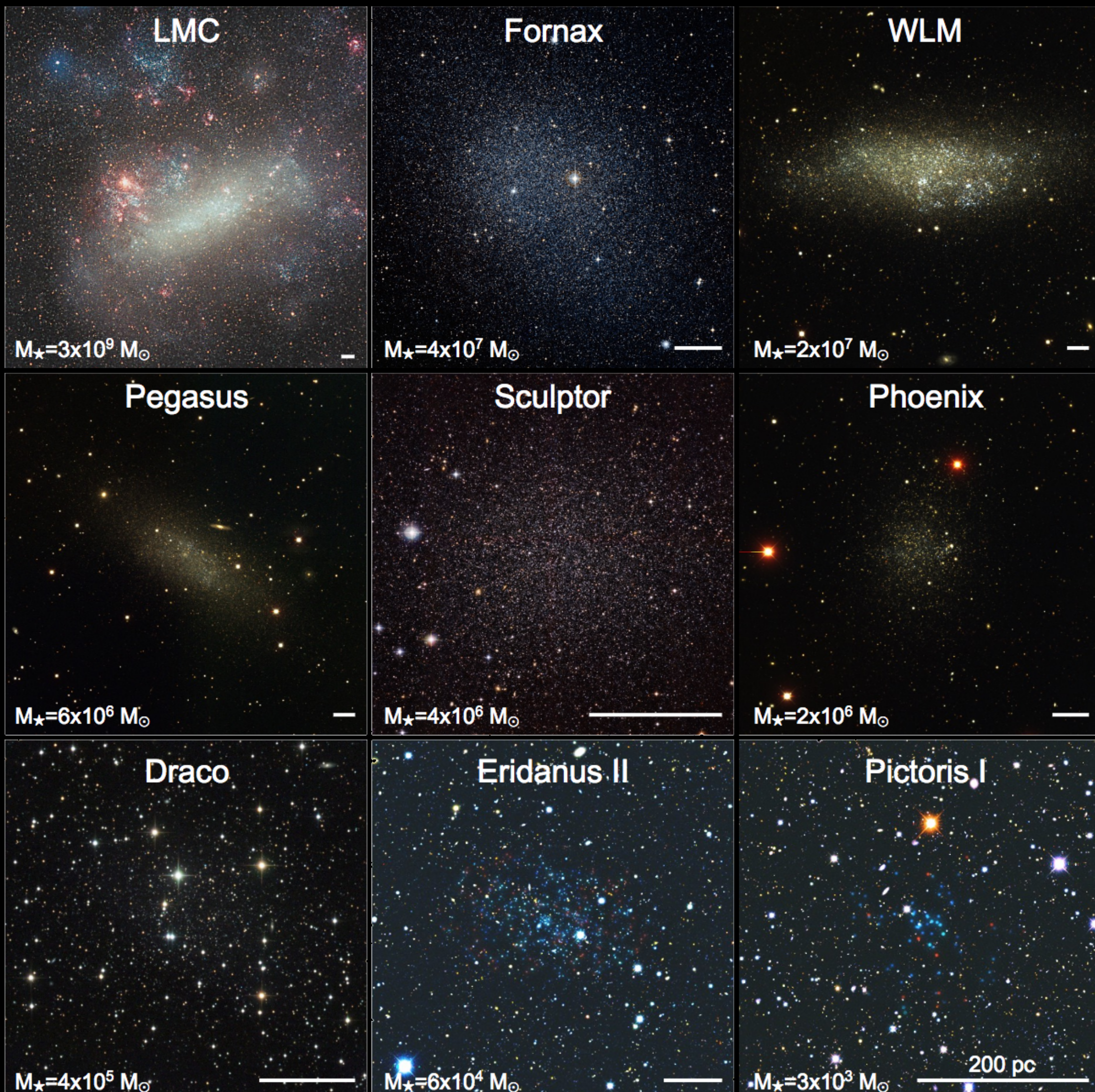
Dwarf galaxies: basic building blocks

What physical processes shape star formation (SF) in dwarfs?

- SF efficiency
- stellar feedback
- reionization
- environmental effects

How small is a small galaxy?



Bullock & Boylan-Kolchin (2017)

Bright Dwarfs :

$M_* \sim 10^{7\text{-}9}\ M_\odot$

- The faint galaxy completeness limit for field galaxy surveys.

Classical Dwarfs :

$M_* \sim 10^{5\text{-}7}\ M_\odot$

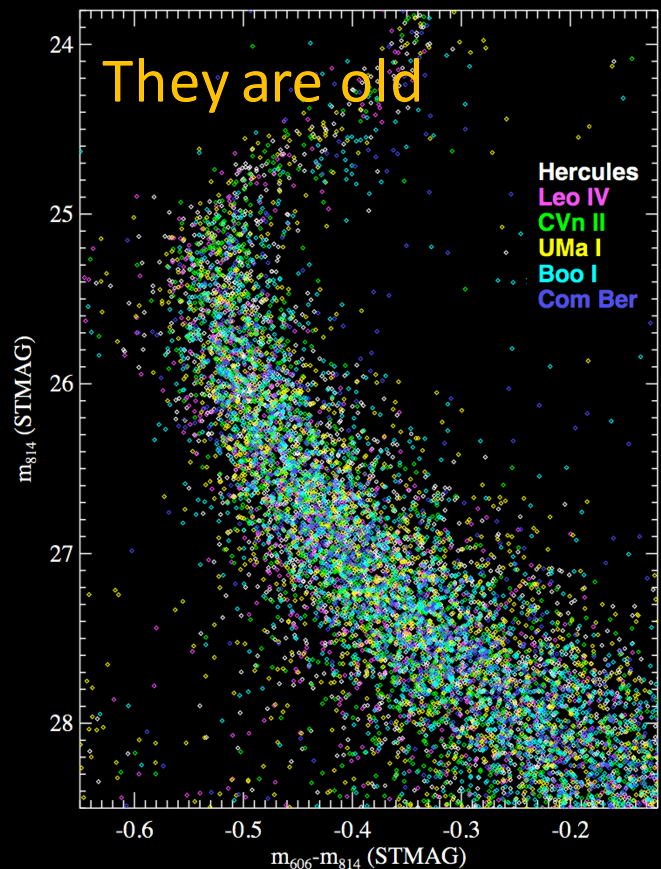
- The faintest galaxies known prior to SDSS.

Ultra-faint Dwarfs :

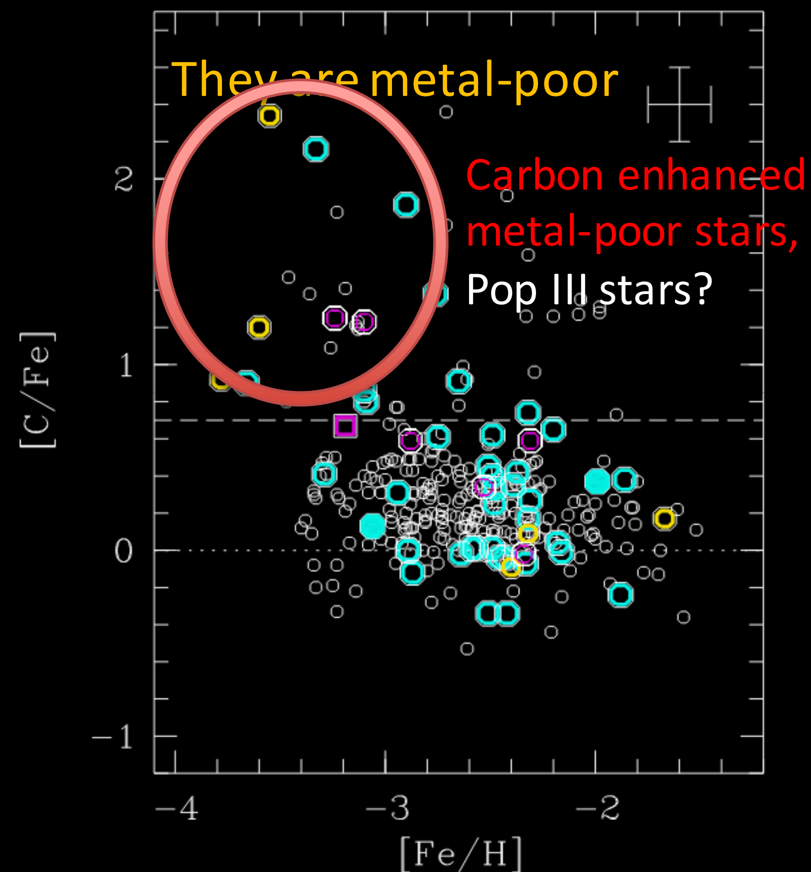
$M_* \sim 10^{2\text{-}5}\ M_\odot$

- Detected within limited volumes around M31 and the Milky Way.

UFDs: the most metal-poor and least massive galaxies



Brown et al. (2014)

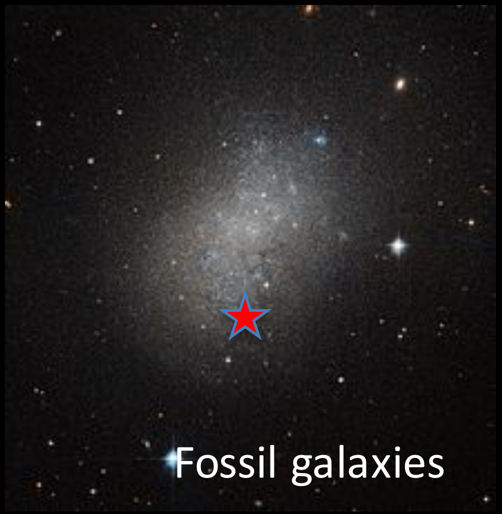


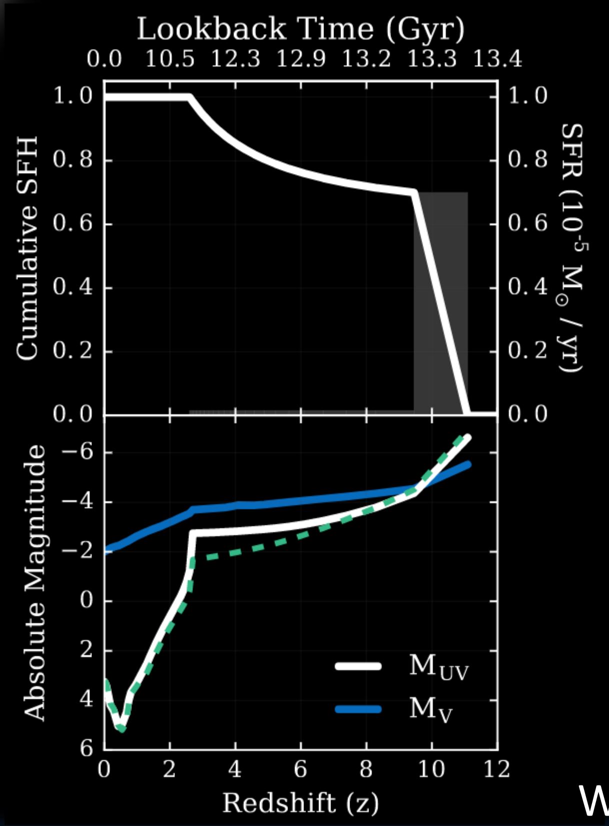
Frebel et al. (2016)

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).

Dwarf galaxies as a time machine
Stellar Archaeology

No/a little star formation for ~ 13 Gyr





Weisz et al. 2017

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

Today z=0

Key Questions

(1) Which physical processes played an important role in determining SFH in UFDs?

(2) Can we understand/reproduce the chemical abundances observed UFDs.

From first stars to local dwarfs

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

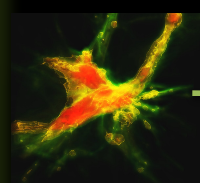
at z>15, primordial gas in minihaloes ($M_{vir} = 10^{5\text{-}6}\ M_\odot$)

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

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

First galaxies

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



No or a little additional star formation

Dwarf galaxies could preserve chemical signatures of early stars.

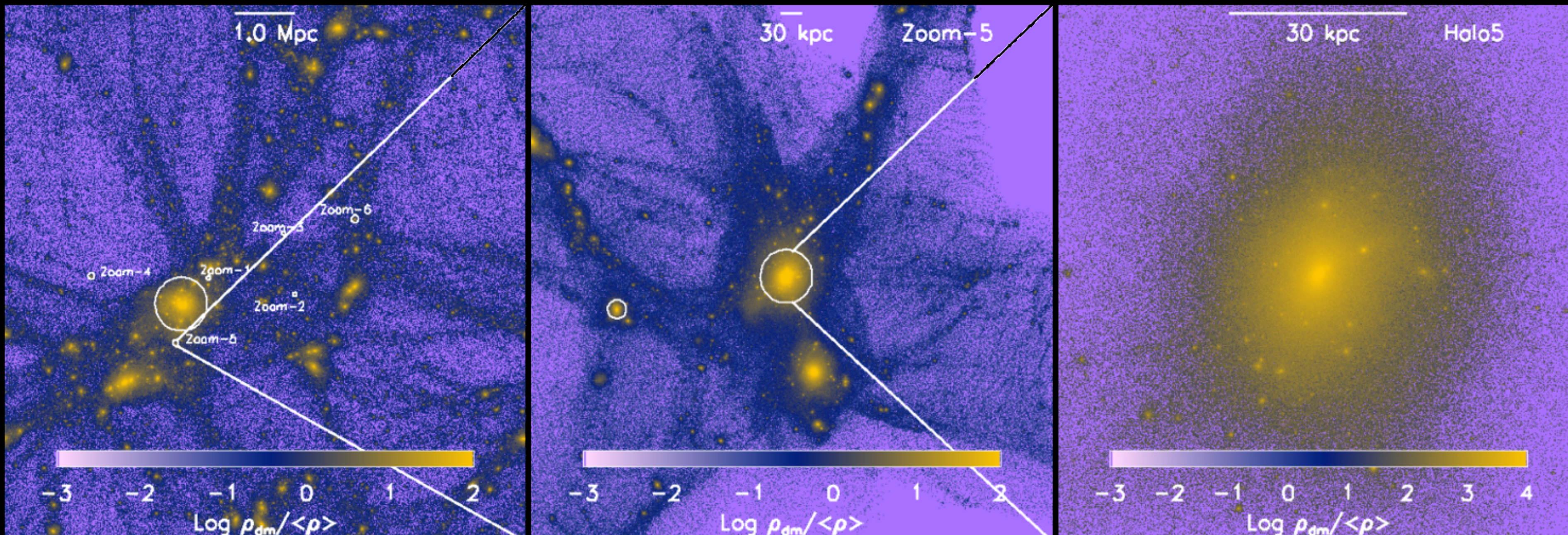
Fossil galaxies?

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

Reionization (t_H ~ 1 Gyr)

Today z=0

Simulated Dwarfs



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

Halo Unit	$M_{\rm vir}$ [$10^9\ M_\odot$]	$r_{\rm v}$ [kpc]	M_* [$10^4\ M_\odot$]	$D_{\rm h}$ [Mpc]	$f_{\rm b}$ [%]	$r^*_{1/2}$ [pc]	[Fe/H] -	[α/Fe] -	σ_* [$\rm km s^{-1}$]	$\rm SF_{trun}$ -
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 et al. 2017)

Simulation detail

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

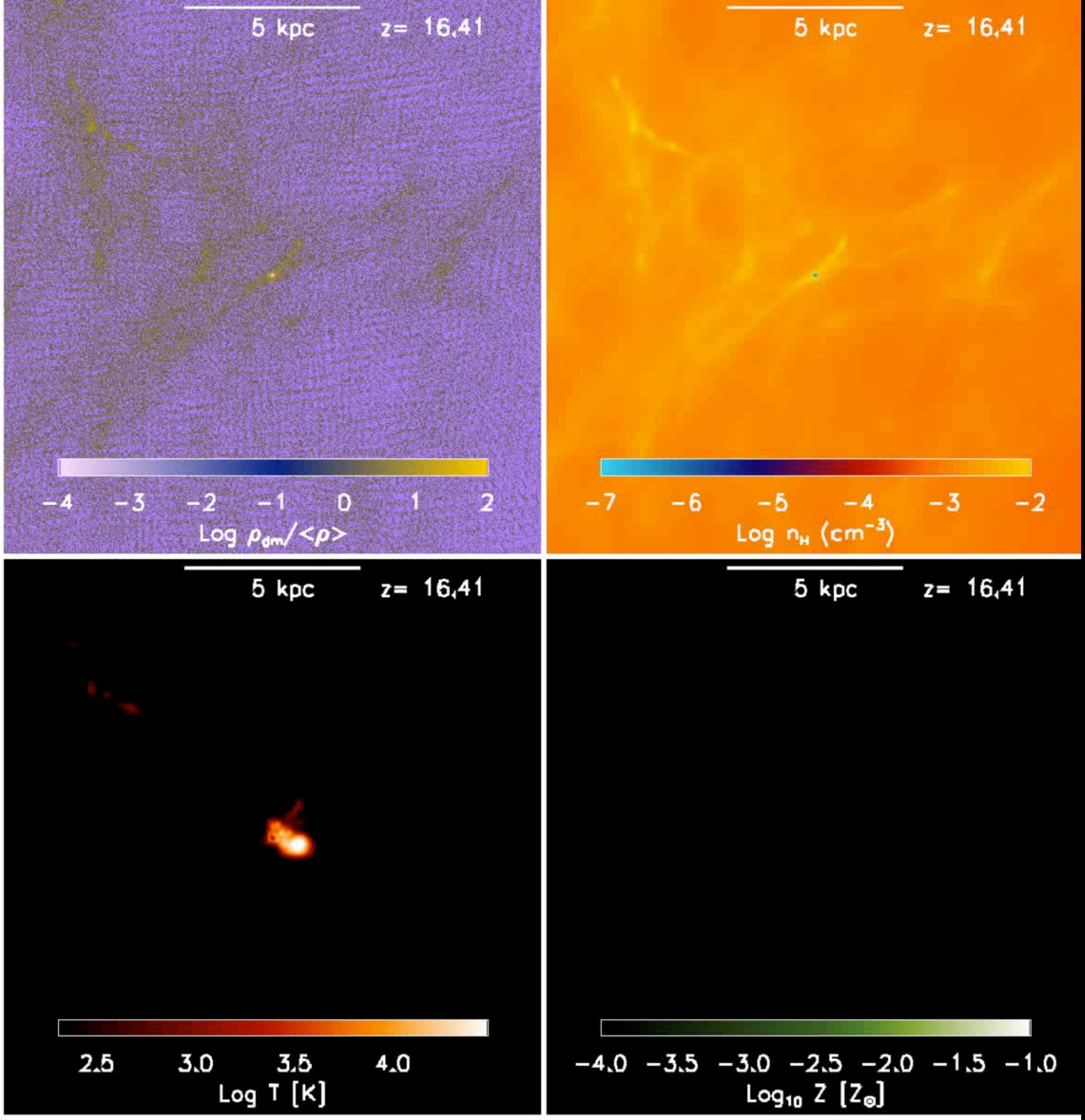
- Star formation :
  - Schmidt law
  - Density threshold of n_H = 100 cm^{-3}, critical metallicity $Z_{crit} = 10^{-5.5} Z_\odot$ (PopII/I)
  - Pop III : top-heavy IMF, [10, 100] $M_\odot$
  - Pop II/I : Chabrier IMF, [0.1, 100] $M_\odot$

- 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 : 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

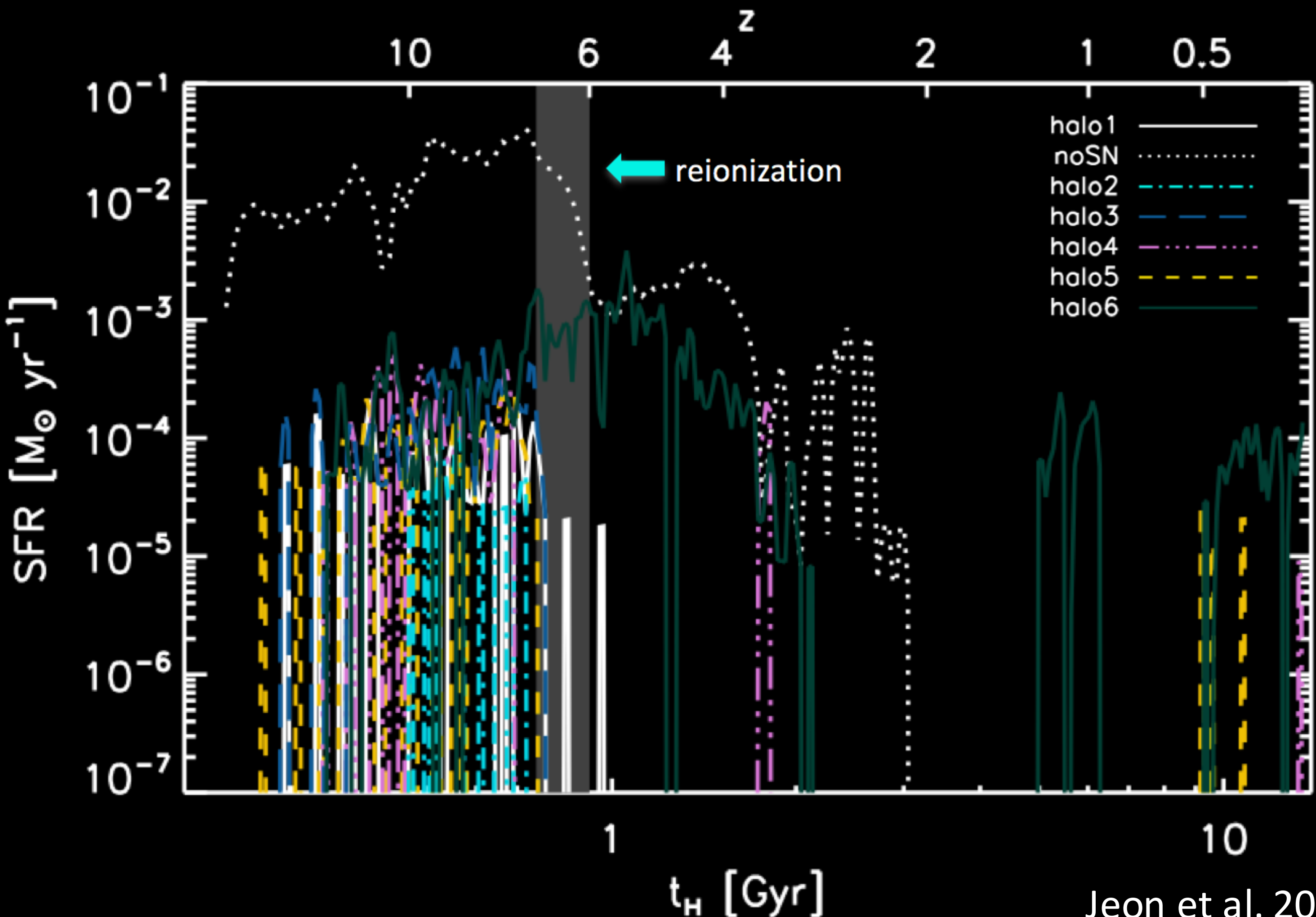
Gas Density



Temp.

Metals

Truncated star formation haloes by reionization



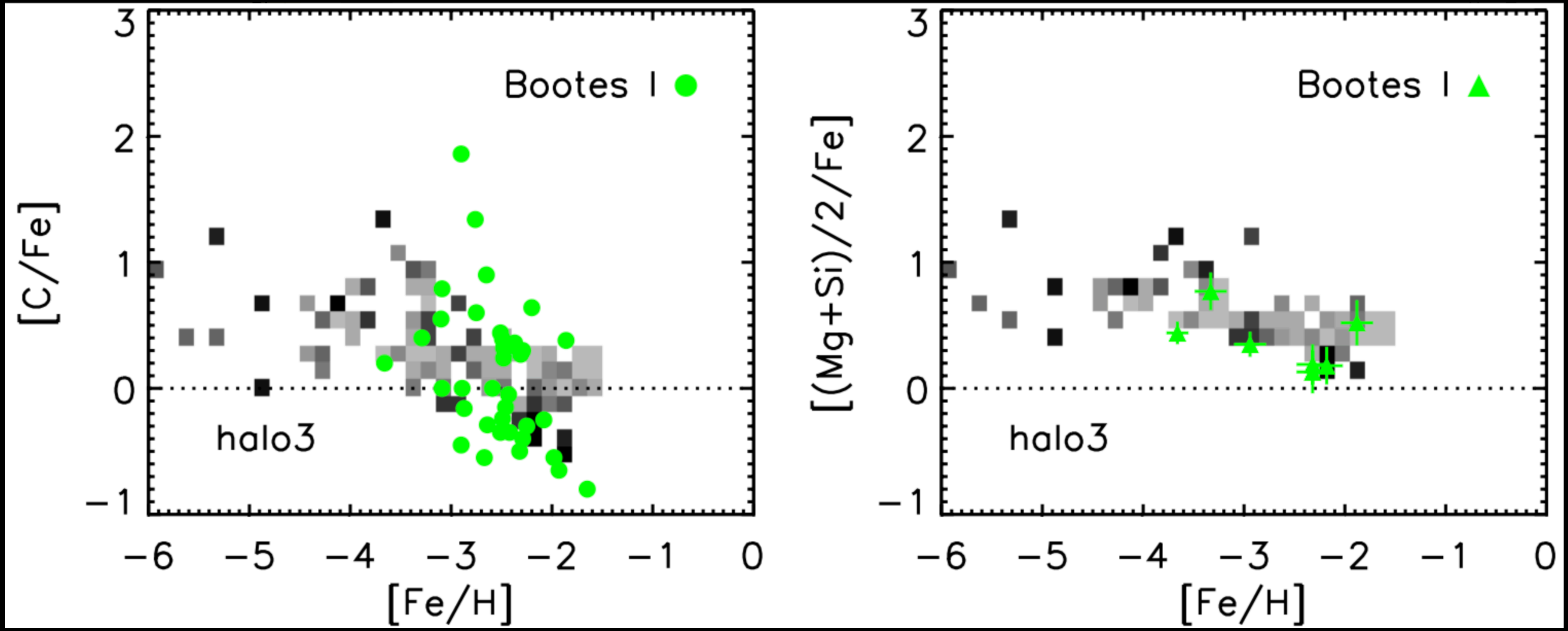
Jeon et al. 2017

Quenching of SF by reionization and SNe in low-mass galaxies ($M_h < 2x10^9$ $M_\odot$)
Continuous SF in galaxies (M_h > 3-4 x 10^9 $M_\odot$, M_{HI}~10^5 $M_\odot$; Leo P, Leo T)

Stellar abundances: signatures of PopIII

Carbon

Alpha-elements



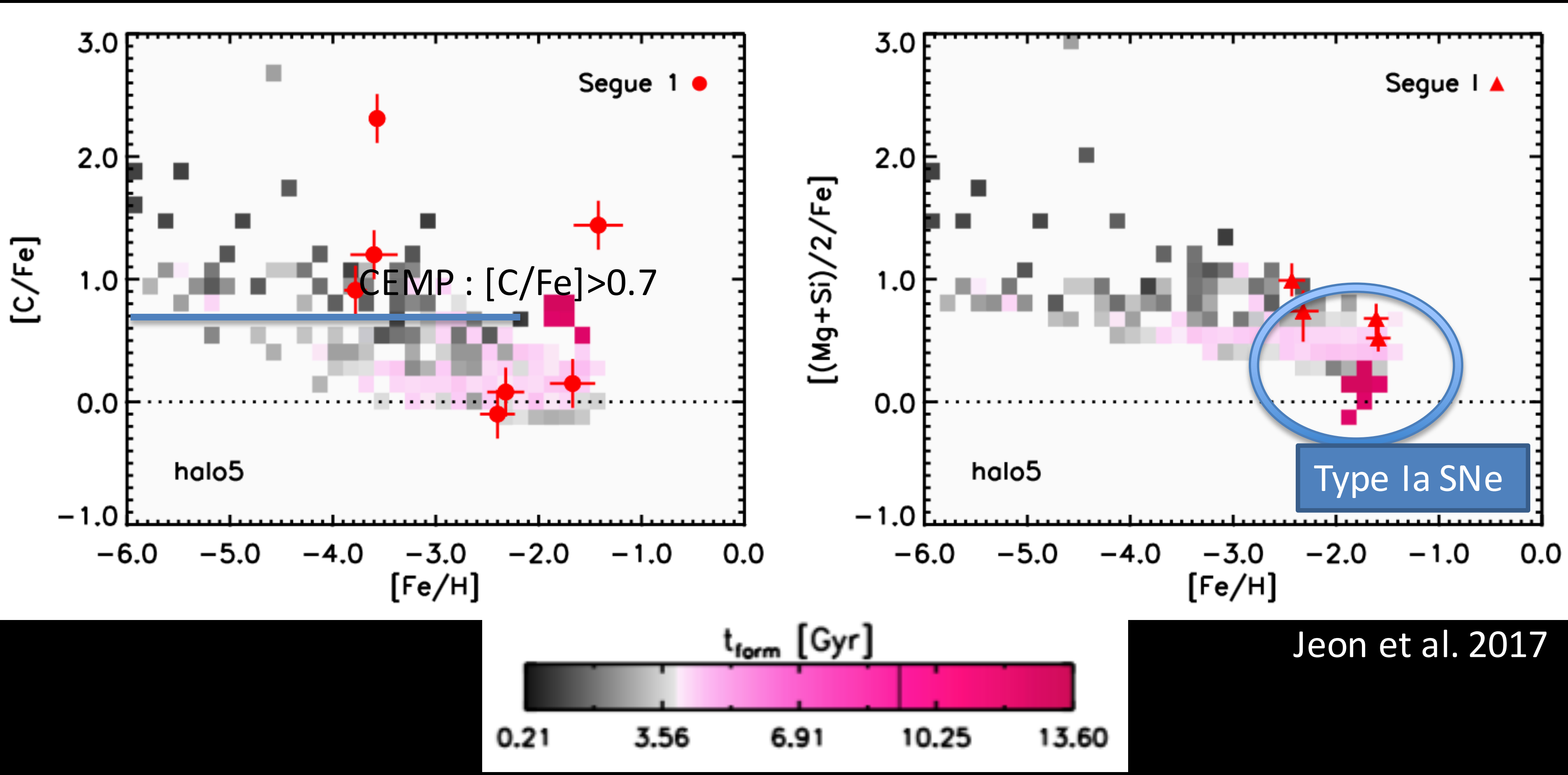
Jeon et al. 2017

- <u>CEMPs – Pop III Sne</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.

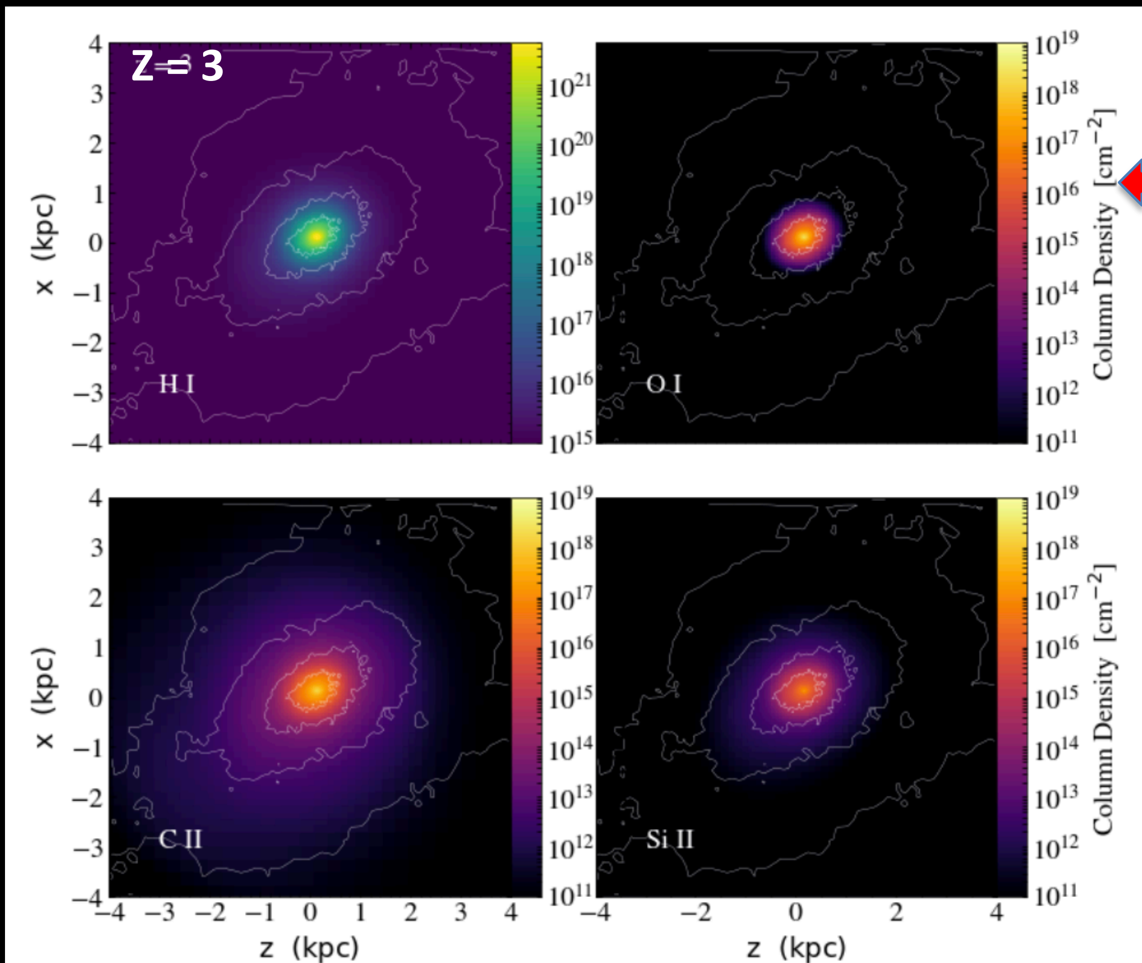
Stellar abundances (Halo5: $M_{star}=2\times10^5\ M_\odot$)

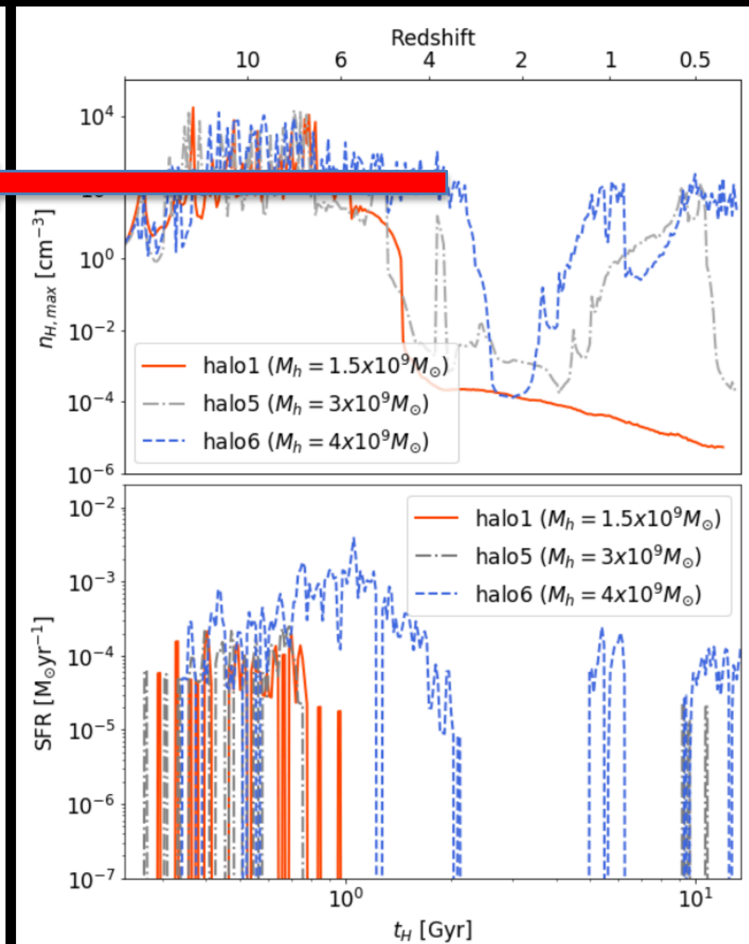
Carbon | Alpha-elements



Jeon et al. 2017

Neutral gas in dwarfs

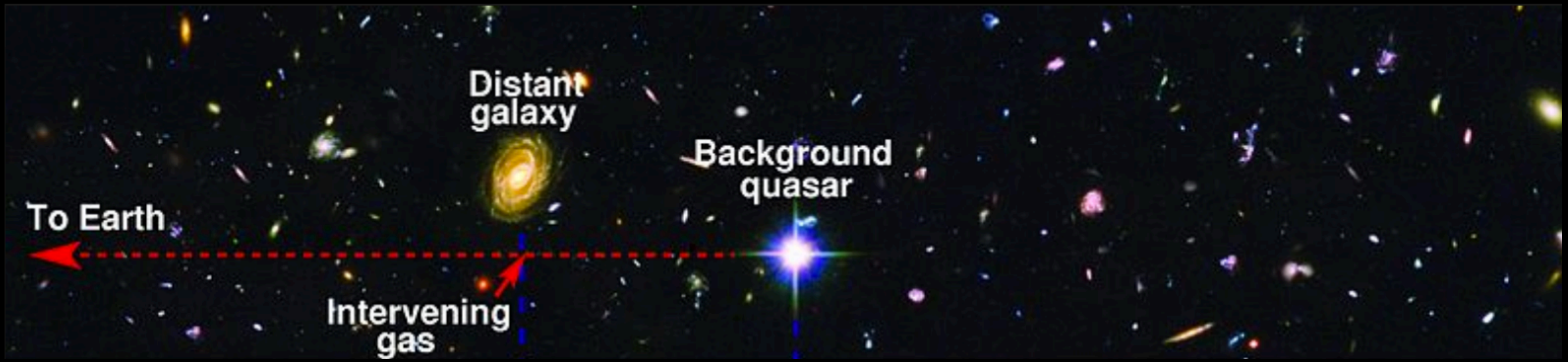


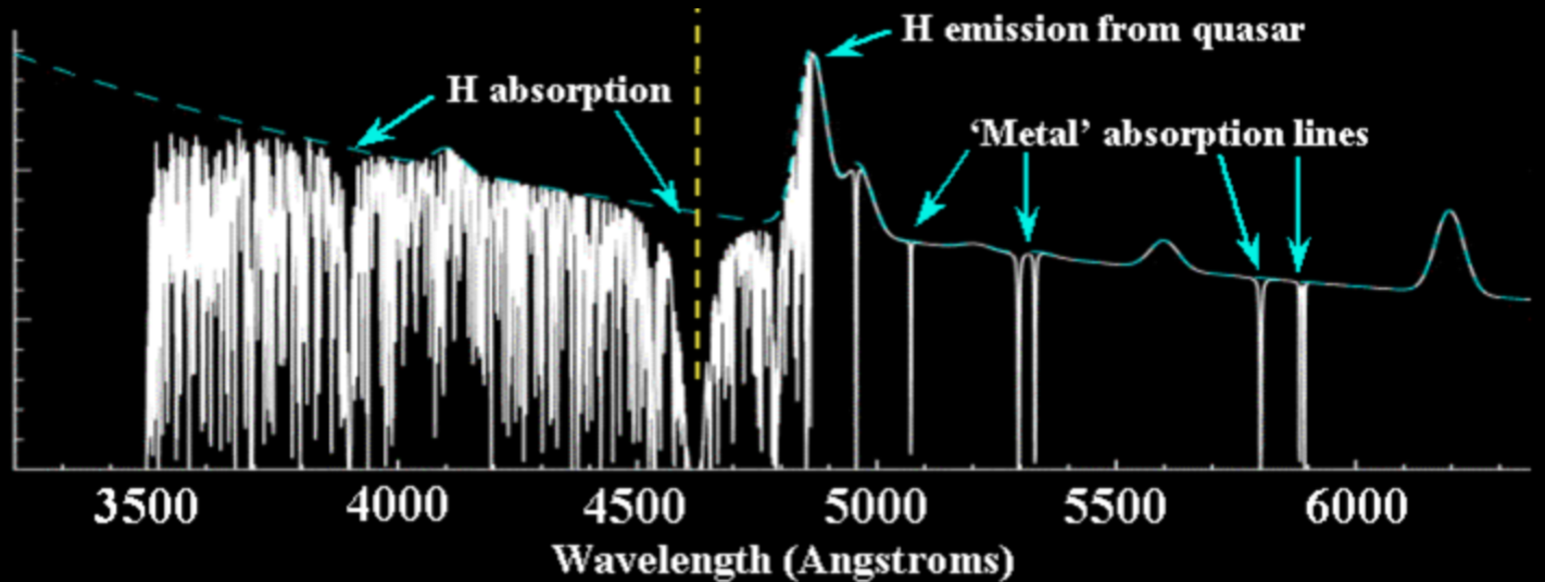


Jeon et al. 2018 (submitted)

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

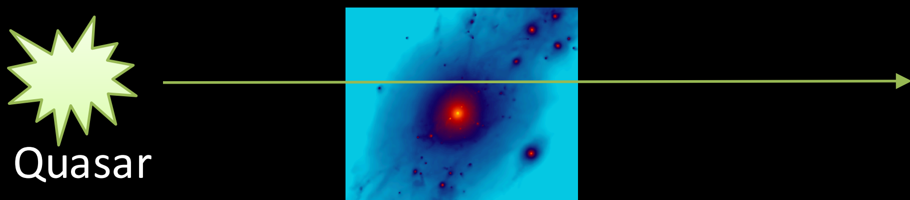
Damped Lyman alpha system (DLAs)



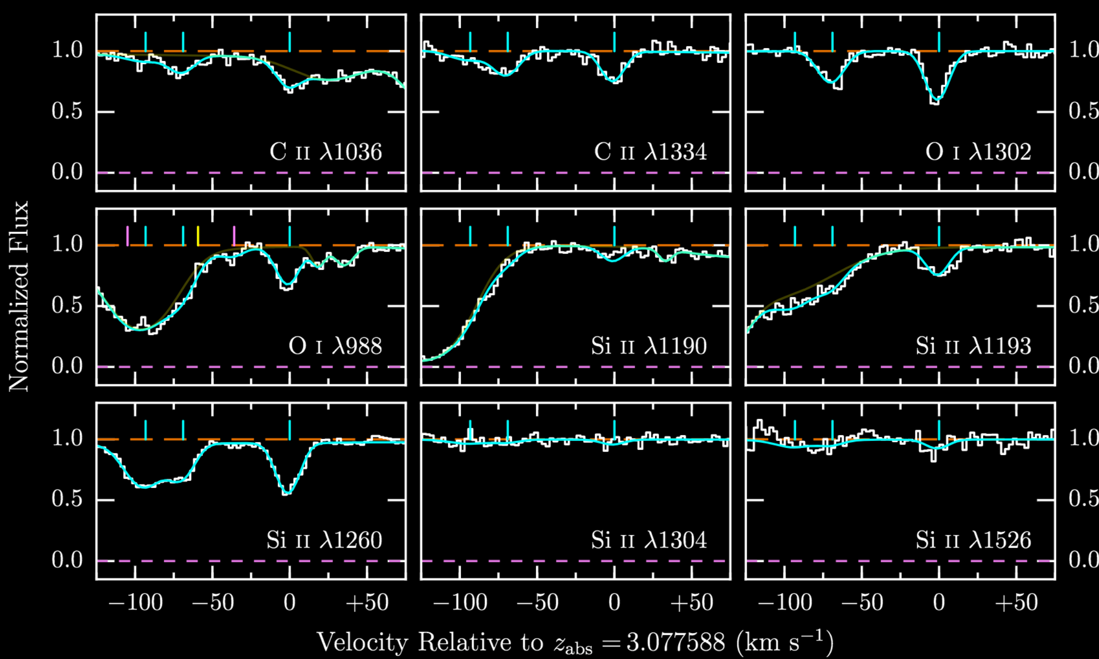


Gas with neutral hydrogen number density of $N_{HI} \sim 10^{20.3}$ cm^{-2}

Metal-poor DLAs as another probe of first stars



neutral gas enriched by Pop III stars

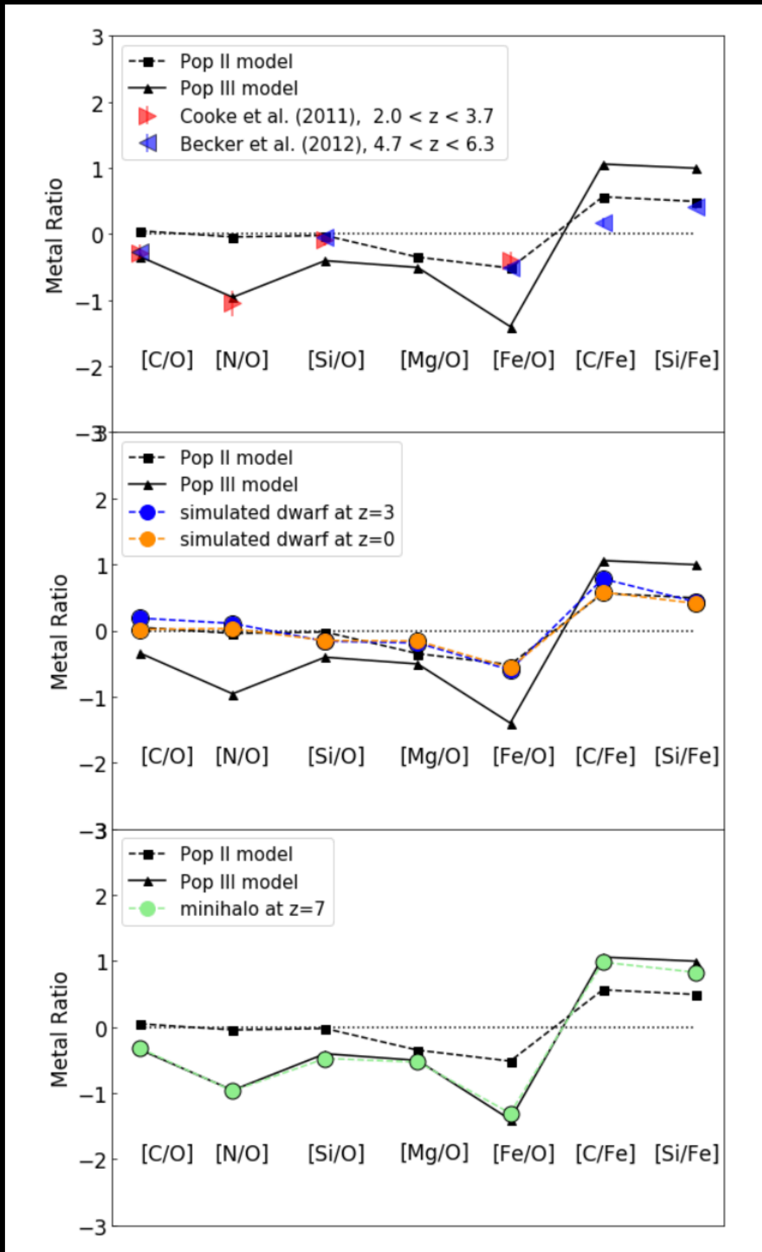


Q: *Is the gas associated with dwarf galaxies?*

Q: Is it the gas that could contain the signatures of Pop III?

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

Can do dwarfs contain Pop III DLAs?



- Extremely metal poor DLA ([Fe/H] ~ -3 at z=3, N_{HI}~10^{21} cm^{-2}) is hard explain in the context of dwarf galaxies.

UFDs → No neutral gas at z=3

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

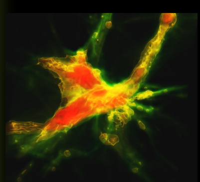
- Pop III DLA could exist at high-z (z > 7), not z=3.

- Rather metal-poor DLAs are likely to be located at the outskirts of massive galaxies.

Jeon et al. submitted (2018)

We are entering an interesting era where we can fill the gap and will get the full picture of the cosmic history!

- Observations will provide observational constraints on the first stars and first galaxies.
    - In the JWST era, we will be able to detect the first light!
    - In the LSST era, the discovery of new faint galaxies will accelerate.
    - In the GMT era, theoretical predictions can be probed with the greatly improved spectroscopic sensitivities of the GMT observations of metal-poor stars and DLAs.



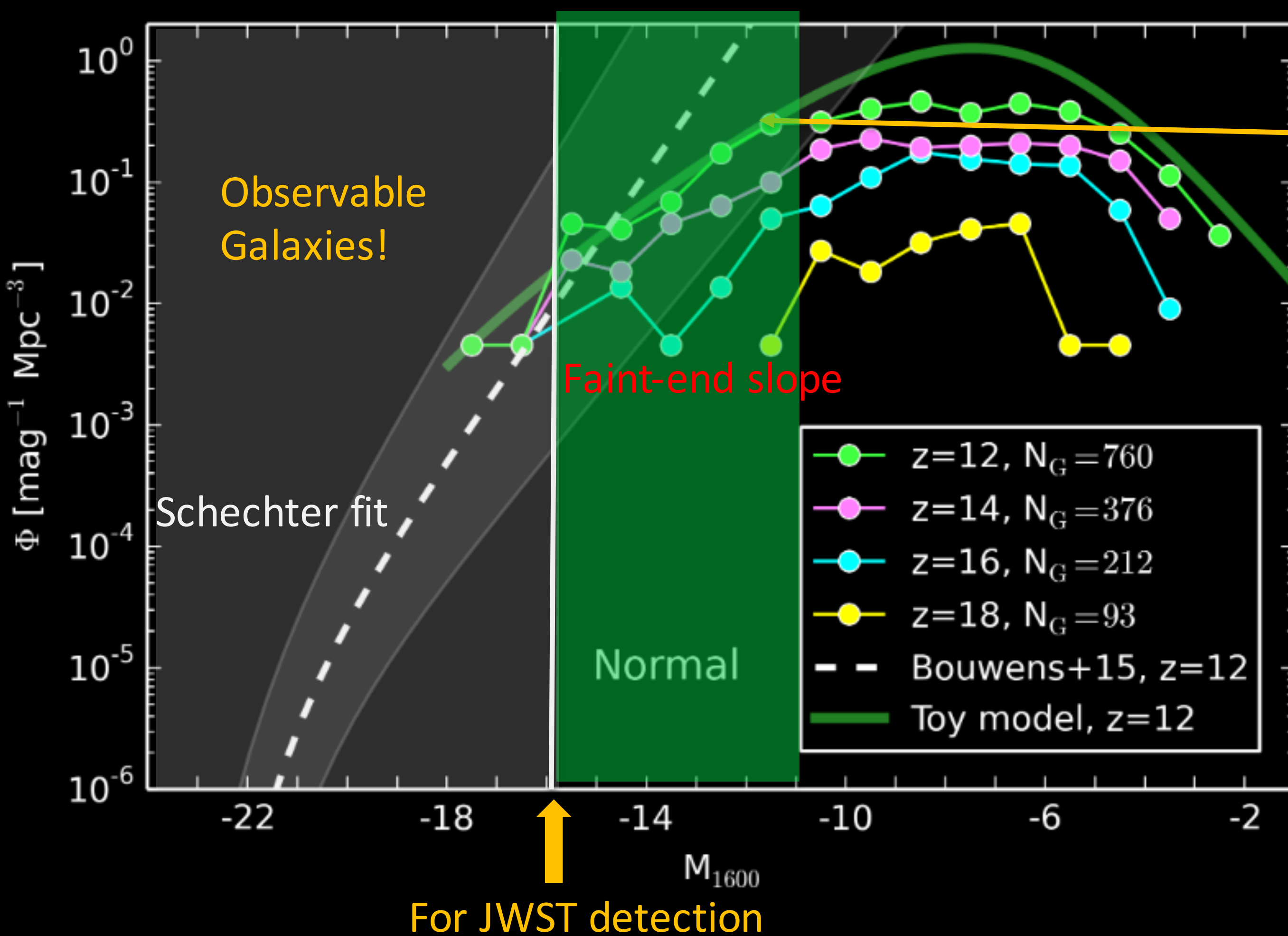
Fossil dwarf galaxies?

z = 0

Reionization
(t_H ~ 1 Gyr)

Thank you!

Understanding the faint-end is a key: How many faint galaxies were there?



Turn over?

M_{vir}~ 10^7 – a few 10^8 $M_\odot$

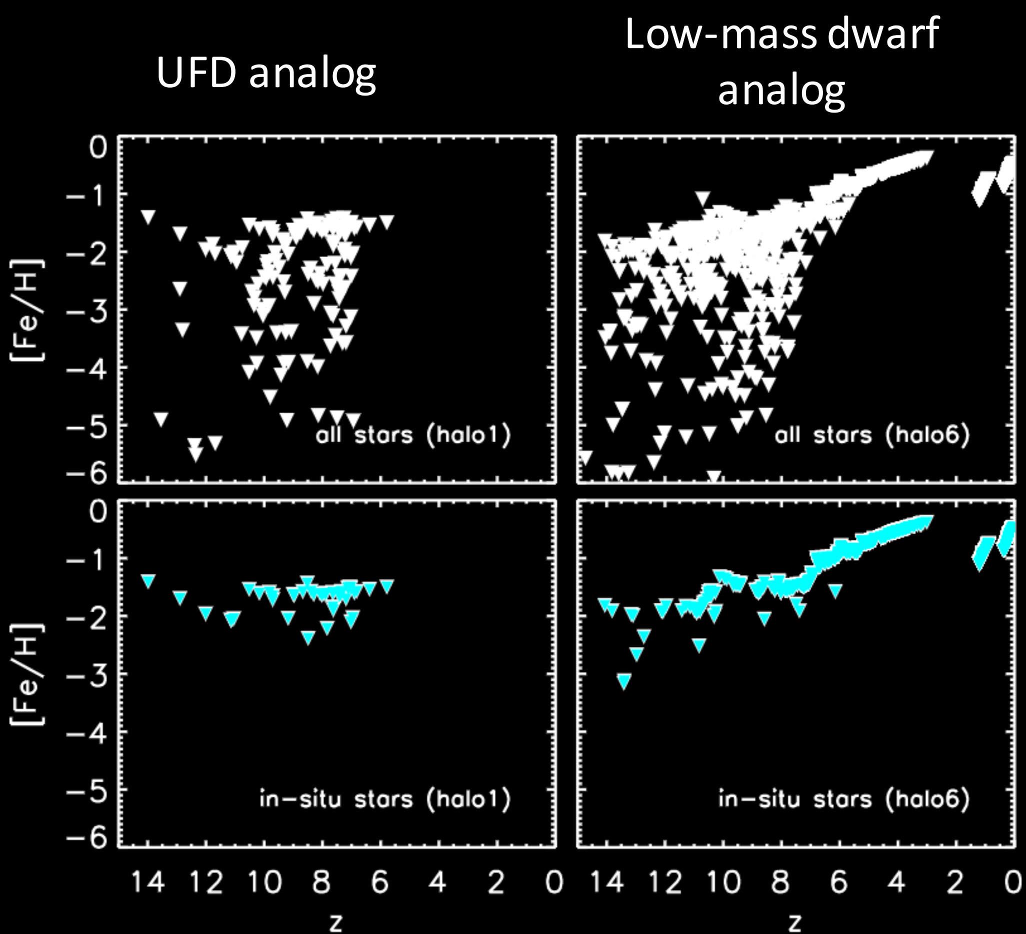
Inefficient SF?

Or,

Quenched SF below a certain mass (2×10^8 $M_\odot$) by feedback /reionization?

Renaissance Simulations (O'shea+2015)

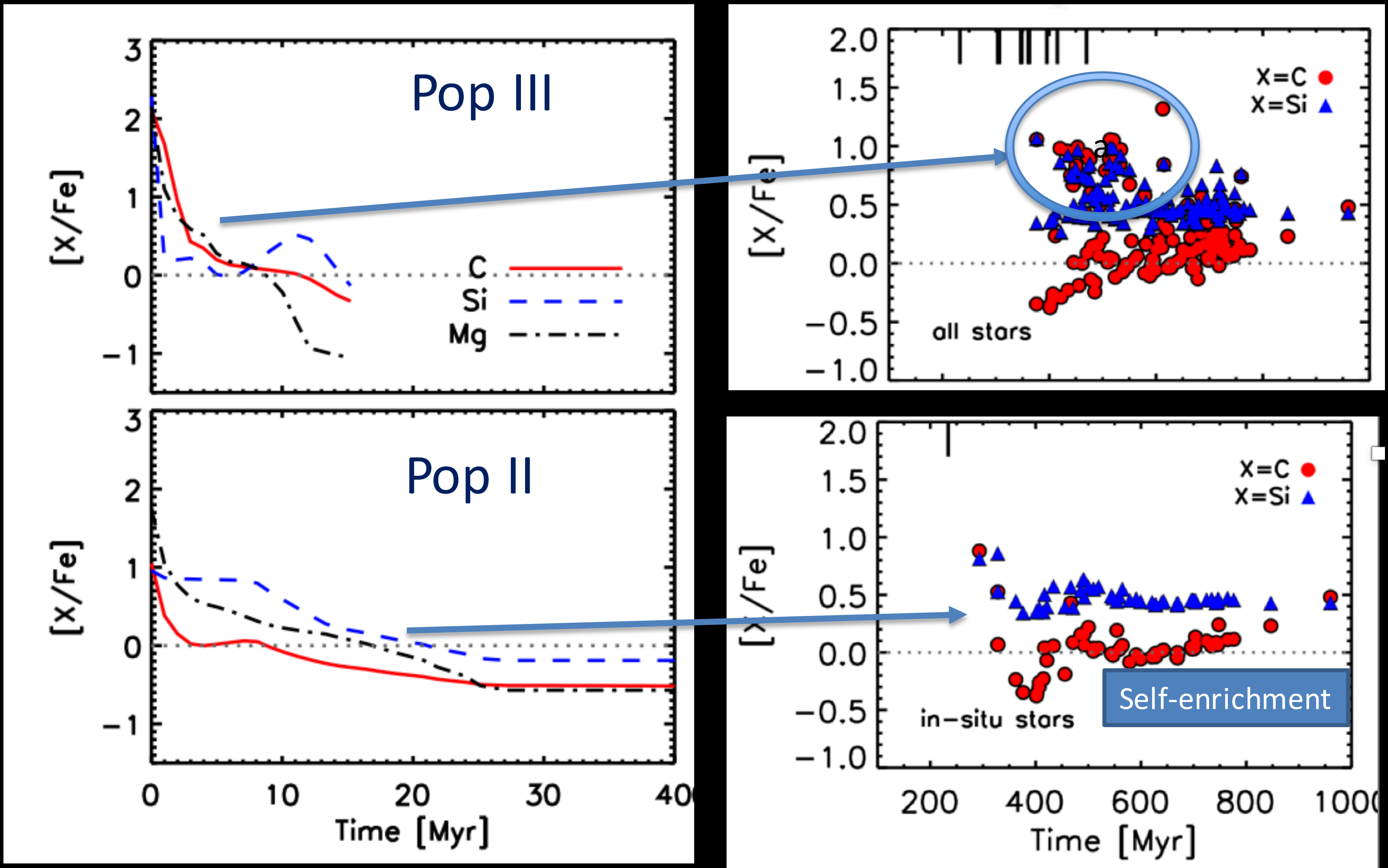
Is the observed DLA associated with a UFD?



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

- unlikely to be associated with UFDs since having neutral gas at z=3 is hard for UFDs.
- not a Pop III DLA since the metal enrichment has already progressed at z=3.

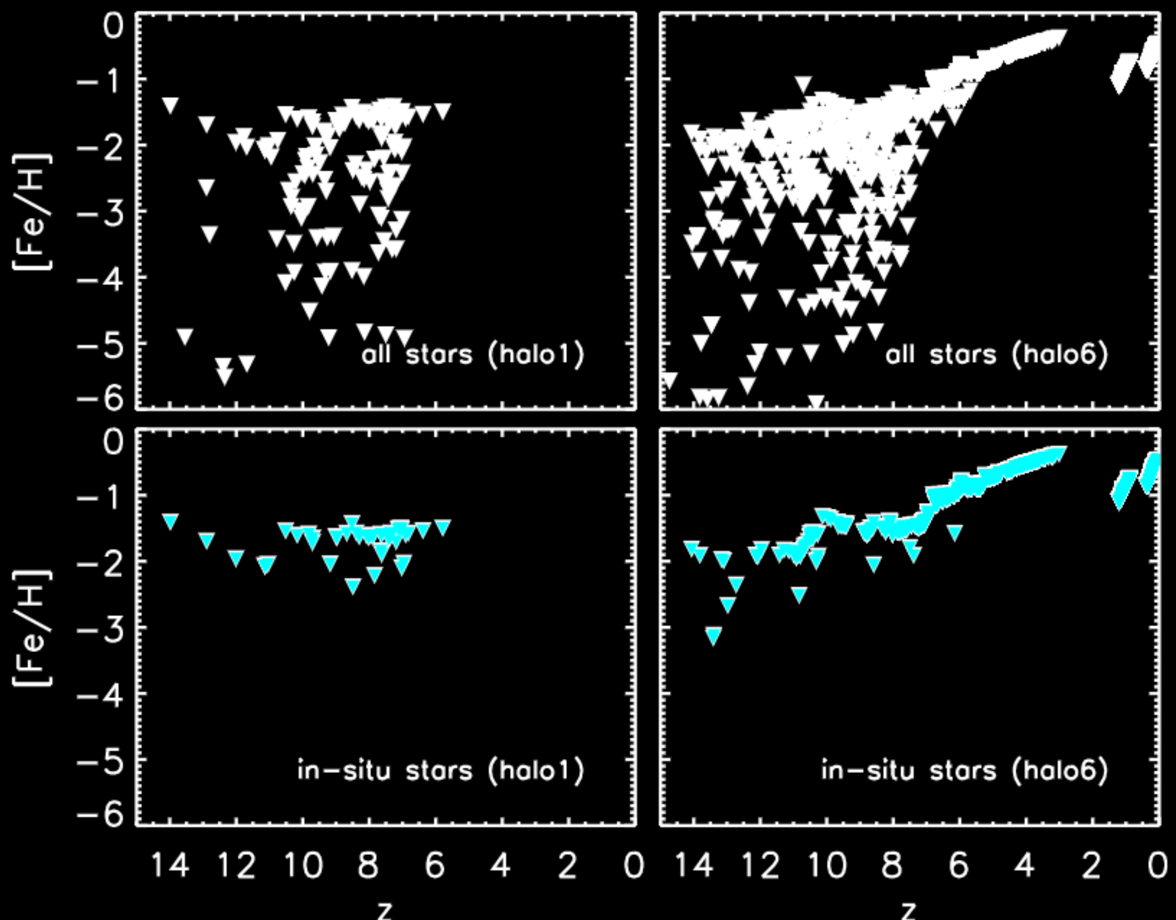
How to distinguish Pop III signatures?



Jeon et al. 2017

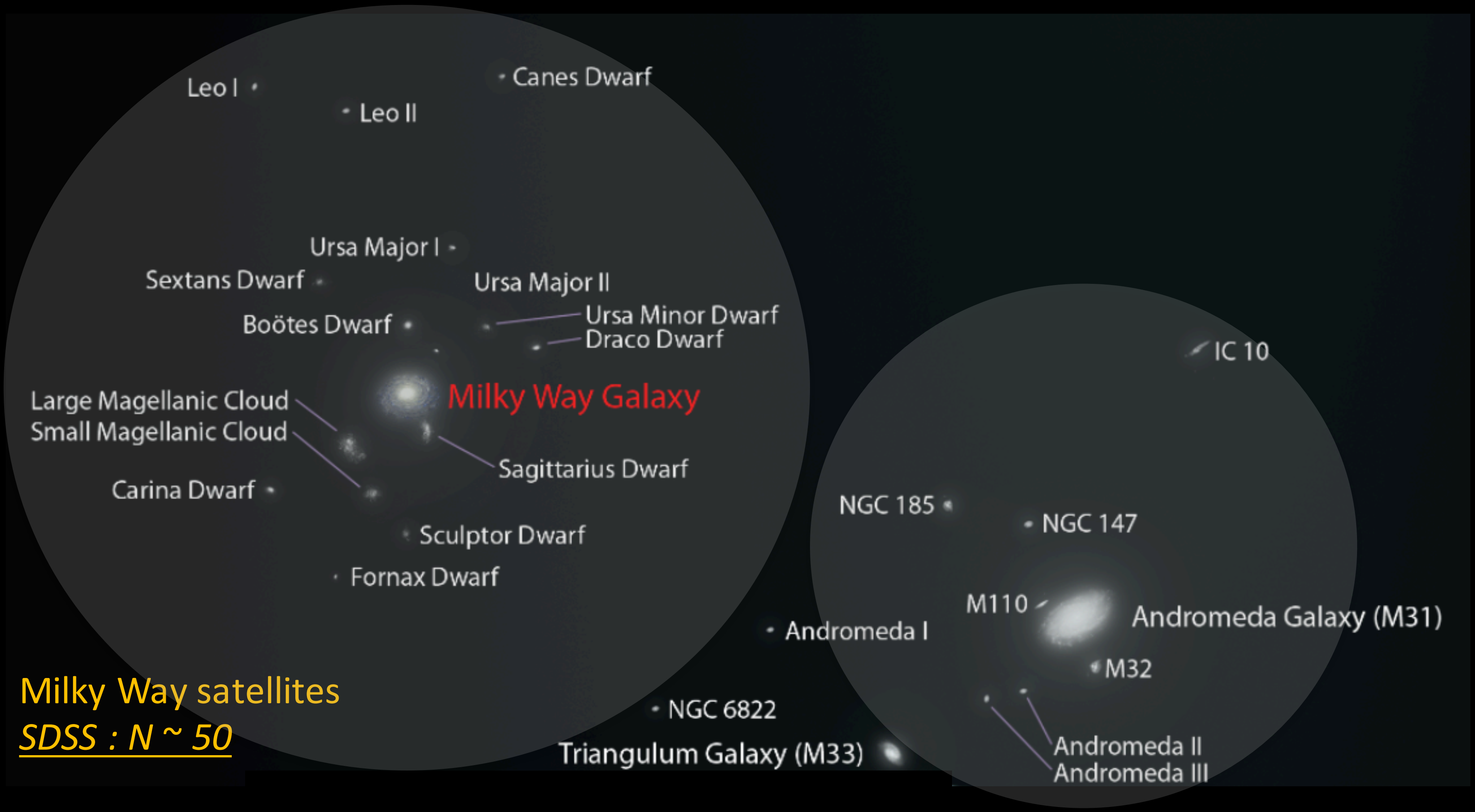
UFD analogs and low-mass dwarfs

($M_{star} < 10^4\ M_\odot$ Halo6: $M_{star} \sim 10^6\ M_\odot$)



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

Dwarf galaxies in Local Group

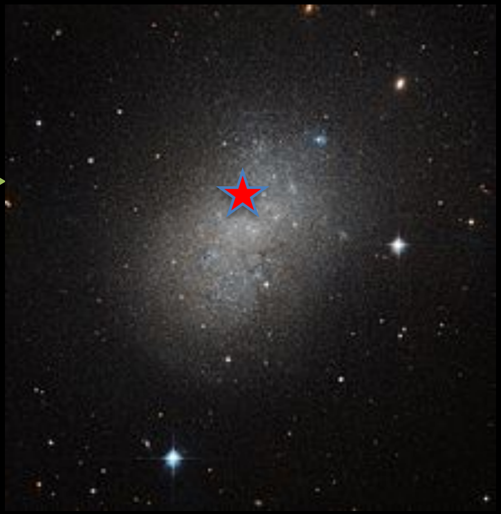


Milky Way satellites
SDSS : N ~ 50

M31 satellites
PAndAs : N ~ 30

Dwarf galaxies as a time machine
Stellar Archaeology

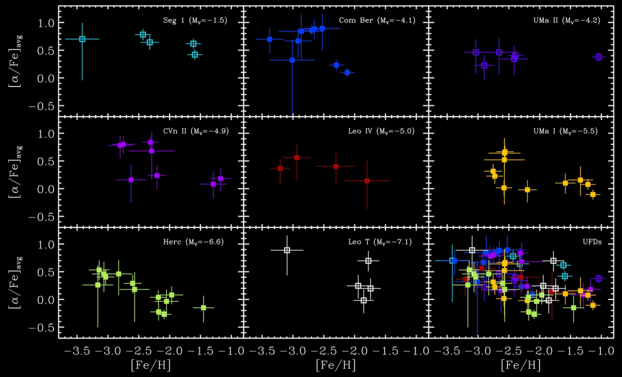
No/a little star formation for ~ 13 Gyr



Fossil galaxies

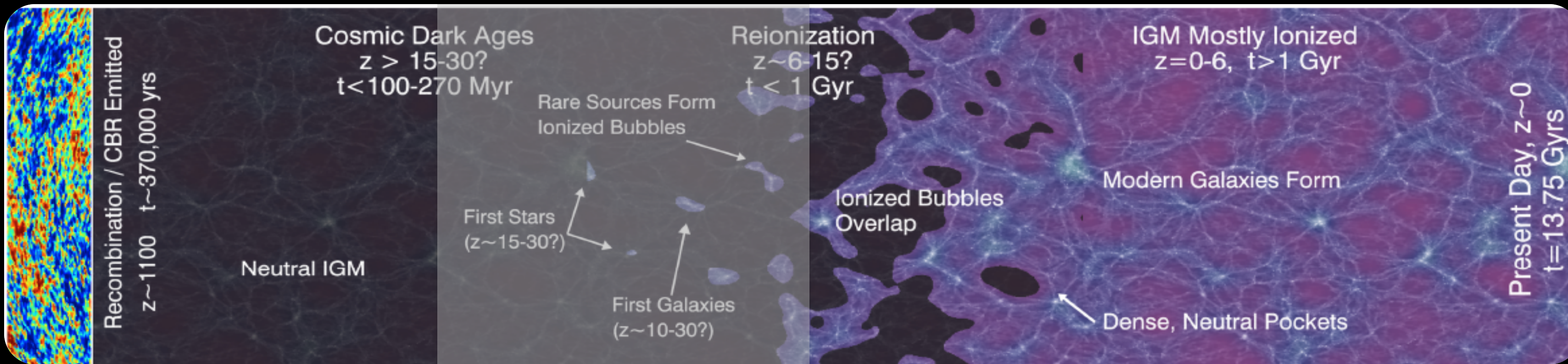
High-z (z > 6)

- The main driver of cosmic reionization.
- can study early stellar populations (first stars and the second generation of stars).



Today z=0

Direct detection of first stars is impossible



First galaxies?

Yes. (JWST, GMT, etc.)

(i.e., Pawlik+2013, Jeon+2015, Barrow+2017, Ma+2017)

First Stars?

Maybe Not for direct light detection.

Possible via pair-instability supernova (PISN), core-collapse supernova (CCSN), or gamma-ray burst (GRB)

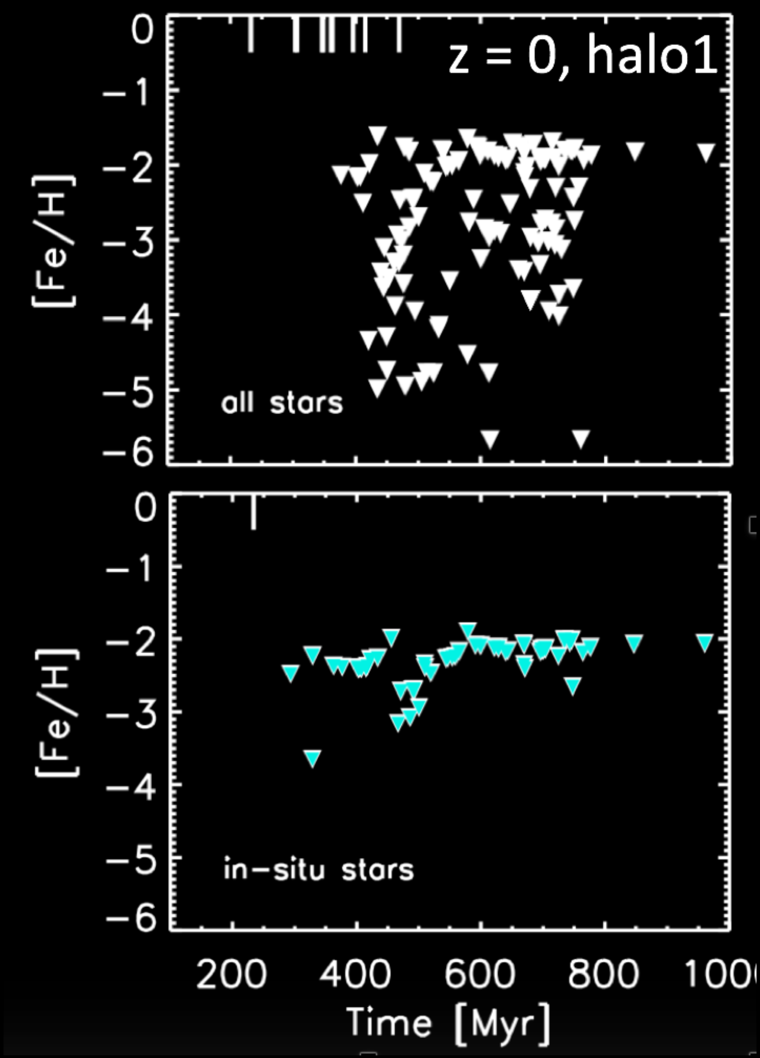
(i.e., Hummel+2012, Whalen+2013)

First star remnants? Yes,

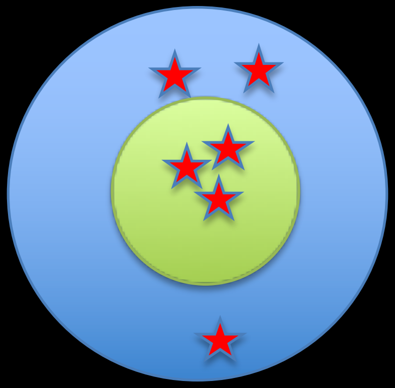
Damped Lyman Alpha systems (DLAs)

Extremely low-metallicity stars in local dwarfs (Jeon+2017).

Presence of metal-poor stars

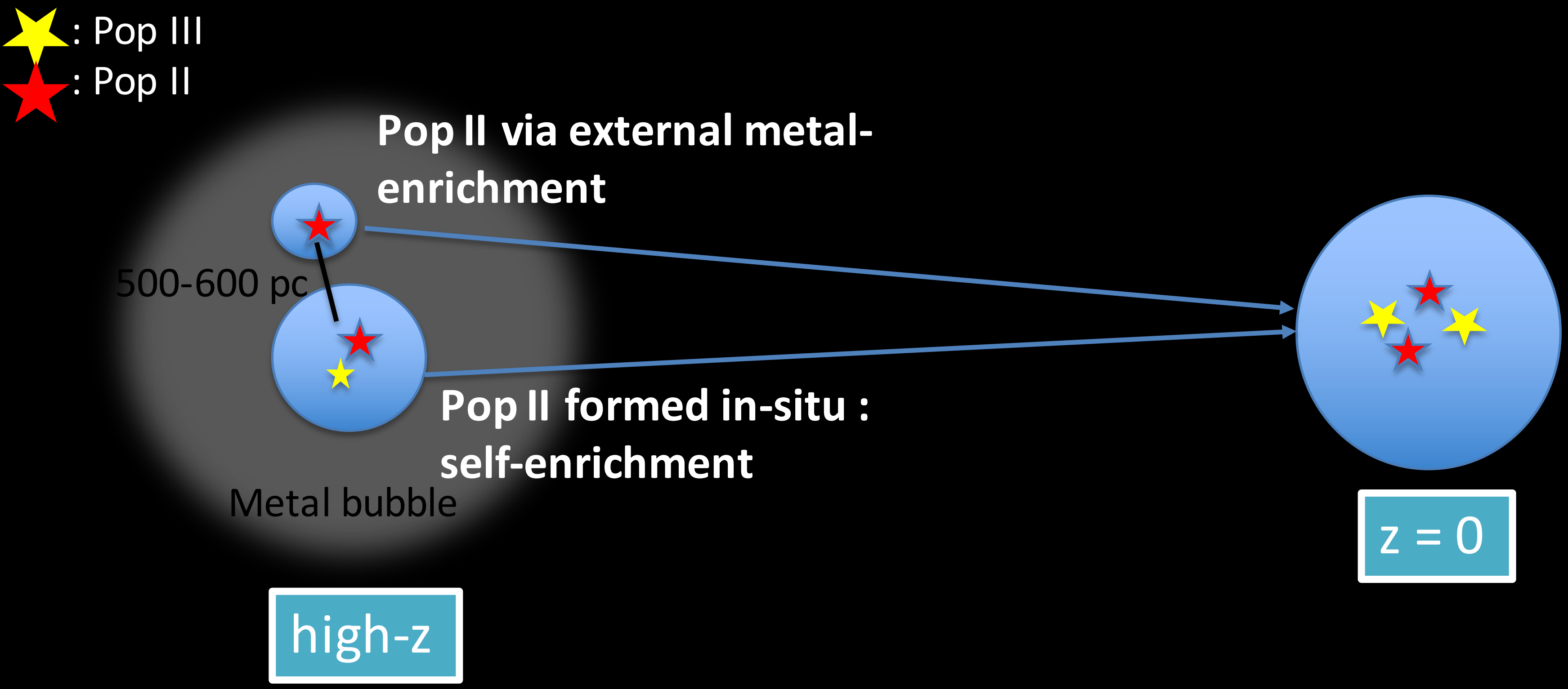


Jeon et al. 2017



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

Internal vs. external enrichment

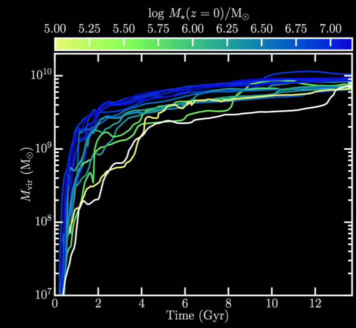


Metal poor stars, [Fe/H<-3], were mainly formed via external metal enrichment.

Recent dwarf galaxy formation

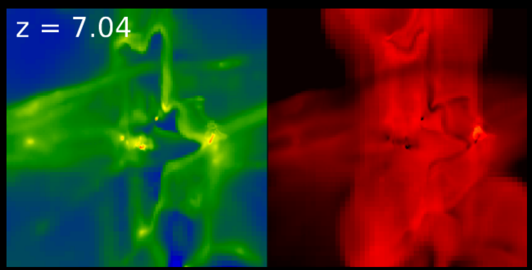
Stellar Mass

10^7 $M_\odot$



Fitts et al. (2016, 2018)
FIRE,
Res. : 500 $M_\odot$ (gas), ~2500 $M_\odot$ (DM)

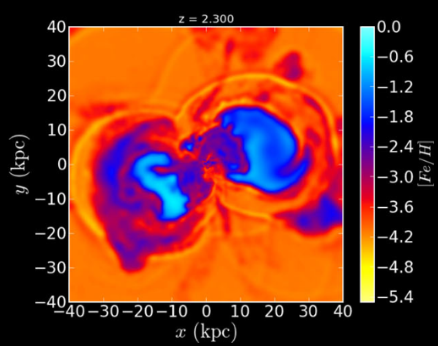
10^6 $M_\odot$

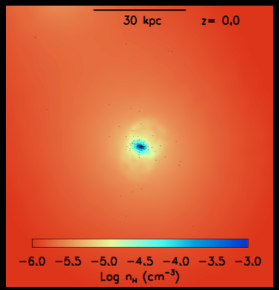


Simpson et al. (2013)
ENZO, Res. : 500 $M_\odot$ (gas), ~2000 $M_\odot$ (DM)

10^5 $M_\odot$

10^4 $M_\odot$



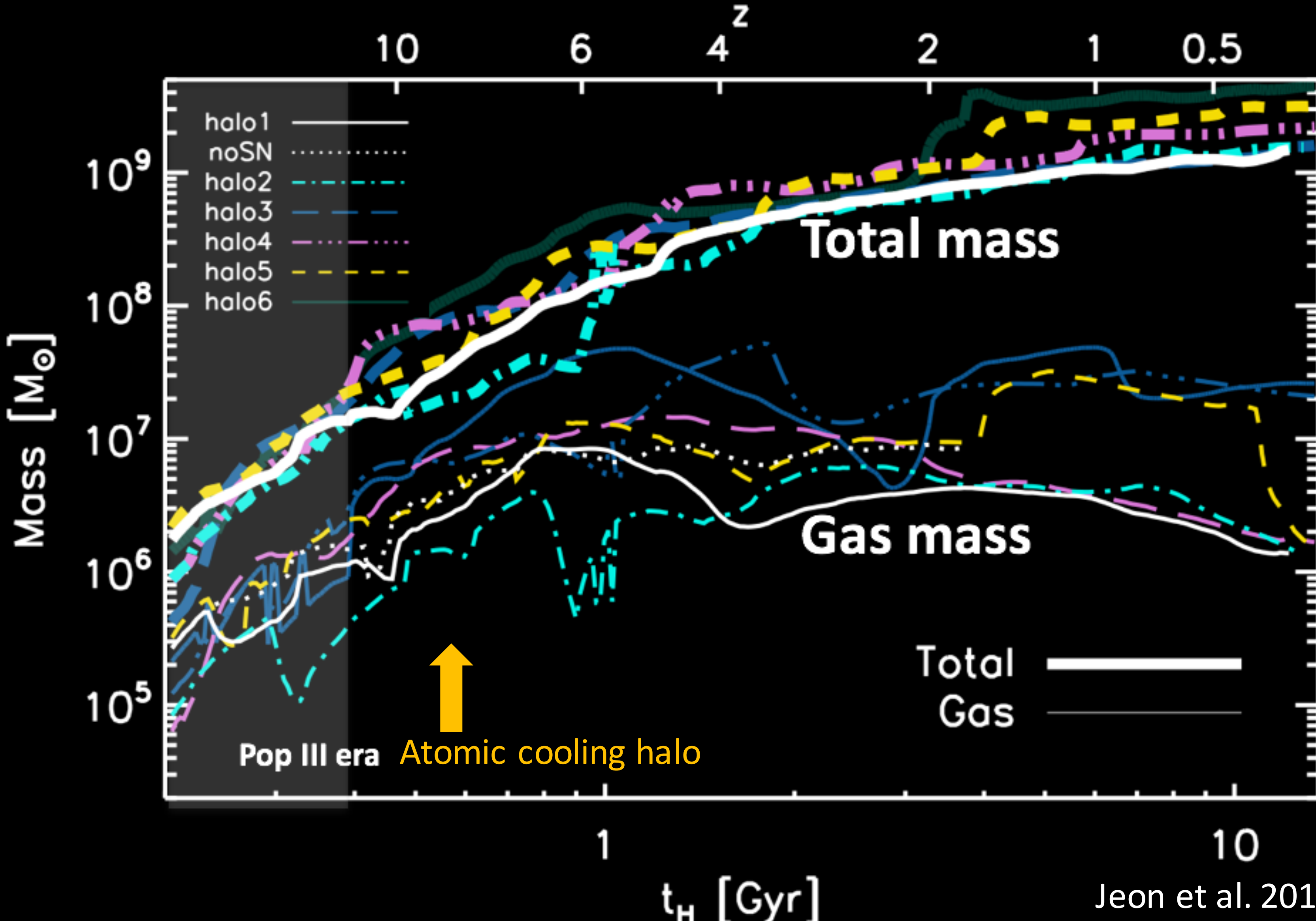


Wheeler et al. (2015), Onorbe et al. (2015)
FIRE , Res. : 125-500 $M_\odot$ (gas), ~700-2000 $M_\odot$ (DM)

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

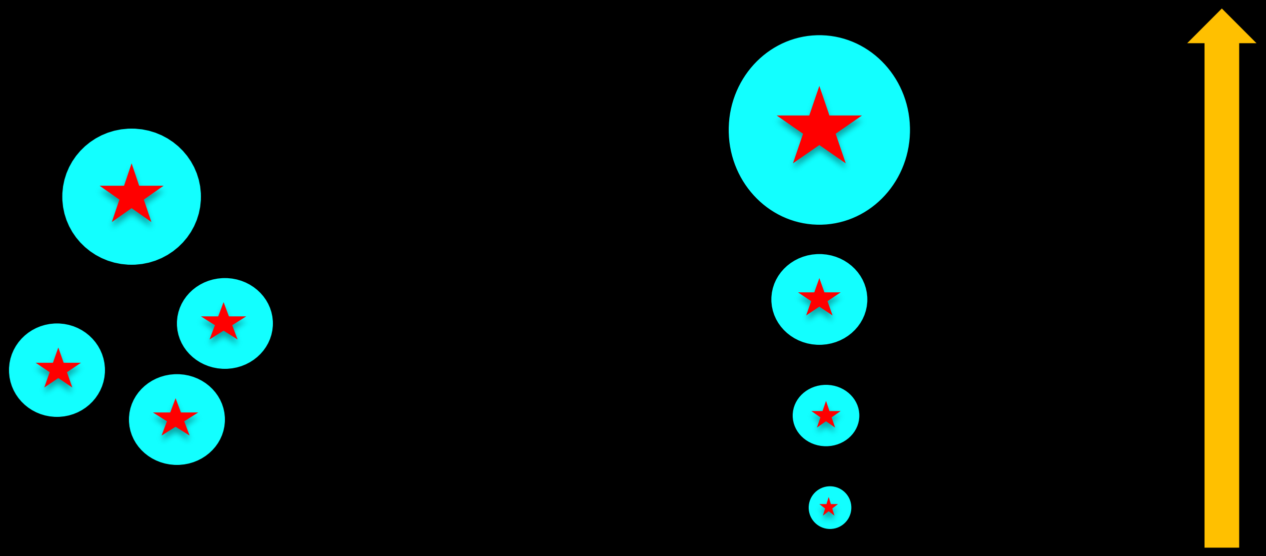
10^9 $M_\odot$ **Halo Mass** 10^{10} $M_\odot$

Mass Growth

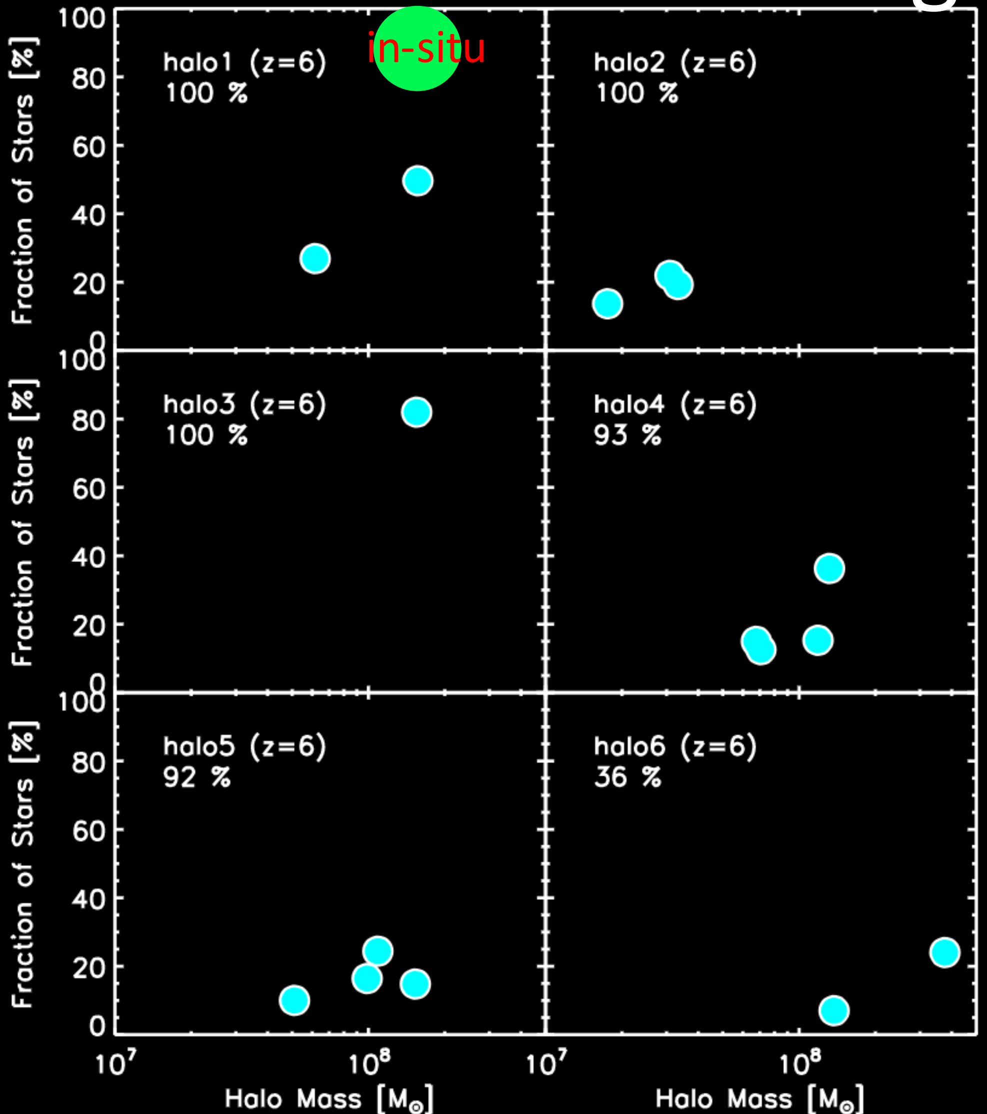


Jeon et al. 2017

Assembly history of UFDs.
Mergers vs. in-situ star formation



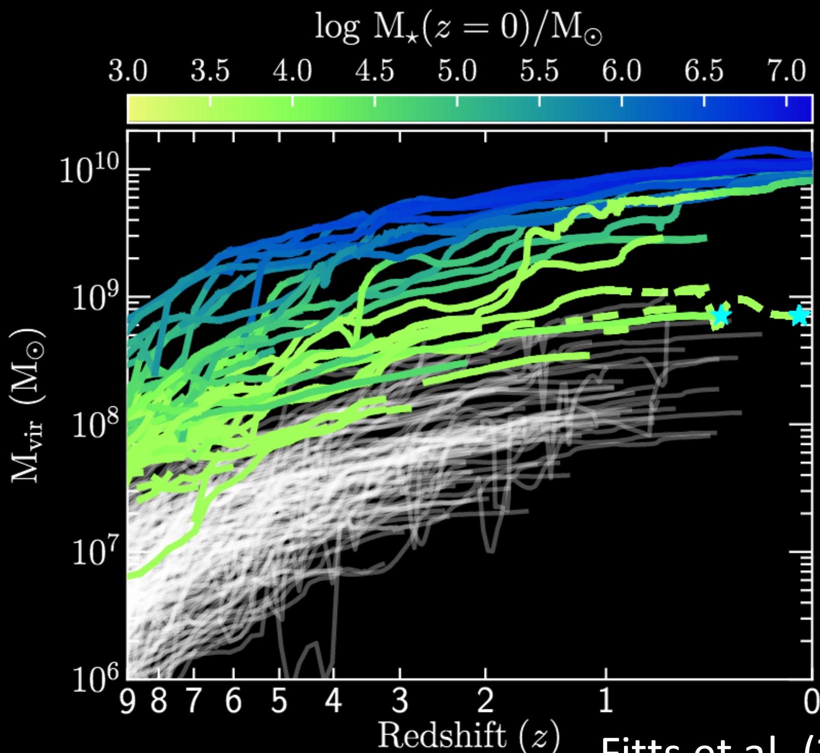
Build up of stellar mass in UFDs : early mergers!



- **Stellar growth is a consequence of the combination of in-situ star formation and <u>significant stellar accretion</u>.**
- **It is not simple to infer where stars have originated..**
- **Stellar growth of low-mass systems conflicts with the prevailing view.**

Jeon et al. 2017

Distinctive assembly history between UFDs and low mass dwarfs?



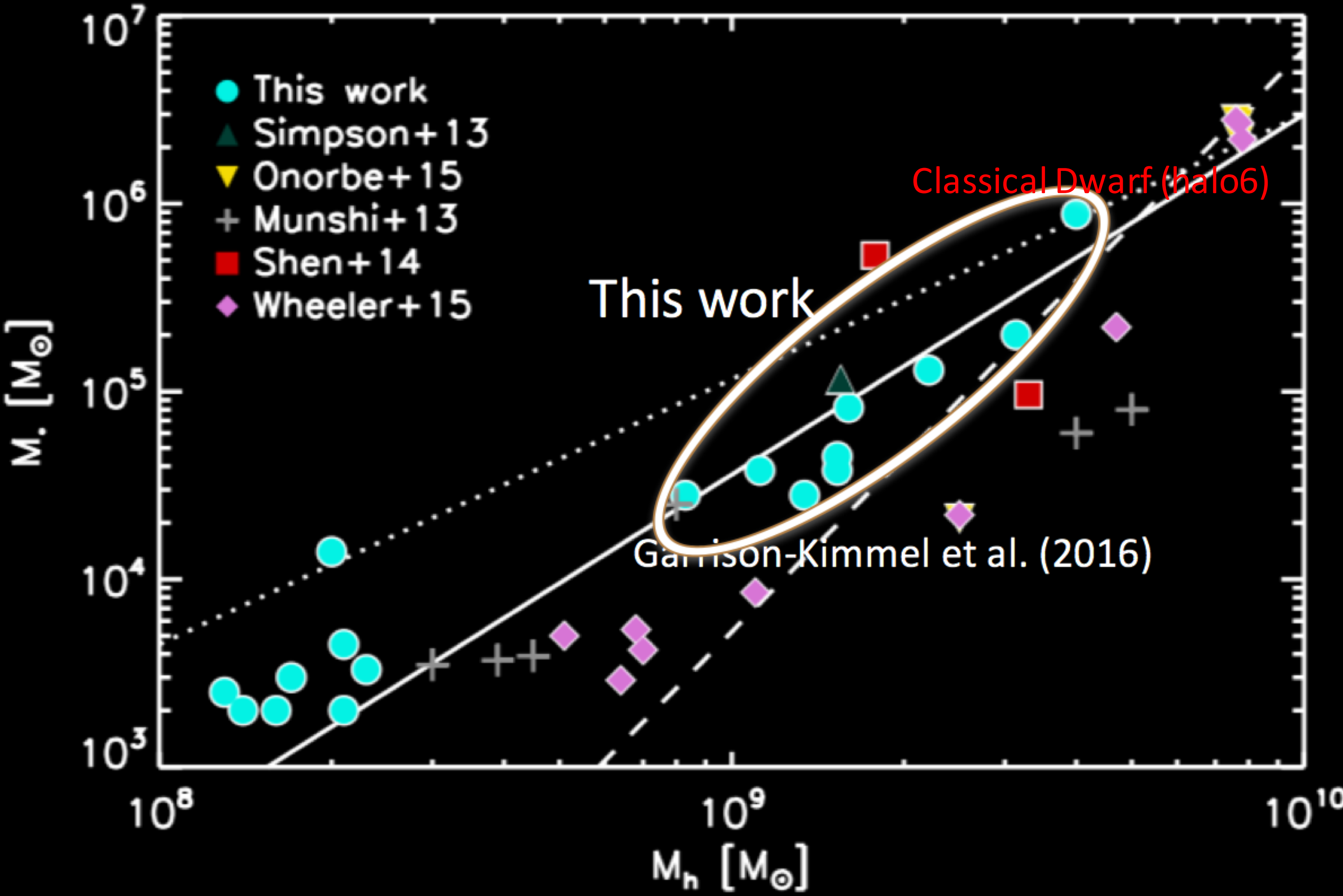
Fitts et al. (2018)

Possible factors:

- H_2 cooling minihalos.
- The onset of reionization.
- A short star formation history of UFDs.

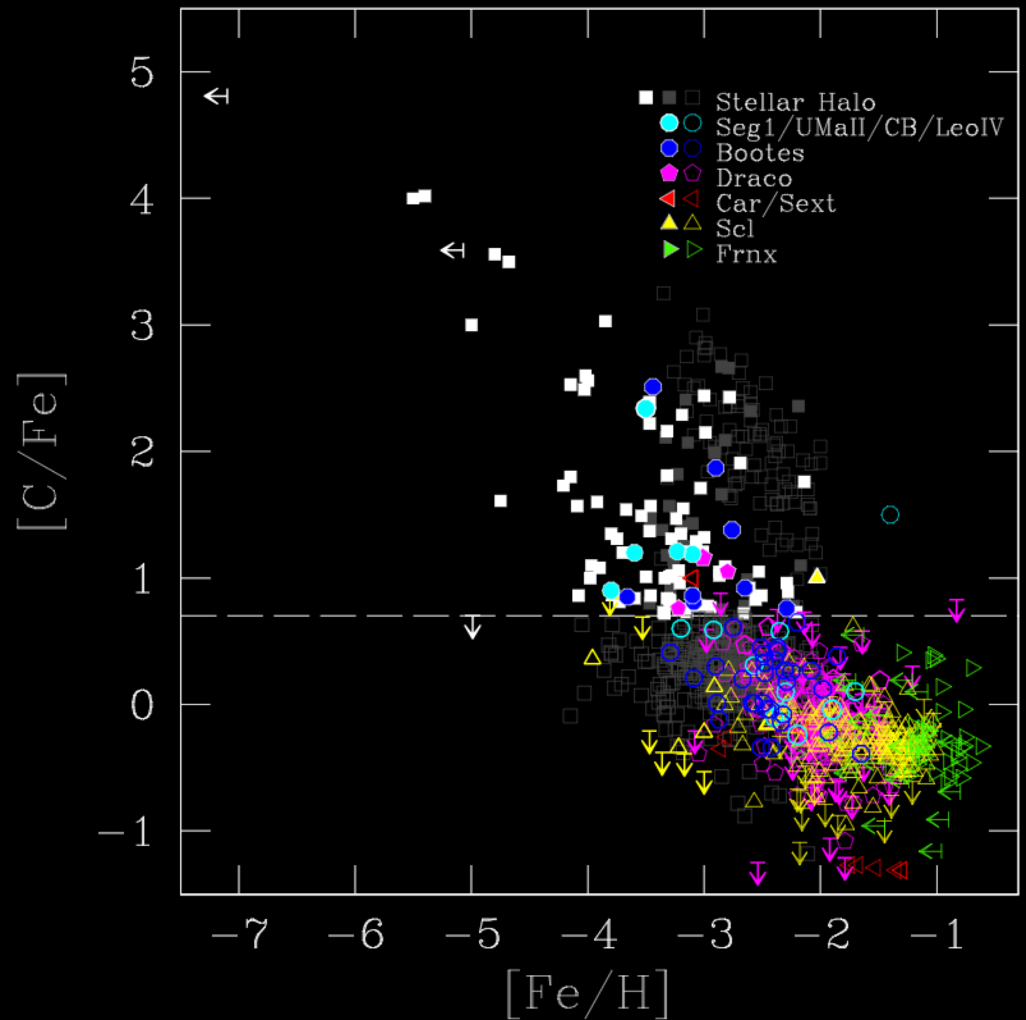
Dwarf galaxies with masses of $M_{halo} \sim 10^{10}\ M_\odot$
: Mergers are mostly irrelevant for the growth of low-mass dwarf galaxies.

Halo mass – stellar mass



Jeon et al. 2017

Pop III signature: Carbon enhanced metal-poor stars (CEMPs) in UFDs



Salvadori et al. 2015

Origin of CEMPs?

1) rapidly-rotating massive Pop III stars, capable of releasing large amounts of CNO-enhanced materials.
2) Binary systems with a companion star that undergoes an AGB phase.
3) Pop III SNe with a low explosion energy.