A Semi-analytic Study of the Formation of Milky Way Dwarf Galaxies Beginning with the Birth of the First Stars

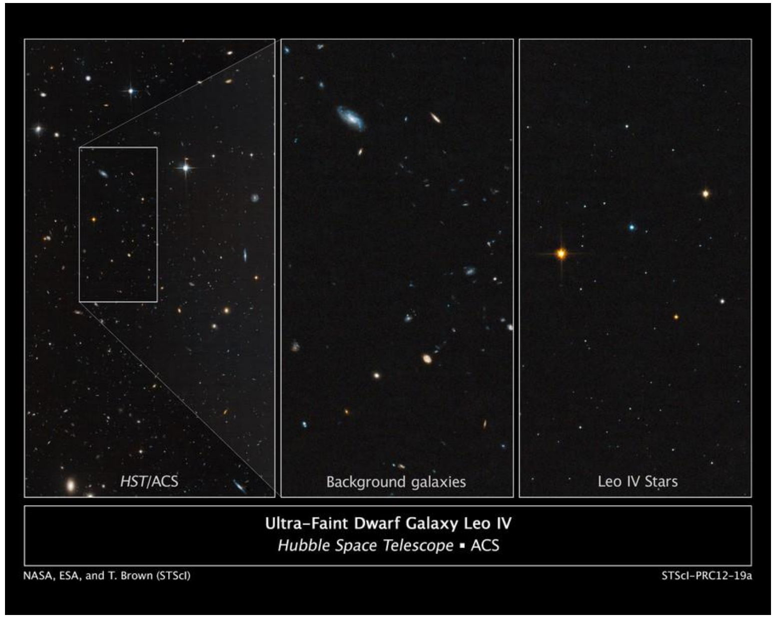
Kodai Takahashi (Chiba University)

2025/09/17 EANAM10, Jeju

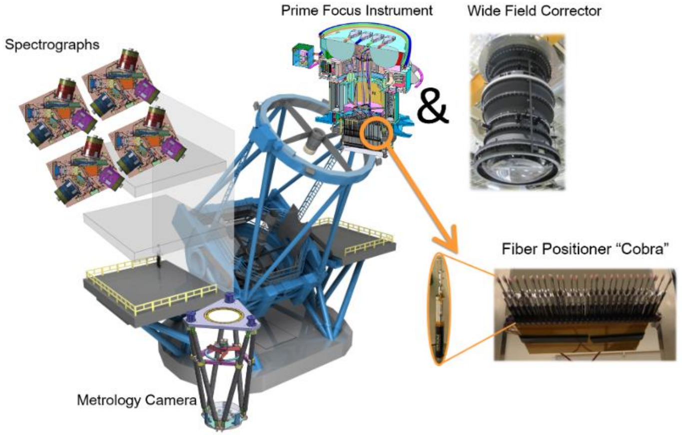
Introduction

- **Star Formation History and Metallicity Distribution Function**
  - The metallicity of dwarf galaxies reflects their star formation history
  - Limited resolution makes ultra-faint dwarfs difficult to resolve in simulations

- **Ongoing survey Subaru PFS**
  - Subaru PFS will provide improved stellar metallicity measurements
  - This study provides a theoretical basis for interpreting upcoming data

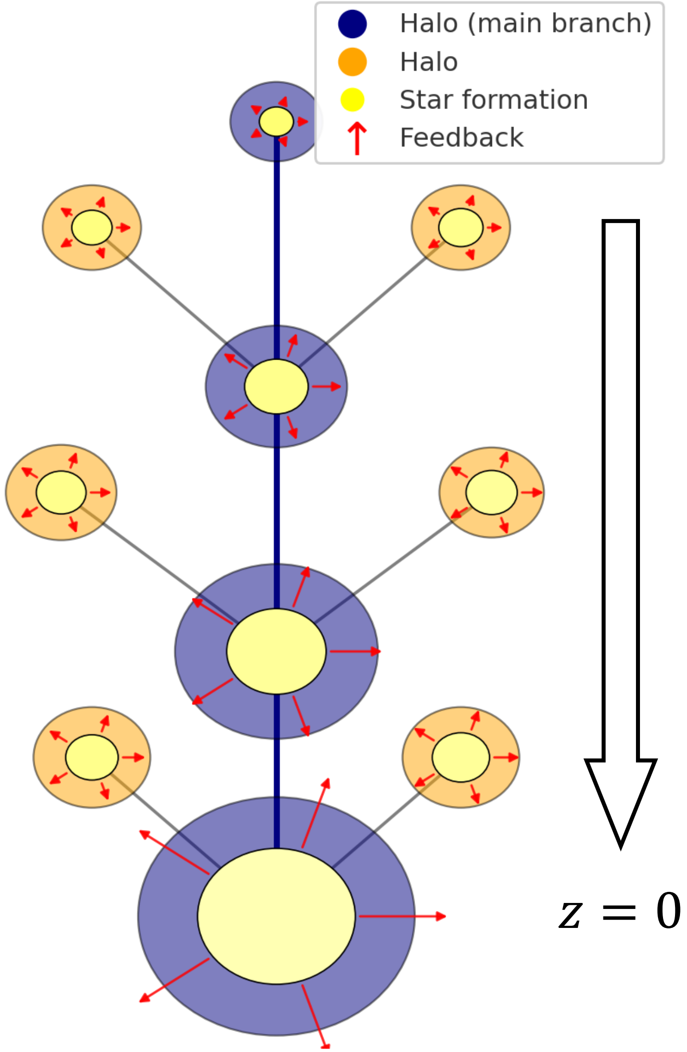


https://science.nasa.gov/asset/hubble/ultra-faint-dwarf-galaxy-leo-iv/



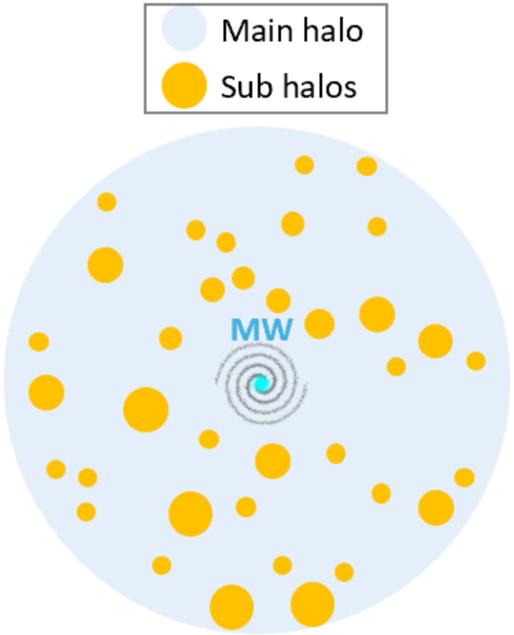
https://pfs.ipmu.jp/ja/instrumentation.html

Method

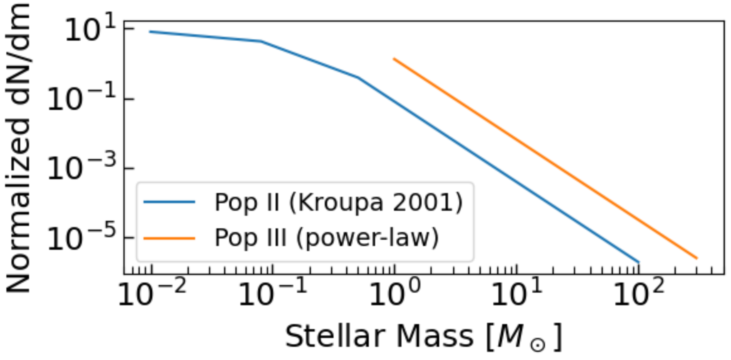


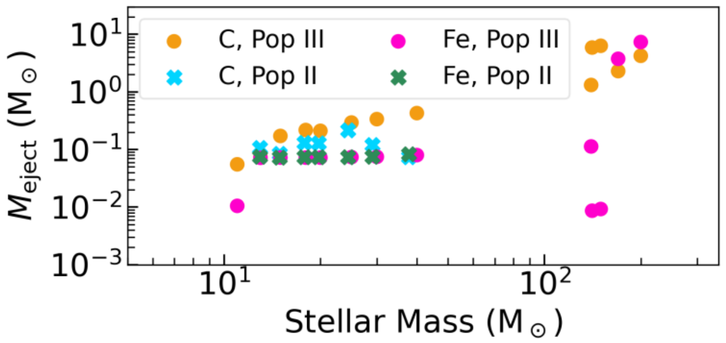
■ A-SLOTH (Hartwig et al. 2022, 2024)

- A semi-analytical model for calculating galaxy formation



Final state of halos in the MW halo (Image)





Pop II condition

$$10^{[C/H]-2.30} + 10^{[Fe/H]} > 10^{-5.07}$$

(1) Public Release of A-SLOTH: Ancient Stars and Local Observables by Tracing Halos, Hartwig et al. 2022, ApJ
(2) A-SLOTH reveals the nature of the first stars, Hartwig et al. 2024, MNRAS

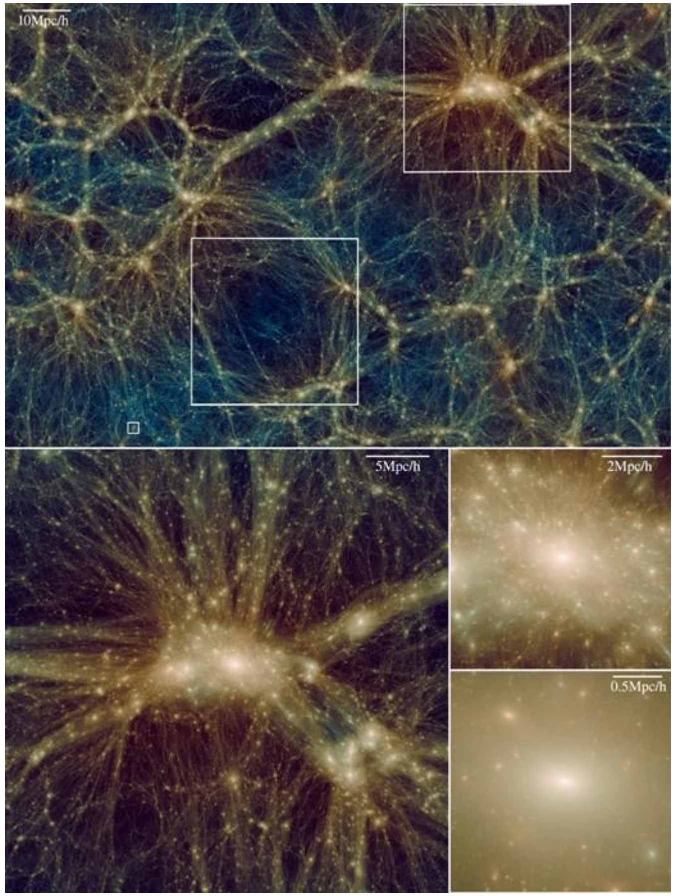
Method

■ Merger tree

- Trees from high resolution N-body simulation
  - 20 Milky Way like tree (Ishiyama et al. 2021, MNRAS)
    Mass range: $0.7 \times 10^{12} - 2.3 \times 10^{12} M_{\odot}$
  - 1 Box tree (Ishiyama et al. 2016, ApJ)
- Only merger trees that can trace Pop III stars

Simulation conditions

	N	L $(h^{-1}\mathrm{Mpc})$	ϵ $(h^{-1}\mathrm{pc})$	m_p $(h^{-1}M_{\odot})$
Milkey Tree	4096^3	16.0	60	5.13×10^3
Box Tree	2048^3	8.0	120	5.13×10^3



https://academic.oup.com/mnras/article/506/3/4210/6307536

(1) The Uchuu simulations: Data Release 1 and dark matter halo concentrations, Ishiyama et al. 2021, MNRAS
(2) WHERE ARE THE LOW-MASS POPULATION III STARS? Ishiyama et al. 2016, ApJ

Calibration Results

Calibrated with Box tree

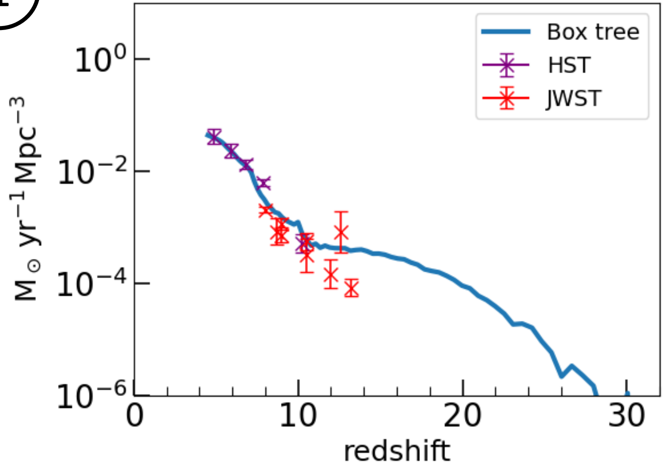
1. Star Formation Rate Density
   - Redshift – SFRD

Calibrated with MW tree

2. Metallicity Distribution Function
   - [Fe/H] – Stellar num
3. Cumulative Satellite Mass Function
   - Stellar mass – Satellite num
4. Mass-Metallicity relation
   - Stellar mass – [Fe/H]

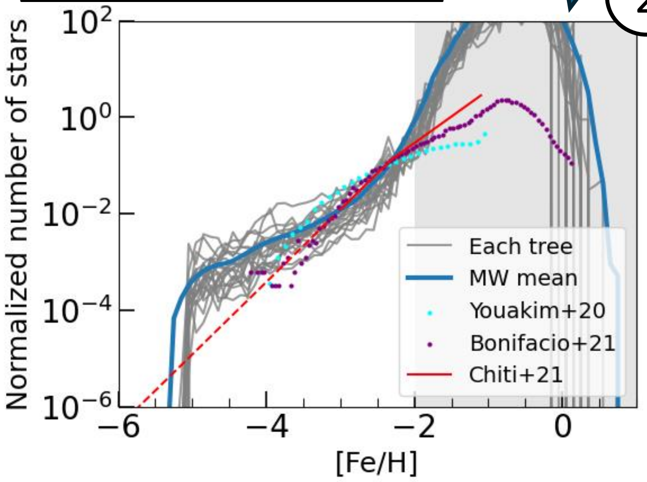
Results broadly consistent with observations

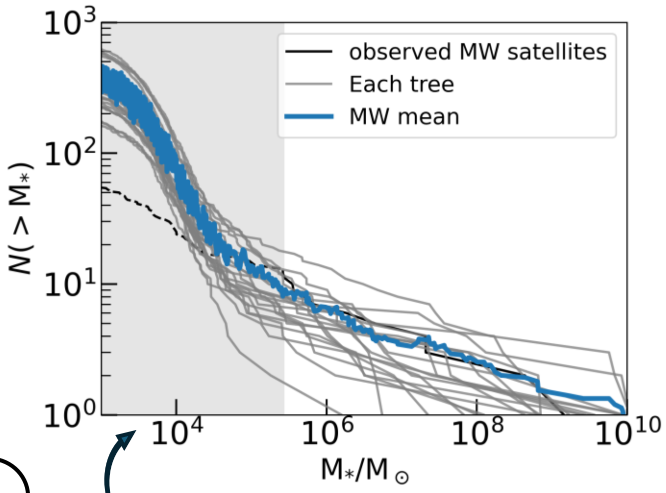
1



Unmodeled regions
(No Type Ia SNe)

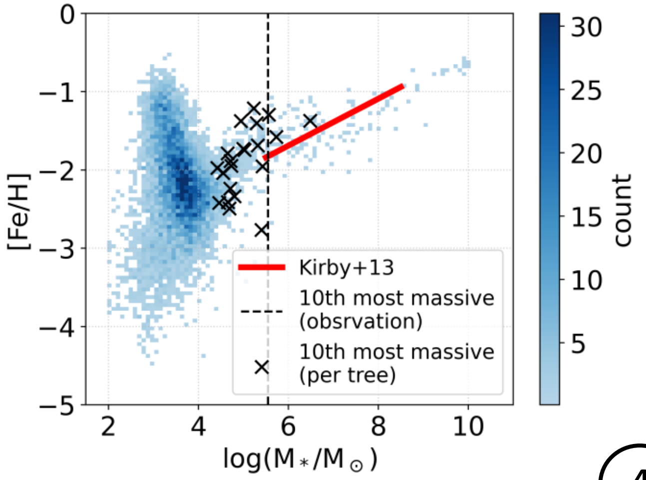
2





3

Observational limits

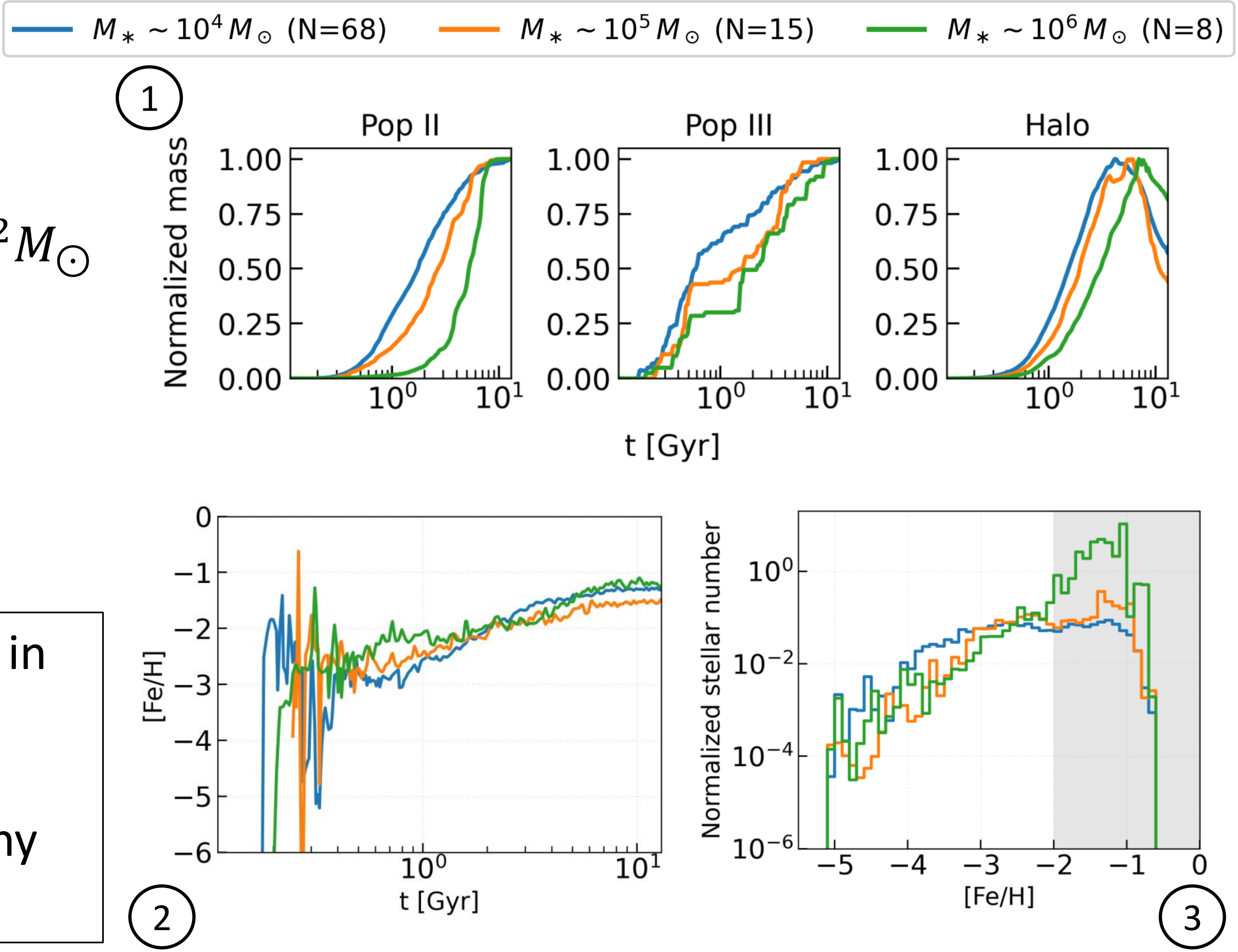


4

Average Trends by Mass Bin

1. Normalized mass evolution
2. Gas metallicity evolution
3. Metallicity distribution function

- Focused tree: $M_{halo}^{main} = 2.4 \times 10^{12} M_{\odot}$
- Mass range : $M_{*} \sim 10^{4} - 10^{6} M_{\odot}$
  - Dwarf spheroidal galaxy
  - Ultra faint dwarf galaxy
- Top 100 most massive galaxies, averaged per mass bin



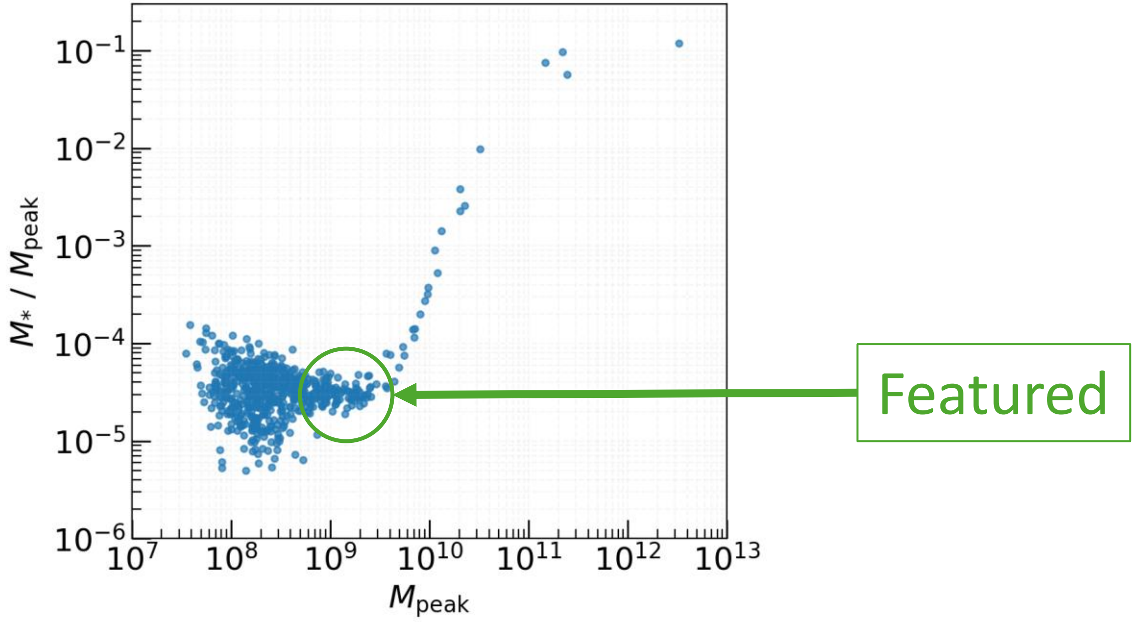
- More massive dwarfs grow rapidly in stellar mass
- Lower-mass dwarfs form earlier
- Ultra faint dwarf galaxies have many metal-poor stars

Extracted Dwarf Galaxies

Extracted dwarf galaxies
(Randomly selected)

Halo ID	M_{halo}	M_{peak}	M_*	[Fe/H]
1	1.5×10^9	3.6×10^9	6.0×10^4	-1.9
2	5.6×10^8	2.5×10^9	5.0×10^4	-2.2
3	7.3×10^8	2.4×10^9	4.9×10^4	-2.1
4	9.7×10^7	2.0×10^9	4.0×10^4	-2.0
5	2.3×10^9	2.6×10^9	3.3×10^4	-2.4
6	6.9×10^8	2.2×10^9	2.8×10^4	-1.9
7	6.4×10^8	1.5×10^9	2.1×10^4	-2.1
8	1.1×10^9	1.1×10^9	1.6×10^4	-2.7
9	1.0×10^8	7.0×10^8	1.3×10^4	-2.7

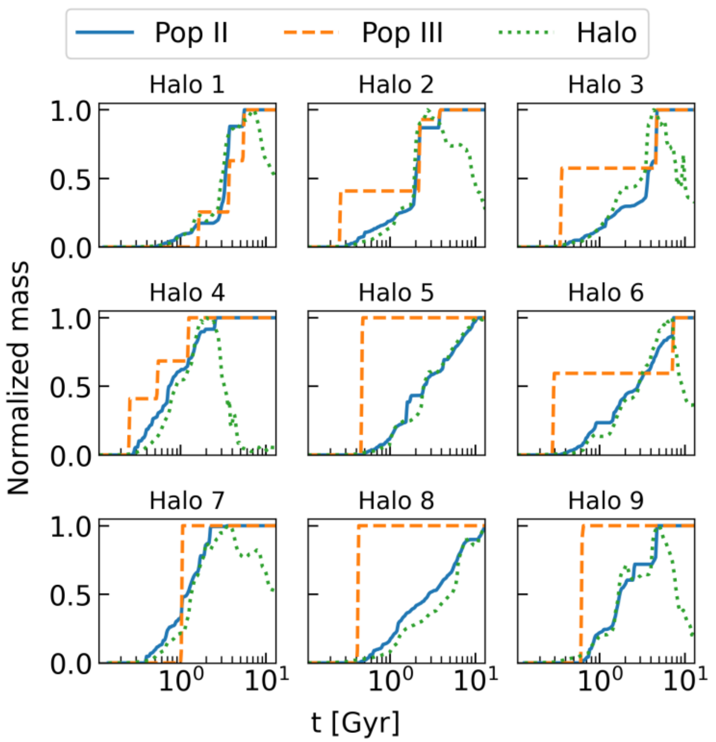
- Galaxies were randomly selected based on stellar mass (M_*)
- We focused on mass range $M_* \sim 10^4 M_\odot$
- This corresponds to the mass ranges of ultra faint dwarf galaxies



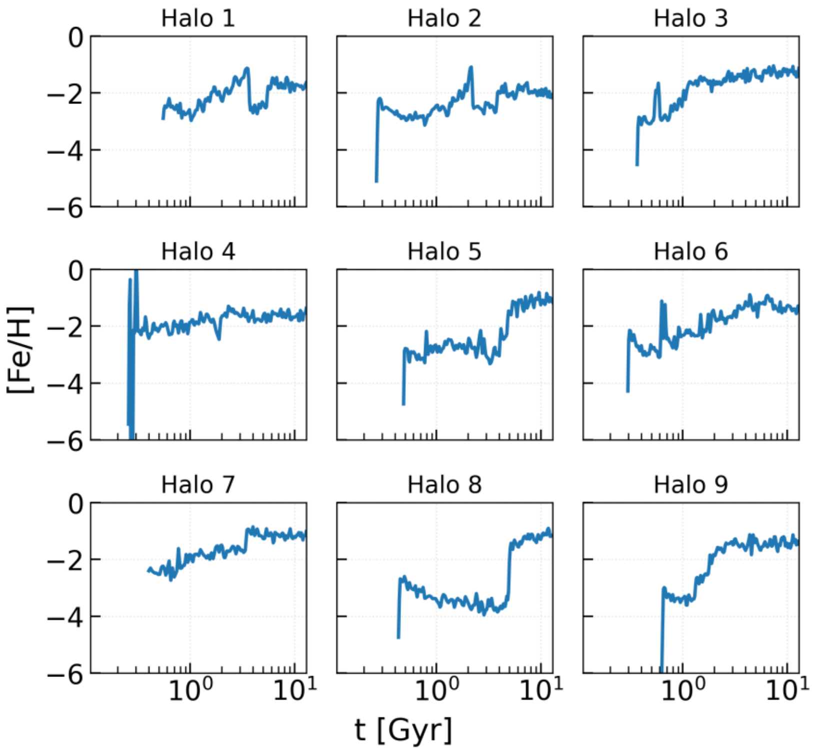
Galaxy Evolution (Main Branch)

- Star formation histories and metallicity distribution functions of ultra faint dwarfs show large variation
- Pop II star formation quenched at peak halo mass
- Some ultra faint dwarfs have a plenty of metal poor stars

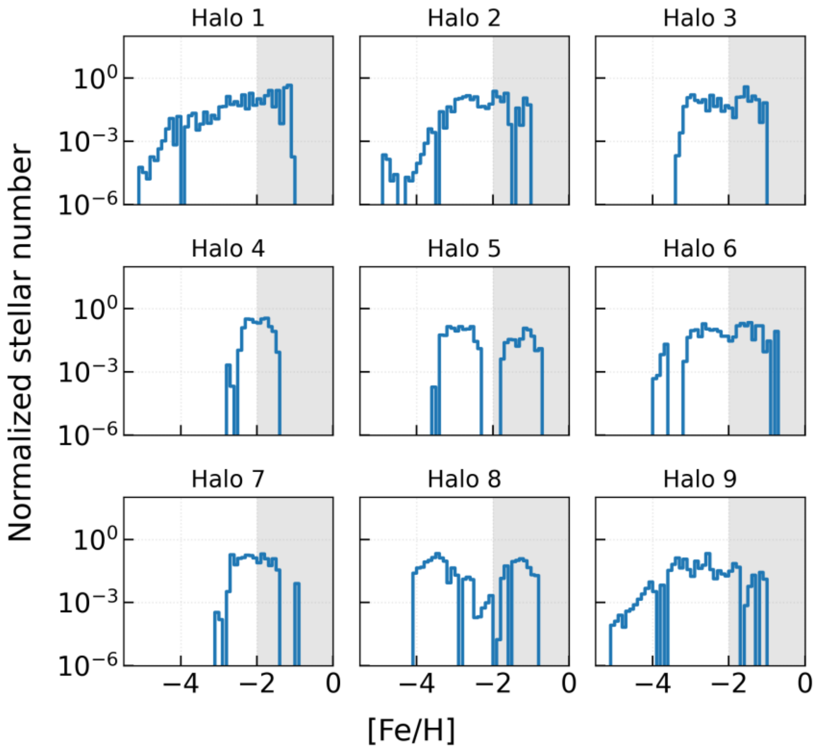
Mass evolution



Metallicity evolution



Metallicity distribution function



Summary and Discussion

- Star Formation Histories
  - More massive dwarfs grow rapidly in stellar mass
  - Ultra faint dwarf galaxies show large variation (MDF also)
  - Pop II star formation quenches at peak halo mass
    - Peak halo mass strongly impacts galaxy evolution

- Metallicity distribution function
  - Low mass galaxies show flatter MDFs
  - Ultra faint dwarf galaxies have many metal-poor stars

- Discussion
  - Tidal stripping reduces gas inflow and metallicity
  - Population III stars are the foundation of early cosmic metals
    - Galaxy with low stellar mass evolutions have two flat