Probing the baryonic processes and the reionization from the Milky Way satellites

Qingjuan Yu

Kavli Institute for Astronomy and Astrophysics / Peking University

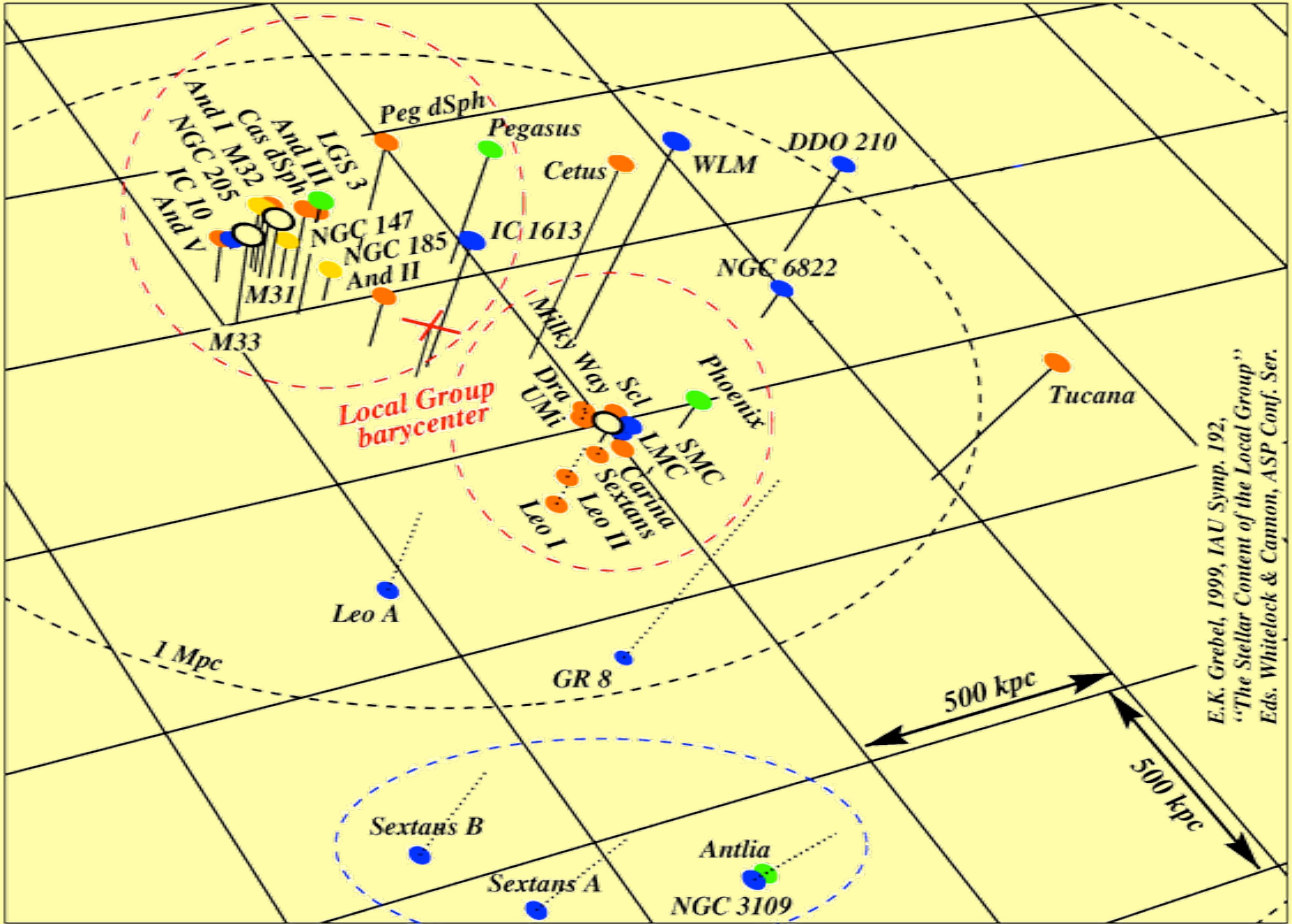
July 18, 2013

Collaborators: Jun Hou (PKU), Youjun Lu (NAOC)

(Papers in preparation)

Outline

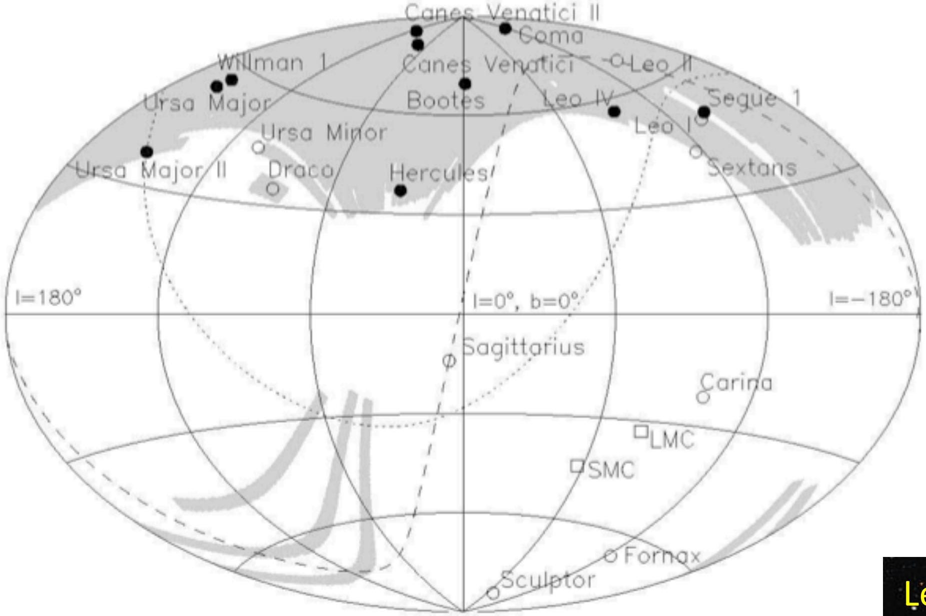
- Introduction
  - Milky Way dwarf satellites
  - Baryonic physical processes
    - Supernova feedback
    - Reionization
    - Molecular hydrogen cooling
- Semi-analytical hierarchical galaxy formation model
- Model results
  - Metallicity distributions
  - Age properties
- Summary



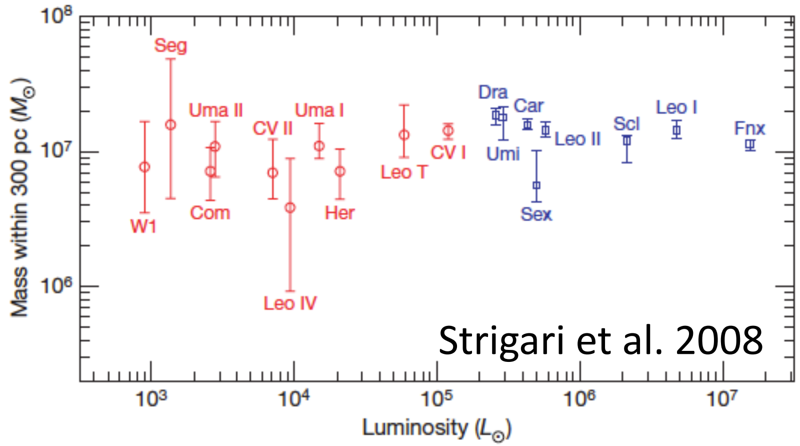
Peg dSph
Pegasus
Cetus
WLM
DDO 210
And I
Cas dSph
And III
LGS 3
NGC 205
M32
IC 10
And V
NGC 147
NGC 185
IC 1613
And II
M31
M33
NGC 6822
Milky Way
Local Group
barycenter
Dra
UMi
Scl
Phoenix
Tucana
LMC
SMC
Carina
Sextans
Leo II
Leo I
Leo A
1 Mpc
GR 8
500 kpc
500 kpc
Sextans B
Antlia
Sextans A
NGC 3109
E.K. Grebel, 1999, IAU Symp. 192,
"The Stellar Content of the Local Group"
Eds. Whitelock & Cannon, ASP Conf. Ser.

The Milky Way dwarf satellites

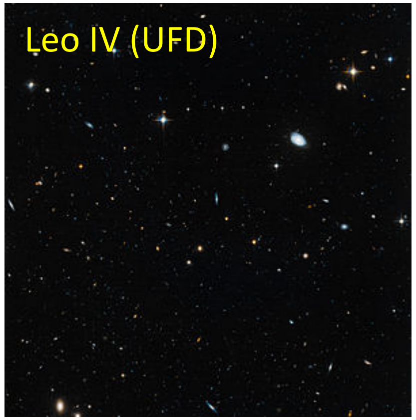
Classical dSphs
SDSS: ultra-faint dwarf galaxies (UFD)

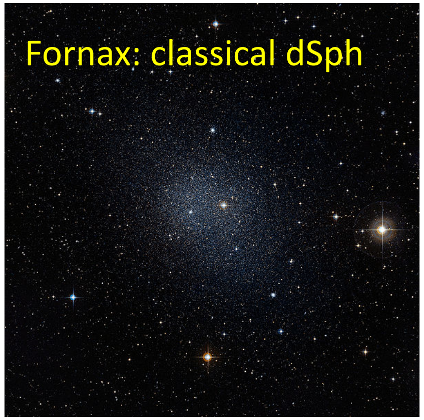


Belokurov et al. (2006)



Strigari et al. 2008





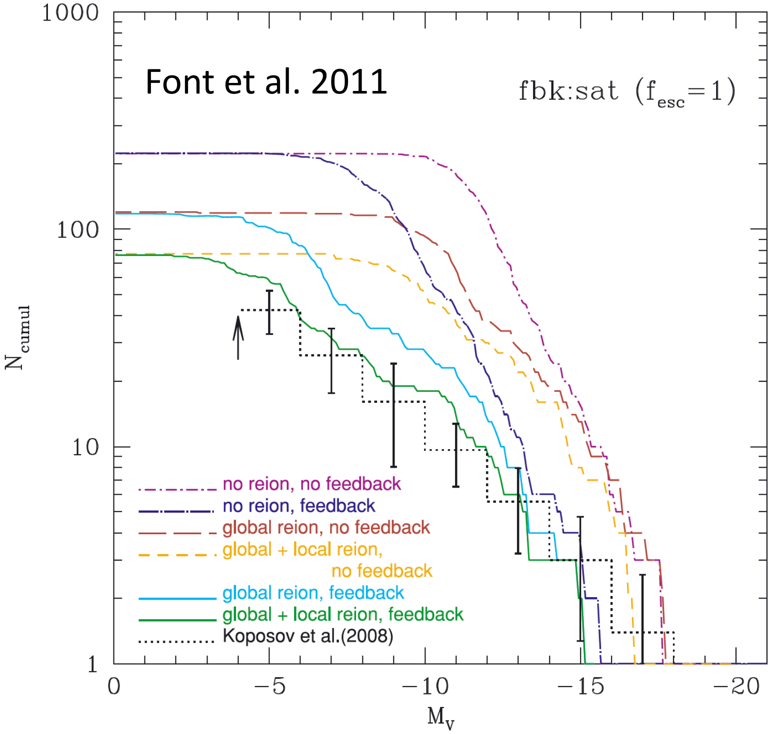
The Milky Way satellites

They are among the least luminous galaxies in today's universe. They have shallow gravitational potential wells and are believed to form at early times of the cosmic history.

- Formation of galaxies and first galaxies
  - Powerful probe of the galaxy formation processes in the early universe: supernova (SN) feedback, reionization, and H_2 cooling
- Understanding the problems that the ΛCDM model faces on small galactic scales
  - The missing satellite problem, the core/cusp problem
- Indirect dark matter detection: dark matter particle annihilation?
- Formation of seed black holes?
- … …

- SN feedback

- The energetic SN explosions can expel the cold gas (and heavy elements) in galaxies and possibly form galactic winds.
- The SFR affects the SN explosion rate, while the reduction of cold gas by SN explosions affects the SFR. This forms a feedback loop.
- SN feedback plays an important role in suppressing star formation in low-mass halos and solving the 'missing satellite problem' within the ΛCDM framework.
- So far, some details on SN feedback processes are still largely unknown.



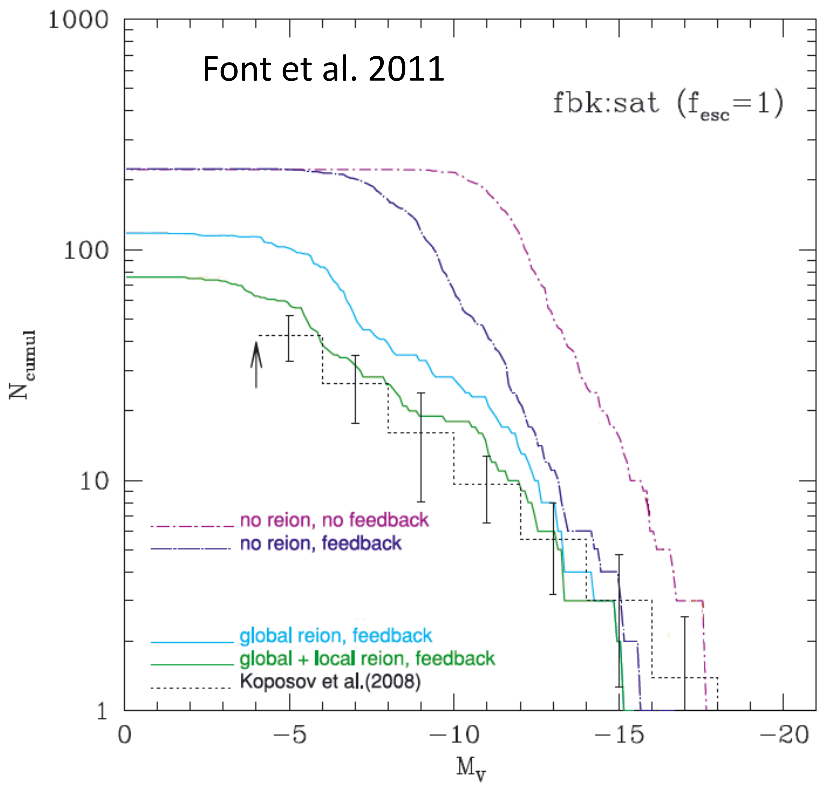
• Reionization of the universe

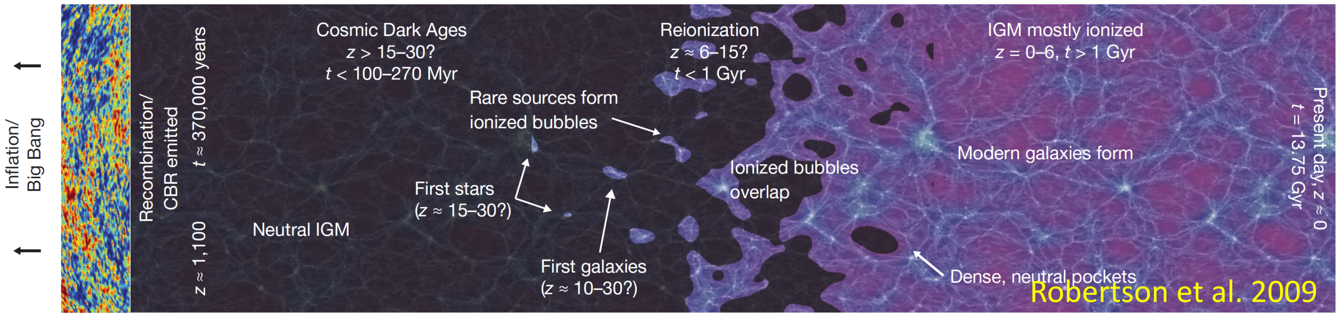
- The ionizing photons from astrophysical objects ionized the whole universe by $z \sim 6$.

- Reionization also plays an important role in solving the 'missing satellite problem'. It is required to suppress the star formation in small halos (gas heating up with increasing pressure & photoevaporation of small gaseous halos).

- The detailed understanding of reionization needs to be explored. (Starting redshift? Duration? Major ionizing sources?)

(Many talks in this conference)





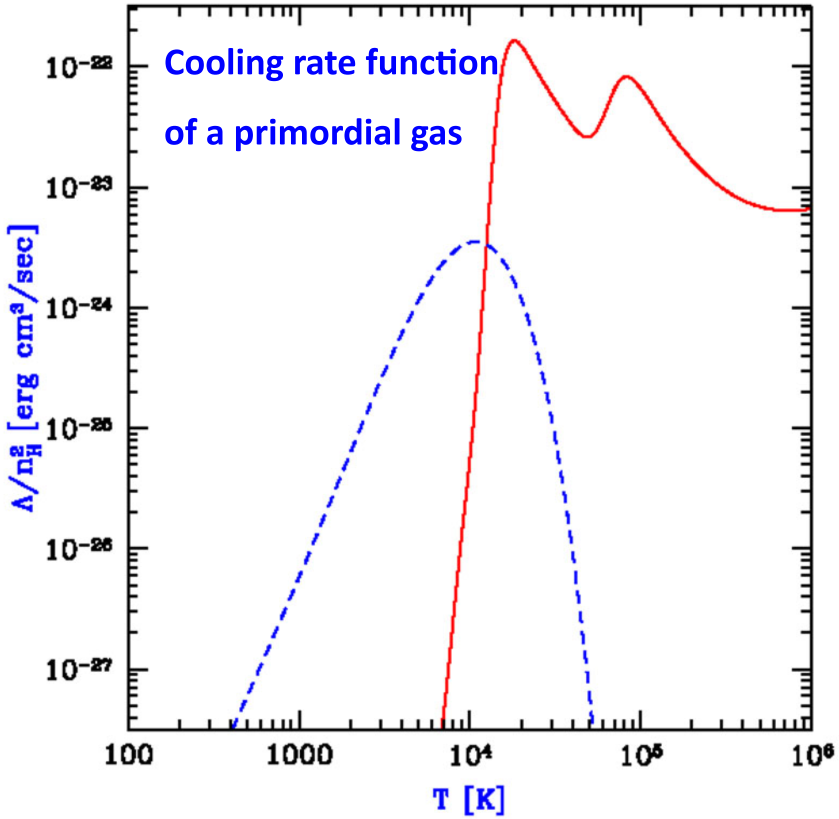
Cosmic Reionization

- H_2 cooling

  - H_2 cooling can be effective below 10^4 K. It is possibly the only cooling mechanism for the mini-halo ($T_V < 10^4$ K) with primordial gas.

  - It determines whether the mini-halos can form stars, and thus potentially affects the chemical enrichment and the reionization of the universe.

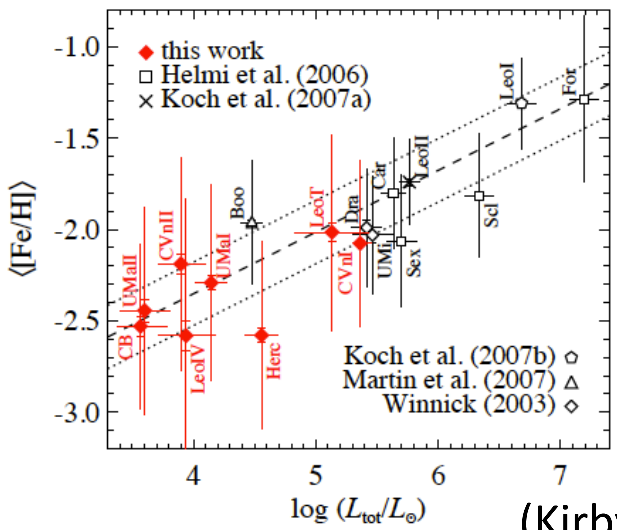
  - However, whether H_2 cooling is effective at high redshift universe is under debate, because H_2 is very sensitive to the UV background.



Barkarnan & Loeb 2001

Some recent observational progress

- Metallicity-luminosity relation



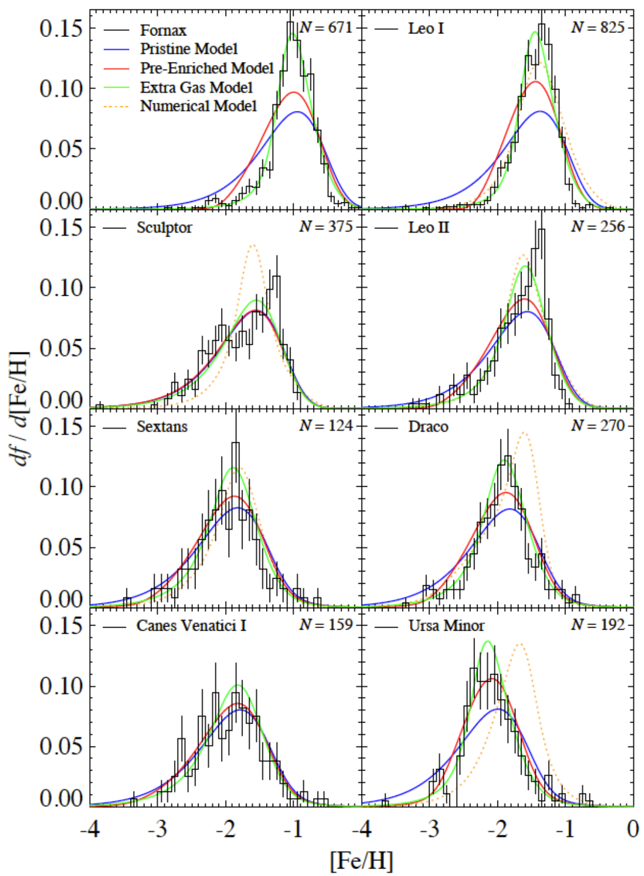
(Kirby et al. 2008)

- Extremely metal-poor stars
  - [Fe/H]<-3.0

- Chemical abundance
- Color-Magnitude diagram: SFH

Frebel's talk

- Metallicity distribution of individual dwarfs

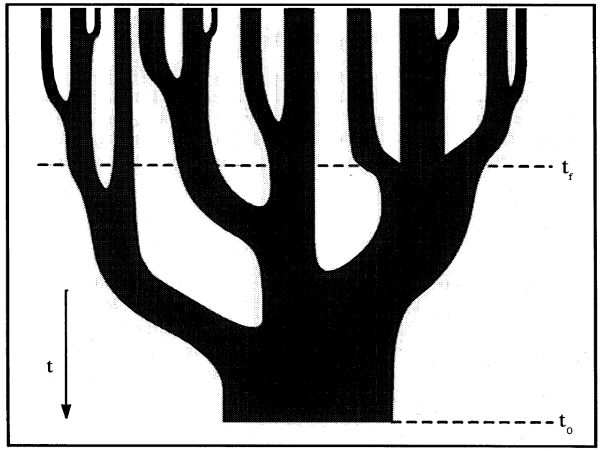


Kirby et al. 2011, 2013

Understanding in a hierarchical galaxy formation picture

Model

- Merger trees of MW-sized dark matter halos
  - modified EPS formula (Parkinson et al. 2008)
  - Redshift: 0-20;
  - halo mass: 1×10^{12}, 2×10^{12} $M_\odot$
  - Resolution: 10^6 $M_\odot$



- Semi-analytical galaxy formation recipes
  - Gas cooling
    - Atomic cooling
    - molecular hydrogen cooling (Benson et al. 2006; Galli & Palla 1998)
  - Star formation and evolution
    - Effects of reionization
  - SN feedback, chemical enrichment
    - SN II
    - SN Ia (0.1Gyr time delay in explorsion; more iron)
  - Galaxy mergers
  - … …

Based on GALFORM (*Cole et al. 2000; Benson et al. 2003; Bower et al. 2006, …*), with some improvements in recipes

- Statistical study: 100 merger trees for each set of parameters

- Understanding in the hierarchical galaxy formation model, instead of assuming simple star formation history
- Including chemical enrichment due to SN Ia
- Quantifying the stellar metallicity distribution and exploring the probe of the physical processes
- A statistical study is allowed:
  - a large number of merger trees generated by the Monte-Calo method.

(cf. Kirby et al. 2011; Salvadori & Ferrara 2009; Nagashima et al. 2005; Yates et al. 2013;
Font et al. 2011; Guo et al. 2011; Li et al. 2010; Munos et al. 2009; Romano & Starkenburg 2013; …)

Reionization

- Reducing the baryon fraction of a dark matter halo

$$f_b = \frac{1}{[1 + (2^{1/3} - 1)M_\mathrm{F}/M_\mathrm{halo}]^3}$$

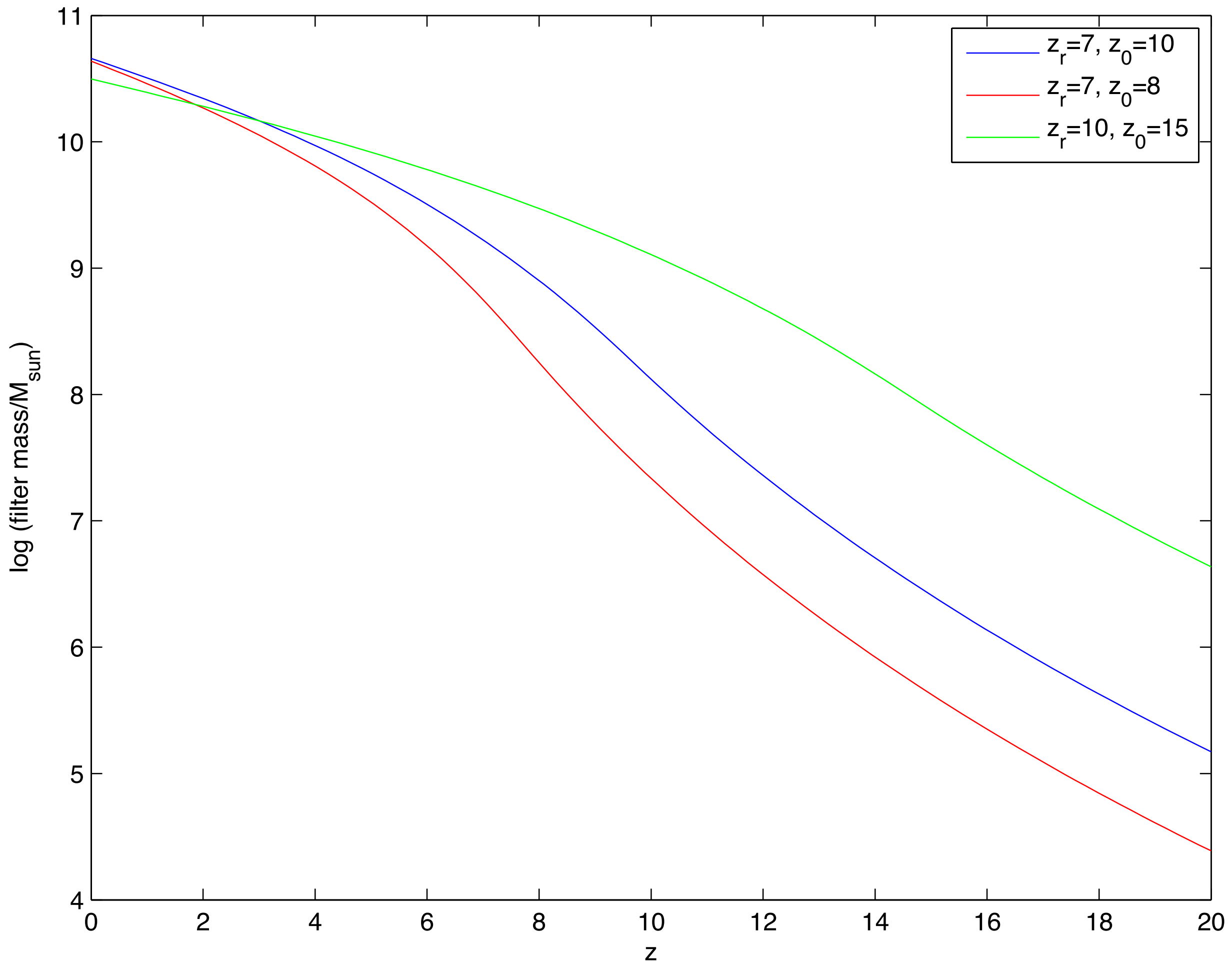
Ratio to the cosmic average

Kravtsov et al. (2004), Gnedin (2000)

- M_F: filtering mass
  - parameters z_0 and z_r indicating the beginning and completing redshift of reionization, respectively
    - **weak reionization model** (z_0=10, z_r=7): the cosmic average reionization;
    - **strong reionization model** (z_0=15, z_r=10): enhancement of reionization in local region by the local sources.

Font et al. 2011

Filtering mass



Supernova feedback

- SN Feedback scale law

$$dM_{\rm reheat} = \beta \psi dt$$
$$\beta = (v_{\rm disk}/v_{\rm hot})^{-\alpha_{\rm hot}}$$

ψ: Star formation rate
β: SN feedback efficiency
(e.g., Cole et al. 2000)

- Energy condition
  - To have all the reheated gas to be expelled from the galaxy, the SN explosion energy should be high enough

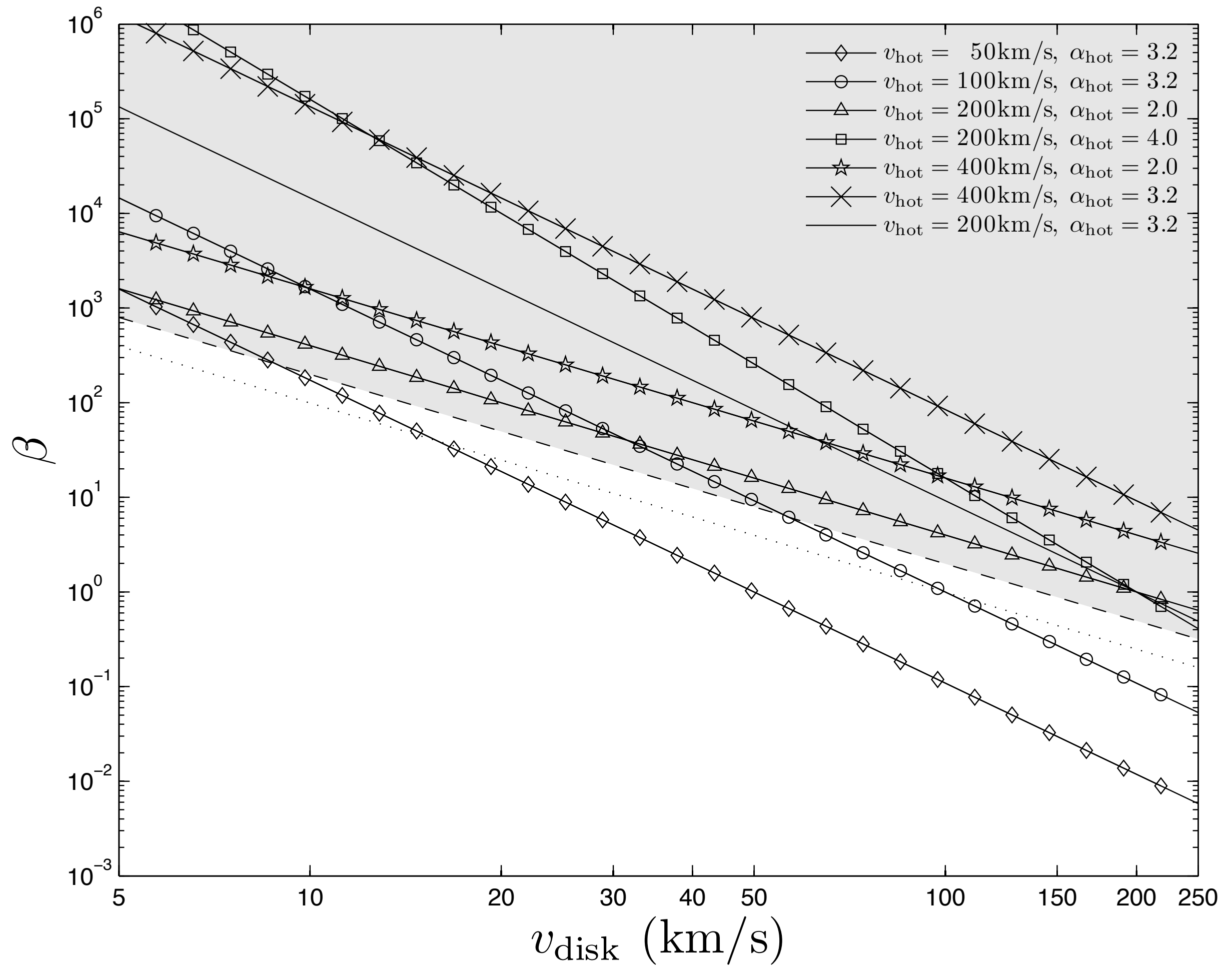
$$dE_{\rm SN} - 0.5 v_{\rm vir}^2 dM_{\rm reheat} \geq 0 \quad dE_{\rm SN} = \epsilon_{\rm halo} \times 0.5 v_{\rm SN}^2 \psi$$

  - Fate of the reheated gas: staying in the halo, or going out of the halo, or falling back to the disk.

(Guo et al. 2011)

  - Applied only before a galaxy becomes a satellite

SN feedback efficiency



Results

- Simulations

v_{hot}(km/s)	α_{hot}	z_0	z_r	$M_{host}(M_\odot)$	H_2 cooling	MW like hosts
200	3.2	15	10	2×10^{12}	on	7
400	3.2	15	10		on	–
100	3.2	15	10		on	–
50	3.2	15	10		on	–
200	4.0	15	10	2×10^{12}	on	9
200	2.0	15	10		on	18
200	3.2	10	7		on	8
200	3.2	15	10		off	9
400	3.2	15	10		on	–
100	3.2	15	10		on	12
50	3.2	15	10		on	13
200	4.0	15	10	1×10^{12}	on	9
200	2.0	15	10		on	10
200	3.2	10	7		on	17
200	3.2	15	10		off	7

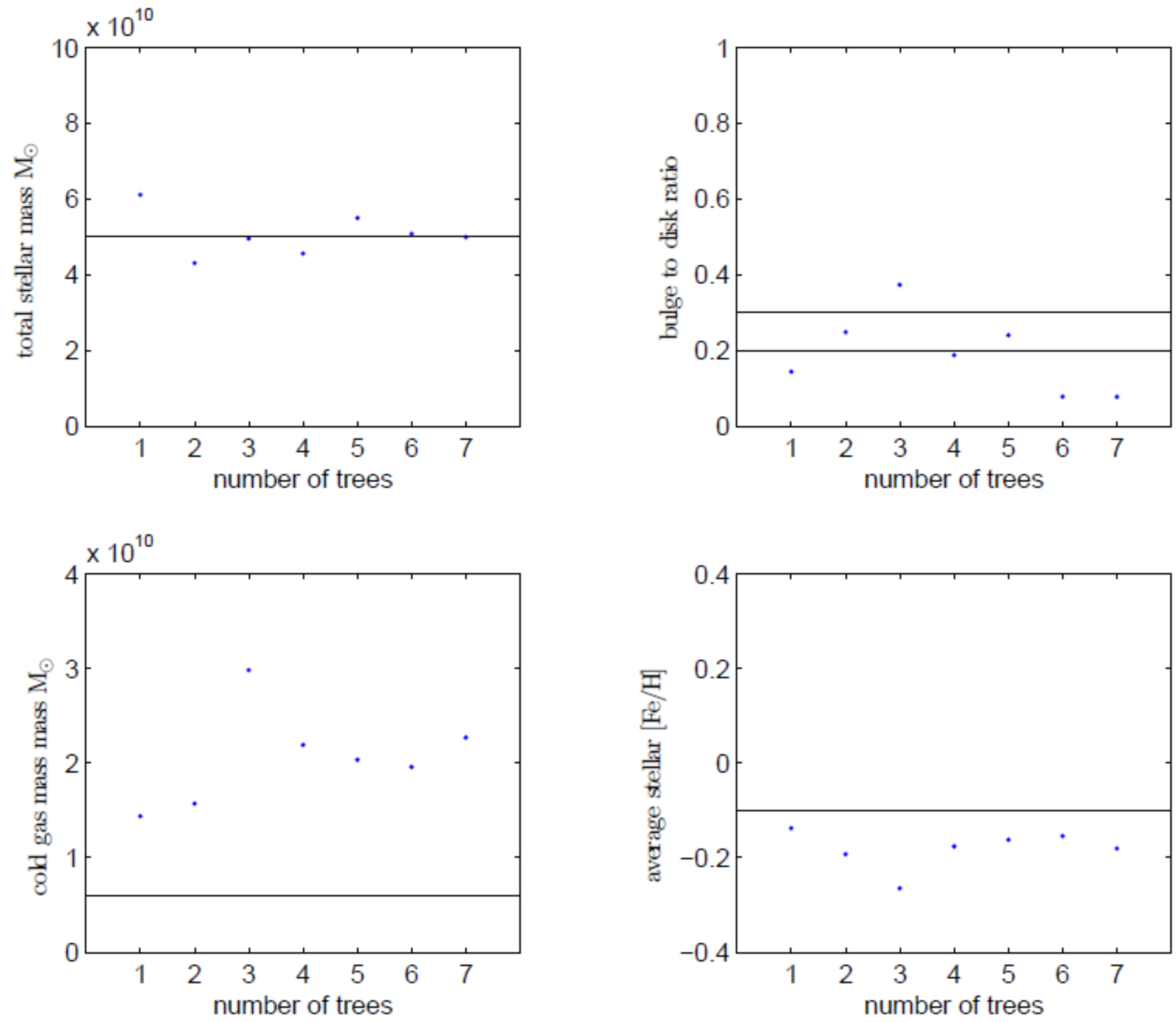
Fiducial model

- Chemical and stellar age properties are not sensitive to the host halo mass

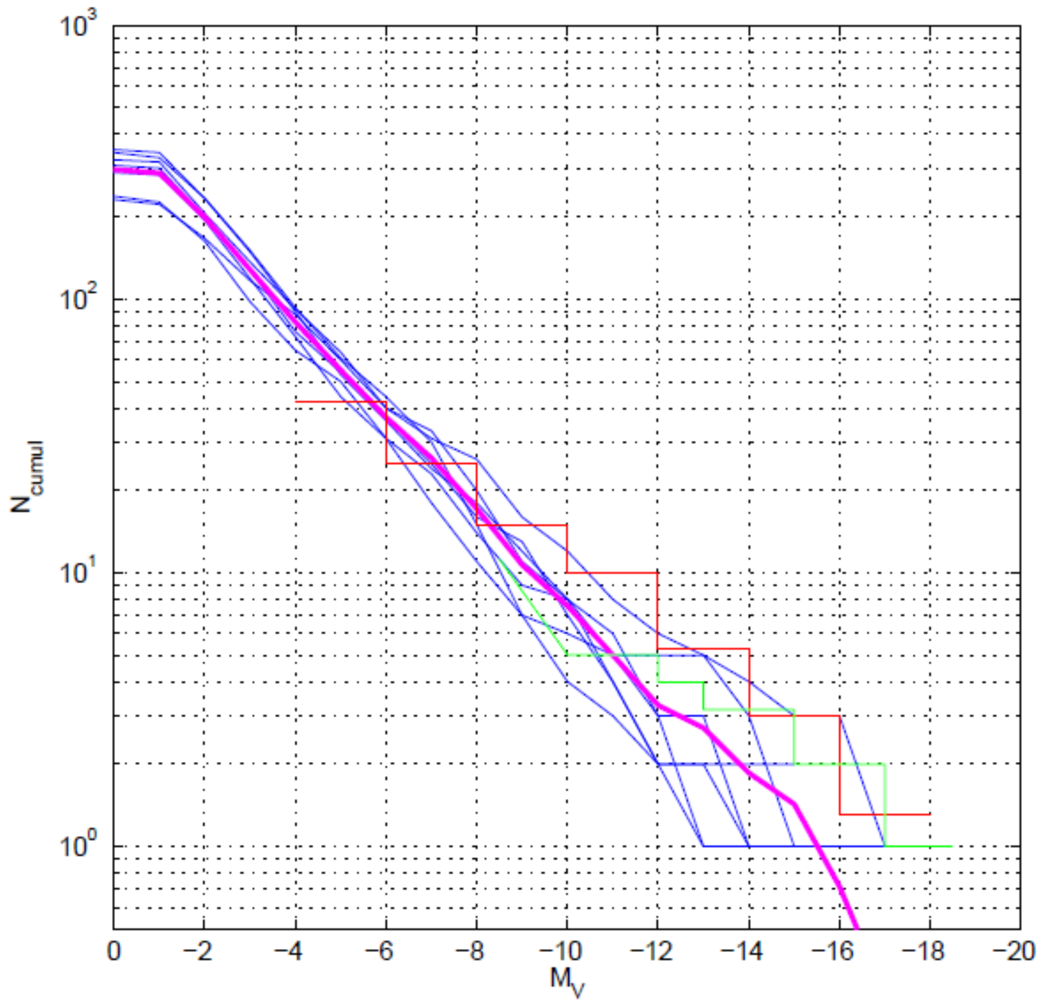
Weak reionization model (z_0=10, z_r=7): the cosmic average reionization

Strong reionization model (z_0=15, z_r=10): the enhancement of reionization in local region by local sources.

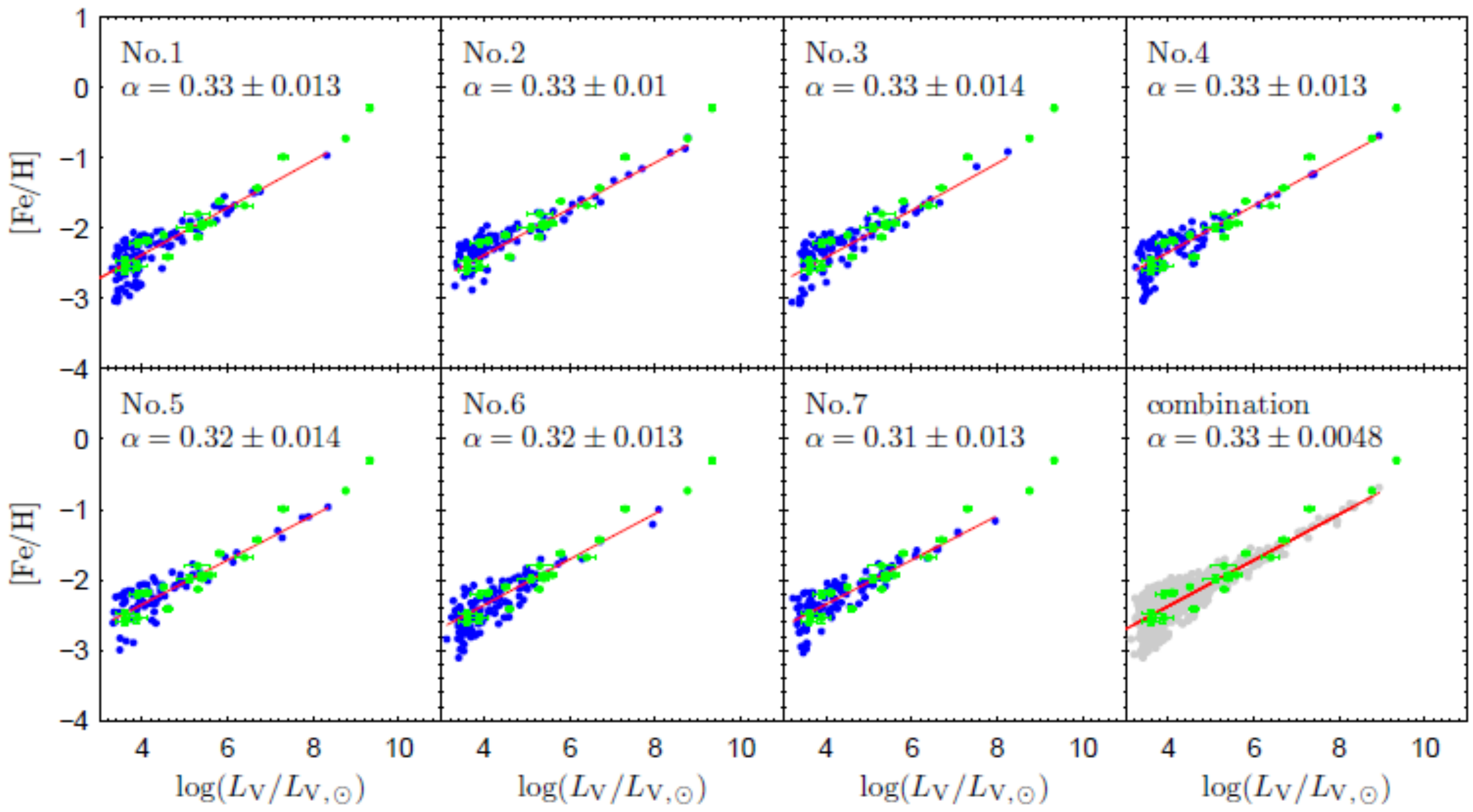
- Fiducial model vs. observations



Satellite luminosity function

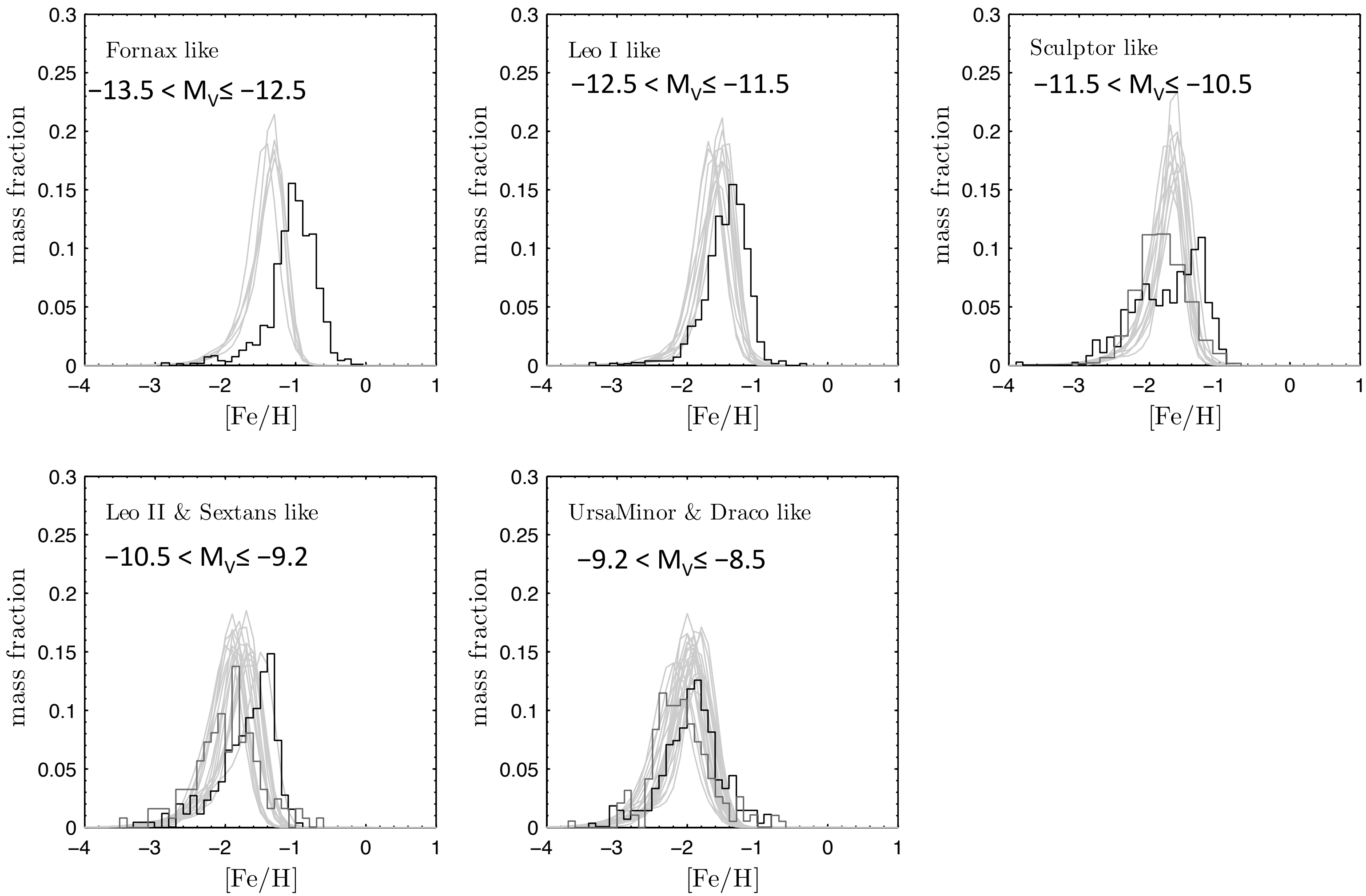


Stellar metallicity versus luminosity correlation



Observational slope: 0.31±0.04 (Kirby et al. 2011)

Metallicity distribution of individual dSphs



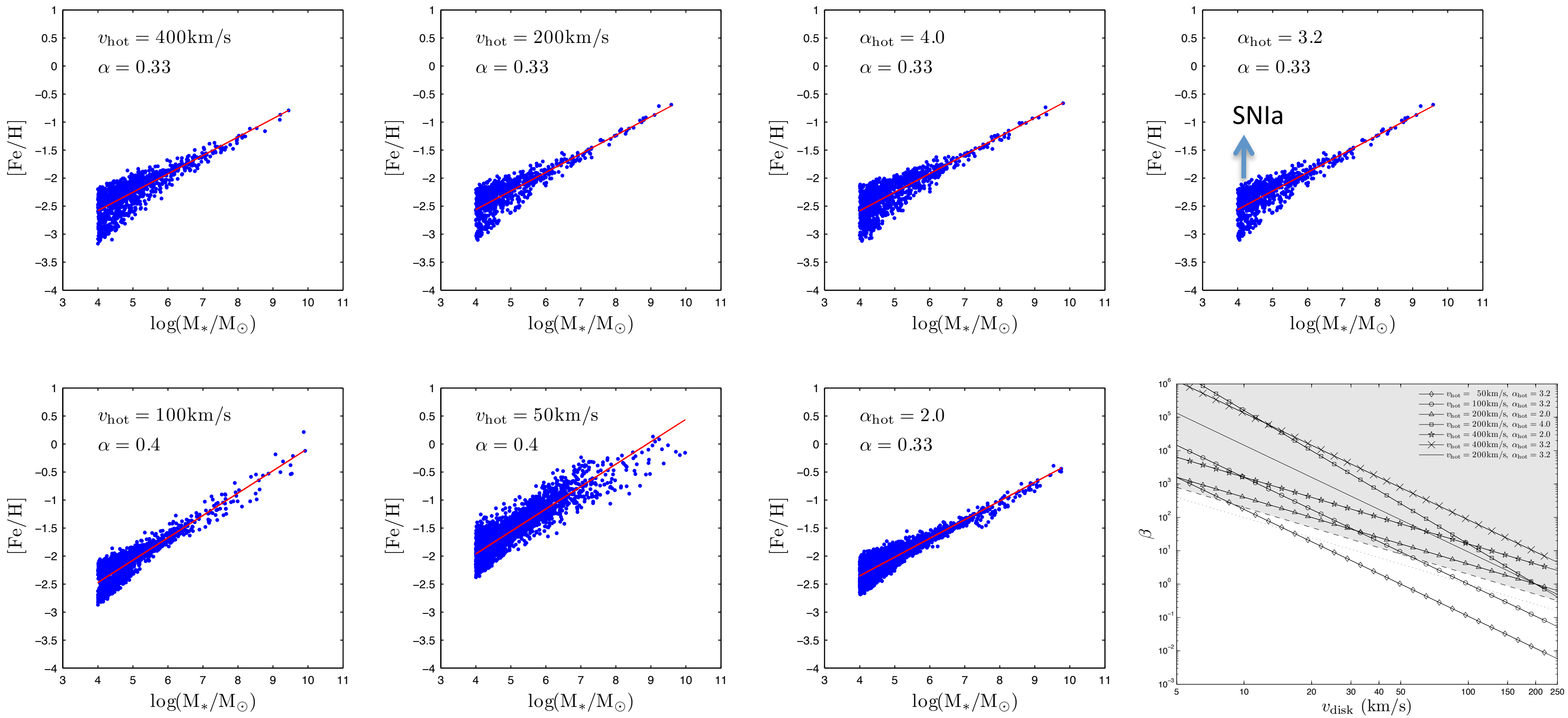
Histogram:
Observation from Kirby et al. 2011

- Effects on chemical properties
  - Metallicity v.s. mass/luminosity correlation
  - Metallicity distribution of individual dwarfs

$$dM_{\rm reheat} = \beta\psi dt$$
$$\beta = (v_{\rm disk}/v_{\rm hot})^{-\alpha_{\rm hot}}$$

SN feedback

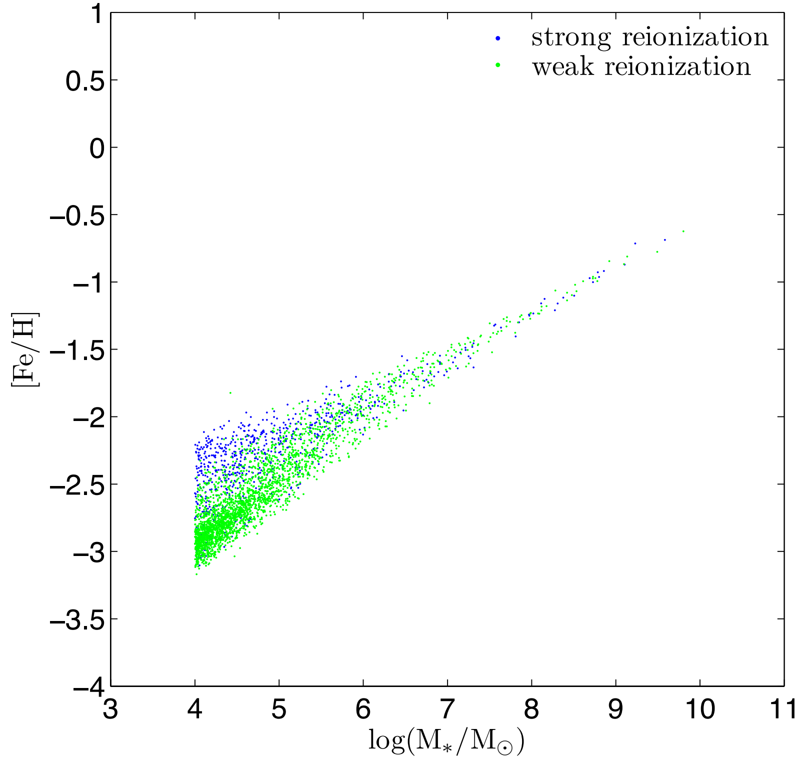
- v_{hot}
- α_{hot}



Reionization

A steeper slope in weak reionization

- Strong: α=0.33
- Weak: α=0.45

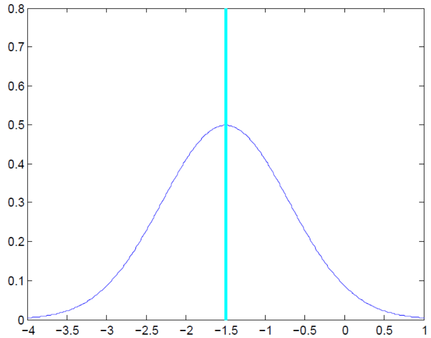


The strong reionization → evaporate relatively more gas from a halo and less gas in the halo cools to form a galaxy.

The weak reionization: the halo where the galaxy of a given mass forms is likely to be less massive

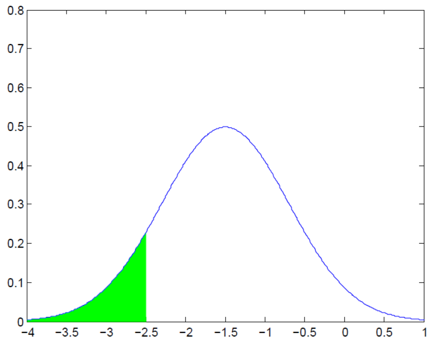
Only affects low-mass halos strongly.

Metallicity distributions



Peak Position:

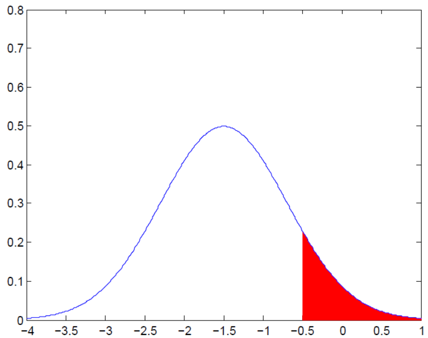
roughly equivalent to the average metallicity.



$\sigma(Z')/\bar{Z}'$ **(Metal-Poor Tail)**

$$Z' = \sqrt{1/10^{[\mathrm{Fe/H}]}} \quad \bar{Z}' = \int Z' \times P(Z')dZ'$$

$$\sigma(Z') = \left[\int (Z' - \bar{Z}')^2 P(Z')dZ'\right]^{1/2}$$

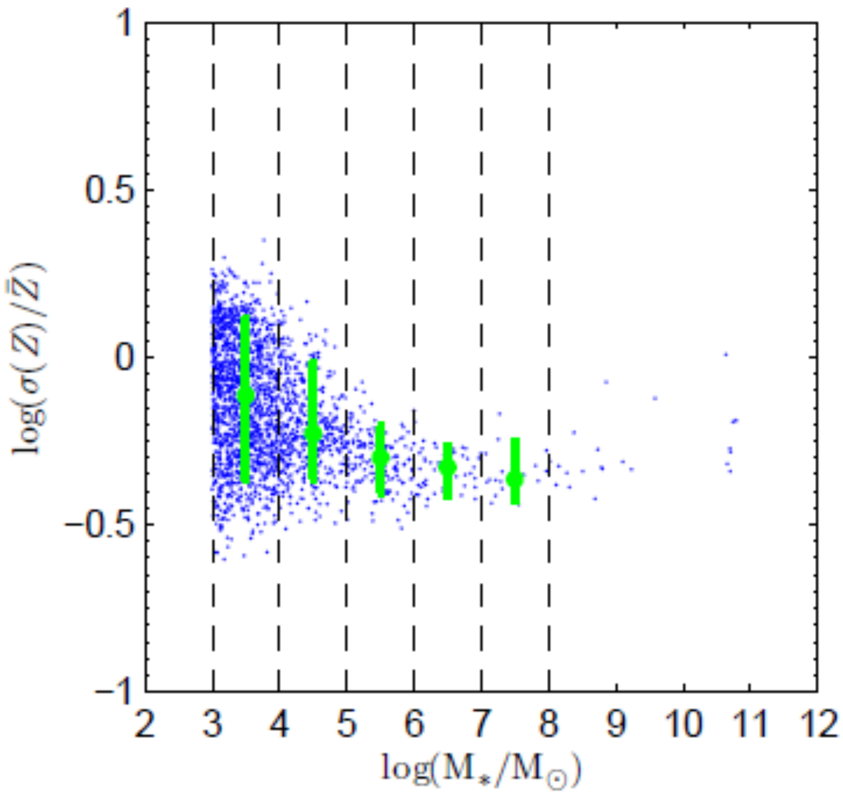


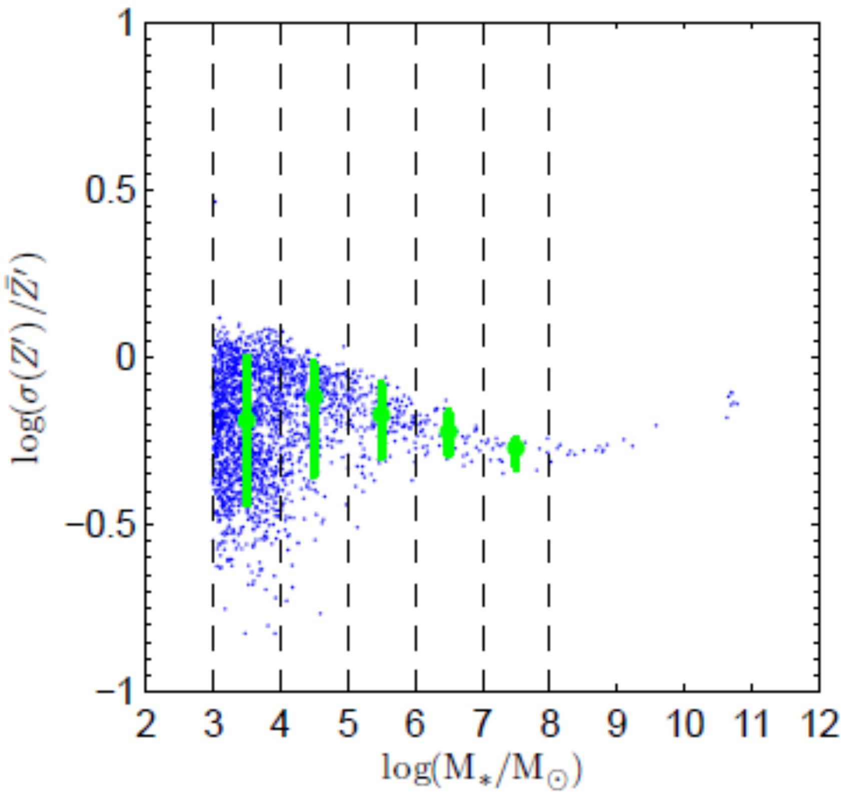
$\sigma(Z)/\bar{Z}$ **(Metal-Rich Tail)**

$$Z = 10^{[\mathrm{Fe/H}]} \quad \bar{Z} = \int Z \times P(Z)dZ$$

$$\sigma(Z) = \left[\int (Z - \bar{Z})^2 P(Z)dZ\right]^{1/2}$$

Metal-rich tail **Metal-poor tail**

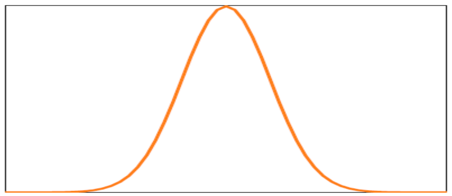




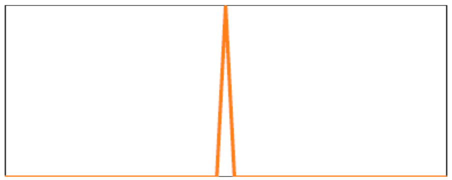
Results

Metallicity distributions: metal-poor tails

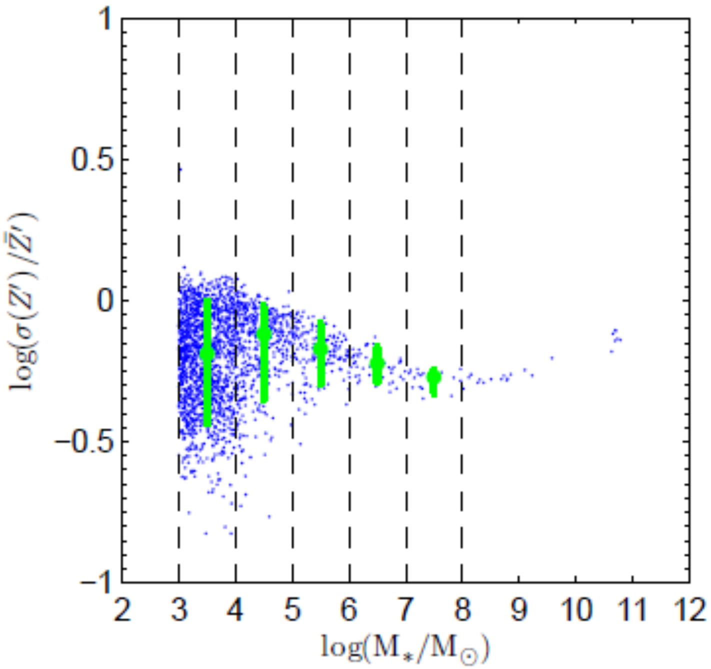
Star formation duration



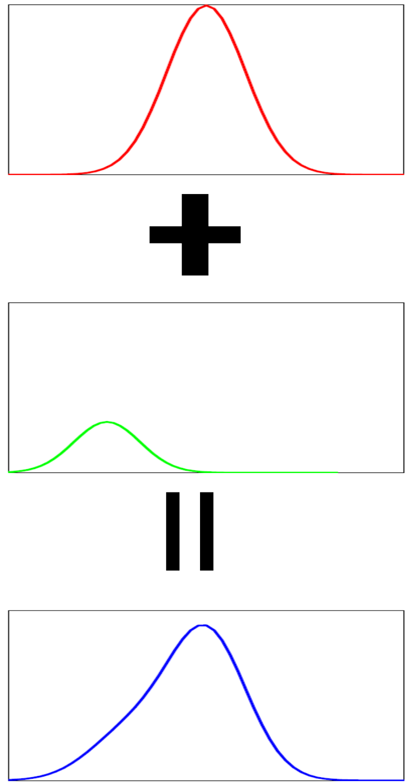
long duration



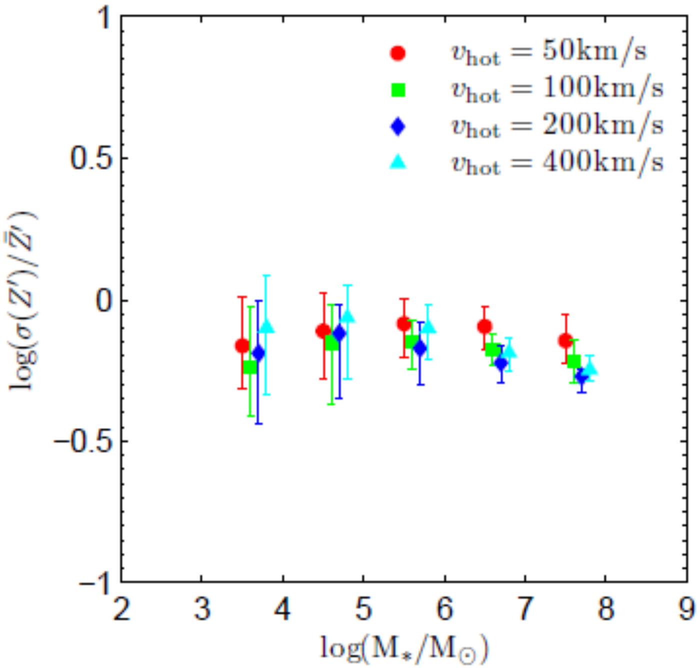
short duration

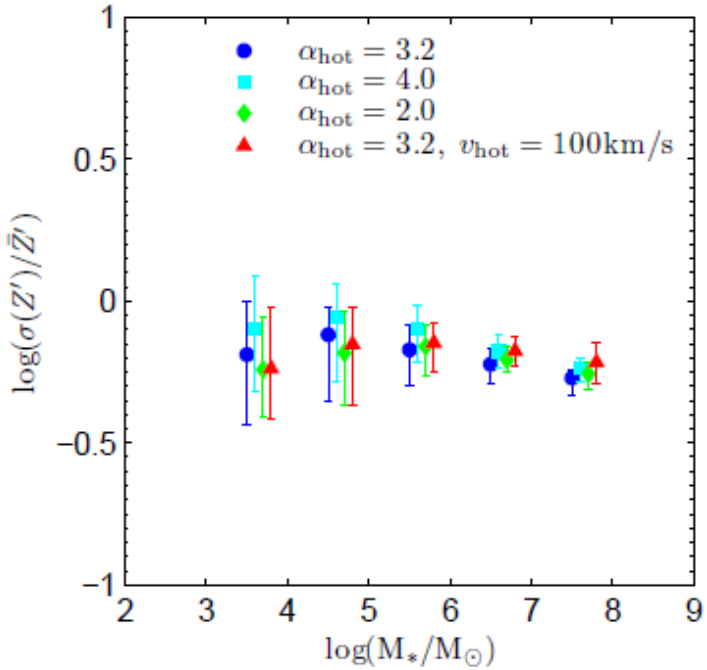


Minor merger

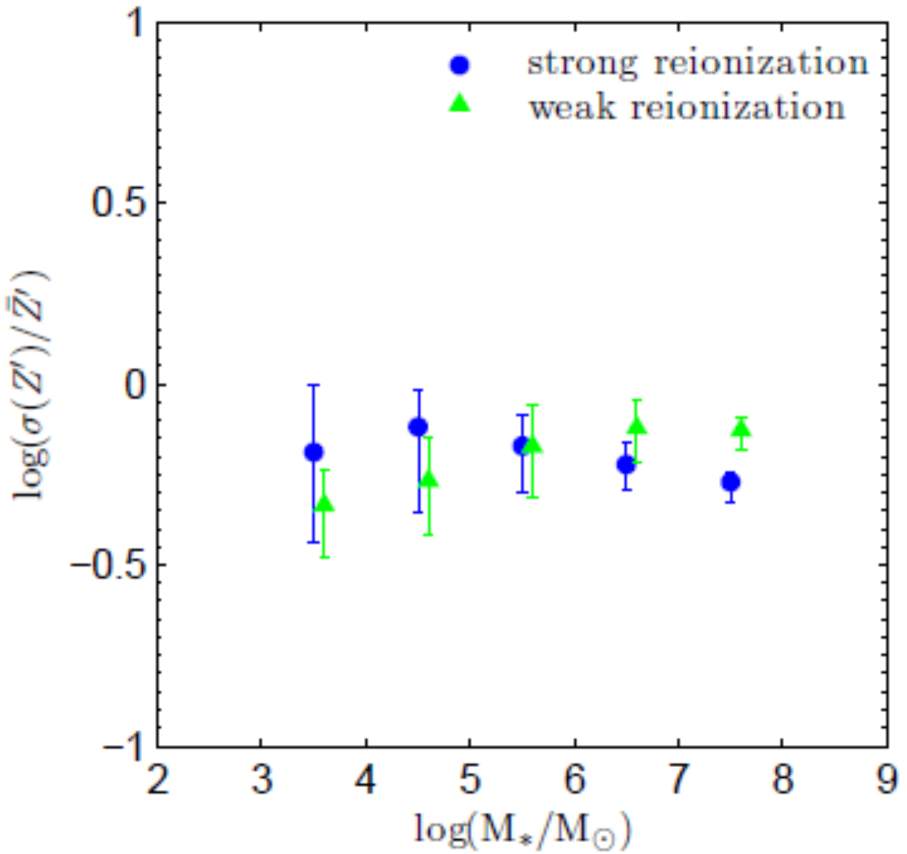


Metal-poor tails: different feedback





Metal-poor tails: different reionization

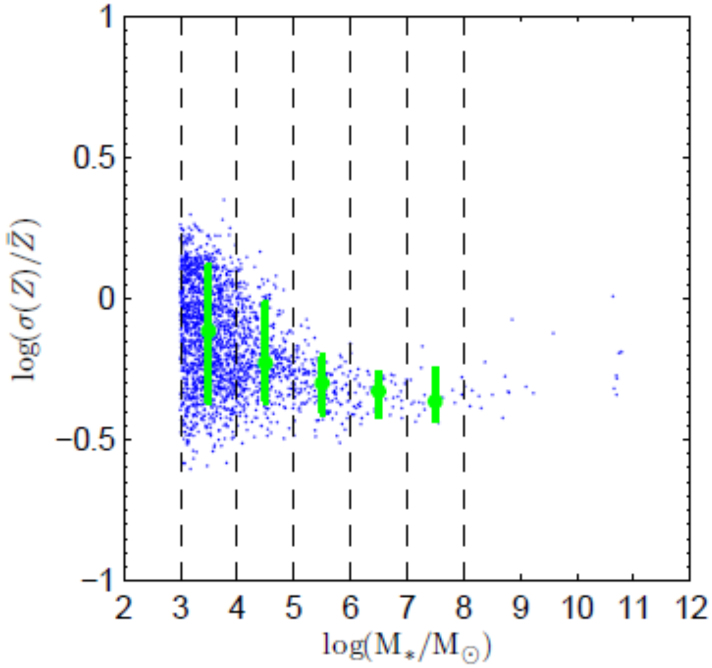


Weak reionization:

- low stellar mass: smaller halo→ fewer minor mergers & high SFR
- large stellar mass: enhanced difference in metallicities of large galaxies and small accreted galaxies

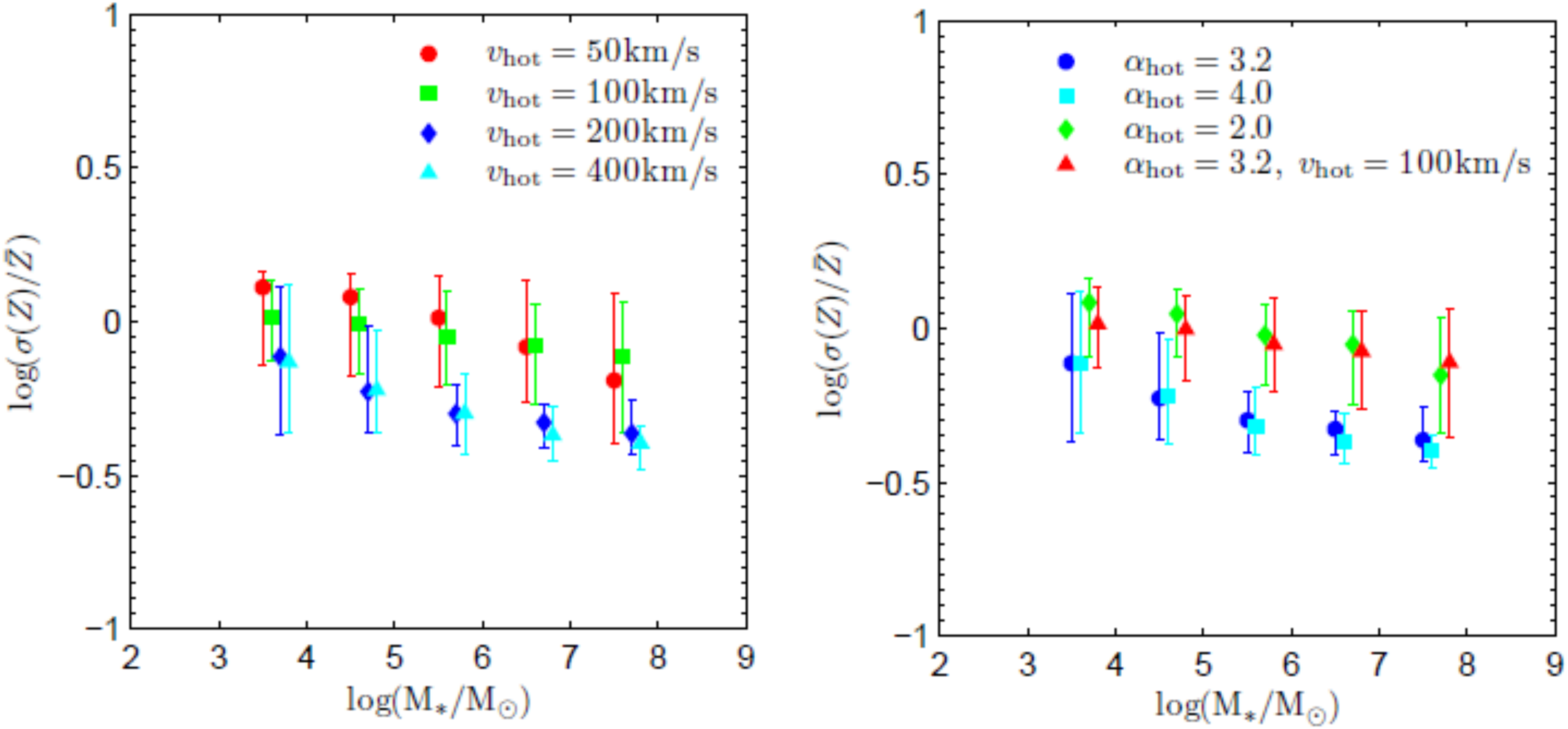
Metallicity distributions: metal-rich tails

- For most dwarfs, the metal-rich tails are cast after the galaxy becomes a satellite.
- In this stage, the energy condition turns off and typically the feedback is strong.
- This strong feedback can strongly affect the amount of stars on the metal-rich tails, and thus becomes the dominant factor to determine the value of $\sigma(Z)/\overline{Z}$.

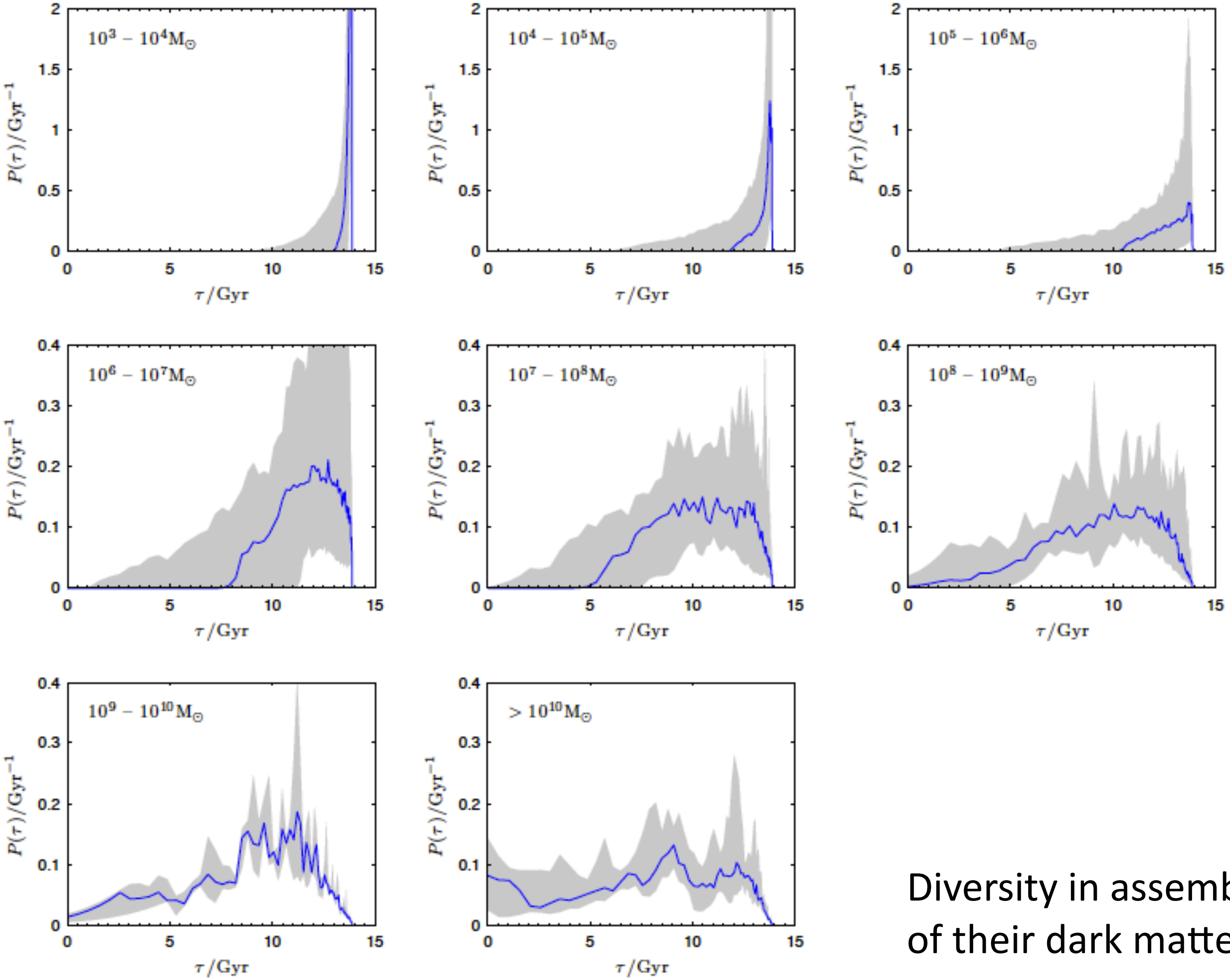


- For very small galaxies, it is possible that some of them can turn most of the gas into stars before infall, thus cast their metal-rich tails before infall.
- At that moment, the energy condition is still working and the feedback strength is much weaker than that of the post-infall stage. This would lead to large $\sigma(Z)/\overline{Z}$ value.

Metal-rich tails: different feedback

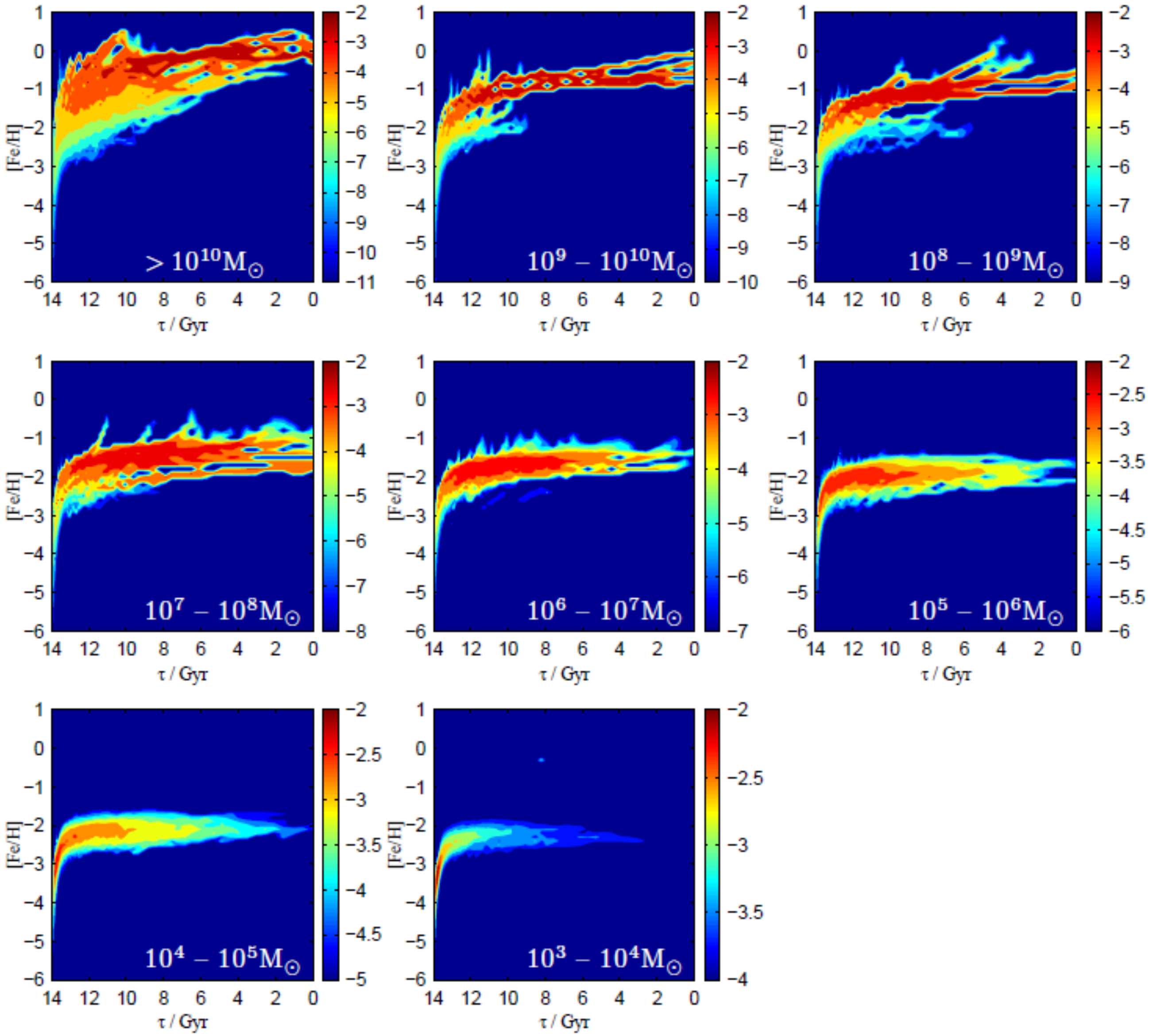


Stellar mass weighted age: stellar age distribution



Diversity in assembling history of their dark matter halos

Stellar age – metallicity map



Summary

- We study the chemical and age properties of the stars in the dwarf satellites around MW-like host galaxies, and explore the possible effects of SN feedback, reionization, H_2 cooling and how the current or further observations may put some constraints on these processes.

- We find the slope in the stellar mass-metallicity relation is sensitive to the SN feedback (v_{hot}) and reionization models, and the current observed slope, 0.31 ± 0.04 supports the strong reionization scenario and $v_{hot} > 100$ km/s.

- The metal-poor tail and stellar mass weighted age are also sensitive to the reionization model and can be used to further examine the constraint on it.

- The metal-rich tail can partly break the degeneracy in SN feedback model parameters.

- The moments when the galaxies with total stellar mass between 10^3 and 10^4 $M_\odot$ formed 10% of their stars are sensitive to H_2 cooling.

Future questions/work

- The local group
- Self-consistency model of the reionization from local sources
- Alpha-elements
- Extremely metal-poor stars
- Individual dwarfs
- Observations
- … …