Towards understanding the Milky Way formation: Insight from the enrichment of r-process elements

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The abundance of r-process elements of stars in the Milky Way (MW) provides clues to clarify the early evolutionary history of galaxies. Astronomical high dispersion observations show that metal-poor stars in the MW halo have large star-to-star scatters in the distribution of r-process elements. Neutron star mergers (NSMs) are one of the most promising sites of r-process. However, several studies suggest that the merger timescale of NSMs is too long to reproduce the observed scatters. In this study, we performed a series of N-body/hydrodynamic simulations of the MW progenitor galaxies. We show that the scatters can be explained by NSMs due to a slow chemical enrichment of such galaxies. These results suggest that stars in the MW halo formed with a star formation rate of less than 10^{-3} M_{sun}/yr. We also find that the dynamical time of halos affects the early evolutionary history of galaxies. We show that early enrichment of the MW halo occurred in the framework of hierarchical structure formation.

1. Introduction

Neutron star mergers (NSMs): one of the promising astrophysical sites of r-process.

Argast et al. (2004) suggest that it is difficult to reproduce the observation due to long merger time ($t_{NSM} \sim 100$ Myr) and low rate ($\sim 10^{-4}$ yr^{-1} for a Milky Way size galaxy) of NSMs.

Ishimaru et al. show the possibility to solve this problem if smaller mass sub-halos have lower star formation efficiency forms the MW halo (Ishimaru, Y., Wanajo, S., & Prantzos, N., 2015, ApJL, 804, L35).

We aim to clarify the enrichment of r-process elements in dwarf galaxies with high-resolution chemo-dynamical evolution model assuming NSMs are the major site of r-process.

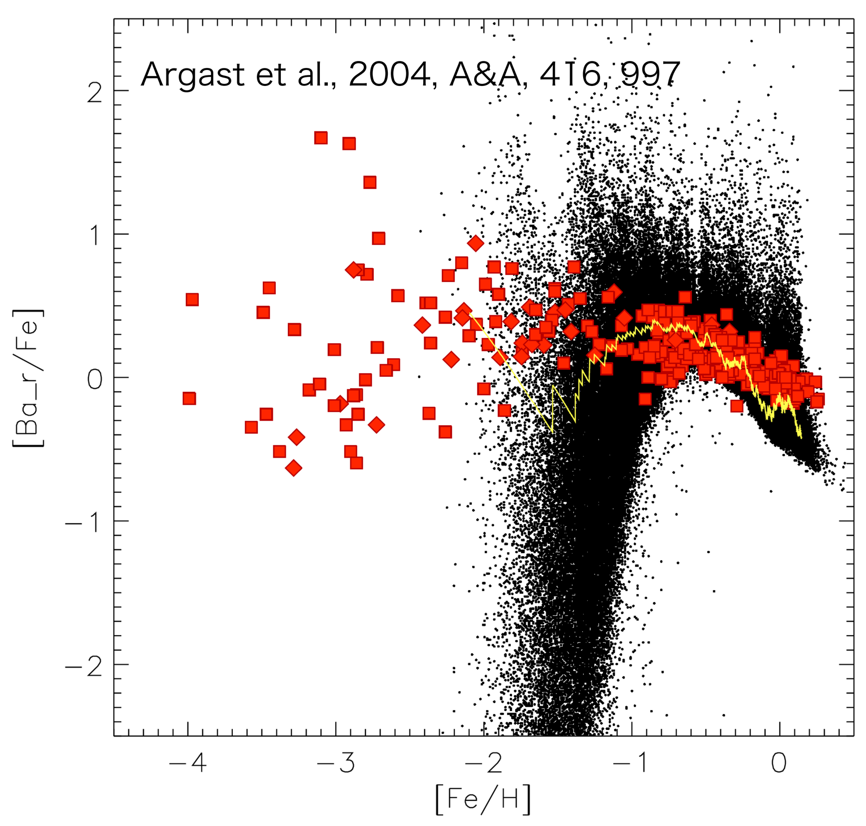

Fig. 1. [Ba/Fe] as a function of [Fe/H] (Argast+04). Black dots, red filled squares, and the yellow curve represent model stars, observation, and average ISM abundances of their model.

2. Method & models

2.1 Method

N-body/SPH code, ASURA

(Saitoh, T. R. et al. 2008, PASJ, 60, 667; 2009, PASJ, 61, 481)

→includes cooling, star formation, supernova feedback, as well as metal mixing in a star-forming region: we adopt the average metallicity of surrounding gas particles for the metallicity of a newly formed star particles.

Parameters: see Table 1

Table1 Parameters of this simulation

Quantity	Fiducial values[a]
Merger time of NSMs	100 Myr
Fraction of NSMs	0.01
Yields of core-collapse supernovae	Nomoto et al. (2006)
Dimensionless star formation efficiency parameter	0.033
Threshold density for star formation	100 cm^{-3}
Threshold temperature for star formation	1000 K
SN explosion energy	10^{51} erg
Gravitational softening length	7 pc

[a] Fiducial values of c_*, n_{th}, T_{th}, ϵ_{SN} are taken from Saitoh et al. (2008). Fraction of NSMs is a number fraction of NSMs to the total number of neutron stars.

2.2 Isolated dwarf galaxy model

Pseudo isothermal profile :

(Revas & Jablonka 2012)

$$\rho_i(r) = \frac{\rho_{c,i}}{1+\left(\frac{r}{r_c}\right)^2}$$

Parameters: see Table 2

Table 2 Parameters of the initial condition

Quantity	Values[a]
Initial total number of particles	5×10^5
Total mass	$7\times10^8 M_\odot$
Mass of one gas particle	$4\times10^2 M_\odot$
Core radius	1 kpc
Initial outer radius	7.1 kpc

[a] Values are taken from Revaz et al. (2009); Revaz & Jablonka (2012).

3. Chemo-dynamical evolution of dwarf galaxies

We confirmed that our results are consistent with observed properties of the Local Group dwarf galaxies.

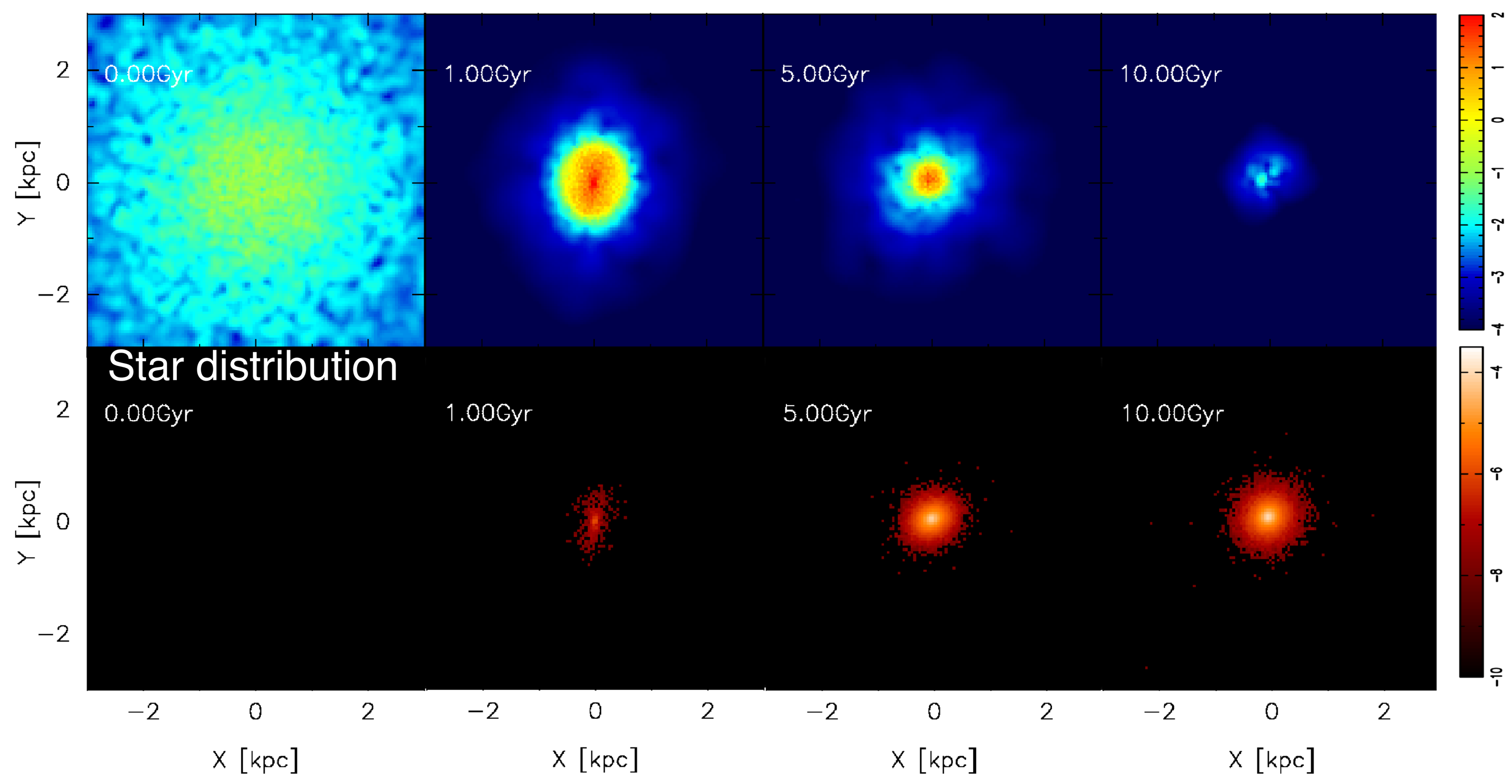

Fig. 2. Upper panels: snapshots of slice gas density in log scale, between 10^{-4} cm^{-3} (blue) and 10^2cm^{-3}(red).
Lower panels: snapshots of stellar surface density in log scale, between 10^{-10} $10^{10}M_\odot$kpc^{-3}(black) and $10^{-3.5}$ $10^{10}M_\odot$kpc^{-3} (white).

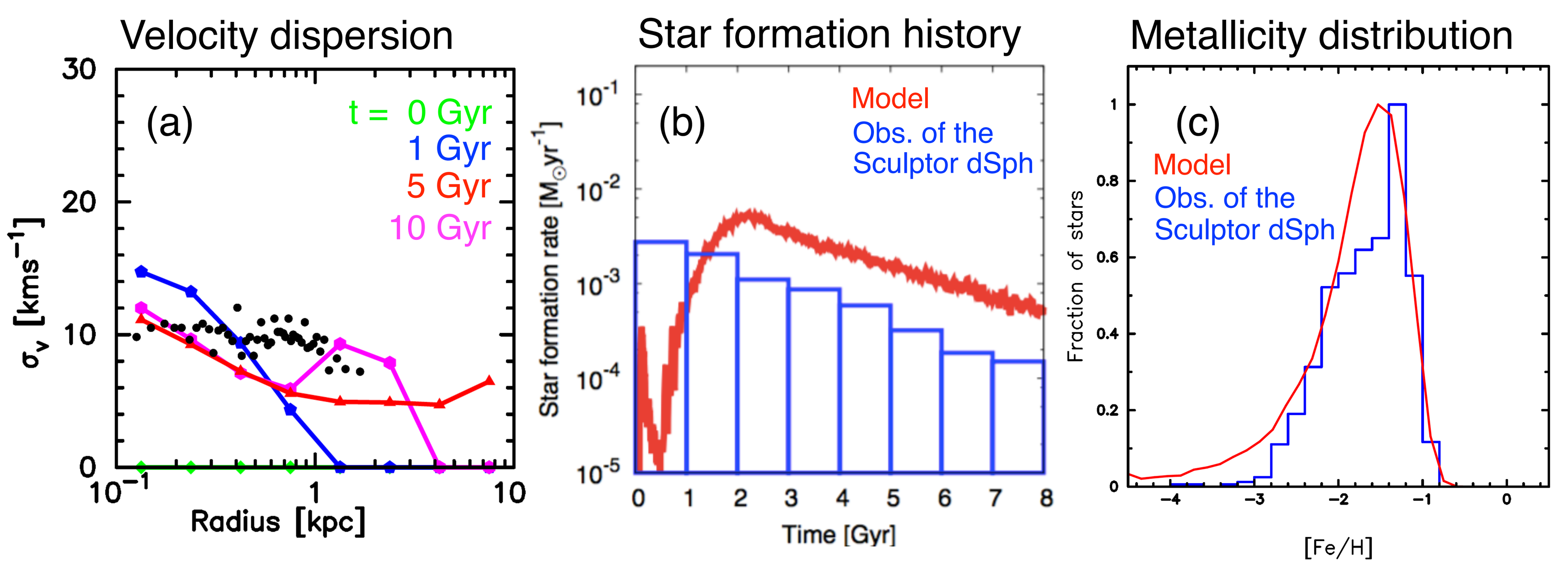

Fig. 3. (a): Radial velocity dispersion profiles of the model at t = 0 Gyr (green), 1 Gyr (blue), 5 Gyr (magenta), and 10 Gyr (red). Black dots are the observed stellar velocity dispersion in the Fornax dSph (Walker et al. 2009). (b): SFRs as a function of time. The red curve and the blue histogram represent SFR of the model and the Sculptor dSph (de Boer et al. 2012), respectively. (c): Metallicity distribution of the model (red curve) and the Sculptor dSph (Kirby et al. 2010).

4. Enrichment of r-process elements

Models with long merger times (t_{NSM} = 100 Myr) successfully reproduce the observational scatters in [Eu/Fe] of EMP stars (Fig. 4). Our model does not require the assumption of short merger times (t_{NSM} < 10 Myr), which is required to reproduce observations in previous studies (e.g., Matteucci et al. 2014, Tsujimoto & Shigeyama 2014).

The model with t_{NSM} = 10 Myr (Fig. 5a) has a similar pattern with the model of t_{NSM} = 100 Myr (Fig.4). On the other hand, the model with t_{NSM} = 500 Myr (Fig. 5b) shows large scatters in [Eu/Fe] at higher metallicity and cannot account for the observed scatters in [Fe/H] ~ –3.

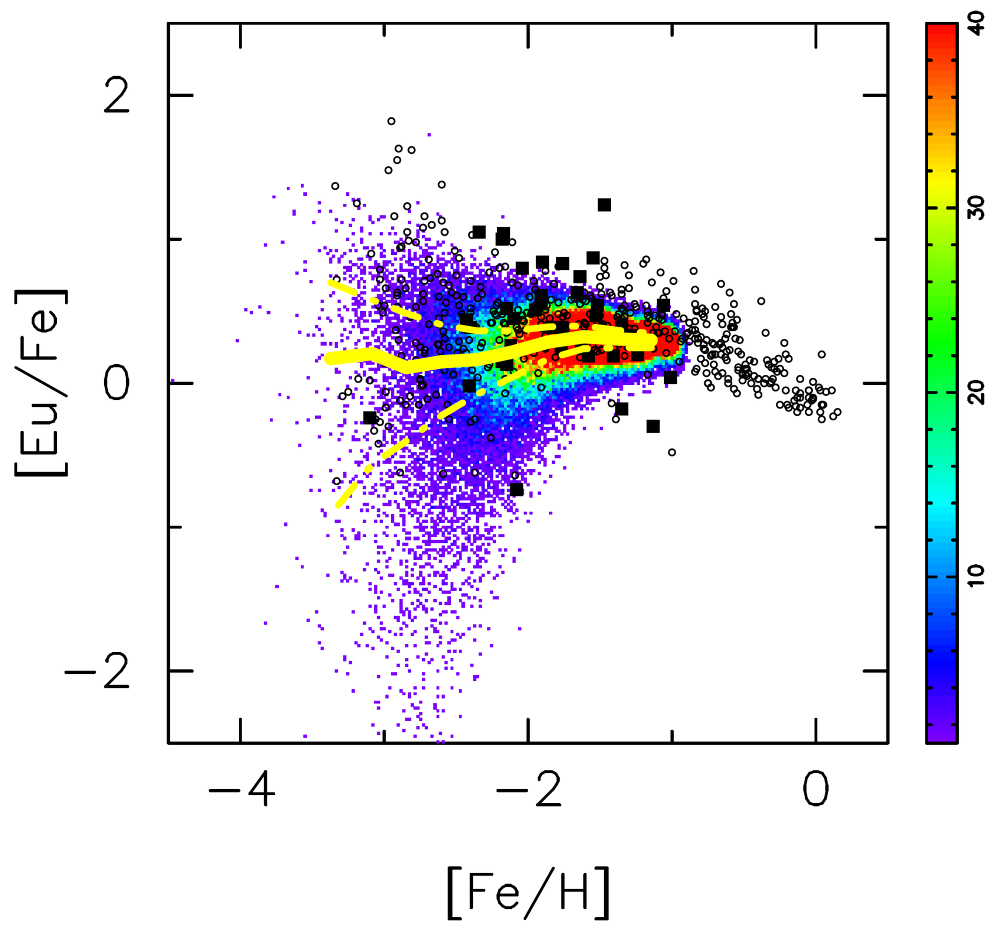

Fig. 4. [Eu/Fe] as a function of [Fe/H] of the model with t_{NSM} =100 Myr. Contour is the number of stars produced in our model, between 0 (purple) and 40 (red). Yellow curve is median of model prediction. Dash-dotted curves are the first and third quartiles, respectively. Circles are the observed value of the Galactic halo stars (SAGA database, Suda et al. 2008). Squares are the observed value of stars in Carina, Draco, Leo I, Sculptor, and Ursa Minor dSphs (SAGA database, Suda et al. 2014).

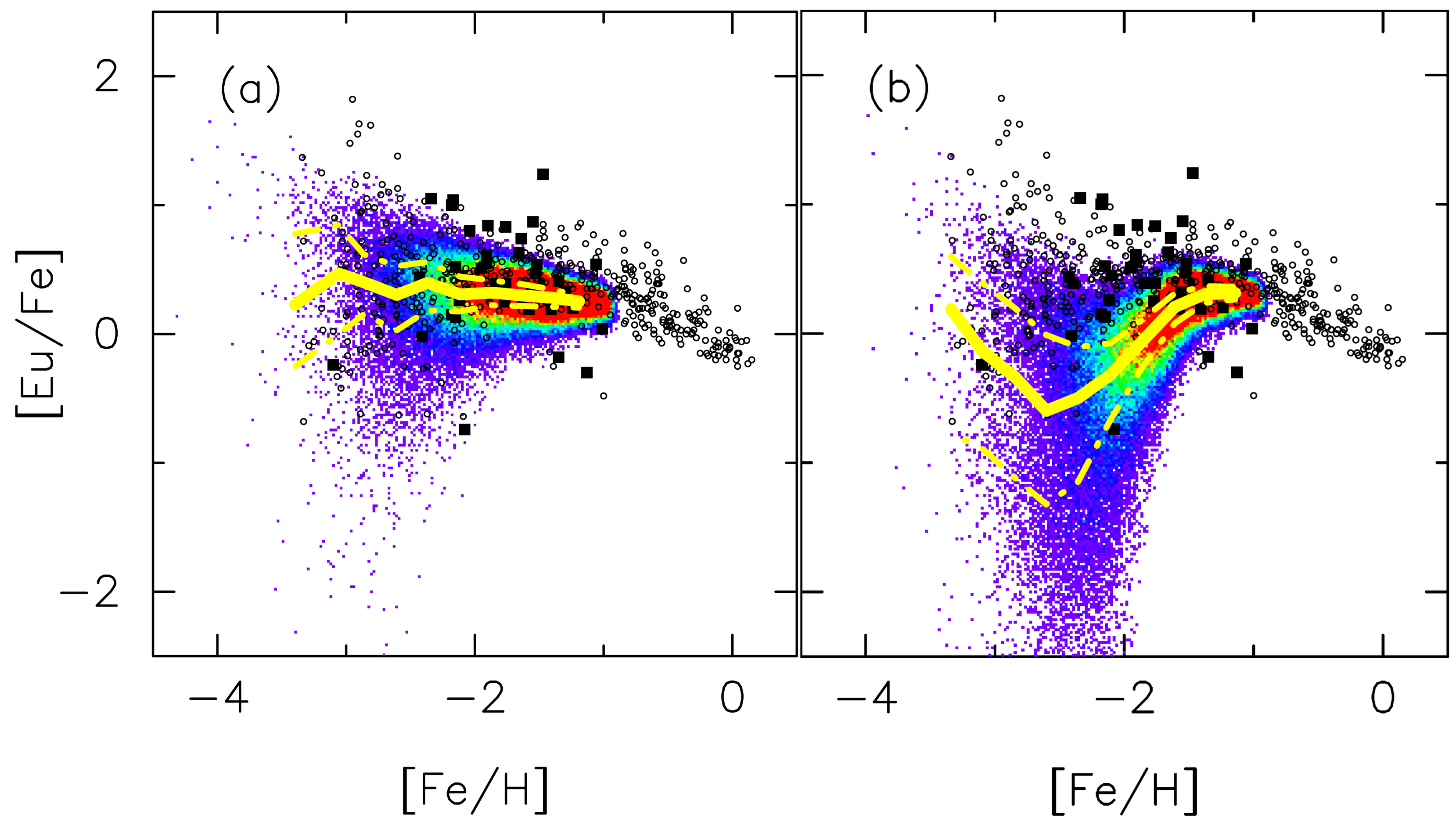

Fig. 5. [Eu/Fe] as a function of [Fe/H] of models with (a) t_{NSM} =10 Myr and (b) t_{NSM} =500 Myr. Symbols are the same as Fig. 4.

The average metallicity of stars is almost constant during the first ~ 300 Myr (Fig. 6). Due to low star formation efficiency of the galaxy, the spatial distribution of metallicity is highly inhomogeneous in < 300 Myr. Since a single SN enriches most of the gas particles in this epoch, the distance from each SN to the gas particles, which formed the stars mainly determines the metallicity of stars. Therefore, **NSMs with t_{NSM} ~ 100 Myr can account for the observation of EMP stars.** In contrast, **metallicity well correlates with the galactic age after ~ 300 Myr, irrespective of the distance from each SN to the gas particles.** Because the metallicity has already been well mixed in a galaxy, the number of the SNe determines the stellar metallicity. Therefore, if t_{NSM} > 300 Myr, it is too long to reproduce observations.

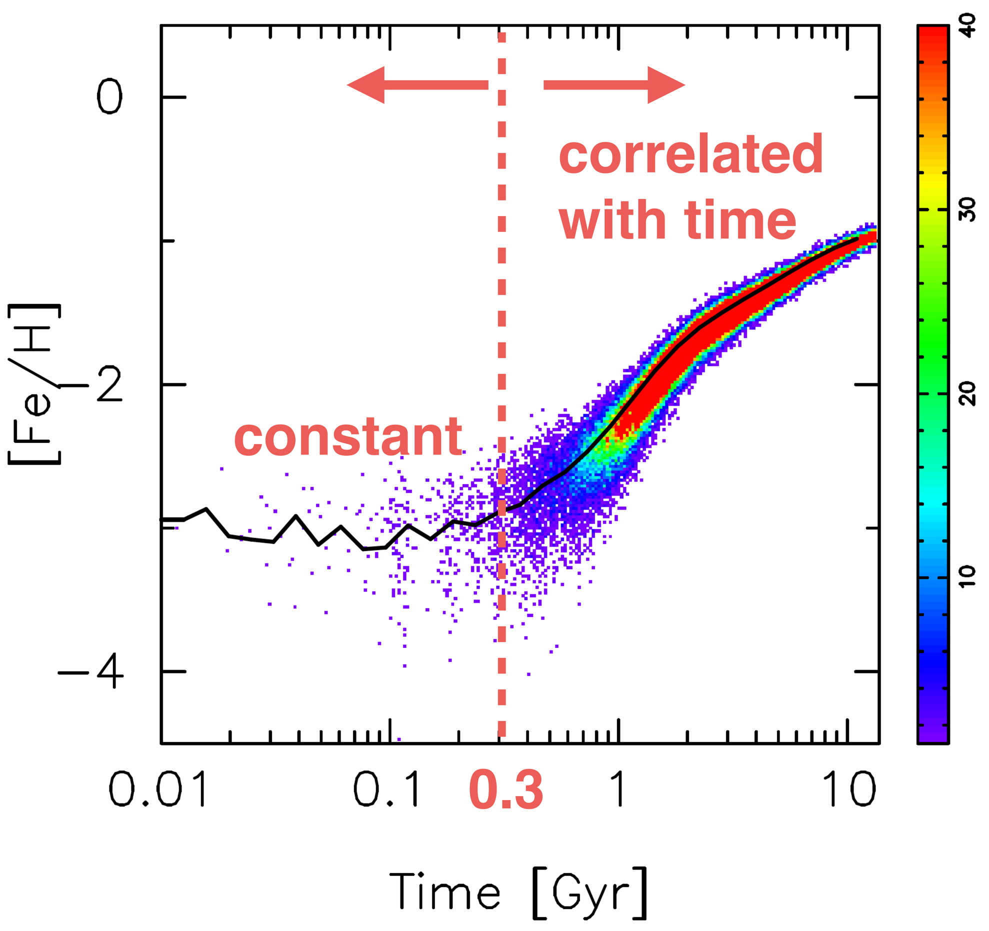

Fig. 6. [Fe/H] as a function of time in the model. The black curve is the average of the metallicity in each age. Contour is the same as Fig. 4.

5. Summary

We have carried out numerical simulations of the chemo-dynamical evolution of dwarf galaxies using N-body/SPH code, ASURA to investigate enrichment history of the r-process elements. We find that **NSMs with merger time of ~100 Myr** and the Galactic NSM rate of ~10^{-4} yr^{-1} **produce the dispersion of r-process abundances [Eu/Fe] in reasonable agreement with observations in EMP stars.** Our simulations support the scenario that early enrichment of MW halo occurred in the framework of hierarchical structure formation.