Chemo-dynamical evolution of the Local Group dwarf galaxies: The origin of r-process elements

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The r-process elements such as Au, Eu, and U are observed in the extremely metal-poor stars in the Milky Way halo and the Local Group dwarf galaxies. However, the origin of r-process elements has not yet been identified. The abundance of r-process elements of stars in the Local Group galaxies provides clues to clarify early evolutionary history of galaxies. It is important to understand the chemical evolution of the Local Group dwarf galaxies which would be building blocks of the Milky Way. In this study, we perform a series of *N*-body/smoothed particle hydrodynamics simulations of dwarf galaxies. We show that neutron star mergers can reproduce the observation of r-process elements. We find that the effects of gas mixing processes including metals in the star-forming region of a typical scale of giant molecular clouds ~ 10 – 100 pc play significant roles in the early chemical enrichment of dwarf galaxies. We also find that the star formation rate of ~ 10^{-3} Msun/yr in early epoch (< 1 Gyr) of galactic halo evolution is necessary for these results. Our results suggest that neutron star mergers are a major site of r-process.

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} ~ 100 Myr) and low rate (~ 10^{-4} yr^{-1} for a Milky Way size galaxy) of NSMs.

It has been pointed out that this problem can be solved if the MW halo was formed from sub-haloes with low star formation efficiency (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.

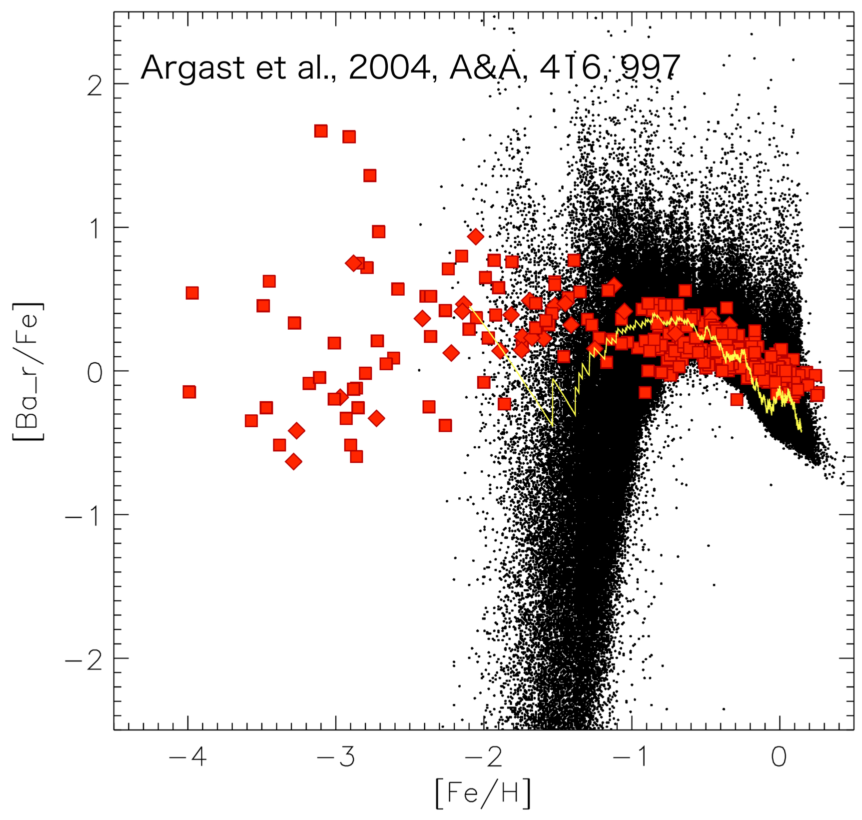

Fig. 1. [Ba/Fe] as a function of [Fe/H] (Argast+04). Black dots, red filled squares, and the yellow curve represent model stars, observation, and average ISM abundances of their model.

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 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 $c_\star$, 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.

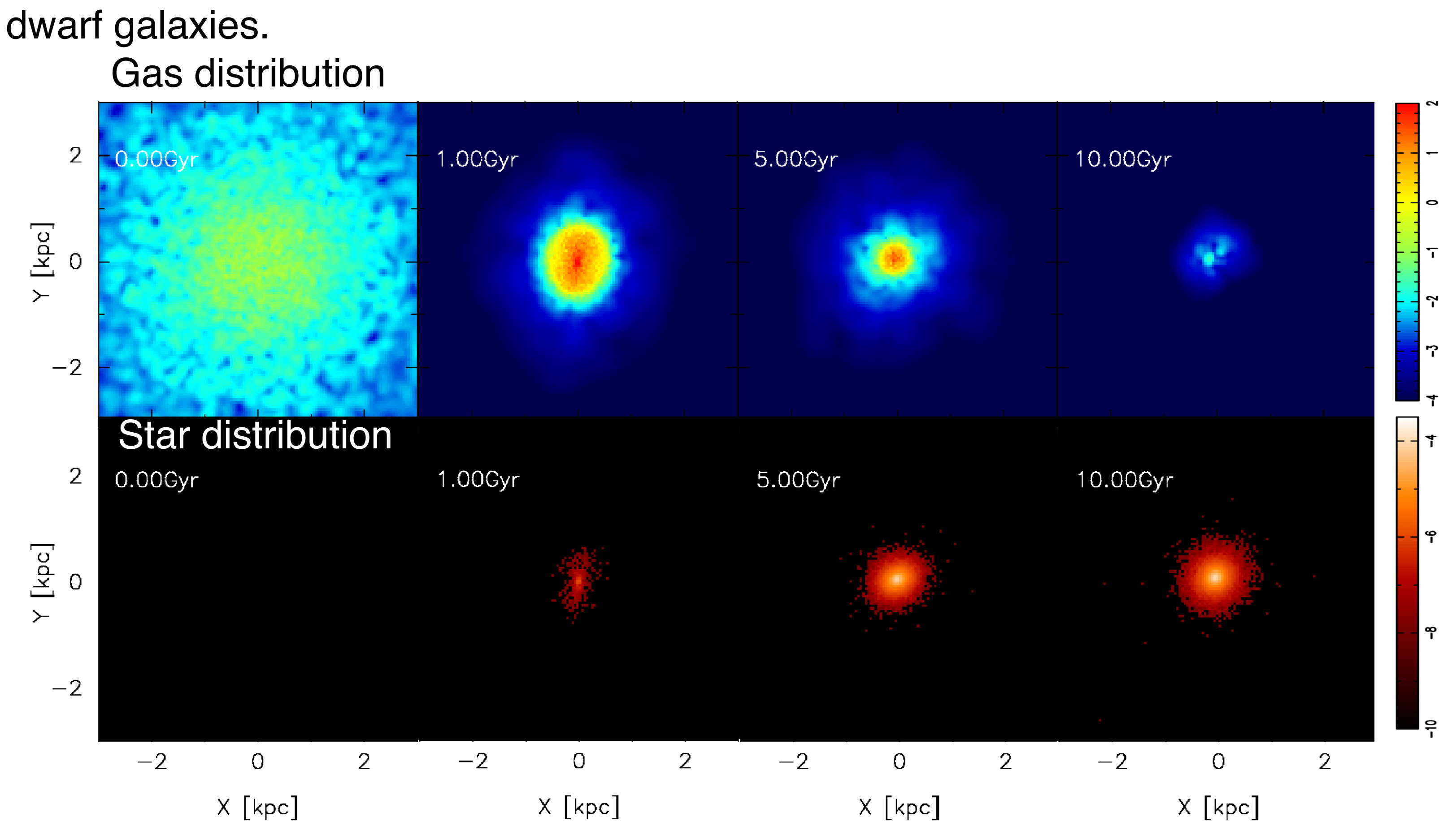

Fig. 2. Upper panels: snapshots of slice gas density in log scale, between 10^{-4} cm^{-3} (blue) and $10^{2}cm^{-3}$(red). Lower panels: snapshots of stellar surface density in log scale, between 10^{-10} $10^{10}M_\odot kpc^{-3}$(black) and $10^{-3.5}$ $10^{10}M_\odot kpc$ (white).

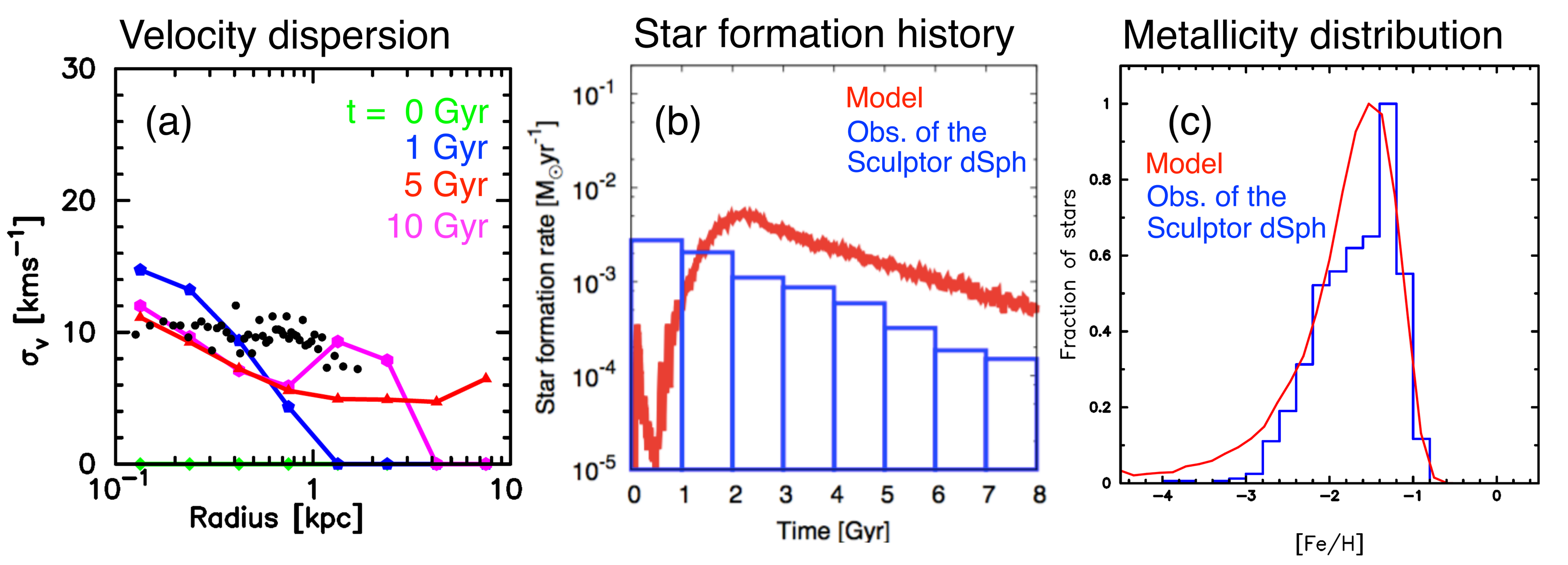

Fig. 3. (a): Radial velocity dispersion profiles of the model at t = 0 Gyr (green), 1 Gyr (blue), 5 Gyr (magenta), and 10 Gyr (red). Black dots are the observed stellar velocity dispersion in the Fornax dSph (Walker et al. 2009). (b): SFR as a function of time. The red curve and the blue histogram represent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

Observational scatters in [Eu/Fe] of EMP stars are successfully reproduced by this model with long merger time (t_{NSM} = 100 Myr) (Fig. 4). Our model does not require the assumption of short merger time (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.

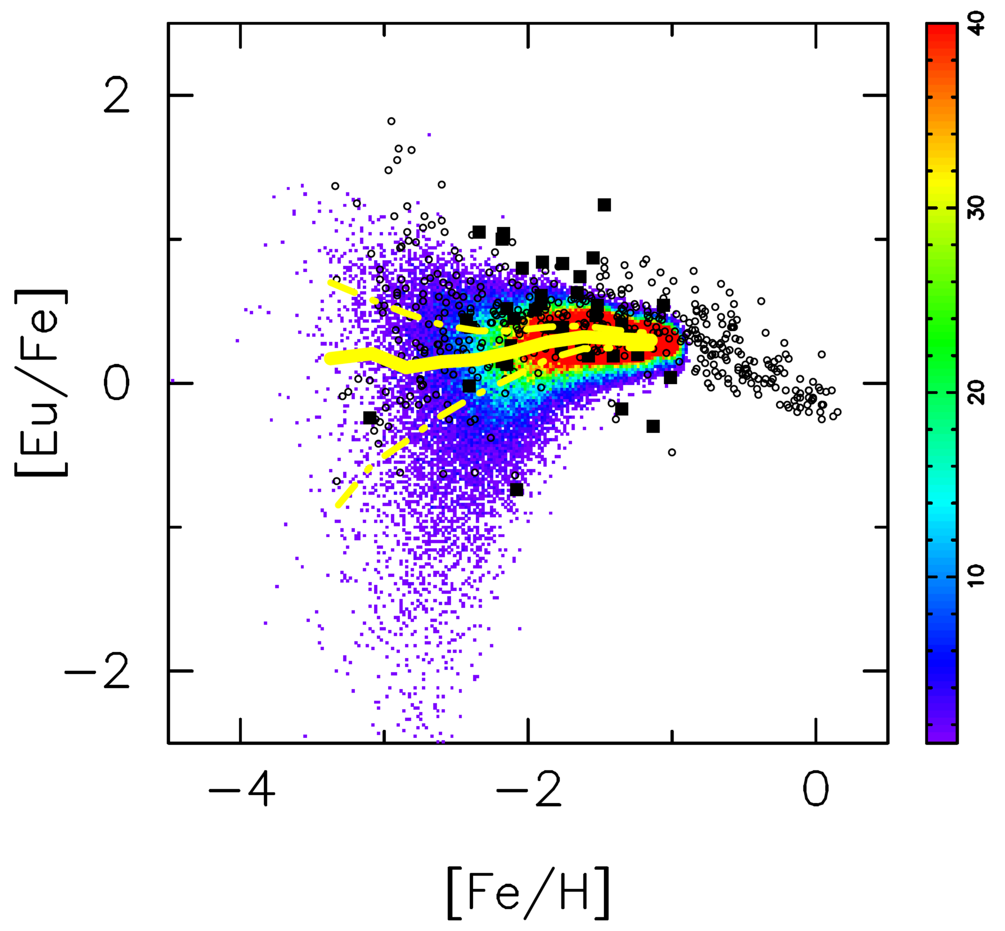

Fig. 4. [Eu/Fe] as a function of [Fe/H] of the model with t_{NSM} =100 Myr. Contour is the number of stars produced in our model, between 0 (purple) and 40 (red). Yellow curve is median of model prediction. Dash-dotted curves are the first and third quartiles, respectively. Circles are observed value 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).

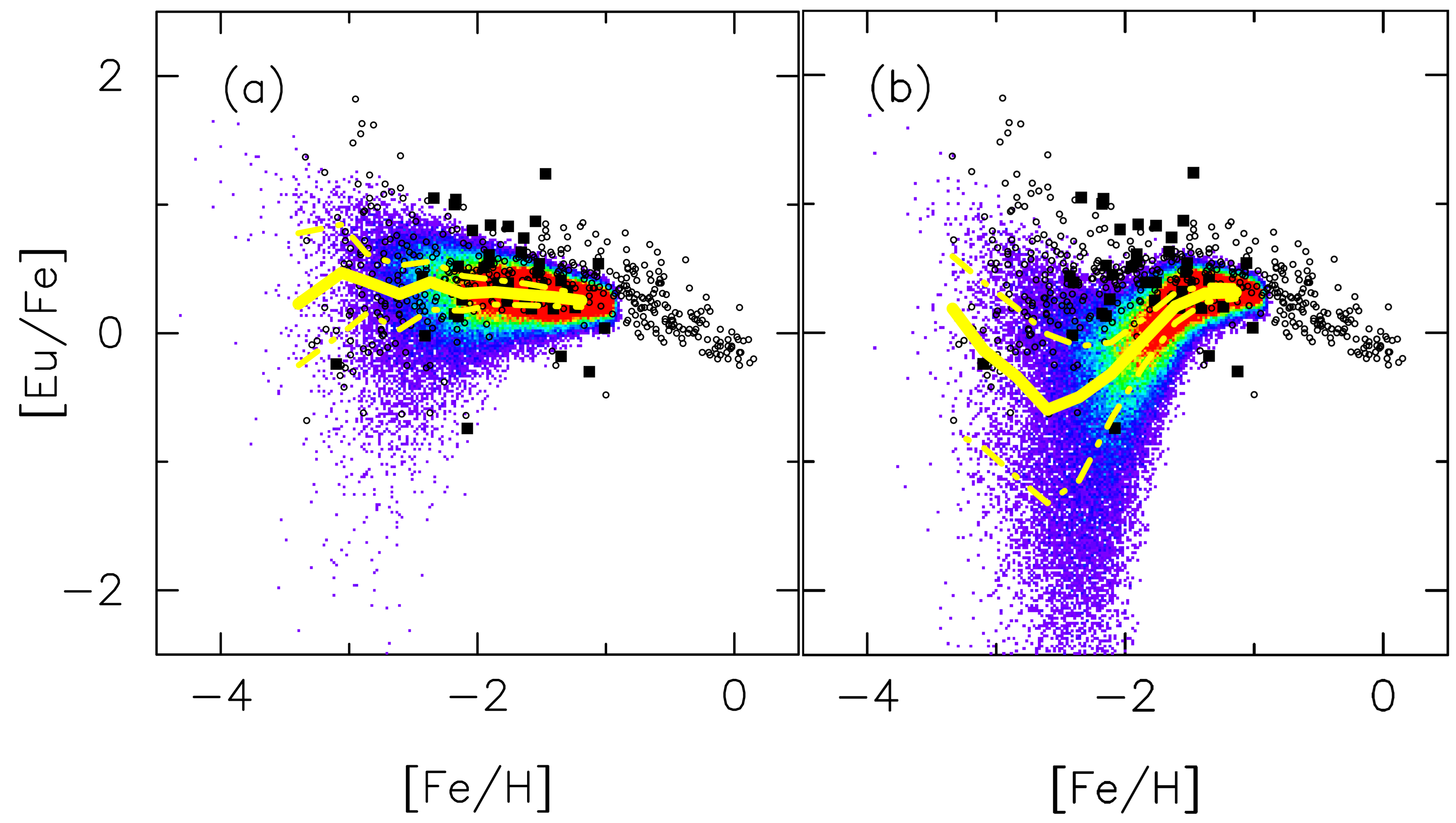

Fig. 5. [Eu/Fe] as a function of [Fe/H] of models with (a) t_{NSM} =10 Myr and (b) t_{NSM} =500 Myr. Symbols are the same as Fig. 4.

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

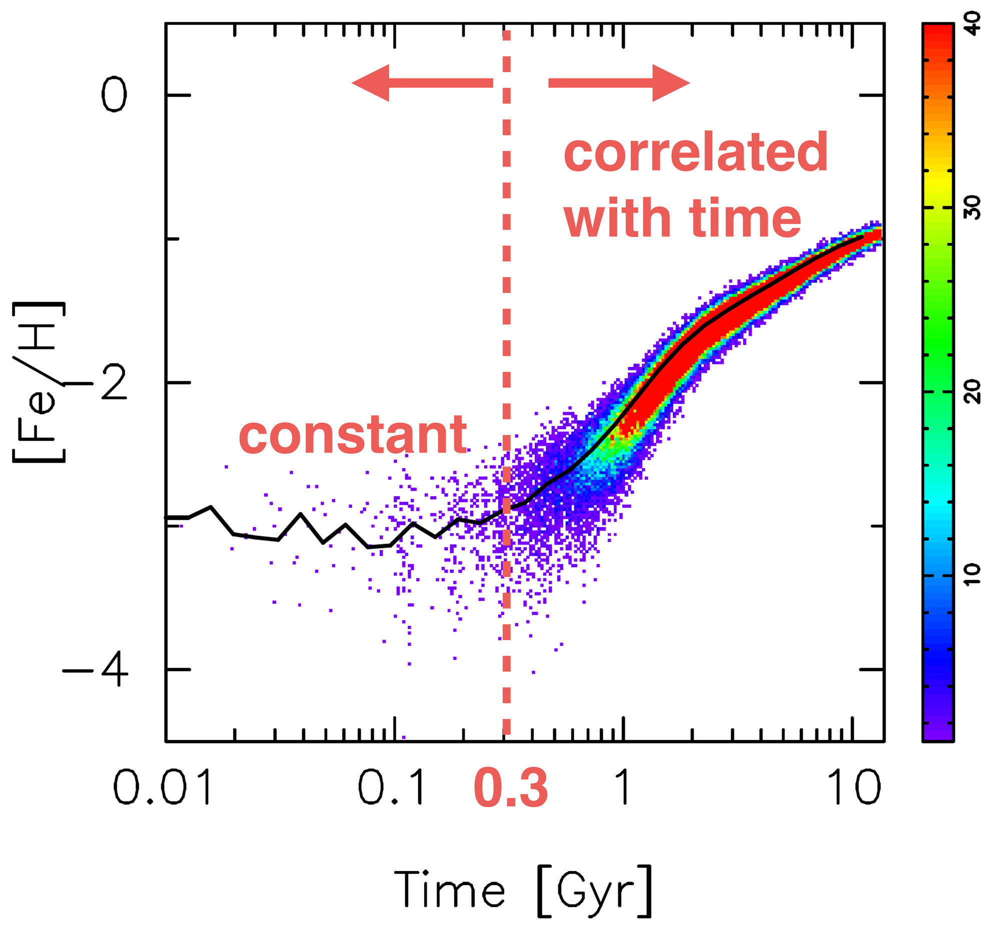

Fig. 6. [Fe/H] as a function of time in the model. The black curve is the average of the metallicity in each age. Contour is the same as Fig. 4.

5. Summary

We have carried out numerical simulations of chemo-dynamical evolution of dSphs 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. This study supports that NSMs are the major astrophysical site of the r-process.**