Enrichment of Heavy Elements in Chemodynamical Evolution Models

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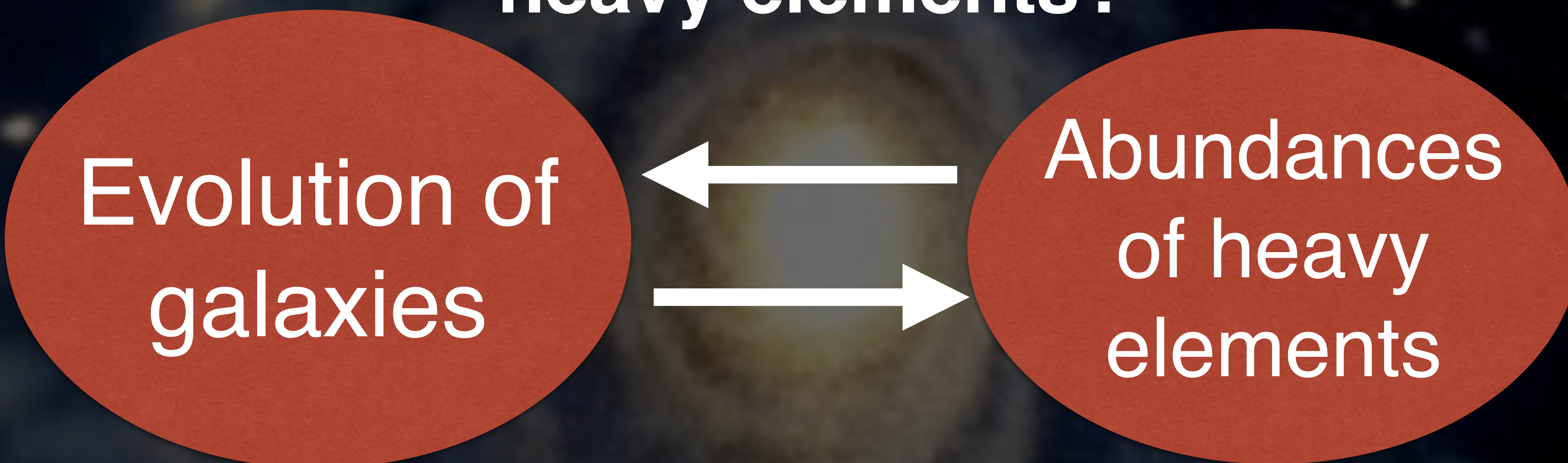
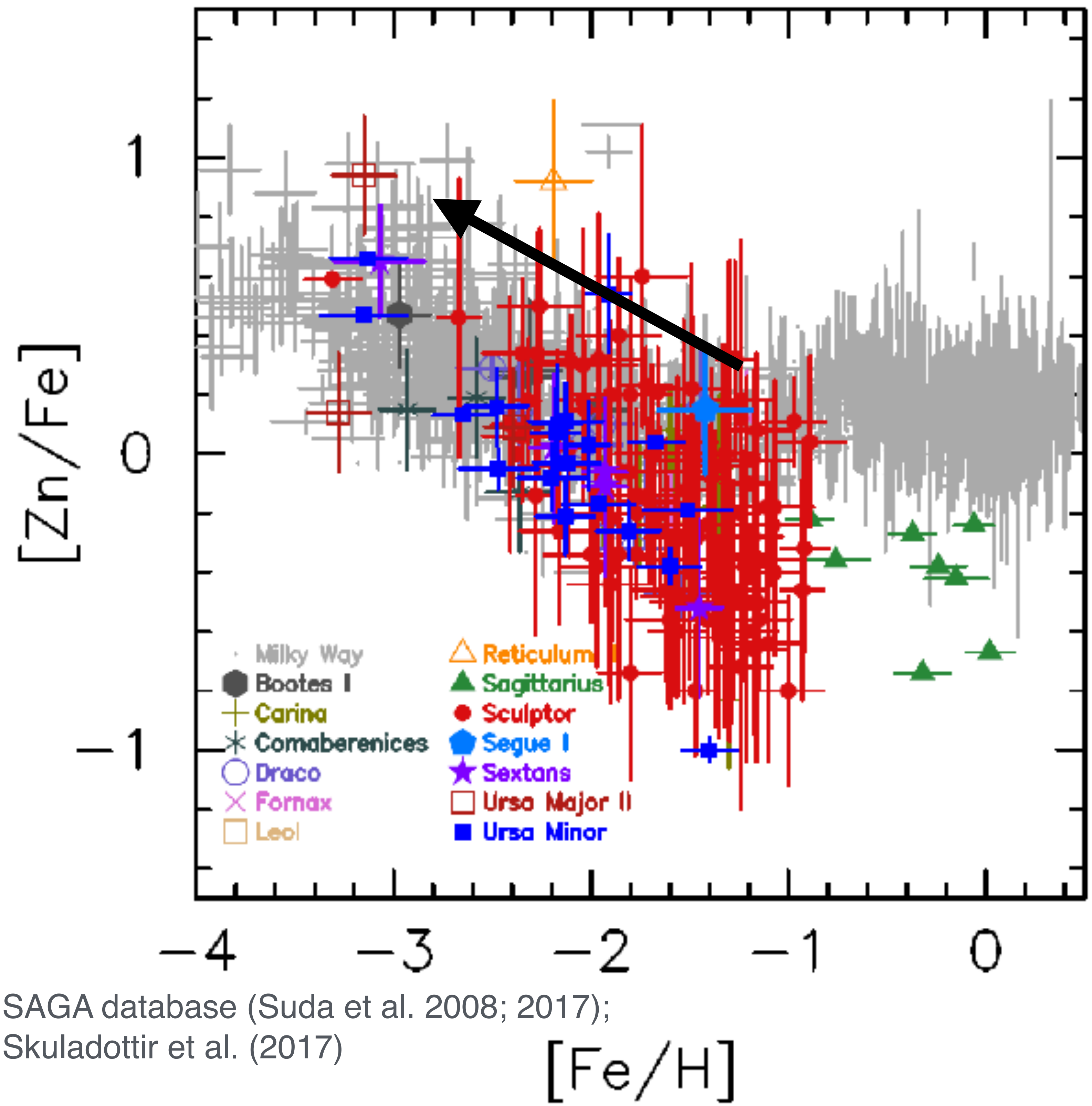
Key questions

1. Where are the astrophysical sites of heavy elements?



2. How the evolutionary histories of galaxies affect the enrichment of heavy elements?

Observations of [Zn/Fe] in the Local Group galaxies

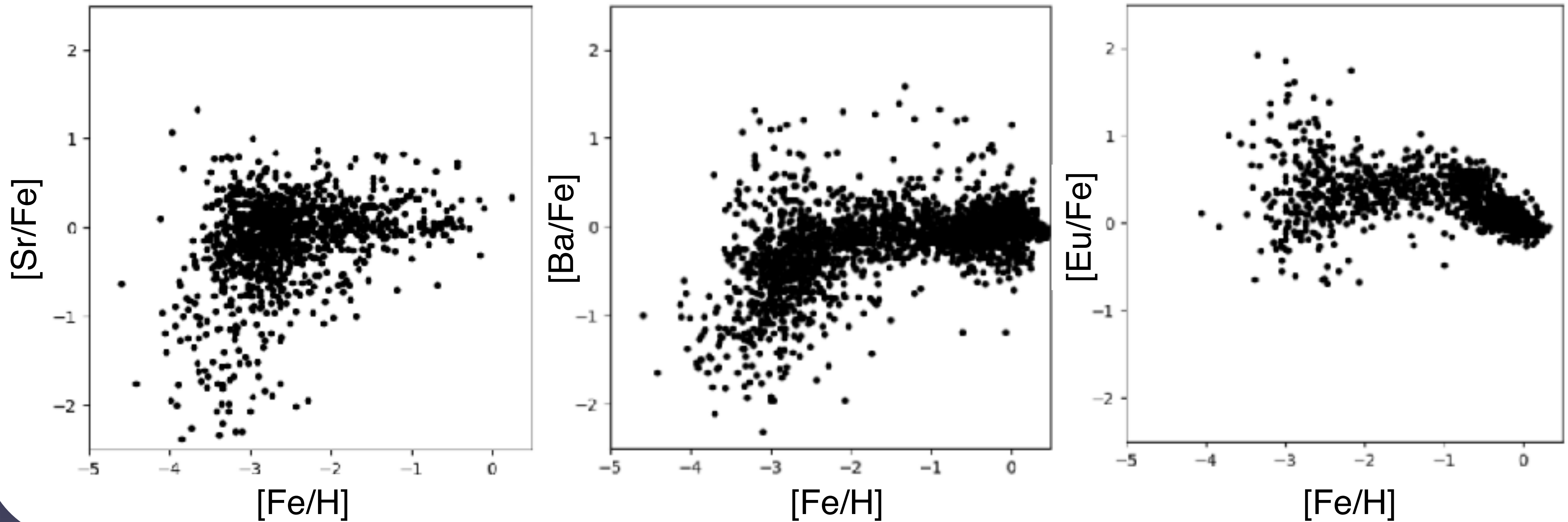


SAGA database (Suda et al. 2008; 2017);
Skuladottir et al. (2017)

An increasing trend toward lower metallicity

Observations of the neutron-capture elements

SAGA database (Suda et al. 2008; 2017)

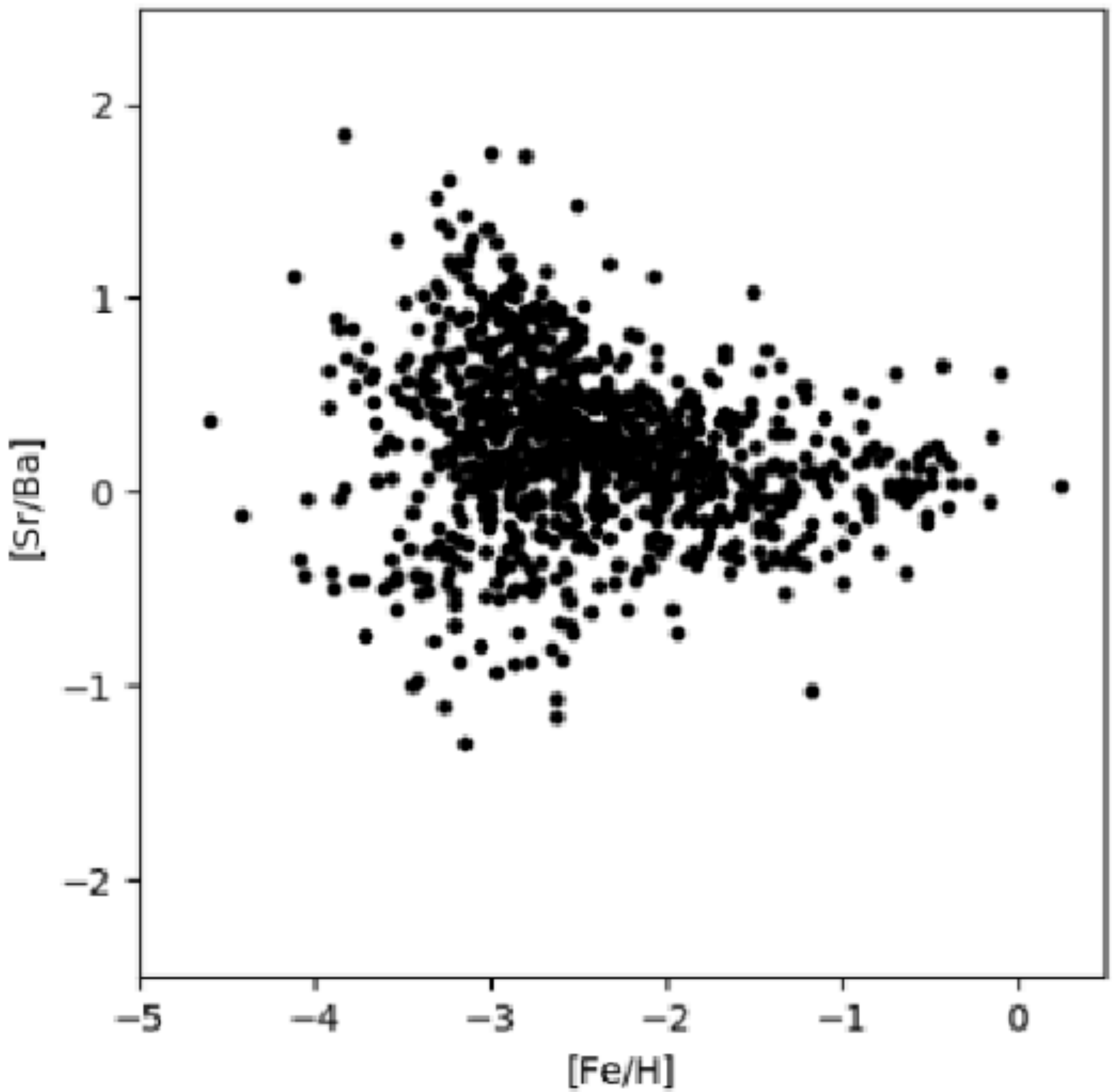


Scatters of [Sr, Ba, Eu/Fe] at [Fe/H] < –2.5

Heavy neutron-capture elements (e.g., Ba, Eu) at low metallicity may come from **neutron star mergers.**

Astrophysical sites of the light neutron-capture elements (Sr) are not well understood.

Ratios of light to heavy neutron-capture elements



SAGA database (Suda et al. 2008; 2017)

Astrophysical sites of **light neutron-capture elements** (e.g., Sr, Y, Zr) and **heavy neutron-capture elements** (e.g., Ba, Eu) **may be different.**

Purpose of this study

Clarify the enrichment of heavy elements (e.g., Zn, Sr, and Eu) in dwarf galaxies

Method

N-body/SPH code ASURA (Saitoh et al. 2008; 2009)

- Star Formation
- Cooling and Heating Function (Cloudy, Ferland et al. 2013)
- Supernova Feedback
- Chemical Evolution (CELib, Saitoh 2017)
  - Core-Collapse Supernovae, Hypernovae (yield: Nomoto et al. 2013, mass range: 8-100 Msun)
  - Electron-Capture Supernovae (yield: Wanajo et al. 2018, mass range: Doherty et al. 2015)
  - Neutron Star Mergers (yield: Wanajo et al. 2014)
  - Type Ia Supernovae (yield: Seitenzahl et al. 2013)
  - AGB stars (yield: Cristallo et al. 2015)

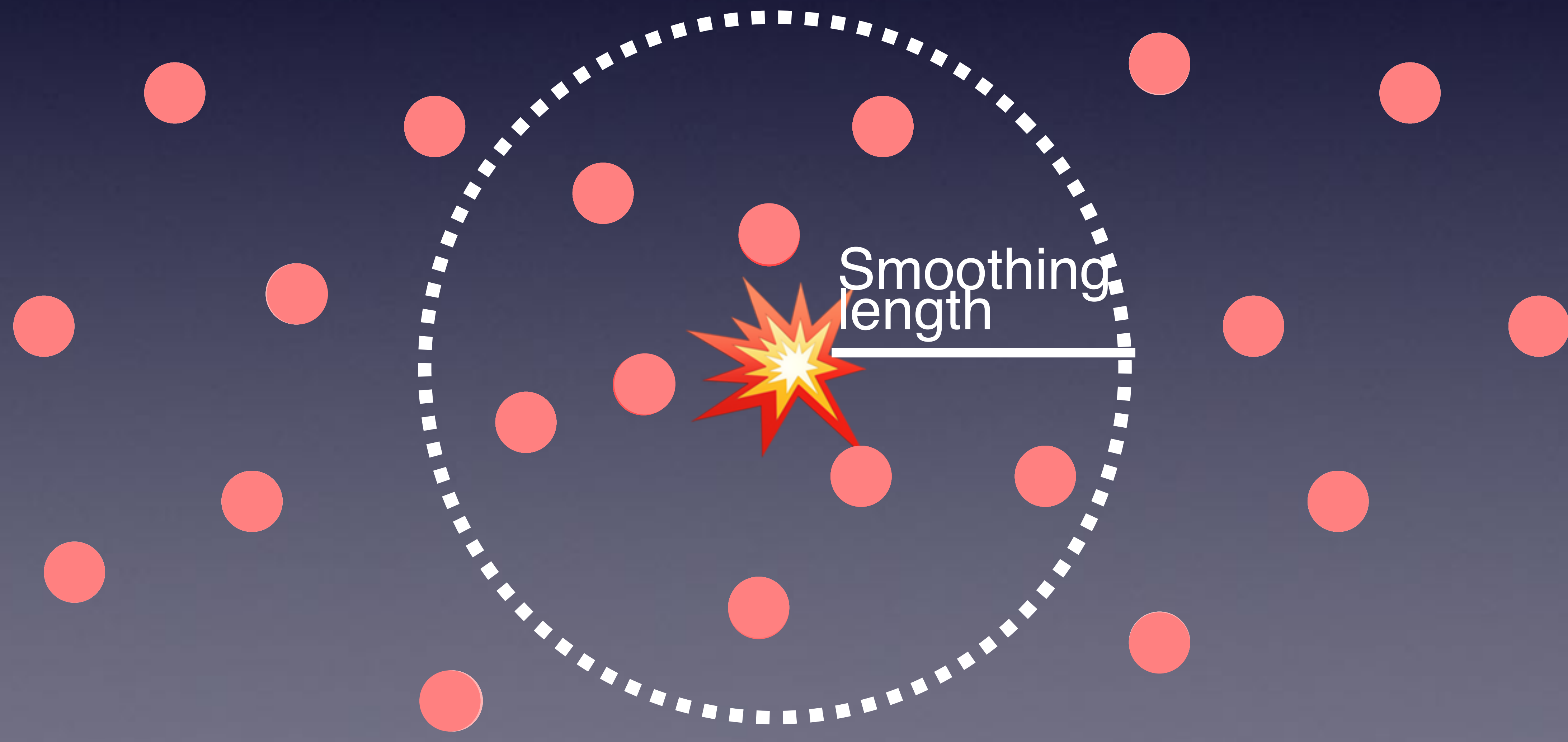
Treatment of metal mixing in SPH simulations

Metal diffusion

(e.g., Greif et al. 2009, MNRAS, 392, 1381; Shen et al. 2010, MNRAS, 407, 1581; Hirai & Saitoh 2017, ApJ, 838, L23)

$$\frac{\mathrm{d}Z_i}{\mathrm{d}t} = \nabla(D\nabla Z_i)$$

$$D = C_\mathrm{d}|S_{ij}|h^2$$



Isolated dwarf spheroidal galaxy model

Gas and dark matter density profile：

pseudo-isothermal profile

(e.g., Revaz & Jablonka 2012, A&A, 538, A82)

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

Total mass of the halo:

$7\times10^{8}\ M_\odot$

Final stellar mass of the galaxy:

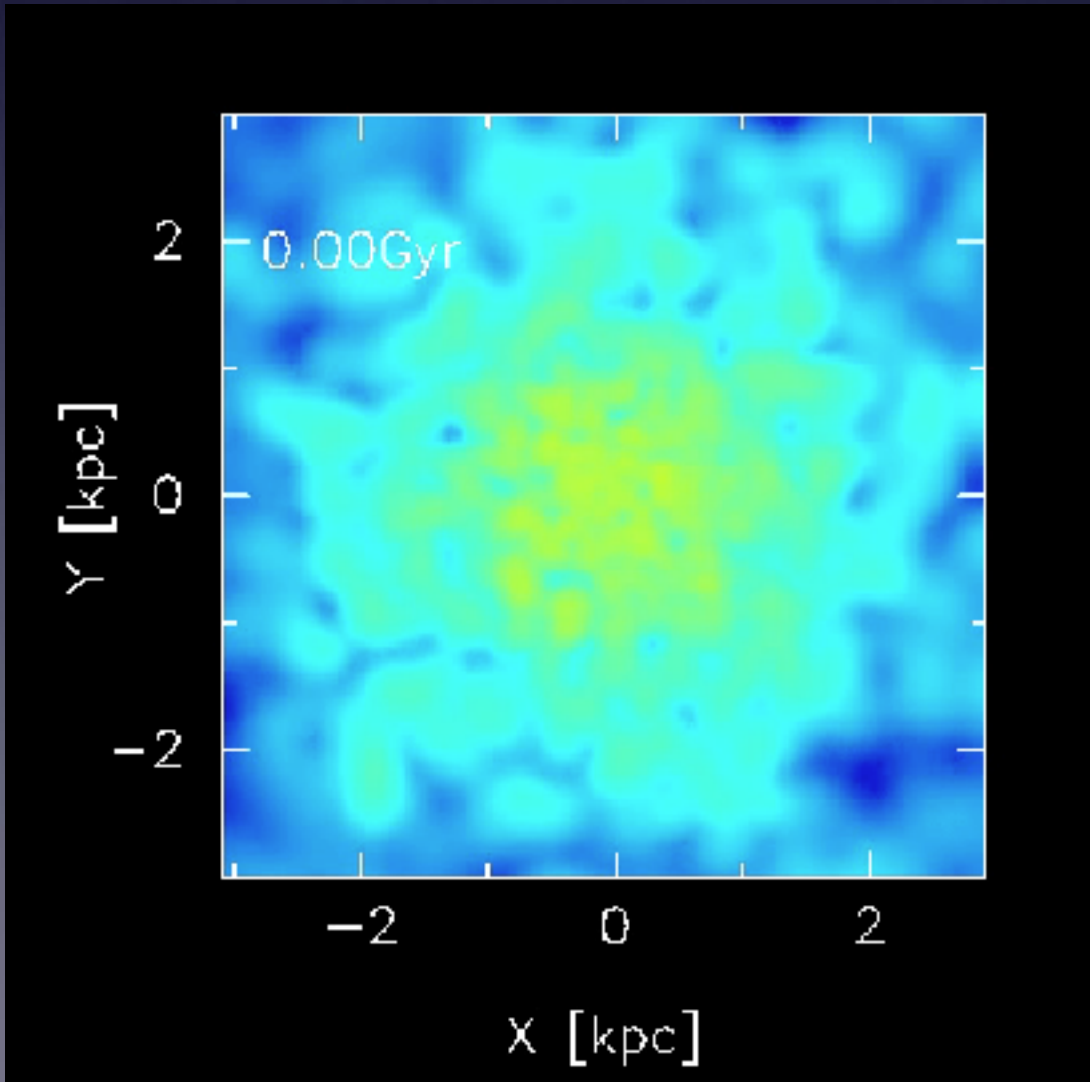
$3\times10^{6}\ M_\odot$

Total number of particles:

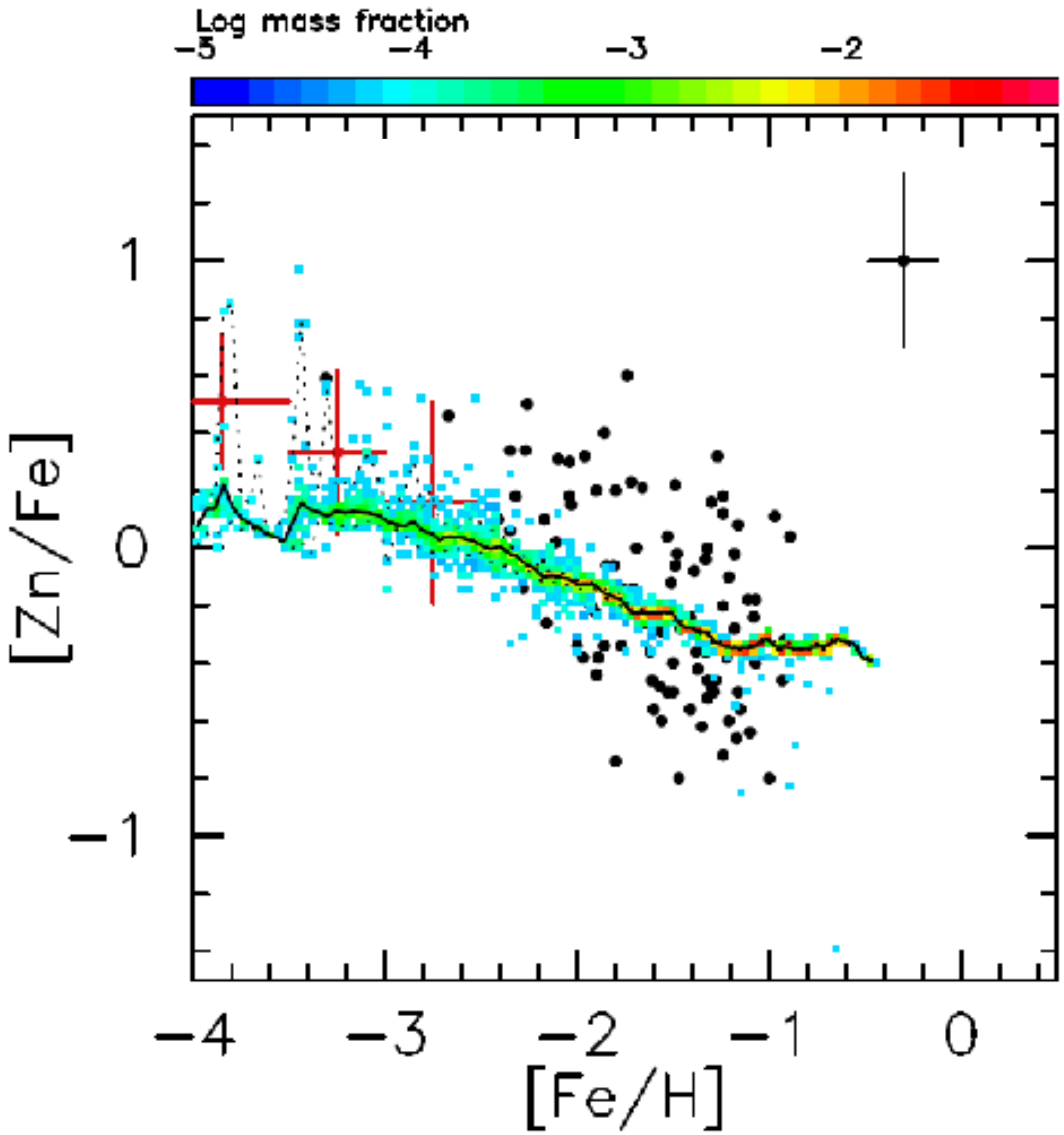
3×10^{5}

Gravitational softening length:

7.8 pc



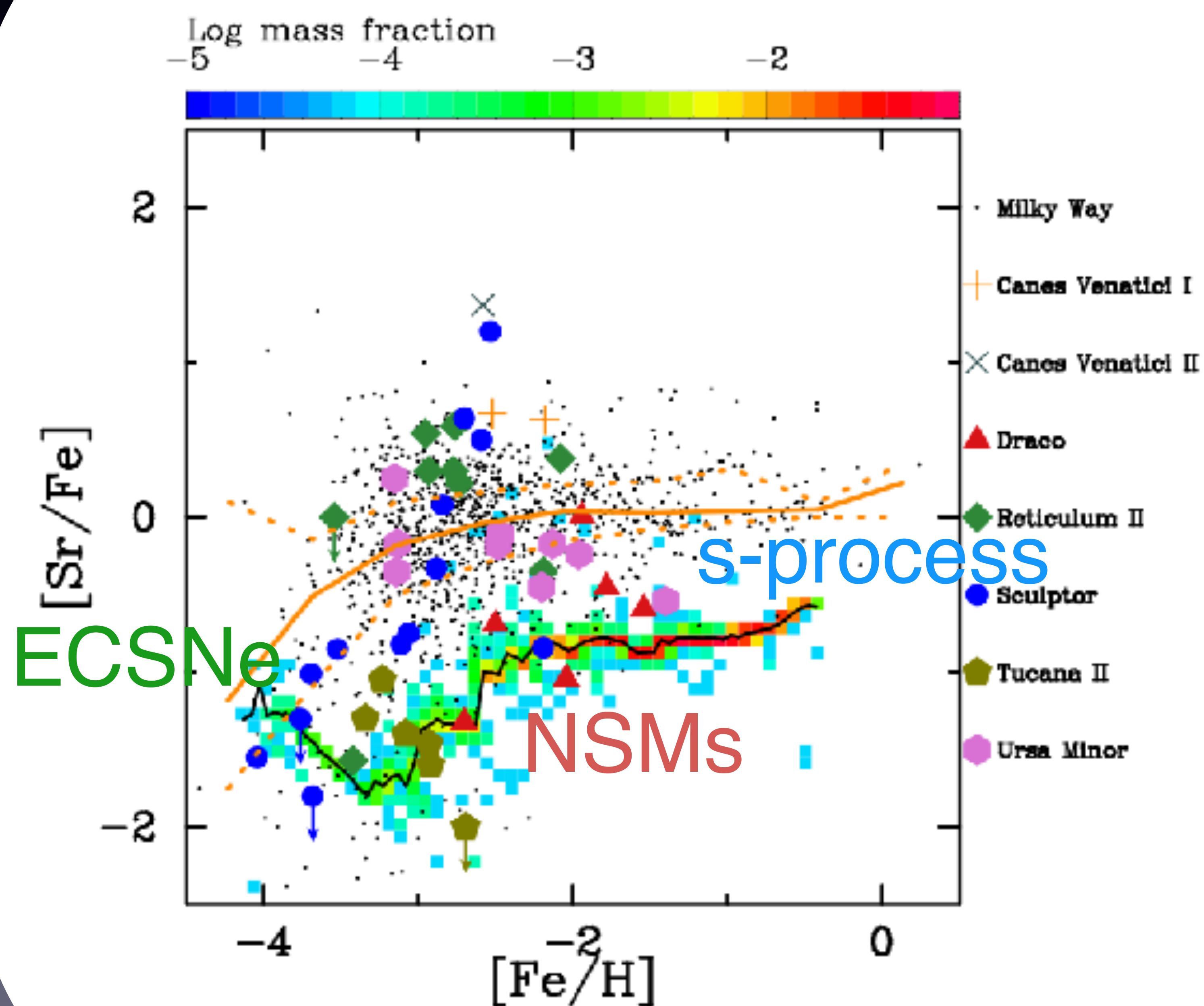
[Zn/Fe] vs. [Fe/H]



Hirai et al. 2018, ApJ, 855, 63

Electron-capture supernovae can produce Zn at [Fe/H] < -3

Enrichment of Sr

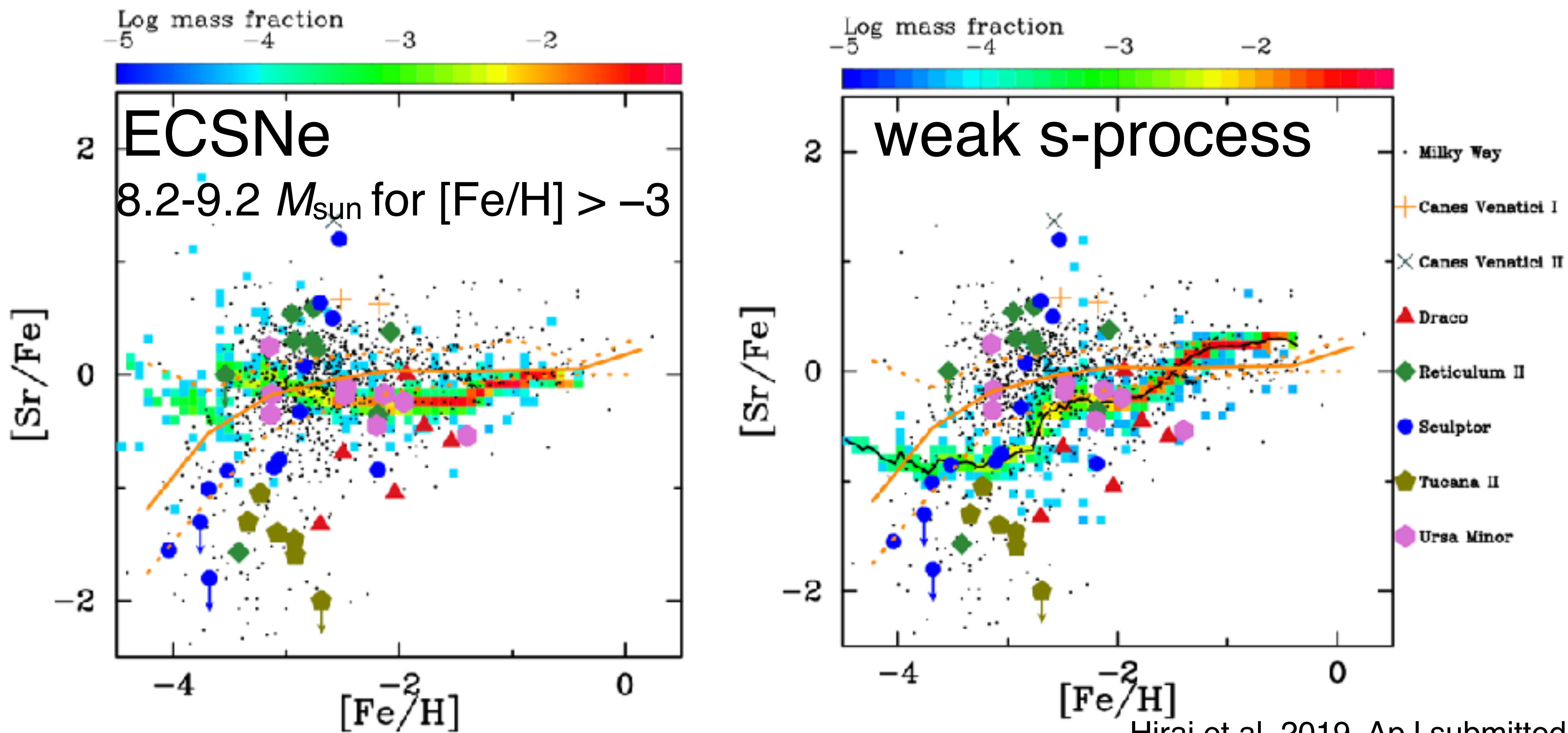


Hirai et al. 2019, ApJ submitted

Electron-Capture Supernovae + Neutron Star Mergers

- Main contributors on the enrichment of Sr at [Fe/H] < −2.5
- ~ 20 % of the total mass of Sr comes from ECSNe and NSMs

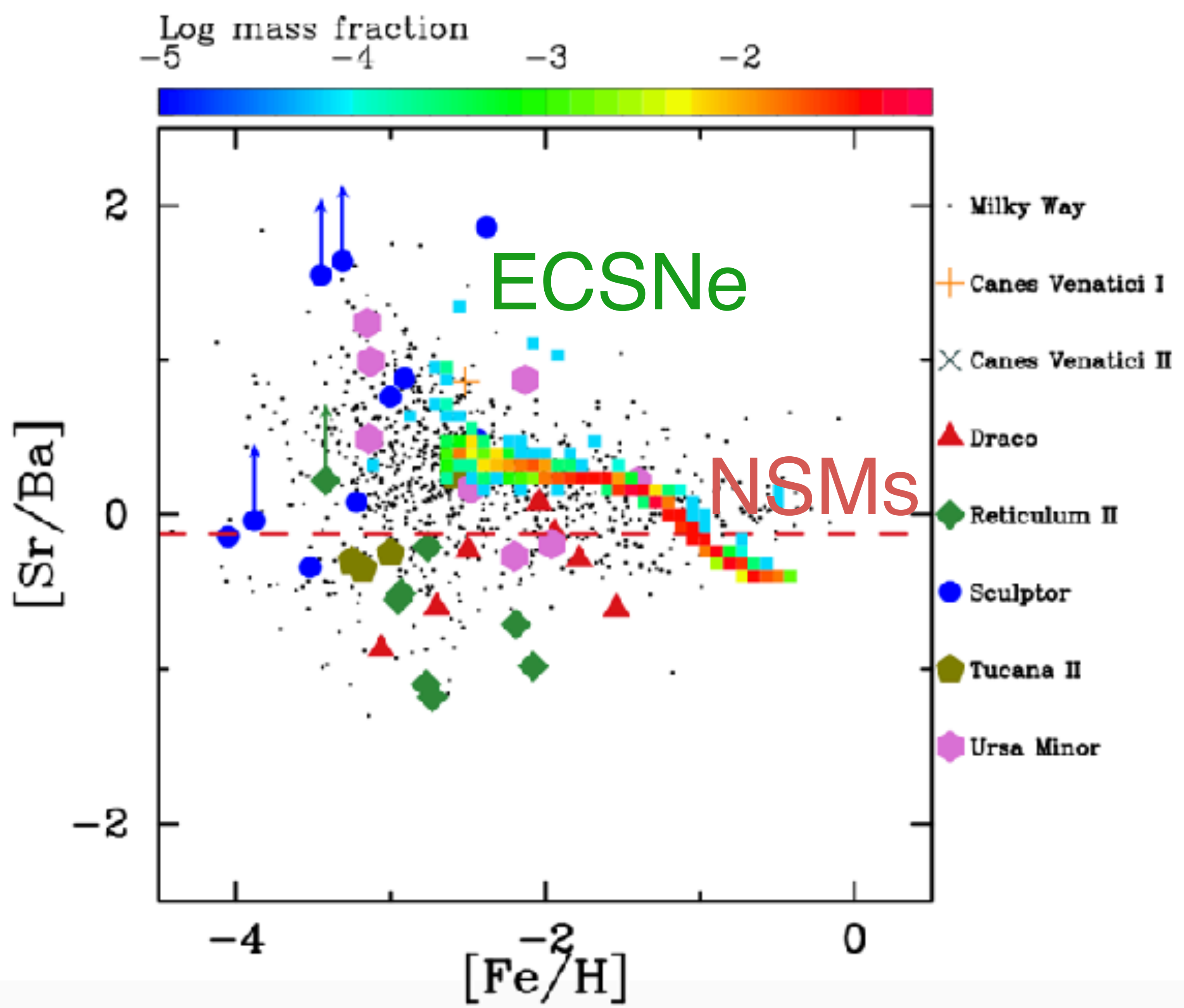
Effects of the mass range of ECSNe and weak-s process



Hirai et al. 2019, ApJ submitted

Wider mass ranges of ECSNe or weak-s process in rotating massive stars can increase the mean [Sr/Fe] ratios

[Sr/Ba] as a function of [Fe/H]



Hirai et al. 2019, ApJ submitted

Ejecta from ECSNe produce high [Sr/Ba] ratios

~ 5 % of stars has [Sr/Ba] > 1

Cosmological zoom-in simulations

Conclusions

- Electron-capture supernovae (ECSNe) can contribute to the enrichment of Zn and Sr.
- Neutron star mergers also contribute to the enrichment of Sr at [Fe/H] $\gtrsim -3$
- The mean [Sr/Fe] ratio is affected by the mass ranges of ECSNe or weak s-process in rotating massive stars.
- Stars with the high [Sr/Ba] ratio are likely to be formed from the ejecta from ECSNe.
- High-resolution cosmological zoom-in simulations will connect the enrichment of heavy elements and galaxy formation.