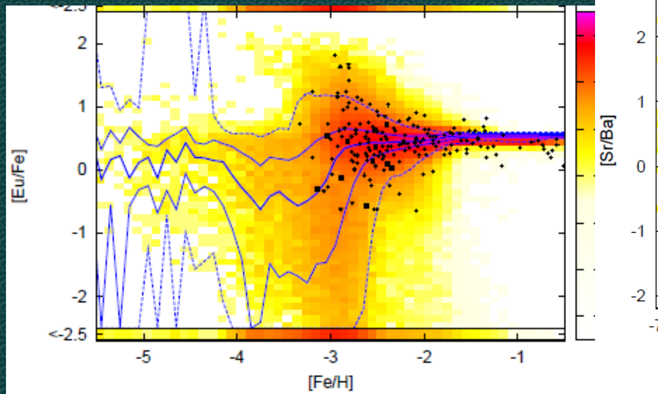
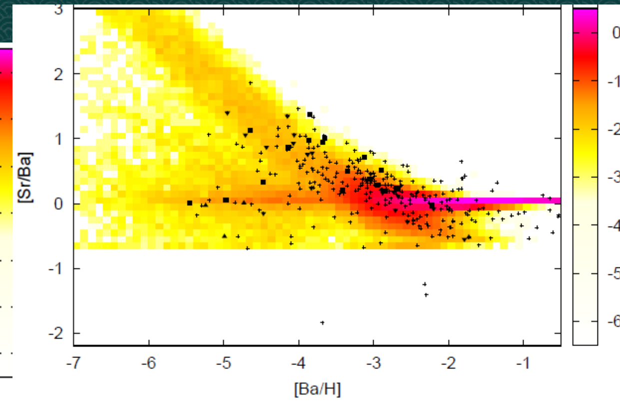
R-process WS
INT, Seattle
30/July/2014





R-process elements on the extremely metal-poor (EMP) stars & effects of the surface pollution

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Observations of r-process elements on EMP stars

- Large scatter (2-3 dex)
  - R-II stars: [Eu/Fe]>1. at [Fe/H]~ -2.8

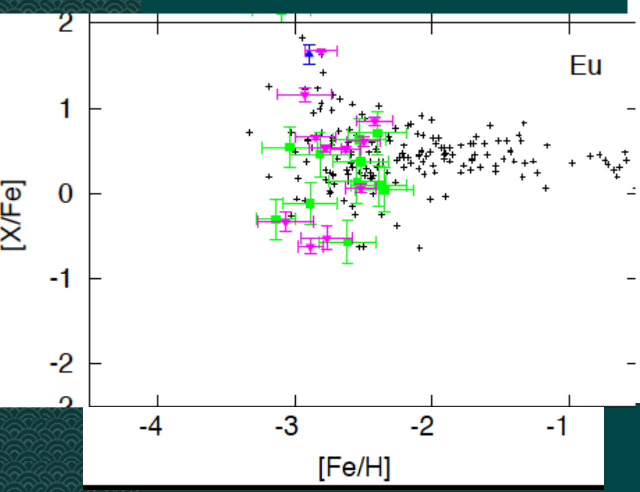
  Inhomogeneous chemical evolution

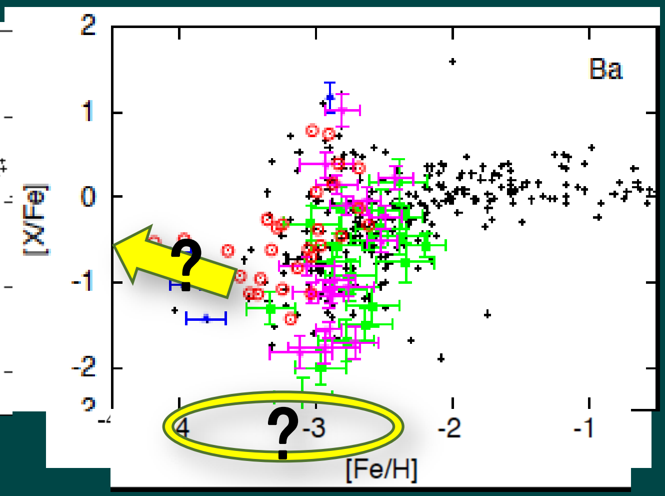
- Decreasing trend as metallicity decrease at [Fe/H]< -2.3 on average

But, Ba is detected for almost all EMP stars.

SAGA database:
http://saga.sci.hokudai.ac.jp
216 giant stars with [Fe/H]<-2.5
184 stars: Ba detection
4 stars: only upper limit

But, at [Fe/H]<-3.3, plateau is reached



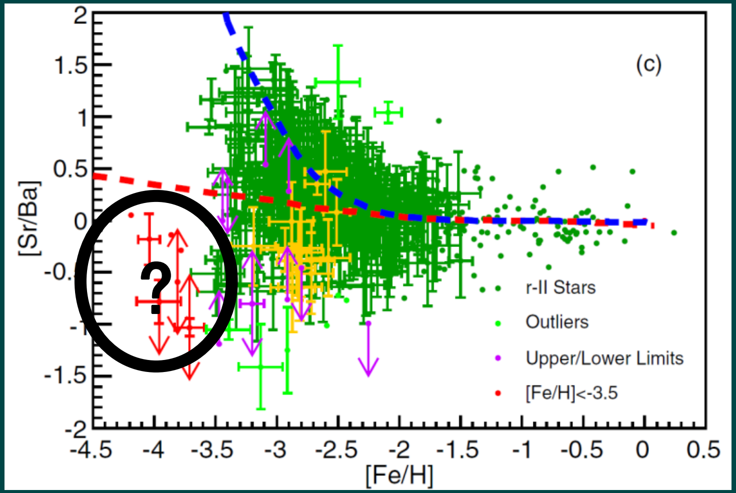


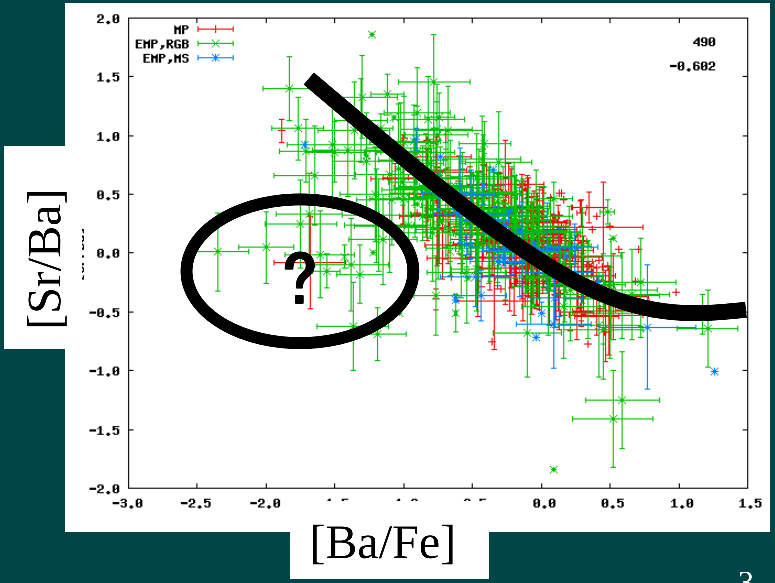
Observations: Sr/Ba

- Light-element primary process (LEPP) (weak r-process)
  - Enhancements of lighter r-process elements (Z<56; Sr, Y, Zr…) relative to heavier elements (Ba, Eu, Pb…)
  - Anti correlation between [Sr/Ba] – [Ba/Fe]

But, at [Fe/H]<-3.6, no light element enhanced stars

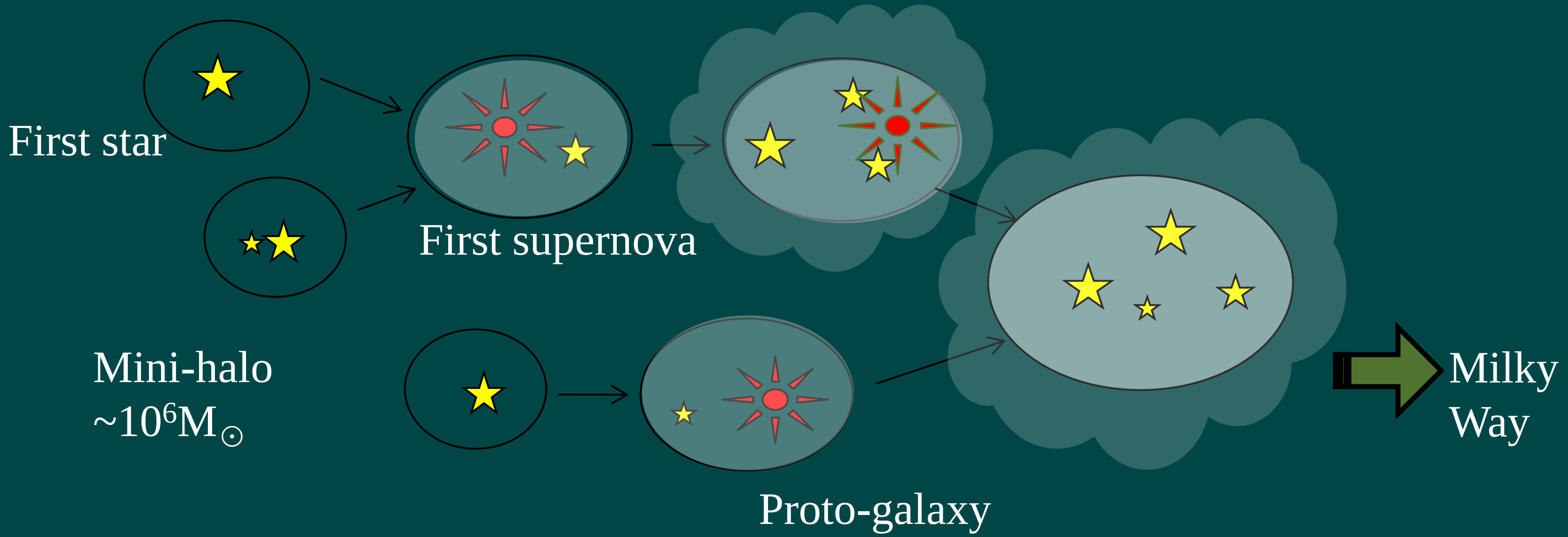
But, stars with small [Ba/Fe] and [Sr/Ba]~0





(Aoki+ 2013)

Hierarchical model for chemical evolution



- Chemical evolution along a merger tree
- All the individual EMP stars are registered
  - Yield from each individual SN
- Metal pre-enrichment of intergalactic medium (IGM)
- Surface pollution of EMP stars by accretion of interstellar medium (ISM)

Model: Chemical evolution

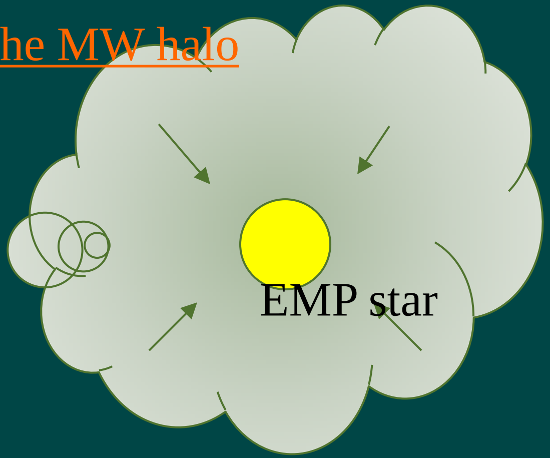
- **Star formation**
  - All the individual EMP stars are registered in computations
  - Star Formation Rate: $\psi = M_{gas} \times 10^{-10}$/yr
  - Lognormal IMF:
    - Pop.III stars ($Z<10^{-6}Z_{\odot}$)
      Pop. III.1: $M_{md} = 200\ M_{\odot}$,
      Pop.III.2 : $M_{md} = 40\ M_{\odot}$
    - EMP (Pop.II) stars: $\mathbf{M_{md} = 10\ M_{\odot}}$ (Komiya et al. 2007)

$$\xi(\log m) \propto \begin{cases} \exp\left[-\frac{\{\log(m/M_{\rm md})\}^2}{2\times\Delta_M^2}\right] & (m \leq m_{norm}) \\ m^{-1.35} & (m > m_{norm}). \end{cases}$$

  - Binary fraction: 50%
    - Mass ratio distribution: $n(q) = 1$
  - Massive Pop.III.1 stars suppress star formation in their host halos.
- **Metal enrichment**
  - Stellar lifetime : Schaerer et al. (2002)
  - Instantaneous mixing inside mini-halos.
  - Yield : (He-Zn)
    Kobayashi et al.(2006, Type II SN)
    Nomoto et al. (1984, Type Ia SN)
    Umeda & Nomoto (2002, Pair-instability SN; PISN)

Model: Accretion of interstellar matter (ISM)

- Surface abundances of EMP stars can be changed by accretion of ISM.
  - Trace the changes of the surface abundance of EMP stars along the evolution of galaxies
  - Accretion rate in mini-halos are much higher than in the MW halo due to small relative velocity between stars and ISM.



- Accretion rate
  - Bondi accretion

$$\dot{m} = \pi \left(\frac{2Gm}{v^2 + c_s^2} \right)^2 \sqrt{v^2 + c_s^2}\, \rho$$

  - In the mini-halos in which stars are formed,
    $v = c_s(T)$, $\rho = \rho_{av} \times (T_{vir}/T)$
    T = 200K for primordial clouds,
    $T = \max(10K, T_{CMB})$ for $Z > 10^{-6} Z_\odot$
  - After their host halos merge with larger halo, stars moves with circular velocity
    $v = v_{cir}$, ρ_{av} (average density of virialized halo)
- Accreted matter is mixed in surface convective zone of EMP stars.
  - $Mscz = 0.2 M_\odot$ for giant
  - $= 0.0035 M_\odot$ for main sequence

R-process source

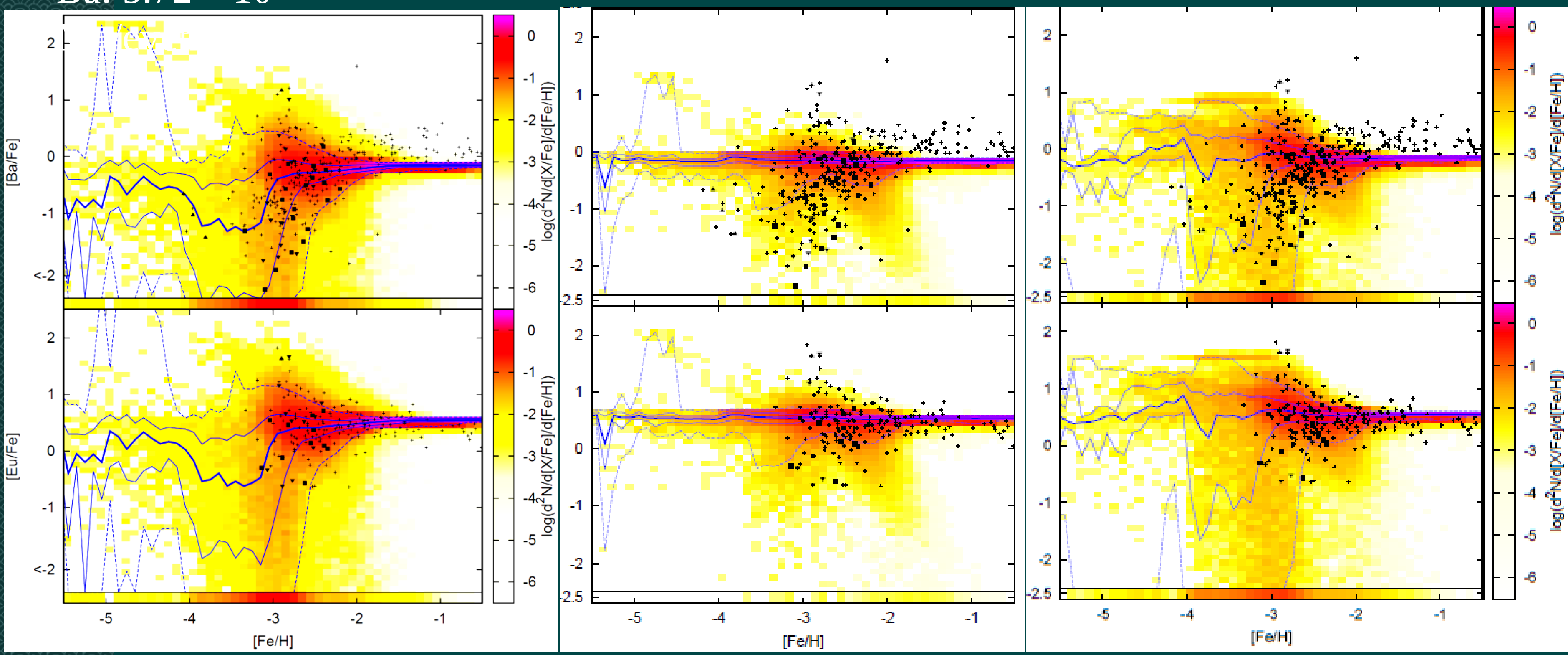
- Core-collapse SN (e.g. Burbidge+ 1957)
  - Neutrino driven wind
    - $>20M_\odot$ (Woosley & Hoffman 1992)
    - Very high entropy is required to synthesize heavy r-process elements
  - Electron-capture (O-Ne-Mg) SN ($8\text{-}12M_\odot$) (e.g. Wheeler et al. 1998)
    - Artificial enhancement of the explosion energy (Wanajo et al. 2003)
    - $n + \nu_e \rightarrow p^+ + e^-$:not so n rich
  - (Light r-process elements can be synthesized)

- Neutron star merger (e.g. Lattimer+ 1974, Rosswog+ 1999)
  - Abundance pattern : ○ (e.g. Wanajo & Janka 2011)
  - Chemical evolution: ×(Argast et al. 2004)
    - Event rate: ~1/1000 of SN
    - Long delay time (~ Gyr)

Mass range of r-process source

9-10 $M_\odot$ 10-40 $M_\odot$ 30-40 $M_\odot$

Ba: 5.72×10^{-6}



Color : predicted

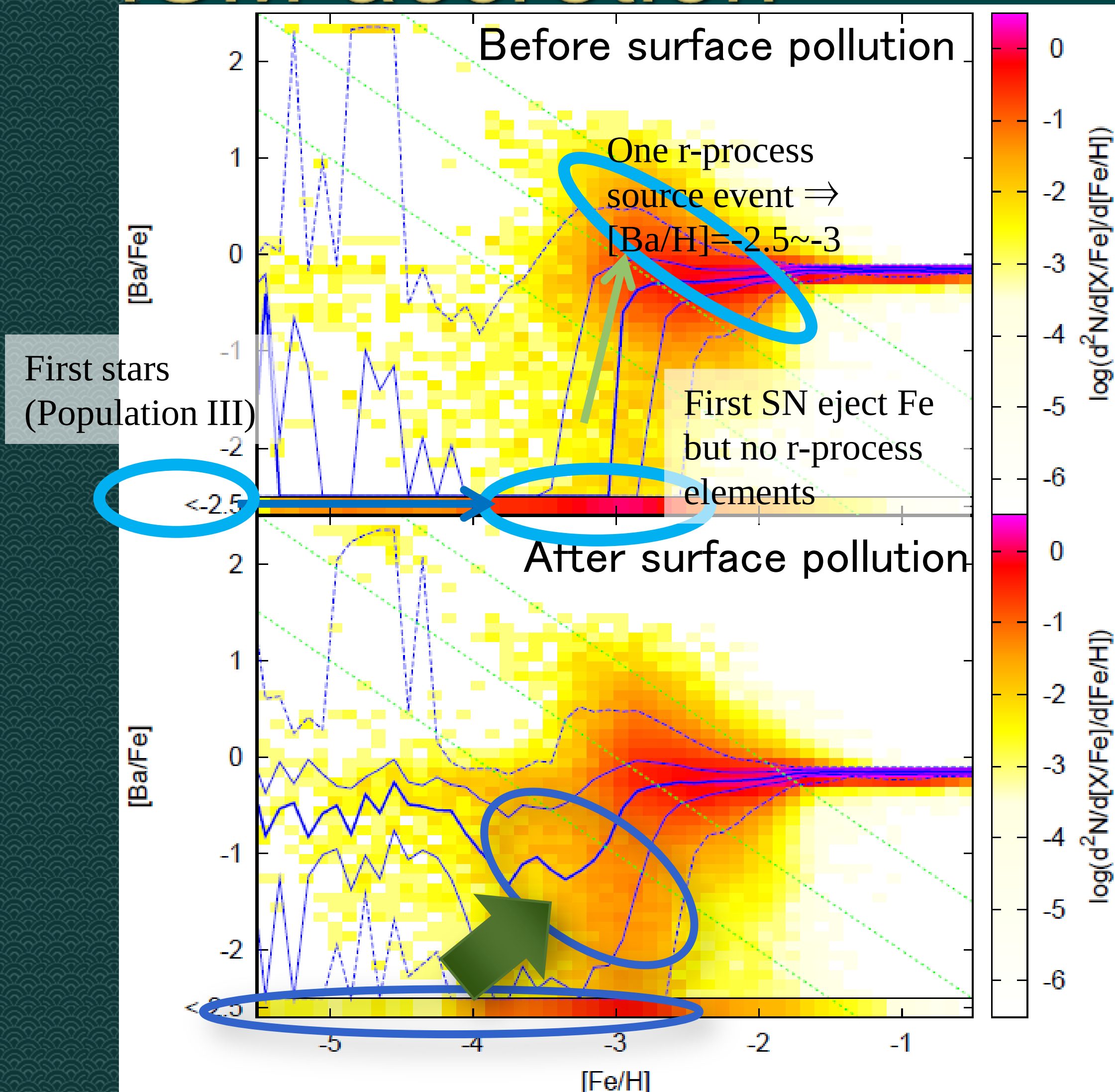
Blue lines: 95, 75

curves of predicte

Black symbols: SAGA sample

Main R-process site is ~10% of SN with progenitor stars at low-mass end of SN mass range.

Chemical evolution, ISM accretion



Majority of stars with [Fe/H]<-3 was [Ba/H] = -∞.

Accretion rate: ~10^{-11} $M_{\odot}$/yr

Mini-halo merger timescale: ~10^{8-9} yr

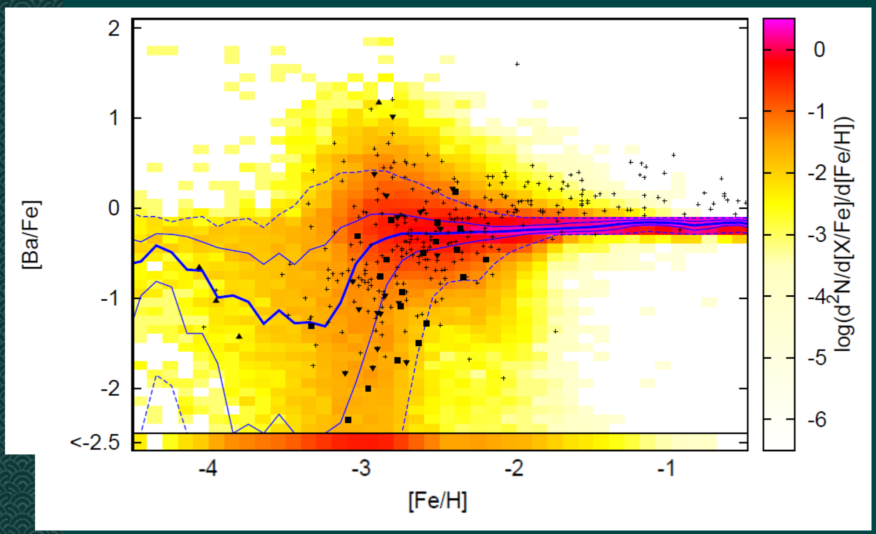
ISM abundance: [Ba/H] ~ -2

→ stellar surface: [Ba/H] ~ -4

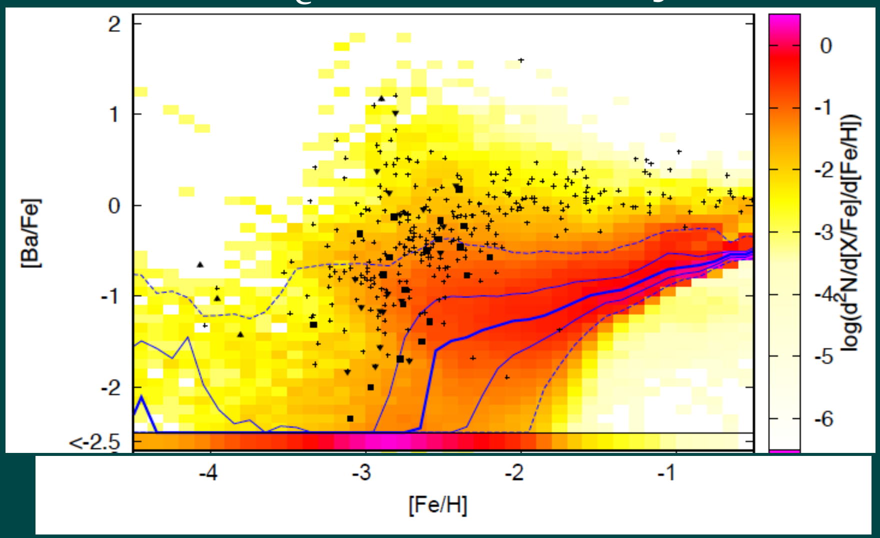
For stars with [Ba/H] ≲ -3.5, accretion of ISM is the dominate source of heavier r-process elements on their surface.

NS merger scenario ?
timescale t_c

9-10 $M_\odot$ SN ($\sim 2 \times 10^7$ yr)



$t_c = 10^8 - 10^{10}$ yr



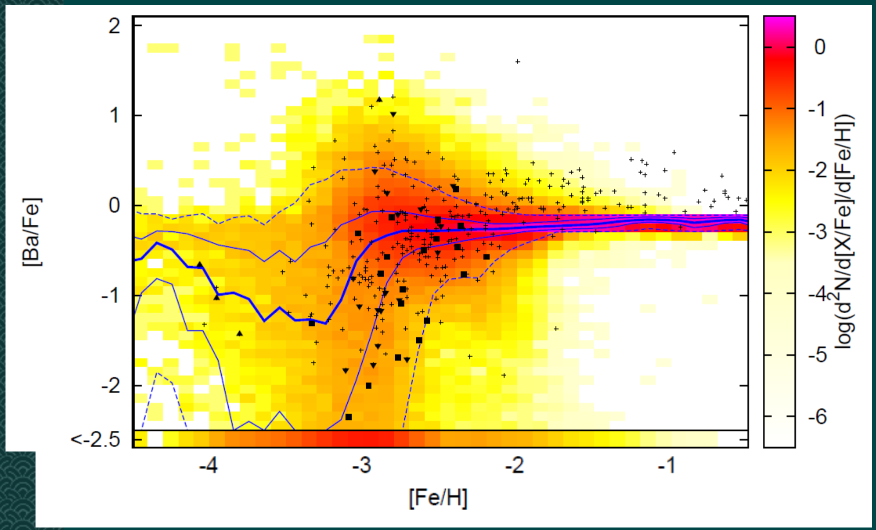
- Short delay time ($\sim 10^7$yr)

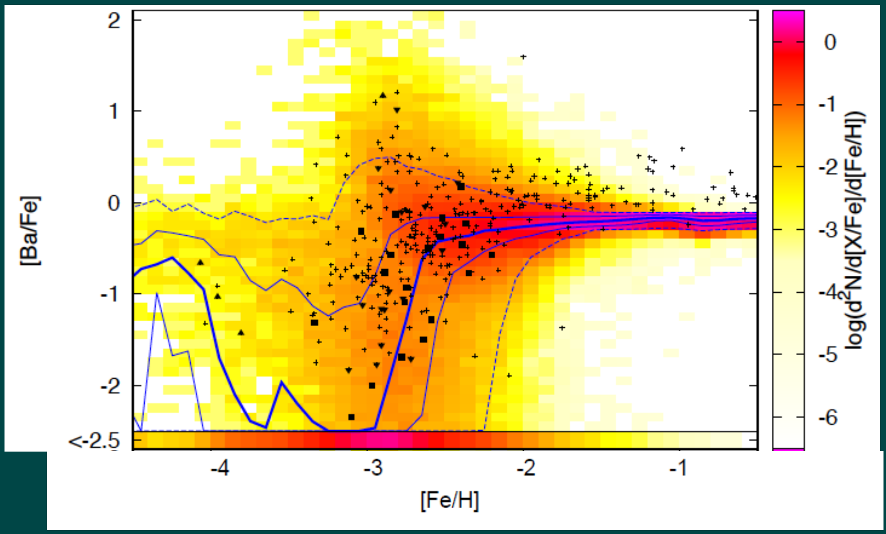
NS merger scenario Event rate

9-10 $M_\odot$ SN

$t_c = 10^7$ yr

Event rate = 0.01 × SN rate





- Even with surface pollution, a half of stars with [Fe/H] < -3 is [Ba/Fe]<-2.5
- But, dynamics of the high velocity ejecta (~0.2c) is different from SN ejecta.

Observations: Sr/Ba

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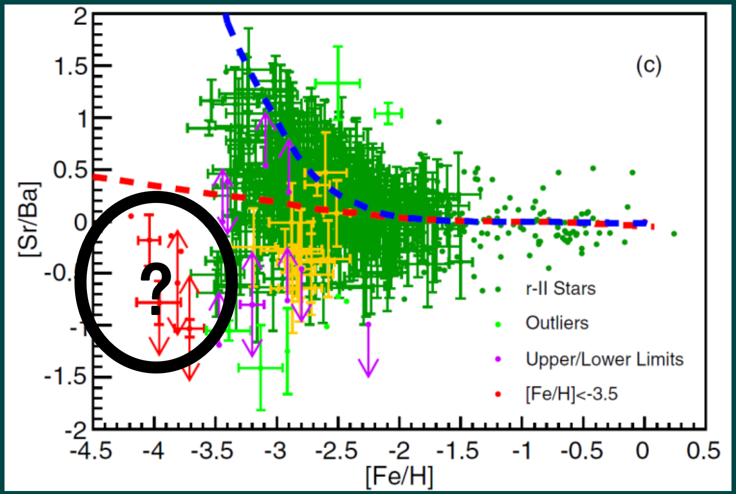
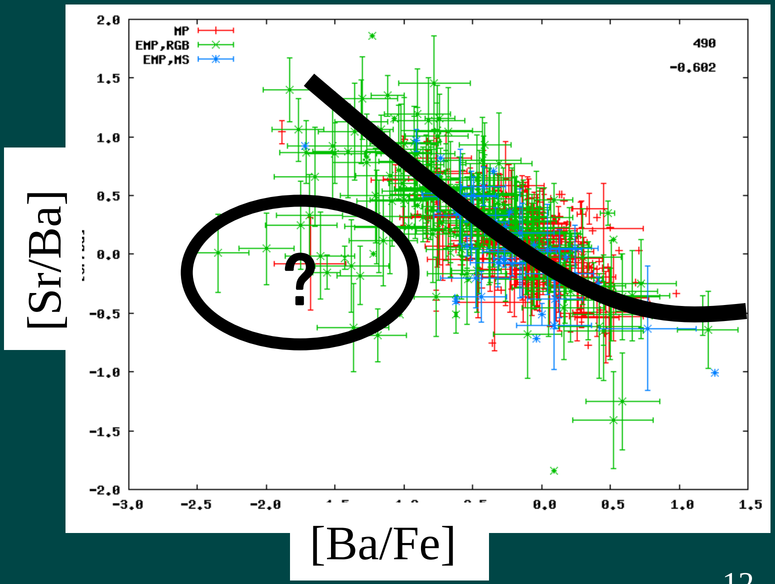




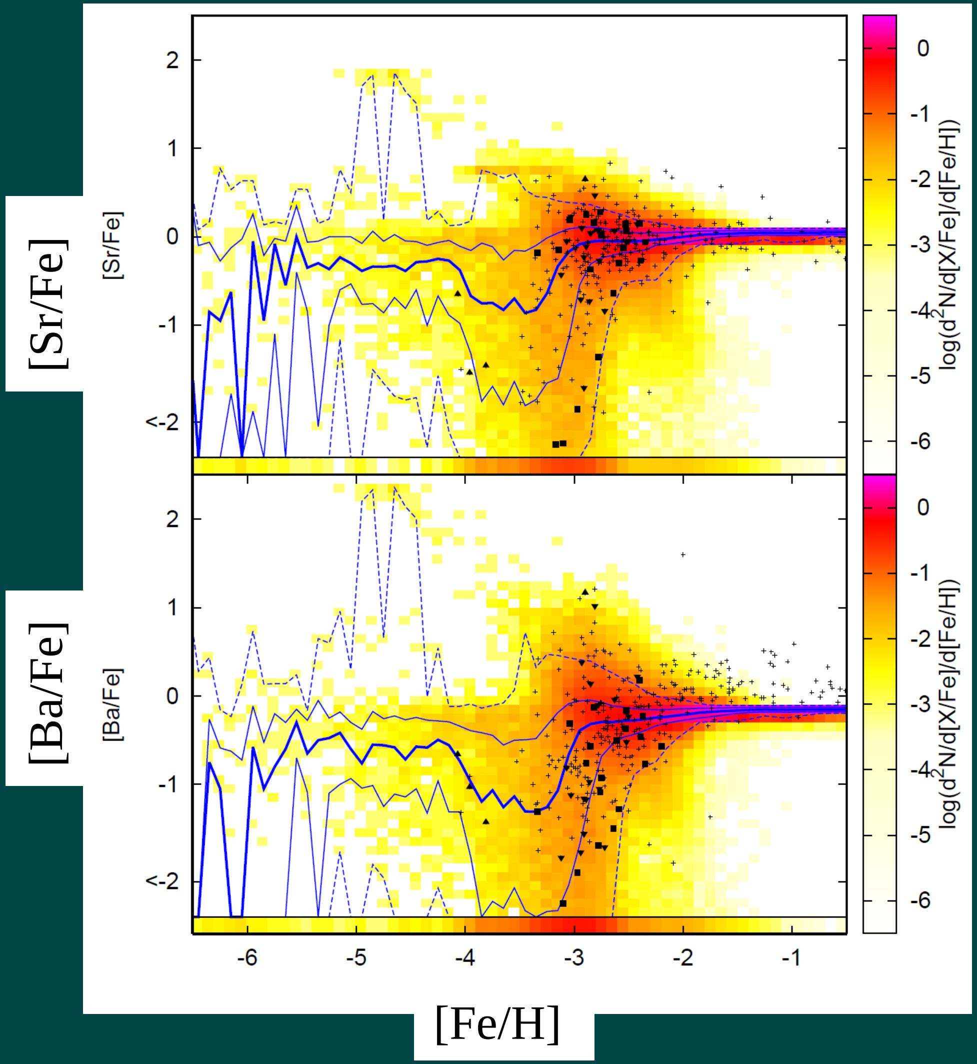
(Aoki+ 2013)

LEPP

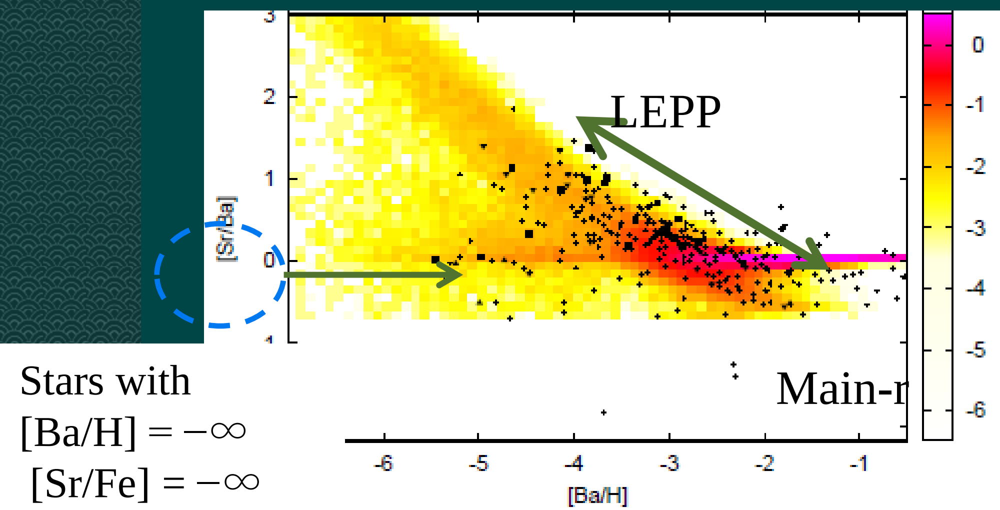
SN with the progenitor mass of 10-12 $M_\odot$

$Y_{Ba} = 0$
Y_{Sr} is set to be
<Sr/Ba> = solar r-process

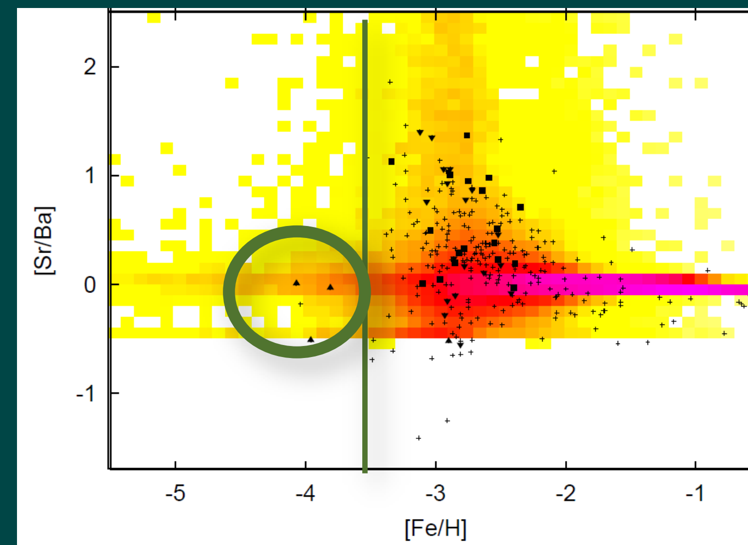
Main-r source: 9 -10 $M_\odot$
[Sr/Ba] = - 0.5



Result



LEPP
Main-r
Stars with
$[Ba/H] = -\infty$
$[Sr/Fe] = -\infty$
[Sr/Ba]
[Ba/H]
-6 -5 -4 -3 -2 -1
3 2 1 0 -1
0 -1 -2 -3 -4 -5 -6



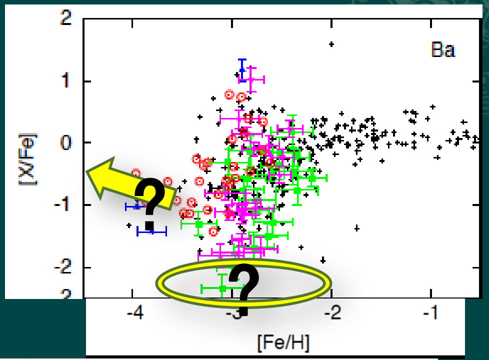
[Sr/Ba]
[Fe/H]
-5 -4 -3 -2 -1
2 1 0 -1

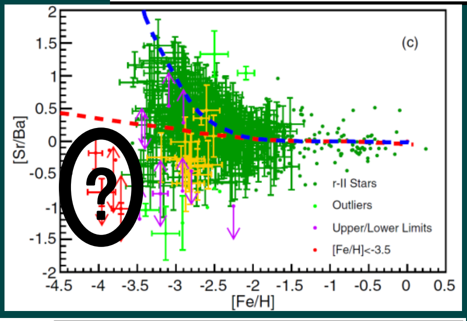
Summary

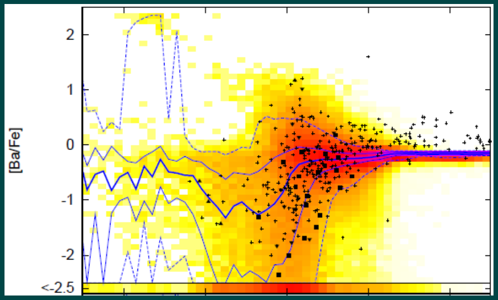
- In spite of a large abundance scatter, Ba is detected for almost all EMP stars.
  - Plateau at [Fe/H] < -3.3
- No star with [Sr/Ba] > 0 at [Fe/H] < -3.6

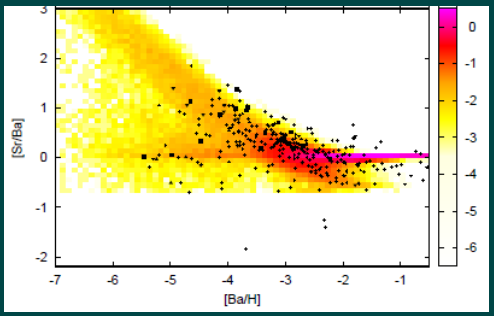
◎ Low mass (9 – 10$M_\odot$) SN + surface pollution

- Light elements (Sr): ~10-12 $M_\odot$ (9-10$M_\odot$ also eject light r-process elements, [Sr/Ba] ~ -0.5)
- NS merger
  - Additional r-process source



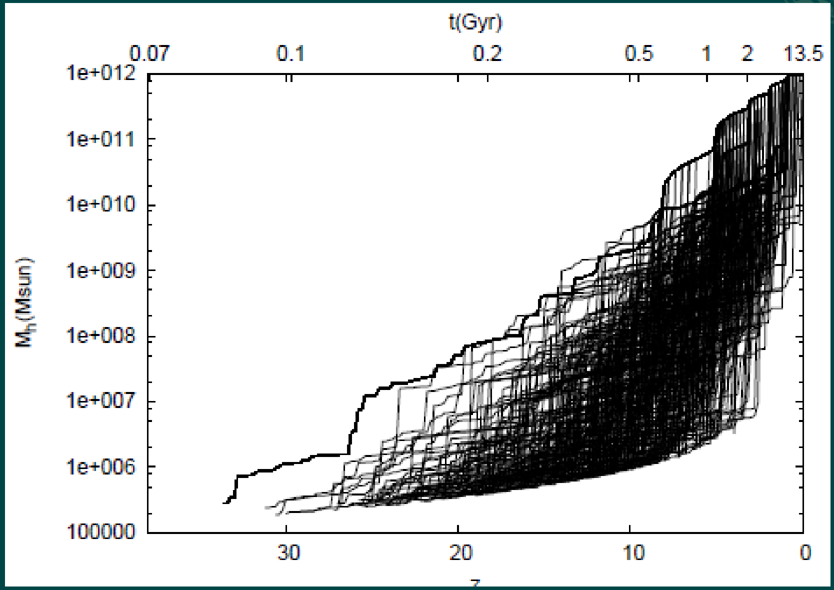






Model: Galaxy formation

- <u>Merger tree:</u>
  - Extended Press-Schechter Method
    Somerville & Kollat (1999)
  - $M_{MW}=10^{12}\ M_{\odot}$,
    $M_{min}=M(T_{vir}=10^{3}K)$



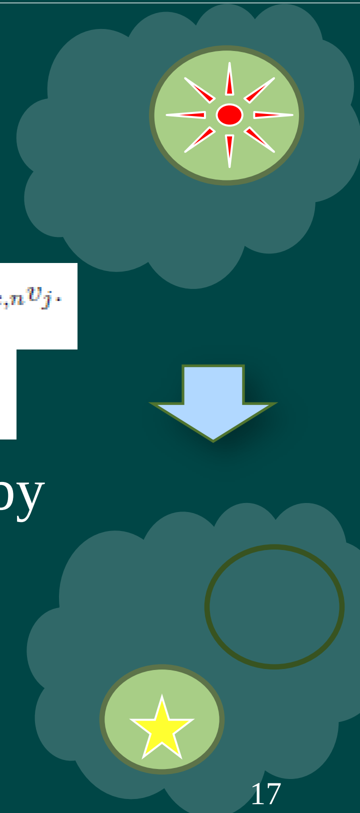
- <u>Proto-galaxy</u>
  - Gass infall: $\triangle M_h \times \Omega_b/\Omega_M$
  - At the beginning, stars are formed in mini-halo with $T_{vir} > 10^{3}K$ (Tegmark+ 1997, Yoshida+ 2003)
  - At z < 20, by Lyman-Werner photon, stars are not formed in newly formed mini-halos with $T_{vir} < 10^{4}K$
  - Reionization: At z < 10 gas do not accrete to mini-halos with $T_{vir} < 10^{4}K$
  - Proto galaxies are chemically homogeneous

Model: Metal pollution of intergalactic matter (IGM)

- SN driven galactic wind
  - Energy injection: $E_w = E_k (\varepsilon + E_k/E_{bin})/(1+E_k/E_{bin})$
  - Mass loading: $M_w = M_{gas} E_w/(E_{bin}+E_w)$
  - Metal loading: $f_W = (M_w/M_{sw} + E_k/E_{bin})/(1+E_k/E_{bin})$.

E_k: SN kinetic energy = $0.1 * E_{exp}$
E_{bin}: binding energy of a proto-glaxy
$E_{bin} = ½ \, GM_{halo} M_{gas}/R_{vir}$
ε(=0.1): minimum value of E_W/E_k
M_{sw}: mass swept up by a SN shell

- Evolution of galactic wind in the IGM (momentum-conserving snowplow model)
  - Mass: $\frac{d}{dt}M_{b,j} = (v_j - r_j H_r) r^2 \rho_{IGM} + \sum_i M_{w,i}\delta(t-t_i) - \sum_{n\in p(j)} \dot{M}_{acc,n}$
  - Momentum: $\frac{d}{dt}(M_{b,j}v_j) = \frac{dM_{b,j}}{dt} r_j H_r + \sum_i \sqrt{2E_{w,i}M_{w,i}}\,\delta(t-t_i) - \sum_{n\in p(j)} \dot{M}_{acc,n} v_j.$
  - Metal: $\frac{d}{dt}M_{A,j} = \sum_i (M_{w,i}X_{A,g} + f_{w,i}Y_{A,i})\delta(t-t_i) - \sum_{n\in p(j)} \dot{M}_{acc,n}\frac{M_{A,j}}{M_{b,j}},$



- Some proto-galaxies are formed with IGM enriched by metal ejected by SNe occurred in other galaxies.
  - Random spatial distribution of mini-halos
  - Winds “merge” when mini-halos merge