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RIKEN-RESCEU joint seminar

Contribution of Neutron-Star Merger to the R-process Chemical Evolution

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Collaborators

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- Introduction
  - Neutron Star Merger (NSM)
  - Observations of metal-poor stars
  - R-process Chemical Evolution
- Chemical Evolution Model
  - Hierarchical galaxy formation
  - Escape of NSM ejecta from proto-galaxy
- Results

R-process source

- Core collapse Supernova (CCSN)

  e.g. Hillebrandt+ (1976)

- R-process site
  - Neutrino wind (Woosley & Hoffman 1992)
  - Electron capture supernova (Wheeler et al. 1998, Wanajo et al. 2003)

- Neutron Star Merger (NSM)

  e.g. Lattimer & Schramm (1974)

- R-process site
  - Dynamical ejecta
  - Evaporating disk
  - Neutrino wind

NSM ejecta
r-process

- Dynamic ejecta
  - Tidally disrupted
  - Shock heated
- Evaporating disk
- Neutrino driven wind

- Ejecta mass ： (dynamical)

  $4\times10^{-3} - 4\times10^{-2}\ M_{\odot}$ (Rosswog+ 1999)

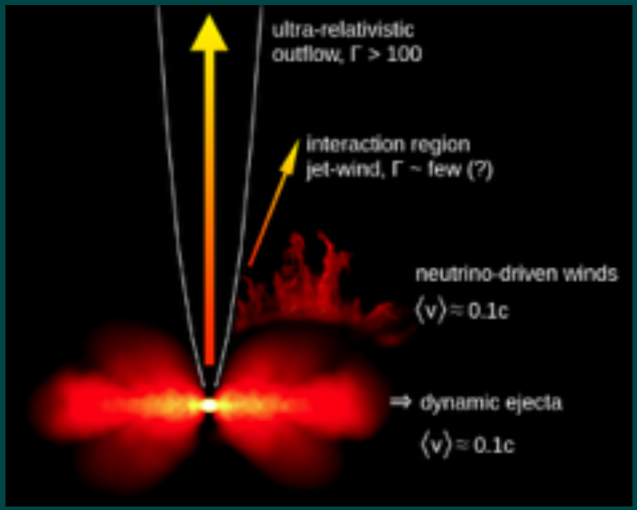
  $10^{-3} - 2\times10^{-2}\ M_{\odot}$ (Bauswein+ 2013)

  $10^{-4} - 2\times10^{-2}\ M_{\odot}$ (Hotokezaka+ 2013)
  - $0.01 - 0.15\ M_{\odot}$ for NS-BH merger
- Velocity ： **0.1 – 0.3 c**
  - ~escape velocity of a NS

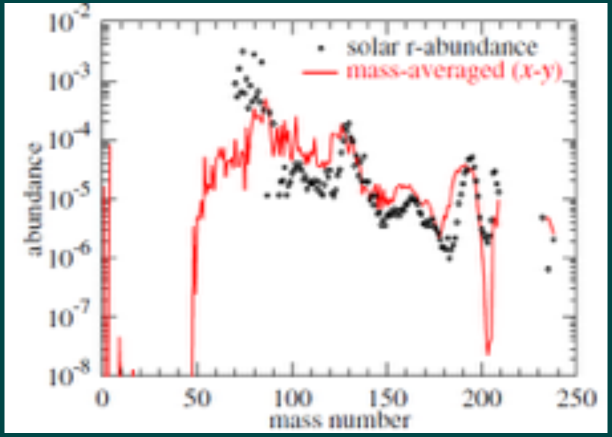
- R-process
  - Ye ~ 0.1
  - scaled solar abundance (at A≳80)

Short GRB (?)

Martin+ (2015)

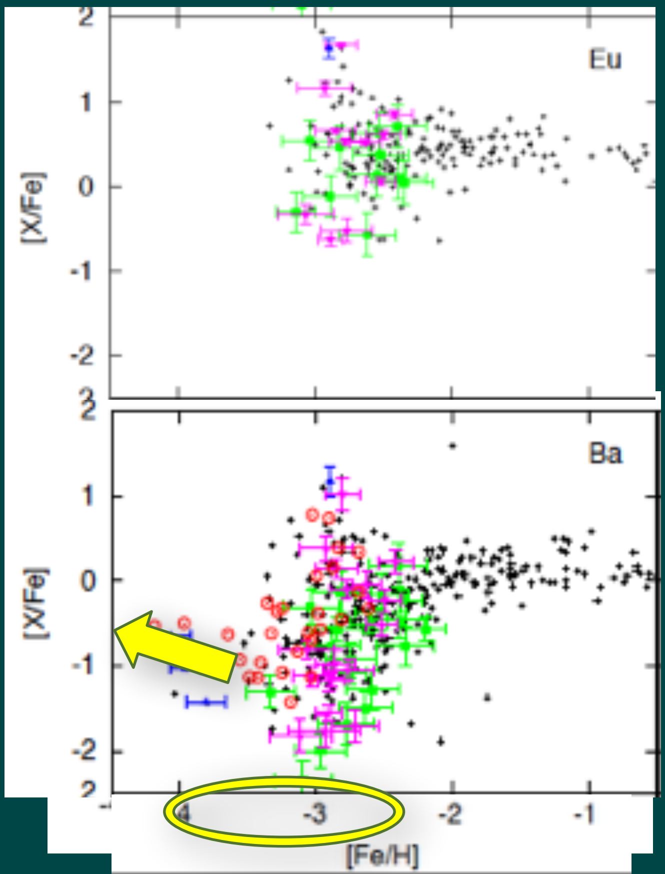


Wanajo+ (2014)



Observations of Extremely metal-poor (EMP) stars

- Large abundance scatter (2-3 dex)
  - Rare event
- Decreasing trend as metallicity decrease at [Fe/H]< -2.3 on average
  - But, at [Fe/H]<-3.3, plateau is reached
- **Scarcity of stars lacking r-process elements**
  (Roederer+ 2013, Komiya+ 2014)
  - Ba is detected for almost all EMP stars.
  - **R-process is ubiquitous ?**



※ Ba in EMP stars is originated with r-process

Chemical evolution:

Metal-poor stars:

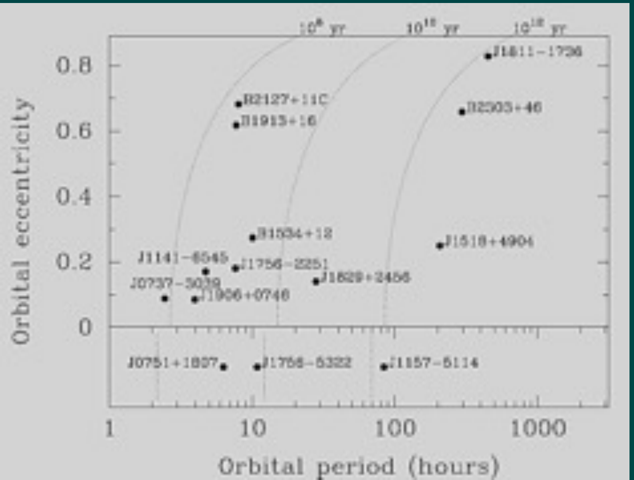
probes for enrichment history of heavy elements

Extremely metal poor (EMP) stars

= Second (or very early) generations of stars

⇒ nucleosynthetic yield of an individual SN or NSM

- CCSN
  - Event rate: $\sim 10^{-2}$ yr^{-1}
  - Delay time: $\sim 10^{7}$ yr
- NSM
  - Event rate: $\sim 10^{-4}$ or 10^{-5} yr^{-1}
  - Delay time: $\sim 10^{9}$ yr



Lorimer (2008)

Chemical evolution:

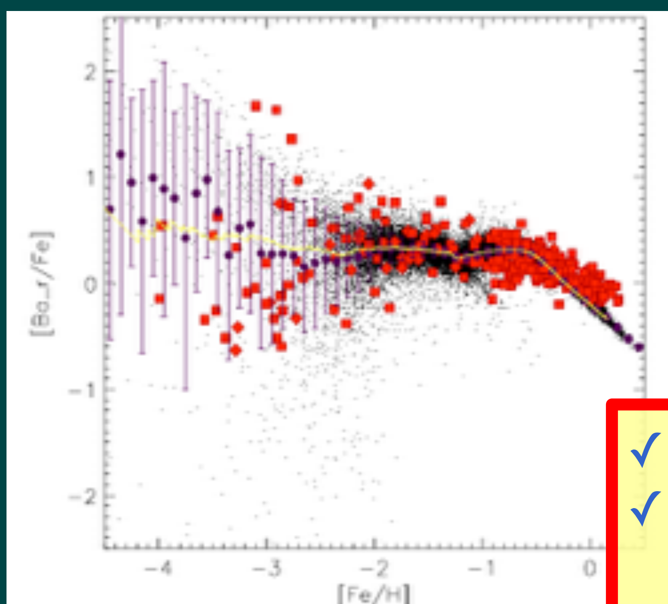
- <u>CCSN scenario</u>
  - Event rate: ~10^{-2} yr^{-1}
  - Yield: ~10^{-5} M_{sun}
  - Delay time: ~10^7yr

× 1/1000

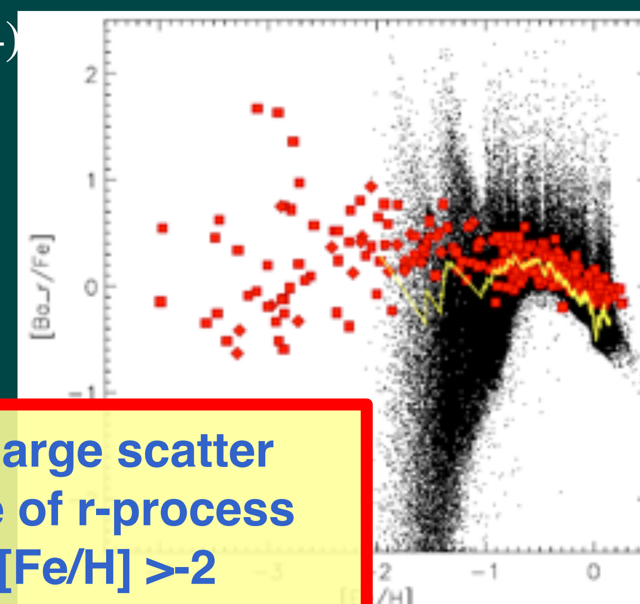
× 1000

× 10 - 100

- <u>NSM scenario</u>
  - Event rate: 10^{-4} or 10^{-5} yr^{-1}
  - Yield: Yr~10^{-2} M_{sun}
  - Delay time: t_d ~ 10^8 - 10^9yr



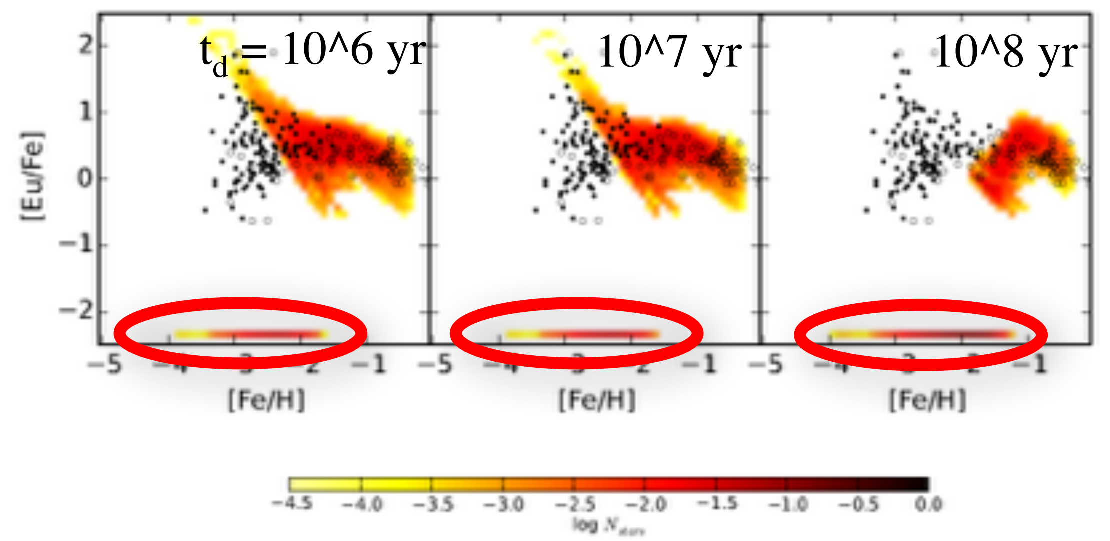
(Argast+ 2004)



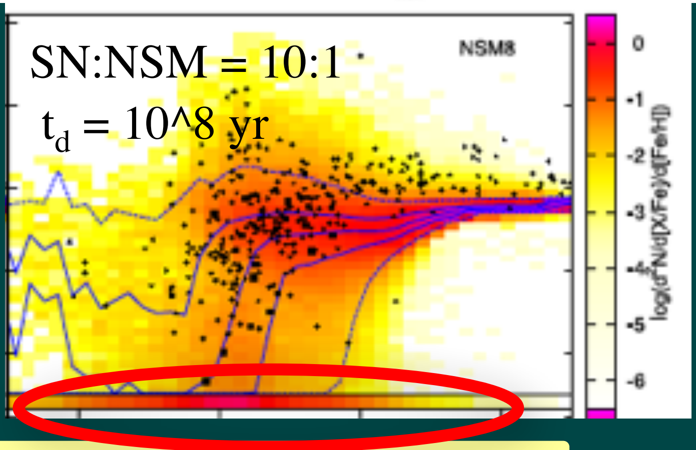
- ✓ Extremely large scatter
- ✓ Emergence of r-process element at [Fe/H] >-2
- ✓ Many stars lacking r-process elements

Chemical evolution

- Cescutti+ (2015)



- Komiya+ (2014)



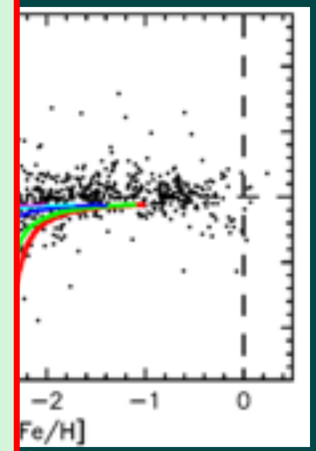
Very short (10^7 yr) delay time is required
Many stars lacking r-process elements

- Tsujimoto & Shigeyama (2014)
  - **Propagation of NSM ejecta**
  - R-process elements from NSM have large kinetic energy (v~0.2c)

    →<u>cannot be trated as “fluid”</u>
  - Stopping length of ^{153}Eu with $v_r = 0.2c$ (~2.9 Gev)

    $l_s \sim 2.6/(n/1cm^{-3})$ kpc
  - NSM
    volu
- Ishimaru
  - Longe
    major
    <u>forma</u>
    <u>massi</u>

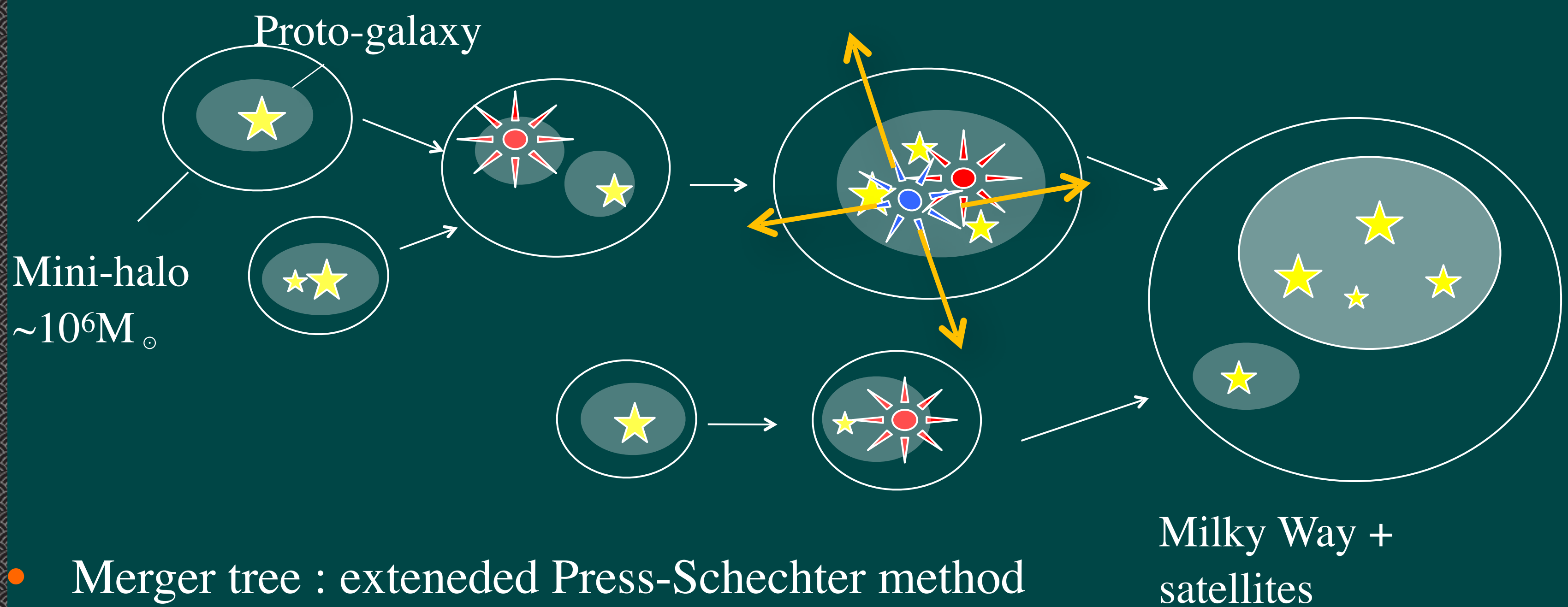
<u>Revisit the chemical evolution of r-process elements considering the large scale propagation and the hierarchical galaxy formation</u>



CHEMICAL EVOLUTION MODEL

Hierarchical chemical evolution model

Komiya et al. (2014, 2015)



- Merger tree : exteneded Press-Schechter method
- Chemical evolution in merger trees
  - Different chemical abundance between proto-galaxies (Homogeneous chemical abundance inside each proto-galaxy)
- Register all the individual EMP stars
- SN triggered galactic wind →Metal pre-enrichment of intergalactic medium (IGM)
- NSM ejecta (r-process elements) spread beyond the proto-galaxy
- Metal pollution by ISM accretion for surfaces of EMP stars

Star formation, gas outflow

- **Star formation rate**
  - $M_* = \varepsilon_* M_{gas}$
    - Constant : $\varepsilon_* = 1.2\times10^{11}$/yr
    - $\varepsilon_* \propto M_h^{0.3}$ (Ishimaru 2015) ($10^{\langle [Fe/H] \rangle} \propto M_*^{0.3}$, Kirby+ 2013)

- **Gas outflow**
  - SN energy driven :
    - $E_{out} = E_k$ ($E_k >> E_{bin}$)
    - $E_{out} = \varepsilon_o E_k$ ($E_k << E_{bin}$)

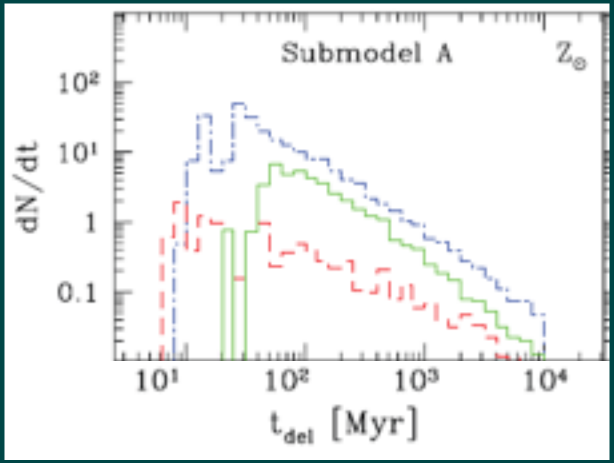
$$E_w = E_k \frac{\epsilon_o + E_k/E_{bin}}{1 + E_k/E_{bin}}$$

$$M_w = M_{gas} \frac{E_w}{E_{bin} + E_w}$$

  - $\varepsilon_o = 0.1, 0.5$

NSM

- 1% of binary stars with NS mass range form coalescing NS binary
  - 8 – 25 $M_{\odot}$ stars leave NSs
  - (CCSN:NSM = 1000:1)



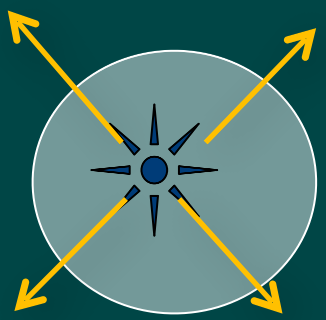
- Delay time :t_d (Dominik+ 2012)
  - $dN/dt_d \propto t_d^{-1}$
  - $10^7 - 10^{10}$ yr (<t_d>~10^9 yr)

- Ejecta velocity: $v_r = 0.2c$

- Yield
  - $Y_r = 0.03M_{\odot}$ (**kilonova observations** GRB 130603B , Tanvir+ 2013; Berger+ 2013)
  - Scaled solar abundance pattern
    ($Y_{Eu} = 1.5\times10^{-4}M_{\odot}$, $Y_{Ba} = 1.2\times10^{-3}M_{\odot}$)

Propagation of NSM ejecta

- Proto-galaxy
  - Energy loss rate (Schlickeiser 2002)
    - $\dot{E} = 1.82 \times 10^{-7} n_{\mathrm{H}} Z_{\mathrm{eff}}^2 (\beta)(1 + 0.00185 \ln \beta)/\beta$ [eV/s] (ionization)
    - $\dot{E} = 3.1 \times 10^{-7} Z^2 n_{\mathrm{e}} / \beta$ [eV/s] (Coulomb)
  - Stopping length (neutral gas)
    - $l_s = (\gamma-1) mc^2/(dE/dt)\, v_r \sim 2.6\mathrm{kpc}/(n/1\mathrm{cm}^{-3})$ (^{153}Eu)
  - Homogeneous mixing in each proto-galaxy



- **Escape fraction: f_{esc}** (from proto-galaxy)
  - $f_{\mathrm{esc}} = \exp(-R_g / l_s)$

R_g: radius of a proto-galxy

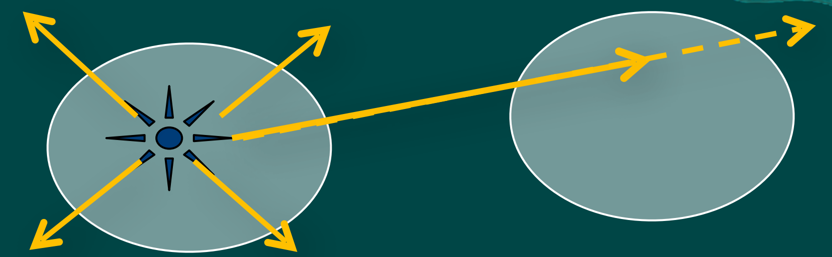
- Intergalactic medium
  - Energy loss timescale in IGM:

    $\tau_{\mathrm{stop}} \sim 4.3\times(n_{\mathrm{IGM}}/10^{-5}\ \mathrm{cm}^{-3})^{-1}$ Gyr (neutral)

    $\sim 0.3\times(n_{\mathrm{IGM}}/10^{-5}\ \mathrm{cm}^{-3})^{-1}$ Gyr (ionized)
  - Cooled r-process elements mixed with IGM

Propagation of NSM ejecta

- Escape fraction: $f_{\rm esc} = \exp(-R_g / l_s)$



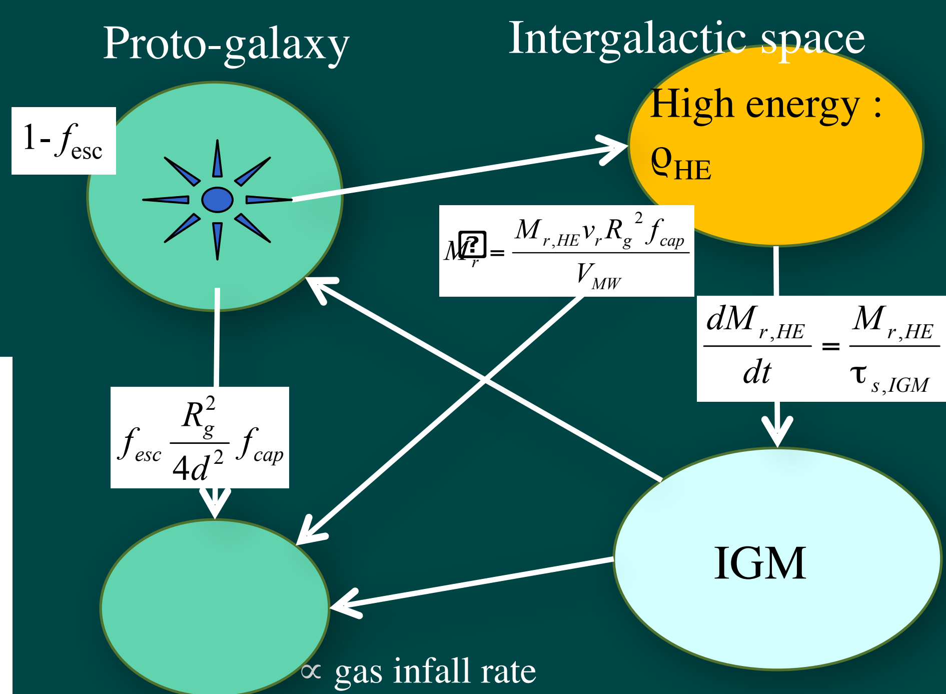
- Capture by other proto-galaxies

$$f_{esc} \frac{\pi R_g^{\,2}}{4\pi d^2} \left\langle 1 - \exp\left(- \frac{R_g}{l_s} \right) \right\rangle$$

- Accretion of enriched IGM

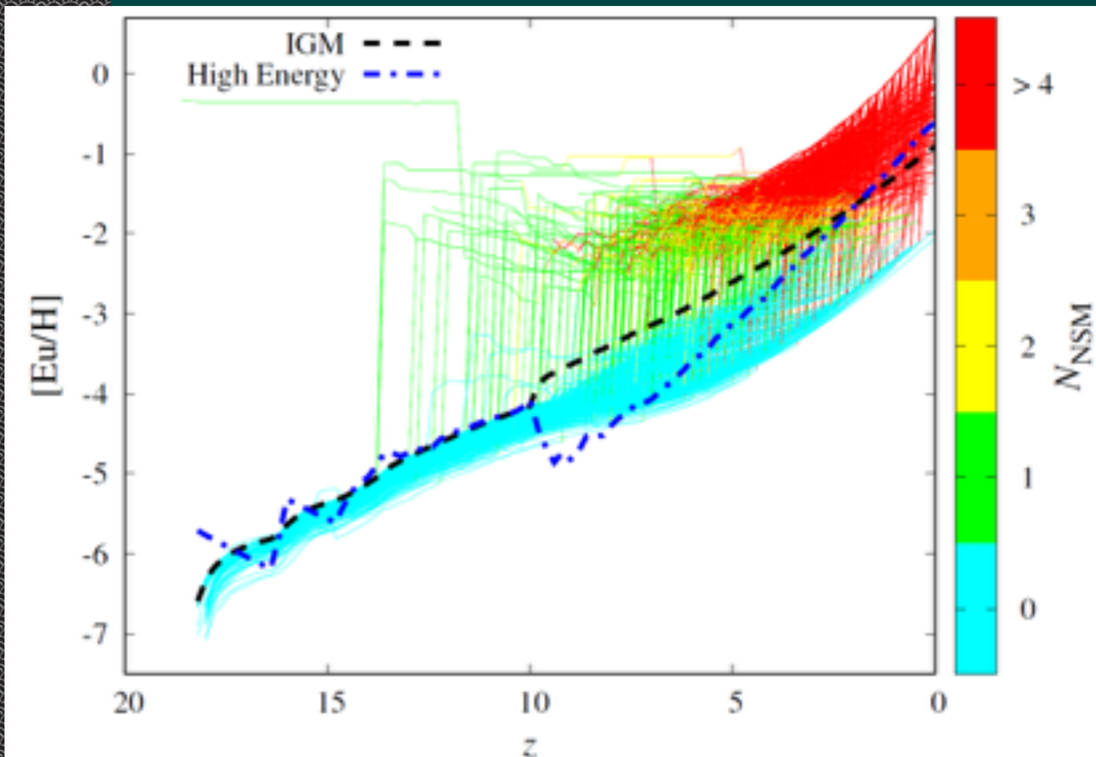
- Enrichment of r-process elements in proto-galaxies

$$\frac{dM_{\rm gas,n}X_{i,n}}{dt} = Y_i \sum_k \delta(t - t_{{\rm NSM},n,k})(1 - f_{{\rm esc},n,i}) + Y_i \sum_{m \neq n} \sum_k \delta(t - t_{{\rm NSM},m,k}) f_{{\rm esc},m,i} \frac{\pi R^2_{{\rm g},n}}{4\pi d^2_{n,m}} f_{{\rm cap},n,i} + \frac{M_{i,{\rm HE}} \pi R^2_{{\rm g},n} v_r}{V_{\rm MW}} f_{{\rm cap},n,i} + \dot{M}_{{\rm acc},n} X_{i,{\rm IGM}}$$



RESULTS

Enrichment history of r-process elements



The first NSM event
→ most of the ejecta escape

$$[\mathrm{Eu/H}]_{\mathrm{HE}} = \log\left(\frac{Y_{\mathrm{Eu}} f_{\mathrm{esc}}}{M_{\mathrm{IGM}} X_{\mathrm{H,IGM}}}\right) - \log\left(\frac{X_{\mathrm{Eu}}}{X_{\mathrm{H}}}\right)_{\odot}$$
$$= -5.6 + \log\left[\left(\frac{f_{\mathrm{esc}}}{1}\right)\left(\frac{M_{\mathrm{IGM}}}{M_{\mathrm{MW}}\frac{\Omega_b}{\Omega_M}}\right)^{-1}\left(\frac{X_{\mathrm{H,IGM}}}{0.8}\right)^{-1}\right]$$

The high energy r-process elements in IGM cool

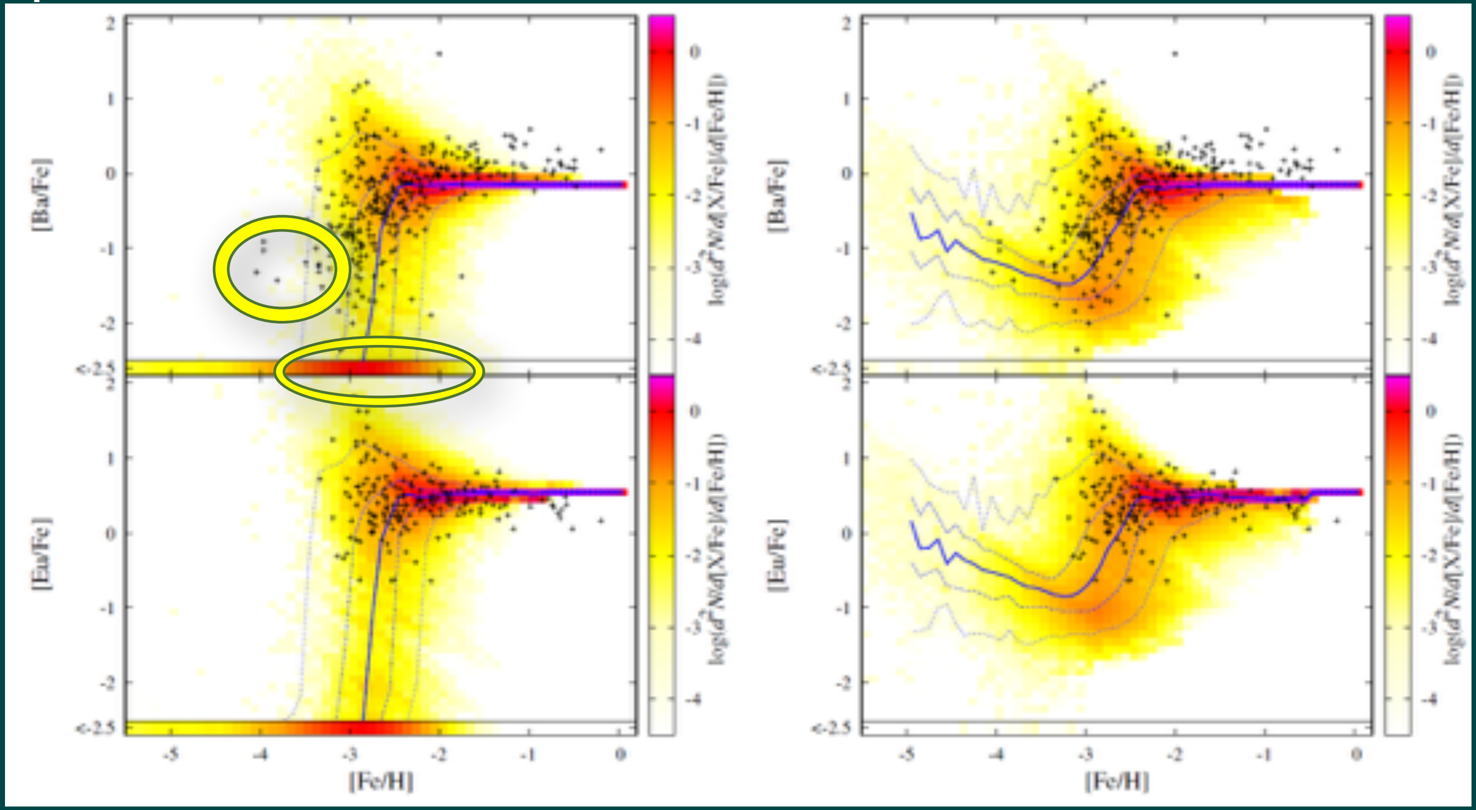
$$\tau_{s,\mathrm{IGM}} = \begin{cases} 430\left(\frac{n_{\mathrm{IGM}}}{10^{-4}\mathrm{cm}^{-3}}\right)^{-1}\mathrm{Myr} & \text{(before reionization)} \\ 31\left(\frac{n_{\mathrm{IGM}}}{10^{-4}\mathrm{cm}^{-3}}\right)^{-1}\mathrm{Myr} & \text{(after reionization)} \end{cases}$$

One NSM event enrich its host proto-galaxy to

$$[\mathrm{Eu/H}] = \log\left(\frac{Y_{\mathrm{Eu}}(1-f_{\mathrm{esc}})}{M_{\mathrm{gas}} X_{\mathrm{H}}}\right) - \log\left(\frac{X_{\mathrm{Eu}}}{X_{\mathrm{H}}}\right)_{\odot}$$
$$\sim -1.8 + \log\left[\left(\frac{Y_{\mathrm{Eu}}}{1.5\times 10^{-4} M_{\odot}}\right)\left(\frac{R_{\mathrm{g}}}{1\mathrm{kpc}}\right)\left(\frac{n}{1\mathrm{cm}^{-3}}\right)\left(\frac{M_{\mathrm{gas}}}{10^{7} M_{\odot}}\right)^{-1}\right]$$

Abundance distribution

- $\varepsilon_{*} \propto M_h^{0.3}$

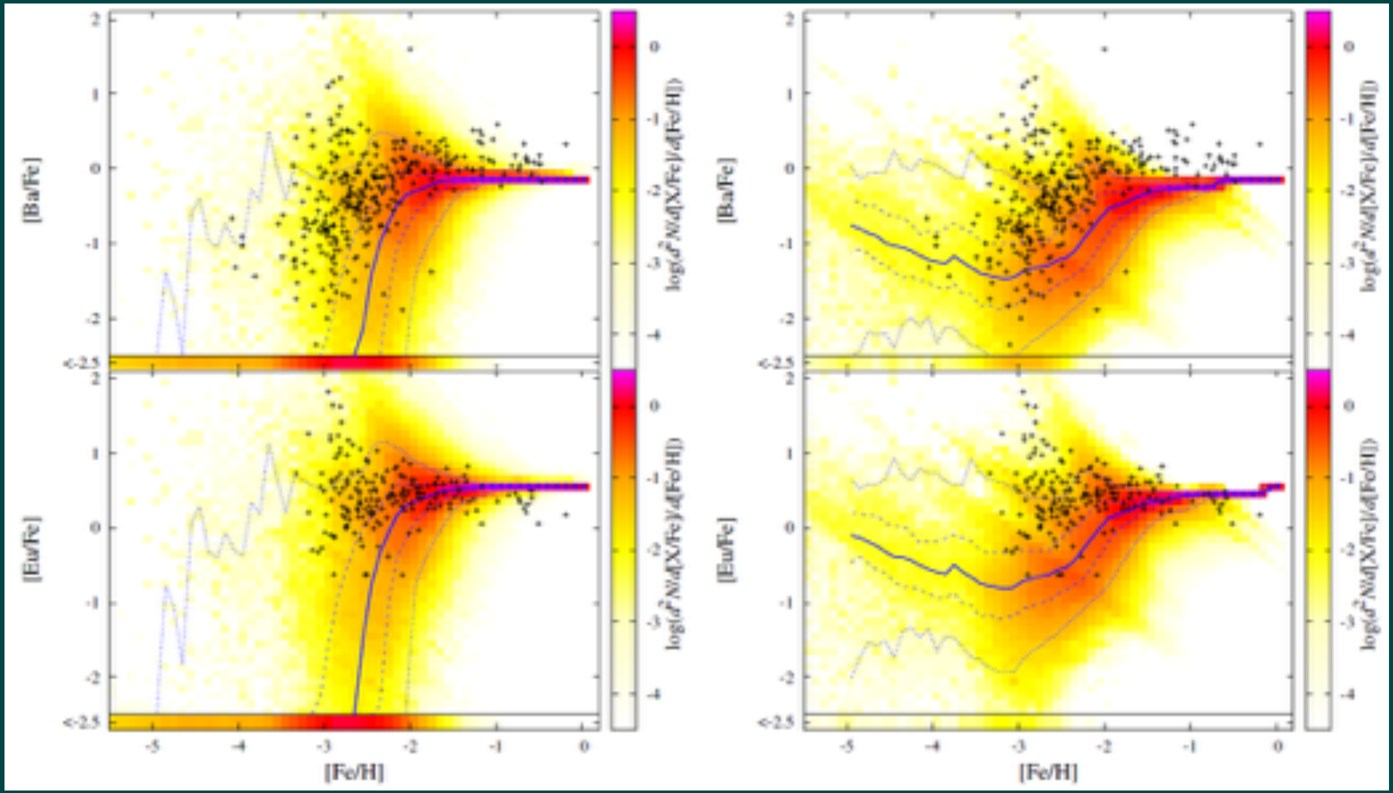


$f_{esc} = 0$

$f_{esc} = \exp(-R_g / l_s)$

Abundance distribution

- Constant SFE

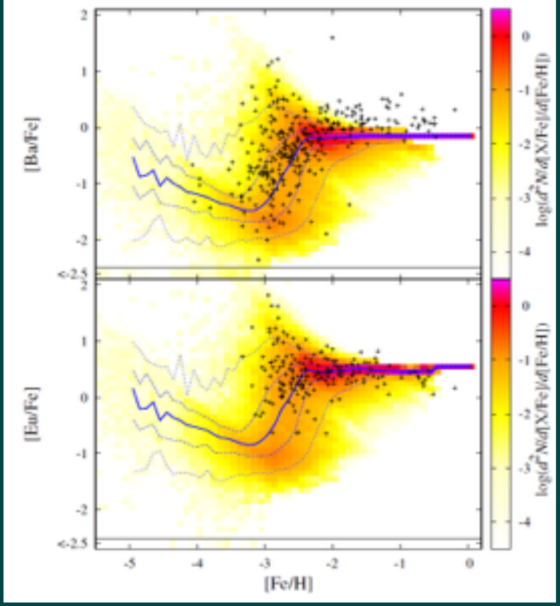


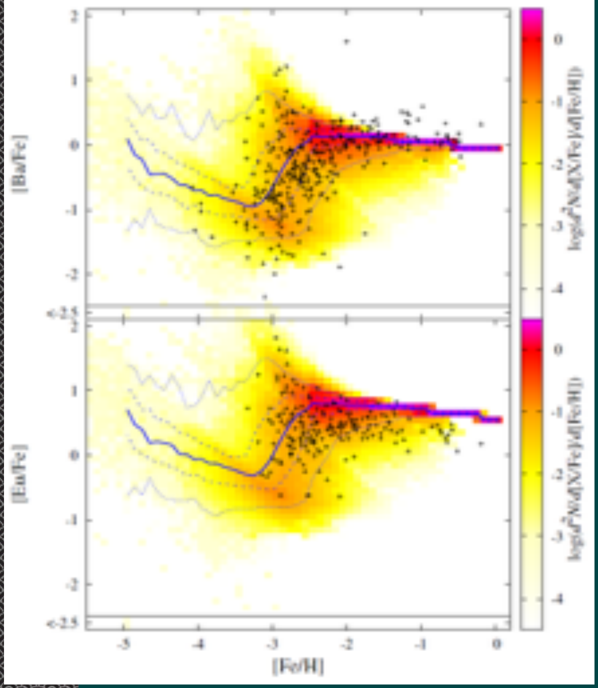
$f_{esc} = 0$

$f_{esc} = \exp(-R_g / l_s)$

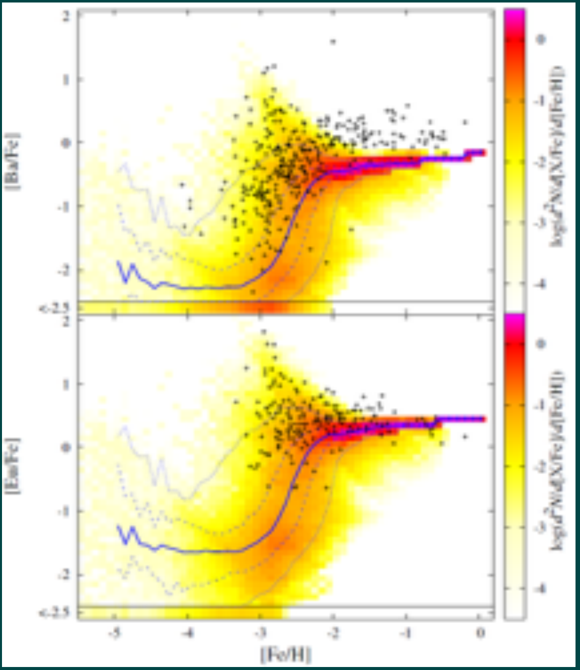
Delay time

t_d = 10^7 – 10^10 yr



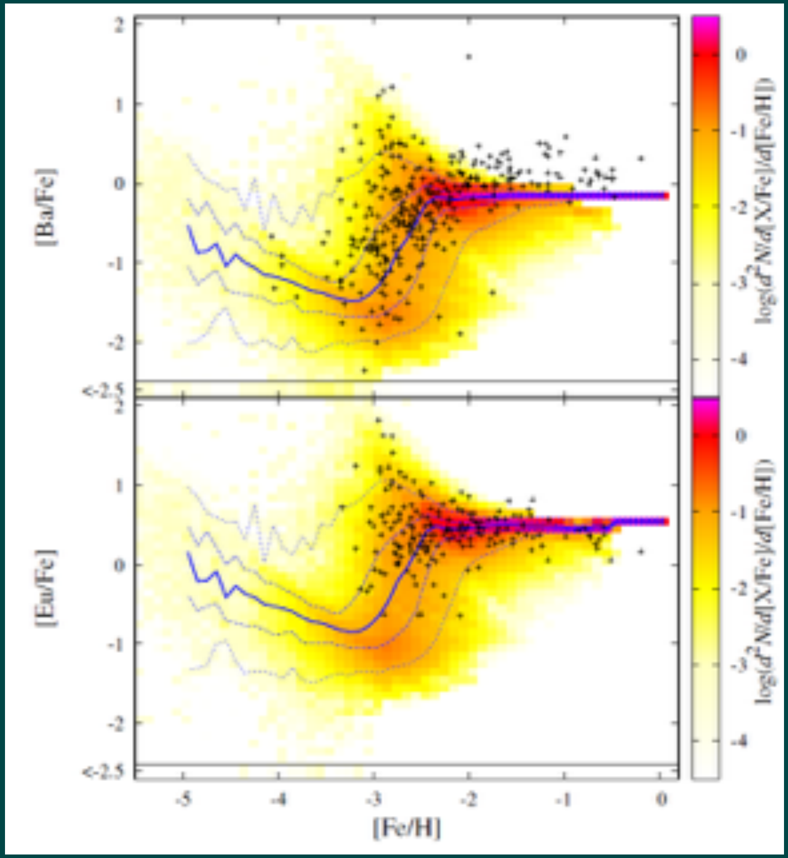


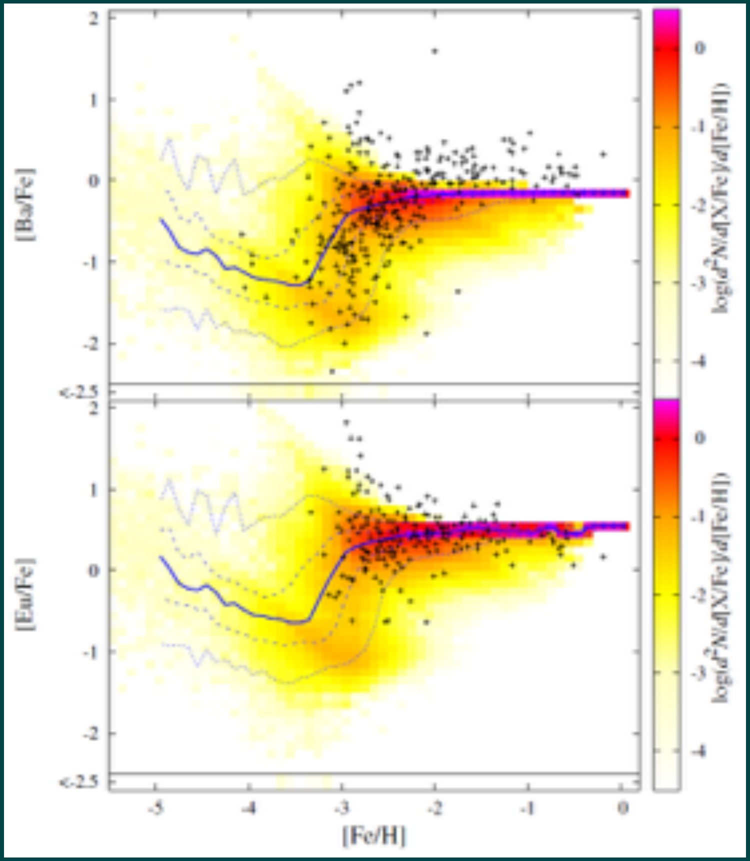
t_d = 10^6 – 10^8 yr



t_d = 10^8 – 10^10 yr

Event rate





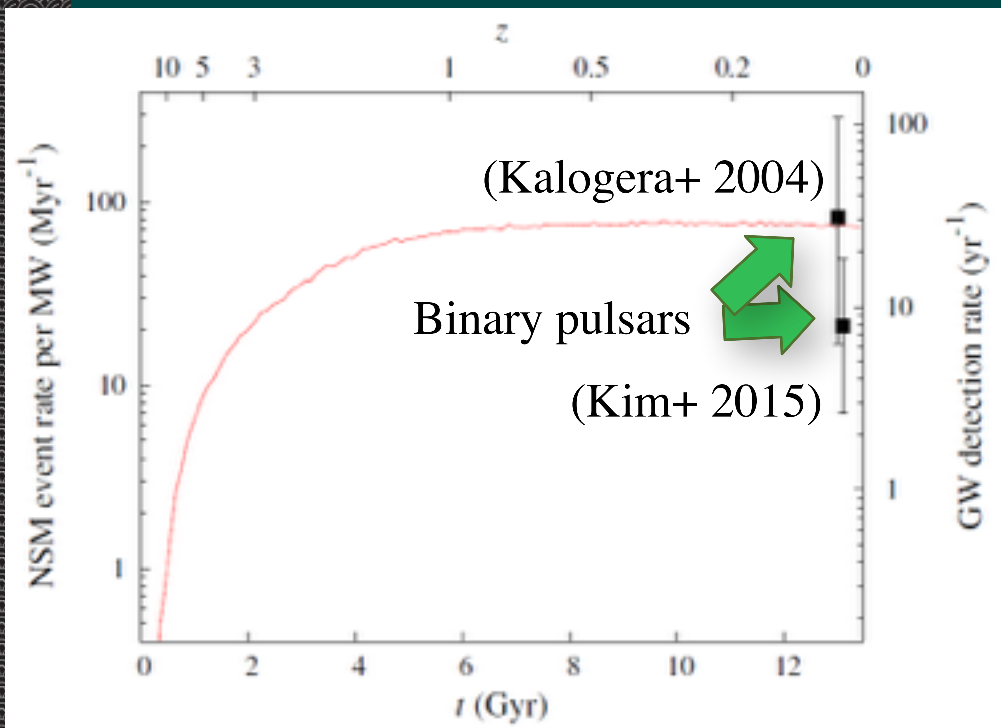
1% of binaries with M = 8 – 25 $M_\odot$

Yr = 0.03$M_\odot$

10%,

Yr = 0.003$M_\odot$

Event rate



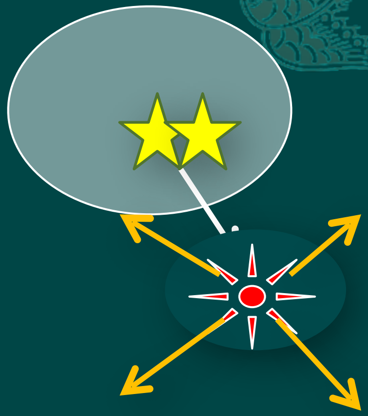
1% of binaries with m = 8 – 25 $M_\odot$

= ~70 NSMs/Myr in the MW

= ~30 GW events /yr

(Advanced LIGO-Virgo)

Proper motion of NS binary



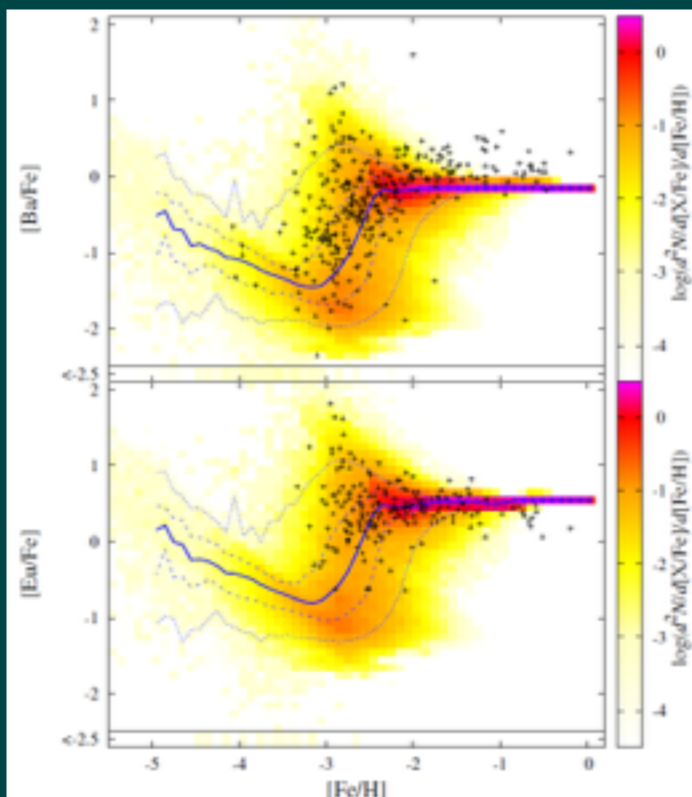
- NS binary can go away from mini-halo
- ATNF pulsar catalog
  - 12 binary pulsars
  - v_z = distance from the Galactic disk / age
    - 10 binaries $v_z < 5$km/s
    - v_z =58km/s
    - v_z =170km/s (but z=0.02kpc, age ~ 10^5 yr)

Proper motion of NS binary

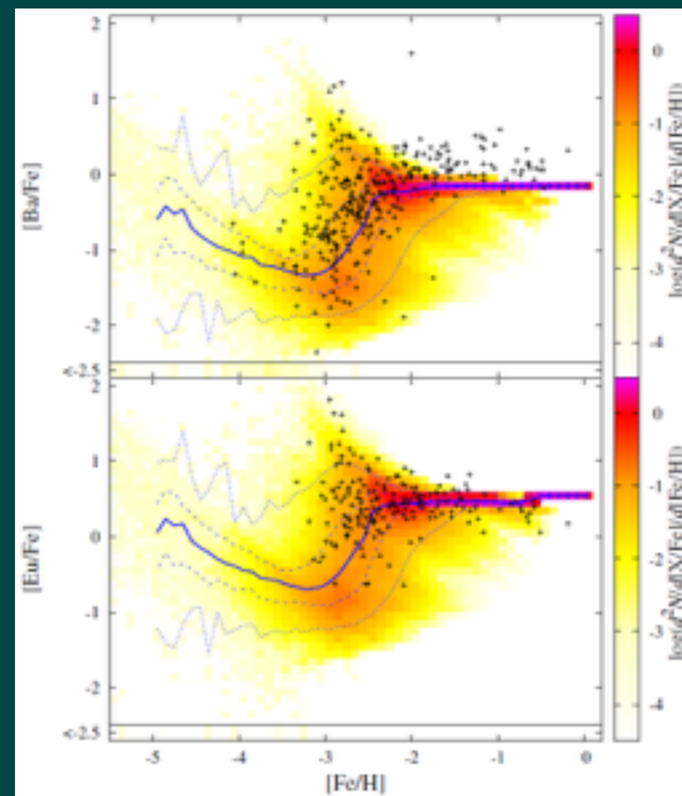
Preliminar
y

Kick velocity: v_{kick} Maxwellian velocity distribution wit

If v_{kick} > escape velocity, a NS binary go to intergalactic space



$f_{esc} = 0$



$f_{esc} = \exp(-R_g / l_s)$

Summary

Chemical evolution of r-process element with the Neutron Star Merger scenario considering the hierarchical formation of galaxies

- Previous studies point out inconsistency between the NSM scenario and observations of metal-poor halo stars

- Spread of NSM ejecta beyond a proto-galaxy (l_s ~2.6kpc)
  ⇒ Escape of r-process elements

- Our model can successfully reproduce the observations of r-process elements in very metal-poor stars when we assume
  - Lower SFE in less massive galaxies
  - Escape of NSM ejecta from proto-galaxy

  - Pre-enrichment of IGM
  - Capture of high energy r-process elements

- NSM
  - Short delay time evets (~10^7 yr) are required.
  - High yield (~0.03 $M_\odot$) & low event rate (1% of NS binary) is preferred

- Proper motion of NS binary can contribute the pre-enrichment of IGM