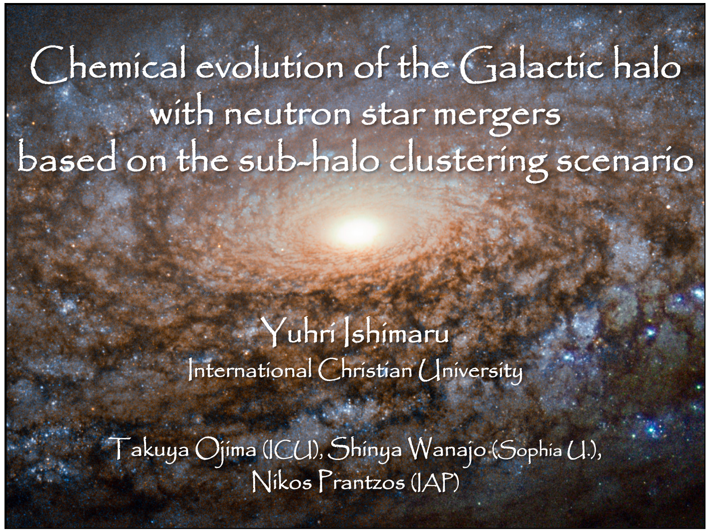
Chemical evolution of the Galactic halo
with neutron star mergers
based on the sub-halo clustering scenario
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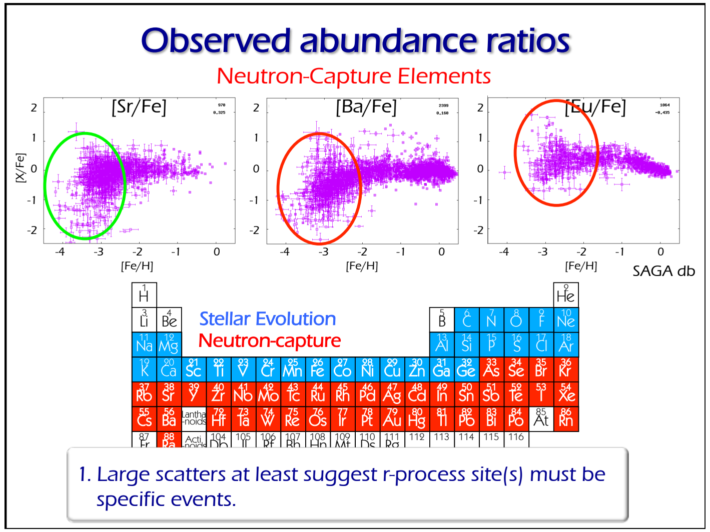
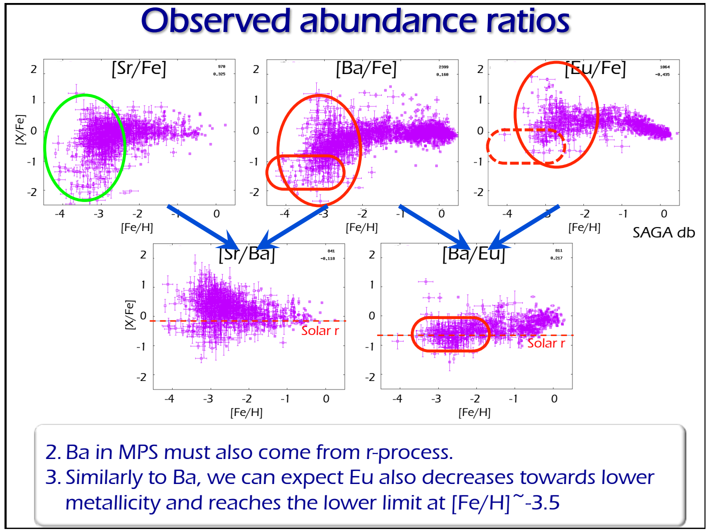
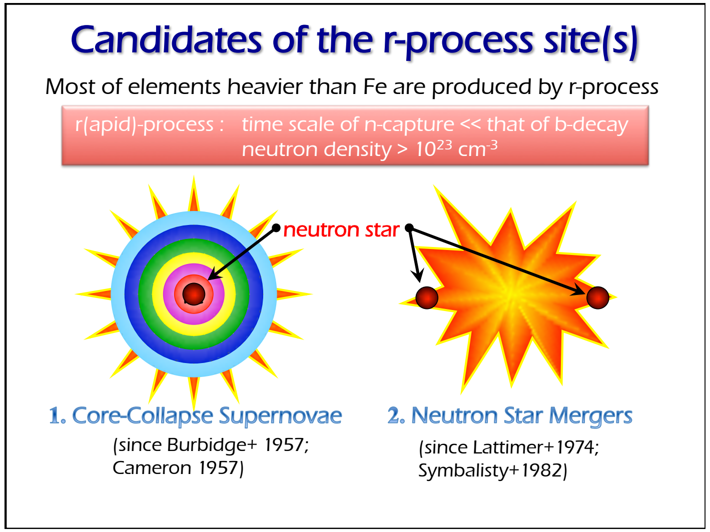
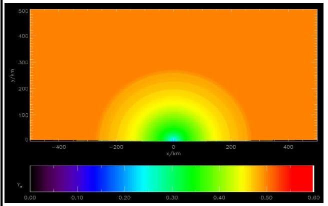

Observed abundance ratios
Neutron-Capture Elements
[Sr/Fe]
[Ba/Fe]
[Eu/Fe]
[X/Fe]
[Fe/H]
SAGA db
Stellar Evolution
Neutron-capture
1. Large scatters at least suggest r-process site(s) must be specific events.

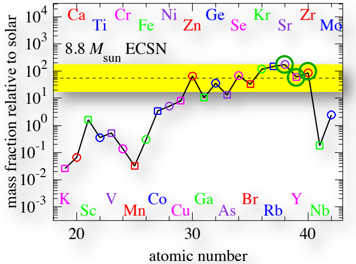

Observed abundance ratios
[Sr/Fe]
[Ba/Fe]
[Eu/Fe]
[X/Fe]
[Fe/H]
SAGA db
[Sr/Ba]
[Ba/Eu]
Solar r
2. Ba in MPS must also come from r-process.
3. Similarly to Ba, we can expect Eu also decreases towards lower metallicity and reaches the lower limit at [Fe/H]~-3.5


Candidates of the r-process site(s)
Most of elements heavier than Fe are produced by r-process
r(apid)-process : time scale of n-capture << that of b-decay
neutron density > 10^{23} cm^{-3}
neutron star
1. Core-Collapse Supernovae
(since Burbidge+ 1957; Cameron 1957)
2. Neutron Star Mergers
(since Lattimer+1974; Symbalisty+1982)

But SNe are difficult to produce heavier r-elements…

Wanajo, Janka, Müller (2011, 2014) suggests that
electron capture SNe can be the souce of lighter r-nuclei,
using self consistent exploding model of ECSNe.

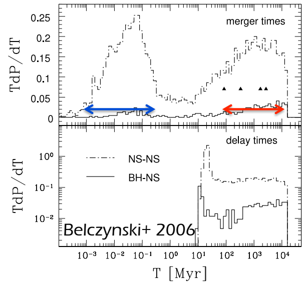




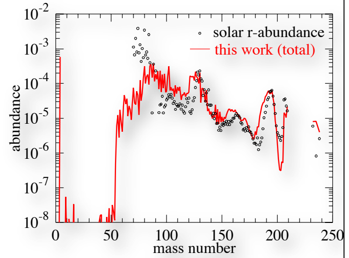
ECSNe possibly be the site of trans-Fe including weak r-process,
but cannot produce main r-process elements.…

Can NS merger be the r-process site?

NSM Time Scale



Nucleosynthesis of NSM



Wanajo et al. (2013)

Time scale of merger

- Classical formation channel : t_{NSM} ~ 100 Myr – 10 Gyr
- New formation channel t_{NSM} ~ 10^3 – 10^5 yr

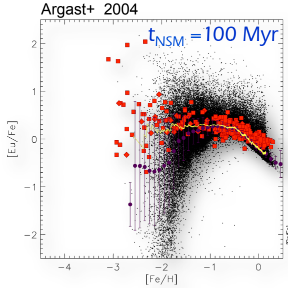
➔ less than 8% of NSMs (Dominik+13)

- good agreement with the full range of the solar r-pattern
- strong support for NS mergers being the origin of r-elements

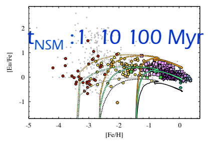
Serious Problem in Chem. Evol. with NSMs

Long merger timescale (~100 Myr) would cause
the delayed appearance of Eu !?

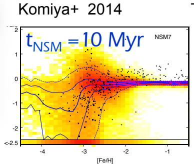
Argast+ 2004



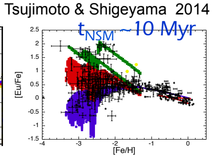
Matteucci+ 2013



Komiya+ 2014



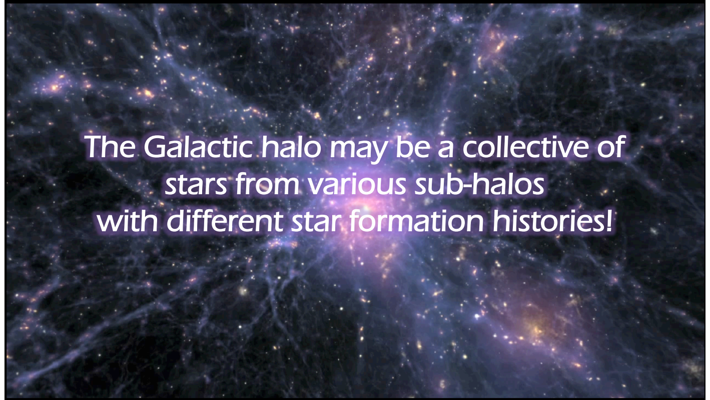
Tsujimoto & Shigeyama 2014



NSMs with long merger time
cannot explain observed scatters in MPS??

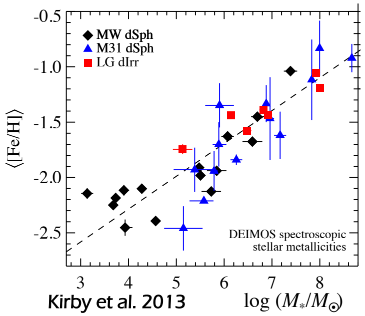
BUT
hierarchical galaxy formation scenario
may not exclude
neutron star mergers !!

According to the ΛCDM model, our Galaxy is formed from clusterings of sub-halos such as dSphs in the local group.



Mass-metallicity Relation

Observations of dwarf galaxies show good correlation between average metallicity and stellar mass, irrespective of their morphologies:



Kirby et al. 2013

$\langle[Fe/H]\rangle \propto (M_*)^{0.3}$

Average metallicity indicates the metal productivity (so-called "galactic yield") of each galaxy.

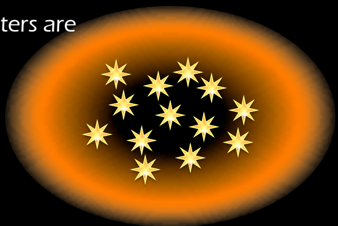
Massive sub-halos must have higher metal productivity!

Formation Scenario of Sub-halos

One of the most plausible formation scenarios of dwarf galaxies: As stars are formed, the ISM is ejected from a galaxy by SNe because of shallow grav. potential.

The key parameters are

Star Formation Rate (SFR)



and Gas Outflow Rate (OFR)

Basic chemical evolution suggests

$$\langle[Fe/H]\rangle \propto \frac{SFR}{OFR}$$

if IMF is universal. (e.g., Pagel 1991, Prantzos 2008)

Chemical Evolution of Sub-halos with NSMs

Ishimaru, Wanajo, Prantzos 2015

MMR suggests $\langle[Fe/H]\rangle \propto \frac{SFR}{OFR} \propto (M_*)^{0.3}$

Therefore, more massive sub-halos have higher SFR or lower OFR.

Two extreme cases are considered:

Case 1:

$SFR / M_{gas} \propto (M_*)^{+0.3}$

OFR / M_{gas} = const.

Case 2:

SFR / M_{gas} = const.

$OFR / M_{gas} \propto (M_*)^{-0.3}$

Fixed values: SFR/M_{gas} = 0.20 Gyr^{-1}, OFR/M_{gas} = 1.0Gyr^{-1} for $M^*=10^8 M_\odot$

NSM:

Merger time: 100 Myr : 1 Myr = 95% : 5%

NSM event rate: 1 per 1000 SNe

Constant Eu yield: 2 x 10^{-5} $M_\odot$

Metallicity Distribution Functions

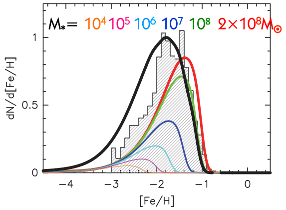
Taking into account of the structure formation simulations and MMR, we obtain the sub-halo mass function as: $dN/dM_* \propto M_*^{-1.7}$

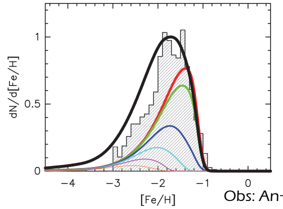
The Galactic halo is regarded as the sum of sub-halos with the weight of the sub-halo mass function.

This scenario can confirm the observed MDF of the Galactic halo.

Case 1: $SFR / M_{gas} \propto (M_*)^{+0.3}$, $OFR / M_{gas} = const.$

Case 2: $SFR / M_{gas} = const.$, $OFR / M_{gas} \propto (M_*)^{-0.3}$



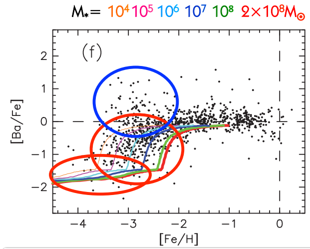


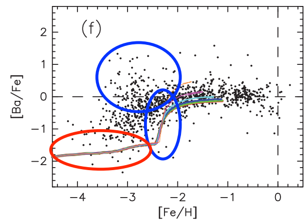
Obs: An+ 2012

Eu & Ba Enrichment with NSMs

Case 1: $SFR / M_{gas} \propto (M_*)^{+0.3}$, $OFR / M_{gas} = const.$

Case 2: $SFR / M_{gas} = const.$, $OFR / M_{gas} \propto (M_*)^{-0.3}$



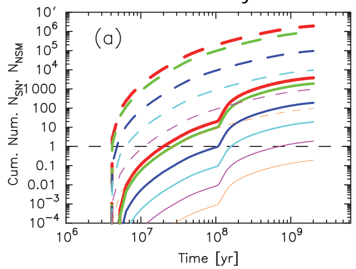


Case 1 suggests that scatters in [Eu/Fe] can be reproduced with NSM, if the Galactic halo are formed from sub-halos with different SFR.

Plateau of [Ba/Fe] at [Fe/H] ≦ -3 possibly come from new formation channel of NSMs with shorter merger time scale

High [r/Fe] stars?

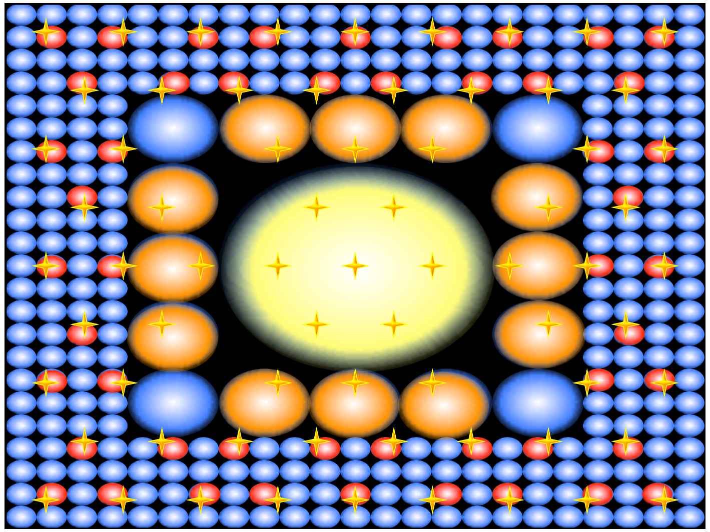
Actually, the total number of NSM in low mass sub-halos must be extremely small!!



In case of 10^4 $M_\odot$ sub-halos, the average of total number of NSMs is as low as 0.1

It means only one sub-halo out of ten suffers NSM!

But stars in such sub-halo must show strong enhancement of Eu!



Stochastic Chemical Evolution of sub-halos with NSMs

Ojima, Ishimaru, Wanajo, & Prantzos in prep.

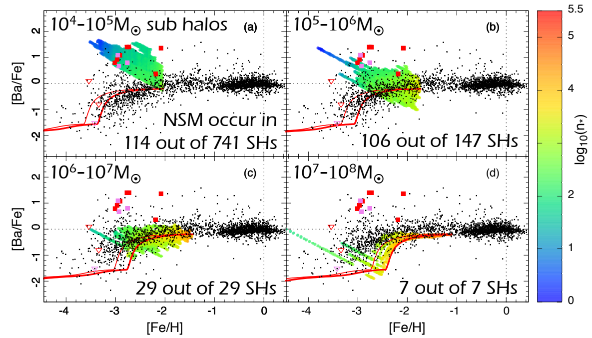
Based on such scenario, we examine enrichment of each sub-halo by NSMs, using Monte-Carlo method.

According to the sub-halo mass function; $dN/dM_* \propto M_*^{-1.7}$, total number of model sub-halos which form the Galactic halo are given as follows:

Stellar Mass [$M_\odot$]	10^4–10^5	10^5–10^6	10^6–10^7	10^7–10^8	10^8 –2×10^8
Num. of sub-halos	741	147	29	6	1
Mean Num. of NSMs /SH	0.174	1.75	19.1	184	694

[Eu/Fe] vs. [Fe/H] in sub-halos

Case 1: $SFR / M_{gas} \propto (M_*)^{+0.3}$ OFR / M_{gas} = const.

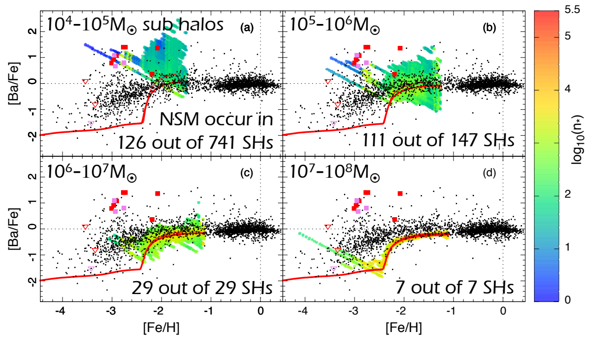


Stars in low mass sub-halos show strong enhancement of Eu!

Stars in massive sub-halos distribute on the average values.

[Eu/Fe] vs. [Fe/H] in sub-halos

Case 2: SFR / M_{gas} = const. $OFR / M_{gas} \propto (M_*)^{-0.3}$



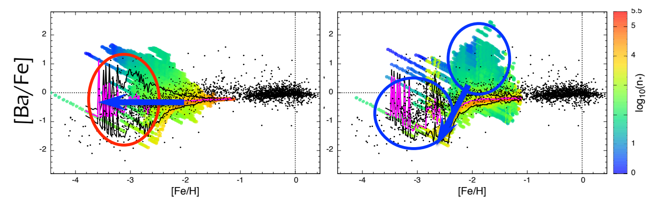
Because of high SFR, enhancement of Eu appears at [Fe/H]=-2

Some stars show extreme high [r/Fe], because of high OFR

Galactic Halo: sum of sub-halos

Case 1: $SFR / M_{gas} \propto (M_*)^{+0.3}$ OFR / M_{gas} = const.

Case 2: SFR / M_{gas} = const. $OFR / M_{gas} \propto (M_*)^{-0.3}$

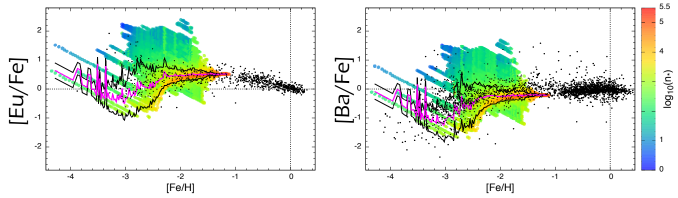


Case 1 reproduce large scatters of [r/Fe] in MPS. But the trend is rather flat.

Case 2 shows clear correlation of [r/Fe] with [Fe/H]. But the dispersion is small for MPS, and high enhancement of [Ba/Fe] is seen at [Fe/H]~-2

The best fit model

SFR / $M_{gas} \propto (M_*)^{+0.2}$ OFR / $M_{gas} \propto (M_*)^{-0.1}$

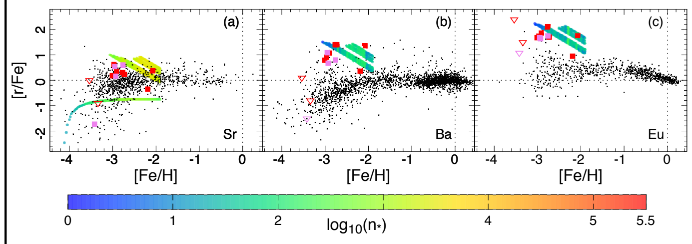


If the Galactic halo was formed from sub-halos with mass-dependent SFR & OFR, NSMs with long coalescence time can well explain observed [r/Fe] of MPS!

UfD: Reticullum II

10^4-$10^{4.1} M_\odot$ sub halos
NSMs occur in 9 out of 138 SHs

●, ●: Reticulum II
(Roederer+16, Ji+16)



In particular, this scenario predict 1 out of 10 UfDs (~$10^4 M_\odot$) shows extremely high [r/Fe], which is consistent with observational data of UfDs!

Conclusions

If the Galactic halo are formed from clusterings of sub-halos with mass depend SFH, i.e.,
SFR / $M_{gas} \propto (M_*)^{+0.2}$, and OFR / $M_{gas} \propto (M_*)^{-0.1}$,

NSMs with long coalescence time, ~100Myr, well explain [r/Fe] in MPS.

This scenario is also consistent with obs. of UfDs:
~90%: (Almost) No r-process
~10%: Strong r-enhanced stars such as Ret II.

These results strongly support NSMs as the site of r-process!