compact binary mergers as the origins of r-process elements

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with

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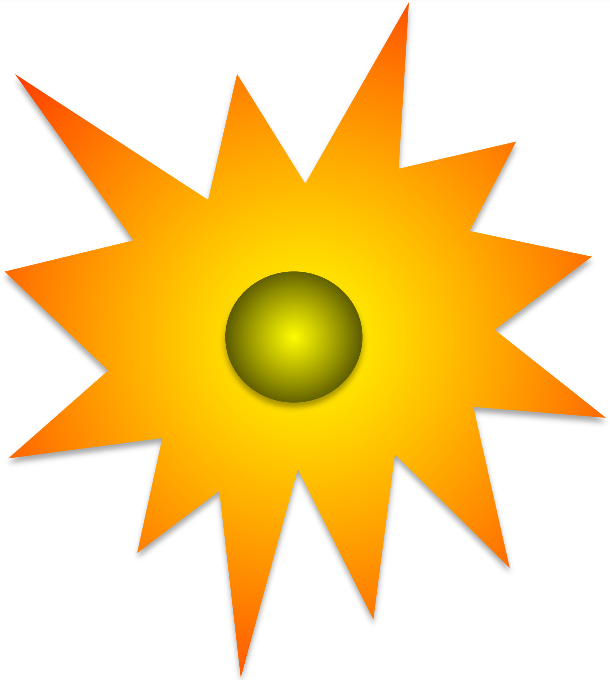
origin of gold (r-process elements) is still unknown...

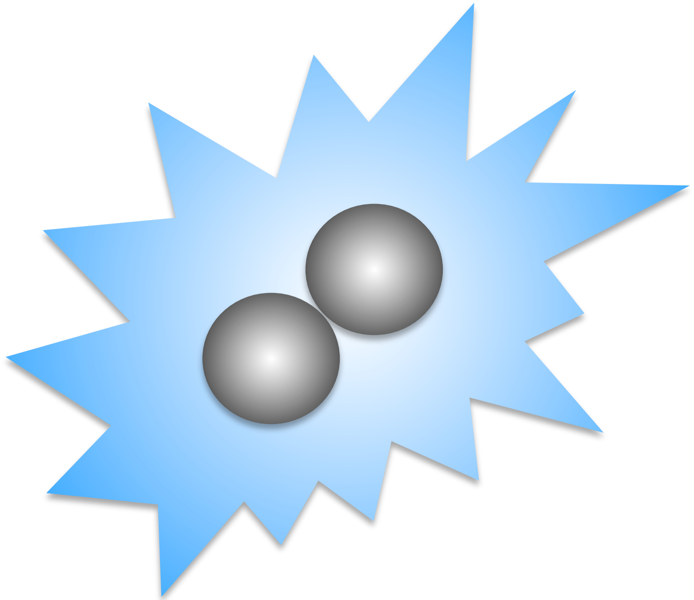
www.cartier.jp

who made the r-process elements?



core-collapse supernovae
(since Burbidge+1957;
Cameron 1957)

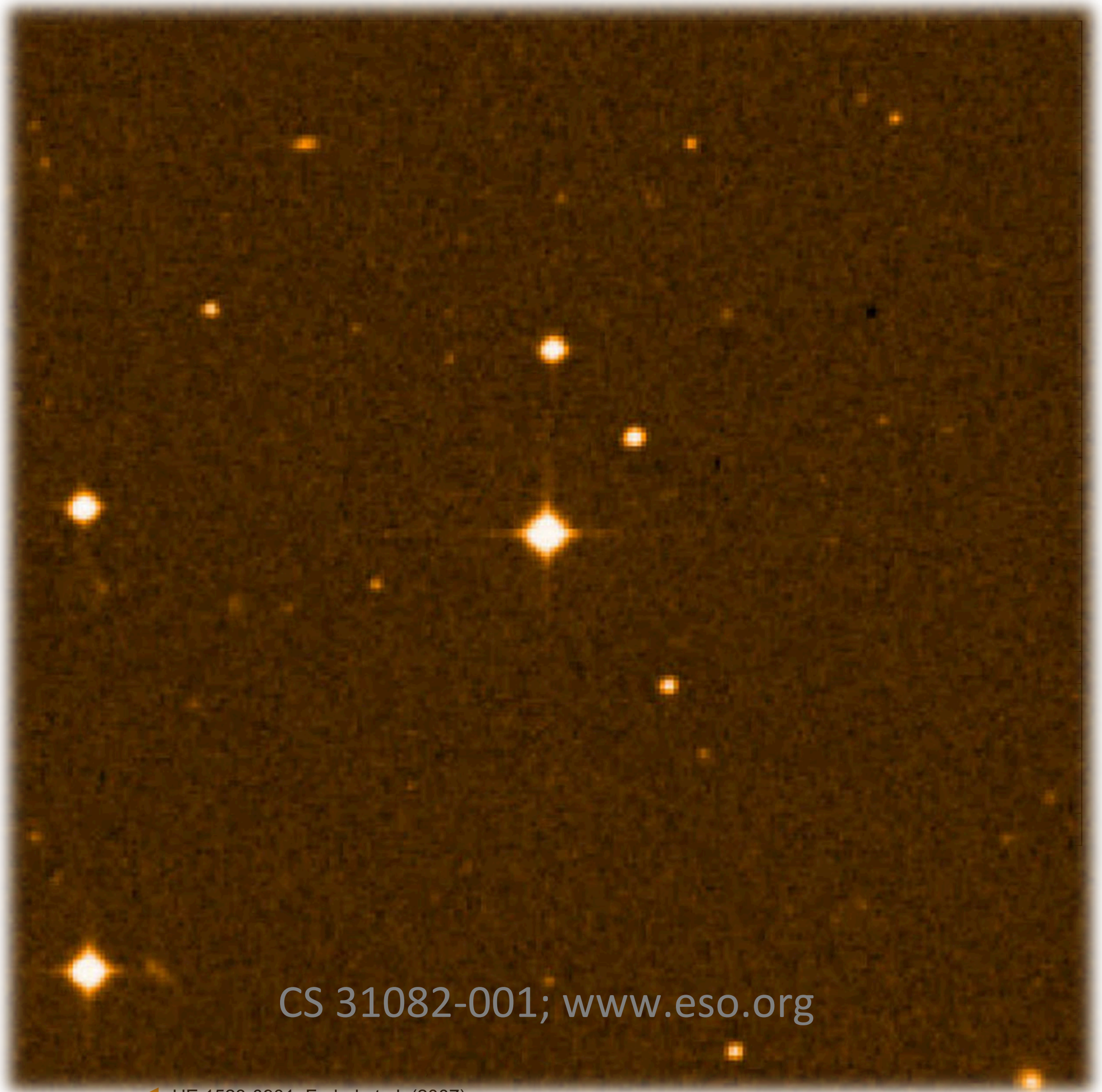
- n-rich ejecta nearby proto-NS
- typical SNe appear to make only weak r-process nuclei



neutron-star mergers
(since Lattimer+1974;
Symbalisty+1982)

- n-rich ejecta from coalescing NS-NS or BH-NS
- recent studies show promise

"universality" of the r-process



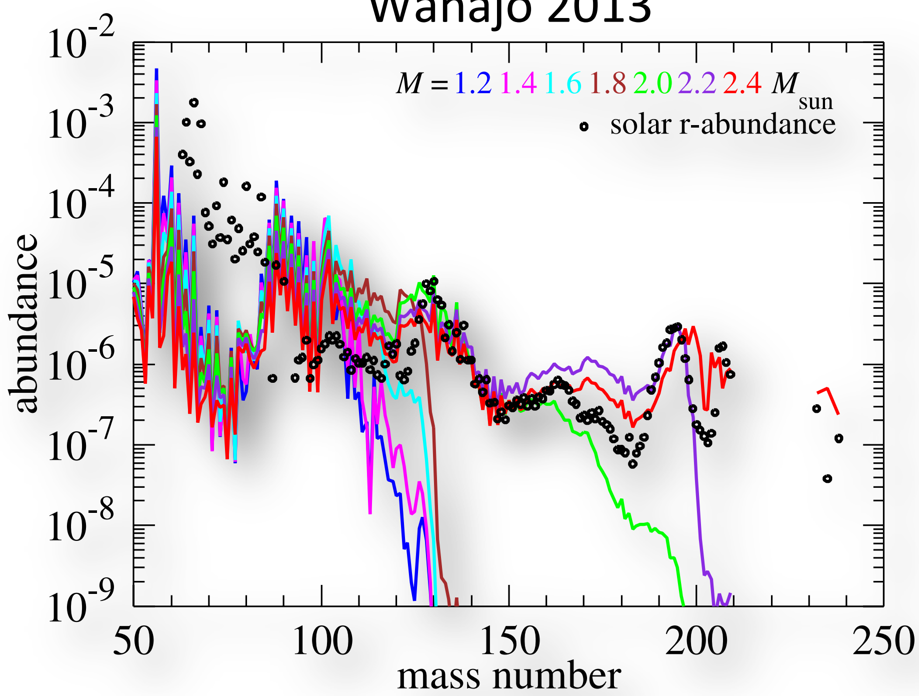
HE 1523-0901: Frebel et al. (2007)

surviving old stars record nucleosynthesis memories in the early universe

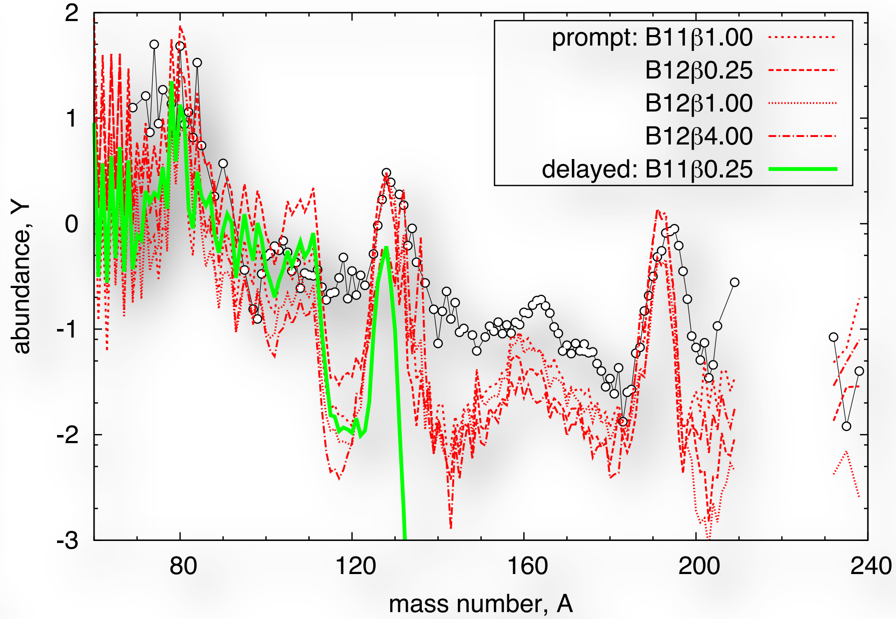
- r-process enhanced stars show constant abundance patterns for $50 < A < 80$
- the r-process appears to be robust for $A \geq 56$ and to have variations for $A < 50$ and $A > 80$

supernovae: not such neutron-rich?

Wanajo 2013

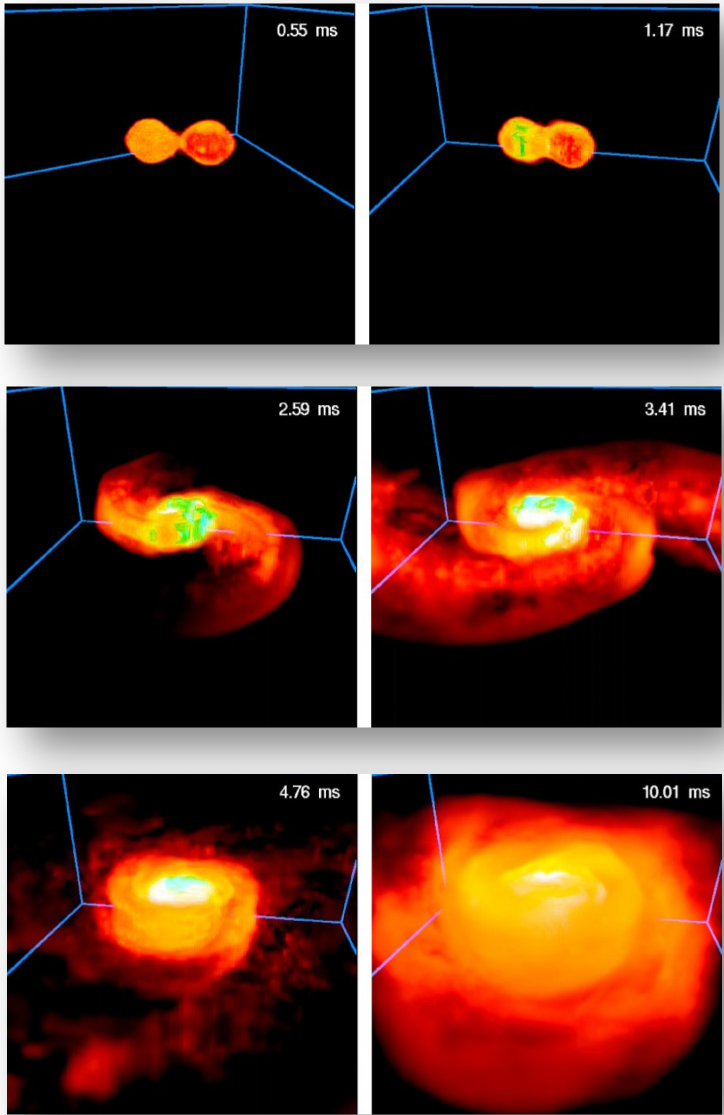


Nishimura, Takiwaki, Thielemann 2015



- ❖ supernova models (ECSN and neutrino-driven wind) explain production of only weak r-elements up to A ~ 110
- ❖ magnetically driven explosions may produce heavy r-process elements (but depending on unconstrained free parameters)

NS merger scenario: most promising?



www.mpa-garching.mpg.de

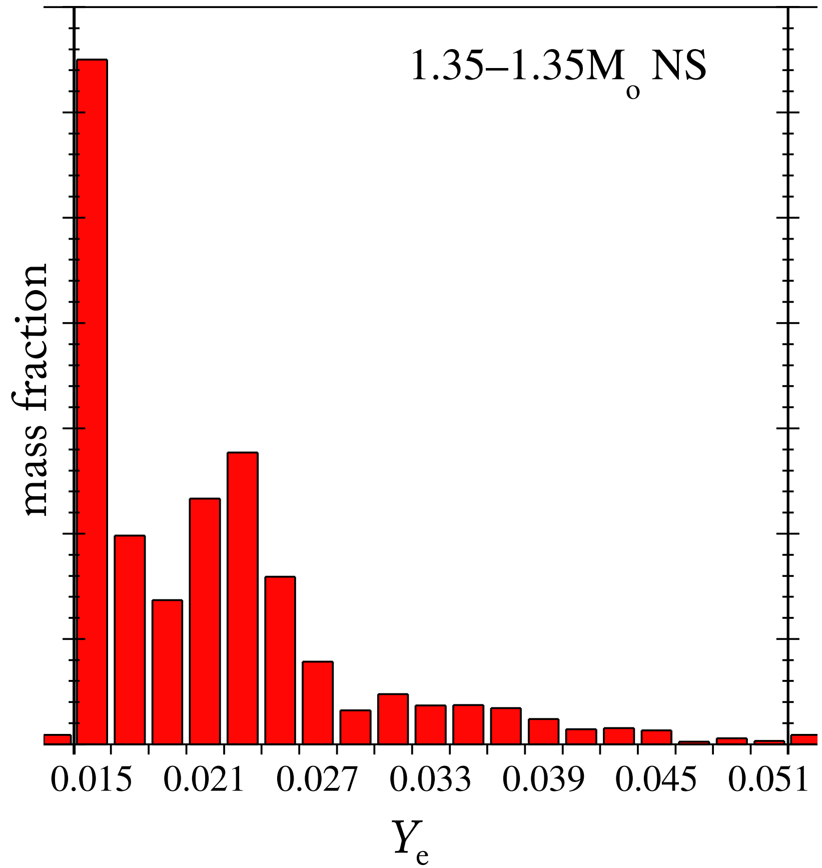
- coalescence of binary NSs expected ~ 10 – 100 per Myr in the Galaxy

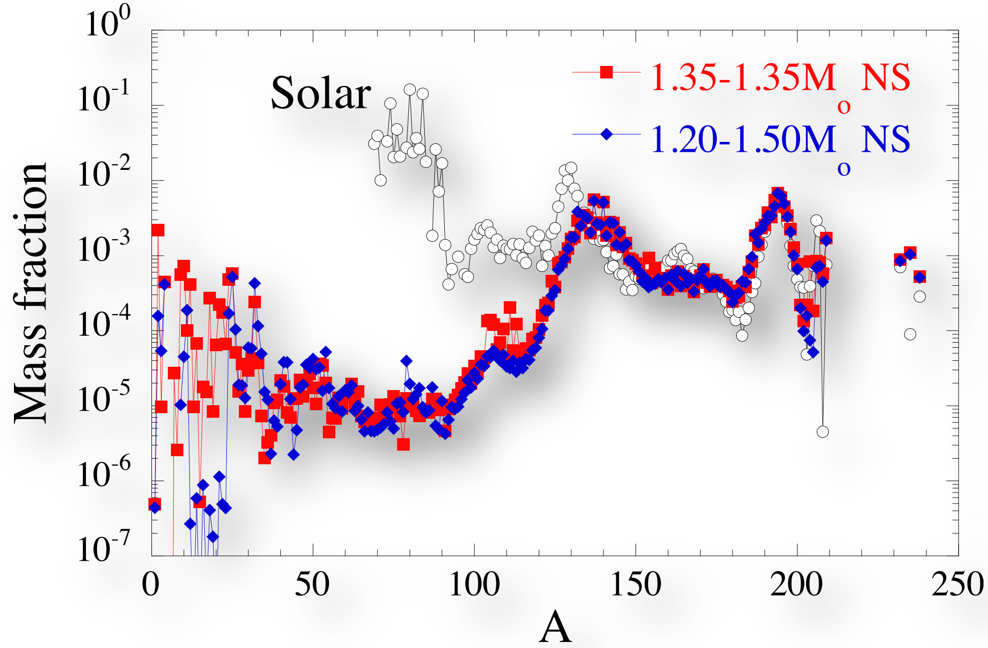
- first ~ 0.1 seconds
  dynamical ejection of n-rich matter up to M_{ej} ~ 10^{-2} $M_{\odot}$ (today's talk)

- next ~ 1 second
  neutrino or viscously driven wind from the BH accretion torus up to M_{ej} ~ 10^{-2} $M_{\odot}$??
  (see the talk by R. Fernandez)

neutron star mergers: too neutron-rich?

Goriely+2011 (also similar results by Korobkin+2011; Rosswog+2013)





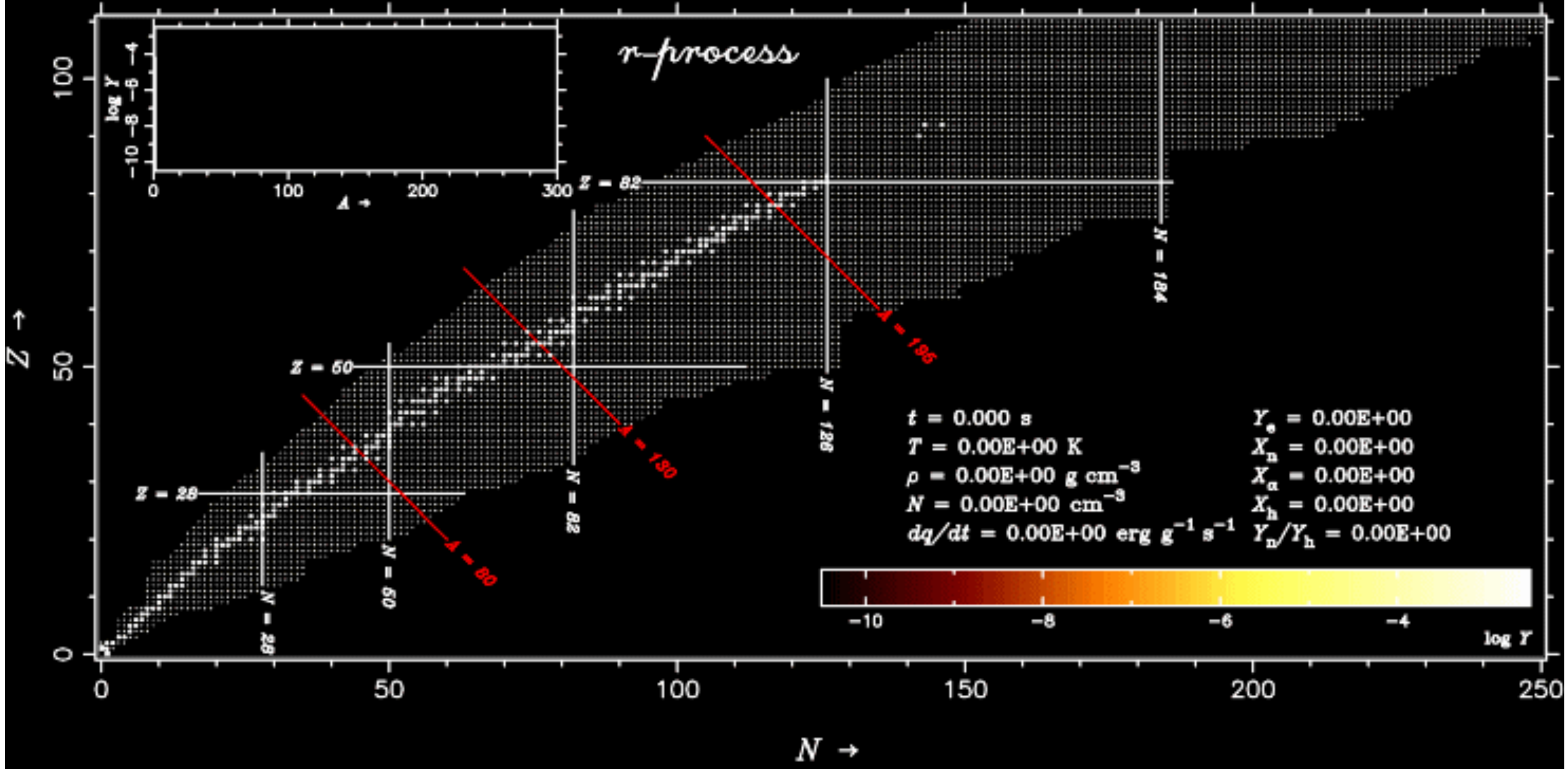
tidal (or weakly shocked) ejection of "pure" n-matter with $Y_e < 0.1$

- ❖ fission cycle leads to robust r-pattern for only $A > 120$ with too small $A < 120$ nuclei
- ❖ fission cycle itself is not "the" r-process

$1.3+1.3\ M_{\odot}$ neutron star merger with full-GR and neutrino transport (SFHo)

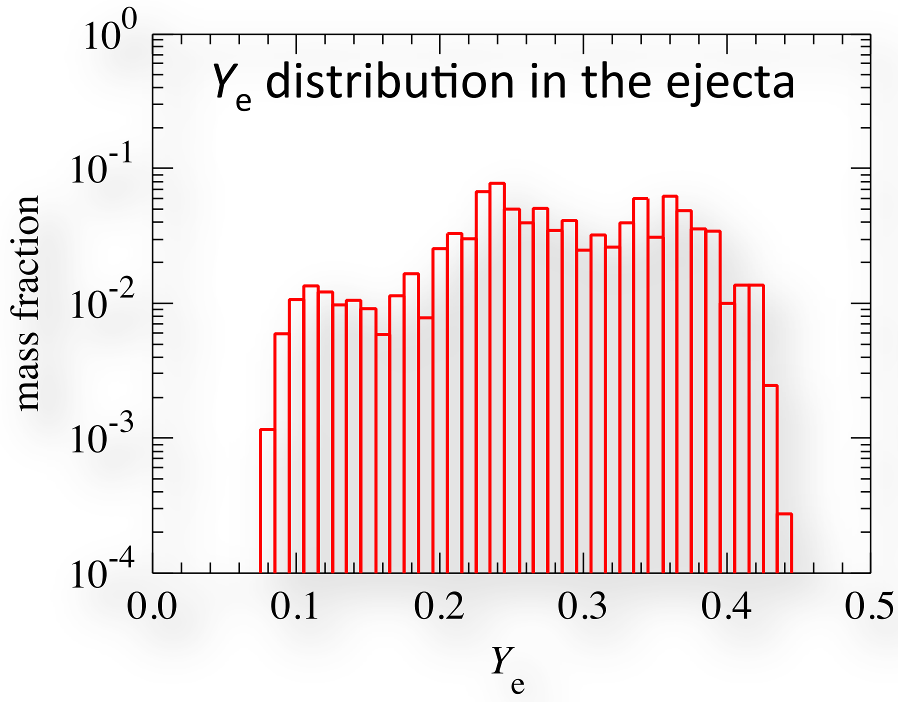
simulation by Yuichiro Sekiguchi

r-process in merger ejecta (Y_e = 0.09)
(n, γ) and β-decay based on HFB-21

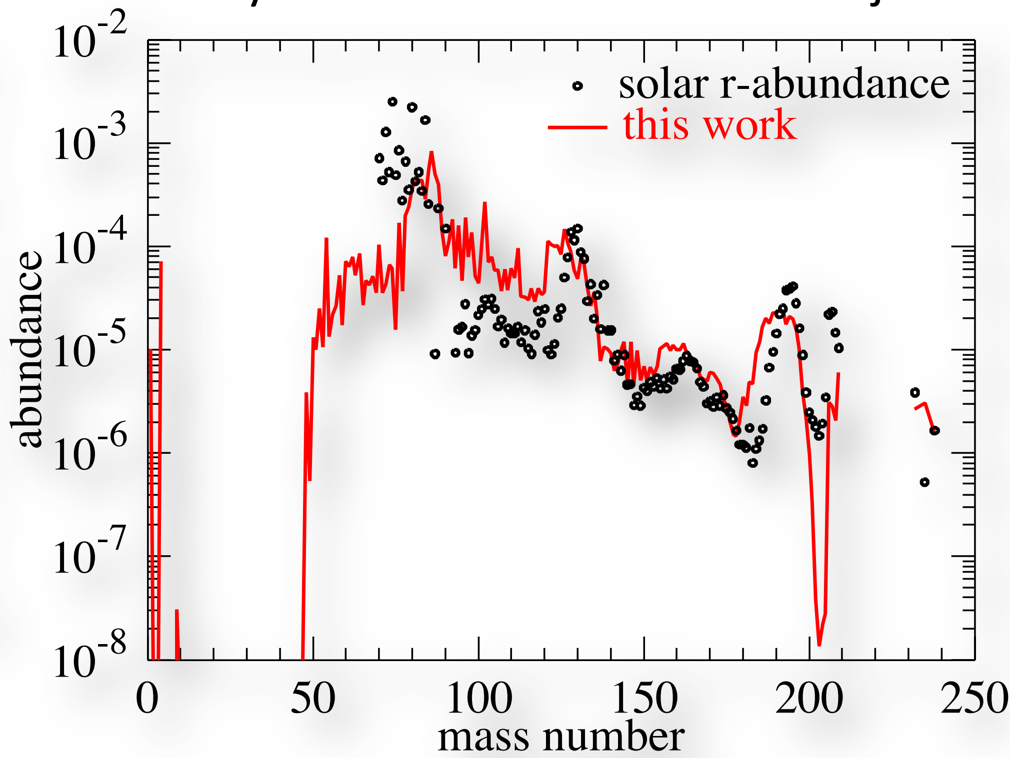


weak interaction saves merger scenario

Wanajo+2014



nucleosynthesis abundances in the ejecta



- positron capture and neutrino absorption on free nucleons result in less neutron-rich ejecta with Y_e ~ 0.1-0.45
- good agreement with full solar r-process range for *A* = 90-240 (similar result by Goriely+2015 but by Radice+2016)

Sekiguchi+2015; 1.35+1.35 $M_\odot$ NSs

Recent result with finite-temperature EOS

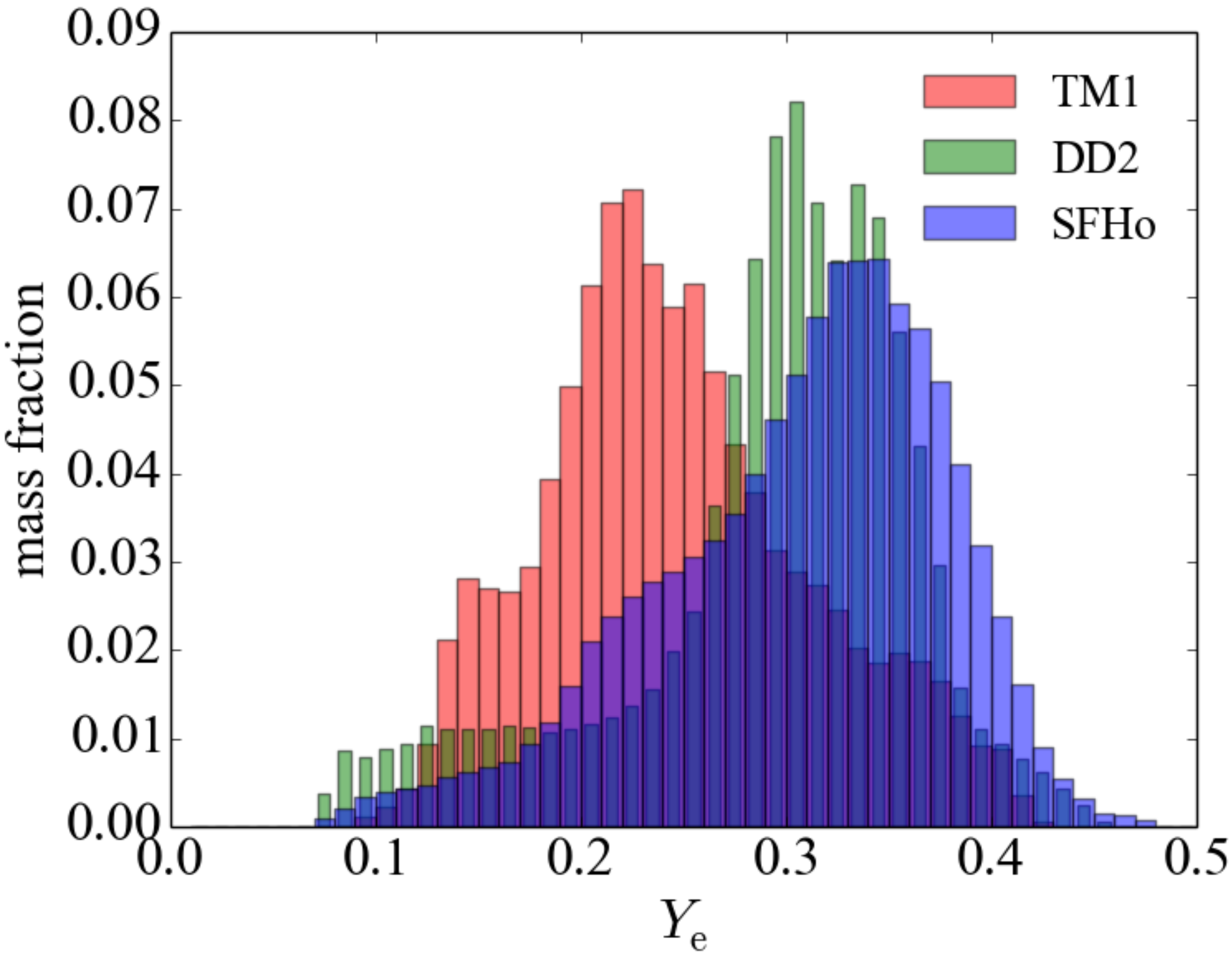
- Multi-EOS study (Thanks to ***M. Hempel***)
- GR approximate ν-hydro simulation
- Adopted EOS

14.5km
- **TM1 (Shen EOS)**
  - **TMA**

13.2km
- **DD2**
  - **IUFSU**

11.8km
- **SFHo**

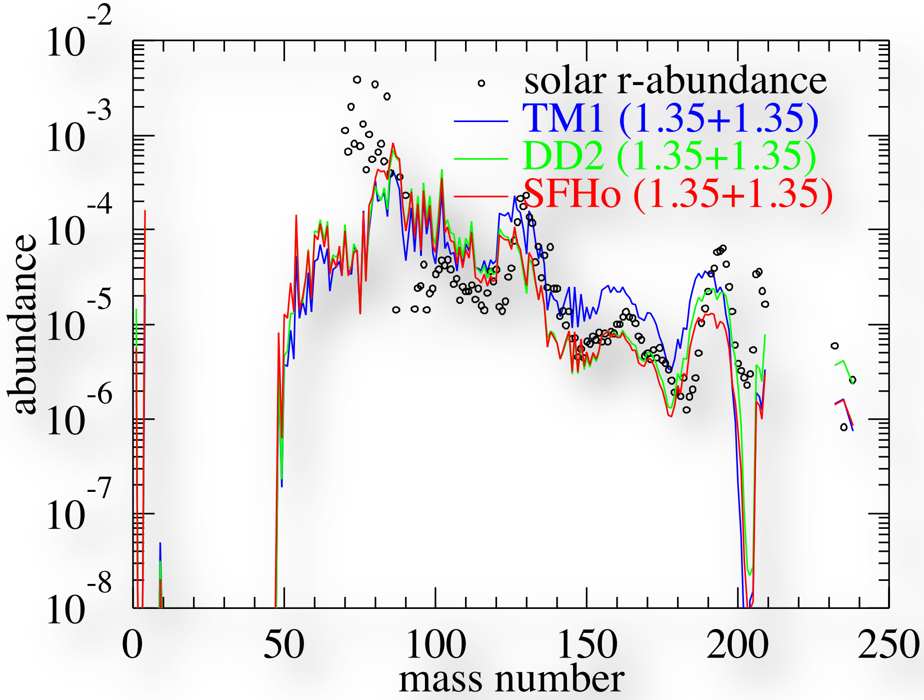
Consistent with
  - NS radius estimat
  - Chiral effective t

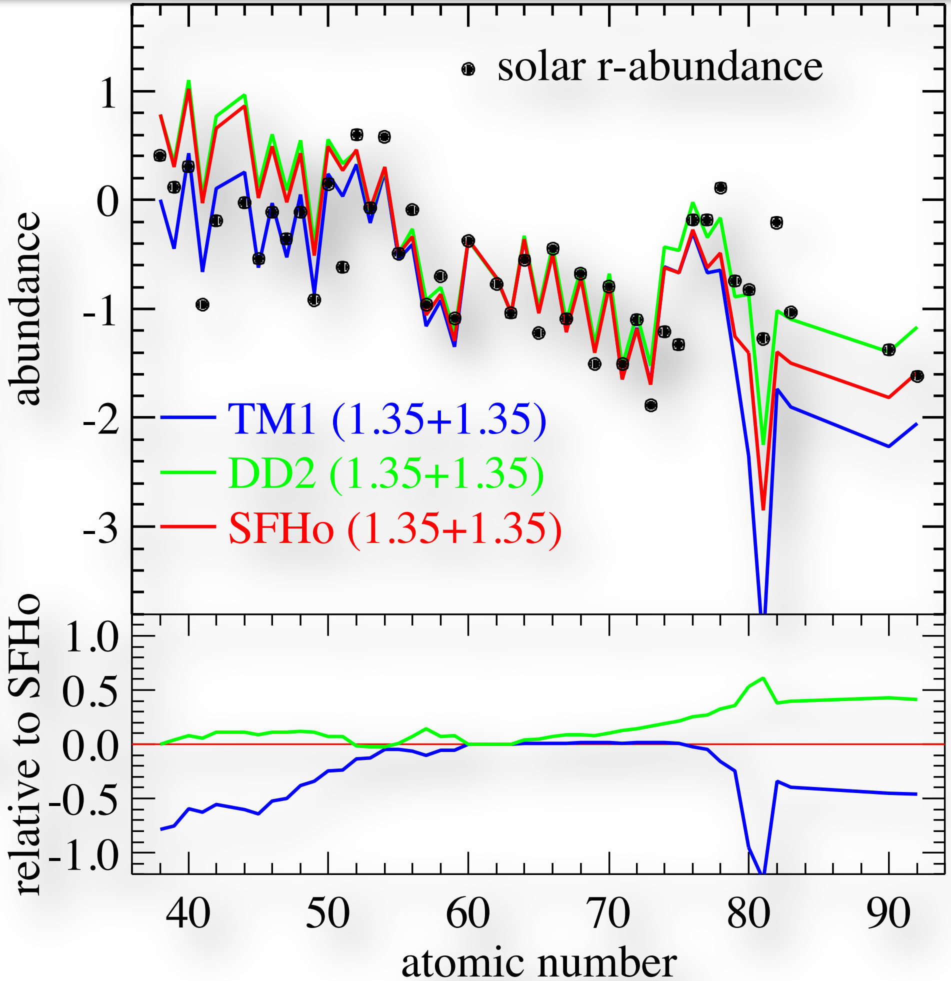


Radius R [km]

dependence on EOSs

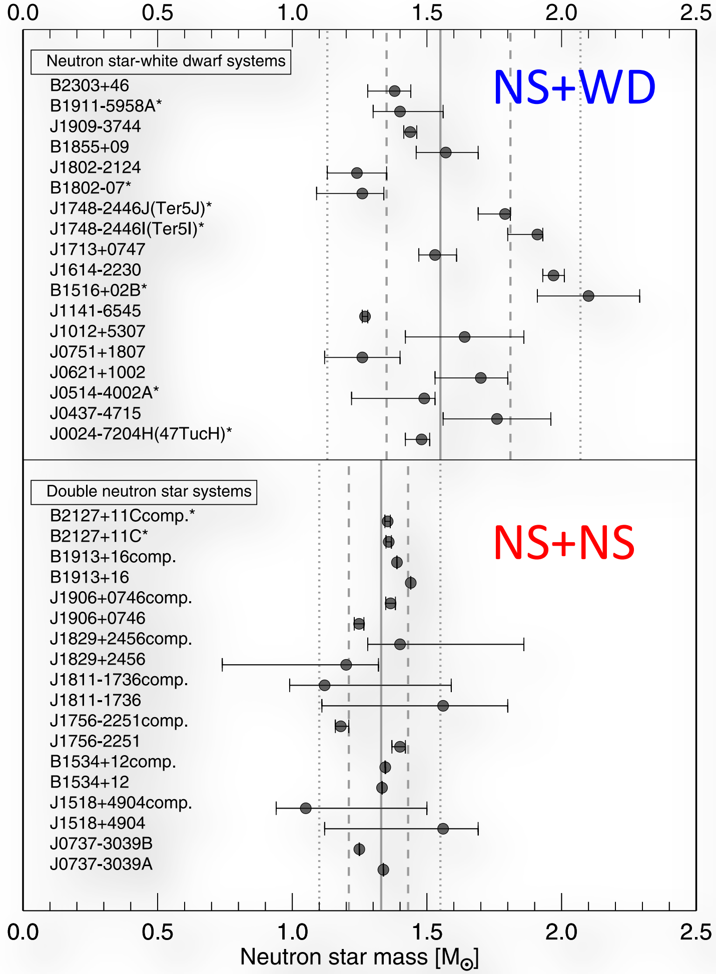
Wanajo+2016; in prep.



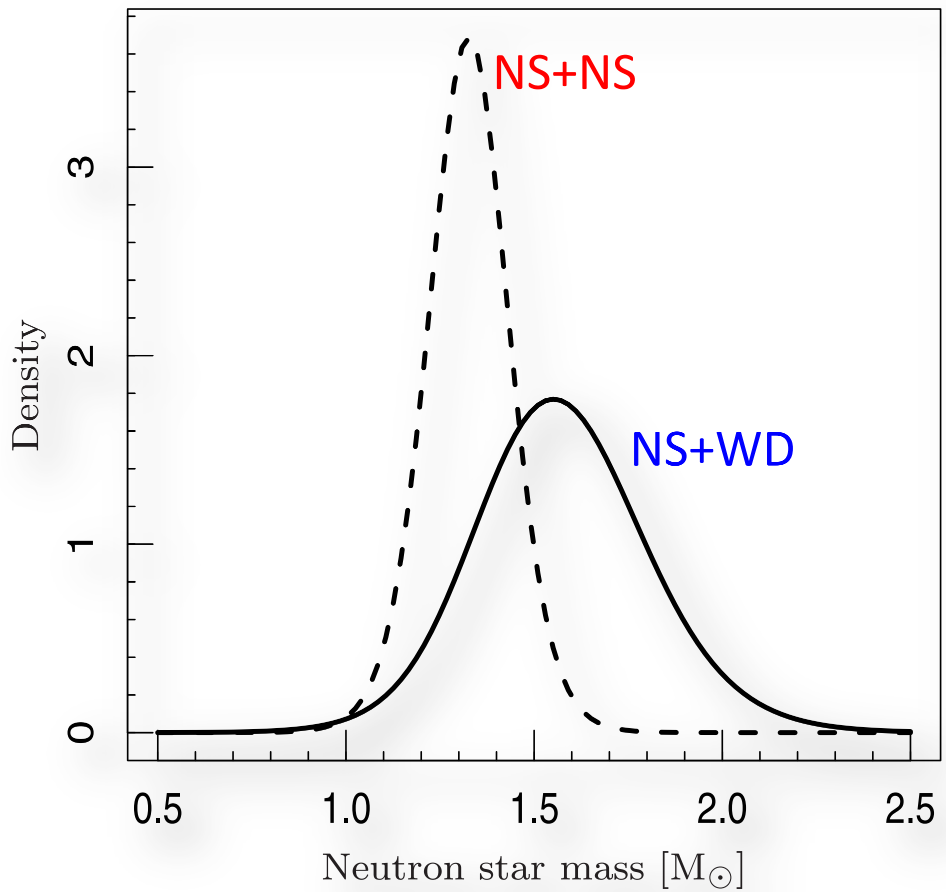


- ❖ softer EOS predicts less heavy r-process products, but
- ❖ effects of EOSs are mild to r-process (good for universality?)

uniqueness of double NS binaries



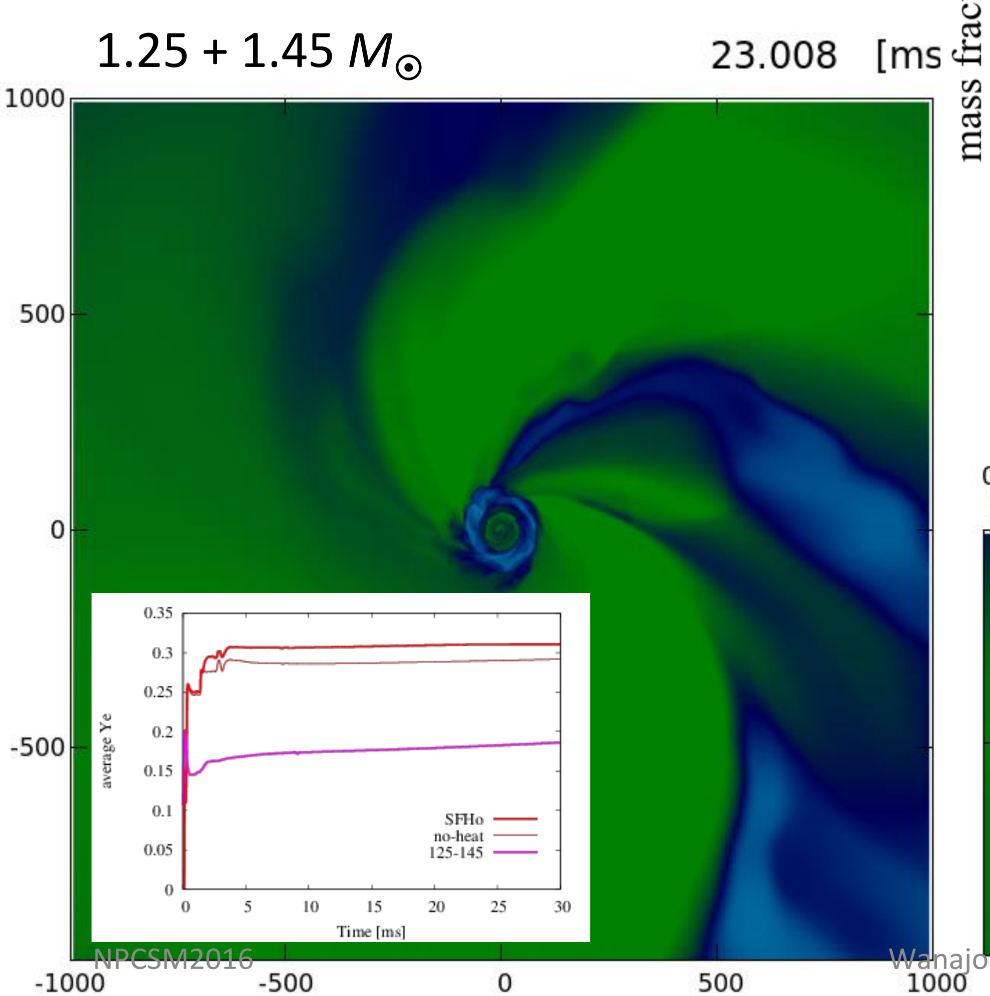
Kiziltan+2013

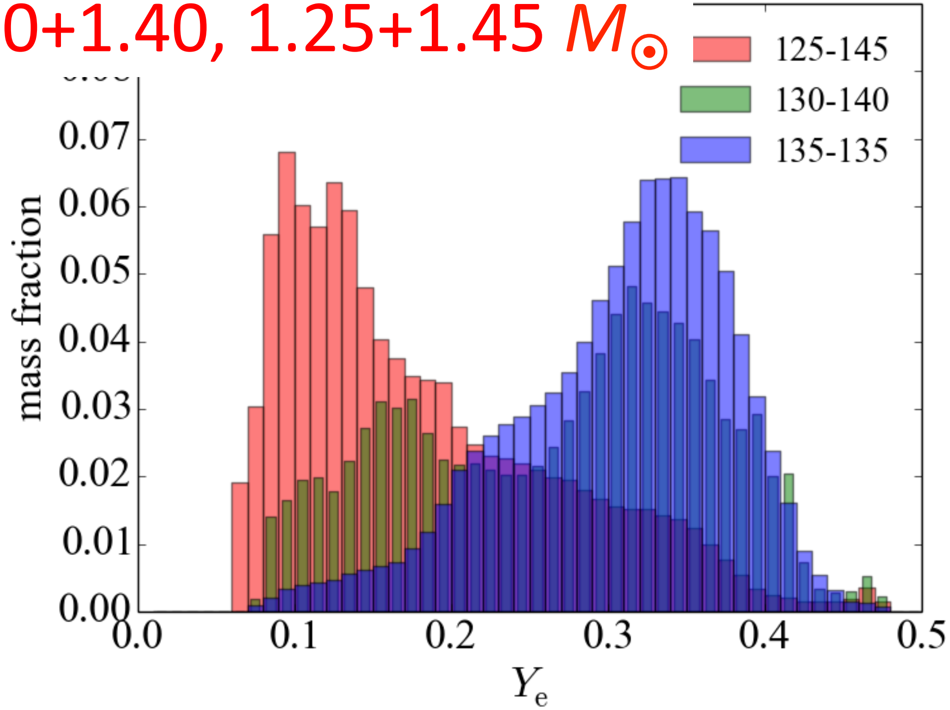


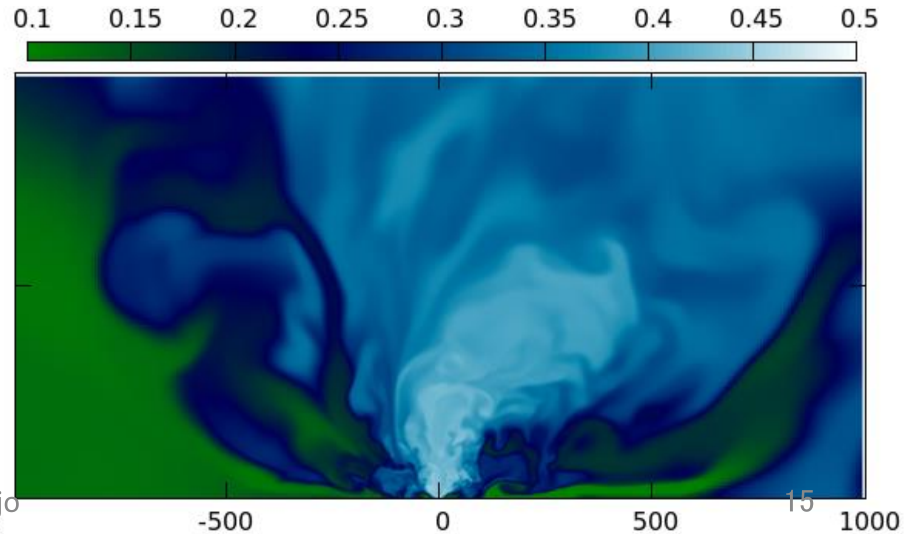
- binaries have various NS masses (1.2-2.0 $M_{\odot}$), but for
- double NS binaries (~ 1.21-1.43 $M_{\odot}$, but see Martinez+2015)

Sekiguchi+2016; 1.35+1.35, 1.30+1.40, 1.25+1.45 $M_\odot$

- Orbital plane : Tidal effects play a role,
- Meridian plane : shock + neutrinos play

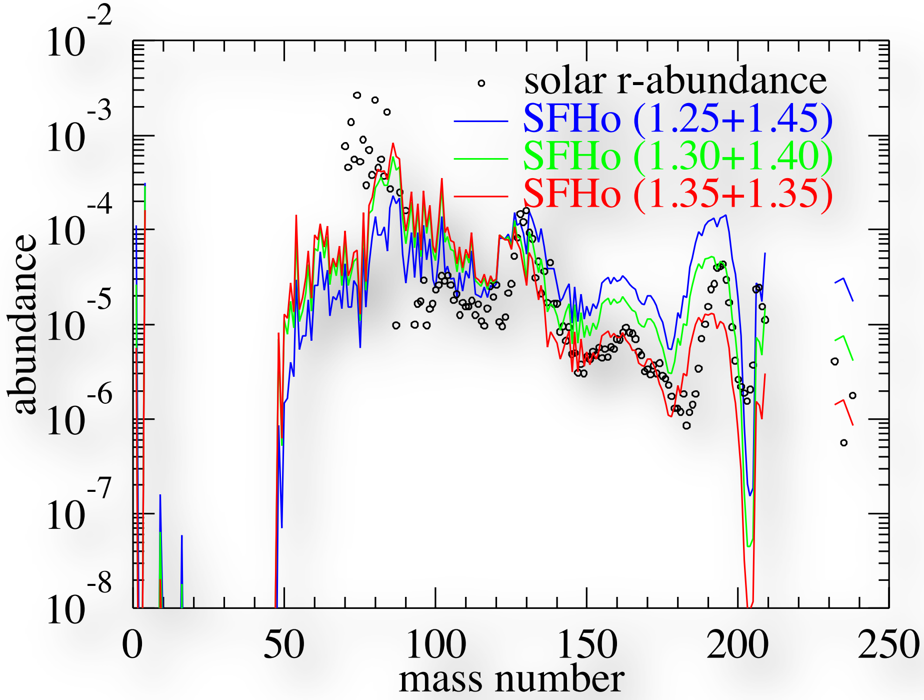


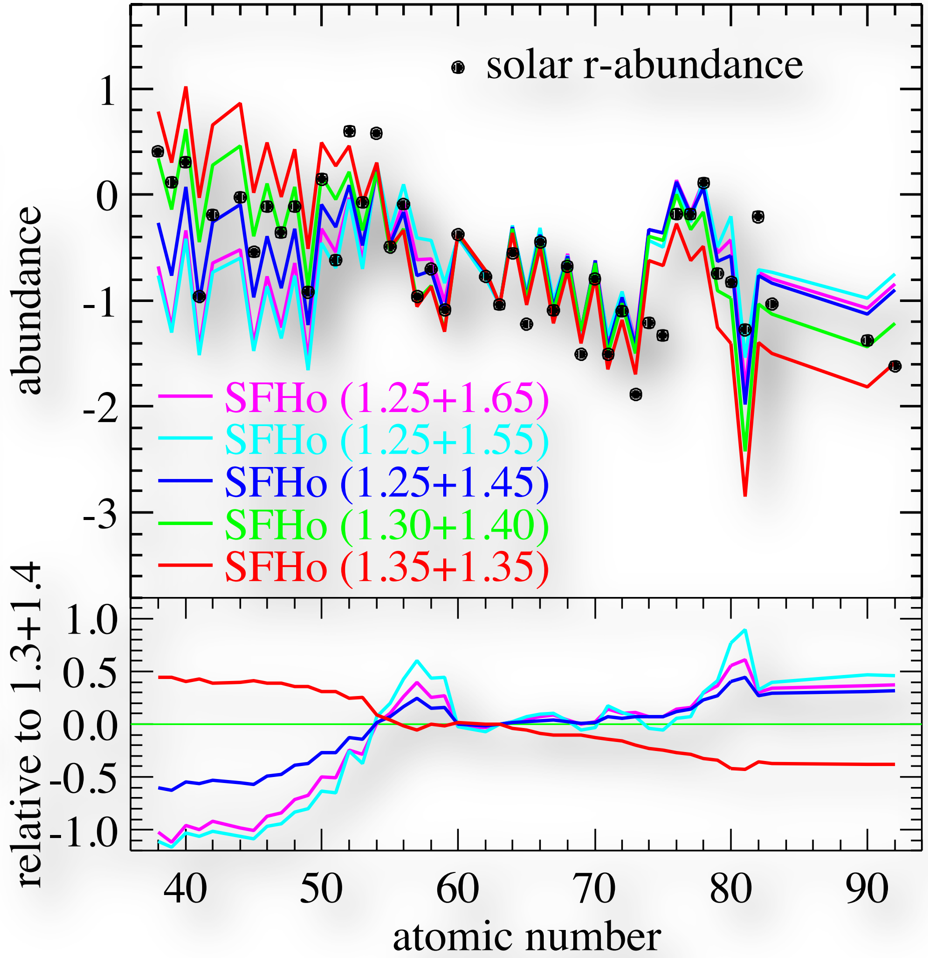




dependence on mass ratios (SFHo)

Wanajo+2016; in prep.



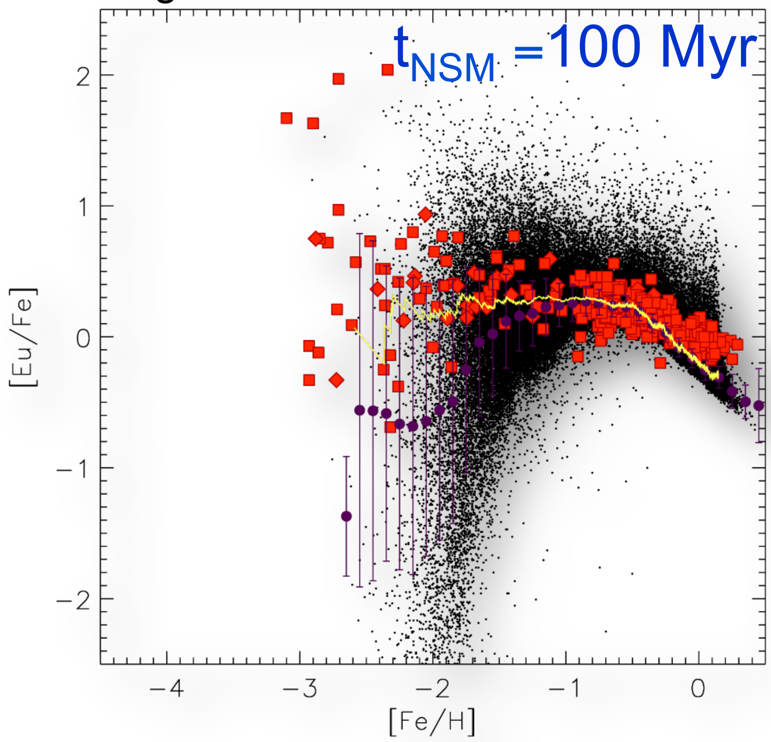


- ❖ small asymmetry predicts small variation in light r-process products
- ❖ uniqueness of the double NSs may be the origin of the universality?

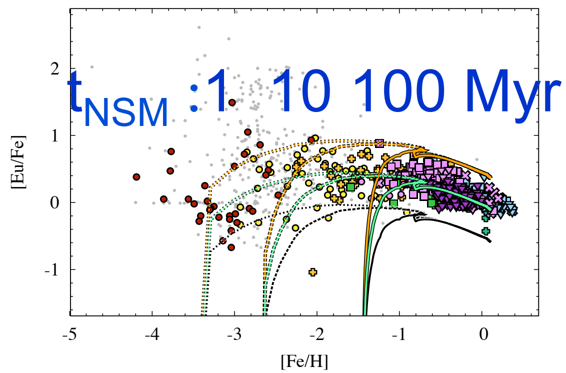
Serious Problem in Chem. Evol. with NSMs

Long merger timescale (∼100 Myr) could cause
the "delayed" appearance of Eu !?

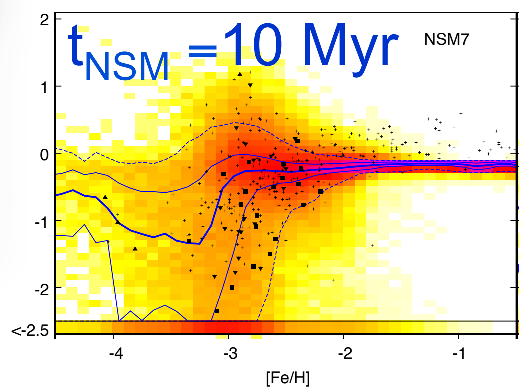
Argast+2004



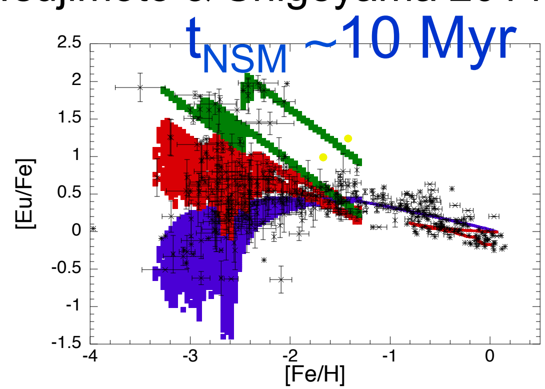
Matteucci+2013



Komiya+2014



Tsujimoto & Shigeyama 2014



NSMs with long merger time
cannot explain observed scatters in metal poor stars??

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)

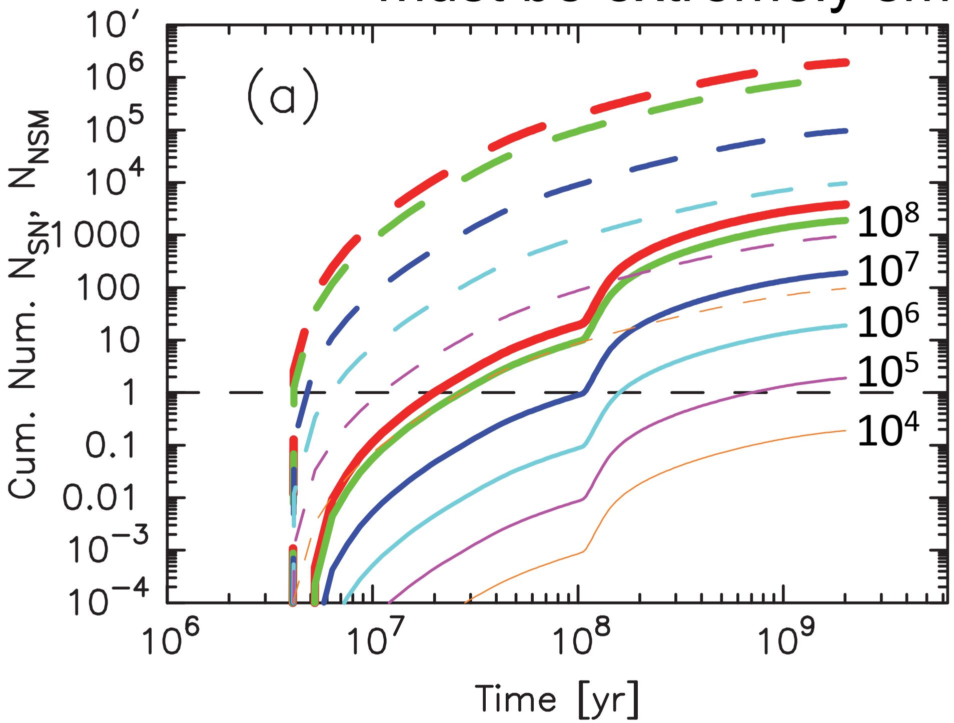
Basic chemical evolution suggests

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

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

rareness of mergers in low-mass sub-halos

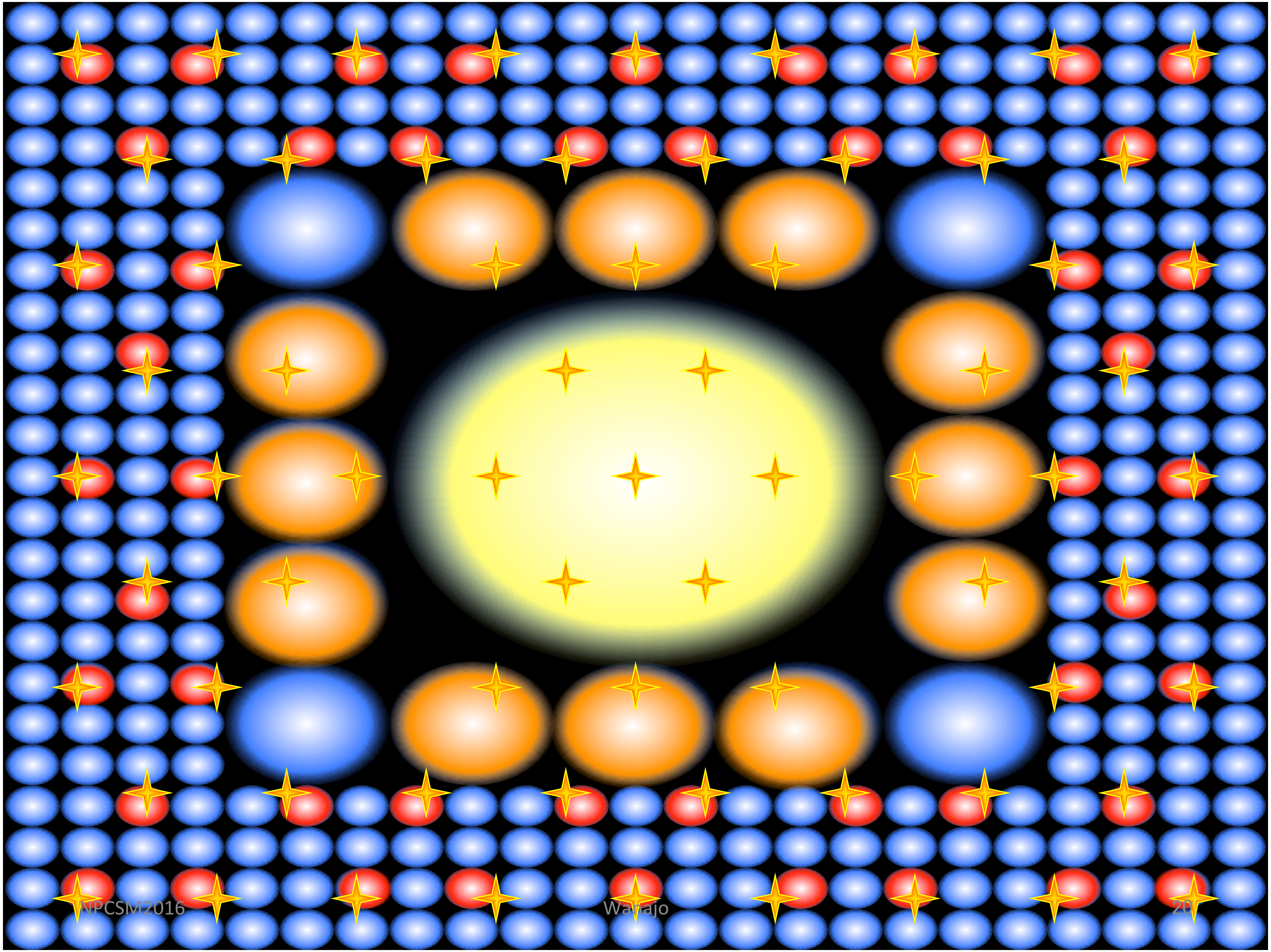
the total number of NSMs in low mass sub-halos
must be extremely small!!



Ishimaru, Wanajo, Prantzos 2015

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

It means only one sub-halo out of ten experiences a NSM event
and stars in such sub-halo should show strong enhancement in Eu



Stochastic Chemical Evolution of sub-halos with NSMs

Ojima, Ishimaru, Wanajo, & Prantzos, in prep.

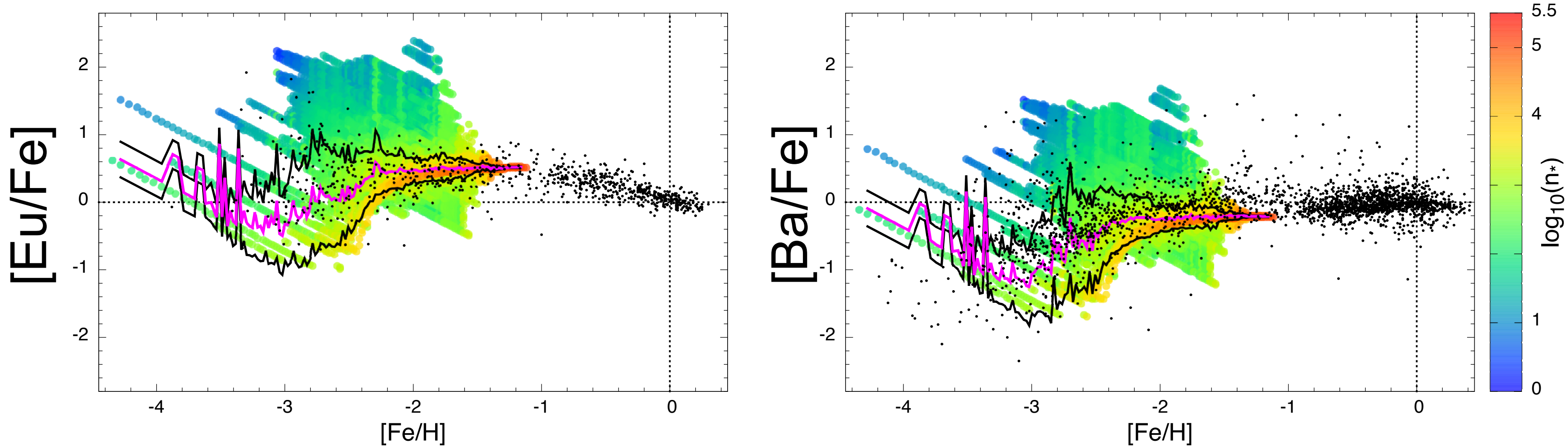
Based on this scenario, we examine enrichment of each sub-halo by NSMs, using a Monte-Carlo method.

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

the best fit model (t_{NSM} = 100 Myr)

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



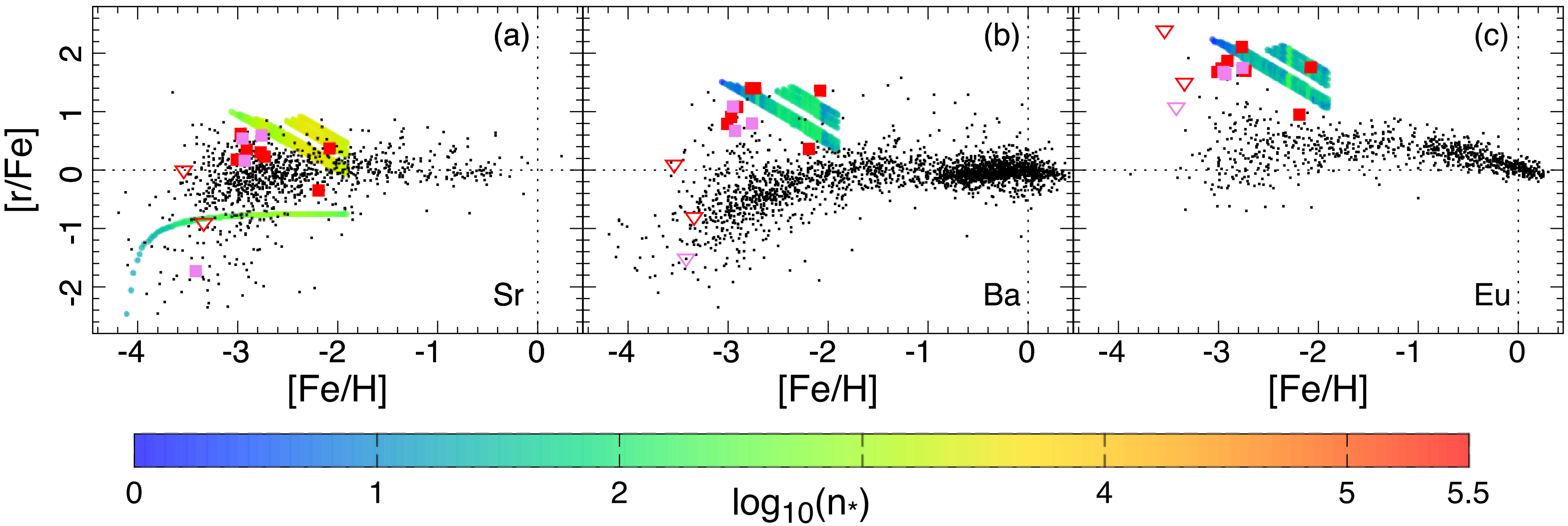
If the Galactic halo was formed from sub-halos with mass-dependent SFR & OFR, NSMs with long coalescence time (~100 Myr) can well explain observed [r/Fe] in metal-poor stars

ultra-faint dwarf (UfD) : Reticullum II

10^4-$10^{4.1}M_\odot$ sub halos

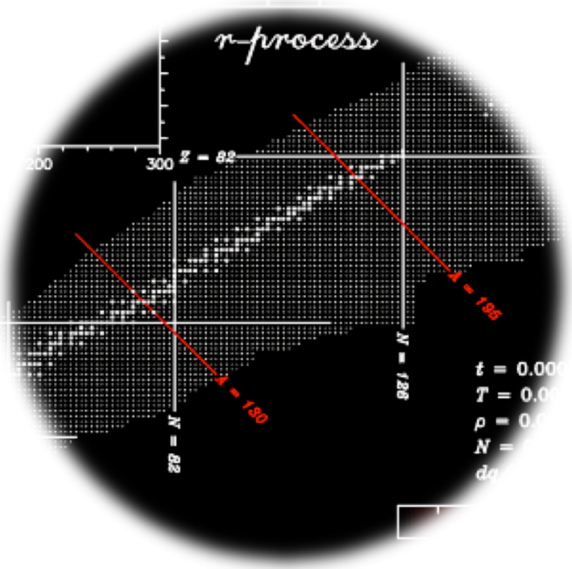
NSMs occur in 9 out of 138 SHs

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



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

summary and outlook



❖ NS mergers: very promising site of r-process
- dynamical ejecta can explain the r-abundances in metal-poor stars
- uniqueness of double NS masses may be origin of the universality

❖ hierarchical, stochastic Galactic chemical evolution of r-elements
- observational aspects of r/Fe are well explained with t_{NSM} = 100 Myr
- consistent with high r/Fe in one (Reticullum II) out of 10 UfDs