origin of r-process elements

Shinya Wanajo (Sophia Univ. / RIKEN iTHES)

with

Y. Sekiguchi (Toho U), N. Nishimura (Keele U),K. Kiuchi (YITP), K. Kyutoku (RIKEN),
M. Shibata (YITP), Hotokezaka, K. (Hebrew U), Tanaka, M. (NAOJ)

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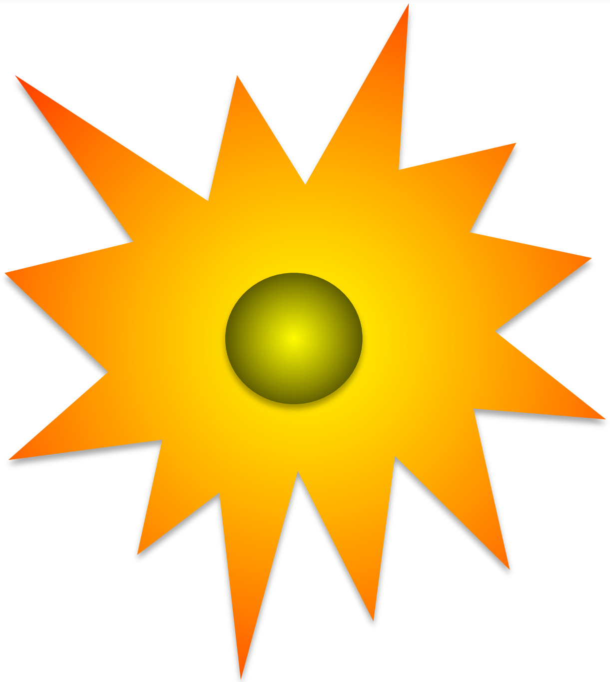
gaining insights into the drivers of galaxy formation and evolution
September 19-23, 2016, Institut d'Astrophysique de Paris, Paris, France

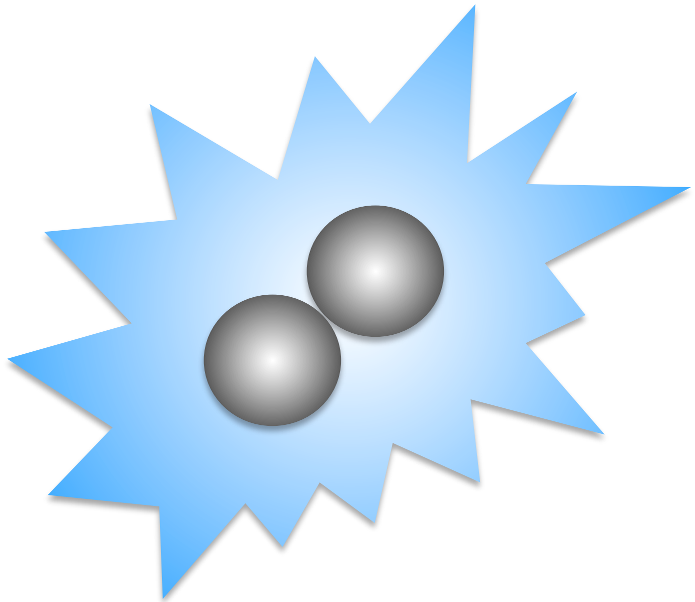
who made the r-process elements?



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

❖ n-rich ejecta nearby proto-NS

❖ typical SNe appear to make only weak r-process nuclei

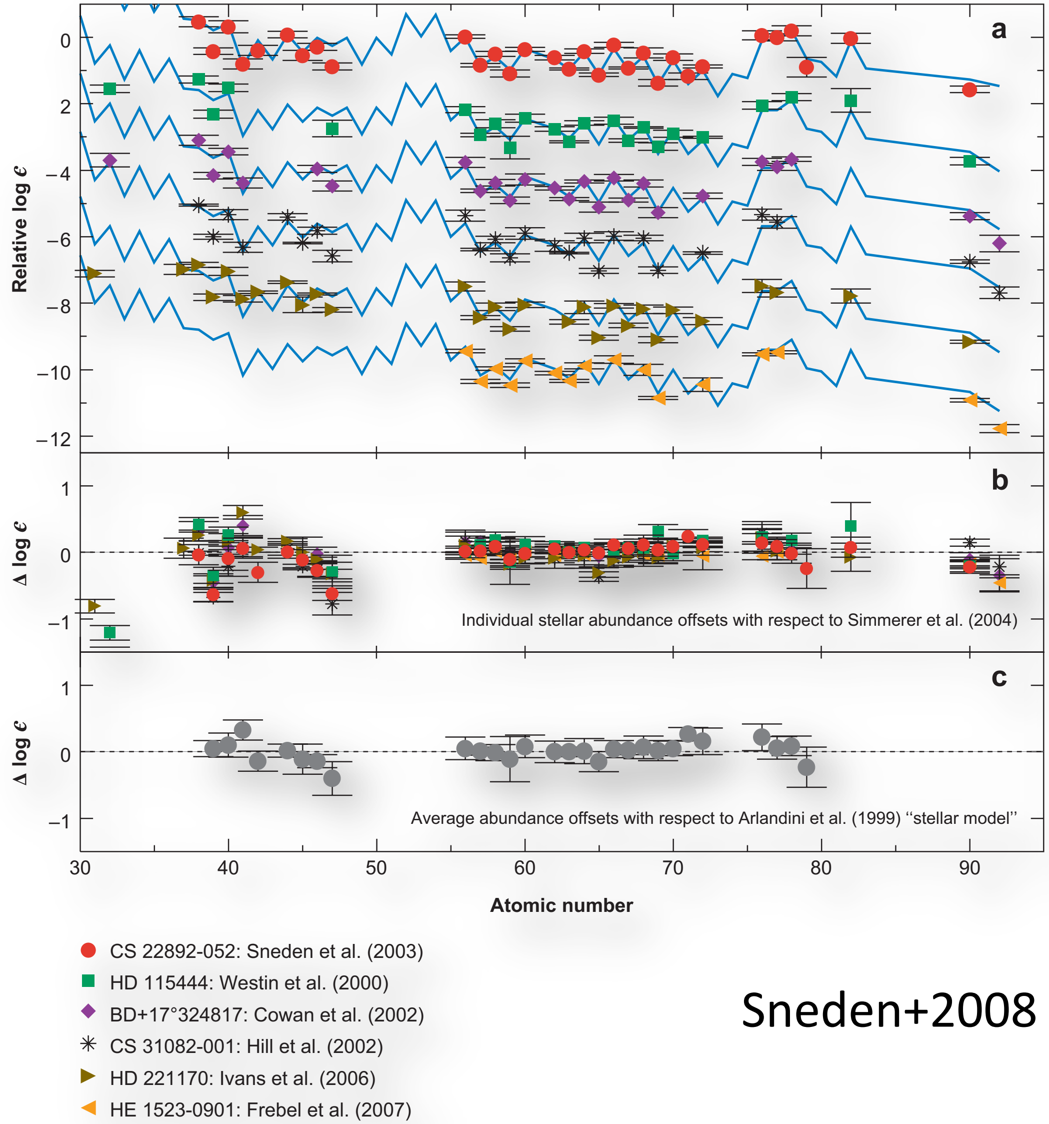


neutron-star mergers
(since Lattimer+1974;
Symbalisty+1982)

❖ n-rich ejecta from coalescing NS-NS or BH-NS

❖ recent studies show promise

"universality" of the r-process



Sneden+2008

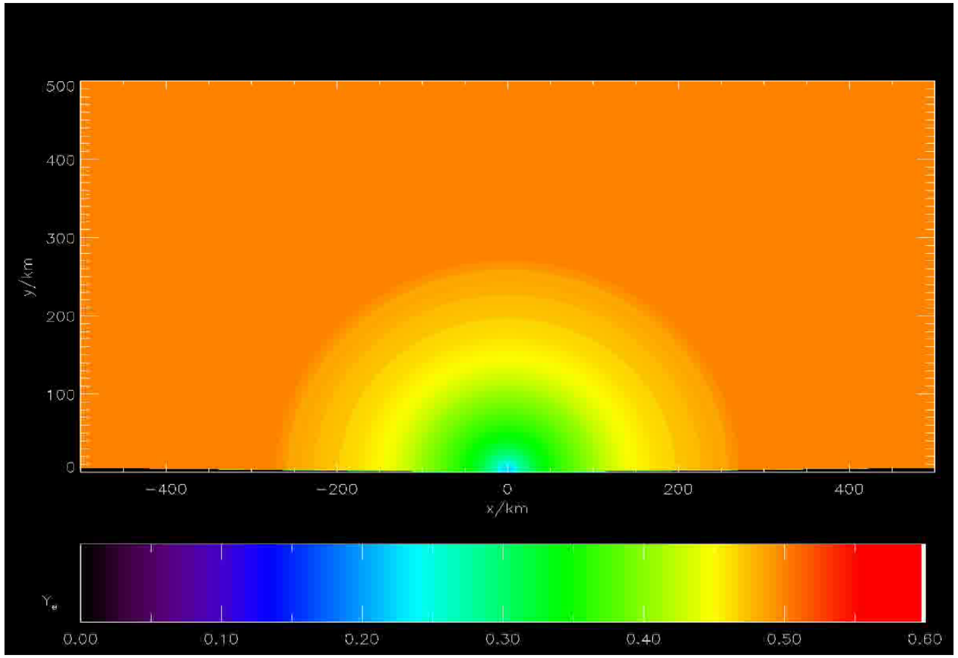
surviving old stars record nucleosynthesis memories in the early universe

- 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 do not make gold?

computer simulation of a supernova explosion



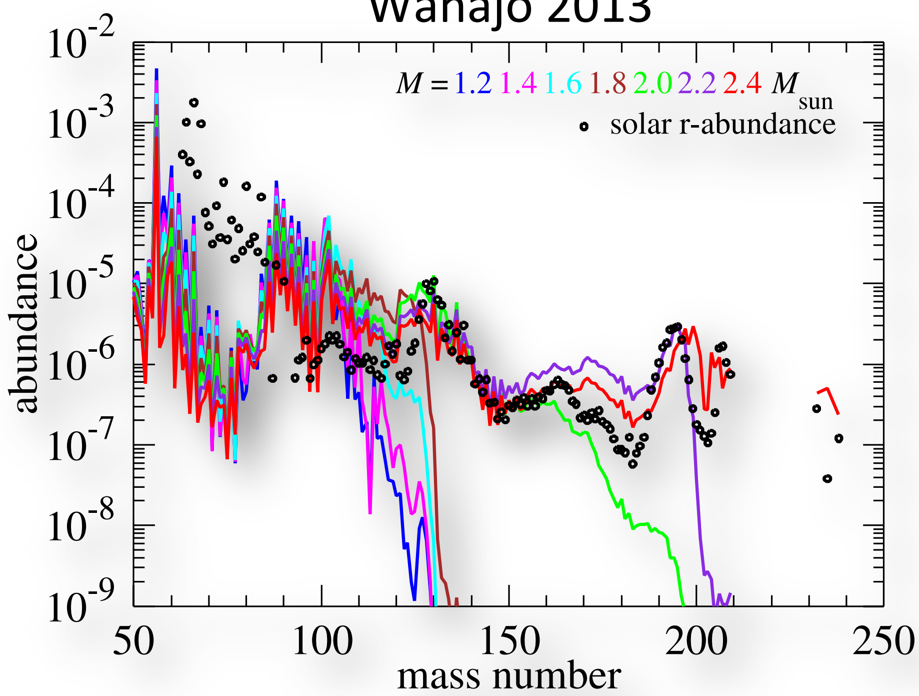
↑ neutron 100%
proton 0%

↑ neutron 50%
proton 50%

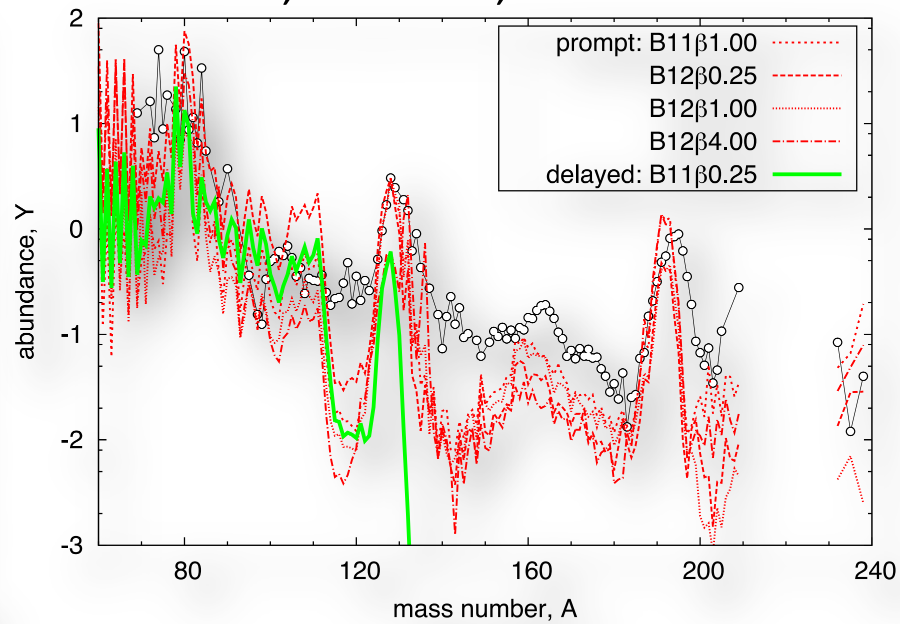
- electron captures
  $p + e^- \rightarrow n + \nu$
  make neutrons in neutron star
- neutrino absorption drives matter ejection (and explosion)
- inverse process
  $n + \nu \rightarrow p + e^-$
  converts neutrons to protons
- ejecta are not neutron-rich!

supernovae: not such neutron-rich?

Wanajo 2013

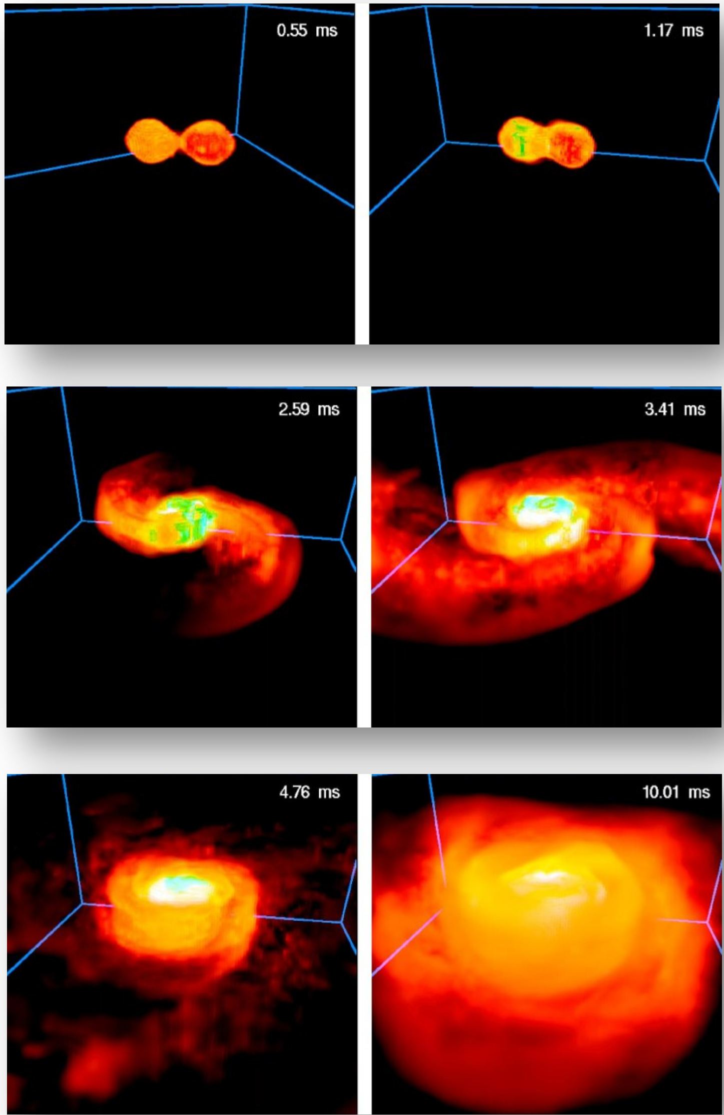


Nishimura, Takiwaki, Thielemann 2015



- ❖ neutrino-driven wind models explain production of only weak r-process 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

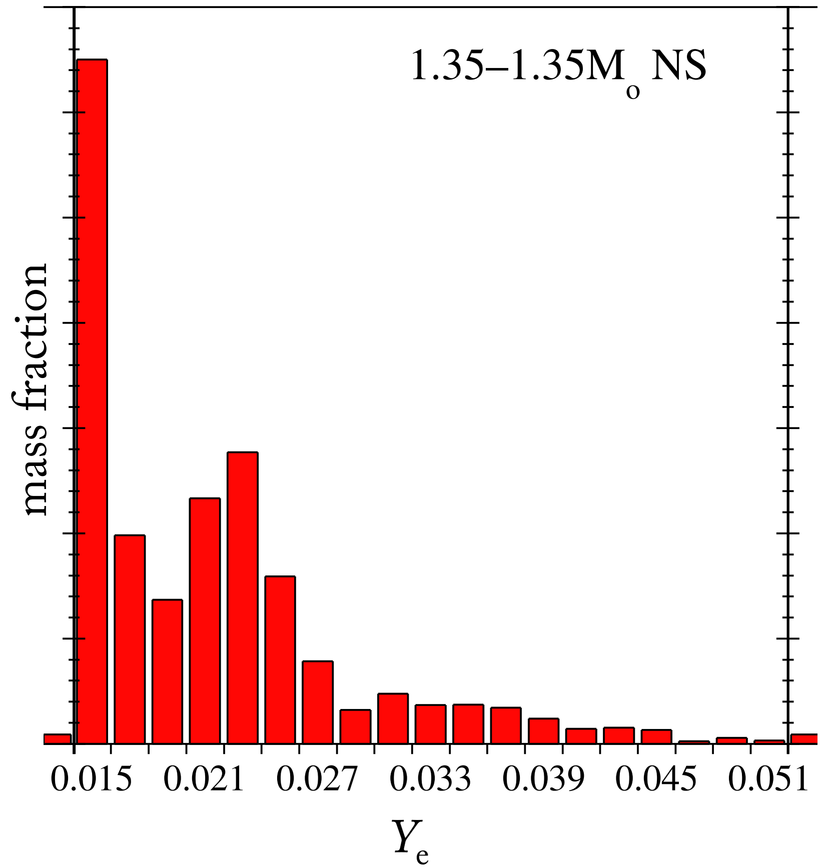
- coalescence of binary NSs expected ~ 10 – 100 per Myr in the Galaxy

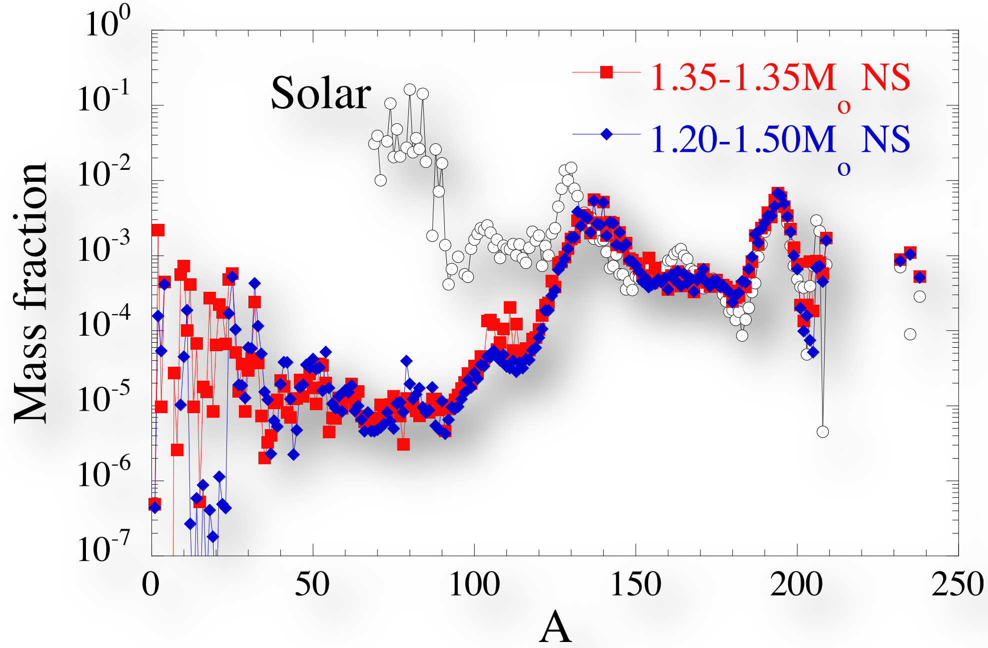
- first ~ 0.1 seconds
  dynamical ejection of n-rich matter up to $M_{ej} \sim 10^{-2}\ M_{\odot}$

- next ~ 1 second
  neutrino or viscously driven wind from the BH accretion torus up to $M_{ej} \sim 10^{-2}\ M_{\odot}$??

neutron star mergers: too neutron-rich?

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



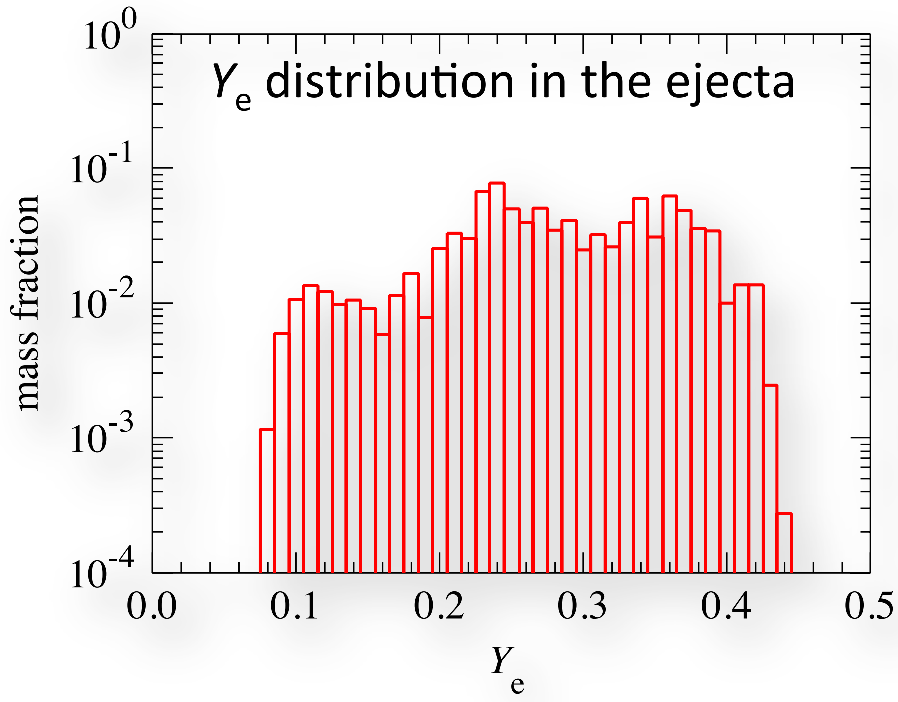


tidal (or weakly shocked) ejection of "pure" n-matter with $Y_e < 0.1$

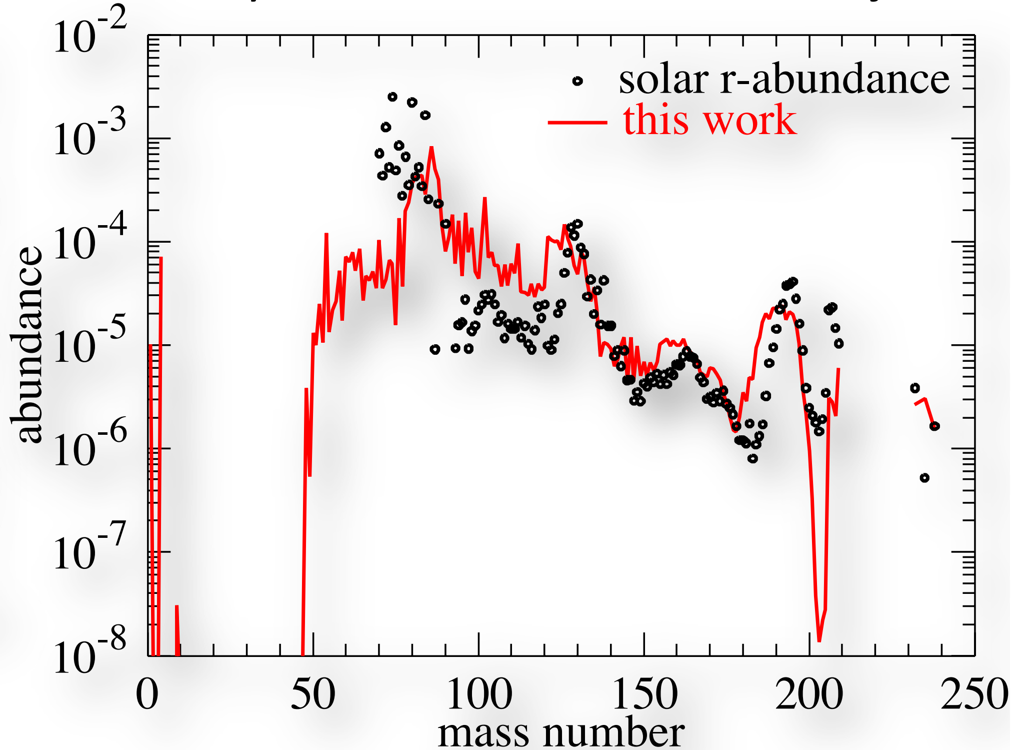
- fission cycle leads to robust r-pattern for only $A > 120$ with too small $A < 120$ nuclei
- fission cycle itself is not "the" r-process

weak interaction saves merger scenario

Wanajo+2014



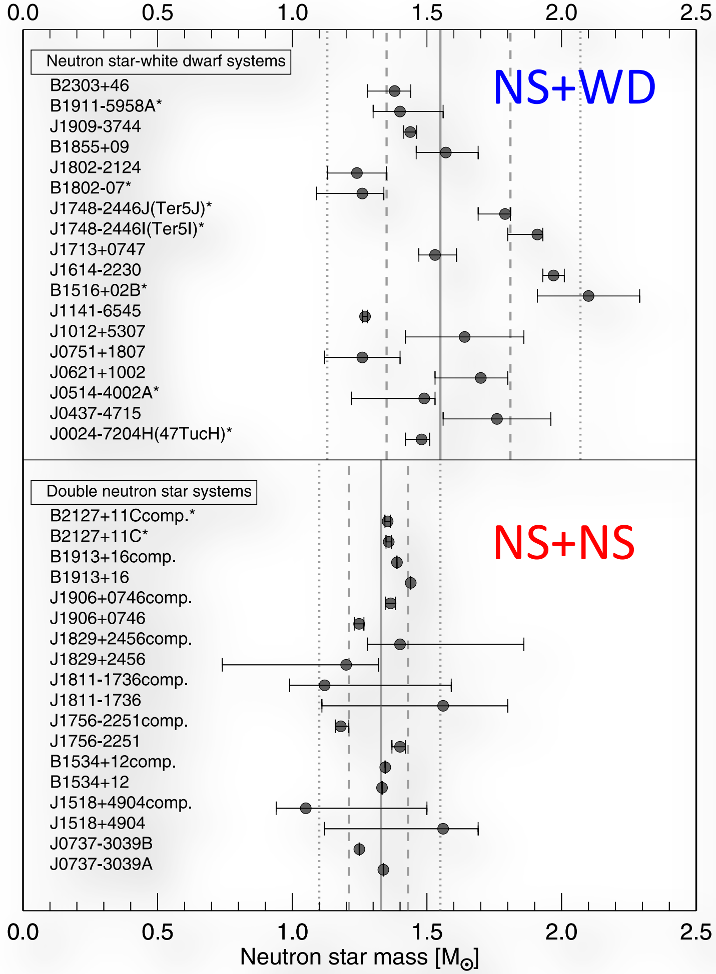
nucleosynthesis abundances in the ejecta

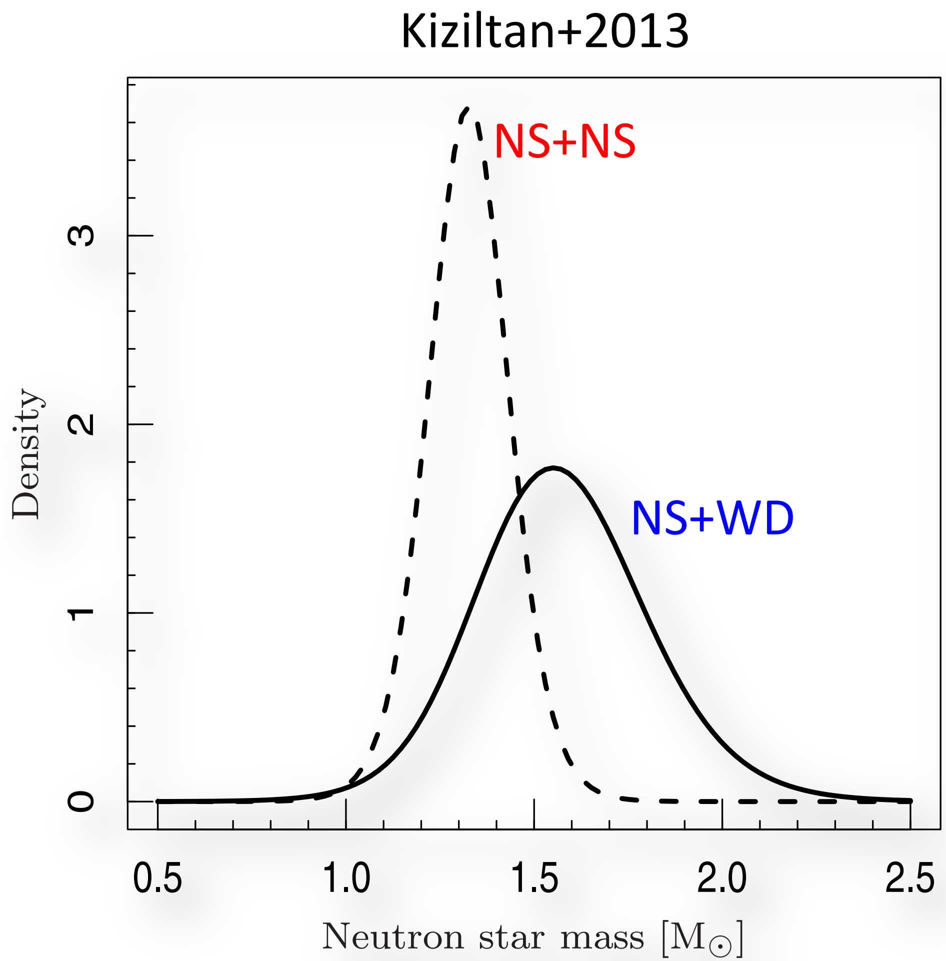


- positron capture and neutrino absorption on free nucleons result in less neutron-rich ejecta with Y_e ~ 0.1-0.45

- good agreement with full solar r-process range for A = 90-240 (similar result by Goriely+2015 but by Radice+2016)

uniqueness of double NS binaries

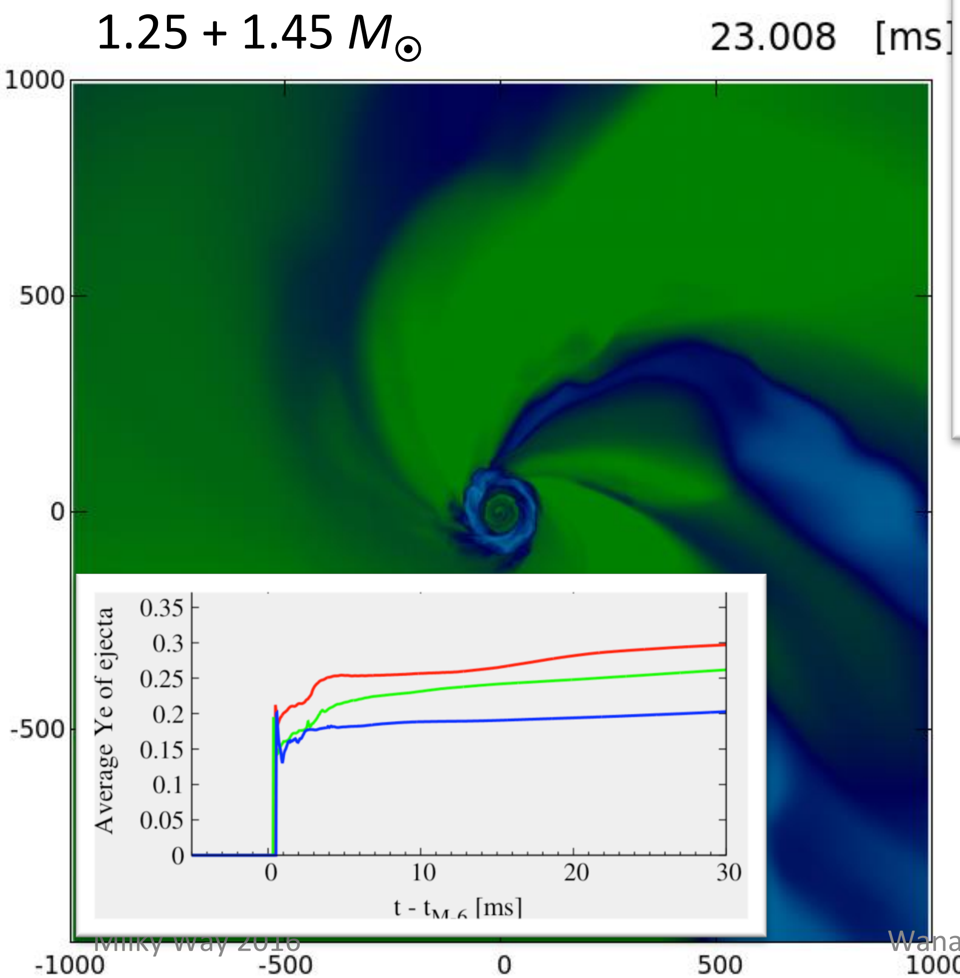


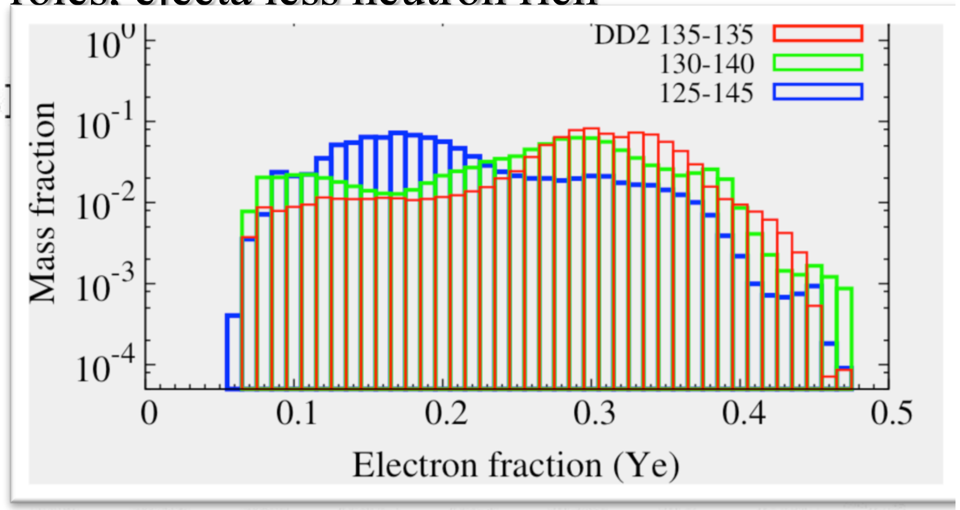


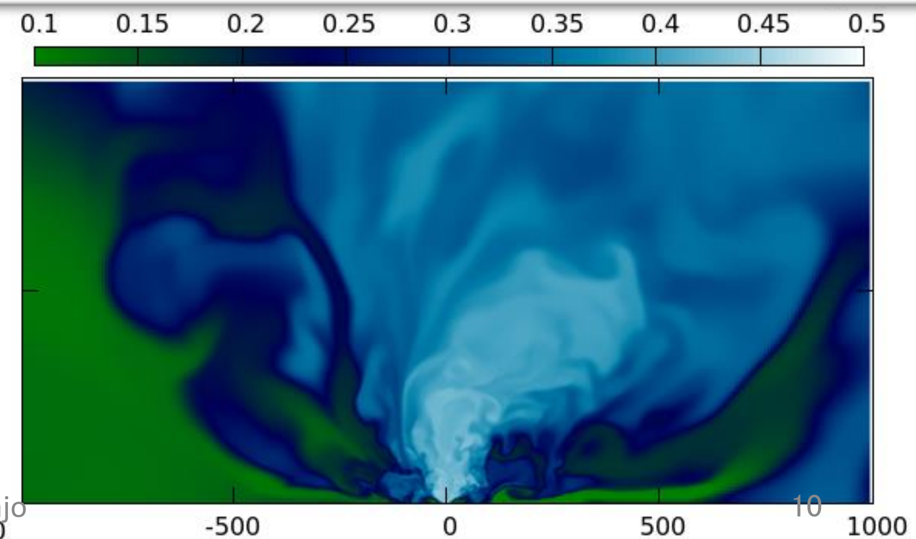
- ❖ binaries have various NS masses (1.2-2.0 $M_{\odot}$)
- ❖ but for double NS binaries (1.21-1.43 $M_{\odot}$ at the 68% interval)

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

- Orbital plane : Tidal effects play a role, ejecta is neutron rich
- Meridian plane : shock + neutrinos play roles, ejecta less neutron rich

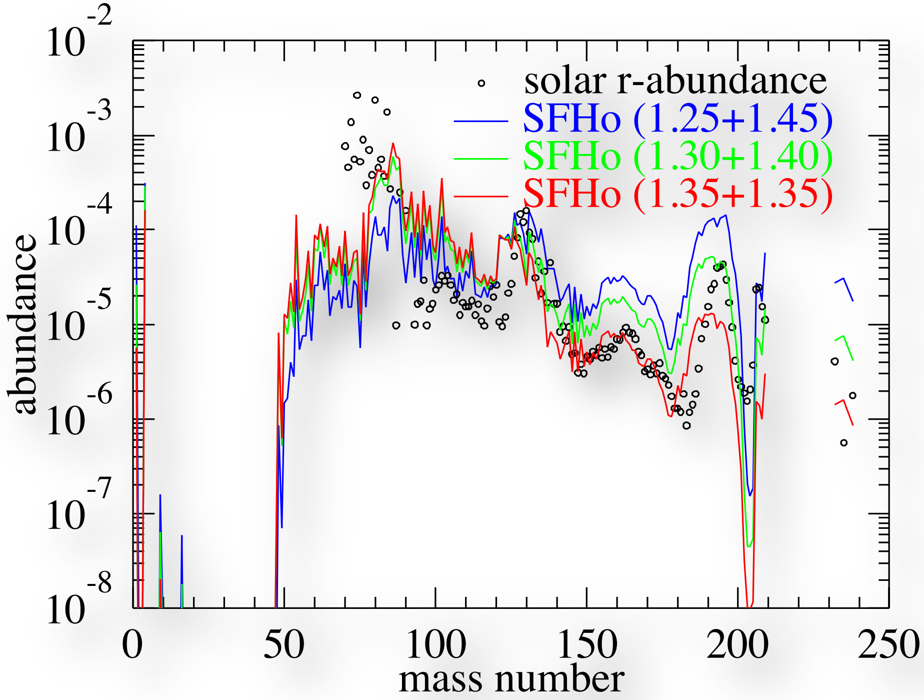


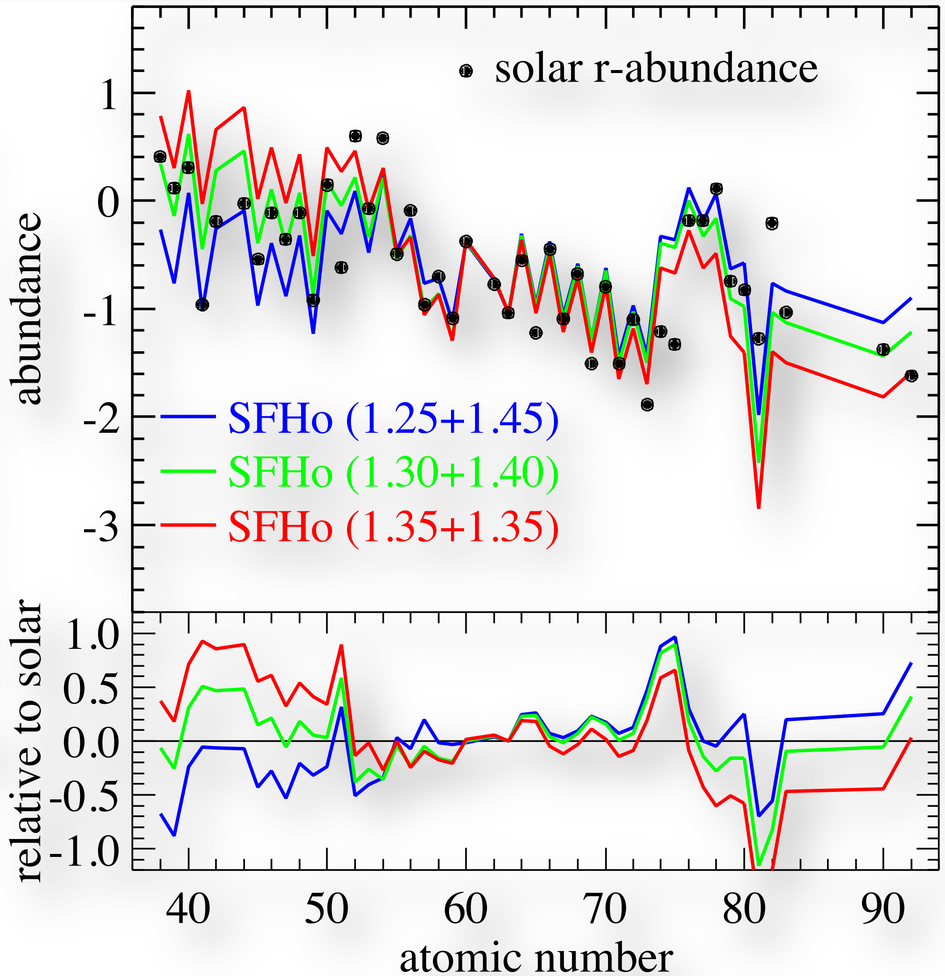




dependence on mass ratios (SFHo)

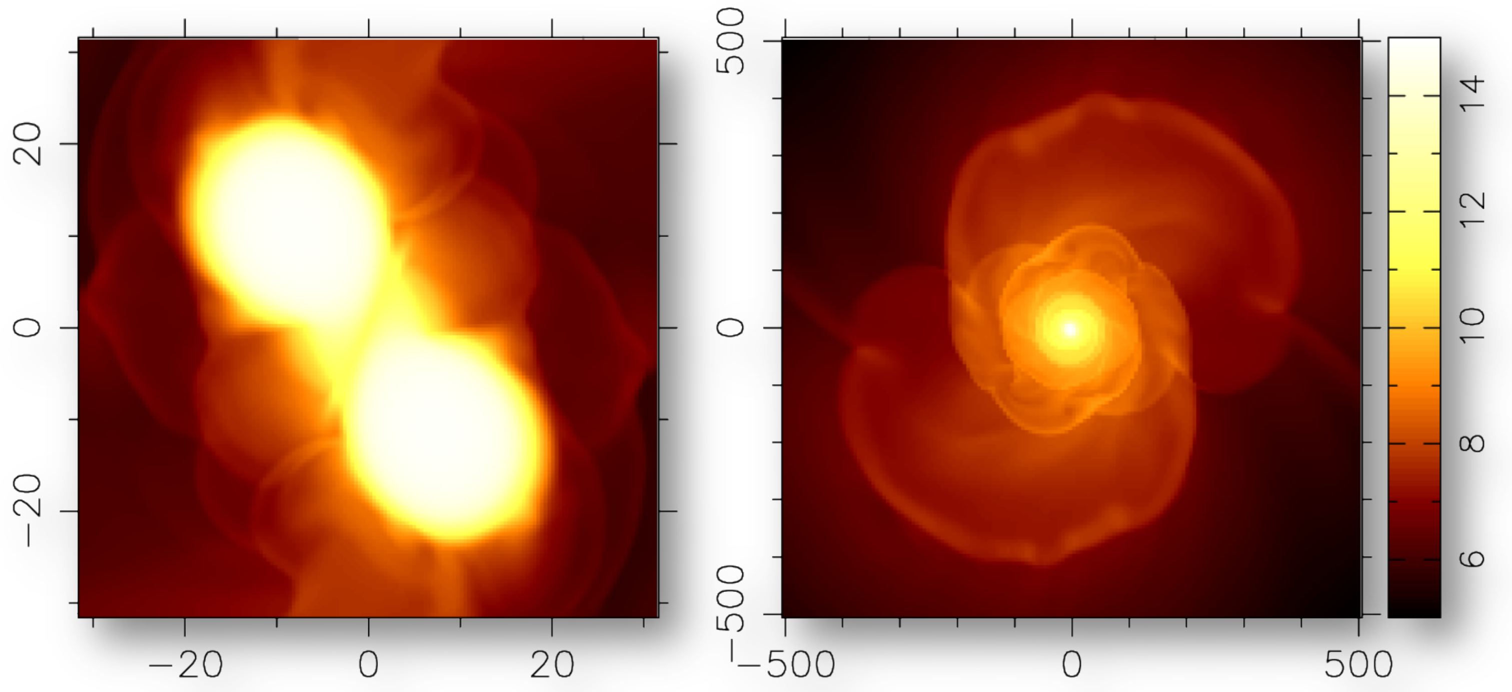
Wanajo+2016; in prep.





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

summary



- 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