origin of the r-process nuclei

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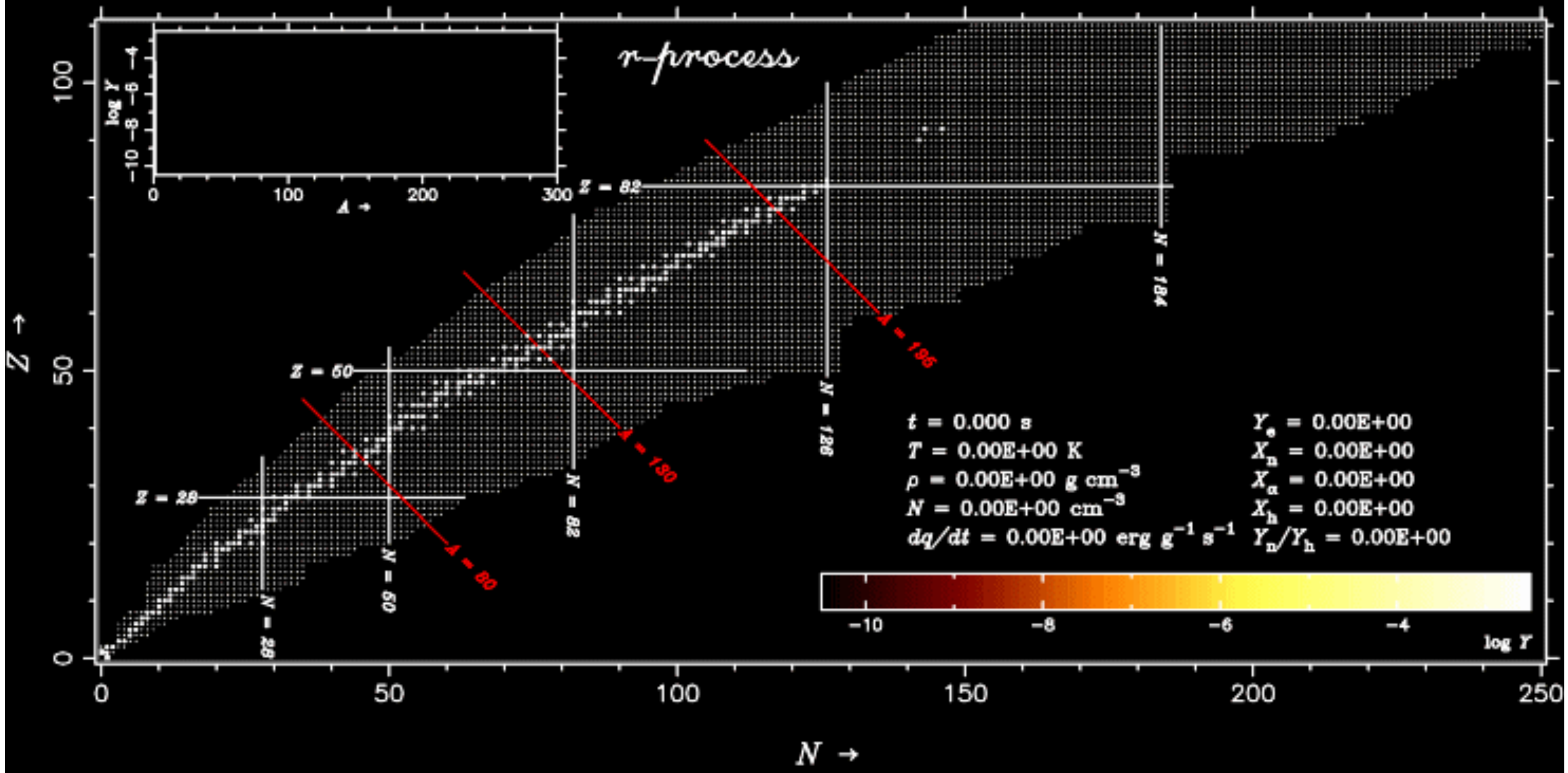
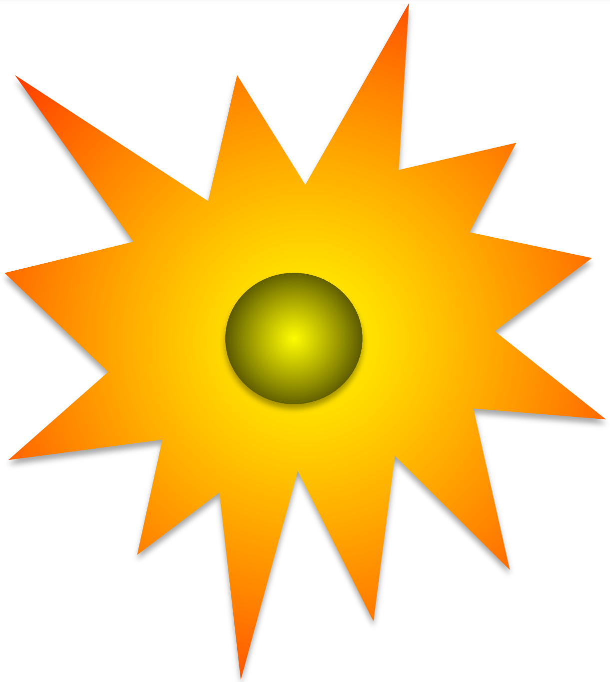
1. overview

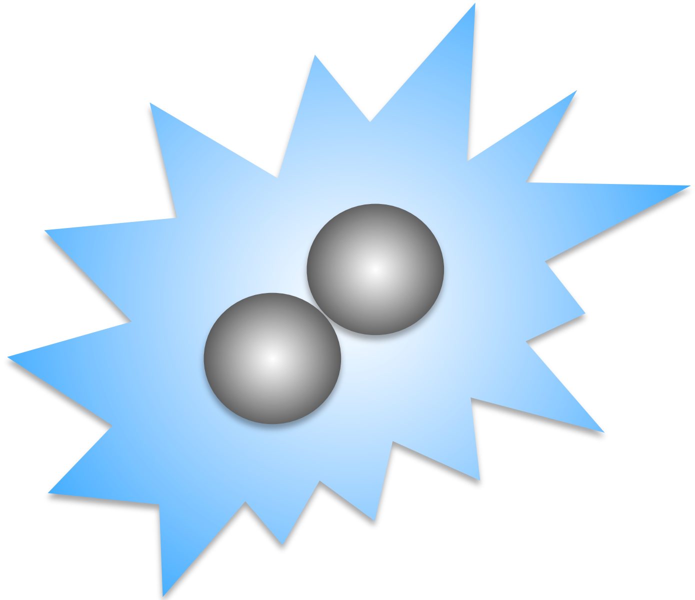
origin of gold (r-process elements) is still unknown…

Y_e = 0.09


r-process
log Y
−10
−8
−6
−4
0
100
200
300
A →
Z = 82
Z = 50
Z = 28
N = 28
N = 50
N = 82
N = 126
N = 184
A = 80
A = 130
A = 195
t = 0.000 s
T = 0.00E+00 K
ρ = 0.00E+00 g cm−3
N = 0.00E+00 cm−3
dq/dt = 0.00E+00 erg g−1 s−1
Ye = 0.00E+00
Xn = 0.00E+00
Xα = 0.00E+00
Xh = 0.00E+00
Yn/Yh = 0.00E+00
−10
−8
−6
−4
log Y
Z →
0
50
100
N →
0
50
100
150
200
250

where do we have neutrons?





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

- ❖ n-rich ejecta nearby proto-NS
- ❖ not promising according to recent studies

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

- ❖ n-rich ejecta from coalescing NS-NS or BH-NS
- ❖ few nucleosynthesis studies

SN neutrino wind: not so neutron-rich

- Y_e is determined by

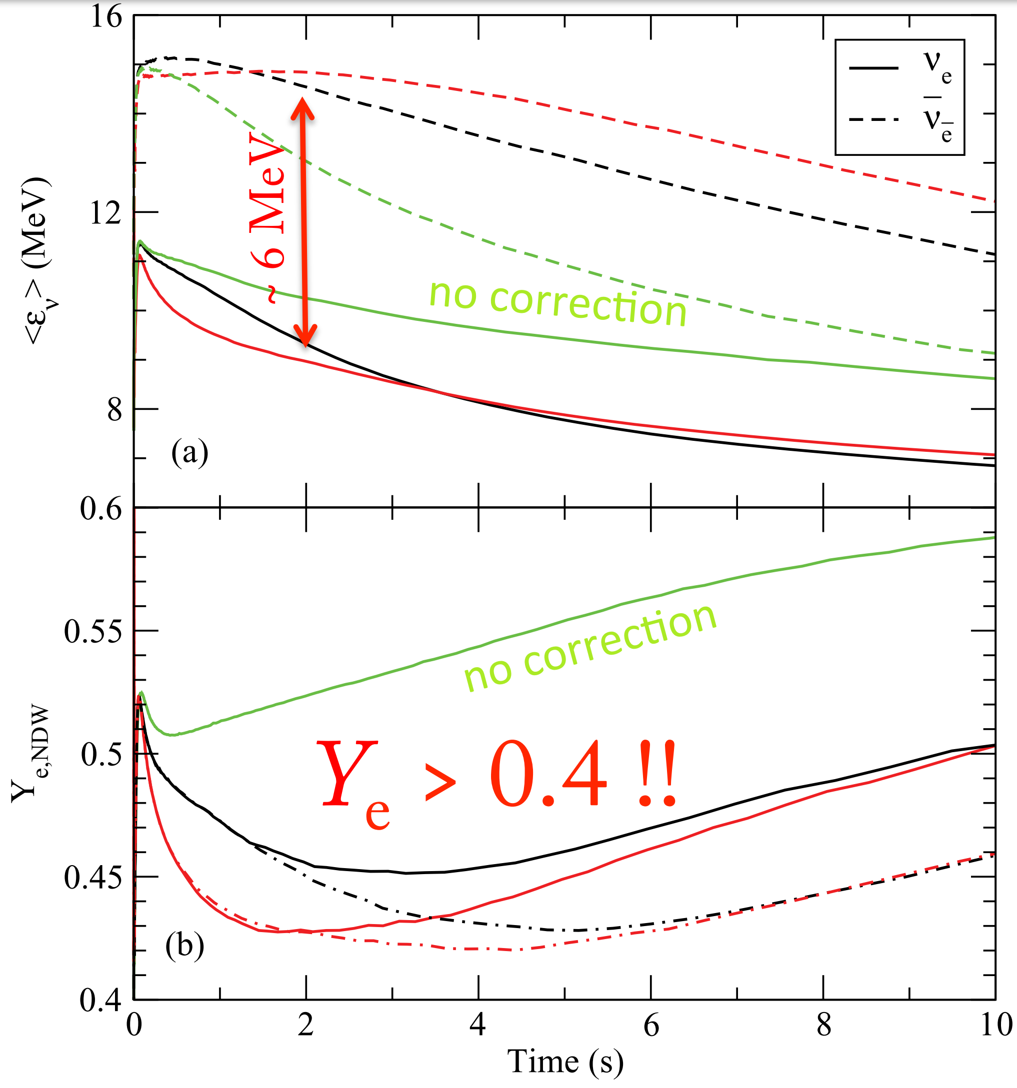
$$\nu_e + n \rightarrow p + e^-$$
$$\bar{\nu}_e + p \rightarrow n + e^+$$

- equilibrium value is

$$Y_e \sim \left[1 + \frac{L_{\bar{\nu}e}}{L_{\nu e}} \frac{\varepsilon_{\bar{\nu}e} - 2\Delta}{\varepsilon_{\nu e} + 2\Delta}\right]^{-1},$$
$$\Delta = M_n - M_p \approx 1.29 \text{ MeV}$$

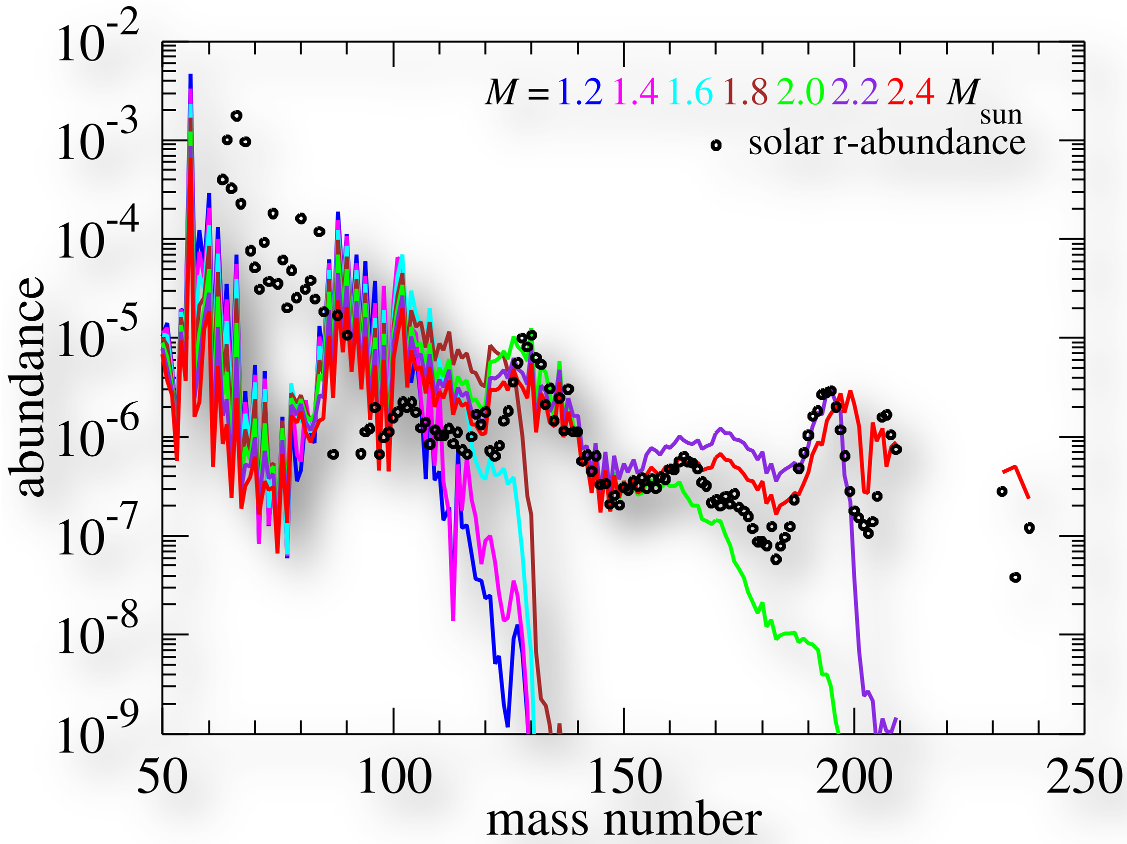
- for $Y_e < 0.5$ (i.e., n-rich)

$$\varepsilon_{\bar{\nu}e} - \varepsilon_{\nu e} > 4\Delta \sim 5 \text{ MeV}$$
$$\text{if } L_{\bar{\nu}e} \approx L_{\nu e}$$



Roberts+2012

is the answer blowing in the wind?



Wanajo 2013

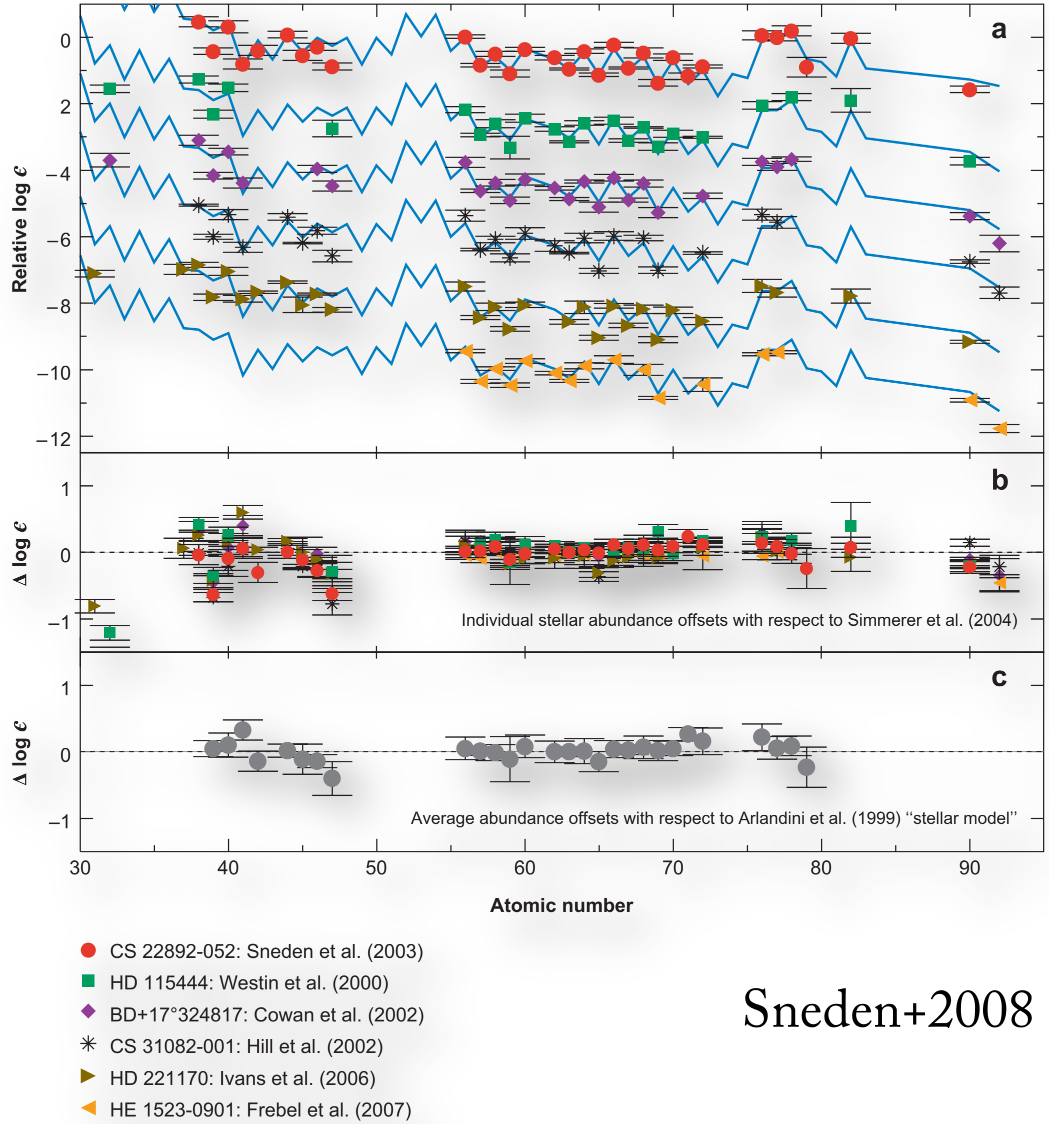
- only very massive proto-NSs (> 2.2 $M_{\odot}$) make the heavy r-elements
- typical proto-NSs (< 2.0 $M_{\odot}$) probably make weak r-elements (A ~ 90 – 130)

supernovae can be the origin only if …

the explosion is not due to neutrino heating (but, e.g., magneto-rotational jet; Nishimura's talk) or our knowledge of neutrino physics is insufficient.

CAUTION!!! EXPLOSION MECHANISM IS STILL UNCLEAR…

r-process in the early Galaxy



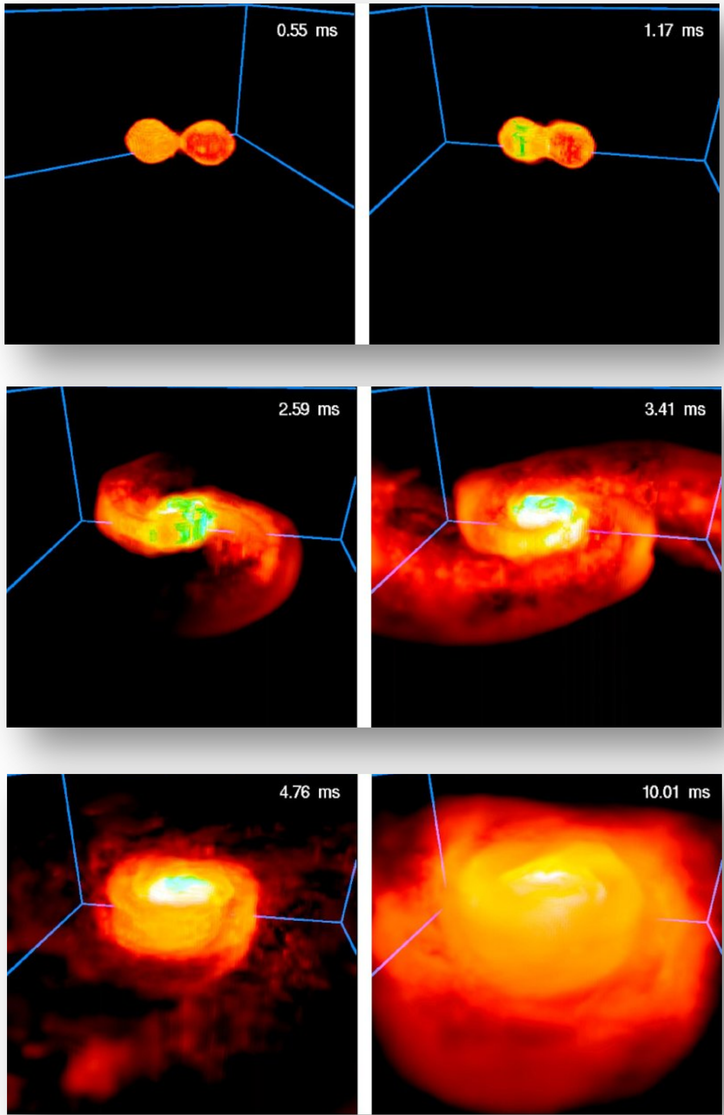
Sneden+2008

all r-rich Galactic halo stars show remarkable agreement with the solar r-pattern

- r-process should have operated in the early Galaxy;
  SNe 😃, mergers 😢 ?
- astrophysical models should reproduce the "universal" solar-like r-process pattern
  (for $Z \geq 40$; $A \geq 90$)

NS merger scenario: most promising?

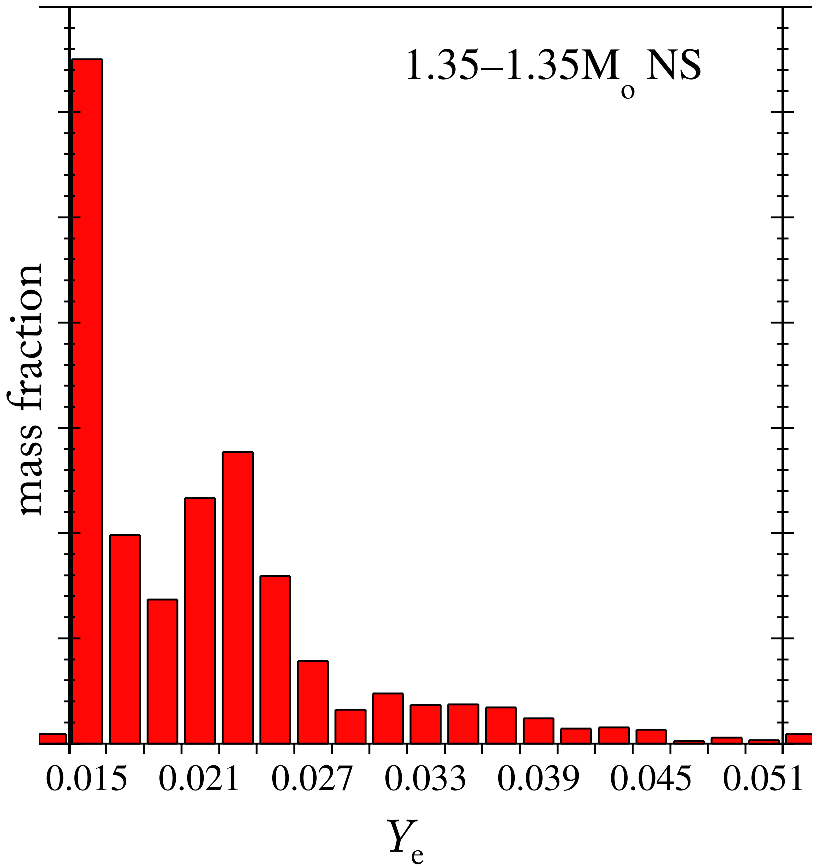
www.mpa-garching.mpg.de

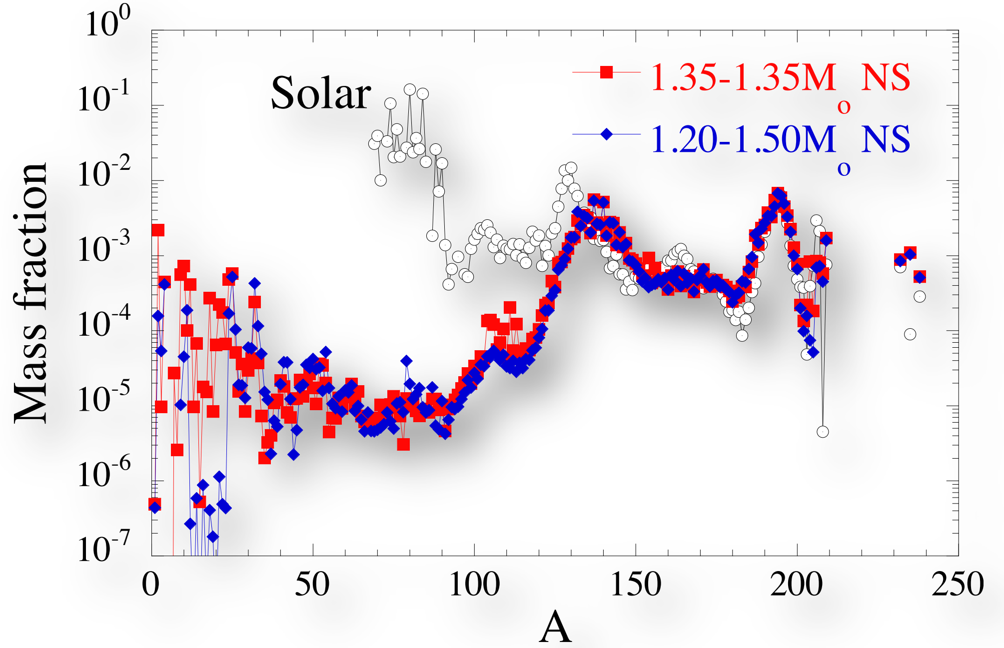


- coalescence of binary NSs expected ~ 10 – 100 per Myr in the Galaxy (also possible sources of short GRB)
- first ~ 0.1 seconds
  dynamical ejection of n-rich matter up to $M_{ej} \sim 10^{-2}\ M_{\odot}$
- next ~ 1 second
  neutrino or viscously driven wind from the BH accretion torus up to $M_{ej} \sim 10^{-2}\ M_{\odot}$??

previous works: too neutron-rich ?

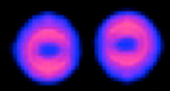
Goriely+2011 (also similar results by Korobkin+2011; Rosswog+2013)





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

- strong r-process leading to fission recycling
- severe problem: only $A > 130$; another source is needed for the lighter counterpart

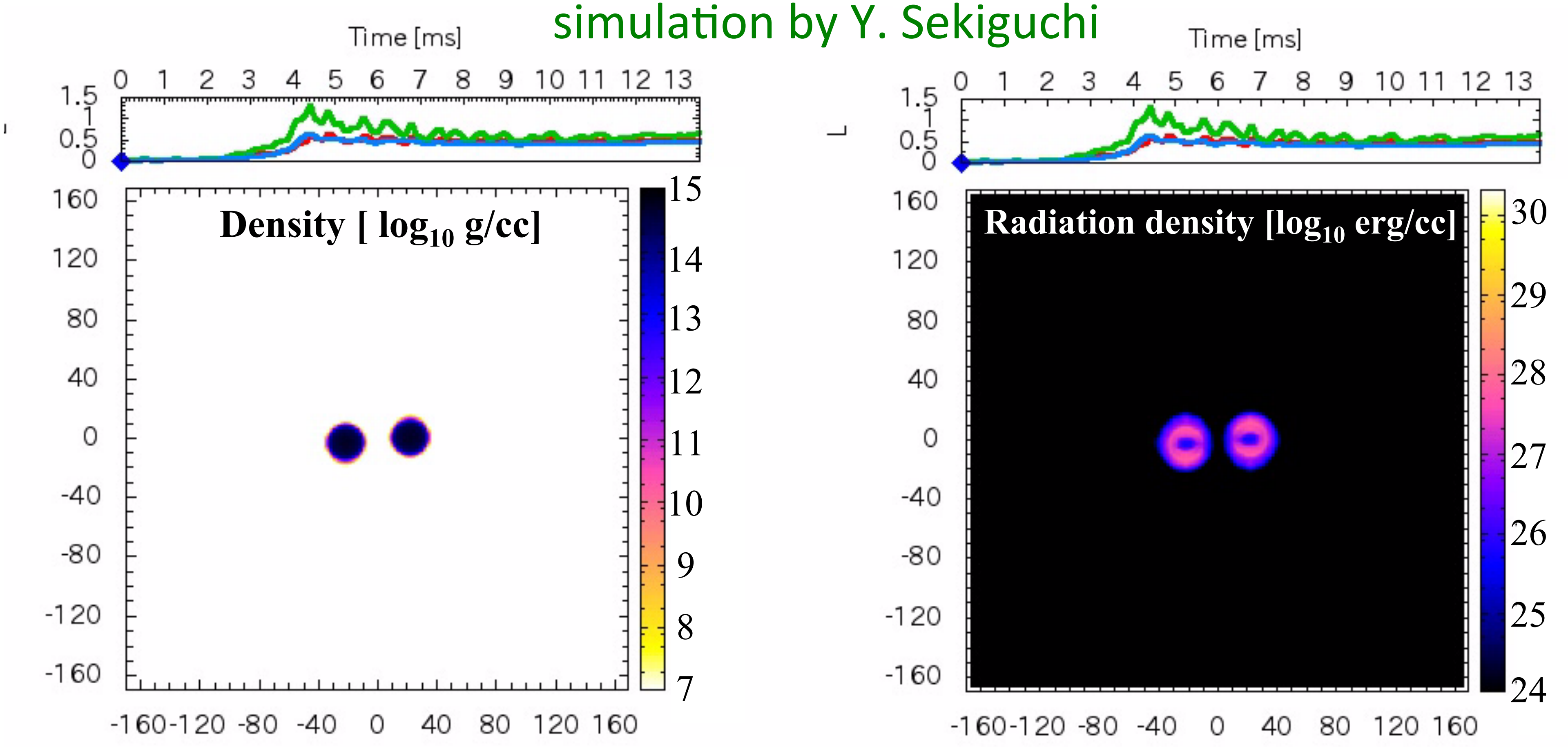


2. neutron star mergers
(Wanajo+2014)

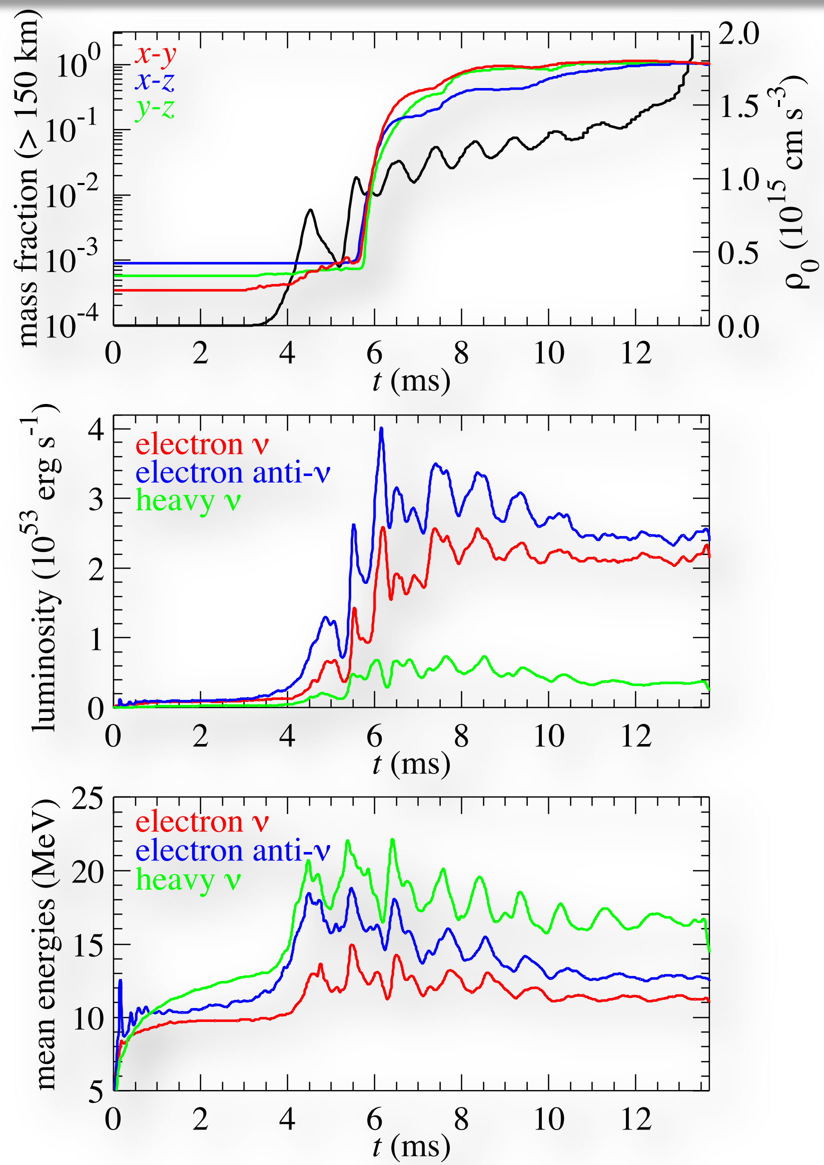
first simulation with full-GR and ν

- Approximate solution by Thorne's Moment scheme with a closure relation
- Leakage + Neutrino heating (absorption on proton/neutron) included

simulation by Y. Sekiguchi

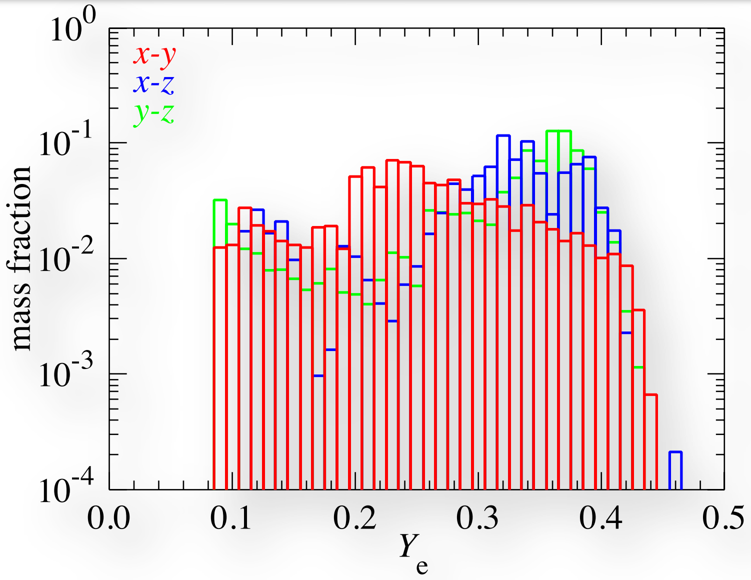


neutrino properties (Steiner's EOS)

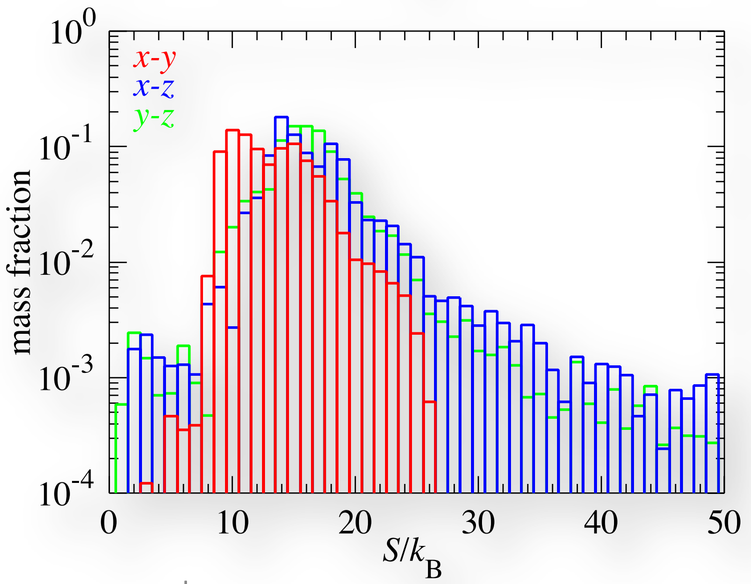


- mass ejection before (40%) and after (60%) HMNS formation; 70% ejecta reside near orbital
- neutrino luminosities similar between ν_e and anti-ν_e
- neutrino mean energies similar between ν_e and anti-ν_e

nucleosynthesis in the NS ejecta



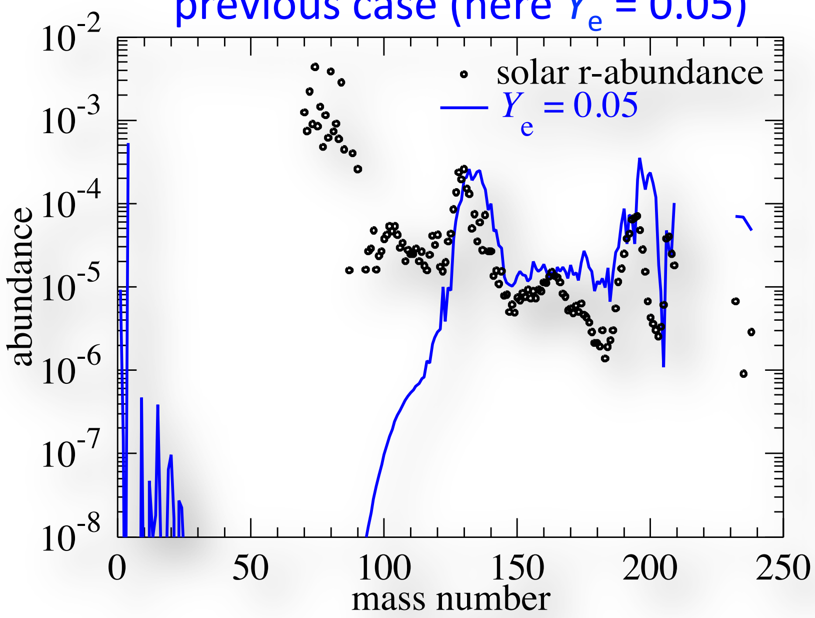
- higher and wider range of Y_e (~ 0.1-0.5) in contrast to previous cases Y_e (= 0.01-0.05)



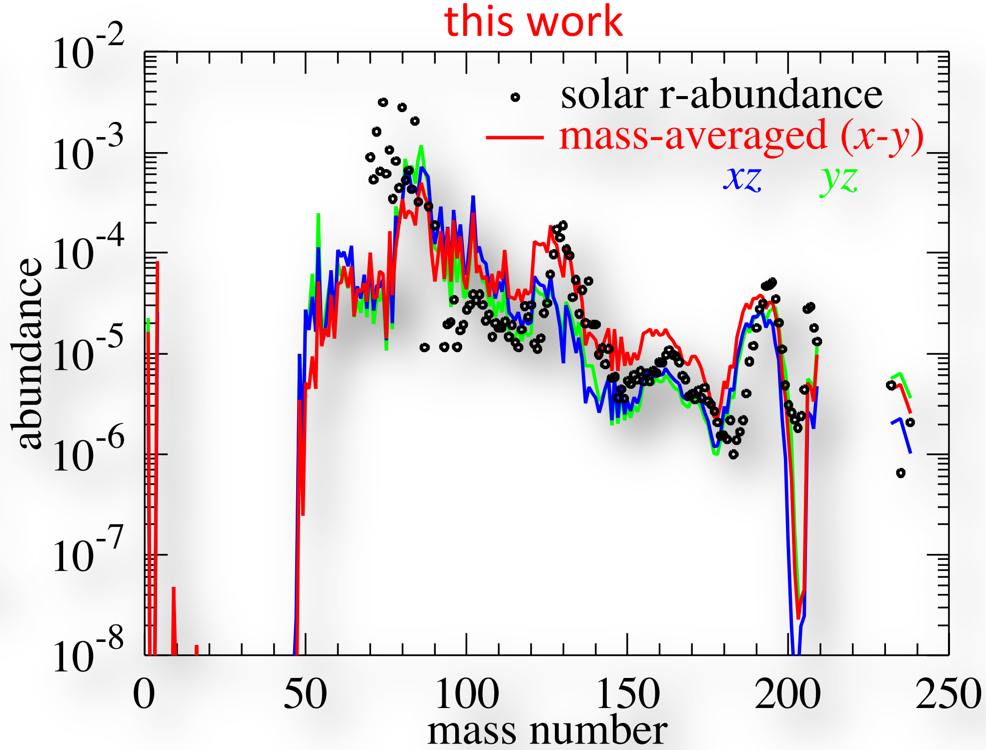
- higher and wider range of entropy per baryon (= 0-50) in contrast to previous cases (= 0-3)

mass-integrated abundances

previous case (here Y_e = 0.05)



this work



- previous case: not in agreement with solar r-pattern
  → need additional sources for *A* < 130 and even *A* ~ 130 elements
- this work: reasonable agreement with solar r-pattern for *A* = 90-240
  → no need of additional (e.g., BH-torus) sources for light r-elements
  → no fission recycling in this case

summary and outlook

- NS mergers: very promising site of r-process
  - neutrinos play a crucial role (in particular for a soft EOS)
- still many things yet to be answered…
  - dependence on mass ratios of NSs and EOSs; how about BH-NS?
  - how the subsequent BH-tori contribute to the r-abundances?
  - can mergers be the origin of r-process elements in the Galaxy?