The r-process nucleosynthesis

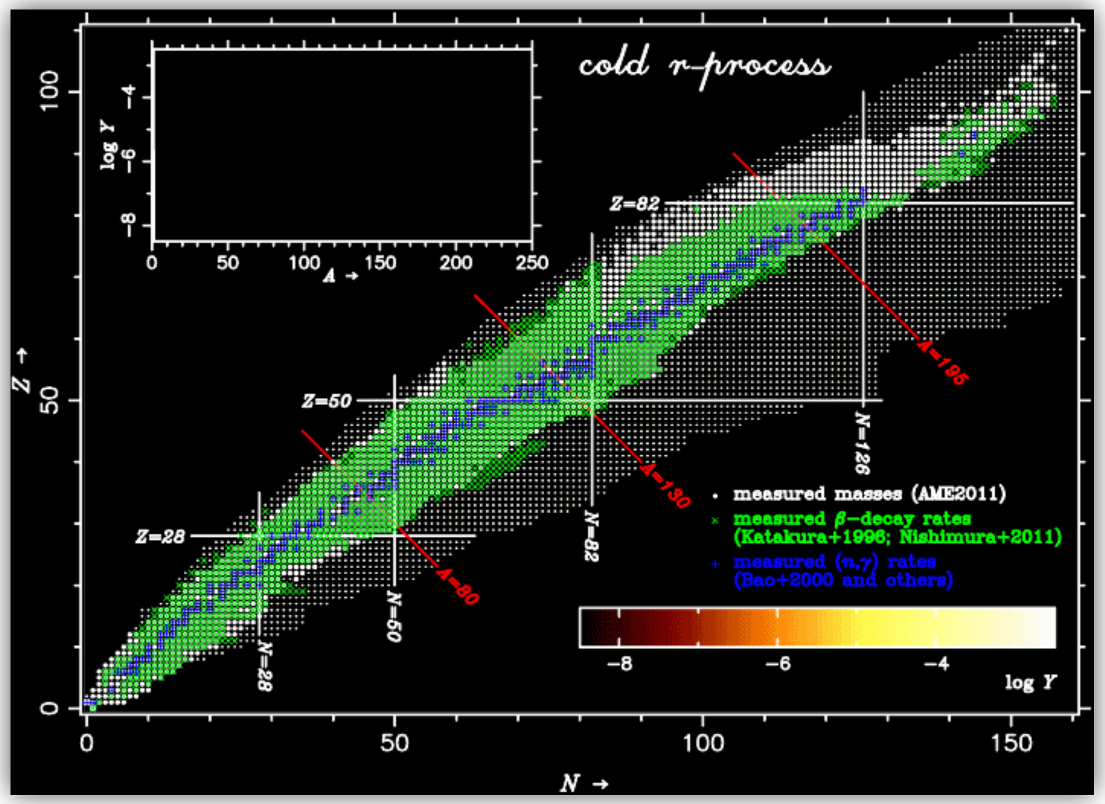
Shinya Wanajo (RIKEN iTHES)
with
Y. Sekiguchi (YITP), N. Nishimura (Keele Univ.),
K. Kiuchi (YITP), K. Kyutoku (RIKEN), M. Shibata (YITP)

コンパクト連星合体からの重力波・電磁波放射とその周辺領域
2014年2月12-14日, 京大基研

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

www.cartier.jp

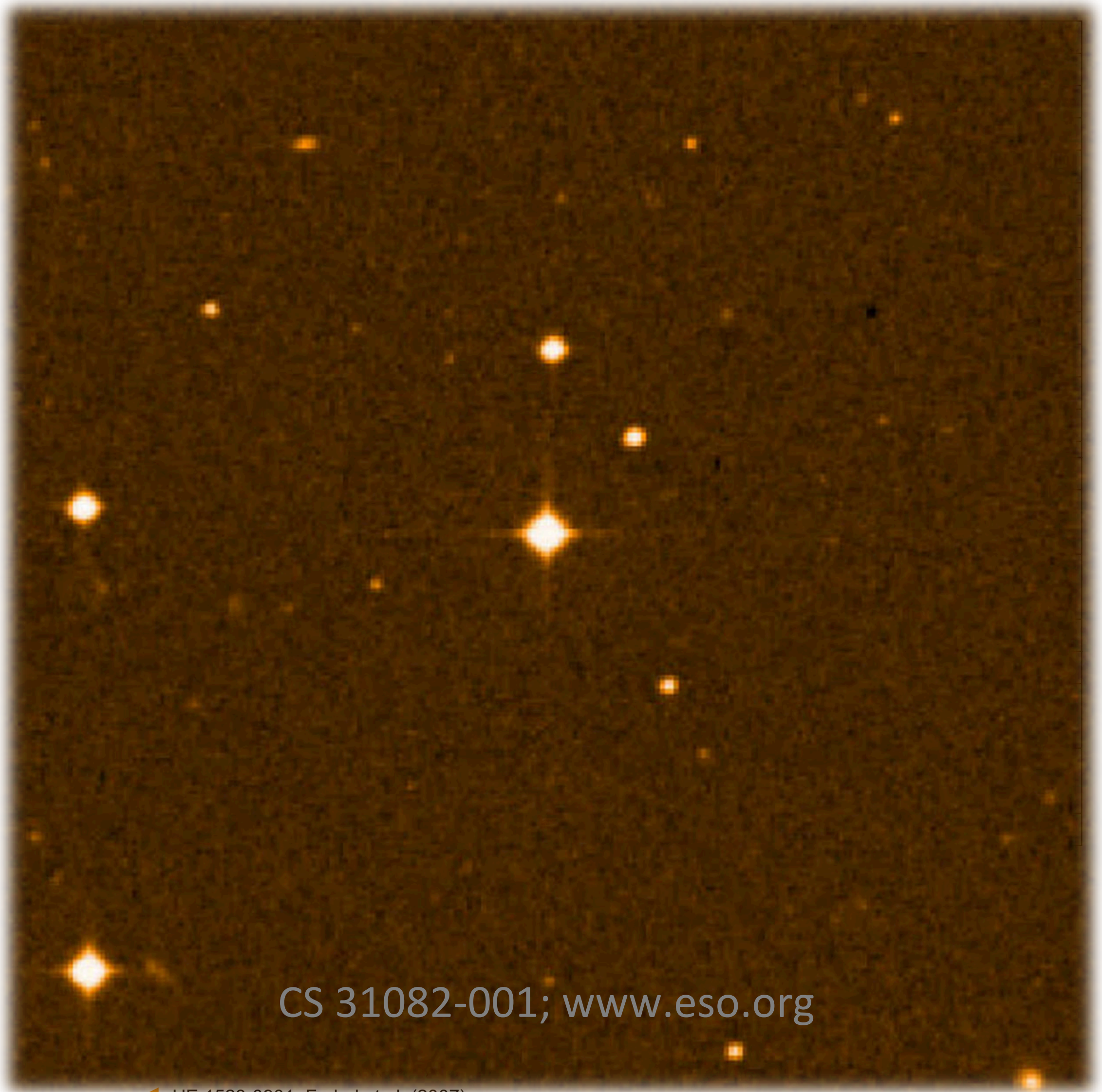
r-process: the last mystery of nucleosynthesis



r-process (rapid neutron capture nucleosynthesis)

- ❖ astrophysical sources are unidentified
- ❖ nuclear physics is poorly understood

"universality" of the r-process



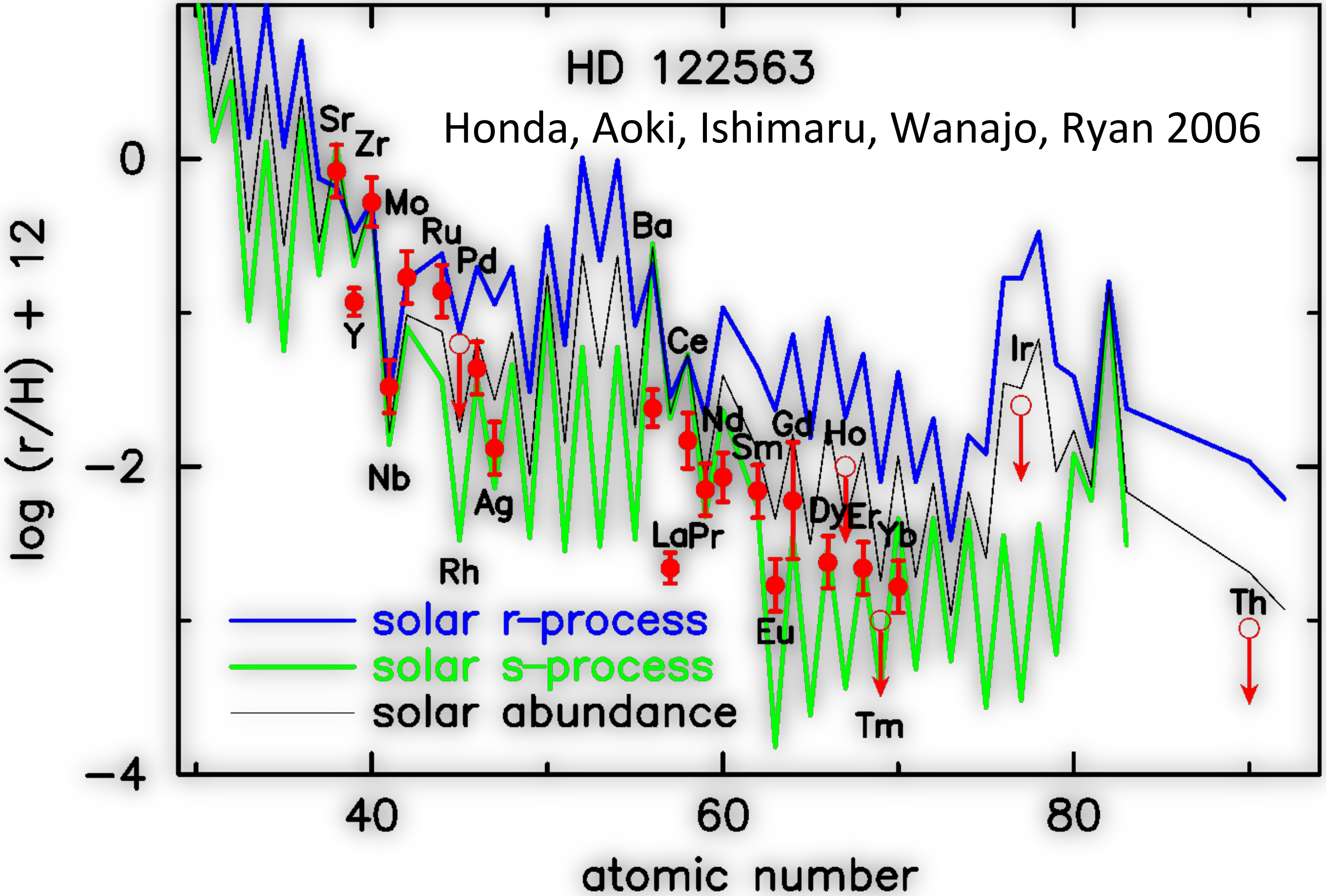
HE 1523-0901: Frebel et al. (2007)

surviving old stars record nucleosynthesis memories in the early universe

- r-process enhanced stars show constant abundance patterns

- the r-process should be "universal", always having solar-like abundance patterns

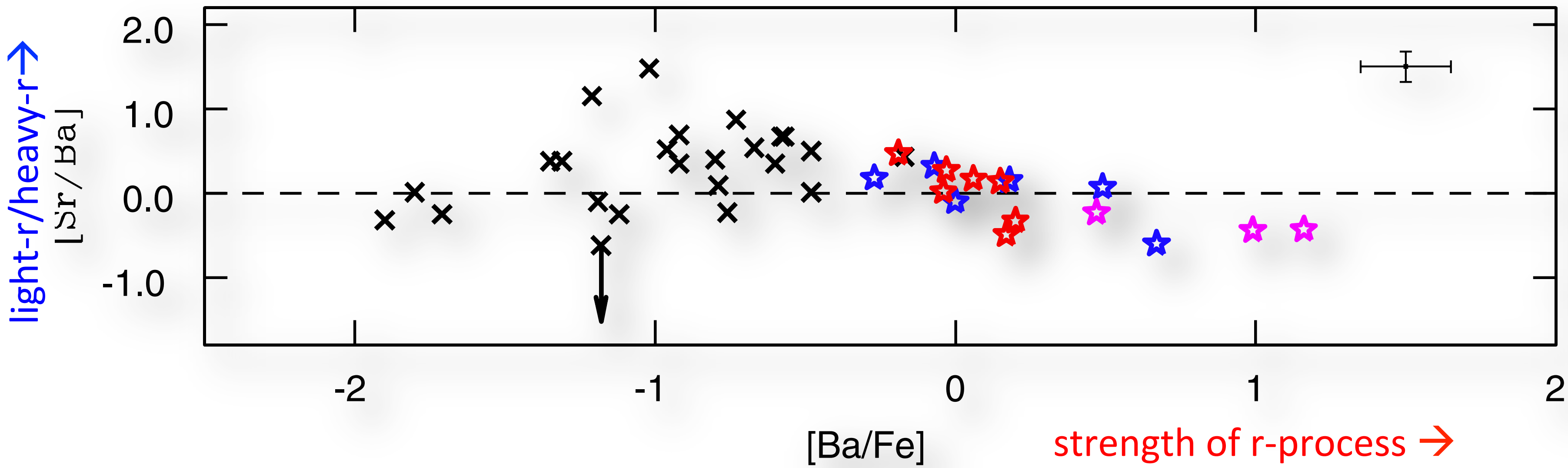
“weak” r-process?



❖ “normal” (or r-deficient) stars show high Sr/Eu ratios
a sign of “weak” r-process?

what is “true” r-process ?

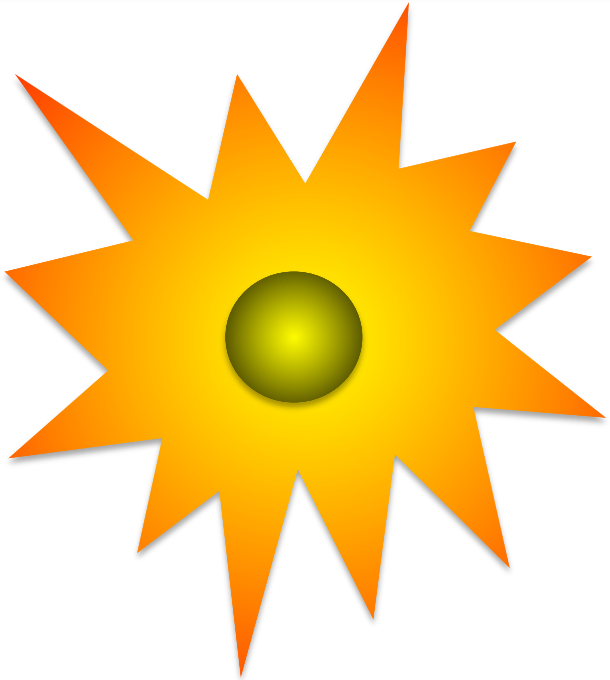
Siqueira Mello+…+ Wanajo 2014



VLT observations give tight constraint for light-to-heavy r-abundances

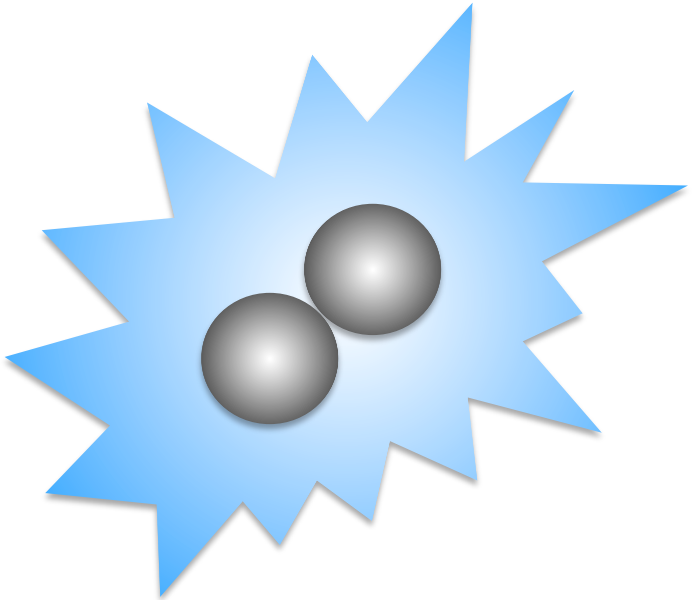
- [light-r/heavy-r] ≥ -0.3; no stars below this constraint
- “the true r-process” must make lighter r-elements with at least half of the solar r-ratio

where do we have neutrons?



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

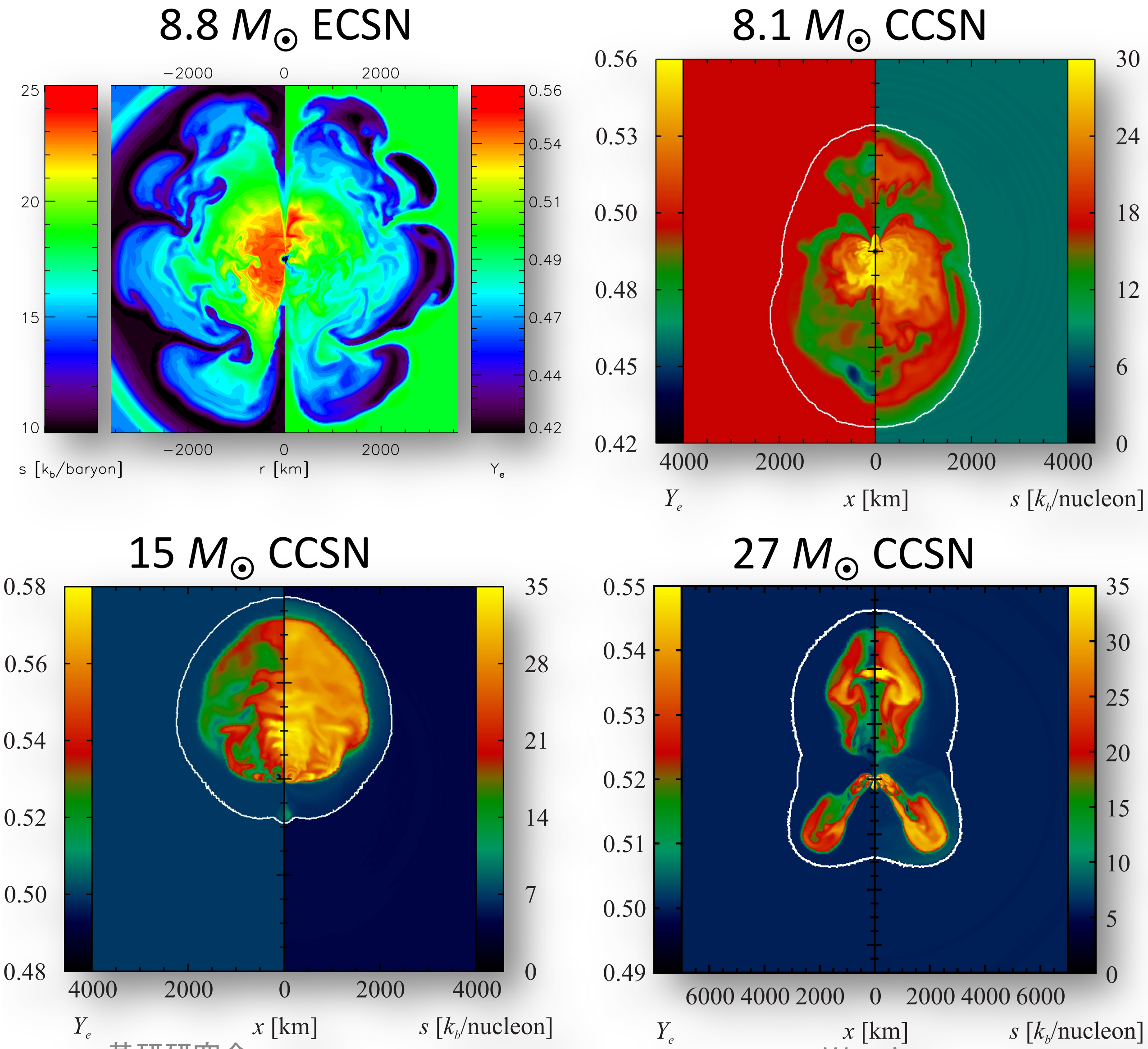
- ❖ n-rich ejecta nearby proto-NS
- ❖ not promising according to recent studies



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

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

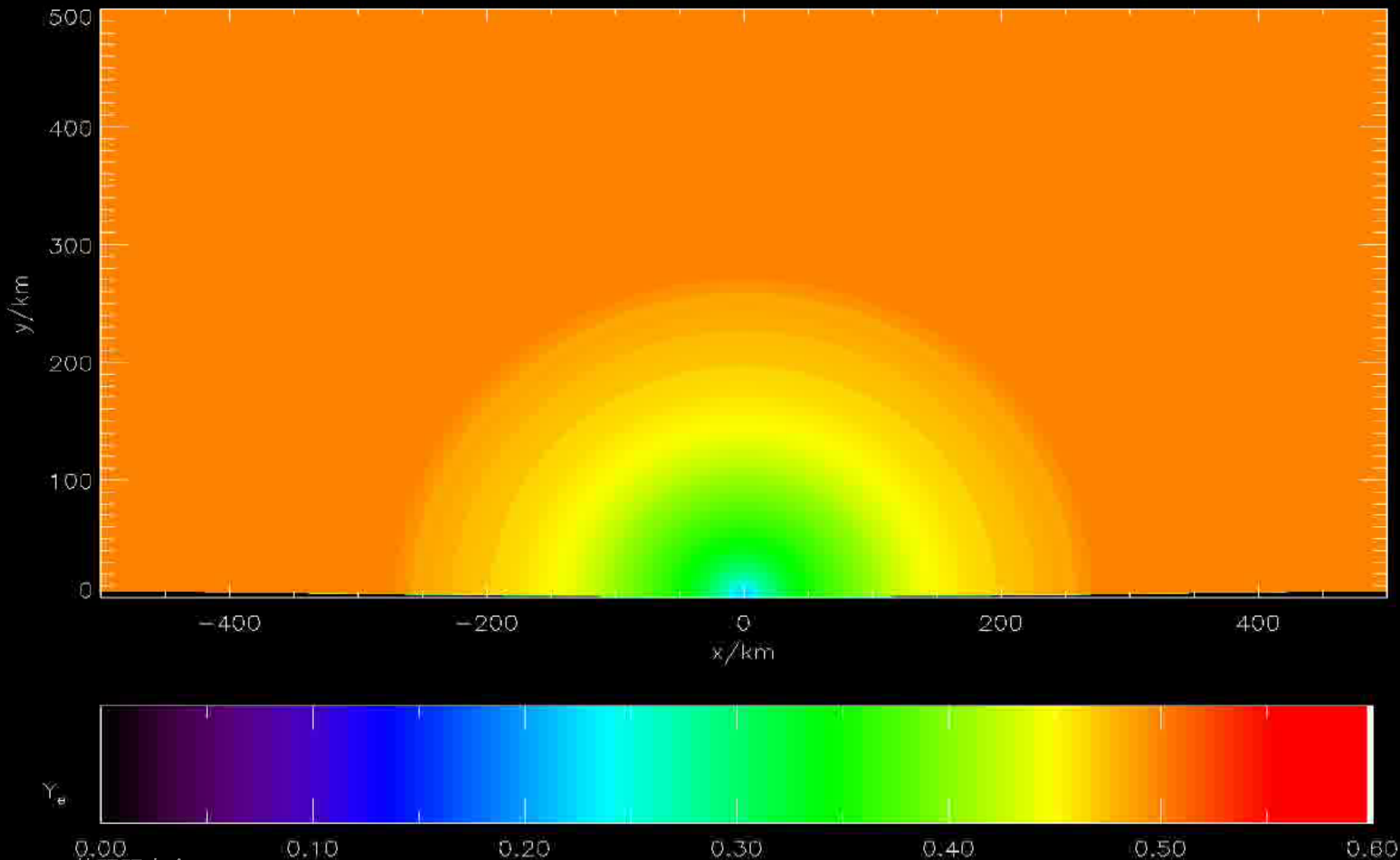
2D SN simulations with ν-transport



- a number of self-consistent SN models with ν-transport are now available (at MPA)
- very first result of SN nucleosynthesis with such models
- can we confirm production of light trans-iron nuclei (and beyond) ?

$8.8\ M_{\odot}$ self-consistently exploding ONeMg core supernova

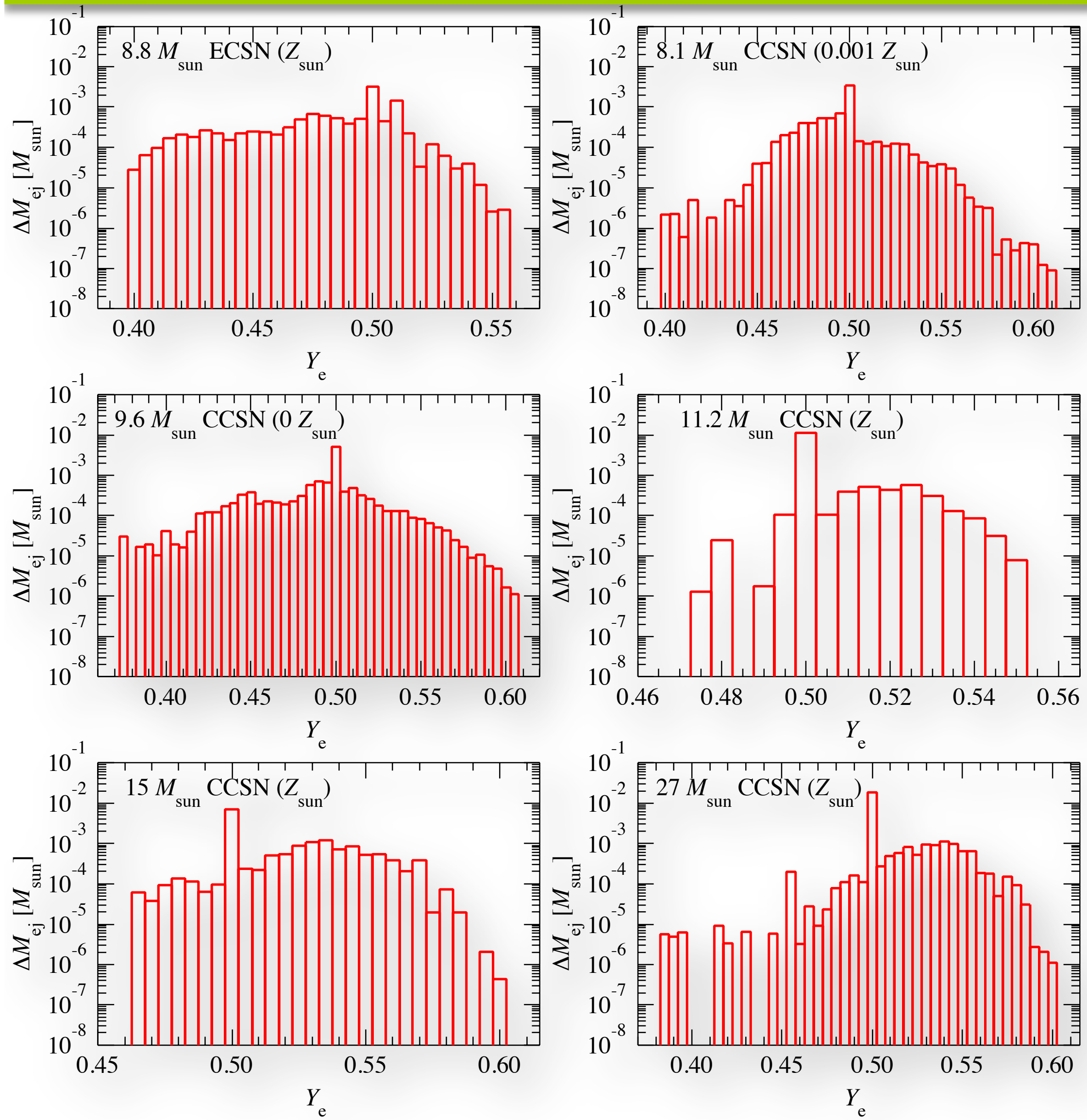
simulation by Bernhard Müller


500
400
300
200
100
0
y/km
−400
−200
0
200
400
x/km
Y_e
0.00
0.10
0.20
0.30
0.40
0.50
0.60

27 $M_\odot$ self-consistently exploding Fe core

simulation by Bernhard Müller

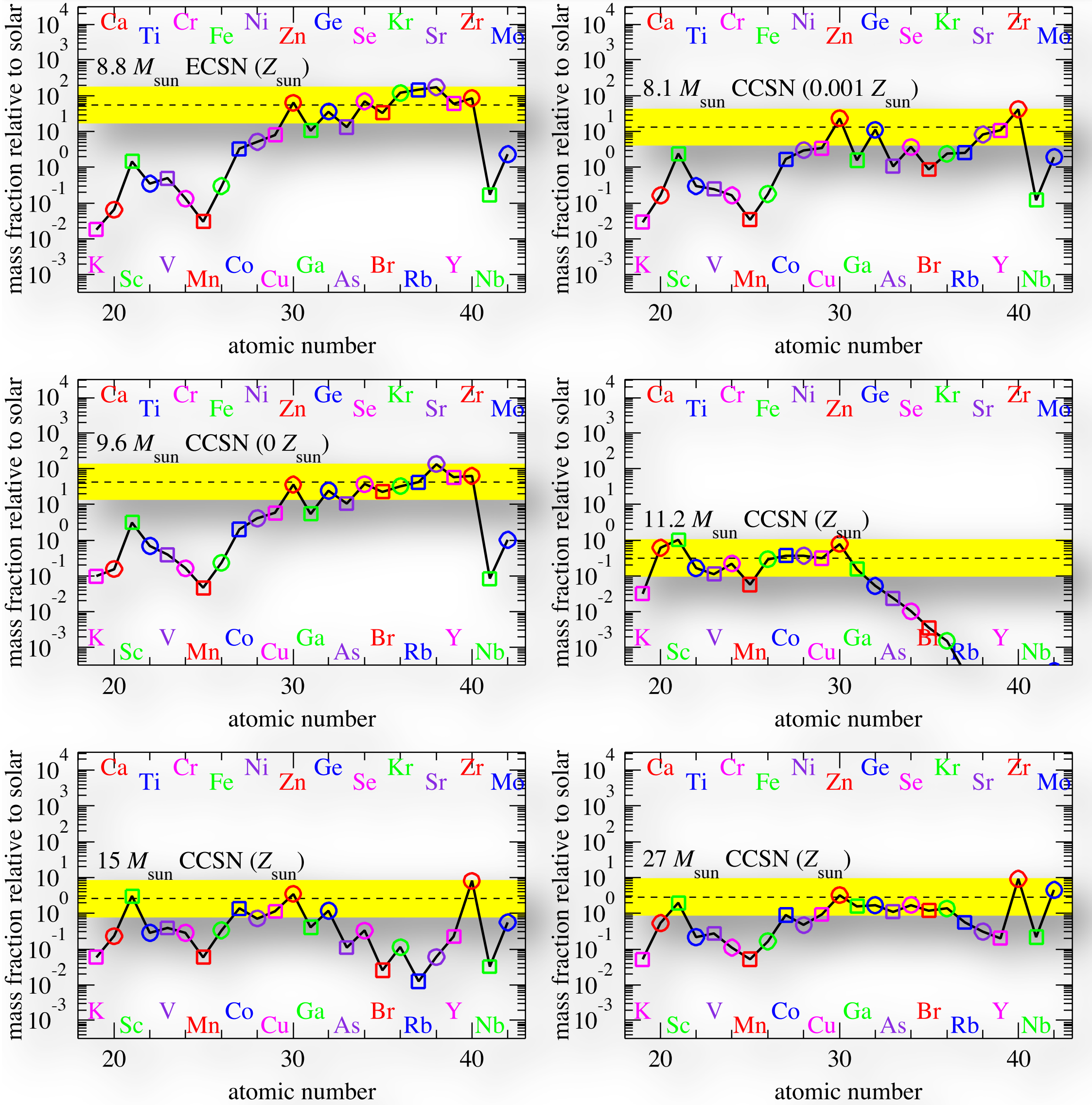
neutron-richness in the ejecta



Y_e distribution in the innermost ejecta (~ 0.01 $M_\odot$)

- lighter SNe have more n-rich ejecta due to rapid expansions (less ν-processed)
- more massive SNe have more p-rich ejecta due to slow expansions (more ν-processed)

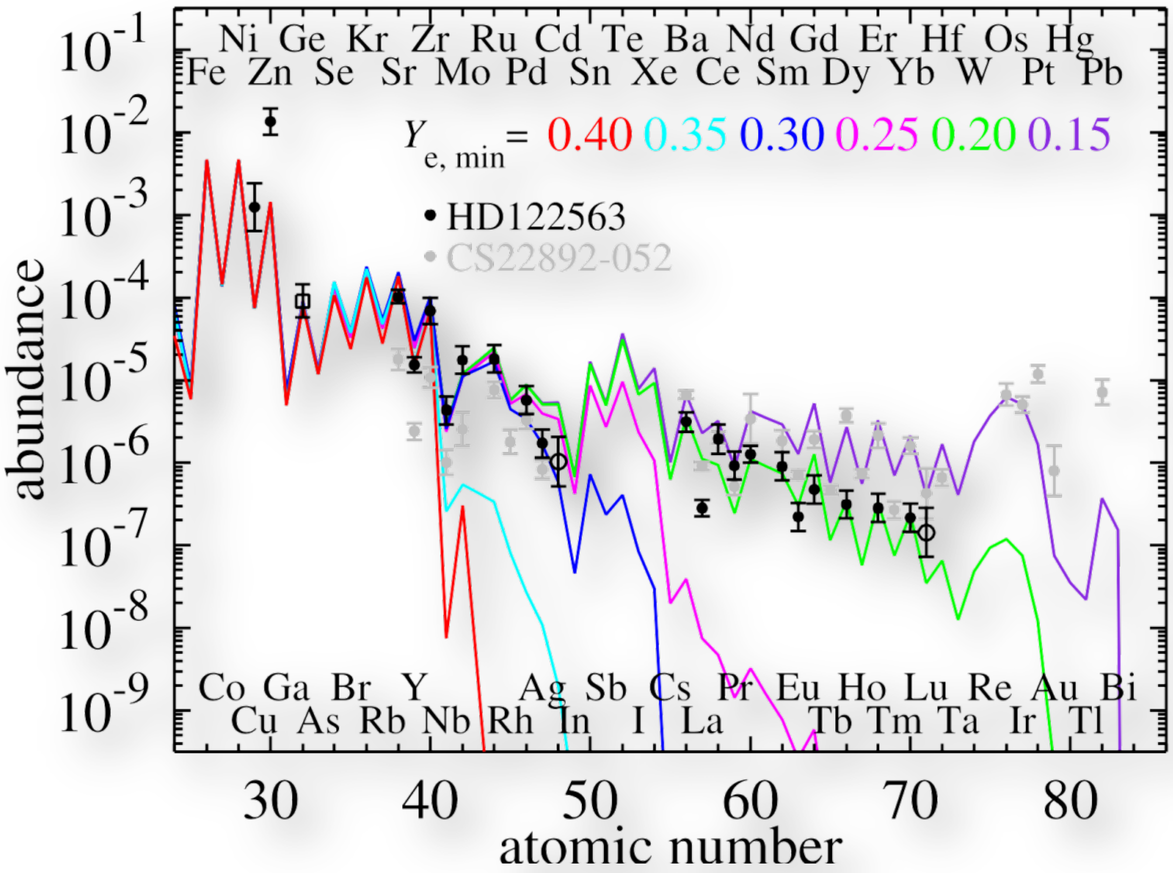
elemental abundances for each SN



nucelosynthesis in the innermost ejecta (M_{ej} ~ 0.01 $M_\odot$)

- light SNe have NSE-like features (intermediate light trans-iron more produced)
- massive SNe have QSE-like features (Zn and Zr more produced)

supernovae at the low-mass end



- no r-process (up to Sr-Y-Zr)
- weak r-process may be possible?

SN neutrino wind: not so neutron-rich

- Y_e is determined by

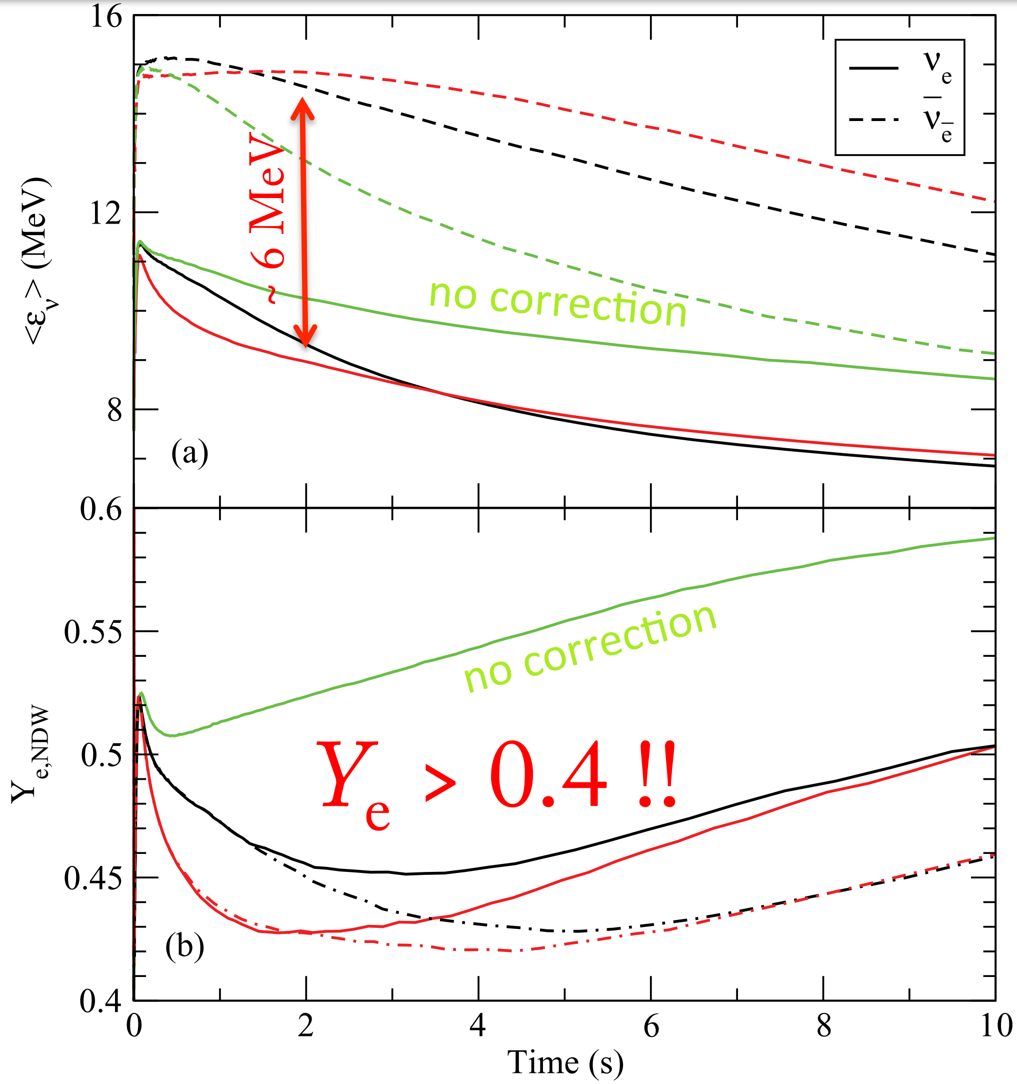
$$\nu_e + n \rightarrow p + e^-$$
$$\bar{\nu}_e + p \rightarrow n + e^+$$

- equilibrium value is

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

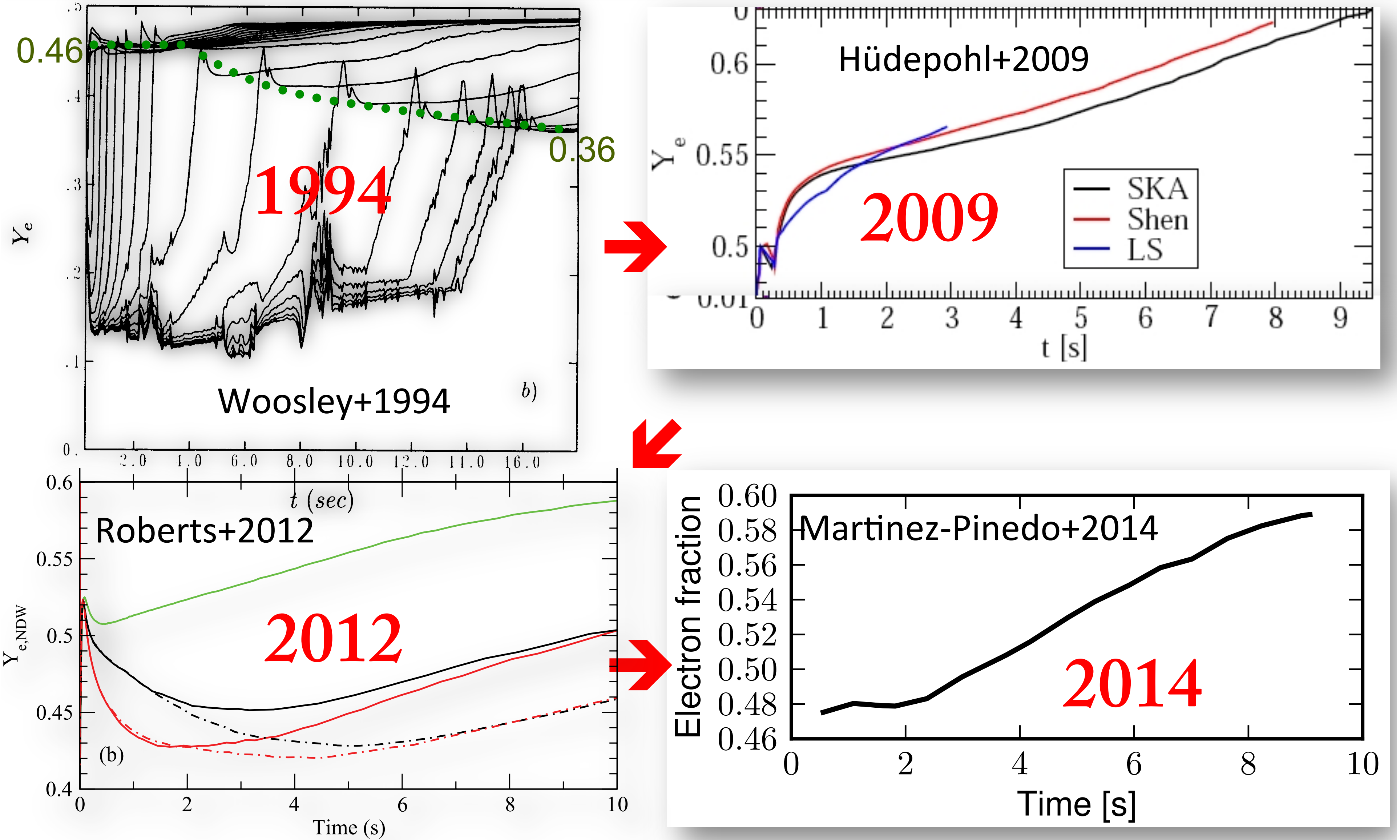
- for $Y_e < 0.5$ (i.e., n-rich)

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

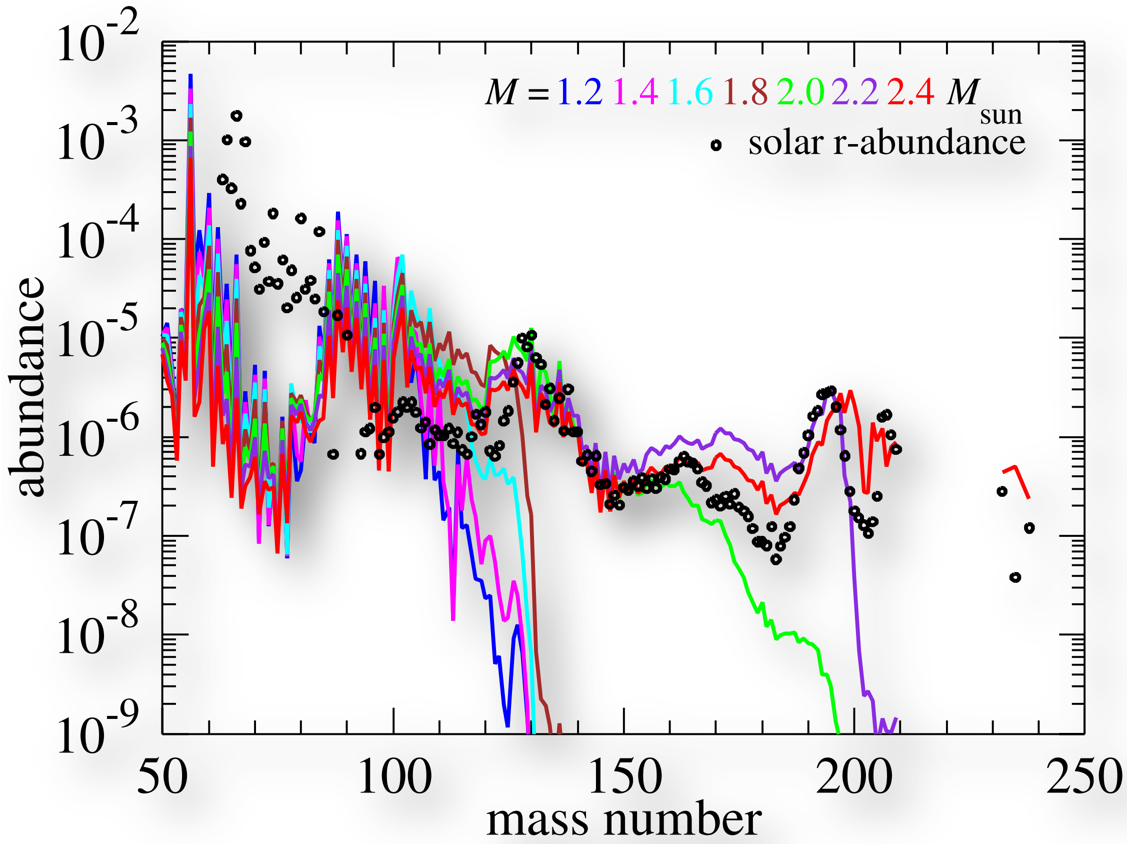


Roberts+2012

“history” of Y_e evolutions: who is right?



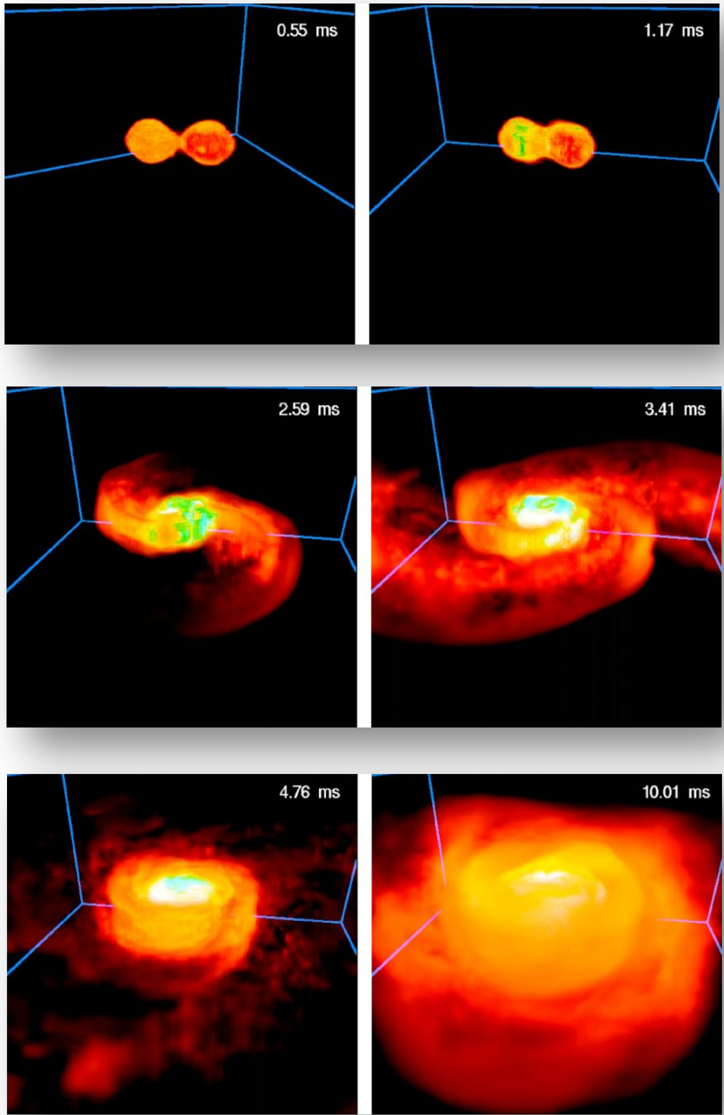
is the answer blowing in the wind?



Wanajo 2013

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

NS merger scenario: most promising?

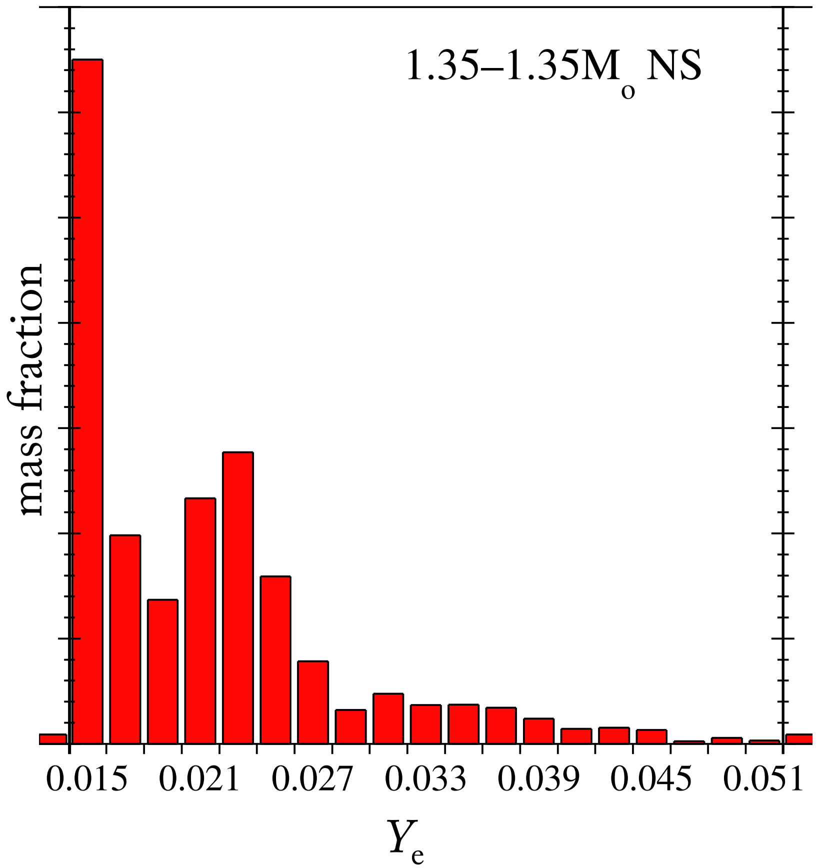


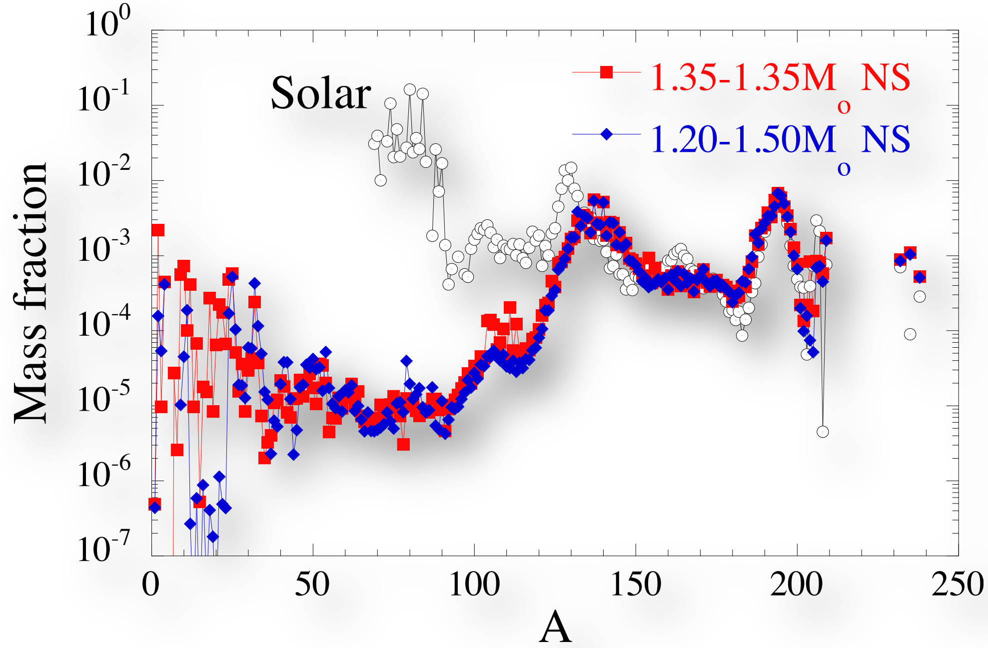
www.mpa-garching.mpg.de

- 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)





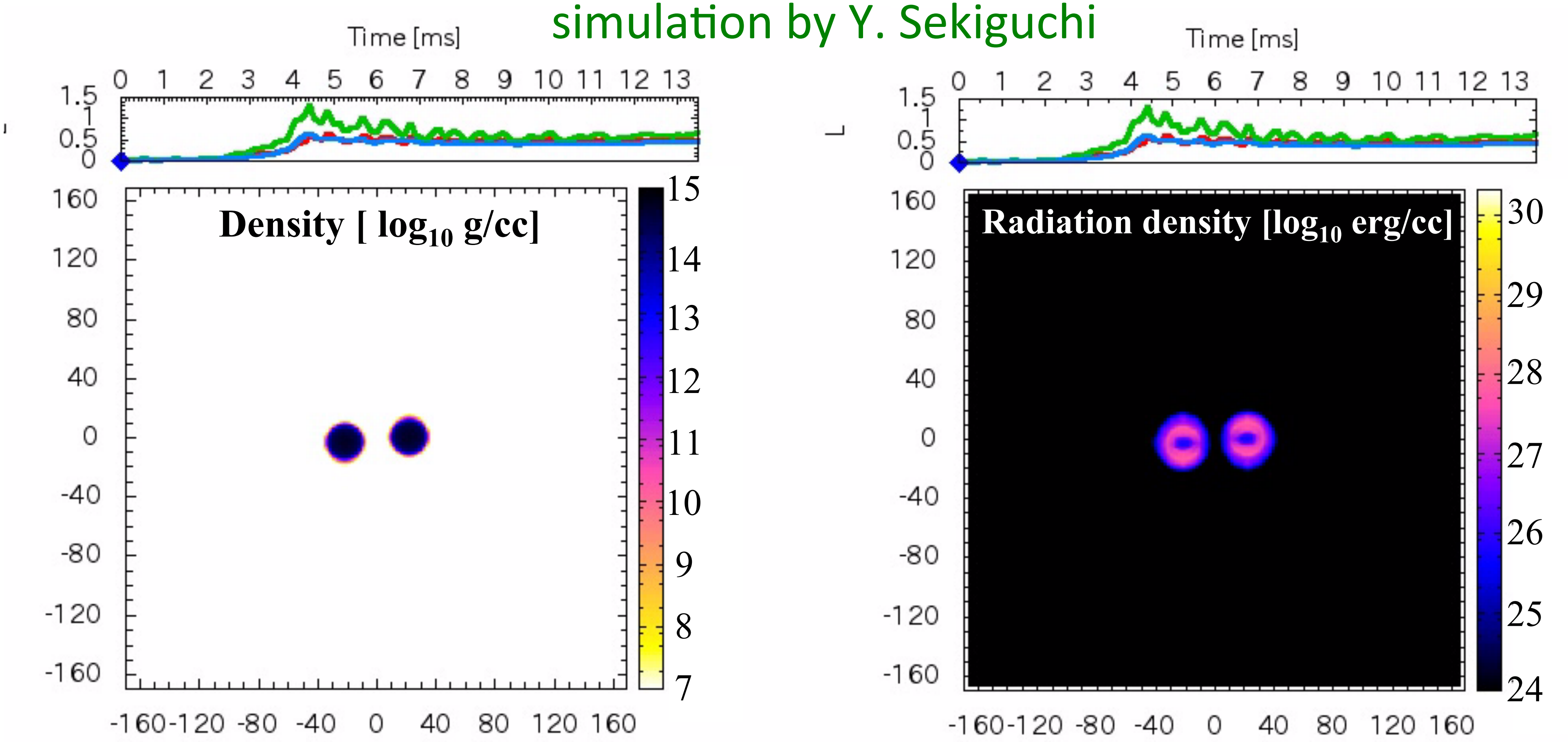
tidal (or weakly shocked) ejection of "pure" n-matter with $Y_e < 0.1$

- strong r-process leading to fission recycling
- severe problem: only $A > 120$; another source is needed for the lighter counterpart

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

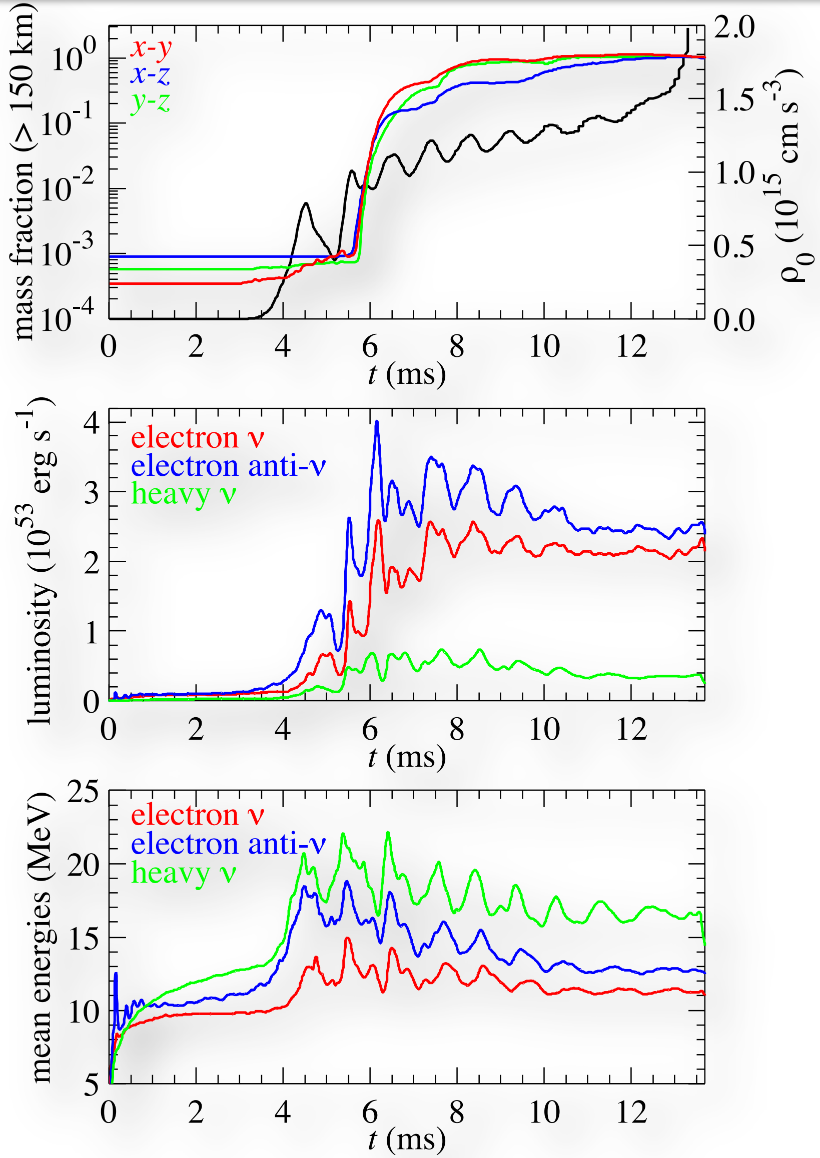
simulation by Y. Sekiguchi



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

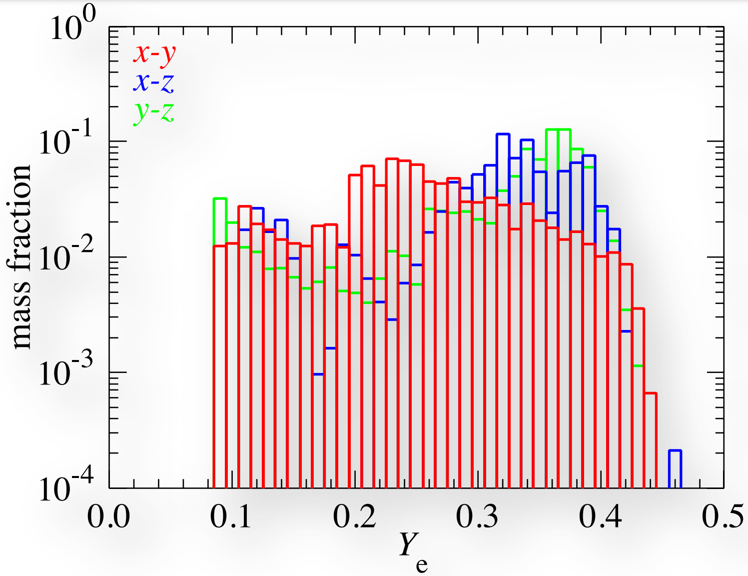
simulation by Yuichiro Sekiguchi

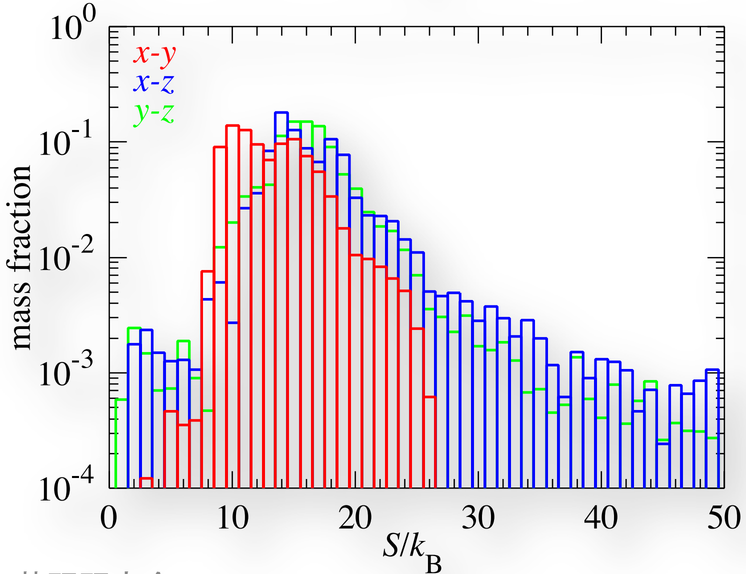
neutrino properties (Steiner's EOS)



- 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



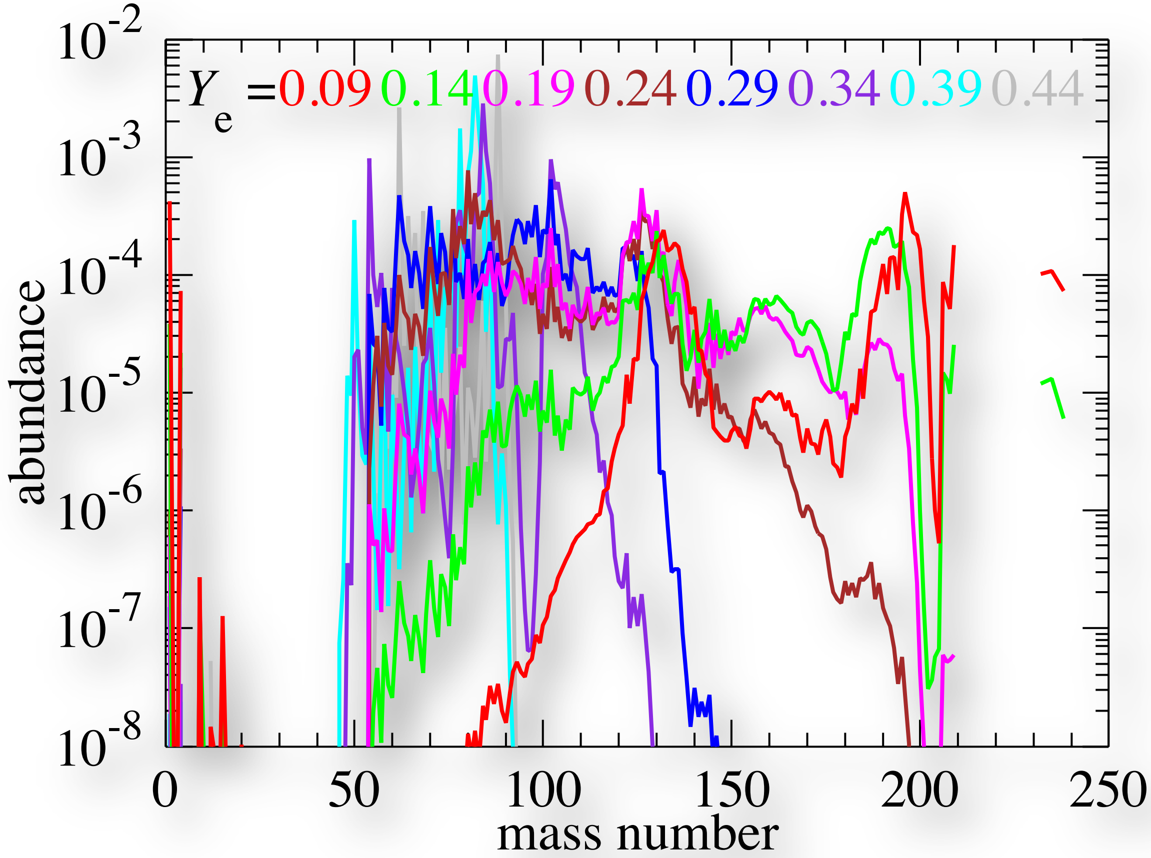


- higher and wider range of Y_e (~ 0.1-0.5) in contrast to previous cases Y_e (= 0.01-0.05)
- values do not fully asymptote to Y_e ~ 0.5 because of v/c ~ 0.1-0.3

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

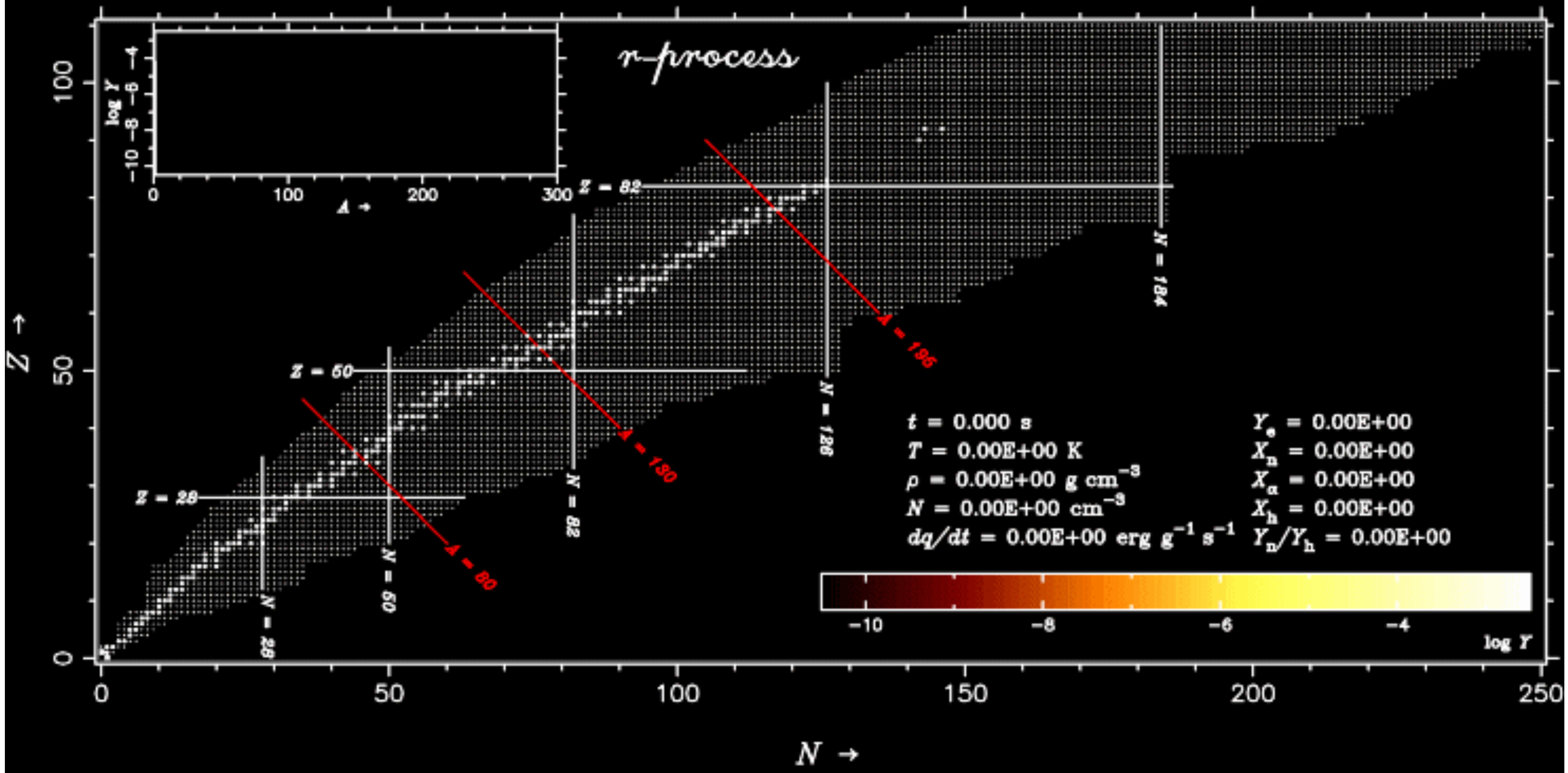
post-process nucleosynthesis

nucleosynthesis for selected Y_e



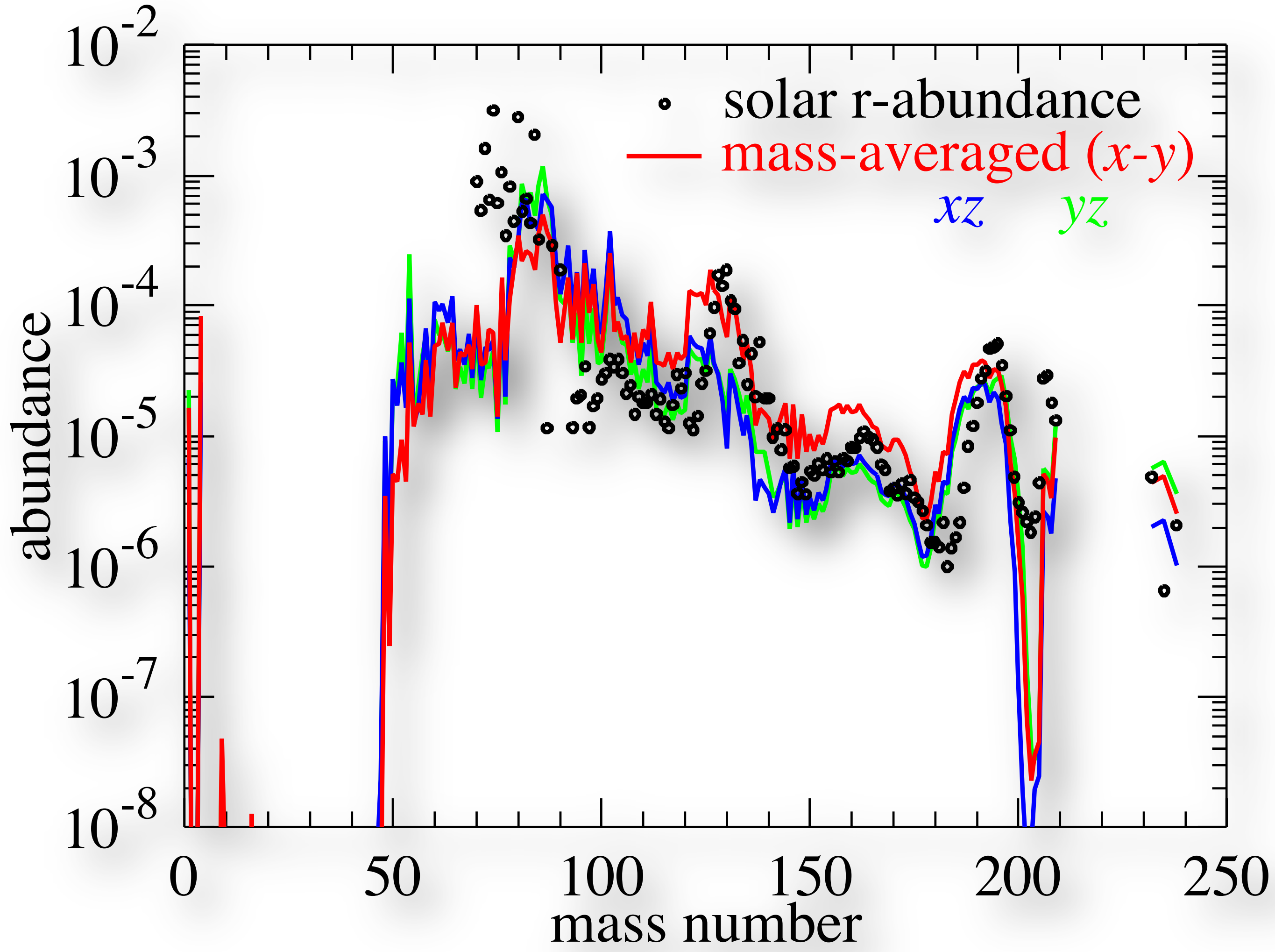
- variation of r-processes depending on Y_e
- production of iron to uranium
- no fission recycling

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

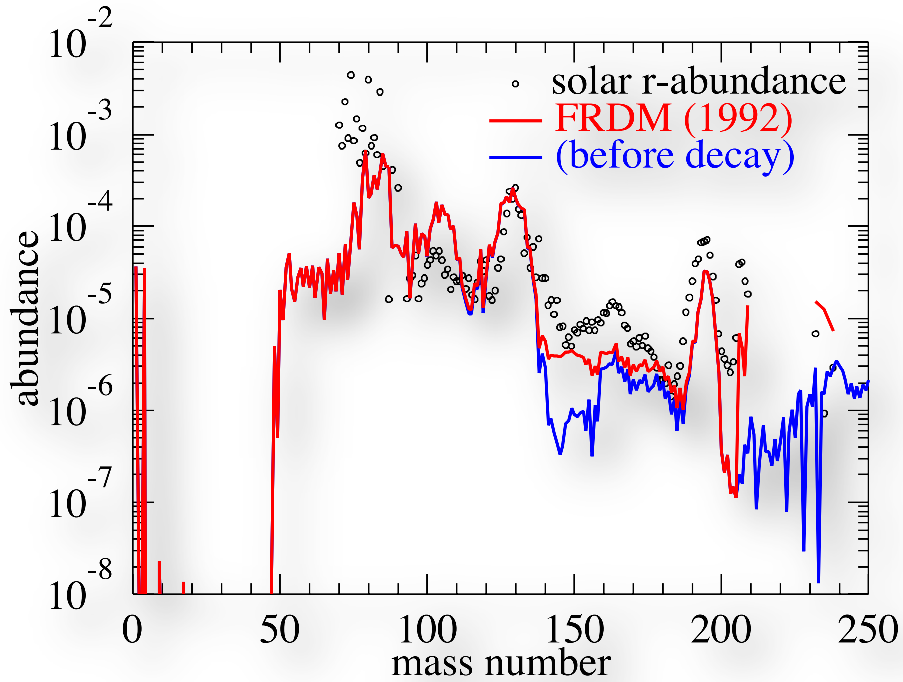
mass-integrated abundances

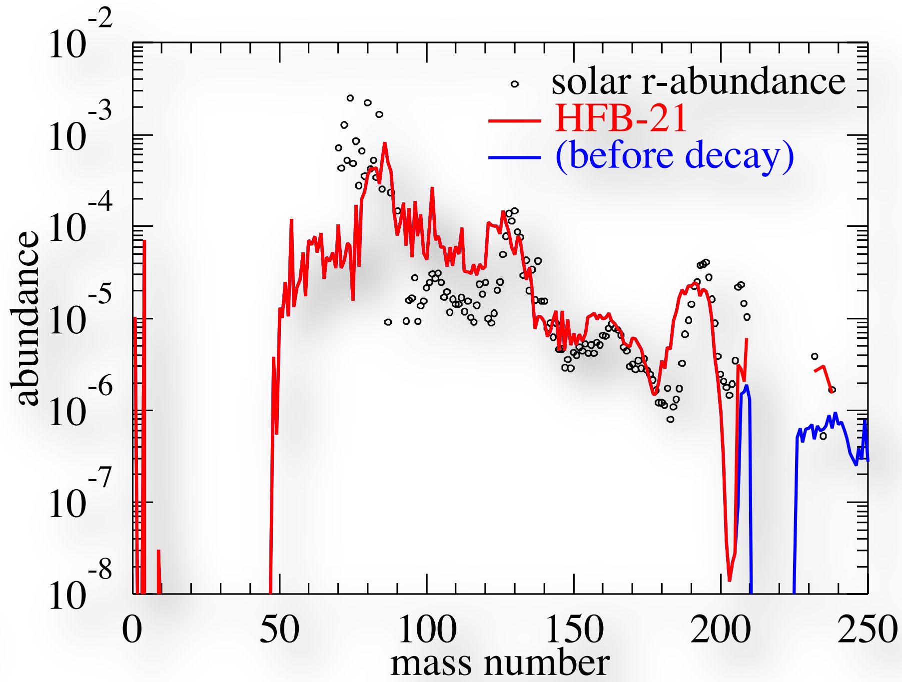


❖ reasonable agreement with full solar r-process range for *A* = 90-240

comparison for different mass models

for neutron star mergers in Wanajo+2014; without fission

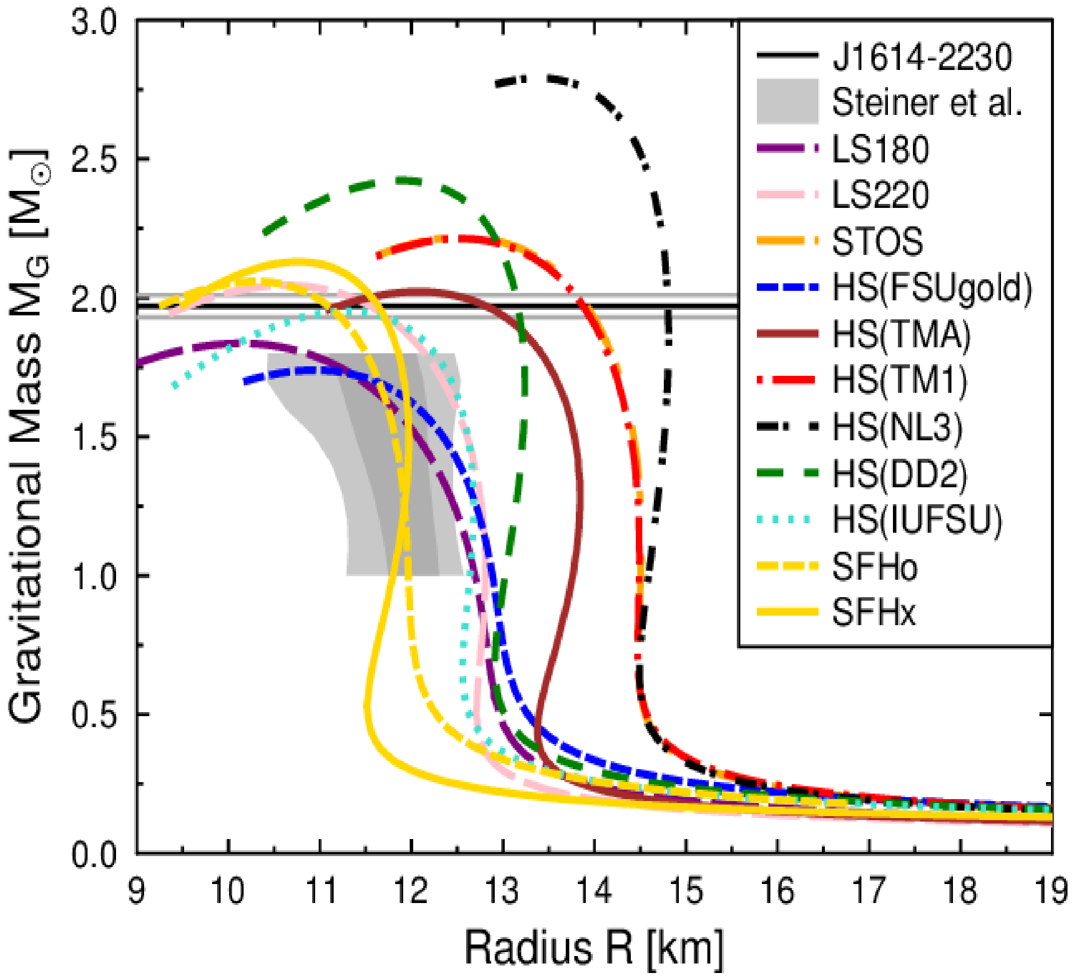




❖ large differences between FRDM (1992, not 2012!) and HFB-21 slide by Y. Sekiguchi

Dynamical mass ejection mechanism & EOS

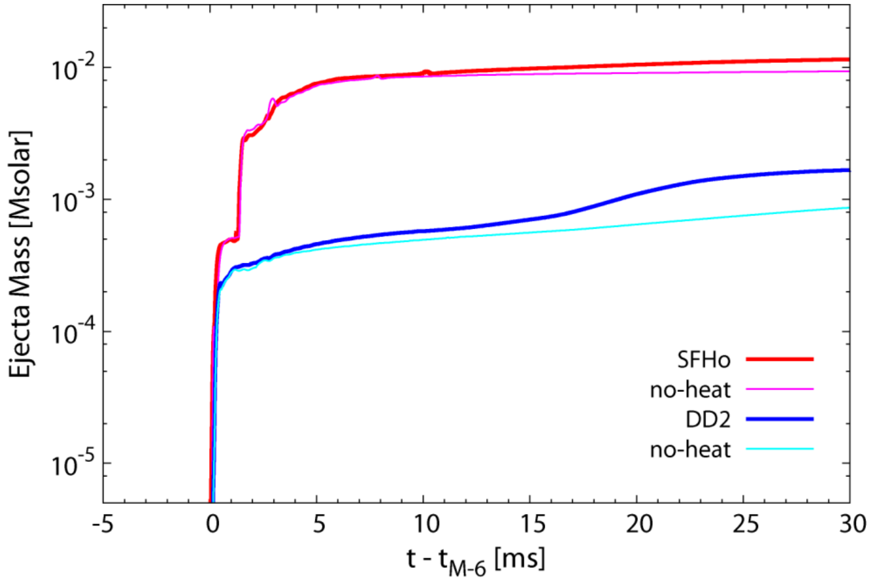
- 'Stiffer EOS'
  - **TM1, TMA**
  - R_{NS} : lager
  - Tidal-driven dominant
  - **Ejecta consist of low T & Ye NS matter**
- 'Intermediate EOS'
  - **DD2**
- 'Softer EOS'
  - **SFHo, IUFSU**
  - R_{NS} : smaller
  - Tidal-driven less dominant
  - Shock-driven dominant
  - **Ye can change via weak processes**

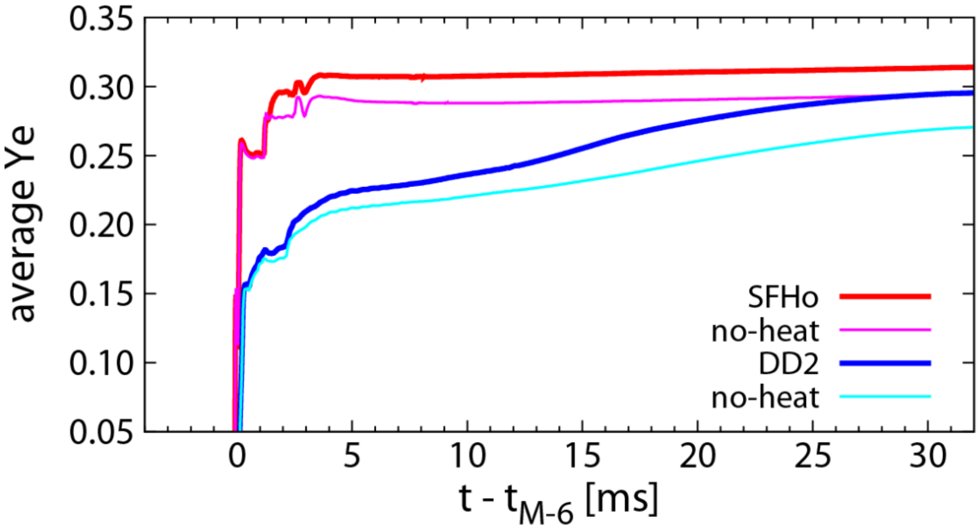


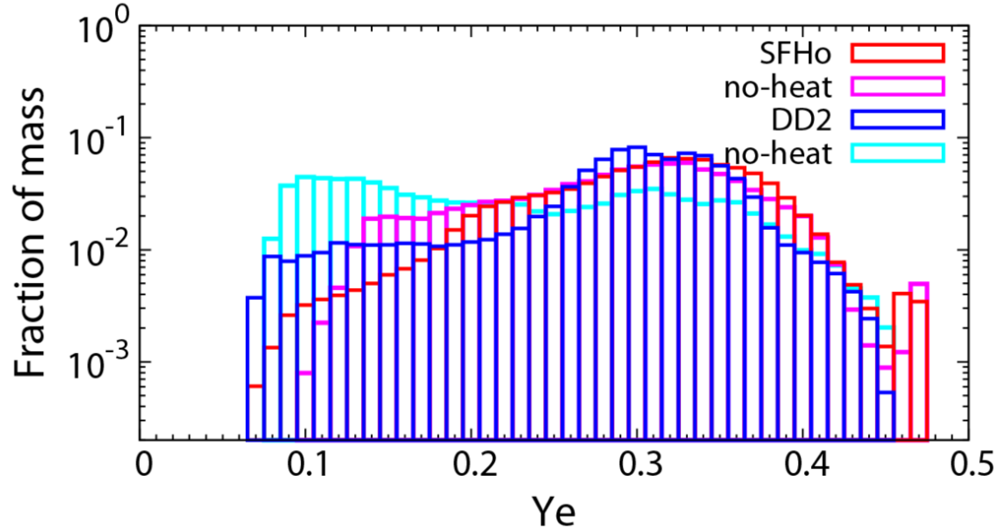
See also, Bauswein et al. (2013); Just et al. (2014)

slide by Y. Sekiguchi

Effects of neutrino heating



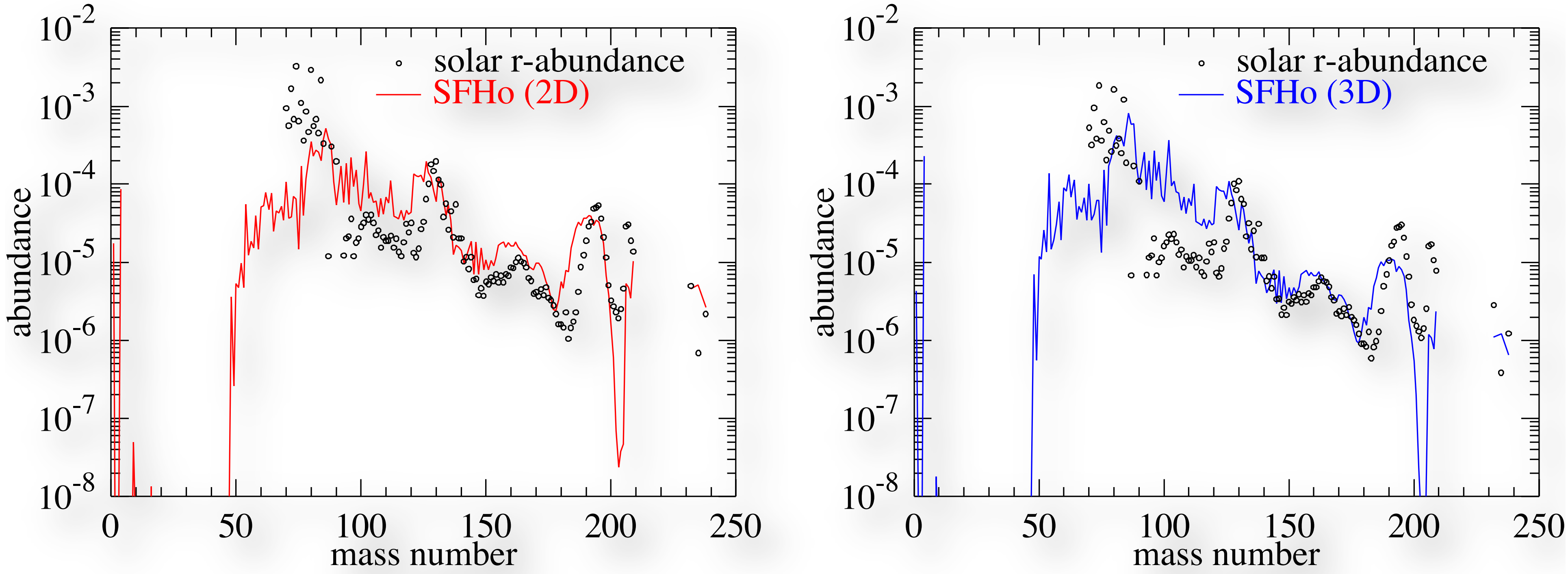




- Amount of ejecta mass can be increased ~ 10^{-3} Msun
- Average Ye can change 0.02~0.03 depending on EOS : effect is stronger for stiffer EOS where HMNS survive in a longer time

2D (orbital pl.) vs 3D

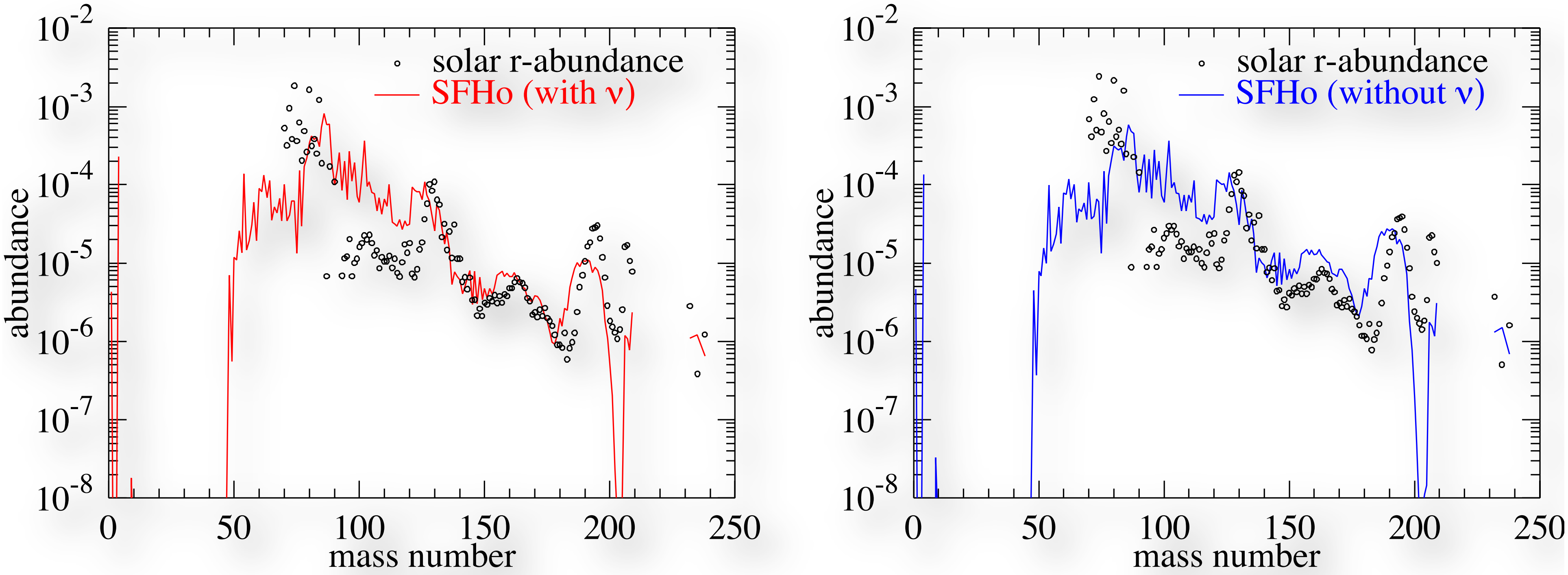
adopting nucleosynthesis of Wanajo+2014



❖ full 3D nucleosynthesis predicts smaller heavy r-process products

effect of neutrinos

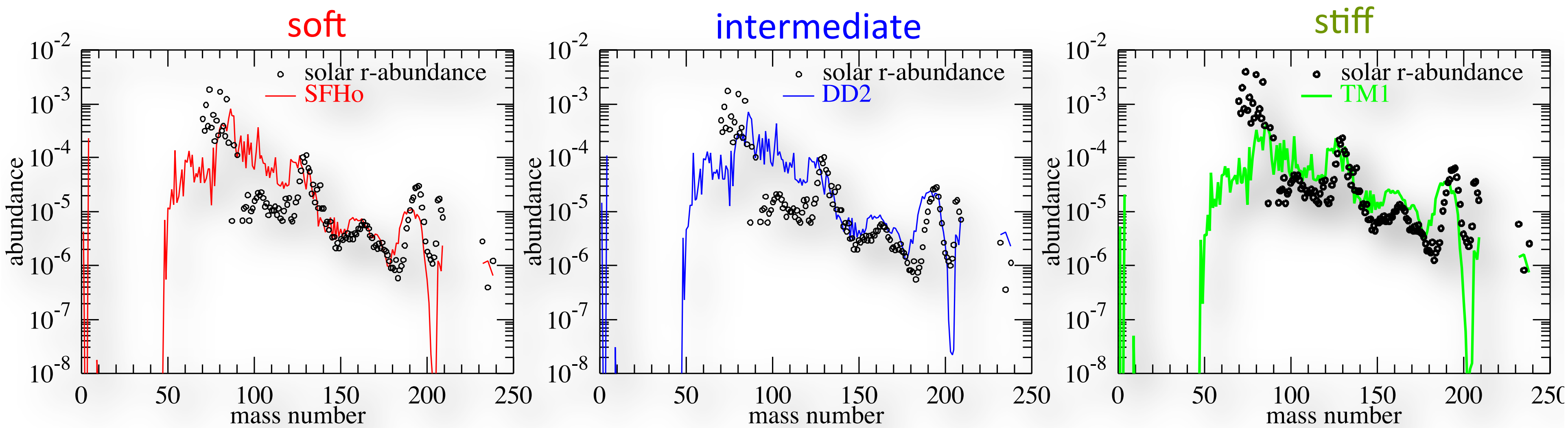
adopting nucleosynthesis of Wanajo+2014



❖ neutrino absorption leads to less heavy r-process products

dependence on EOSs

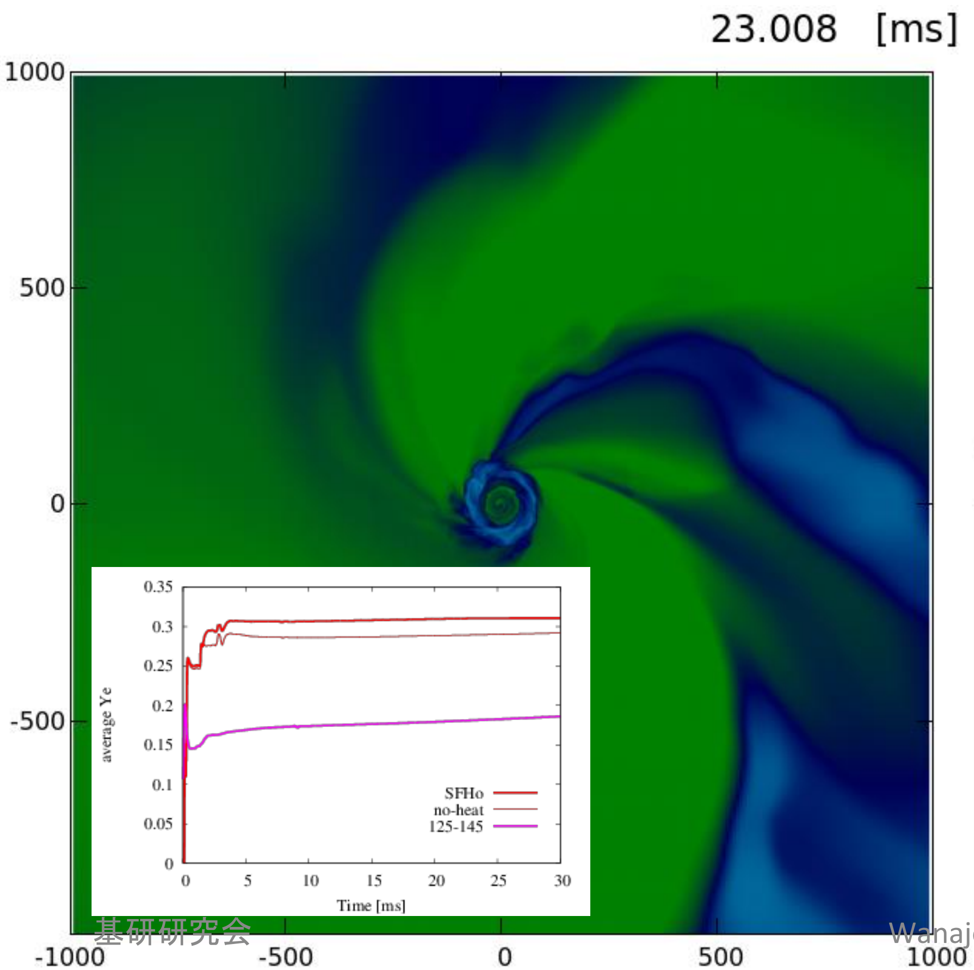
adopting nucleosynthesis of Wanajo+2014

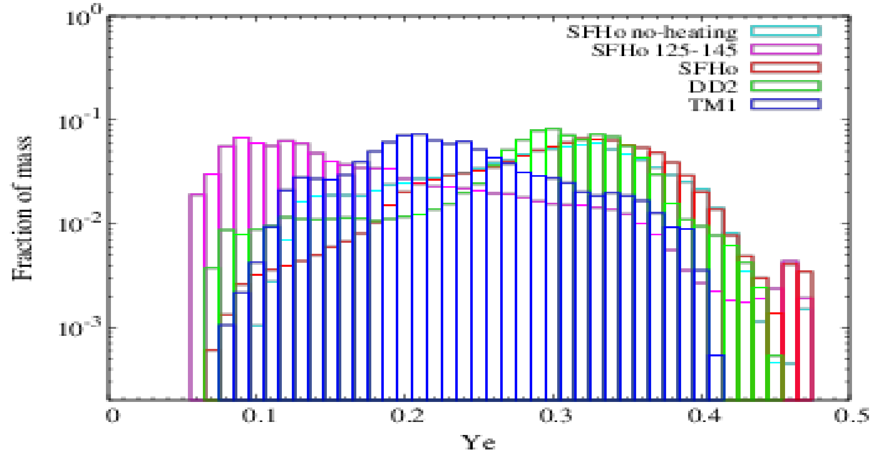


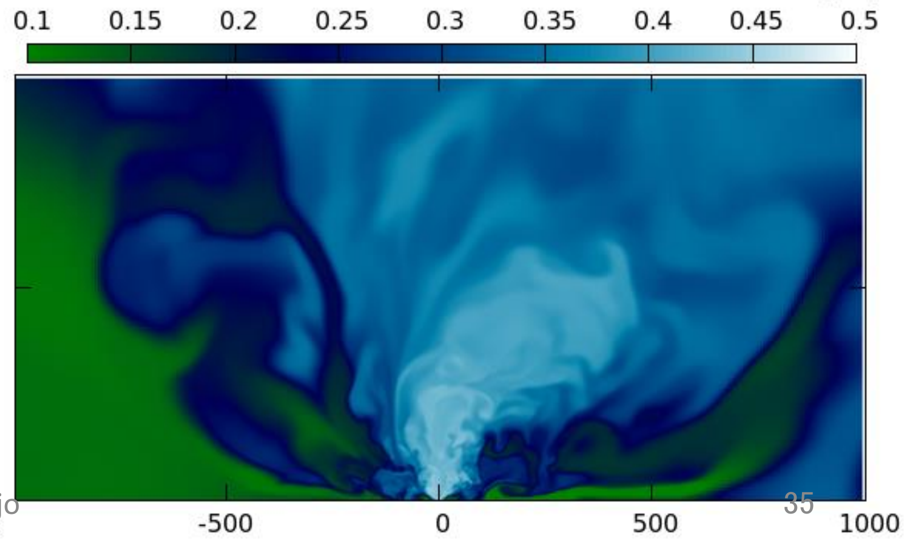
- ❖ softer EOS predicts less heavy r-process products, but
- ❖ effects of EOSs are not large (good for the universality?)

Unequal mass NS-NS system: SFHo1.25-1.45

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

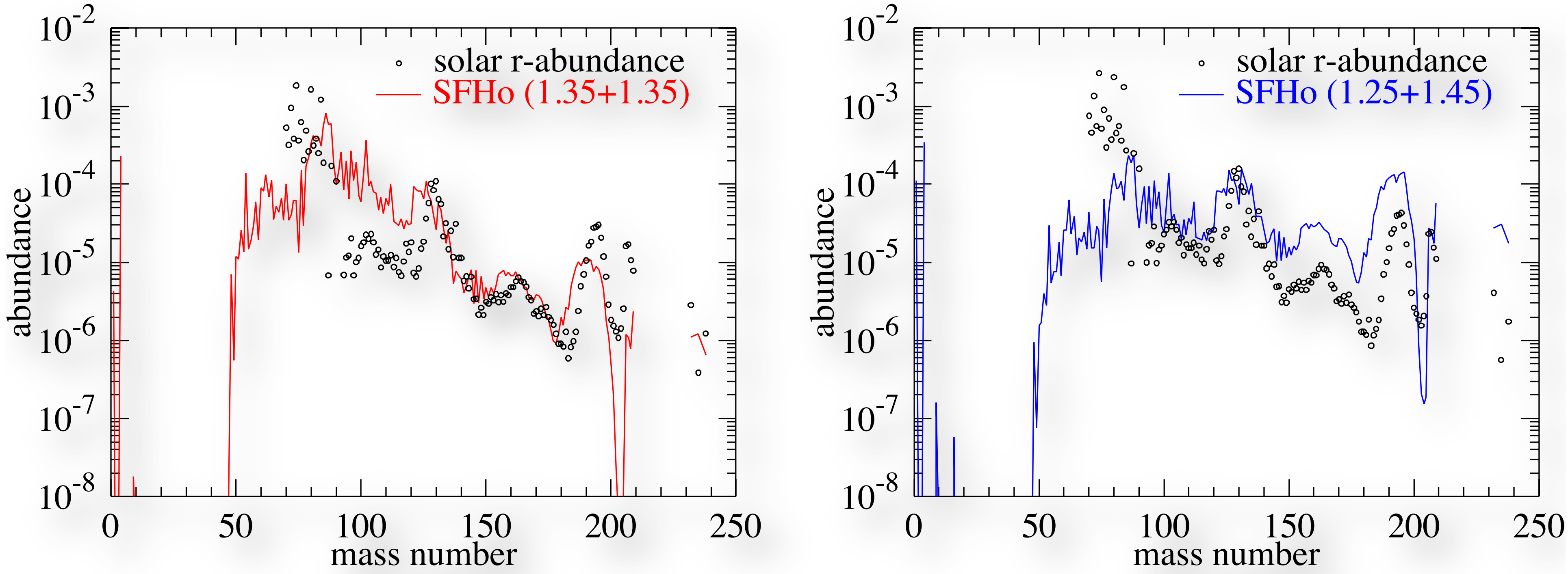






dependence on the NS mass ratio

adopting nucleosynthesis of Wanajo+2014



❖ small asymmetry predicts less heavy r-process products

❖ moderate asymmetry is the best? (e.g., 1.3+1.4)

summary and outlook

- NS mergers: very promising site of r-process
  - GR and weak interactions play crucial roles
- still many things yet to be answered…
  - dependence on NS masses, EOSs, and nuclear masses?
  - how the subsequent BH-tori contribute to the r-abundances?
  - how do they shine as electro-magnetic transients?
  - can mergers be the origin of r-process elements in the Galaxy?