The r-process and electromagnetic emission from neutron star mergers

Shinya Wanajo (RIKEN iTHES)

with

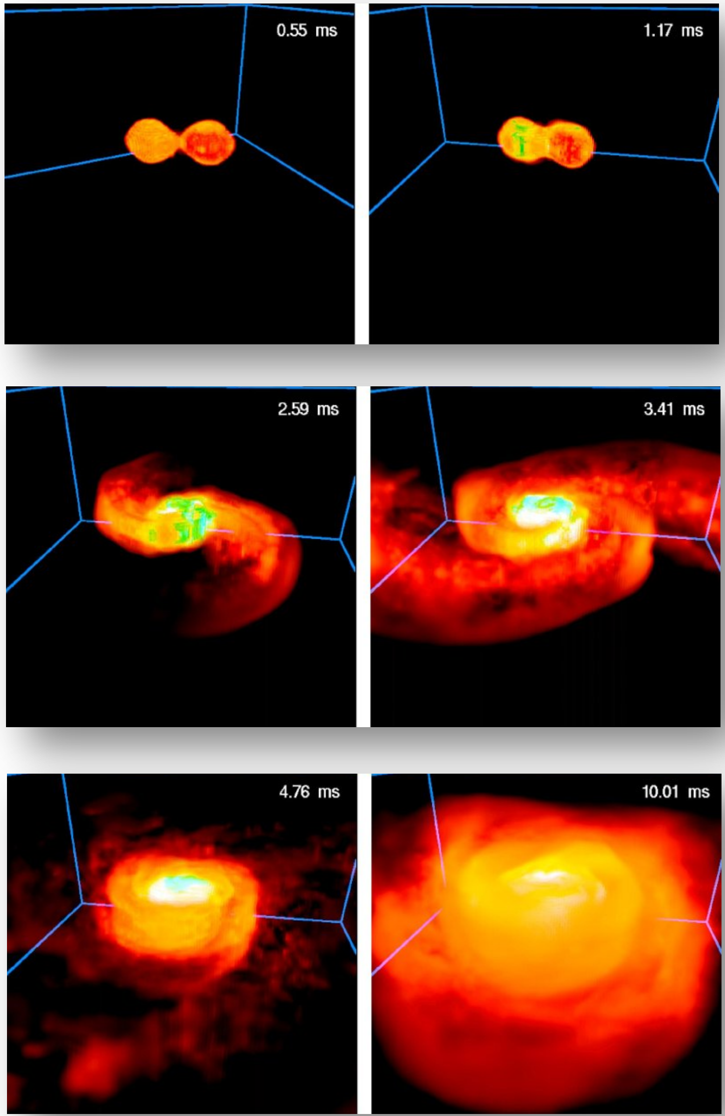
Y. Sekiguchi (YITP), N. Nishimura (Keele Univ.),
K. Kiuchi (YITP), K. Kyutoku (RIKEN), M. Shibata (YITP)
M. Tanaka (NAOJ), K. Hotokezaka (Hebrew Univ.)

GRB Workshop 2015
2015年8月31-9月2日, RIKEN

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

www.cartier.jp

NS mergers: sRGB and r-process



www.mpa-garching.mpg.de

- coalescence of binary NSs expected ~ 10 – 100 per Myr in the Galaxy (possible sources of short GRB as well as r-process)
- 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 $M_{ej} \sim 10^{-2}\ M_{\odot}$??

NS mergers: sGRB and r-process

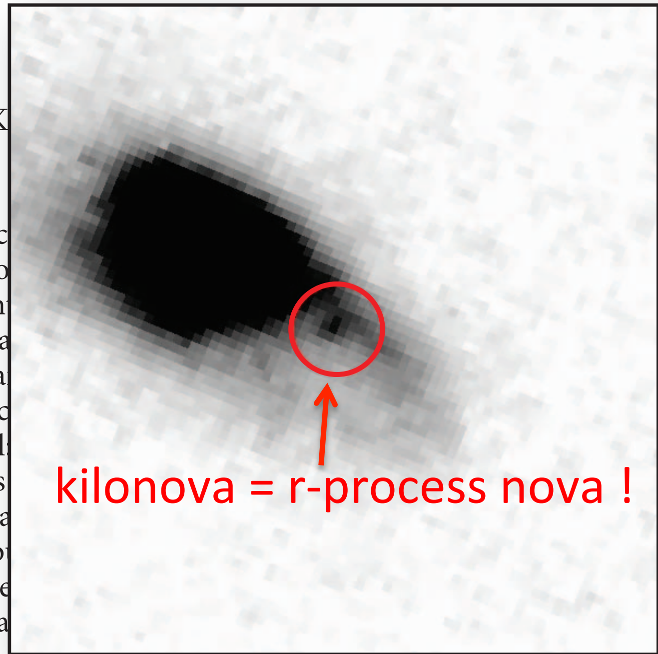
LETTER

doi:10.1038/nature12505

A 'kilonova' associated with the short-duration γ-ray burst GRB 130603B

N. R. Tanvir[1], A. J. Levan[2], A. S. Fruchter[3], J. Hjorth[4], R. A. Hounsell[3], K

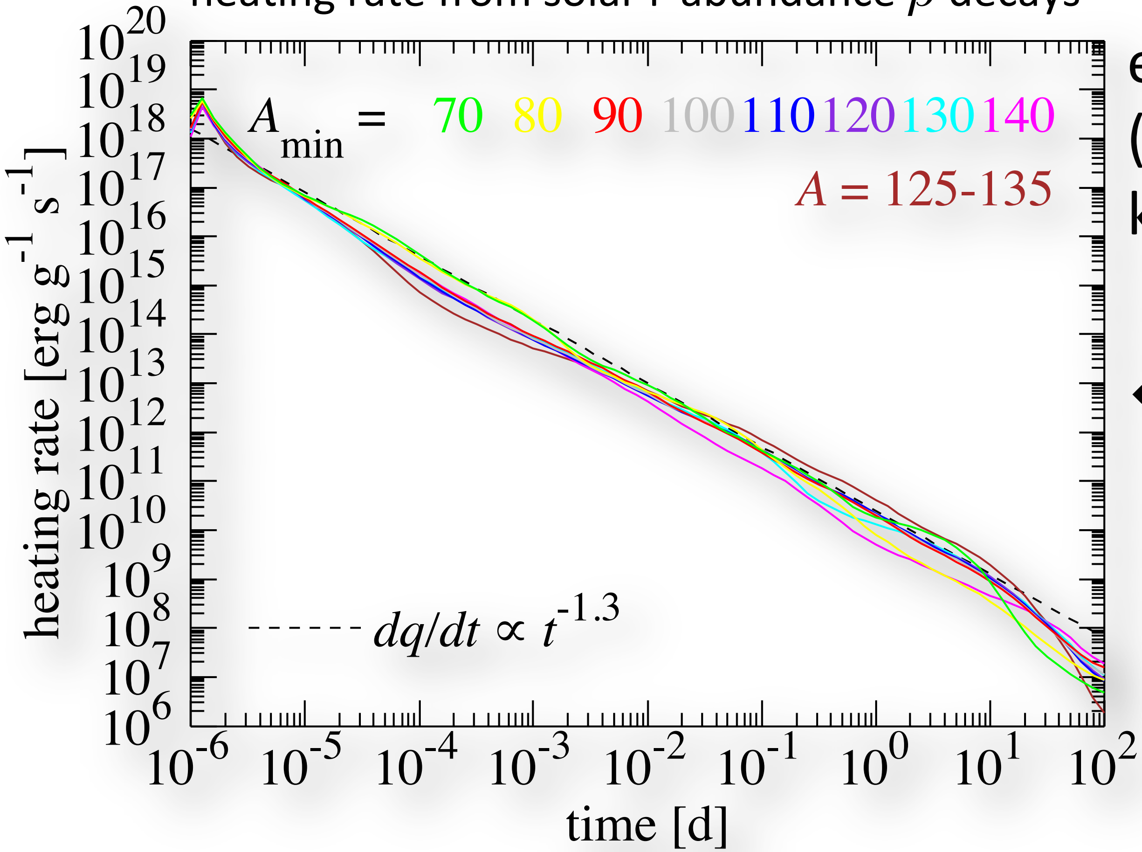
Short-duration γ-ray bursts are intense flashes of cosmic γ-rays, lasting less than about two seconds, whose origin is unclear[1,2]. The favoured hypothesis is that they are produced by a relativistic jet created by the merger of two compact stellar objects (specifically two neutron stars or a neutron star and a black hole). This is supported by indirect evidence such as the properties of their host galaxies[3], but unambiguous confirmation of the model is still lacking. Mergers of this kind are also expected to create significant quantities of neutron-rich radioactive species[4,5], whose decay should result in a faint transient, known as a 'kilonova', in the days following the burst[6–8]. Indeed, it is speculated that this mechanism may be the predominant source of stable r-process elements in the Universe[5,9].



Tanvir+2013, Nature, Aug. 29

r-process novae (kilonovae)

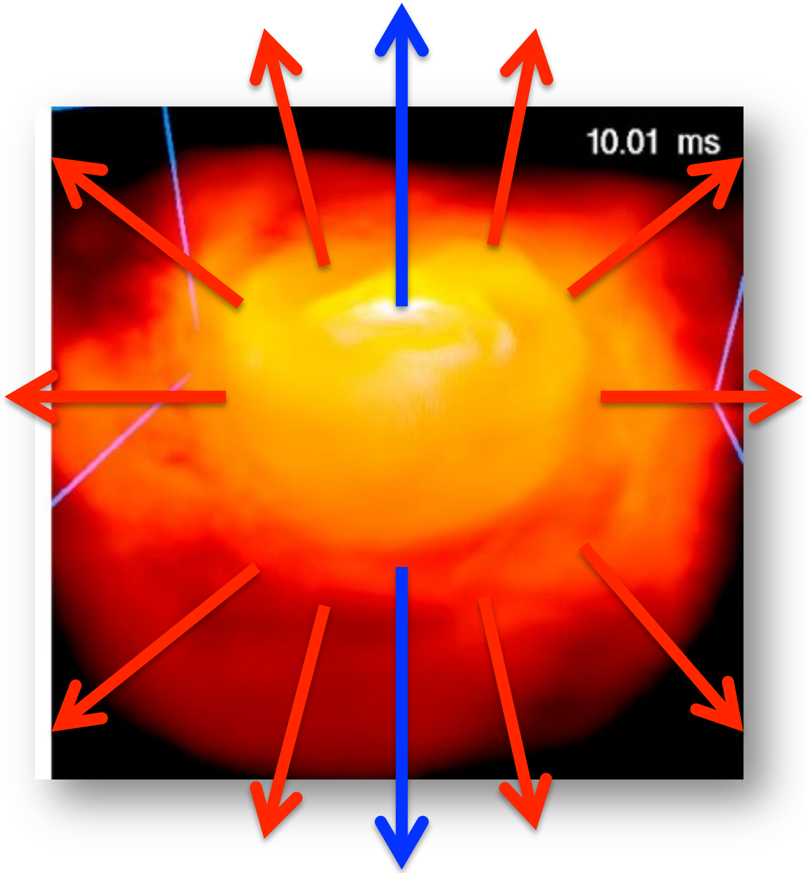
Wanajo+2014;
heating rate from solar r-abundance β-decays



electro-magnetic transients (macronova, Kulkarni 2005; kilonova, Metzger+2010)

- ❖ heating from decays of radionuclides well scaled as $dq/dt \sim t^{-1.3}$

EM counterparts of GW signals



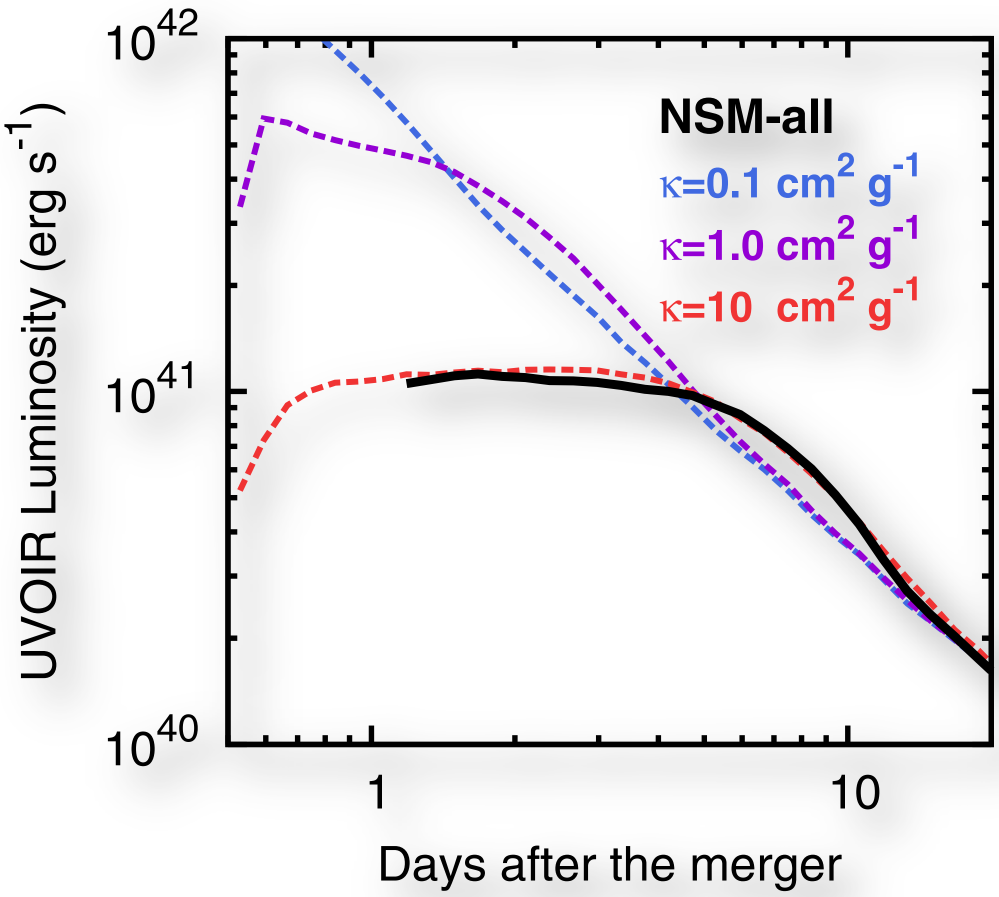
GW signal can be spatially resolved only ~ 100 deg^2 by KAGRA/a.LIGO/a.Virgo (from 2017)
→ EM counterparts are needed

❖ SGRBs
events should be restricted due to narrow beaming

❖ r-process novae
detectable (by, e.g., Subaru/HSC) from all directions!

lanthanide curtain for r-process novae

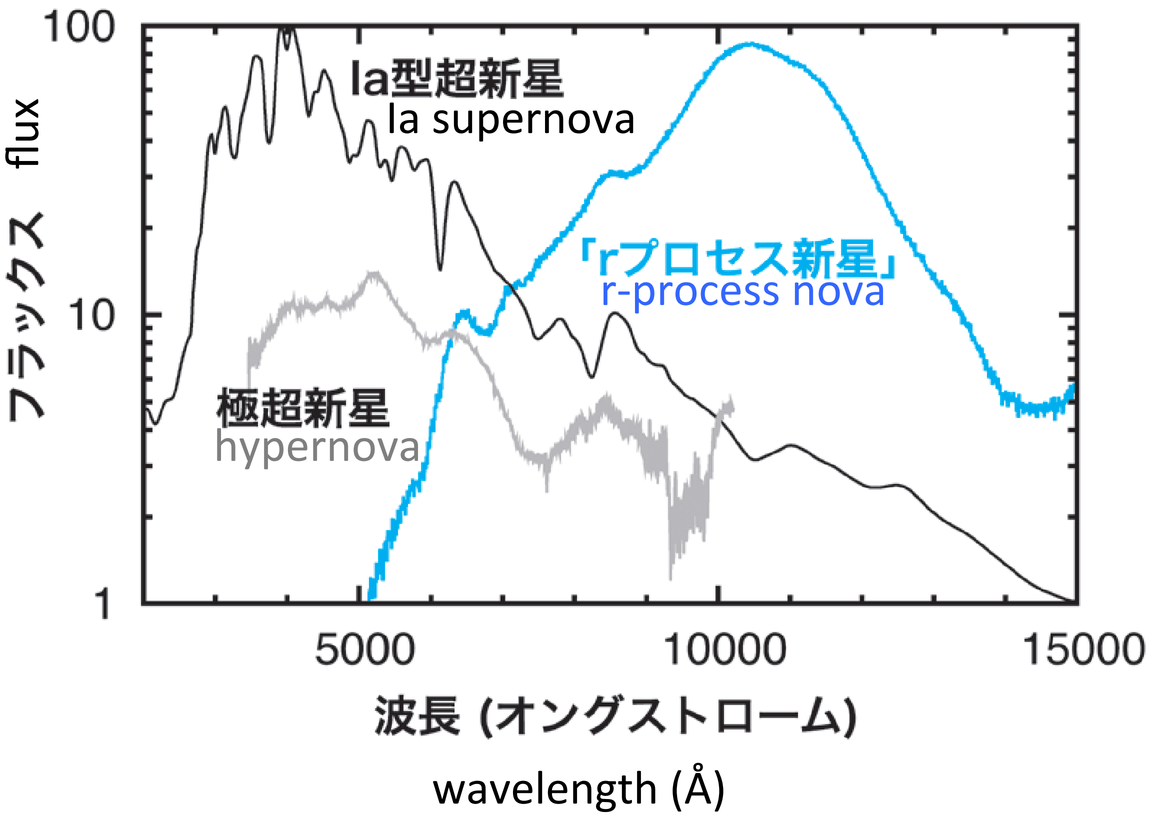
Tanaka & Hotokezaka 2013;
NS+NS models



- large opacities of lanthanides (A > 130); ~ 100 times greater than those of iron group elements
- brightness of r-process novae should be highly dependent on the nucleosynthetic abundances

what is a smoking gun of the r-process?

田中，天文月報2014年1月

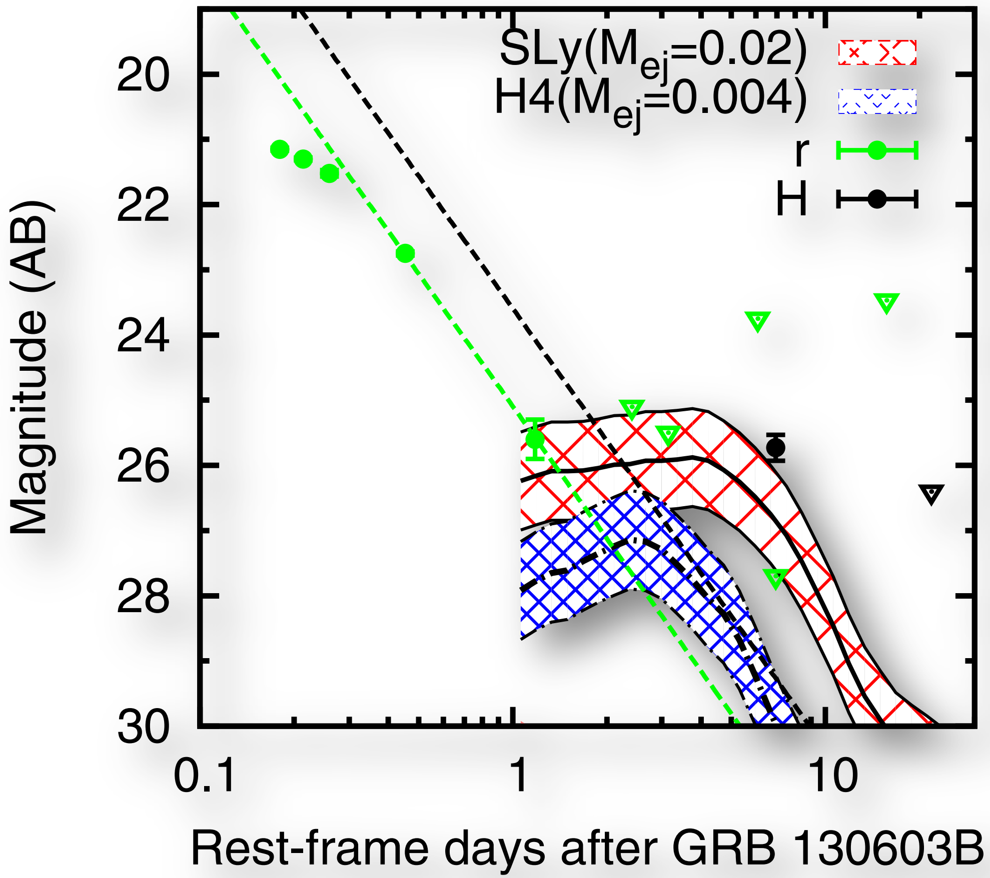


can we see r-abundances in the spectra?

- almost featureless because of too many bound-bound lines and Doppler shifts (v/c ~ 0.1-0.3)
- identification of red, featureless spectral shape can be an unambiguous evidence of an r-process

r-process nova in the SGRB afterglow?

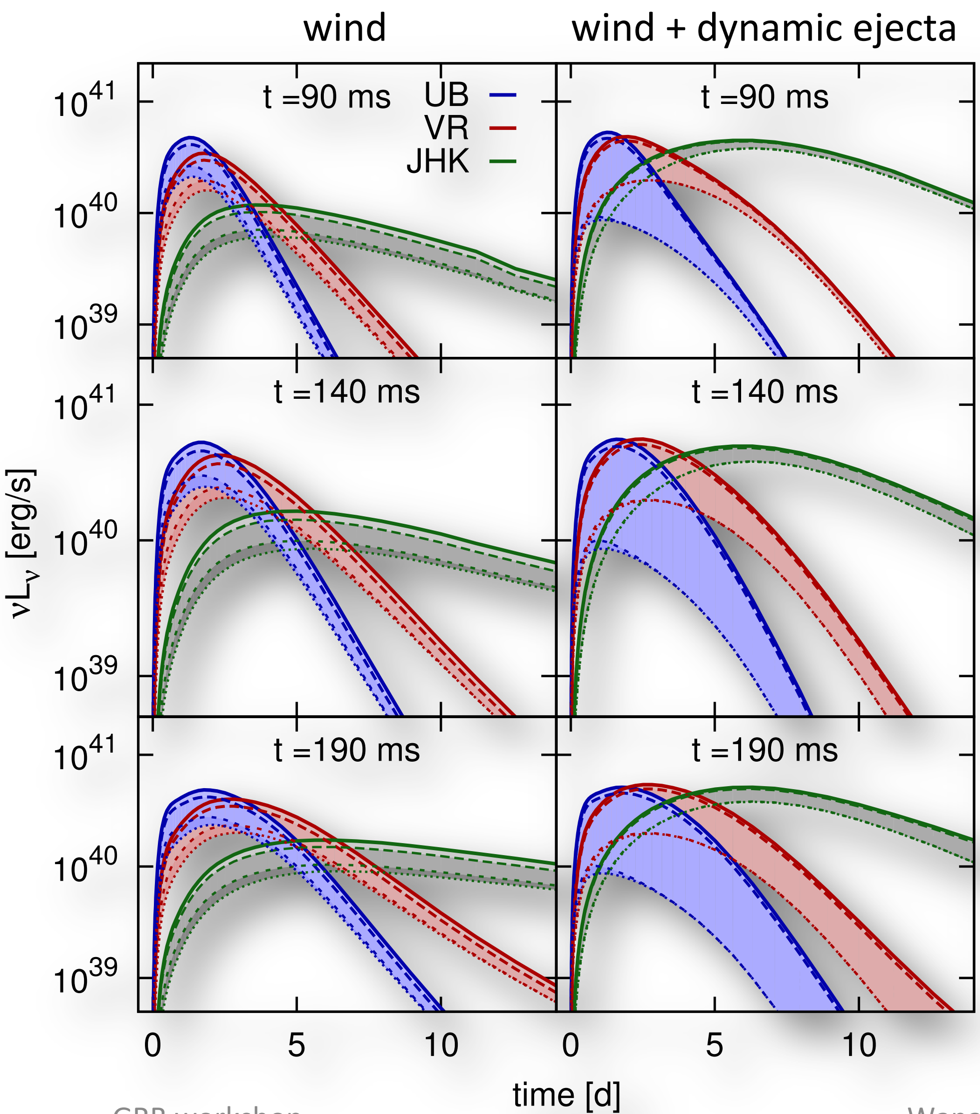
Hotokezaka+Tanaka…+Wanajo 2013;
NS+NS models



- late-time excess NIR flux requires an additional component (most likely an r-process nova)
- the excess NIR indicates the NS-NS ejecta with $M_{ej} \sim 0.02\ M_{\odot}$

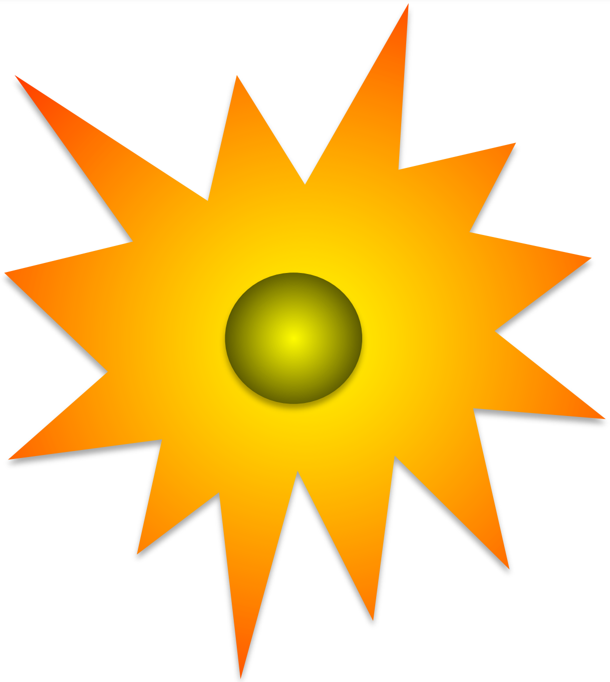
late-time wind and viewing angle

Martin+2015; kilonova light curves (0-90 deg)



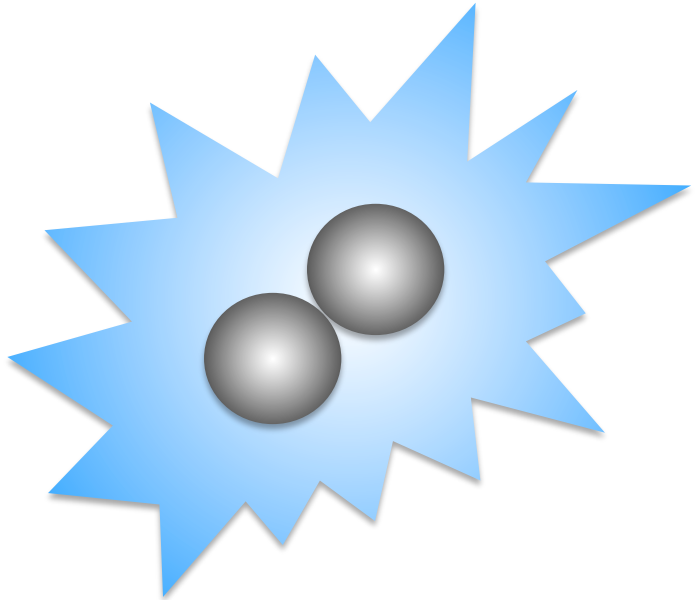
- effects of wind components as well as viewing angles (e.g., Martin+2015 with Newtonian simulations)
- wind component (~0-60 deg) is lanthanide free (*A* < 130)
- r-process novae can be bright in UV and VR in the first few days; detailed nucleosynthetic information (abundances as function of viewing angle) should be important

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

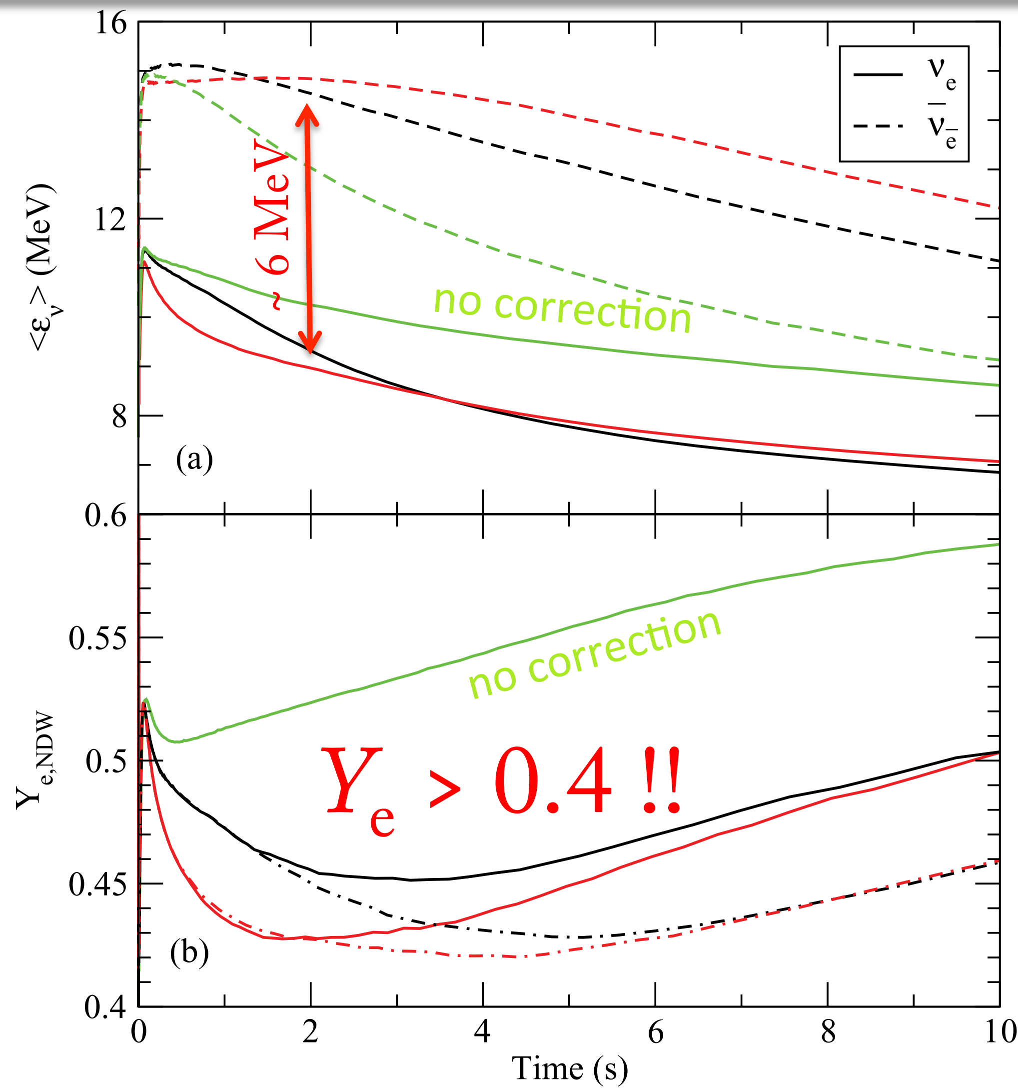
$$\nu_e + n \rightarrow p + e^-$$
$$\bar{\nu}_e + p \rightarrow n + e^+$$

- 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)

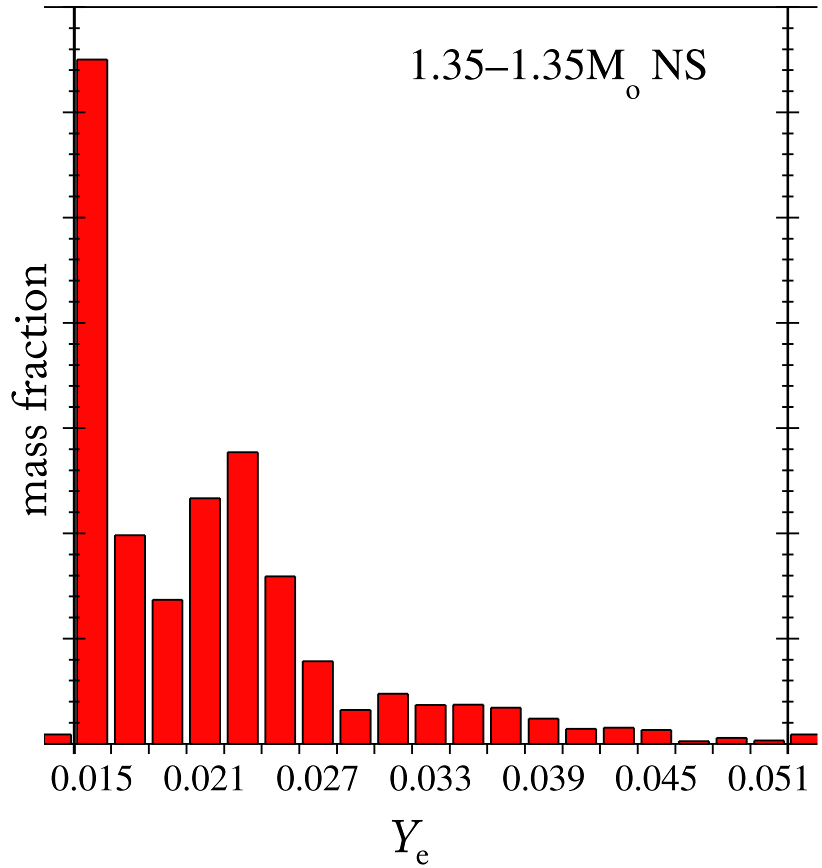
$$\varepsilon_{\bar{\nu}e} - \varepsilon_{\nu e} > 4\Delta \sim 5 \text{ MeV}$$
$$\text{if } L_{\bar{\nu}e} \approx L_{\nu e}$$

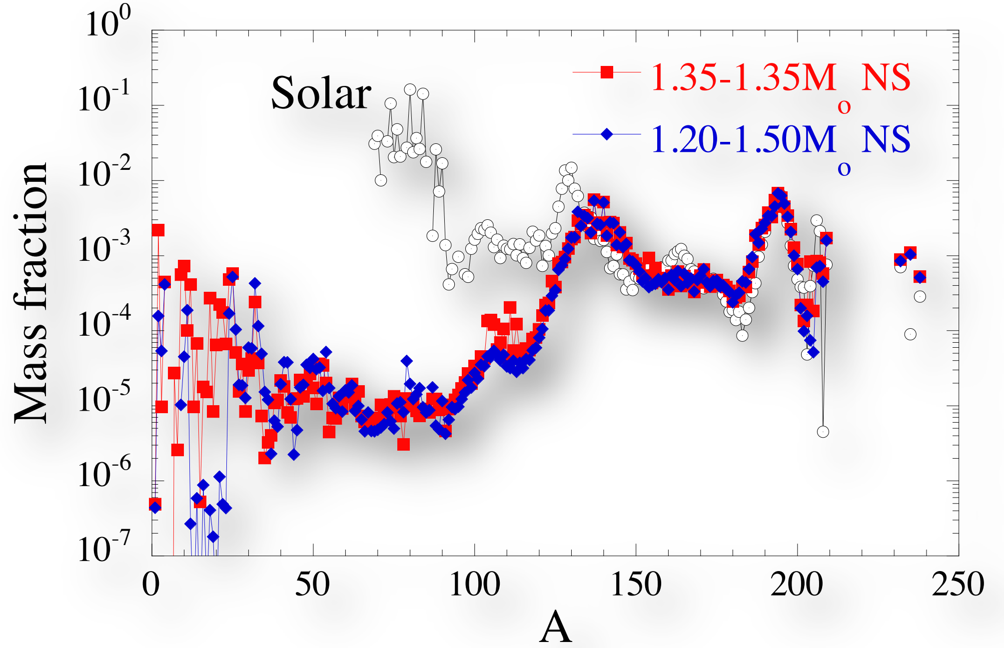


Roberts+2012

previous works: too neutron-rich ?

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





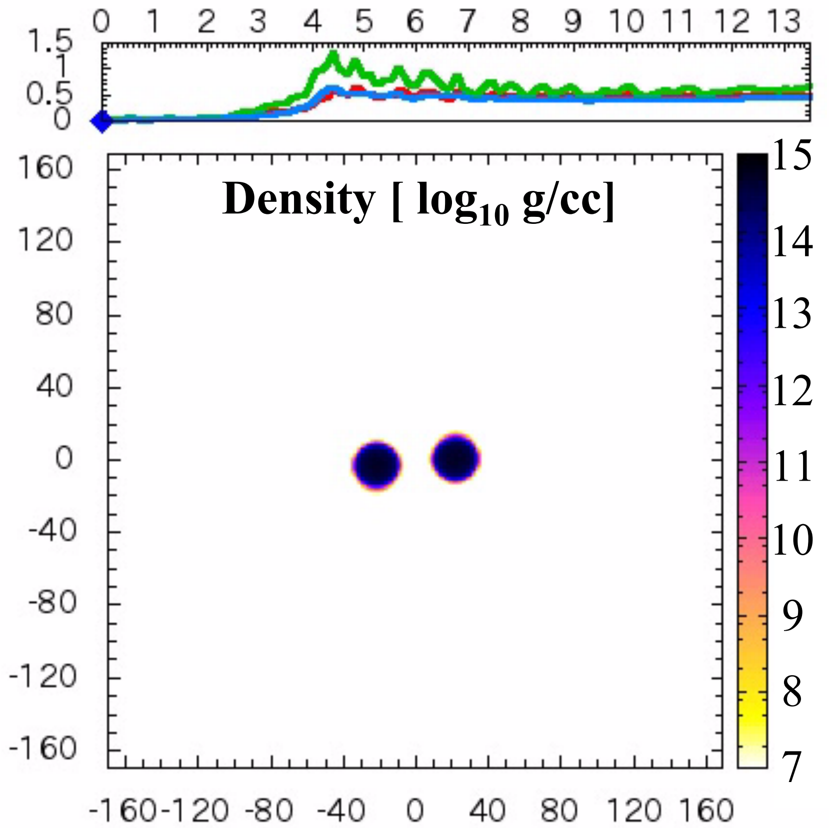
tidal (or weakly shocked) ejection of "pure" n-matter with $Y_e < 0.1$

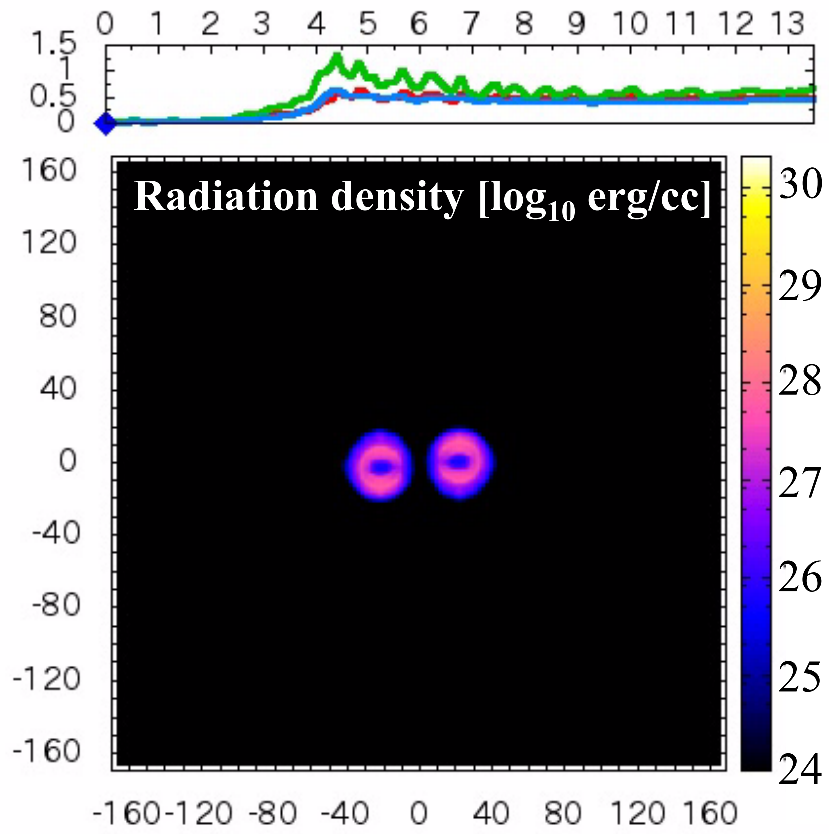
- strong r-process leading to fission recycling
- severe problem: only $A > 120$; another source is needed for the lighter counterpart

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

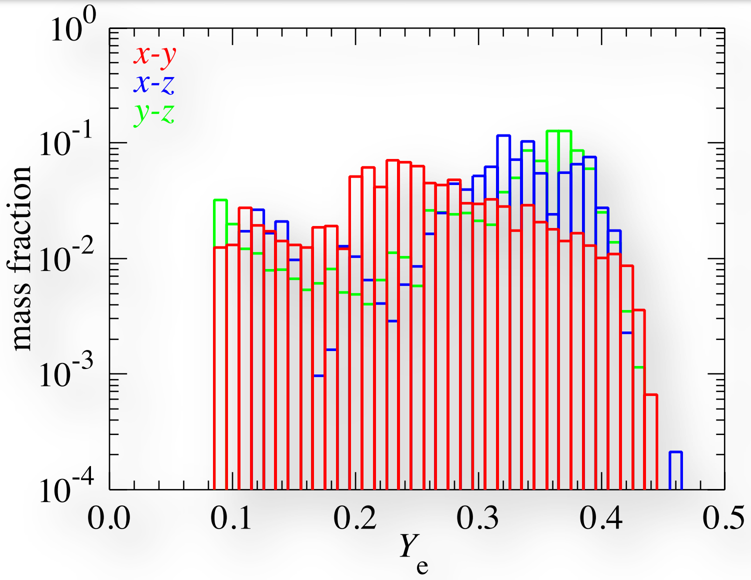


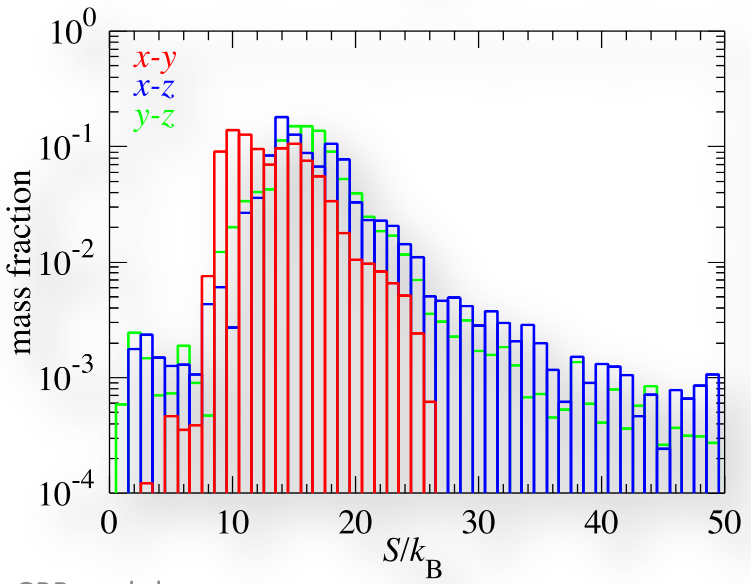


$1.3+1.3\ M_\odot$ neutron star merger with full-GR and neutrino transport (SFHo)

simulation by Yuichiro Sekiguchi

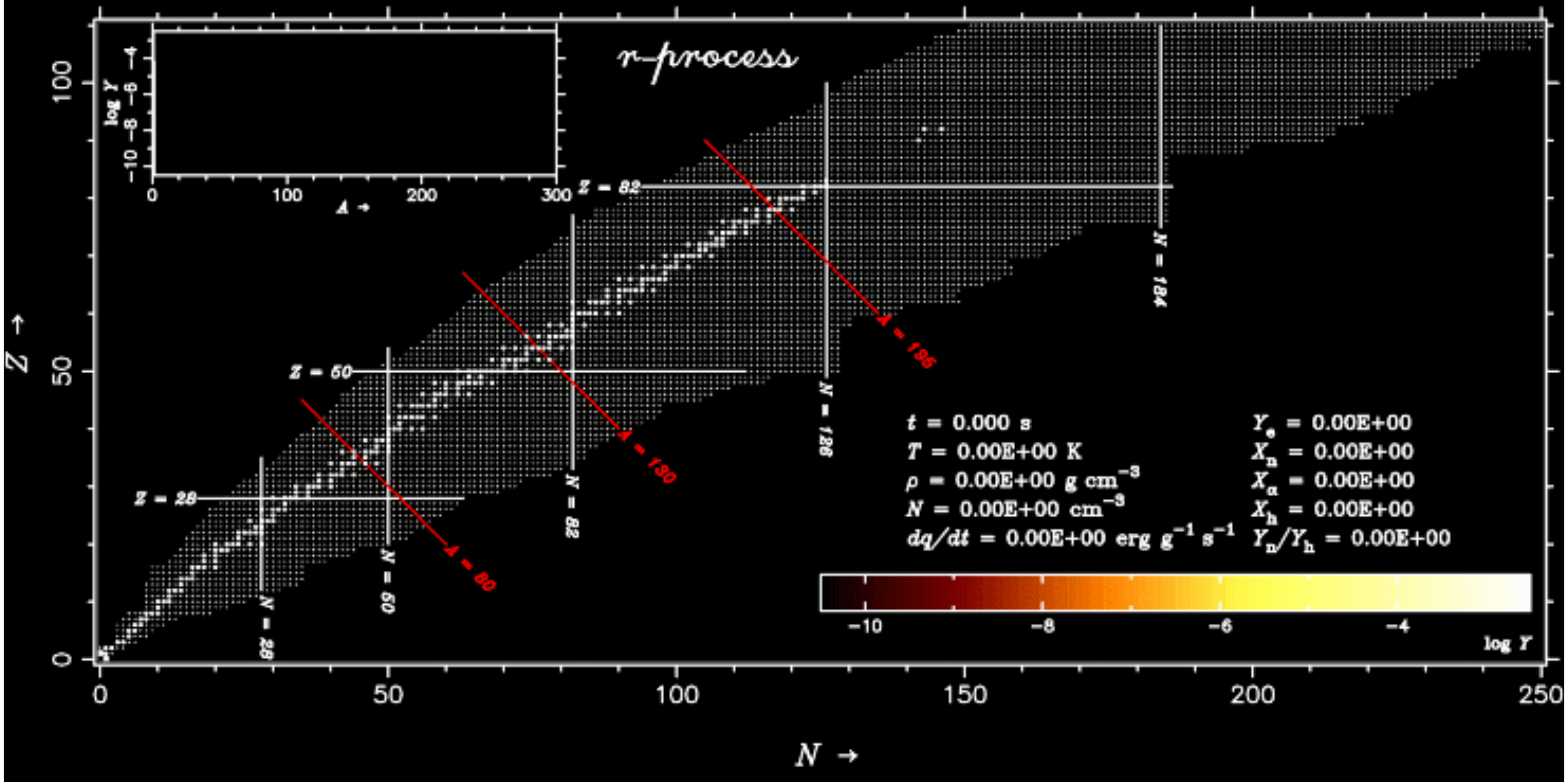
nucleosynthesis in the NS ejecta





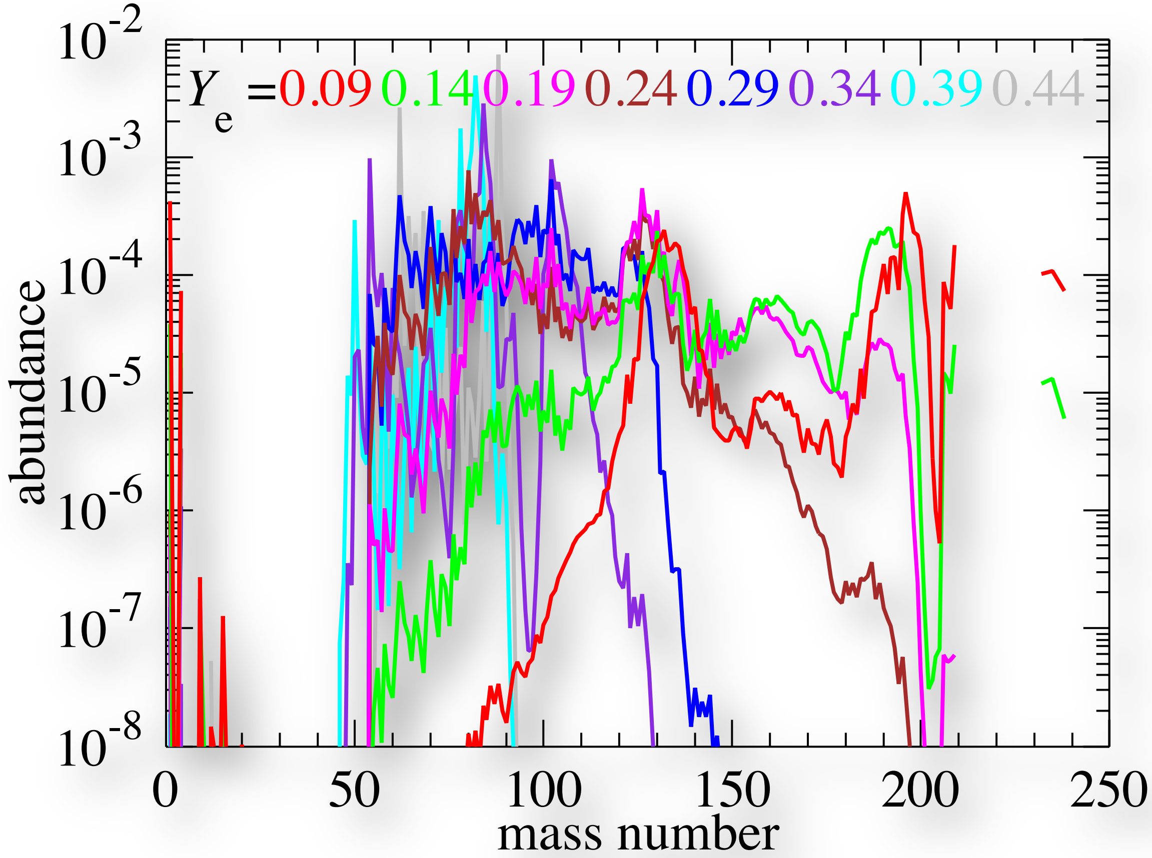
- ❖ higher and wider range of Y_e (~ 0.1-0.5) in contrast to previous cases Y_e (= 0.01-0.05)
- ❖ values do not fully asymptote to Y_e ~ 0.5 because of v/c ~ 0.1-0.3
- ❖ higher and wider range of entropy per baryon (= 0-50) in contrast to previous cases (= 0-3)

Y_e = 0.09


r-process
log Y
A →
Z = 28
Z = 50
Z = 82
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
Y_e = 0.00E+00
X_n = 0.00E+00
X_α = 0.00E+00
X_h = 0.00E+00
Y_n/Y_h = 0.00E+00
log Y
Z →
N →

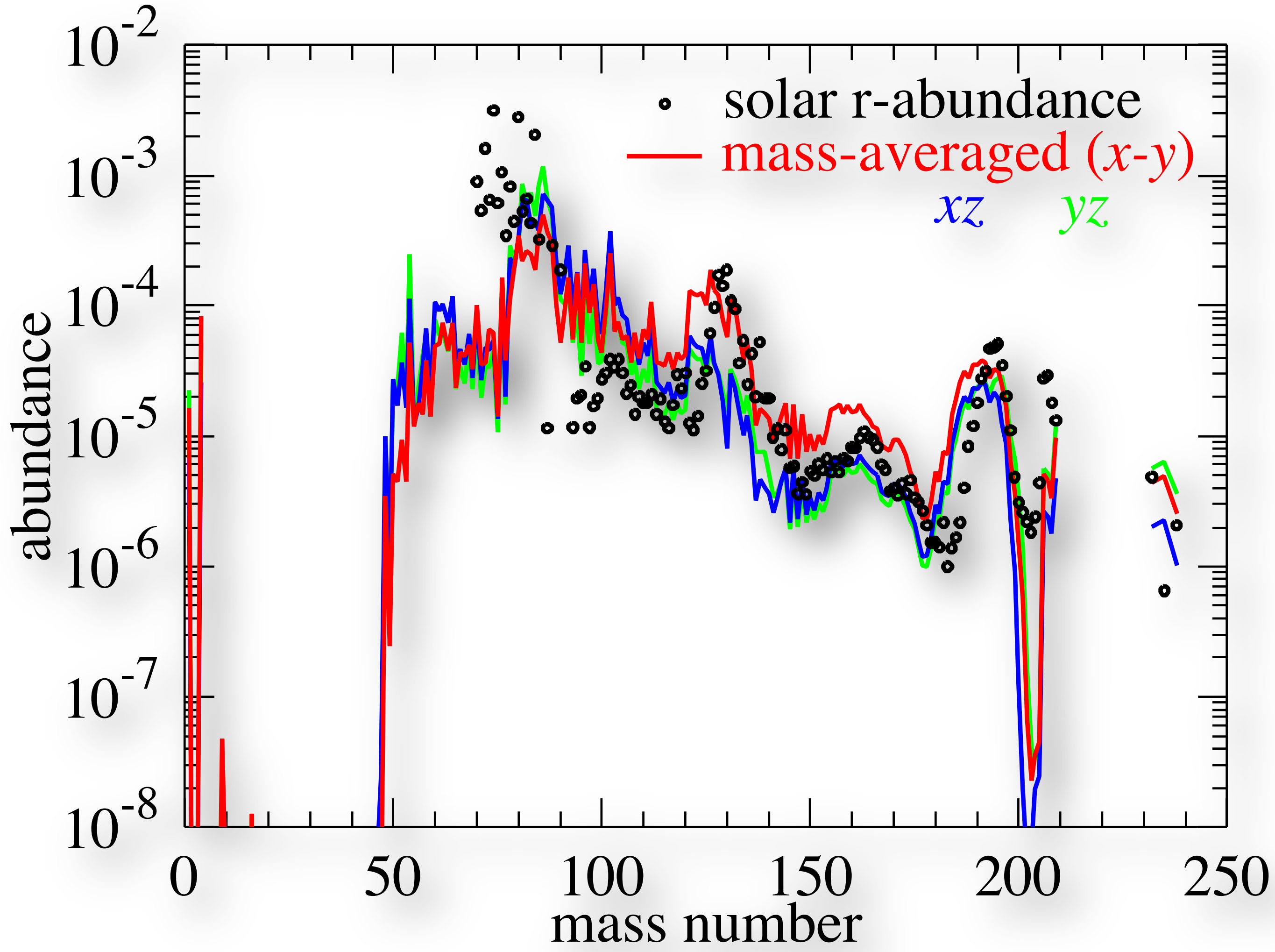
post-process nucleosynthesis

nucleosynthesis for selected Y_e



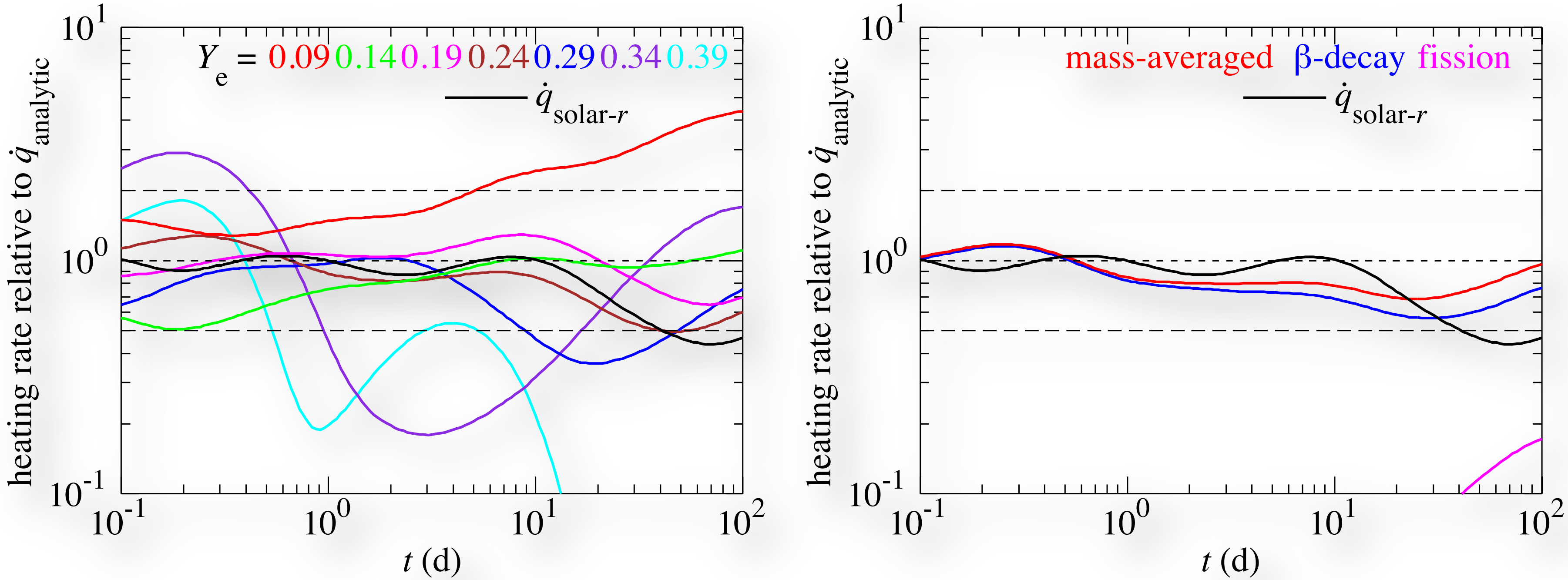
- variation of r-processes depending on Y_e
- production of iron to uranium
- no fission recycling

mass-integrated abundances



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

heating rate for the NS-NS ejecta

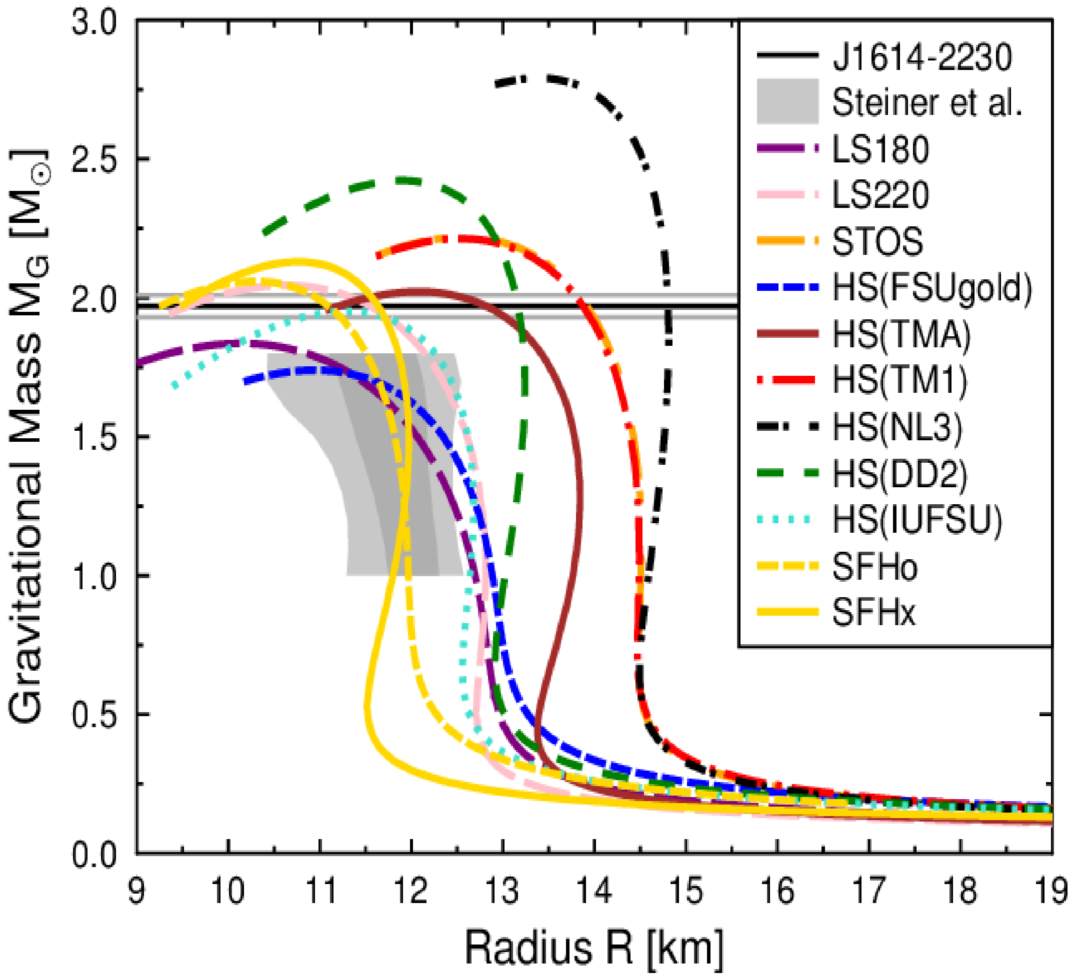


- heating rate for the mass-averaged abundances well fitted by the scaling law $dq/dt \sim t^{-1.3}$ (as well as by the solar r-pattern case)
- but dependent on Y_e; there might be directional (polar to equatorial) differences

slide by Y. Sekiguchi

Dynamical mass ejection mechanism & EOS

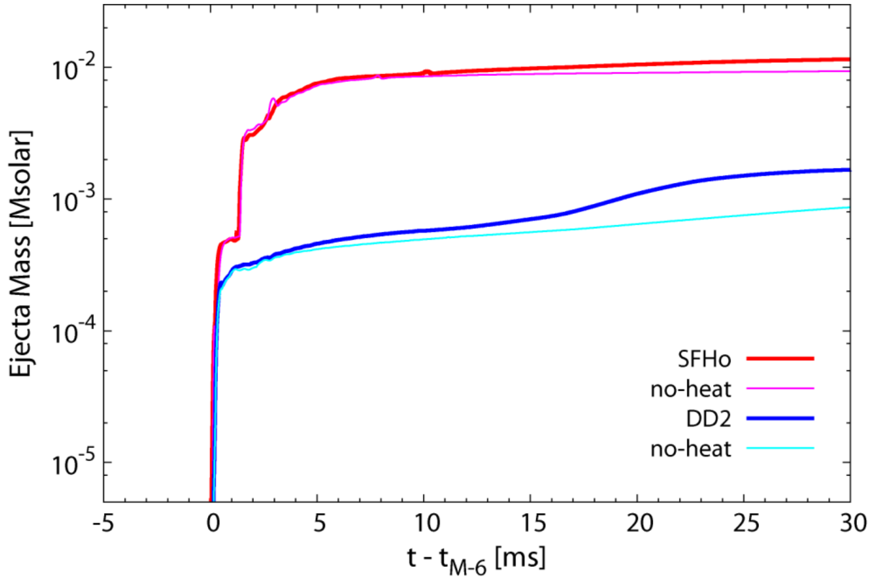
- 'Stiffer EOS'
  - **TM1, TMA**
  - R_{NS} : lager
  - Tidal-driven dominant
  - **Ejecta consist of low T & Ye NS matter**
- 'Intermediate EOS'
  - **DD2**
- 'Softer EOS'
  - **SFHo, IUFSU**
  - R_{NS} : smaller
  - Tidal-driven less dominant
  - Shock-driven dominant
  - **Ye can change via weak processes**

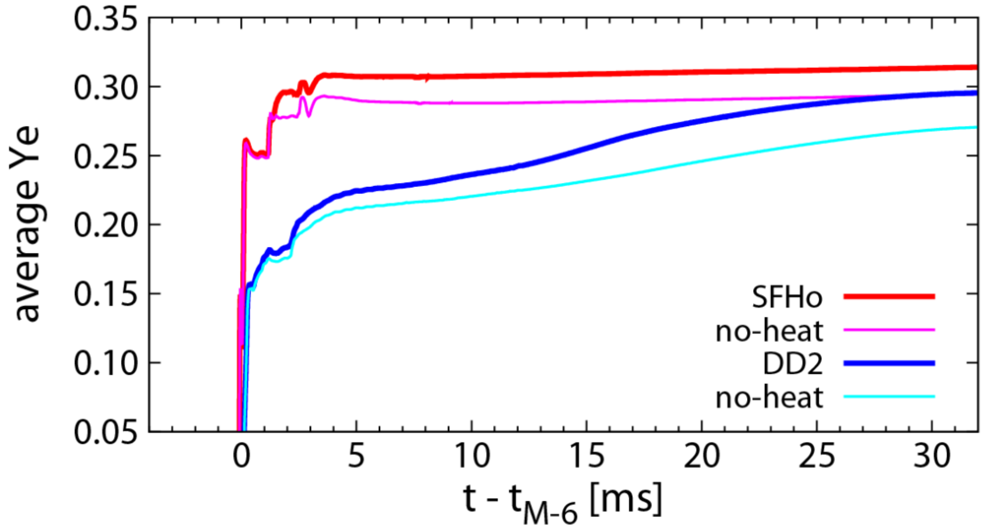


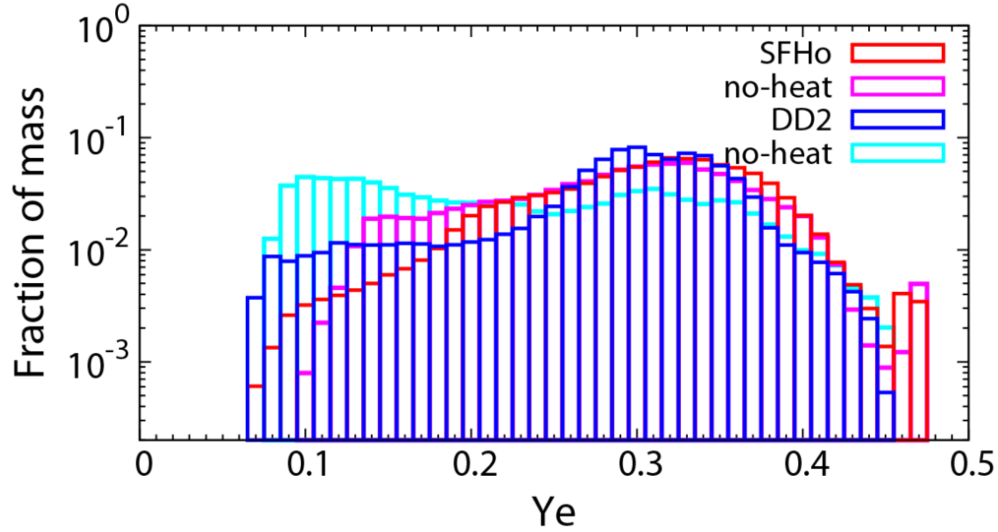
See also, Bauswein et al. (2013); Just et al. (2014)

slide by Y. Sekiguchi

Effects of neutrino heating



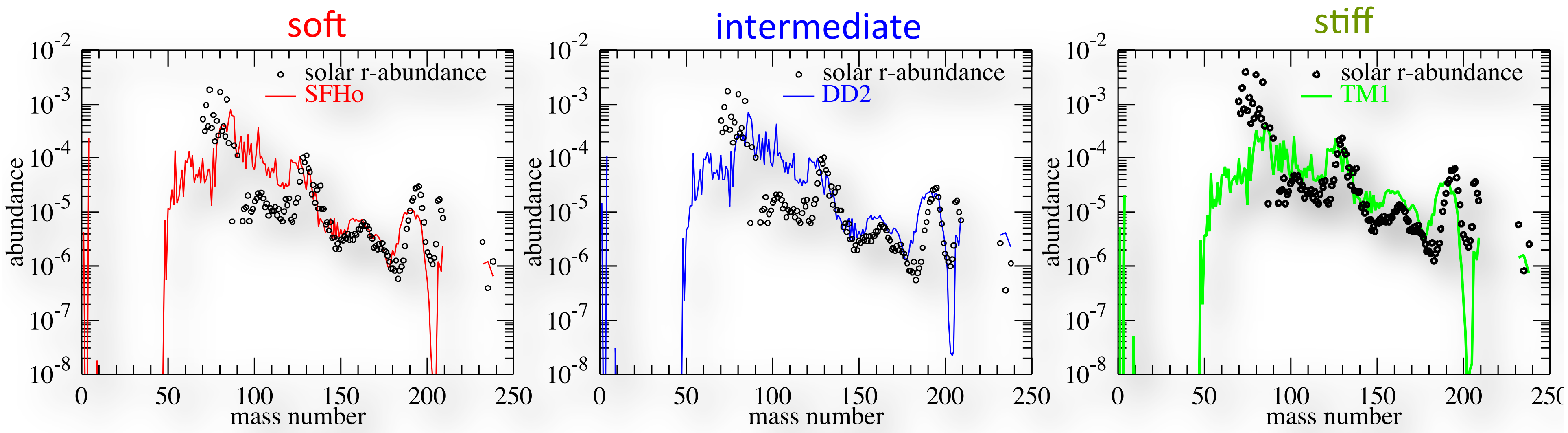




- Amount of ejecta mass can be increased ~ 10^{-3} Msun
- Average Ye can change 0.02~0.03 depending on EOS : effect is stronger for stiffer EOS where HMNS survive in a longer time

dependence on EOSs

adopting nucleosynthesis of Wanajo+2014

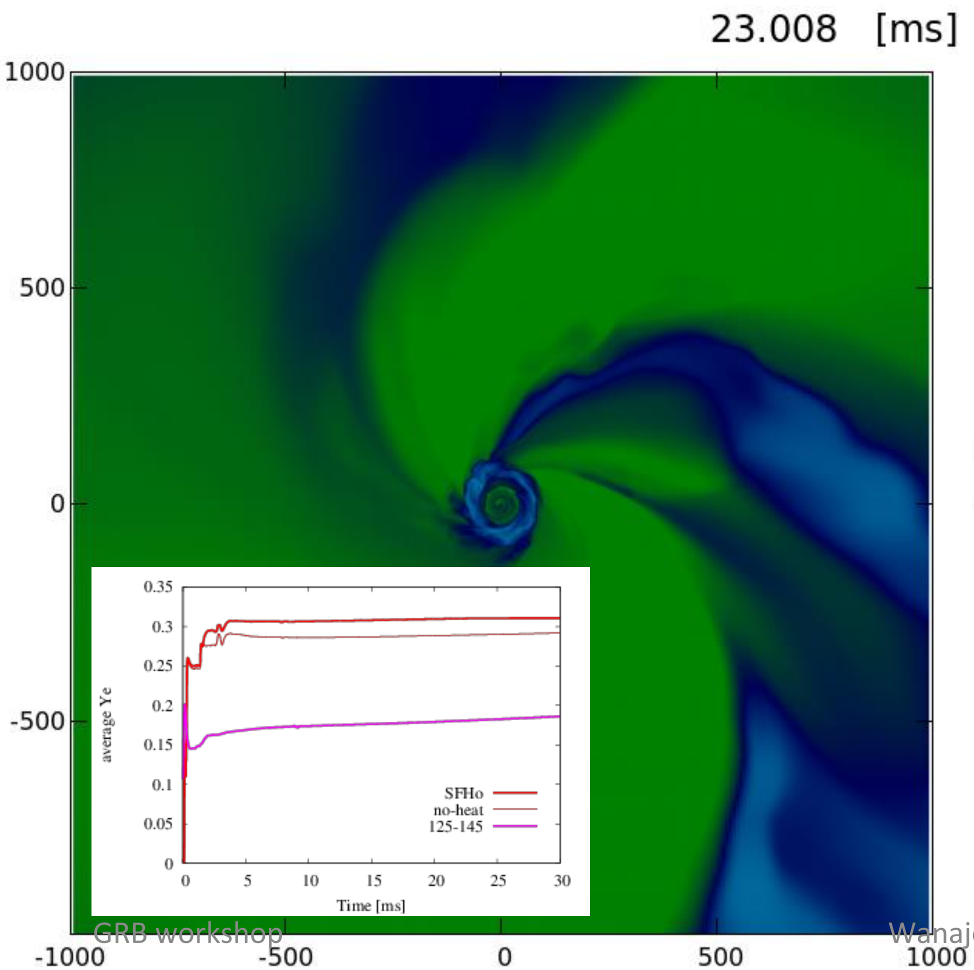


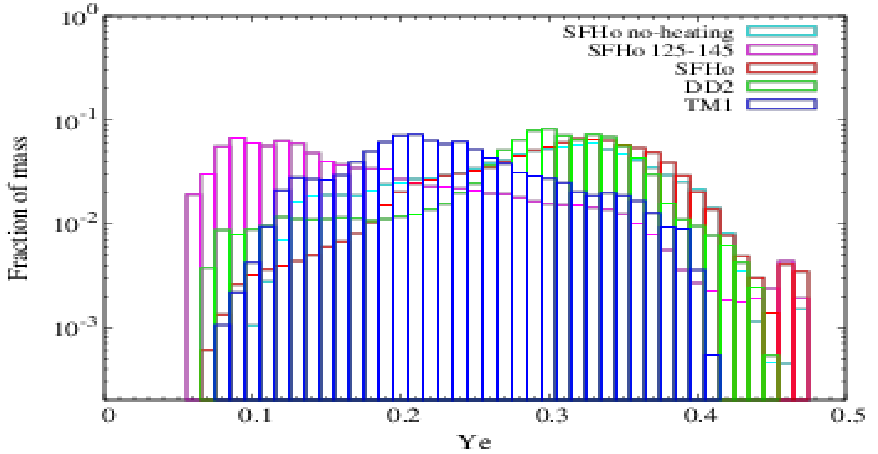
- ❖ softer EOS predicts less heavy r-process products, but
- ❖ effects of EOSs are not large (good for the universality?)

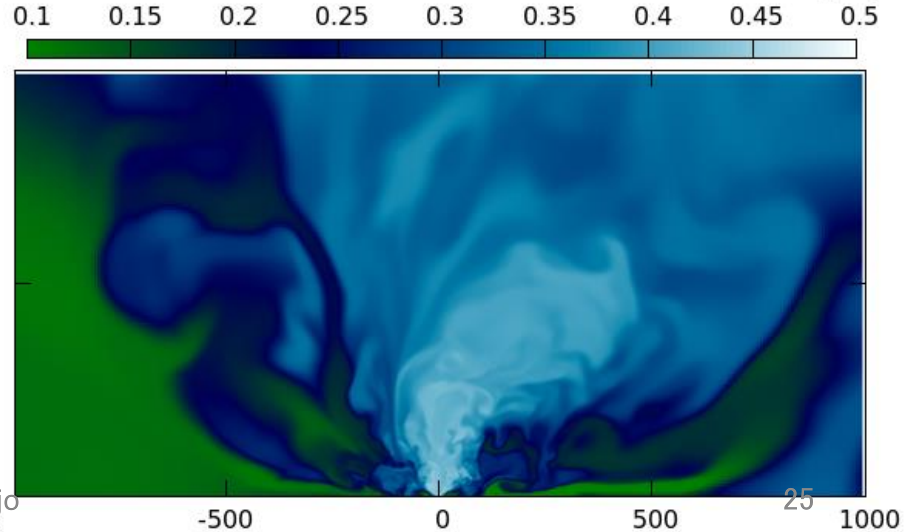
slide by Y. Sekiguchi

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

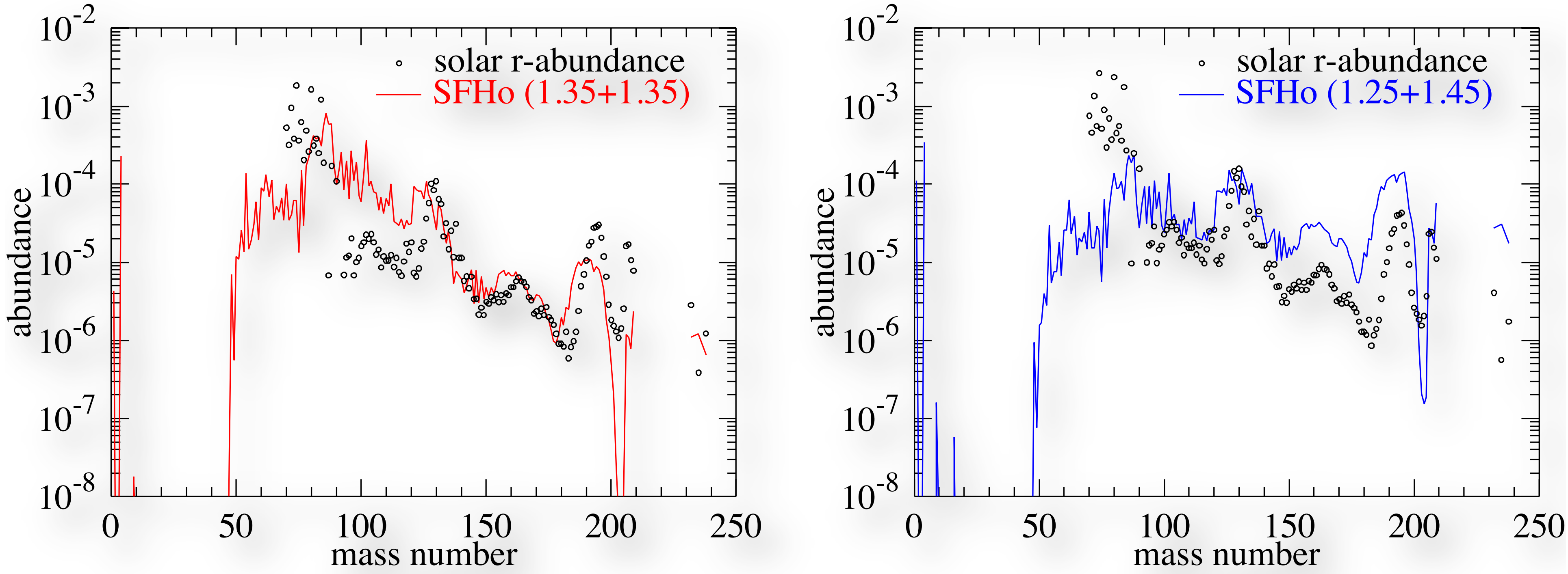






dependence on the NS mass ratio

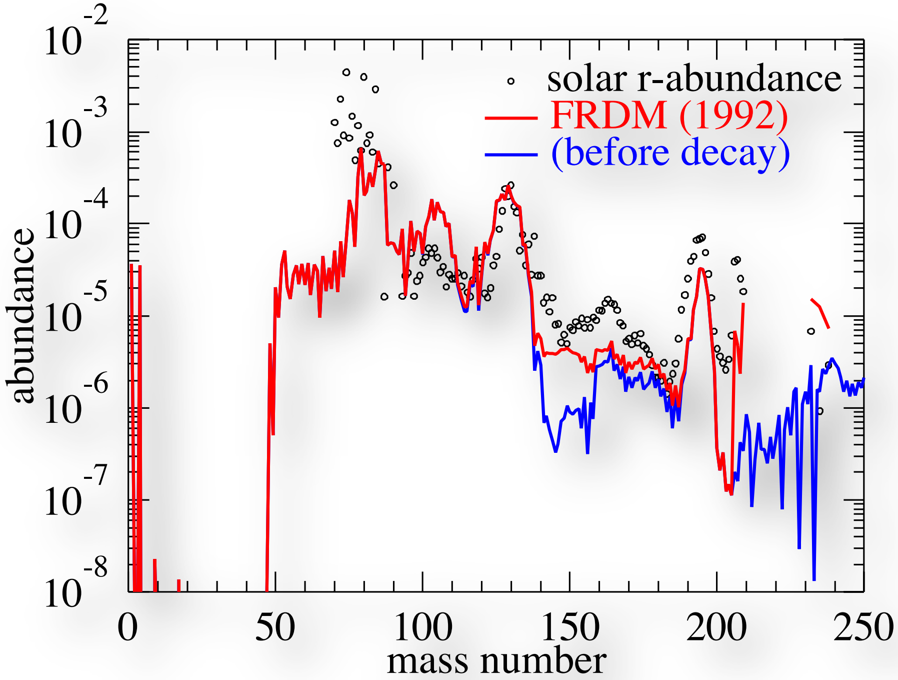
adopting nucleosynthesis of Wanajo+2014

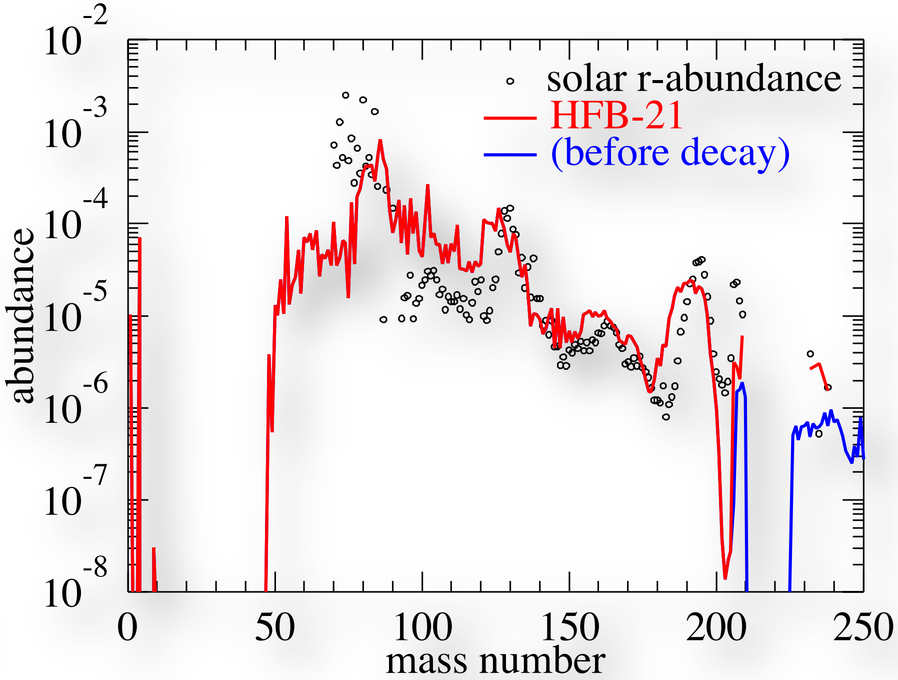


- ❖ small asymmetry predicts less heavy r-process products
- ❖ moderate asymmetry is the best? (e.g., 1.3+1.4)

comparison for different mass models

for neutron star mergers in Wanajo+2014; without fission





❖ large differences between FRDM (1992, not 2012!) and HFB-21

summary and outlook

- NS mergers: very promising site of r-process and sRGBs
  - 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?
  - r-process nova light curves as functions of time and viewing angle?