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Studies of r-process nucleosynthesis based on recent hydrodynamical models of NS-NS mergers

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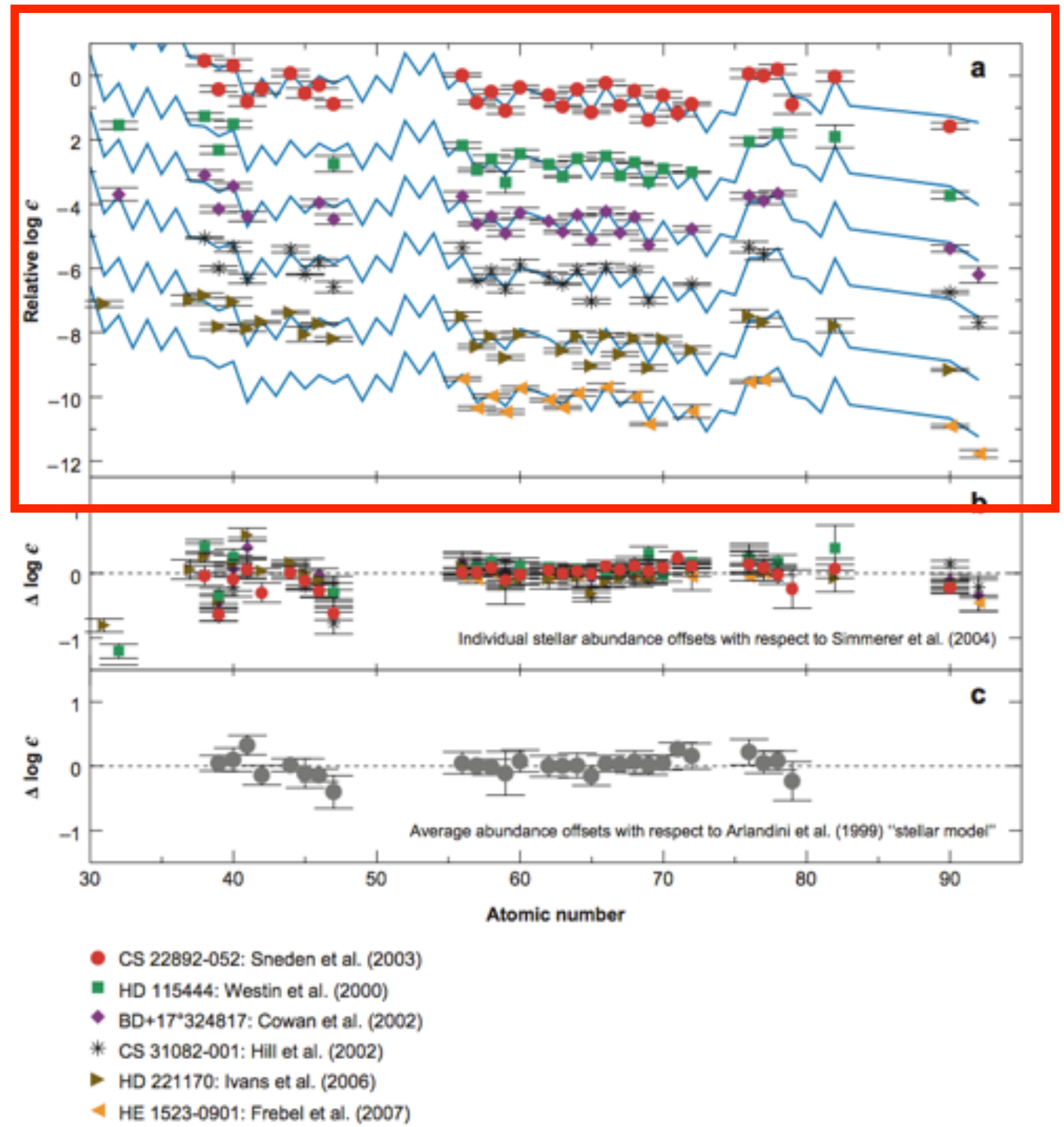
The *r*-process: observational request

- many r-rich Galactic halo stars show remarkable agreement with solar pattern
- r-process must occur in the early Galaxy
- astrophysical events must reproduce this common pattern (Z>40; A>90)

→ suggests existence of "main" r-process sites producing a (solar-like) common pattern

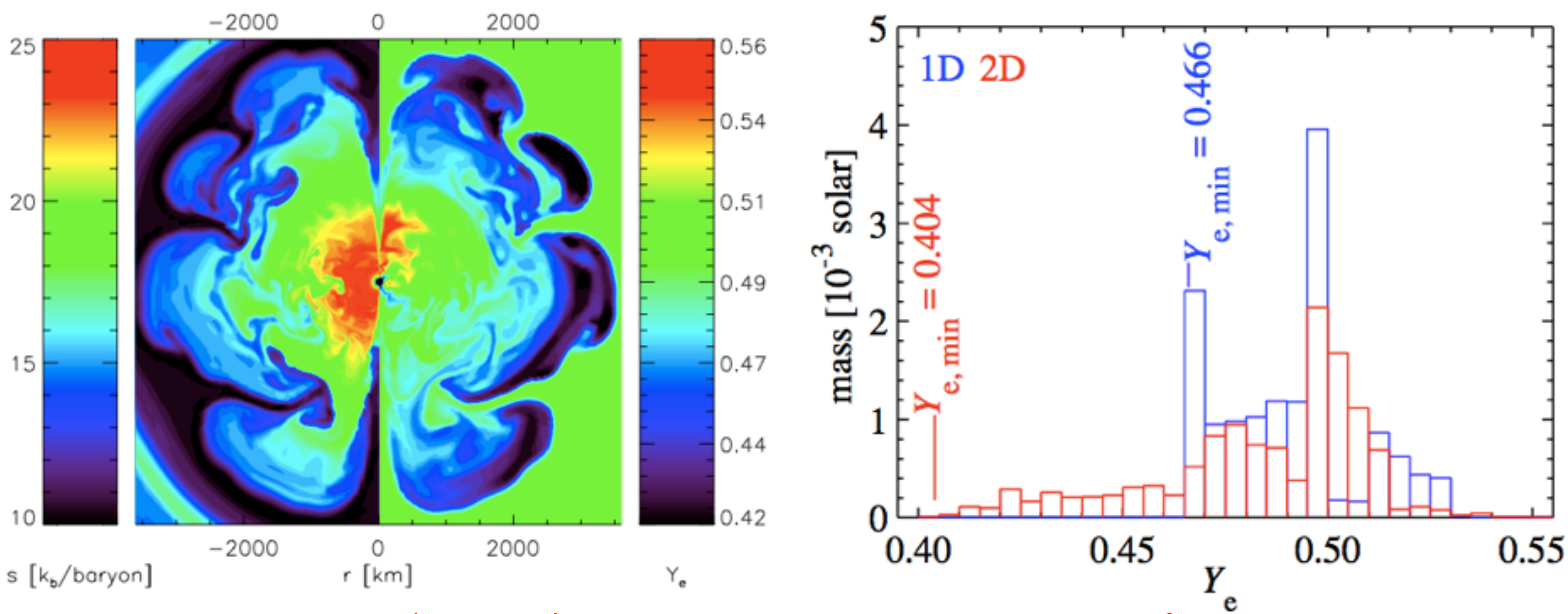
Sneden+ (2008) ARAA



Dynamical ejecta of supernova explosion?

- neutrino-driven proto-neutron star wind
- supernova ejecta → iron group elements including ^{56}Ni
  - EC-SNe are exception? (c.f., Wanajo+ 2011)
    But, not enough to produce heavy r-process elements

Wanajo+ ApJL, 2011, 2013 (EC-SNe, MPA group)



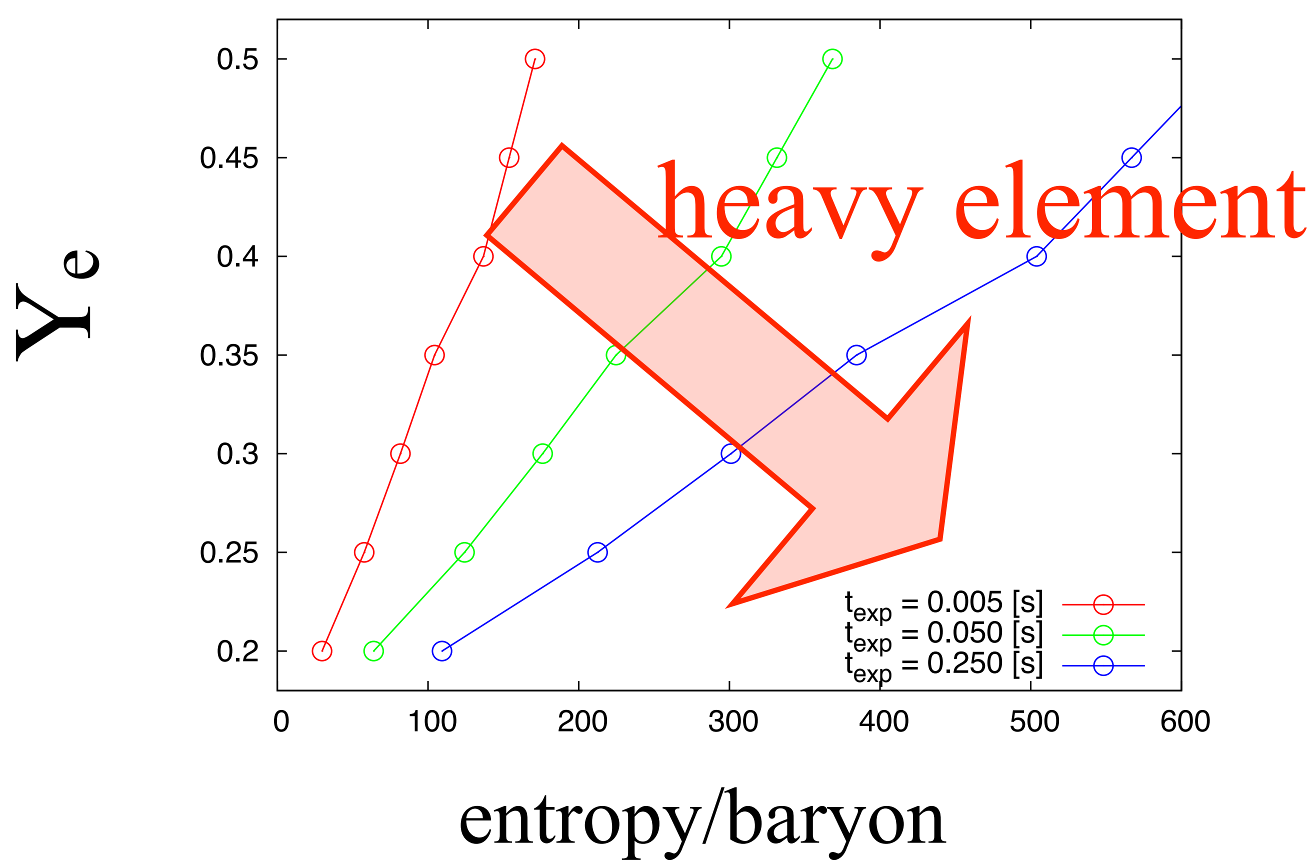
→ needs other components of SNe?

needs for neutron-rich ejecta (and failure of PNS wind)

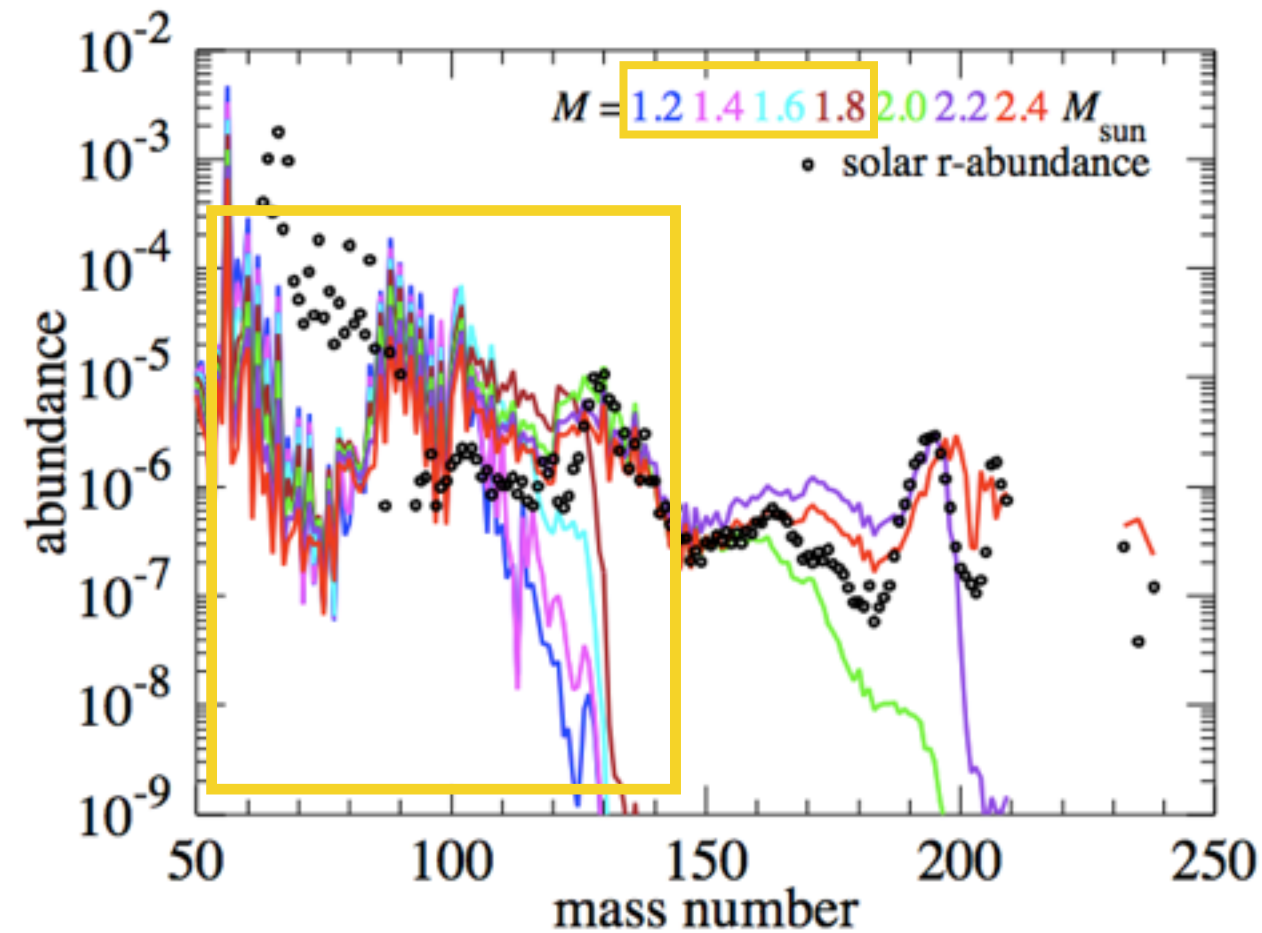
condition for r-process 3rd peak

based on Hoffman et al. (1997)

hight entropy
→ high T
→ low seed
→ high n /seed



Wanajo 2013



- not very neutron-rich (> 0.4)
- not high entropy (< 200)
- supported by several studies
  Fischer et al. 2010,
  Hüdepohl et al. 2010 etc.

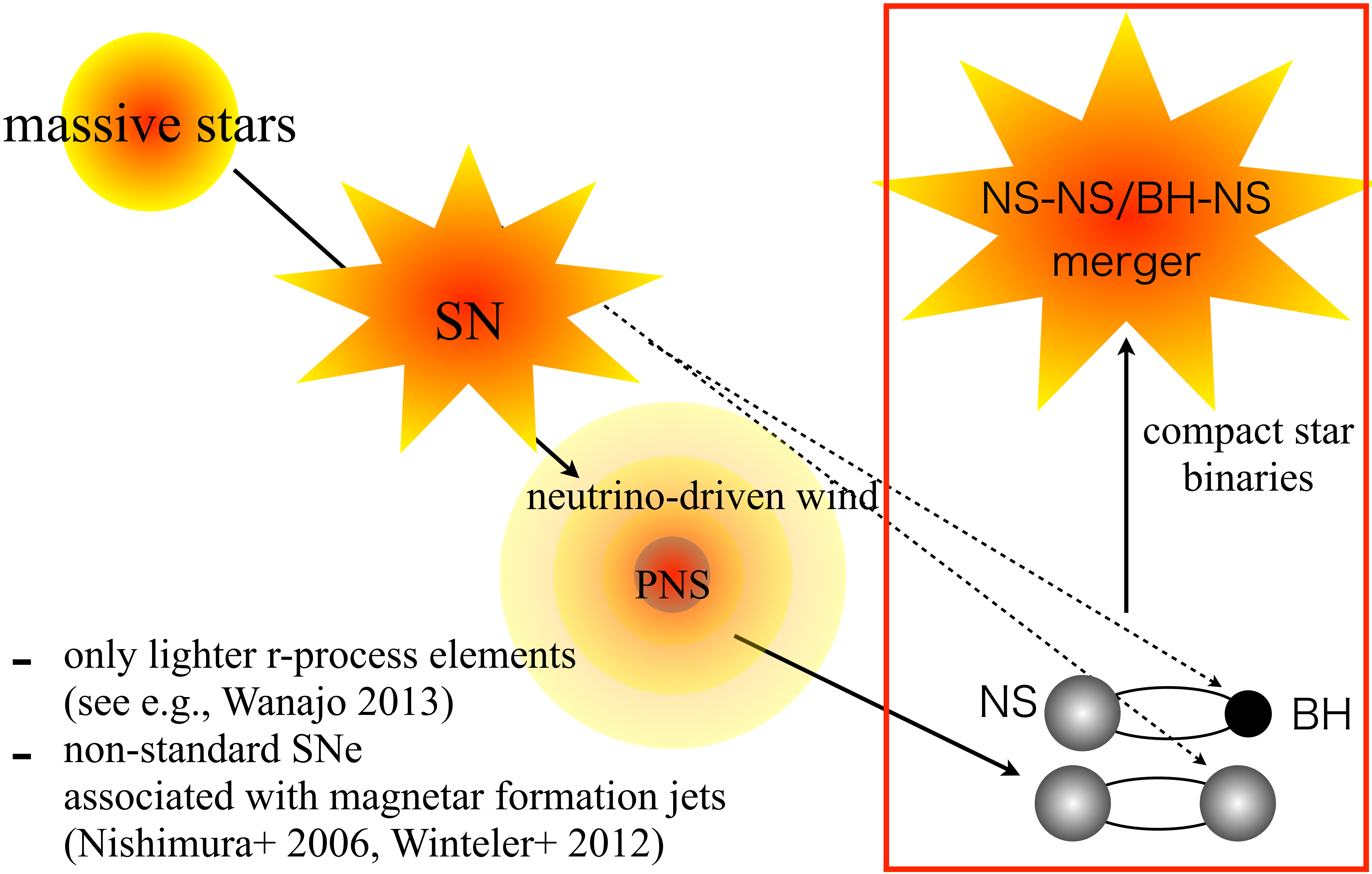
→ needs other astronomical sites

NS-NS mergers

collaboration with
S. Wanajo (NAOJ)
Y. Sekiguchi, K. Kiuchi and M.Shibata (YITP, Kyoto U)
K. Kyutoku (UW-Milwaukee)

Wanajo et al., ApJL 789, 2014
Sekiguchi et al. (in prep.)
Nishimura et al. (in prep.)

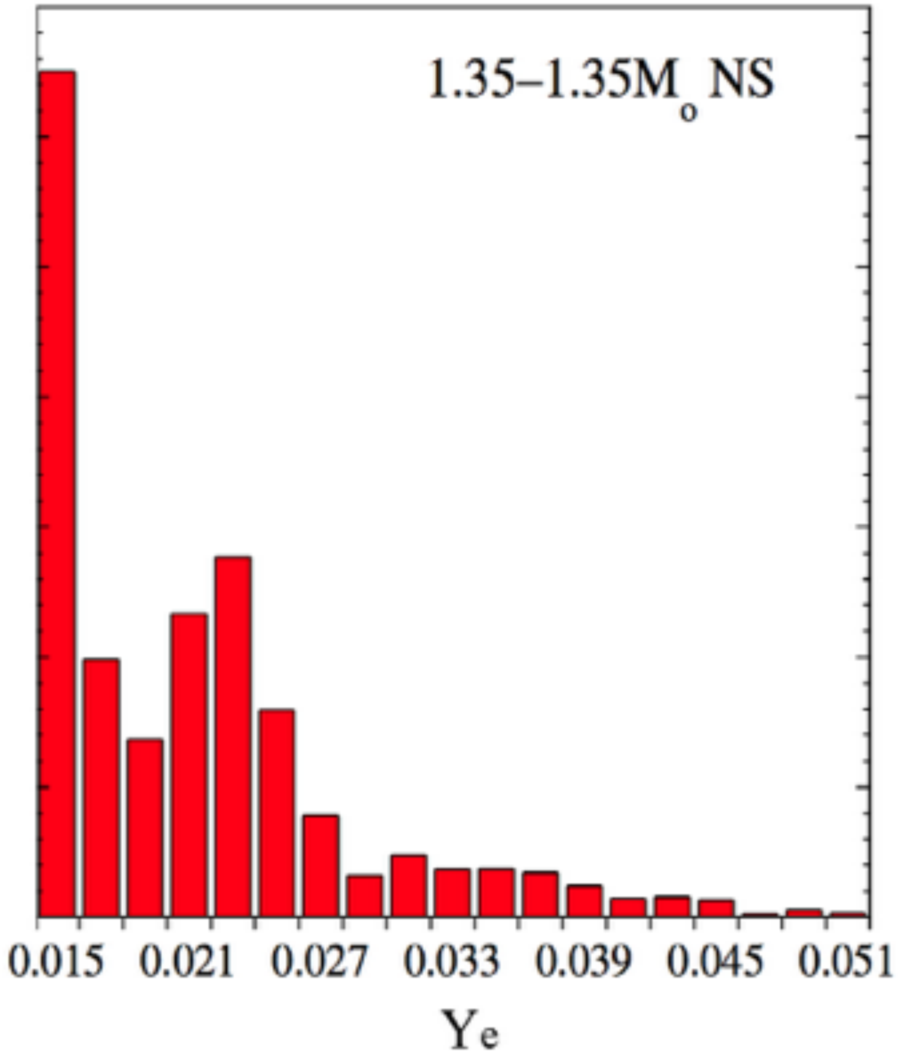
Astronomical sites/scenarios for r-process

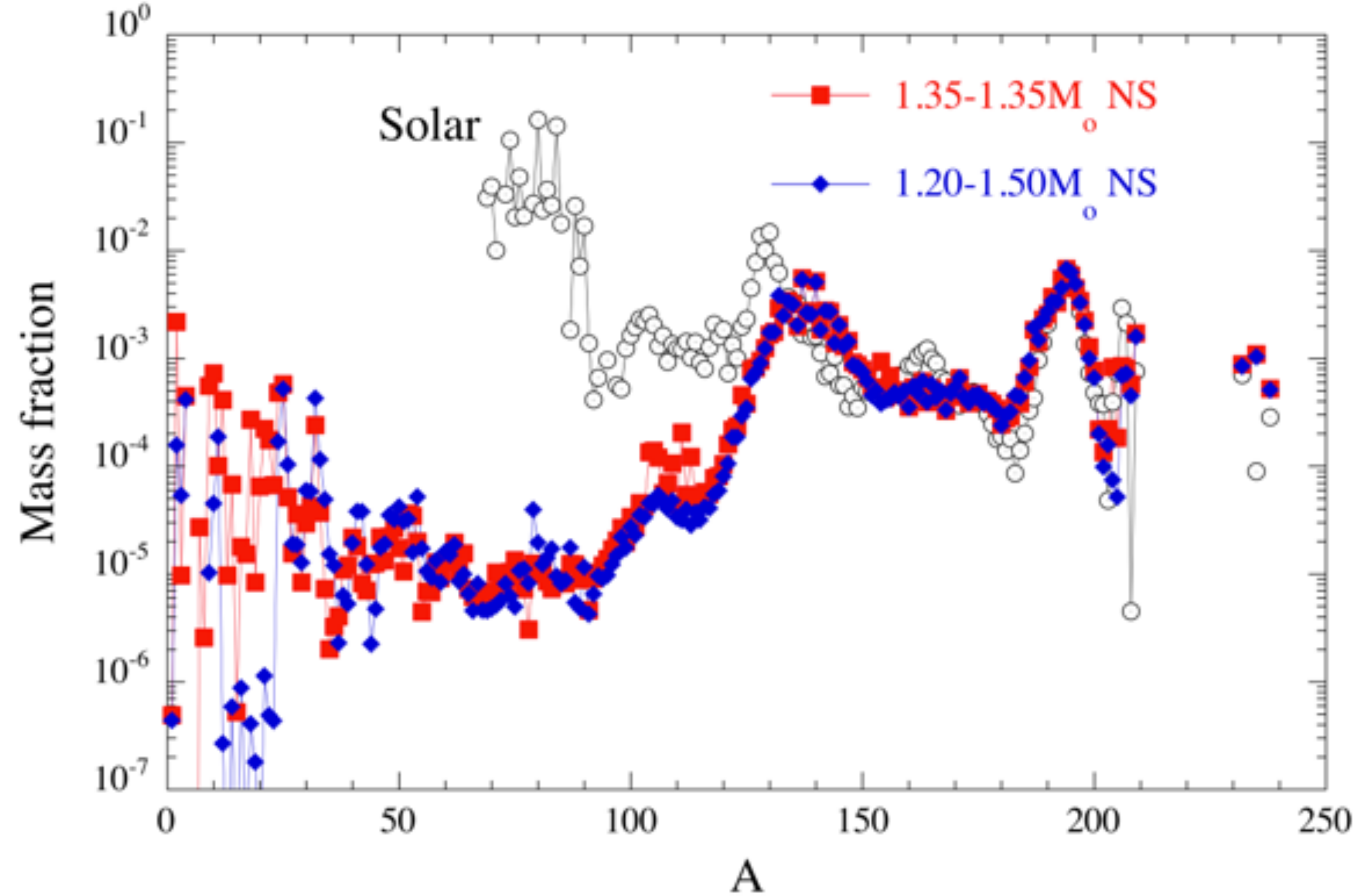


- only lighter r-process elements
  (see e.g., Wanajo 2013)
- non-standard SNe
  associated with magnetar formation jets
  (Nishimura+ 2006, Winteler+ 2012)

Big problem: too neutron-rich?

Goriely+ 2011 (e.g., Korobkin+ 2011, Rosswog+ 2013)





mass number

tidal ejection
of “pure” n-rich matter
with $Y_e << 0.1$

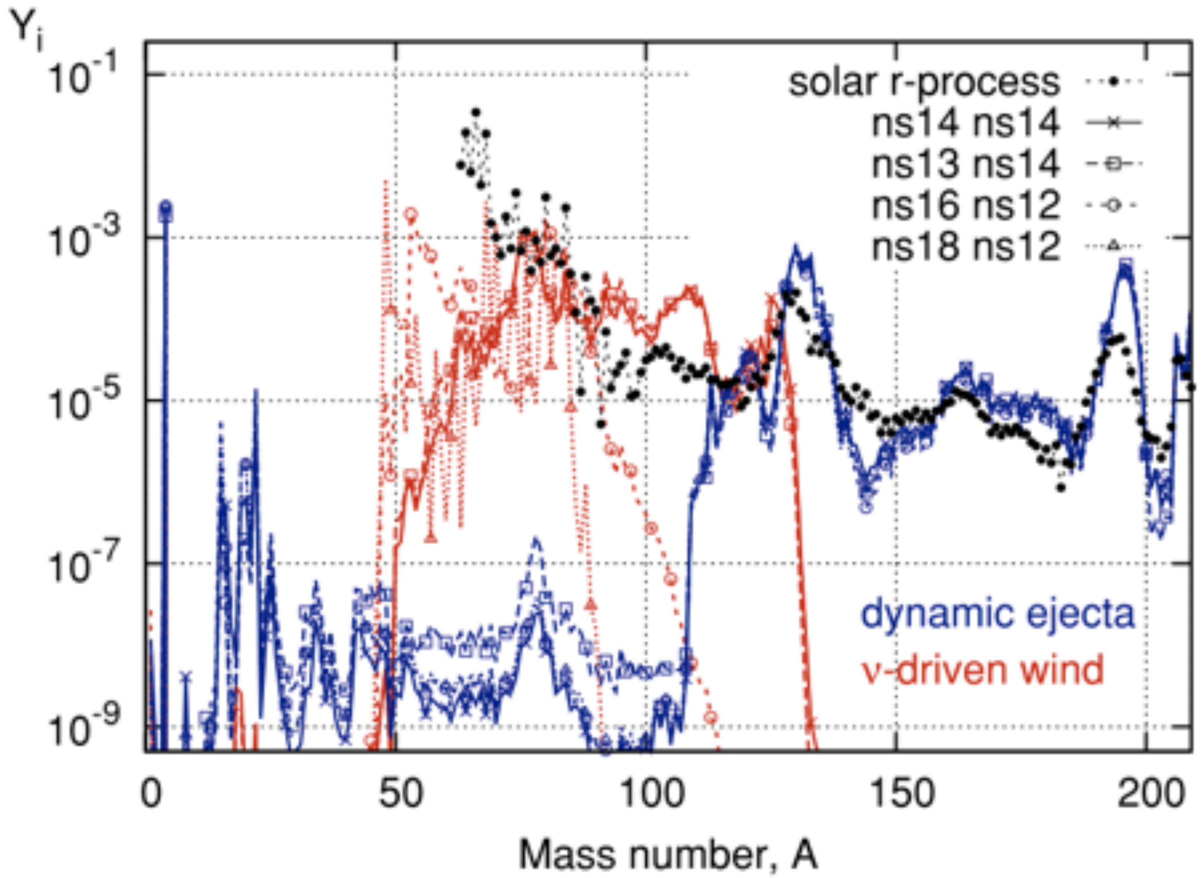
$(Y_e = Y_p = 1 - Y_n)$

strong r-process
with fission recycling
severe problem: only $A > 130$
with fission recycling

Solution?: wind ejecta driven by neutrino

see also, talks by A. Perego and O. Just last week

Rosswog 2014+



dynamical ejecta
(Ye < 0.1)
+
neutrino-driven wind
(Ye > 0.3)

- wind ejecta has enough mass?
- two different components can explain “universality”?
- modeling dynamical ejecta has physical uncertainties
  - general Relativistic (GR) hydrodynamics
  - nuclear equation of state (EOS)
  - neutrino transport

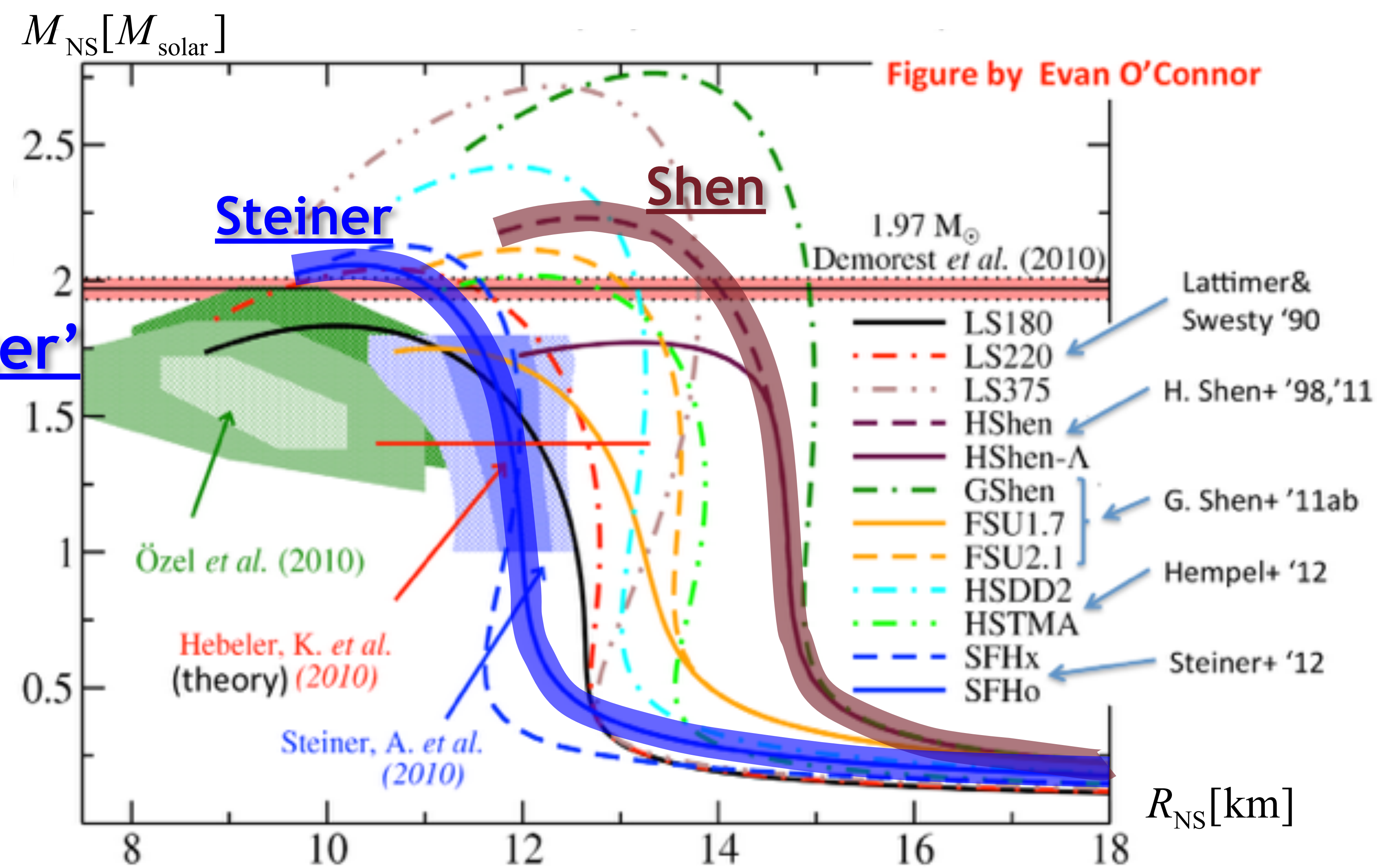
slide by Y.Sekiguchi

'Robustness' of r-process in NS-NS merger ?

- **Korobkin et al. 2012 :** Newtonian SPH simulations
- **Bauswein et al. 2013:** Relativistic SPH simulations with multiple EOS but weak interactions are not implemented
- **This Study :** Full GR, rad-hydro.simulation with SFHo(Steiner)and Shen EoS

- **Shen EOS: 'Stiffer'**
  - Larger NS radius
  - Mass ejection is driven mainly by Tidal force
- **SFHo (Steiner) EOS: 'Softer'**
  - Smaller NS radius
  - Tidal effects are less important in mass ejection
  - Stronger bounce

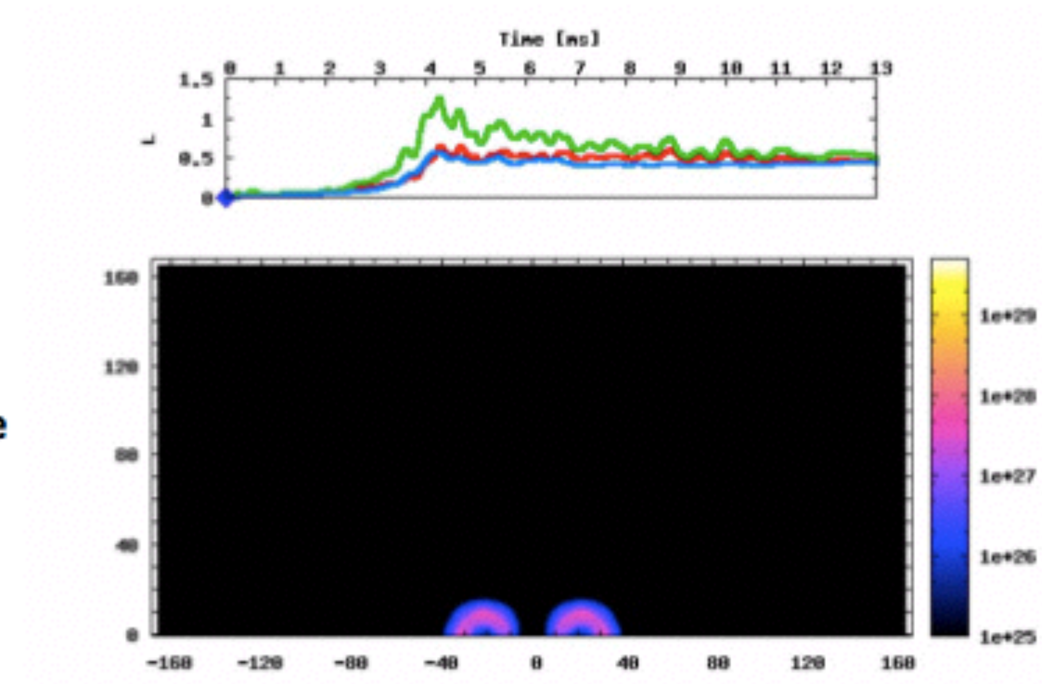
$$F \sim k_{\mathrm{EOS}} \Delta x \sim M_{\mathrm{NS}},$$
$$E \sim k_{\mathrm{EOS}} (\Delta x)^2 \sim M_{\mathrm{NS}}^2 k_{\mathrm{EOS}}^{-1}$$



new challenge: GR-hydro model

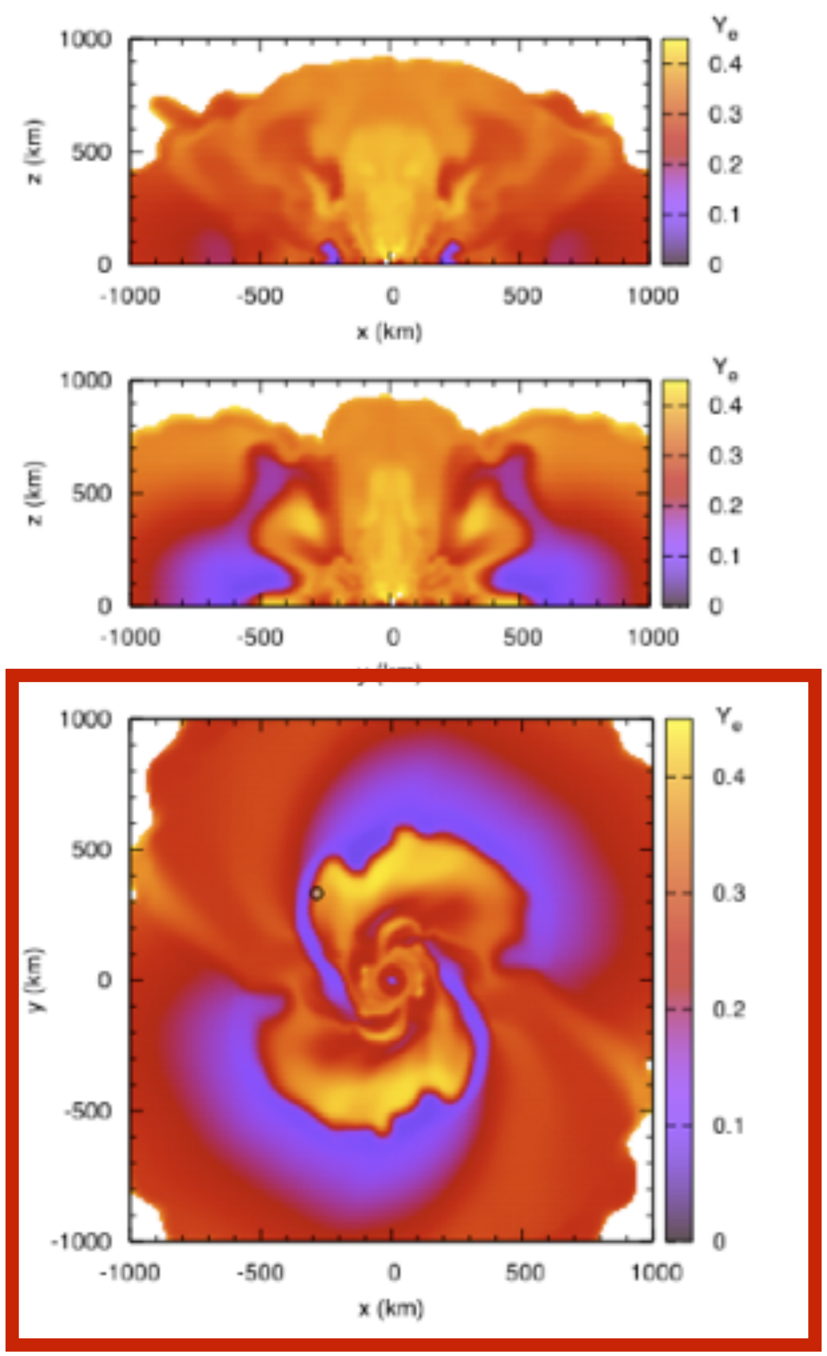
slide by Y.Sekiguchi

- Einstein's equations: Puncture-BSSN/Z4c formalism
- GR radiation-hydrodynamics (Sekiguchi + 2013)
  - **Advection terms :** Truncated **Moment scheme** (based on Shibata et al. 2011)
    - Fully covariant and relativistic
    - gray or multi-energy but advection in energy is not included
    - M-1 closure
    - EOS : any tabulated EOS with 3D smooth connection to Timmes EOS
  - **Source terms :** two options
    - Implicit treatment : Bruenn's prescription
    - Explicit treatment : trapped /streaming ν's
      - e-captures: thermal unblocking/weak magnetism; NSE rate
      - Iso-energy scattering : recoil, Coulomb, finite size
      - e±annihilation, plasmon decay, bremsstrahlung
      - diffusion rate (Rosswog & Liebendoerfer 2004)
      - two (beta- and non-beta) EOS method



NEW NS-NS simulation

"Production of all the r-process nuclides in the dynamical ejecta of neutron star mergers"
(Wanajo, Sekiguchi, NN, Kiuchi, Kyutoku, Shibata, ApJL, 2014)



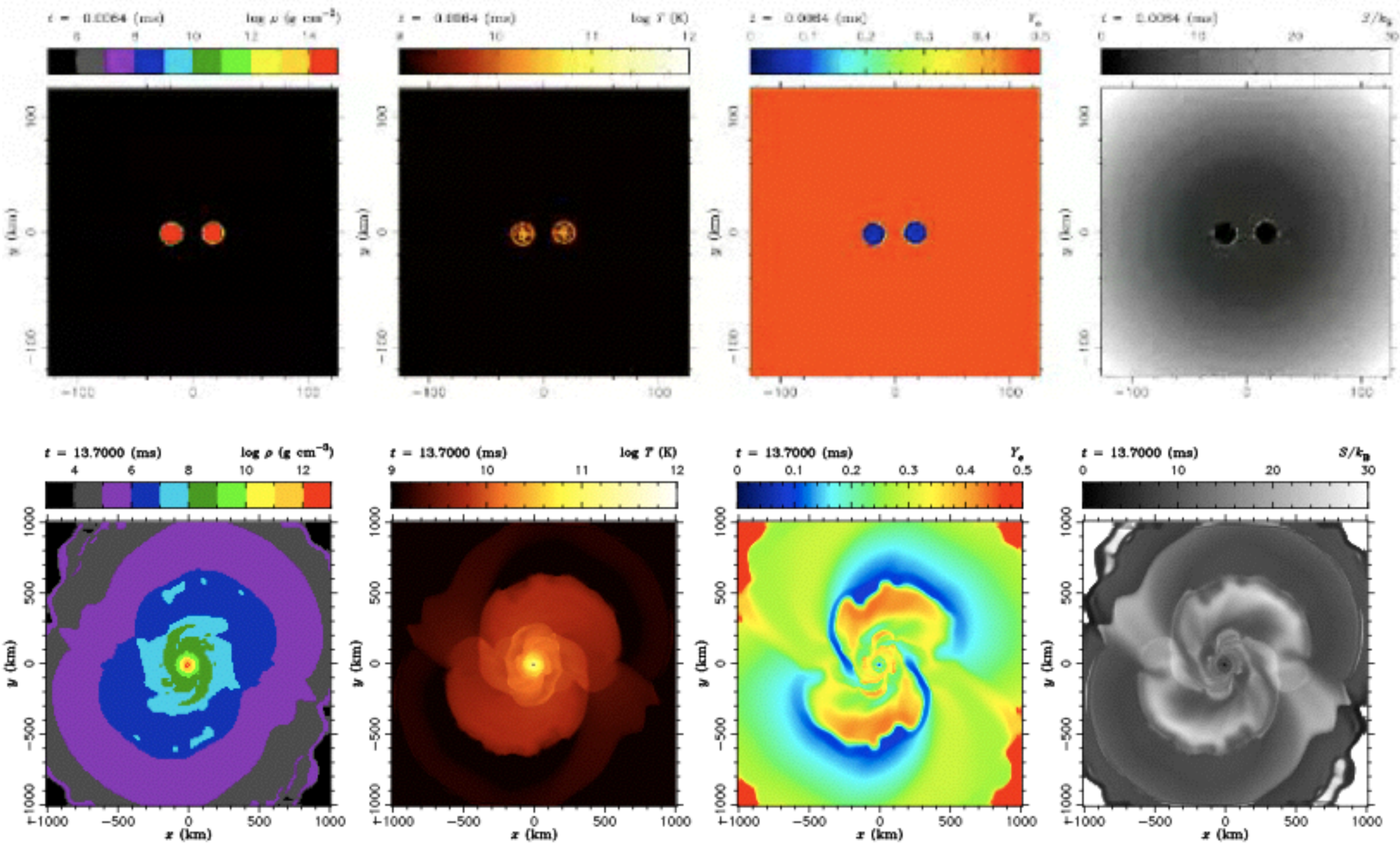
- fully general relativity
- approximate neutrino transport
- realistic EOS
  - Steiner's EOS (2013, SFXo)
- 1.3 $M_\odot$ NSs

ejected matter
on the orbital plane

dynamics

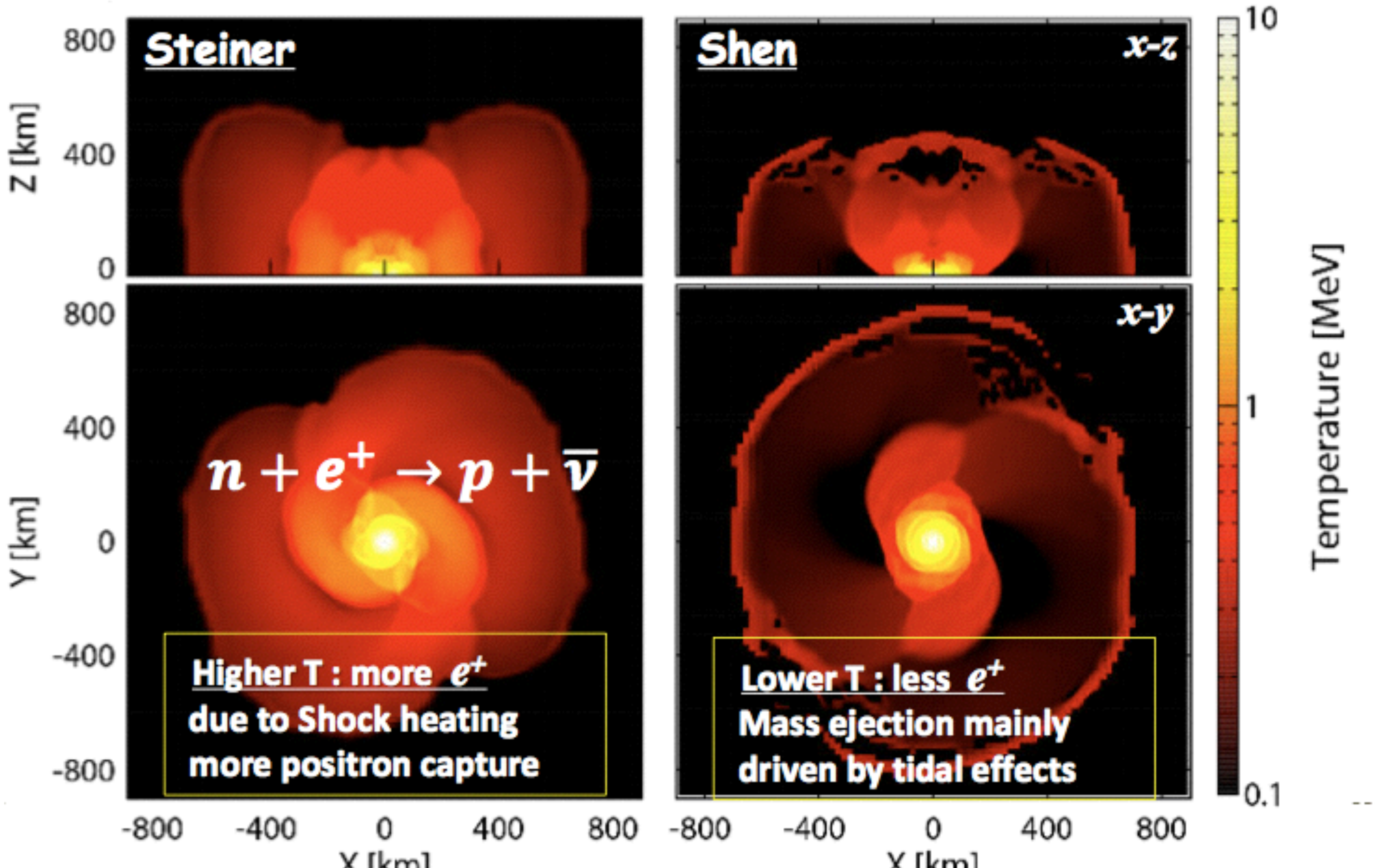
Wanajo+ 2014

density temperature Ye entropy



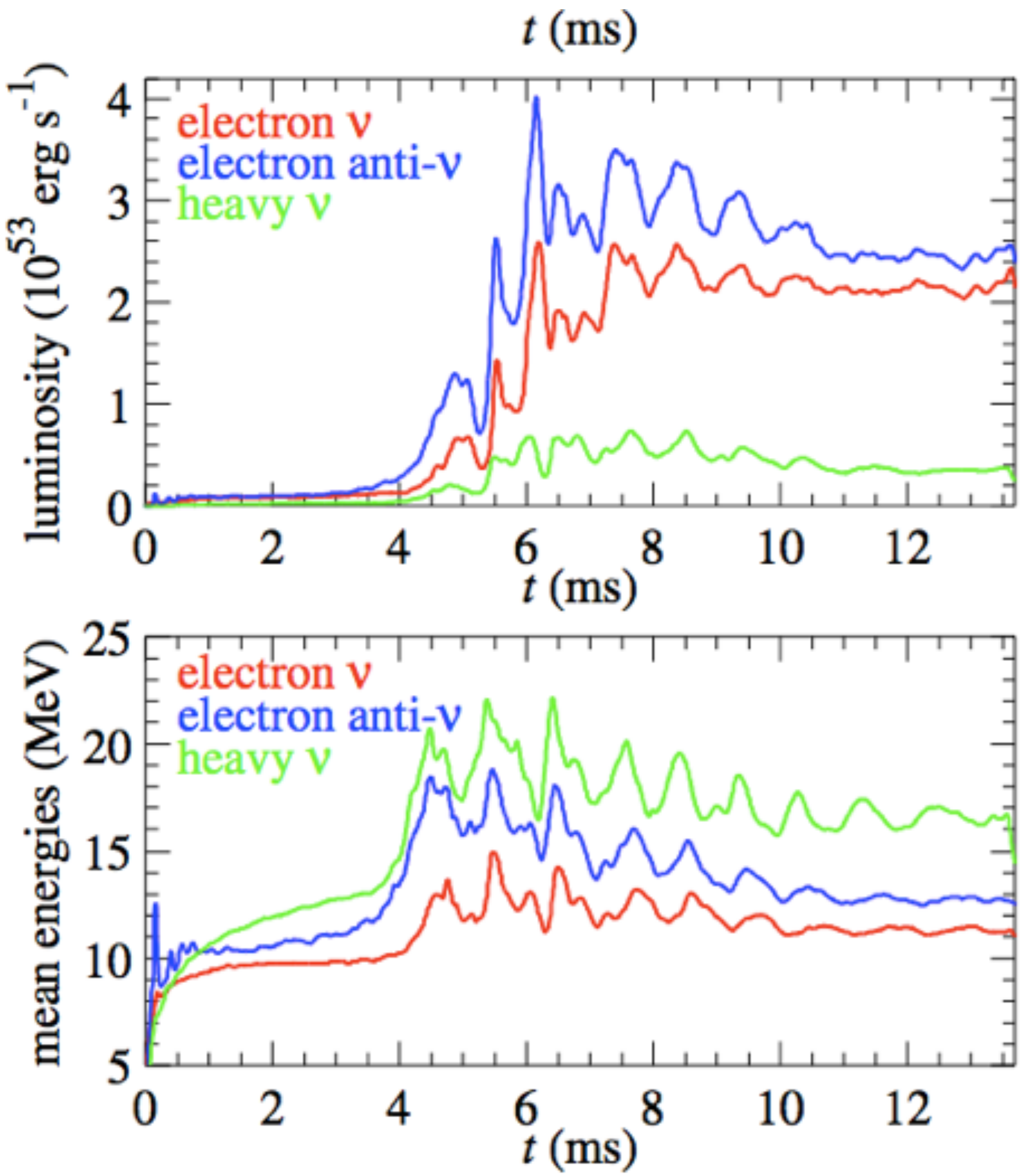
Impact of EOS (vs Shen EOS 1998)

- Steiner's EOS makes compact NS
- compact NS
  → less tidal disruption + strong collision

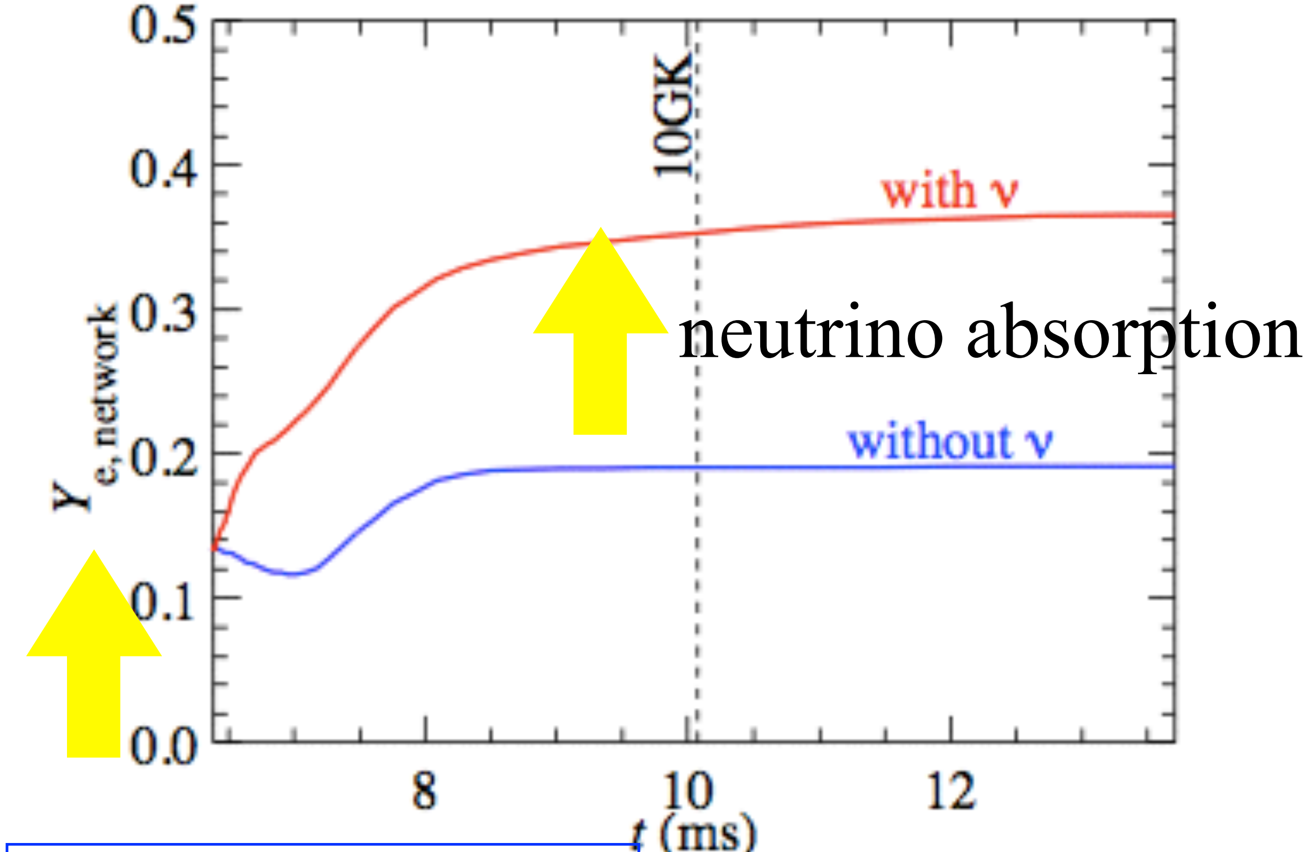


Neutrino burst and Ye

“Protonization” Burst



Ye changes due to positron capture and neutrino absorption

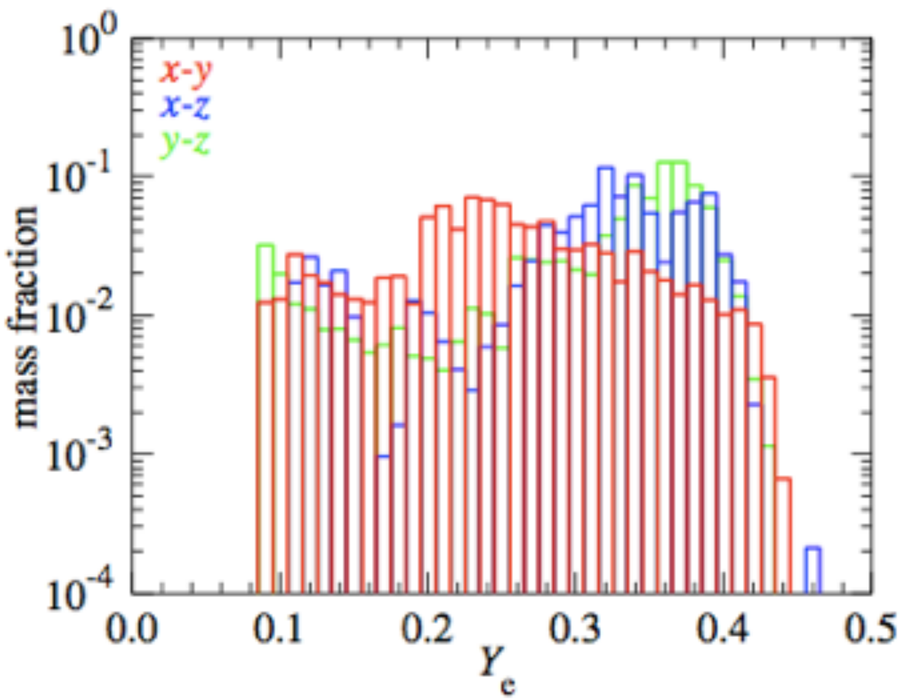


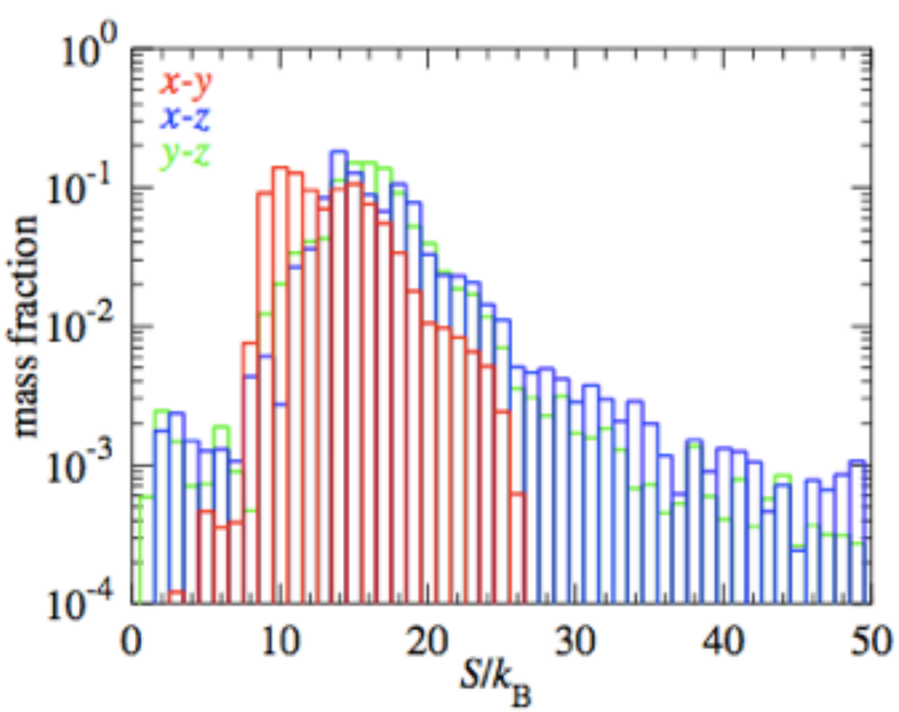
$$n + e^{+} \rightarrow p + \overline{\nu_e}$$

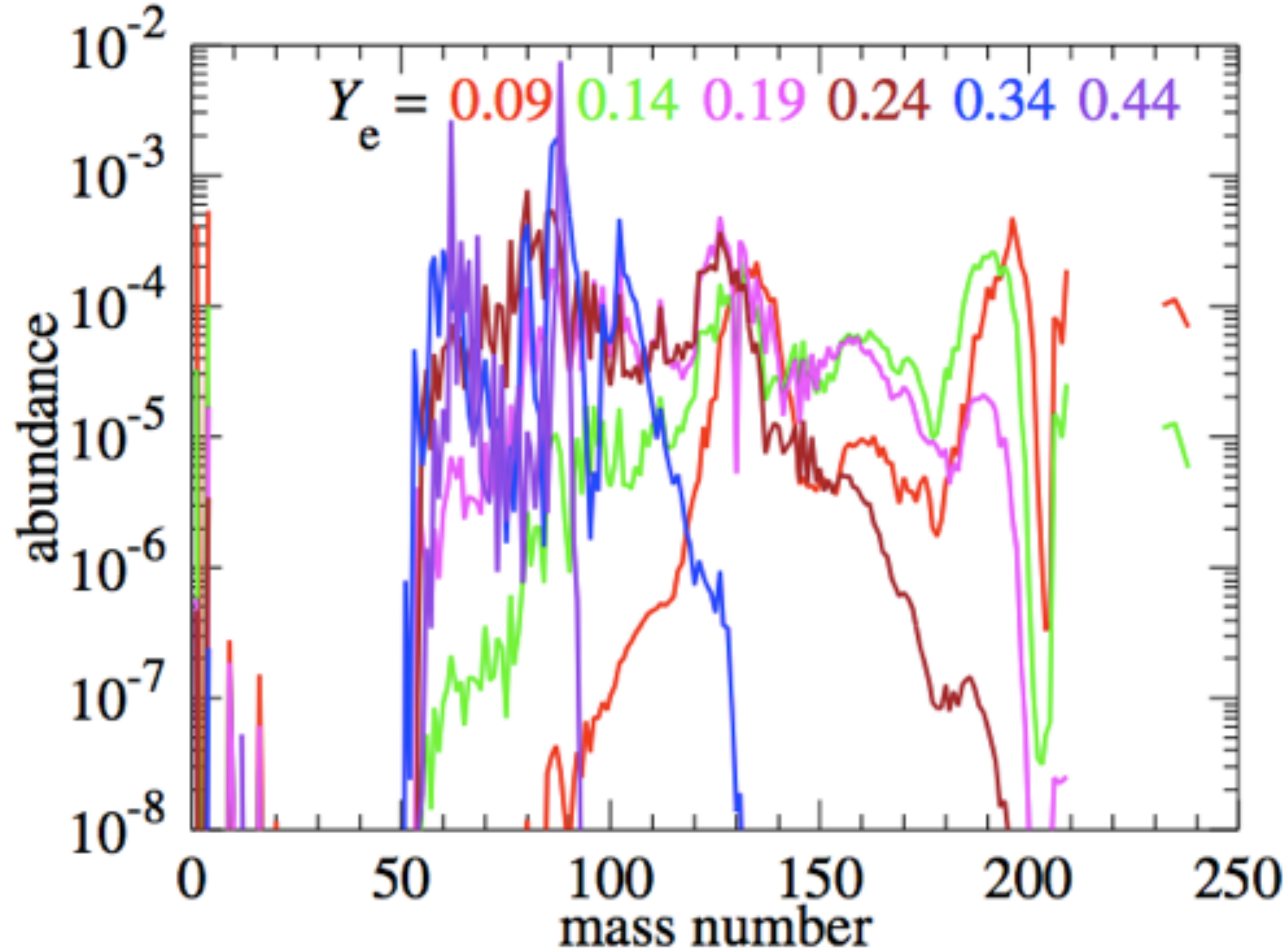
Wanajo+ 2014

ejecta of NS-NS model

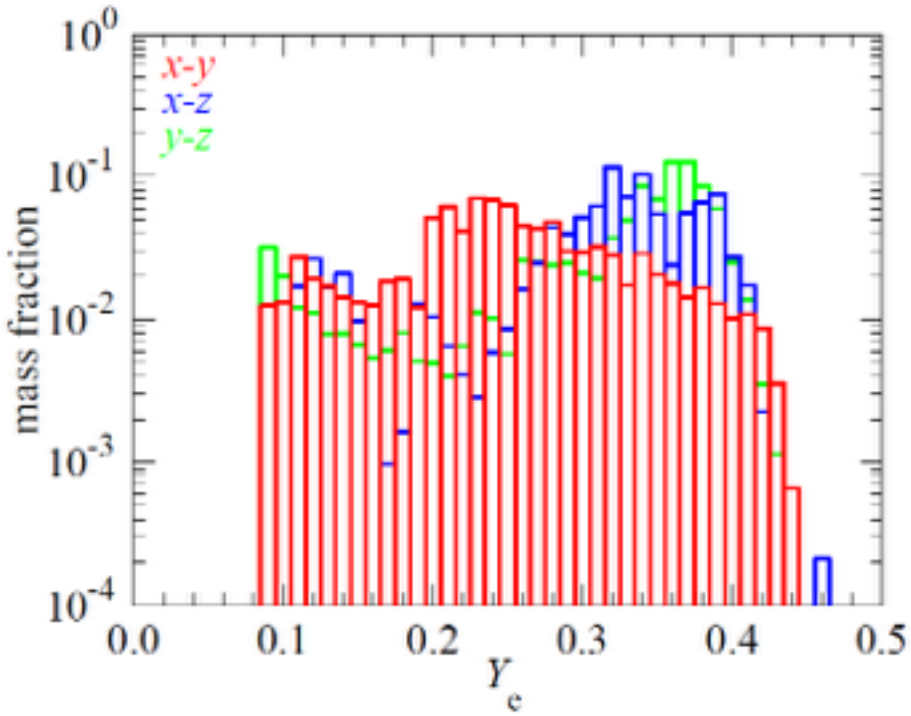
- mild neutron-rich ($Y_e = 0.1$ — 0.4)
- low entropy

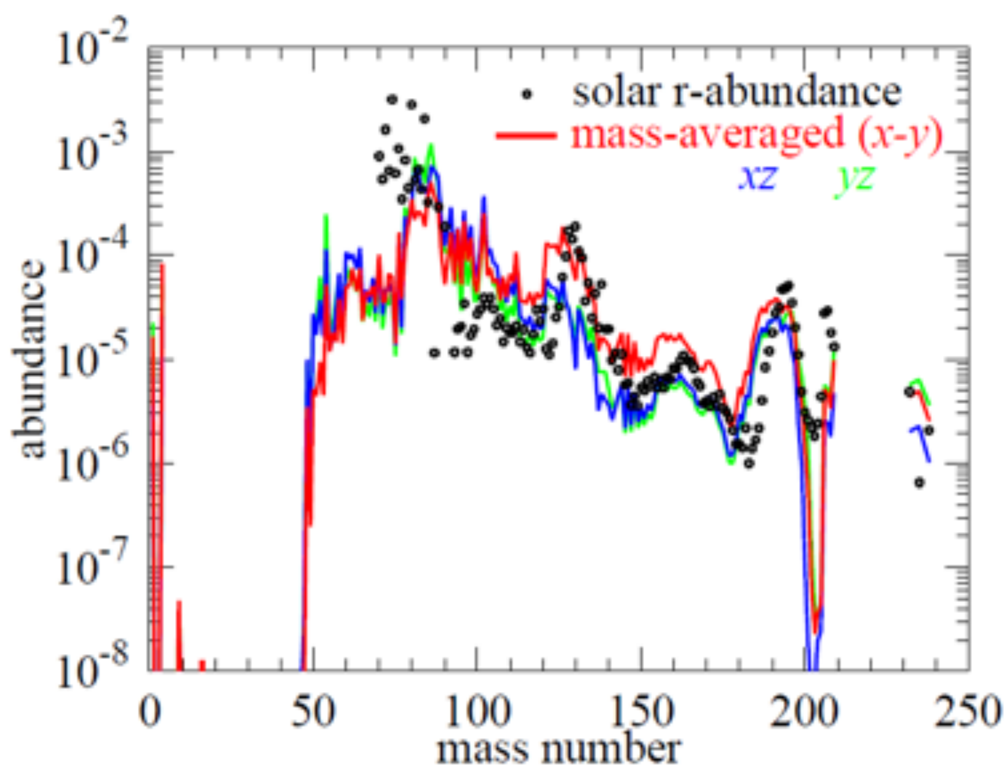






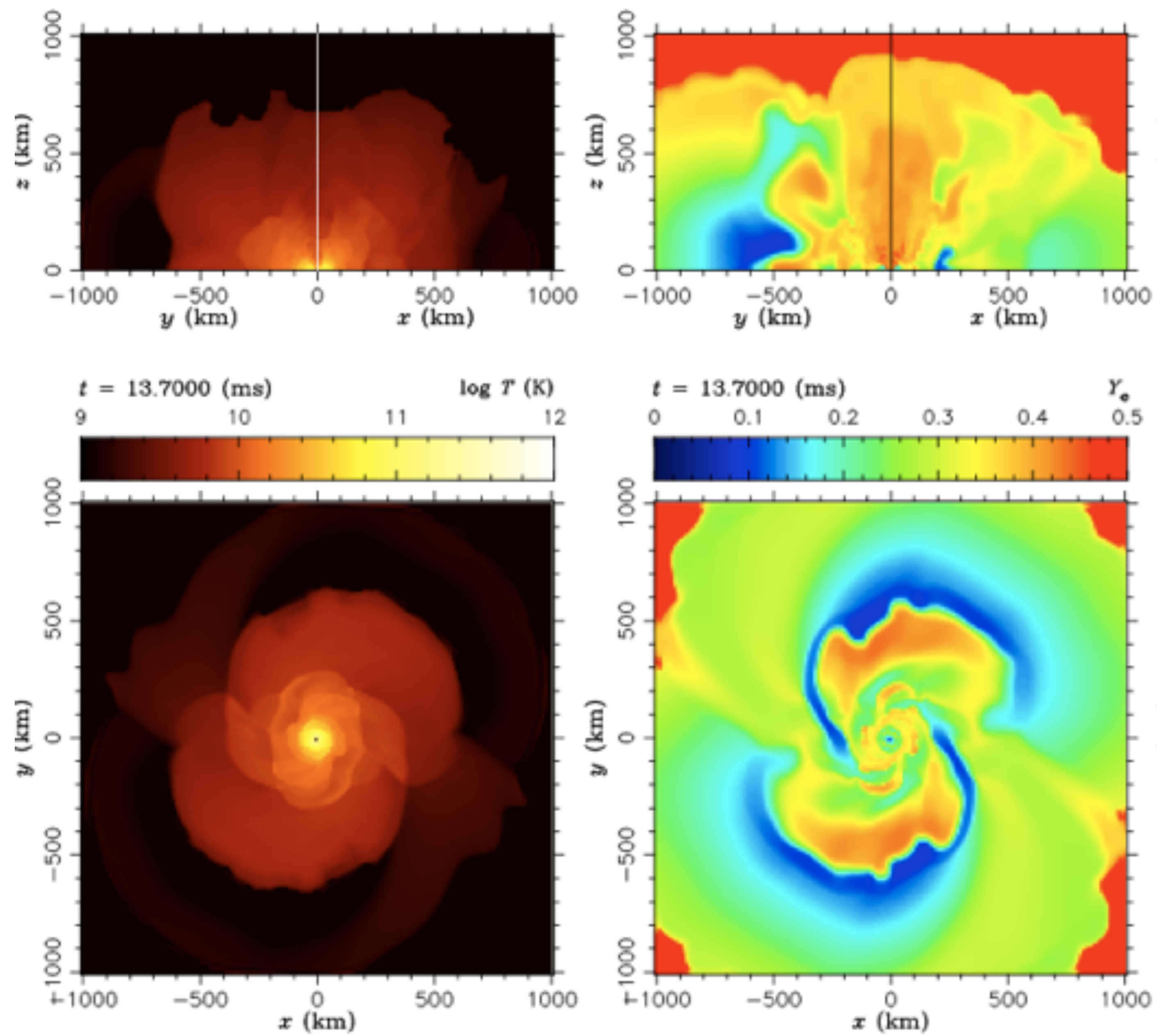
3D-geometry





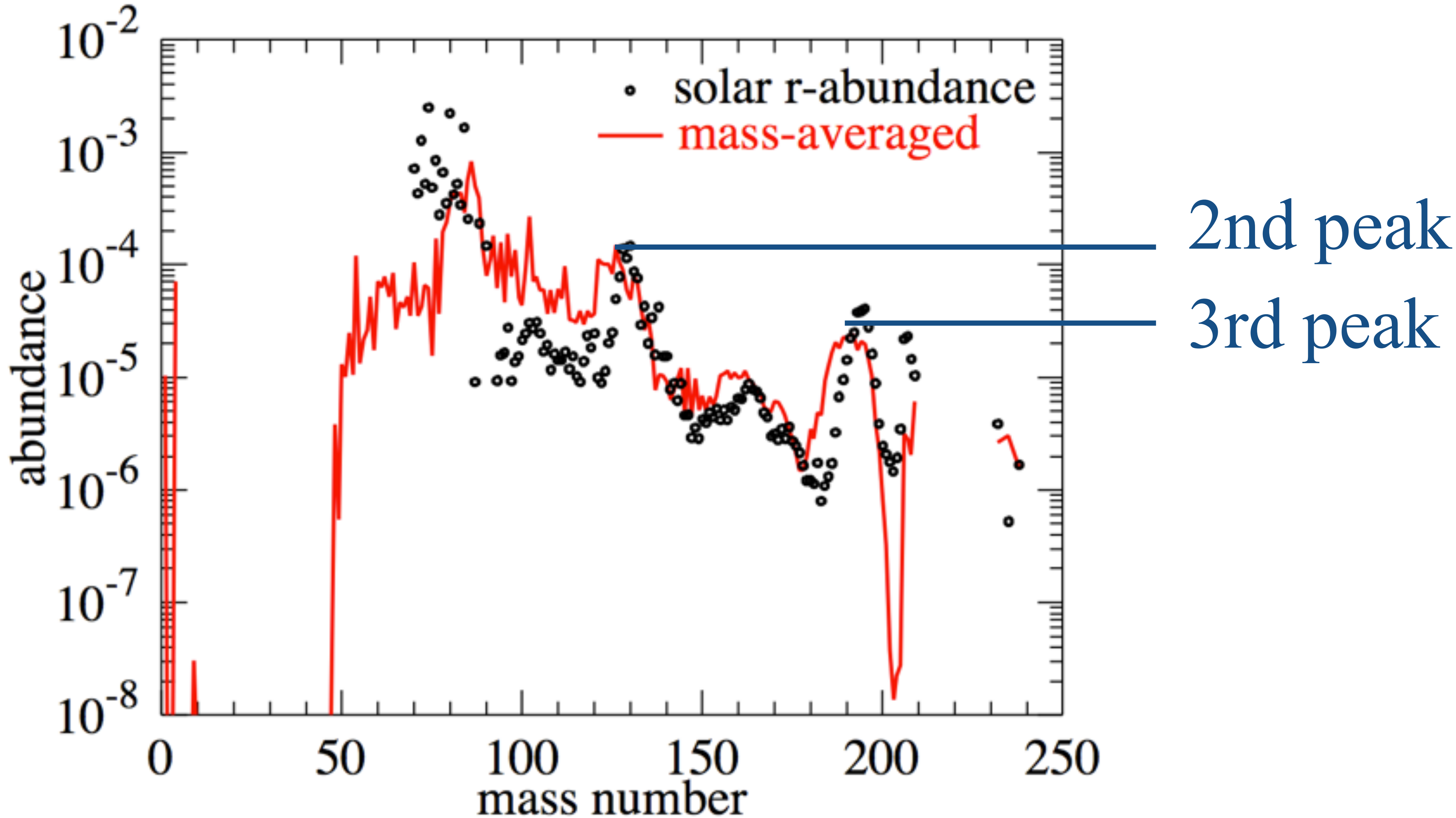
temperature

Ye



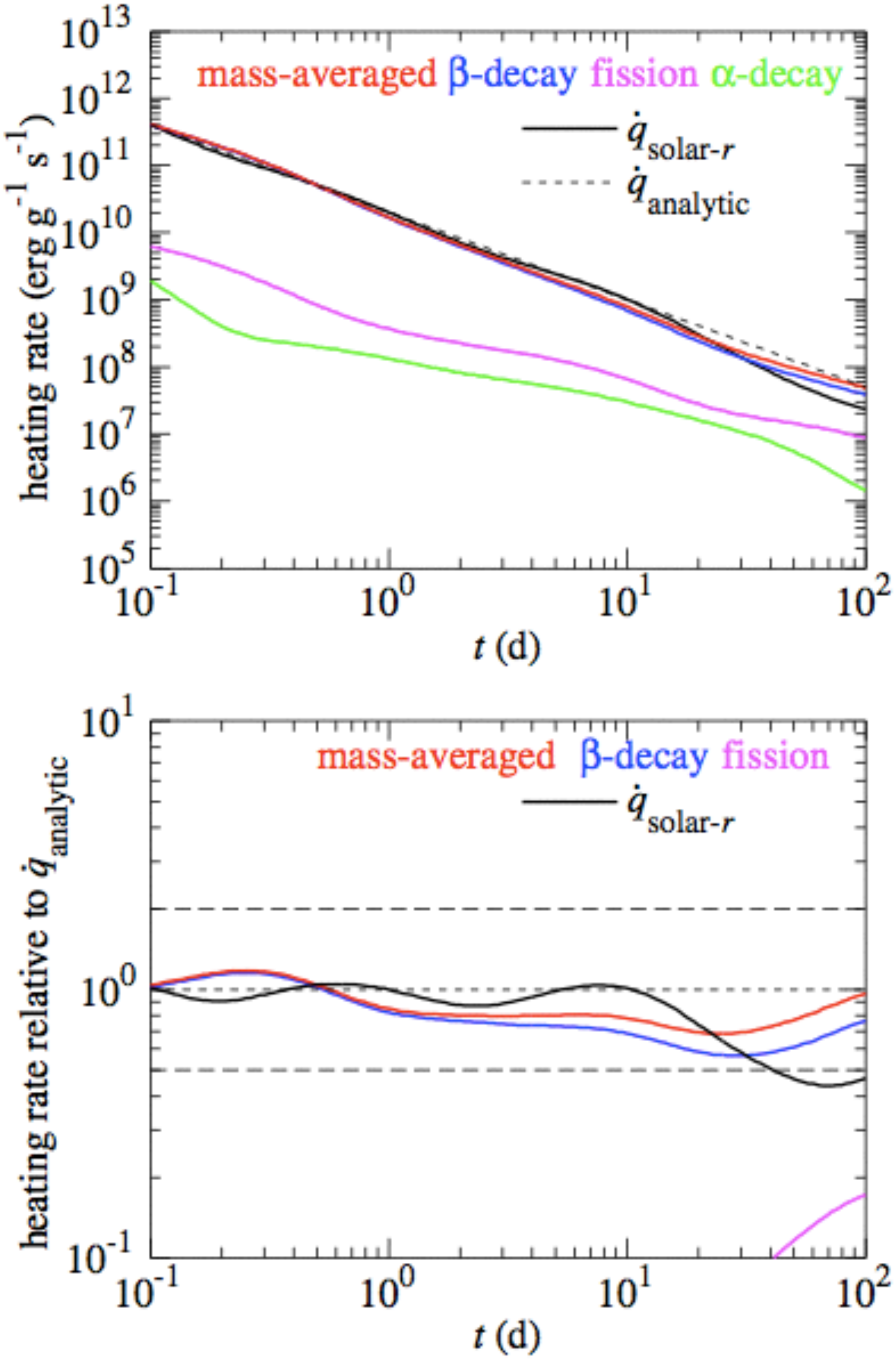
ejecta of NS-NS model

solar-like r-process pattern
NO strong fission cycling



Theoretical reaction rates are based on mass model HFB-21 (Goriely)
(fission properties are based on HFB-14, Goriely)

as a source for “kilonova”



main source (β-decay)

～1days

(^{85}Kr, ^{89}Sr, ^{103}Ru)

～10 days

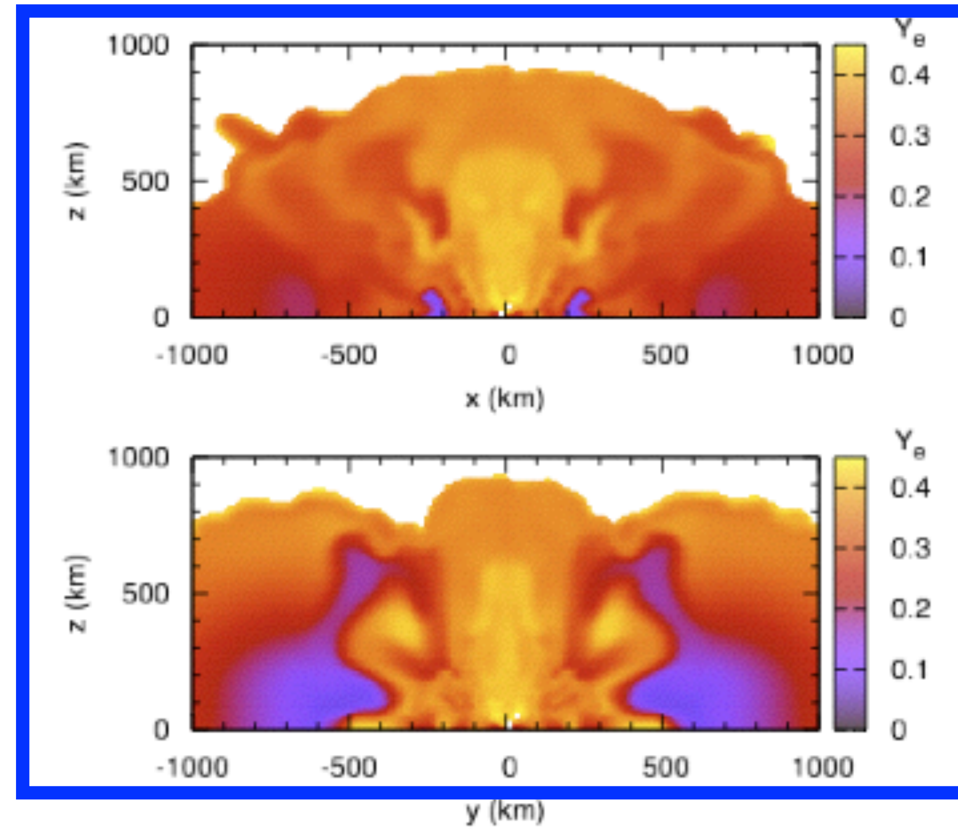
(^{123}Sn, ^{125}Sn)

※fission does not play significant role

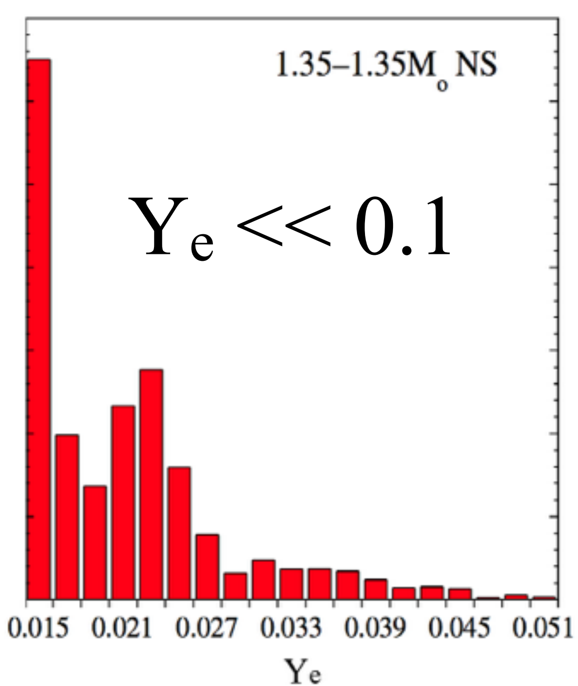
NS-NS as a Galactic r-process source

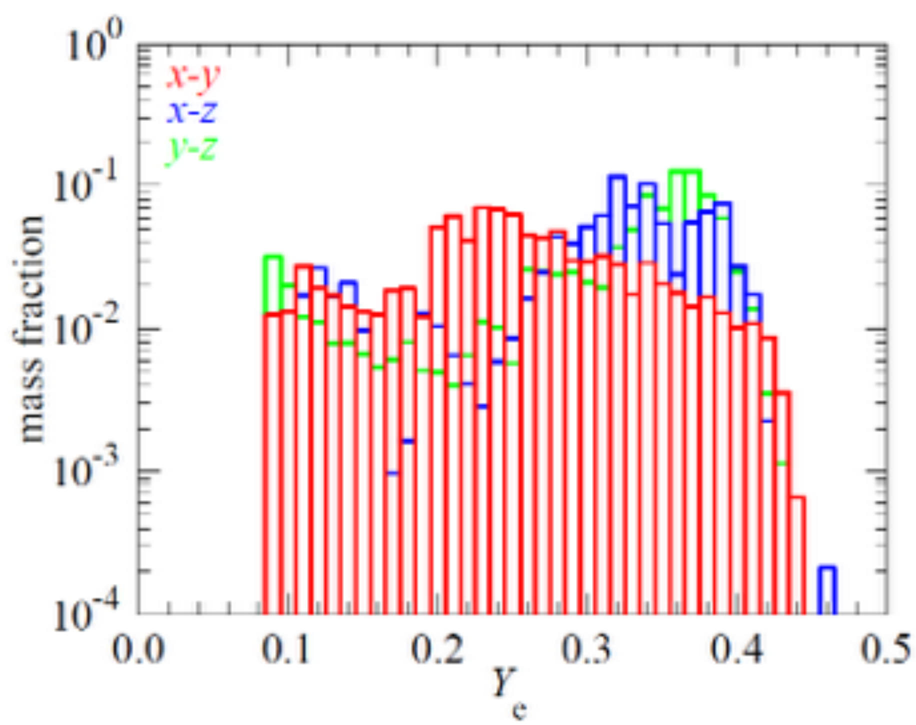
- amount of ejecta
  - ~ 0.01 $M_\odot$
  - estimated rate 10^{-5} /year (agree with other estimation) (e.g., Dominik et al. 2012)

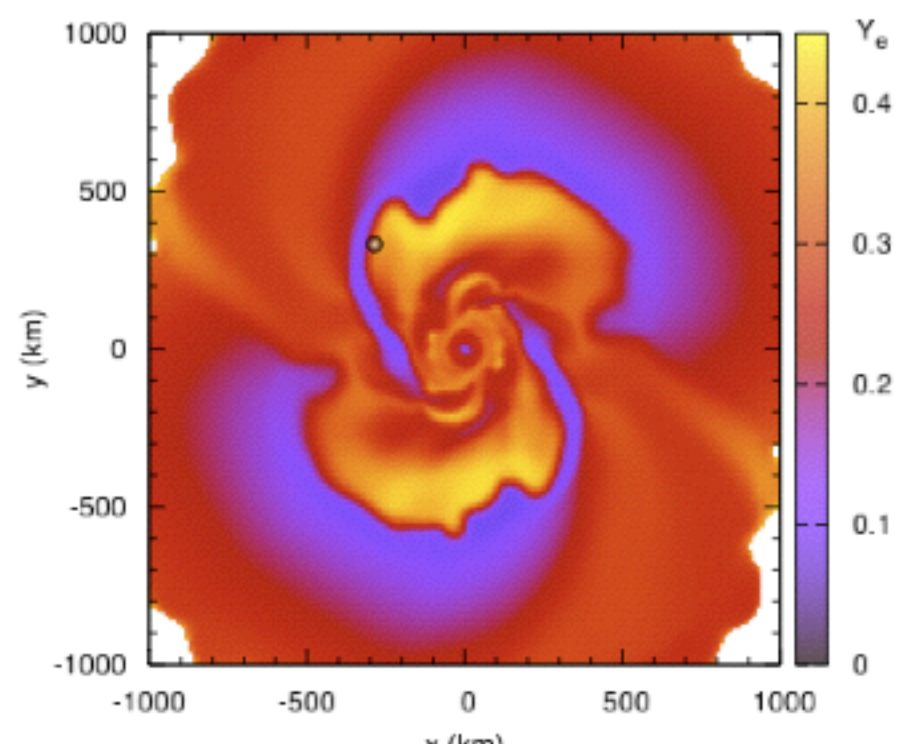
non-orbital plane



Goriely+ 2011

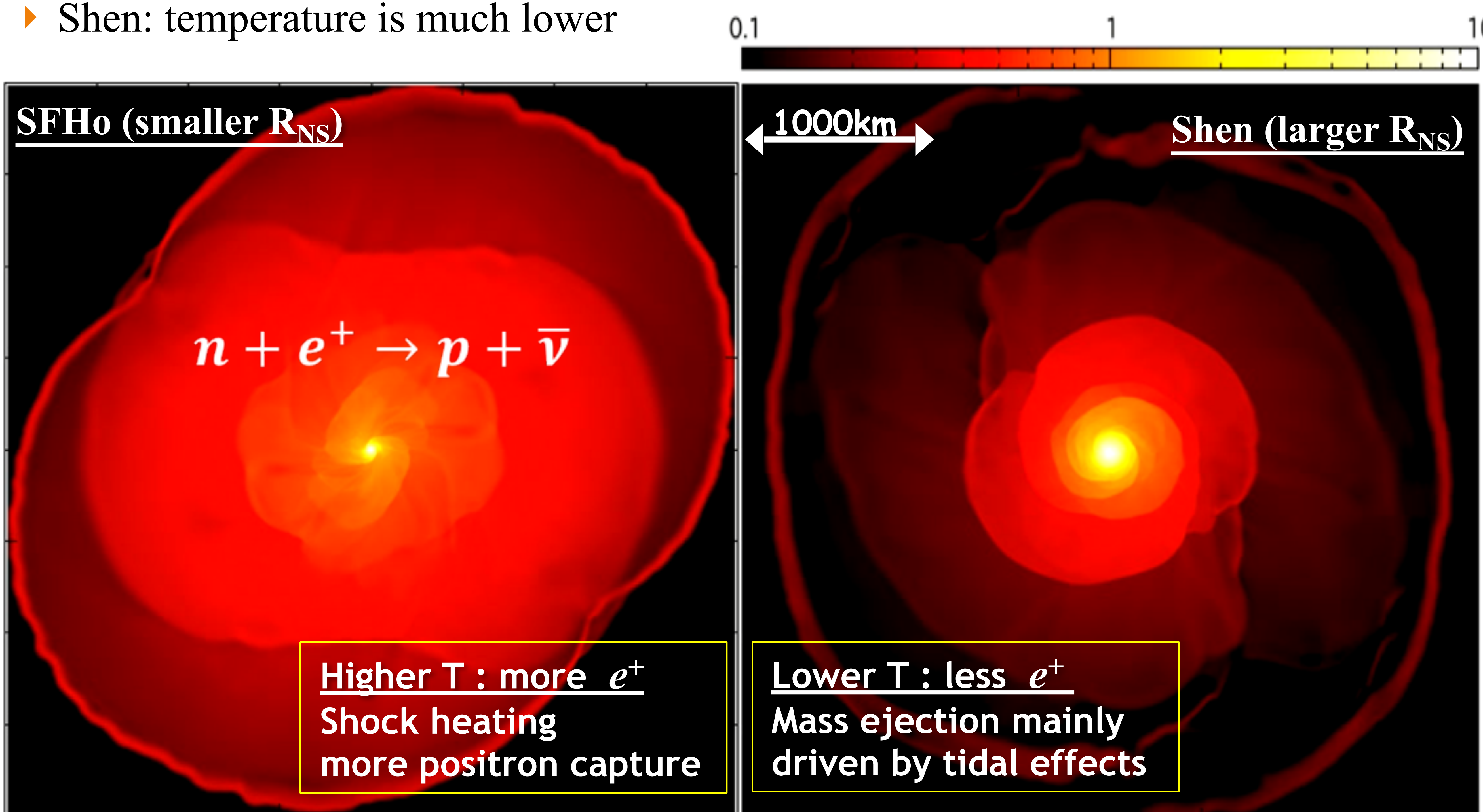






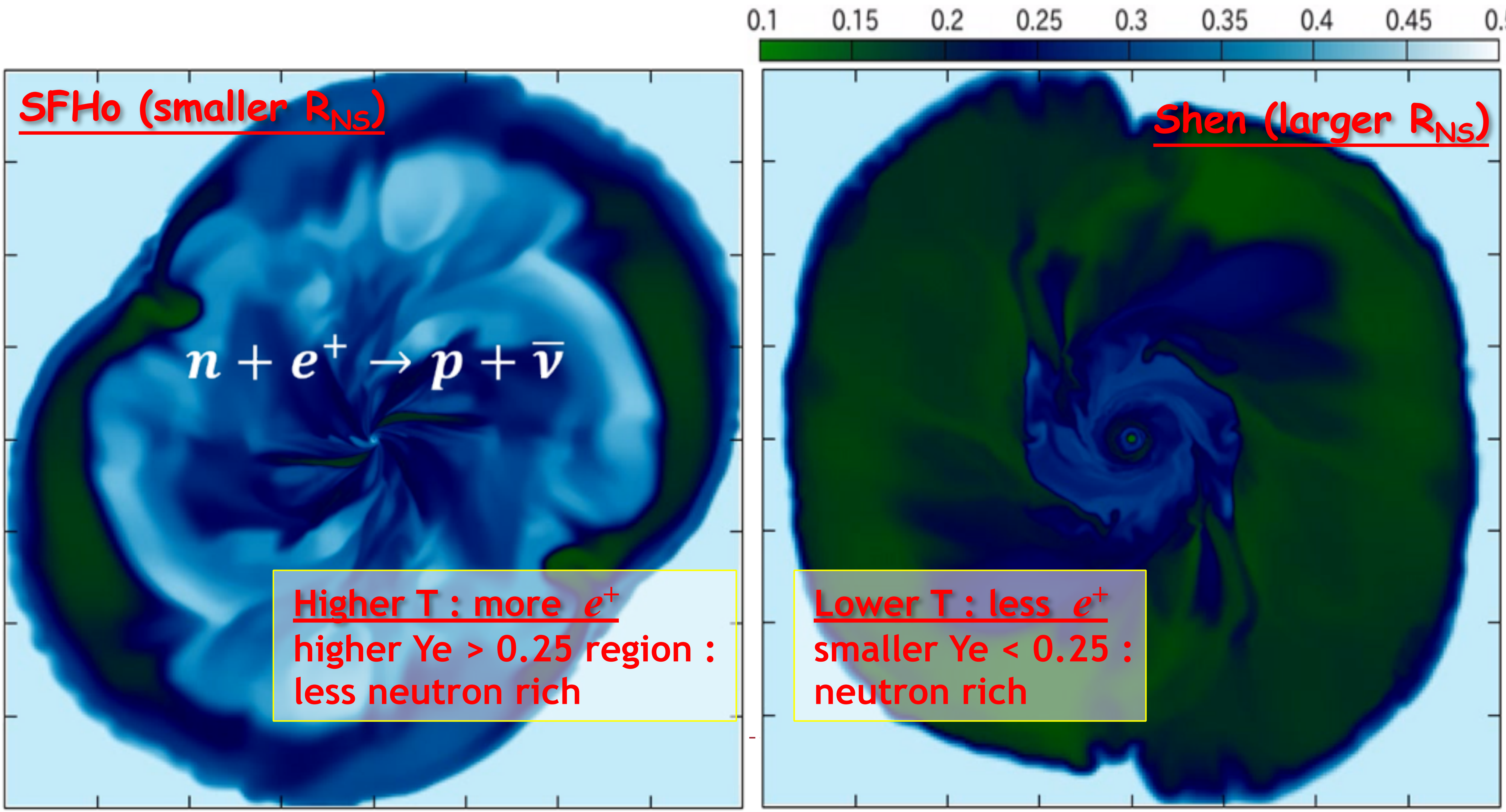
SFHo vs. Shen (high resolution): temperature

- SFHo: temperature is higher (as 1MeV) due to the shock heating, and produce copious positrons
- Shen: temperature is much lower



SFHo vs. Shen (high resolution): Y_e

- SFHo: In the shocked regions, Ye increases to be >> 0.2 by weak processes
- Shen: Ye is low as < 0.2 (only strong r-process expected)



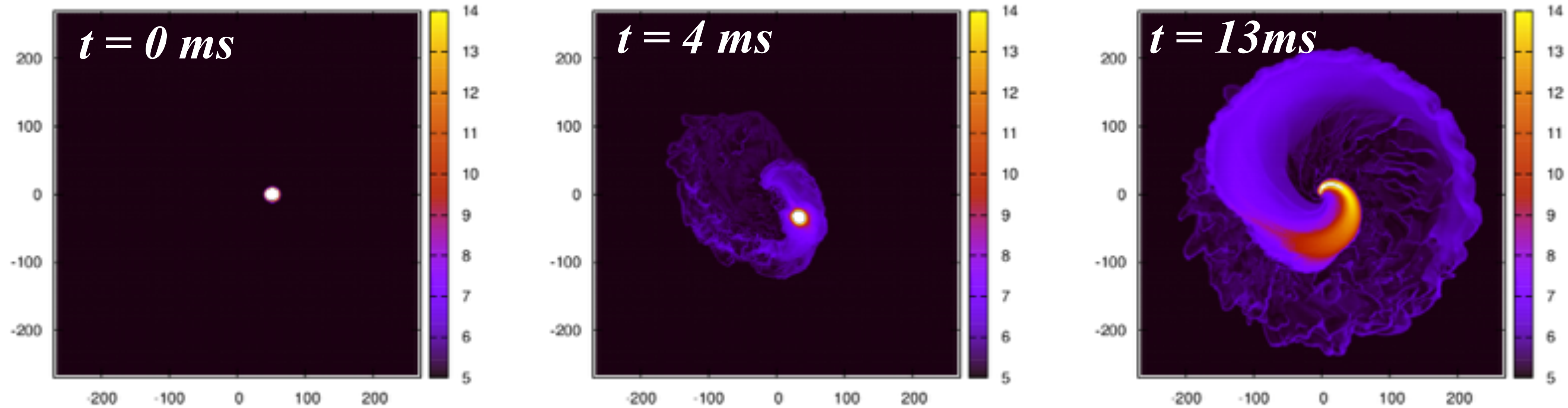
BH-NS merger?: extremely neutron-rich matter

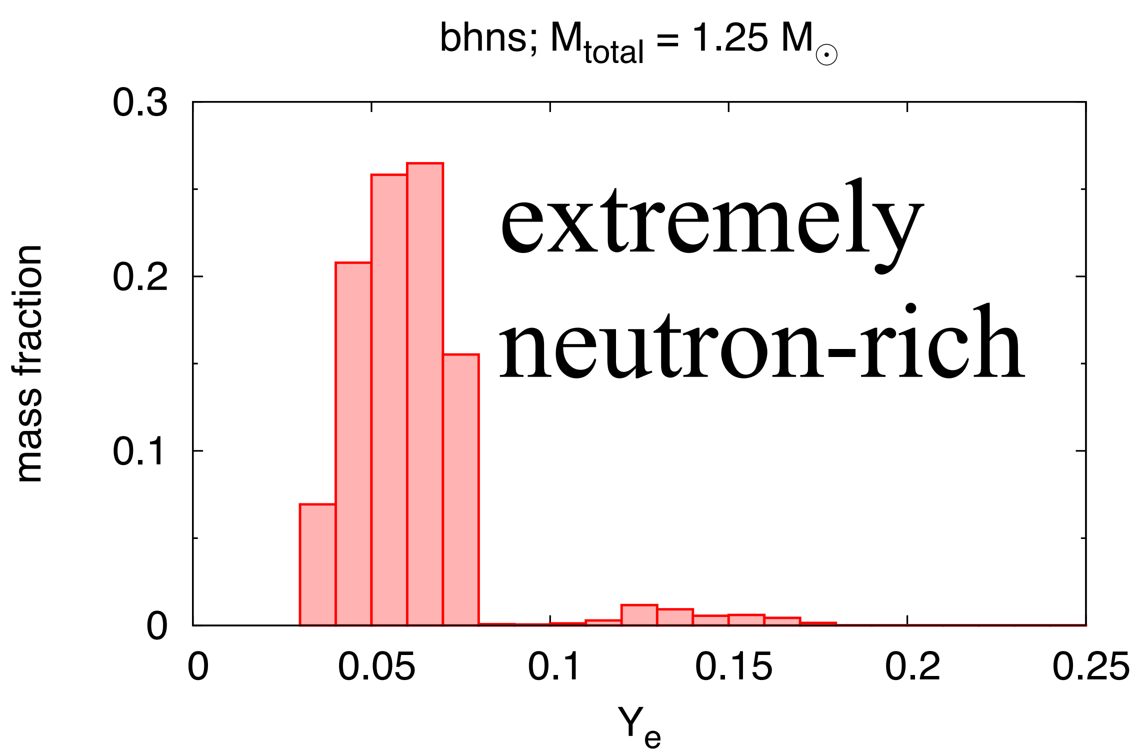
Nishimura et al. (2013); NPA VI Conf.

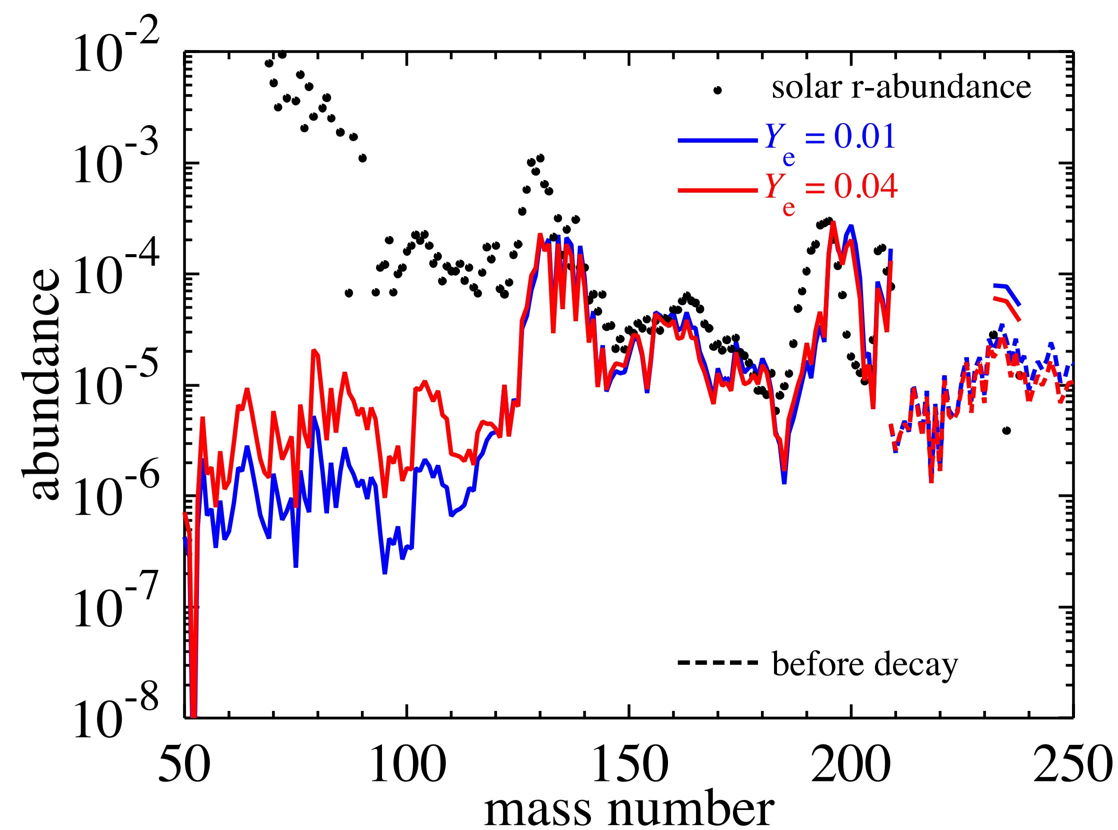
ejected matter by strong tidal disruption:

BH ($4M_\odot$) — NS ($1.25M_\odot$)

→ maintaing initial Y_e (neutron rich)







Summary

- NS mergers
  - dynamical ejecta can produce full range of r-process nuclei
  - sophisticated EOS, GR, neutrino are significant impacts on the nucleosynthesis
  - the r-process study is a new probe to examine nuclear EOS and binary stars (NS-NS) evolution
  - (can make a precise predict for "kilonova")
- open question
  - dependences on mass of NSs, EOS etc. (robustness of our present results)
  - BH-NS ?
  - needs to change galactic chemical evolution scenario?