Gravitational waves and dynamical mass ejection from binary neutron-star mergers

Masaru Shibata
Yukawa Institute for Theoretical Physics,
Kyoto University

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

In collaboration with Hotokezaka, Kiuchi, Kyutoku, Okawa
Sekiguchi, M. Tanaka, & Wanajo

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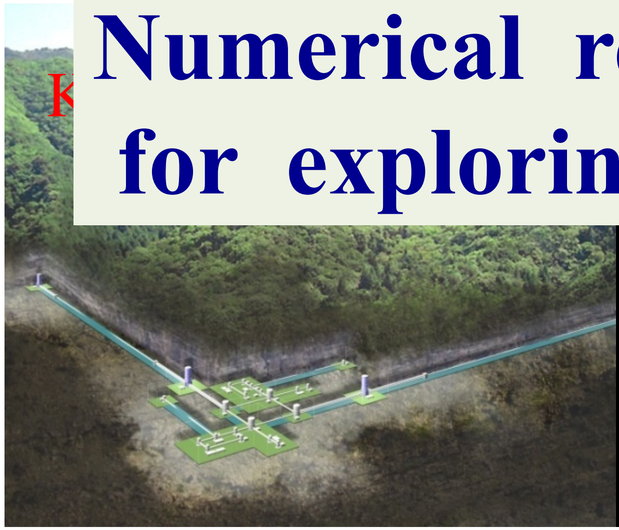
1. **One page introduction**
2. **Our latest numerical-relativity activity for NS-NS**

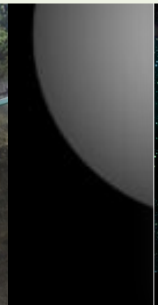
- **Gravitational waves from late inspiral**
- **Dynamical mass ejection**

Why NS-NS mergers are important ?

1. **Most promising sources of gravitational waves for LIGO/VIRGO/KAGRA**
2. Invaluable **laboratory for studying high-density nuclear matter**
3. Promising origins of **short-hard GRBs**
4. Sources of strong transient **EM emission**
5. Possible site for **r-process heavy elements**



Numerical relativity is the powerful tool for exploring these issues quantitatively



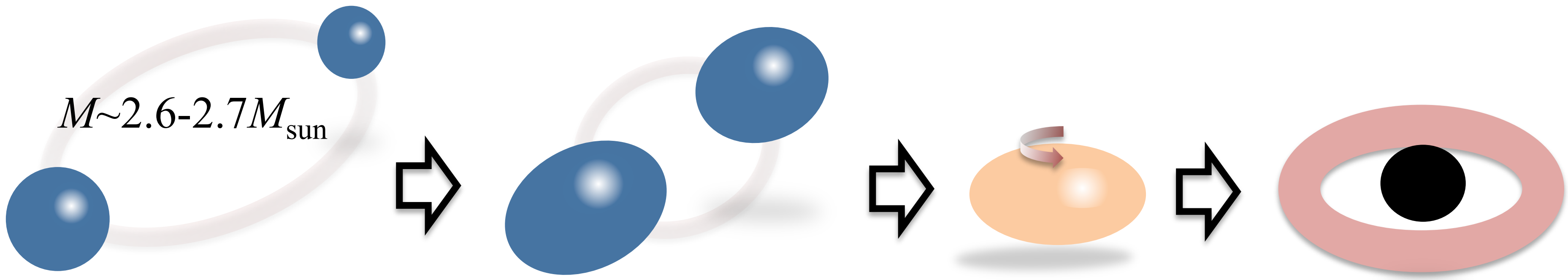
2A Gravitational waves (see John's talk)

Early Inspiral ($r_{orb} >> R_{NS}$)

Late inspiral ($r_{orb} \le 5R_{NS}$)

Merger => Hypermassive NS

Black hole & torus & GRB?



Point mass phase
Adiabatic phase

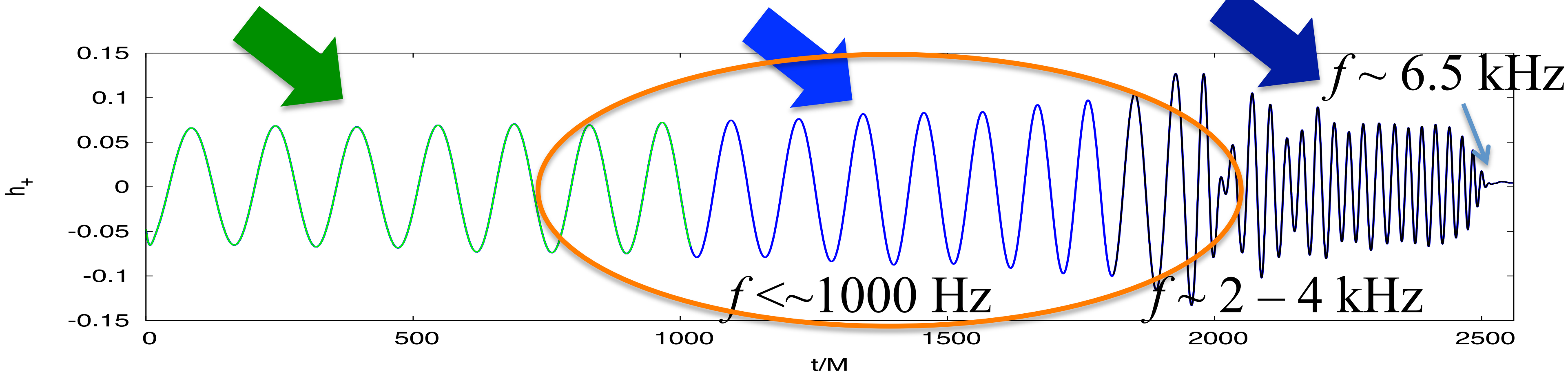
Tidally deformed phase

Dynamical & GR phase

Post-Newton

Late inspiral

Post merger

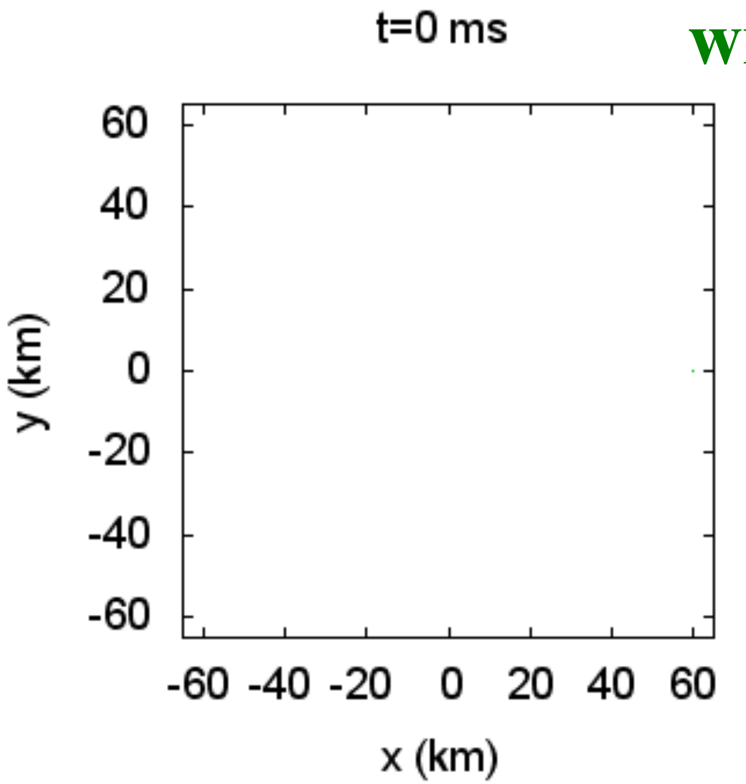


Analytic Computation (Effective One-Body)

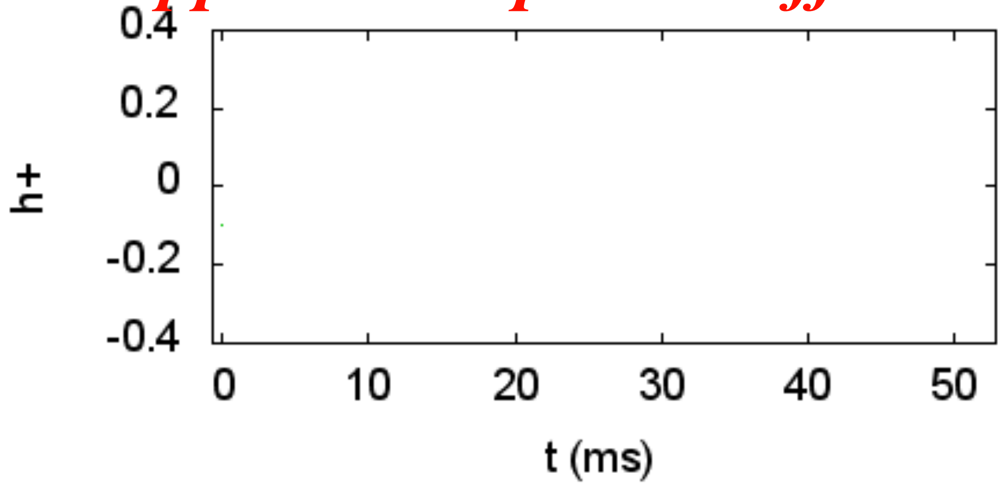
1.35-1.35 M_{sun}, EOS: MS1 (R=14.5km)

without tidal effects

with tidal effects



Appreciable phase difference



Calculation by Hotokezaka

EOB version (a bit old):
Damour et al., (2012)

Predicting more accurate GWs is urgent

Three key elements for deriving accurate gravitational waves in numerical rela

- ✧ Longterm simulation
- ✧ Eccentricity reduction for initial condition
- ✧ Extrapolation using high-quality data

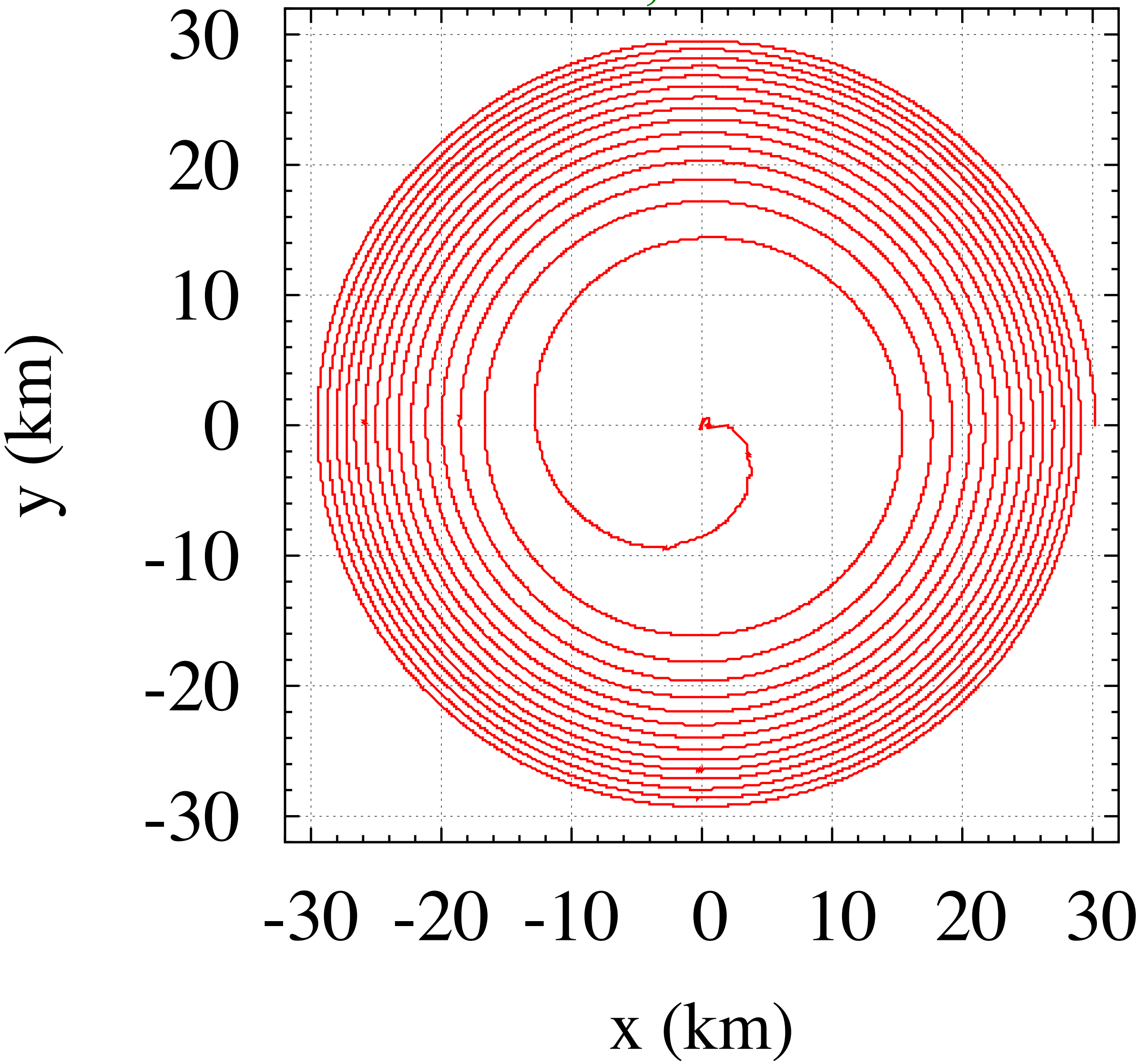
↓

Eccentricity reduction by Kyutoku+ 2014 (e <~0.001)
Constraint propagation by BSSN+Z4c prescription
(we locally used Z4c) (Hilditch & Bernuzzi)
→ less numerical error & good convergence

◆ See also the talk by Roland Haas

Our 15-orbits simulation with eccentricity reduction

It looks nice, however….



Hotokezaka, Kyutoku, Okawa, Shibata, PRD 91, 2015

H4-EOS:
R=13.6km
Mass:1.35-1.35M_{sun}

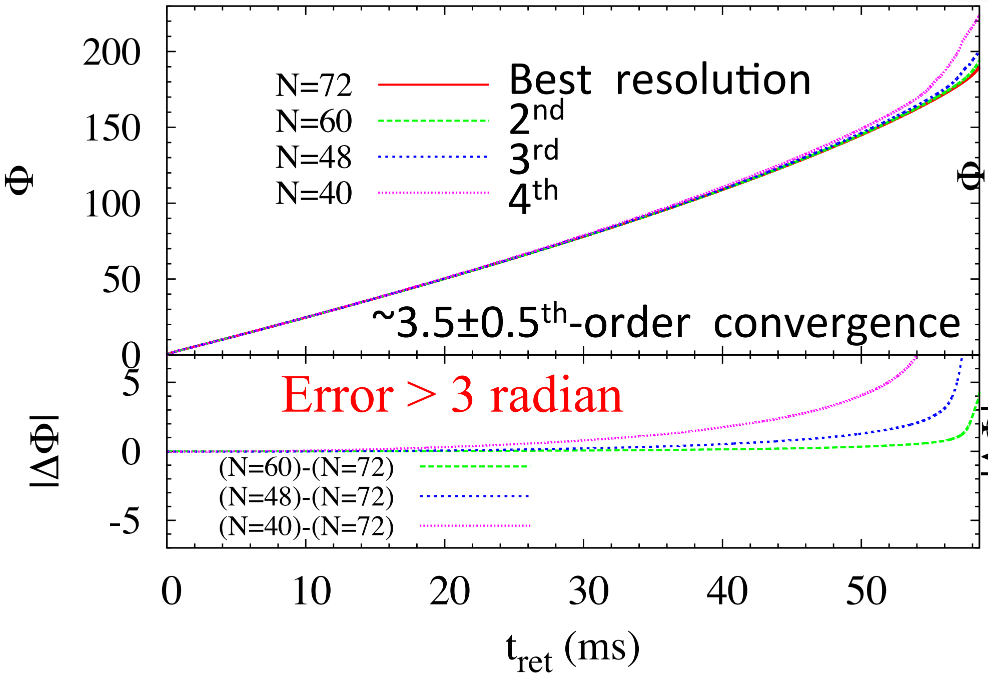
However, at best, 3rd—4th-order convergence

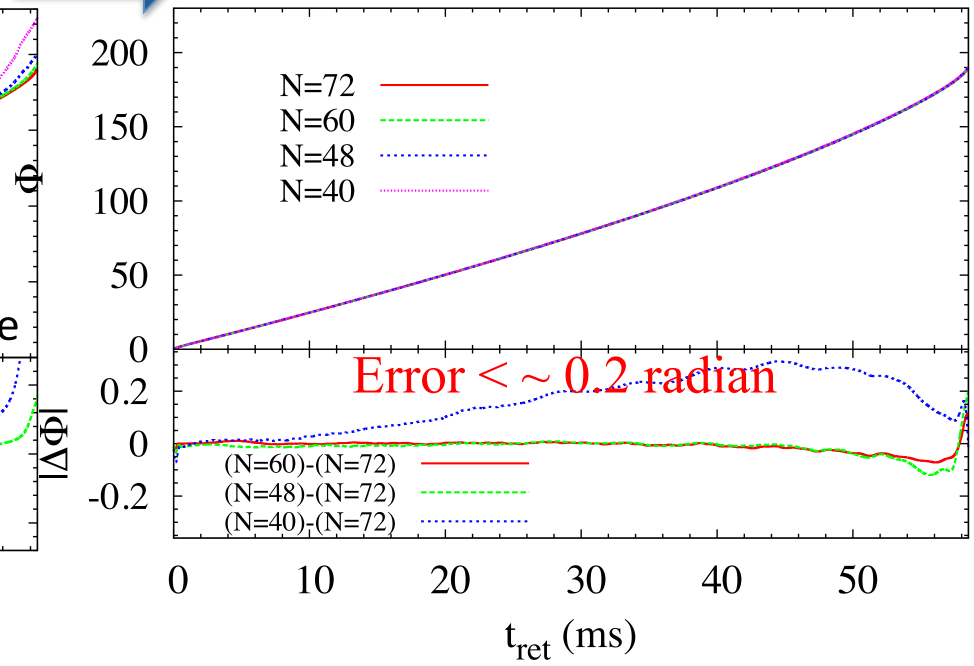
We can never obtain exact numerical waveform in hydrodynamics simulation !!

→ Extrapolation is needed for an "almost" solution

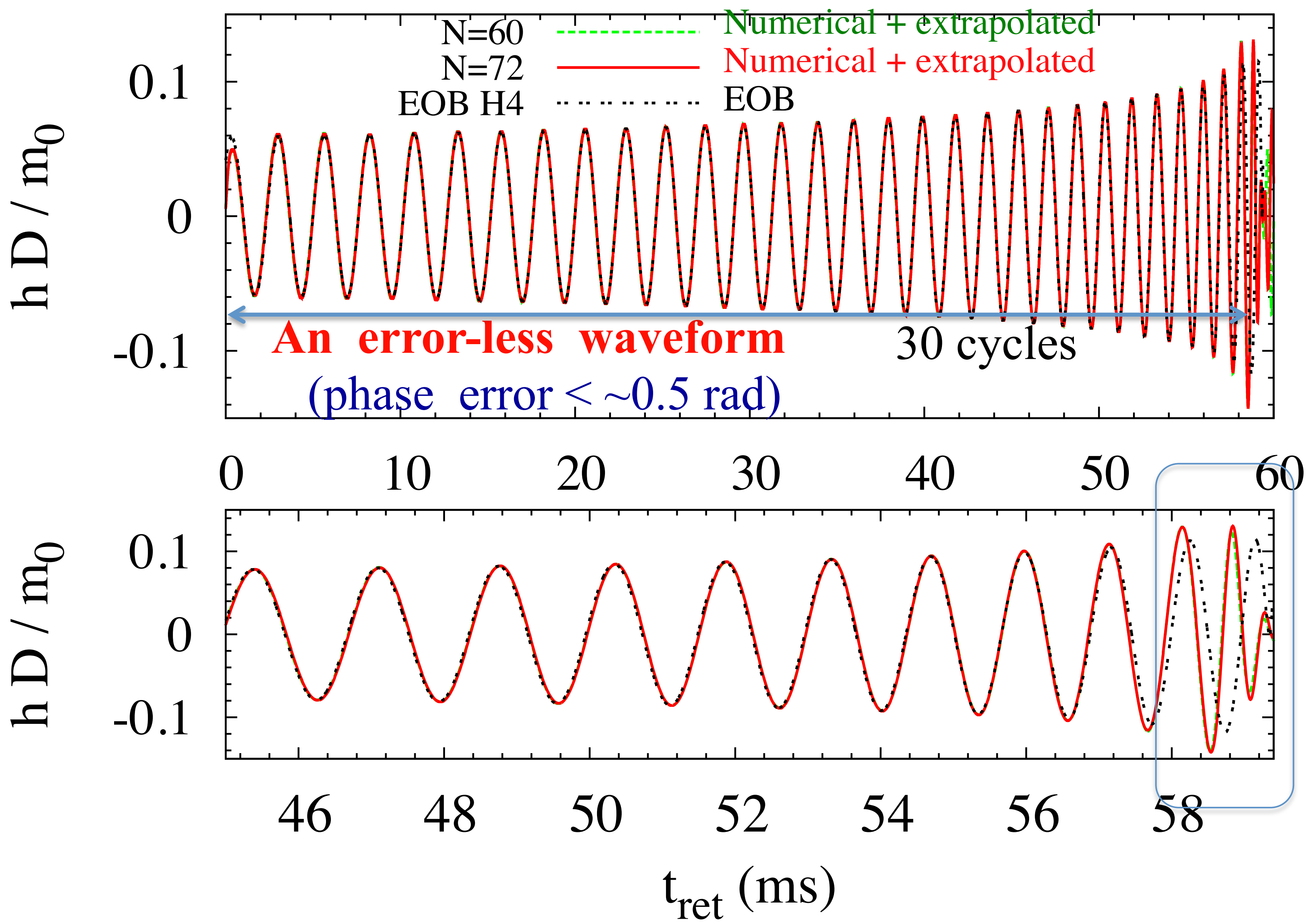
$$t \rightarrow \eta\, t, \quad \Phi = \int 2\pi f \; d(\eta\, t) : \quad \eta = \text{const}$$

Gravitational wave phase **Extrapolated phase**

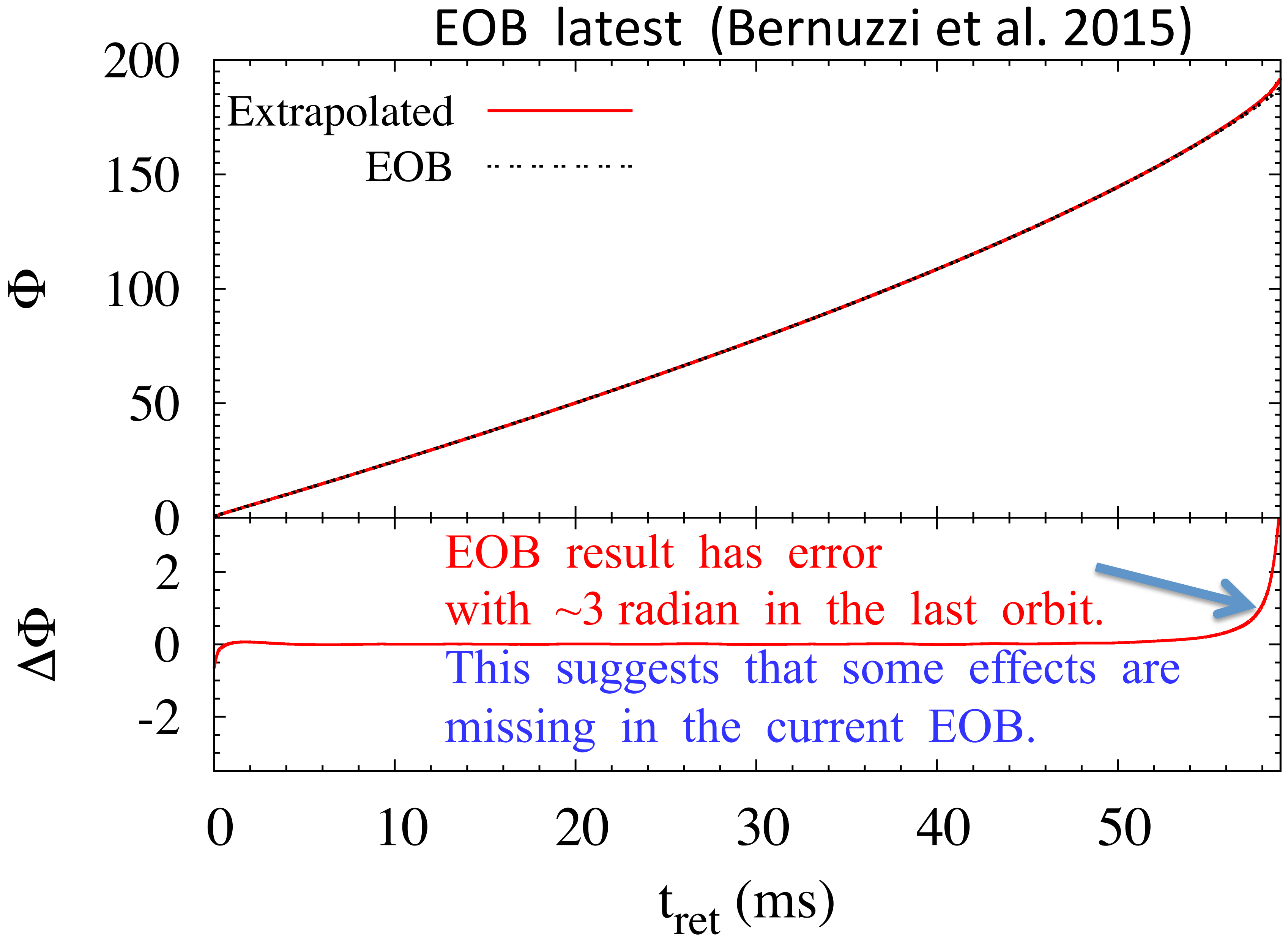




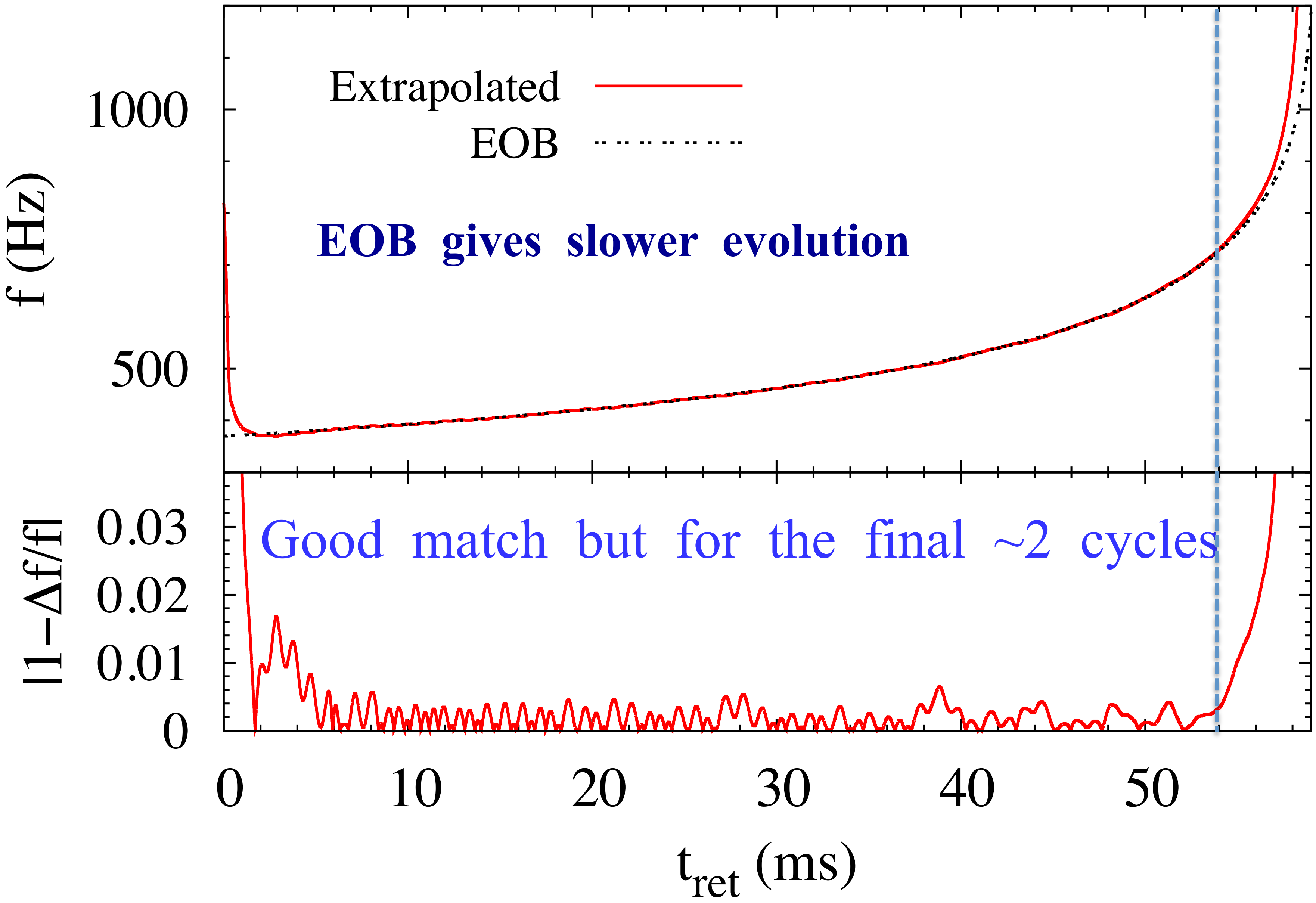
Extrapolated waveform for R=13.6 km



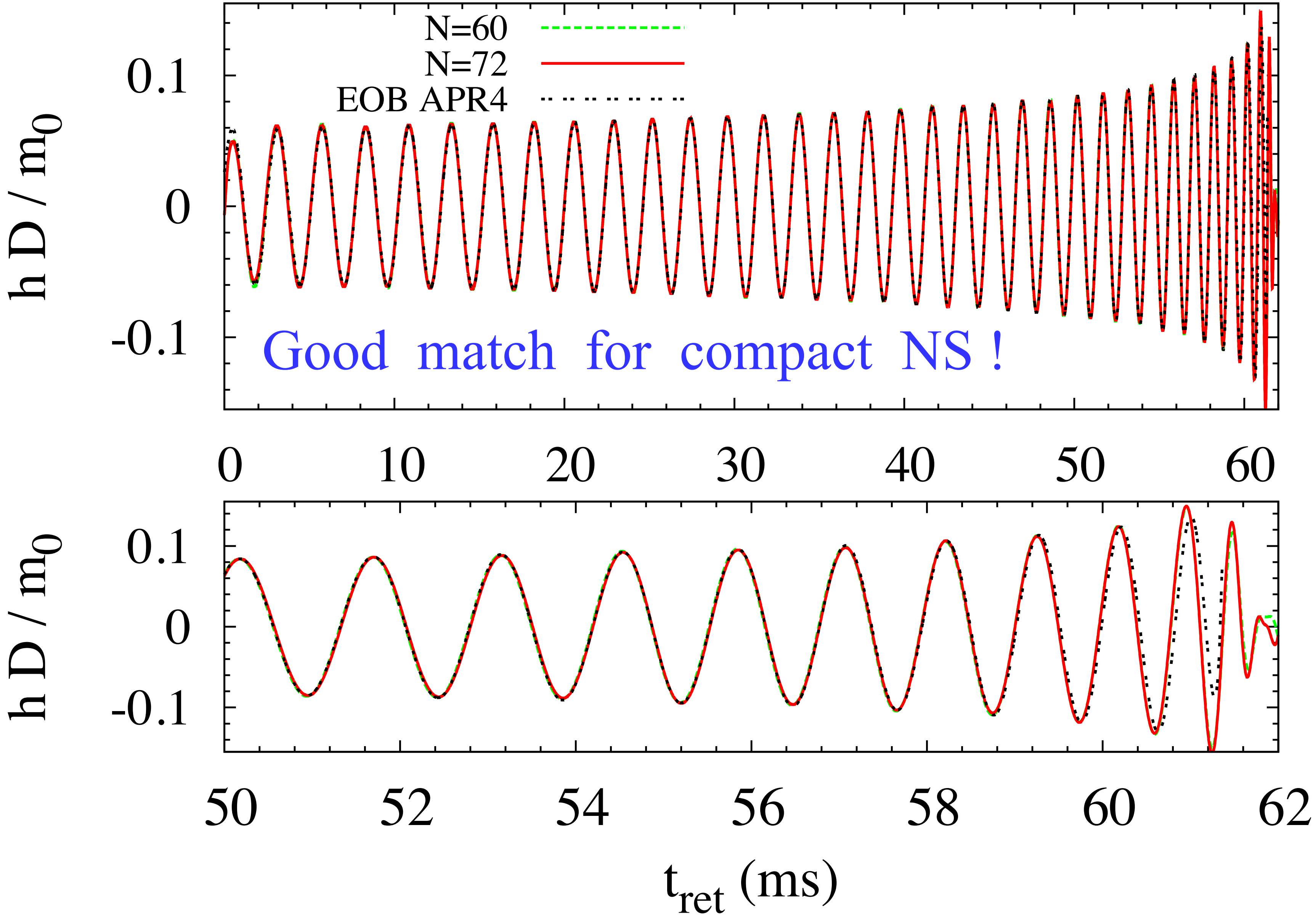
Comparison with effective-one-body approach



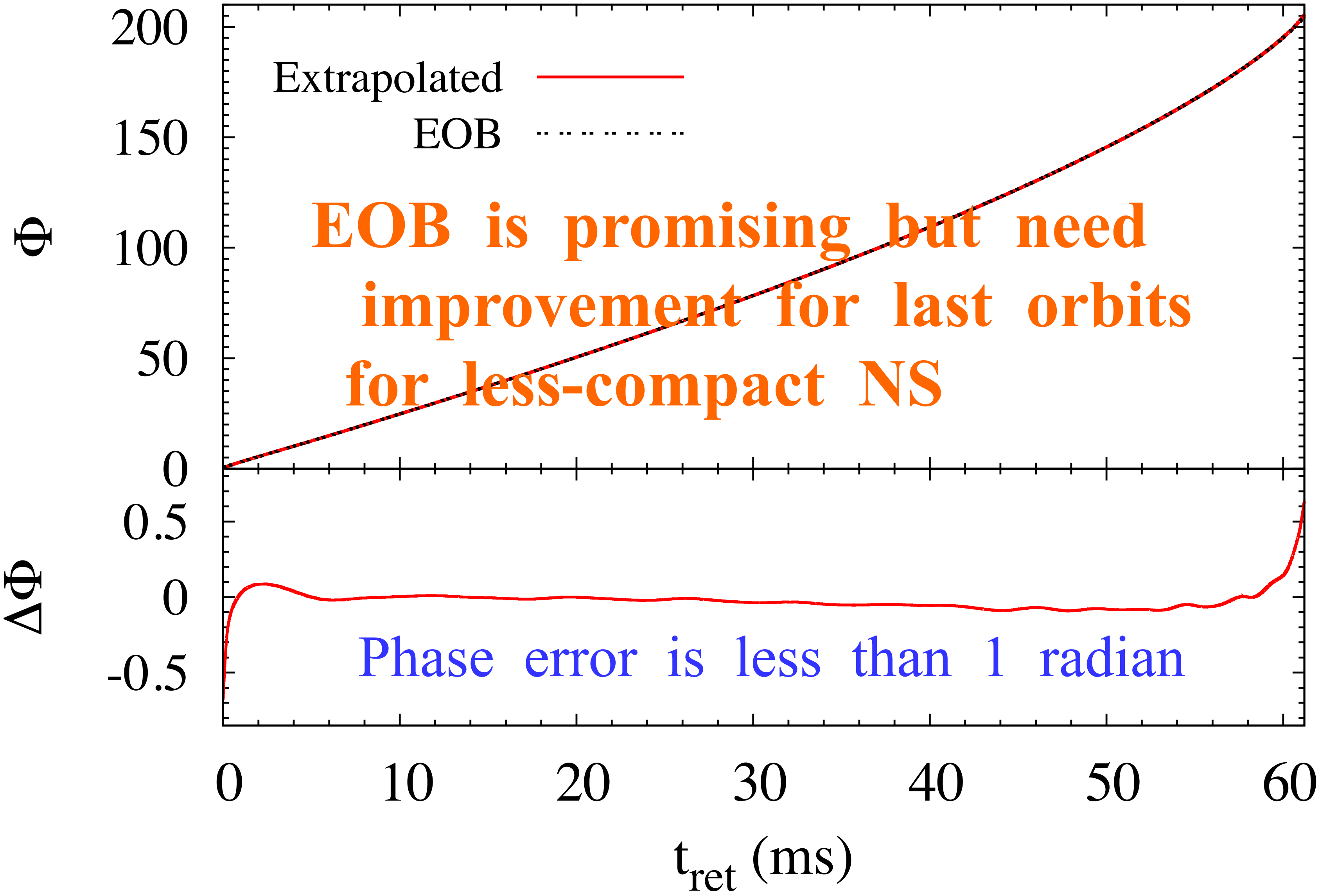
Comparison with EOB: frequency



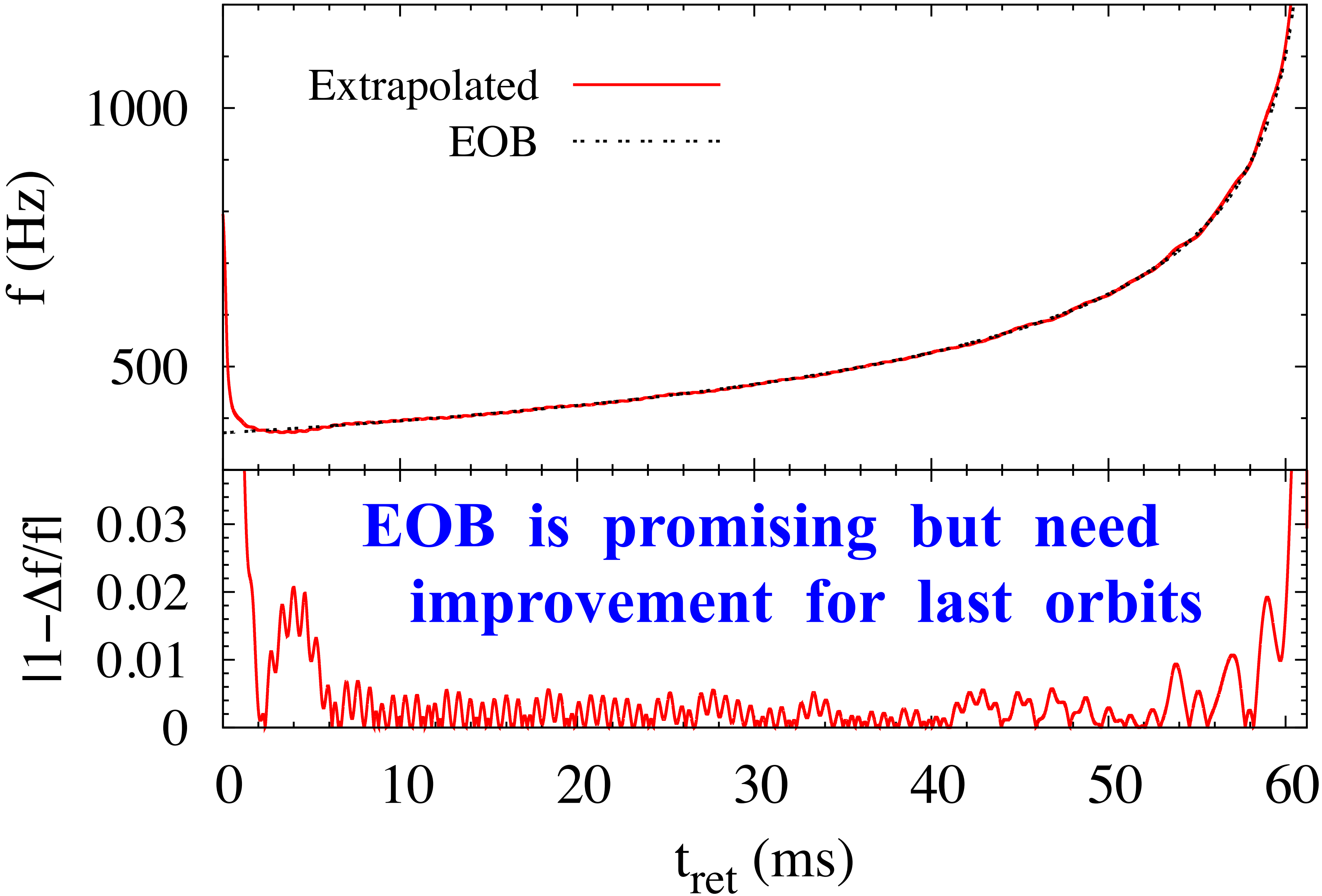
Extrapolated waveform for R=11.1 km



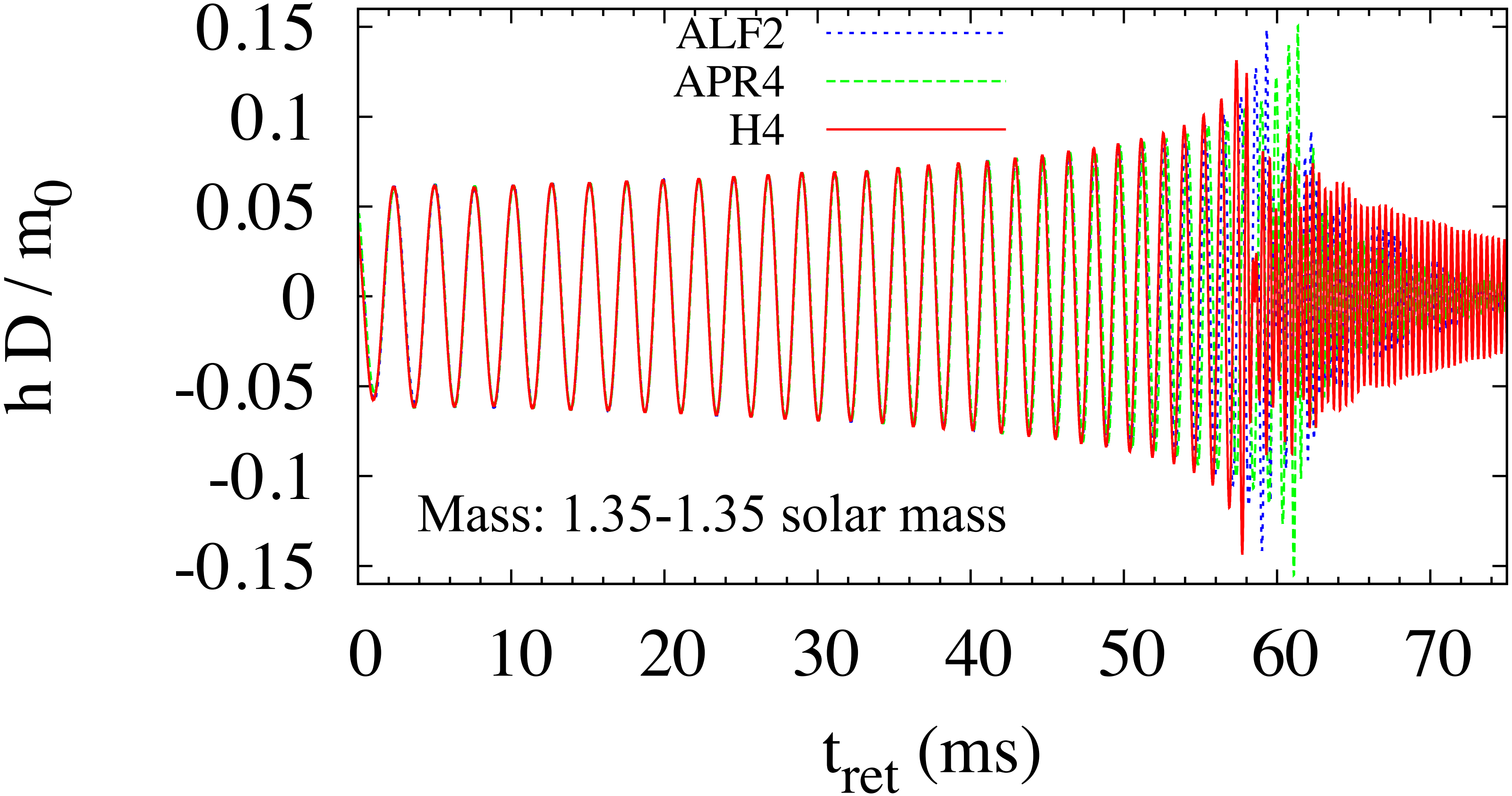
For soft EOS, current EOB is good



Good match

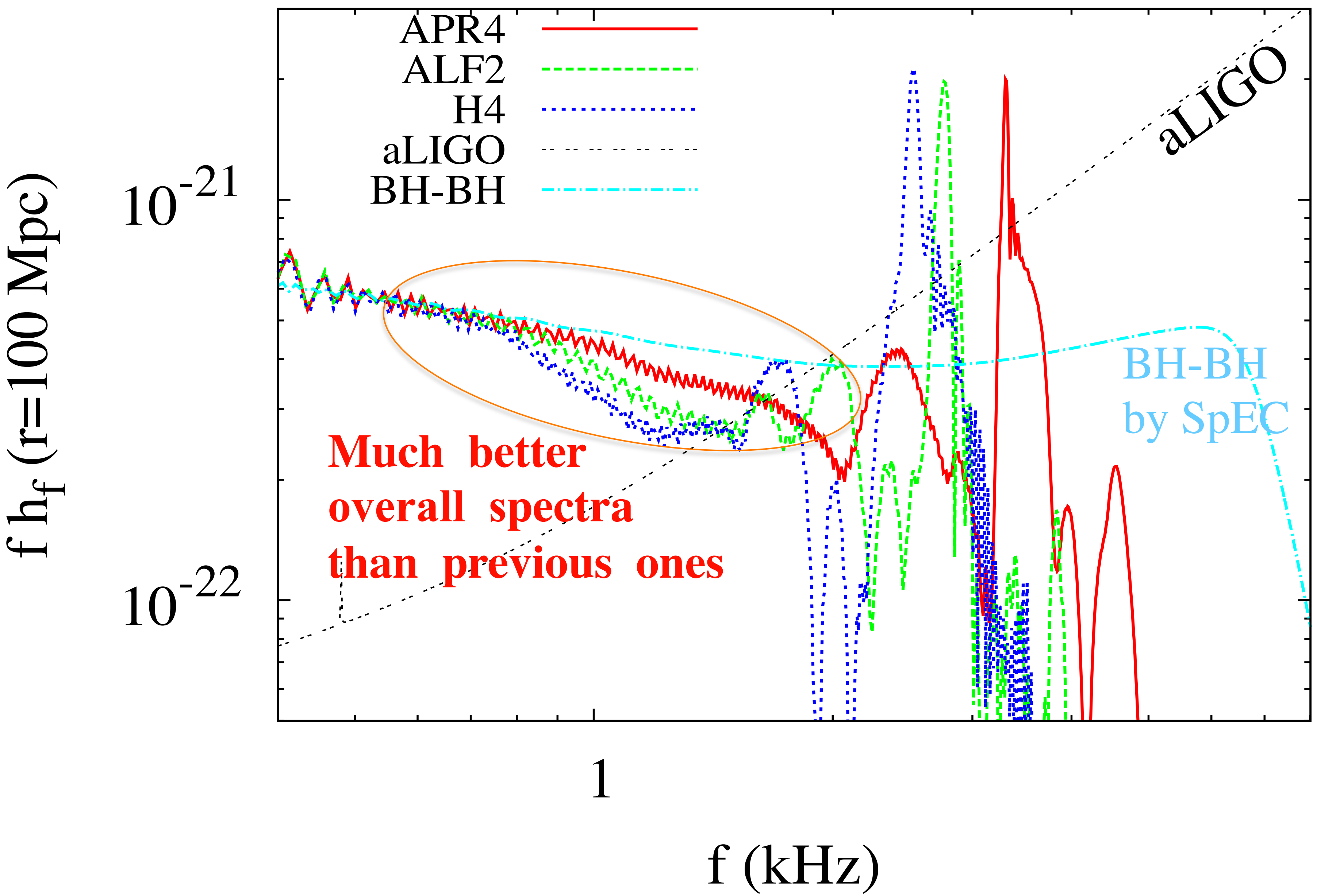

Extrapolated
EOB
1000
500
f (Hz)
0.03
0.02
0.01
0
|1−Δf/f|
EOB is promising but need
improvement for last orbits
0
10
20
30
40
50
60
t_{ret} (ms)

These data will be used for data analysis simulation (Talk by John)



Many simulations with a variety of tabulated EOS are ongoing.

Overall spectrum



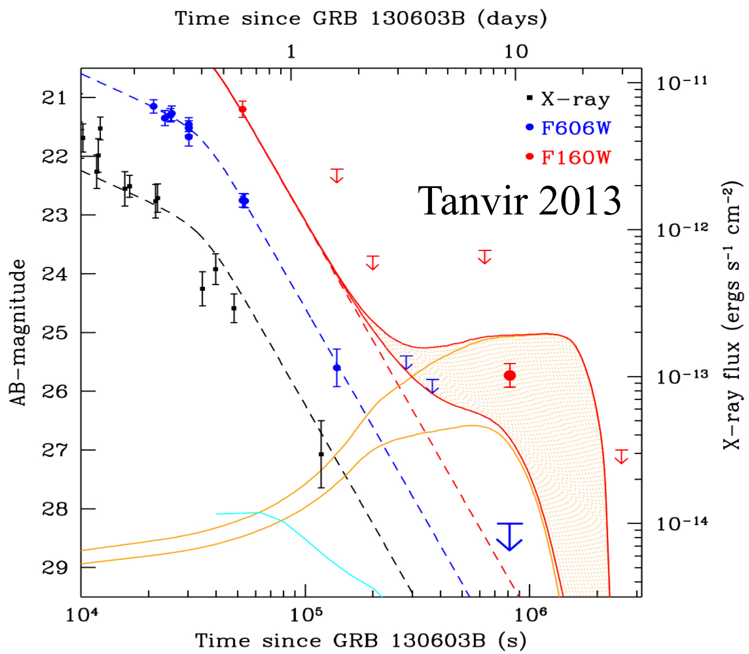
2A Dynamical mass ejection

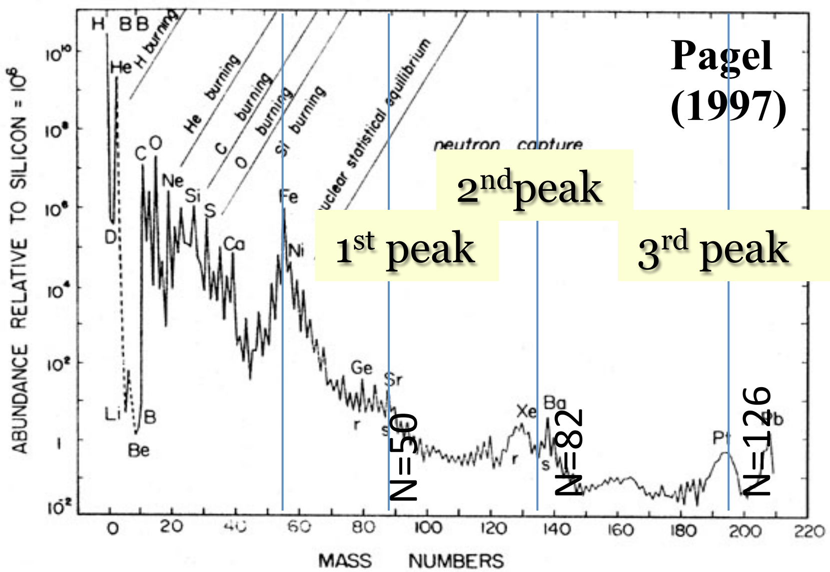
- **WHY important ?**

➢ That could shine and be an EM counterpart of GW source (radioactively-powered nova, radio flare, …)

➢ That could be main source of r-process elements

New topics in numerical relativity !





Dynamical mass ejection mechanism

2 major effects drive ejection

1) **Strong shock at the merger** → enhanced thermal pressure ejects material (like supernova)

2) **Tidal torque by *non-axisymmetric merger remnant*** → Give angular momentum to the material in the envelope, subsequently ejected.

❖ Note that other effects like magnetic or viscous or neutrino wind could play a role (e.g., talks by Kiuchi, Just, …)

Mass ejection at merger

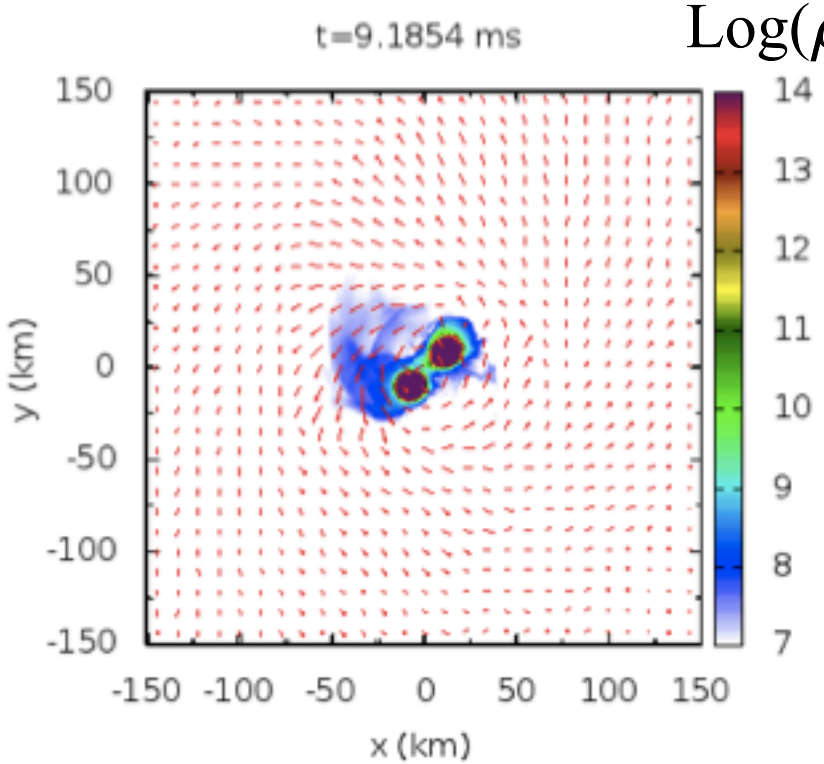
Model : $1.2M_{sun} – 1.5M_{sun}$, EOS=APR4, R ~11 km

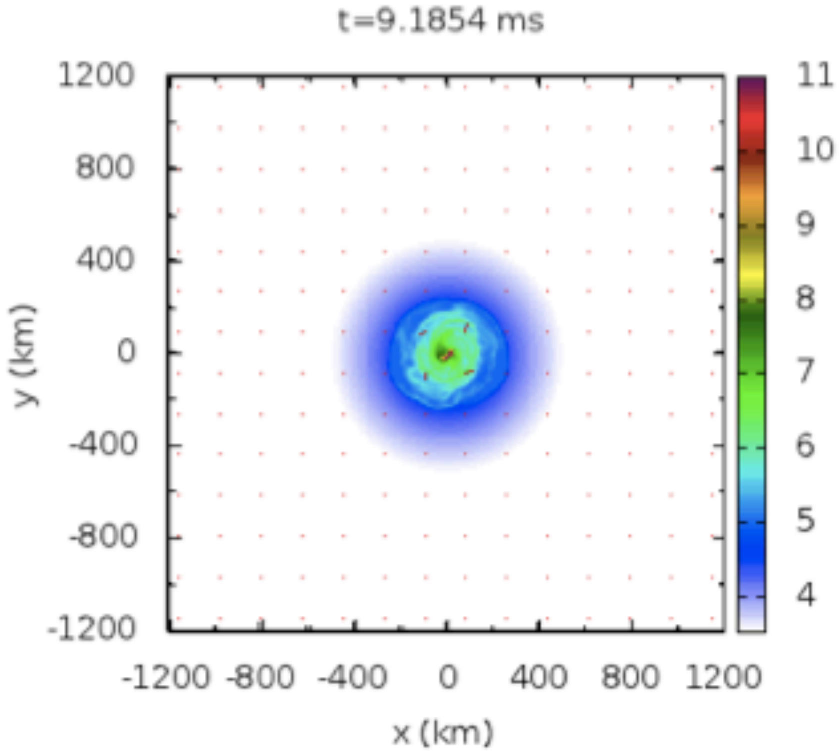
Equatorial plane

300 km x 300 km

Log(ρ g/cc)

2400 km x 2400 km





Hotokezaka + PRD 2013

Mass ejection at merger

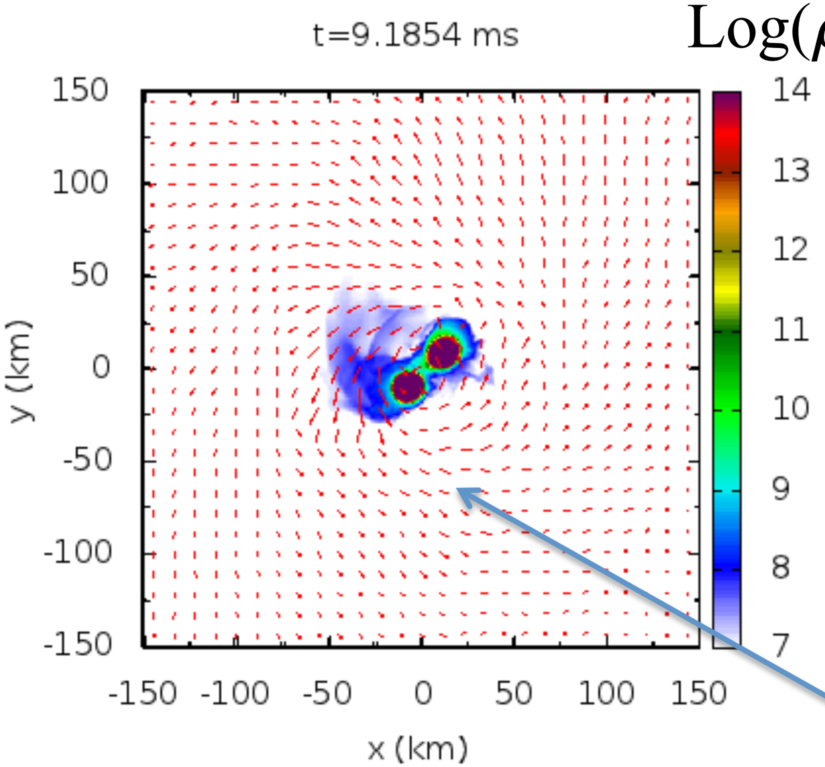
Model : $1.2M_{sun} – 1.5M_{sun}$, EOS=APR4, R ~11 km

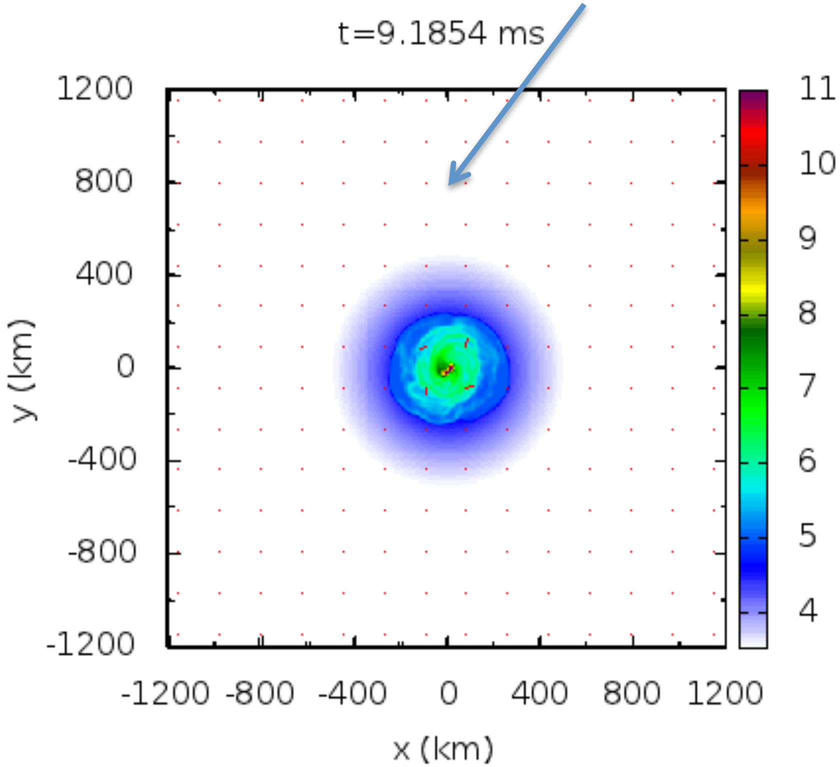
Equatorial plane

300 ∗ 300 km

Log(ρ g/cc)

Head speed $v \sim 0.8c$





Tidal torque plays an important role

Ejecta mass ~ $0.01M_{sun}$, $v \sim 0.2c$ in average

Mass ejection on the meridian plane

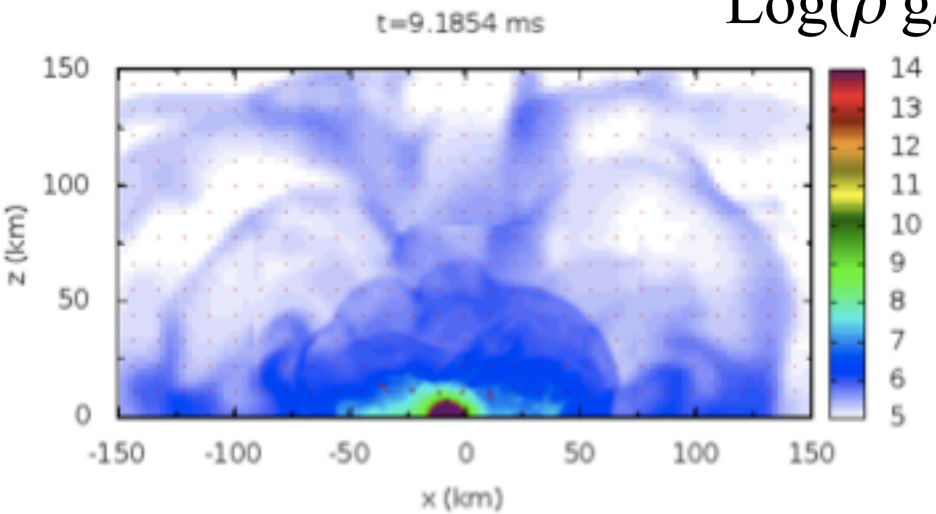
(*x*-*z* plane)

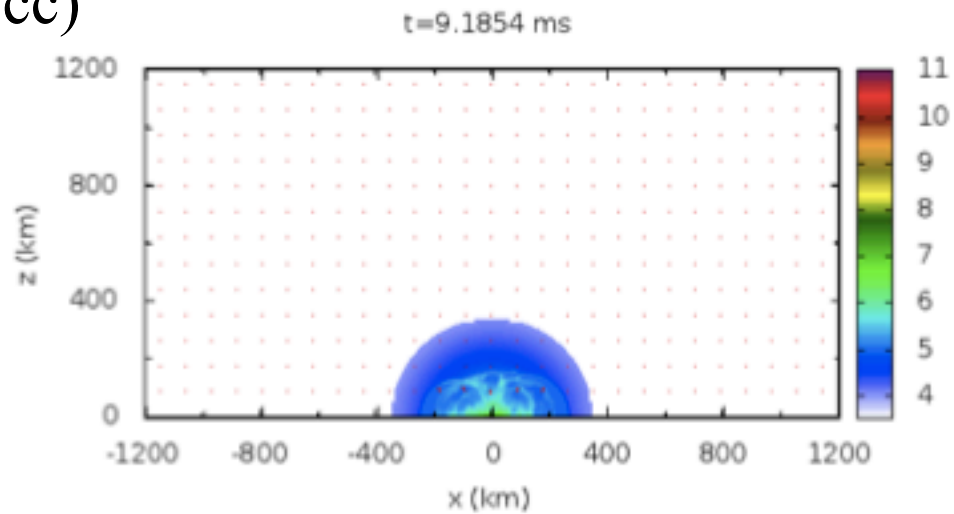
Model : $1.2M_{sun} - 1.5M_{sun}$, EOS=APR4, R ~11 km

300 km x 150 km

2400 km x 1200 km

Log(ρ g/cc)





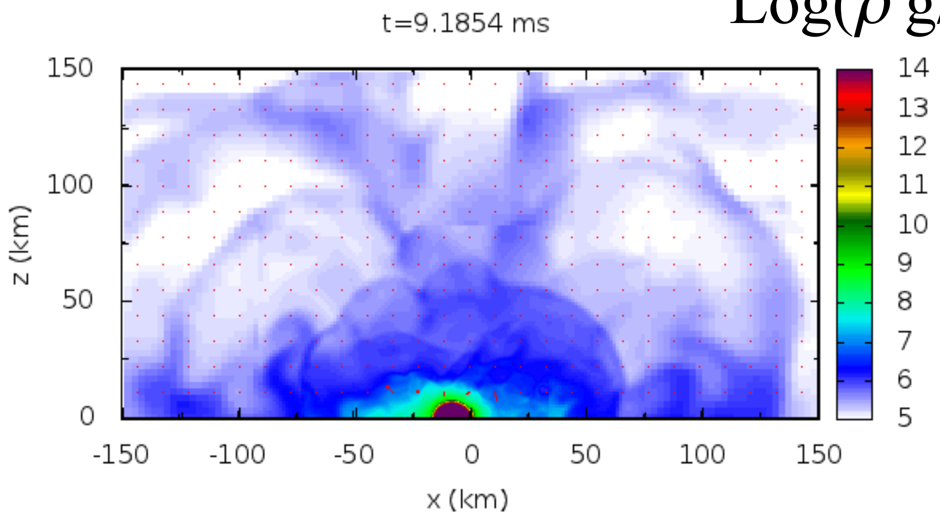
Mass ejection on the meridian plane

(x-z plane)

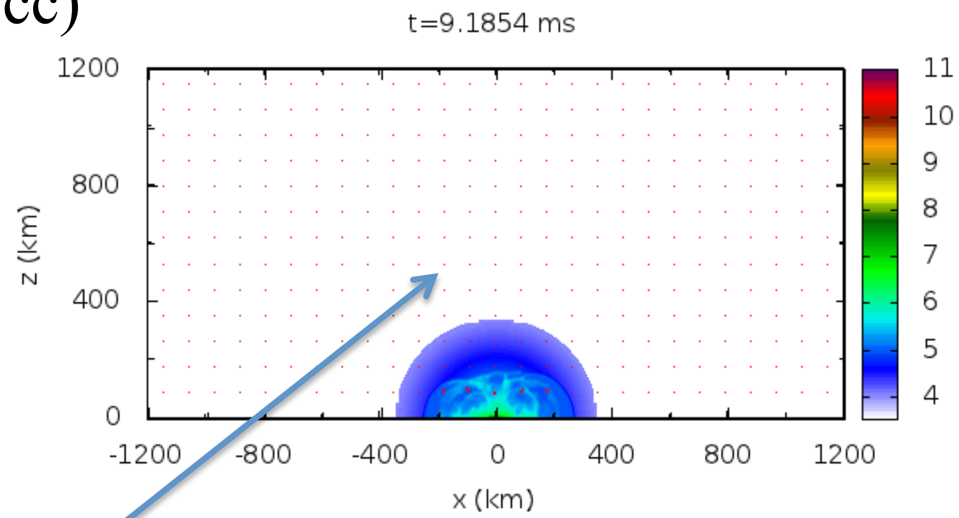
Model : 1.2M_{sun} – 1.5M_{sun}, EOS=APR4, R ~11 km

300 ∗ 150 km

Log(ρ g/cc)



2400 ∗ 1200 km



Ejecta is quasi-spherical:

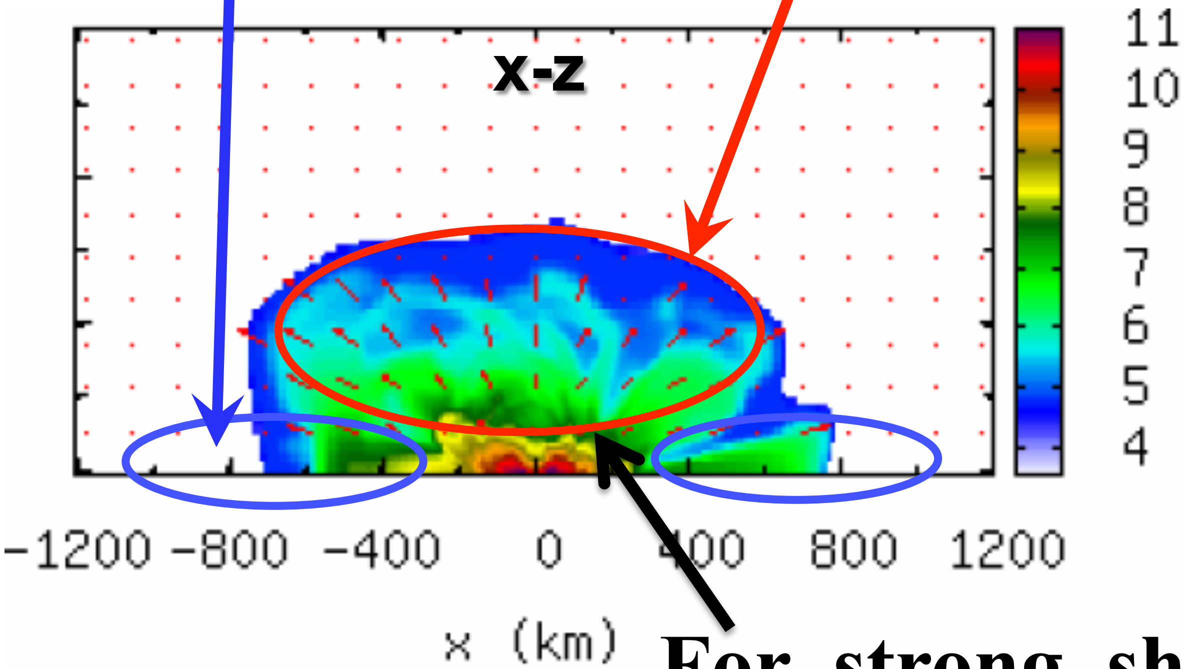
Shock heating plays a key role.

Dynamical ejection mechanism

Two components

- Tidal component
- Low-temperature

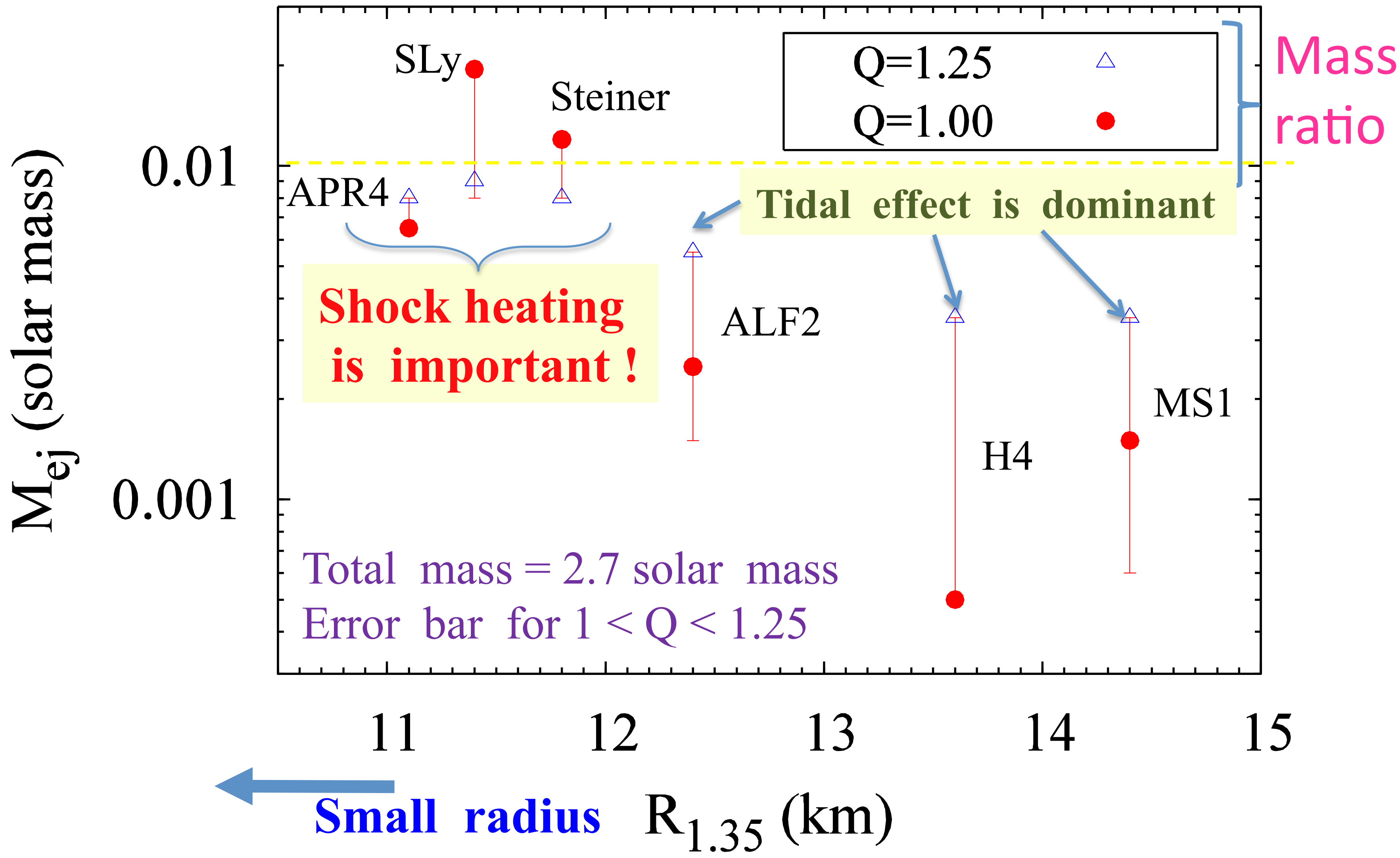
- Shock-heated component
- High-temerature



For strong shock, GR gravity is crucial

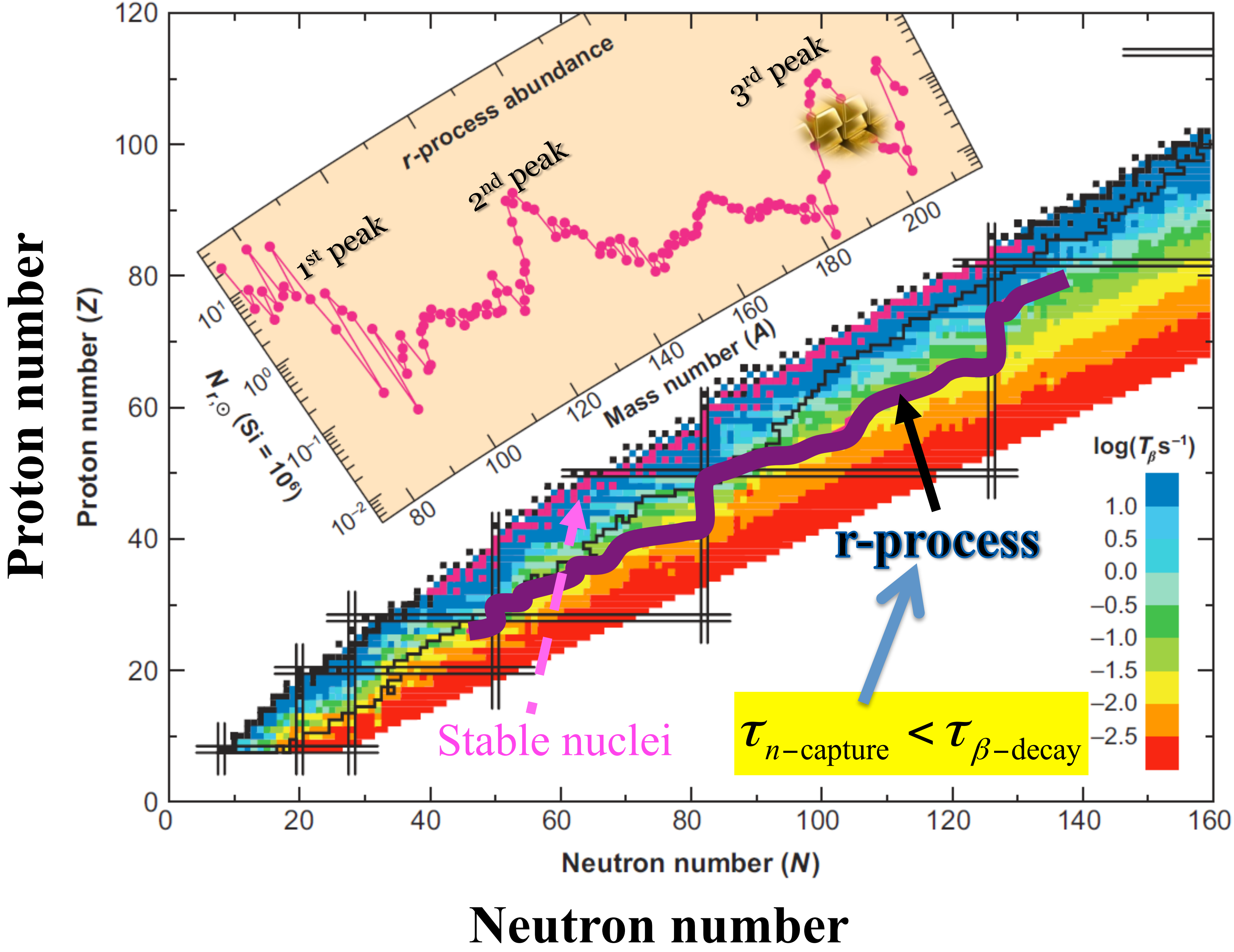
Amount of ejecta depends strongly on EOS

Soft EOS → strong gravity → high-mass ejection



Hotokezaka + PRD 2013

(See also Bauswein+ 2013)


r-process abundance
1st peak
2nd peak
3rd peak
Mass number (A)
$N_{r,\odot}$ (Si = 10^6)
Proton number (Z)
Neutron number (N)
Proton number
Neutron number
Stable nuclei
r-process
$\tau_{n-\text{capture}} < \tau_{\beta-\text{decay}}$
log(T_β s^{-1})

Galactic r-process elements

- Numerical-relativity simulations show ejected mass per event of NS-NS could be ~0.001-0.01 M_{sun}
- Total amount of observed r-process elements in our galaxy is $\sim 10^4$ solar mass
- Predicted merger rate ~ one every 10^4 yrs or less → total merger events $\sim 10^6$ or less in our Galaxy
- We want mass ejection per event ~ 0.01 M_{sun} → **If other contributions were absent, relatively soft EOS would be necessary**

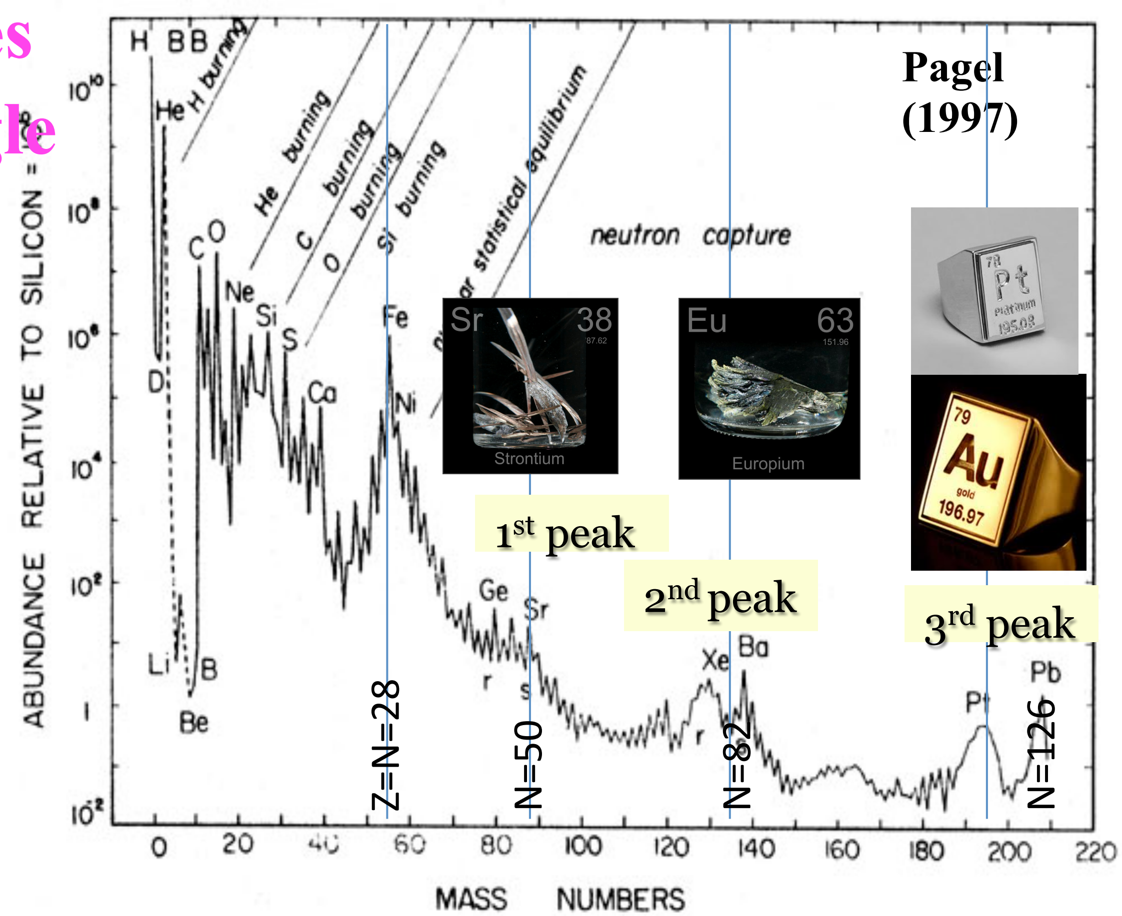
- **IF EOS is stiff (NS has a large radius), we would need other sources or other mechanisms**

r-process nucleosynthesis study of ejecta

(By Sekiguchi & Wanajo +)

Universality of three peaks for heavy elements found in solar system & metal-poor stars

- **Universality indicates the presence of single main origin**
- **Question:**
  Could NS-binary merger reproduce abundance pattern (all three peaks) ?

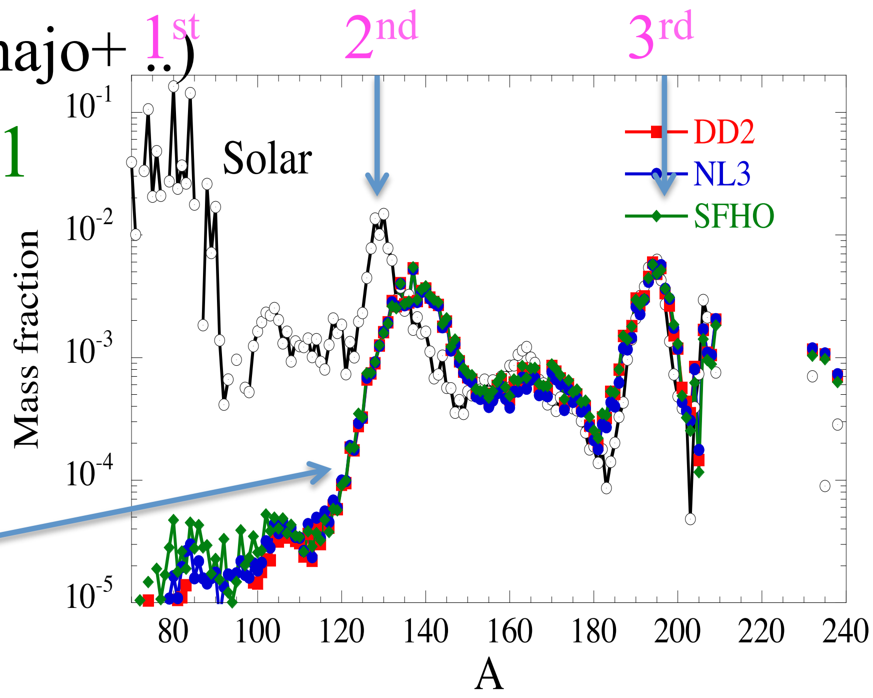


Key quantity for producing heavy elements:
electron fraction per baryon: $Y_e=[p]/([n]+[p])$

E.g., Korobkin+ (2012)

- If high $Y_e > 0.45$ = neutron less-rich
  → 3rd peak is not well reproduced
  (e.g., CCSN, Roberts, Janka+, Wanajo+ ..)

- If too neutron rich, $Y_e \sim 0.1$
  e.g., BH-NS or NS-NS in Newtonian simulation
  → 3rd peak dominant; no/weak 1st & 2nd peaks
  e.g., Goriely et al. 2011



- **Appropriate blending of Y_e is needed: HOW ?**
  → Perform numerical relativity simulation !

GR neutrino-radiation hydrodynamics

(Sekiguchi's GR radiation hydro code)

- Einstein's eq : BSSN + puncture (+ local Z4c)
- Radiation : Leakage + fully covariant truncated moment scheme with M1 closure (gray) for heating

  # pure M1 scheme (gray) works but expensive
- EOS : SFHo, IUFSU, DD2, TMA, TM1
- Grid size : 580*580*290*9 level (fixed mesh refinement) with Δx=150—160 m for the finest domain
- CPU time : 500-700k node-hours by K-computer with ~7000 cores (864 nodes)
- Binary mass : 1.30-1.30, 1.35-1.35, 1.30-1.40, 1.25-1.45, 1.40-1.40 (ongoing)

Variety of EOS table (we appreciate Hempel)

14.5km – **TM1 (Shen EOS)**

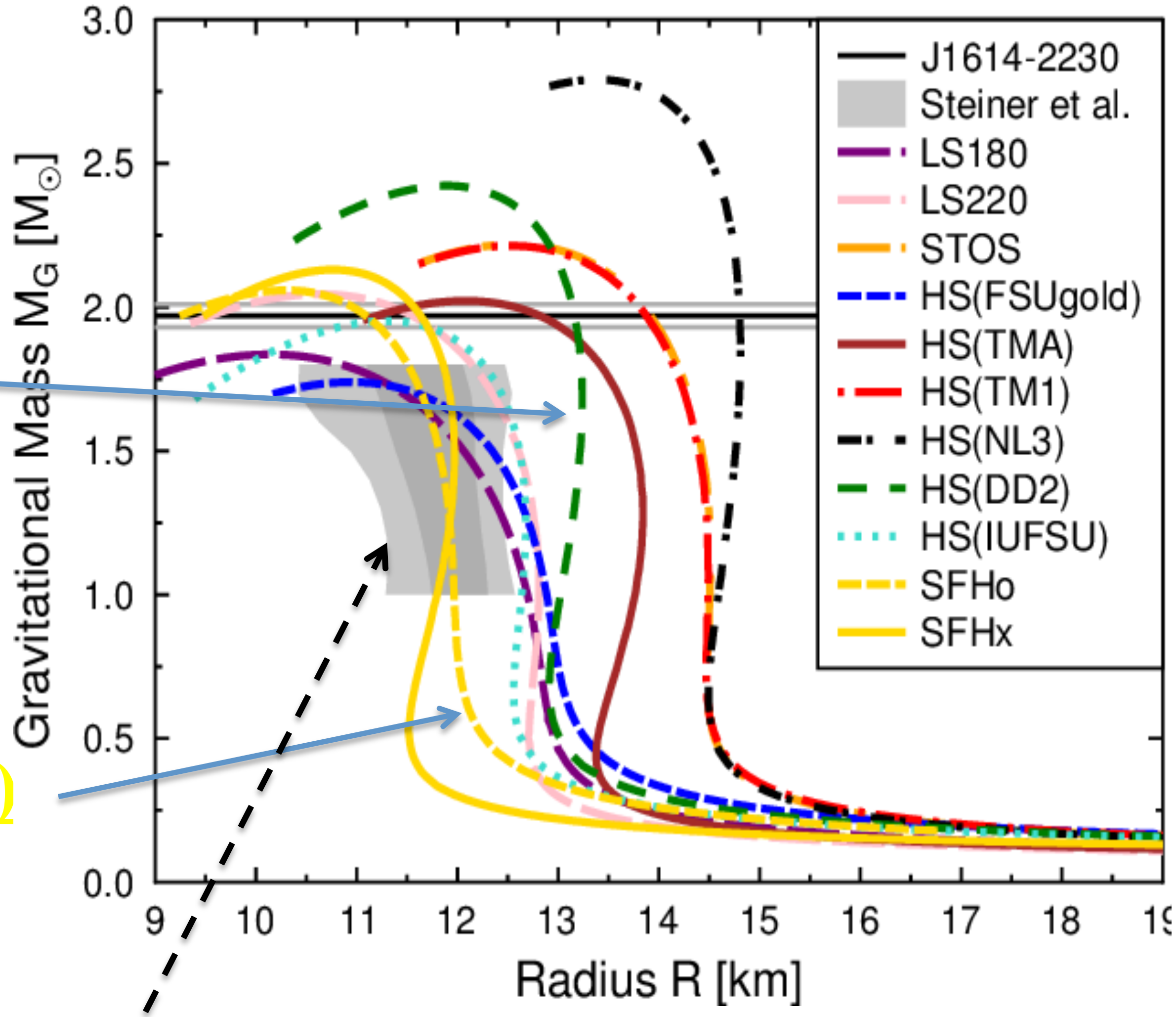
- **TMA**

13.2km – **DD2**

- **IUFSU**

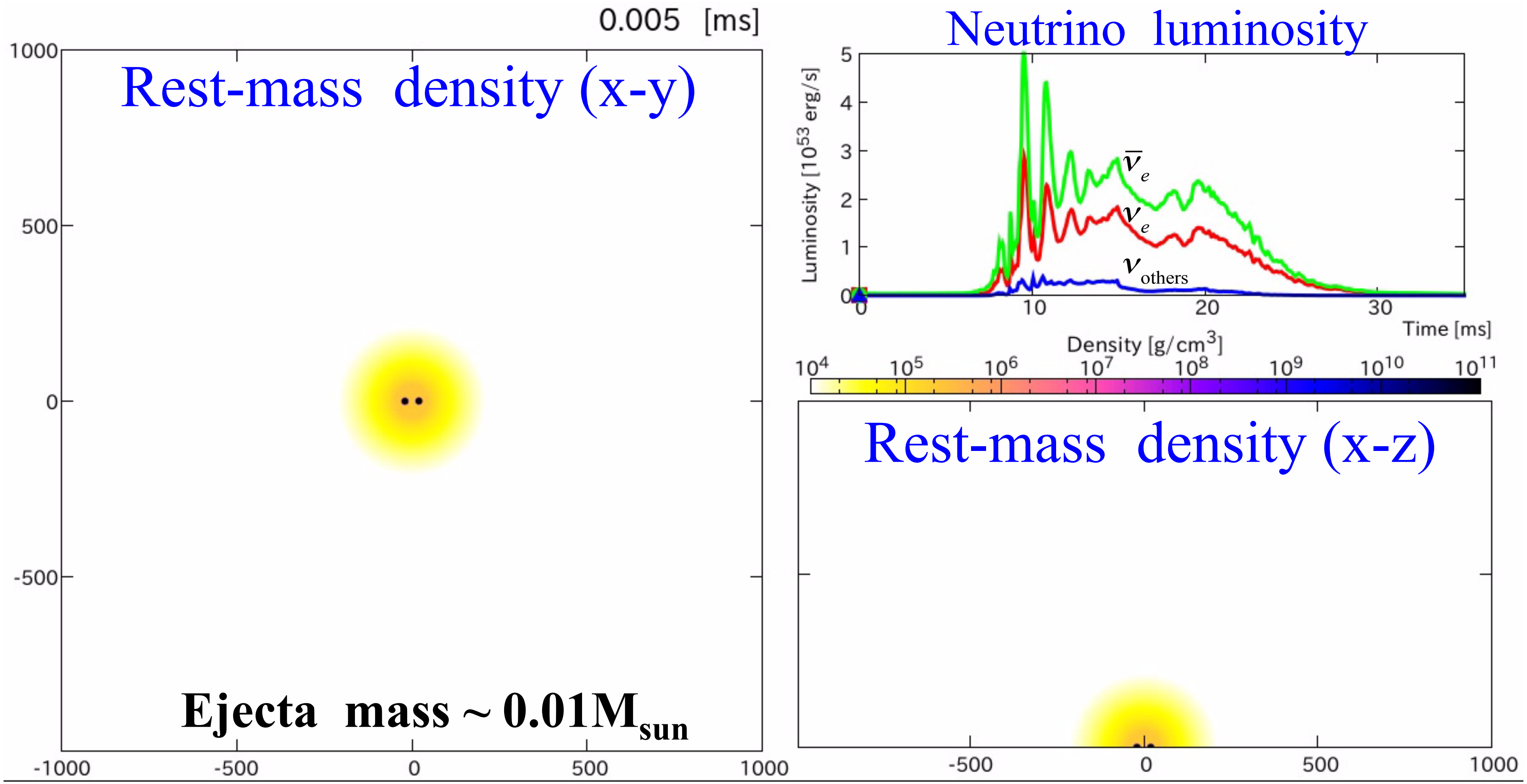
11.8km – **SFHo (Steiner)**

Smaller radius



Lattimer's recommended region

SFHo (R~11.9 km): 1.35-1.35 M_{sun} ρ

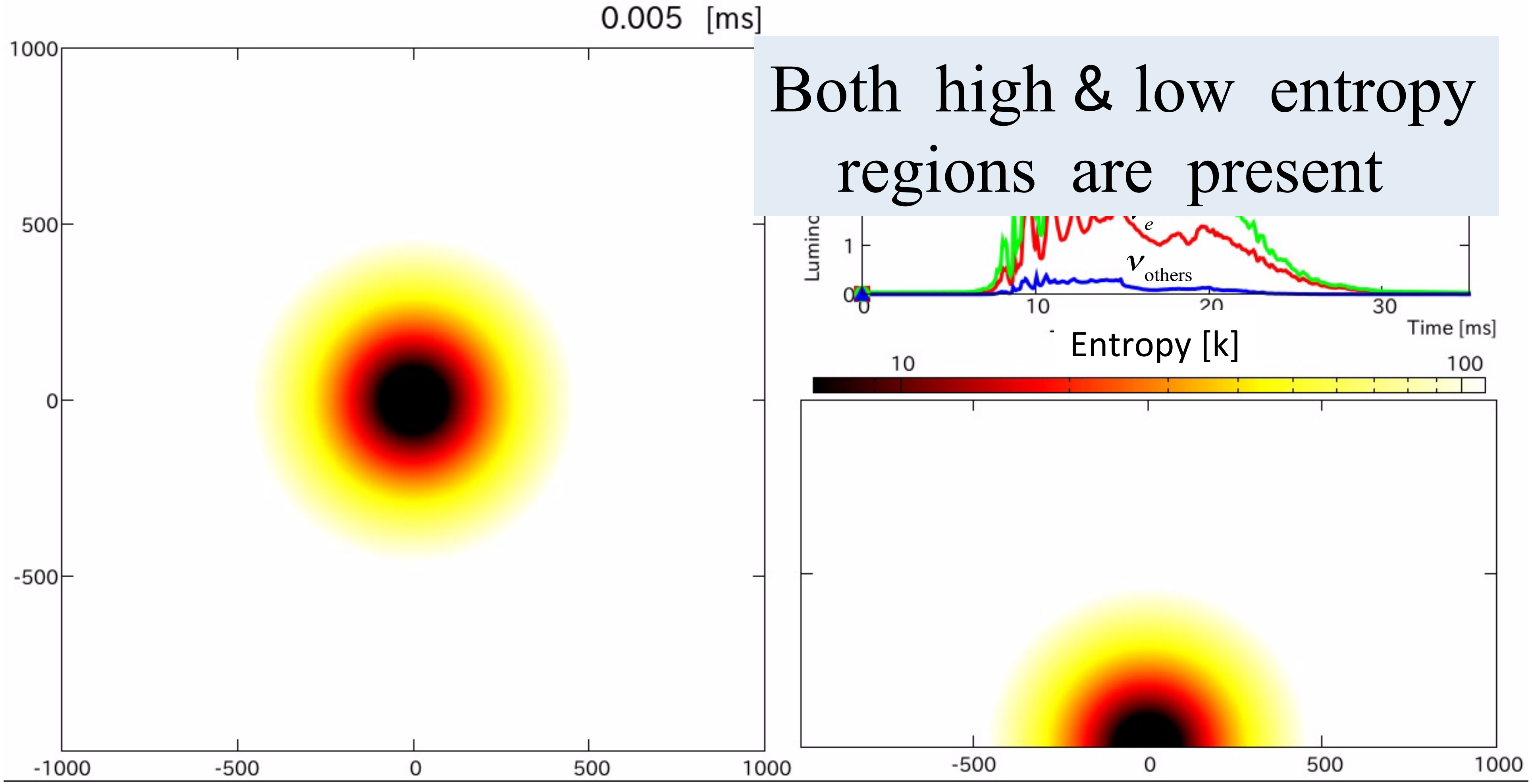


Sekiguchi et al. (2015)

SFHo (R~11.9 km): 1.35-1.35 M_{sun}

S

Specific entropy

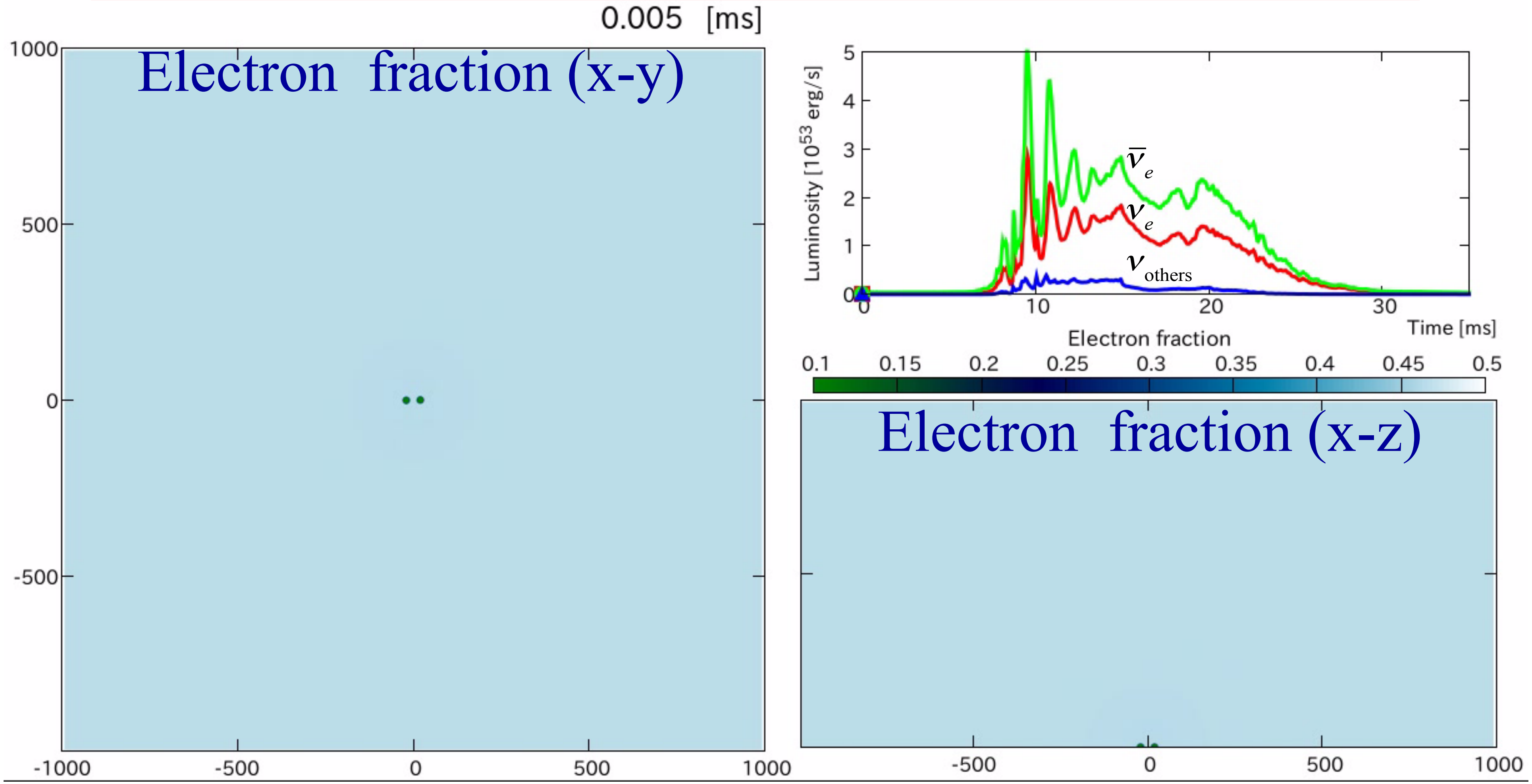


Sekiguchi et al. (2015)

SFHo (R~11.9 km): 1.35-1.35 M_{sun}

Y_e

High temperature $\Rightarrow \gamma\gamma \rightarrow e^- + e^+, \quad n + e^+ \rightarrow p + \bar{\nu}_e$



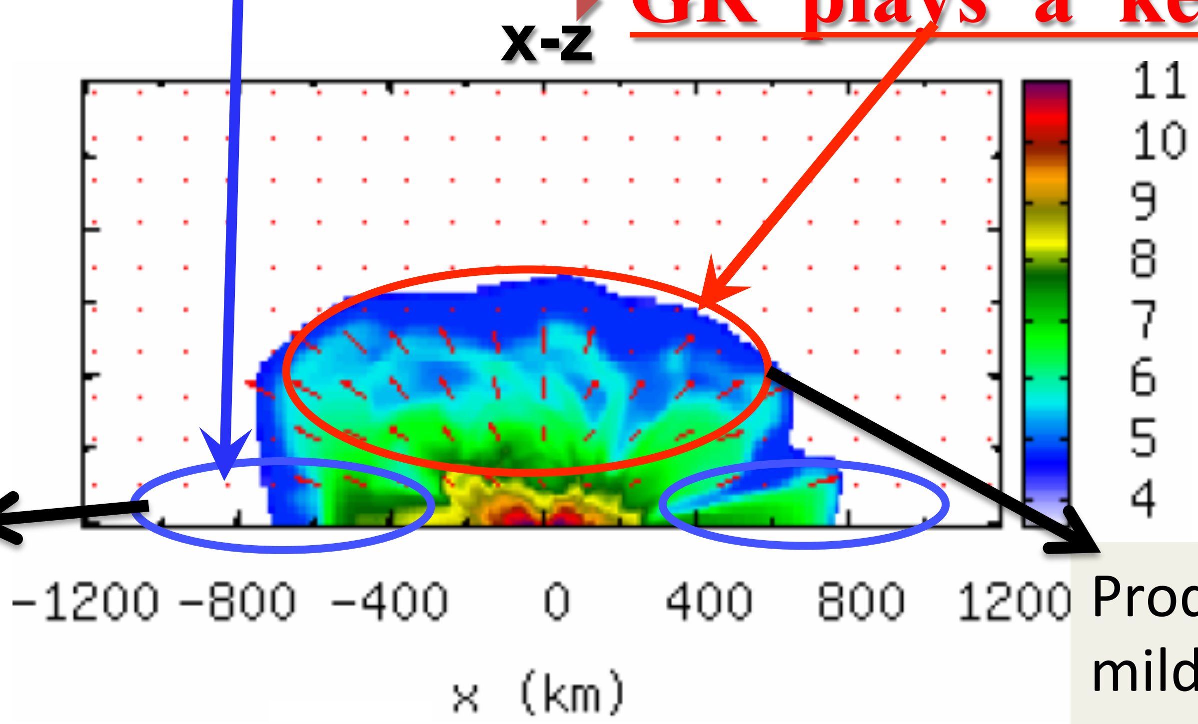
Sekiguchi et al. (2015)

Thermodynamical properties of ejecta

Mass ejection from BNS merger : two components

- Tidal component
- Low-temp, low Ye

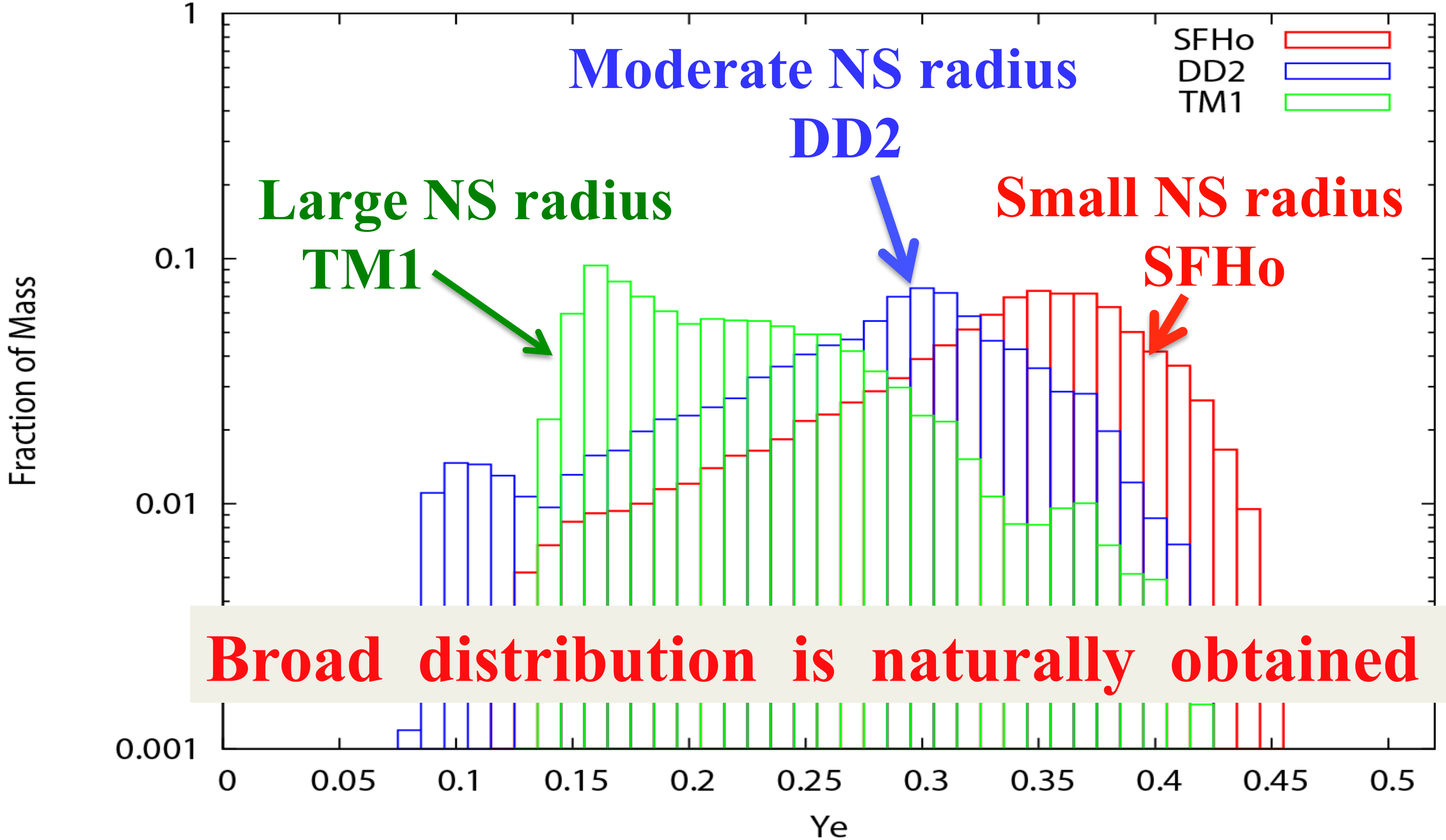
- Shock-heated component
- High-temp, high Ye
- **GR plays a key role**



Produce very heavy elements

Produce mildly heavy elements

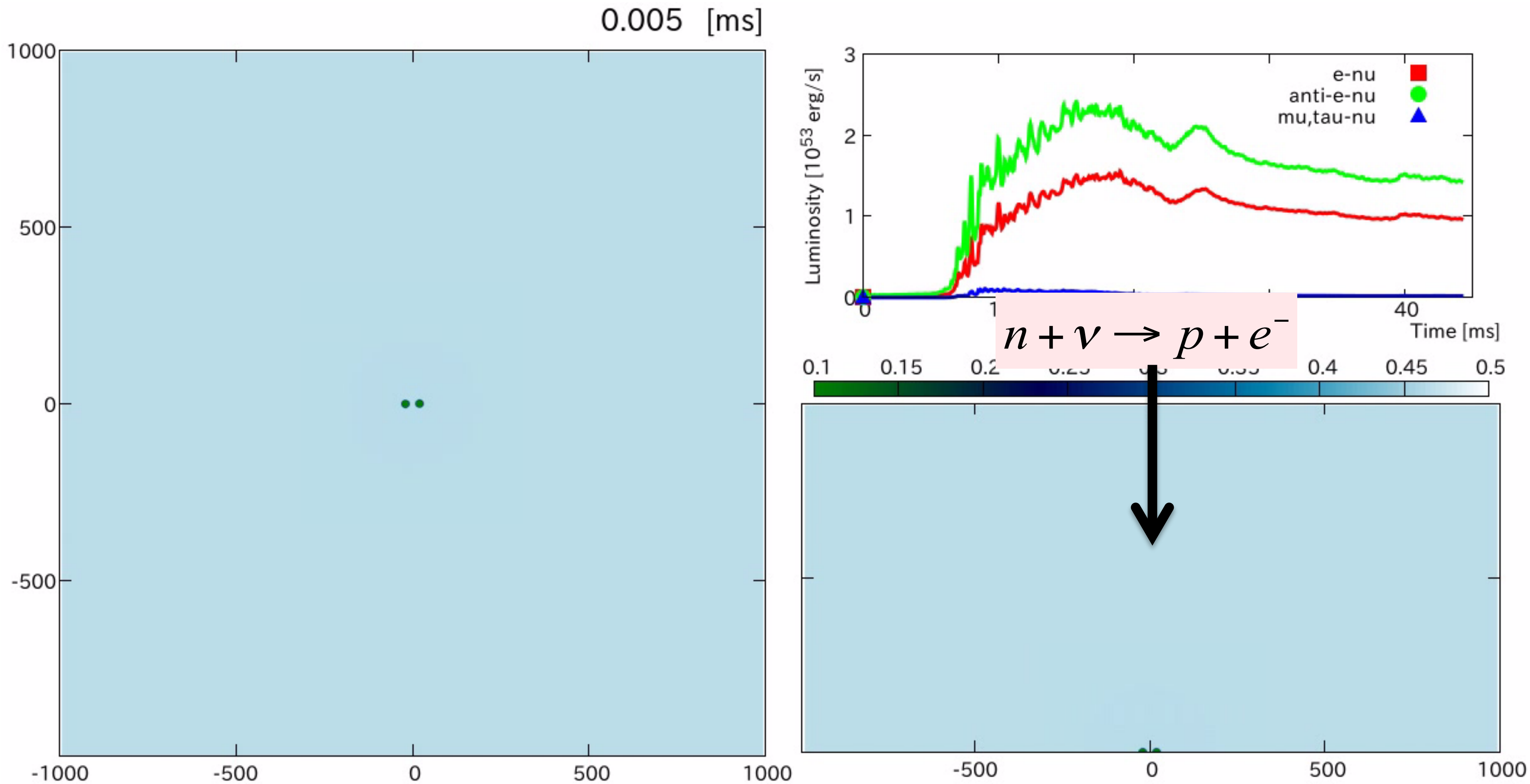
Fraction of mass as a function of Y_e



Sekiguchi et al. (2015)

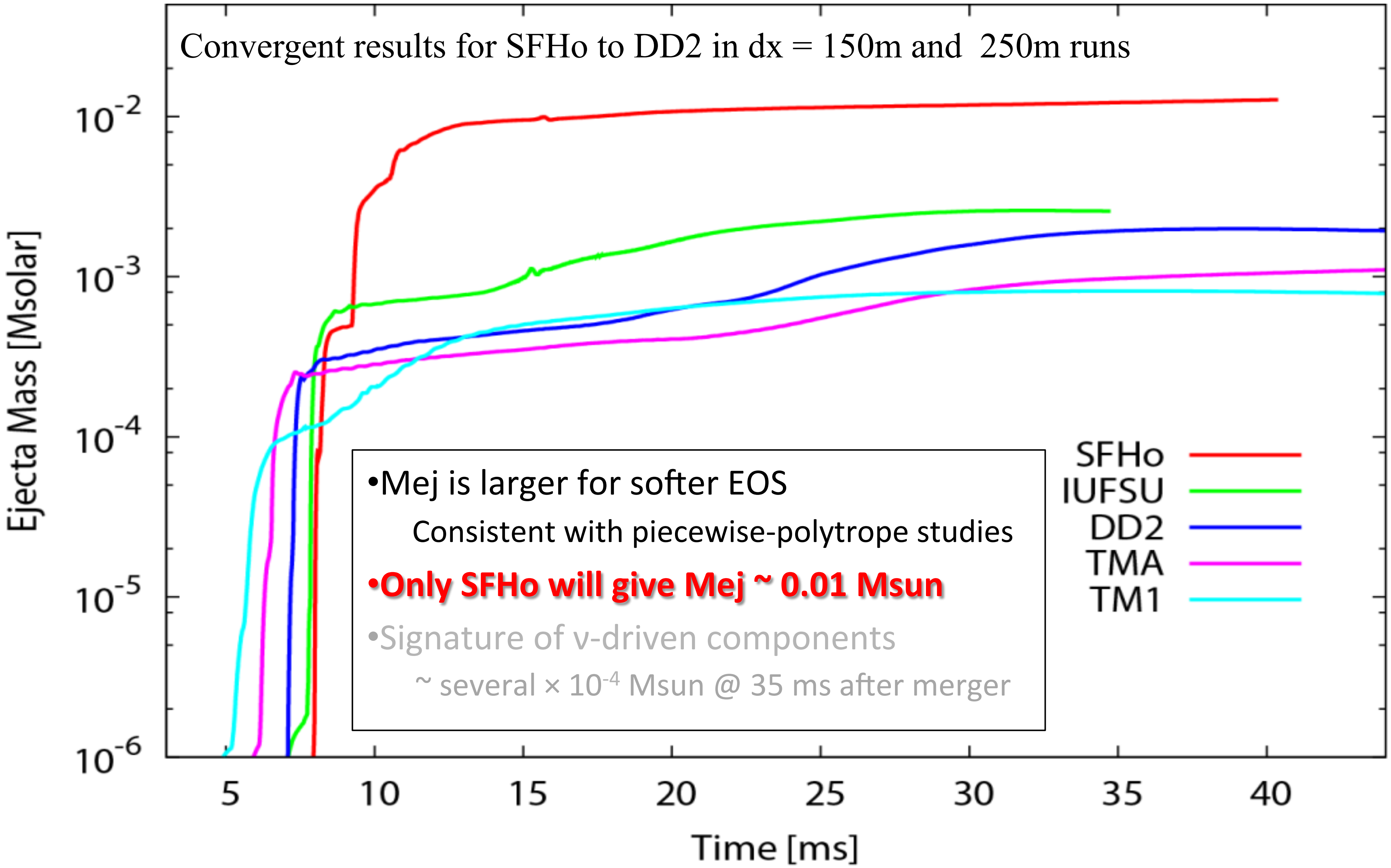
DD2 (R~13.2 km): 1.35-1.35 M_{sun} Y_e

Neutrino heating from remnant MNS is important !



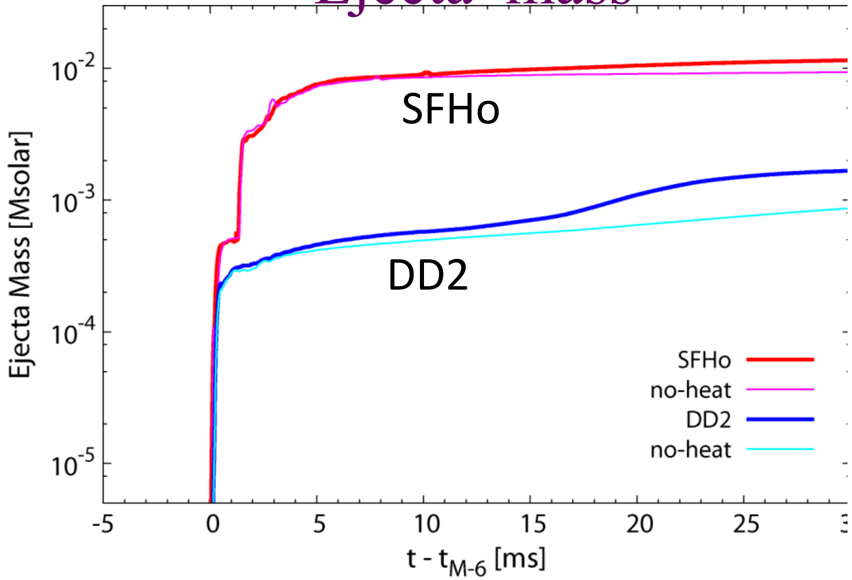
$n + \nu \rightarrow p + e^-$

However, for stiff EOS, ejecta mass is small

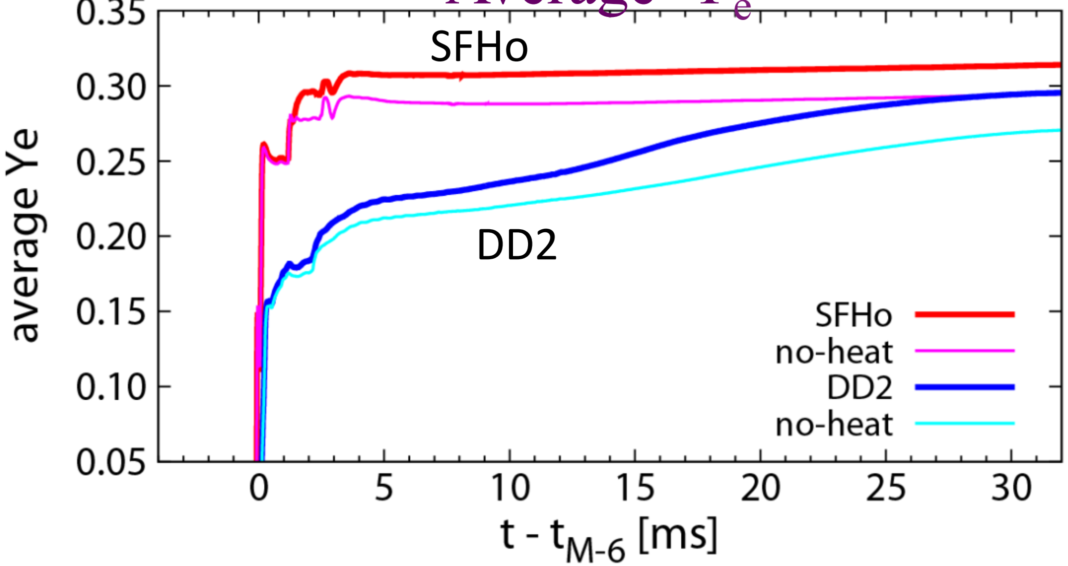


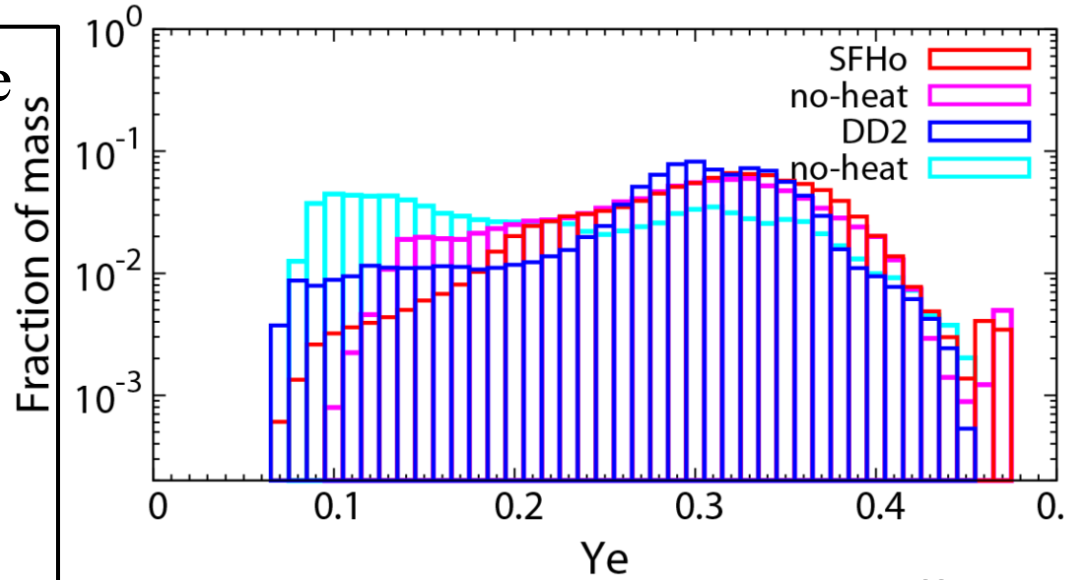
Effects of neutrino heating

Ejecta mass



Average Y_e

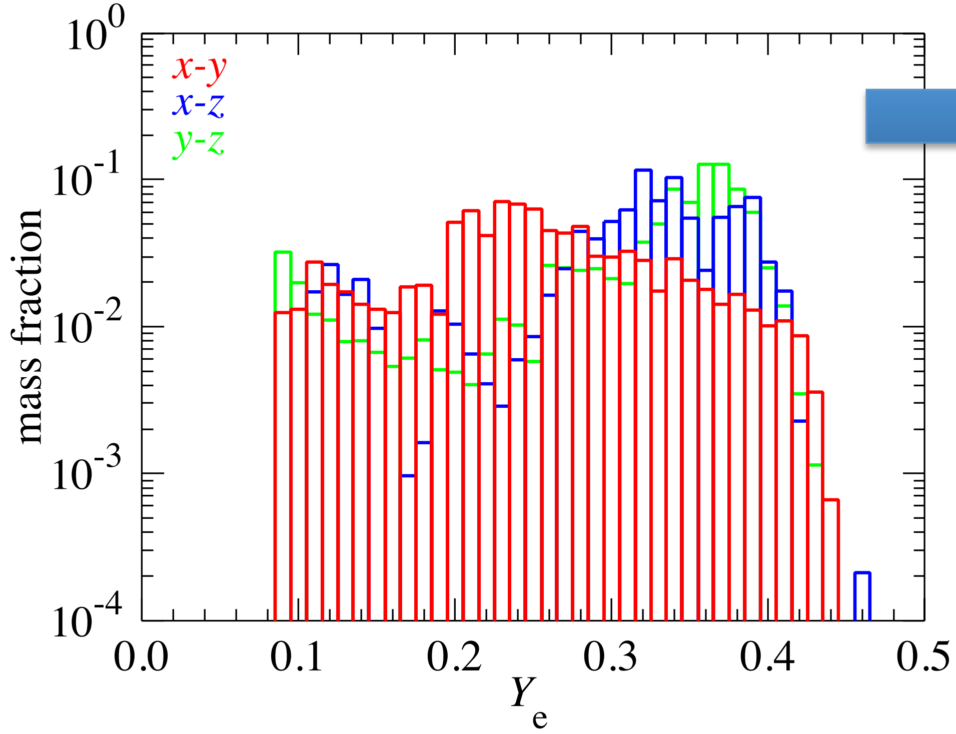


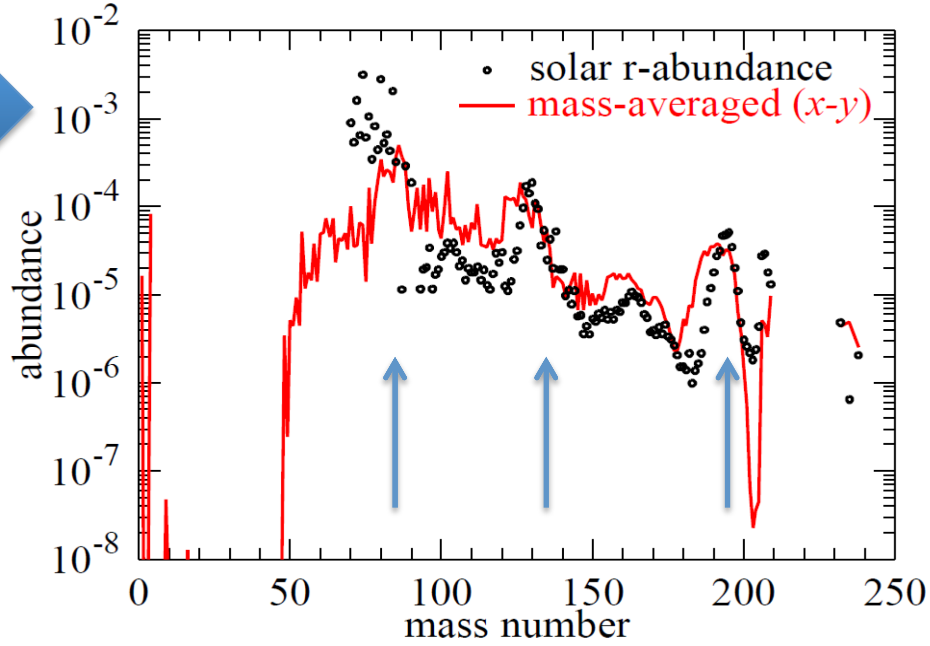


- Amount of ejecta mass can be increased by $\sim 10^{-3}\ M_{sun}$
- Average Y_e can change by 0.02~0.03
- For DD2 & TM1, ejecta mass is O(0.001 solar)
- Viscous heating ??

Our first result

(Wanajo et al. ApJ 2014)





Broad distribution for Y_e could be suitable for reproducing wide abundance pattern

Project is ongoing by Wanajo, Nishimura, Sekiguchi+

Summary

- Gravitational waves from late inspiraling phase of NS-NS is a valuable site for exploring NS EOS → high-resolution numerical-relativity simulations are ongoing for constructing templates (also by Bernuzzi-Nagar +, Haas +, ….)
- Mass ejected in NS-NS merger is ~ 0.001-0.01 solar mass → EM counterparts (tomorrow's talks)
- NS-NS could be r-process nucleosynthesis site: Three peaks could be well reproduced by shock + neutrino heating (Sekiguchi + 2015; works ongoing)
- Next issue: Adding viscous effects to remnant NS and/or BH+torus

Announcement from Yukawa Institute, Kyoto University

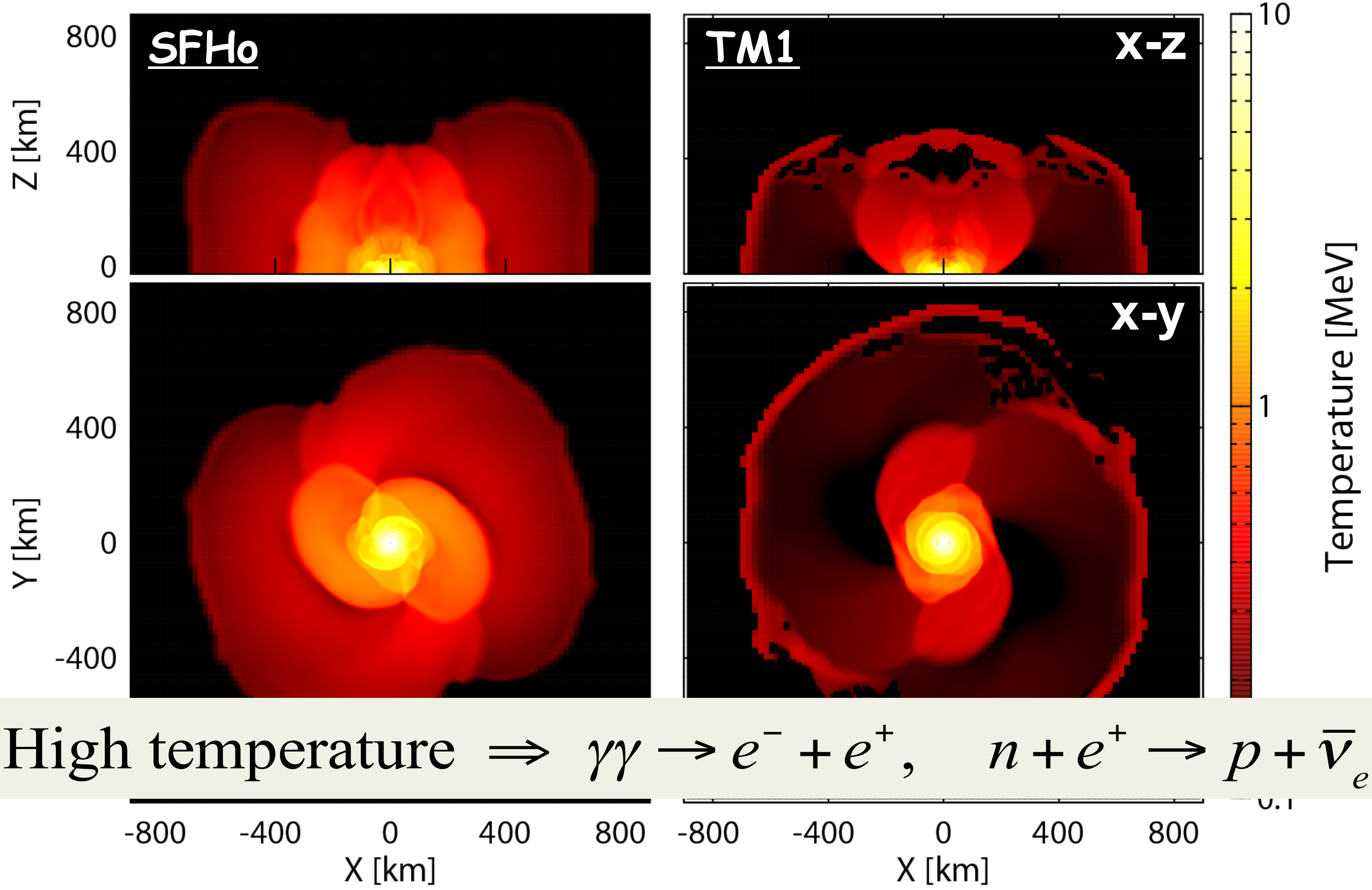
- **Longterm workshop on "Nuclear Physics and Compact Stars 2016 (NPACS 2016)"**
  Oct.17 (Mon.), 2016 -- Nov.18 (Fri.), 2016.

- **In the third week, conference on "Birth, Life, and Death of Neutron Stars and Nuclei (YKIS 2016)" will be held**
  Oct.31 (Mon.), 2016 -- Nov.4 (Fri.), 2016

Ejecta temperature: Depends on EOS

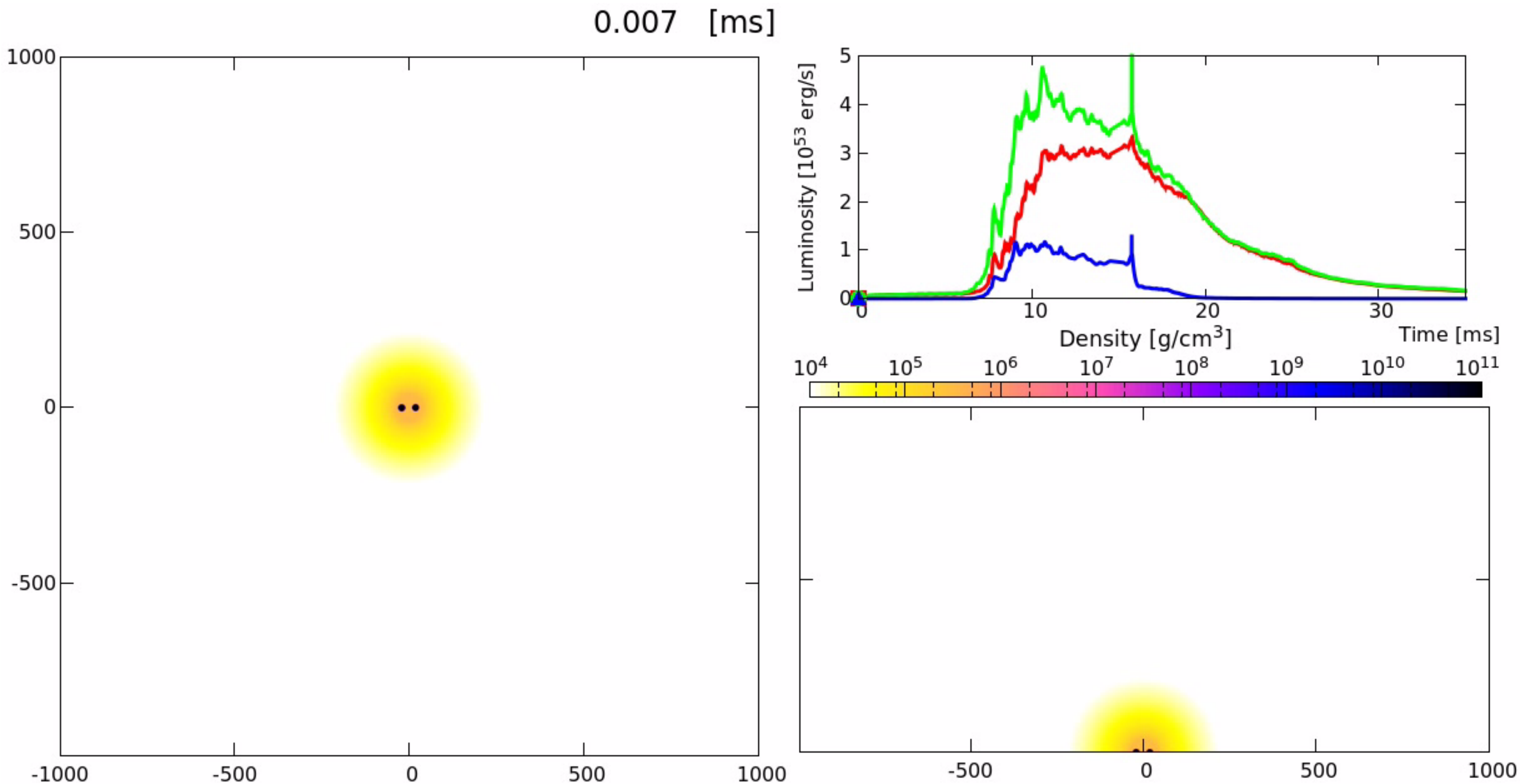
- SFHo EOS: NS=Small radius
- High temperature

- TM1 EOS: NS=Large radius
- Low temperature → n rich

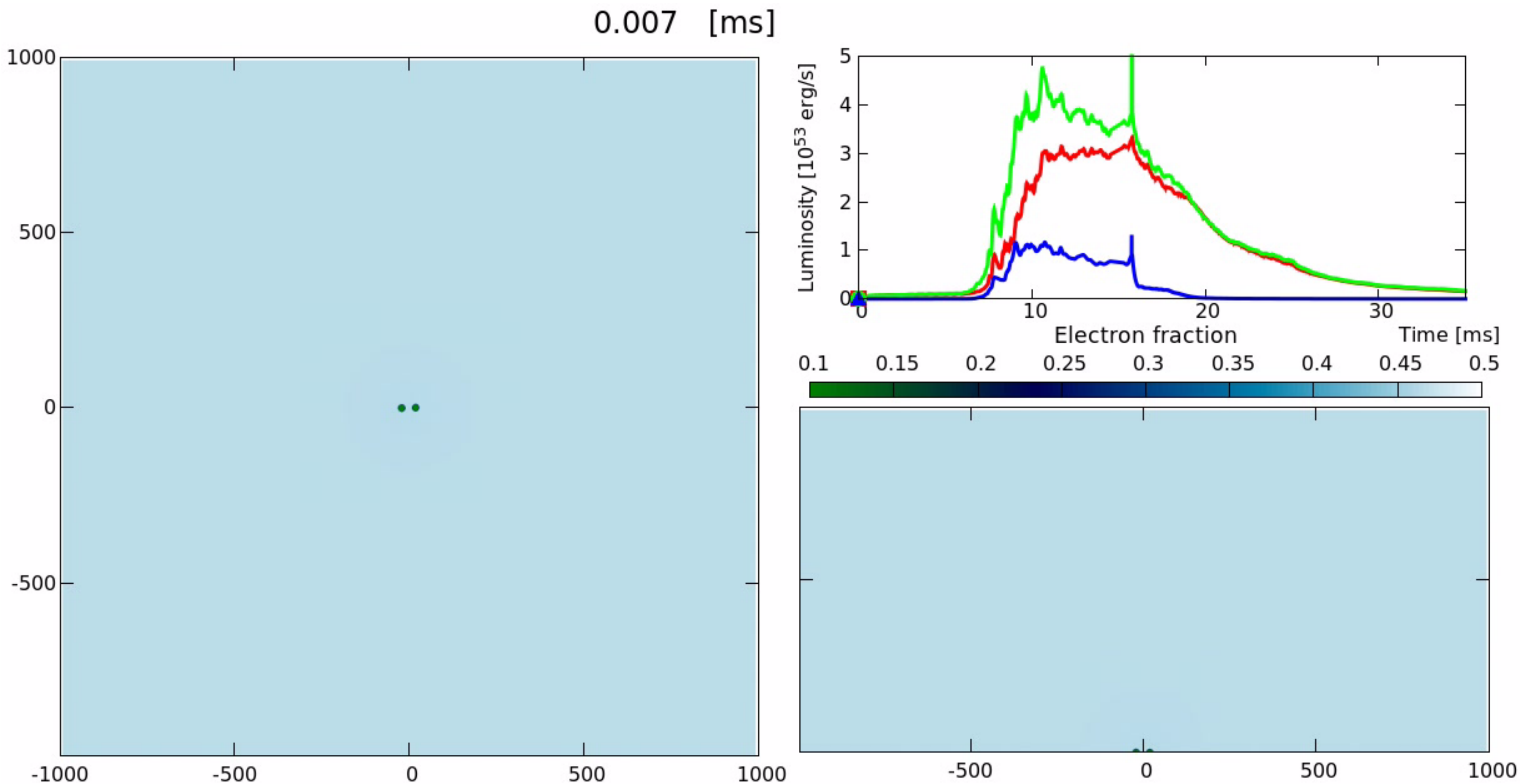


High temperature $\Rightarrow \gamma\gamma \rightarrow e^- + e^+, \quad n + e^+ \rightarrow p + \bar{\nu}_e$

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



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



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

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