Merger of binary neutron stars: Gravitational waves and electromagnetic counterparts

Numerical-relativity study

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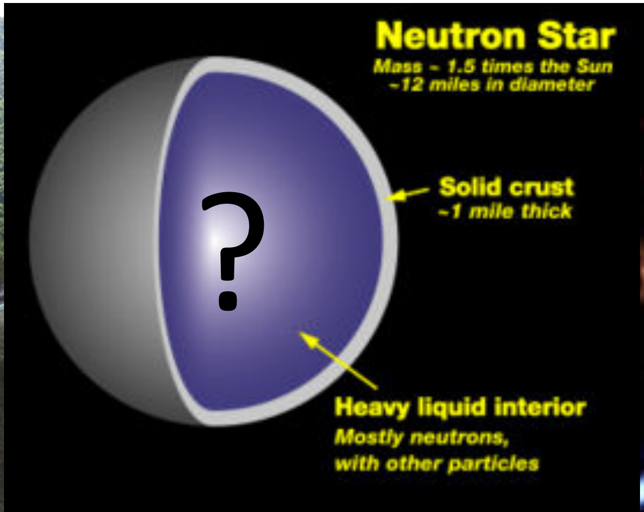
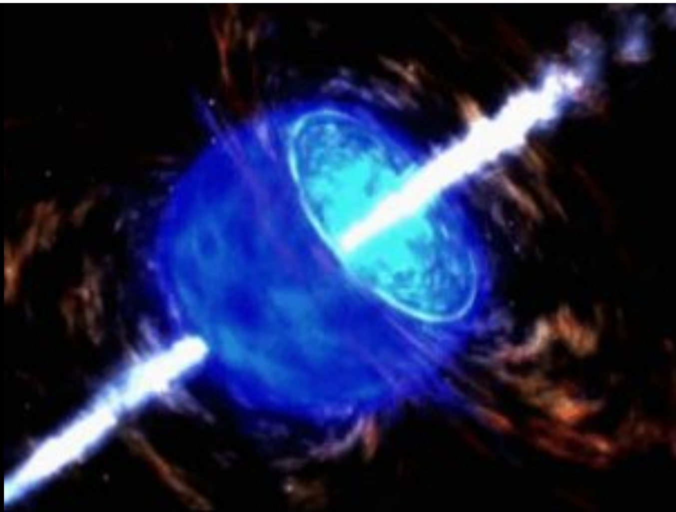
Why NS-NS mergers are important ?

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**





2 Current understanding of NS-NS Mergers by numerical relativity

- Initial condition to be employed ?

Parameters of *compact* NS-NS binaries

	PSR	log B(G)	$P_{\rm rot}$ (ms)	$M(M_{\rm sun})$	$T_{\rm Mag}$	$T_{\rm GW}$
1.	B1913+16	10.4	59.0	1.441/1.387	1.0	3.0
2.	B1534+12	10.0	37.9	1.333/1.345	2.5	27
3.	B2127+11C	10.7	30.5	1.36/1.35	1.0	2.2
4.	J0737-3039	9.8/12.2	22.7/2770	1.34/1.25	2.0/0.5	0.86
5.	J1756-2251	9.7	28.5	1.34/1.23	4.0	17
6.	J1906+746	(12.2)	(144)	1.29/1.32	(<0.1)	3.1

$*10^8$ yrs

1.23-1.44 $M_{\rm sun}$

Spindown time

Merger time

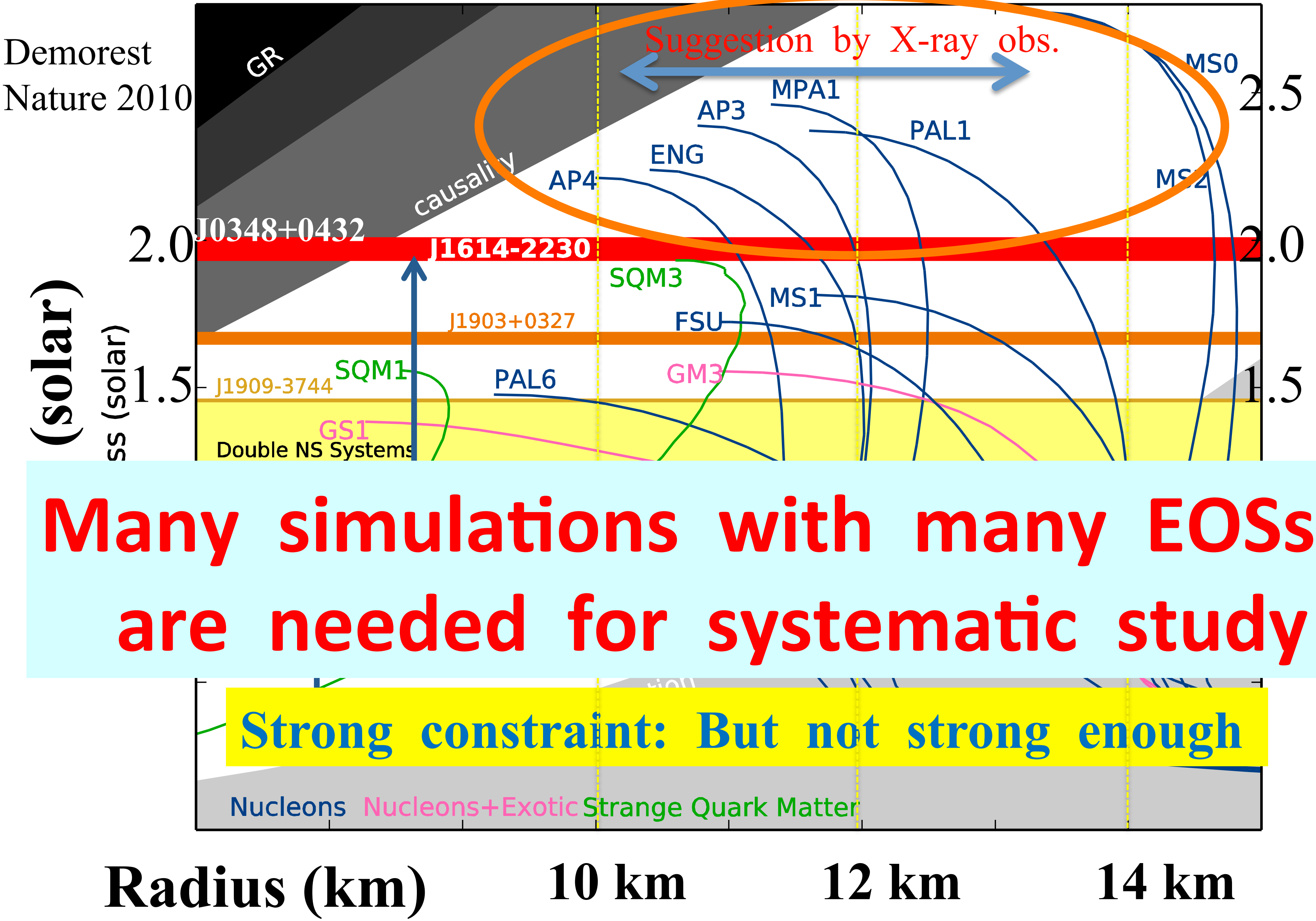
B-field and spin period
of the first NS
(perhaps second NS
observed for J1906+746)

$T_{\rm Mag} \leq T_{\rm GW}$ for many

$\Rightarrow$ Small spin

E.g., Lorimer Living Review

The most crucial uncertainty is EOS



Demorest
Nature 2010

Suggestion by X-ray obs.

Many simulations with many EOSs are needed for systematic study

Strong constraint: But not strong enough

NS-NS mergers:

Initial conditions to be employed

- **Parameters:** Observations of NS-NS suggest

◆ **Mass**: Likely to be in a narrow range
$m = 1.2—1.45\ M_{\rm sun}$

◆ **Spin**: Likely negligible or small :
$P_{\rm rot} > 20$ ms & $T_{\rm Mag} < T_{\rm GW}$ for many cases

◆ B-field: $1^{\rm st}$ NS ~ 10^{10} G, $2^{\rm nd}$ NS ~ 10^{12} G

◆ NS radius (**EOS**) is still uncertain

→**Well-defined problem except for EOS**

For extra gal, metalicity may change this distribution

Expected fate

- **Broadly speaking, there are two fates:**

1. BH is formed promptly after the merger
2. Massive NS is formed at least transiently

- The fate could depend strongly on total mass & EOS employed
- **However, latest observations constrain the EOS & mass of NS-NS certainly**

→ Numerical-relativity shows Fate-2 is the case

Merger of 1.35-1.35M_{sun} NS with four EOSs

APR4: R=11.1km

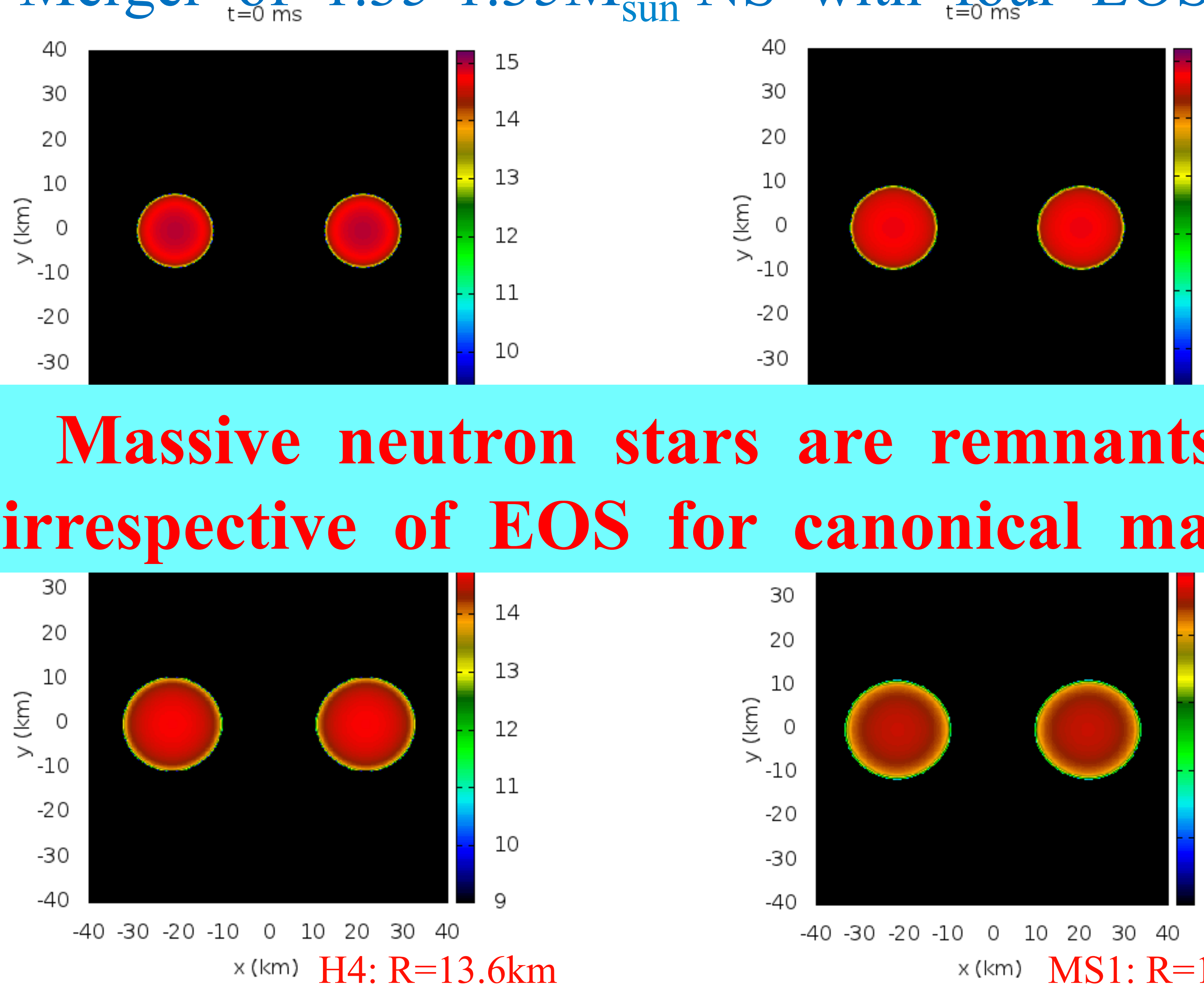
ALF2: R=12.4km

H4: R=13.6km

MS1: R=14.5km

Merger of 1.35-1.35M_{sun} NS with four EOSs

By hotokezaka + 2013



Massive neutron stars are remnants irrespective of EOS for canonical mass

H4: R=13.6km

MS1: R=14.5km

Evolution of remnant

EOS=SLy, Mass=1.35-1.35 M_{sun}

Meridian plane

BH + torus: BH spin ~ 0.6-0.7

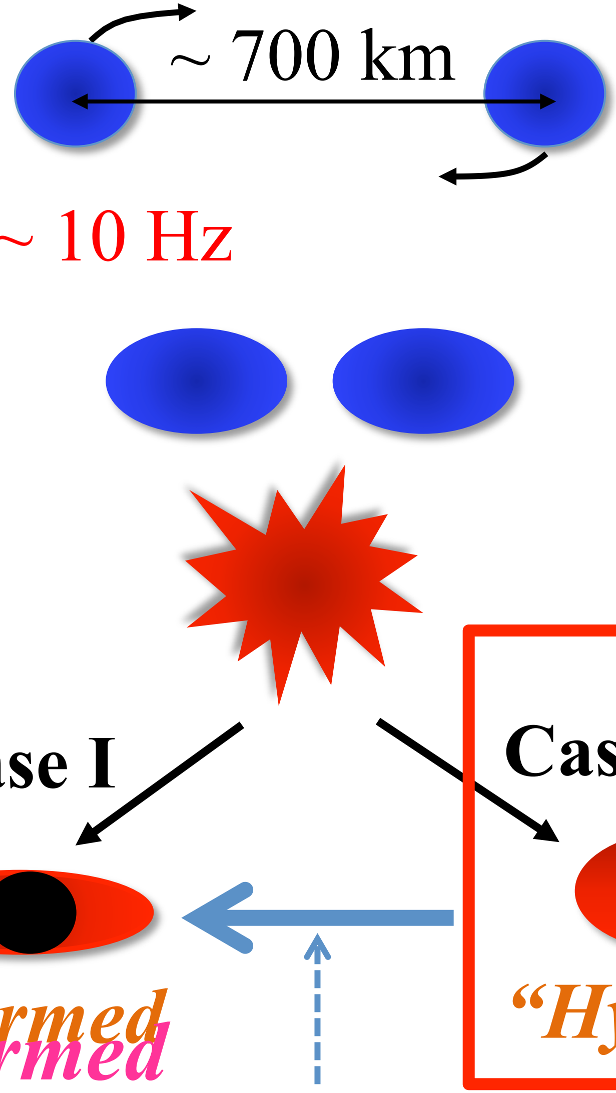
torus-mass ~ 0.05-0.1 M_{sun}

HMNS=Hyper Massive Neutron Star

Last 15 min of NS-NS $(1.35M_{\rm sun}$-$1.35M_{\rm sun})$

Evolve by
GW emission

Last 15 min; $f_{\rm GW} \sim 10$ Hz



GW detectors
will start
detecting GWs

Merger sets in
at $r \sim 30$ km;
$f_{\rm GW} \sim 1$ kHz

Case I

Black hole

Soft EOS

$(a \sim 0.6)$

Black hole is formed

+ torus are formed

Case II

Stiff EOS

"Hypermasive NS"

Angular momentum transport

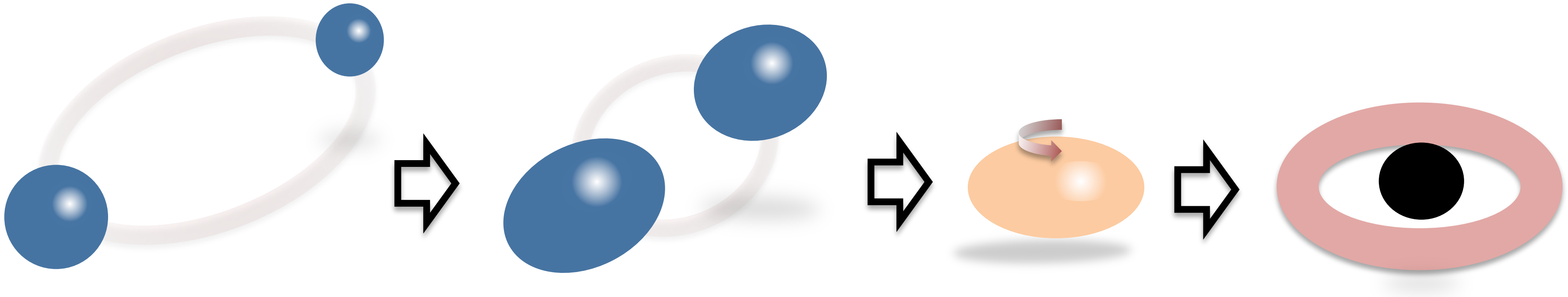
3 Gravitational waves & EOS

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

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

Merger =>
Hypermassive NS

Black hole & torus
& GRB?



Point mass phase
Adiabatic phase

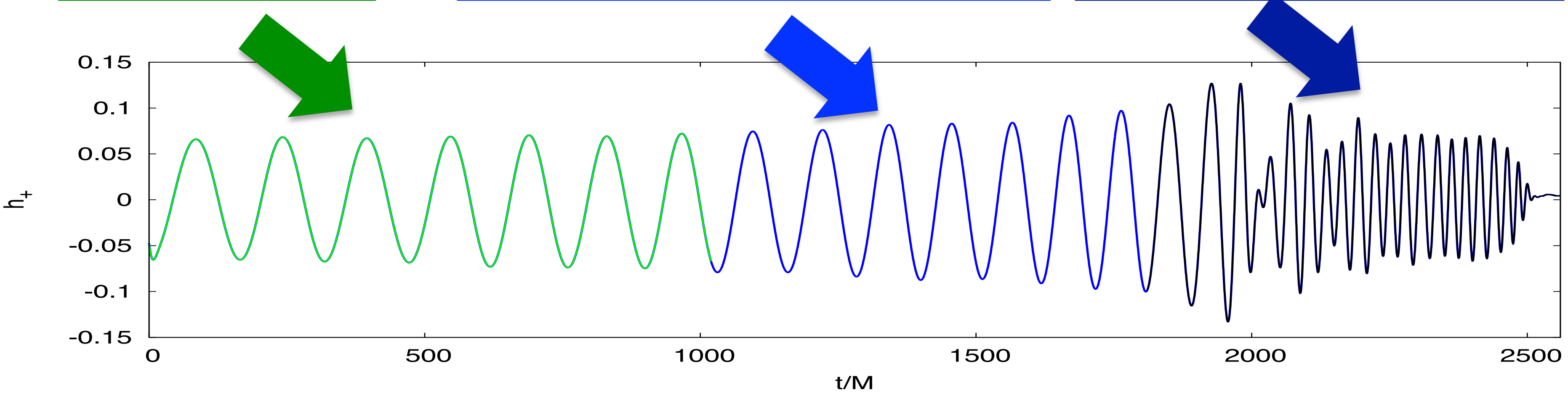
Tidally dominated phase

Dynamical & GR phase

Post-Newton

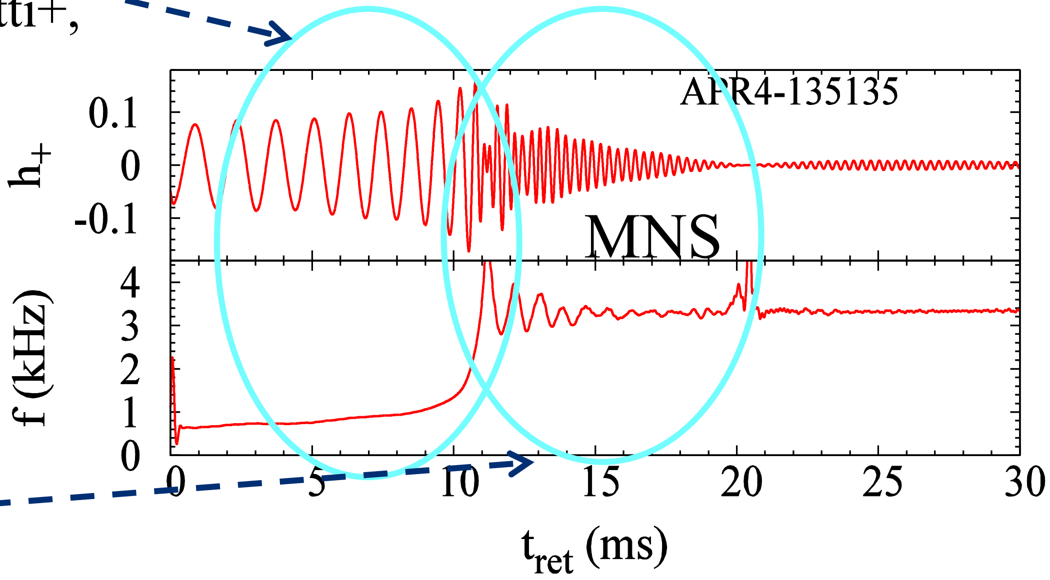
Post-Newton
with tidal coupling or NR

Numerical relativity



Two interesting phases for EOS study

Chirp ↔ GWs from MNS



A. Late Inspiral

(Lai+, Hinderer+, Damour+, Baiotti+, Bernuzzi+, Hotokezaka+) :

Effects of *tidal deformation enhanced*

***f* ~ 0.5 – 1kHz**

B. Merger → MNS

(Basuwein+, Hotokezaka+)

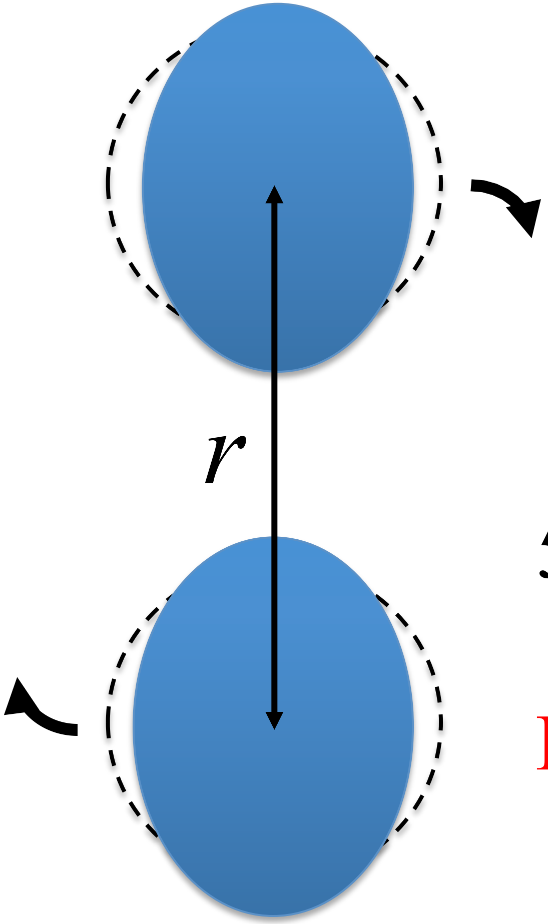
GW from *MNS/HMNS*

***f* ~ 2k – 4kHz**

Both waveforms could be used for constraining EOS of neutron stars

A Tidal effects in a binary inspiral

(originally pointed out by Lai+ 1992)



Close Binary System

➡ Tidal deformation;
Quadrupole is induced

$$\phi \sim -\frac{GM}{r} - \frac{C}{r^6}$$

5PN correction but large coefficient

$C \sim MR^5$, $R \sim 5$—$8\,M$

For $r \sim 2R$, it could play a role.

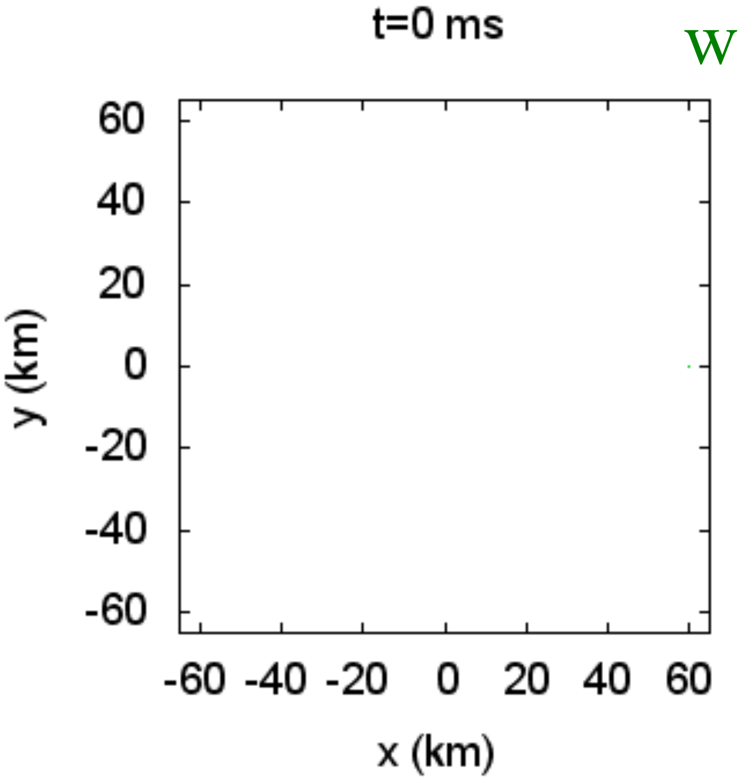
$$\boxed{h = h(t, M_1, M_2, C_1, C_2)}$$

Analytic Computation (Effective One-Body)

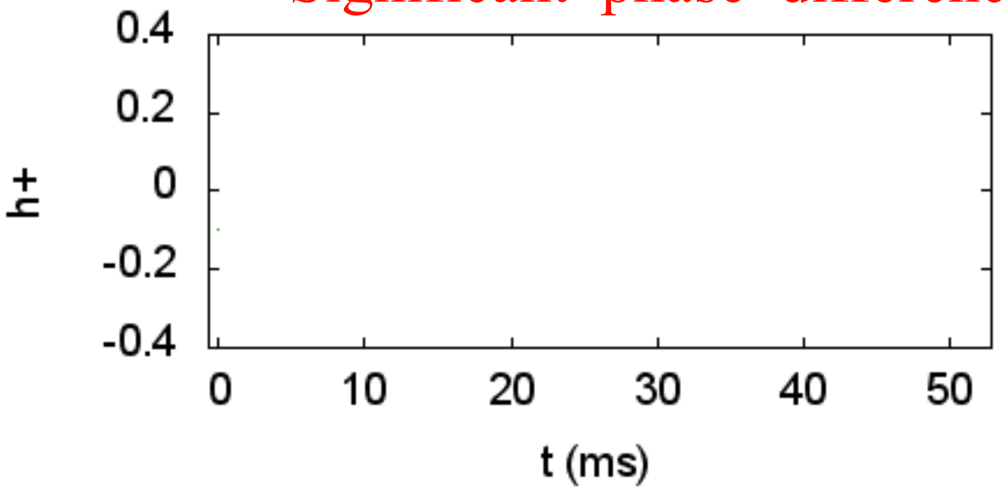
1.35-1.35 M_{sun}, EOS: MS1 (R=14.5km)

without tidal effects

with tidal effects



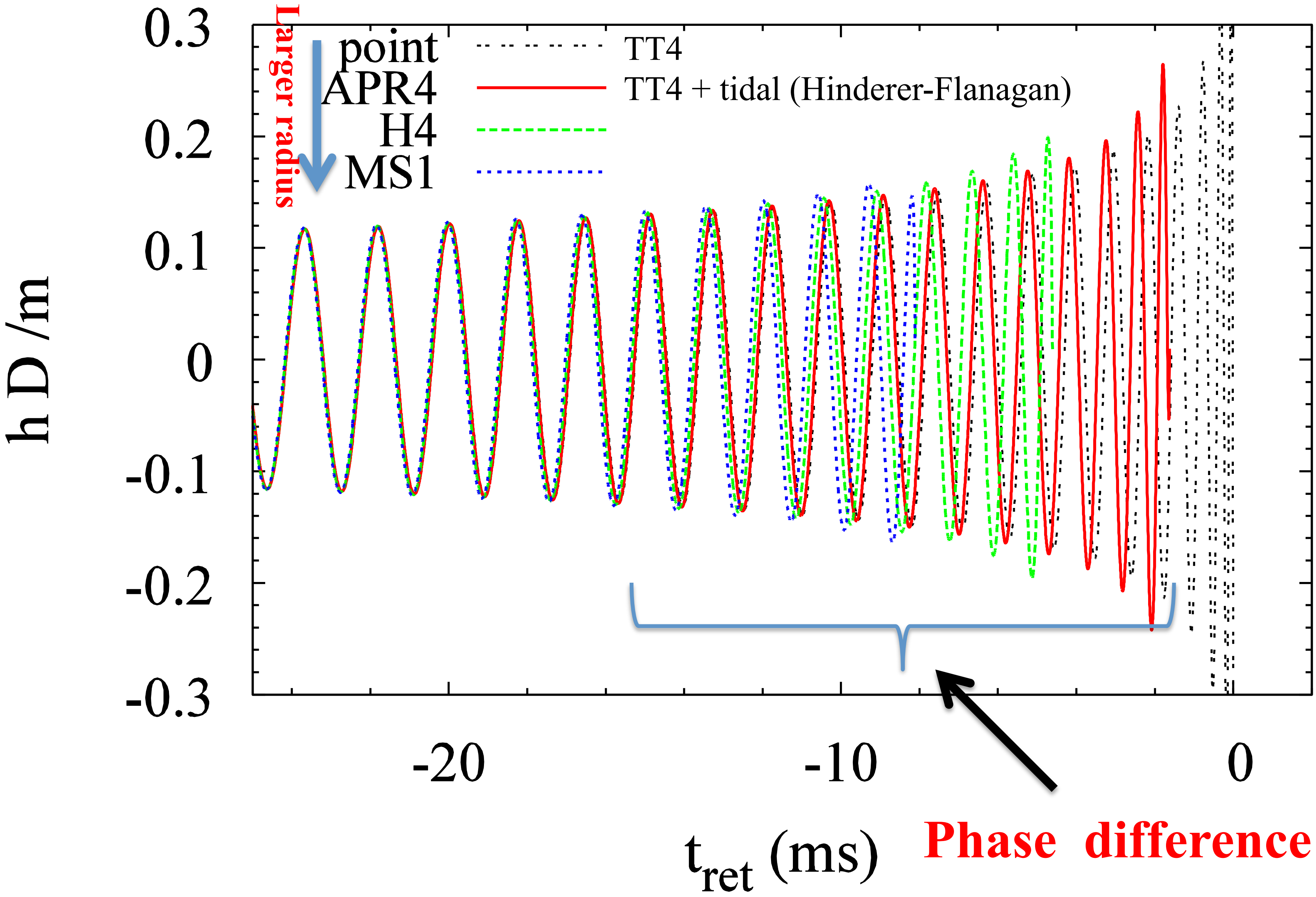
Significant phase difference



Calculation by Hotokezaka

For EOB, see, e.g.,
Pan et al., (2011)
Damour et al., (2012)

Late-phase chirp signal by TT4



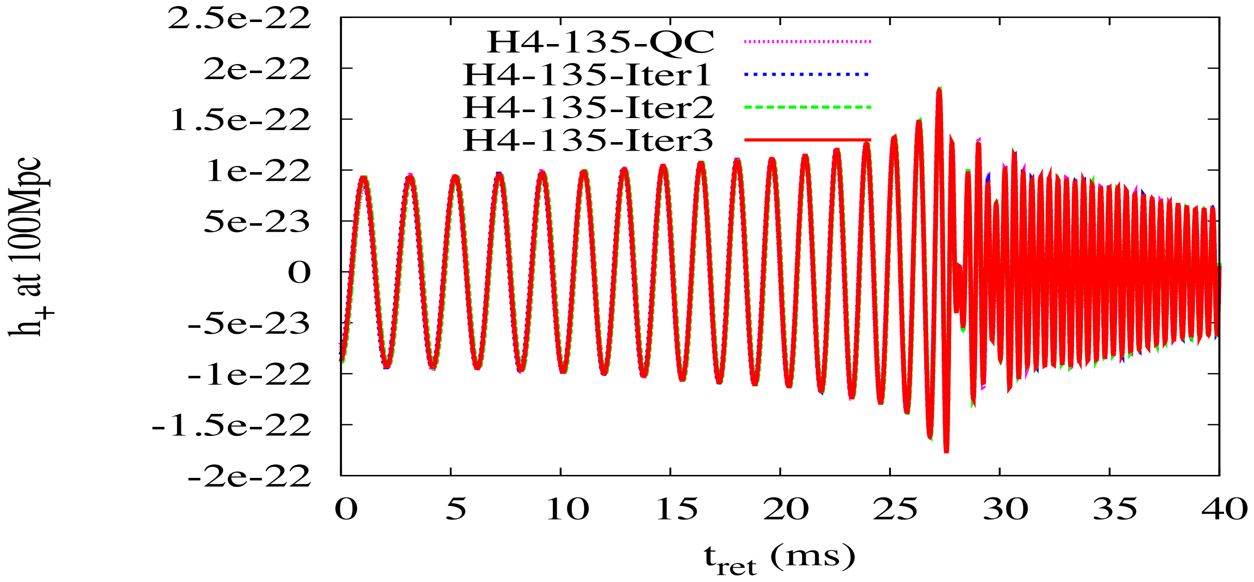
Phase difference

Status of this reserach

- Analysis in terms of EOB by Damour, Nagar (2012) suggests that for 1.4-1.4M_{sun} (or less massive) NS-NS, EOS could be constrained for S/N > 16 events
- Wade+, PRD89 103012 show that systematic error in the template will give ***serious damage***
- *Can EOB provide accurate templates ?*
  → Bernuzzi+, Hotokezaka+ showed it acceptable for most of inspiral phase except last a few orbits
- But, their simulations are not very long, and initial condition has non-negligible eccentricity
- **More sophisticated study is necessary**

Efforts in numerical relativity

- Effort of eccentricity reduction by Kyutoku (UWM)



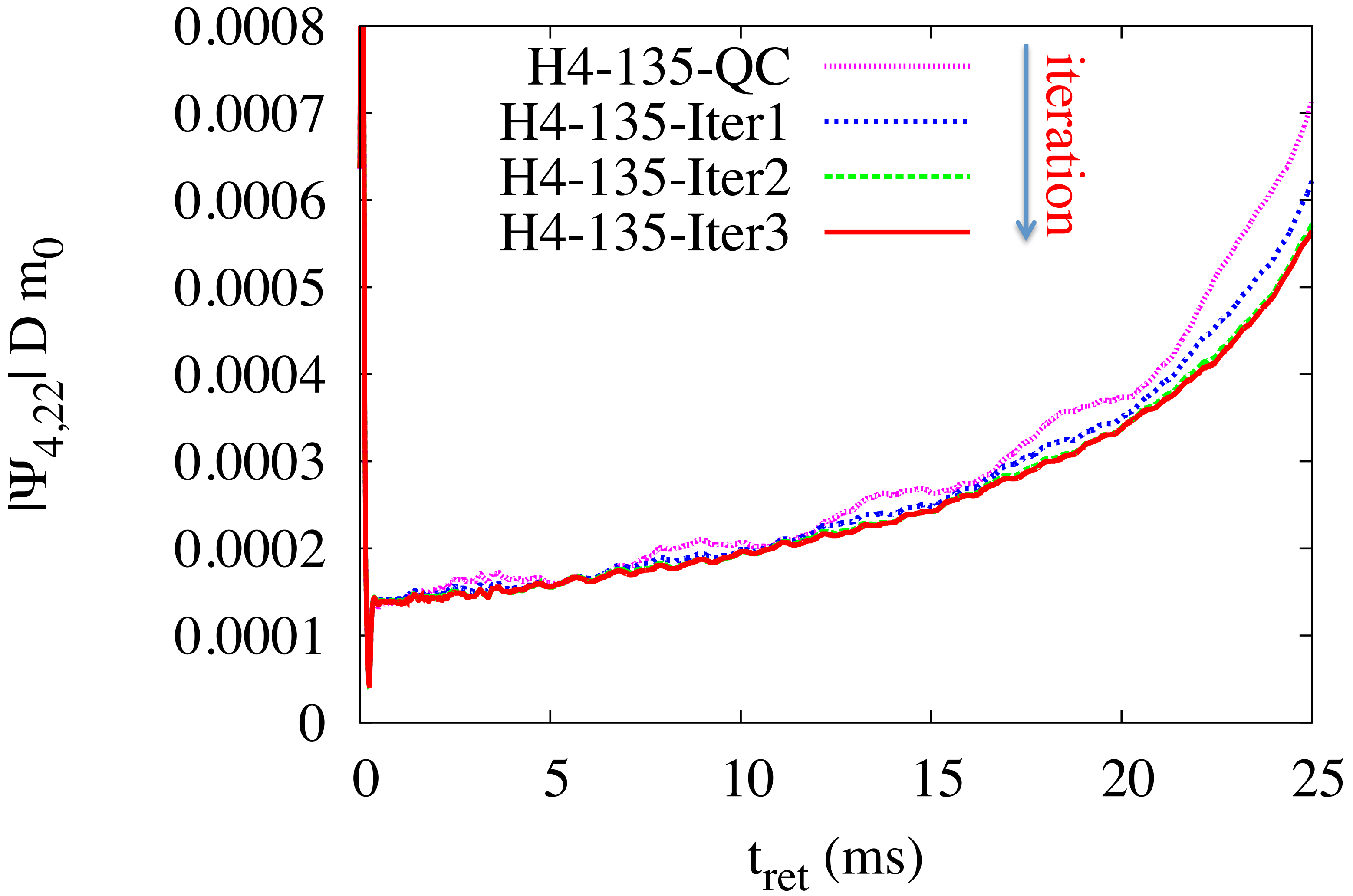
arXiv1405.6207
(PRD2014)

Initial eccentricity
$\sim 10^{-3}$

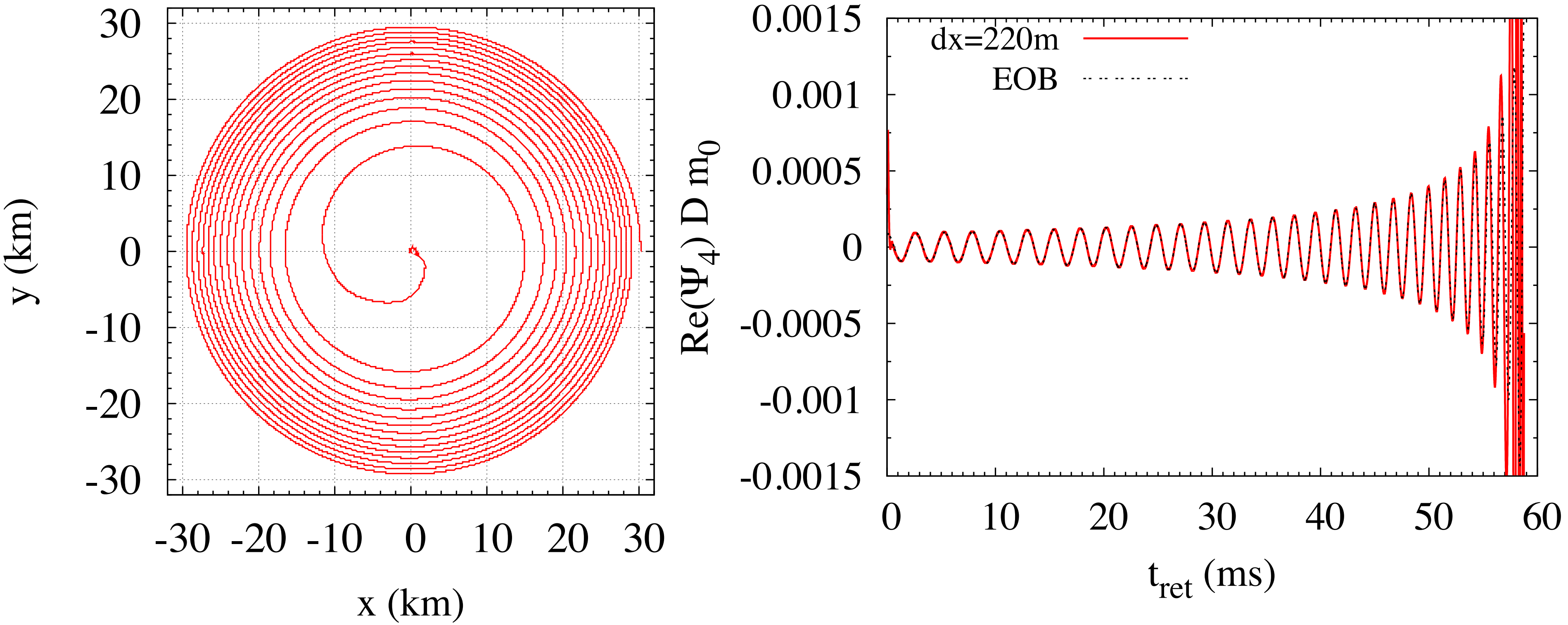
- **Caltech team (R. Haas et al.) is also working in very long-term accurate simulations**

These further studies are necessary and ongoing

Amplitude: Modulation is suppressed



Our 15 orbits simulation: *Preliminary*

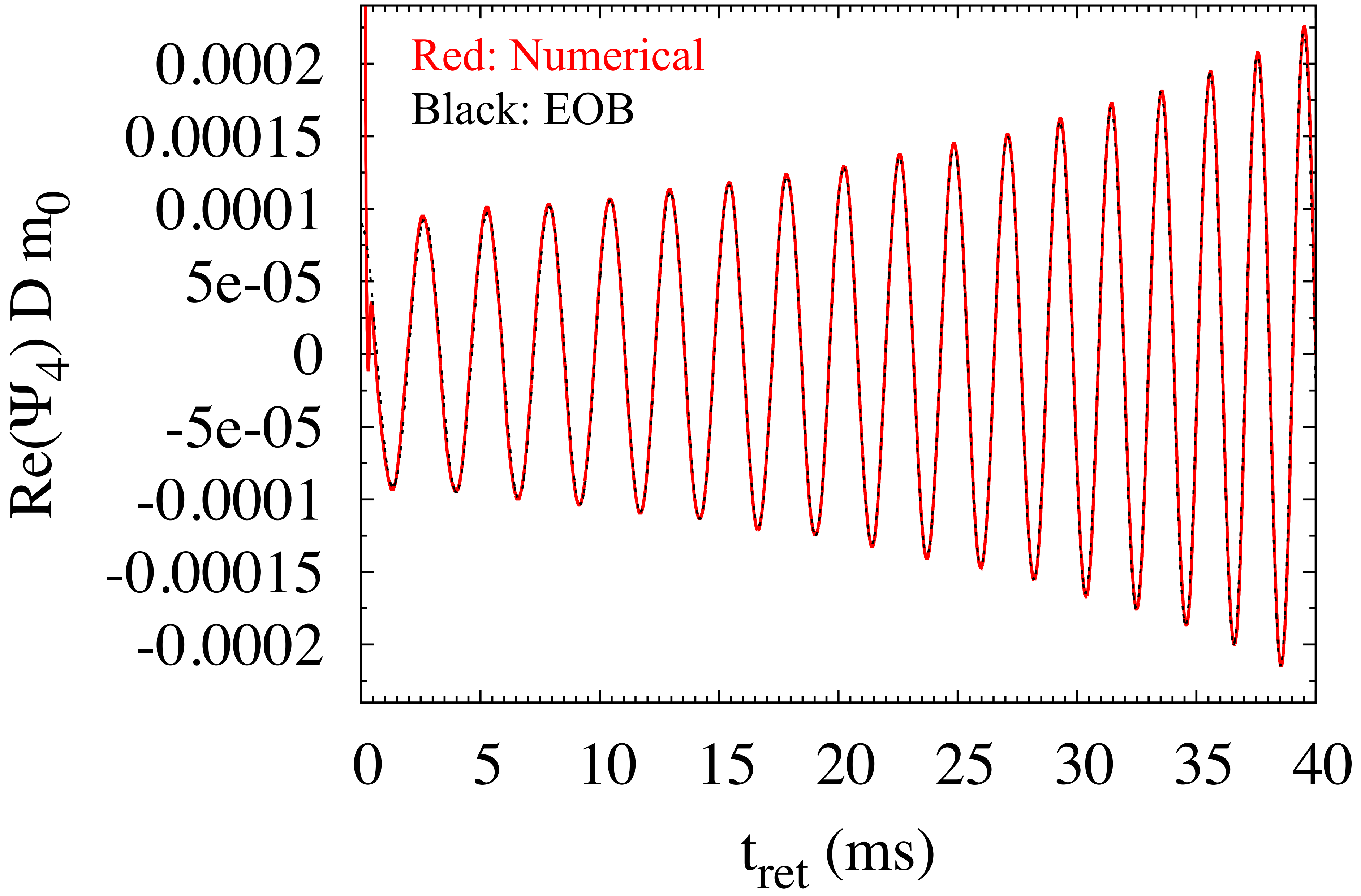


Eccentricity <~ 0.001

Z4c formulation
(Hilditch & Bernuzzi)
H4-EOS: R=13.6km
1.35-1.35M_{sun}

Hotoke, Kyutoku, Okawa, Shibata

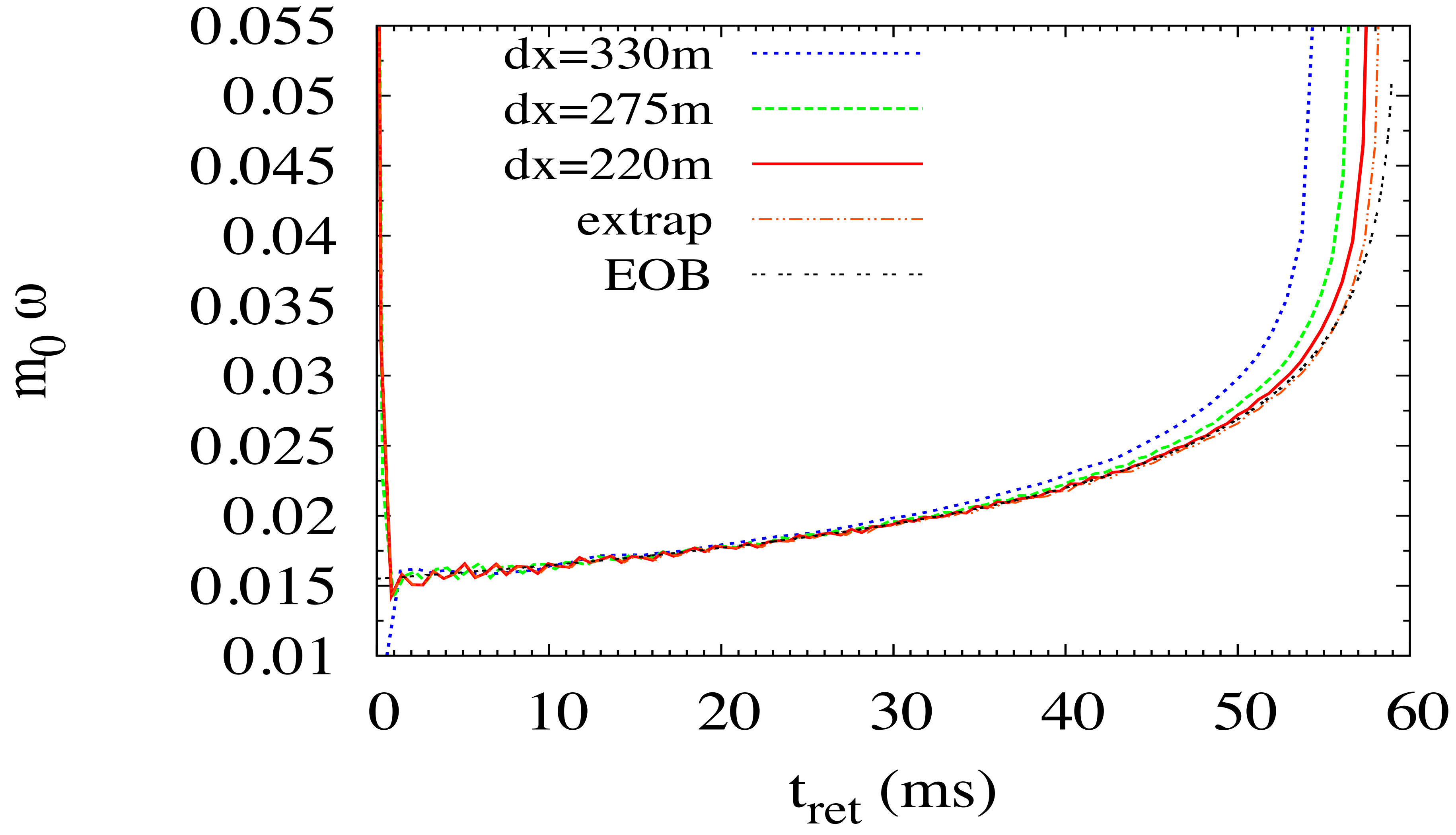
Early phase: I plotted two curves



Preliminary

Convergence ~ 4th order

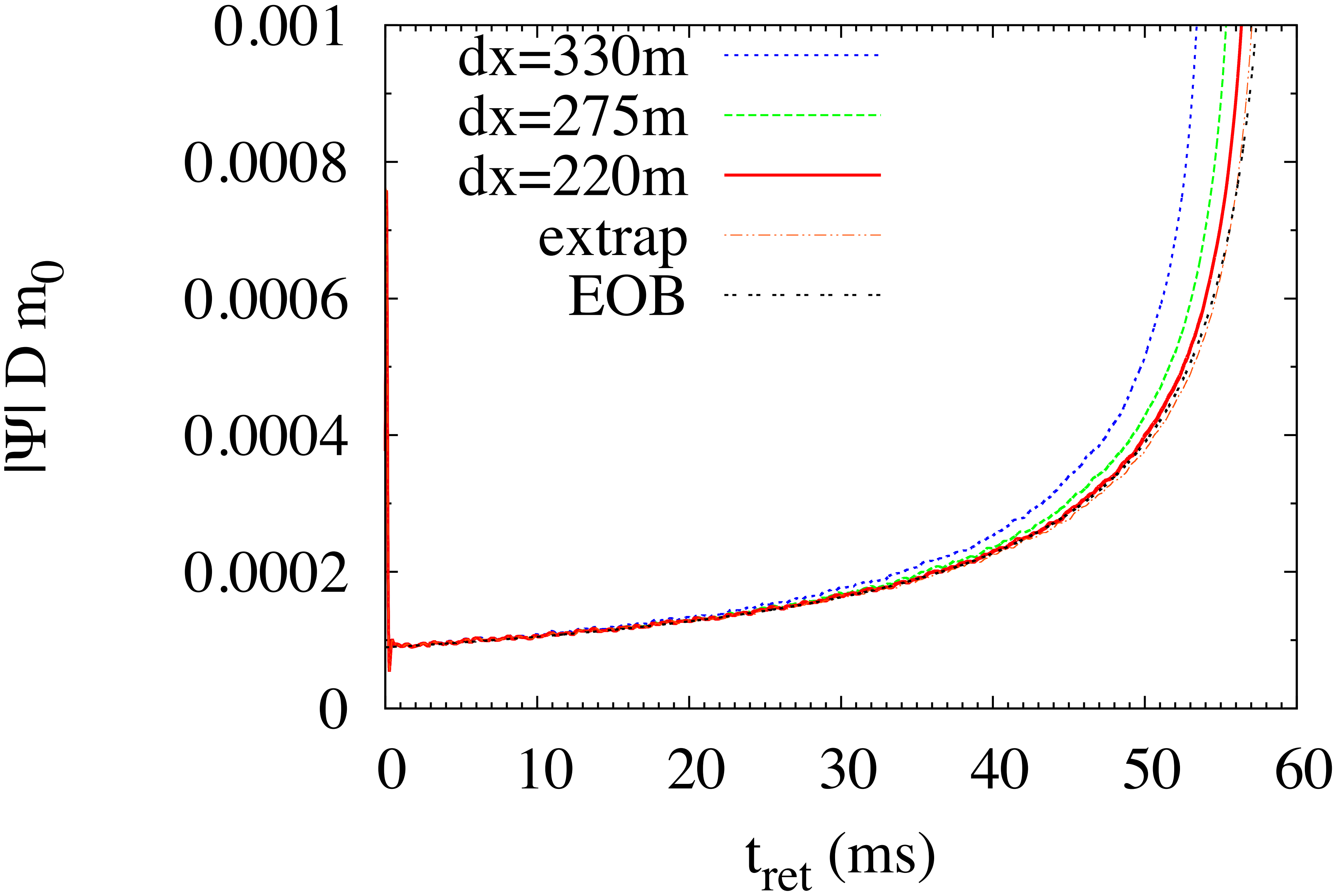
Final phase: need more consideration



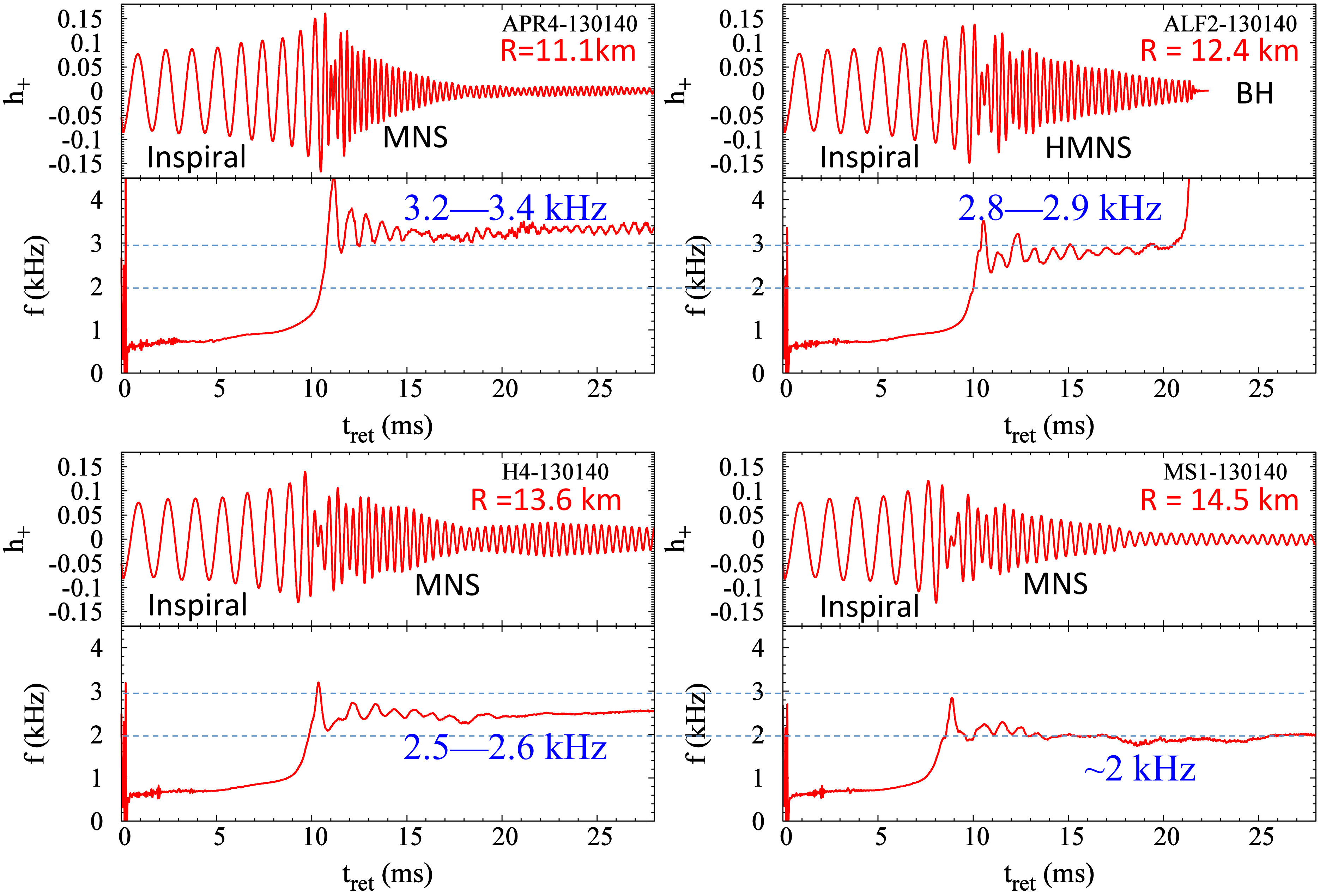
Convergence ~ 4th order

Preliminary

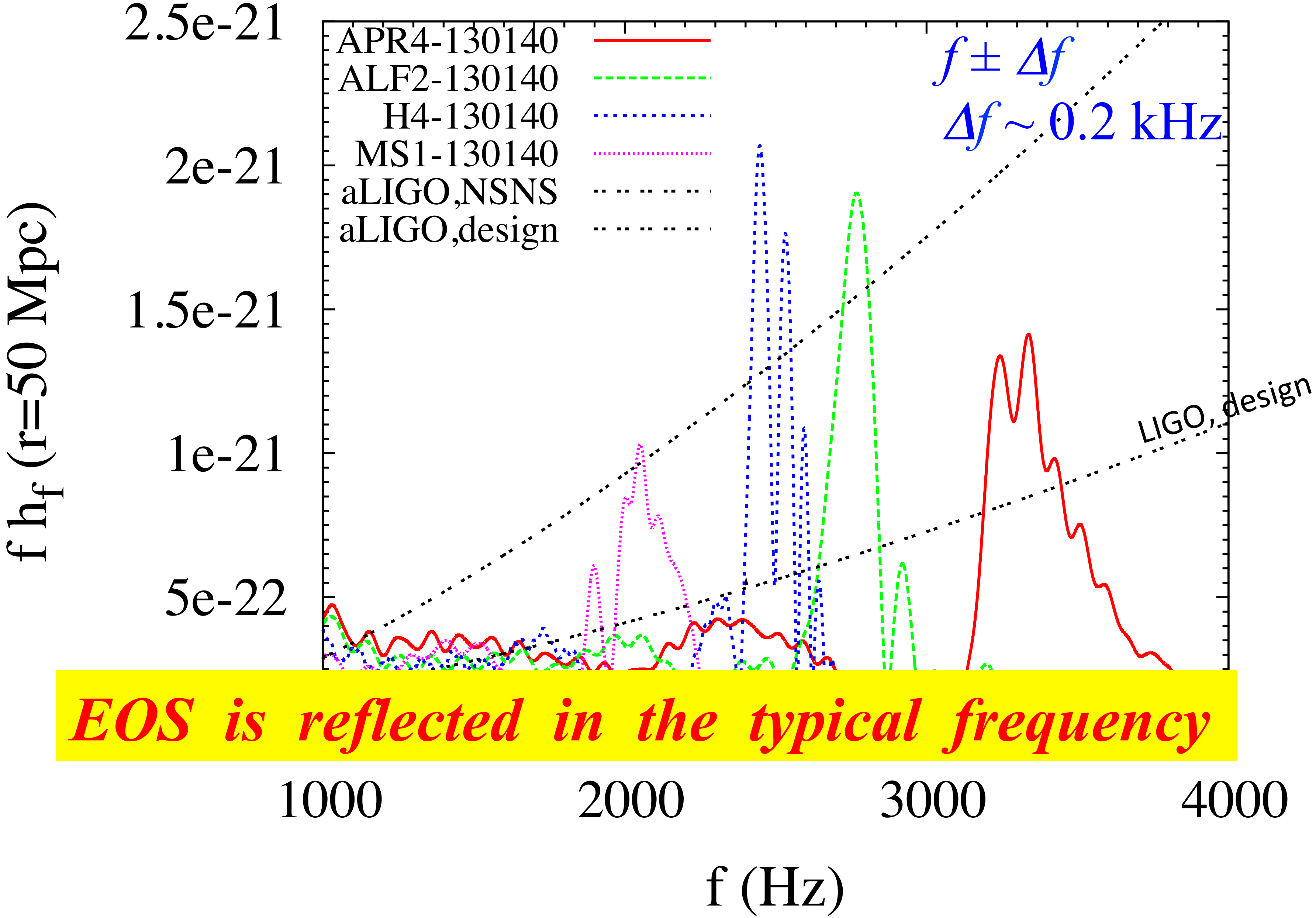
Final phase: need more consideration



B GW from MNS: M_1=1.3, M_2=1.4$M_{\rm sun}$



Fourier spectrum



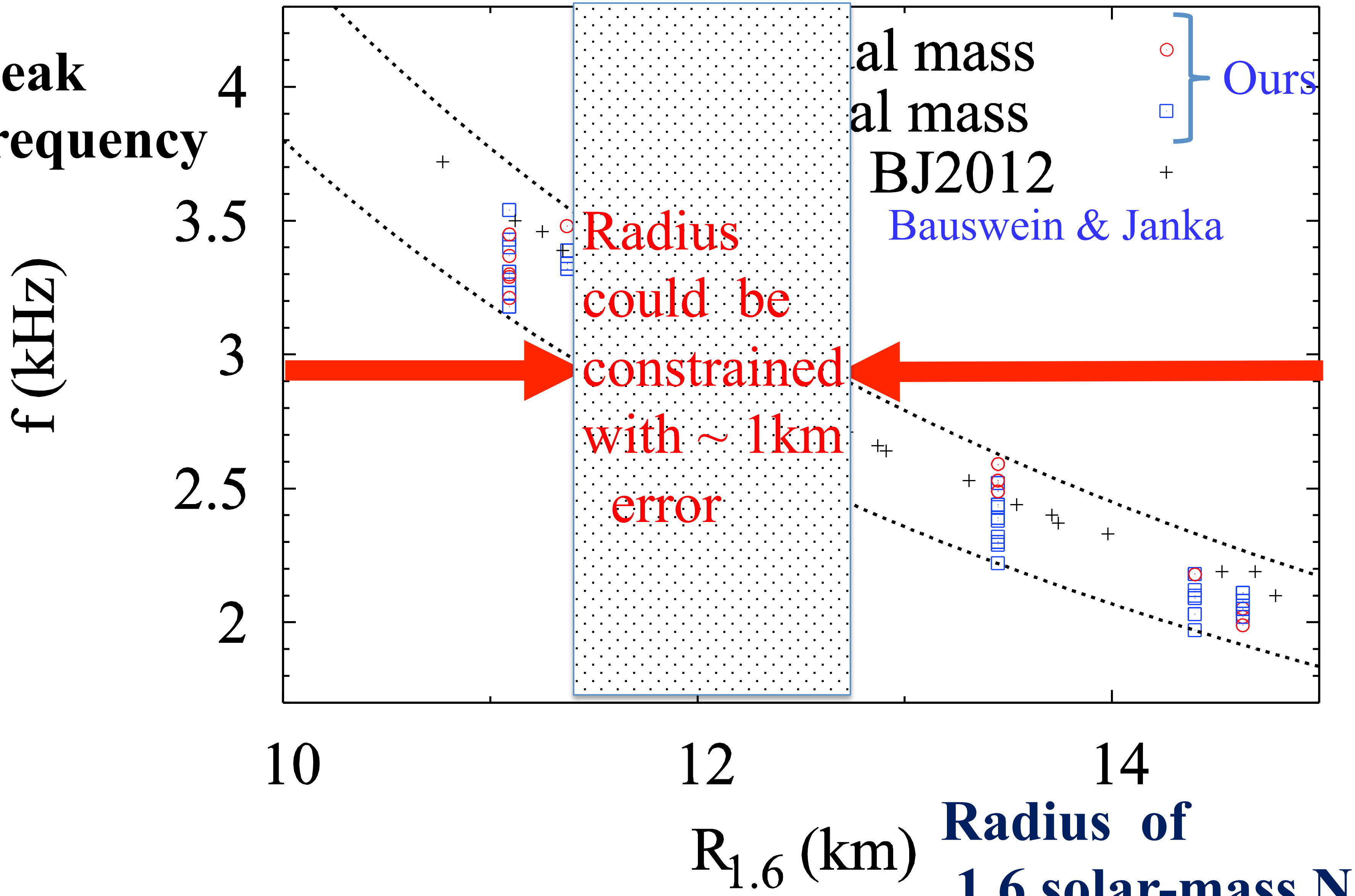
$f \pm \Delta f$

$\Delta f \sim 0.2$ kHz

EOS is reflected in the typical frequency

Clear correlation between peak and radius

Peak frequency



Radius could be constrained with ~ 1km error

Radius of 1.6 solar-mass NS

GWs from NS-NS & EOS: Summary

- If $D < \sim 100$ Mpc, late inspiral waveforms could be used to constrain EOS (aLIGO/VIRGO/KAGRA):
  → But, need a more precise template for late inspiral (Wade+, PRD89 103012 2014) → NR
- If $D < \sim 30$ Mpc, merger waveforms could be used to constrain EOS (aLIGO/VIRGO/KAGRA)
  → Need a data-analysis study; how accurate ?

✧ Note that if GR is violated, the situation could be different (MS+, PRD 2014 for a scalar-tensor theory)

4 Mass ejection and EM counterparts

In NS-NS merger at least 2 effects drive ejection

1) At the merger, **strong shock** is generated, thermal pressure is enhanced, and material is ejected from the system (like supernova).

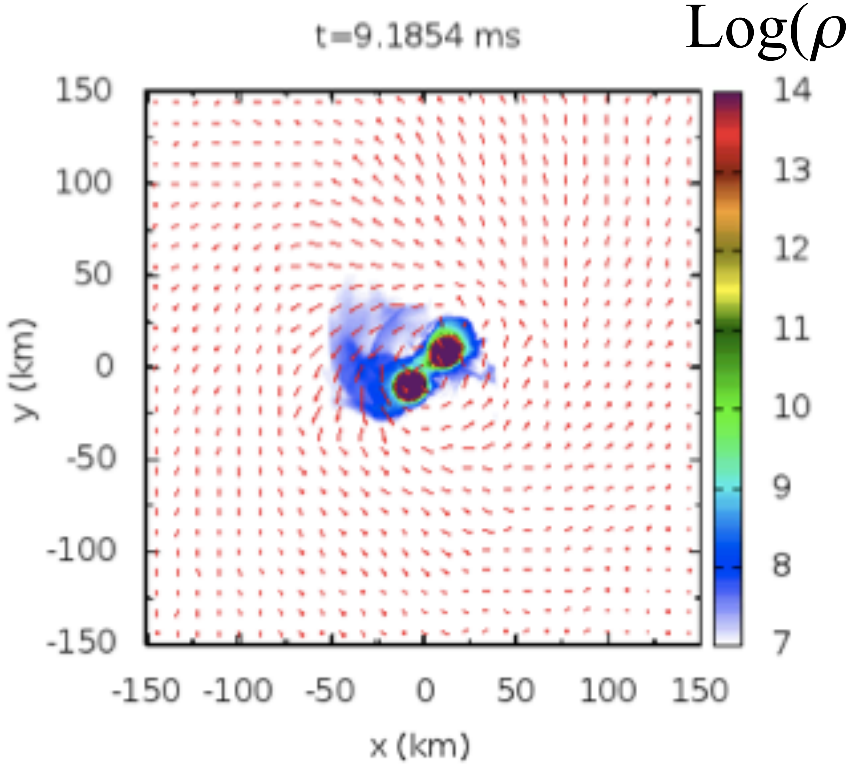
2) During the merger, *non-axisymmetric merger remnant* is formed. Also, after the merger, a massive *ellipsoidal* NS is formed.
→ **These non-axisymmetric objects exert torque** to the material in the envelope, which is subsequently ejected.

✓ Other effects like neutrino or magnetic wind may play a role

Mass ejection at merger

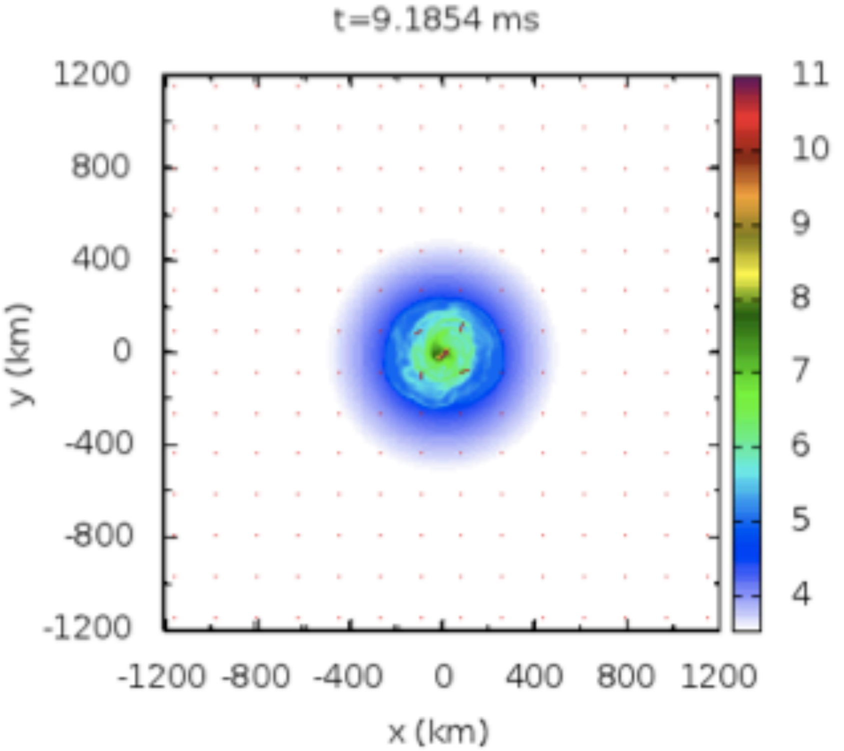
Model : 1.2M$_{\text{sun}}$ – 1.5M$_{\text{sun}}$, EOS=APR4, R ~11 km

300 km x 300 km



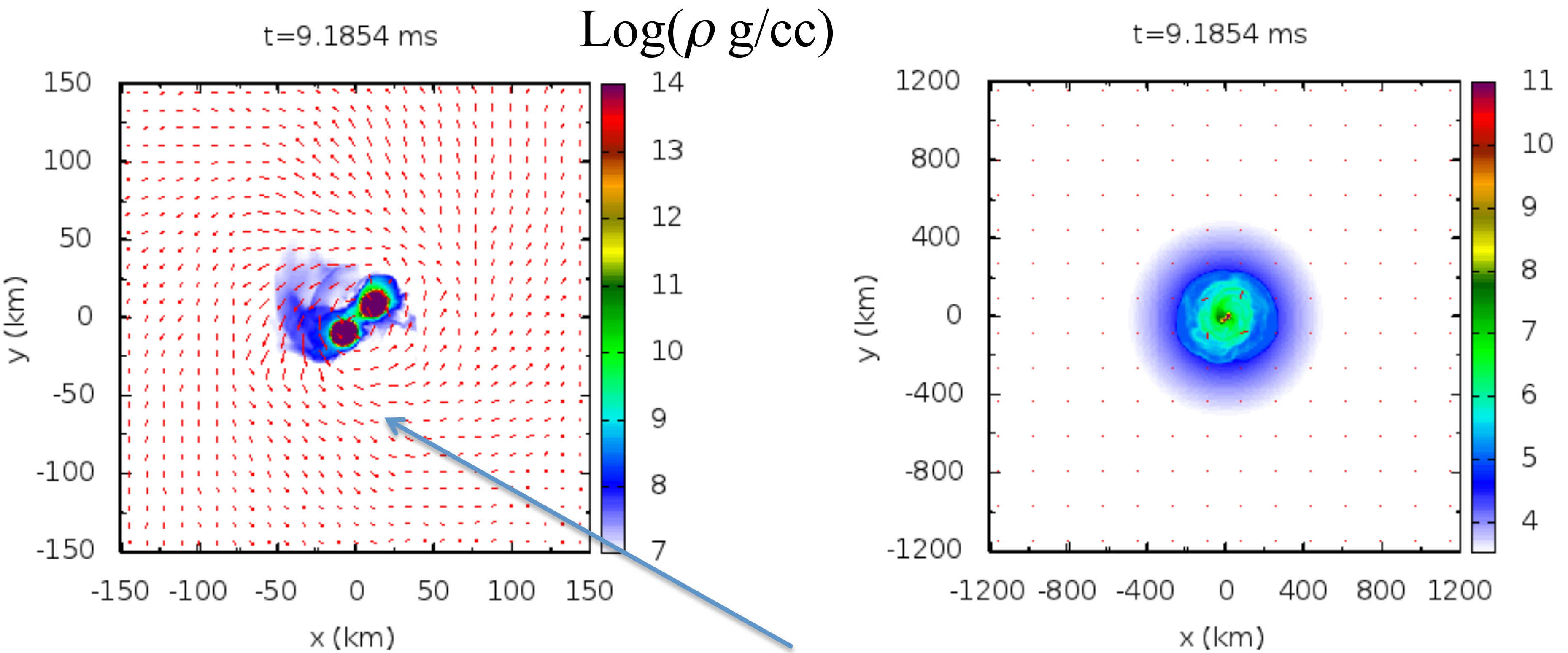
Log(ρ g/cc)

2400 km x 2400 km



Mass ejection at merger

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



Tidal torque plays an important role

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

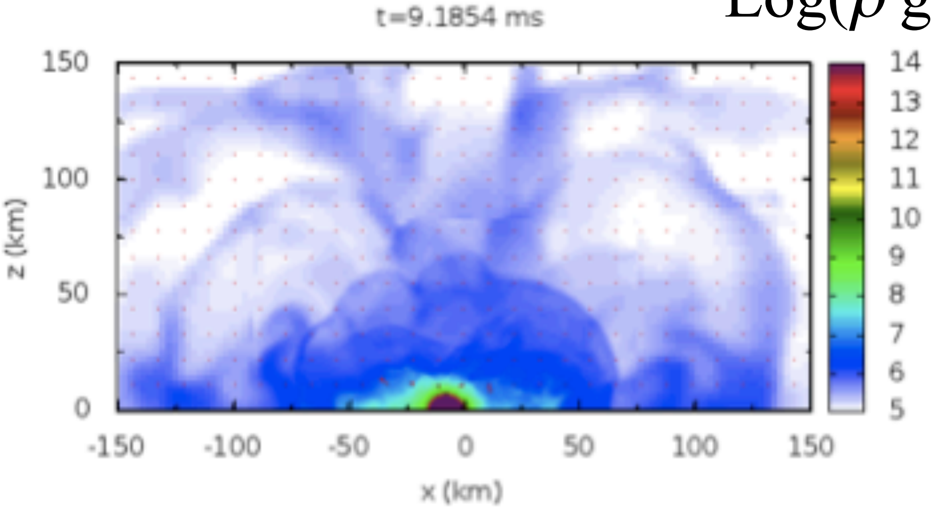
Mass ejection on the meridian plane

(x-z plane)

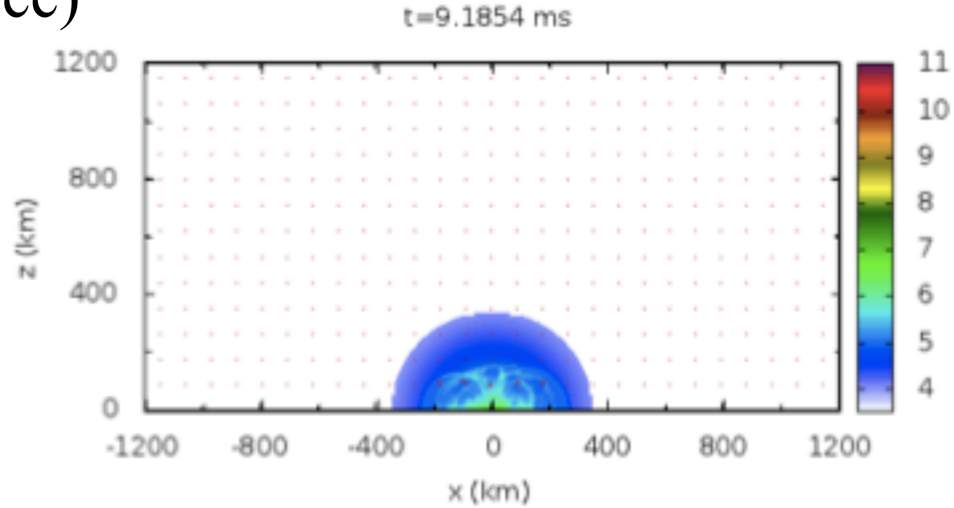
Model : $1.2M_{sun} – 1.5M_{sun}$, EOS=APR4, R ~11 km

300 km x 150 km

Log(ρ g/cc)



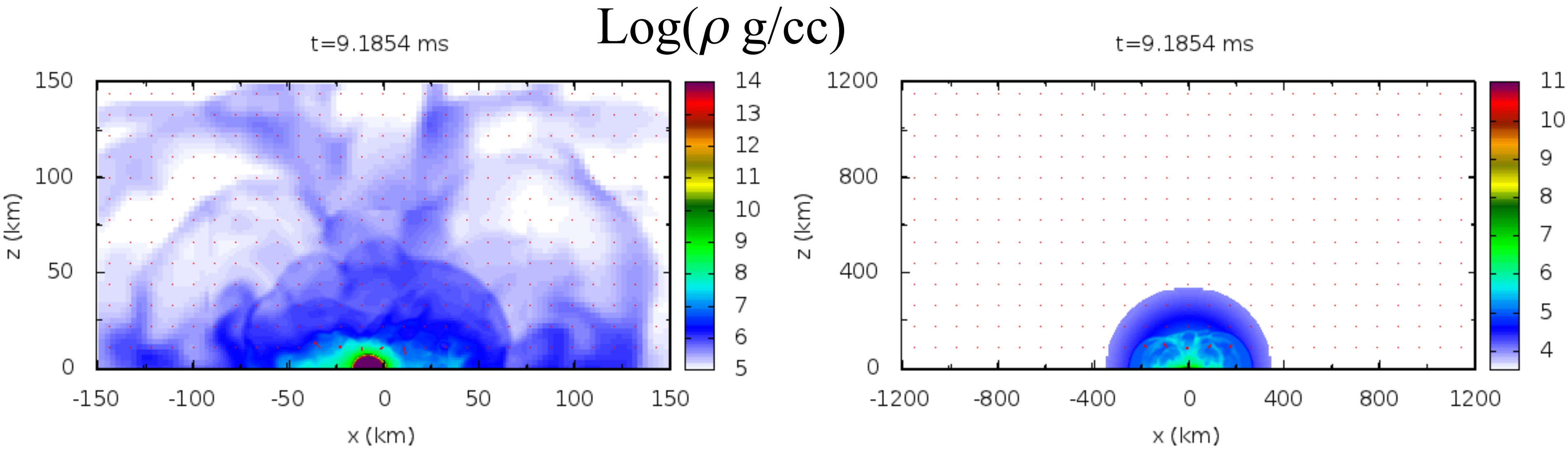
2400 km x 1200 km



Mass ejection on the meridian plane

(x-z plane)

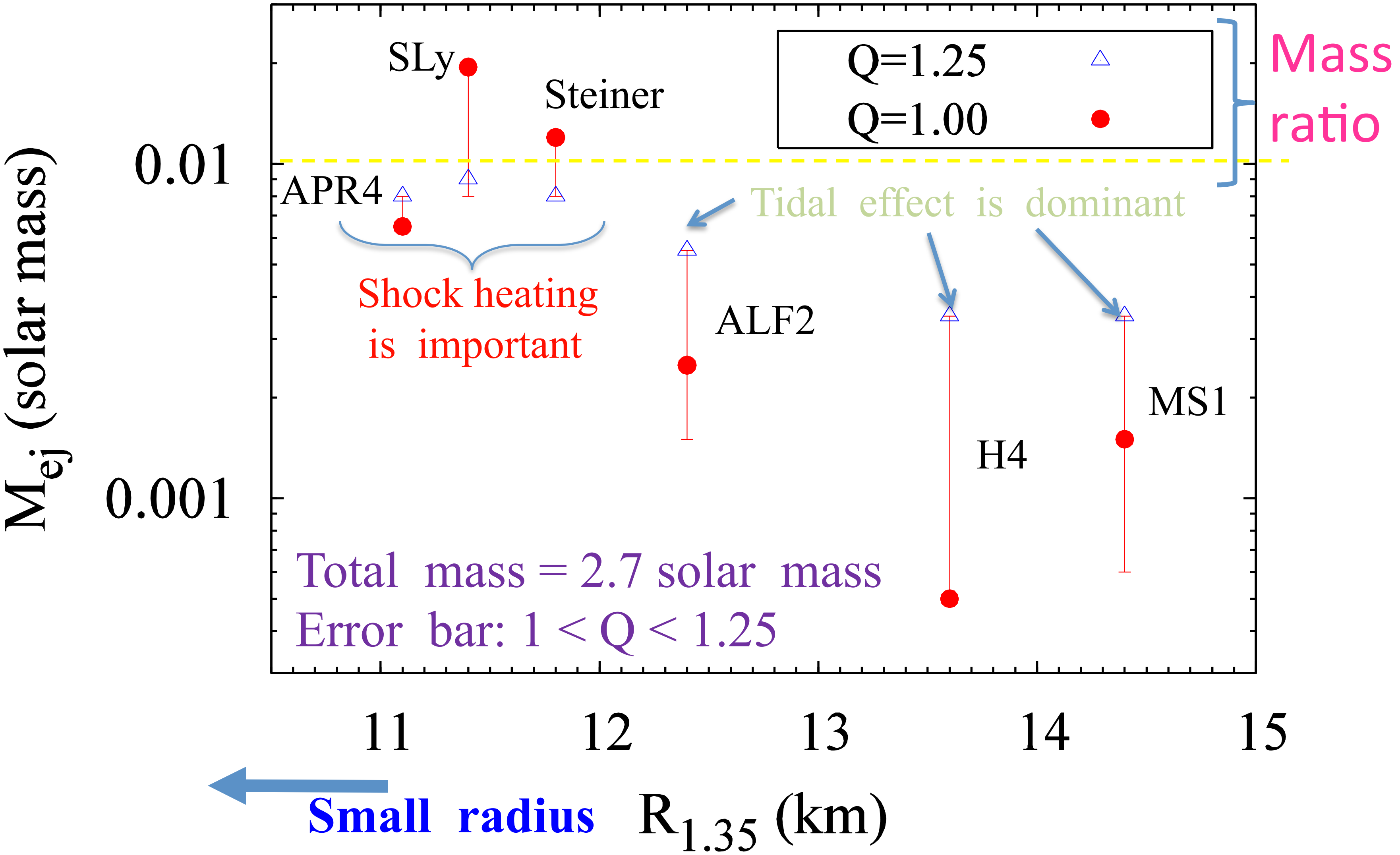
Model : $1.2M_{sun} – 1.5M_{sun}$, EOS=APR4, R ~11 km



Ejecta is quasi-spherical:
Shock heating plays a key role.

Amount of ejection depends strongly on EOS

(Relatively) Soft EOS is favored



Hotokezaka + PRD 2013

(See also Bauswein+ 2013)

Mass ejection and EM signals

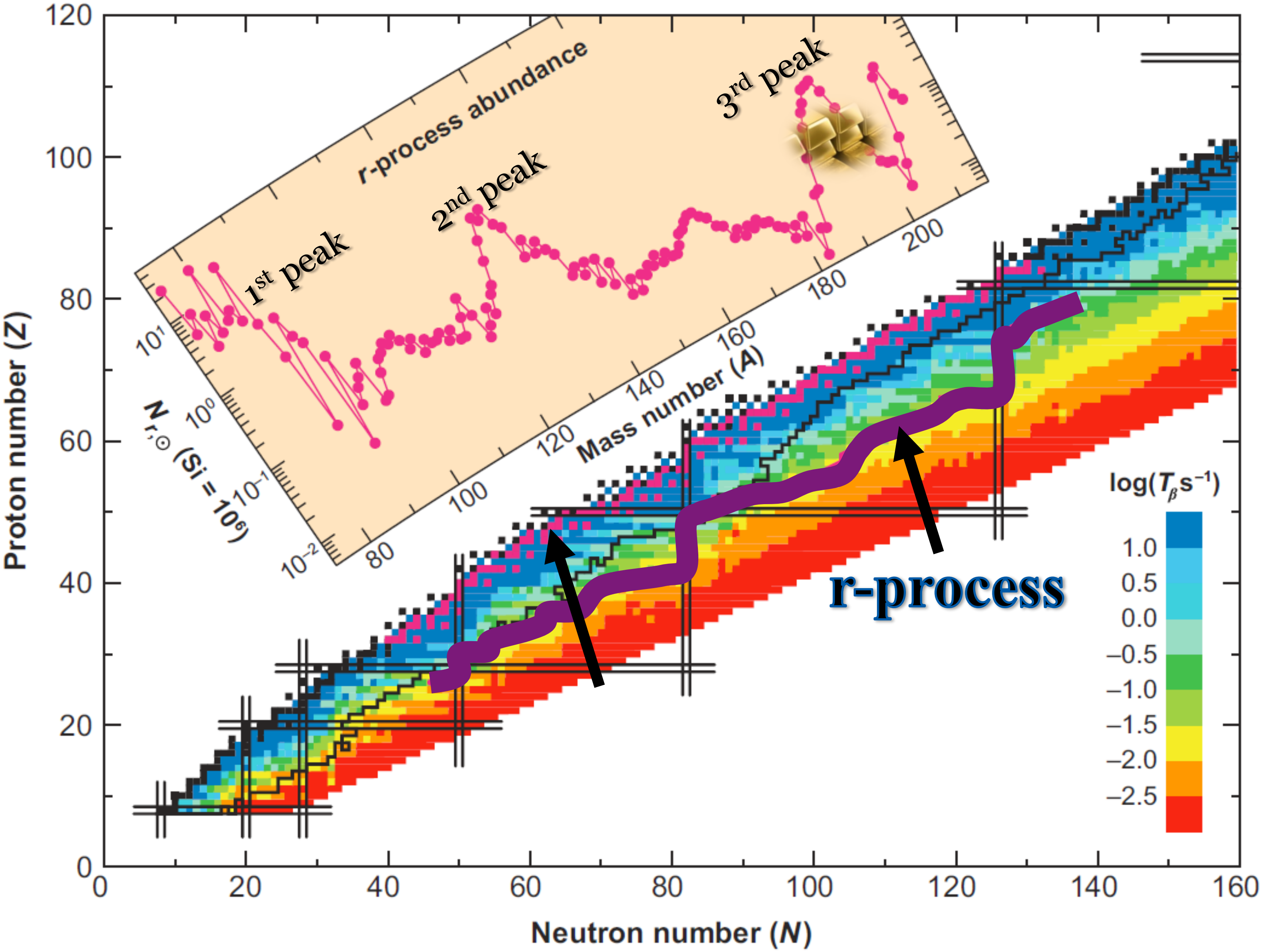
- Material ejected could generate astronomically observable EM signals via

➢ **Kilonova/Macronova** = radioactively powered: Decay of r-process-heavy nuclei
(Li & Paczynski 1998, Kulkarni 05, Metzger+ '10, … **Barnes, Kasen+ '13, Tanaka-Hotokezaka '13**)

→ Signal appears for 1—10 days after merger

➢ Afterglow-type radio flare: shock powered
(Nakar-Piran 2011)

→ Signal appears for ~ 1—10 years after merger



$$\tau_{n\text{-capture}} < \tau_{\beta\text{-decay}}$$

Kilonova/macronova Scenario

(Li-Paczyski 1998)

- Neutron-rich ejecta $\tau_{n-\mathrm{capture}} < \tau_{\beta-\mathrm{decay}}$

→ **r-process nucleosynthesis**

(Lattimer-Schramm '74, Symbalisty-Schramm '82)

→ **Production of unstable nuclei**

→ β-decay/fission

→ heating material

→ After adiabatic expansion

→ $\tau_{\mathrm{diffusion}} \leq \tau_{\mathrm{expansion}}$

→ UV ~ IR (Li-Paczynski '98)

Estimate by Li-Paczynski (ApJ 1998)

Maximum Luminosity @ $R / v = R^2 \rho\kappa / c$:

$$L_{\rm max} \sim 4\times10^{41}\ \text{ergs/s} \left(\frac{M}{0.01M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{1/2} \times \left(\frac{\kappa}{10\ \text{cm}^2/\text{g}}\right)^{-1/2} \left(\frac{f_{\text{r-proc}}}{3\times10^{-6}}\right)$$

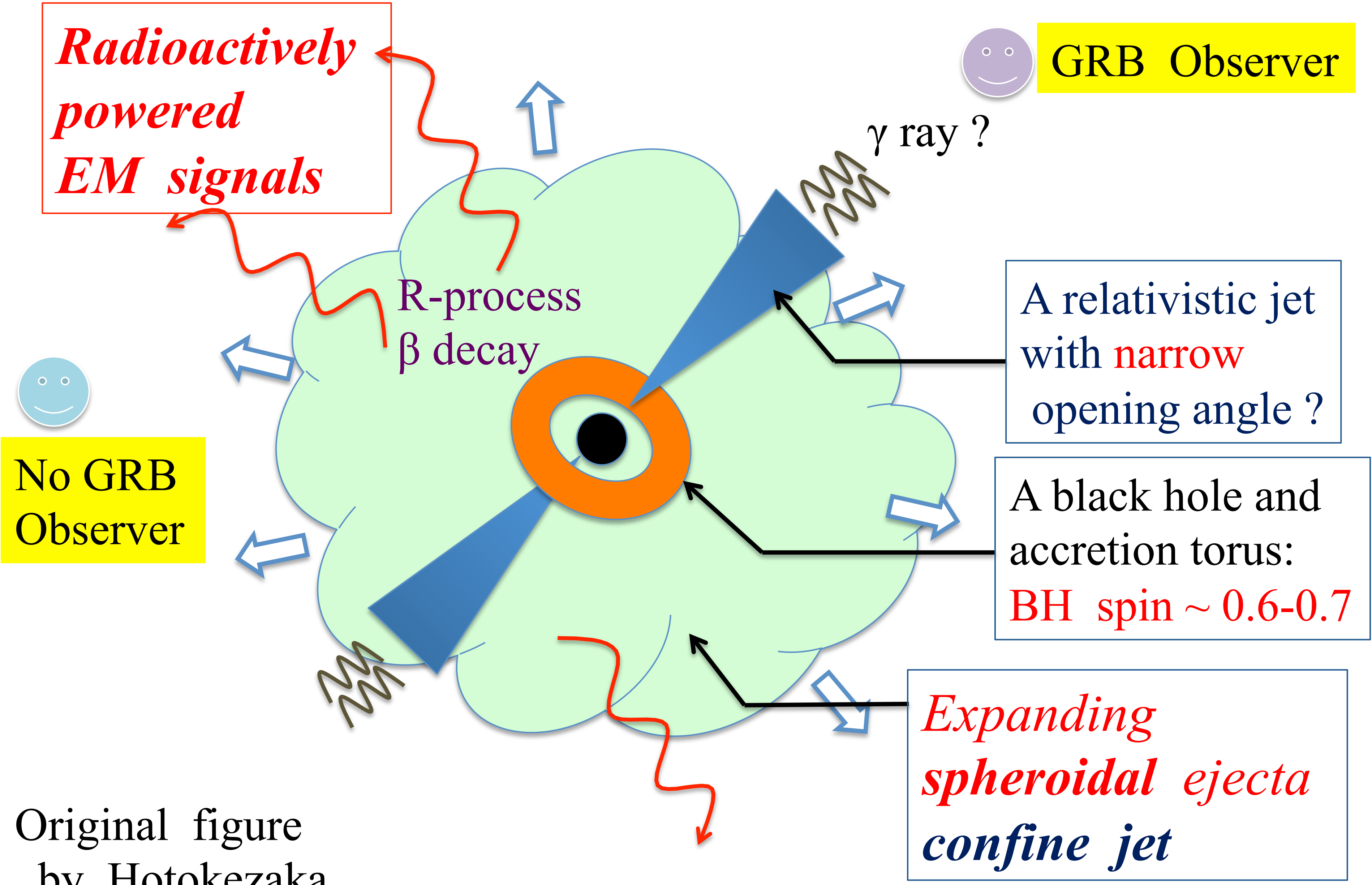
~ 10^3 times higher than Eddington luminosity

$$\text{at}\ \ t \sim 5\ \text{days} \left(\frac{M}{0.01M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{-1/2} \left(\frac{\kappa}{10\ \text{cm}^2/\text{g}}\right)^{1/2}$$

3×10^{41} ergs/s ⇔ $M = -15.0$ mag ⇒ m=21.5 mag @ 200Mpc

These depend strongly on mass, velocity, & opacity;
Opacity ~ 10 cm^2/g (Kasen+, Tanaka-Hotokezaka 2013)

2.7 M_{sun} NS-NS Merger and remnant



Radioactively powered EM signals

GRB Observer

γ ray ?

R-process
β decay

A relativistic jet
with narrow
opening angle ?

No GRB
Observer

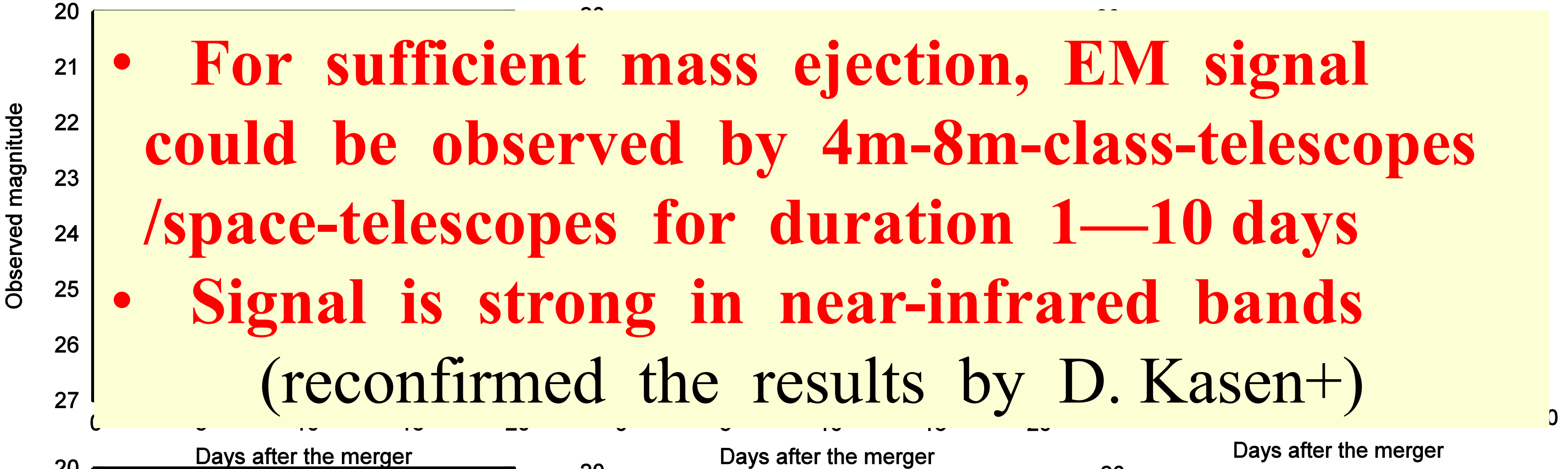
A black hole and
accretion torus:
BH spin ~ 0.6-0.7

Expanding
spheroidal *ejecta*
confine jet

Original figure
by Hotokezaka

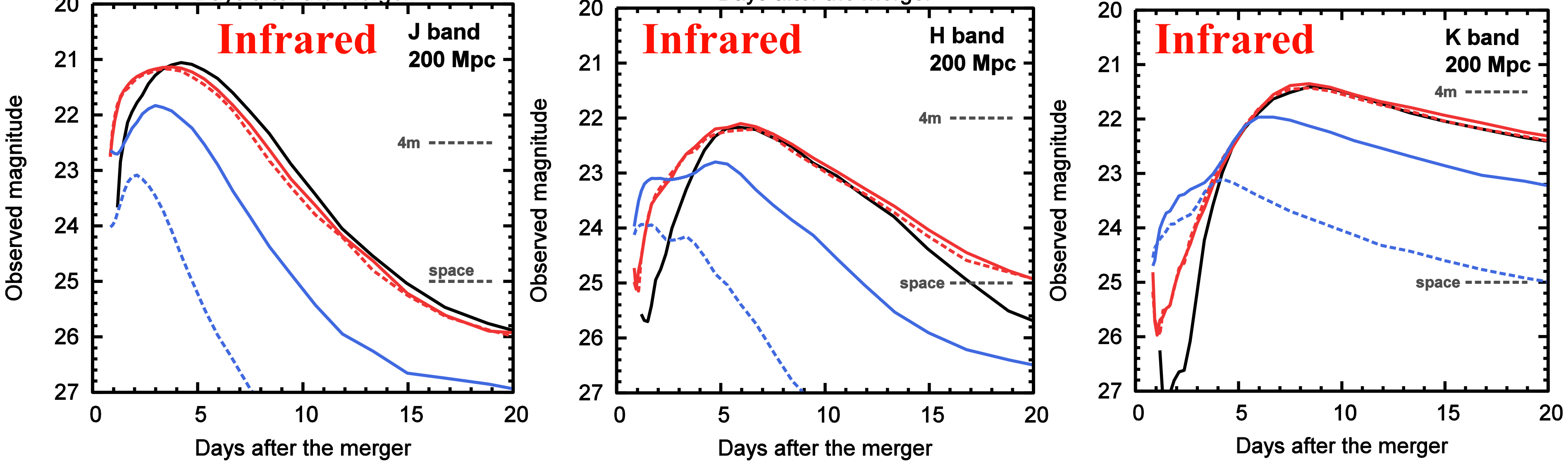
Model luminosity curve of NS-NS @ 200Mpc

(Numerical-relativity + radiation transfer simulation
by M. Tanaka & Hotokezaka, ApJ **775**, 2013)



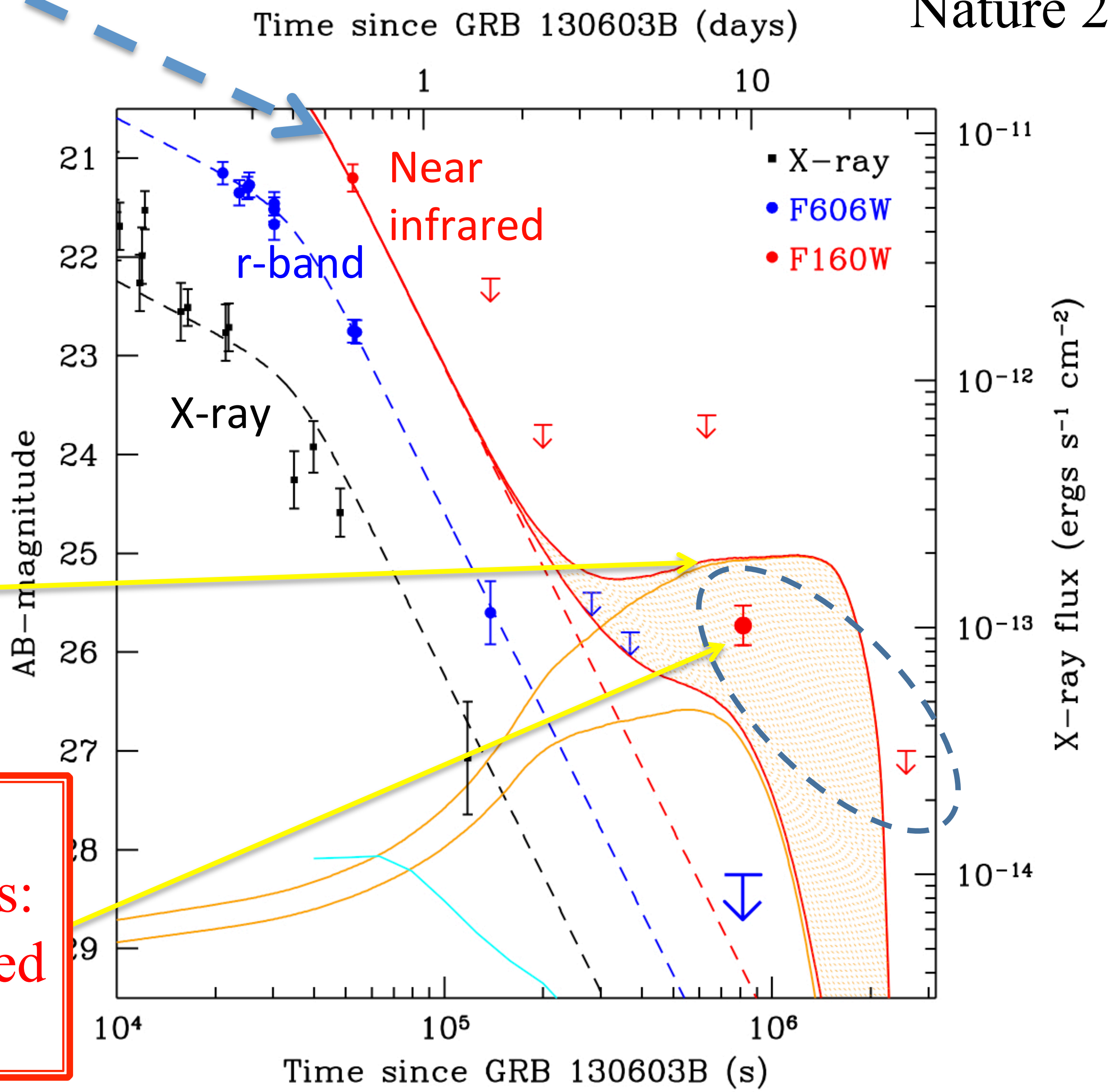
- **For sufficient mass ejection, EM signal could be observed by 4m-8m-class-telescopes /space-telescopes for duration 1—10 days**
- **Signal is strong in near-infrared bands**

(reconfirmed the results by D. Kasen+)



Kilonova 130603

Tanvir et al.
Nature 2013



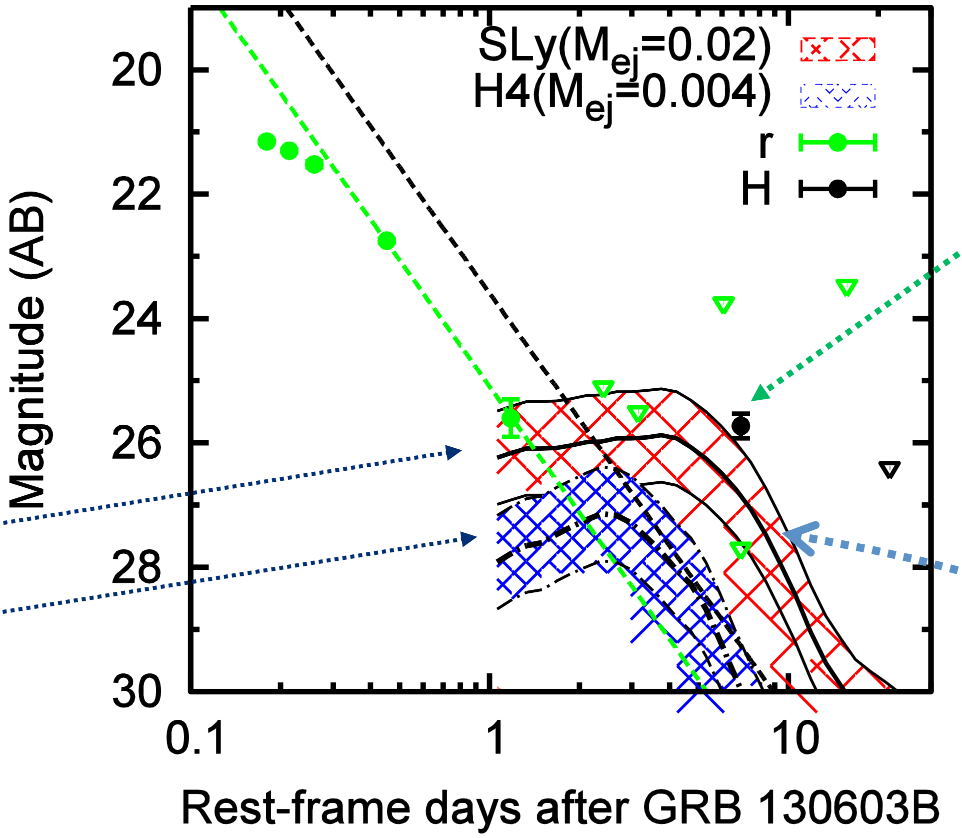
Straight lines are models of GRB afterglow

Approximate kilo/macronova models

This bump is an evidence of excess: Cannot be explained by GRB afterglow

Progenitor models of GRB130603B: NS-NS case

GR+radiation transfer work by Hotokezaka +, ApJL778, 2013



Infrared excess observation

Ejecta mass

- 0.02 M_{sun}
- 0.004 M_{sun}

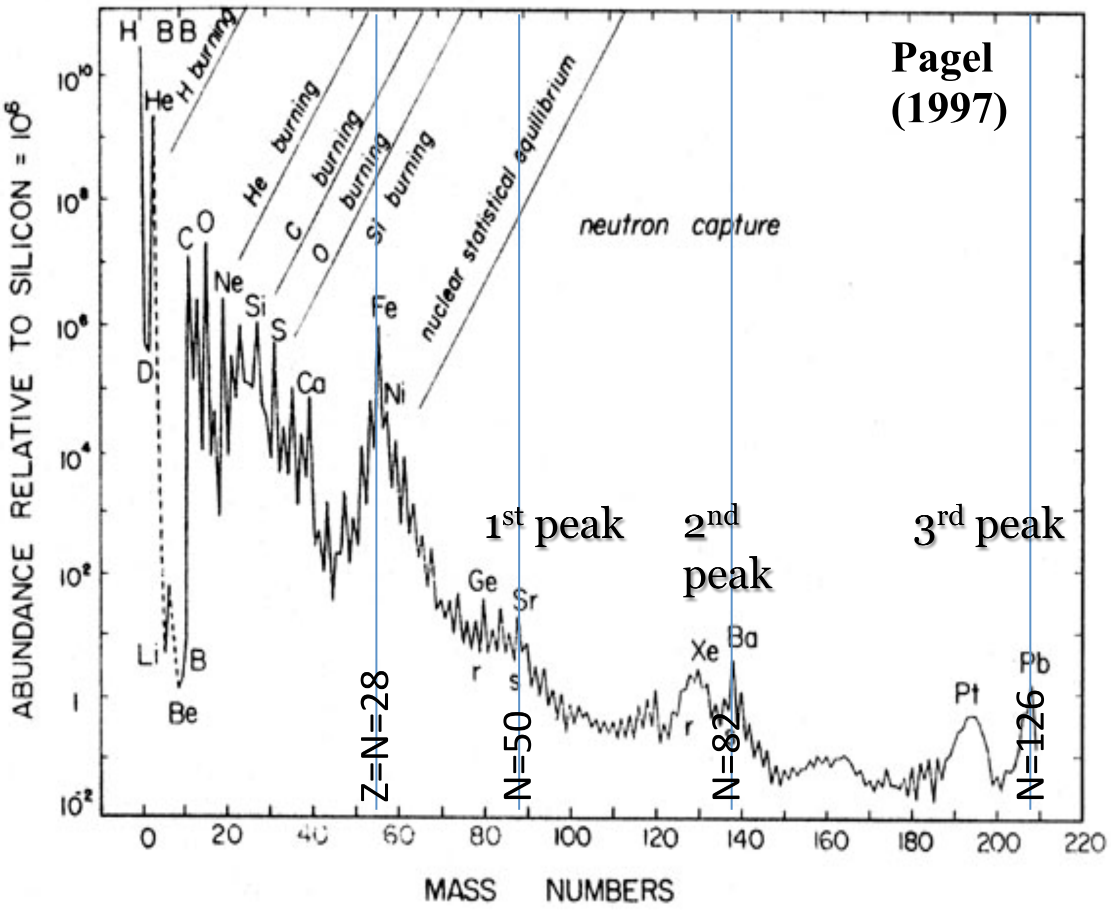
➢ **Small-radius EOS & high-heating rate can reproduce this event**

Heating rate has uncertainty of factor of ~2

5 r-process nucleosynthesis study of ejecta

(By Sekiguchi & Wanajo +: Note: I am a beginner)

- **Question: Could NS-NS merger reproduce solar abundance ?**
  → Simulation for various EOS



Pagel (1997)

Key quantity: electron fraction per baryon Y_e

◆ High $Y_e > 0.4$ → neutron less-rich
→ Third peak is not reproduced (e.g., CCSN)

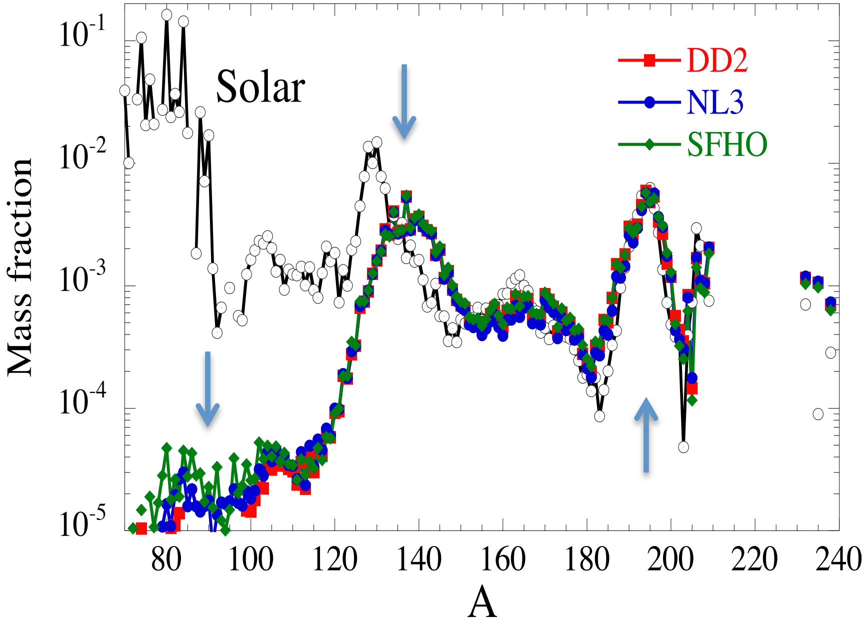
◆ neutron rich, $\langle Y_e \rangle \sim 0.1$
e.g., BH-NS or tidal-effect dominant NS-NS
→ 2nd & 3rd peak dominant
(e.g., Janka, Goriely, Rosswog)

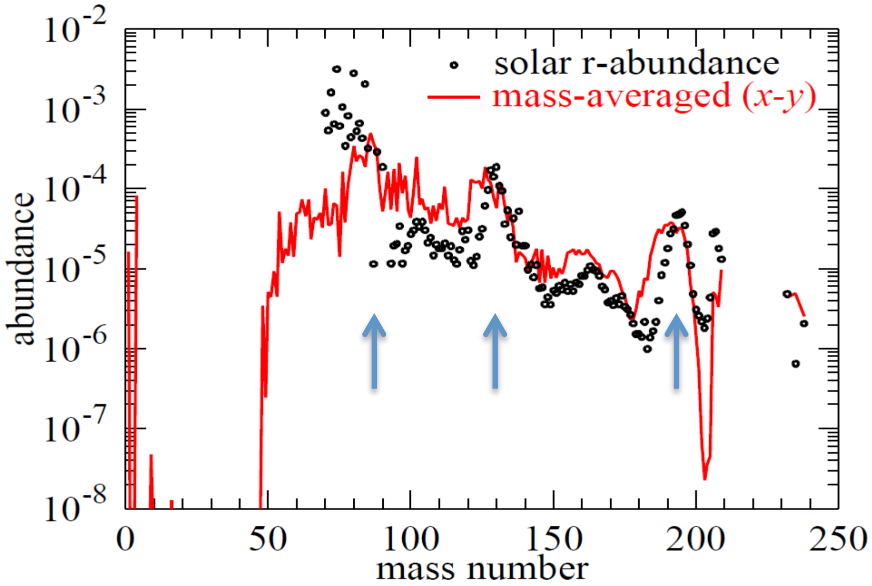
- Appropriate value of $\langle Y_e \rangle$, i.e., appropriate blending is needed: HOW ?

Earlier result

Our latest result

(Wanajo et al. ApJ)





Bauswain, Goriely, & Janka (2013)
See also Korobkin et al. (2012)

Non-GR simulation
Tidal-effect dominant
→ Neutron-rich ejecta

GR simulation
Particular EOS (SFHo)
Particular mass 1.3-1.3solar
Tidal-effect + shock
play roles

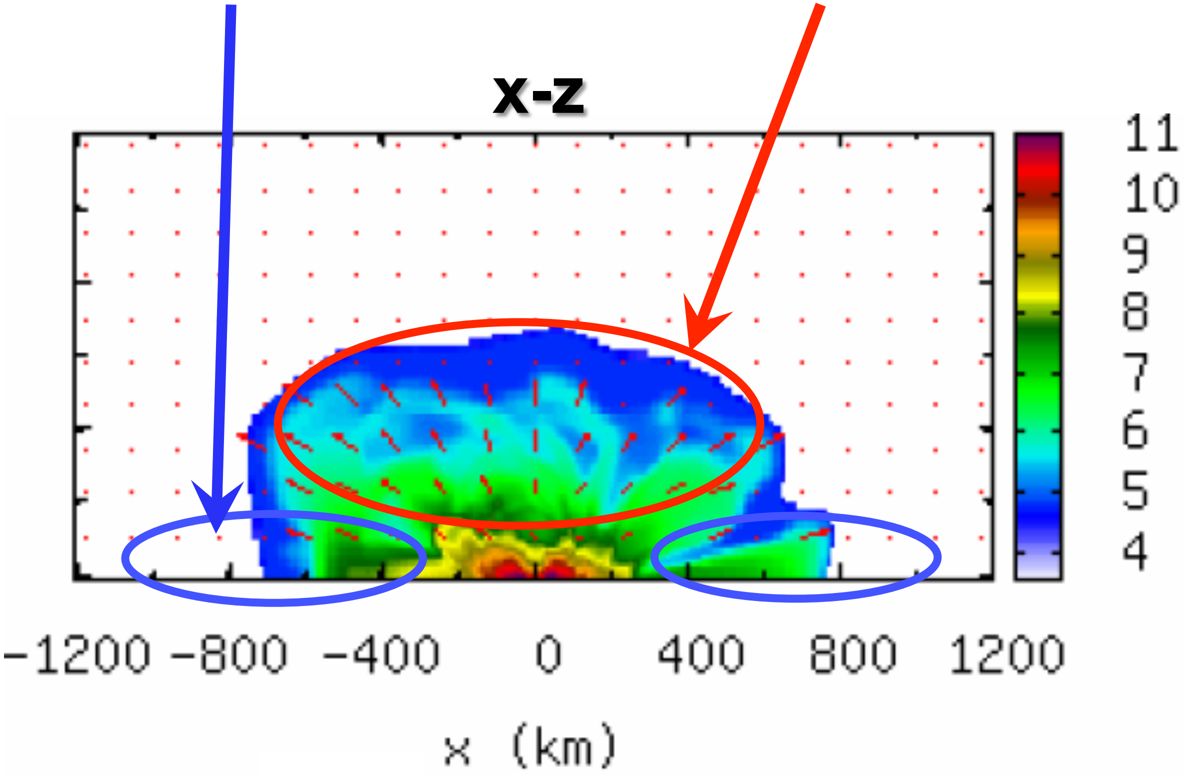
But no neutrino heating
in GR simulation

Thermodynamical properties of ejecta

Mass ejection from BNS merger : two components

- **Tidal component**
- **Low-temp, low Ye**

- **Shock-heated component**
- **High-temp, high Ye**



Variety of EOS table (we appreciate Hempel)

14.5km – **TM1 (Shen EOS)**

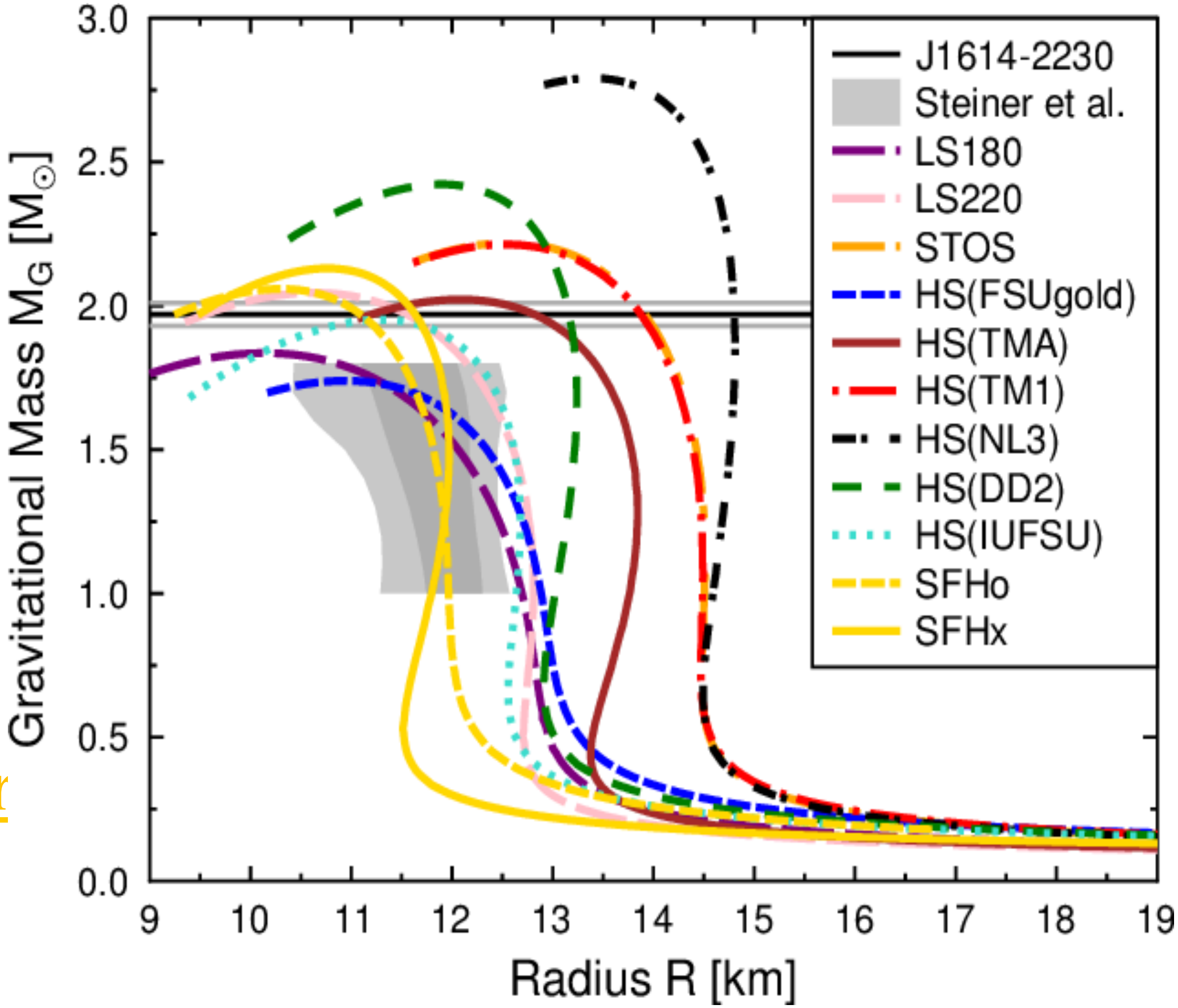
- **TMA**

13.2km – **DD2**

- **IUFSU**

11.8km – **SFHo (Steiner**

Smaller radius



Our latest study (Sekiguchi’s code)

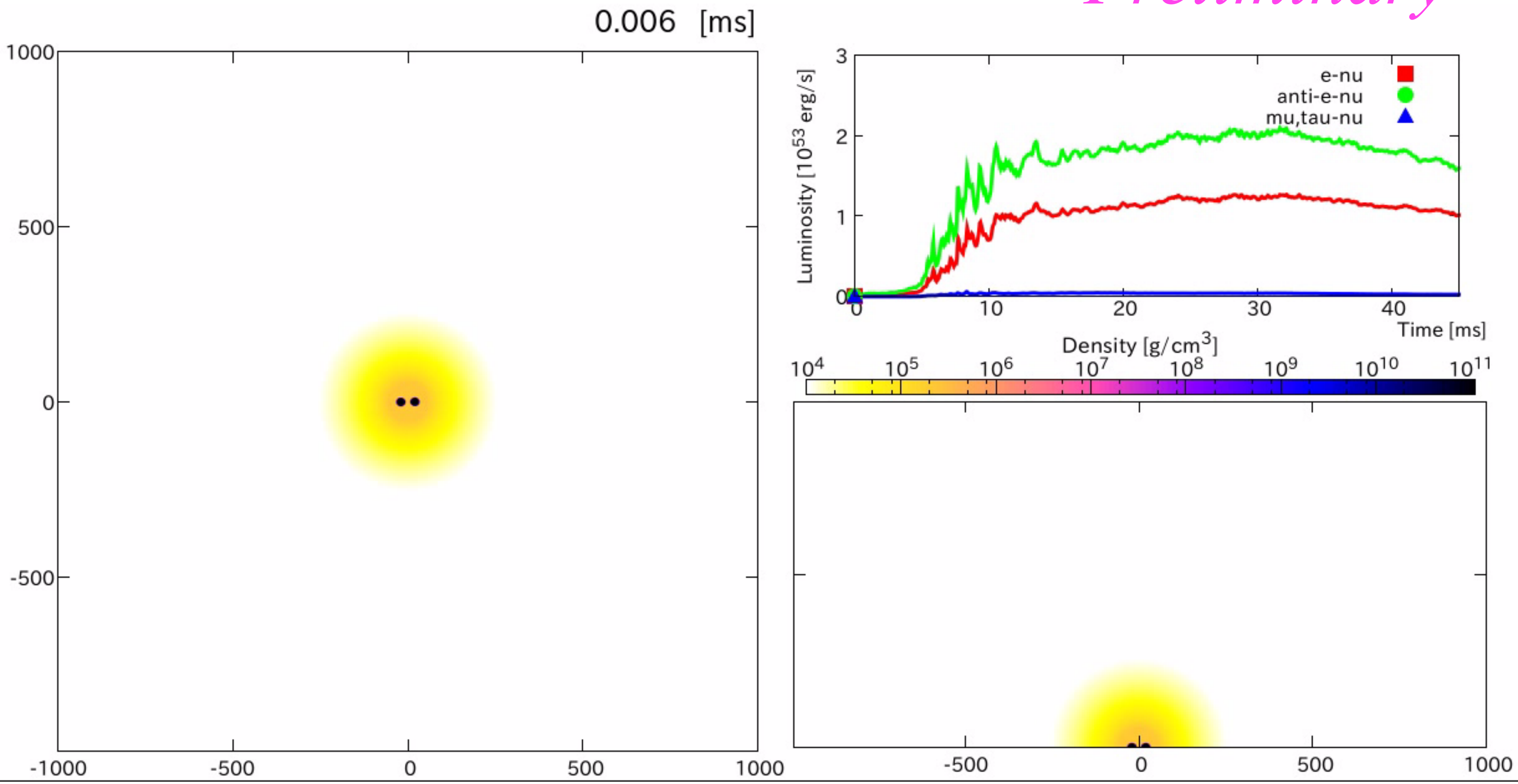
- GR: BSSN/Z4c + moving puncture gauge
- Radiation Hydro: Leakage+ (see below)
- Evolution of electron fraction per baryon
- Variety of EOS based on relativistic mean field theory by Hempel

- Leakage for optically thick region
- Radiation-moment formulation for free-streaming region with neutrino heating

TM1 (R~14.5 km): 1.35-1.35 M_{sun}

Rest-mass density

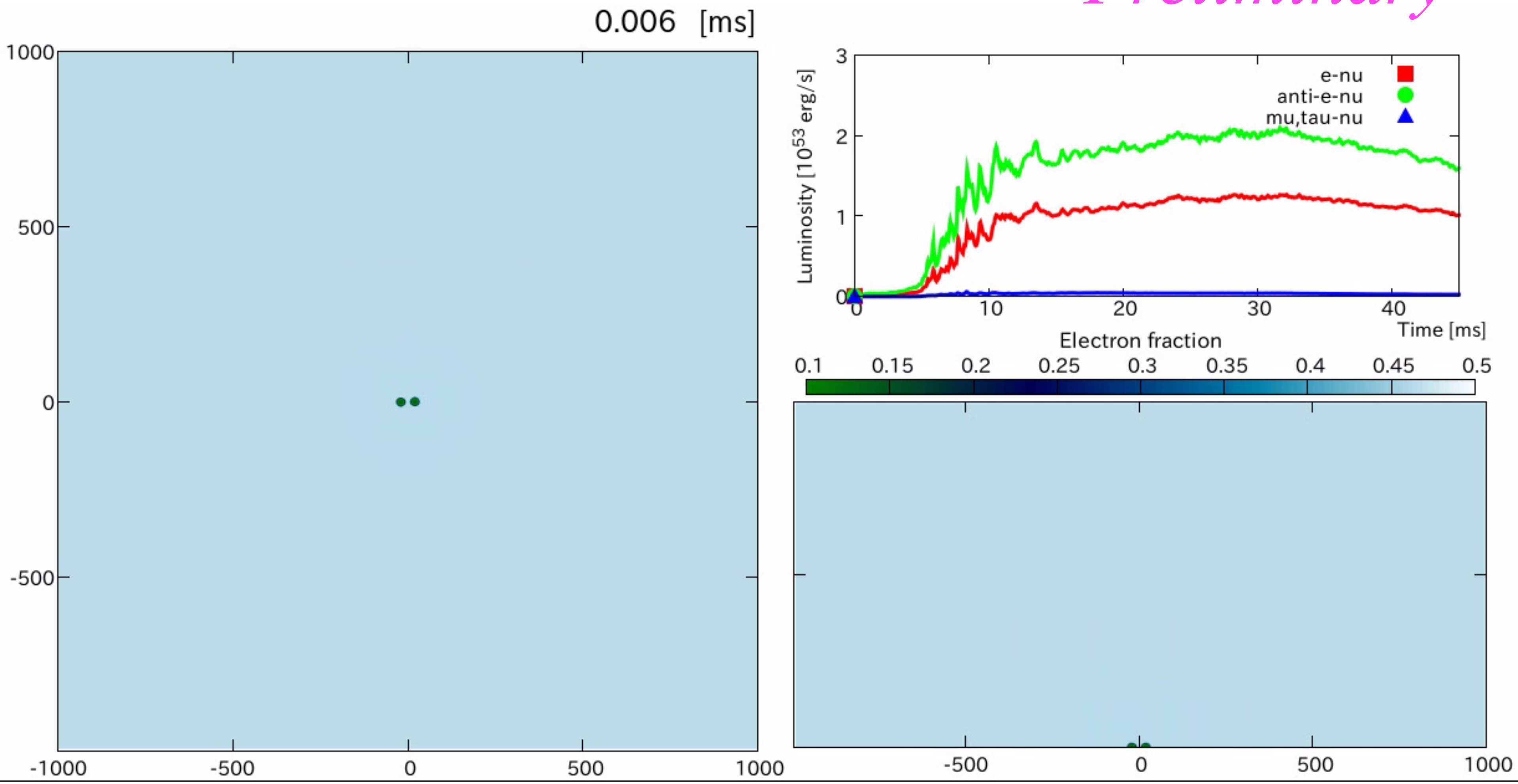
Preliminary



TM1 (R~14.5 km): 1.35-1.35 M_{sun}

Electron fraction

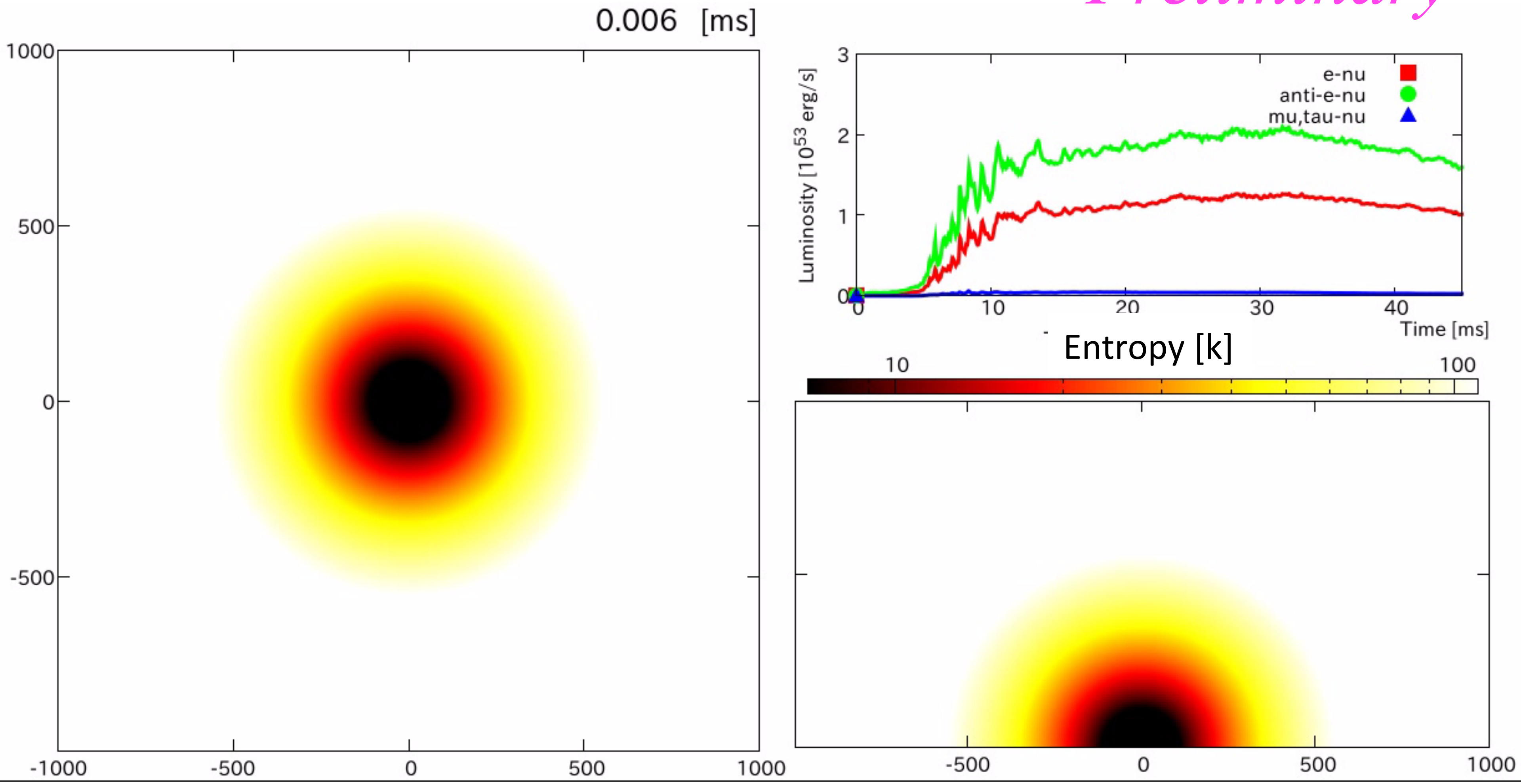
Preliminary



TM1 (R~14.5 km): 1.35-1.35 M_{sun}

Specific entropy

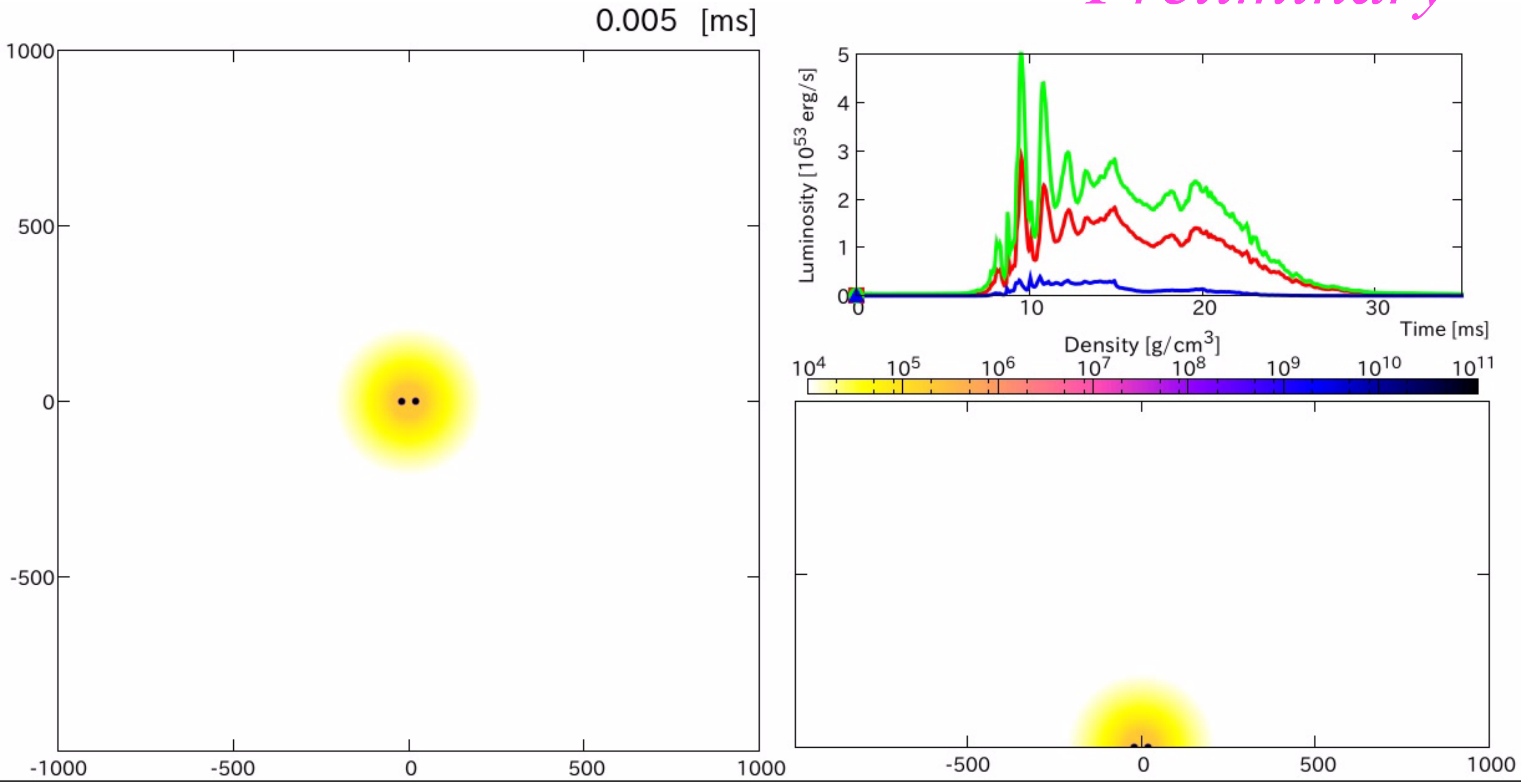
Preliminary



SFHo (R~11.8 km): 1.35-1.35 $M_{\rm sun}$

Rest-mass density

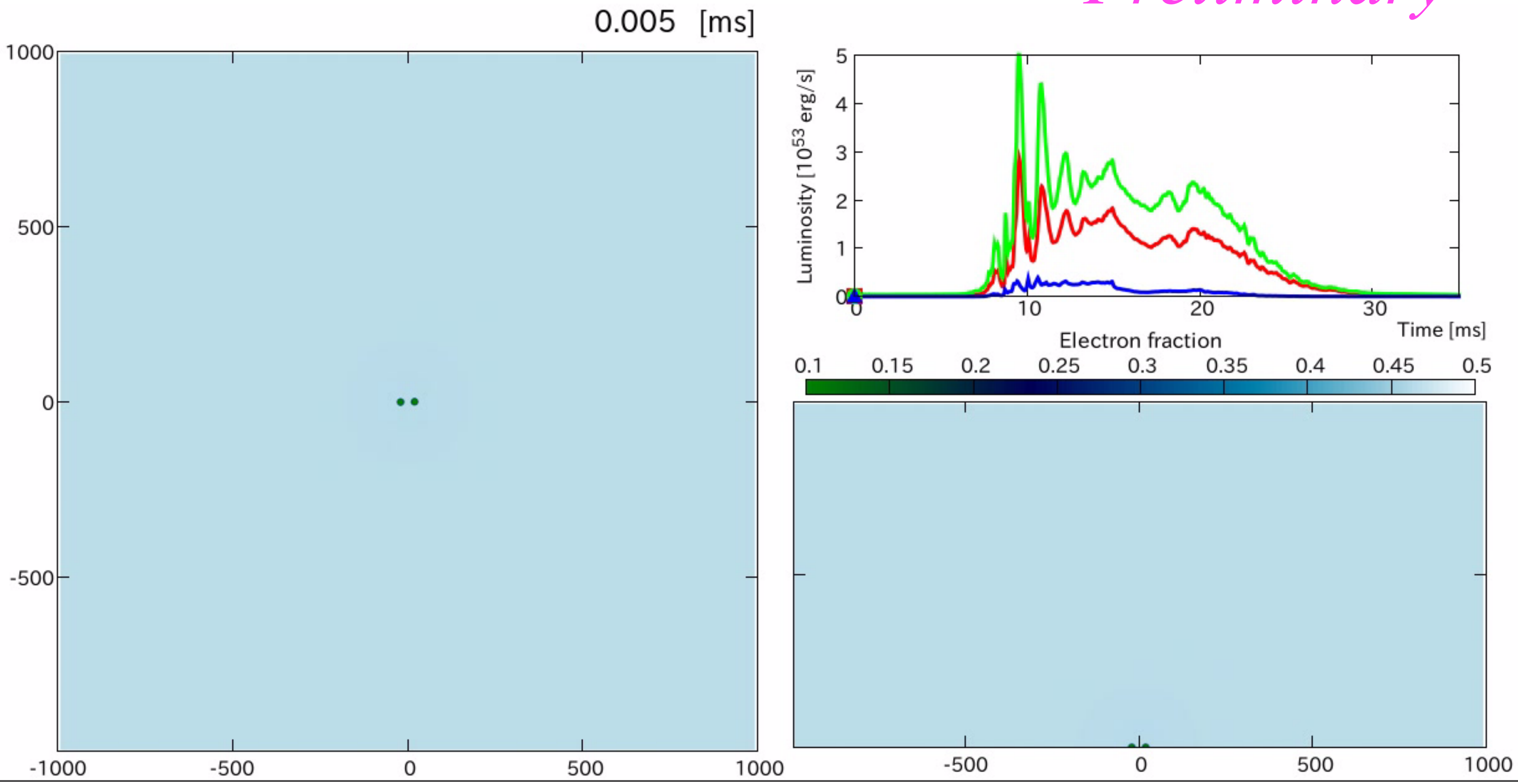
Preliminary



SFHo (R~11.8 km): 1.35-1.35 M_{sun}

Electron fraction

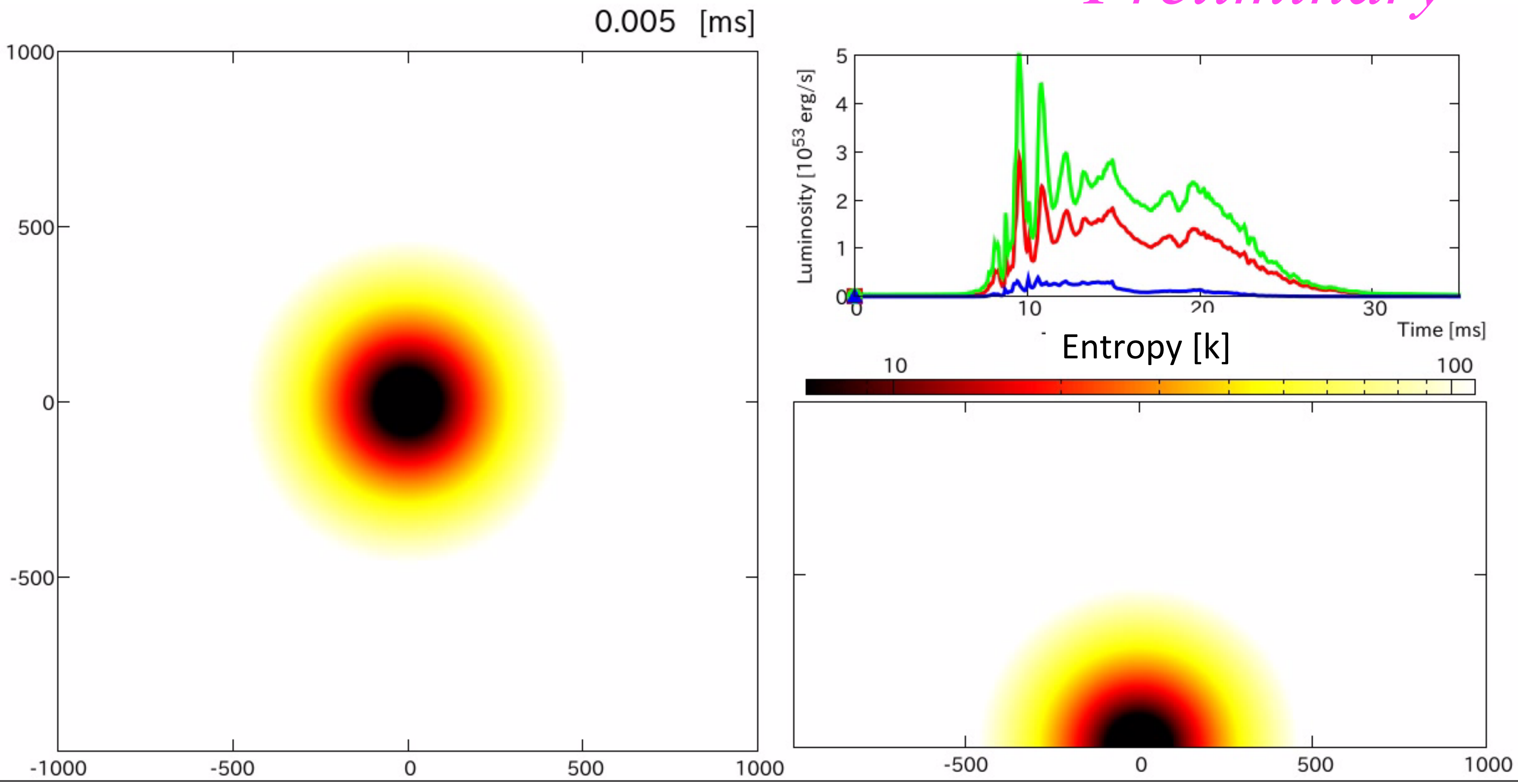
Preliminary



SFHo (R~11.8 km): 1.35-1.35 M_{sun}

Specific entropy

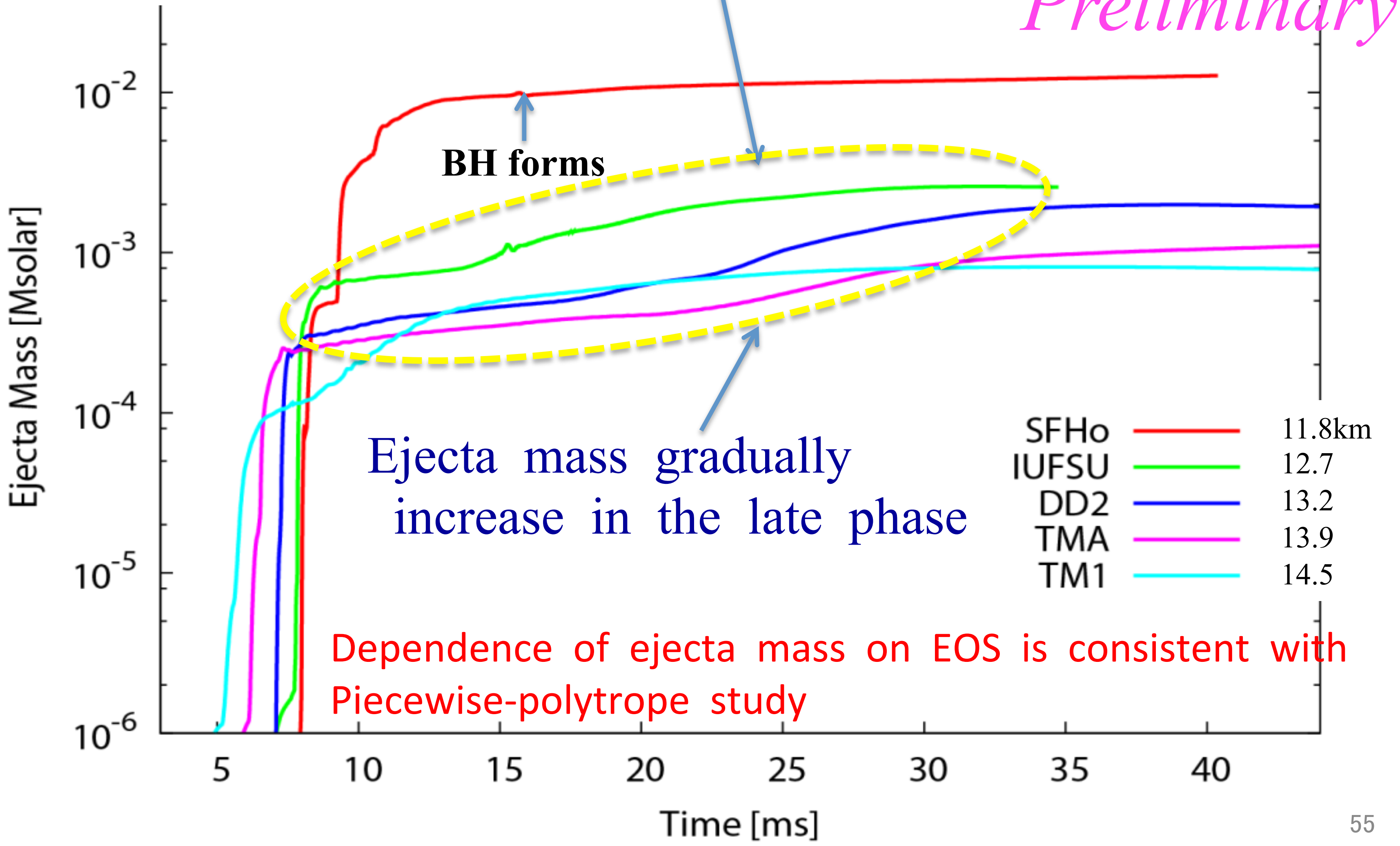
Preliminary



Ejecta rest mass

- Reconfirm larger mass for smaller NS radius
- Evidence for neutrino-driven wind

Preliminary



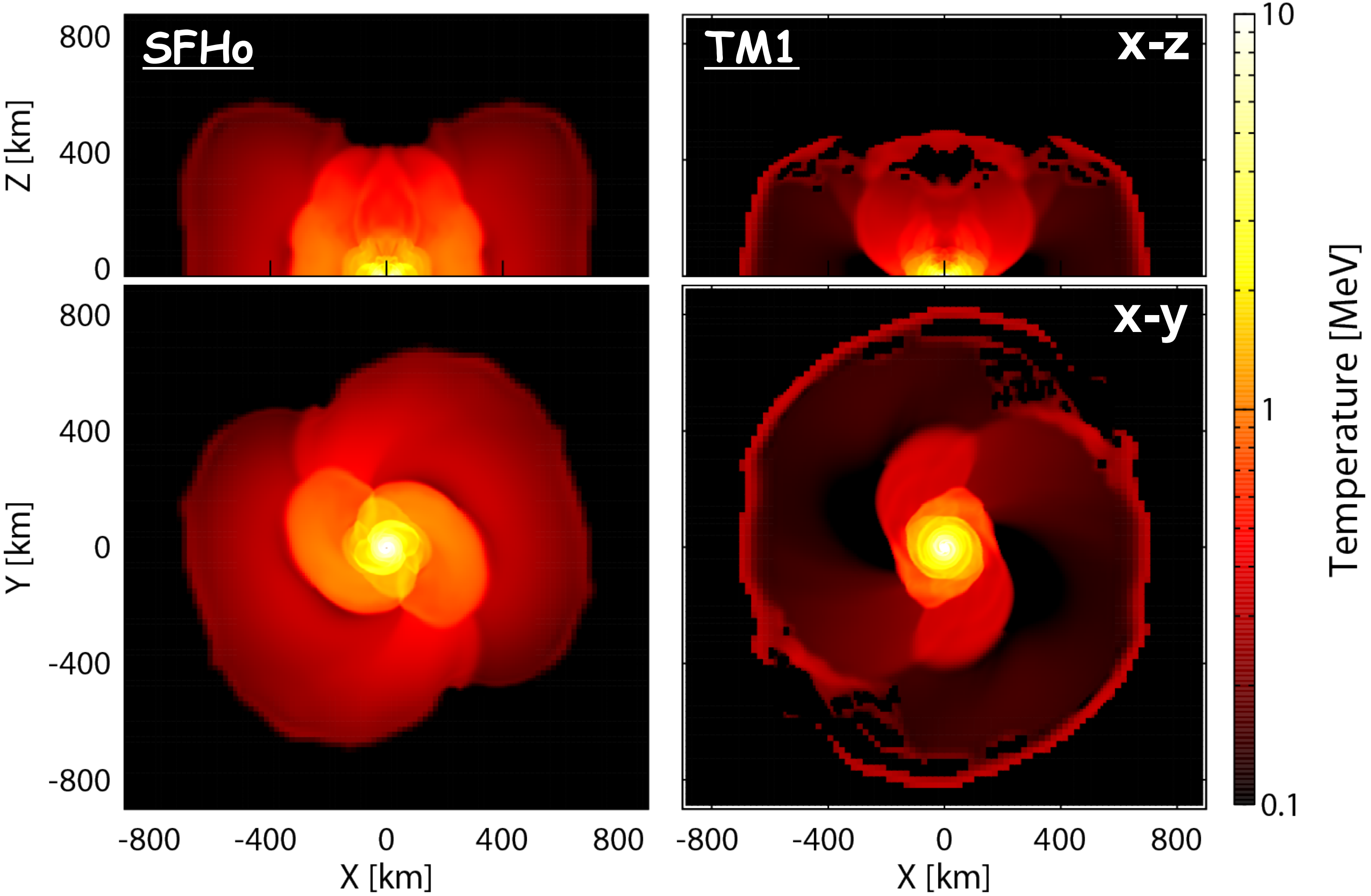
Ejecta mass gradually increase in the late phase

Dependence of ejecta mass on EOS is consistent with Piecewise-polytrope study

Ejecta temperature *Preliminary*

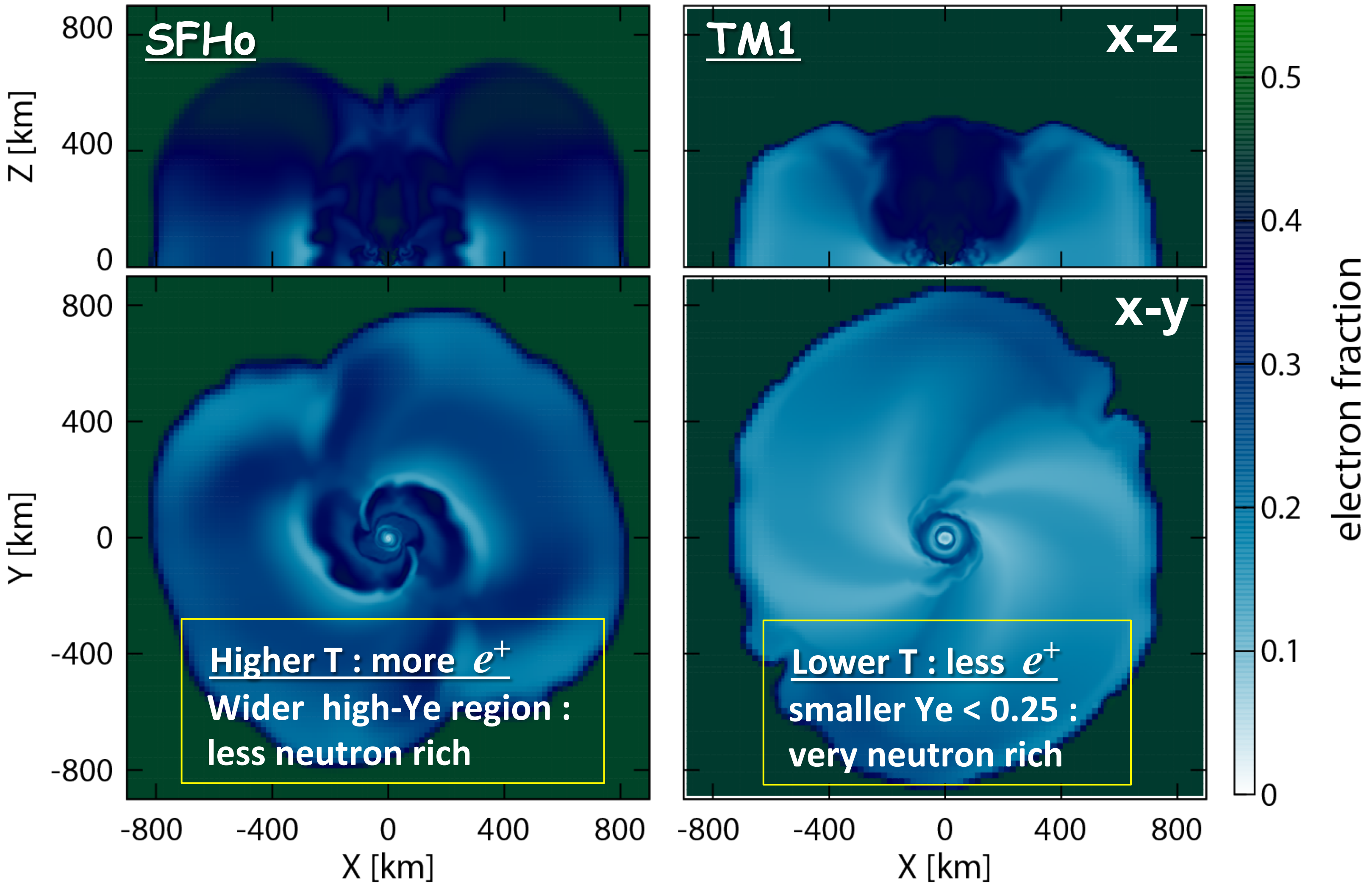
- SFHo EOS: shock heating
- High temperature

- TM1 EOS: tidal orogin
- Low temperature



SFHo EOS *Preliminary*

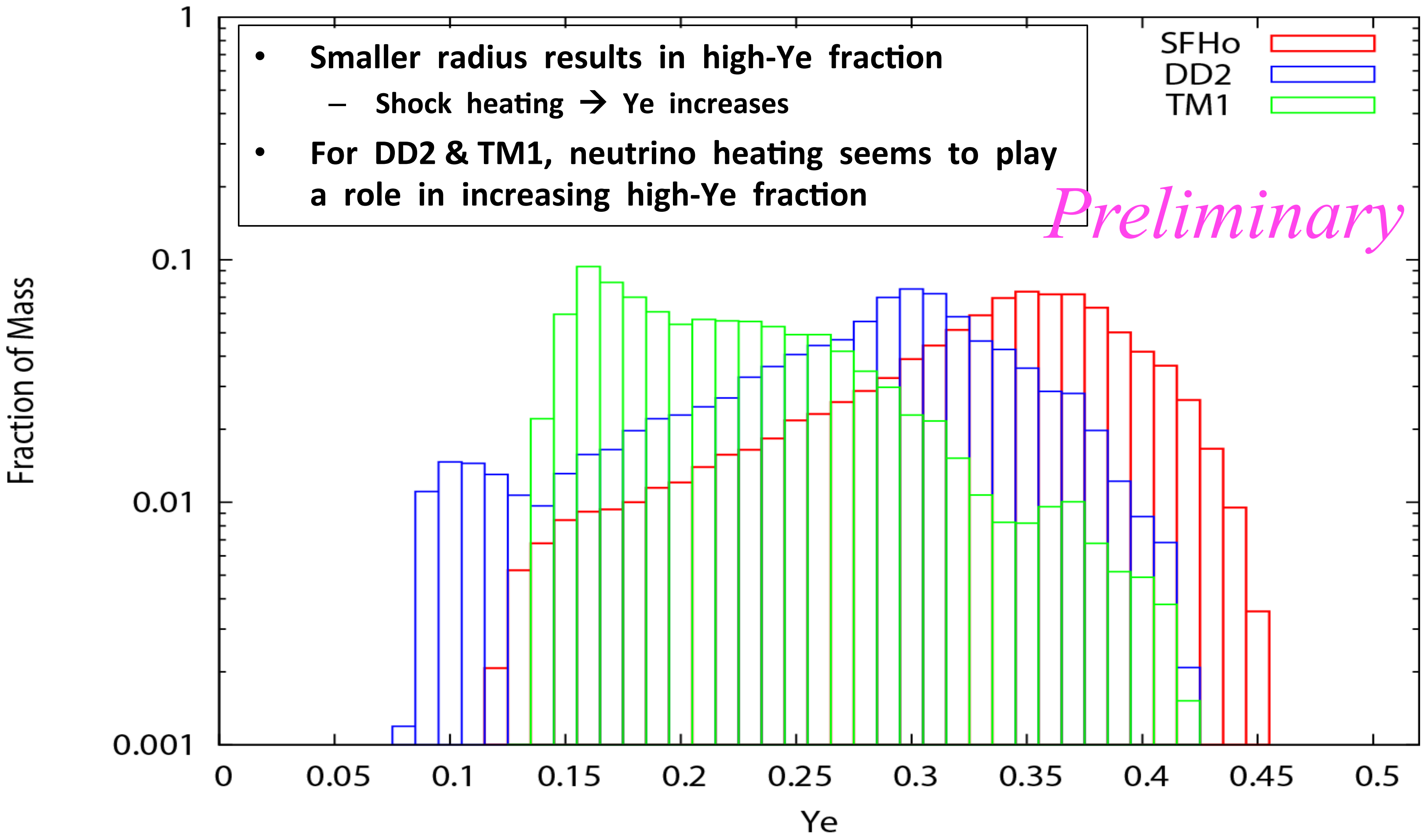
$\gamma\gamma \rightarrow e^{+} + e^{-}$, $n + e^{+} \rightarrow p + \nu$: Y_e increases



Higher T : more e^{+}
Wider high-Ye region : less neutron rich

Lower T : less e^{+}
smaller Ye < 0.25 : very neutron rich

Fraction of mass as a function of Ye



- Smaller radius results in high-Ye fraction
  - Shock heating → Ye increases
- For DD2 & TM1, neutrino heating seems to play a role in increasing high-Ye fraction

Preliminary

Which is good for solar abundance ?

→ Work ongoing by Wanajo, Nishimura, & Sekiguchi.

Summary

- Gravitational waves from NS-NS merger is a valuable site for exploring EOS of NS:
  Efforts in numerical relativity are ongoing
- Mass ejection in NS-NS merger is likely to emit strong EM signal, in particular for EOS with relatively small-NS radius
- Total mass of ejecta depends strongly on the EOS of NS
  → EM counterpart observation together with GW observation may be used to constrain EOS
- Study for r-process is ongoing

Leakage scheme with heating

- ***Step 1.*** Neutrinos are divided into ‘trapped’ and ‘streaming’ parts

$$\boxed{T_{ab}^{(\nu)} = T_{ab}^{(\nu,\mathrm{trap})} + T_{ab}^{(\nu,\mathrm{stream})}}$$

$$\nabla_a (T_b^{a\,(\nu,\mathrm{trap})} + T_b^{a\,(\nu,\mathrm{stream})}) = Q_b^{(\mathrm{weak})}$$

$$\nabla_a T_b^{a\,(\nu,\mathrm{trap})} = Q_b^{(\mathrm{weak})} - Q_b^{(\mathrm{leak})}$$

$$\boxed{\nabla_a T_b^{a\,(\nu,\mathrm{stream})} = Q_b^{(\mathrm{leak})}}$$

  - Trapped : interact sufficiently frequently with matter
  - Streaming : phenomenological flow of freely streaming neutrinos (characterized by **leakage timescale**)

- ***Step2.*** Trapped-ν is combined with fluid part: $\boxed{T_{ab} = T_{ab}^{(\mathrm{fluid})} + T_{ab}^{(\nu,\mathrm{trap})}}$

$$\begin{array}{l} \nabla_a T_b^{a\,(\mathrm{fluid})} = -Q_b^{(\mathrm{weak})} \\ \nabla_a T_b^{a\,(\nu,\mathrm{trap})} = Q_b^{(\mathrm{weak})} - Q_b^{(\mathrm{leak})} \end{array} \Longrightarrow \boxed{\nabla_a T_b^a = -Q_b^{(\mathrm{leak})}}$$

  - Solve advection term using truncated moment formalism with a closure

- ***Source term.*** $\boxed{Q_a^{(\mathrm{leak})} = (1-e^{-\tau})Q_a^{(\mathrm{diff})} + e^{-\tau} Q_a^{(\mathrm{weak})}}$

$$Q_a^{(\mathrm{weak})} = \dot{Q}^{(\mathrm{cool})} u_a + Q_a^{(\mathrm{heat})}$$
$$= \dot{Q}^{(\mathrm{cool})} u_a - \kappa_\nu J_\nu u_a$$

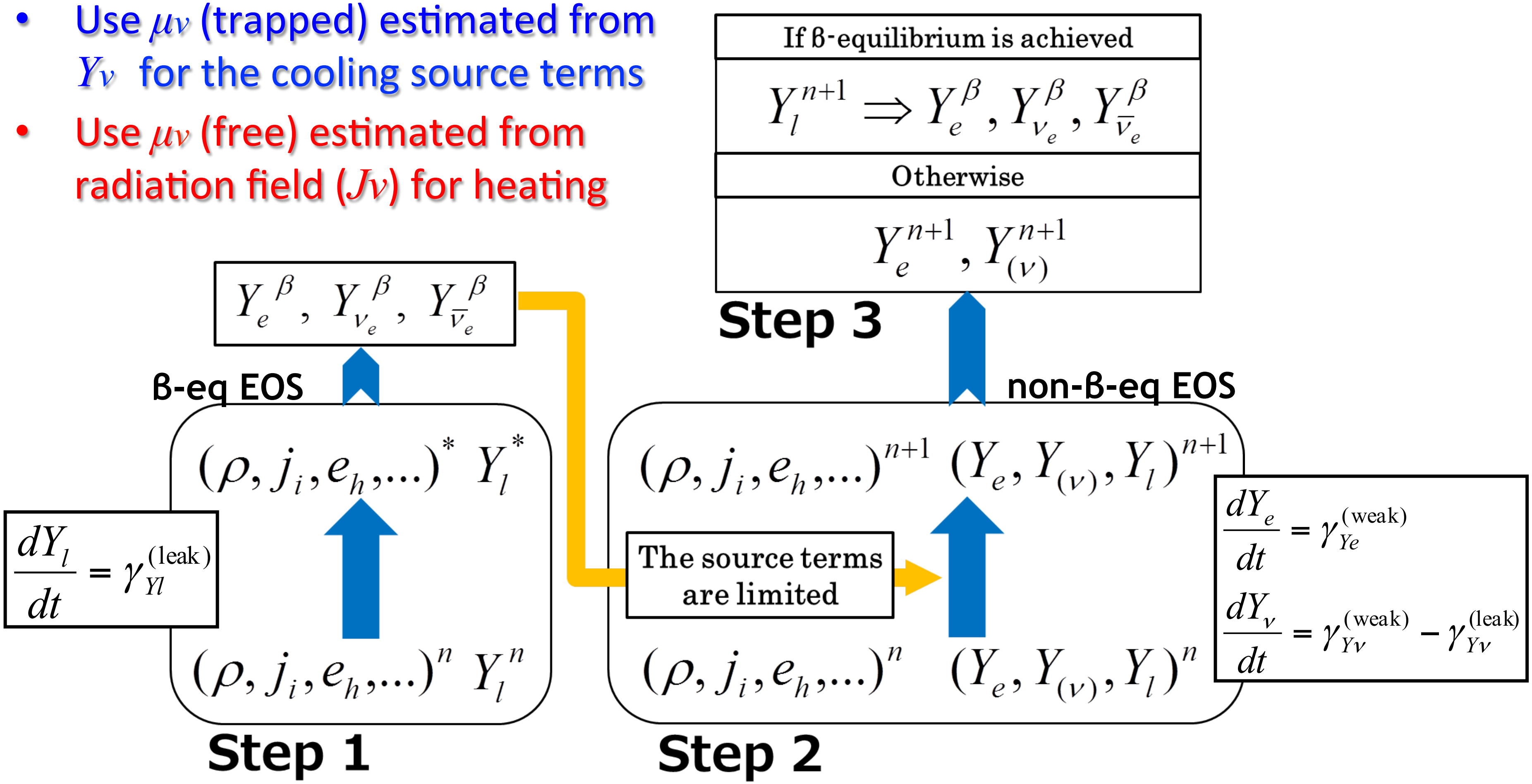
  - Q^{cool} includes e± captures, pair annihilation, plasmon decay, Bremsstrahlung
  - Q^{diff} is calculated based on Rosswog & Liebendoerfer (2004)

- Electron, neutrino, and total lepton fractions are also evolved

Limiter prescription

- Conservation equations for electron and trapped neutrino fractions
  - Weak timescale appears ⇒ <u>We introduce a ‘limiter’ to solve them explicitly</u>

- Use μ_ν (trapped) estimated from Y_ν for the cooling source terms
- Use μ_ν (free) estimated from radiation field (J_ν) for heating



If β-equilibrium is achieved

$$Y_l^{n+1} \Rightarrow Y_e^{\beta}, Y_{\nu_e}^{\beta}, Y_{\bar{\nu}_e}^{\beta}$$

Otherwise

$$Y_e^{n+1}, Y_{(\nu)}^{n+1}$$

Step 3

$$Y_e^{\beta}, Y_{\nu_e}^{\beta}, Y_{\bar{\nu}_e}^{\beta}$$

β-eq EOS

non-β-eq EOS

$$(\rho, j_i, e_h, \ldots)^{*} \quad Y_l^{*}$$

$$\frac{dY_l}{dt} = \gamma_{Yl}^{(\mathrm{leak})}$$

$$(\rho, j_i, e_h, \ldots)^{n} \quad Y_l^{n}$$

Step 1

$$(\rho, j_i, e_h, \ldots)^{n+1} \quad (Y_e, Y_{(\nu)}, Y_l)^{n+1}$$

The source terms are limited

$$\frac{dY_e}{dt} = \gamma_{Ye}^{(\mathrm{weak})}$$

$$\frac{dY_\nu}{dt} = \gamma_{Y\nu}^{(\mathrm{weak})} - \gamma_{Y\nu}^{(\mathrm{leak})}$$

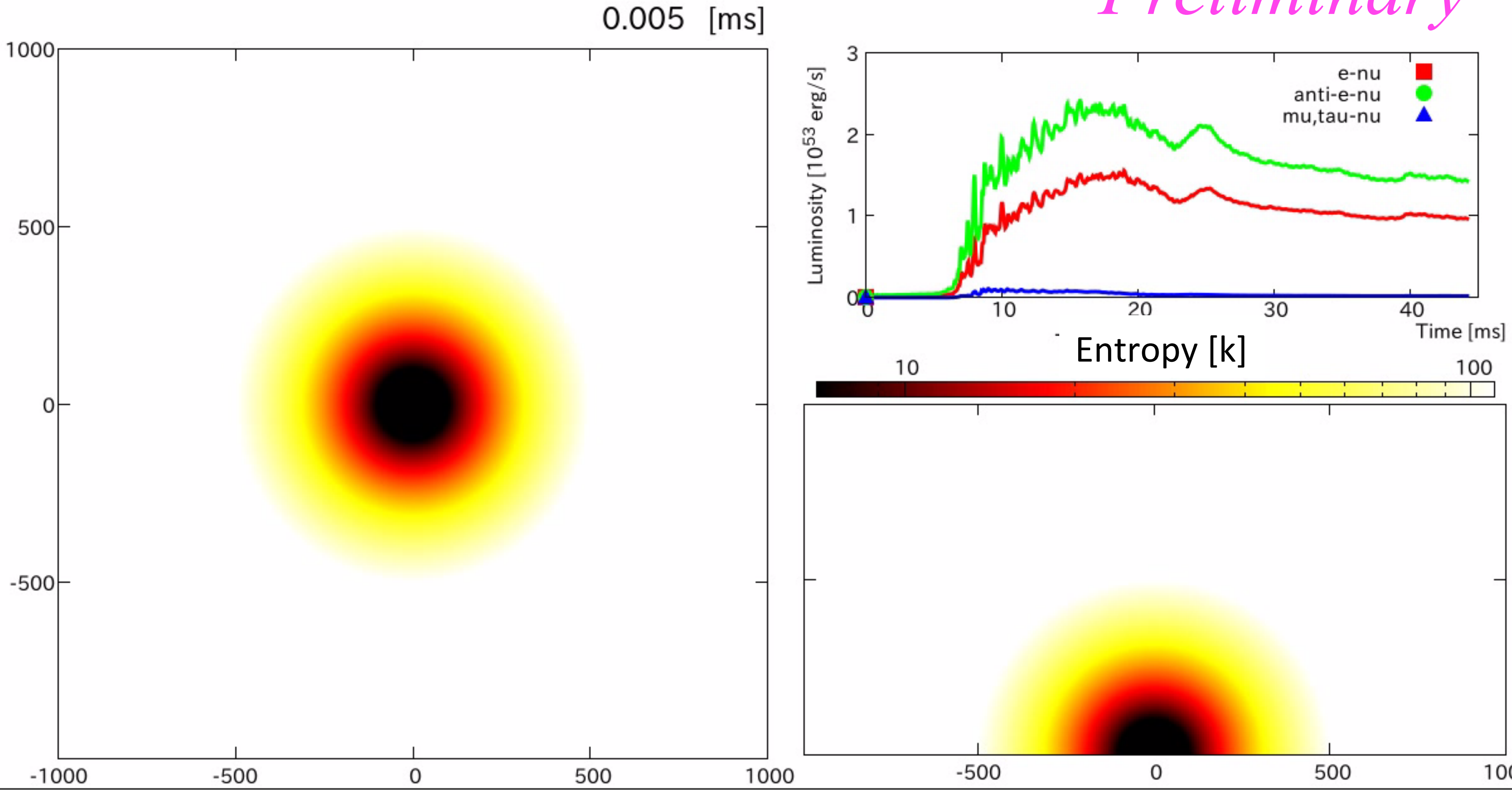
$$(\rho, j_i, e_h, \ldots)^{n} \quad (Y_e, Y_{(\nu)}, Y_l)^{n}$$

Step 2

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

Specific entropy

Preliminary



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

Electon fraction

Preliminary