Setting stages: Status & issues of neutron-star binary merger in numerical relativity

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0 Background

- Numerical-relativity data are required for the coming observations.
- Numerical-relativity data will be tested for the next 5-10 yrs observation.
- Happy epoch will come.
- However, we need more carefulness and more efforts.

Major roles of numerical relativity for neutron-star binary mergers

1. Deriving accurate gravitational waveforms: clarifying dependence on EOS, mass, spin
2. Clarifying the remnant & its evolution: Could it be central engine of short GRBs ?
3. Quantifying ejecta: mass, velocity, temperature, neutron-richness (→ opacity)

1 Gravitational waveforms: Inspiral

- **Goal**: Making an accurate template that depends on mass, spin, & EOS
- **Procedure**: Accurate numerical simulation → analytical or semi-analytical modeling (e.g., by effective-one-body; Bernuzzi's talk)

- **Numerical relativists have to perform accurate simulations for a variety of mass, spin & EOS**

Current status in (my) understanding

Accurate simulations are getting possible:

- Eccentricity reduction for initial condition is crucial → getting standard: SXS, Kyoto, Jena, ..
- Long-term simulations are necessary: expensive but not problem for ~15-20 orbits → More ?? (although I don't think so)
- Taking convergence is a key (note that for hydro simulations, convergence is 3-4th order): Constraint propagation prescription is found to be robust for improving the convergence (e.g., Bernuzzi, Hildtich et al.)

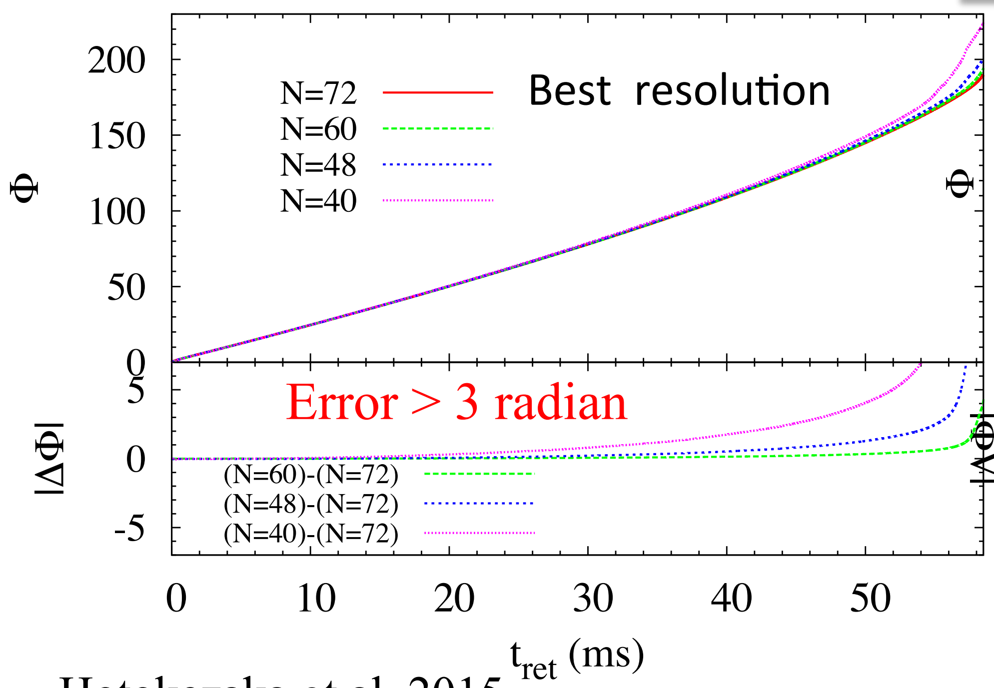
Hydro results are at best, 3rd-4th-order convergence

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

But, extrapolation can give an "almost" solution fortunately

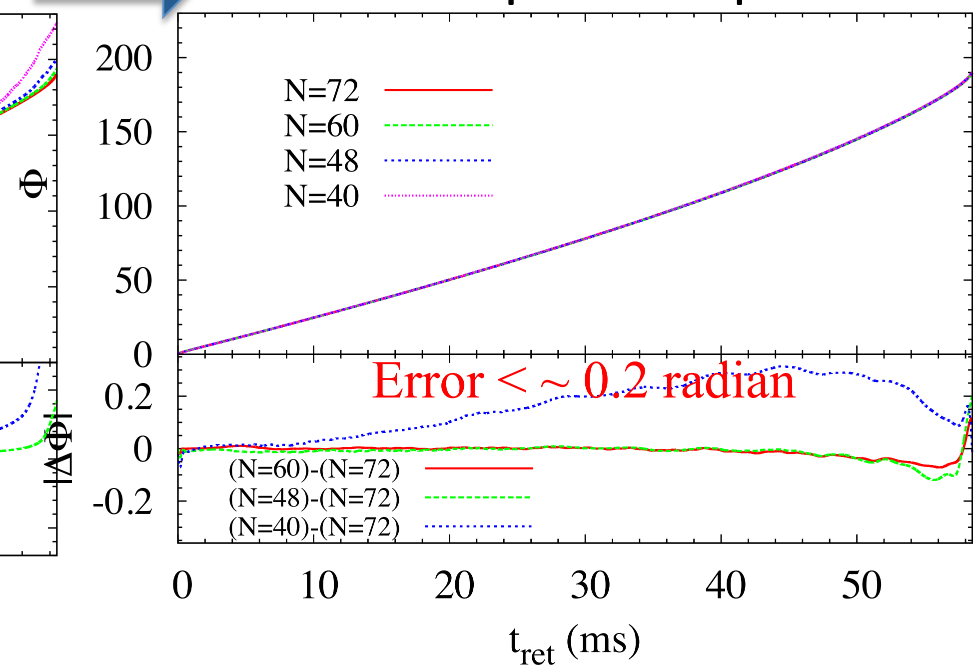
$$t \to \eta\, t, \quad \Phi = \int 2\pi f\, d(\eta\, t)$$

Gravitational wave phase



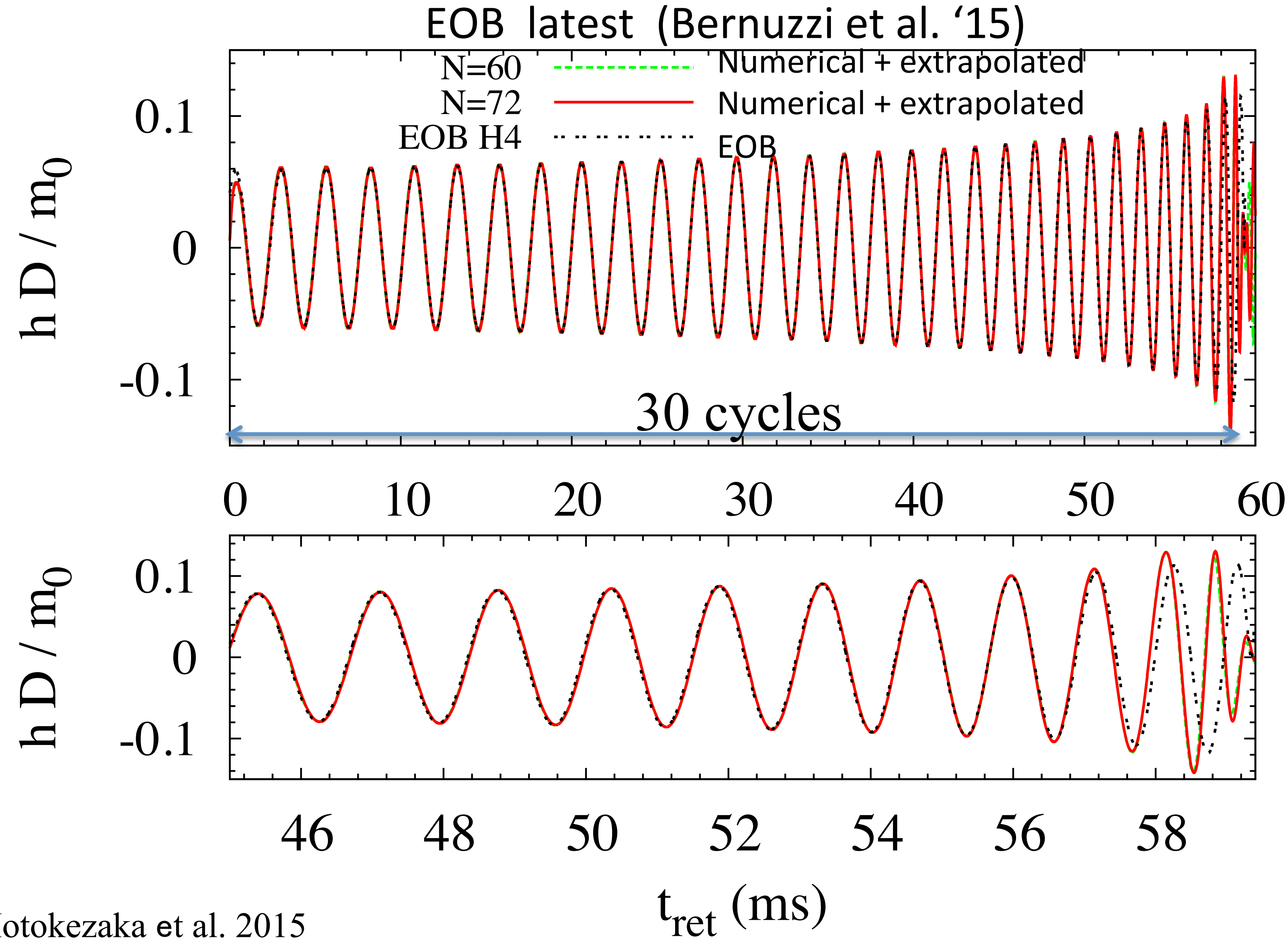
Hotokezaka et al. 2015

Extrapolated phase



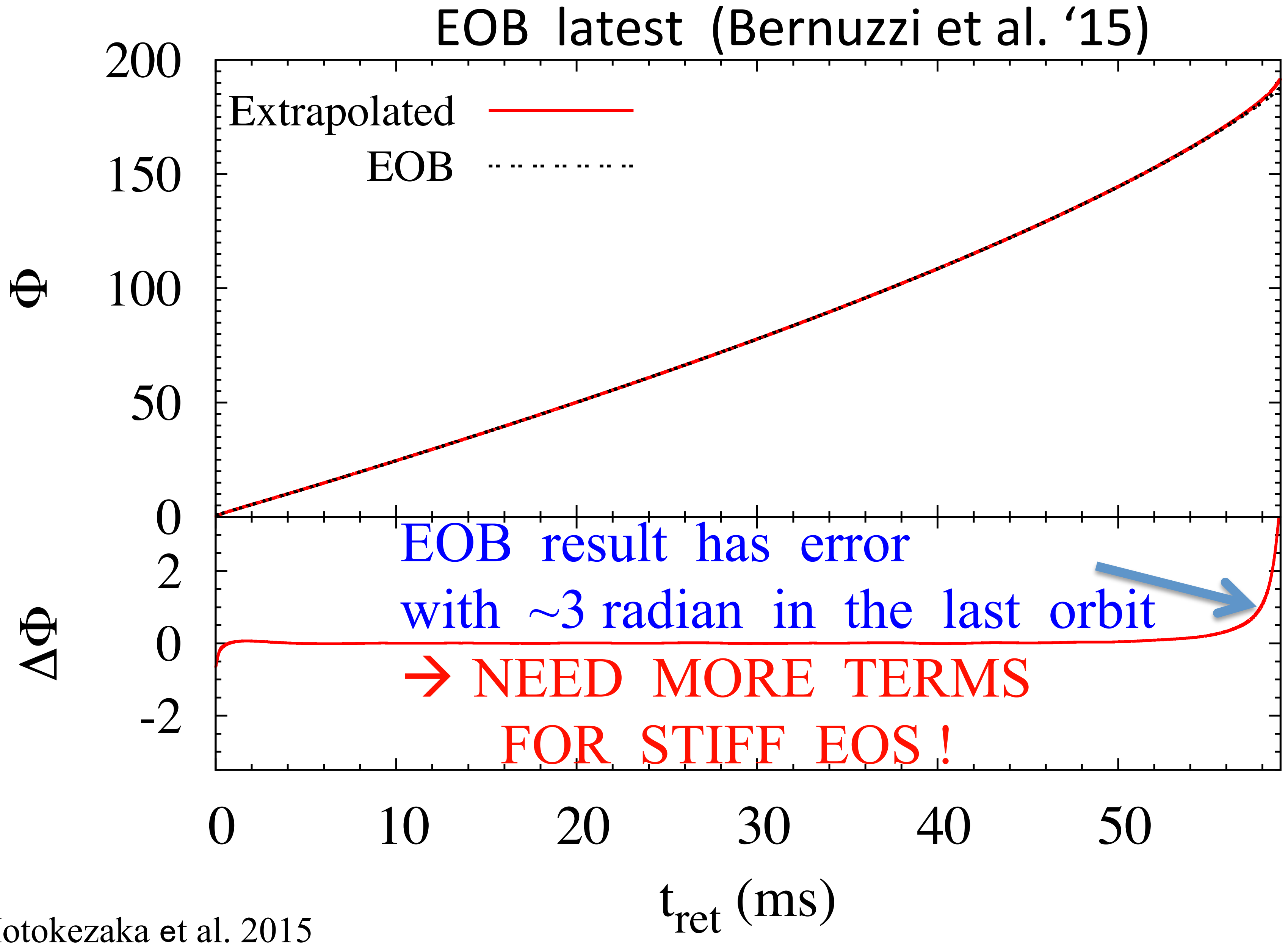
~3.5±0.5th-order convergence

Extrapolated waveform vs EOB for R=13.6 km



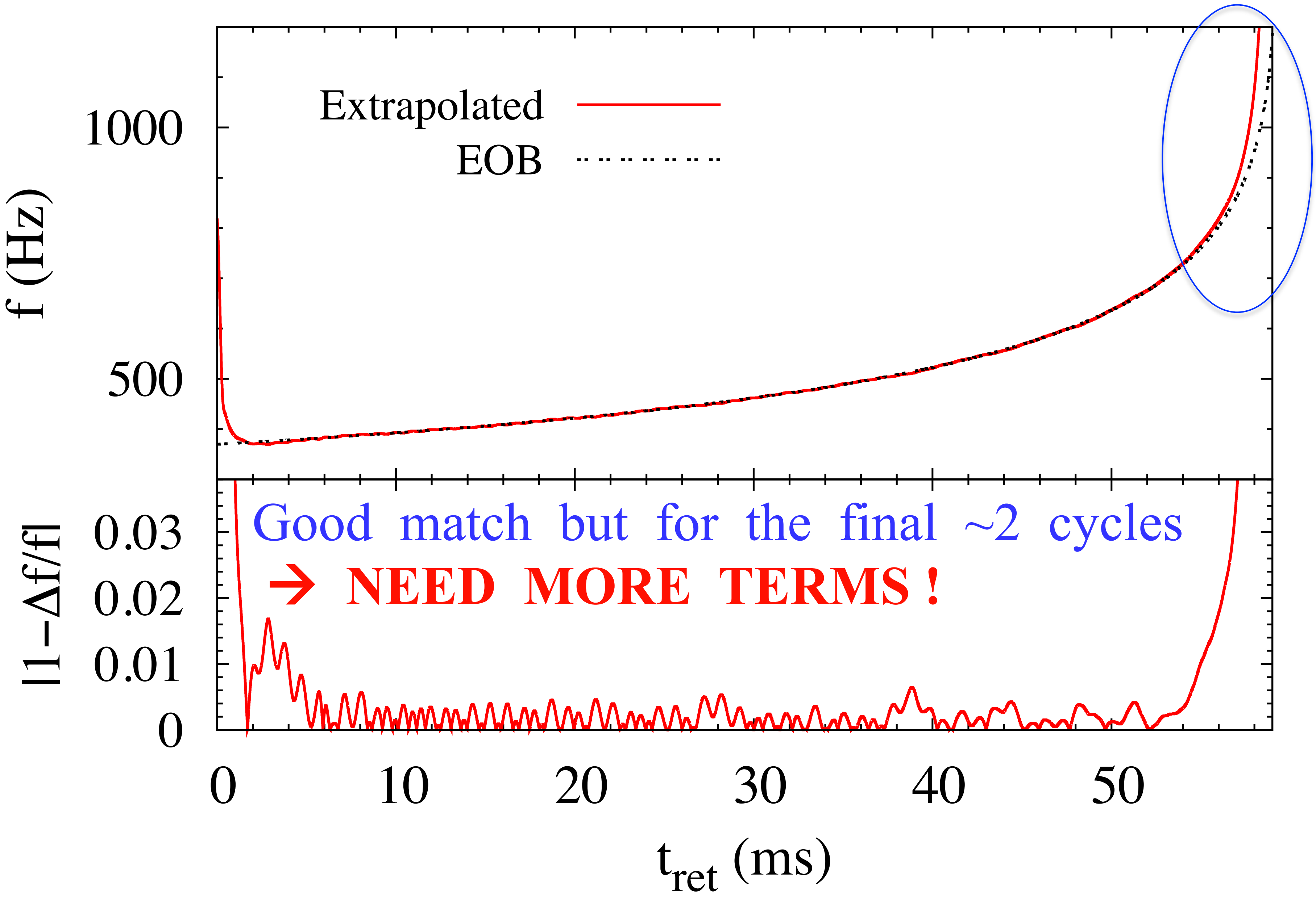
Hotokezaka et al. 2015

Comparison with effective-one-body approach

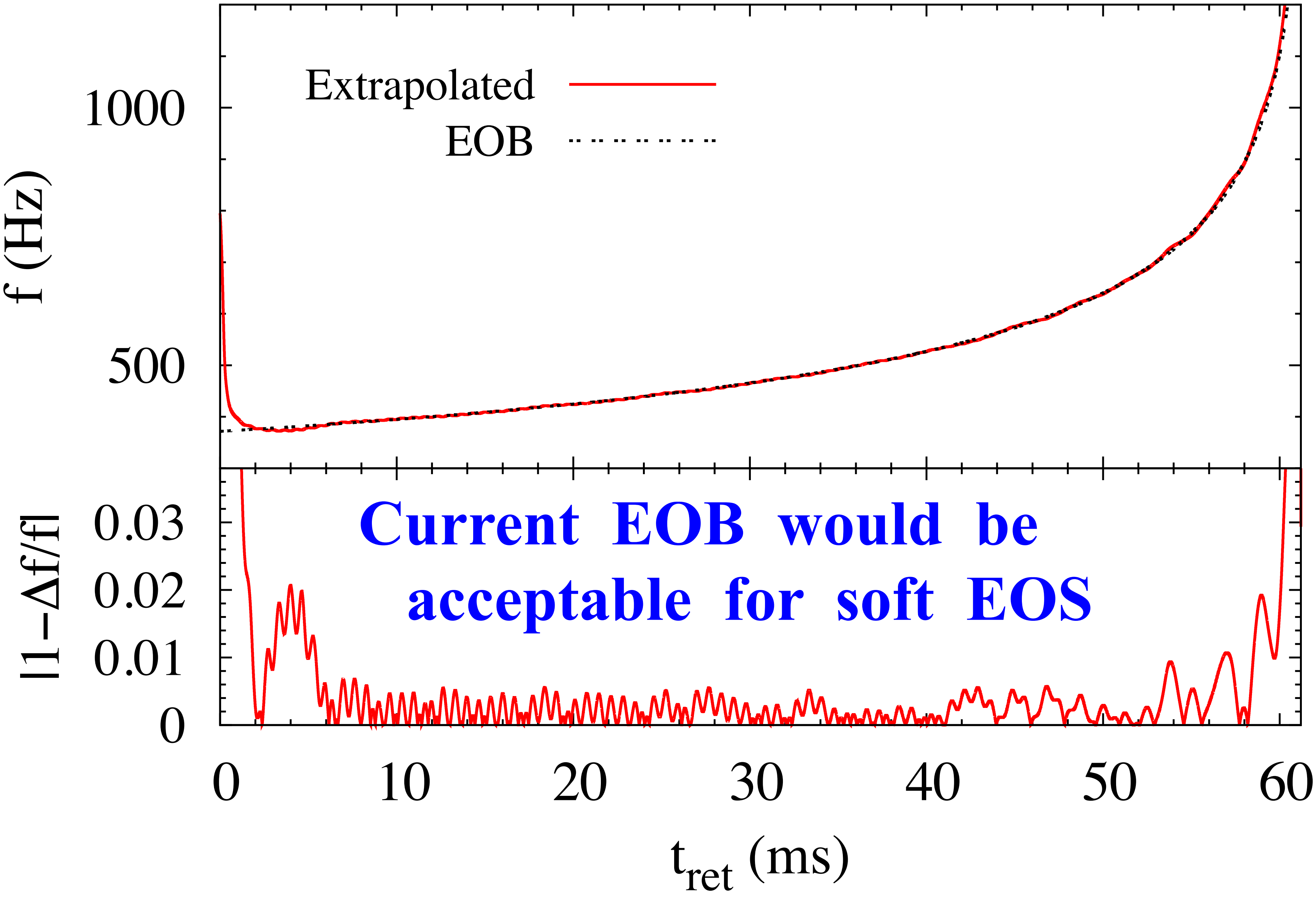


Hotokezaka et al. 2015

Comparison with EOB: frequency



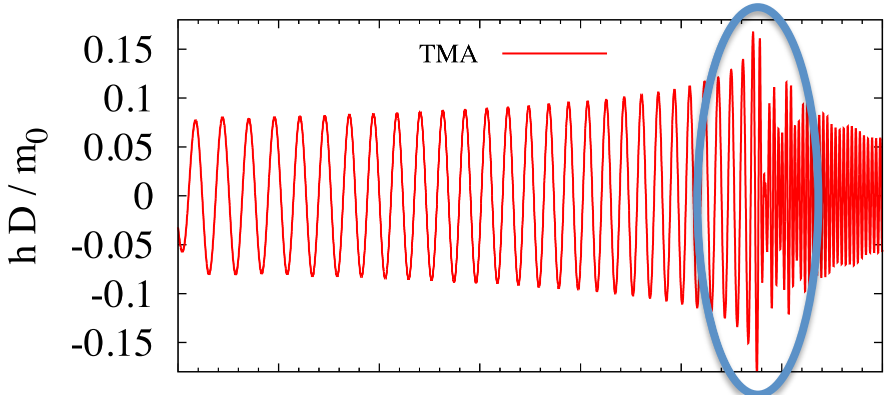
Good match for R=11.1 km (APR4)



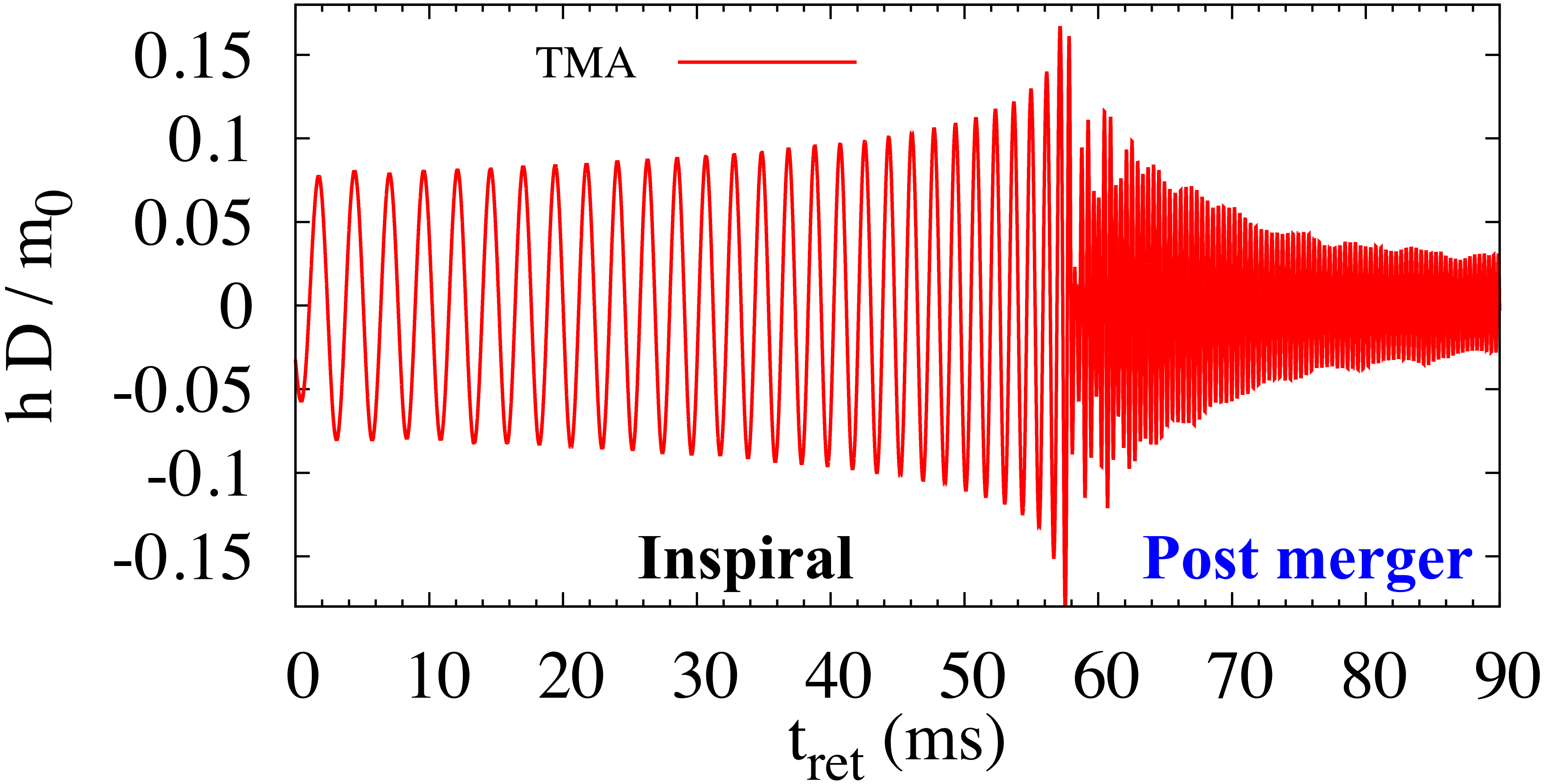
1 Gravitational waveforms: Inspiral

Issues

- EOB is promising (Bernuzzi's talk) but modeling by EOB + static tidal deformability is not enough:
  → + resonance ? (Hinderer et al.) + more ?
- Only a few accurate works for BH-NS (Foucart et al.)
  → need more systematic simulations for this
- How we model NS-NS inspiral + early *merger* waveform ?
  This is crucial for improving of SNR for $f \sim 1$kHz

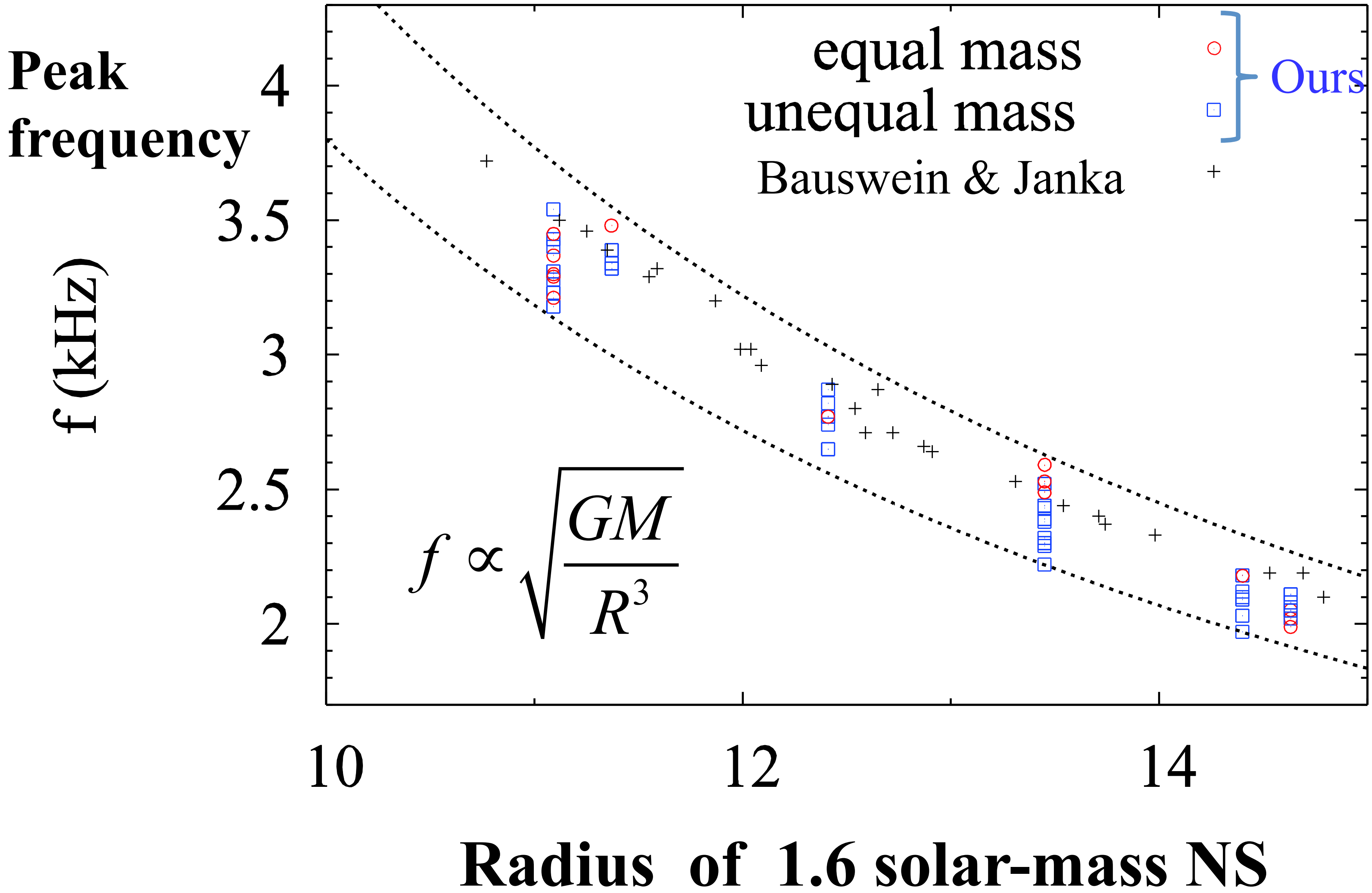


1 Gravitational waveforms: post Merger



- **Inspiral**: cold EOS, no shock heating, no MHD
- **Post merger**: Shock → Hot, MHD, neutrinos …

Clear correlation between peak and radius



Issues

- **After merger = after shock heating**
- Effect of shock heating changes waveforms: $\Delta f \sim 0.1$kHz ?? → **need to clarify systematics**
- MHD/viscous effects may be important
- Effect of microphysics ? Neutrino cooling may play a role for long-term evolution.
- **Note : The latest universal relation argument usually ignores all these uncertainties**

→ **Systematic error should be clarified**

2 Merger & remnant

NS-NS: Typical remnant = massive neutron star for typical mass (e.g., 1.35-1.35 M_{sun} NS)

BH-NS: BH + torus (if NS is tidally disrupted)

Questions:

- **How hyper/supramassive neutron stars evolve ?**
- **How resulting BH + torus evolve ?**

More specifically:

- **How is the neutrino effect ?**
- **How is the magnetohydrodynamics effect ?**

Simulations for merger remnant

Current status:

- GR radiation hydro simulations are ongoing:
  Leakage or M1 grey (Sekiguchi, Foucart, Palenzela ...)
  → semi-quantitative study (quite interesting results)
- A high-resolution MHD simulation is ongoing:
  Kiuchi et al. demonstrate high-resolution is crucial

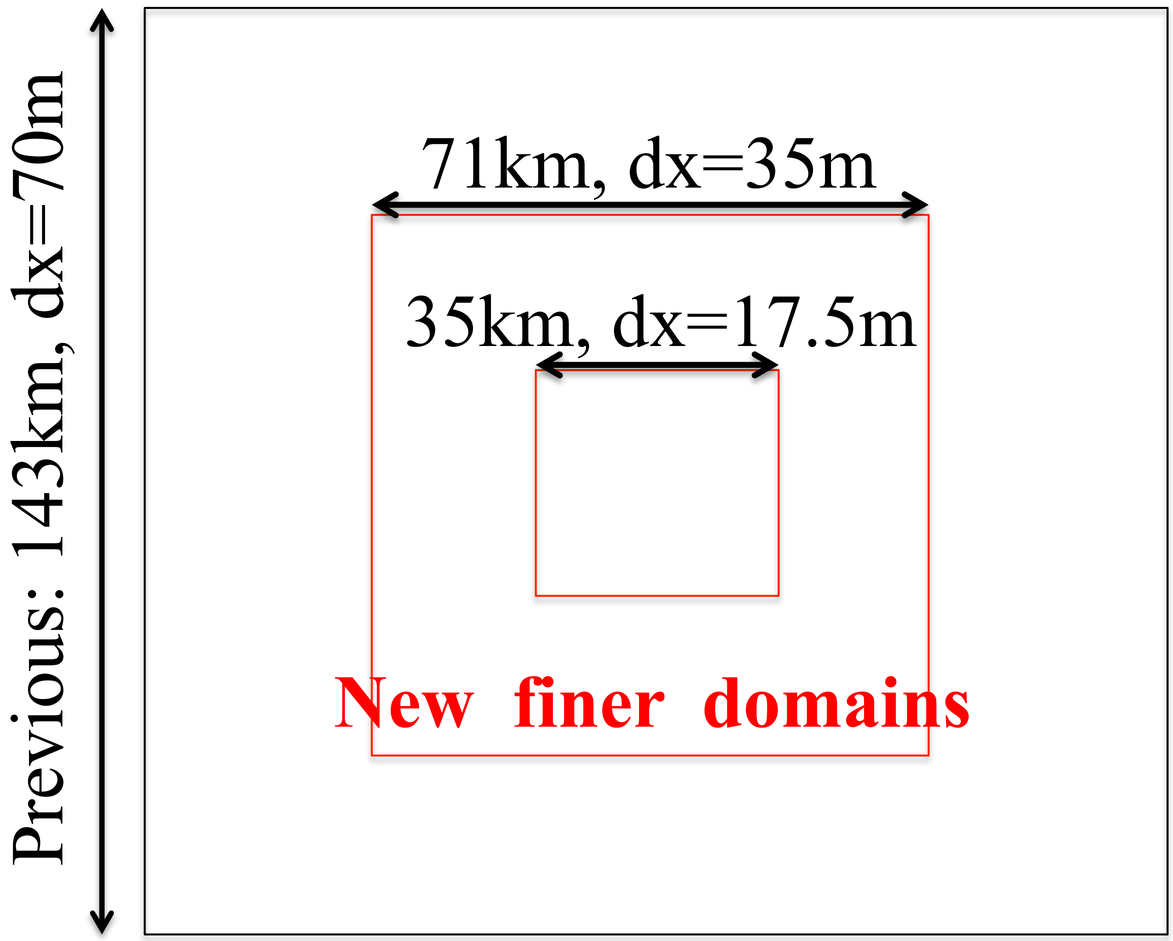
Questions:

- Are more detailed radiation transfer effects needed ?
  → anyway, need try and comparison
- Probably, **radiation hydro + angular momentum transport effects** would be keys → GRRMHD ?
- For GRBs, pair-annihilation should be considered (Just's talk)

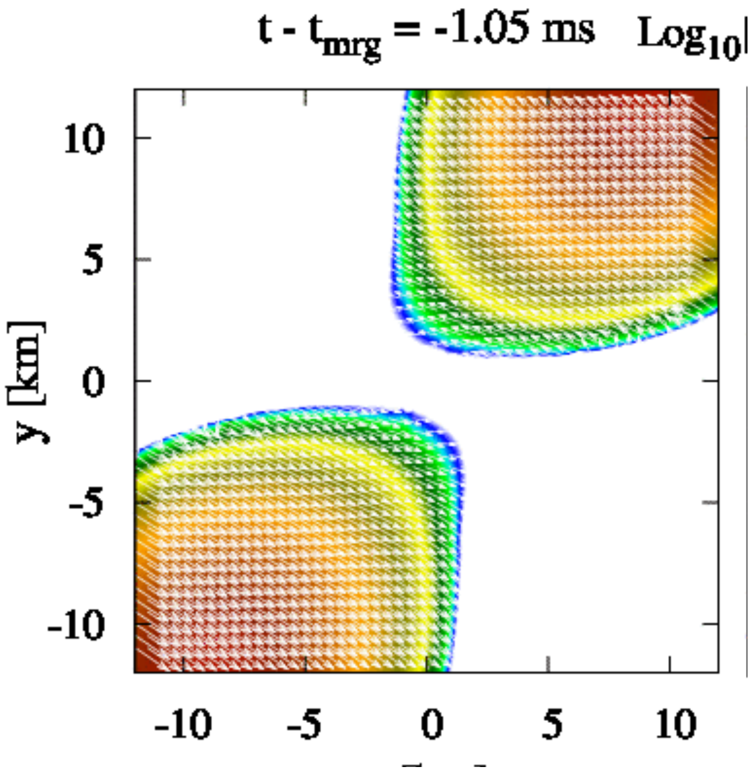
High-resolution GRMHD simulations

Kiuchi et al. 2015 in prep

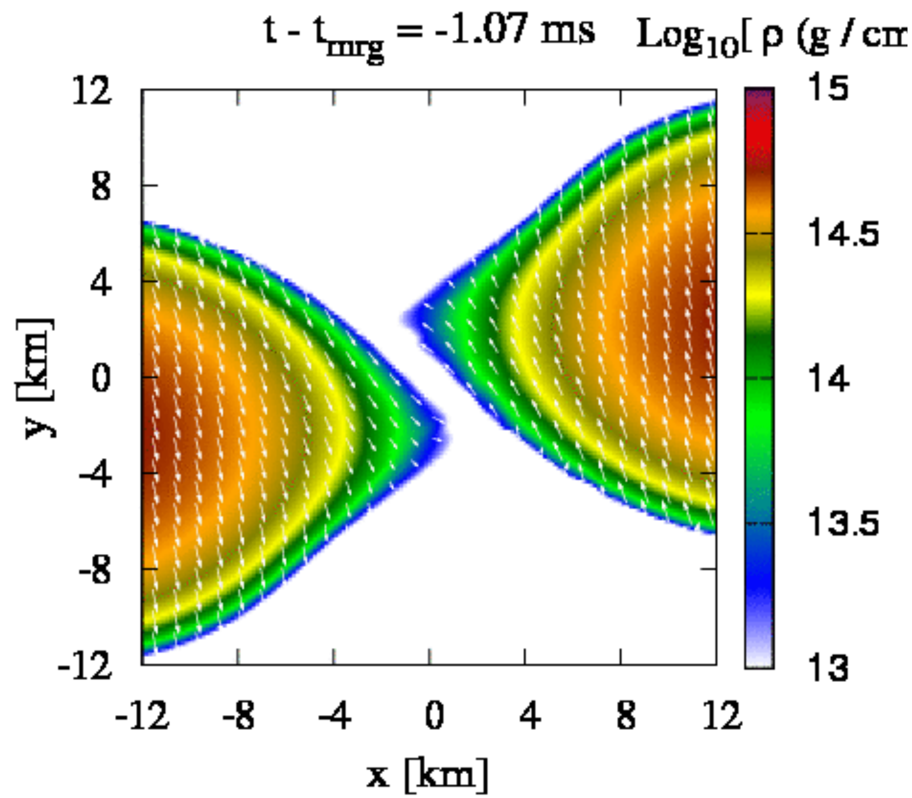
- Fixed mesh refinement: dx=70m→35m→17.5m



High-resolution GRMHD for NS-NS

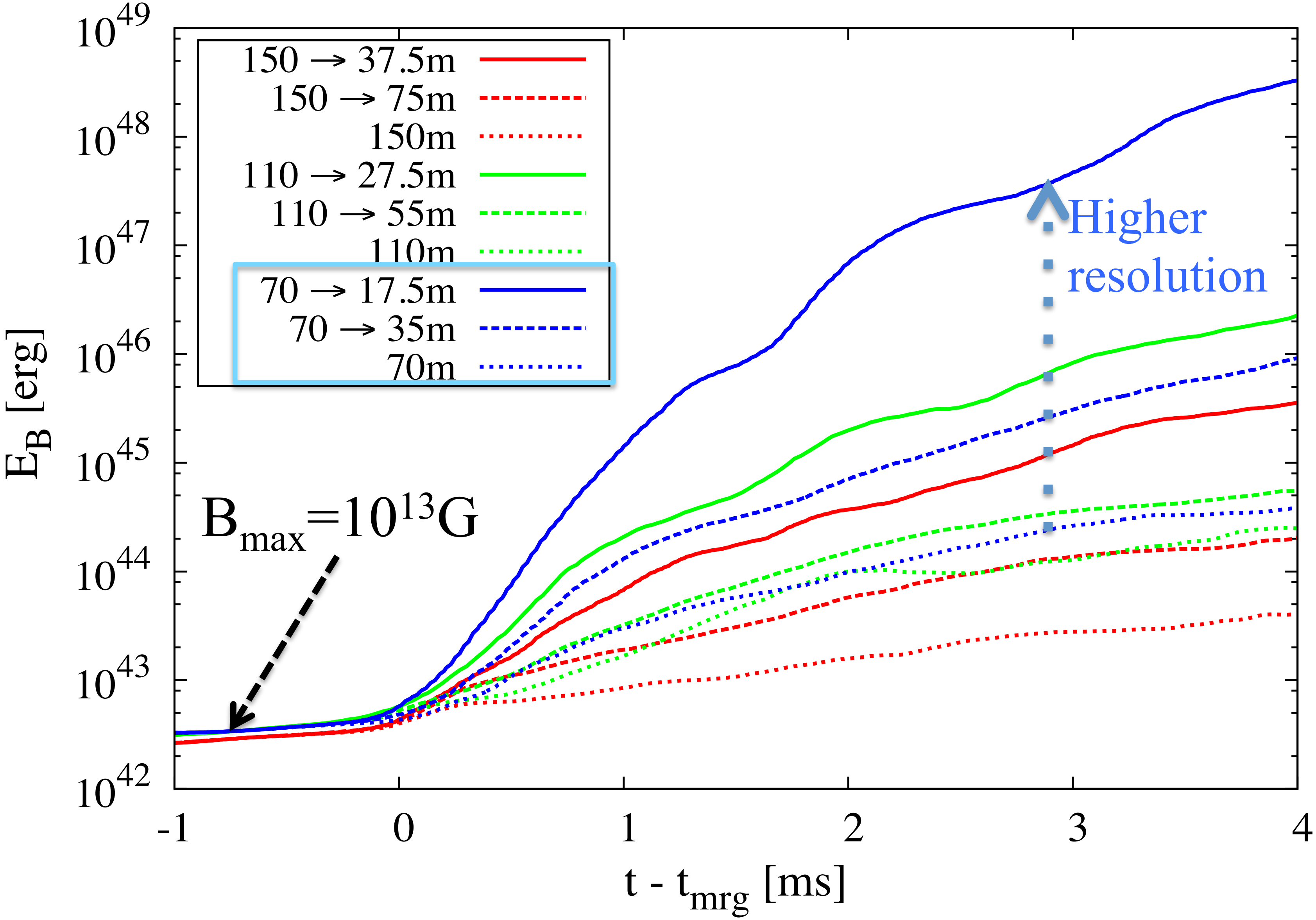


Δx=17.5m

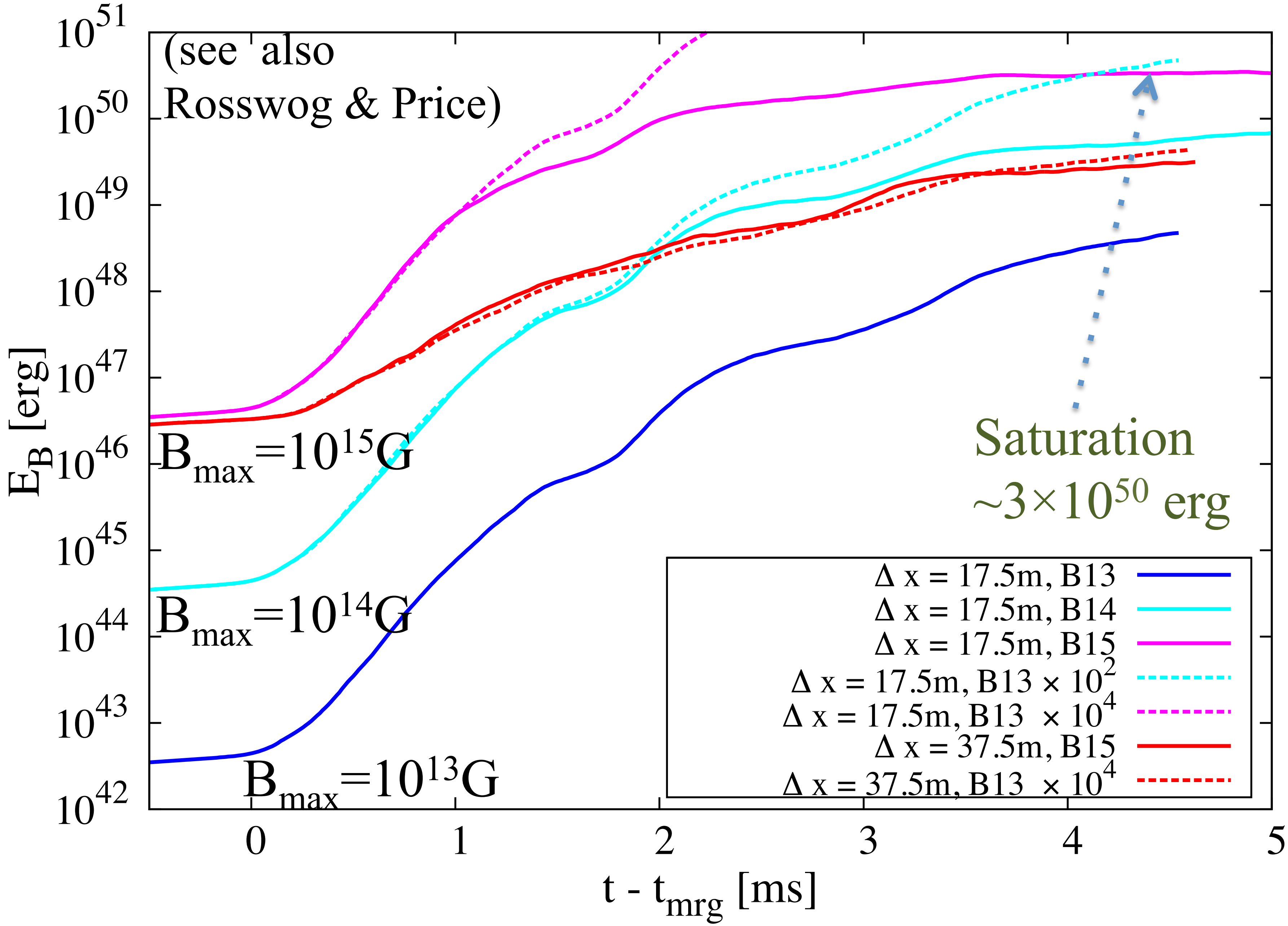


Δx=70m

Magnetic energy: resolution dependence



Magnetic energy soon after merger



Merger remnant would be magnetized

Questions:

- Is highly magnetized remnant NS equivalent to highly viscous NS ?
- If so, how large is the effective viscosity ?
- High-resolution GRRMHD is the best one, but too expensive. Alternative approach ? Sub grid models ? (Giacomazzo et al.)

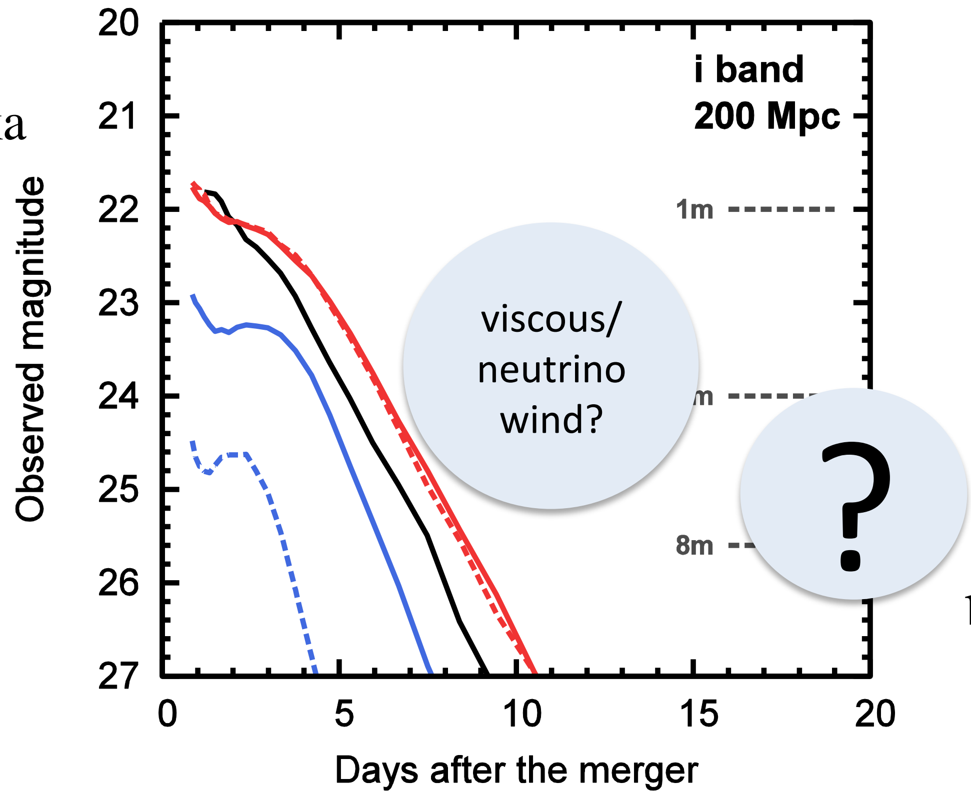
Note: anyway, calibration is necessary for new ideas

- How is magnetar (NS with force-free strong magnetic field) produced ?
  → Ultra long-term run is necessary

3 Merger & mass ejection

Detailed quantitative studies are awaited for an efficient macronova search

Tanaka & Hotokezaka 2013



SUBARU gives only 2 nights in this year

κ is really 10 ?

When we should observe ?

According to Li-Paczynski (ApJ, 1998)

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

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

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

3×10^{41} ergs/s $\Leftrightarrow$ M = −15.0 mag $\Rightarrow$ m=21.5 mag @ 200Mpc

- These depend strongly on *mass, velocity, & opacity*
- Opacity ~ 10 cm^2/g for 2nd--3rd peak elements

(Barnes & Kasen, Tanaka & Hotokezaka 2013)

Mass ejection mechanisms

- Dynamical ejection by tidal torque (Rosswog, ..)
- Dynamical ejection by shock heating with GR gravity (Hotoke+, Bauswein+)
- Ejection by viscous wind from torus surrounding a black hole (Fernandez-Mezger, Just+, …)
- Ejection by neutrino heating (Dessart+, Perego+,…)
- Ejection by magnetohydrodynamics (Kiuchi+)

- **All these effects could play important roles**

Ejecta property

Dynamical ejection

- NS-NS: Mass ~ 0.001-0.02 M_{sun} depending on EOS, v/c ~ 0.15-0.25, $\langle Y_e \rangle$ ~ 0.1-0.4
- BH-NS: Mass ~ 0-0.1 M_{sun}, $\langle Y_e \rangle < 0.1$

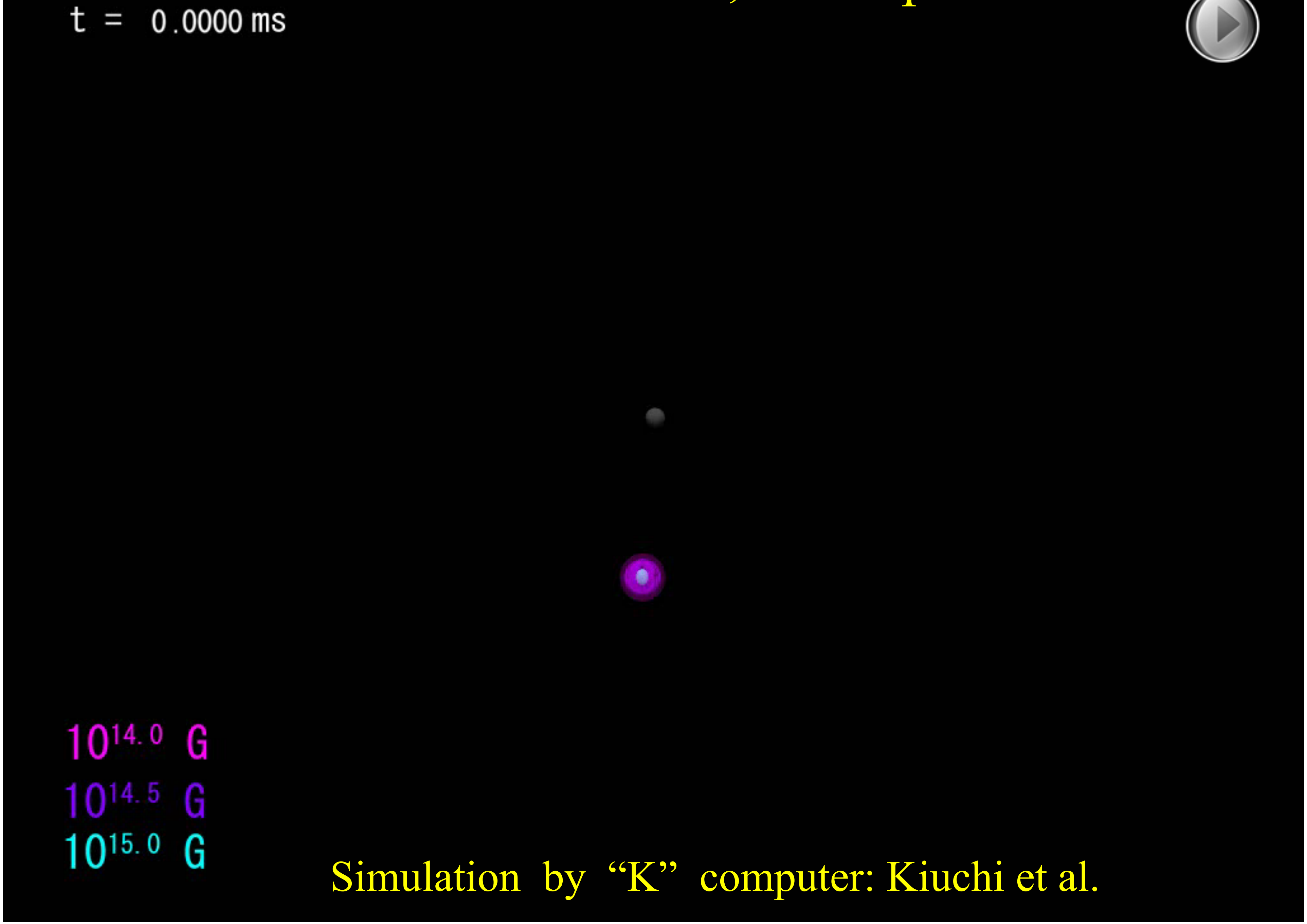
Viscous ejection from torus

- Mass ~ 0.001-0.01 M_{sun} depending on viscous parameter, initial velocity profile: uncertainties
- Velocity < ~ 0.1c, mildly neutron-rich

Neutrino heating

- Mass ~ 0.001-0.01 M_{sun} depending on source model (uncertainty)
- Velocity < ~ 0.1c
- Mildly neutron rich is the result (Perego's talk)

BH-NS: Mass ratio=4, BH spin *a*=0.75



Simulation by "K" computer: Kiuchi et al.

Need self-consistent & systematic study

- **Very long-term self-consistent simulation for merger and remnant evolution is necessary**
- **Both angular momentum transport effect & neutrino transport are the keys for the evolution of remnant**
  → long-term GRRMHD simulation is awaited
  (targets for exa-scale computer) or some effective model simulation ?
- Not only optimistic suggestion but also the **systematic study** is necessary for observers:
  Should clarify the possible systematic error bar

Summary

- Numerical-relativity data will be tested for the next 5-10 yrs observation !
- Happy epoch will come soon

- We need more careful and systematic numerical simulations by many groups

Announcement
from Yukawa Institute,
Kyoto University

- **Long-term workshop on**
  "Nuclear Physics, Compact Stars, Compact-star mergers 2016"
  Oct.17 (Mon.) -- Nov.18 (Fri.), 2016.

Neutron-unrichness (Y_e) and opacity ?

- Is abundance pattern of r-elements similar to solar pattern ?
- Lanthanides (2nd peak) are significant for increasing the opacity (Kasen+, Tanaka+)
- **Are the 3rd-peak elements significant to increase opacity ?**