連星中性子星からの重力波に対する高精度計算

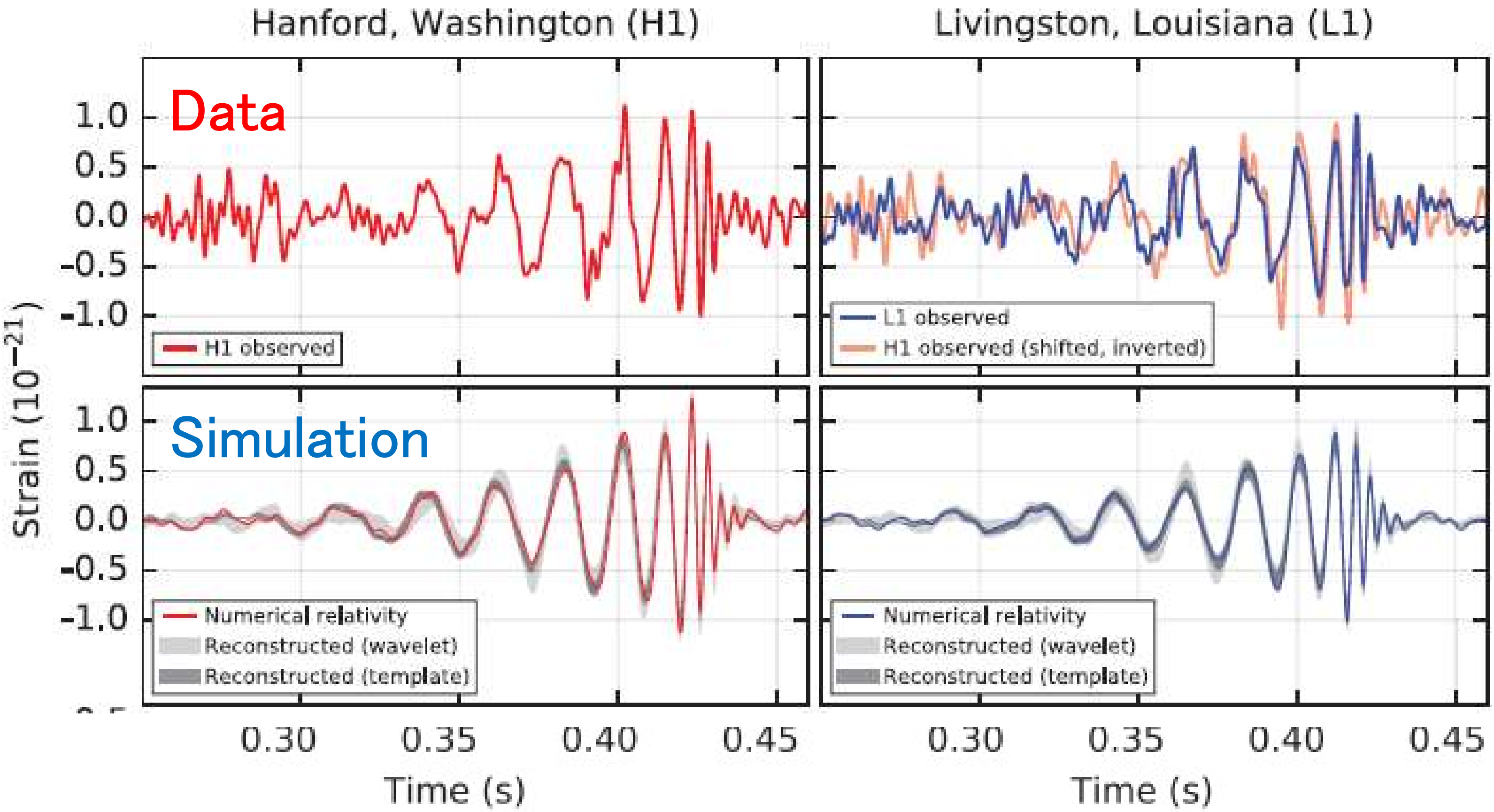
木内建太（京都大学基礎物理学研究所）

柴田大（京大基研）、久徳浩太郎（KEK）、関口雄一郎（東邦大）

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

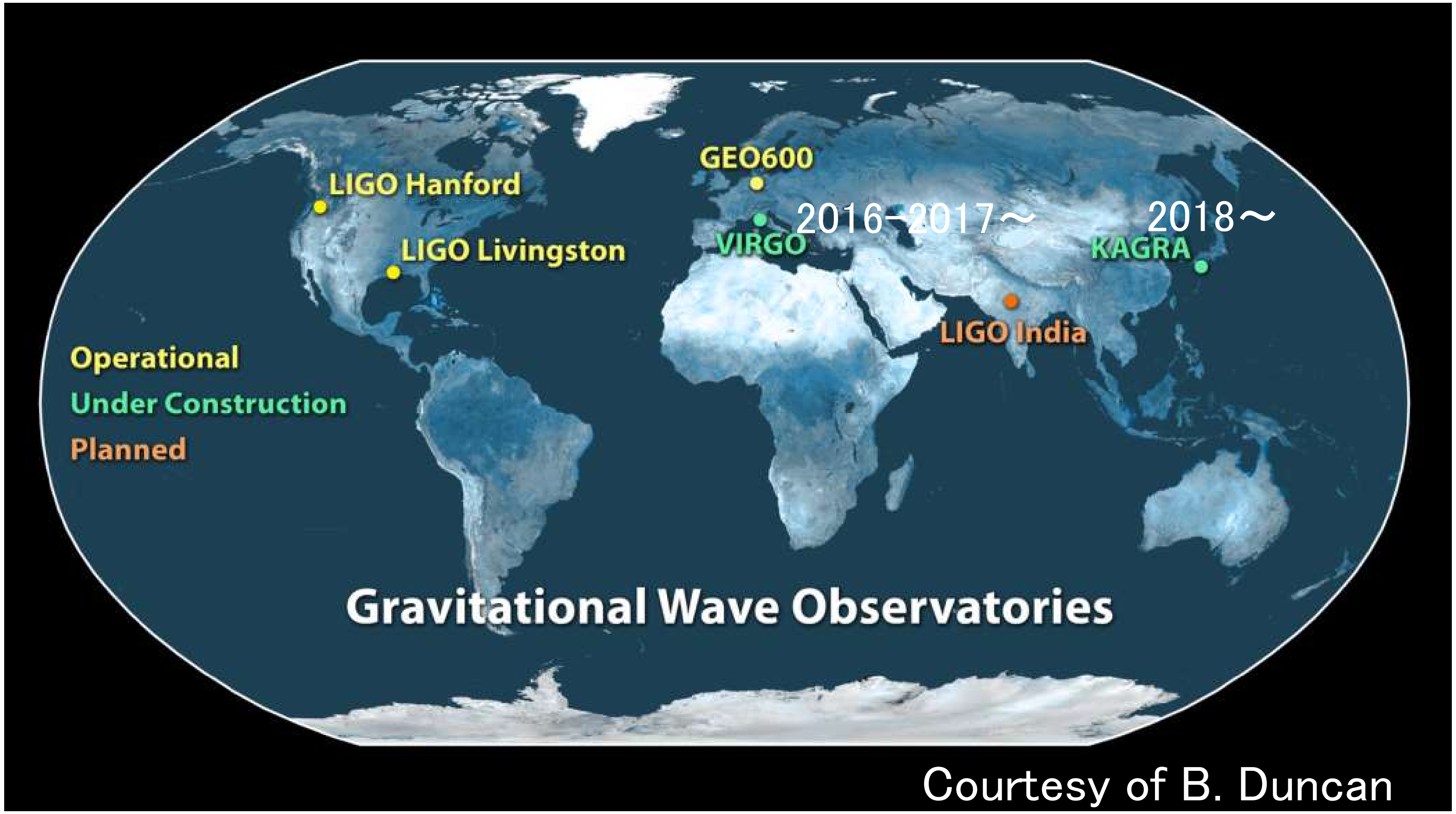
Direct first detection of GWs by advanced LIGO

GW150914 (Abbott et al. 16)



- Binary BH merger of 36 solar mass–29 solar mass
- And GW151226 (Abbott et al. 16)

Dawn of the GW astronomy



- O_2 run of advance LIGO.

⇒Worldwide GW detector network in 2018–2019

- NS–NS merger : 8^{+10}_{-5} events/yr (Kim et al. 15)
- BH–NS merger : 0.2–300 event/yr (Abadie et al. 10)

Role of simulation in GW physics

<u>Figuring out a realistic picture of BH–BH, NS–NS, BH–NS mergers</u>

Numerical relativity simulations on super–computer with a code implementing all the fundamental interactions

- Einstein eq.
- MHD
- Neutrino radiation transfer
- Nuclear EOS

- The NR simulations of the BH–BH merger played an essential role for the first detection

Science target of GWs from compact binary

Exploring the theory of gravity

- GW150914 is consistent with GR prediction (Abott et al. 16)

Exploring the equation of state of neutron star matter

- Determination of NS radius (NS tidal deformability)

(Flanagan & Hinderer 08 etc.)

Revealing the central engine of SGRBs

- Merger hypothesis (Narayan, Paczynski, and Piran 92)

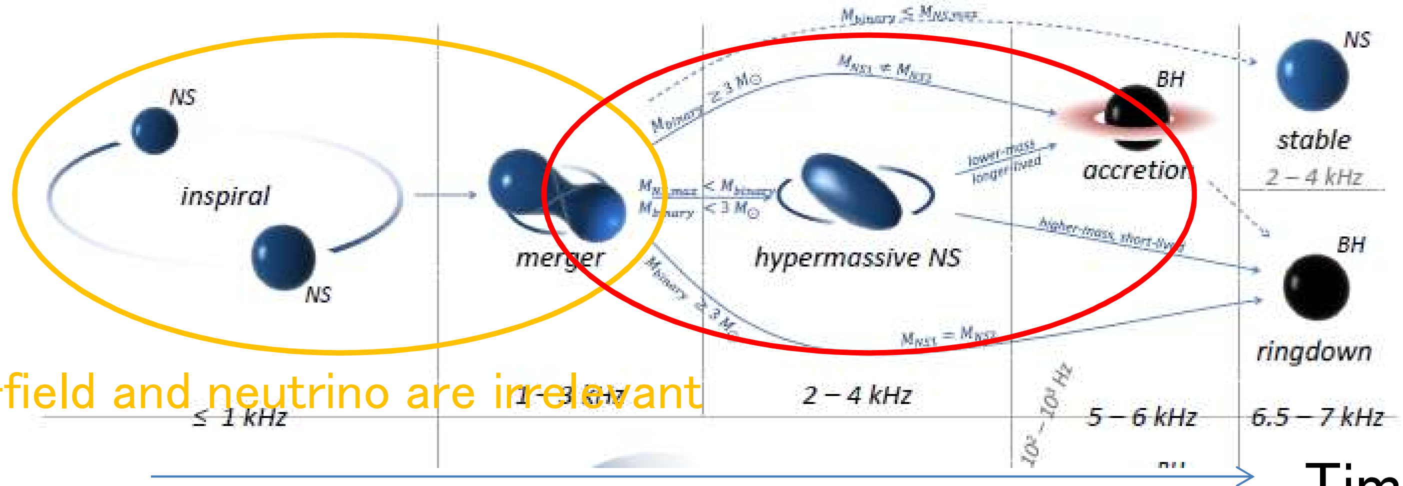
Origin of the heavy elements

- R-process nucleosynthesis site (Lattimer & Schramm 76)
- Electromagnetic counter part (Li & Paczynski 98)

Exploring a realistic picture of NS-NS mergers

(Bartos et al. 13)

B-field and neutrino play an essential role



B-field and neutrino are irrelevant

Time axis

Evolution path depends on the total mass and maximum mass of NSs

Science target of inspiral to late-inspiral phase : Measuring a tidal deformability of NS

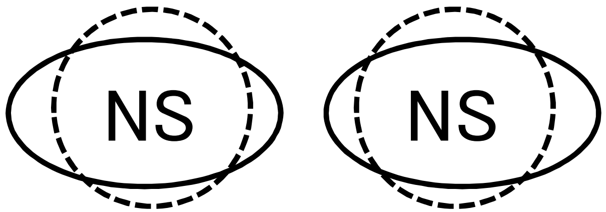
From inspiral to late inspiral phase

Tidal deformation : NS just before the merger could be deformed by a tidal force of its companion.

Tidal deformability depends on NS constituent, i.e., EOS.

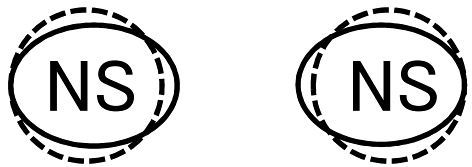
Tidal deformation

Stiff EOS (larger R)



Easily tidally deformed

Soft EOS (small R)

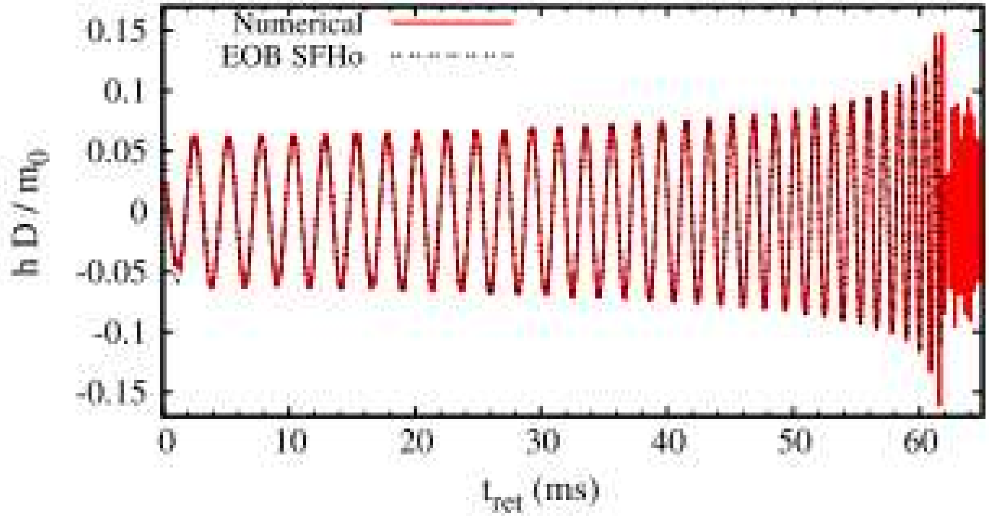


Hard to be tidally deformed

How is tidal deformability imprinted in GWs ?

$$h = \underbrace{A(t)}_{\text{Amplitude}} e^{i\underbrace{\Phi(t)}_{\text{Phase}}} \quad \Phi(t) = \Phi_{\text{Point Particle}}(t) + \Phi_{\text{tidal}}(t)$$

Tidal deformation accelerates the phase evolution.



Post Newton (cf. EOB); Low cost, but inaccurate @ merger

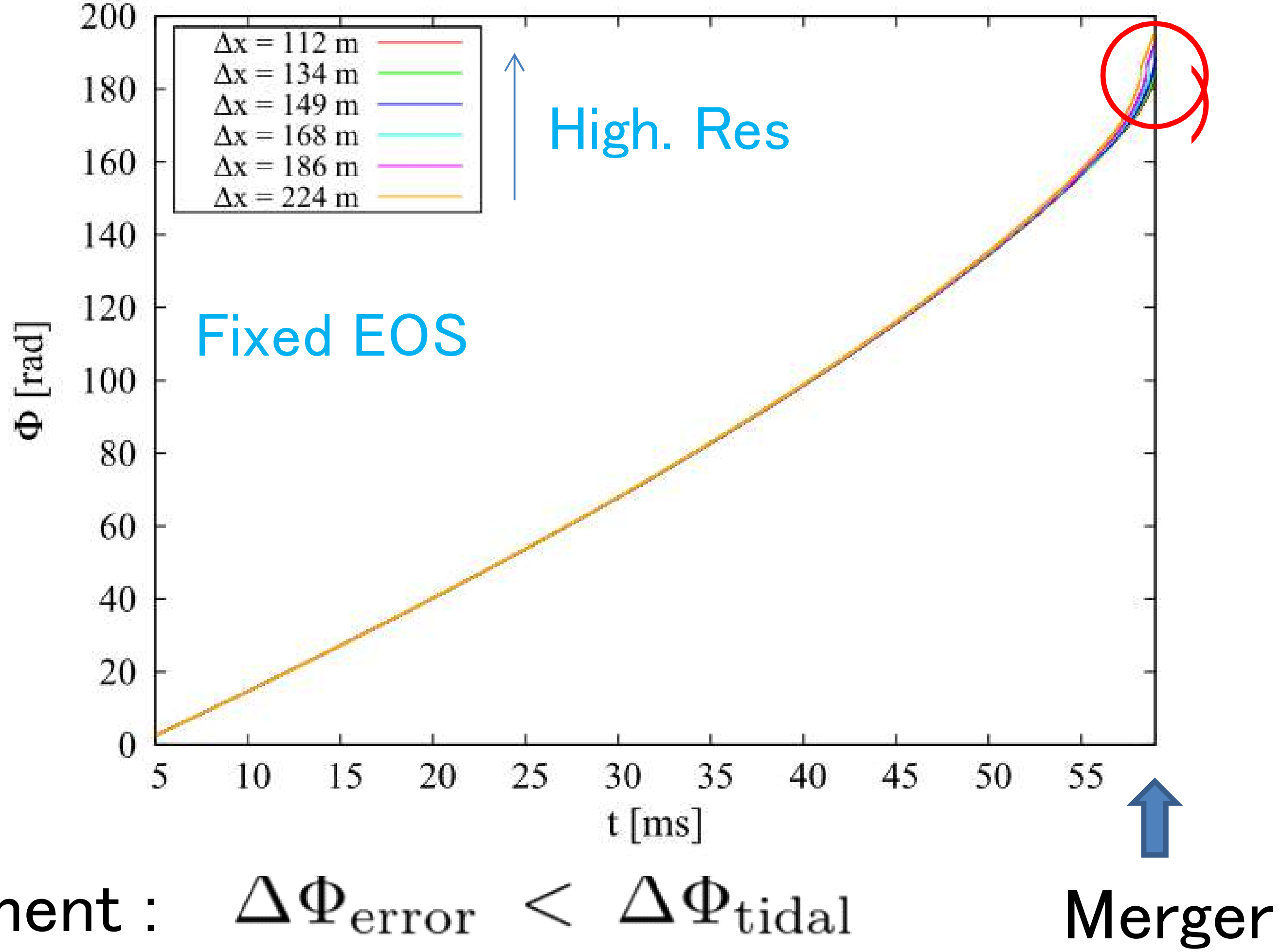
NR; Robust, but expensive

EOB waveforms should be calibrated by NR waveforms

For the calibration of EOS waveforms

Large tidal deformability ⇒ Rapid phase evolution

Numerical diffusion ⇒ Rapid phase evolution



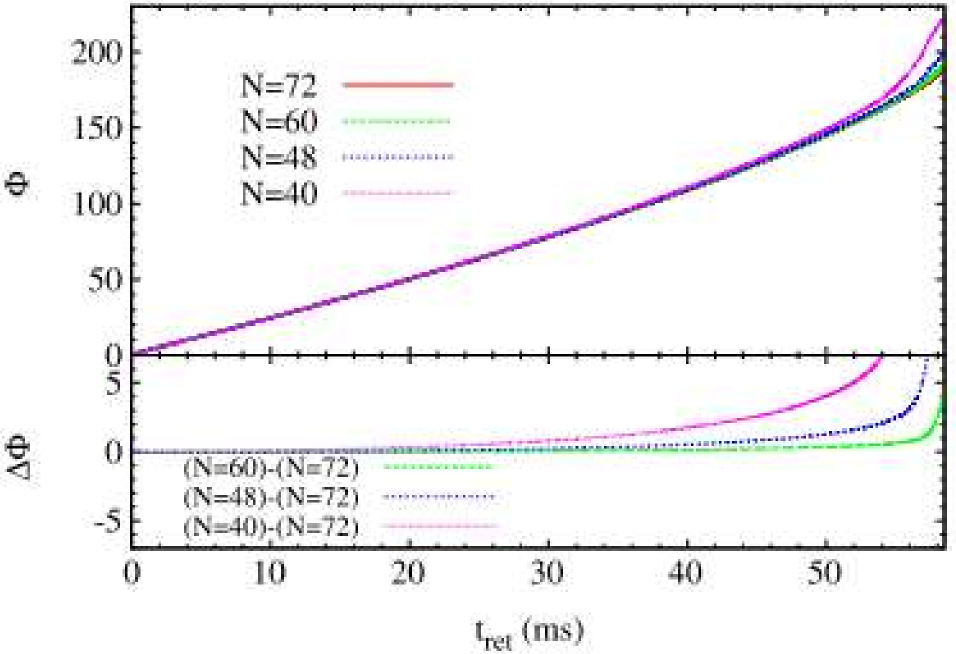
Requirement : $\Delta\Phi_{\rm error} < \Delta\Phi_{\rm tidal}$

Convergence study ⇒ Continuum limit

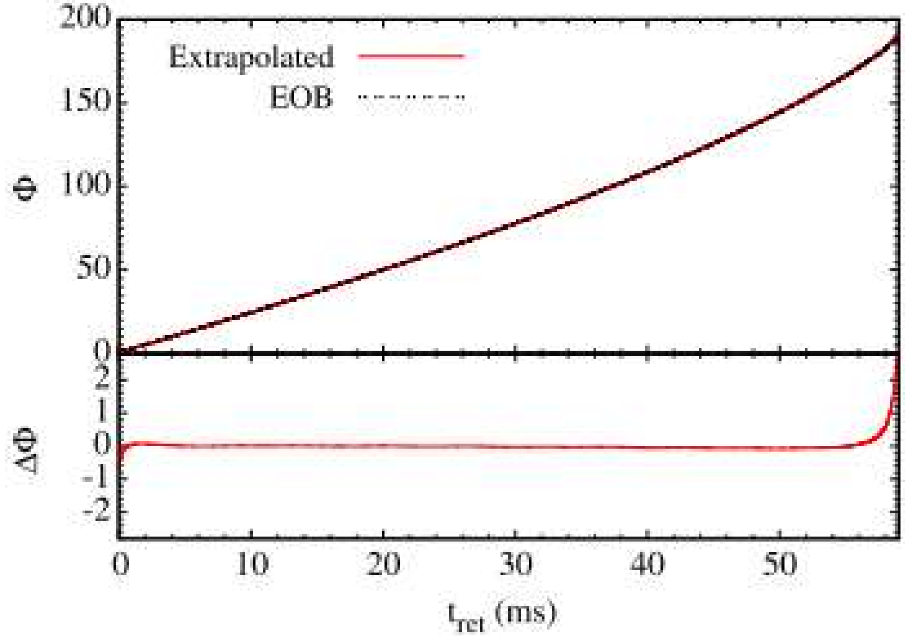
Current status tidal deformability of NSs

Hotokezaka et al. 13, 15, 16

GW phase and phase shift



Extrapolated data vs EOB



- $\Delta\Phi_{\rm error} \approx 3-4\,{\rm radian}$

Still not sufficient for the template
⇒ Need higher res. simulations

A step towards accurate late inspiral waveform

Supercomputers accelerate NR waveform production.

Cost = 1.5–2 month for “best” resolution (1.6 times higher resolution than in Hotokezaka et al.)

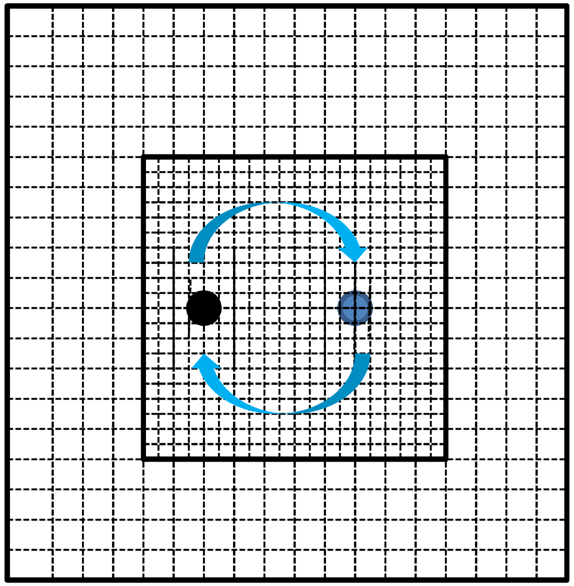
24 TFlops month/model ⇒ Systematic study is possible

Waveform production : over 100 waveforms/yr

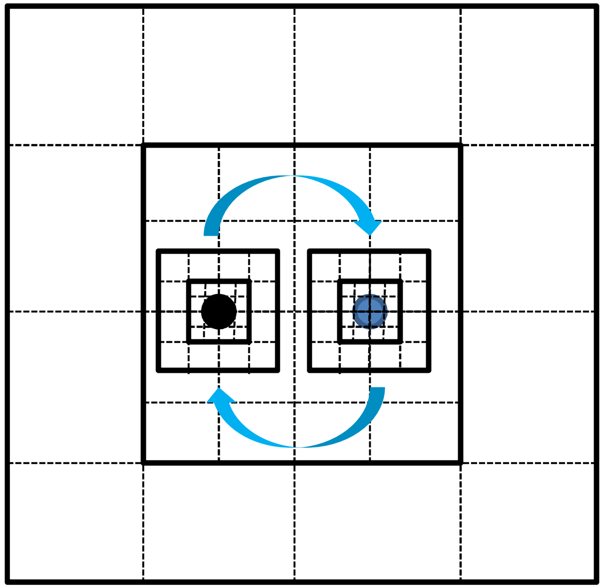
Current run: 5 EOSs × 1.35–1.35$M_\odot$ × 7 resolutions

AMR – NR code SACRA

GRMHD/GRRHD (K project)

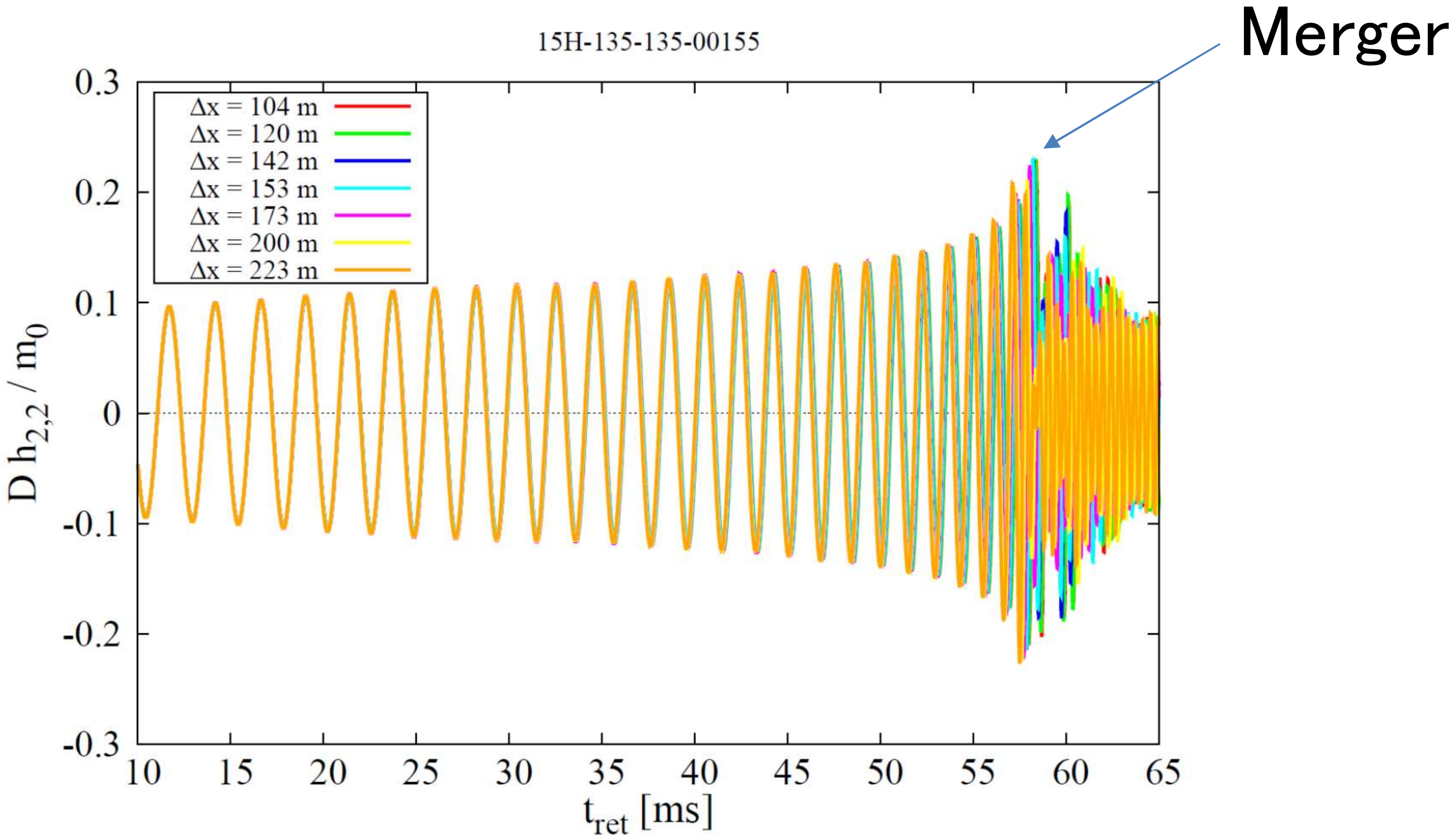


SACRA (AMR)



- Original SACRA (Shared memory ver.) ⇒ Parallelization
- MPI optimization based on K-project code

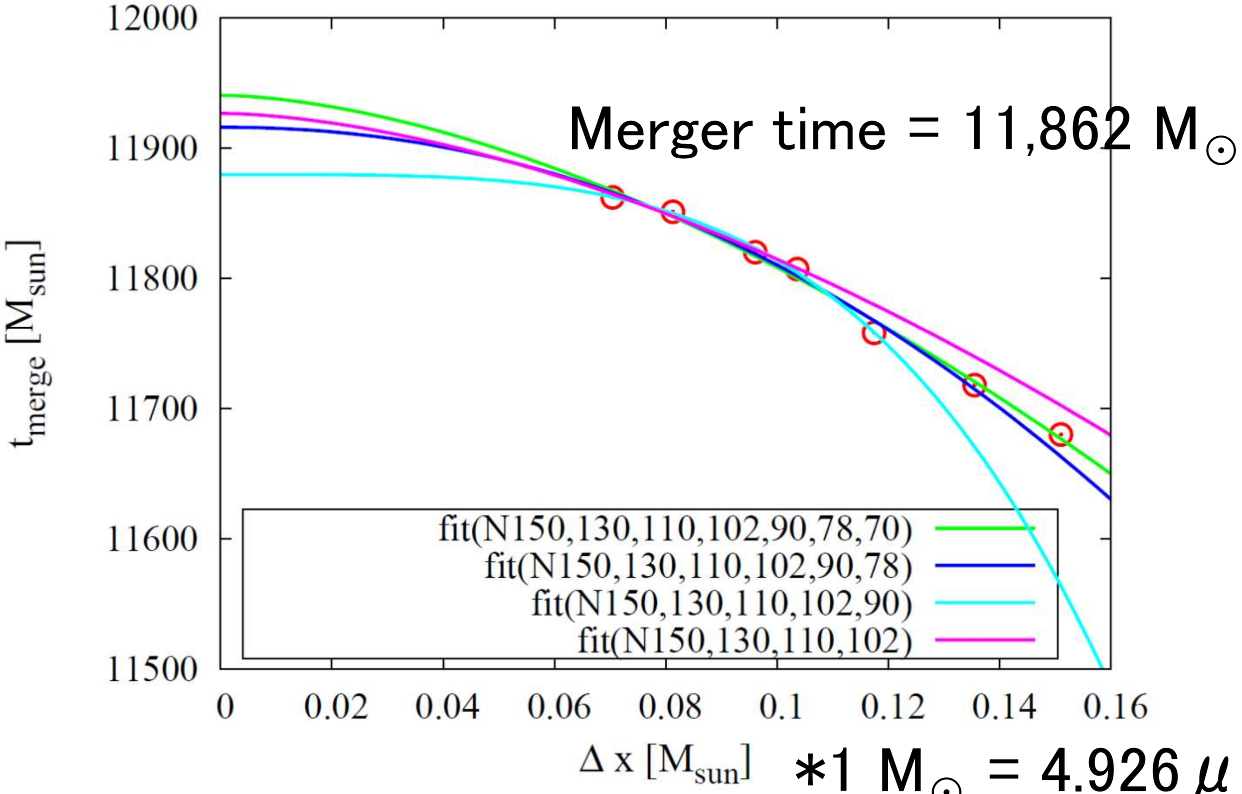
Result of EOS 1.5H ($R_{1.35M_\odot}$ = 13.7 km)



- Merger time $\stackrel{\text{def}}{=}$ Maximum amplitude of GW
- High res. ⇒ Merger time is extended

Result of EOS 1.5H ($R_{1.35M\odot}$ = 13.7 km)

Resolution dependence of merger time

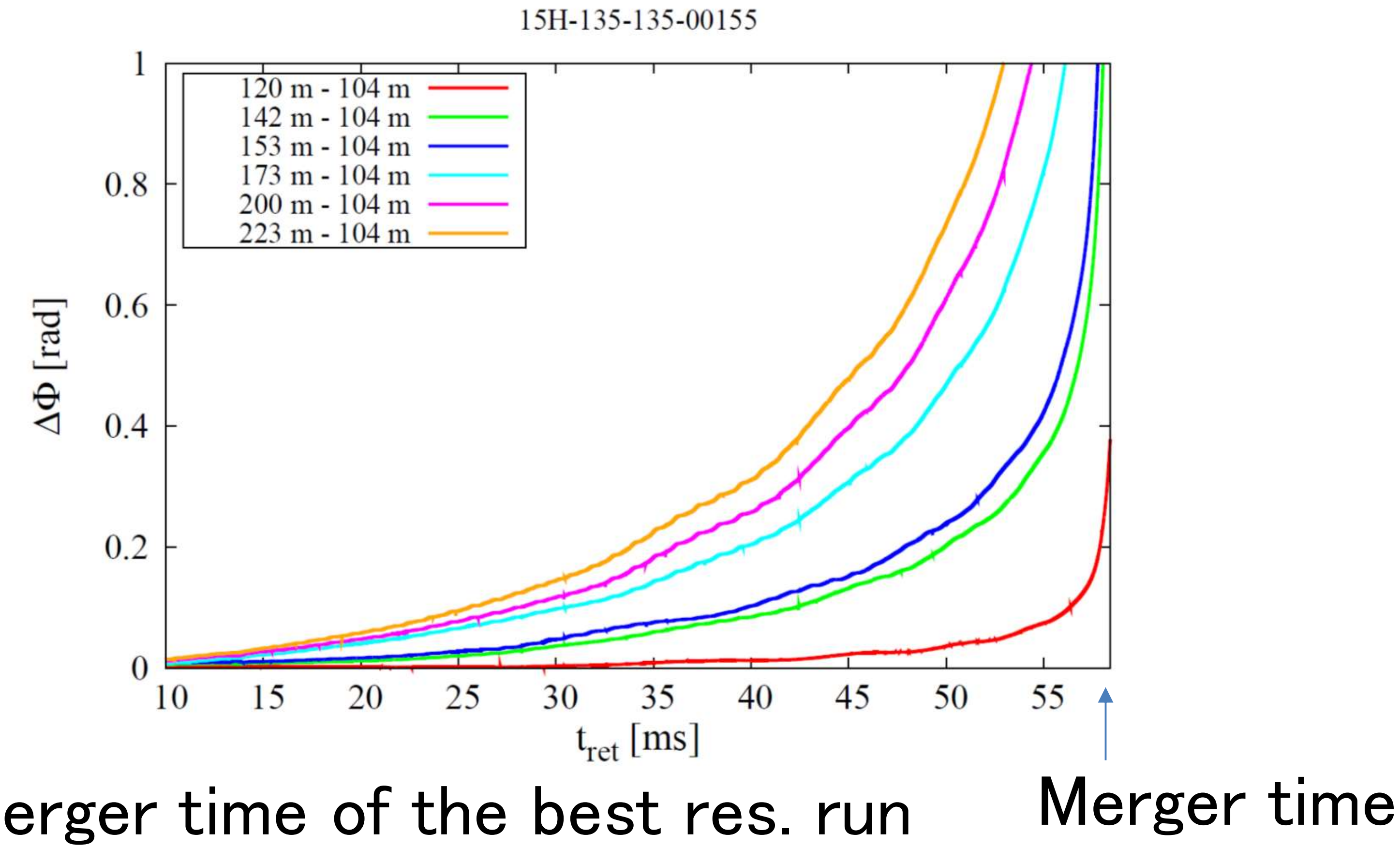


*1 $M_\odot$ = 4.926 μ s = 1.48km

- Convergence order = 1.7, Merger time = 11,926 $M_\odot$
- Convergence order = 2.1, Merger time = 11,915 $M_\odot$
- Convergence order = 3.8, Merger time = 11,879 $M_\odot$
- Convergence order = 1.7, Merger time = 11,926 $M_\odot$

Result of EOS 1.5H ($R_{1.35M\odot}$ = 13.7 km)

Dephase of GWs



- Merger time of the best res. run
- 0.4 rad for best and 2nd best res. run

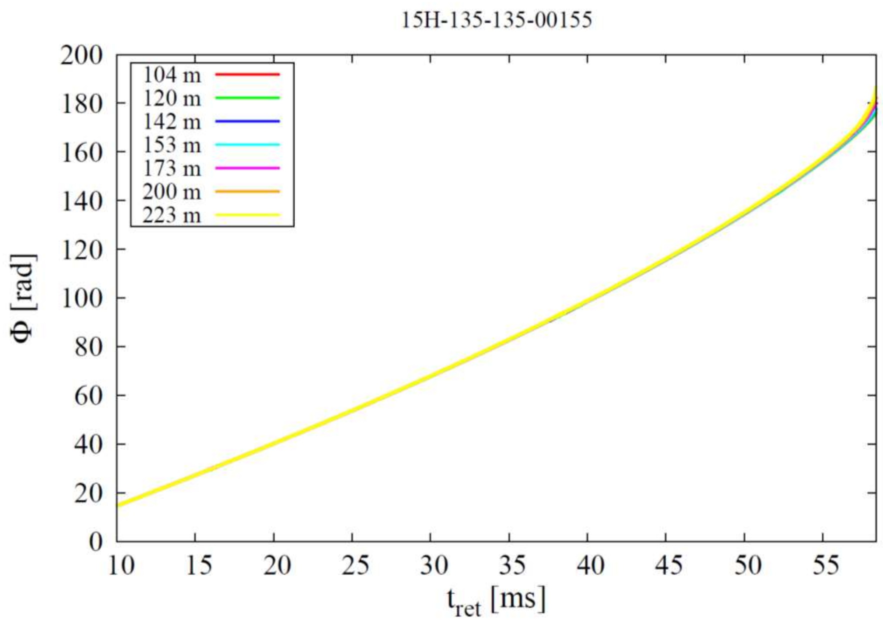
(cf. 3–4 rad in Hotokezaka et al. 15)

- Taking a continuum limit

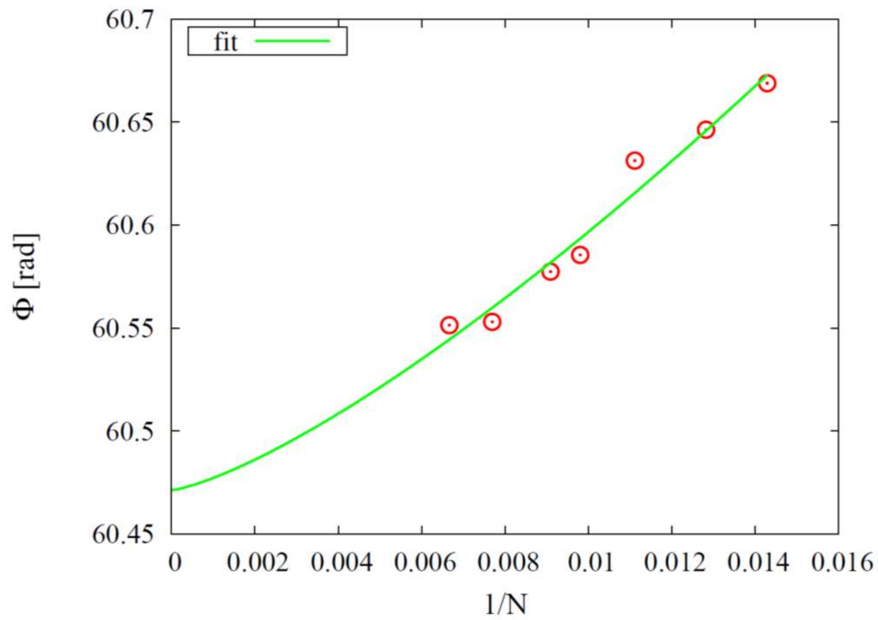
Result of EOS 1.5H ($R_{1.35M\odot}$ = 13.7 km)

Continuum limit on each time slice

Phase evolution



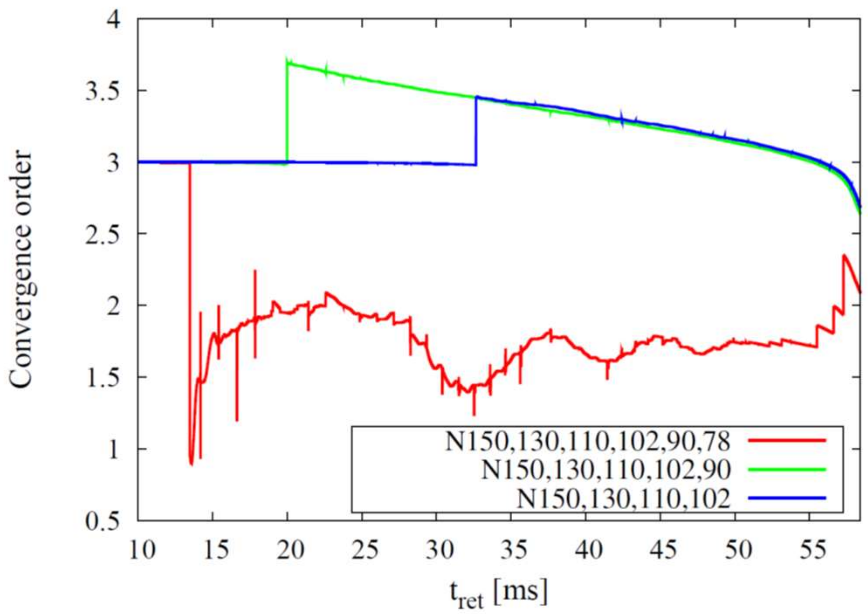
Res. dependence of phase



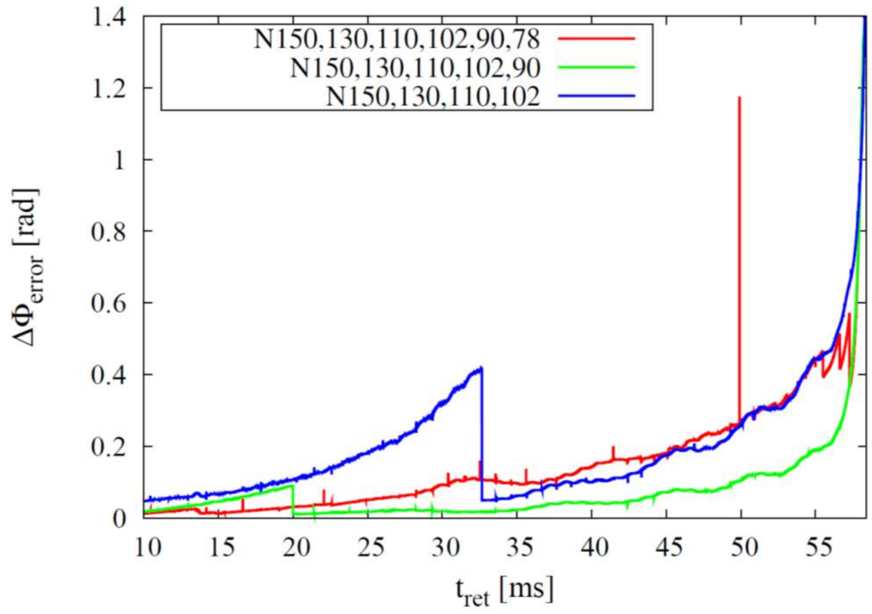
▶ Least-square fit w.r.t. the resolution on each time slice

Result of EOS 1.5H ($R_{1.35M_\odot}$ = 13.7 km)

Convergence order



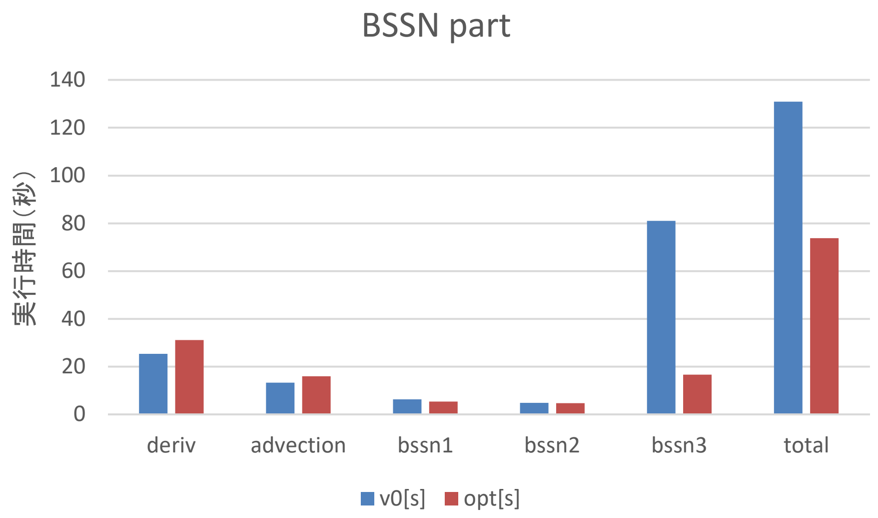
Phase error after continuum limit

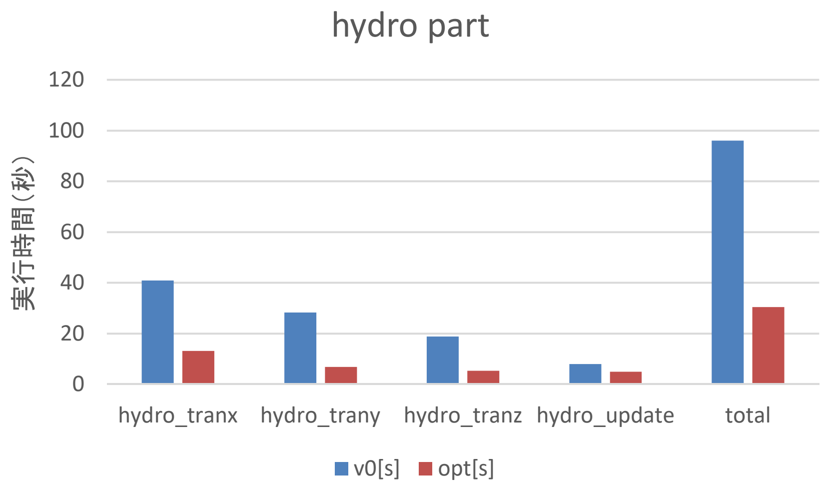


- Improving the convergence order if we use only high res. runs.
- Systematic error in phase is ≈1 rad.
- Phase error due to the merger time is not estimated.
- Effective One Body waveform calibration with the best res. run ? / Higher res. run?

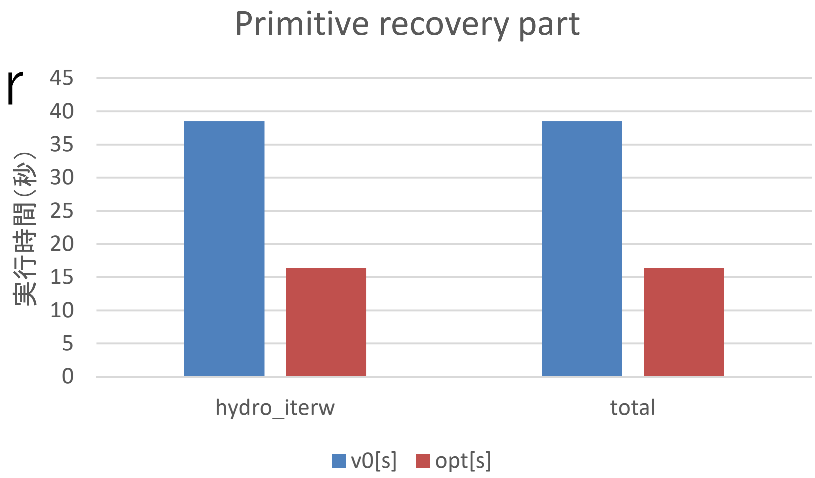
Optimization of SACRA-MPI (AMR-code)

▶ Single node tuning : Repealing of pointer & line access





- Einstein Solver : 1.77 times faster
- Hydro. Solver : 3.16 times faster
- Primitive Recovery:
2.35 times faster
- Total : 2.2 times faster



Summary

▸Deriving a realistic picture of compact binary mergers is an urgent issue

Supercomputers accelerate NR waveform production !!

<u>BNS merger</u>

▸ High-precision GW forms in inspiral and late inspiral phase
⇒ Template bank

▸ Evolution in post merger phase (B-field, Neutrino)