Gravitational waves from a binary composed of BH and/or NS

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K computer

重力波天体の多様な観測による宇宙物理学の新展開

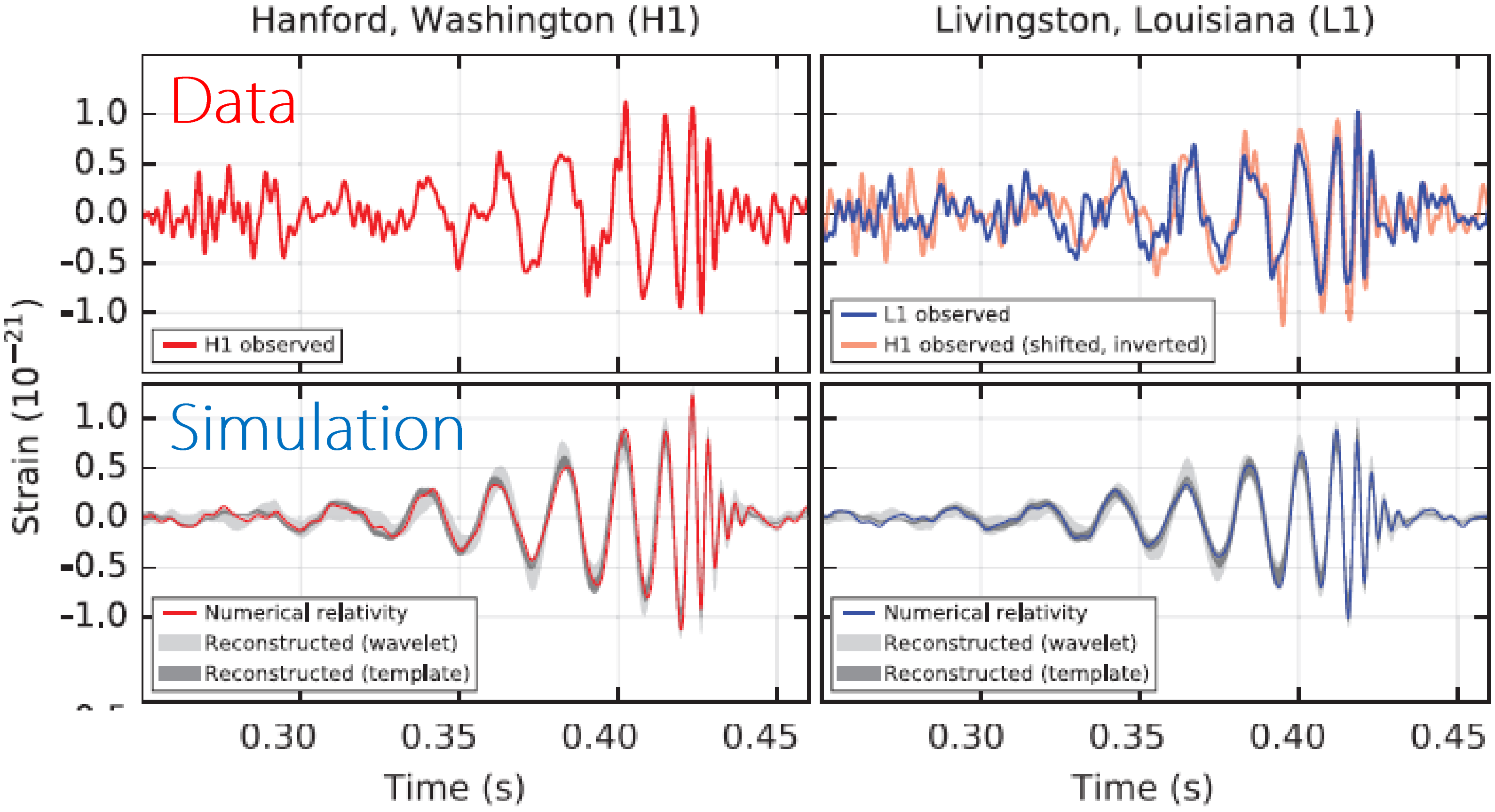
New development in astrophysics through multimessenger observations of gravitational wave sources

新学術領域研究

実験と観測で解き明かす
中性子星の核物質

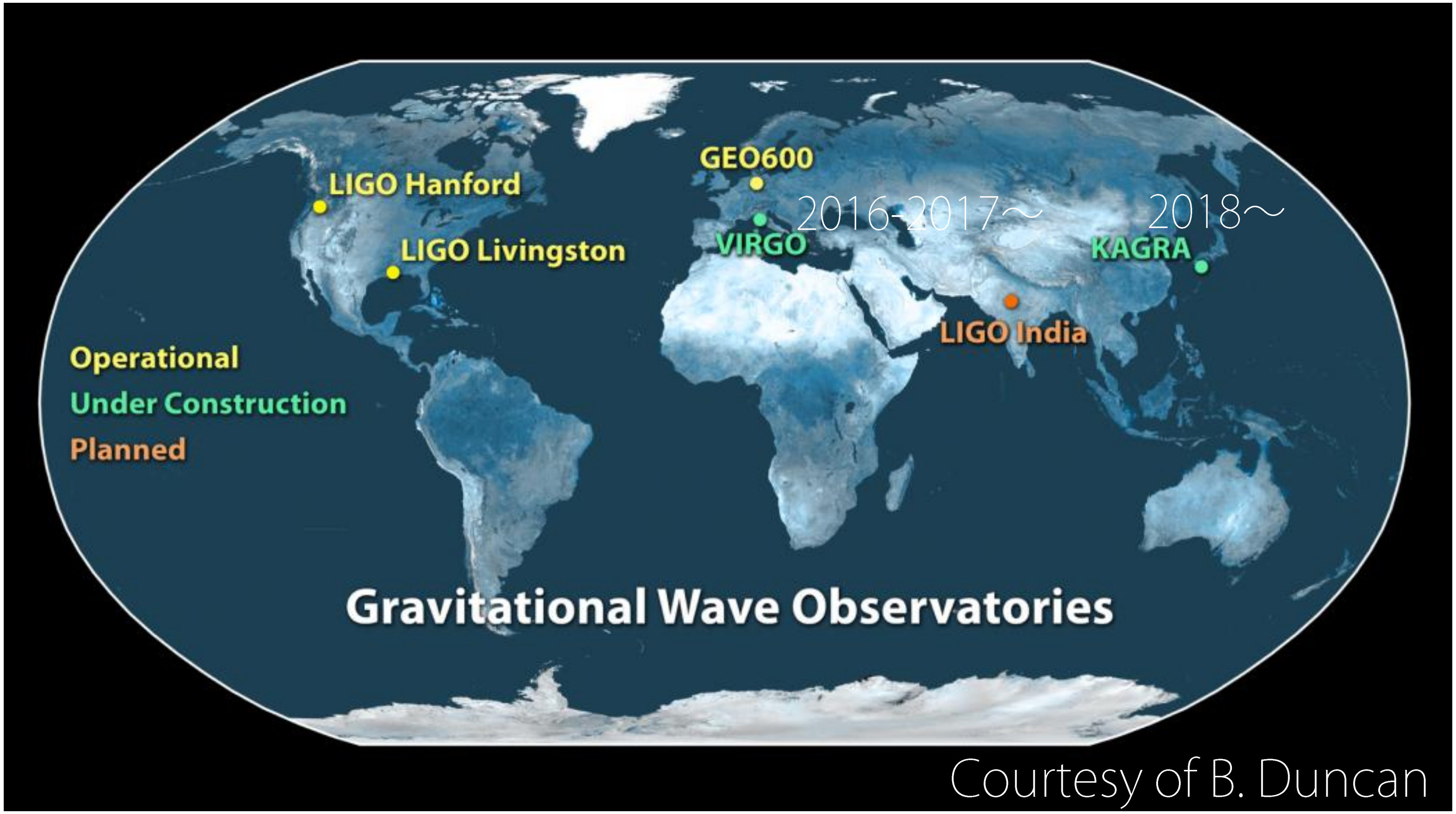
Direct first detection of GWs by advanced LIGO

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



Courtesy of B. Duncan

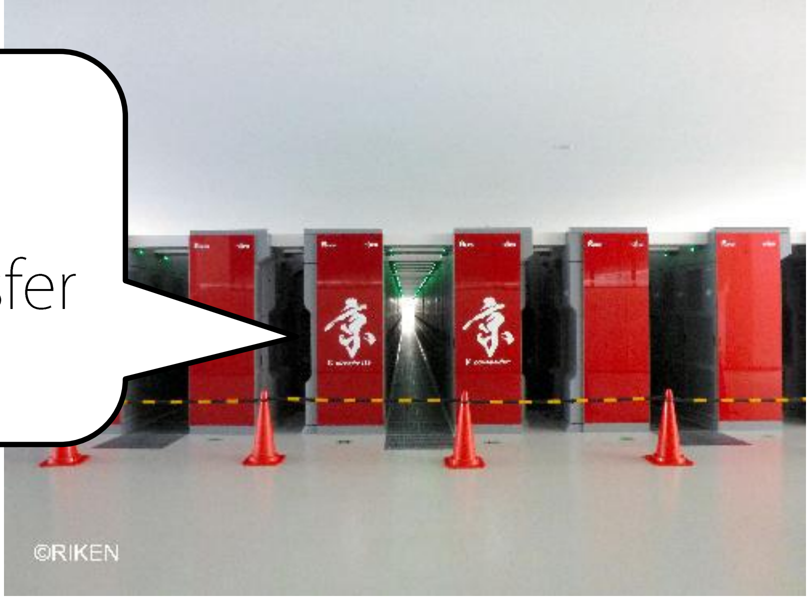
▶O_2 run of advance LIGO in the end of Sep.
⇒Worldwide GW detector network in 2018-2019
▶NS-NS merger : 8^{+10}_{-5} events/yr (Kim et al. 15)
▶BH-NS merger : 0.2-300 event/yr (Abadie et al. 10)

Role of simulation in GW physics

Figuring out a realistic picture of BH-BH, NS-NS, BH-NS mergers

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 compact binary mergers

Exploring the theory of gravity

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

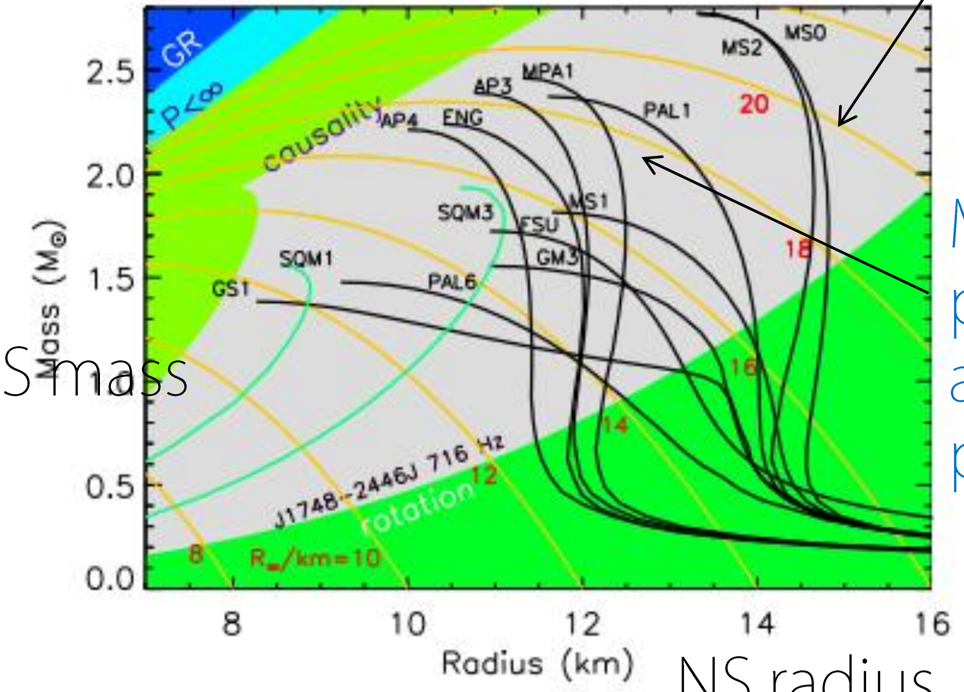
But, it does not imply that GR is the theory of gravity in a strong gravitational field.

cf. Quasi normal mode from a merger remnant of BBH (Nakano san't talk)
Proving gravitational theories with GW observations (Yagi san's talk)

Science target of compact binary mergers

Exploring the EOS of NS matter

NS interior state is poorly known



M-R relation predicted by a nuclear physics theory

M-R relation predicted by another nuclear physics theory

NS mass

NS radius

- Extraction of the information of NS mass and radius imprinted in merger waveforms⇒The EOS of NS matter

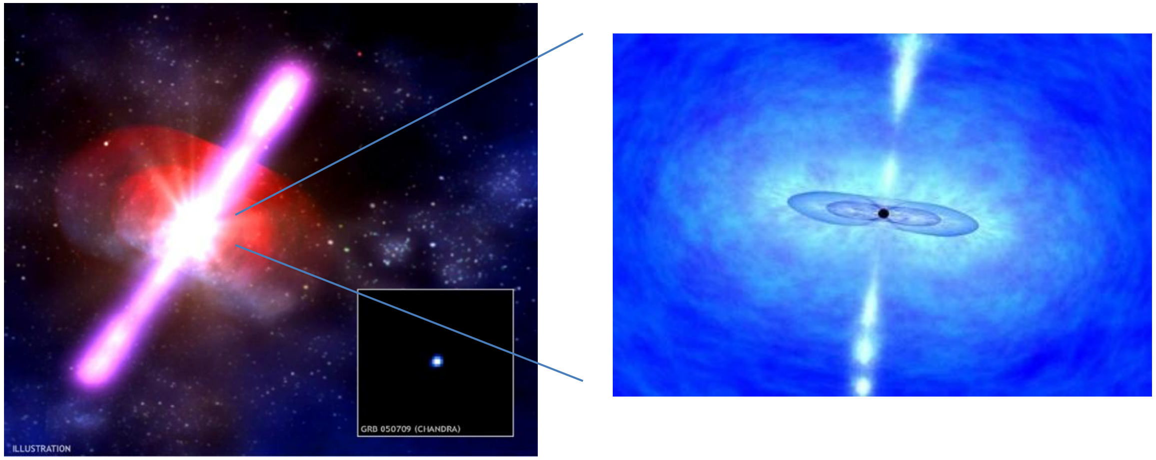
Science target of compact binary mergers

Mystery of the central engine of Short-hard Gamma Ray Burst

(cf. Yonetoku san’s talk)

Imaginary picture of SGRB

Merger remnant drives it ?



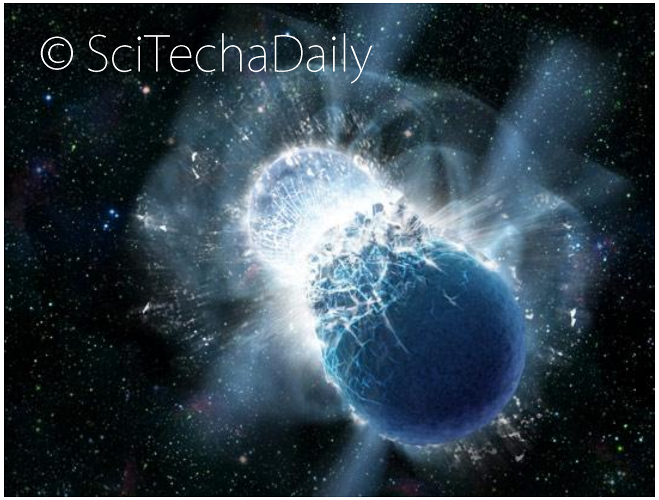
Simultaneous detection of SGRBs and GWs may solve a long-standing puzzle on the central engine (Narayan et al. 92)

Science target of compact binary mergers

Origin of heavy irons in the Universe

Nucleosynthesis by rapid neutron capture process

⇒Mystery of the nucleosynthesis site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- ▶NS-NS/BH-NS merger⇒Mass ejection of the neutron rich matter⇒R-process nucleosynthesis (Lattimer & Schramm 76)
- ▶Radioactive decay of the R-process elements⇒Elemag. emission in near IR band (cf. GRB130603B) (Li & Paczynski 98)

Numerical relativity group map

- For BH-BH mergers, SXS collaboration (Caltech-Cornell-CITA) takes the initiatives.
- For NS-NS and BH-NS mergers, the Japan NR group takes the initiatives.

Exploring a realistic picture of BBH mergers

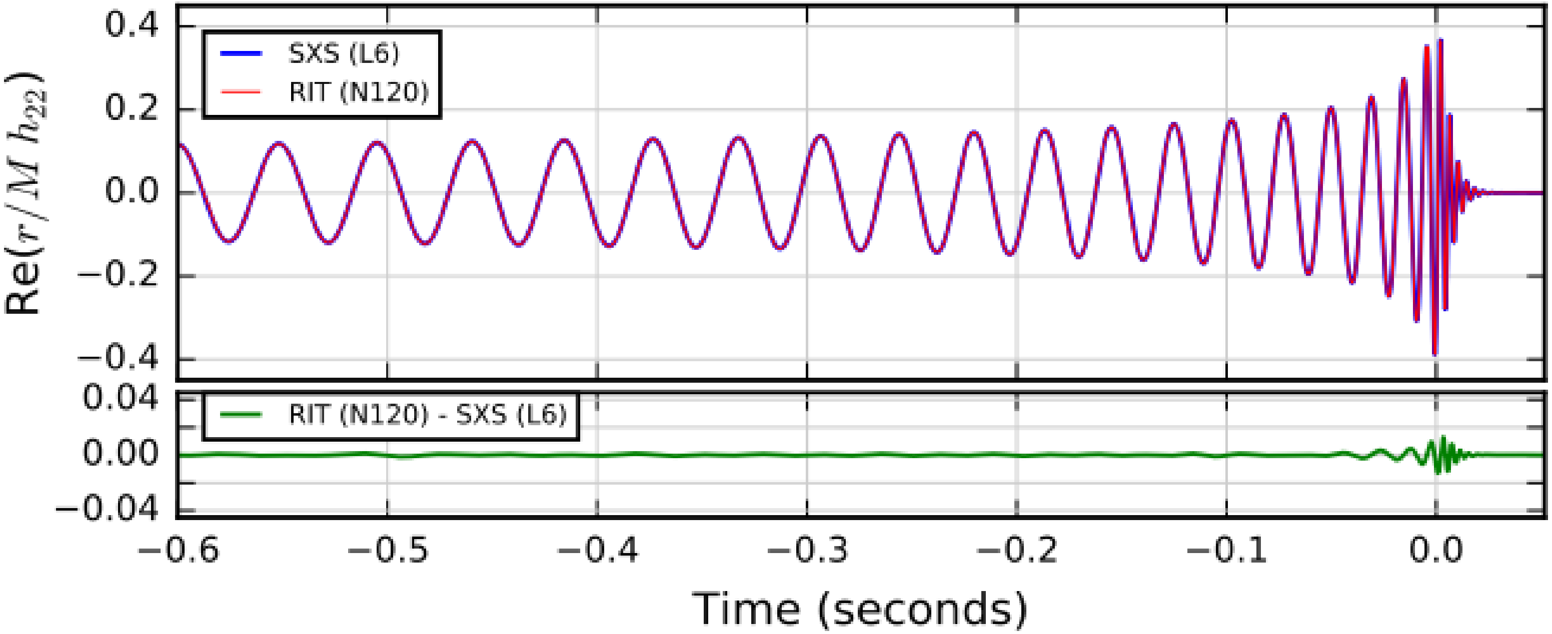
Simulating Extreme Spacetime collaboration
▶ Generalized harmonics formulation (Pretorius 05)
▶ Spectrum method (e.g., spherical harmonics)
Very accurate and efficient simulation

The other groups
▶ Baumgarte-Shapiro-Shibata-Nakamura-puncture formulation (Shibata-Nakamura 95, Baumgarte-Shapiro 98, Campanelli 06, Baker 06)
▶ Finite differencing
Robust for non-vacuum spacetime, but less accurate

Spec vs LazEv code

Two independent simulations by RIT and SXS

(1607.05377 Lovelace et al.)



▶Both results agree quite well

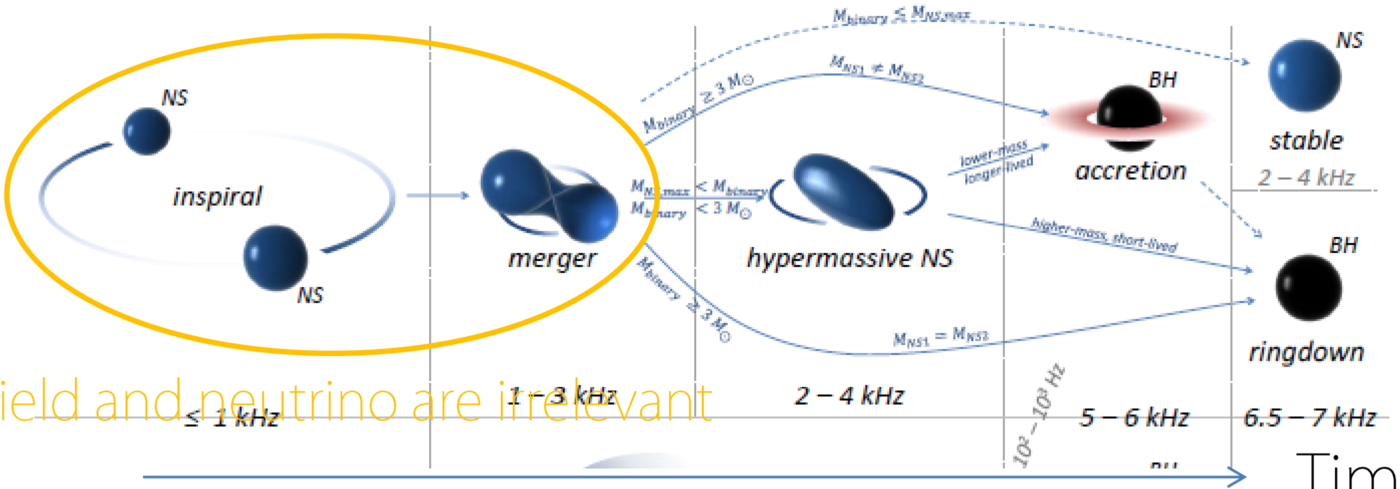
Next target ?

▶ High mass ratio: One simulation for q = 100 (Campanelli et al 10)

▶ High spin: χ =0.97 is the world record (Lovelace et al. 12)

Exploring a realistic picture of NS-NS mergers

(Bartos et al. 13)



B-field and neutrino are irrelevant

Time axis

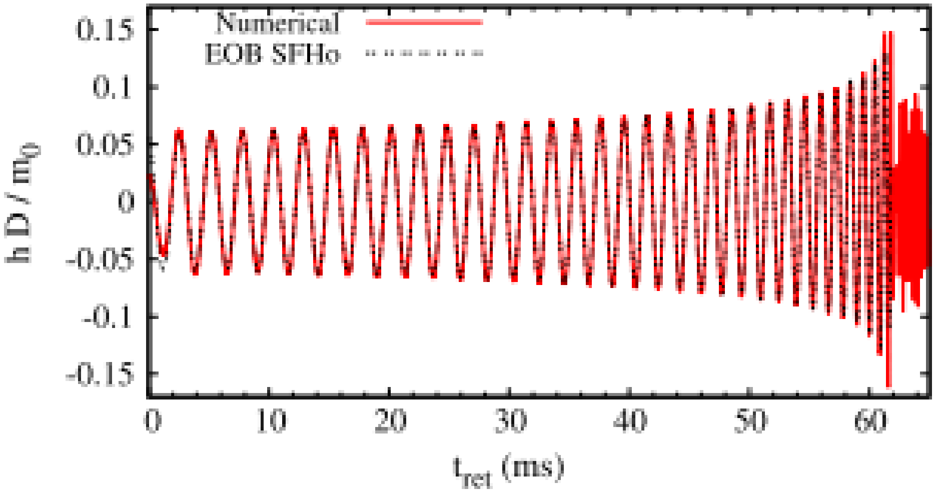
Evolution path depends on the total mass and maximum mass of NSs

- ▶Science goal : Extraction of the tidal deformability of NSs ⇒ the EOS of NS matter
- ▶ Deriving the high-precision GW forms from inspiral to early merger phase ⇒ Construction of the GW template and its application to observation

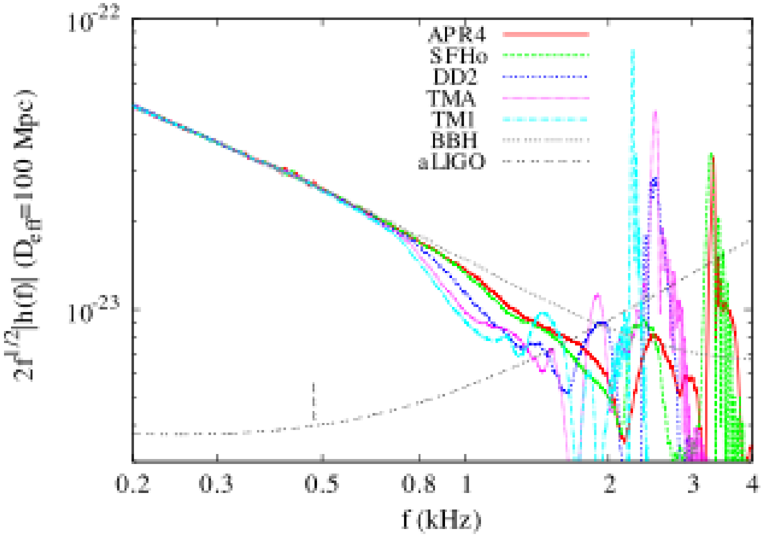
Tidal deformability of NSs

Hotokezaka et al. 13, 15, 16

GW forms



GW spectrum

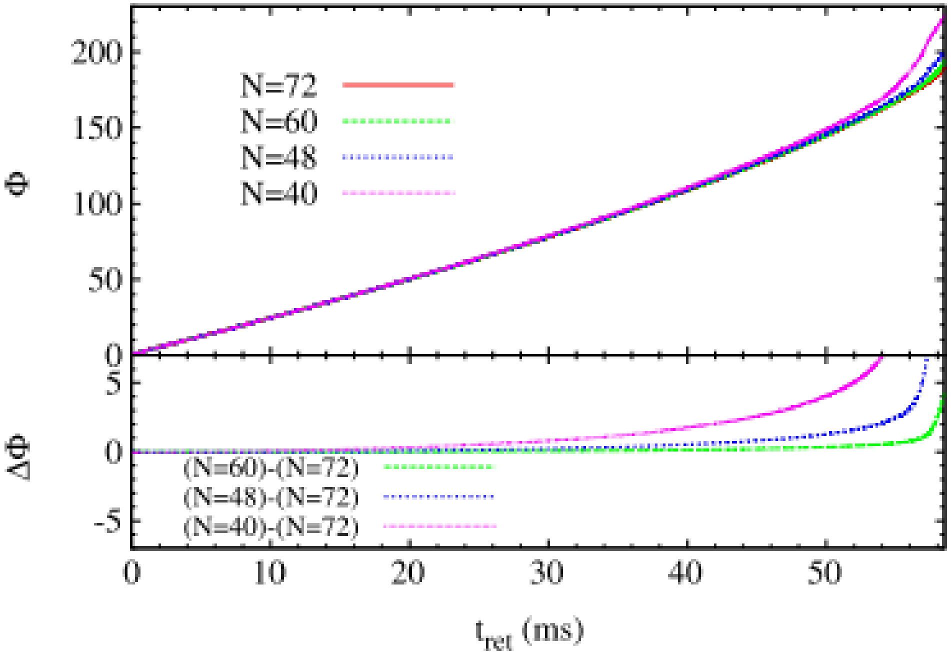


▶GW phase error induce by the numerical diffusion≈0.3radian (Not sufficient for the template)

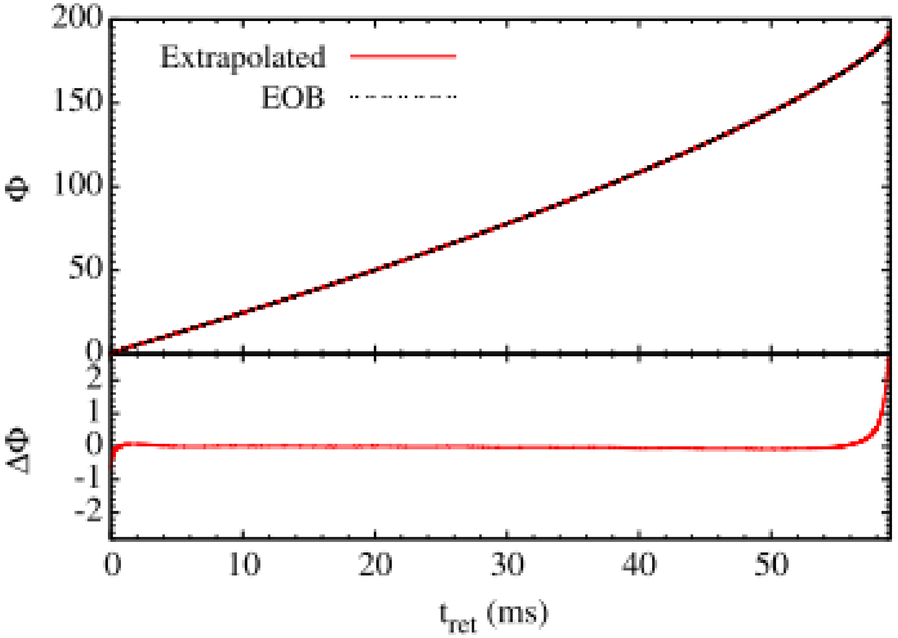
Tidal deformability of NSs

Hotokezaka et al. 13, 15, 16

GW phase



Extrapolated data vs EOB



▶GW phase error induce by the numerical diffusion≈0.3radian (Not sufficient for the template)

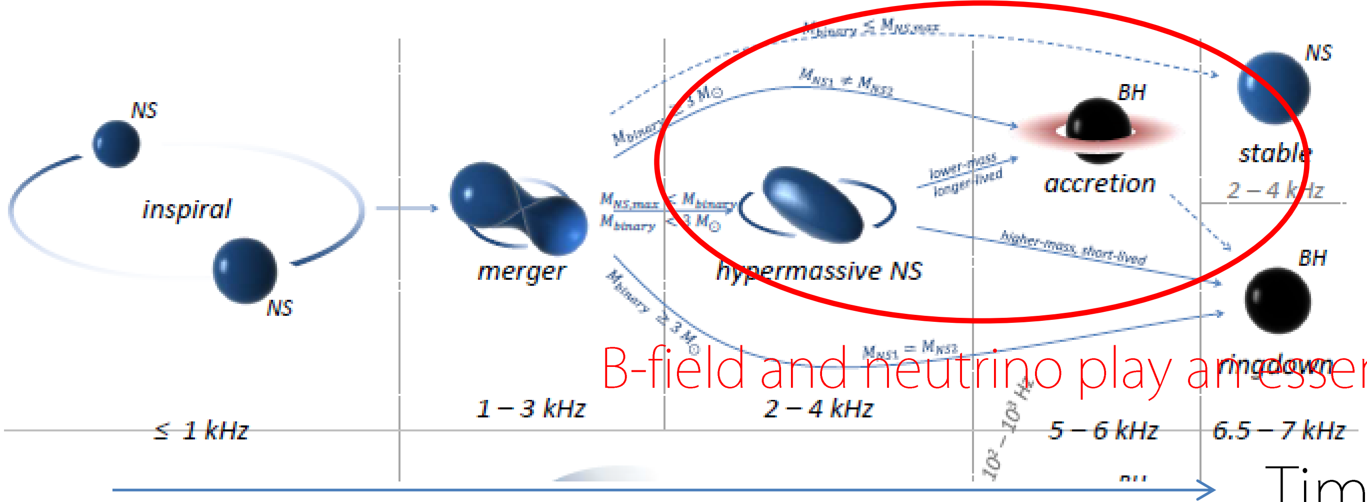
1. High-resolution run (1.5 times finer spatial resolution)

⇒ Extrapolation to the continuum limit

2. Calibration of the Effective One Body template

Exploring a realistic picture of NS-NS mergers

(Bartos et al. 13)



B-field and neutrino play an essential role

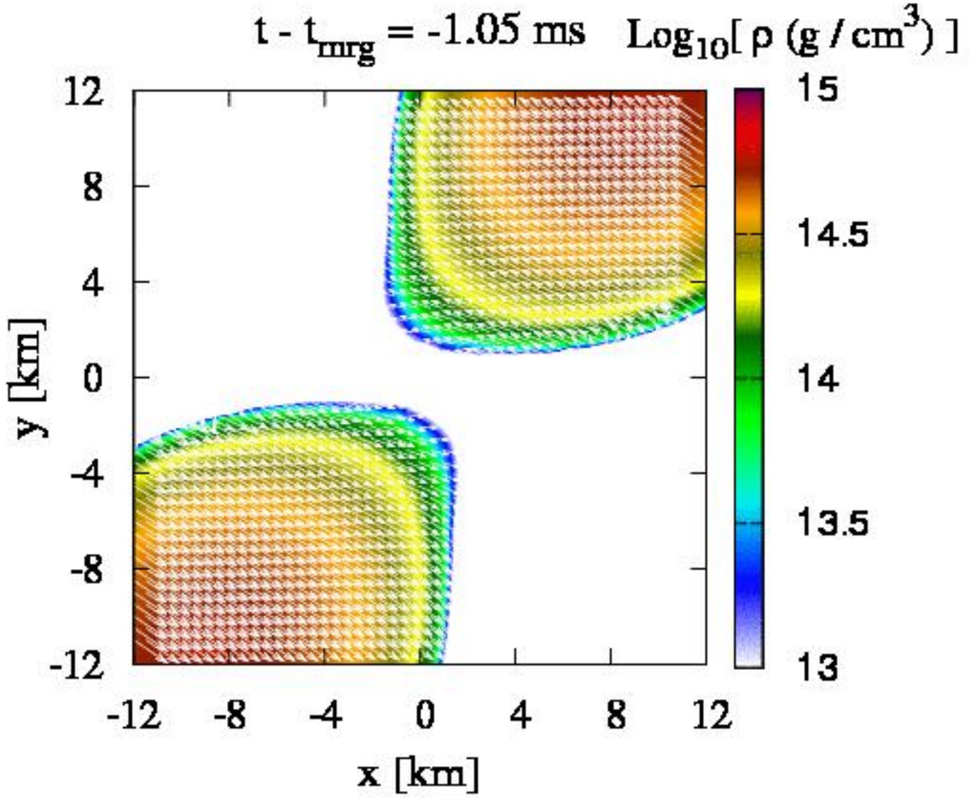
Time axis

- ▶MHD instability-driven viscosity drives the angular momentum transport of remnant massive NSs
- ▶Neutrino radiation determines the chemical composition as well as the thermodynamical properties of the ejecta

Magnetization of the remnant massive NS

Kelvin-Helmholtz instability (KK et al. 14, 15)

Finer resolution (10 times finer than the previous work)

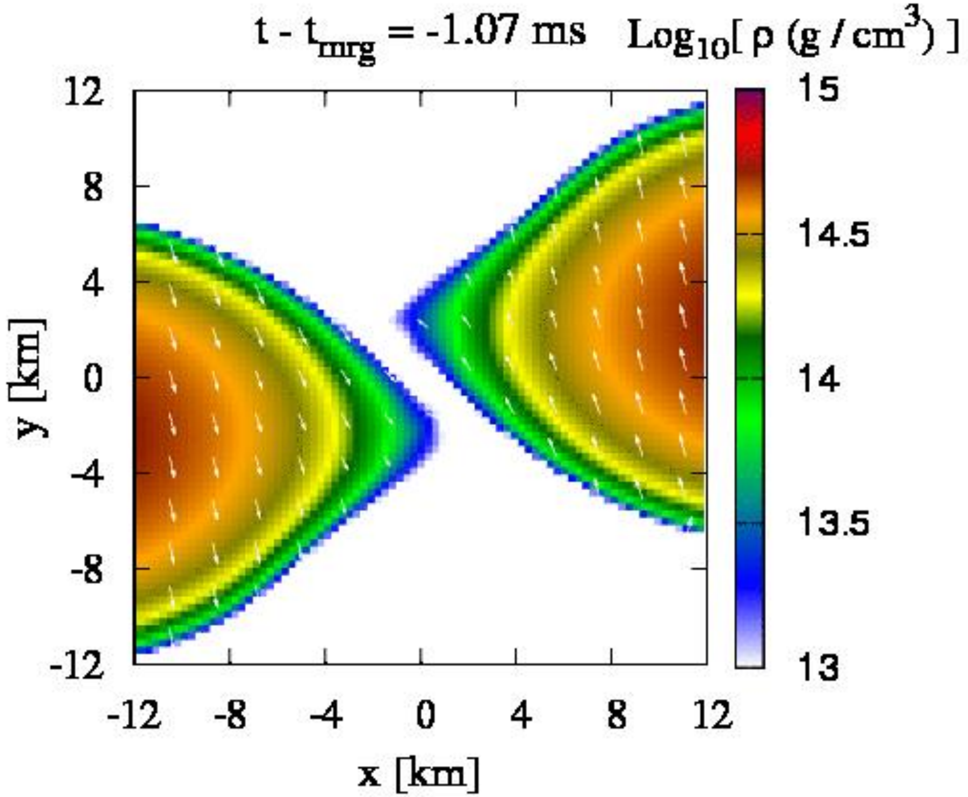


▶Small scale vortices develop rapidly ⇒ Efficient amplification of the B-field

Magnetization of the remnant massive NS

Kelvin-Helmholtz instability (KK et al. 14, 15)

Low resolution



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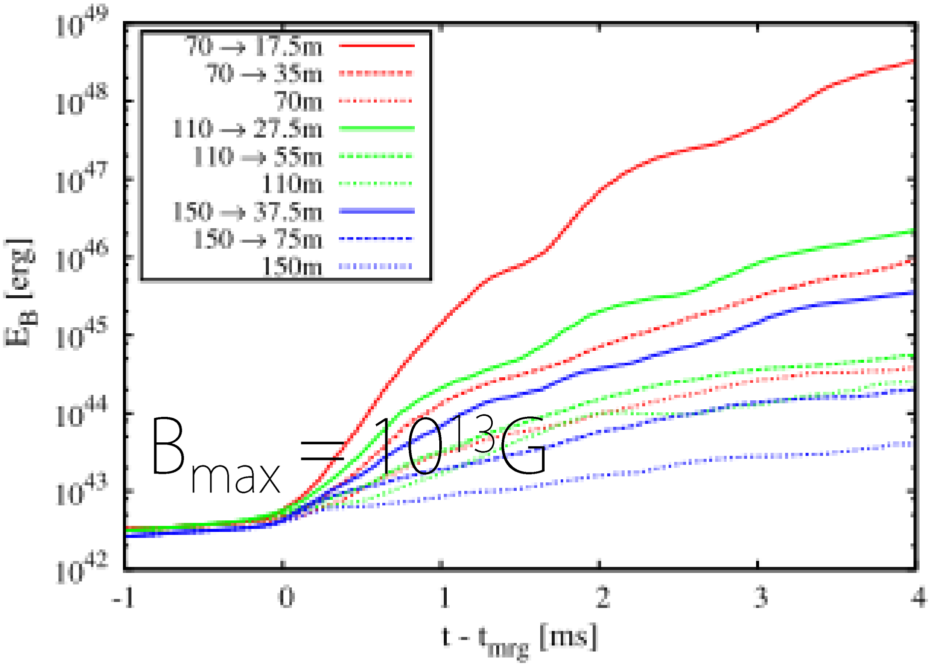
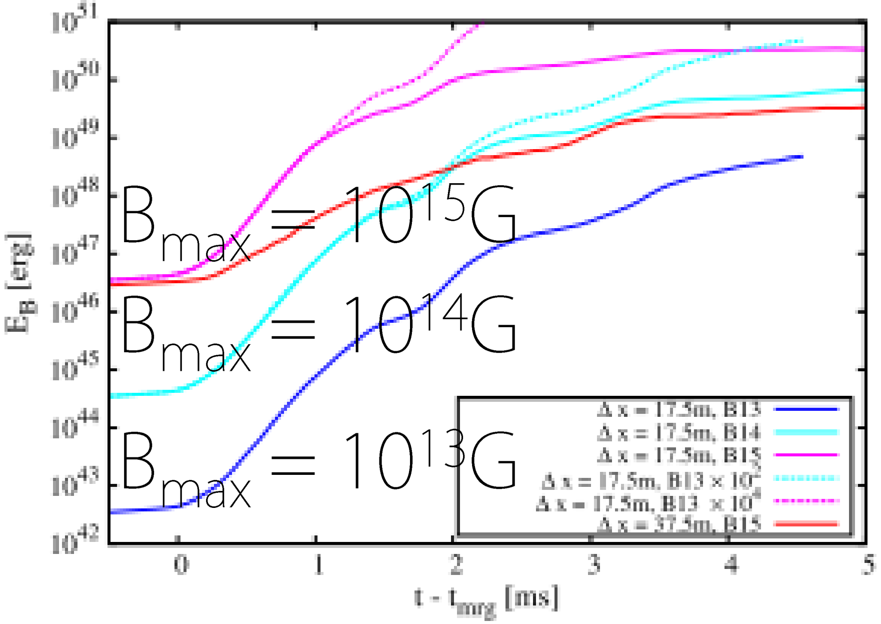
Magnetization of the remnant massive NS





▶Saturation energy ≳10^{50}erg ($B_{RMS}=10^{16}$G)

▶Formation of strongly magnetized remnant NS and switch on of the Magneto Rotation instability

⇒ Turbulent viscosity drives the angular momentum transport

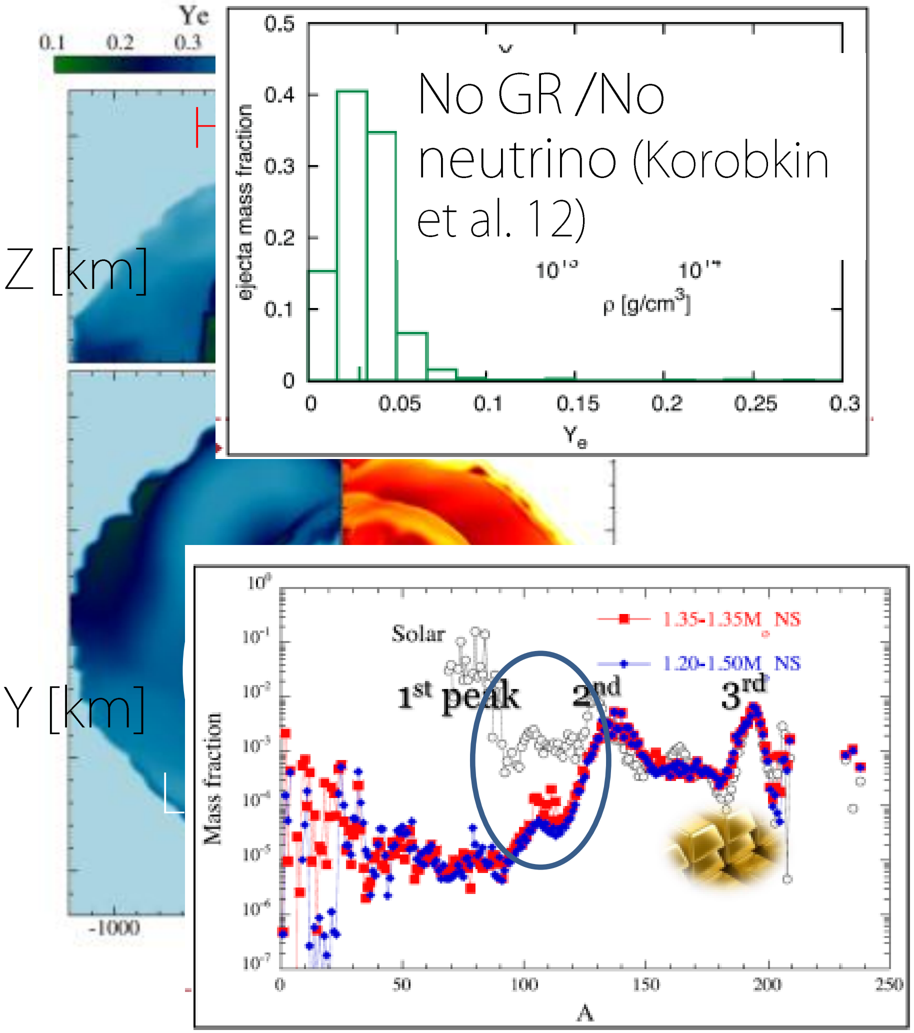
To do list : MHD simulation ⇒Evaluation of alpha viscosity

R-process nucleosynthesis in NS-NS mergers

(Sekiguchi, KK et al, 11, 15,16, Wanajo et al. 14)

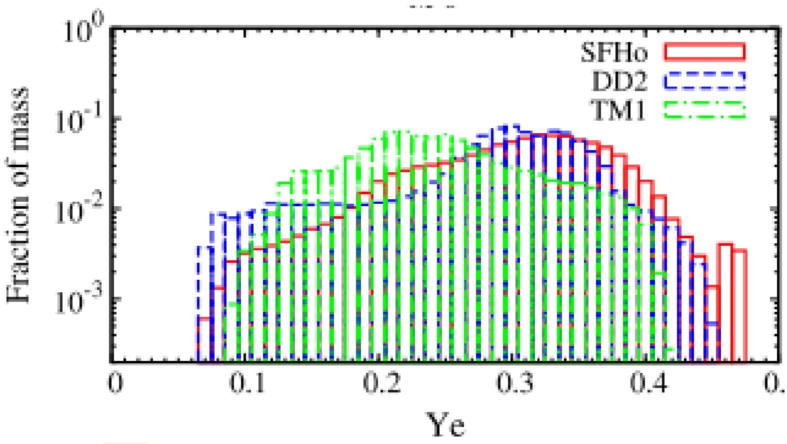
EOS : SFHo (Steiner et al. 2013), Mass : 1.35-1.35M$_\odot$

Electron fraction Entropy

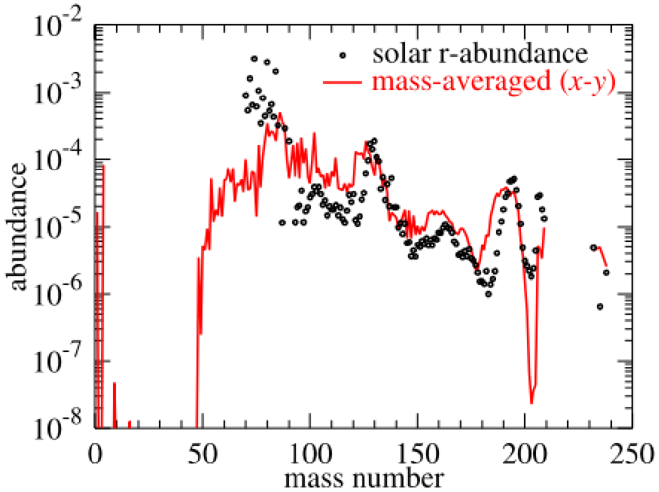


No GR /No neutrino (Korobkin et al. 12)

Mass histogram of the ejecta

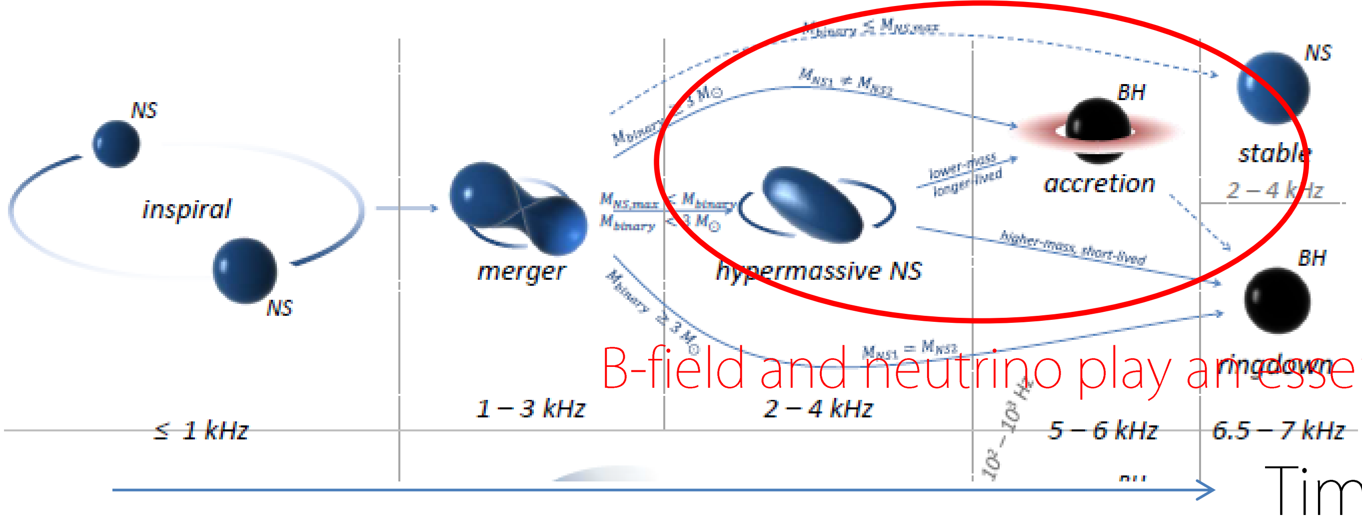


Nucleosynthesis (Wanajo et al. 14)



Exploring a realistic picture of NS-NS mergers

(Bartos et al. 13)



B-field and neutrino play an essential role

Time axis

To do list : High resolution M(HD)-R(adiation)-H(ydrodynamics)

▶Figuring out the evolution process of the remnant massive NS

* Mass ejection by neutrino, viscos, MHD-driven wind

* Modeling of the central engine of SGRBs

t = 0.2270 ms

10^{12} g/cm^3

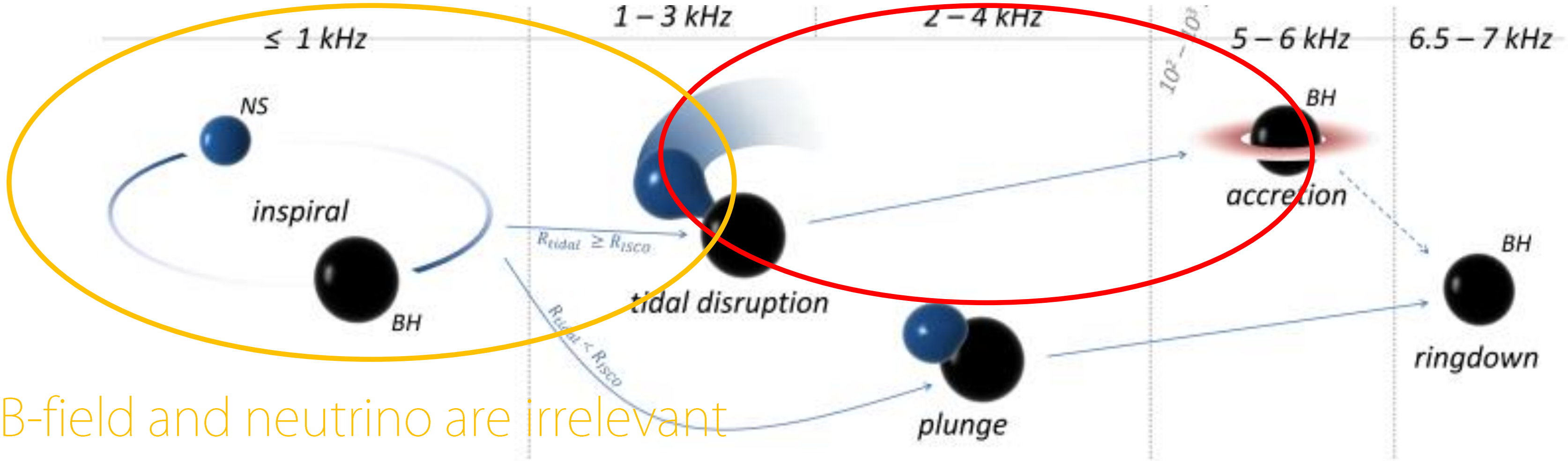
10^{11} g/cm^3

10^{10} g/cm^3

10^{9} g/cm^3

Exploring a realistic picture of BH-NS merger

(Bartos et al. 13)



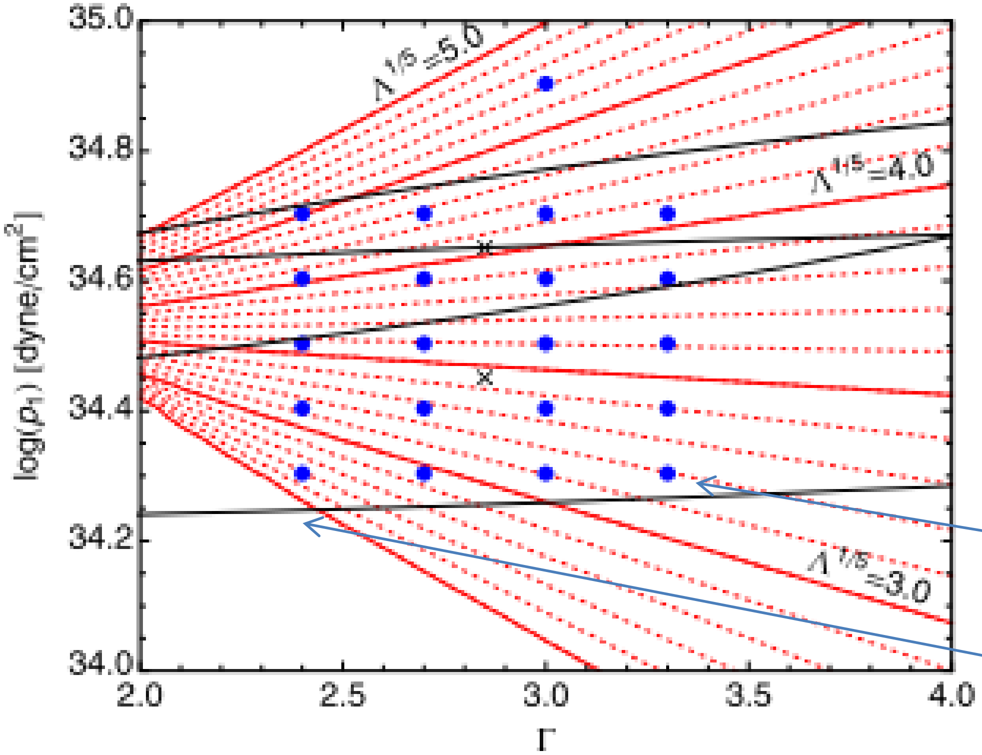
B-field and neutrino are irrelevant

B-field and neutrino play an essential role

▶Inspiral and early merger waveforms
⇒ Tidal deformability of NSs

Tidal deformability of NSs

Lackey et al. 12, 14



$$P = 3.5966 \times 10^{13} \rho^{1.3569} \; (\rho \le \rho_0)$$

$$= \kappa_1 \rho^{\Gamma} \; (\rho \ge \rho_0)$$

$$p_1 = \kappa_1 \rho_1^{\Gamma} \; (\rho_1 = 10^{14.7}\,\mathrm{gcm}^{-3})$$

$$\Lambda = \frac{2}{3} k_2 \left(\frac{G M_{\rm NS}}{R c^2} \right)^{-5}$$

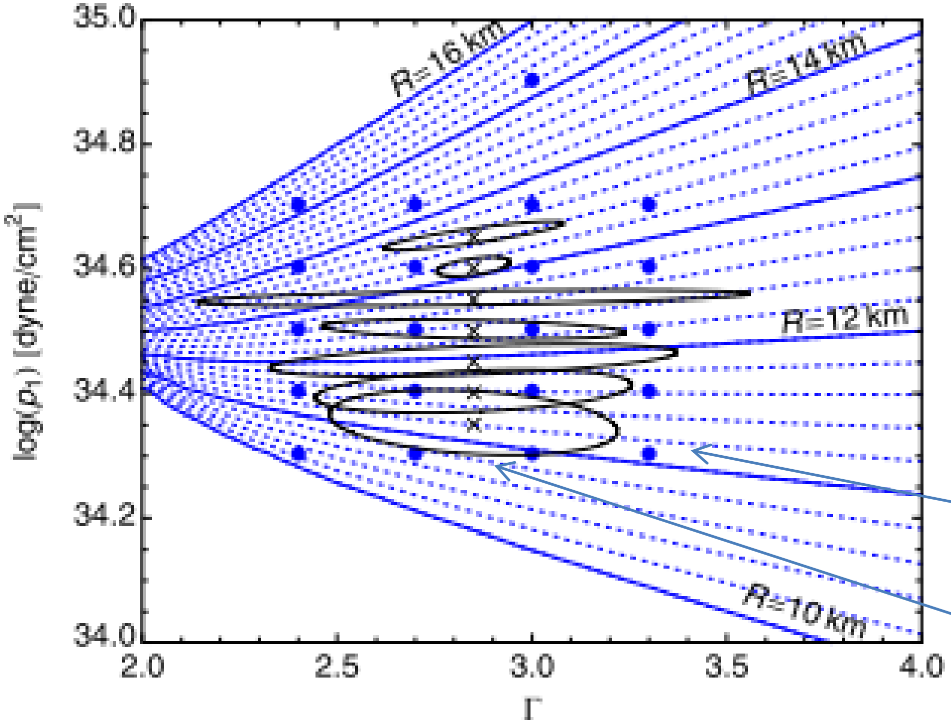
NR simulation data

1 σ error circle

- Error contour for Advanced LIGO with D=100Mpc , $M_{BH}/M_{NS} = 2$, and $M_{NS}=1.35M_{\odot}$

Tidal deformability of NSs

Lackey et al. 12, 14



$$P = 3.5966 \times 10^{13} \rho^{1.3569} \ (\rho \le \rho_0)$$
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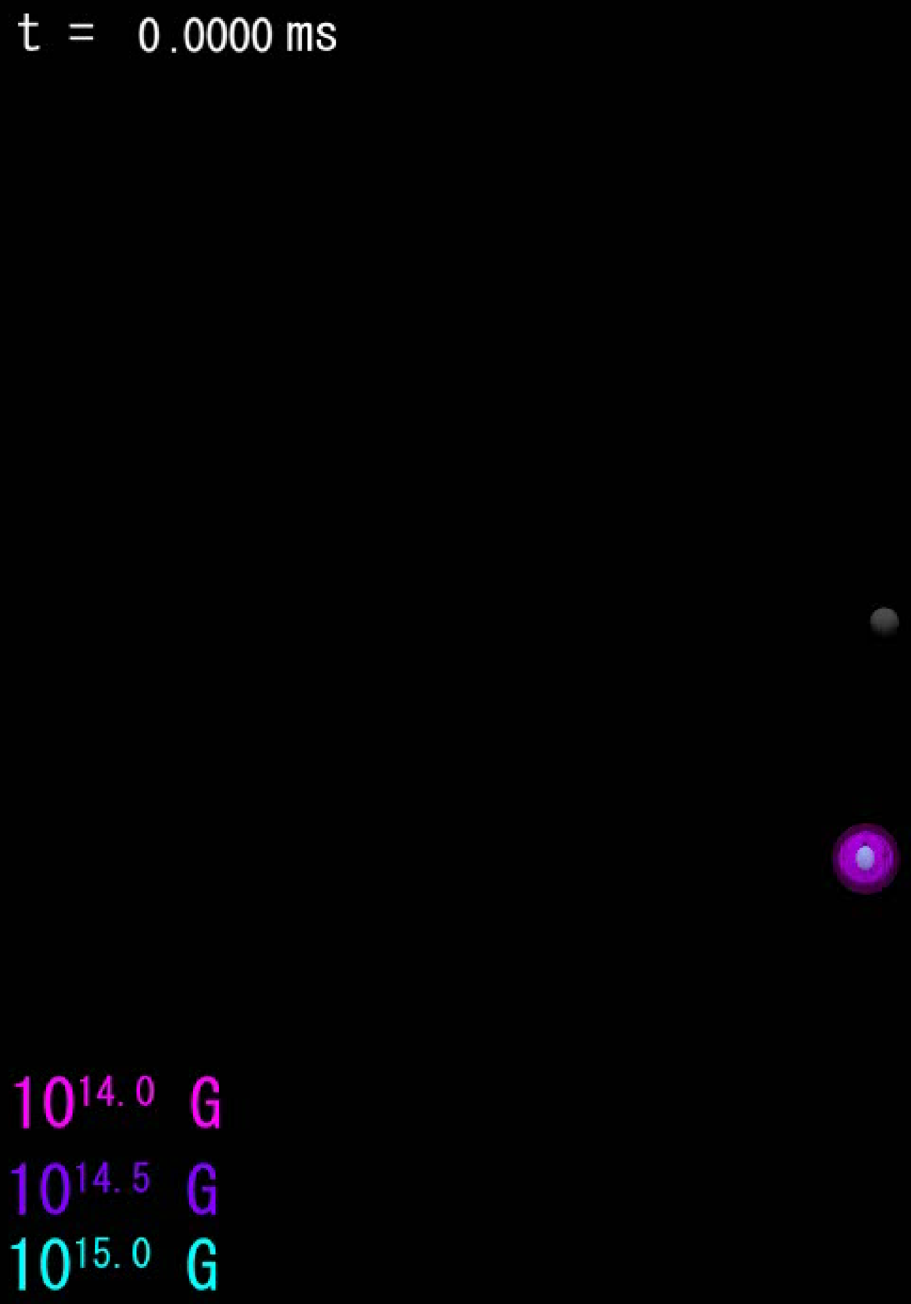
$$\Lambda = \frac{2}{3} k_2 \left(\frac{G M_{\mathrm{NS}}}{R c^2} \right)^{-5}$$

NR simulation data

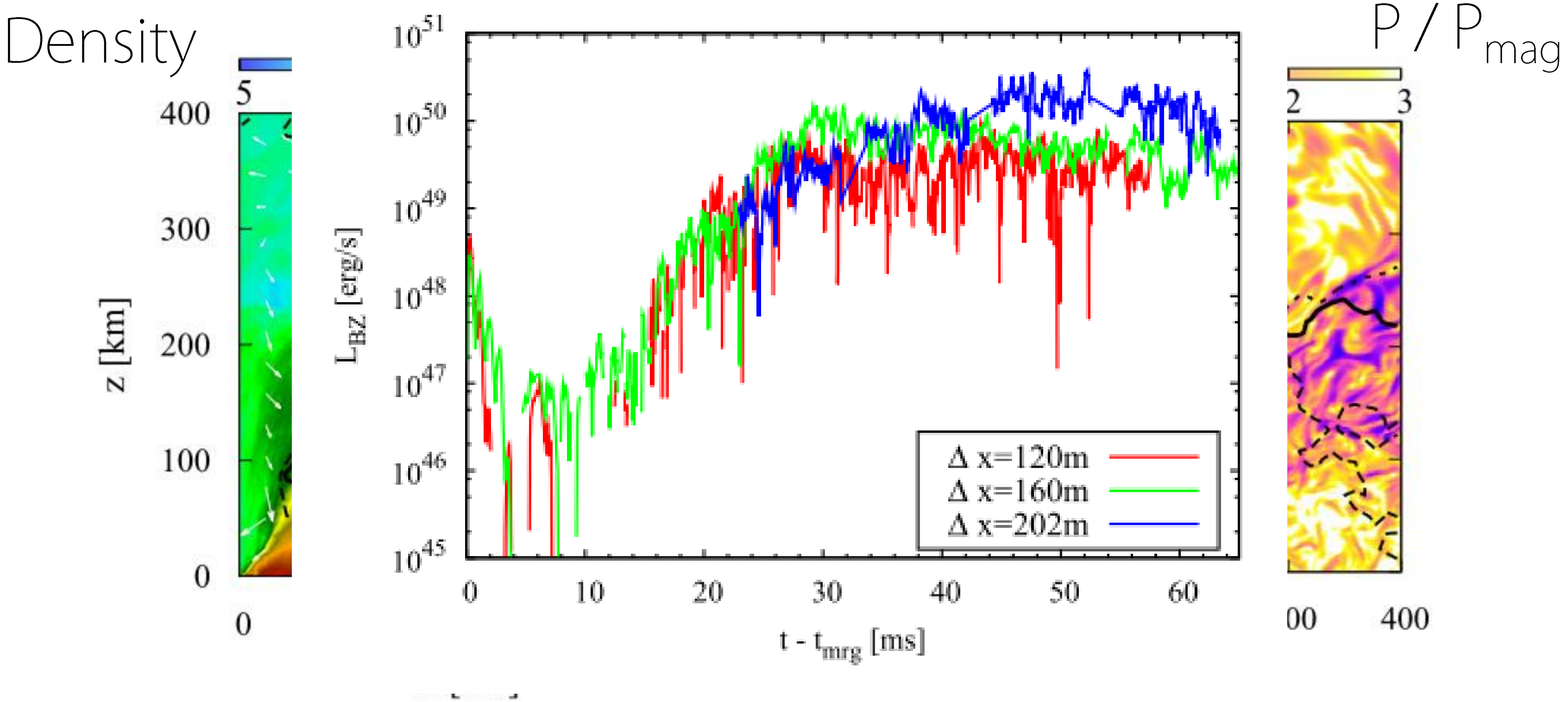
1 σ error circle

▶ Error circle of ET with D=100Mpc, $M_{BH}/M_{NS} = 2$, $M_{NS}=1.35M_\odot$

▶ Need high-precision GW waveforms and large parameter study(M_{BH}/M_{NS}, M_{NS}, EOS, BH spin(dir.,mag))


t = 0.0000 ms
$10^{14.0}$ G
$10^{14.5}$ G
$10^{15.0}$ G

BH-NS merger as a central engine of SGRBs



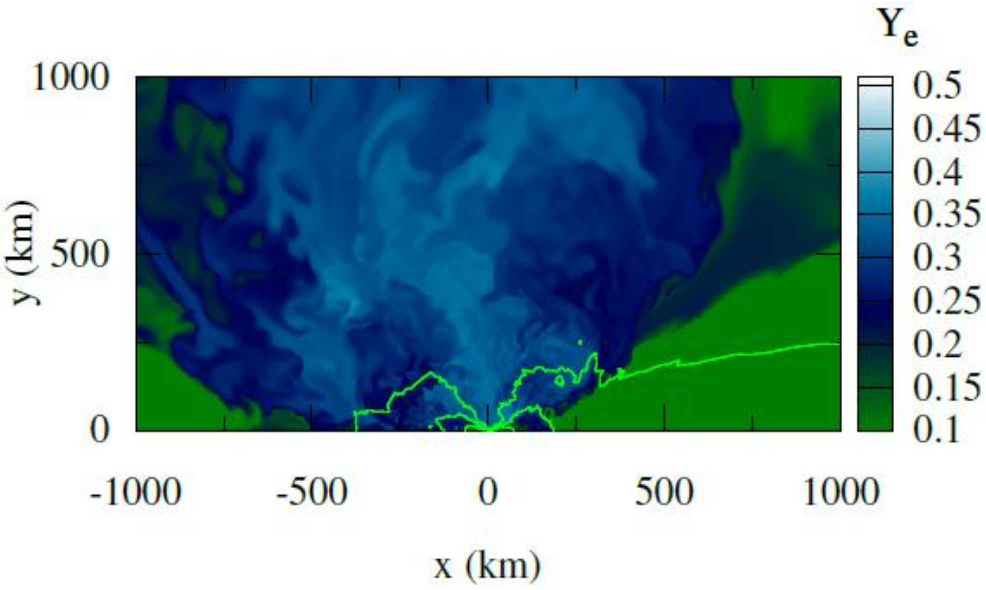
▶ Funnel wall formation by the torus wind

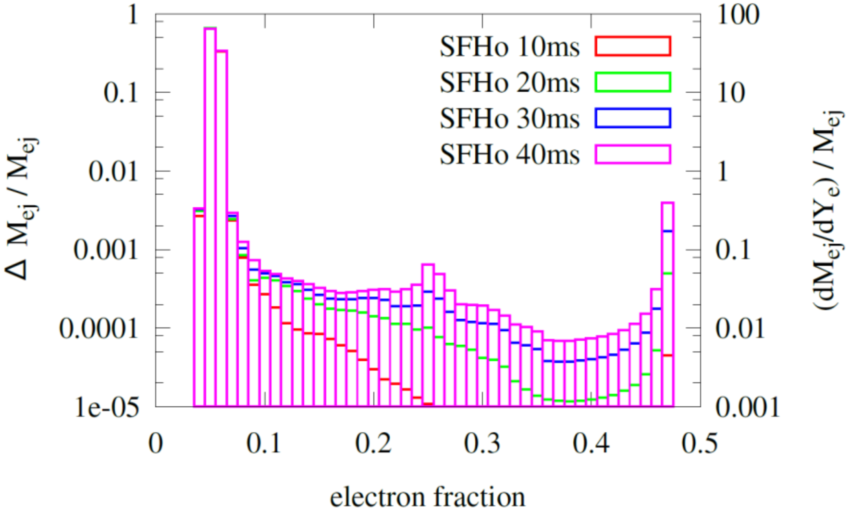
▶Torus wind ⇒ Coherent poloidal B-field ⇒ Formation of a low plasma beta region ⇒ Formation of the magnetosphere

▶ The BH rotational energy is efficiently extracted as the outgoing Poynting flux ; ≈ 2 × 10^{49} erg/s (Blandford-Znajek 77)

R-process nucleosynthesis in BH-NS mergers

(Kyutoku et al. in prep.)

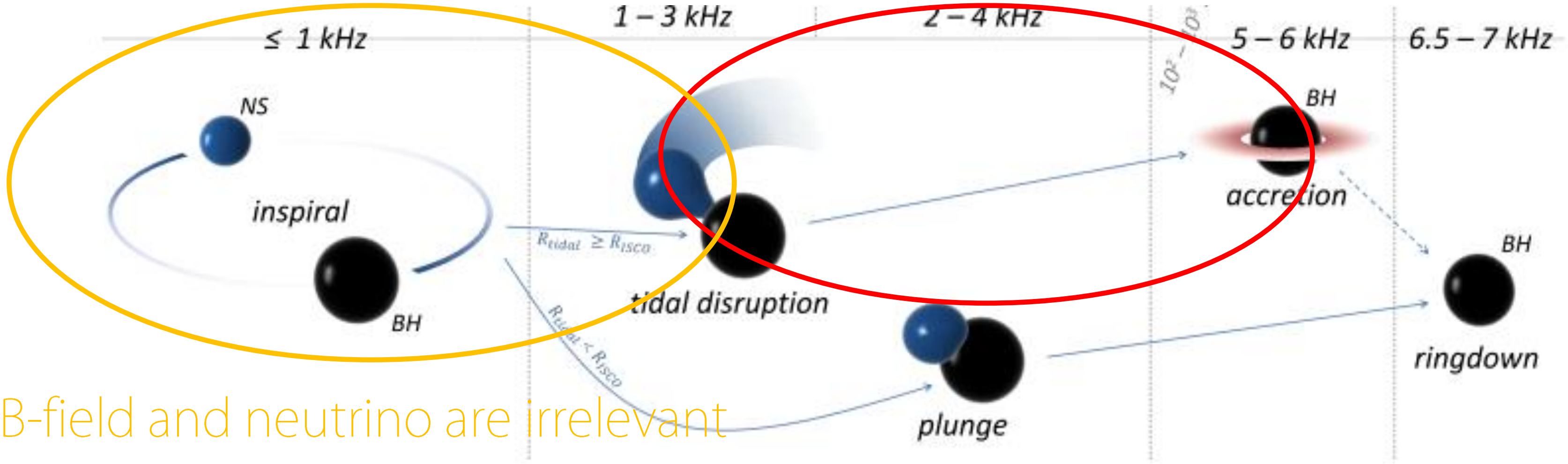




- ▶ Dynamical ejecta ⇒ Low Y_e
- ▶ Torus wind ⇒ High Y_e

Exploring a realistic picture of BH-NS merger

(Bartos et al. 13)



B-field and neutrino are irrelevant

B-field and neutrino play an essential role

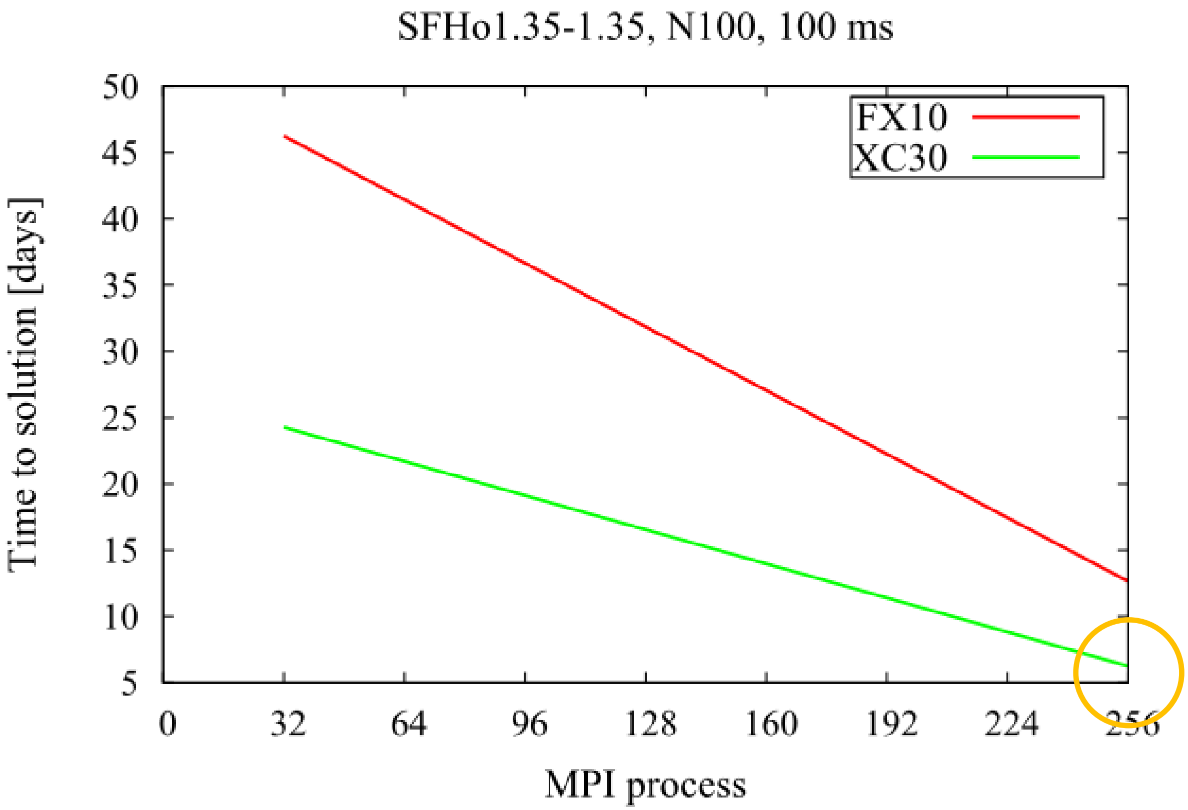
To do list

▶High-precision GW forms⇒EOB calibration and template bank

▶Comprehensive picture of the mass ejection⇒R-process nucleosynthesis & Elemag counerpart

▶Modeling of the central engine of SGRBs

Parallelization of SACRA(AMR) code



- Cost to derive high-precision GW forms from BNS merger
- About one week in NAOJ machine (16 months in the non-parallelized code)
- Applicable to BH-BH simulations

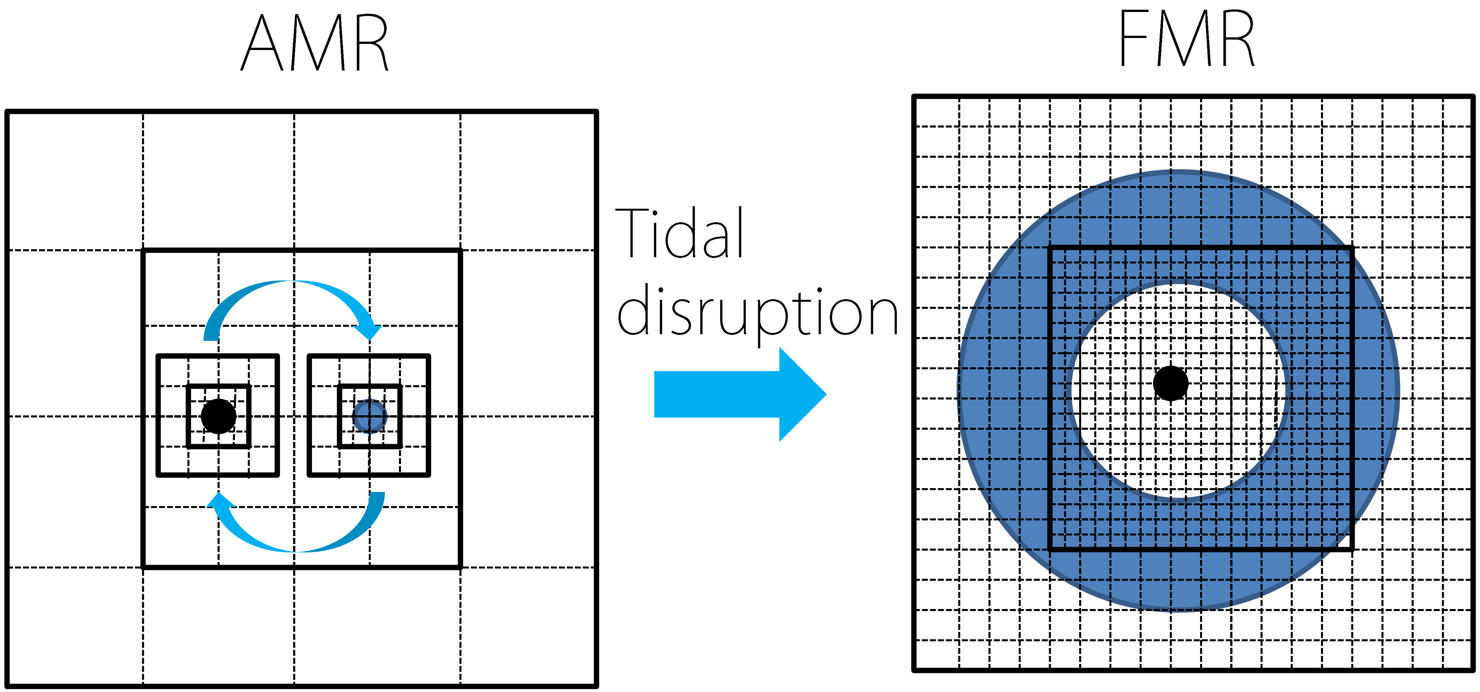
Summary

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

▶For BH-BH mergers, the code is ready
High mass ratio or high BH spin?

▶For NS-NS / BH-NS mergers
○High-precision GW forms in inspiral and early merger phase
○Evolution in post merger phase (B-field, Neutrino)

From Adaptive Mesh Refinement to Fixed Mesh Refinement



- ▶Inspiral and early merger : High-res. AMR
- ▶Early and post merger : High-res. and large domain FMR