Numerical modeling of binary neutron star mergers

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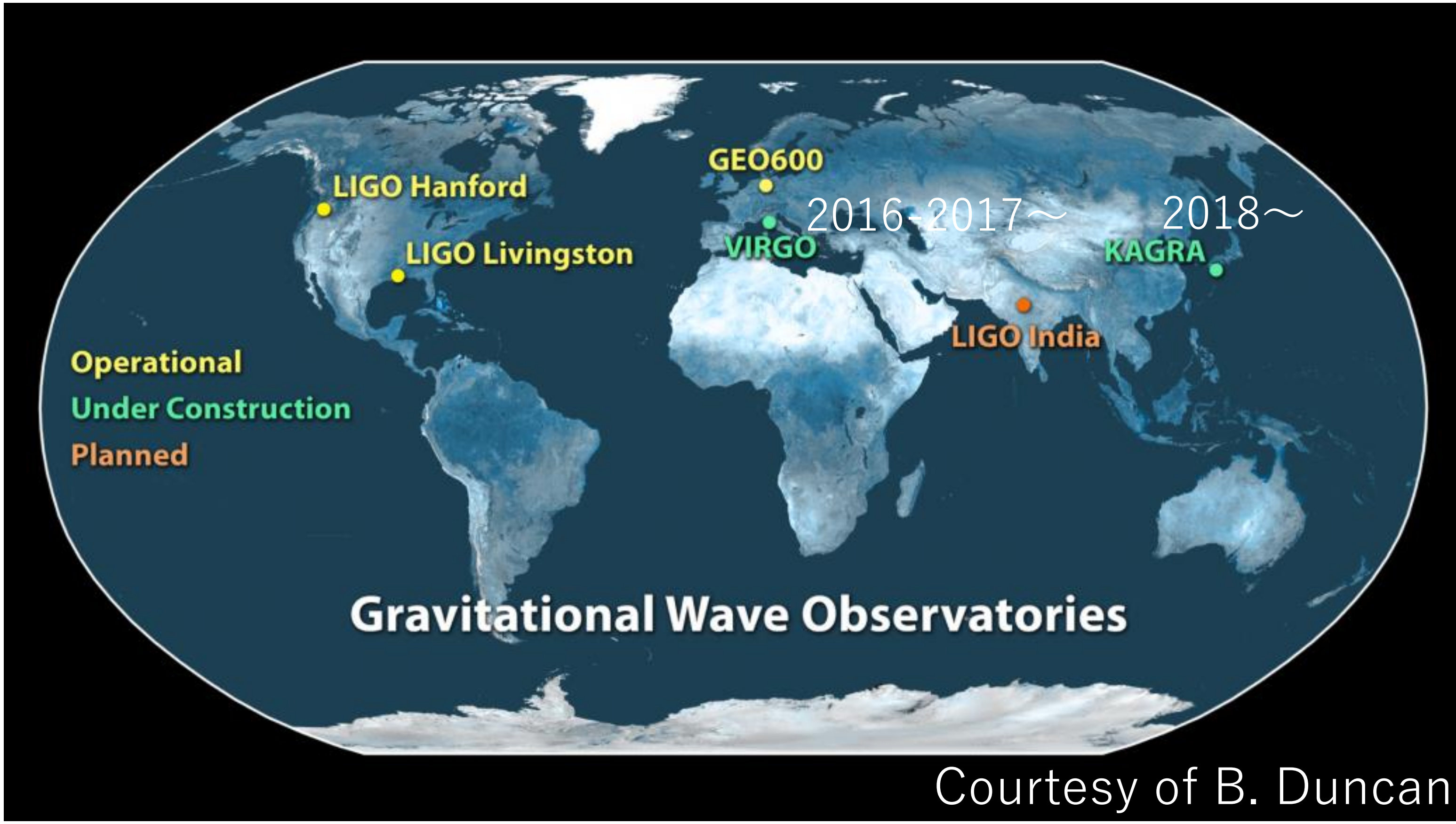
Dawn of the GW astronomy



▶ 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

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 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)

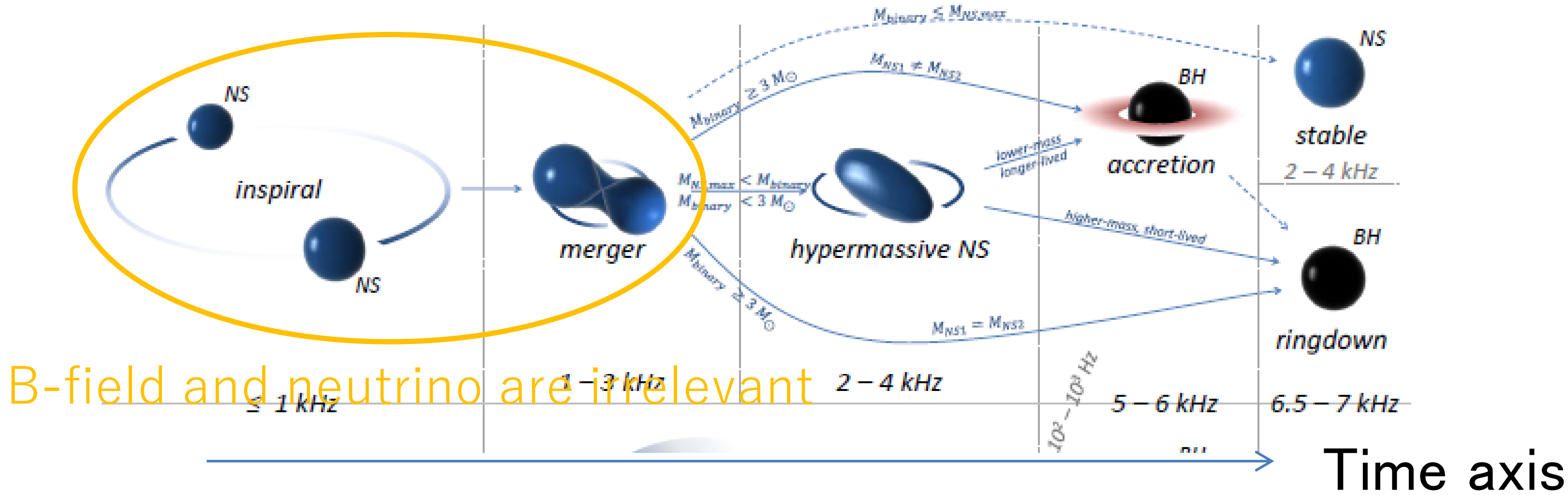
Origin of the heavy elements

▶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)



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

Science target : Measuring a tidal deformability of NS

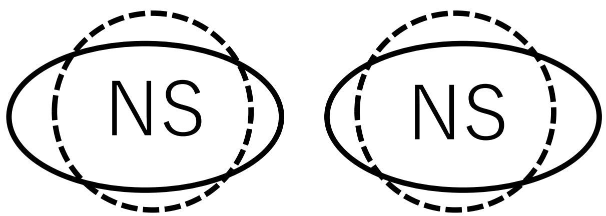
From inspiral to late inspiral phase

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.

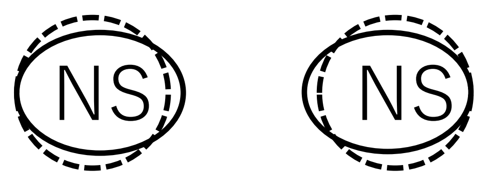
Tidal deformation

Stiff EOS (larger R)



Easily tidally deformed

Soft EOS (small R)

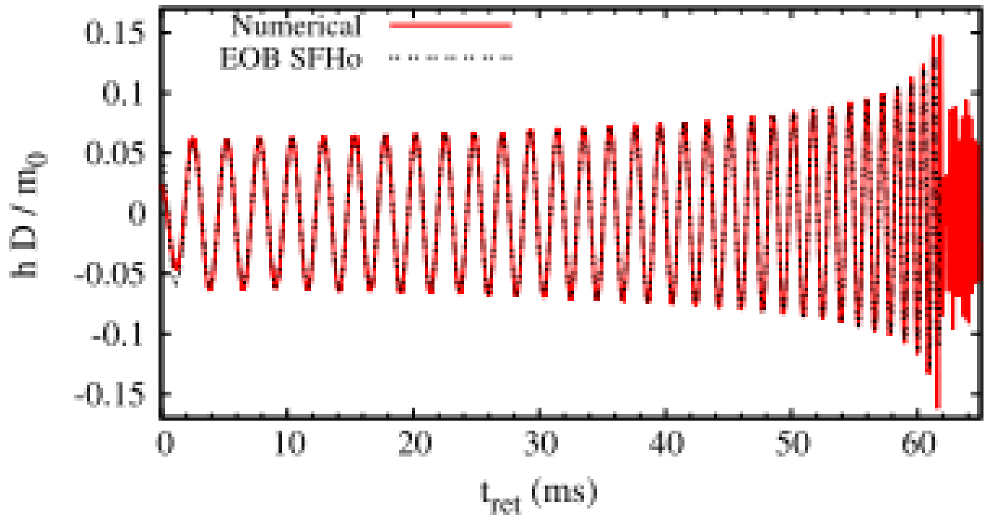


Hard to be tidally deformed

How is tidal deformability imprinted in GWs ?

$$h = \underbrace{A(t)}_{\text{Amplitude}} e^{i\underbrace{\Phi(t)}_{\text{Phase}}}$$

Tidal deformation accelerates the phase evolution



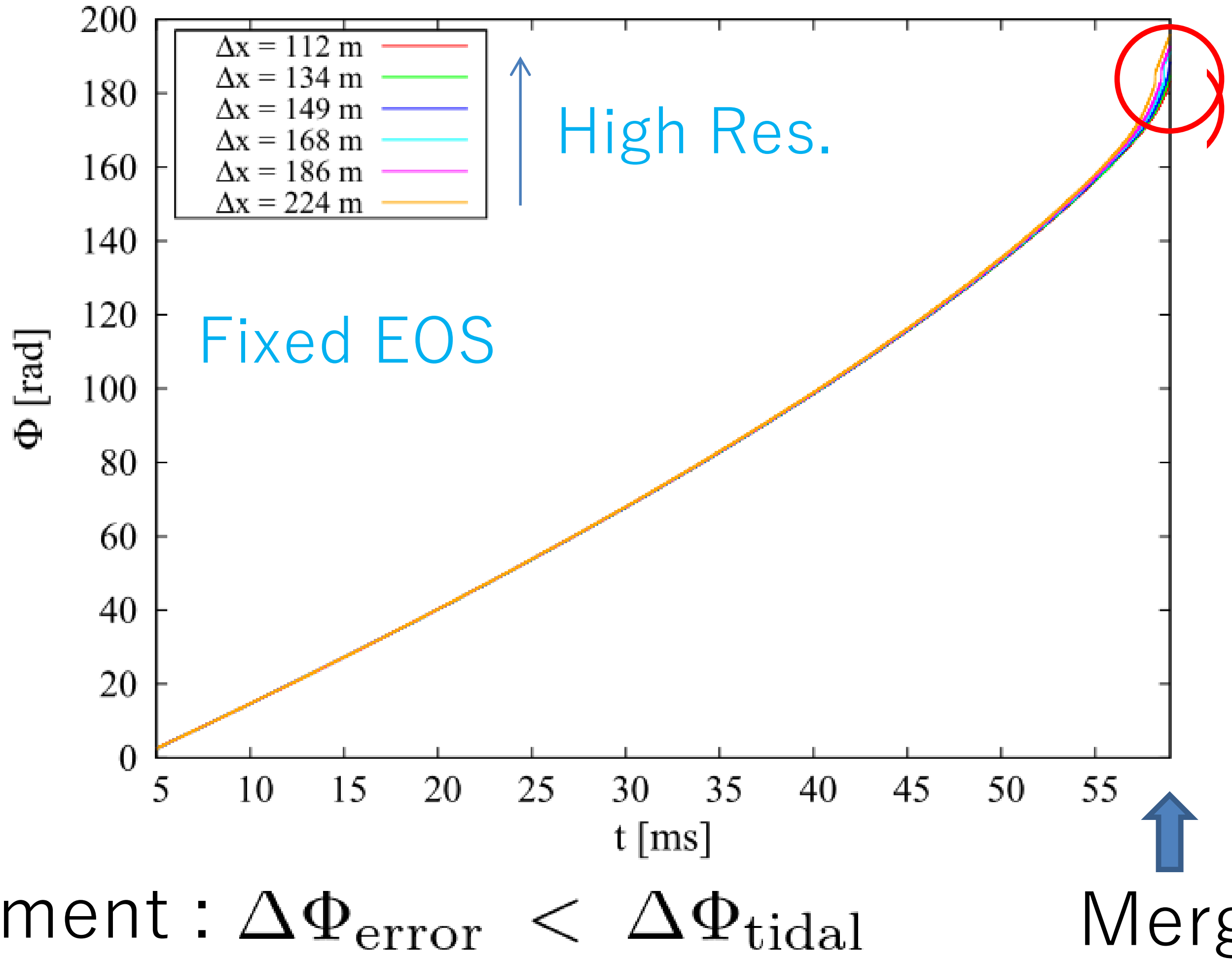
Post Newton (cf. EOB); Low cost, but inaccurate @ merger ⟷ NR; Robust, but high cost

Template bank based on NR simulations should be built

For the calibration of EOS waveforms

Large tidal deformability ⇒ Rapid phase evolution

Numerical diffusion ⇒ Rapid phase evolution



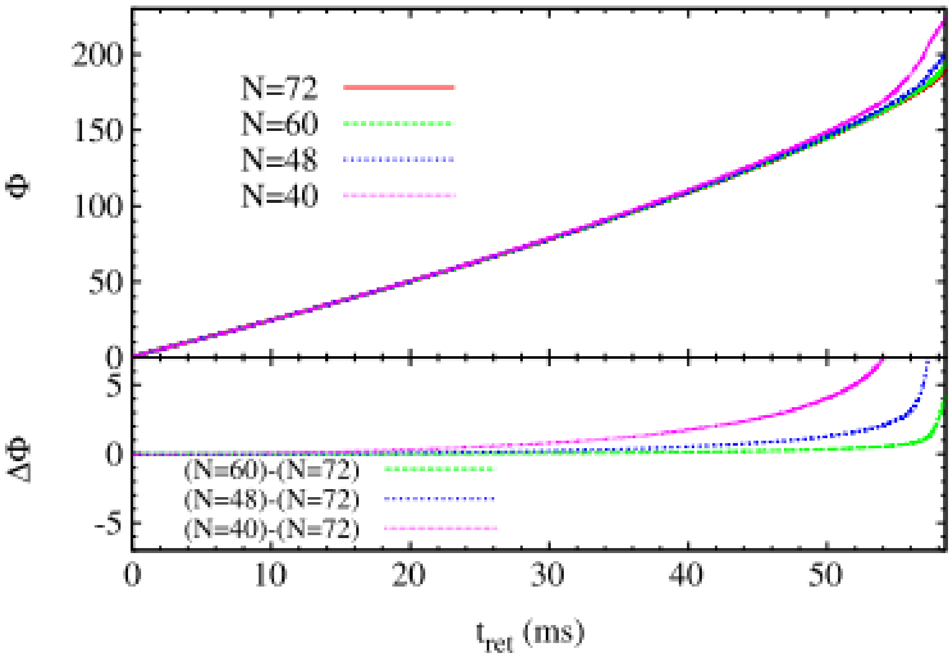
Requirement : $\Delta\Phi_{\mathrm{error}} < \Delta\Phi_{\mathrm{tidal}}$

Convergence study ⇒ Continuum limit

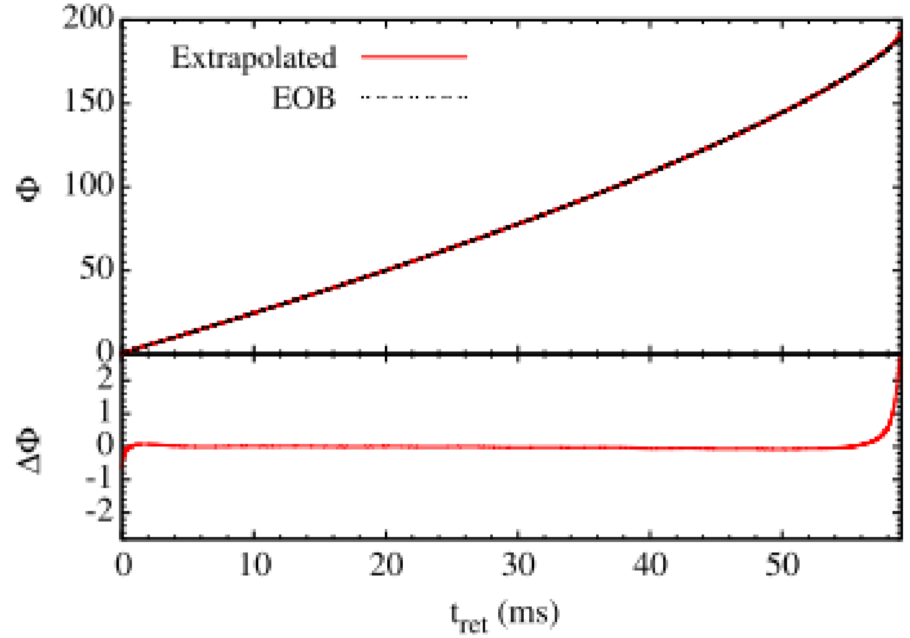
Current status tidal deformability of NSs

Hotokezaka et al. 13, 15, 16, see also Dietrich et al. 17, Beruzzi et al. 15

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. simulation

A step towards accurate late inspiral waveform

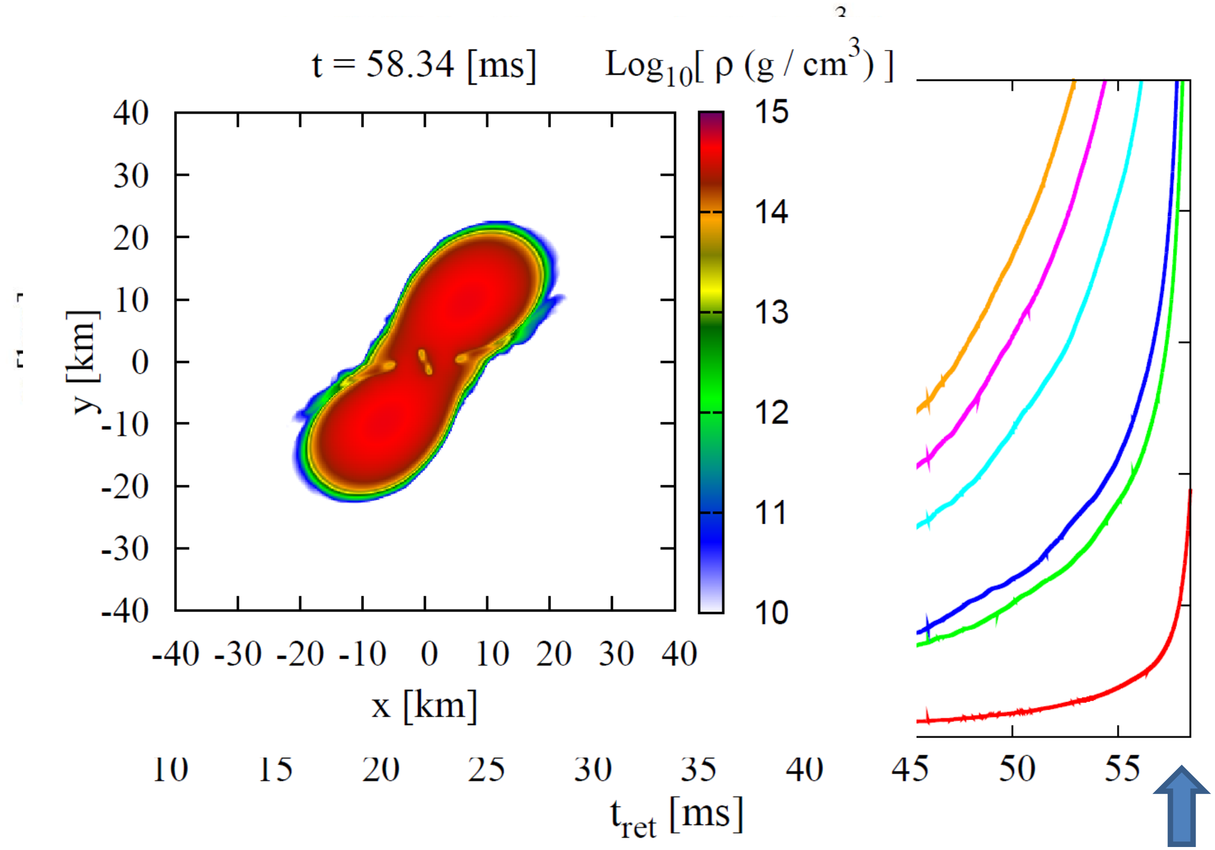
Super computers accelerate NR waveform production.

32 TFlops month/model for "best" resolution (2.2 times higher resolution than in Hotokezaka et al.)
⇒ Systematic study is possible

Waveform production : over 100 waveforms/yr

Key ingredients
▶ Resolution study (4-5 res.)
▶ Low eccentricity initial data ($e \sim 10^{-3}$)
▶ Long term evolution (15-16 orbits before the merger)

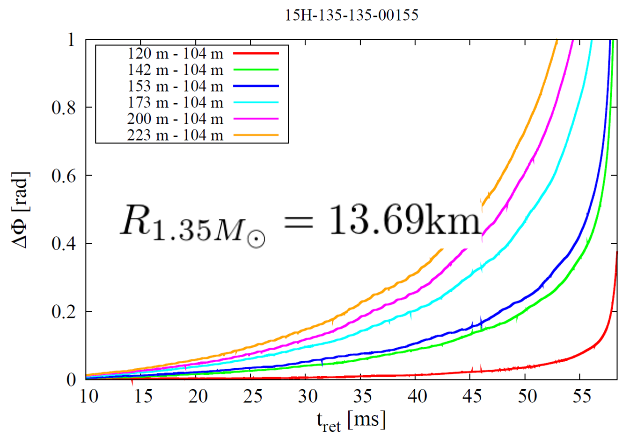
Phase shift of GWs $1.35M_\odot - 1.35M_\odot$

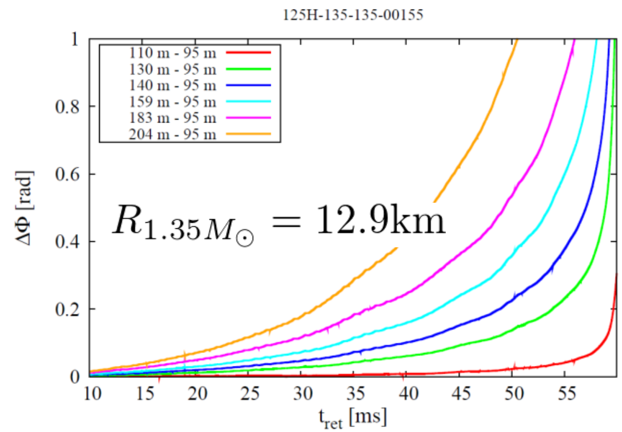


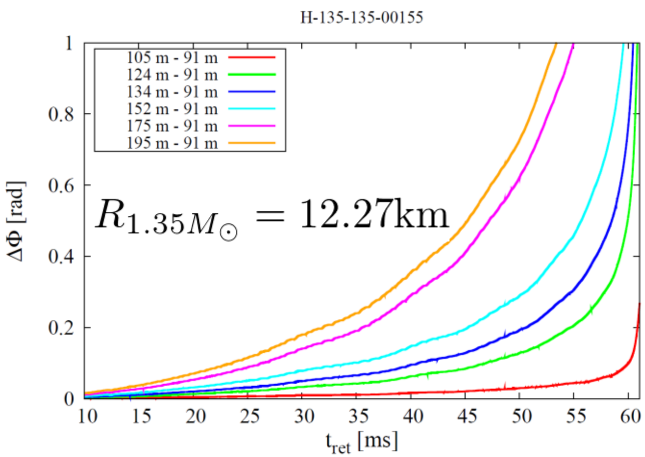
Merger (58.42ms)

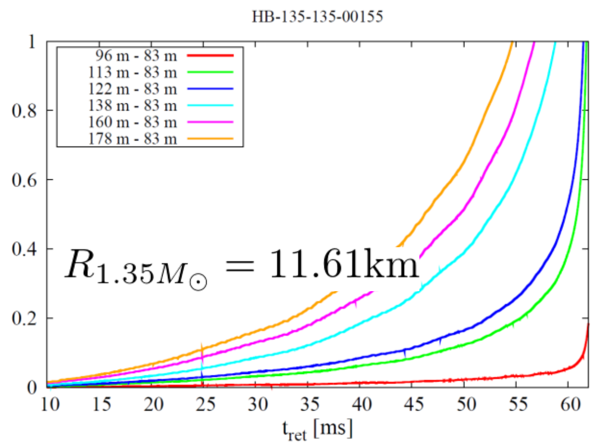
- ▶ Merger time = Time at maximum amplitude of GWs
- ▶ Phase shift is ～0.4 radian over 200 radian
- ▶ Merger before ～0.5 ms may not be described by the analytic modeling (c.f., EOB)

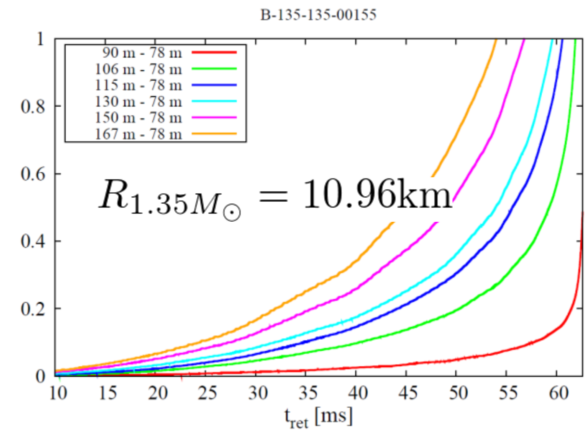
Current status of NR simulations











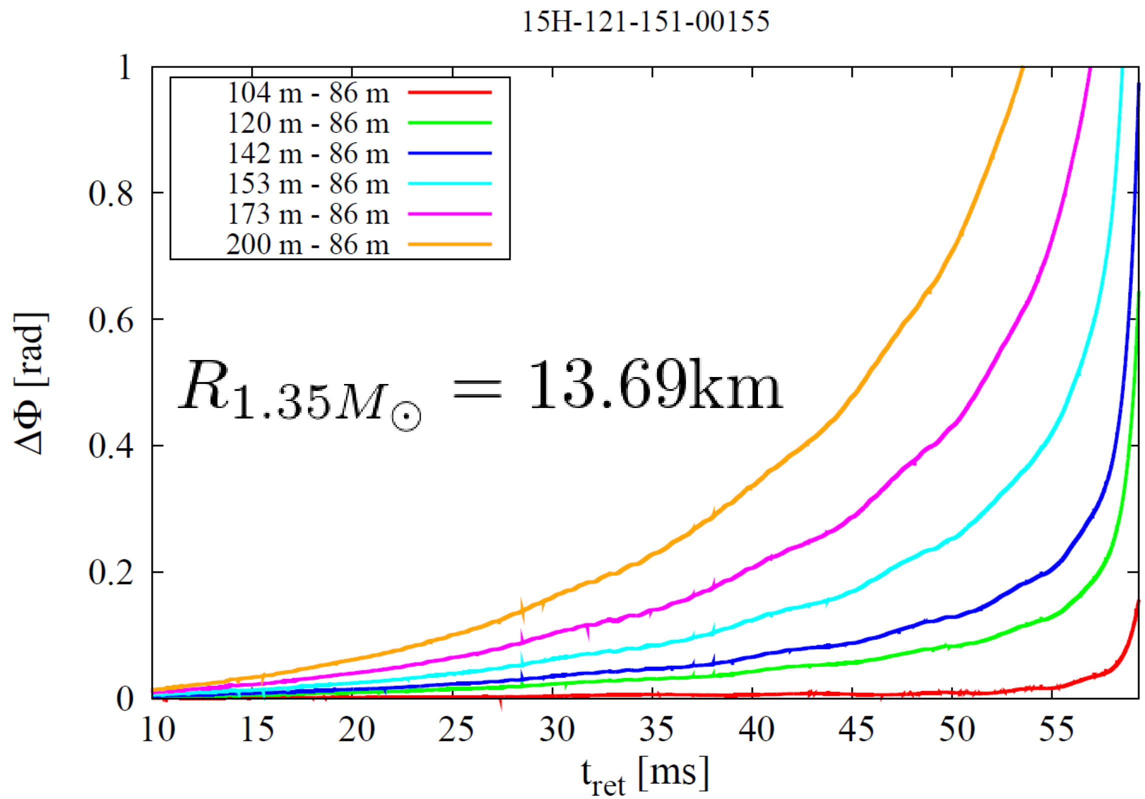
▶ Δx = 78-104 m for the model similar to that in Hotokezaka et al. 15, 16, c.f. Δx = 140-183 m

▶ $\Delta\Phi_{\rm error} \simeq 0.3 - 0.5\,\mathrm{rad.}$

▶ Higher res. (Δx = 64-86 m) run will finish within 1 month

⇒ $\Delta\Phi_{\rm error} \approx 0.1\,\mathrm{rad.}$?

Unequal-mass case $1.21M_\odot - 1.51M_\odot$



▶ $\Delta\Phi_{\rm error} \approx 0.2\,\text{rad}.$

▶ Other models are on going

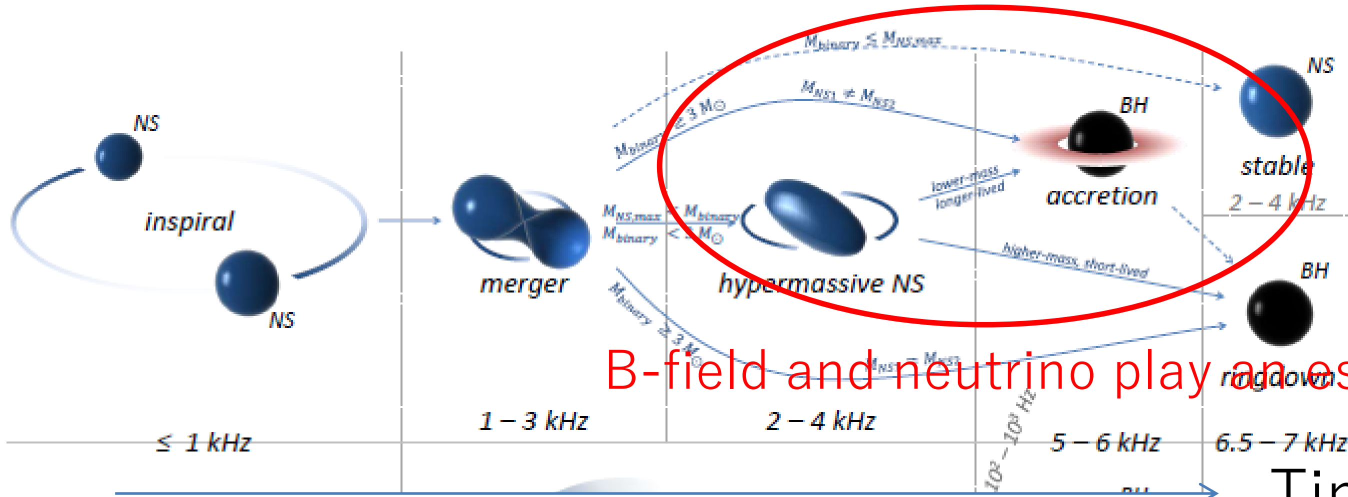
To do list

▶ Take continuum limit

▶ Calibration EOB and construct a template bank

Exploring a realistic picture of NS-NS mergers

(Bartos et al. 13)



B-field and neutrino play an essential role

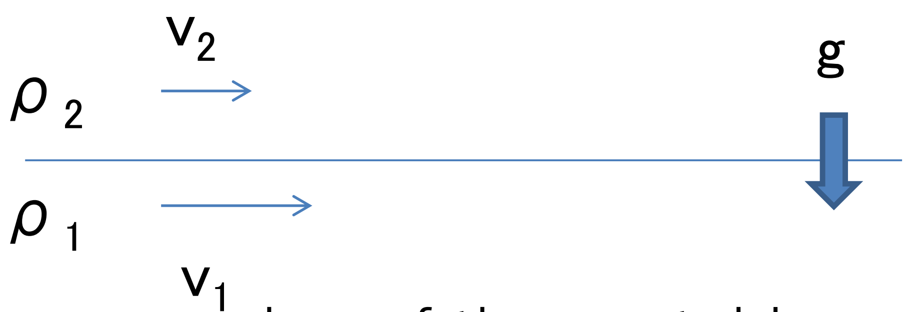
Time axis

▶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.

B-field amplification @ the merger

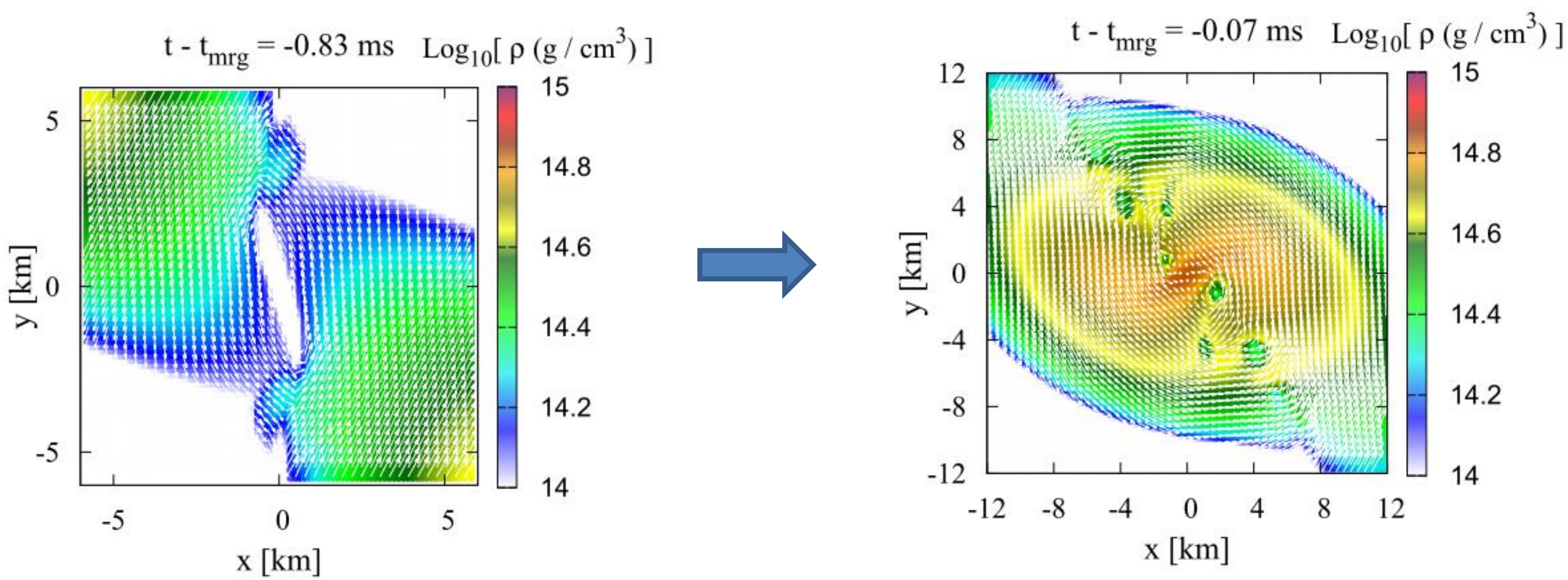
Kelvin Helmholtz instability (Rasio and Shapiro 99, Price & Rosswog 05)



Minimum wave number of the unstable mode ;

$k_{min} \propto g(\rho_1 - \rho_2)/(v_1 - v_2)^2$

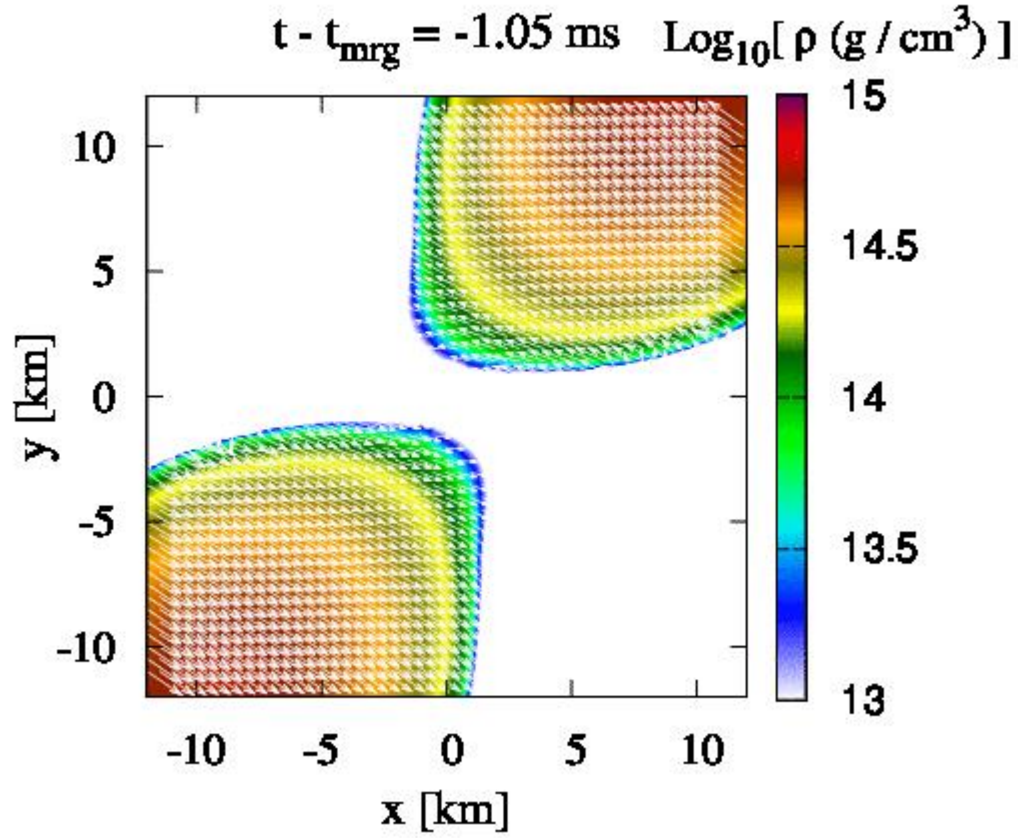
⇒ If g = 0, all the mode are unstable. $\sigma \propto k$



Magnetization of the remnant massive NS

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

Finer resolution (Δx=17.5m, N=1,024^3/2)

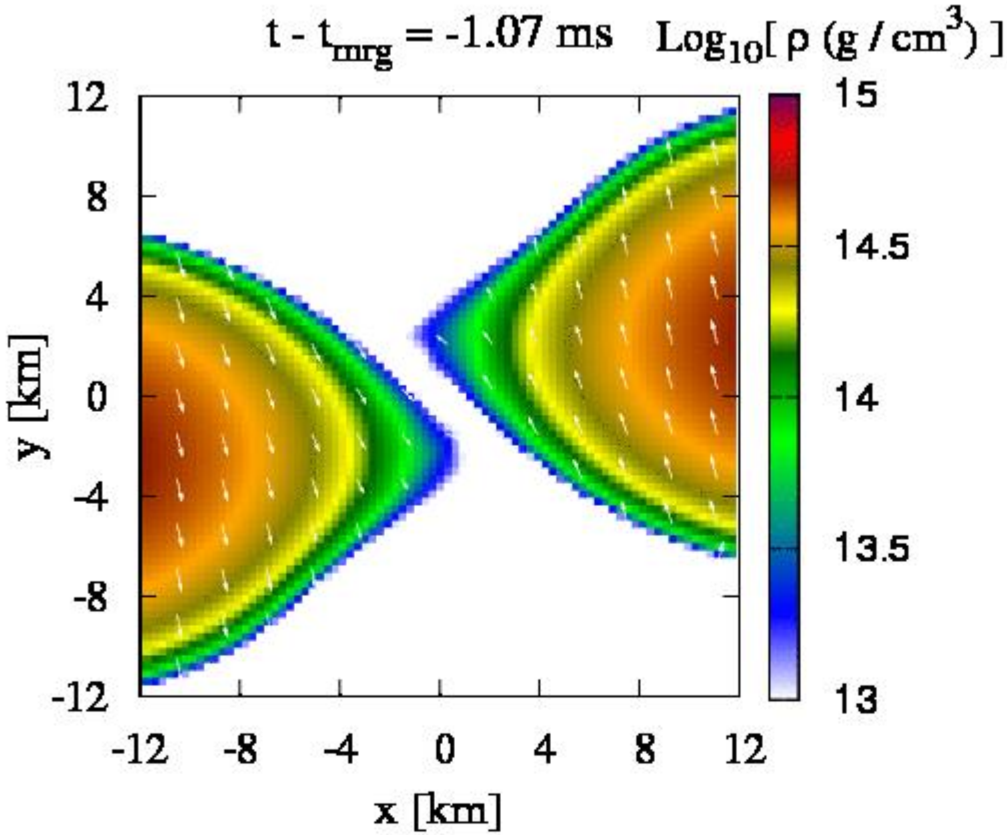


▶Small scale vortices develop rapidly ⇒ Efficient amplification of the B-field

Magnetization of the remnant massive NS

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

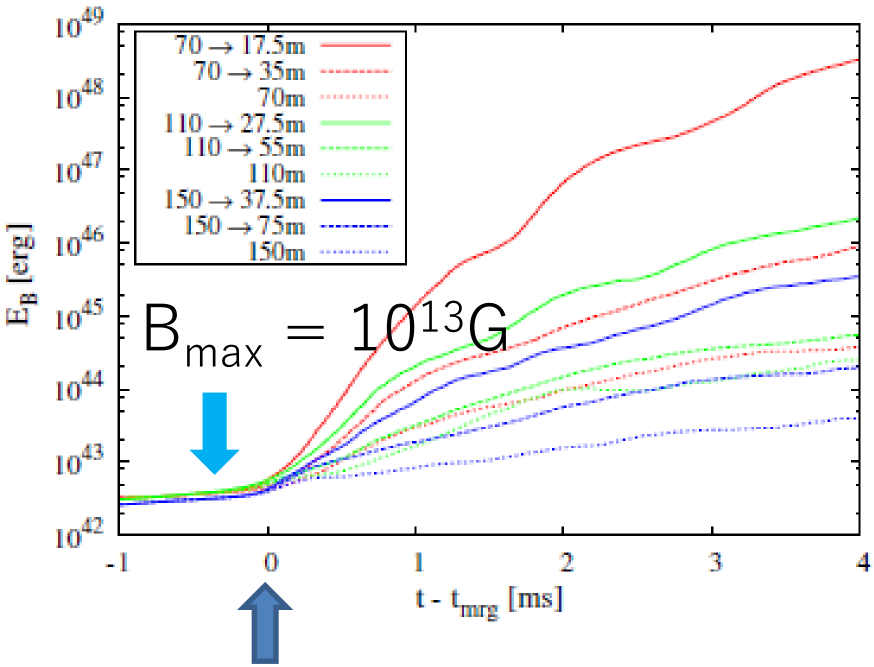
Low resolution (Δx=150m)

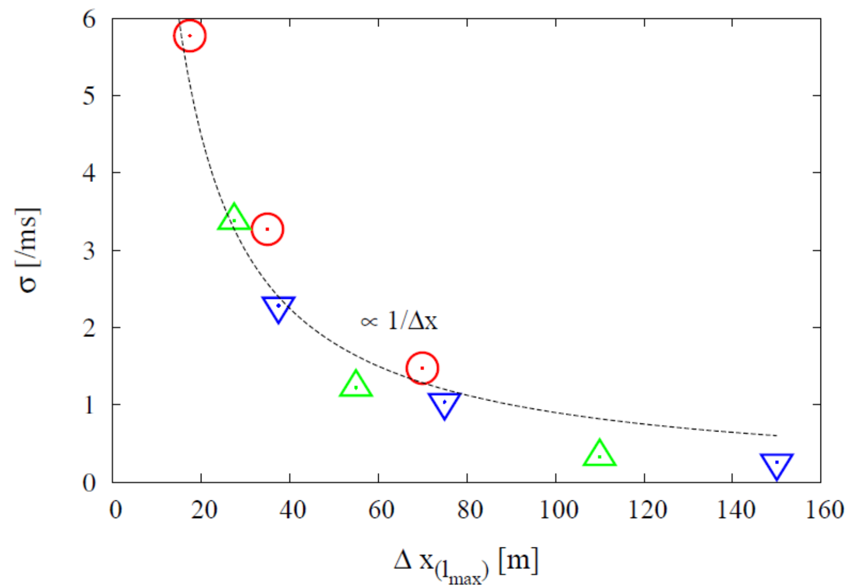


▶Small scale vortices develop rapidly ⇒ Efficient amplification of the B-field

Magnetic field amplification

B-field energy evolution　　Growth rate of the B-field energy





Merger

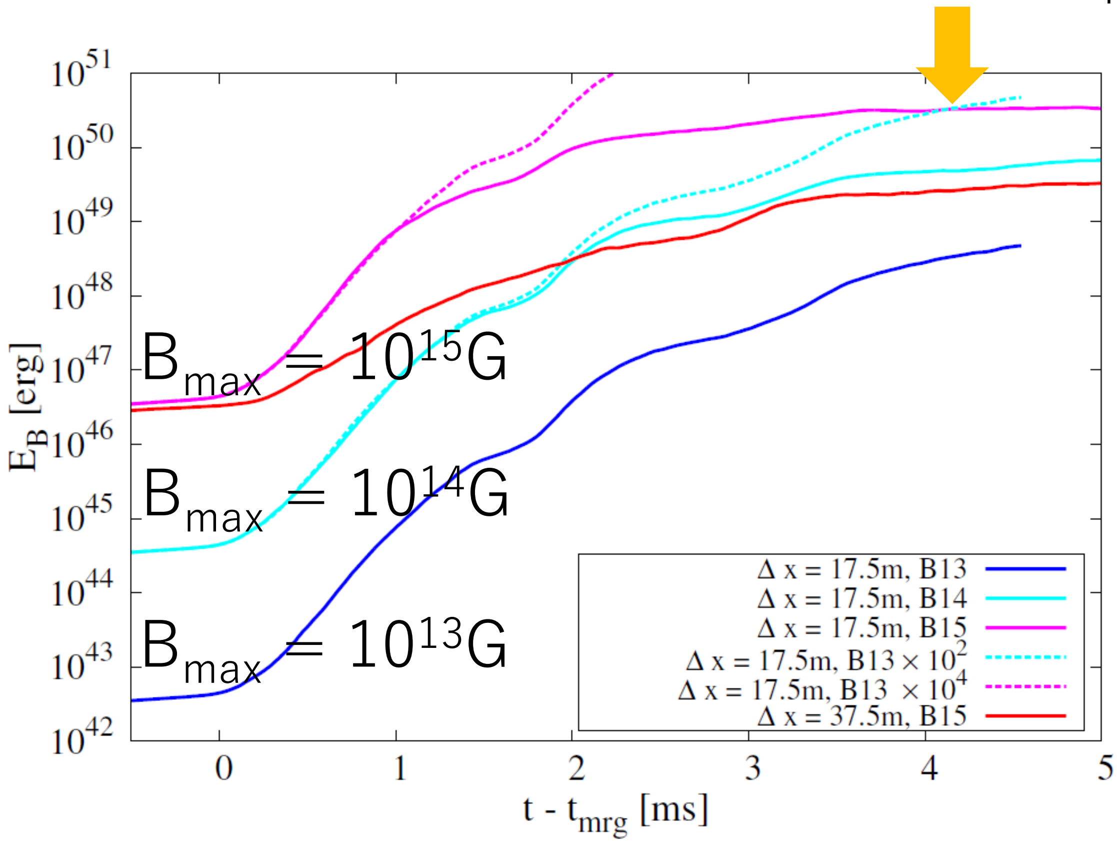
▶ Maximum field is almost virial value ～10^{17}G.

▶ The magnetic field energy is amplified by a factor of 10^6 times at least; The averaged value of the B-fields is amplified by a factor of 10^3 times. Fitting $E_B(t) \propto \exp(\sigma t)$ for $0 \lesssim t - t_{mrg} \lesssim 1$[ms]

▶ The growth rate shows the divergence. c.f. $\sigma \propto$ wave-number for KH instability.

Saturation of magnetic-field energy

Saturation $\gtrsim 4 \times 10^{50}$ erg ($B_{RMS}=10^{16}$G)

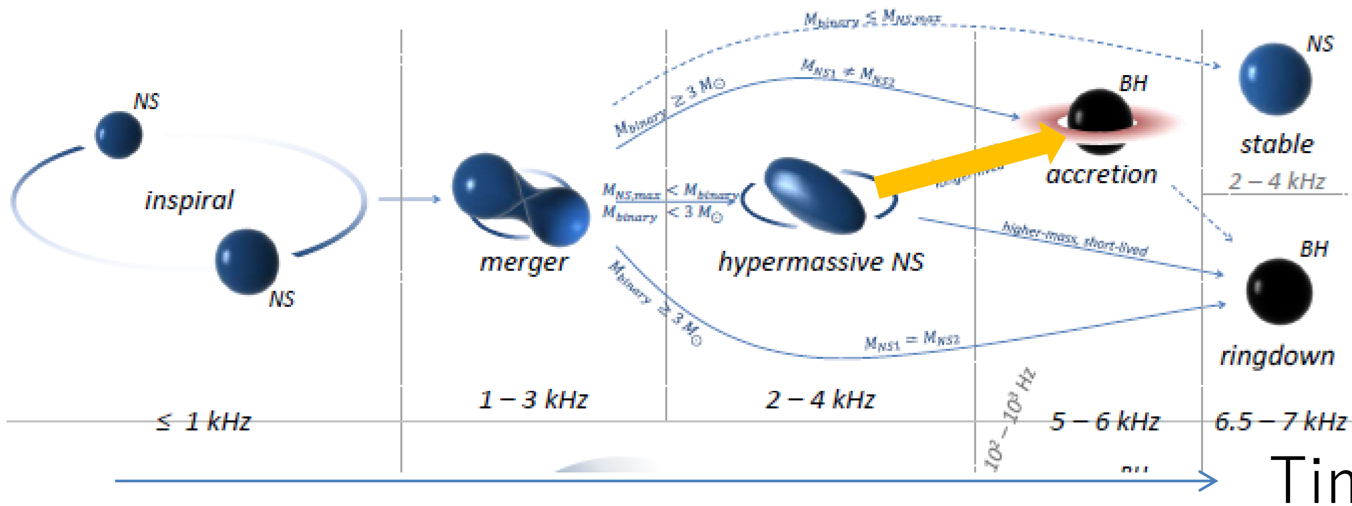


▶ The back reaction turns on at 1 (2) ms for B15 (B14) run.

▶ The saturation energy is likely to be $\sim 10^{50}$erg = 0.1% of the bulk kinetic energy

▶ RMS value of the magnetic field strength of the HMNS is $\sim 10^{16}$G

Long term evolution of remnant massive NS



Time axis

Our strategy

▶High res. GRMHD simulation ⇒ Evaluation of alpha viscosity

▶Relativistic viscous simulation ⇒ Given a viscosity parameter, systematic study is doable.

Importance of MHD turbulence

EOM : $\partial_t(\rho R^2 \Omega) + \partial_R(\rho R^2 \Omega v_A - \eta R^2 \partial_R \Omega) = 0$

ρ =density, Ω =angular velocity, η = viscosity

▶ Angular momentum transfer by the viscous term.

▶ Energy dissipation due to the viscosity

Q. What is the "viscosity" in this system ?

A. Magnetohydrodynamical turbulence ;

$q = q_{ave} + \delta q$ s.t. $\langle q \rangle = q_{ave}$ and $\langle \delta q \rangle = 0$ where $\langle \cdot \rangle$ denotes the time average.

EOM : $\partial_t \langle \rho R^2 \Omega \rangle + \partial_R (\langle \rho R^2 \Omega v_R \rangle + R\, W_{R\phi}) = 0$

$W_{R\phi} = \langle \rho\ \delta v_R \delta v_\phi - B_R B_\phi / 4\pi \rangle$:

Reynolds+Maxwell stress

High res. GRMHD simulation of remnant NS

(KK et al. in prep.)

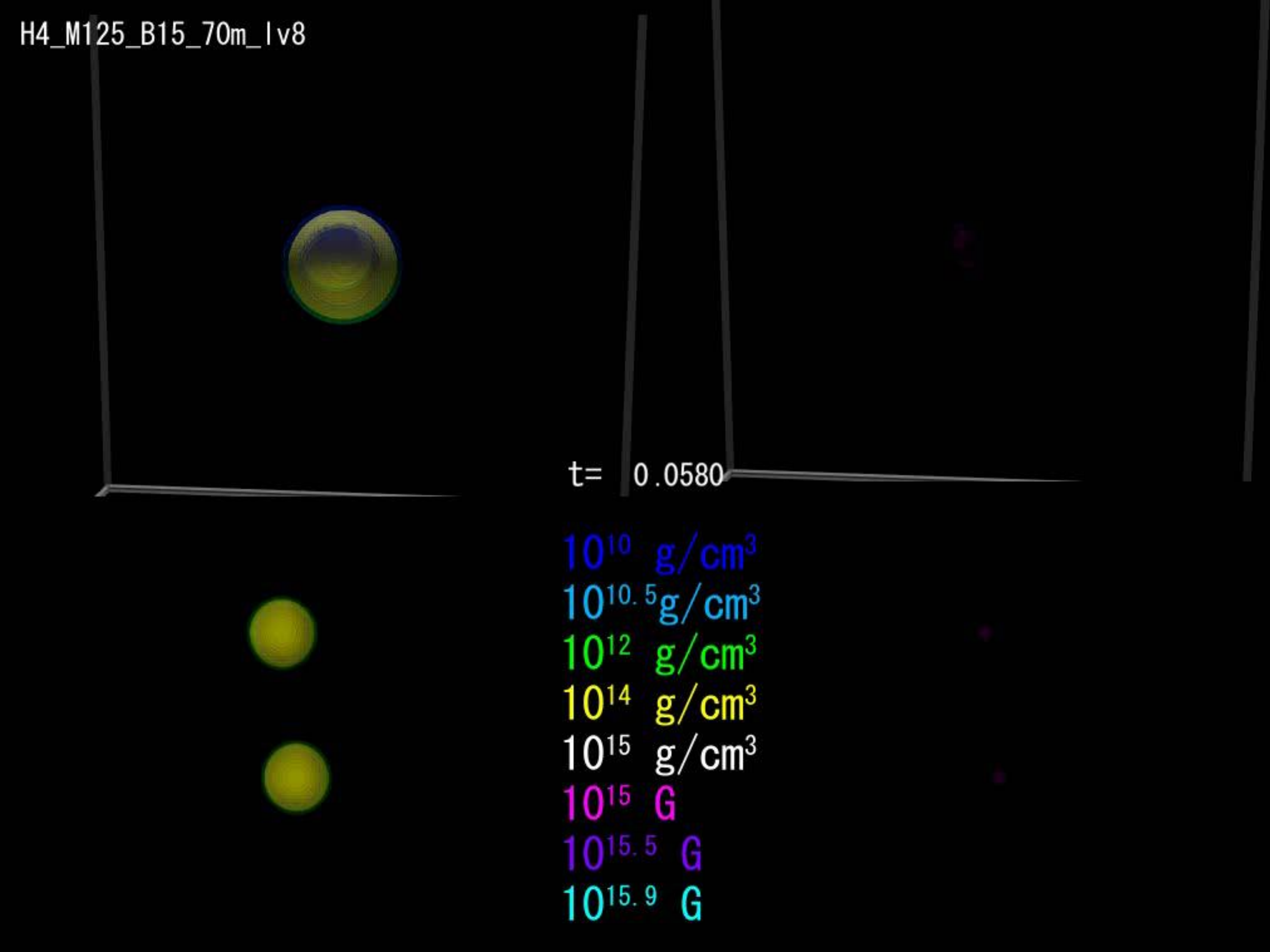
To do list: Read α-viscosity parameter from MHD simulation data

$$\alpha = \left\langle \frac{W_{R\varphi}}{P} \right\rangle$$

$W_{R\phi}$: Reynolds + Maxwell stress

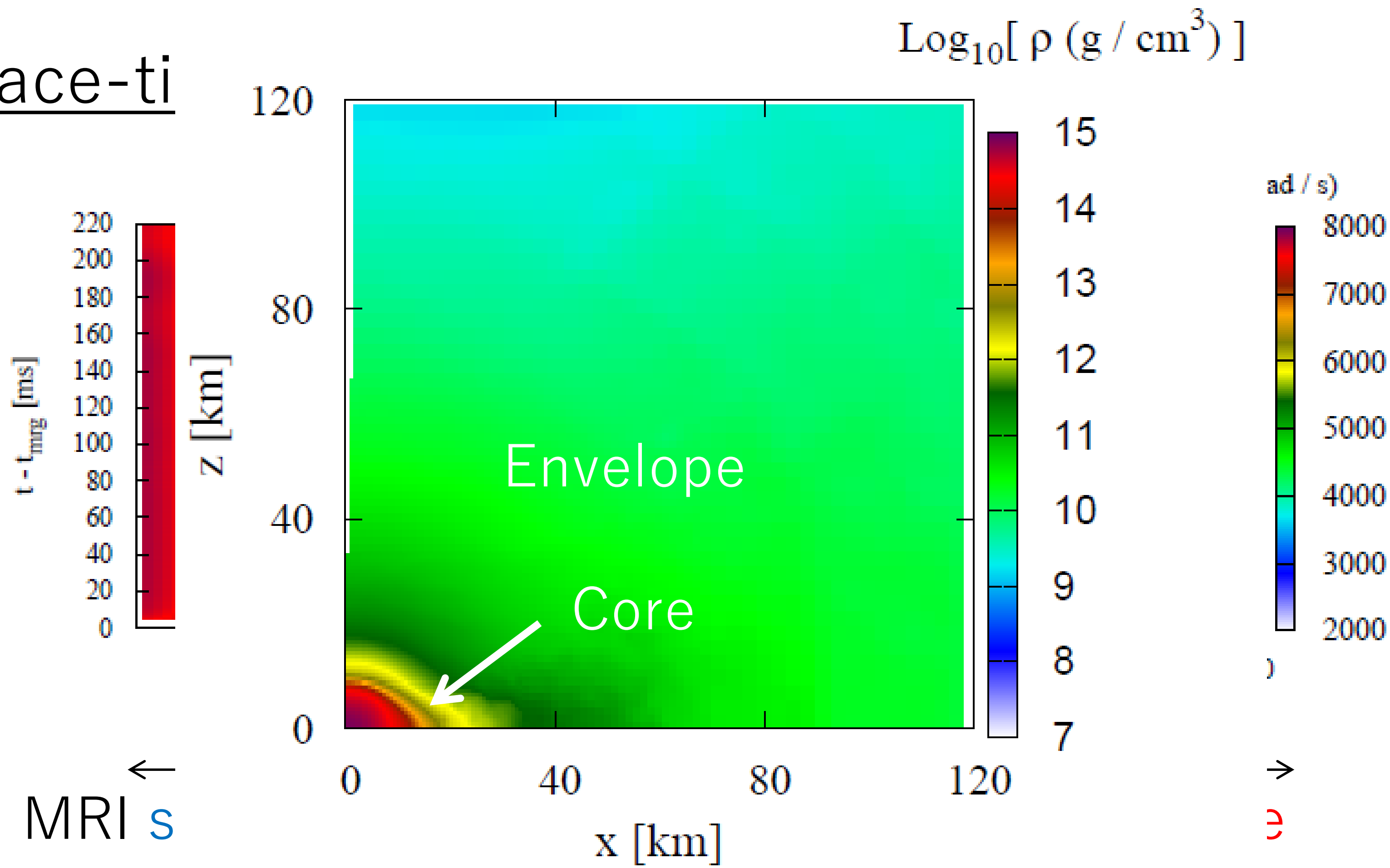
Caution: neutrino viscosity and dragging effect on MRI (Guilet et al. 16); Growth rate could be suppressed if $B_{ini} \lesssim 10^{13}$G

Caveat: Resolution study is essential again because numerical diffusion kills the "turbulence".


H4_M125_B15_70m_lv8
t= 0.0580
10^{10} g/cm^3
$10^{10.5}$g/cm^3
10^{12} g/cm^3
10^{14} g/cm^3
10^{15} g/cm^3
10^{15} G
$10^{15.5}$ G
$10^{15.9}$ G

Structure of the remnant massive NS

Space-ti

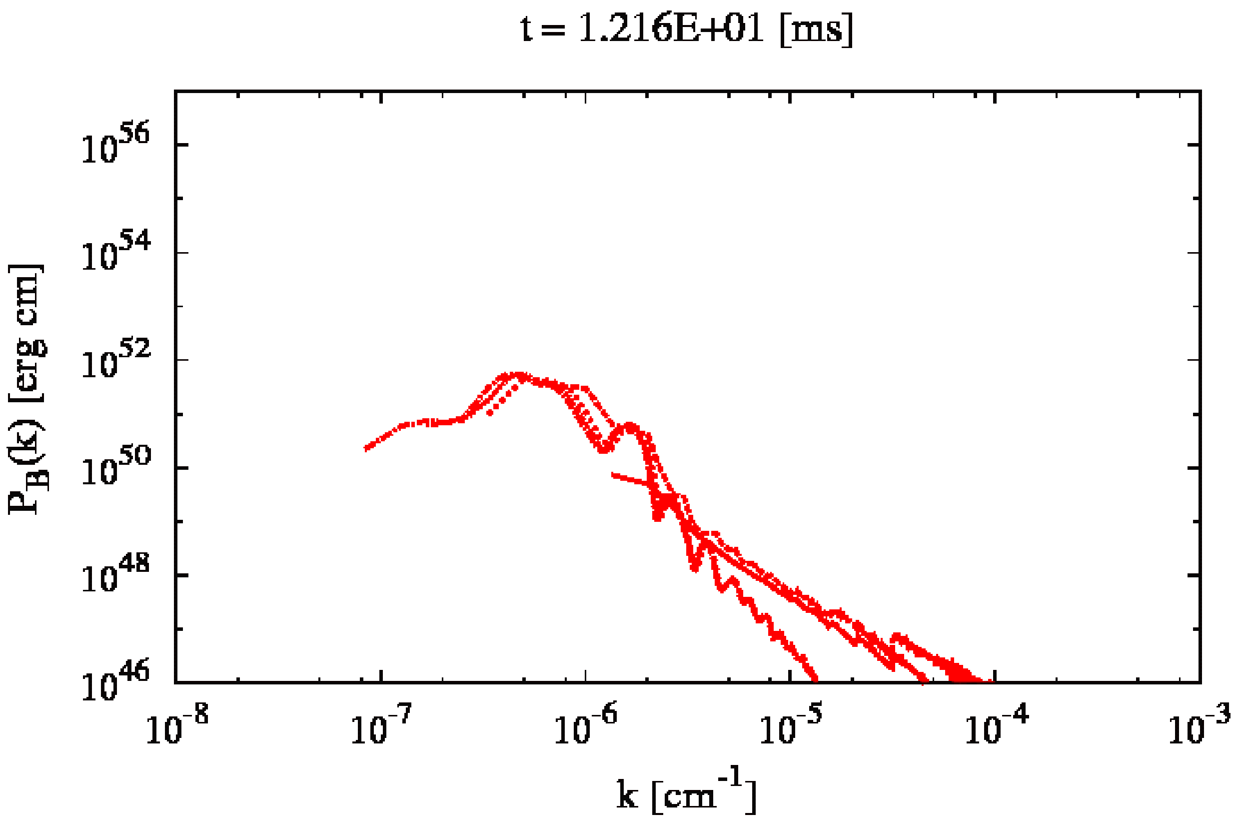


MRI s

e

Magnetic field amplification

Power spectrum (merger time= 13.7ms, Δx=12.5m, N=1,400×1,400×700 & 12 levels)

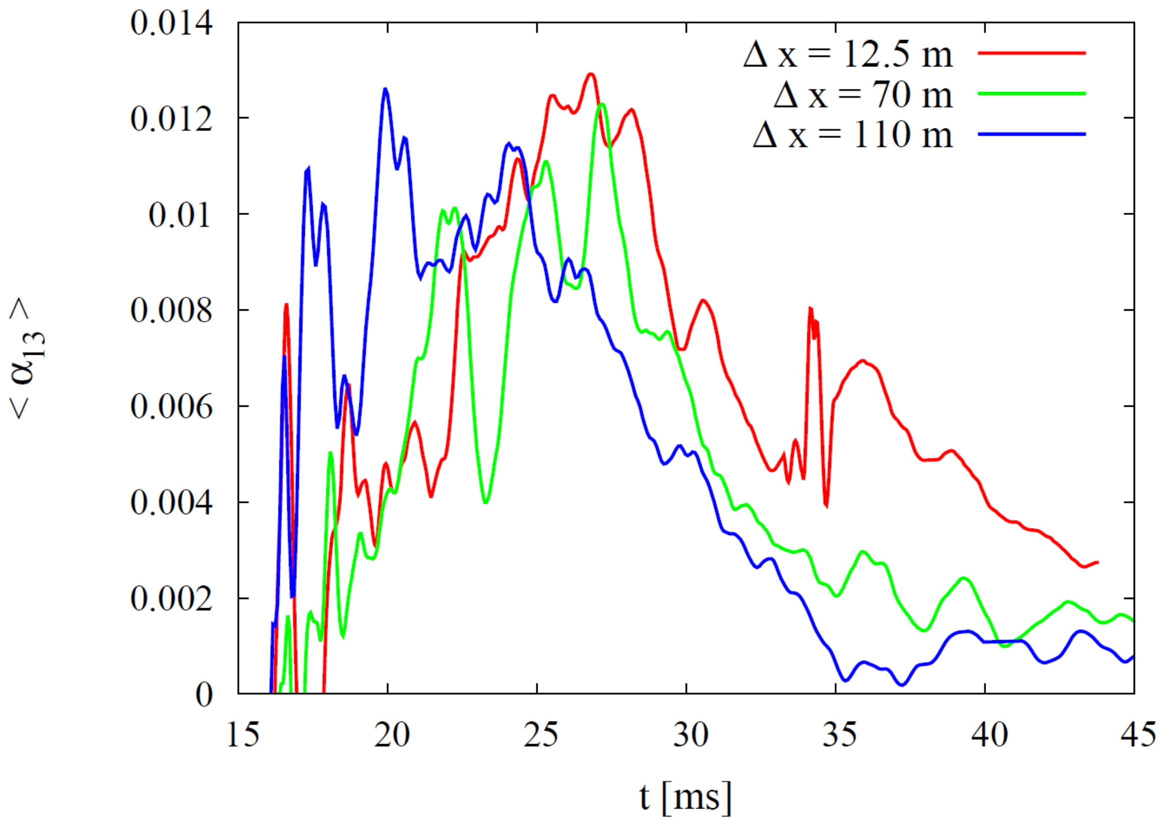


▶ Early phase : KH instability amplifies the small scale magnetic field efficiently

▶ Late phase : Magneto Rotational Instability amplifies the B-field

α -viscosity parameter

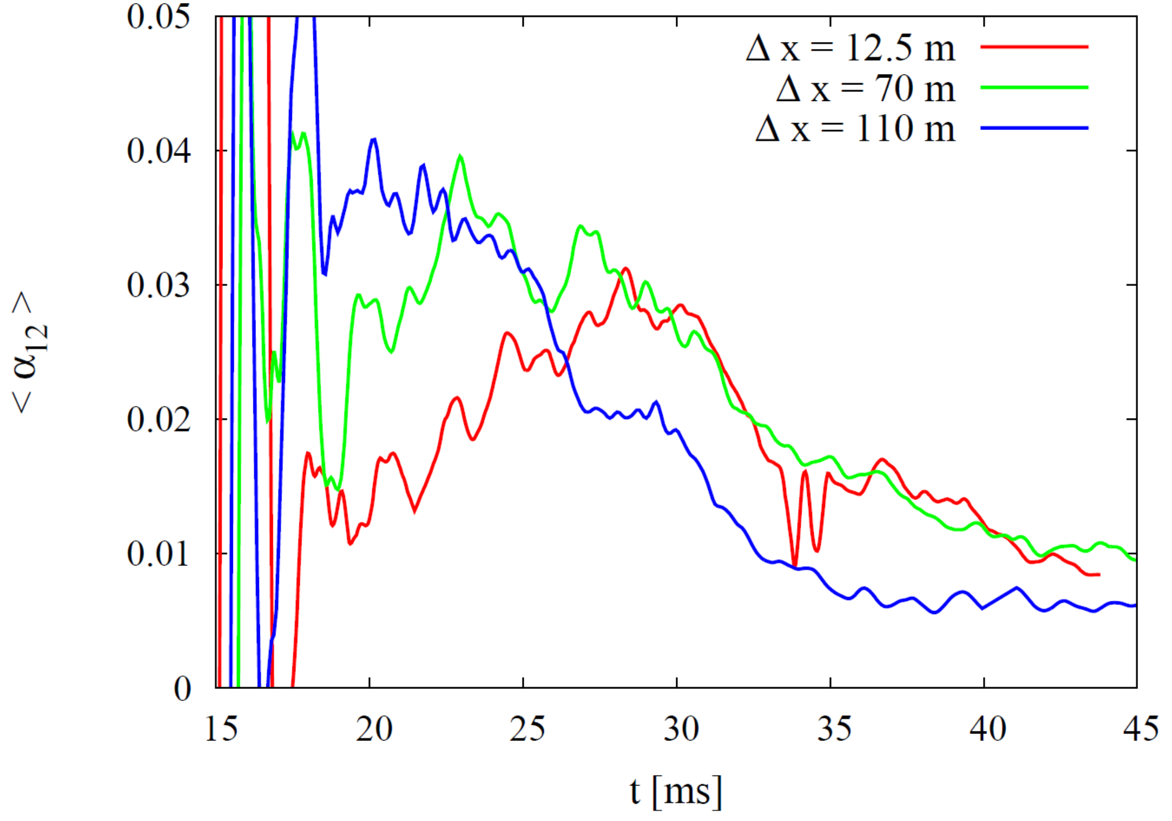
$$13 \leq \log_{10}[\rho\,(\mathrm{g\,cm^{-3}})] < 14$$



- ▶ $<<\alpha>> \gtrsim 4\times10^{-3}$ for the core
- ▶ $t_{vis} \lesssim 120$ ms $(<<\alpha>>/\ 4\times10^{-3})^{-1}$ $\times(<j>/1.7\times10^{16}\mathrm{cm^2s^{-1}})(<c_s>/0.2c)^{-2}$

α -viscosity parameter

$$12 \leq \log_{10}[\rho\ (\mathrm{g\ cm^{-3}})] < 13$$



▶ $<< \alpha >> \approx 1 \times 10^{-2}$ for the envelope

Relativistic viscous hydro. simulation (Shibata & KK 17a, b. see also Radice 17)

▶Israel-Stewart formulation ⇒ Causality preserving formulation

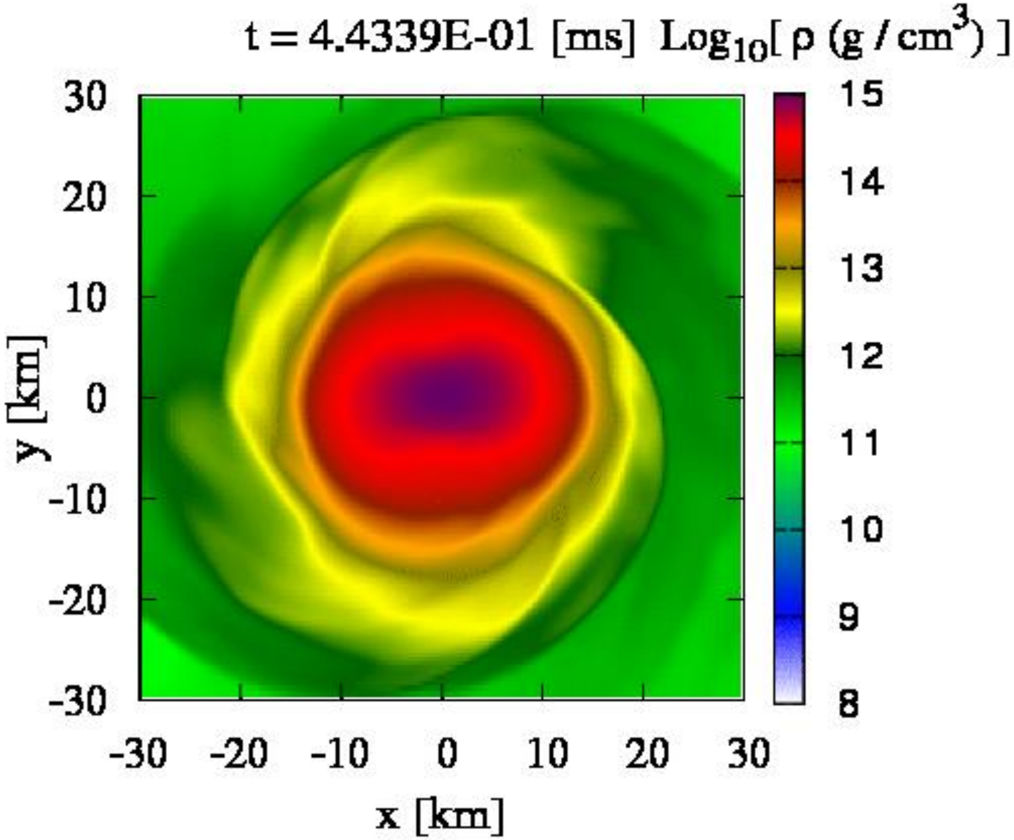
▶Systematic study is possible because of low computational cost.

<u>Set up.</u>
Hydro simulation of BNS merger without viscosity up to ∼5ms after the merger.

⇒ Switch on the viscosity $\nu = \alpha \frac{c_s^2}{\Omega}$

Relativistic viscous hydro. simulation (Shibata & KK 17a, b)

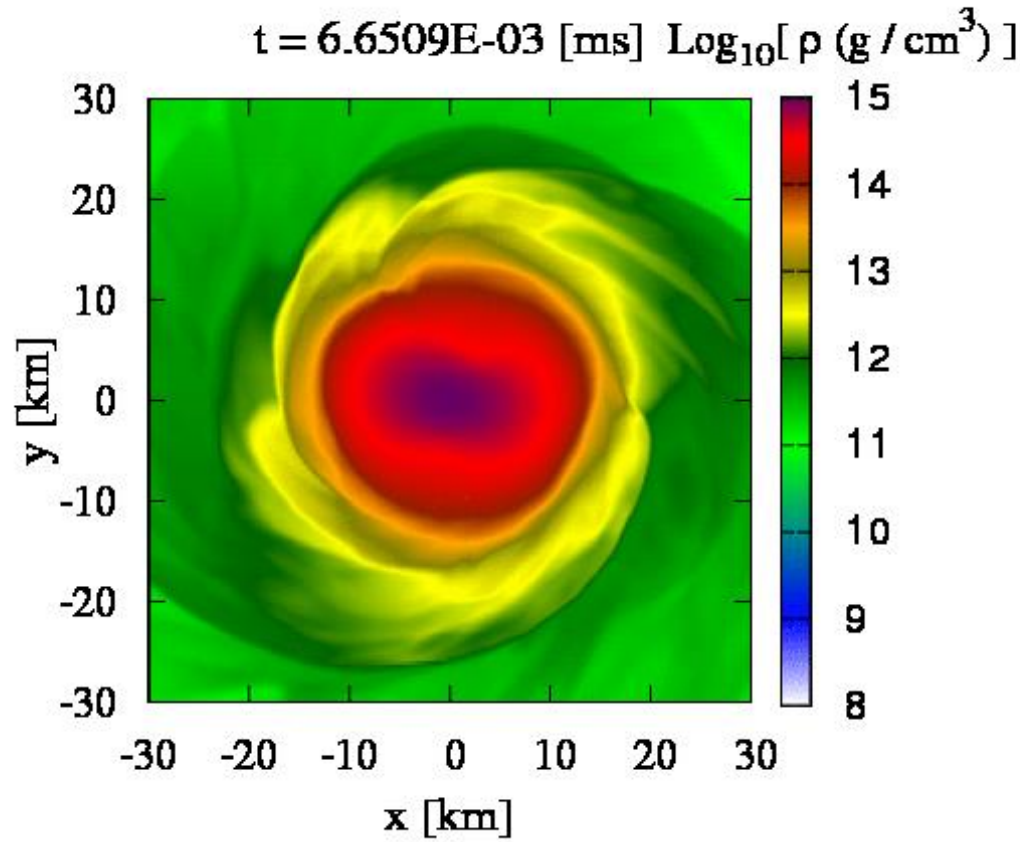
$\alpha = 0$



▶Non-axisymmetric structure of the HMNS remains.

Relativistic viscous hydro. simulation (Shibata & KK 17a, b)

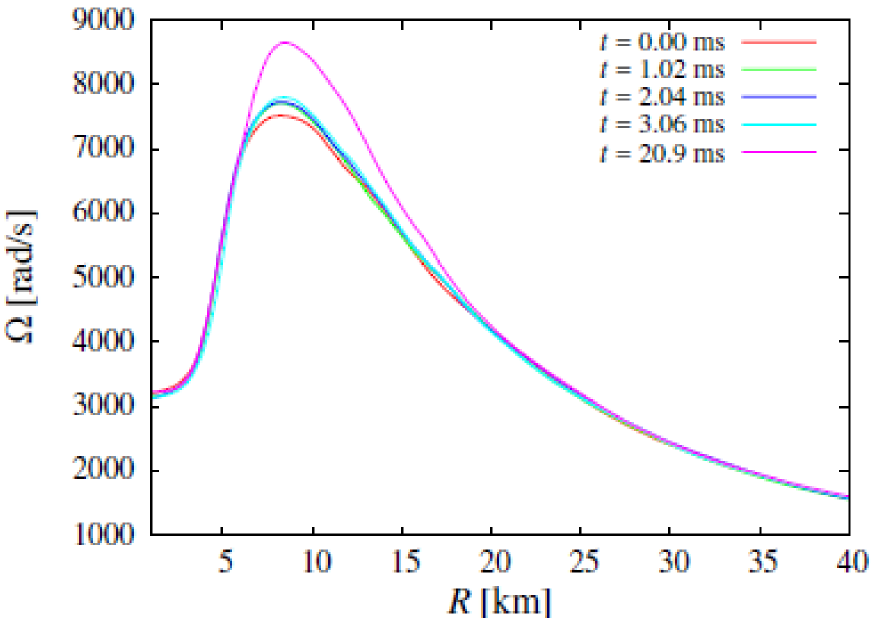
$\alpha = 0.02$

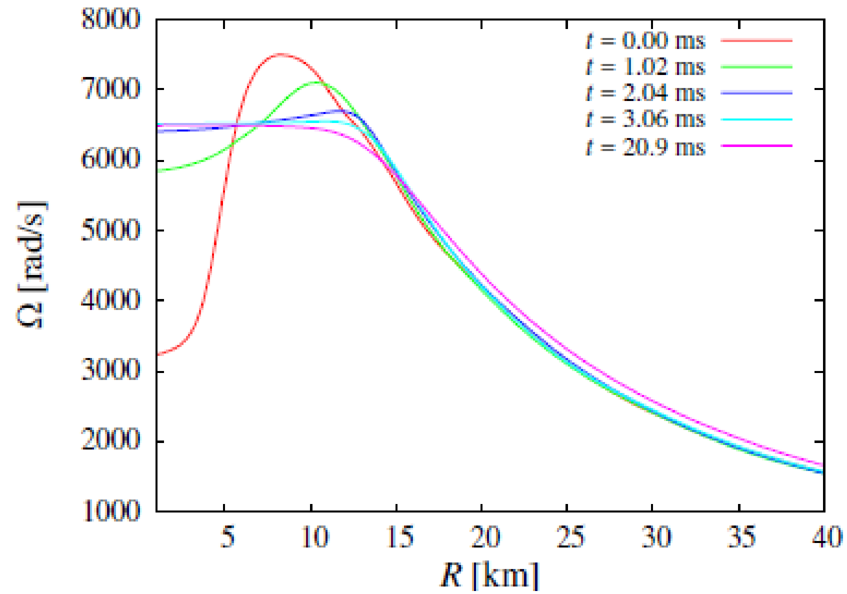


▶ Angular momentum transfer due to the viscosity
⇒ Nearly axi-symmetric configuration

Angular velocity evolution

$\alpha = 0.00$ $\alpha = 0.02$





▶ Inner part quickly relaxes into an uniform rotation

cf. $t_{\rm vis} \approx 4.4\,{\rm ms}(\alpha/0.01)^{-1}(c_s/0.5\,c)^{-2}(R/10\,{\rm km})^2(\Omega/10^4\,{\rm rad/s})$

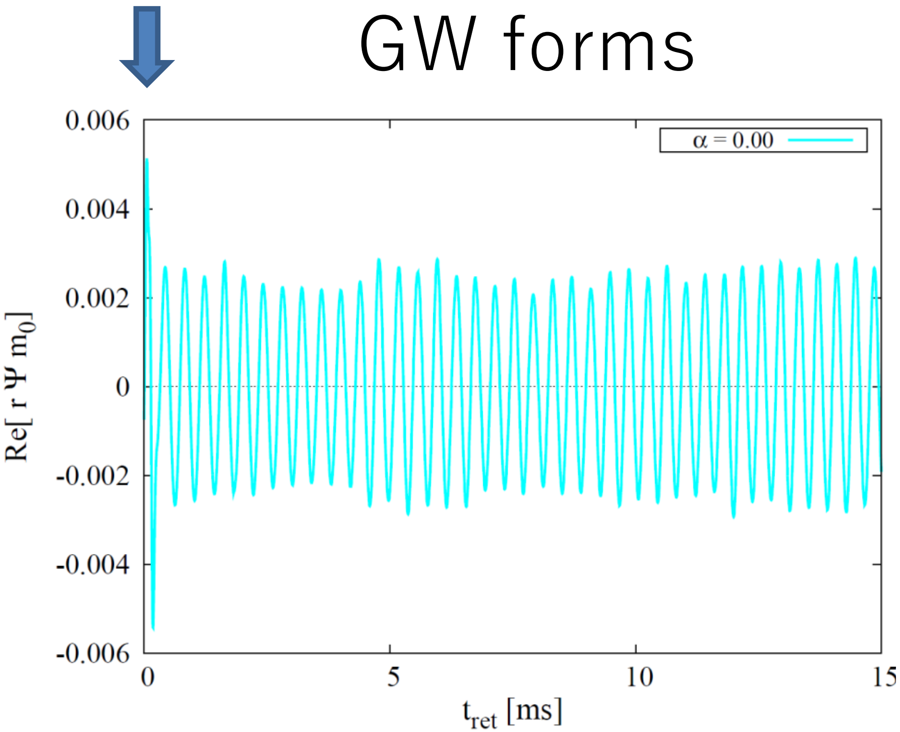
▶ The density structure relaxes into an axi-symmetric structure.

Impact of viscosity on GWs from HMNS

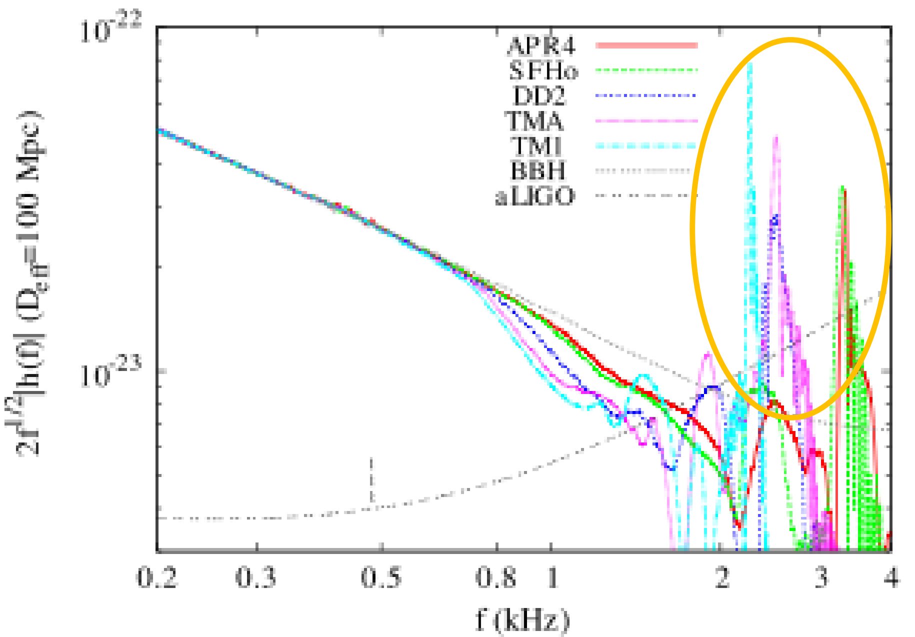
Ideal hydro. case

Merger

GW forms



GW spectra

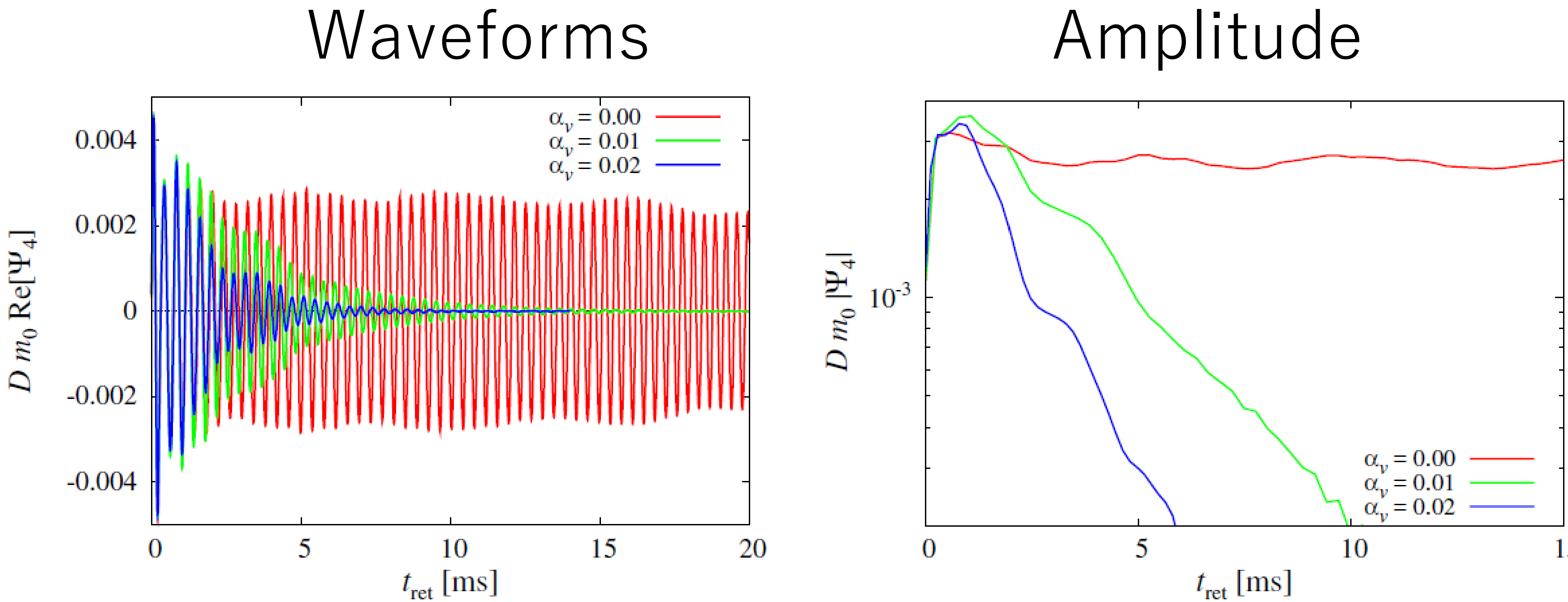


▶ HMNS emits quasi periodic GWs.

▶ Peak frequency around 2-4 kHz depends of the EOS.

Shibata 05, Shibata & Tanguchi 09, Hotokezaka et al. 13, Bawswein et al. 12, 13, 15, Takami et al. 14, 15, 16

Impact of viscosity on GWs from HMNS

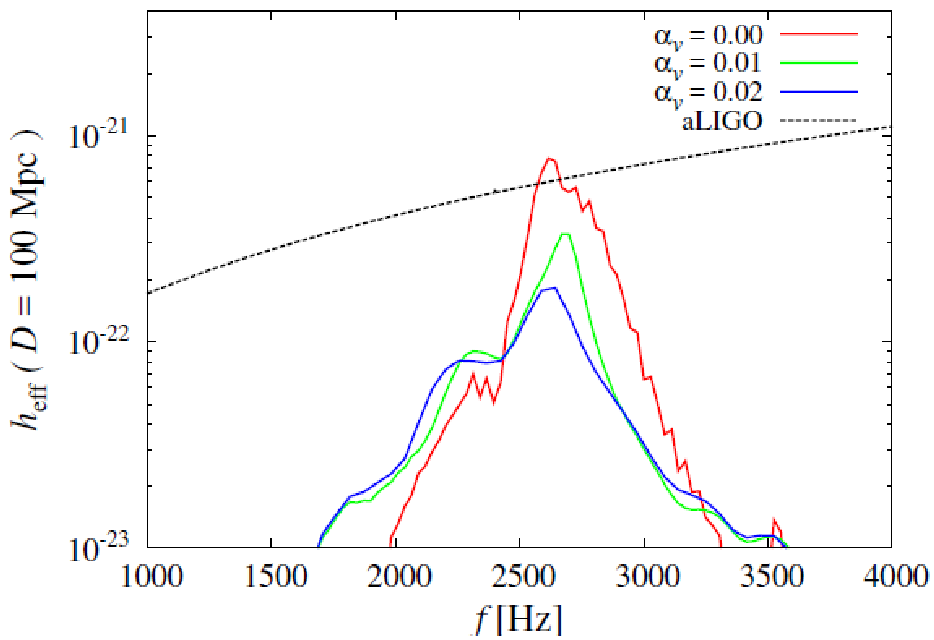


▶ Axisymmetric structure of the HMNS due to the angular momentum transport ⇒ Damp of the GW amplitude

▶ Damping timescale is consistent with the viscous timescale

Viscous hydro. simulation of BNS merger

GW spectrum



▶Remnant massive NS could not be a strong GW emitter ?

<u>Caveat</u>

No physical modeling of remnant massive NSs because of the lack of many ingredients

Summary

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

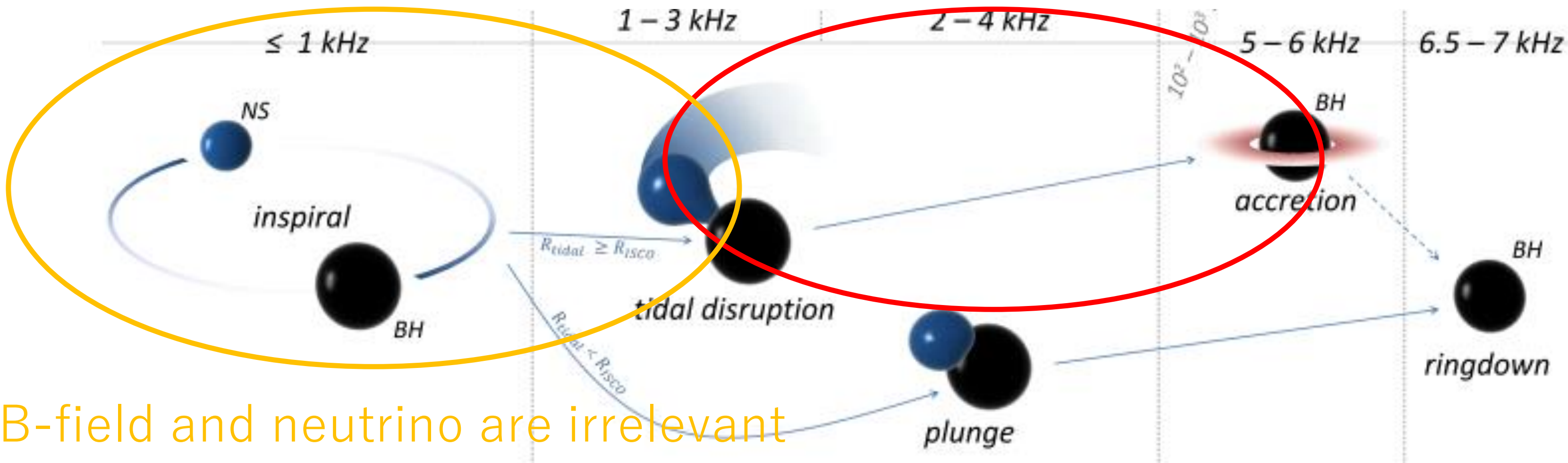
BNS(BH-NS) merger

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

▶ Evolution in post merger phase (B-field, Neutrino)
Remnant massive NS is strongly magnetized ⇒ Angular momentum transport due to MRI.
Neutrino radiation is important for the dynamical ejecta and disk wind from the HMNS.

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

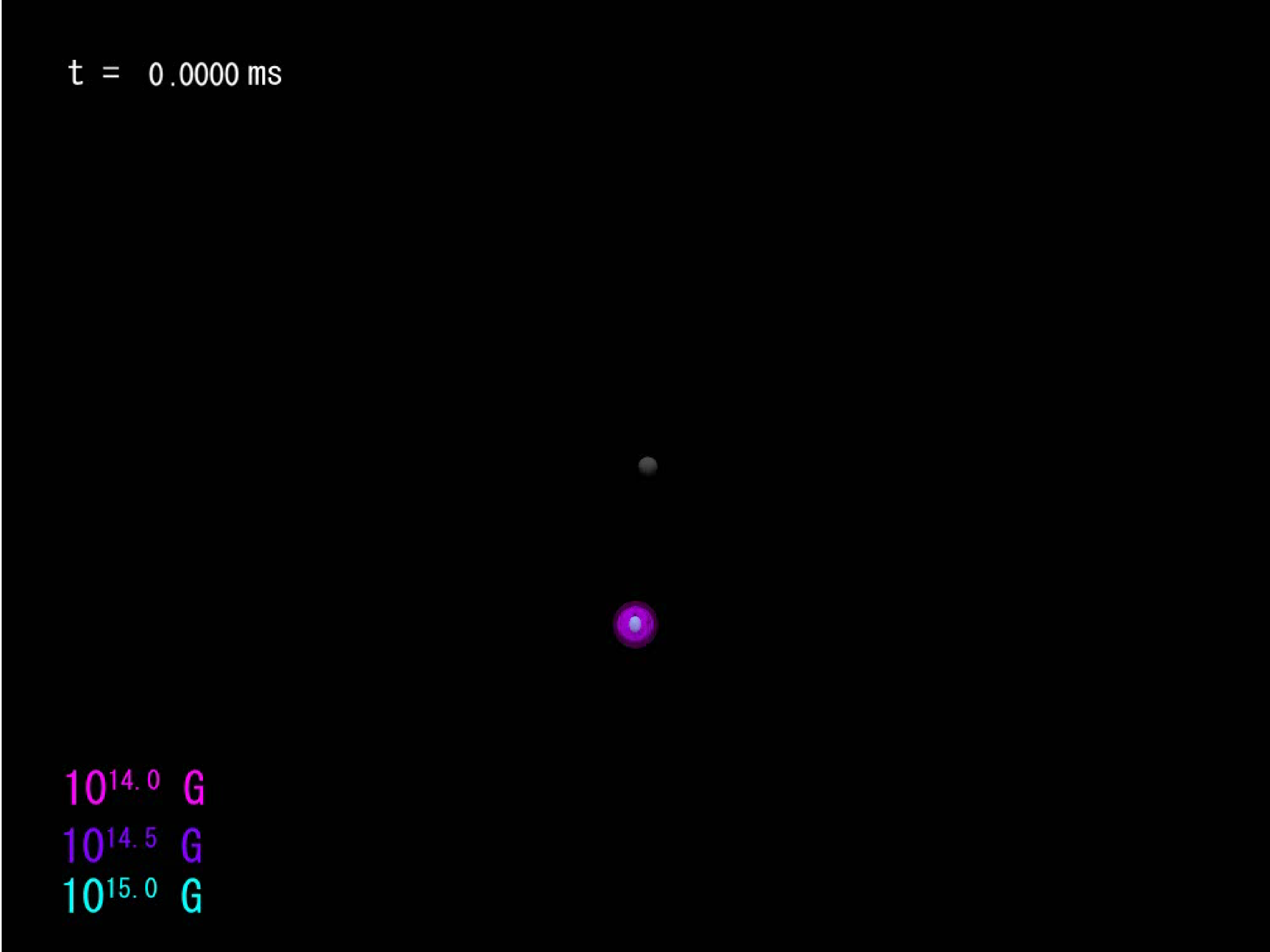
▶Inspiral and early merger waveforms

⇒ Tidal deformability of NSs

▶Post merger evolution:

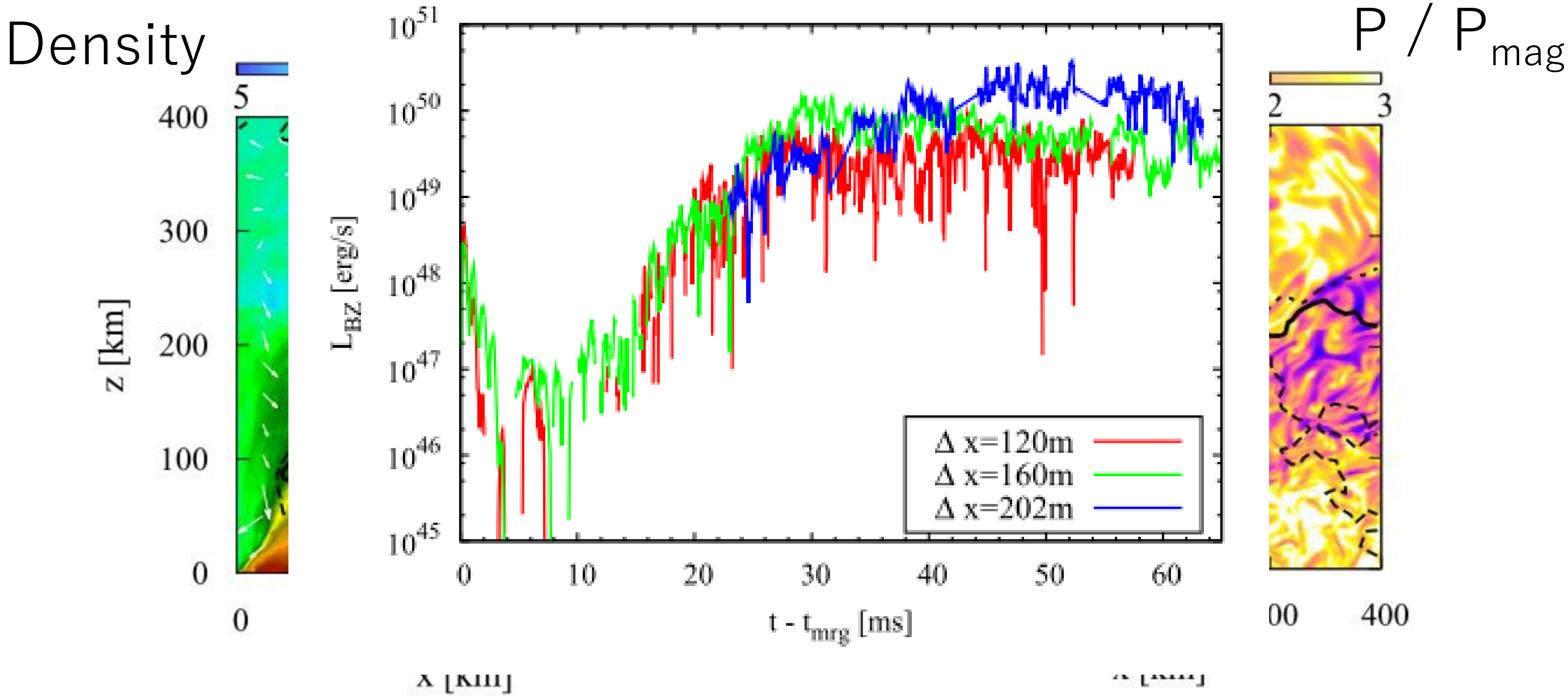
* Mass ejection driven by neutrino, viscous, MHD
* Modeling of the central engine of SGRBs


t = 0.0000
10^{12} g/cm^3
10^{11} g/cm^3
10^{10} g/cm^3
10^{9} g/cm^3



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

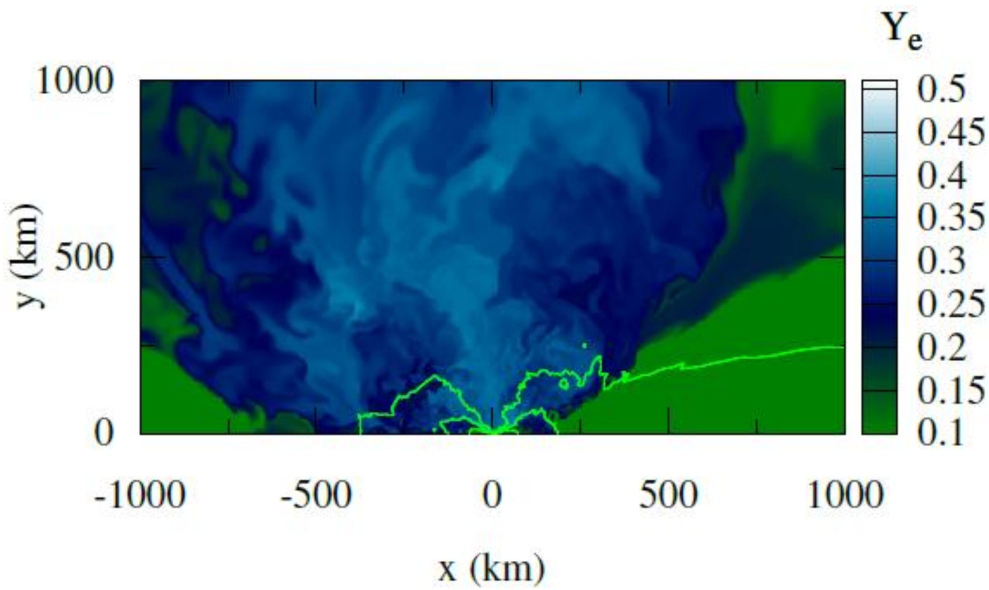


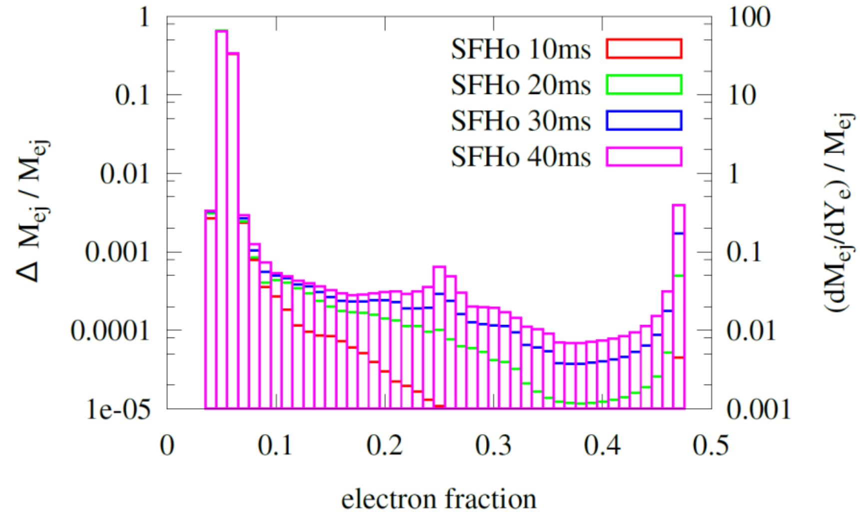
▶ Funnel wall formation by the torus wind

▶Torus wind ⇒ Coherent poloidal B-field ⇒ Formation of the magnetosphere

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

R-process nucleosynthesis in BH-NS mergers
(Kyutoku et al. in prep.)

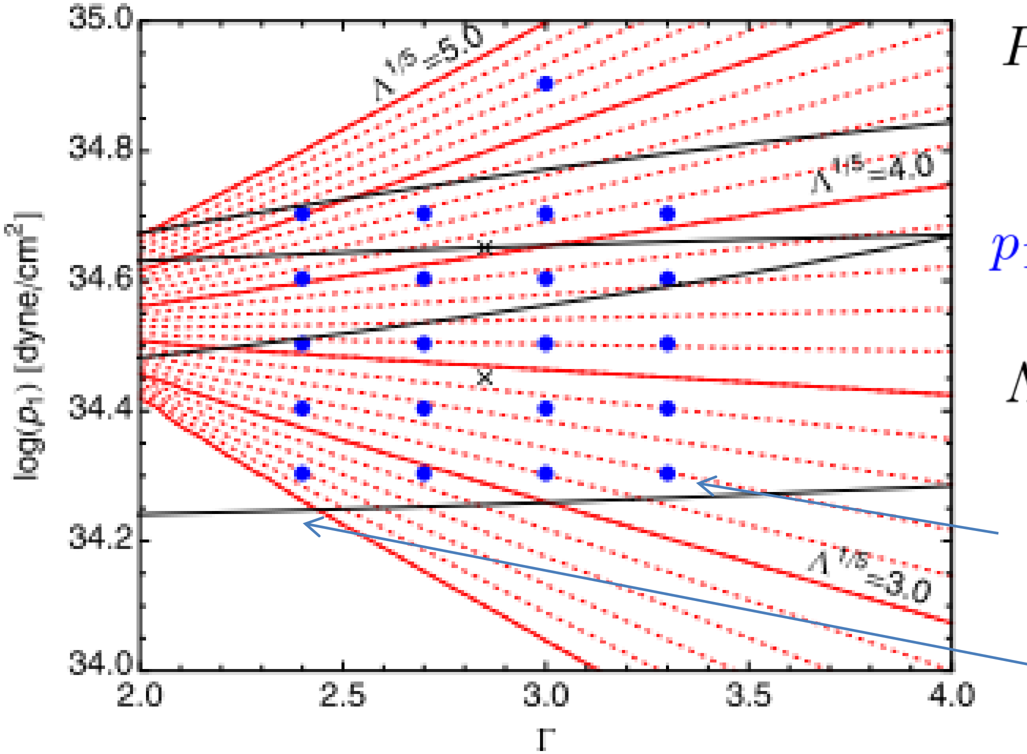




- ▶ Dynamical ejecta ⇒ Low Y_e
- ▶ Torus wind ⇒ High Y_e

Tidal deformability of NSs

Lackey et al. 12, 14



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

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

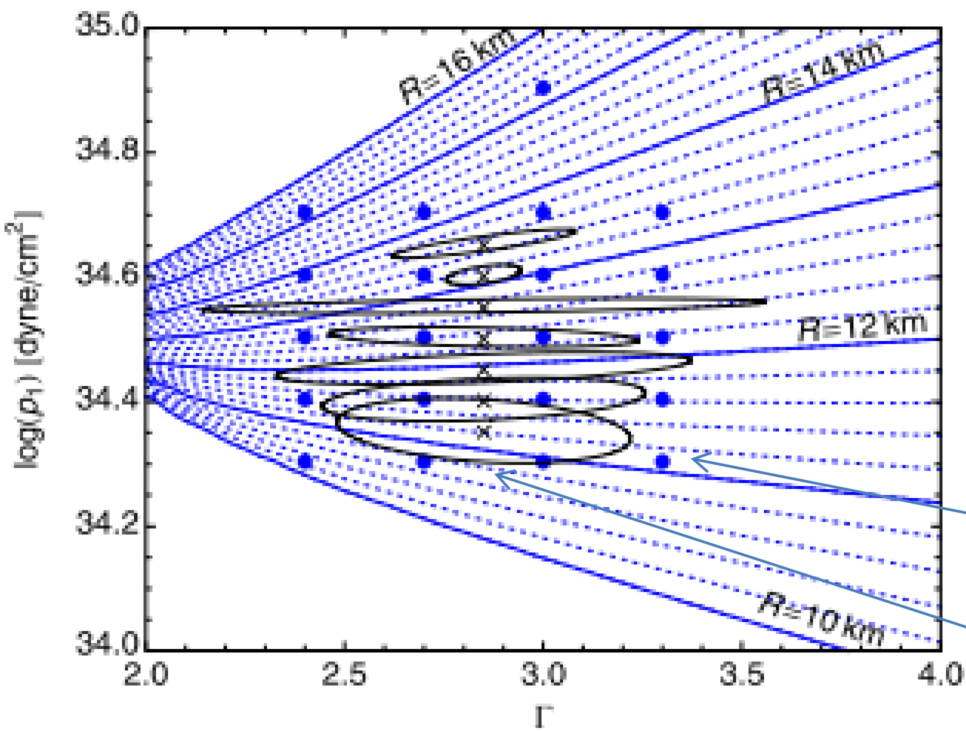
$$p_1 = \kappa_1 \rho_1^{\Gamma} \ (\rho_1 = 10^{14.7} \ \mathrm{gcm}^{-3})$$

$$\Lambda = \frac{2}{3} k_2 \left(\frac{GM_{\mathrm{NS}}}{Rc^2} \right)^{-5}$$

▶ 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



$$P = 3.5966 \times 10^{13} \rho^{1.3569} \; (\rho \leq \rho_0)$$
$$= \kappa_1 \rho^{\Gamma} \; (\rho \geq \rho_0)$$
$$p_1 = \kappa_1 \rho_1^{\Gamma} \; (\rho_1 = 10^{14.7} \, \mathrm{gcm}^{-3})$$
$$\Lambda = \frac{2}{3} k_2 \left(\frac{G M_{\rm NS}}{R c^2} \right)^{-5}$$

NR simulation data

1 σ error circle

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

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