The fate of strongly magnetized remnant massive neutron stars formed in low mass binary neutron star mergers

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Ref.) Kiuchi et al. 2016 in prep.

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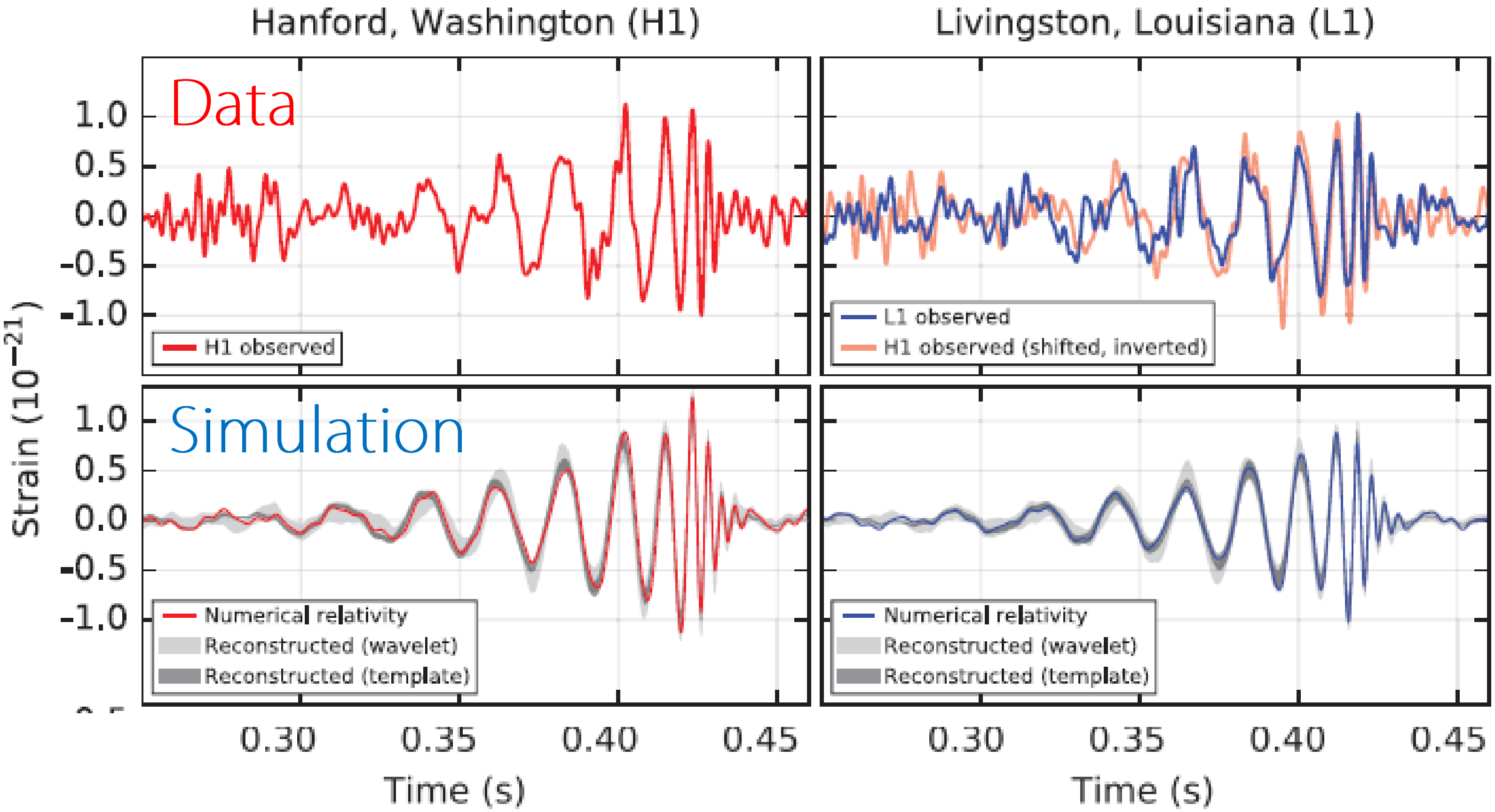
Visualization by T. Wada

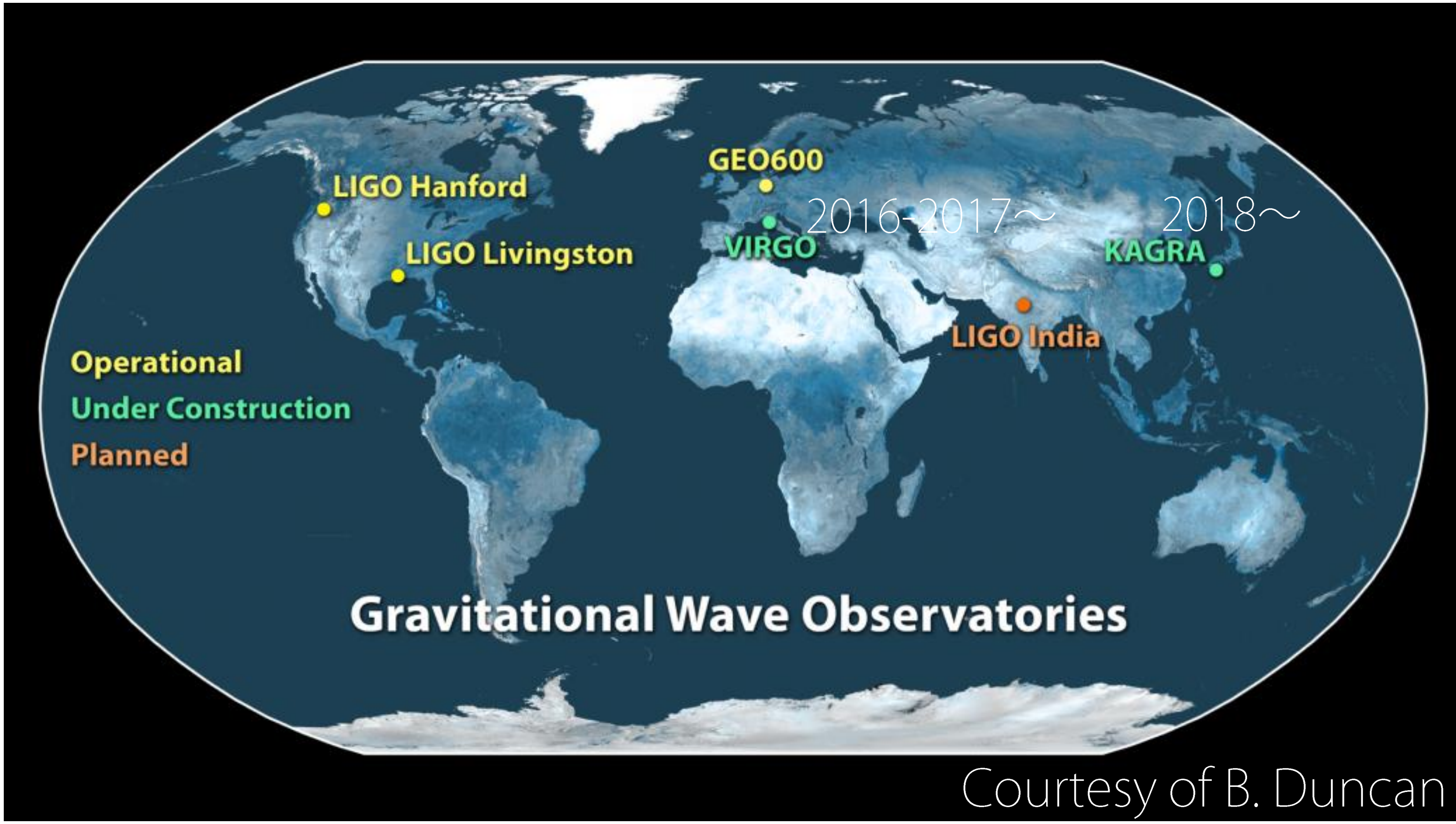
Direct first detection of GWs by advanced LIGO

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 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)

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)

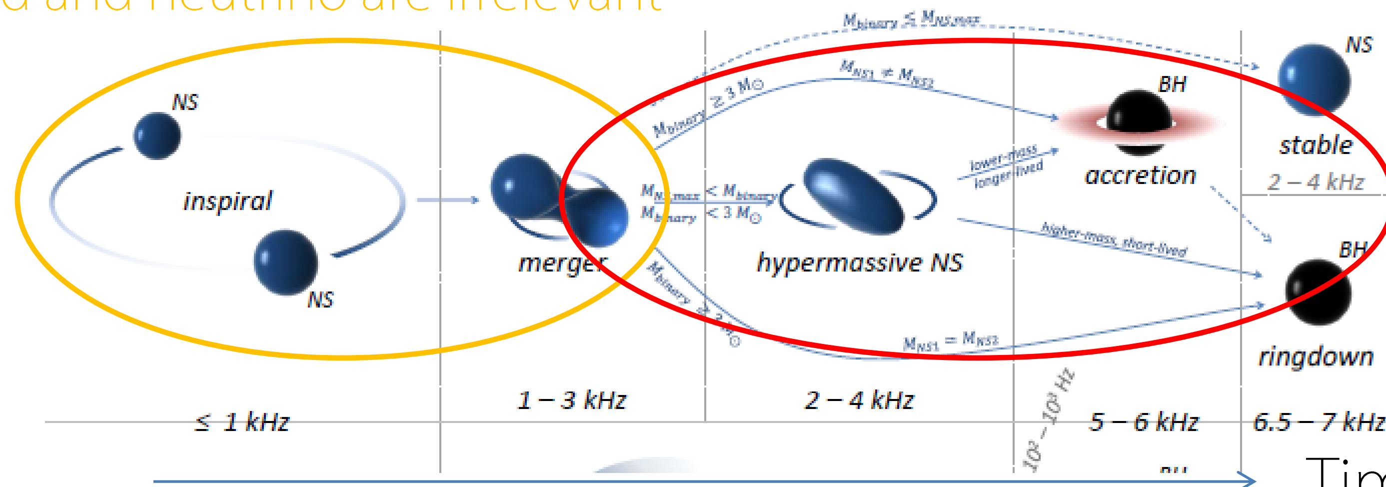
▶Electromagnetic counter part (Li & Paczynski 98)

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

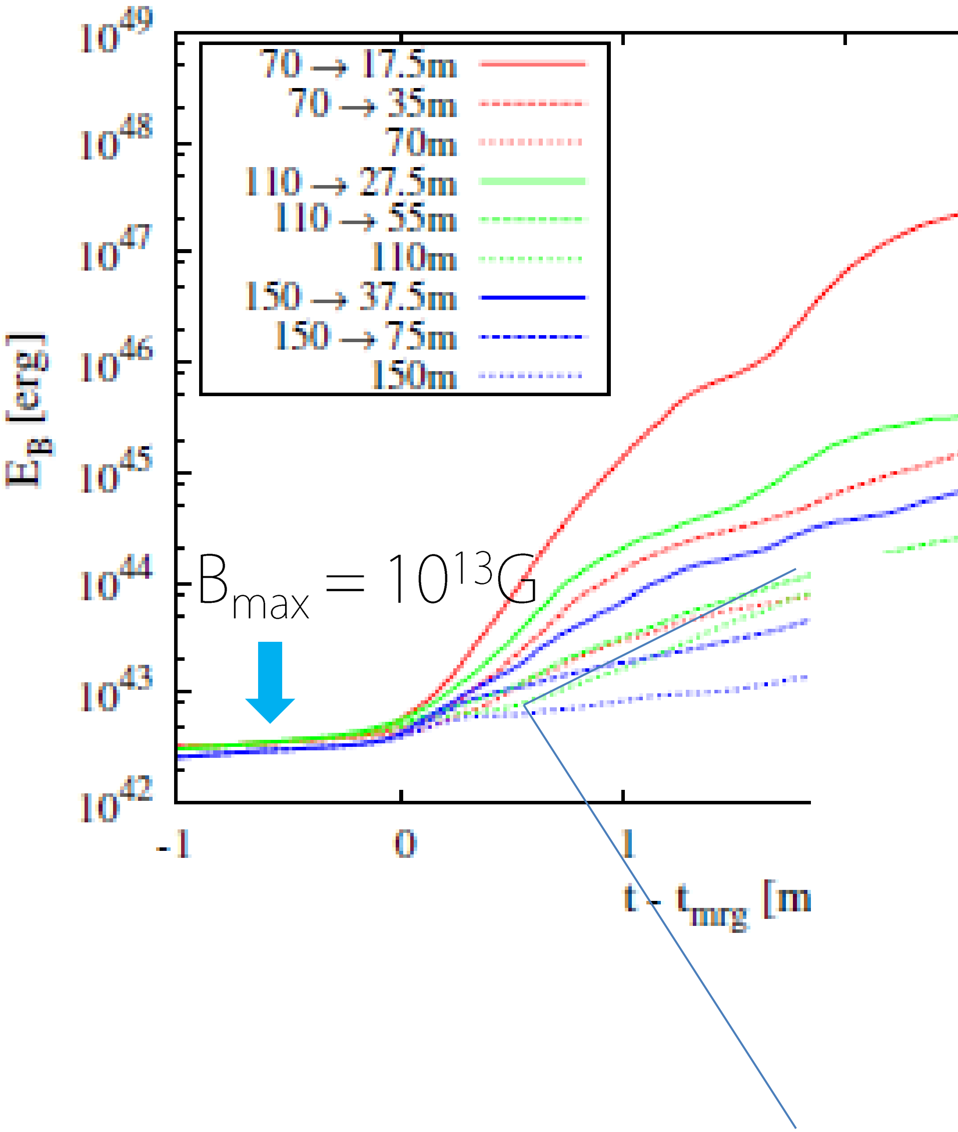


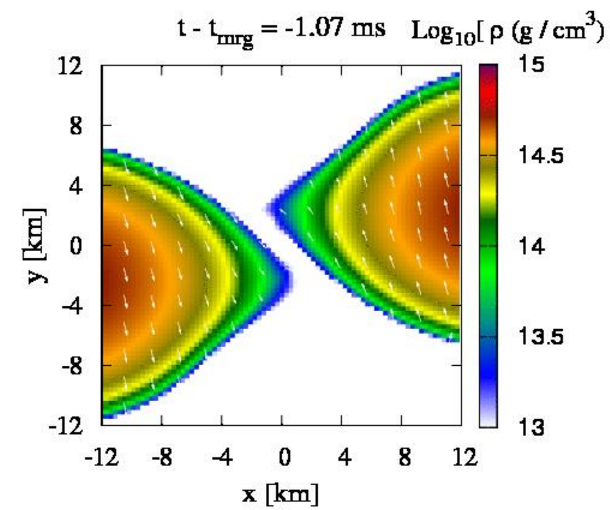
Time axis

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

Efficient B-field amplification at the merger

Kelvin-Helmholtz instability plays an essential role.





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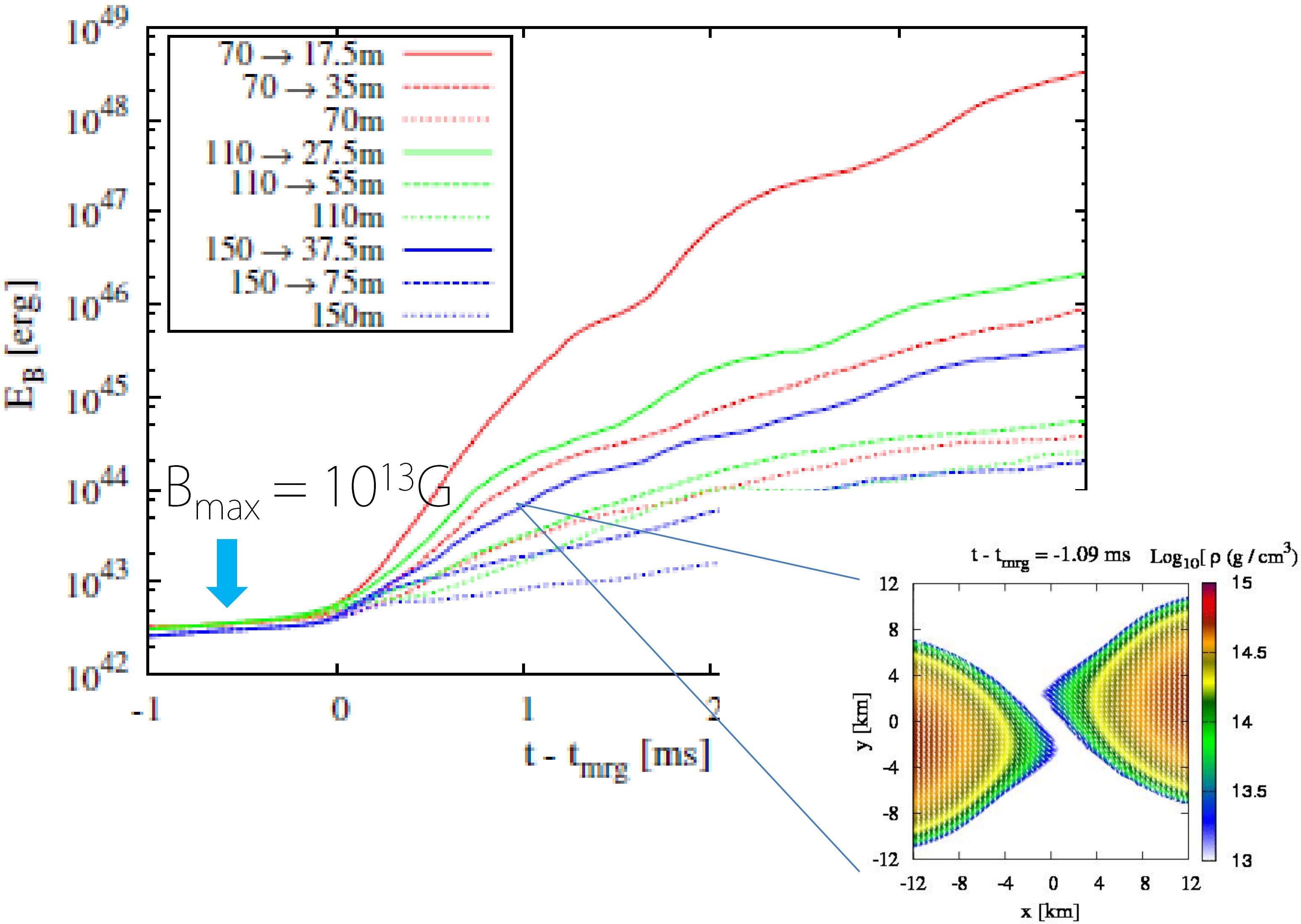

Efficient B-field amplification at the merger

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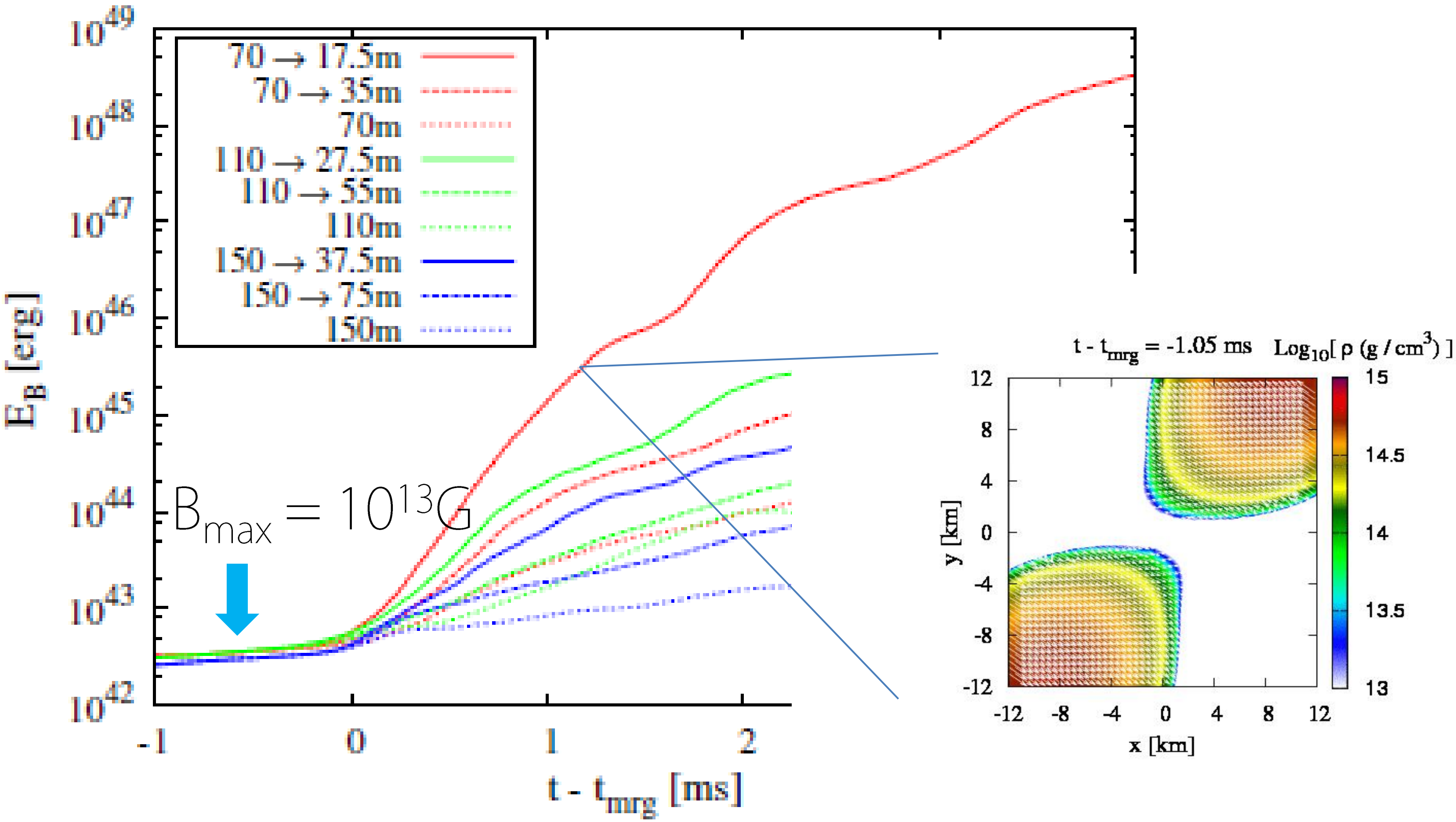
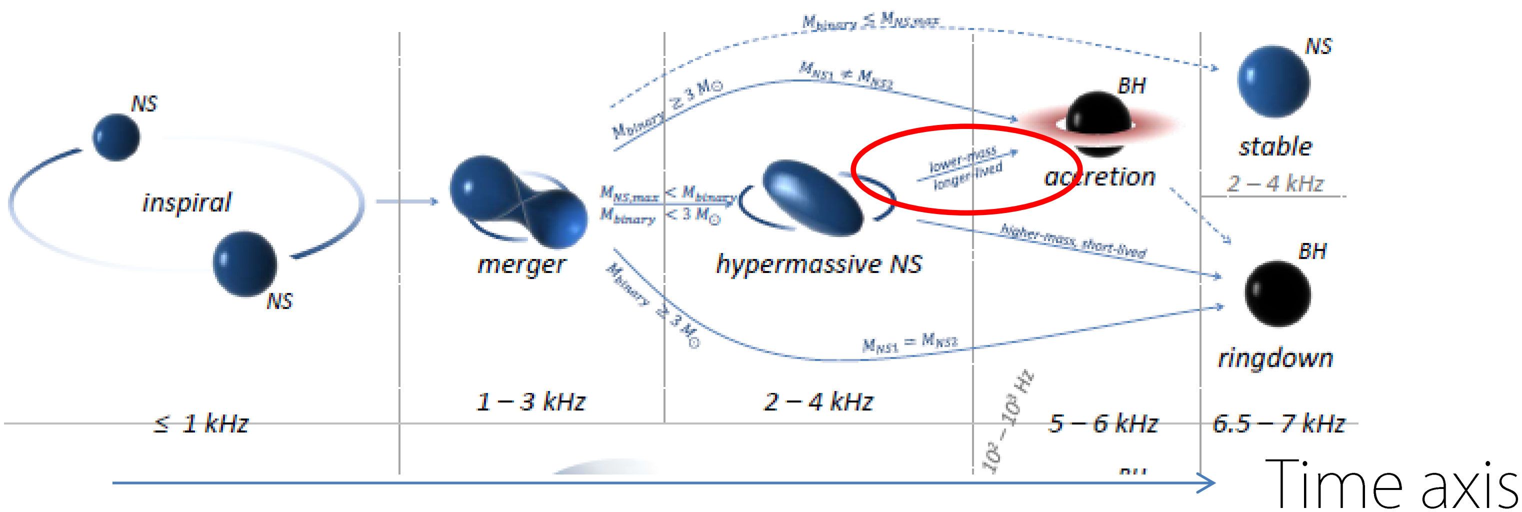


Long-term evolution of the remnant massive NS

▶ Strongly magnetized remnant NS core is inevitably formed shortly after the onset of merger.



▶ During the remnant massive NS phase, the magneto rotational instability (MRI) would drive the angular momentum transfer.

⇒ Primarily agent for the remnant massive NS evolution.

Long-term evolution of the remnant massive NS

Basic picture

▶MRI-driven turbulence ⇒ Effective turbulent viscosity

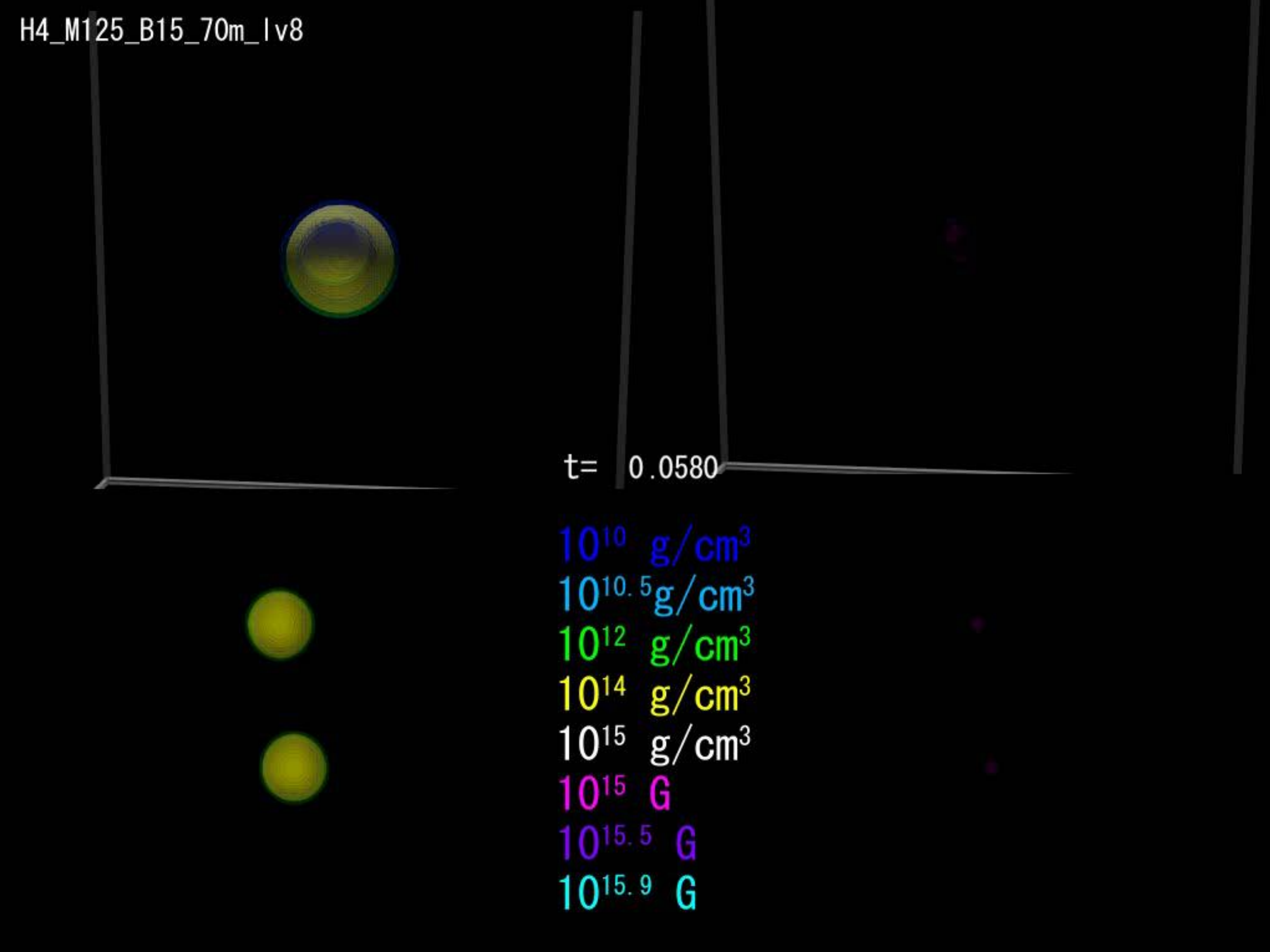
α -viscosity parameter:

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

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

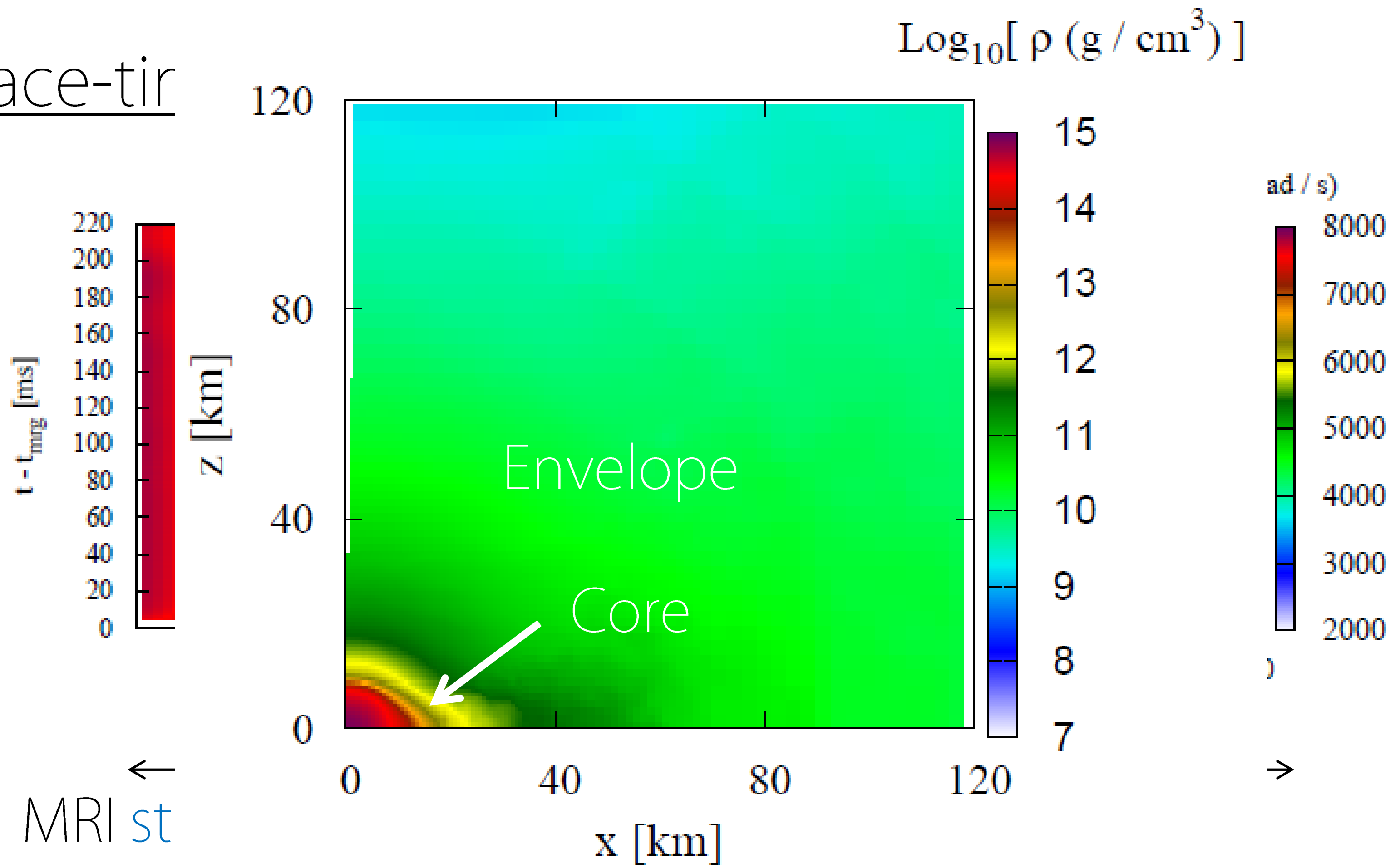
To do list: Read α -viscosity parameter from high-resolution MHD simulation

Caution: neutrino viscosity and dragging effect on MRI (Guilet et al. 16)


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-tir



MRI st

Metrics to measure the sustainability of MRI-turbulence

Convergence metrics (Hawley et al. 11, 13)

- $Q_z = \lambda_{MRI}^{z} / \Delta x$ ($Q_{\varphi} = \lambda_{MRI}^{\varphi} / \Delta x$) $\gtrsim$ 10-15
- $B_R^2 / B_{\varphi}^2 \approx$ 0.1-0.2
- (Maxwell Stress)/$P_{mag} \approx 0.45$

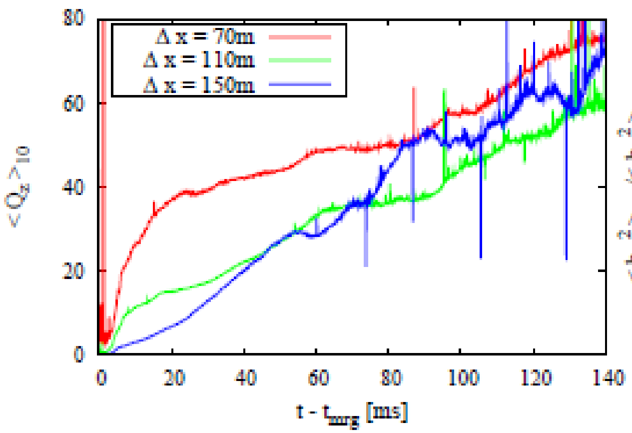
$\langle q \rangle_a = \int_V q \, d^3x \, / \int_V d^3x$

V : a volume with $a \leq \log_{10}[\rho \, (g/cc)] < a+1$

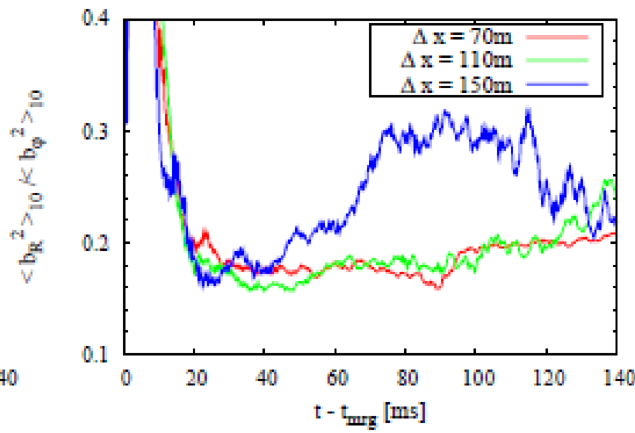
Metrics to measure the sustainability of MRI-turbulence

Envelope ($10^{10} \leq \rho < 10^{11}$ g/cm^3)

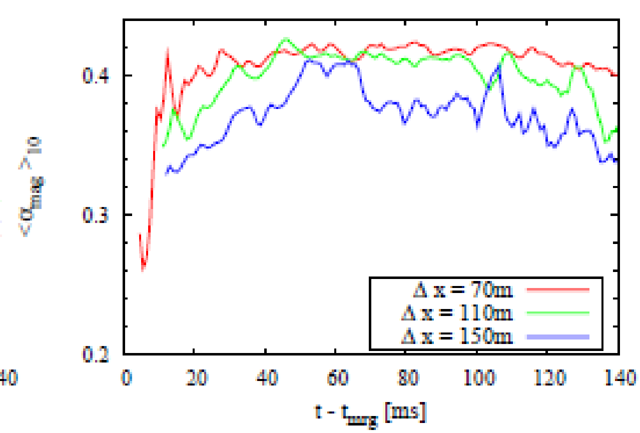
$\langle Q^z \rangle_{10}$



$\langle B^2_R \rangle_{10} / \langle B^2_\varphi \rangle_{10}$



$\langle W_{R\varphi} / P_{mag} \rangle_{10}$



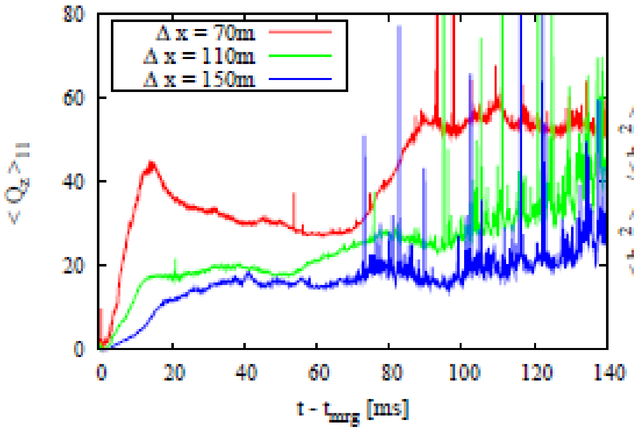
▶ Convergence metrics are likely to be consistent for 70m and 110m runs.

▶ 150m run might be contaminated by a numerical driven outflow.

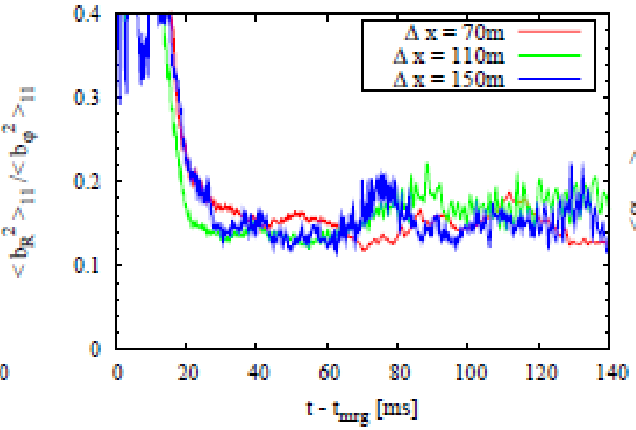
Metrics to measure the sustainability of MRI-turbulence

Envelope ($10^{11} \leq \rho < 10^{12}$ g/cm^3)

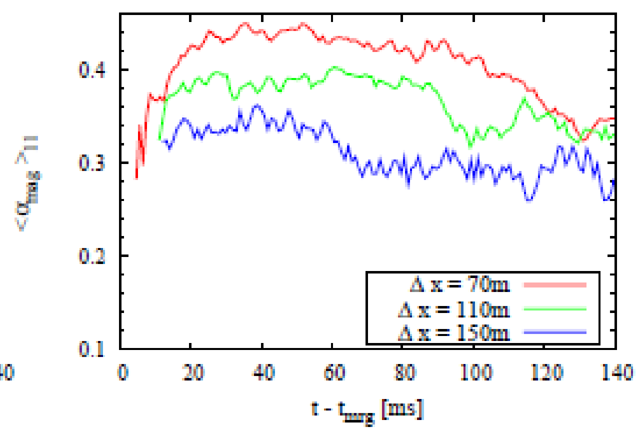
$\langle Q^z \rangle_{11}$



$\langle B^2_R \rangle_{11} / \langle B^2_\varphi \rangle_{11}$



$\langle W_{R\varphi} / P_{mag} \rangle_{11}$

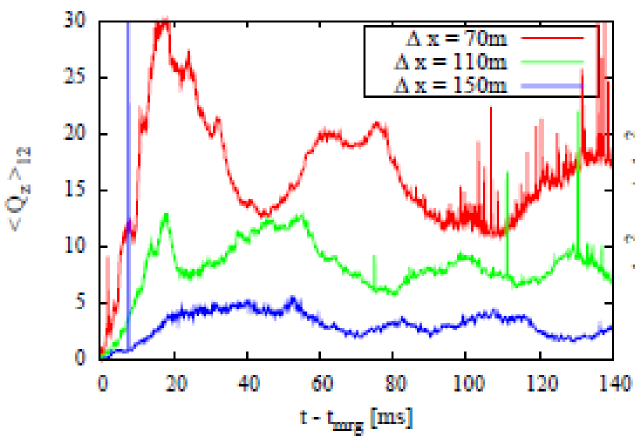


▶ Convergence metrics are likely to be consistent for 70m and 110m runs.

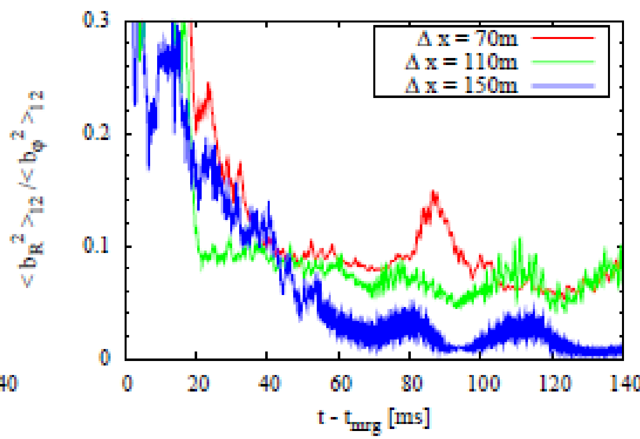
Metrics to measure the sustainability of MRI-turbulence

Core ($10^{12} \leq \rho < 10^{13}$ g/cm^3)

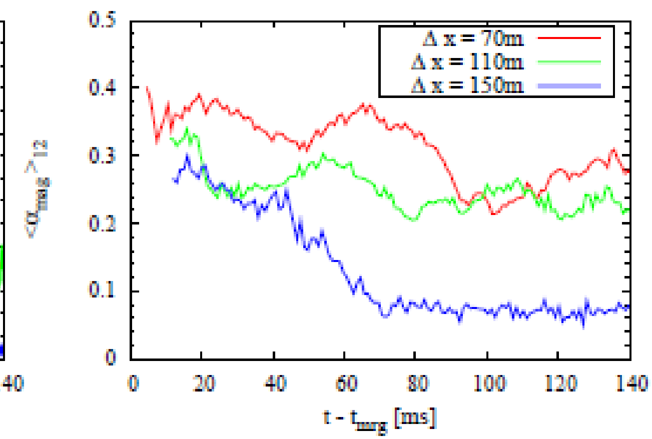
$\langle Q^z \rangle_{12}$



$\langle B^2_R \rangle_{12} / \langle B^2_\varphi \rangle_{12}$



$\langle W_{R\varphi} / P_{mag} \rangle_{12}$

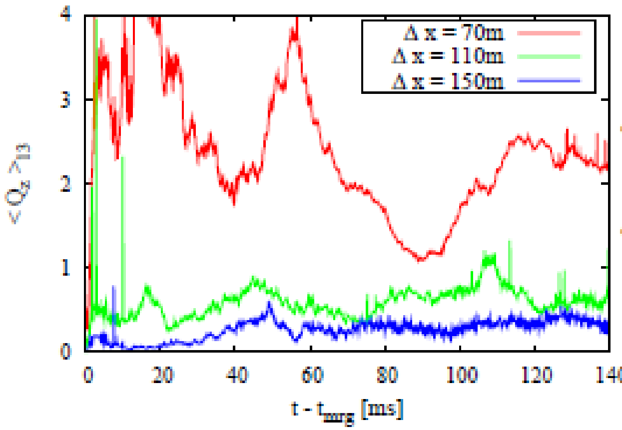


- Convergence metrics for 70m run are "OK".
- 110m run is marginal.
- 150m run is unreliable.

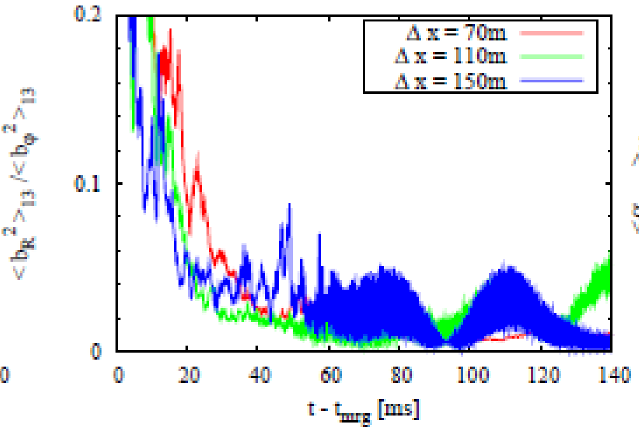
Metrics to measure the sustainability of MRI-turbulence

Core ($10^{13} \leq \rho < 10^{14} g/cm^3$)

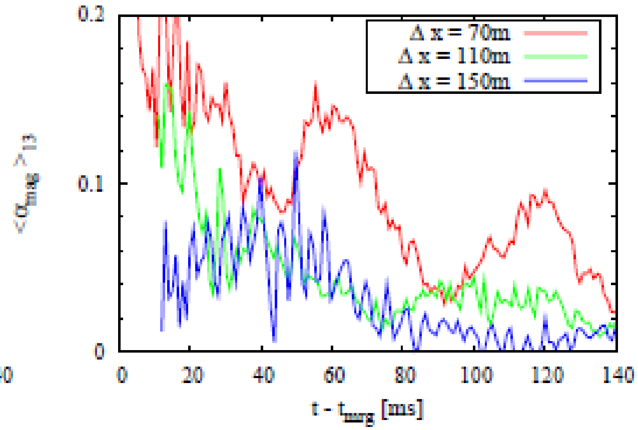
$<Q^z>_{13}$



$<B^2_R>_{13}/<B^2_\varphi>_{13}$



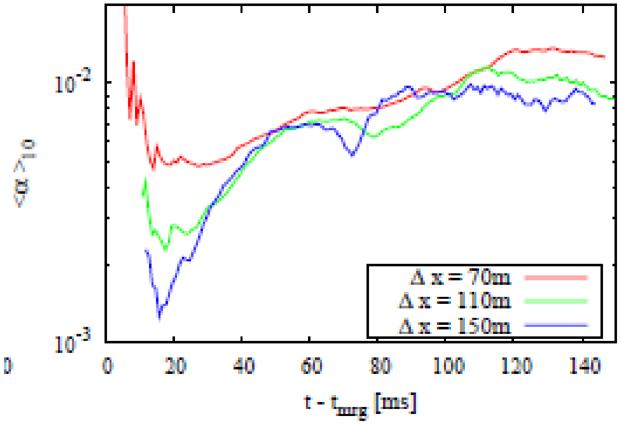
$<W_{R\varphi}/P_{mag}>_{13}$



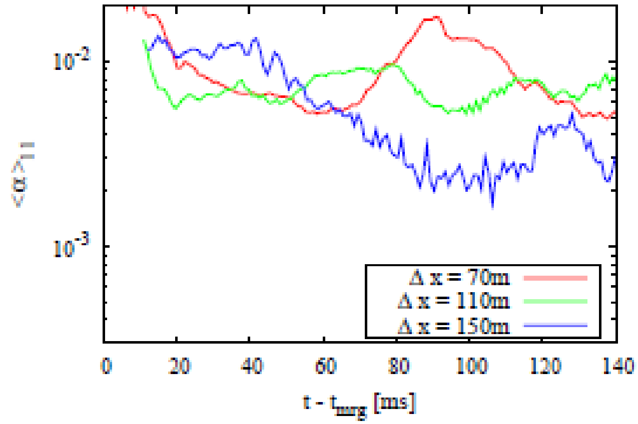
▶All the runs are unreliable.

α -viscosity parameter

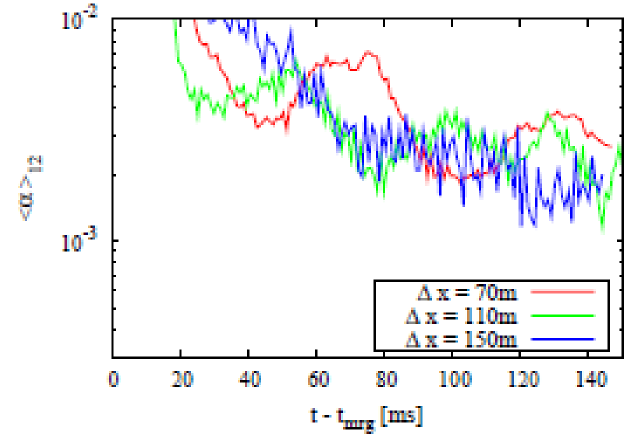
Envelope(a=10)



Envelope(a=11)



Core surface(a=12)



- $<<\alpha>> \approx 1\times10^{-2}$ for the envelope
- $<<\alpha>> \gtrsim 4\times10^{-3}$ for the core

<u>(Upper bound of)angular momentum transport timescale</u>

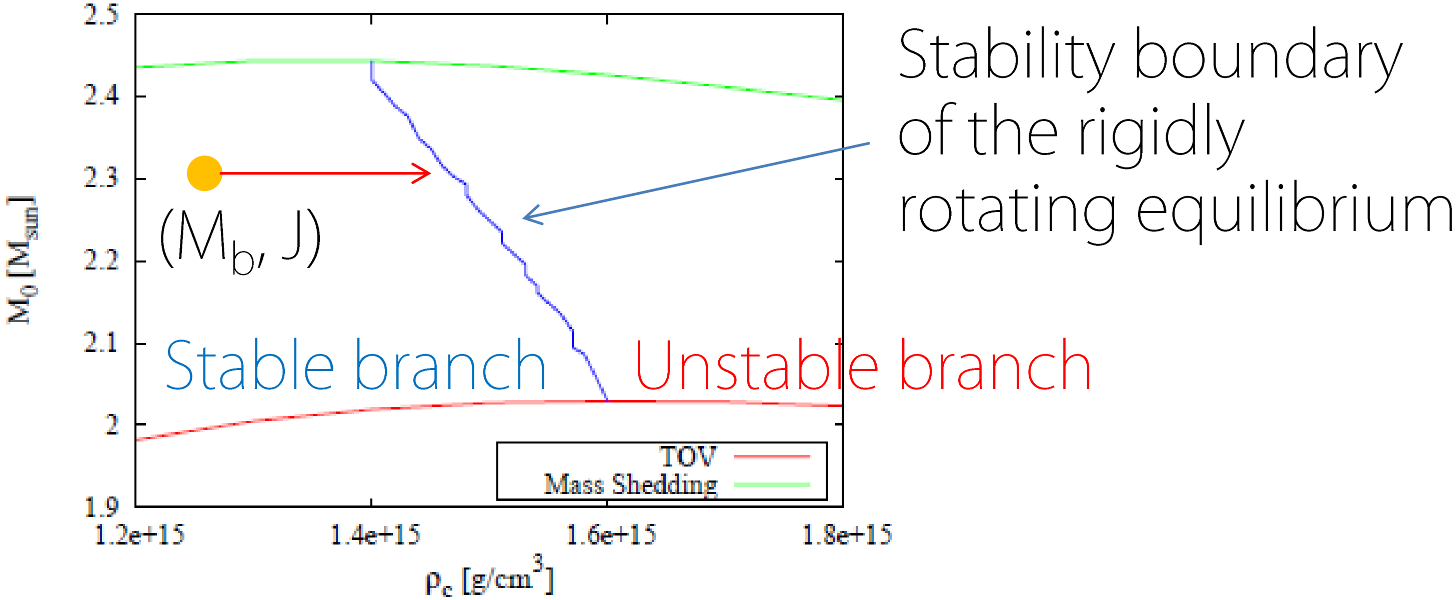
$t_{vis} \lesssim 0.12$ s $(<<\alpha>>/\ 4\times10^{-3})^{-1}$
$\times(<j>/1.7\times10^{16}\mathrm{cm}^2\mathrm{s}^{-1})(<c_s>/0.2c)^{-2}$

The fate of the remnant massive NS core

Rotation of the core ⇒ Uniform rotation in the angular momentum timescale

▸Uniformly rotating core ≈ Rigidly rotating equilibrium

Discussion of the stability of the rigidly rotating core



▸The core will evolve with J dissipation

The fate of the remnant massive NS core

▶Angular momentum dissipation via magnetic-dipole radiation and gravitational wave radiation

$$dE_{rot}/dt = - B_d{}^2 R^6 \Omega^4 / 6c^3 - 32G/5c^5 M_b{}^2 R^4 \varepsilon^2 \Omega^6$$

▶ Magnetic-field energy ≈Dipole magnetic-field energy

$$B_d \lesssim 3 \times 10^{14} G$$

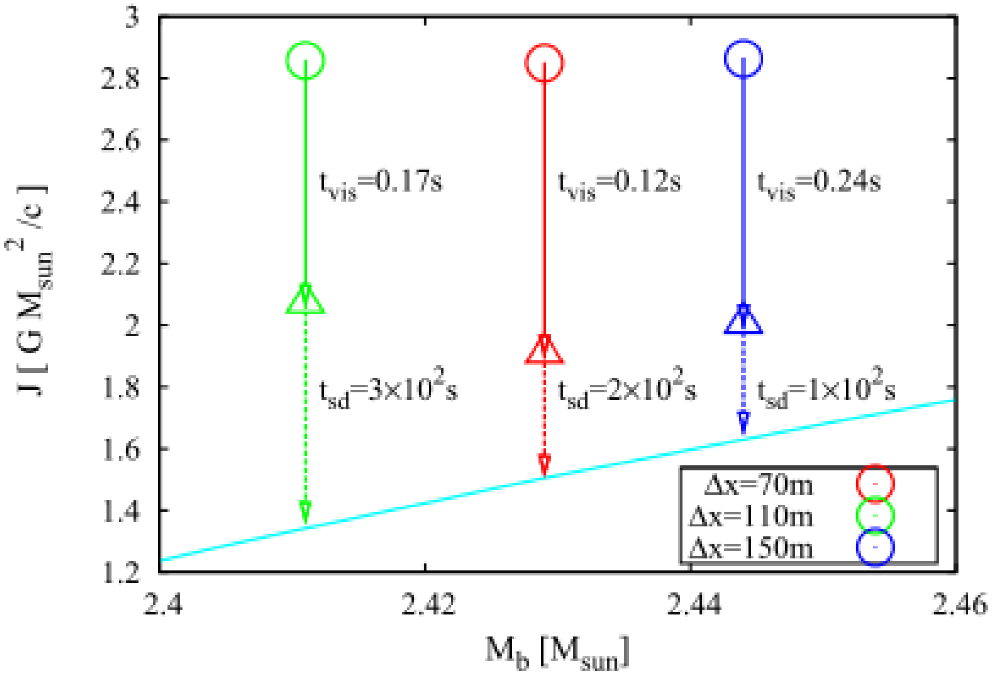
▶ Estimation from the simulation data

$$\varepsilon \lesssim 10^{-3}$$

Spin down timescale

$$t_{sd} \gtrsim 2 \times 10^2 \text{ s}$$

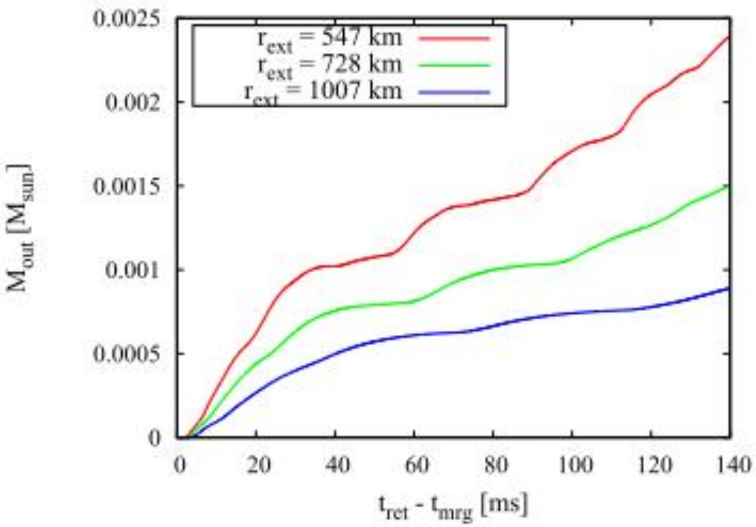
The fate of the remnant massive NS core



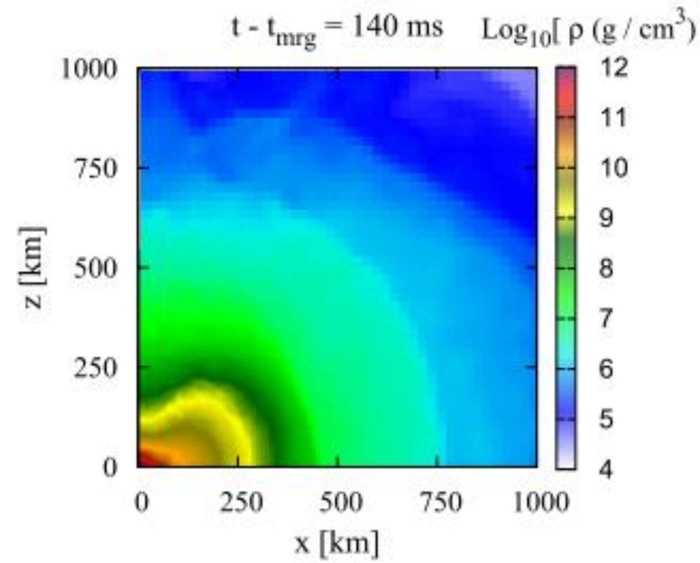
▶Differential rotating core ⇒Uniformly rotating core ⇒ BH formation due to the angular momentum dissipation

Possible outflow

Mass outflow passing through the sphere r_{ex}



Density structure of the envelope



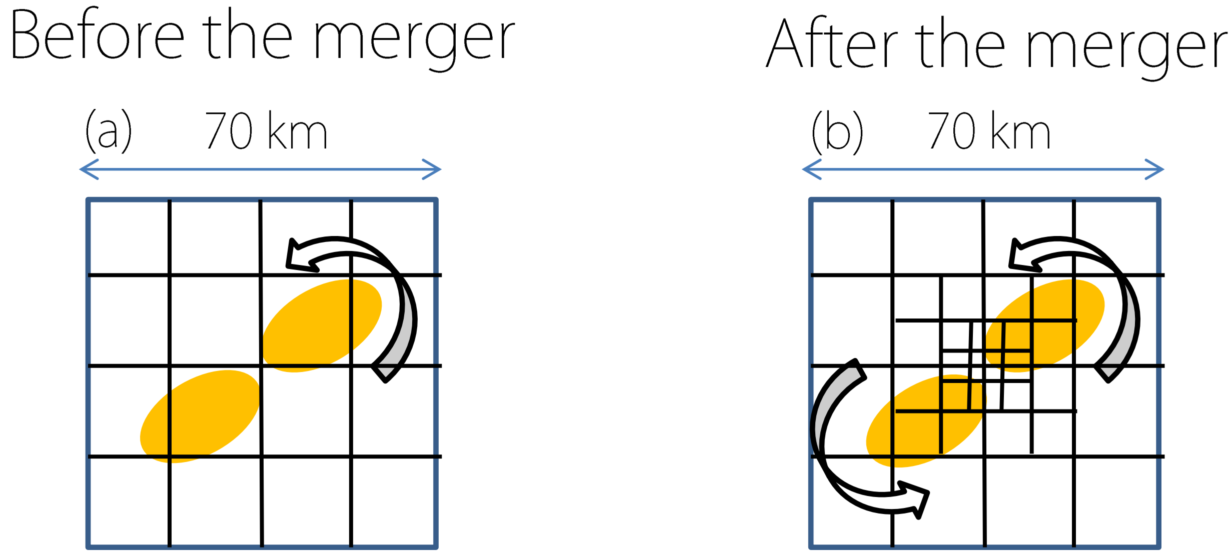
▶ Dynamical ejecta mass is $8\times10^{-4}\,M_\odot$

▶ Possible additional outflow due to the α-recombination, neutrino heating, and MHD-wind.

(Ferndez & Metzger 13, Sekiguchi et al. 15)

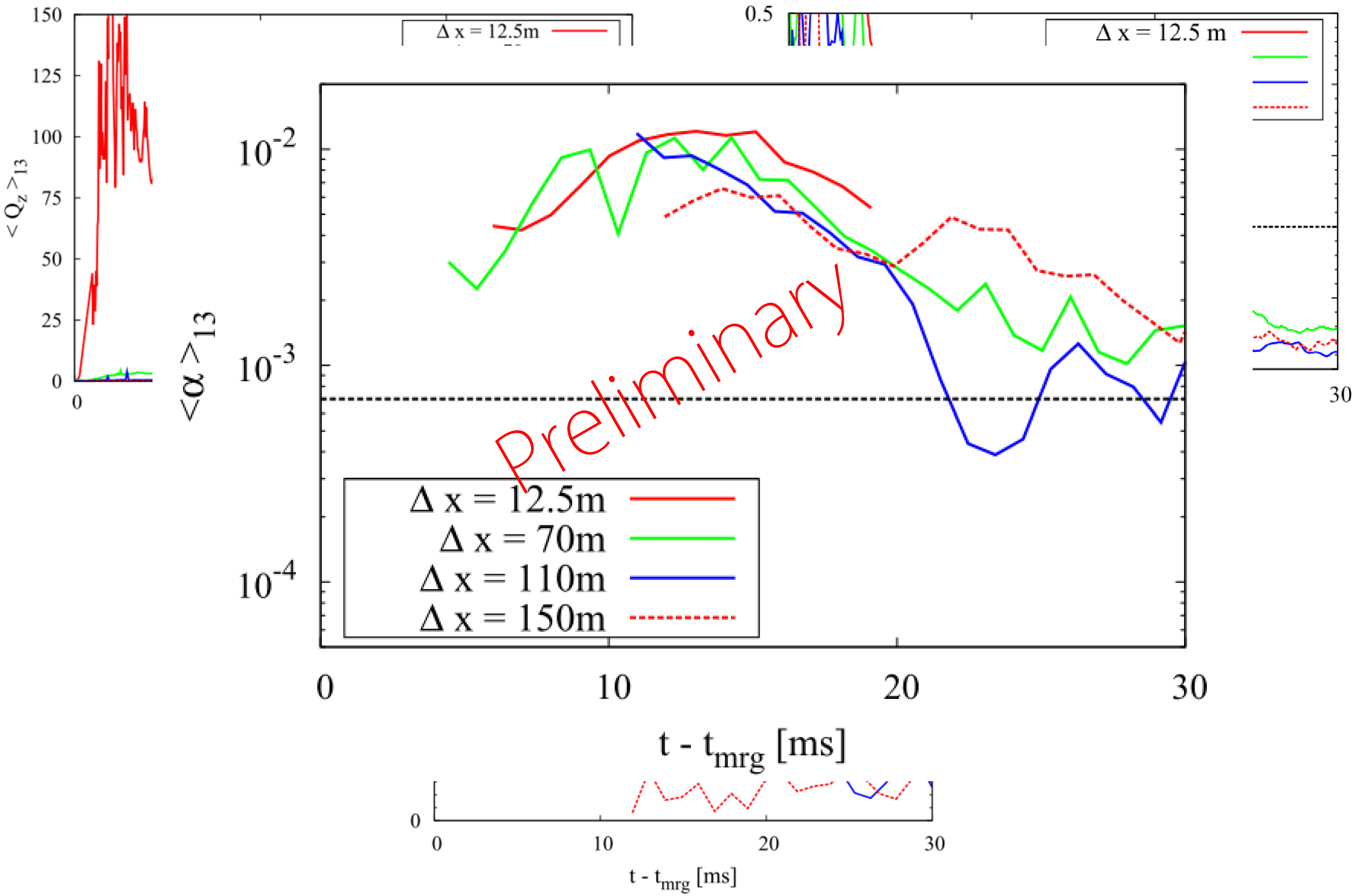
What is the true value of α-parameter ?

Assigning a finer resolution box into the remnant massive NS



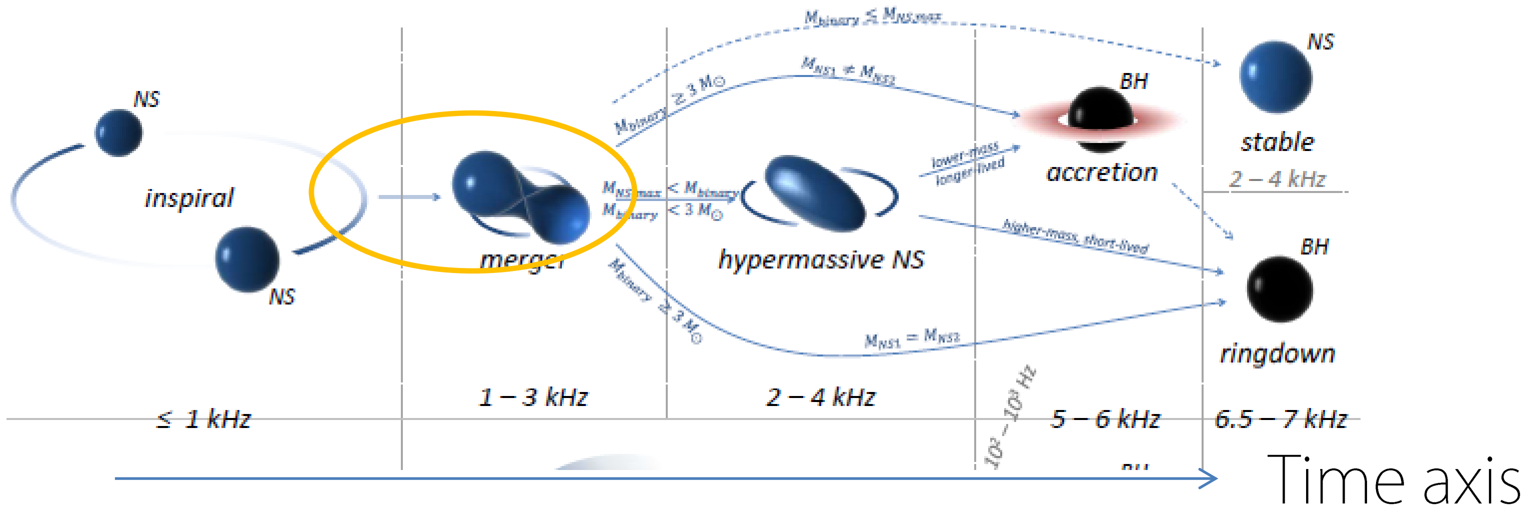
▶ Δx=50m ⇒ Δx=12.5m on K computer

High-res. MHD simulation of the RMNS



Go back to the late inspiral phase

(Bartos et al. 13)



▶ Equation of state is major uncertainty for modeling compact binary merger

▶ Extraction of the tidal deformability of NS from late inspiral GWs

To do list: Derivation of high-precision NR waveforms

Measuring the tidal deformability of NSs

Tidal deformation accelerates the inspiral motion.
⇒ The tidal deformability is imprinted in the GW phase shift.

Numerical viscosity accelerates the inspiral motion as well.

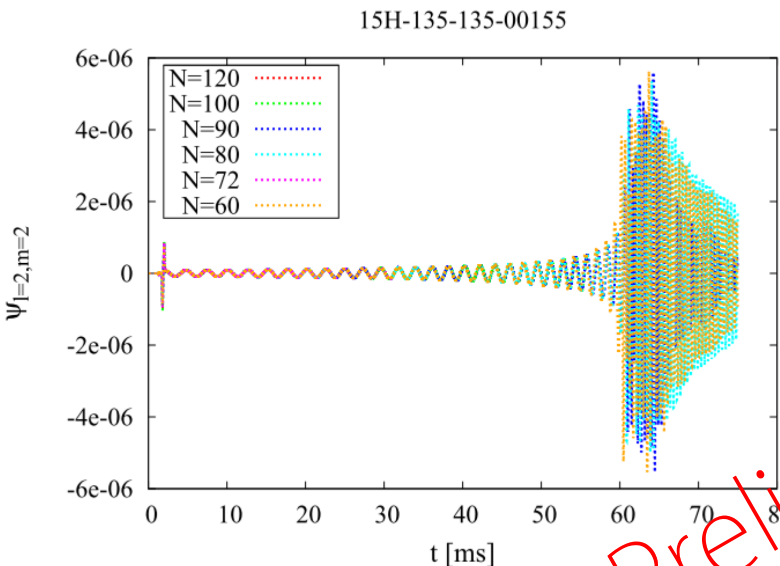
Requirement

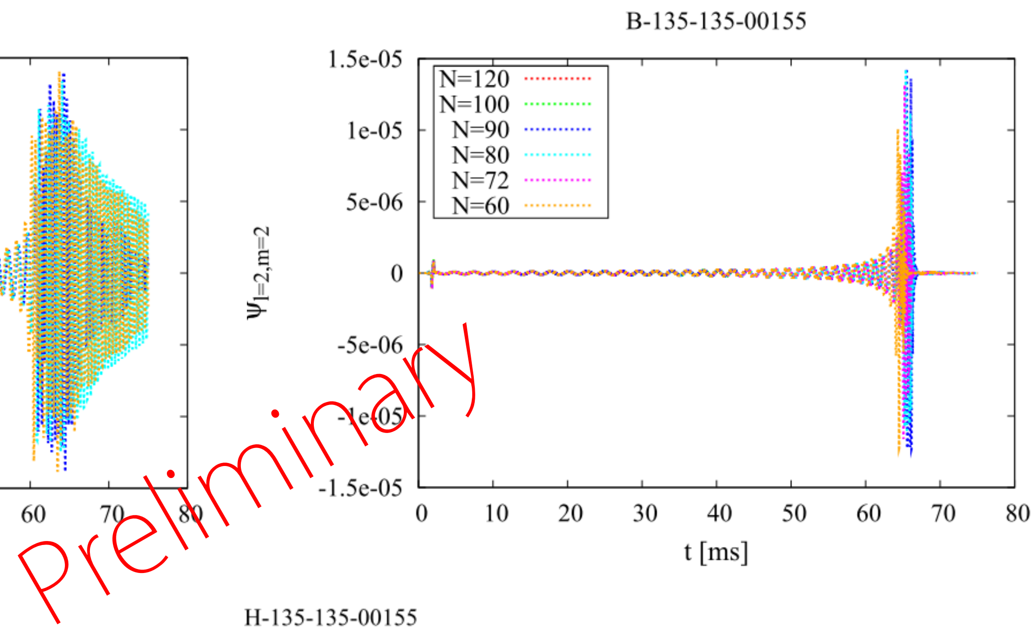
▶ GW phase shift due to the numerical viscosity should be smaller than that due to the tidal deformation.

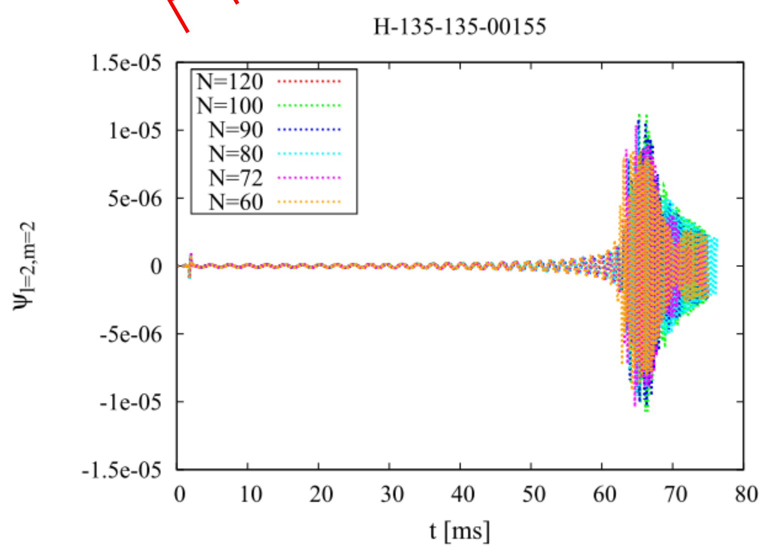
▶ Convergence study ⇒ Continuum limit

Measuring the tidal deformability of NSs

Efficient NR waveform generation by supercomputer







Summary

▶ Exploring the fate of long-lived remnant massive NS formed after BNS mergers.

▶ High-res. GRMHD simulation to explore the angular momentum transfer.
KH instability ⇒ MRI ⇒effective turbulent viscosity

▶ Possible BH-massive torus formation after the star dissipates the angular momentum.

▶ Possible outflow with additional mechanism and/or more efficient angular momentum transport (need higher-res. simulation)