The role of magnetic fields in compact binary mergers

Kenta Kiuchi (YITP)

Masaru Shibata (YITP), Yuichiro Sekiguchi (Toho),
Koutrou Kyutoku (Riken)

Ref.1) Kiuchi et al. PRD 92, 124034 (2015) (NS-NS)
Ref.2) Kiuchi et al. PRD 90, 041502(R) (2014) (NS-NS)
Ref.3) Kiuchi et al. PRD 92, 064034(2015) (BH-NS)
Ref.4) Kiuchi et al. 2016 in prep.

YITP
YUKAWA INSTITUTE FOR
THEORETICAL PHYSICS

K computer

Visualization by T. Wada

Purpose

Revealing a realistic picture of compact binary mergers

- MHD effect (NS magnetic field)
- Neutrino radiation transport (led by Y. Sekiguchi)

Large-scale simulations are necessary to resolve the MHD instabilities ; MRI, Kelvin-Helmholtz instability etc.

- Total peak efficiency is 10.6 PFLOPS (663,552 cores)

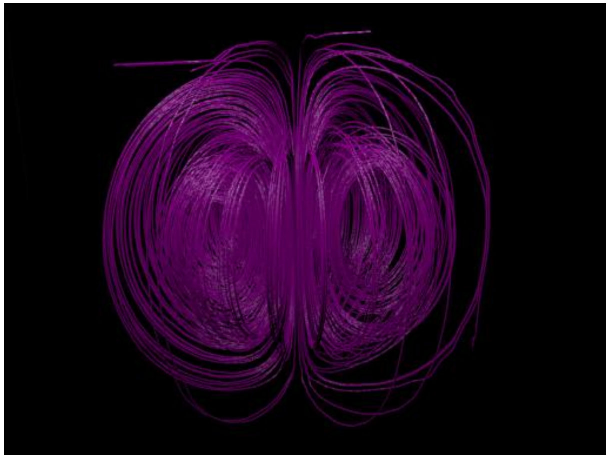
Magnetized binary NS merger simulations

- ▶High resolution Δx=70m ⇒ 17.5m (16,384 cores on K)
- ▶Medium resolution Δx=110m (10,976 cores on K)
- ▶Low resolution Δx=150m (XC30, FX10 etc.)

c.f. Radii of NS～10km, the highest resolution of the previous work is $\Delta x \approx$180m (Liu et al. 08, Giacomazzo et al. 11, Anderson et al. 08)

Nested grid ⇒ Finest box=70km^3, Coarsest grid =4480km^3 (N≈10^9) , a long term simulation of about 100 ms

Magnetic field lines of NS



Fiducial model

EOS : H4 (Gledenning and Moszkoski 91) ($M_{max} \approx 2.03 M_\odot$)

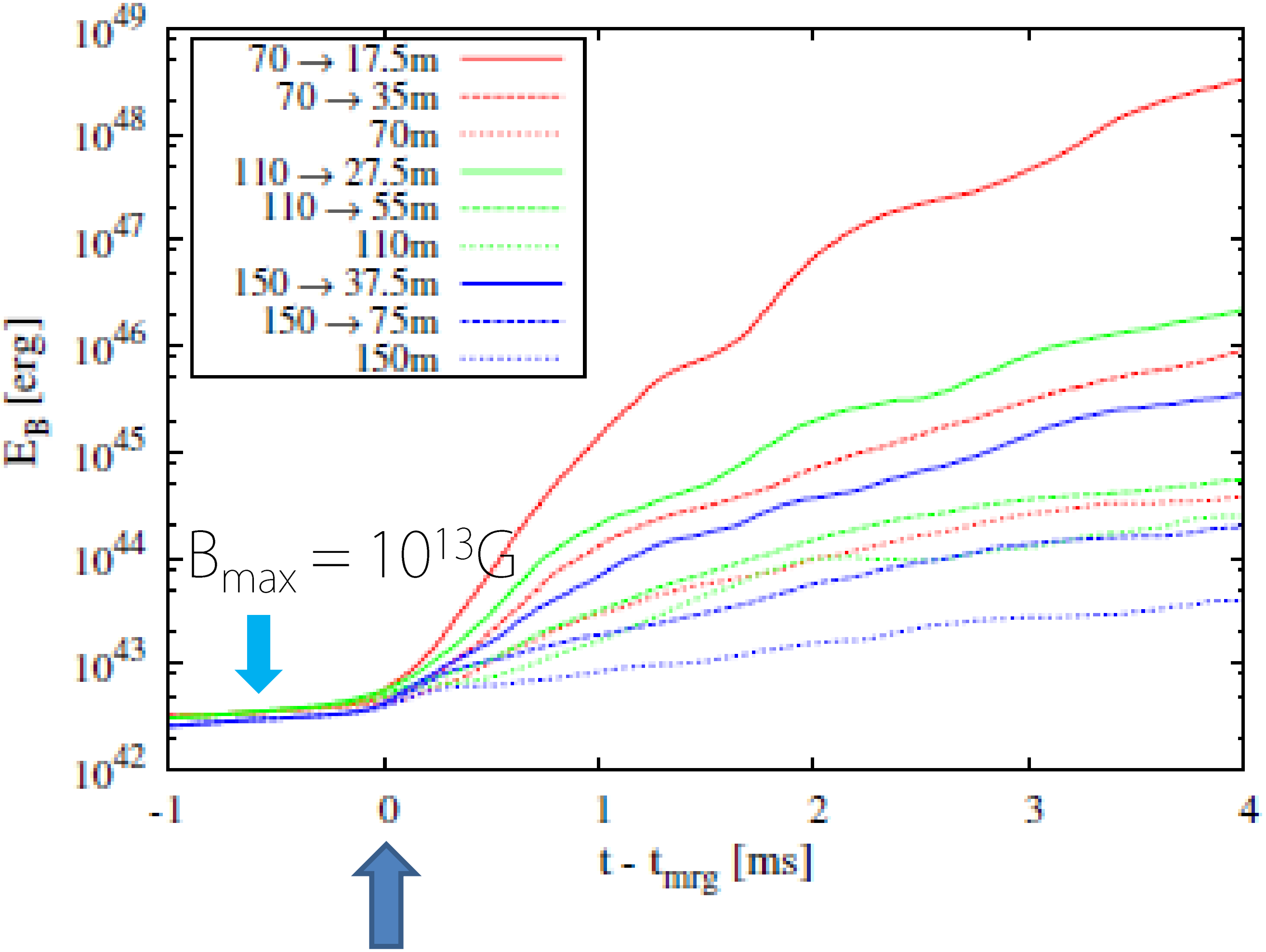
Mass : 1.4-1.4 $M_\odot$

B-field : 10^{13}G - 10^{15}G

Efficient B-field amplification at the mergerrole

(Rasio-Shapiro 99, Price-Rosswog 06, Liu et al. 08, Anderson et al. 08, Giacomazzo et al. 11)

Kelvin-Helmholtz instability plays an essential.

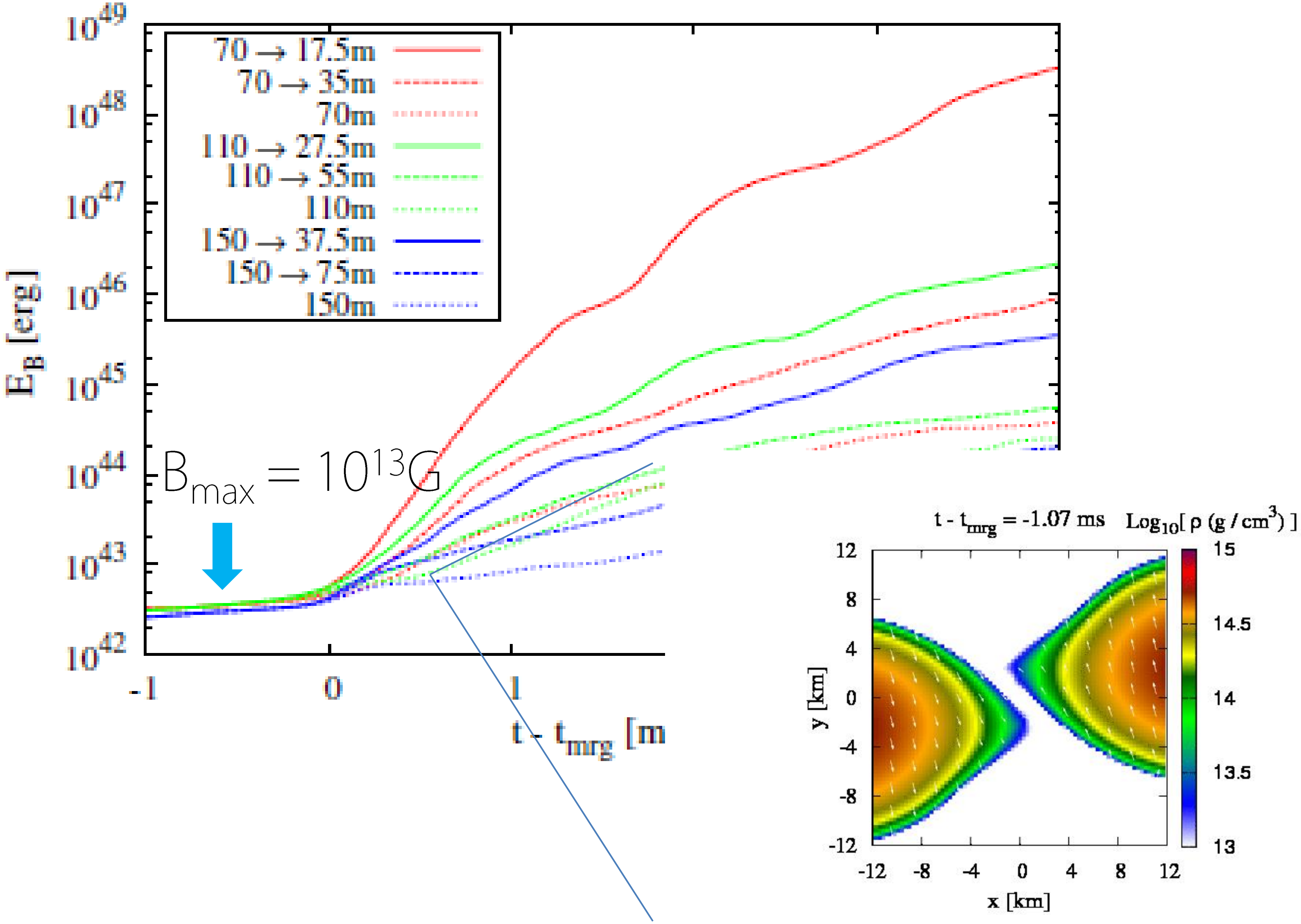


$B_{max} = 10^{13}$G

Merger

Efficient B-field amplification at the merger

Kelvin-Helmholtz instability plays an essential role.



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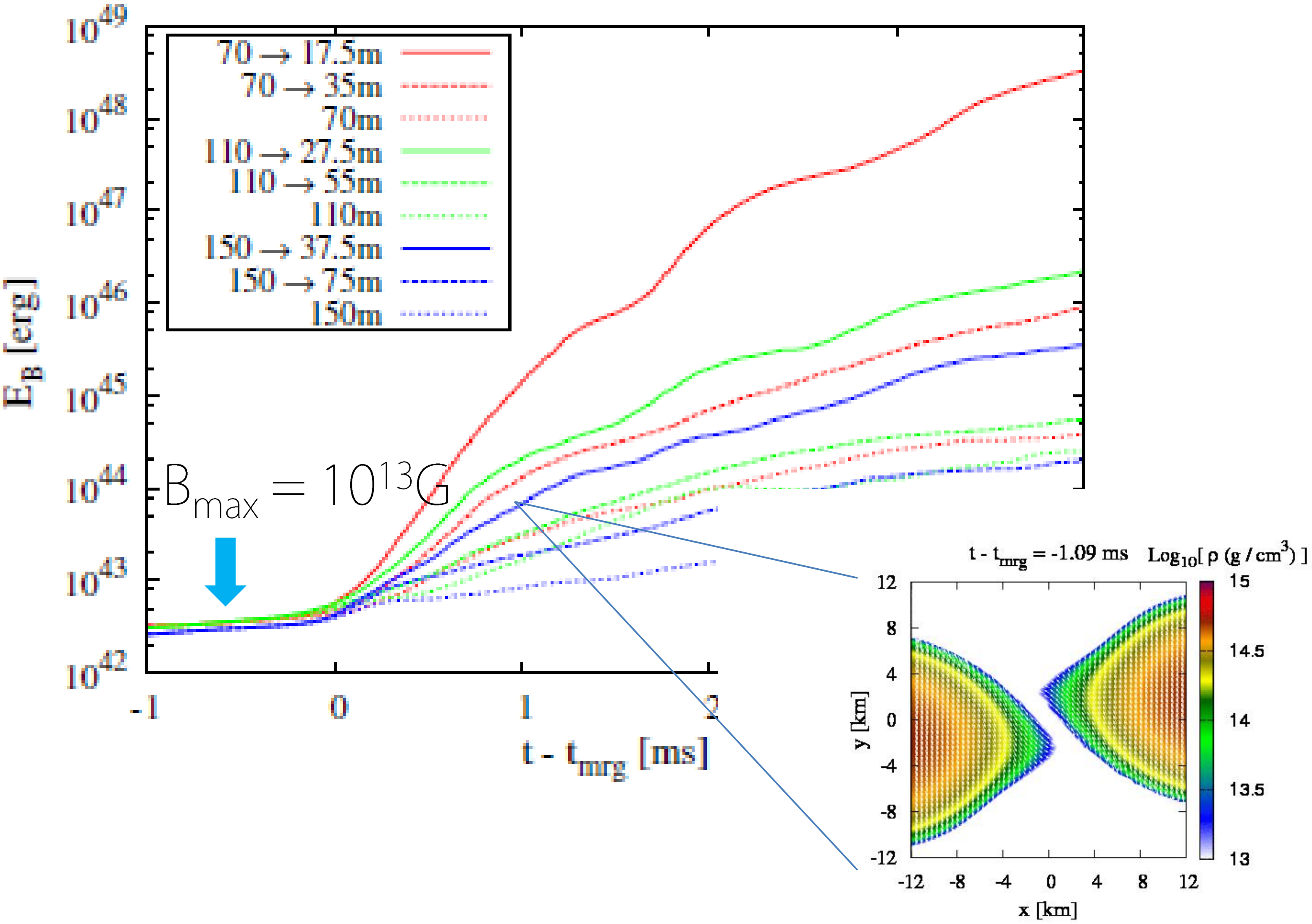

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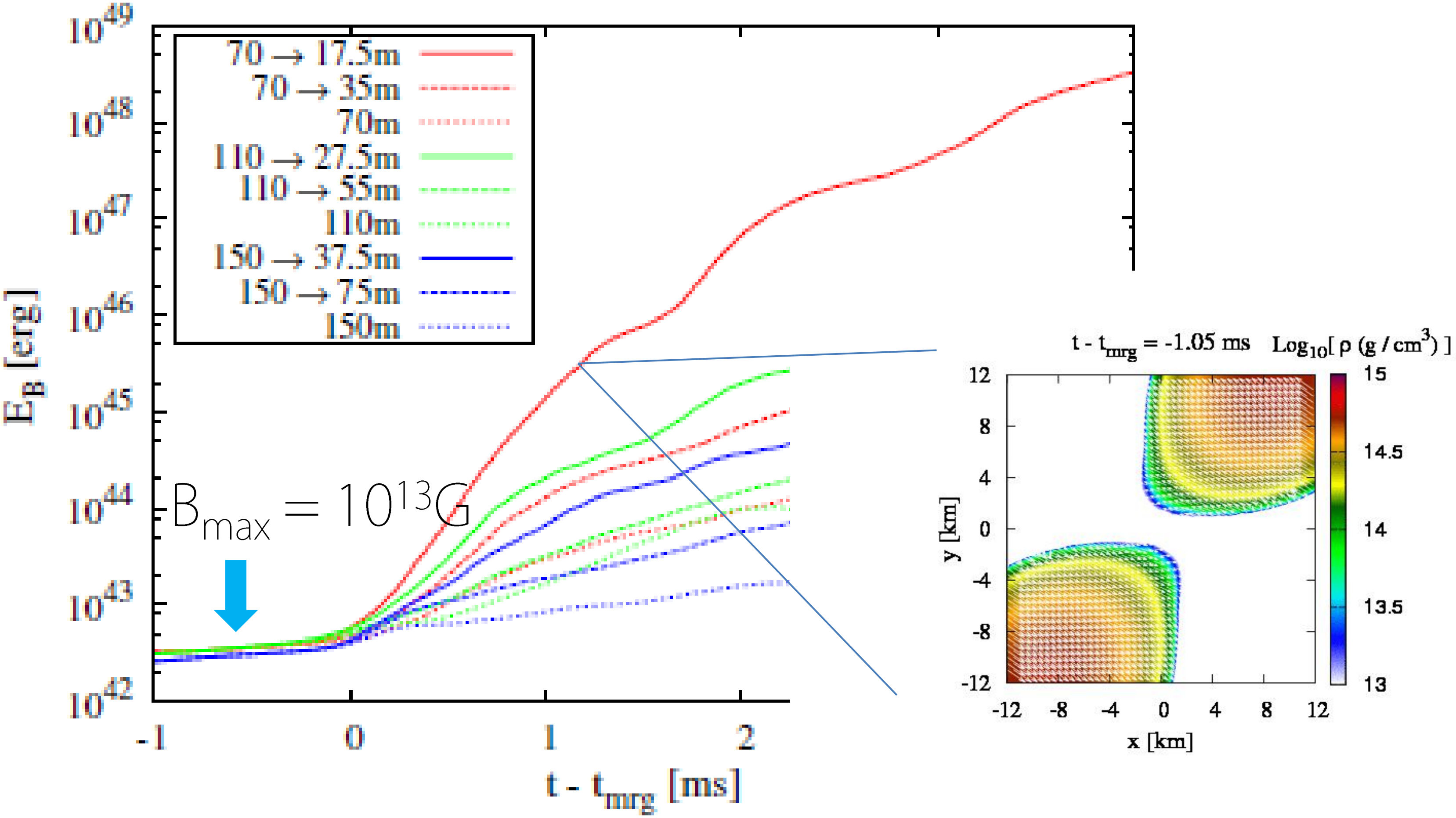
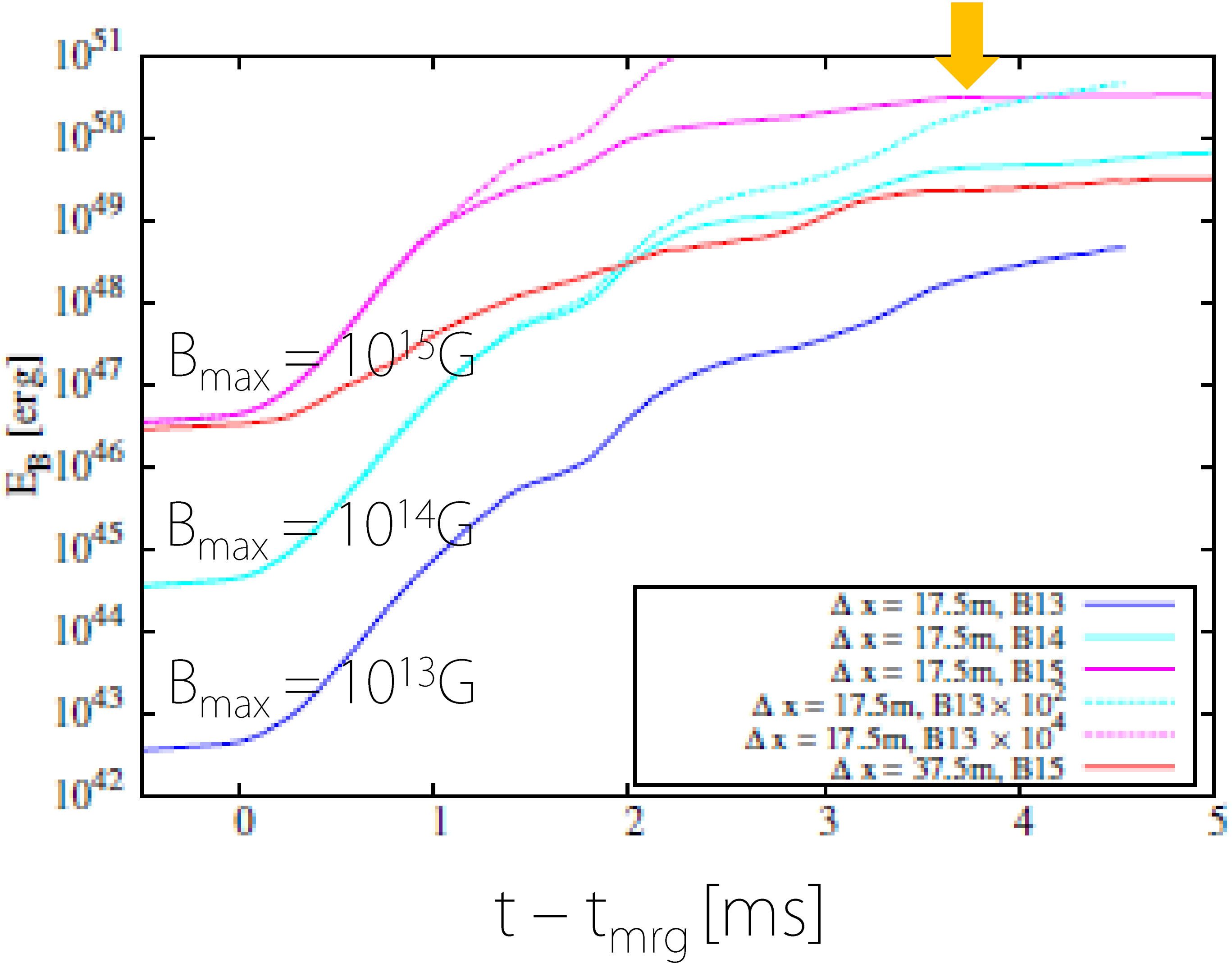


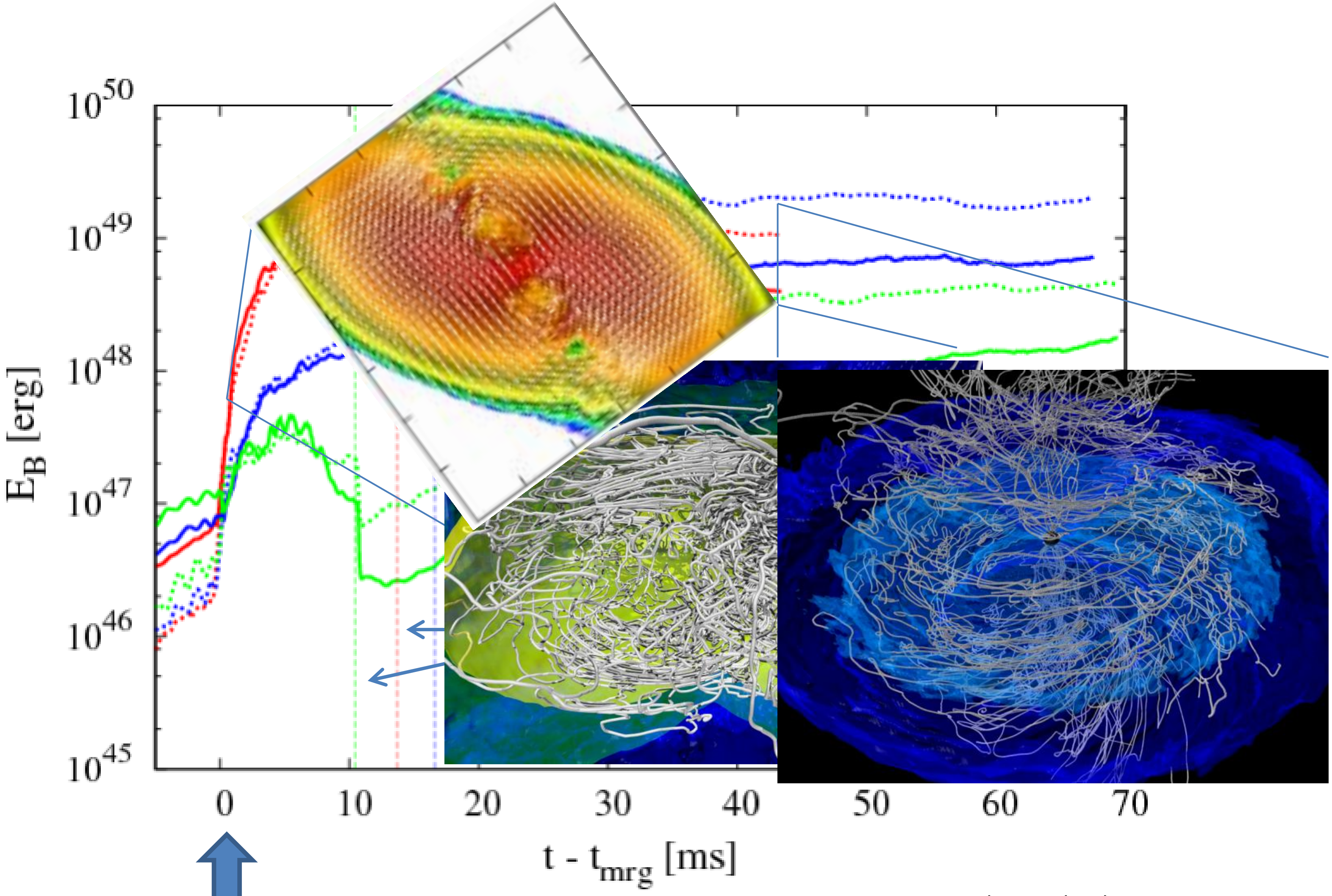
$B_{max} = 10^{13}G$

Highly magnetized neutron stars formation in binary neutron stars

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



Long-term evolution of the magnetic field energy



Merger

P = Poloidal comp.
T = Toroidal comp.

Low-mass binary evolution

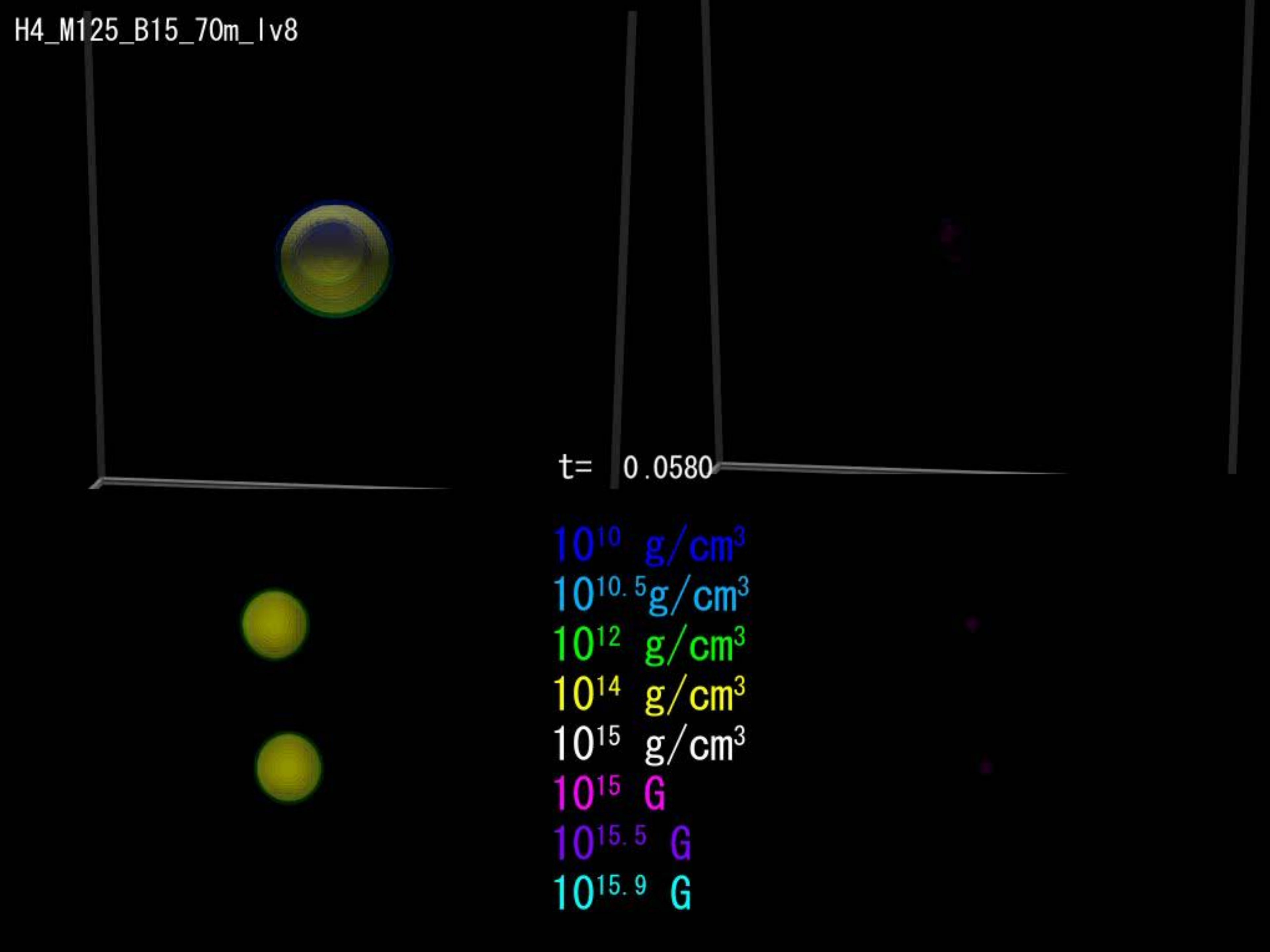
▶1.25 $M_\odot$-1.25 $M_\odot$ BNS with H4 EOS (Glendenning and Moszkowski 91), $M_{max}=2.03\ M_\odot$

▶ "Long" term simulation of 150ms with Δx=70, 110, 150m (Kiuchi et al. 14, 15)

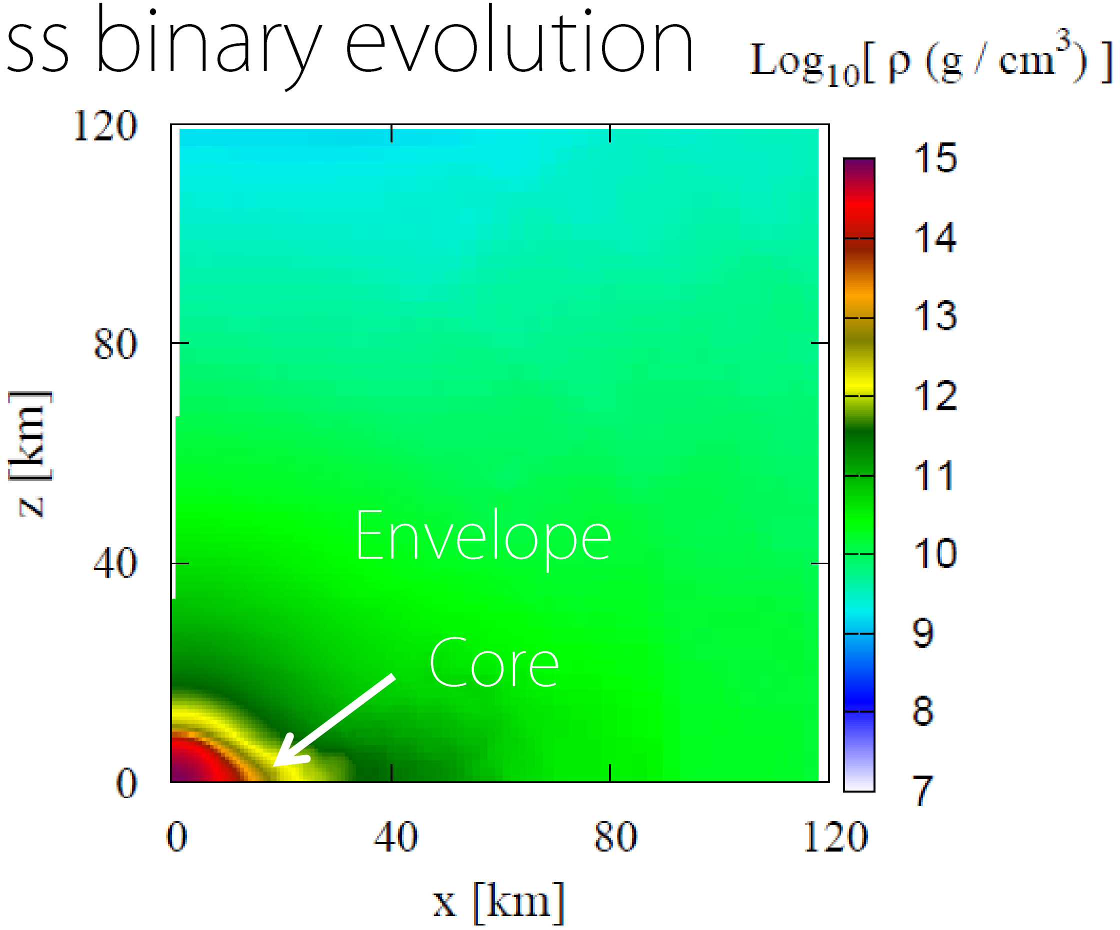
Purpose

Explore the magneto rotational instability driven turbulence effect in a long-lived remnant massive neutron star.

$$\alpha \text{ viscosity} := <\underbrace{\rho\ \delta v^R \delta v^\varphi}_{\text{Reynolds stress}} \underbrace{- B^R B^\varphi/4\pi}_{\text{Maxwell stress}}>/<P>$$


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

Low-mass binary evolution



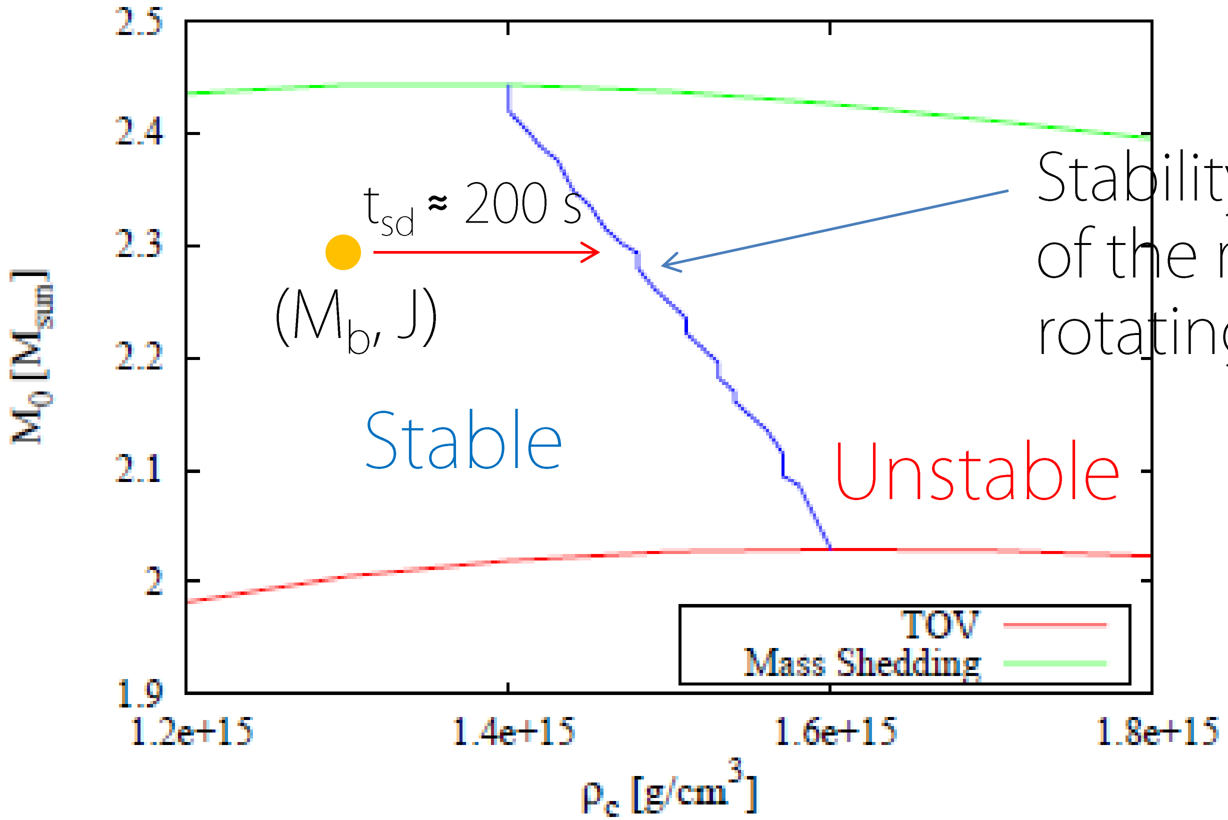
- $\alpha \approx 1\times10^{-2}$ for the envelope
- $\alpha \gtrsim 4\times10^{-3}$ for the core

Angular momentum transport :

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

Spin down via B-dipole radiation : $t_{\mathrm{sd}} \gtrsim 2\times10^2\ \mathrm{s}$

The fate of the low-mass binary neutron star



Stability boundary of the rigidly rotating equilibrium

- ▶ $M_{BH} \sim M_{core} \approx 2.43 M_\odot$
- ▶ $q = J_{BH}/M_{BH}^2 \sim J_{core}/M_{core}^2 \approx 0.5 \Rightarrow j_{ISCO} = 2.9 M_{BH}$

$\Rightarrow M_{disk} \approx 0.2 M_\odot$

Black hole – neutron star binary merger simulation in MHD

- High resolution ; Δx=120m, N=1028^3 (K ; 32,768 cores)
- Middle resolution ; Δx = 160m, N=756^3 (XC30 ; 4,096 cores)
- Normal resolution ; Δx = 202m, N=612^3 (XC30 ; 4,096 cores)
- Low resolution ; Δx = 270m, N=448^3 (FX10 ; 3,456 cores)

c.f. highest-res. in BH-magnetized NS simulation is $\Delta x \approx 260$m, N =140^3

Fiducial model

- EOS : APR4 ($M_{max} \approx 2.2 M_\odot$), $M_{NS} = 1.35\ M_\odot$
- M_{BH}/M_{NS} : 4
- BH spin : 0.75
- B_{max} : 10^{15}G

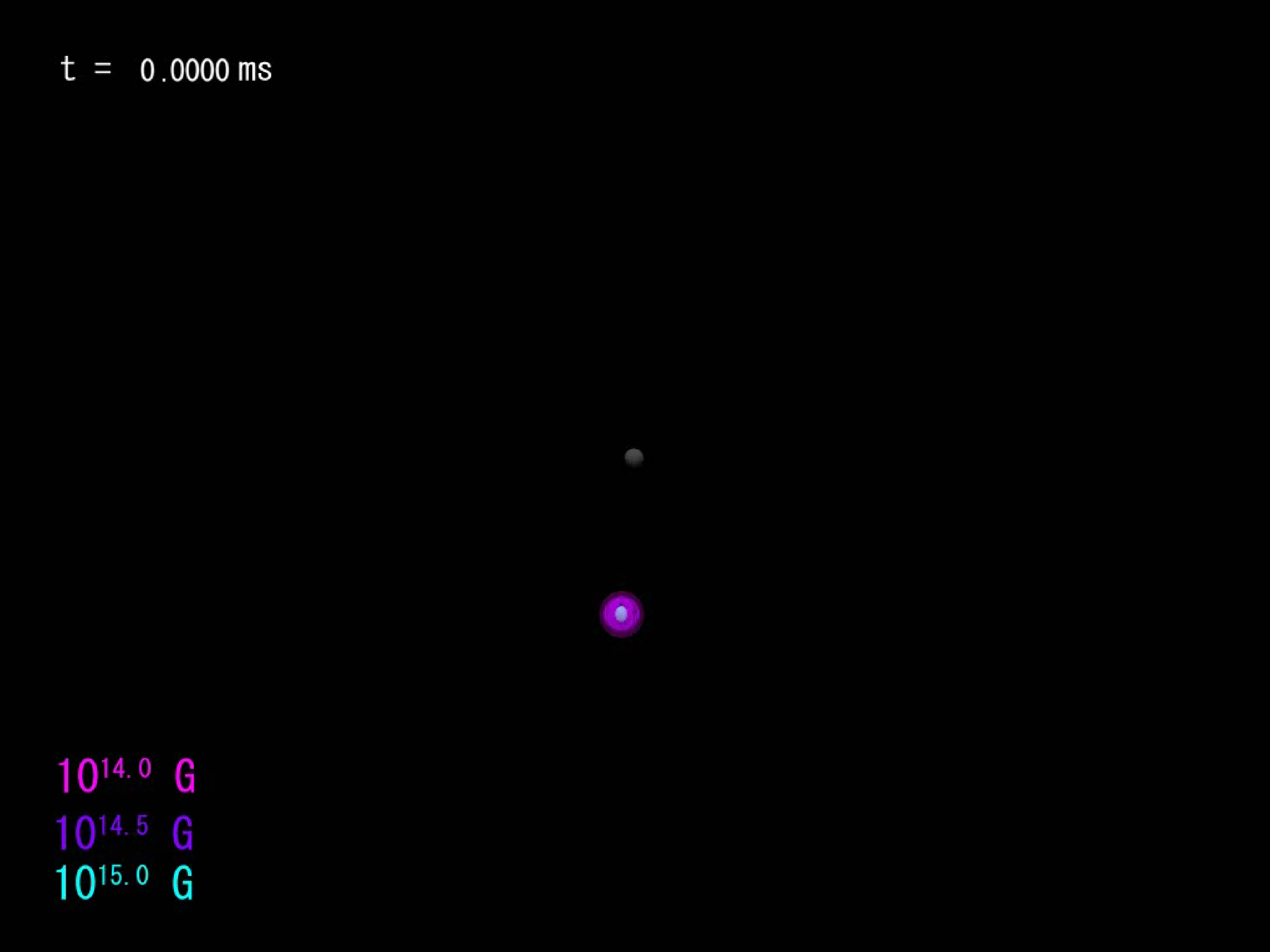
This model is subject to the tidal disruption t = 0.2270 ms

10^{12} g/cm^3

10^{11} g/cm^3

10^{10} g/cm^3

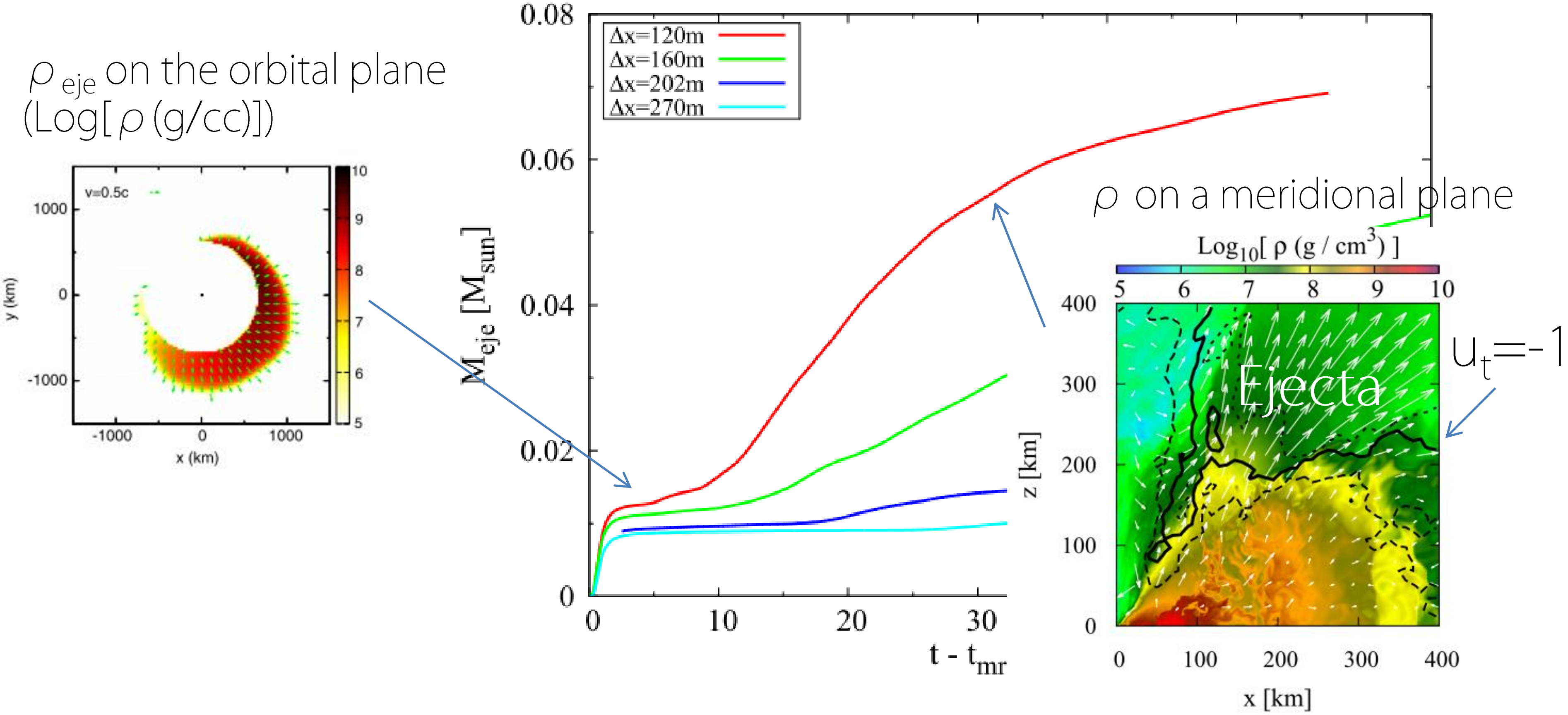
10^{9} g/cm^3


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

Ejecta time evolution

Ejecta $\overset{\text{def}}{=}$ Gravitationally unbounded fluid element (u_t<-1)

ρ_{eje} on the orbital plane (Log[ρ (g/cc)])

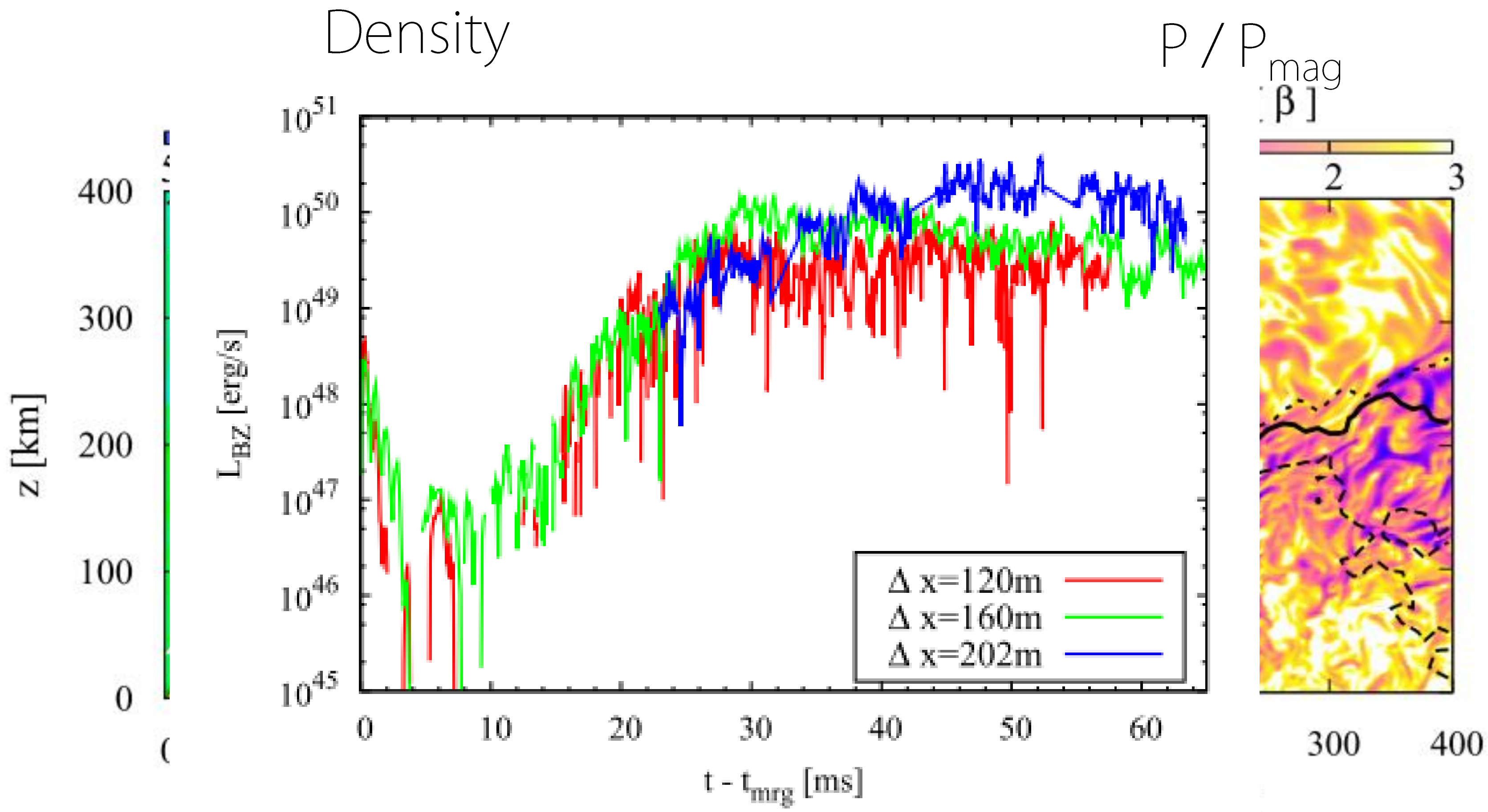


ρ on a meridional plane

u_t=-1

- ▶ Dynamical ejecta due to tidal disruption for t ≲ 10ms
- ▶ A new component for t ≳ 10ms ; Torus wind

Natural consequence of the torus wind



- 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)

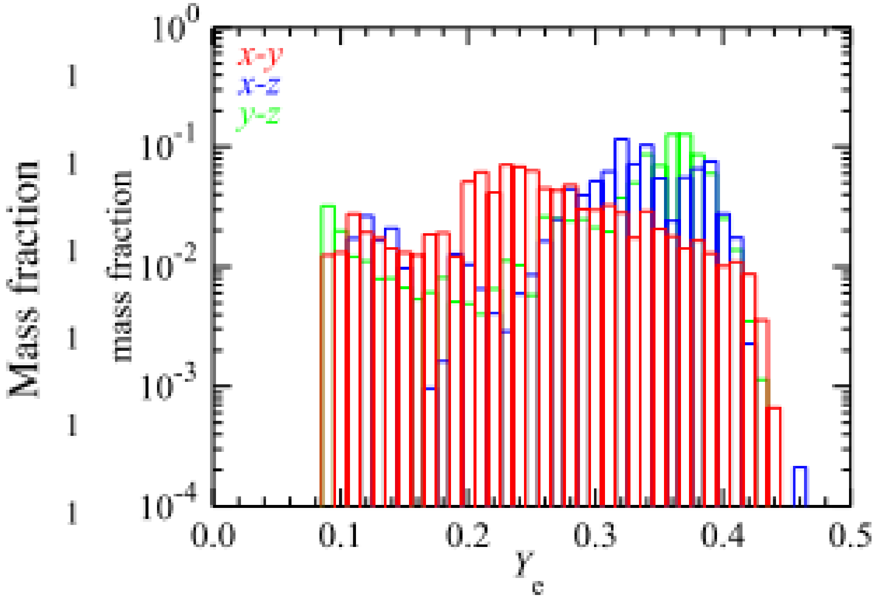
R-process nucleosynthesis in BH-NS merger

▶ Nucleosynthesis in the BH-NS merger

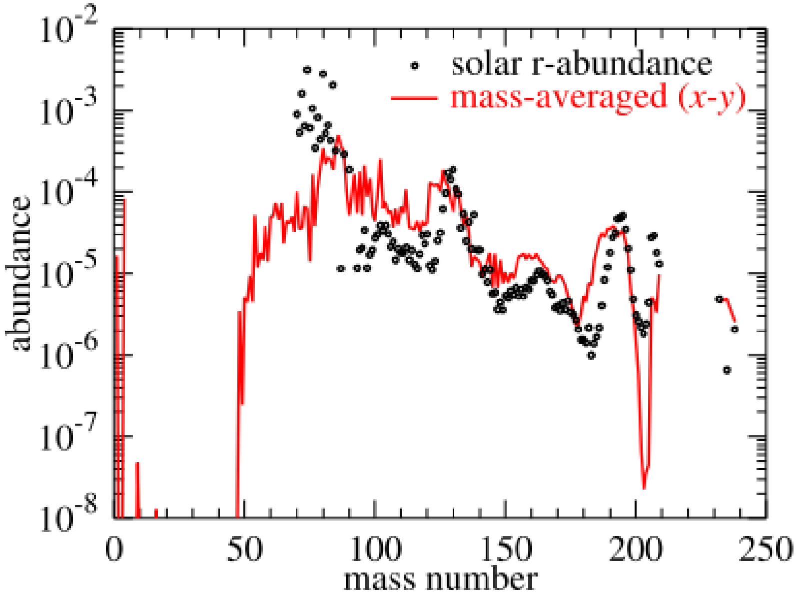
Electron fraction Y_e of the dynamical ejecta is $\lesssim 0.1$

⇒ Reproduce the third peak of the solar abundance

Bauswein et al. 14



Wanajo et al. 14



▶Torus wind is hot ⇒ Y_e would be high due to the weak interaction.

▶ Mixture of the dynamical and wind component could reproduce the solar abundance (BH-NS: Just et al. 15, NS-NS: Sekiguchi et al. 15, Wanajo et al. 14)

Radioactively-powered electromagnetic emission

Heating due to the radioactive decay of R-process elements
⇒ Strong electromagnetic transient (Li & Paczynski 98, Kulkarni 05, Metzger & Berger 12)

Discovery of the excess in the near infrared band in GRB130603B
(Berger et al. 13, Tanvir et al. 13)

A bunch of theoretical models (Kasen et al. 13, Barnes & Kasen 13 , Fernandez & Metzger 13, Tanaka & Hotokezaka 13, Takami et al. 14, Kisaka et al. 15)

▶ The amount of the torus wind mass is larger than that of the dynamical ejecta mass in our model.

⇒ Torus wind component could play a leading part of the radioactively-powered emission in BH-NS mergers.

Summary

▶ We explore the role of B-field in compact binary mergers in numerical relativity.

▶ In BNS merges, strongly magnetized NSs are inevitably formed due to the Kelvin-Helmholtz instability.
The MRI-driven turbulence determines the life-time of the long-lived remnant massive NS.

▶ In BH-NS mergers, the MRI-driven turbulence drives a torus wind formed after the tidal disruption.