京を用いた連星磁場中性子星合体の数値相対論シミュレーション

木内建太（YITP）

Ref.) PRD 90, 041502(R) (2014)

久徳浩太郎 (UWM), 関口雄一郎 (YITP), 柴田大 (YITP), 和田智秀 (筑波技術大)

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

K computer

Motivation

GW detectors

1. Gravitational waves = ripples of the space-time
▶ Verification of GR
▶ The EOS of neutron star matter
▶ The central engine of SGRB
▶~10 events / yr for KAGRA

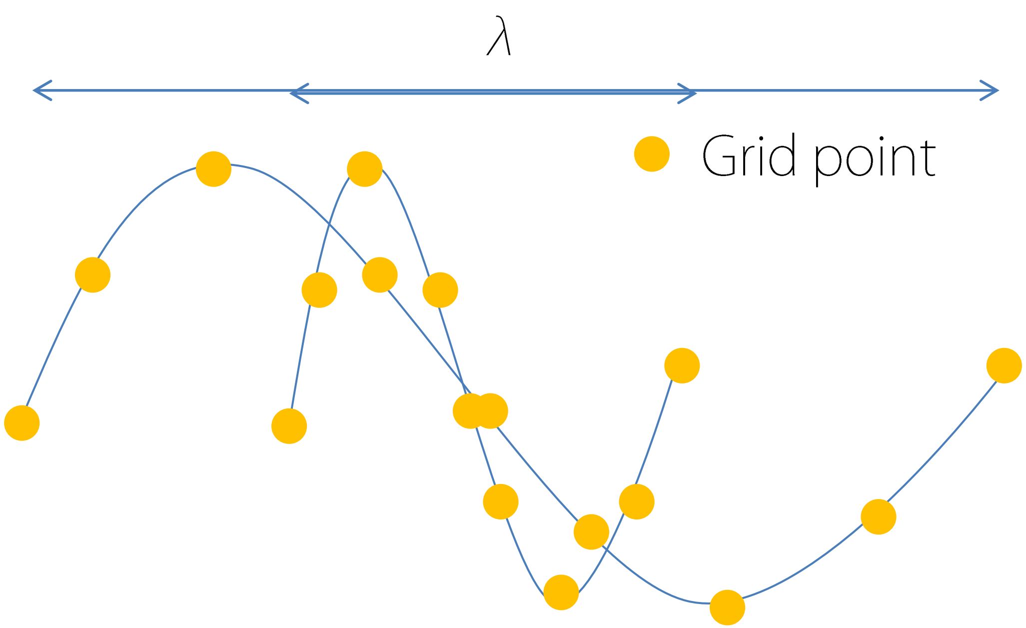
2. A possible site of the r-process synthesis
A significant amount of neutron star matter could be ejected from BNS mergers ($M_{eje} \approx 10^{-4}$-$10^{-2} M_{\odot}$, Hotokezaka et al. 13)
⇒Nuclear synthesis in the ejecta (Lattimer & Schramm 76)

▶ Radio active decay of the r-process elements
▶ Electromagnetic counterpart ＝kilonova (Li-Paczynski 98, Kulkarni 05, Metzger et al. 10, Kasen et al. 13, Barnes-Kasen 13, Tanaka-Hotokezaka 13, Hotokezaka et al. 13, Takami-Nozawa-Ioka 14)
▶ NIR excess in afterglow of GRB130603B (Berger et al.13, Tanvir et al. 13)

A step toward physically reliable model of BNS mergers

Kyoto NR group approaches from two directions;

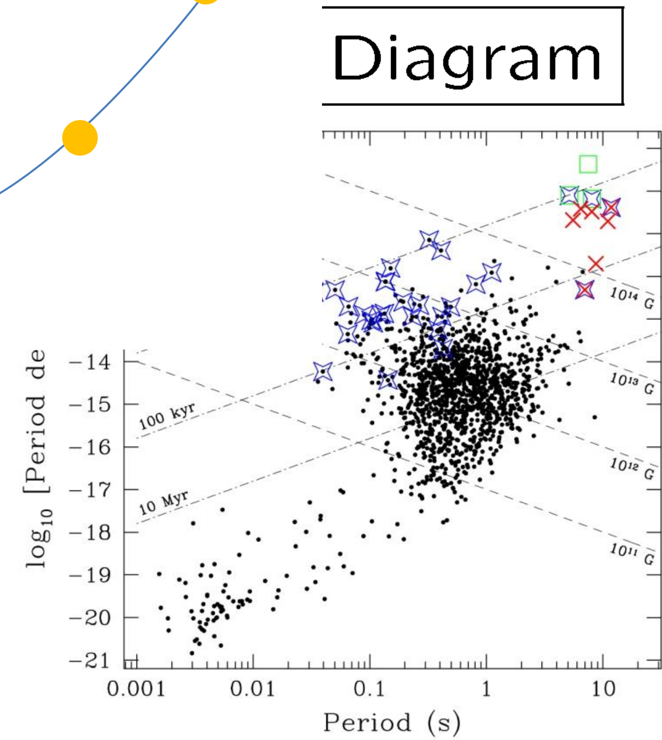
- MHD (KK
- Microphy



Are B-fields
- Observed

The MHD ins
short-wavele

⇒ Necessary
simulation w
range of O(10)km-O(1,000)km.



Japanese supercomputer K @ AICS

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

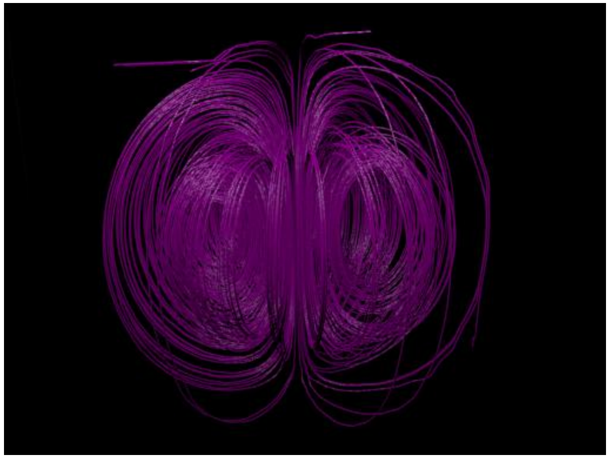
This study is one of the main subject of the HPCI strategic program field 5.

Numerical Relativity simulation of magnetized BNS mergers

▶High resolution Δx=70m （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, Coaserest grid =4480km^3 （N～10^9）, a long term simulation of about 100 ms

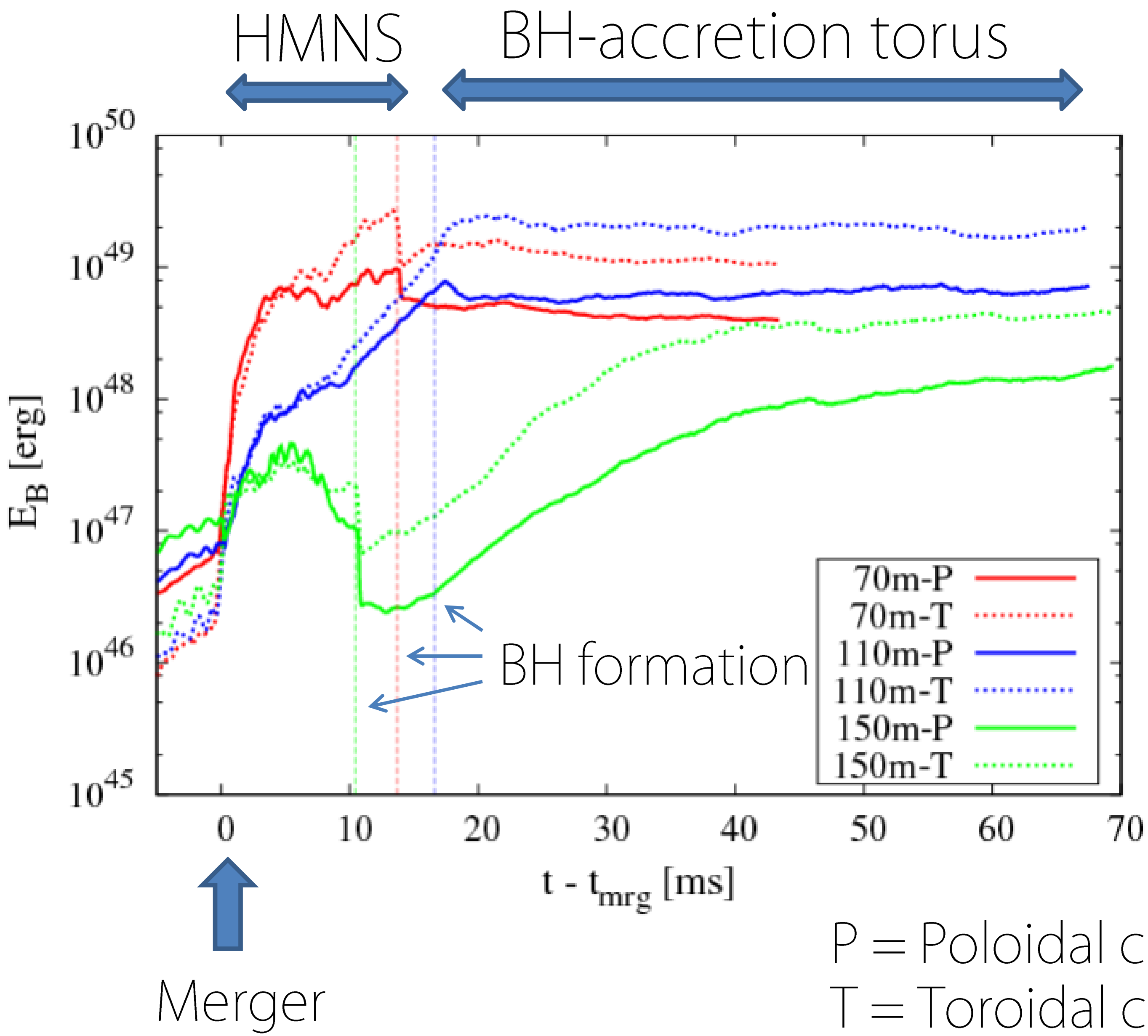
Magnetic field lines of NS



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^{15}G

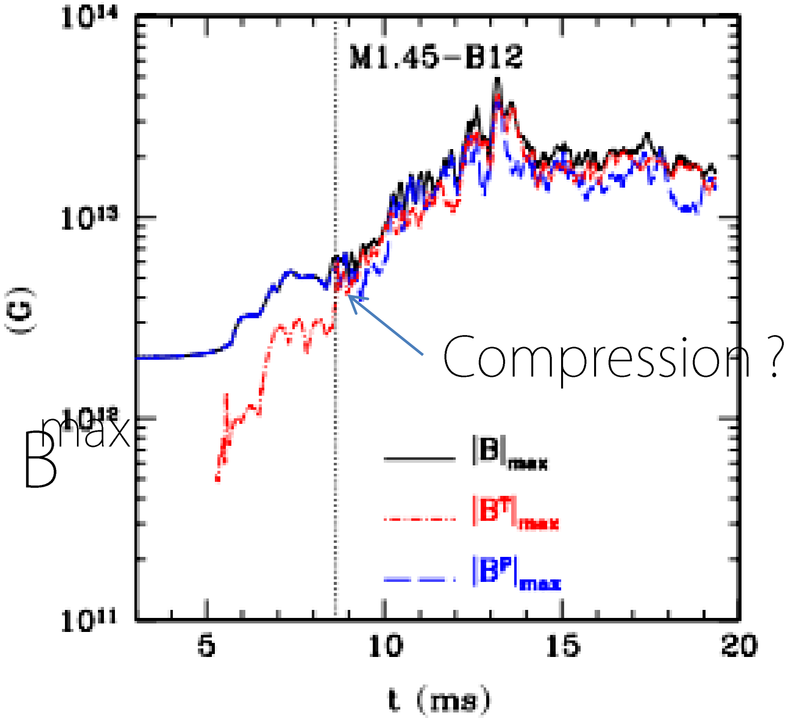
Evolution of the magnetic field energy



P = Poloidal comp.
T = Toroidal comp.

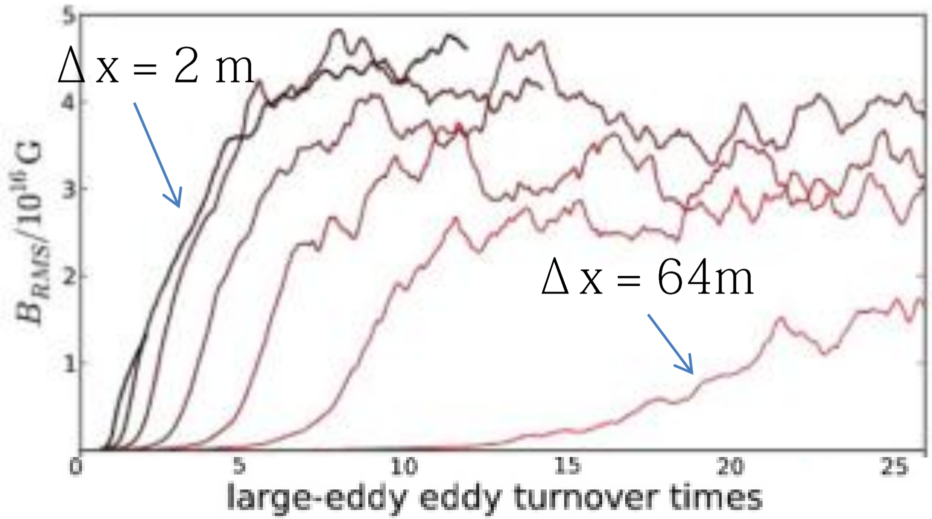
Amplification via KH vortices @ the merger (Rasio and Shapiro 99)

GRMHD by AEI (Giacomazzo et al. 11)



Local box simulation (Zrake and MacFadyen 13, Obergaulinger et al. 10)

Time evolution of <B>

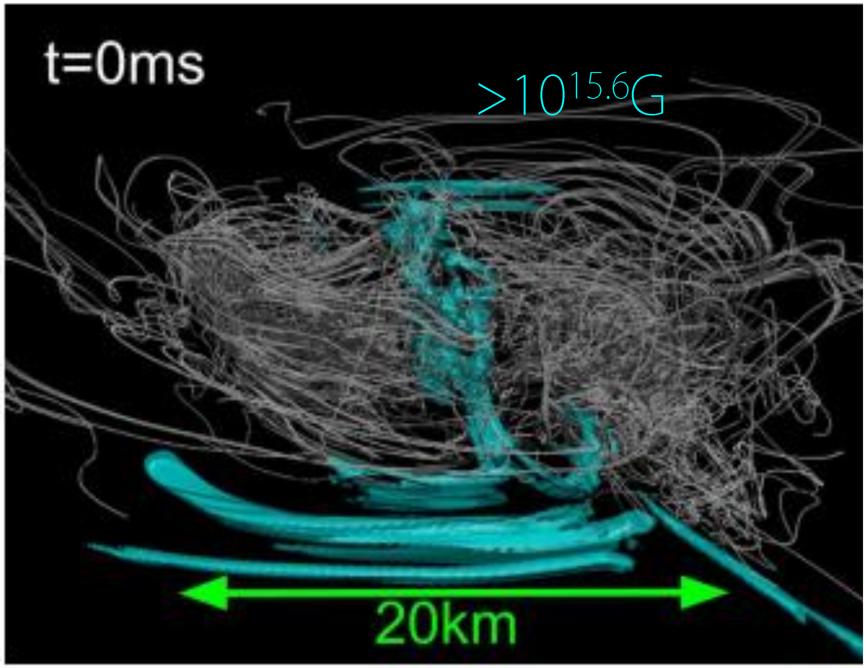


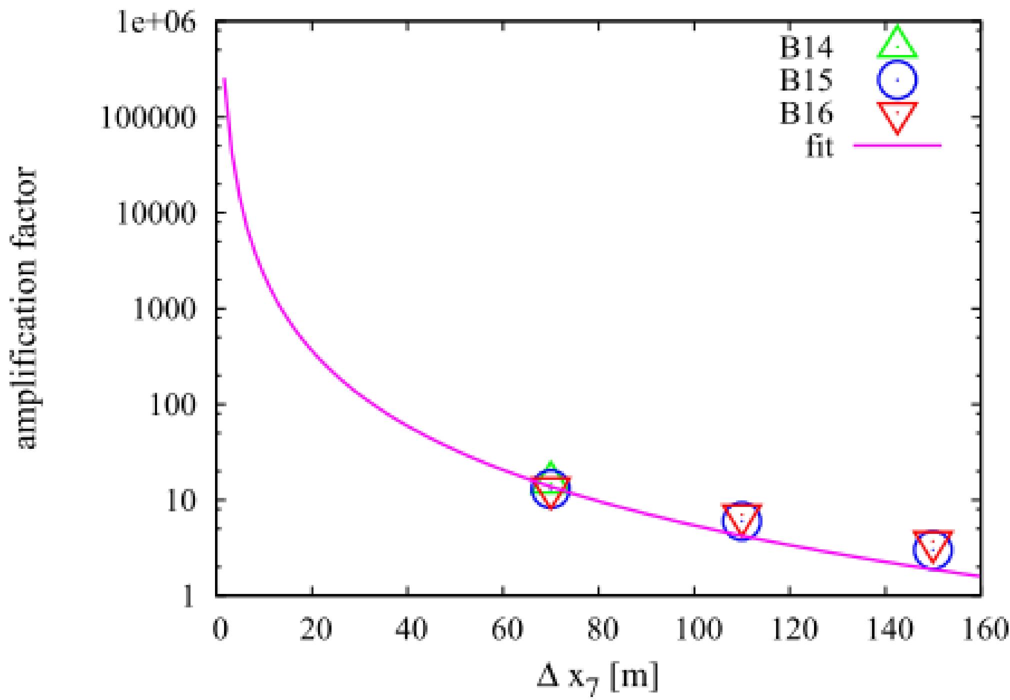
1=0.1ms

Can really the KH vortices amplify the B-fields ?

Yes !

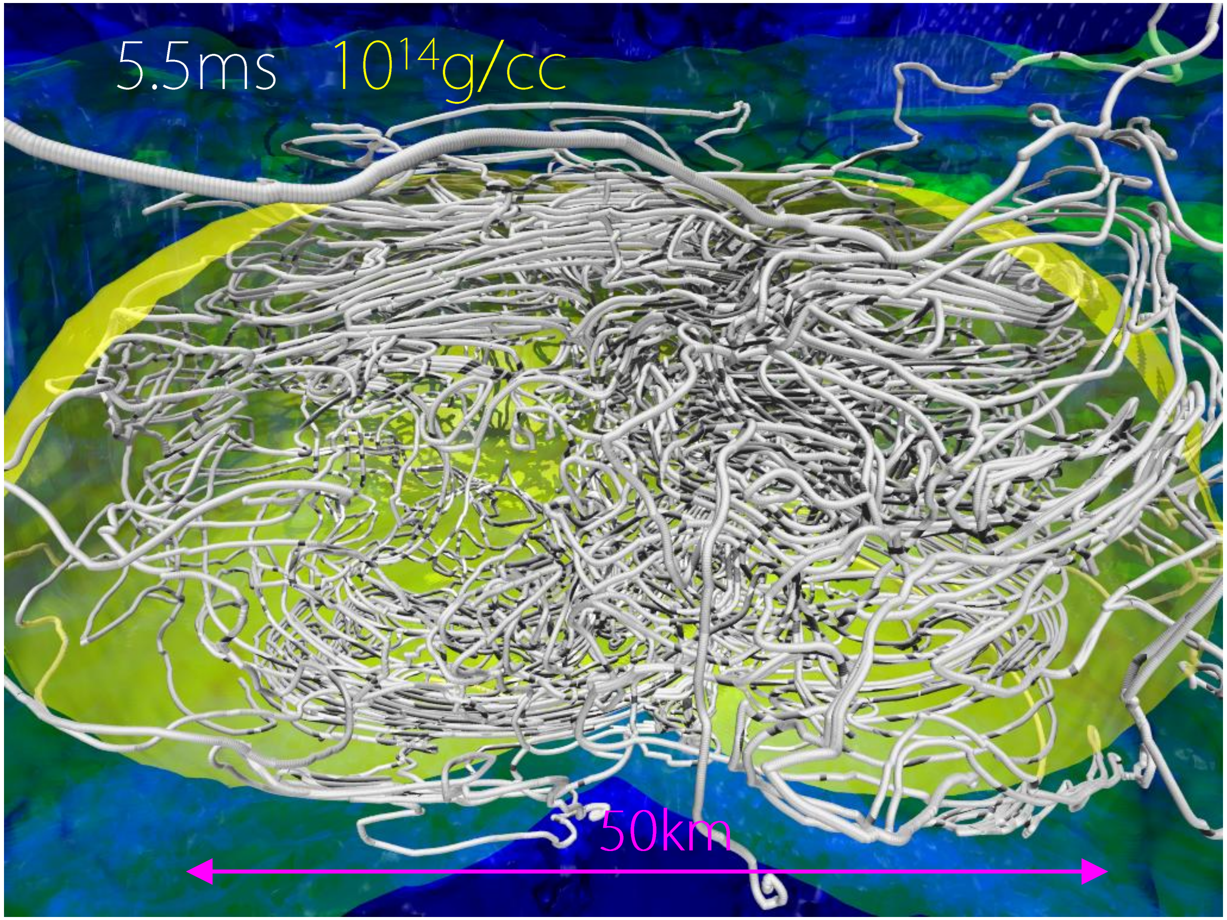
Field lines and strength @ merger   Amplification factor vs resolution





- The smaller Δx is, the higher growth rate is.
- The amplification factor does not depend on the initial magnetic field strength
- It is consistent with the amplification mechanism due to the KH instability. (Obergaulinger et al. 10, Zrake and MacFadyen 13)

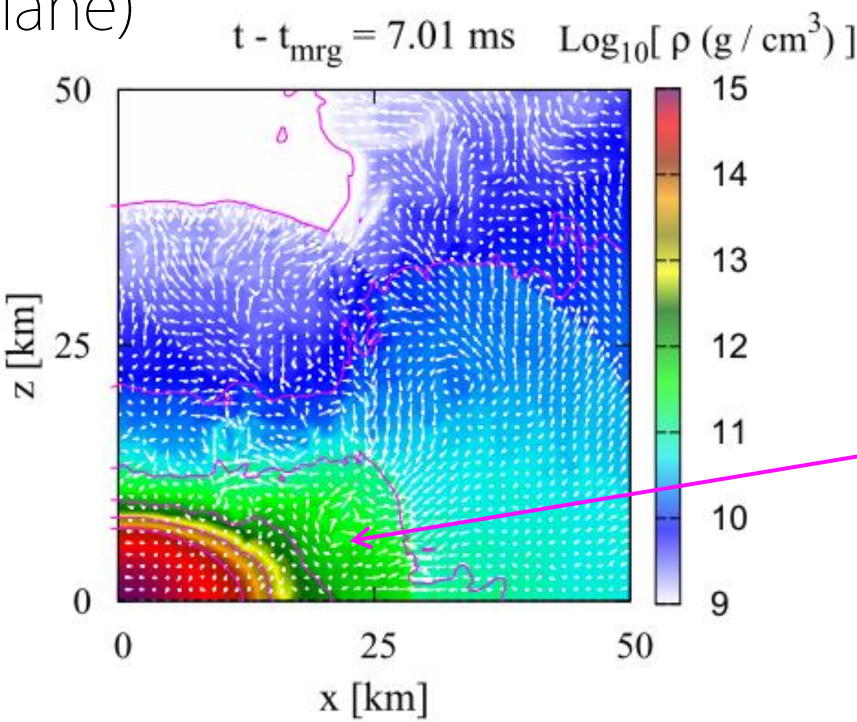
Field lines and density iso-contour inside HMNS



- Turbulent state inside HMNS
- HMNS is differentially rotating ⇒ Unstable against the Magneto Rotational Instability (Balbus-Hawley 92)
- Magnetic winding works as well

B-field amplification inside HMNS

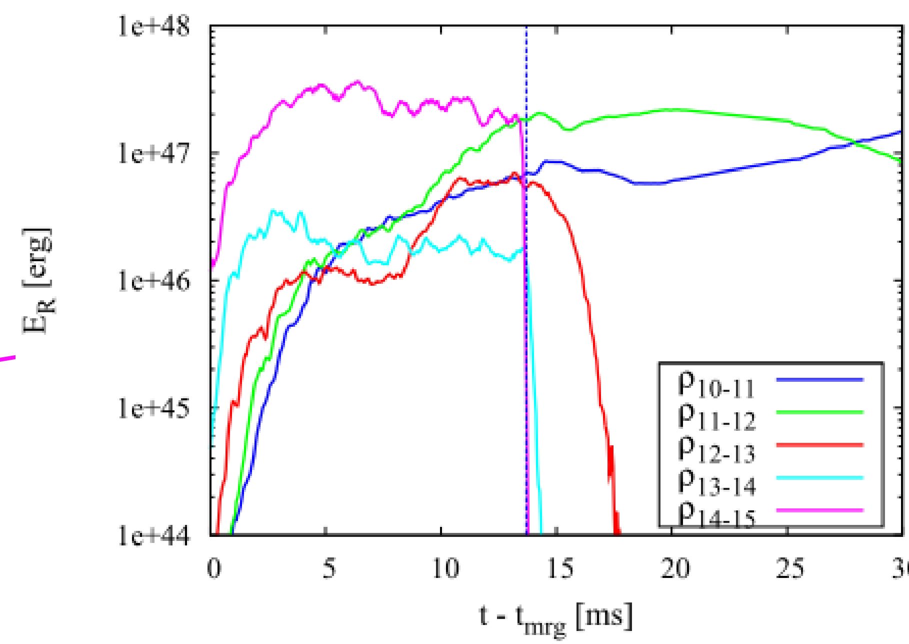
Density contour of HMNS (Meridional plane)



Magnetic field energy inside 10^{11}g/cc ≤ ρ ≤ 10^{12}g/cc

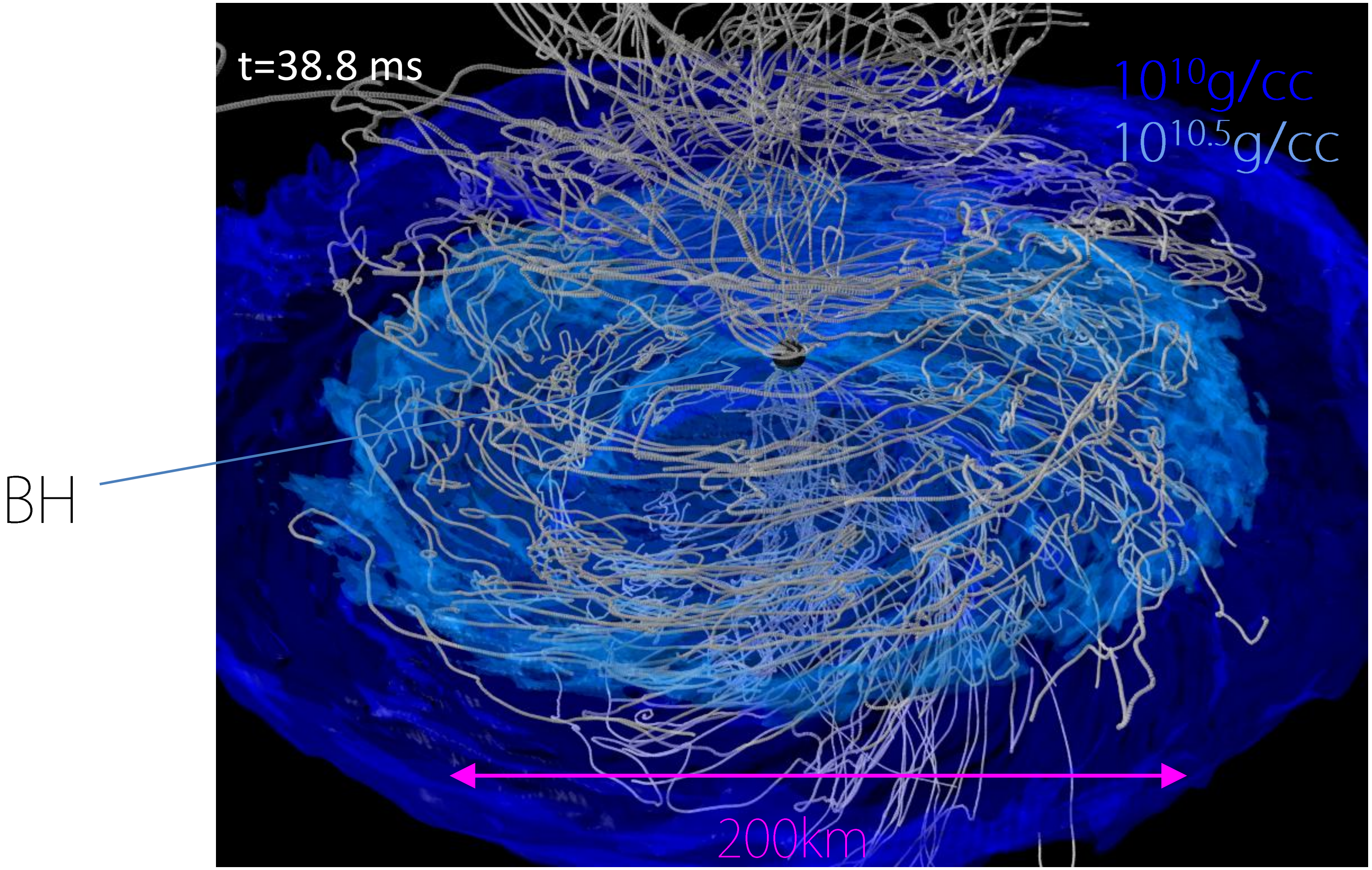
B-fields energy in 10^{a}g/cc ≤ ρ ≤ 10^{a+1}g/cc a=10-14 for high-res. run

BH BH BH



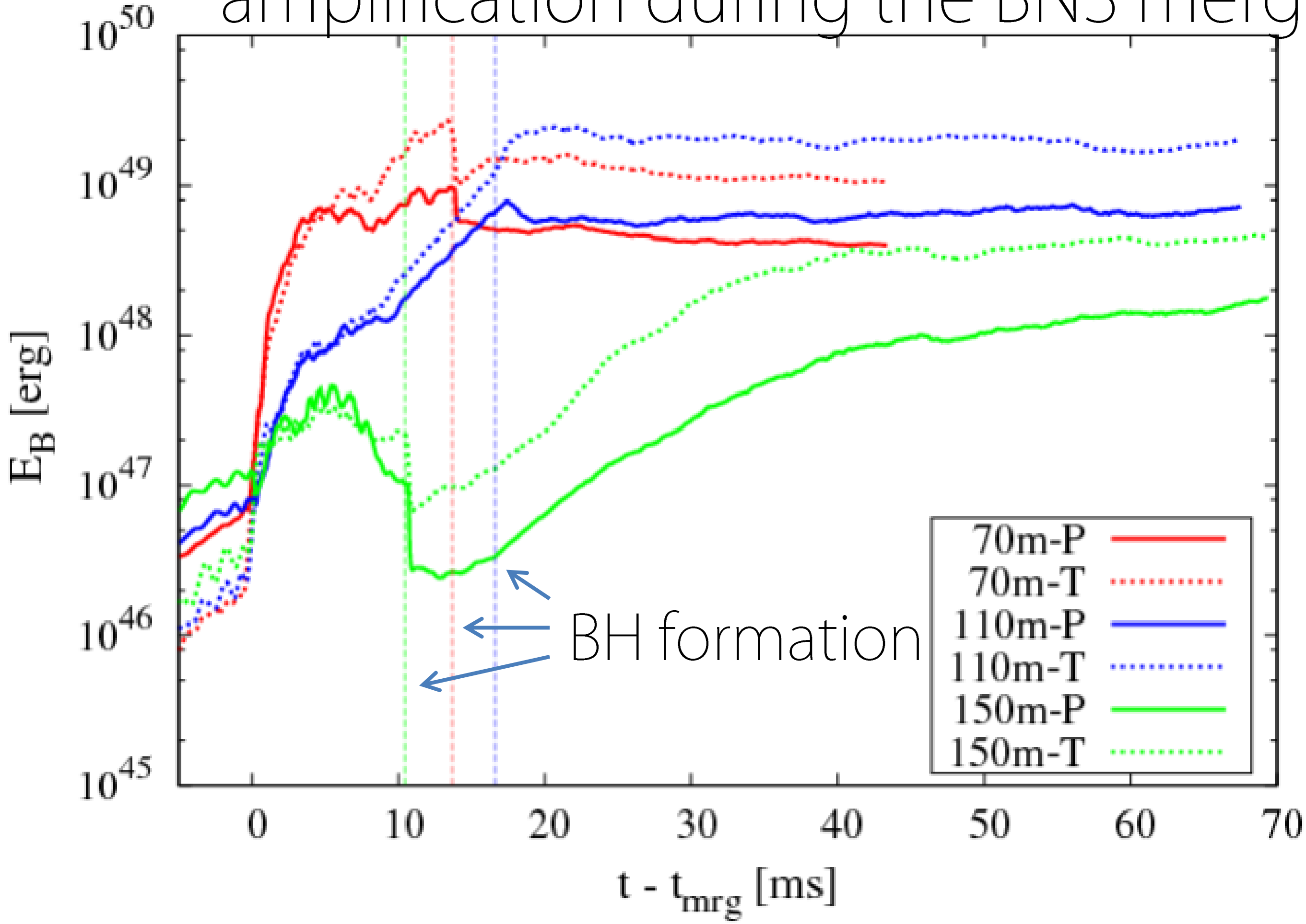
- $\lambda_{MRI} = B/(4\pi\rho)^{1/2}\, 2\pi/\Omega$
- The condition $\lambda_{MRI,\varphi}/\Delta x \gtrsim 10$ is satisfied for the high and medium run, but not in low run. B = Toroidal magnetic field
- Growth rate of B-fields for 8 - 14 ms ≈130-140Hz～O(0.01)Ω
- B-field amplification is cause by the non-axisymmetric MRI (Balbus – Hawley 92)

Black hole—accretion torus



- We have not found a jet launch.
- Ram pressure due to the fall back motion～10^{28} dyn/cm^2(Need 10^{14-15}G in the vicinity of the torus surface)
- Necessity of the poloidal motion to build a global poloidal field

Summary of the magnetic field amplification during the BNS merger



▶KH instability at the merger and MRI inside the HMNS ⇒ Significant amplification of B-fields

▶Low res. run cannot follow this picture ⇒ Amplification inside the BH-torus (picture drawn by the previous works)

Caveats

▶Observation of the BNS ; $B_{dip} = 10^{12.2}$G

▶ We assume that B_{max} is10^{15}G

Criticism ; The magnetic fields chosen correspond to the highest magnetic fields observed for some magnetars. Therefore the present work is still a little academic.

Question ; What's the final value of the amplified magnetic fields ?

▶We are not interested in the magnetar's merger.

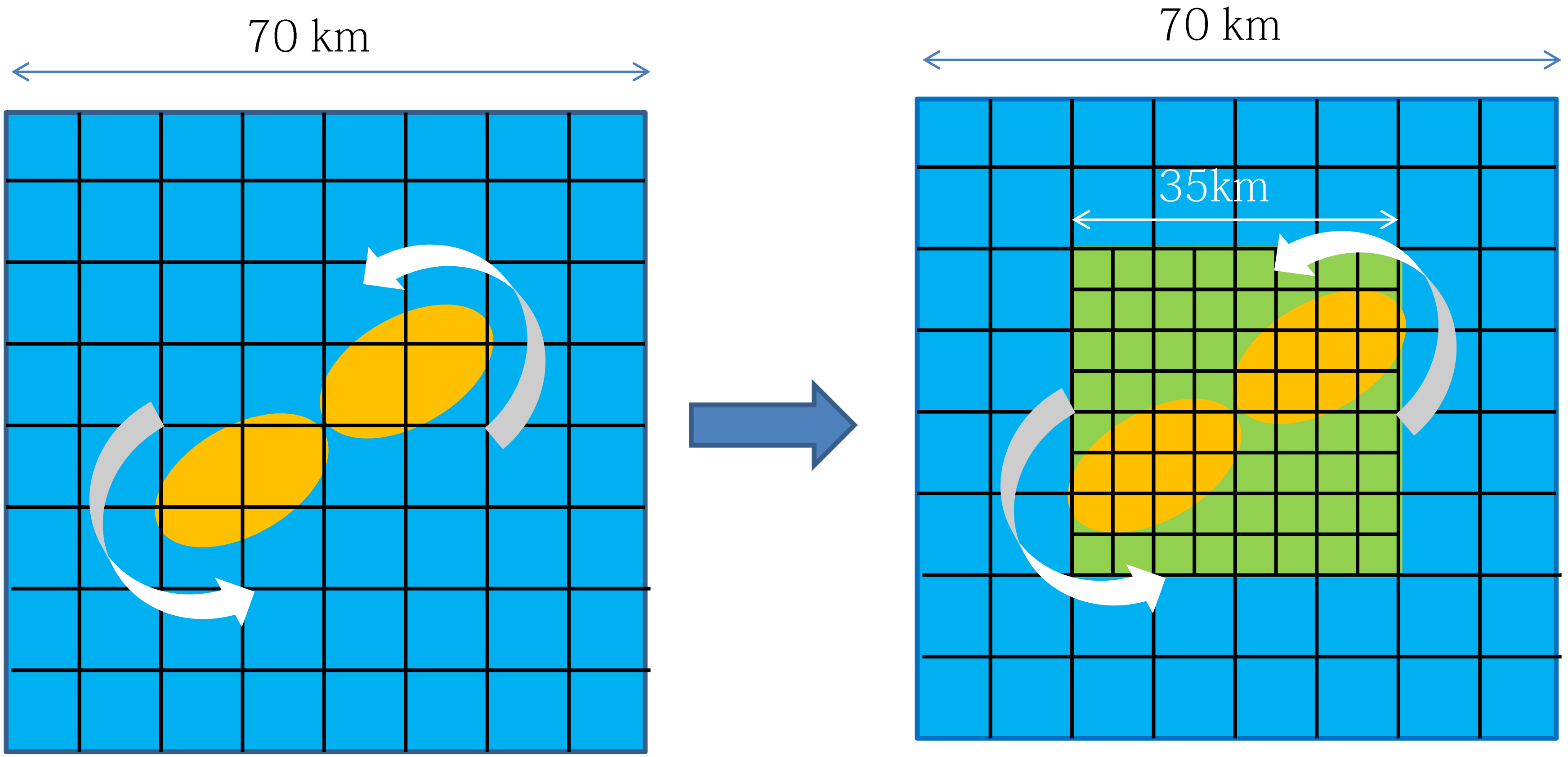
▶If you start a "realistic" value of the magnetic fields, say 10^{13} G, you need more grid resolution. Otherwise, such a simulation will be nonsense.

What's the "realistic" value of the amplified B-fields ?

We are doing higher resolution simulations with "realistic" value of the B-fields.

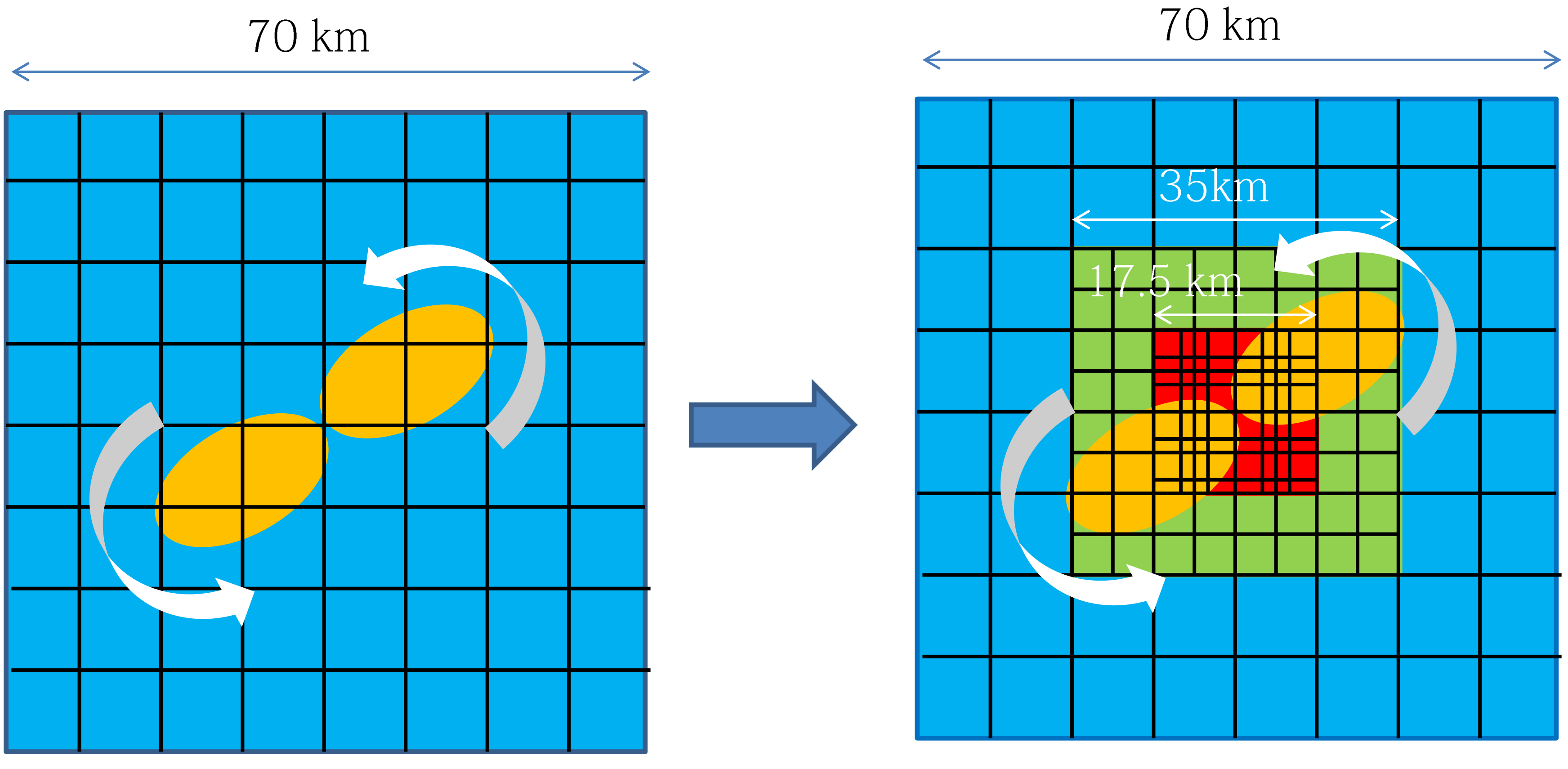
Bridge between global and local simulation

Idea： Just before the merger, we increase the FMR box. The simulation time is about 5 ms.
cf. The size of the shear-layer is ～20km.



Bridge between global and local simulation

Idea： Just before the merger, we increase the FMR box. The simulation time is about 5 ms.
cf. The size of the shear-layer is ～20km.



B-fields amplification via Kelvin-Helmholtz

Model

- ▶ 1.4-1.4$M_\odot$ and H4
- ▶ Start from a quasi equilibrium of a non-magnetized BNS and stop at $\alpha_{min} \approx 0.638$.
- ▶ Add the B-fields by hand and increase refinement boxes. The "realistic value" of $B_{max} \approx 10^{13}$G.
- ▶ 9 models

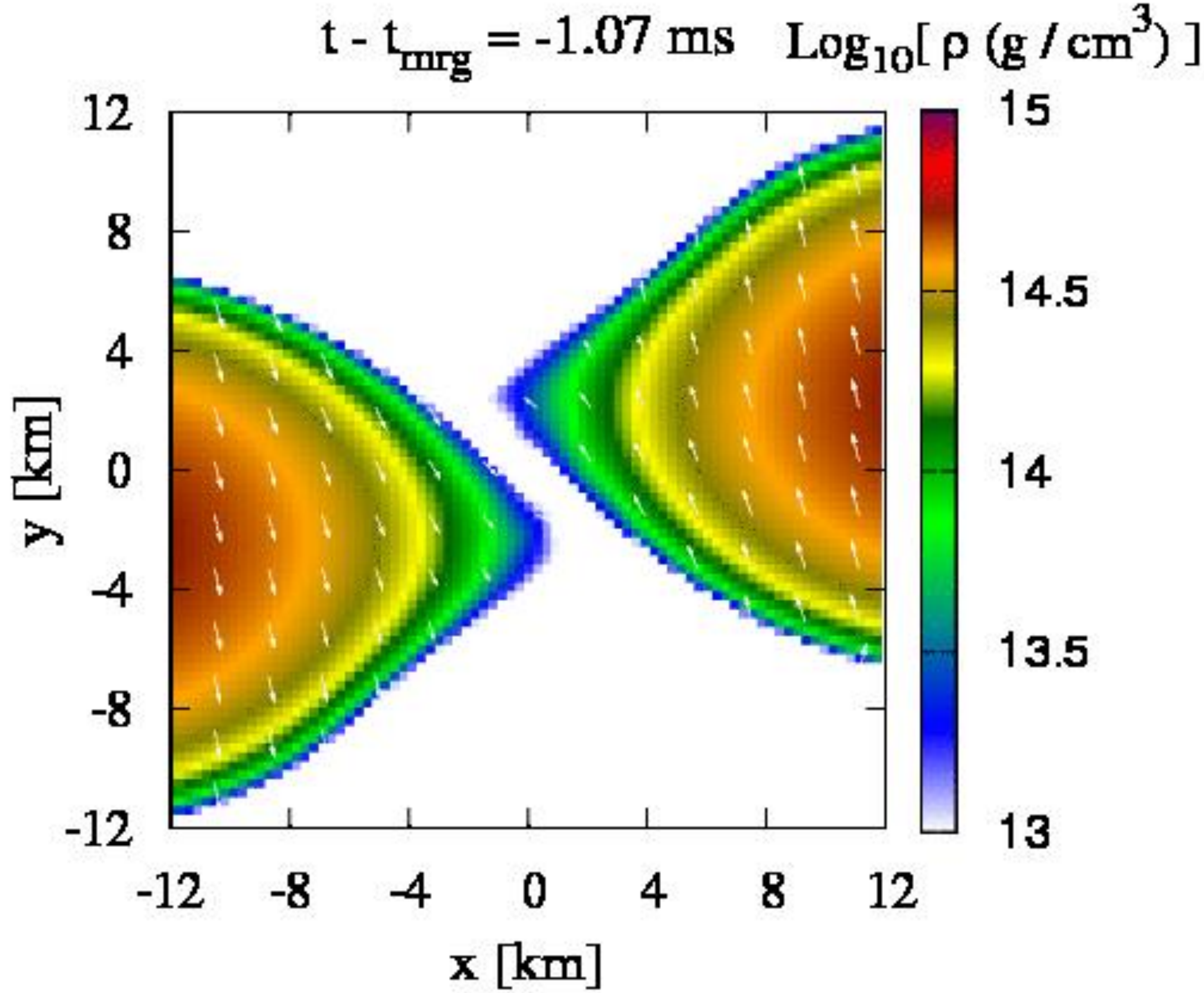
(ia) $\Delta x = 150$m ; no increase the FMR box
(ib) $\Delta x = 150$m $\Rightarrow$ 75m ; one FMR box is added
(ic) $\Delta x = 150$m $\Rightarrow$ 75m $\Rightarrow$ 37.5m ; two FMR boxes are added

(iia) $\Delta x = 110$m ; no increase the FMR box
(iib) $\Delta x = 110$m $\Rightarrow$ 55m ; one FMR box is added
(iic) $\Delta x = 110$m $\Rightarrow$ 55m $\Rightarrow$ 27.5m ; two FMR boxes are added

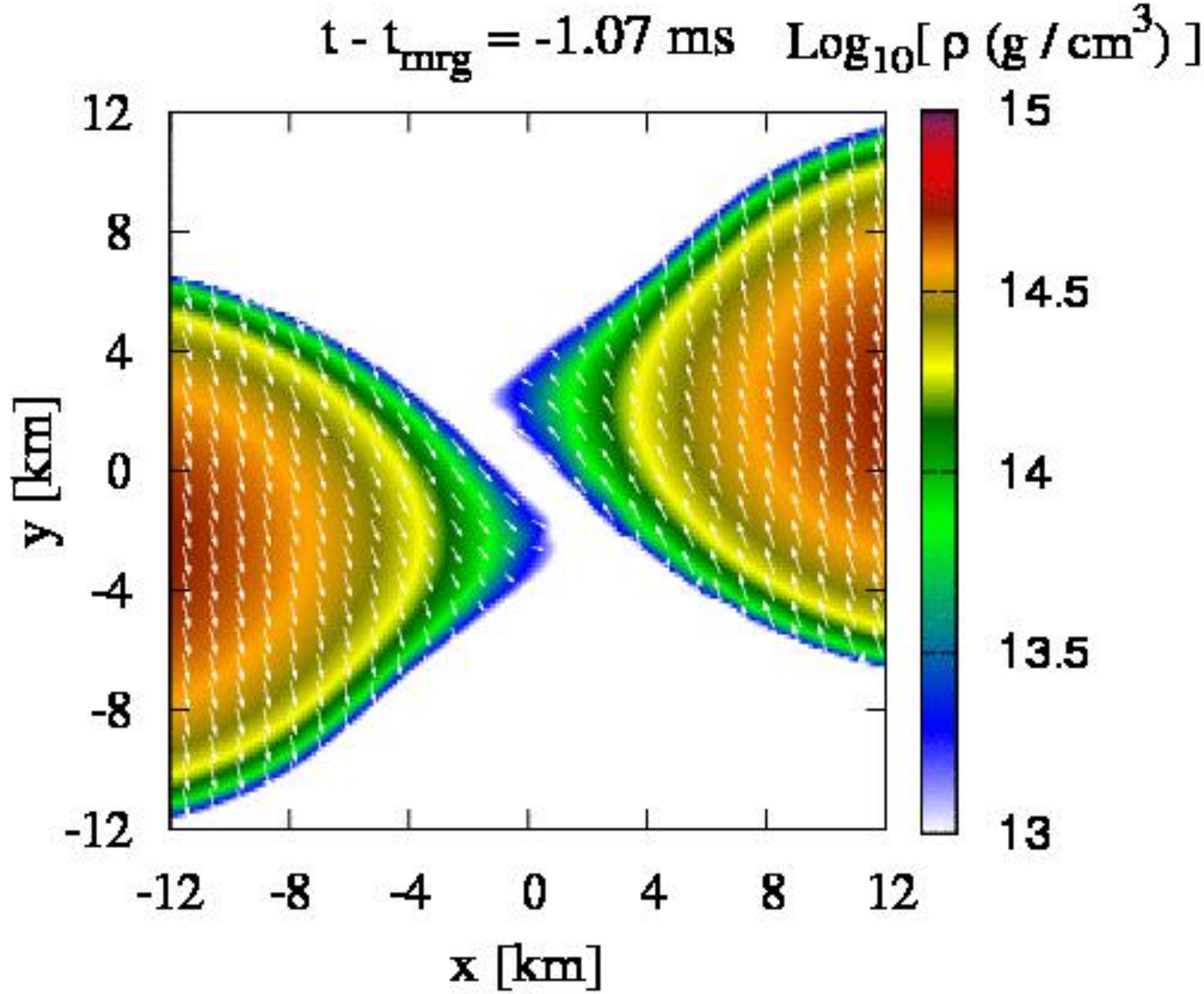
(iiia) $\Delta x = 70$m ; no increase the FMR box
(iiib) $\Delta x = 70$m $\Rightarrow$ 35m ; one FMR box is added
(iiic) $\Delta x = 70$m $\Rightarrow$ 35m $\Rightarrow$ 17.5m ; two FMR boxes are added

In all the models, the finest box size before the merger is about 70 km.

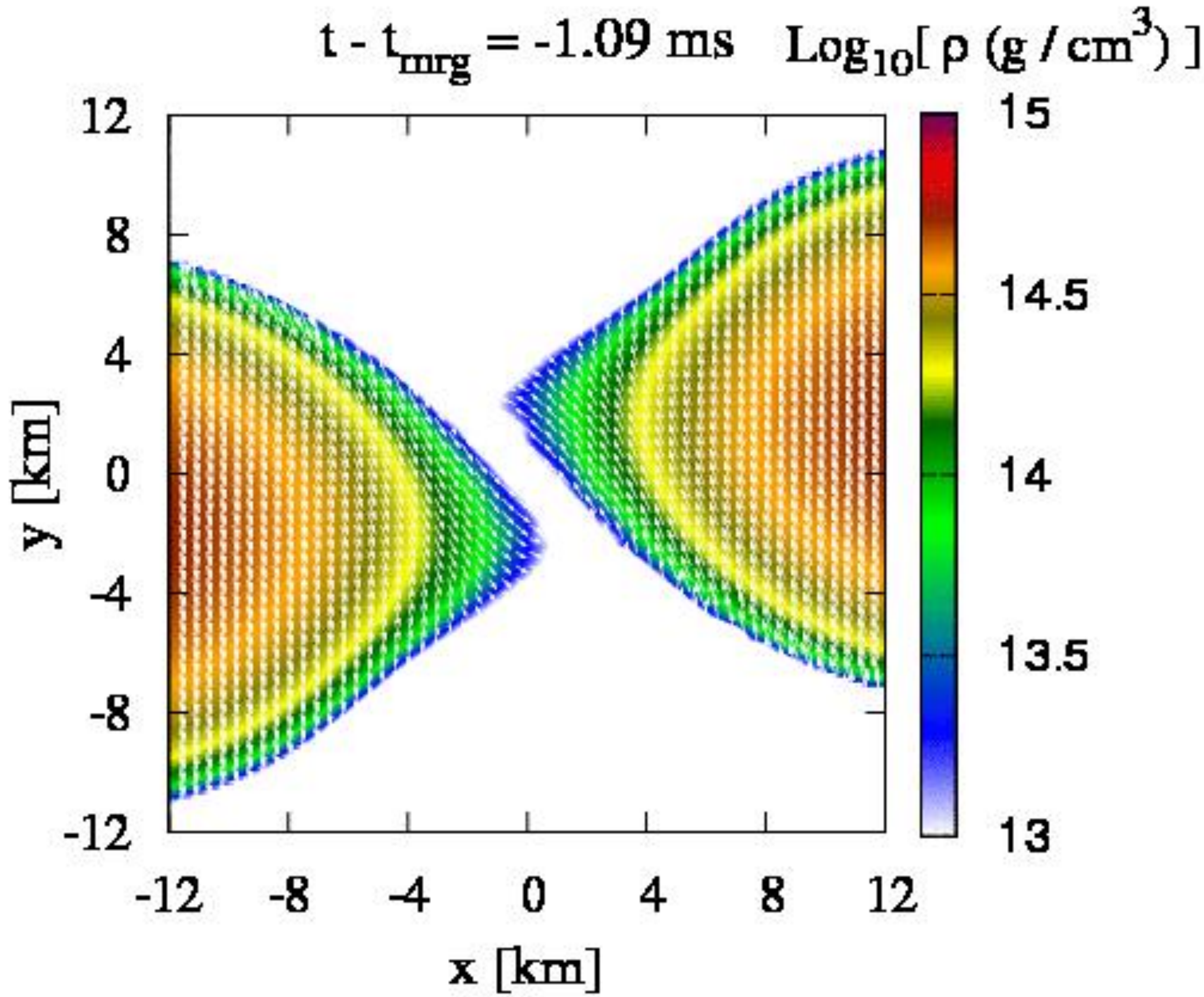
Density and vel. field on the orbital plane (Δx=150m)



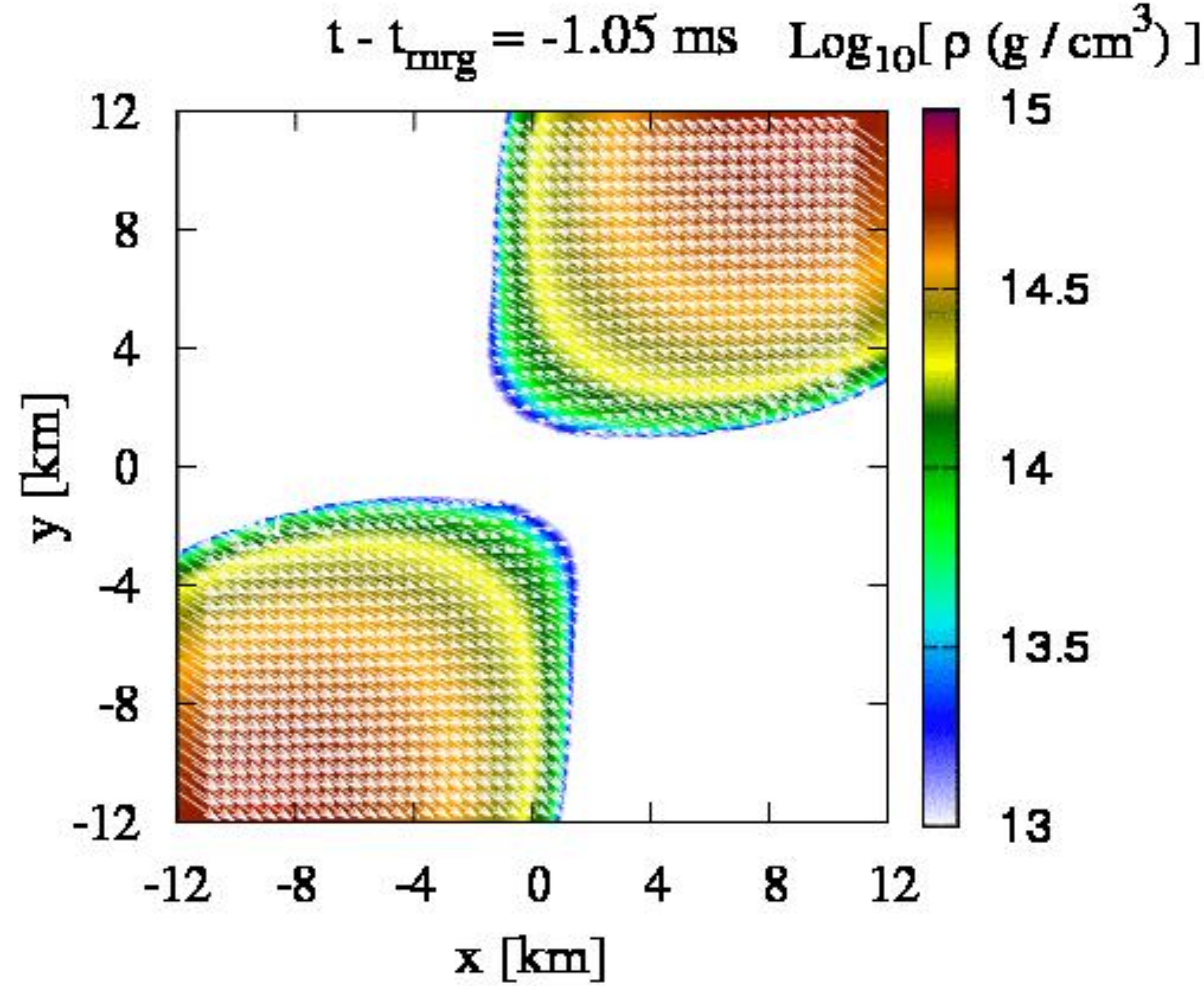
Density and vel. field on the orbital plane (Δx=150m→75m)



Density and vel. field on the orbital plane
(Δx=150m→75m→37.5m)

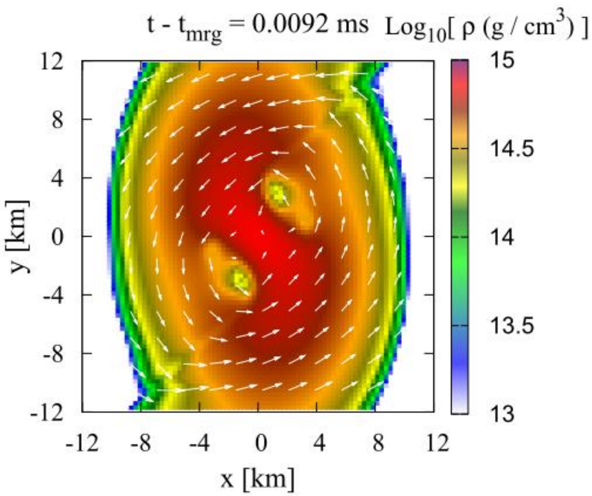


Density and vel. field on the orbital plane (Δx=70m→35m→17.5m)

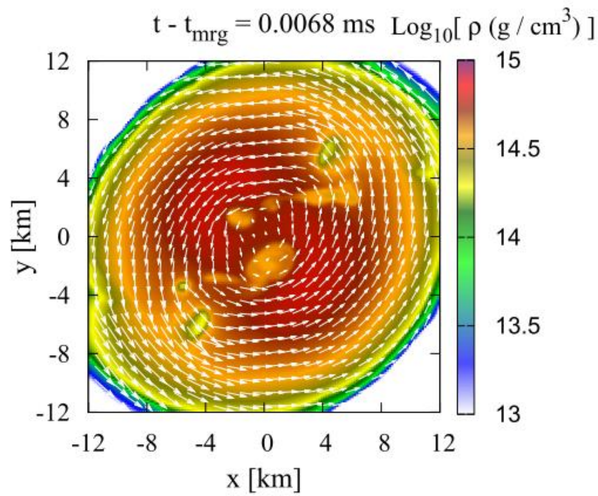


Density and vel. field on the orbital plane

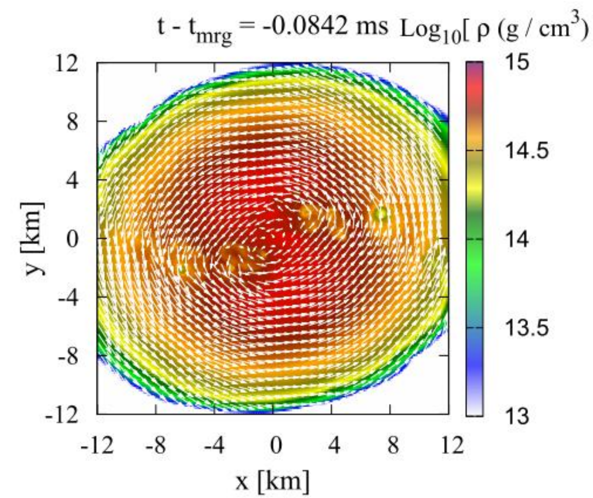
(Δx=150m)



(Δx=150m→75m)



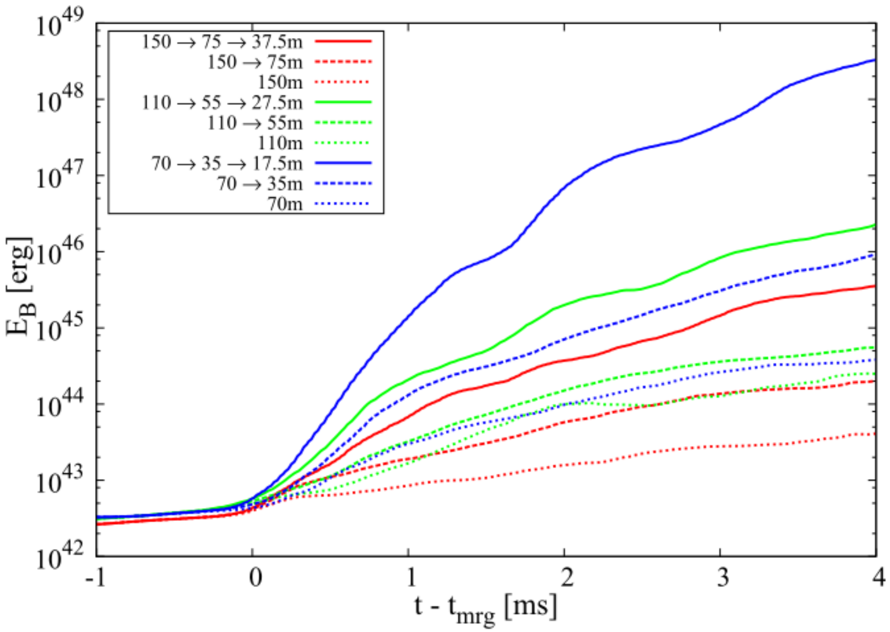
(Δx=150m→75m→37.5m)



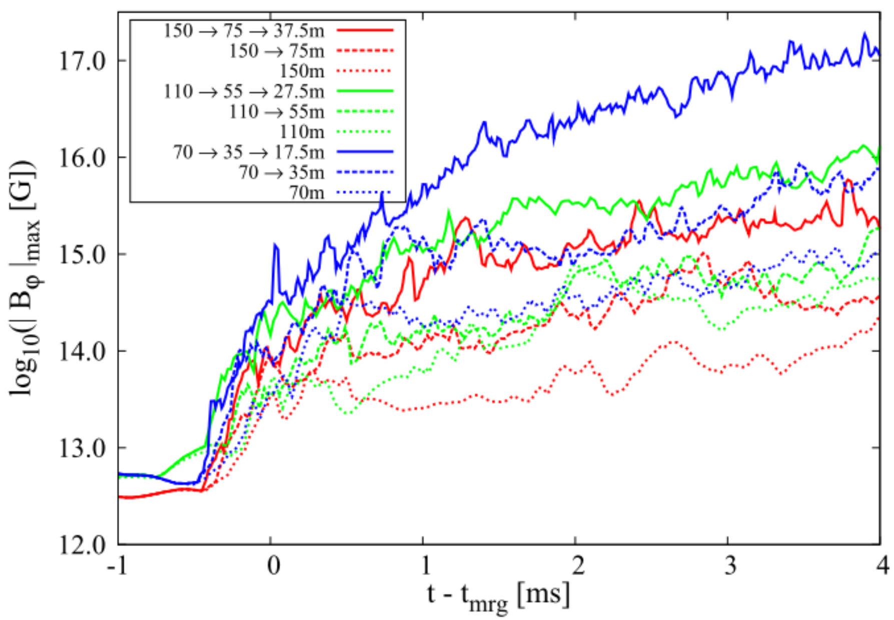
Real

Result (Preliminary)

Magnetic field energy evolution



Maximum field evolution



▶ Still, the amplification is determined by the resolution.

▶ Maximum field is almost virial value, which is comparable to the kinetic energy; i.e., ~10^{17}G.

▶ The magnetic field energy is amplified 10^6 times at least. ; The averaged value of the B-fields is amplified by 10^3 times.

Question ?

▶Angular momentum transport by Reynolds / Maxwell stress ?

▶What happens if the B-fields are dissipated ?

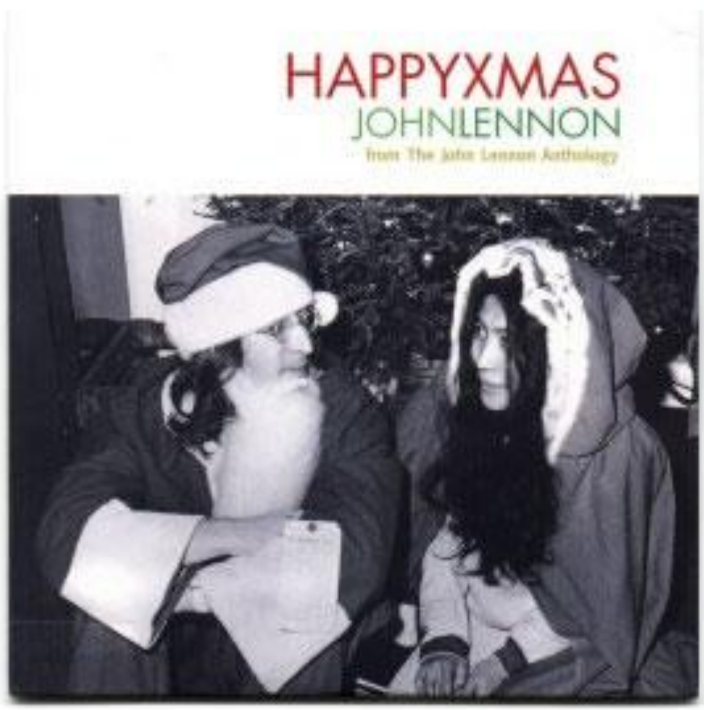
Summary

We have performed a highest resolution simulation of magnetized binary neutron star merger simulation in the framework of Numerical Relativity.

▶ Kelvin-Helmhc … er

▶ Non-axisymme … nassive neutron star

are key ingredier …



The accretion toı … at its birth.

⇒ Qualitatively c … vious works

<u>Caveats</u>

If you start more … netic fields, say 10^{11} G,

you need more ç … such a simulation will

be nonsense.

▶ Necessity to launch an outflow to build a global poloidal magnetic field.