# Magnetized binary neutron star merger simulation on K

Kenta Kiuchi (YITP)

Collabotarion with Koutarou Kyutoku (UWM), Yuichiro Sekiguci (YITP), Masaru Shibata (YITP), Tomohide Wada (NAOJ)

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

京 K computer

$= 10^{16}$
$= 10$ Peta

# Motivation


KAGRA will be in operation in Dec. 2015

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

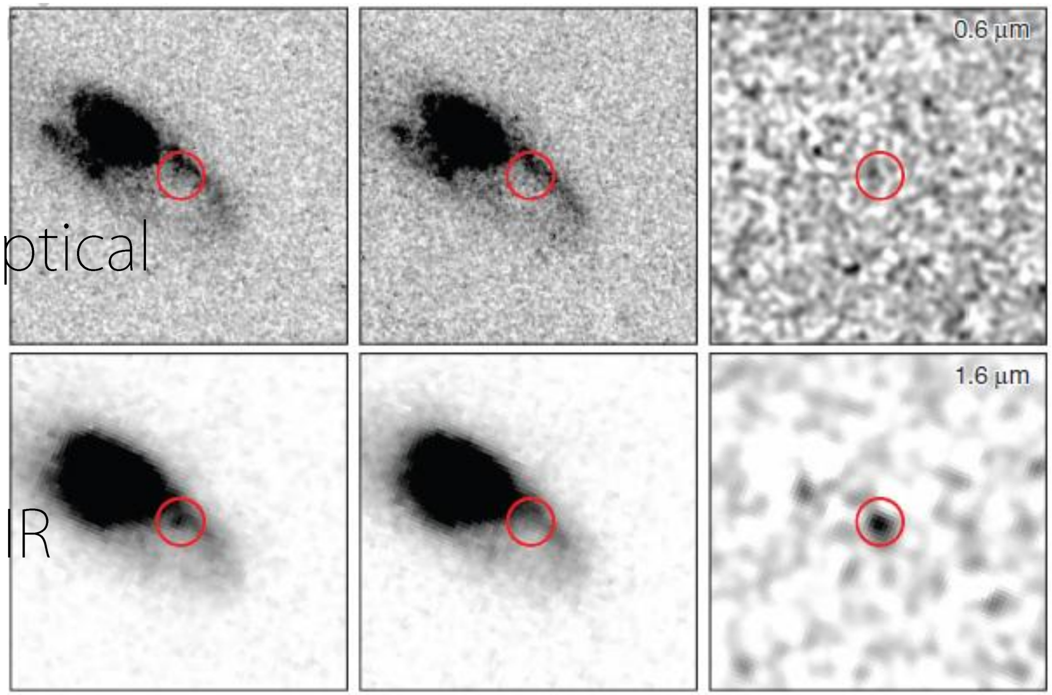
Electromagnetic counterpart ＝kilonova (Li-Paczynski 98, Kulkarni 05, Metzger+10, Kasen et al. 13, Barnes-Kasen 13, Tanaka-Hotokezaka 13)

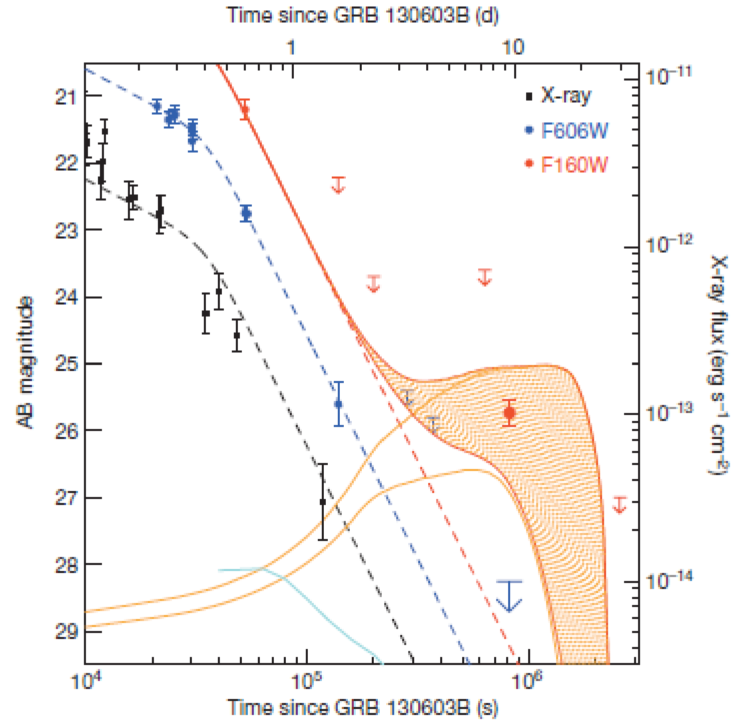
# GRB130603B as a macronova/kilonova event ?

(Berger et al.13, Tanvir et al. 13)

9 days after the burst

30 days after the burst




Point source in NIR, not in optical band ⇒ Transient point source in NIR

If a BNS merger drives this SGRB, $M_{eje} \approx 10^{-2} M_{\odot}$ (Hotokezaka et al.13)

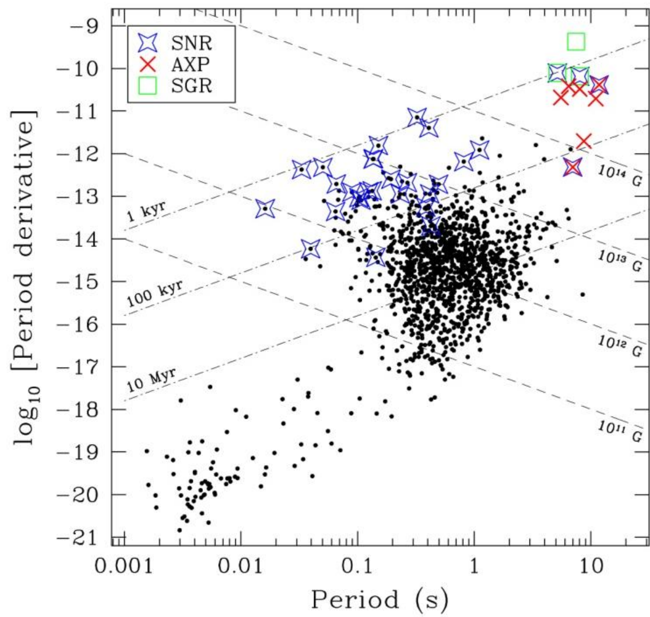
Kyoto NR group approaches from two directions;

- MHD (KK et al. 14)
- Microphysics (Sekiguchi et al. 11a, 11b)

Why B-fields ?

- Observed magnetic field of the pulsars is $10^{11}$-$10^{13}$ G
- The existence of the magnetar, c.f. $10^{14}$-$10^{15}$ G

$P - \dot{P}$ Diagram




The short-wavelength mode is essential for the MHD instabilities which could activate during BNS merger.

⇒ Necessary to perform a high-resolution simulation which covers a large dynamical range of O(10)km-O(1,000)km.

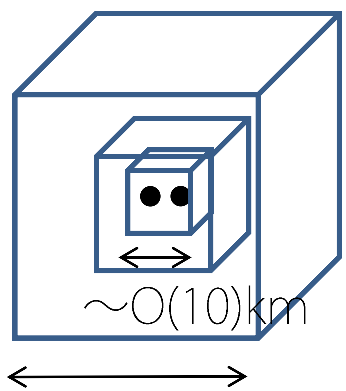
# Japanese supercomputer K @ AICS


- 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.

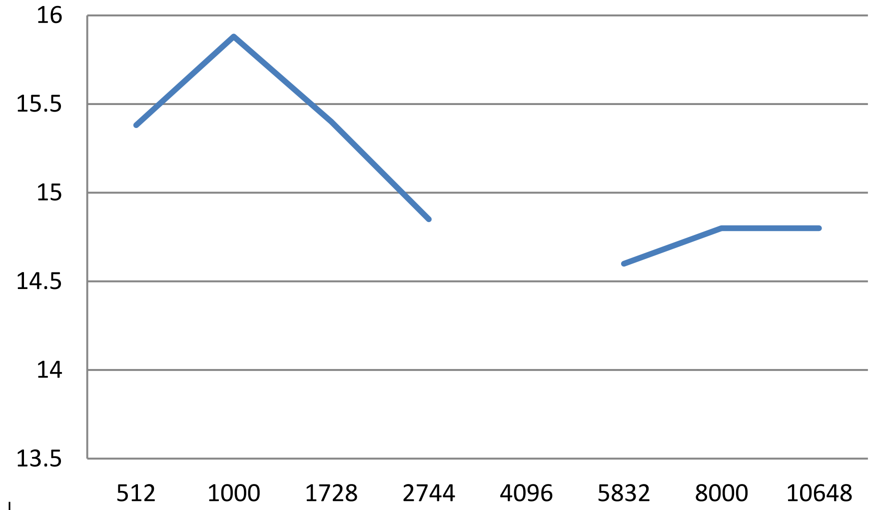
# Outline of numerical relativity-MHD code

Nested grid (KK et al12)




O(1000) km ≳ GW length~several 100 km

Execution performance (%) (Weak scale)

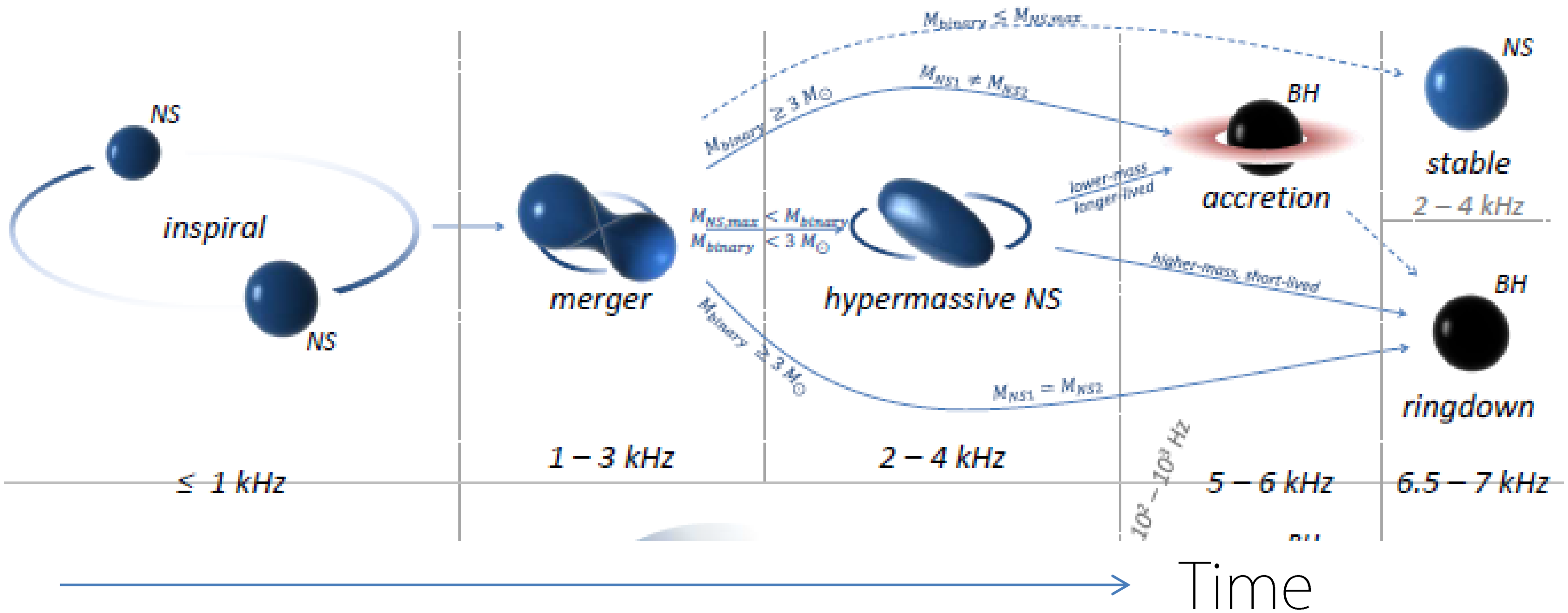



Node number (core ＝8×node)

- Time step is limited by the speed of light
- Interpolation of B-fields on the refinement boundary is non-trivial：Flux conservation and Div B = 0 (KK et al 12, Balsara 01)
- Larger B/F
- MPI communication rule is complicated, e.g., refinement boundary
- Good scaling up to about 80,000 cores

# Overview of BNS mergers

(Bartos et al. 13)




▶Lower limit of the maximum mass of neutron star is about $2M_\odot$ (Antoniadis+13)

▶Observed mass of the BNSs 2.6-2.8$M_\odot$ (Lattimer & Prakash 06)

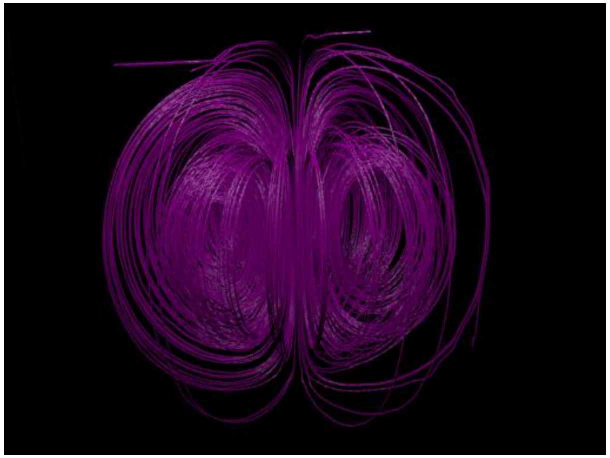
⇒ It is a “realistic” path that a BH-torus is formed via hypermassive NS (HMNS) collapse.

# Numerical Relativity simulation of magnetized BNS mergers

▶High resolution $\Delta x$=70m （16,384 cores on K)
▶Medium resolution $\Delta x$=110m （10,976 cores on K)
▶Low resolution $\Delta x$=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)

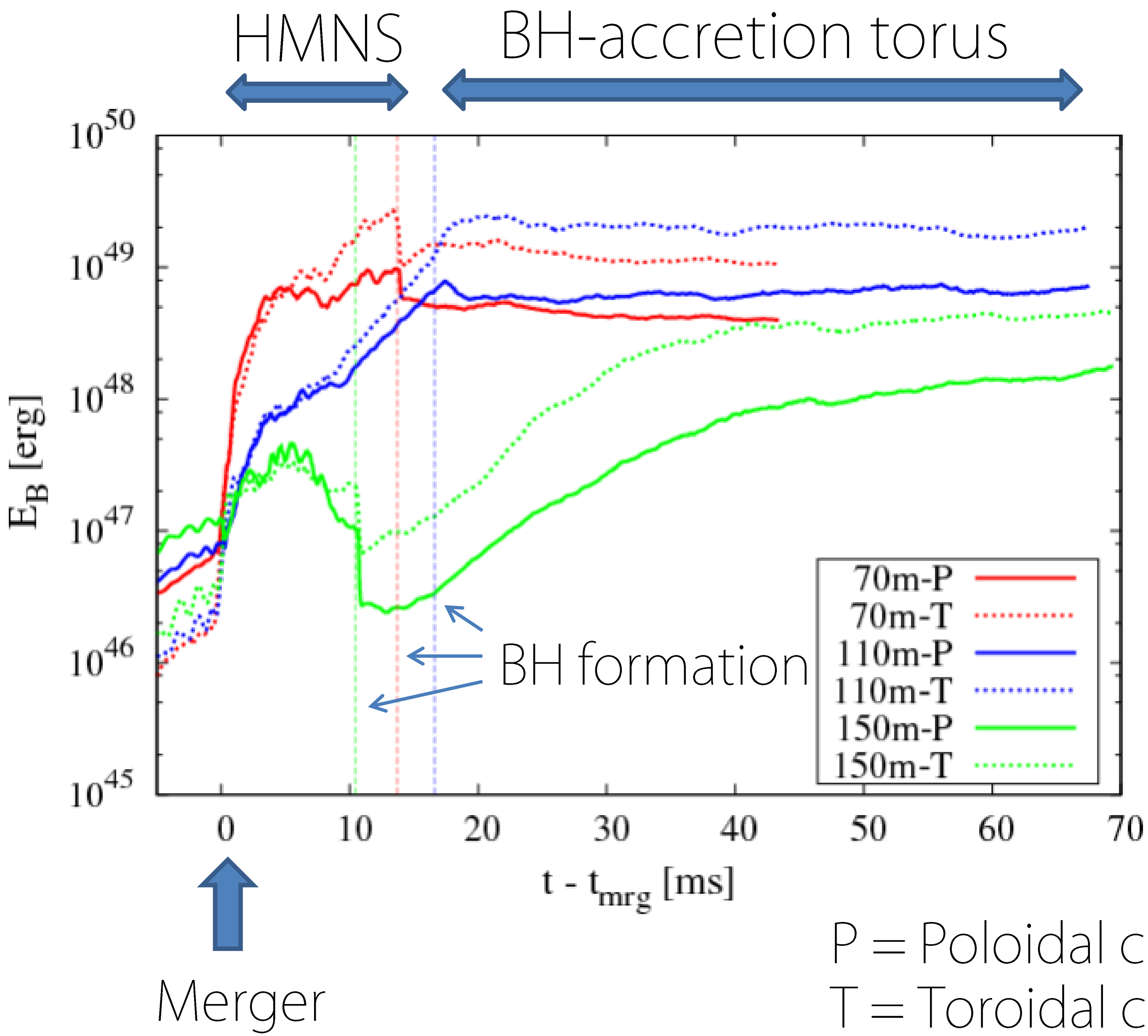
Nested grid ⇒ Finest box=70km$^3$, Coaserest grid =4480km$^3$ （N～10$^9$） , a long term simulation of about 100 ms

Magnetic field lines of NS



<u>Fiducial model</u>
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

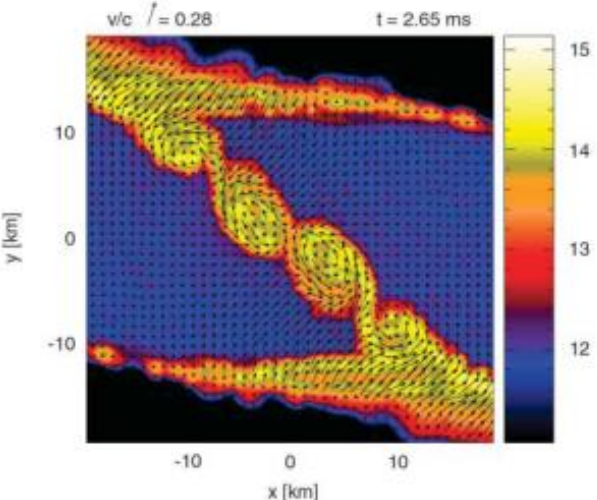


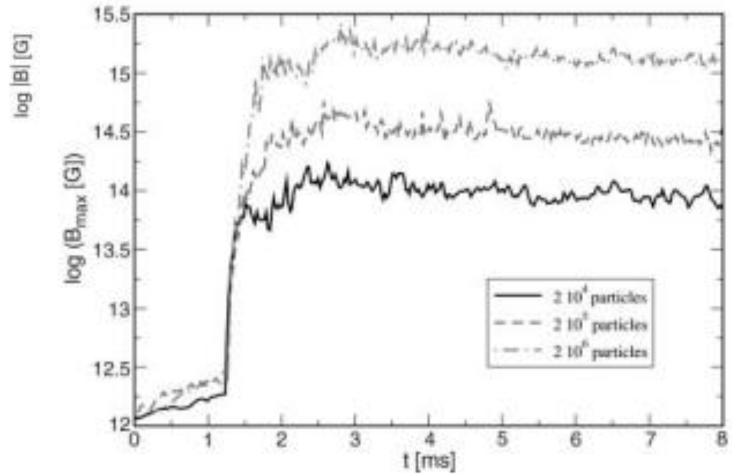

P = Poloidal comp.
T = Toroidal comp.

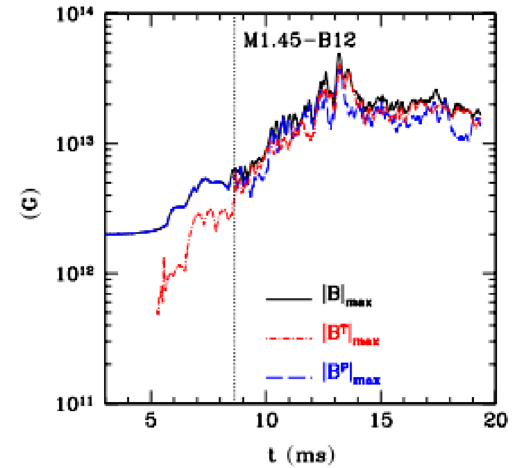
# Magnetic field amplification @ merger (Rasio-Shapiro 99, Price-Rosswog 06, Liu et al. 08, Anderson et al. 08, Giacomazzo et al. 11)

Price-Rosswog 06

Evolution of $B_{max}$




Newtonian SPH

GRMHD

Giacomazzo et al.11

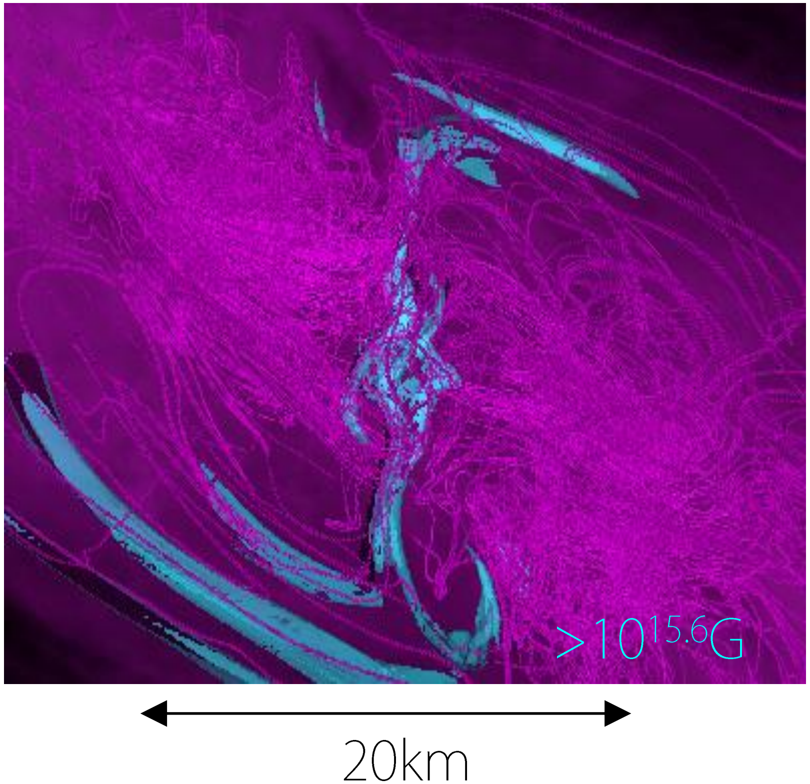
<u>Binary neutron star mergers</u>

▸ The vortices produced by Kelvin Helmholtz instability
⇒Amplification of magnetic field

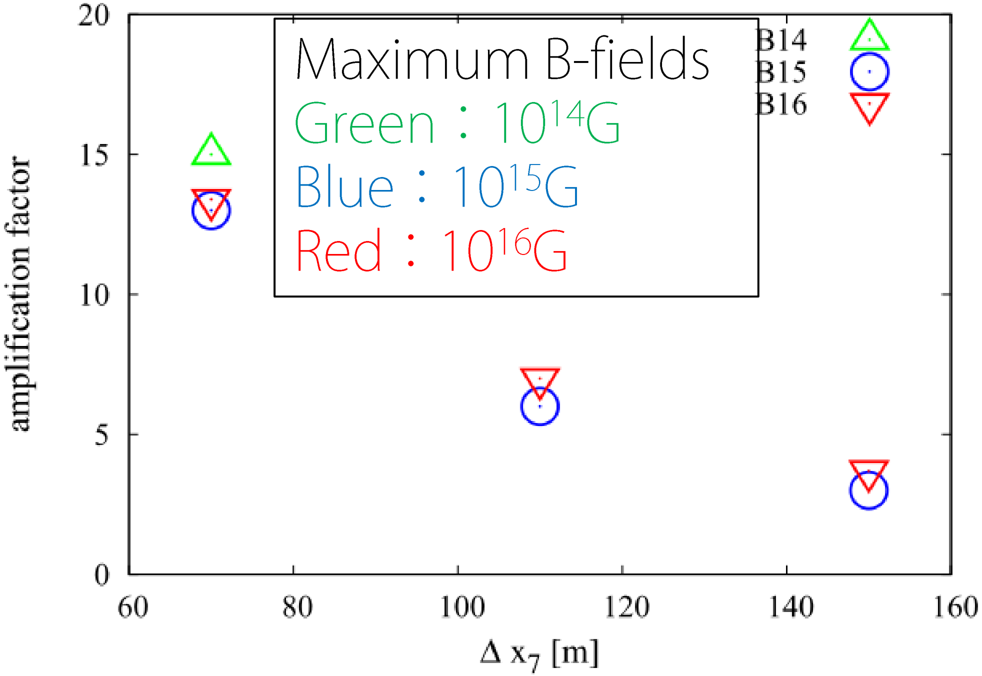
▸Amplification factor：Newtonian>>GR

▸Vortices are disappeared within 0.1s because of the approaching motion

Field lines and strength @ merger

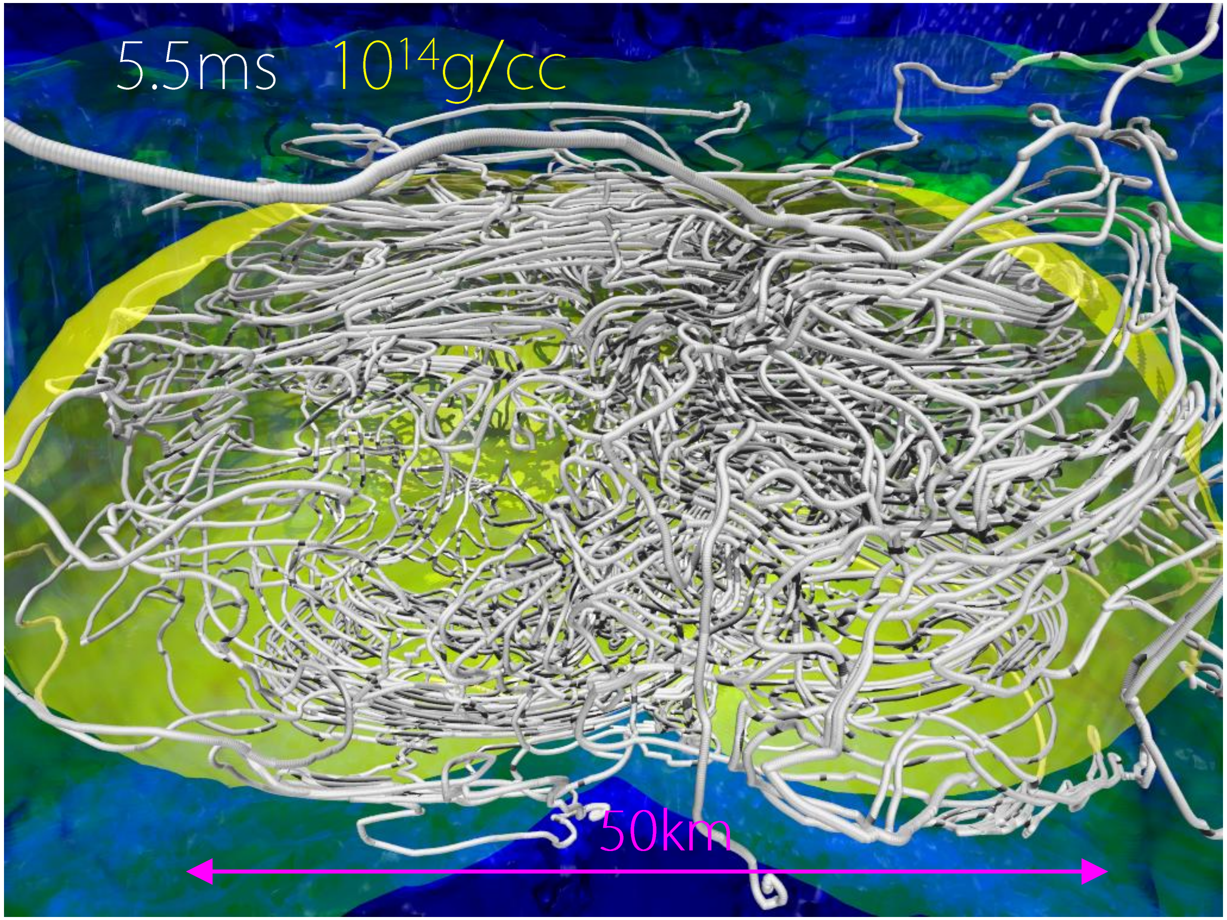



Amplification factor vs resolution




- The smaller $\Delta x$ 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)

# Field lines and density iso-contour inside HMNS



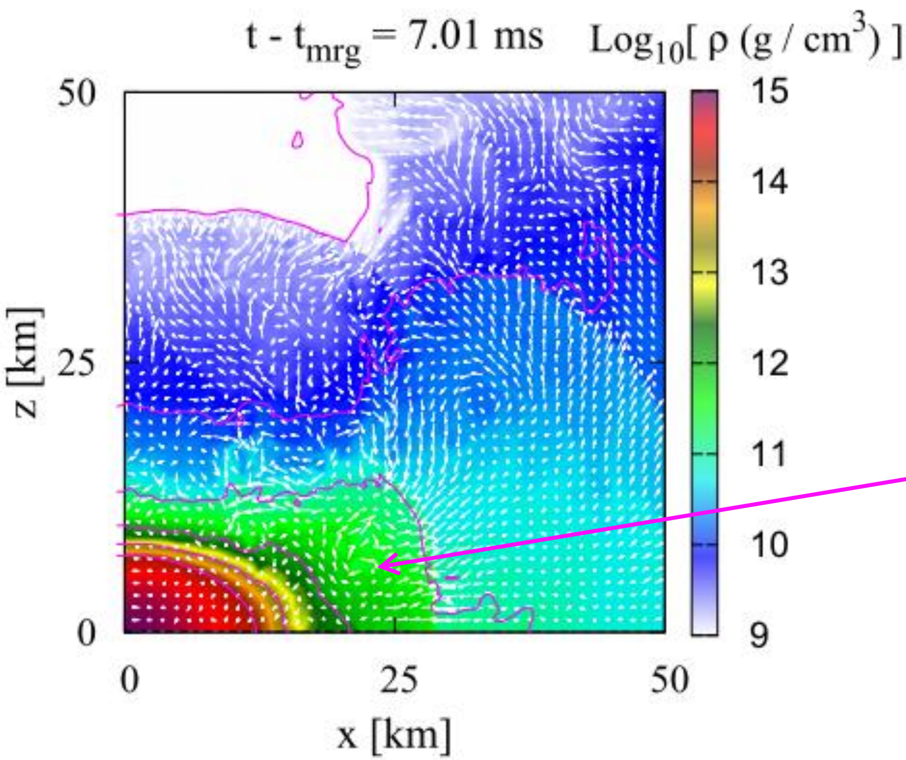

▶ Turbulent state inside HMNS

▶ HMNS is differentially rotating ⇒ Unstable against the Magneto Rotational Instability (Balbus-Hawley 92)

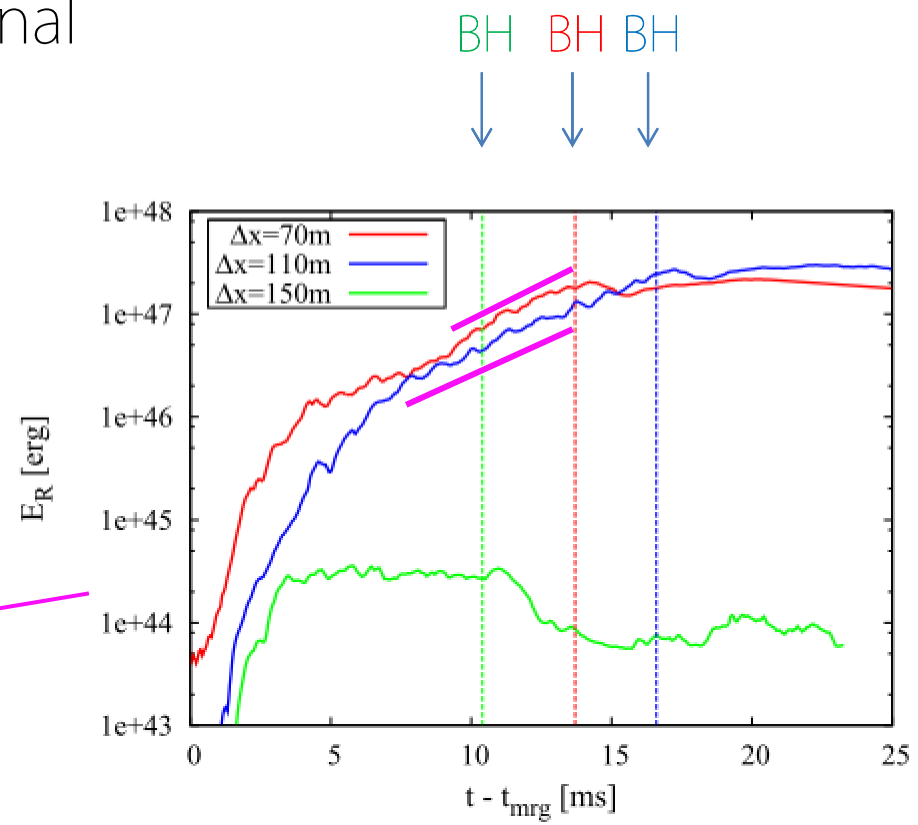
▶Magnetic winding works as well

# B-field amplification inside HMNS

Density contour of HMNS (Meridional plane)



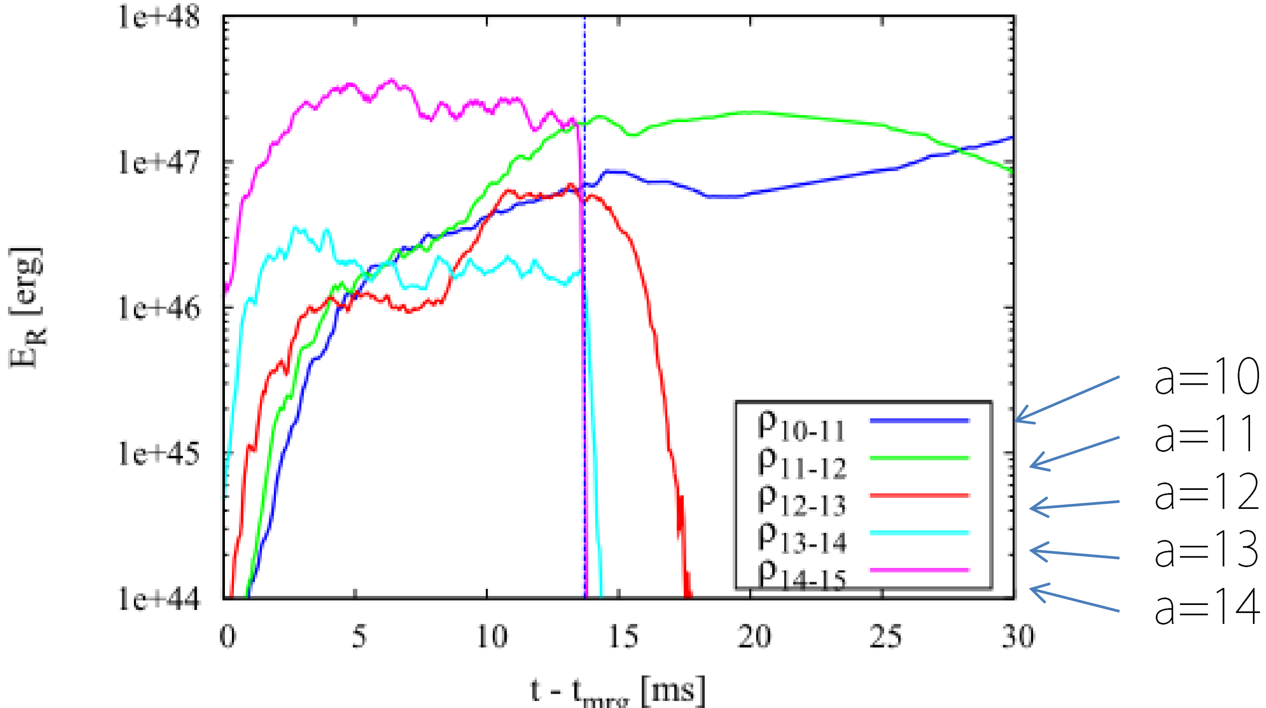

Magnetic field energy inside $10^{11}$g/cc ≤ $\rho$ ≤ $10^{12}$g/cc




- $\lambda_{MRI} = B/(4\pi\rho)^{1/2}\, 2\pi/\Omega$
- 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 inside HMNS

B-fields energy in $10^{a}$g/cc $\leq \rho \leq 10^{a+1}$g/cc   a=10-14 for high-res. run



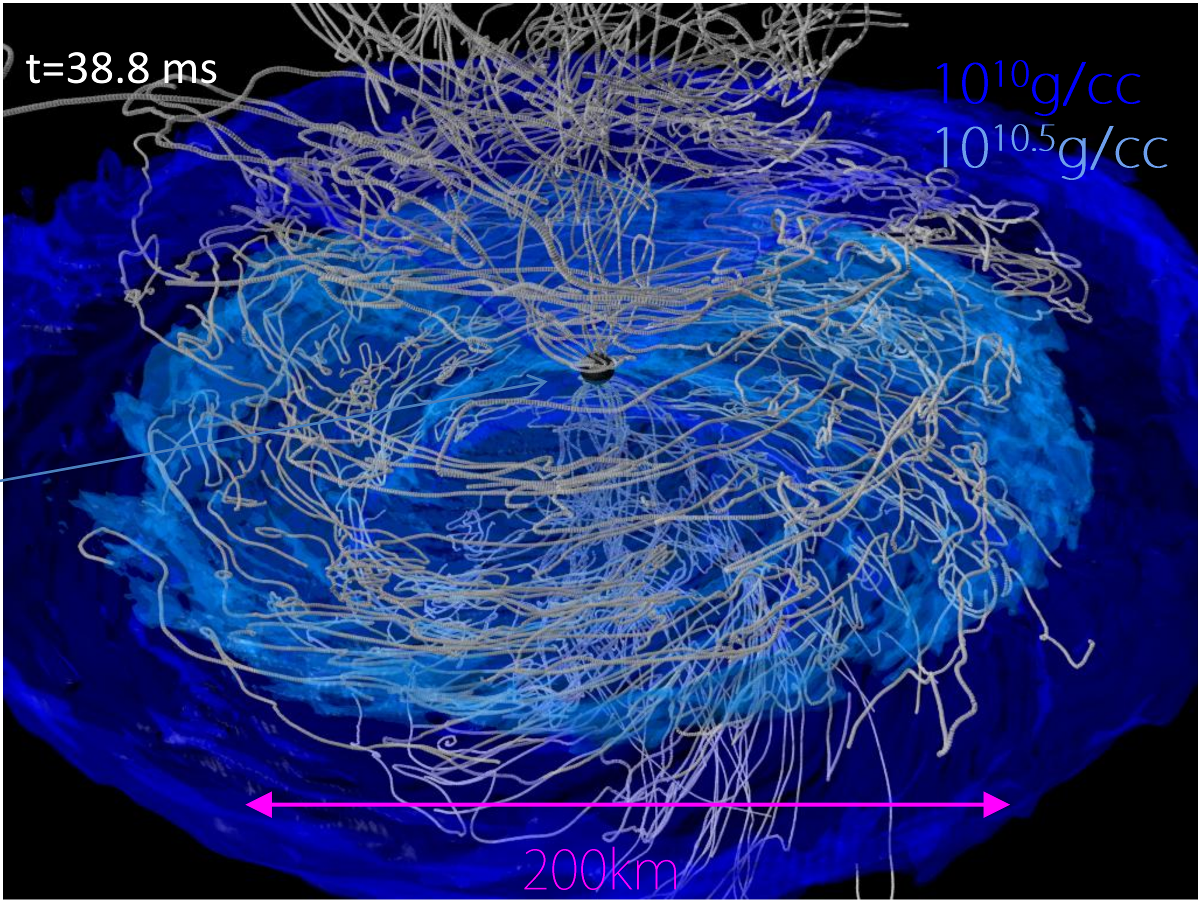

▶The high the density is, the high the growth rate is because of higher angular velocity

▶B-field amplification in relatively low density regions is cause by the non-axisymmetric MRI (Balbus – Hawley 92)

▶Magnetic winding works as well for the toroidal fields

$B_{\varphi} \sim B_R\,\Omega\,t \sim 10^{16}\mathrm{G}(B_R/10^{15}\mathrm{G})(\Omega/10^{3}\mathrm{rad/s})(t/10\mathrm{ms})$

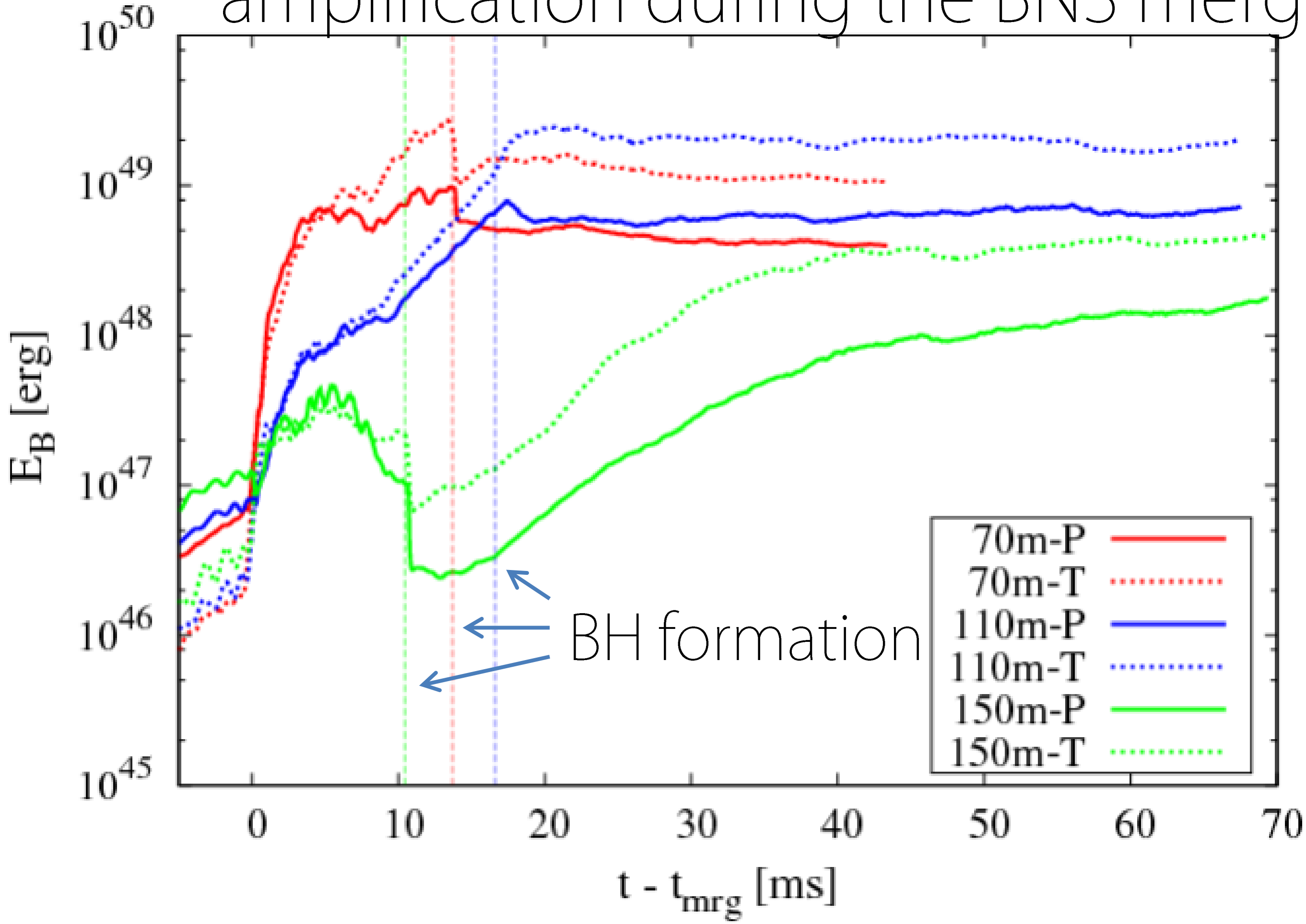
# Black hole—accretion torus




BH

- We have not found a jet launch.
- Ram pressure due to the fall back motion$\sim 10^{28}$ dyn/cm$^2$(Need $10^{14\text{-}15}$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)

# Summary

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

▶ Kelvin-Helmholtz instability at the merger
▶ Non-axisymmetric MRI inside the hyper massive neutron star

are key ingredients.

The accretion torus is strongly magnetized at its birth.
⇒ Qualitatively different picture of the previous works

If the NS magnetic field is weak, e.g., $10^8$ G, this picture is still valid, but more challenging numerically.

Necessity to lunch an outflow to build a global poloidal magnetic field.

# Construction of a physically reliable model of BNS mergers

Method : Numerical Relativity

Figuring out high energy phenomena in a strong gravitational field by including the basic interactions self-consistently.

- Gravity (General Relativity)
- Strong interaction (Neutron star matter)
- Weak interaction (Neutrino)
- Electromagnetic force (Magnetic field)

Einstein eqs.

$$R_{\mu\nu}(\partial^2 g_{\mu\nu}, \partial g_{\mu\nu}) - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi \mathrm{G}}{\mathrm{c}^4} T_{\mu\nu}$$

Conservation laws

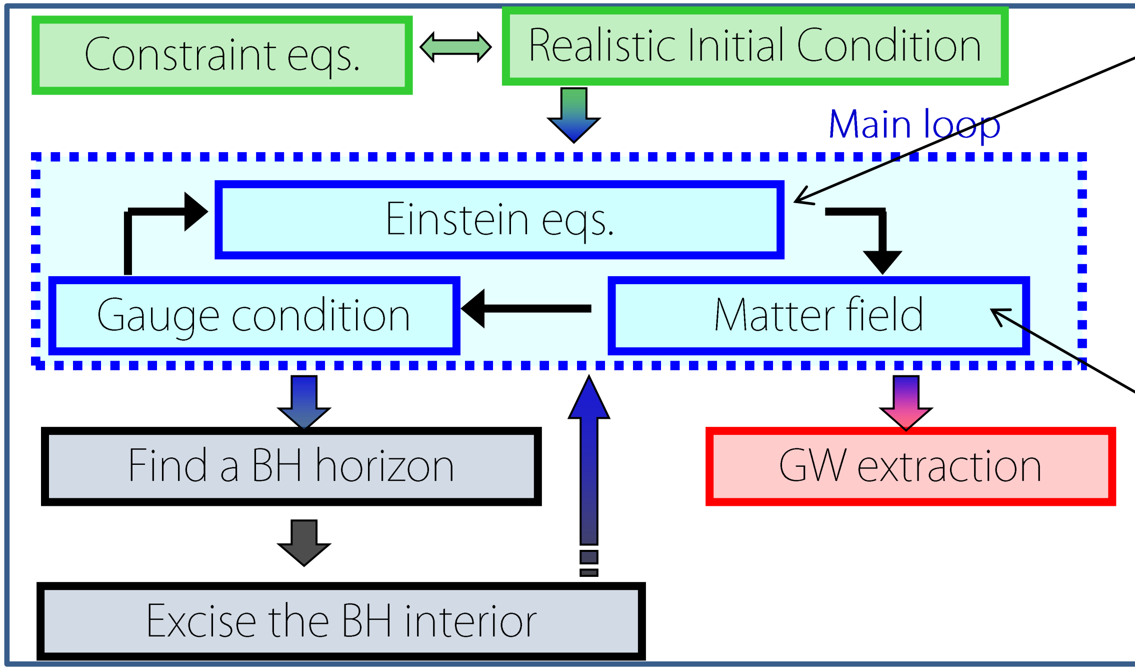
$$\nabla_\mu T^{\mu\nu} = 0, \quad T^{\mu\nu} = T^{\mu\nu}_{(\mathrm{fluid})} + T^{\mu\nu}_{(\mathrm{rad})} + T^{\mu\nu}_{(\mathrm{EM})}$$

$$\nabla_\mu J^{\mu} = 0, \quad J^{\mu} = n_{(\mathrm{baryon})} u^\mu, \; n_{(\mathrm{lepton})} u^\mu, \; \mathrm{etc}$$

Equation of State

$$P = P(\rho, T, Y_{\mathrm{e}})$$

# Recipe of Numerical Relativity




BSSN formulation
(Shibata & Nakamura 95, Baumgrte-Shapiro 99)

- GRHD
- GRMHD
- GRRHD
- GRRMHD

Slide courtesy of Y. Sekiguchi

- General Relativistic Hydro Dynamics (GRHD) (Font 08)
- General Relativistic Magneto Hydro Dynamics (GRMHD) (Shibata & Sekiguchi 05, Duez+ 05)
- General Relativistic Radiation Hydrodynamics(GRRHD) (Sekiguchi 10)
- General Relativistic Radiation Magneto Hydrodynamics(GRRMHD)

# GW, frequency, spectrum