連星中性子星合体における磁場の役割

木内建太（YITP)

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共同研究者：久徳浩太郎 (UWM), 関口雄一郎 (YITP),
柴田大 (YITP), 和田智英 (筑波技術大)

Indirect evidence of GW

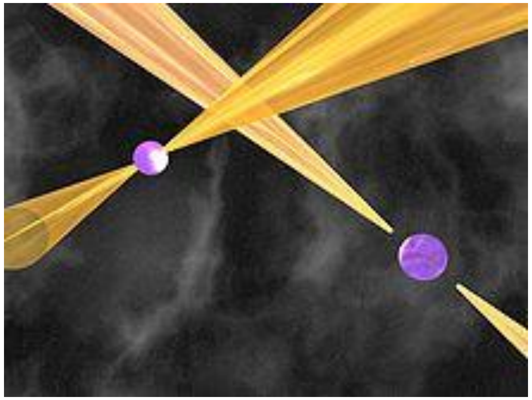


Image of the binary pulsar

Russell Alan Hulse 1950～　　Joseph Hooton Taylor, Jr.、1941～

Hulse and Taylor have found the binary pulsar PSRB1913+16 in the Arecibo observatory.

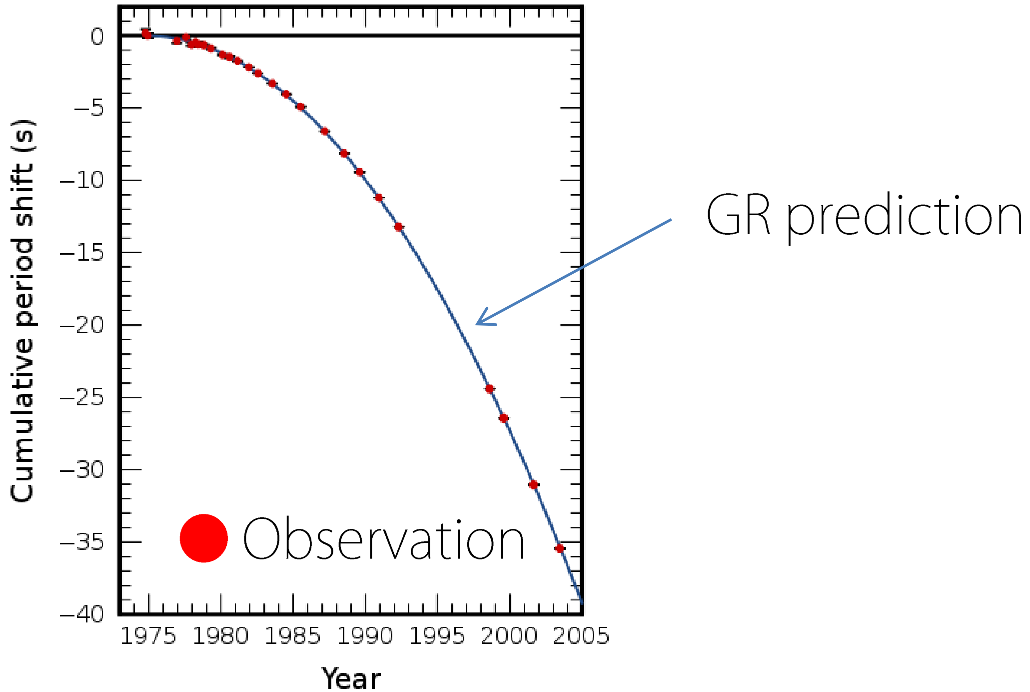
⇒ The orbital period gets shorter in time.

It implies the energy is radiated from the system.

Indirect evidence of GW

GR predicts the GW with which the energy is carries away.

The shift of the orbital period of 1913+16



The GR prediction agrees with the observation within 1 %.

⇒ Hulse and Taylor have gotten the Nobel Prize in 1993.

Their work is recognized as the indirect evidence of GW.

The direct observation is coming true

GW detectors

1. Gravitational waves

- ▶ 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

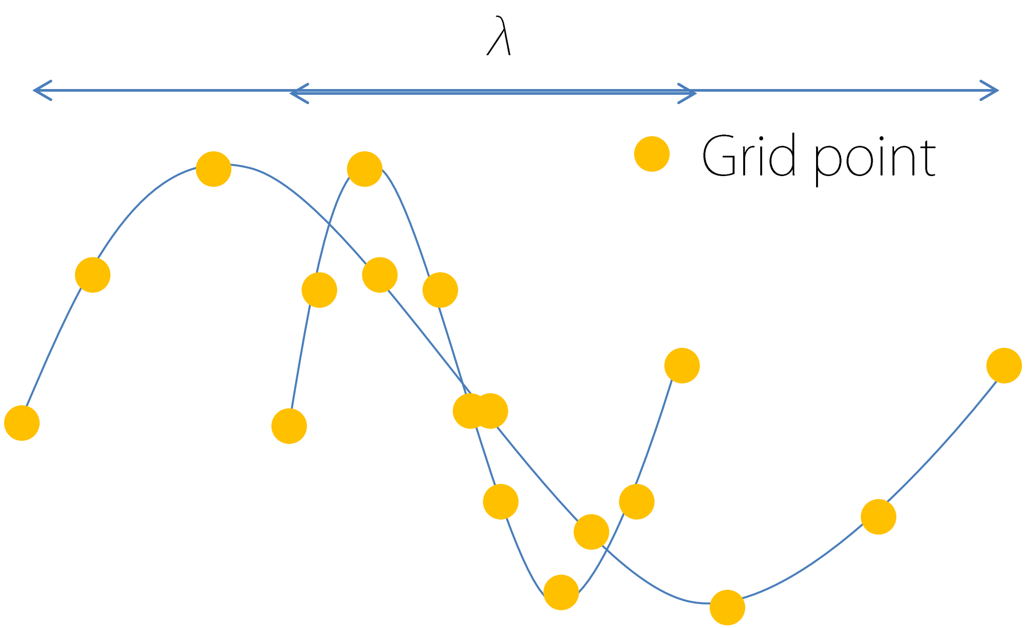
Kyoto NR group approaches from two directions;

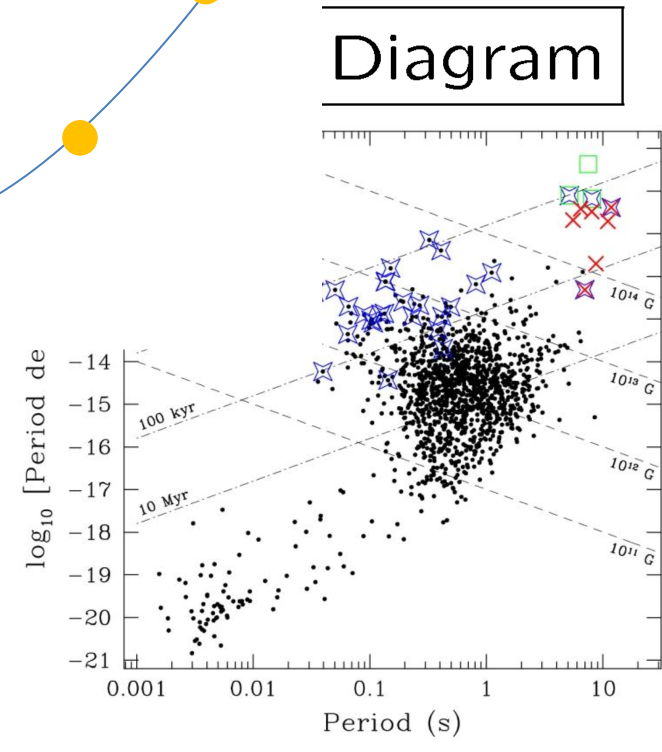
- ▶ MHD (KK
- ▶ Microphy

Are B-fields
▶Observed

The MHD ins
short-wavele

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





A step toward the physical modeling of BNS mergers

Numerical Relativity ; Including the basic interactions,

- Gravity (General Relativity)
- Strong interaction (Nuclear matter)
- Weak interaction (Neutrino)
- Electromagnetic force (Magnetic field, cf. NS B-field $10^{11\text{-}15}$ G)

in self-consistent way to figure out high energy astrophysical phenomena in strong gravitational field.

Einstein equations

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

Conservation laws

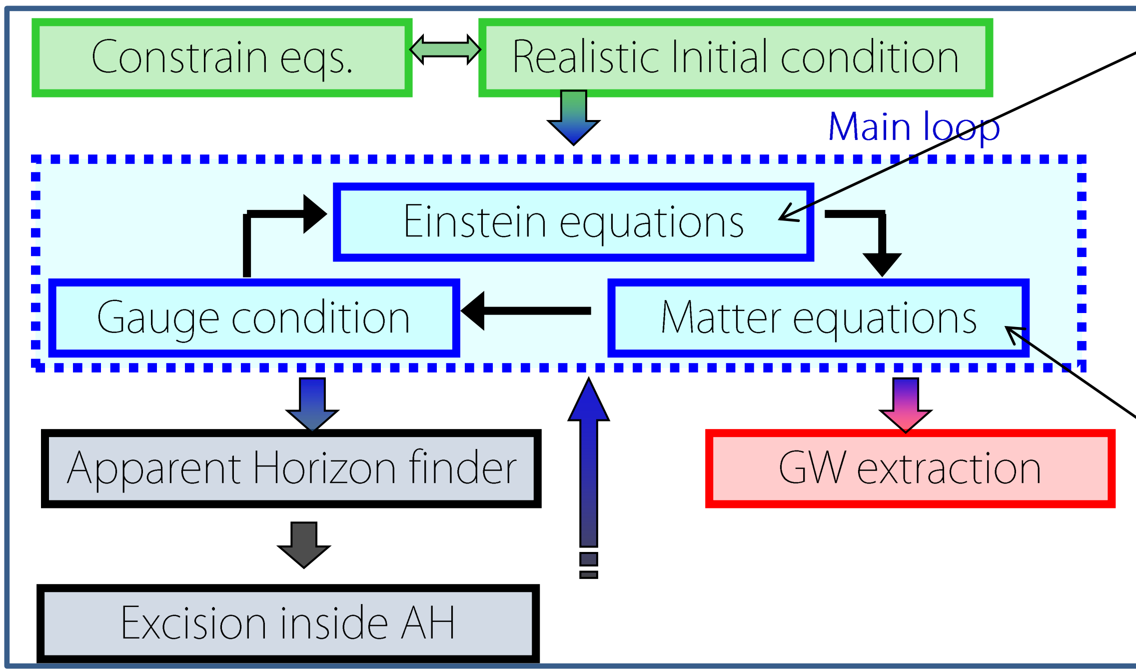
$$\nabla_\mu T^{\mu\nu} = 0, \quad T^{\mu\nu} = T^{\mu\nu}_{(\mathrm{fluid})} + T^{\mu\nu}_{(\mathrm{rad})} + T^{\mu\nu}_{(\mathrm{EM})}$$

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

Equation of state (Closure relation)

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

Current status of Numerical Relativity



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

- GRHD
- GRMHD
- GRRHD
- GRRMHD

Slide courtesy of Sekiguchi

General Relativistic Magneo Hydro Dynamics (GRMHD)

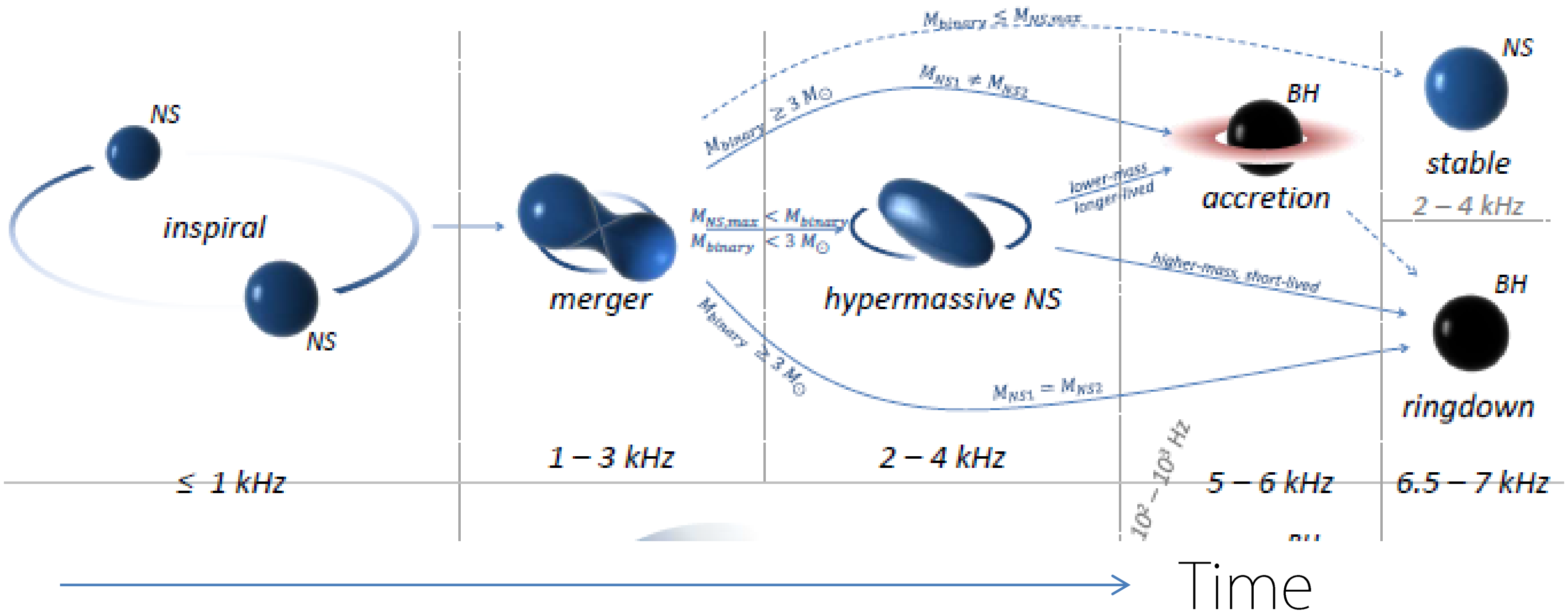
- Formulation by Shibata-Sekiguchi, and Duez et al. (Shibata & Sekiguchi 05, Duez+ 05)

General Relativistic Radiation Hydrodynamics (GRRHD)

- General Relativistic Leakage scheme (Sekiguchi 10)
- Truncated Momentum formalism (Thorne 81, Shibata, KK + 10, Shibata-Sekiguchi 11, Kuroda+12, O'Connor & Ott 13)

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.

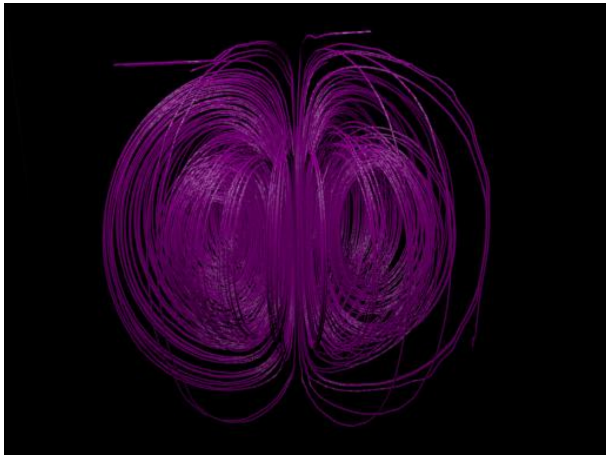
Numerical Relativity simulation of magnetized BNS mergers

▶High resolution 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 Δx≈180m (Liu et al. 08, Giacomazzo et al. 11, Anderson et al. 08)

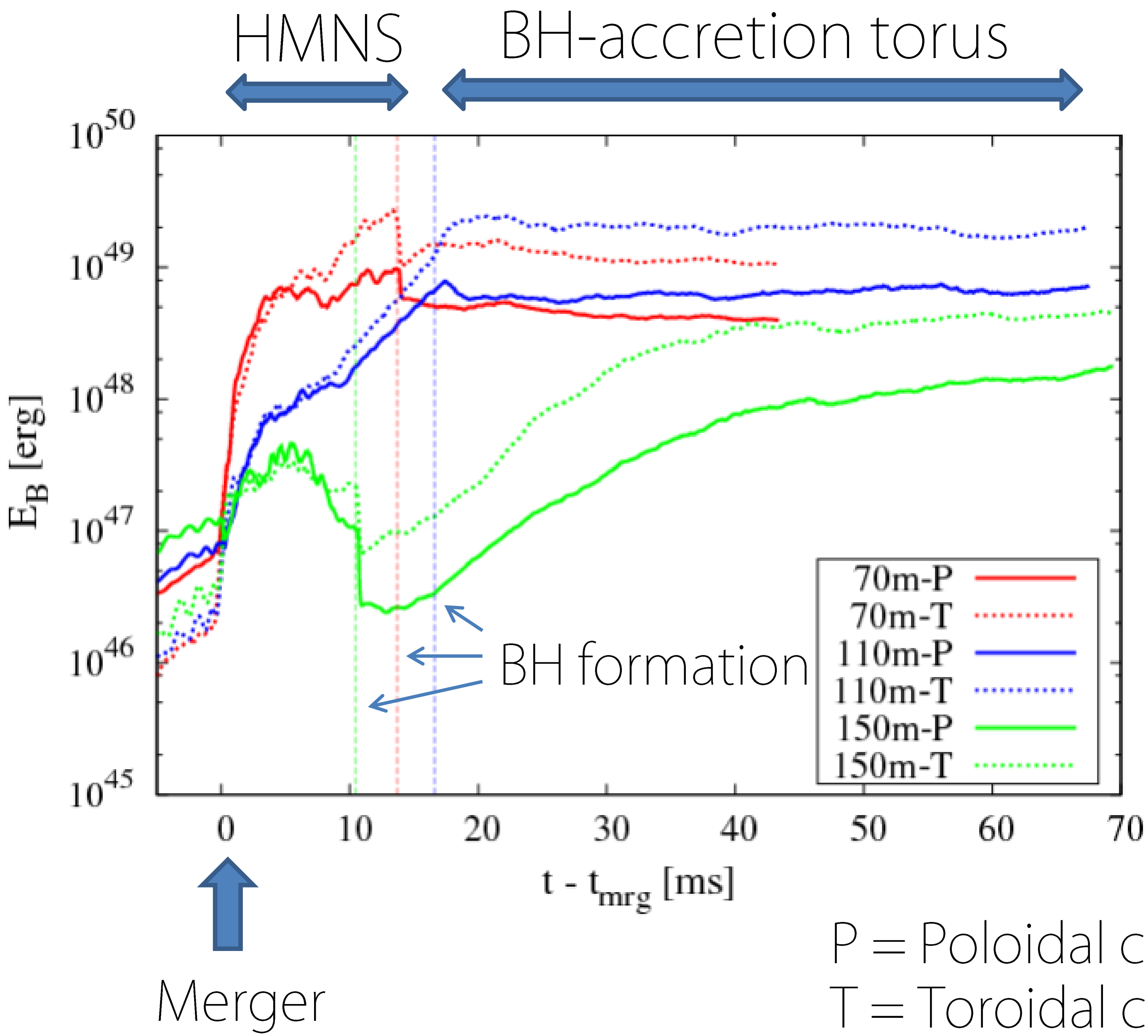
Nested grid ⇒ Finest box=70km^3, Coaserest grid =4480km^3 （N～10^9），a long term simulation of about 100 ms

<u>Fiducial model</u>
EOS : H4 (Gledenning and Moszkoski 91) (M_{max}≈2.03$M_\odot$)
Mass : 1.4-1.4 $M_\odot$
B-field : 10^{15}G

Magnetic field lines of NS



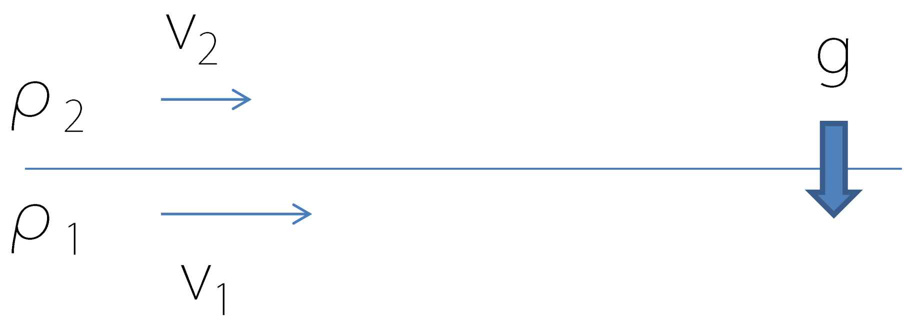
Evolution of the magnetic field energy



P = Poloidal comp.
T = Toroidal comp.

Amplification @ the merger (Rasio and Shapiro 99)

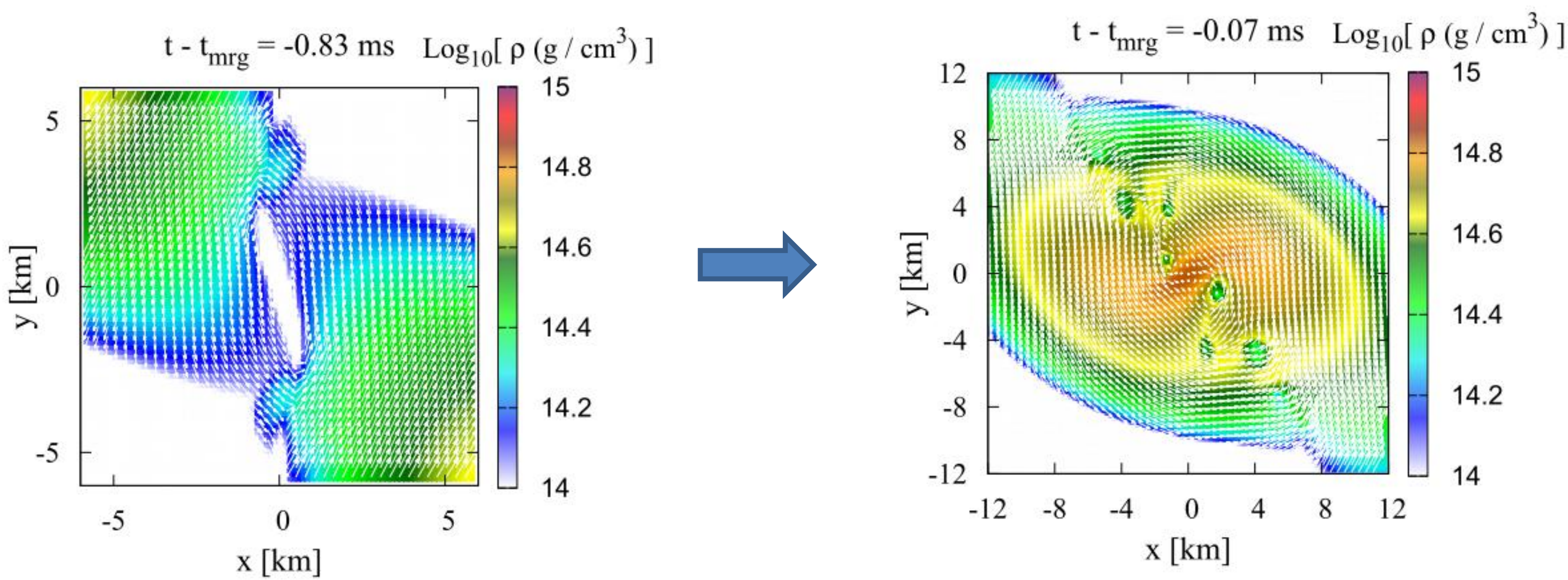
Kelvin Helmholtz instability



Minimum wave number of the unstable mode ;

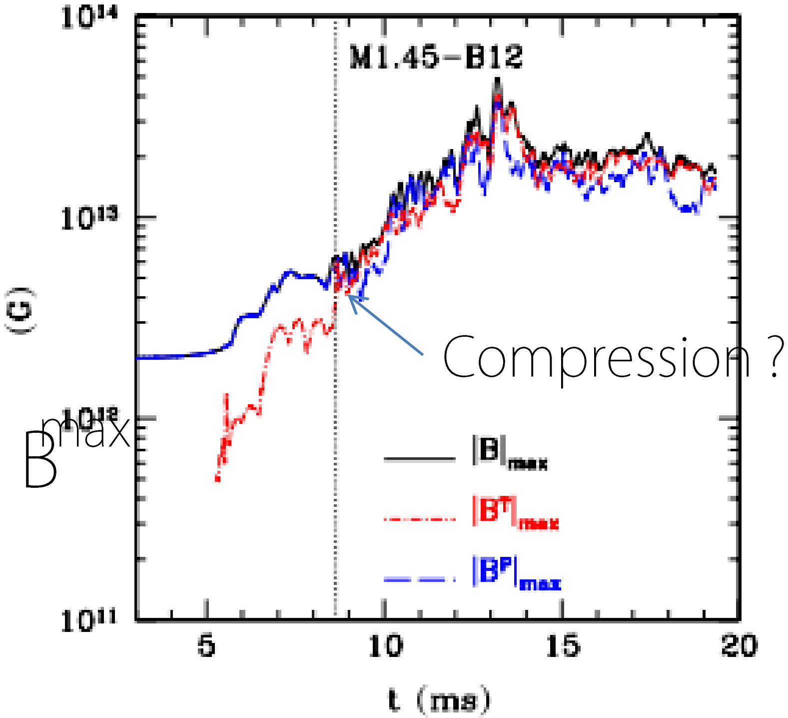
$k_{min} \propto g(\rho_1 - \rho_2)/(v_1 - v_2)^2$

$\Rightarrow$ If $g = 0$, all the mode is unstable. Growth rate $\propto$ wave number



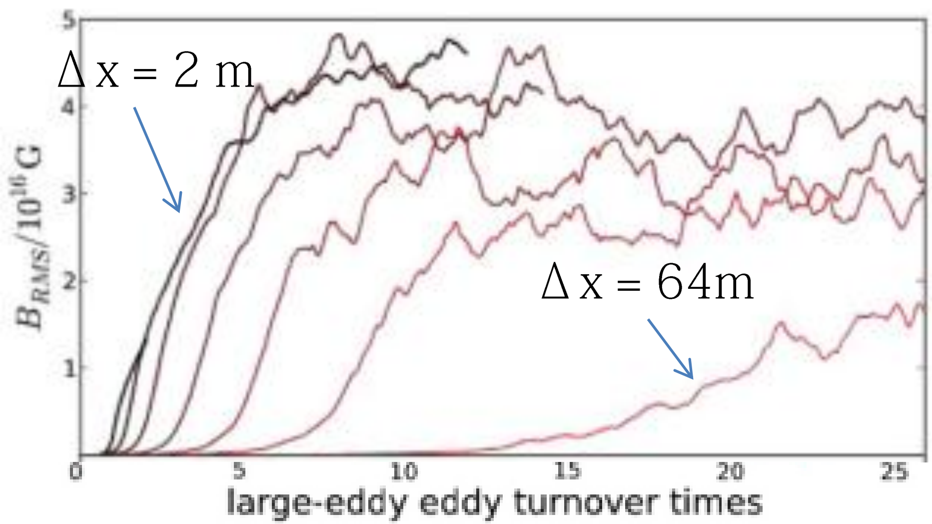
Amplification via KH vortices @ the merger (Rasio and Shapiro 99)

GRMHD by AEI (Giacomazzo et al. 11)



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

Time evolution of <B>

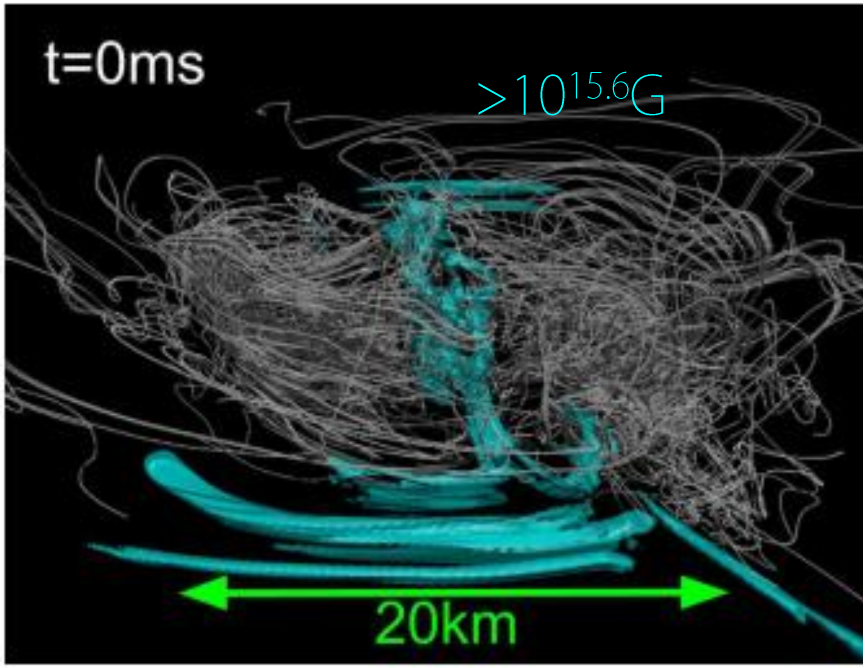


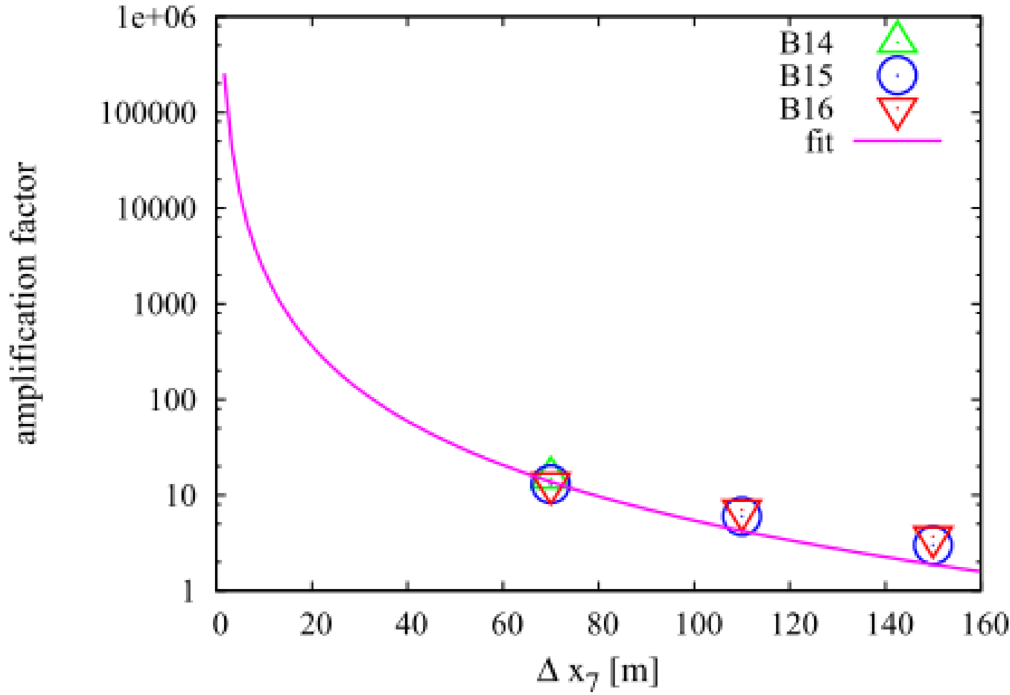
1=0.1ms

Can really the KH vortices amplify the B-fields ?

Yes !

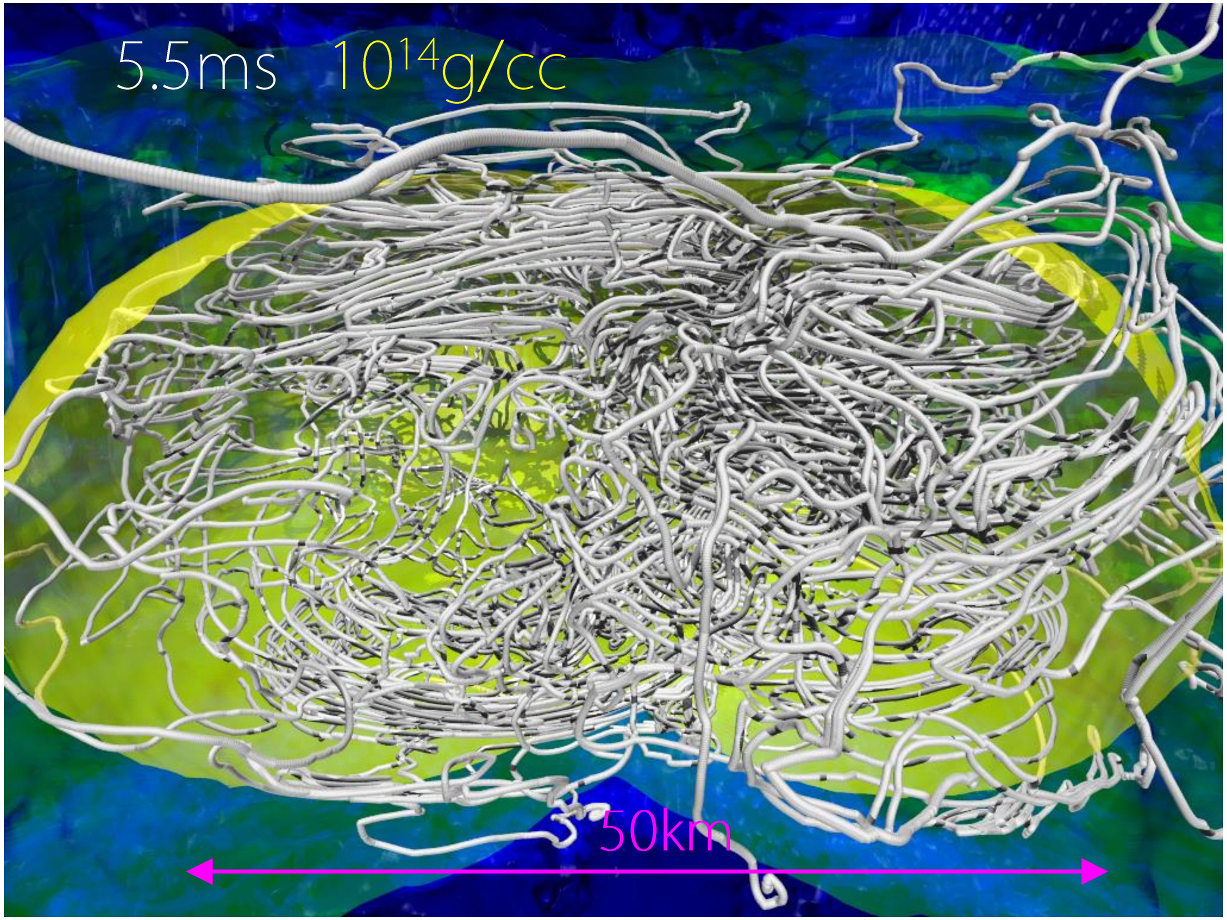
Field lines and strength @ merger   Amplification factor vs resolution





- 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)

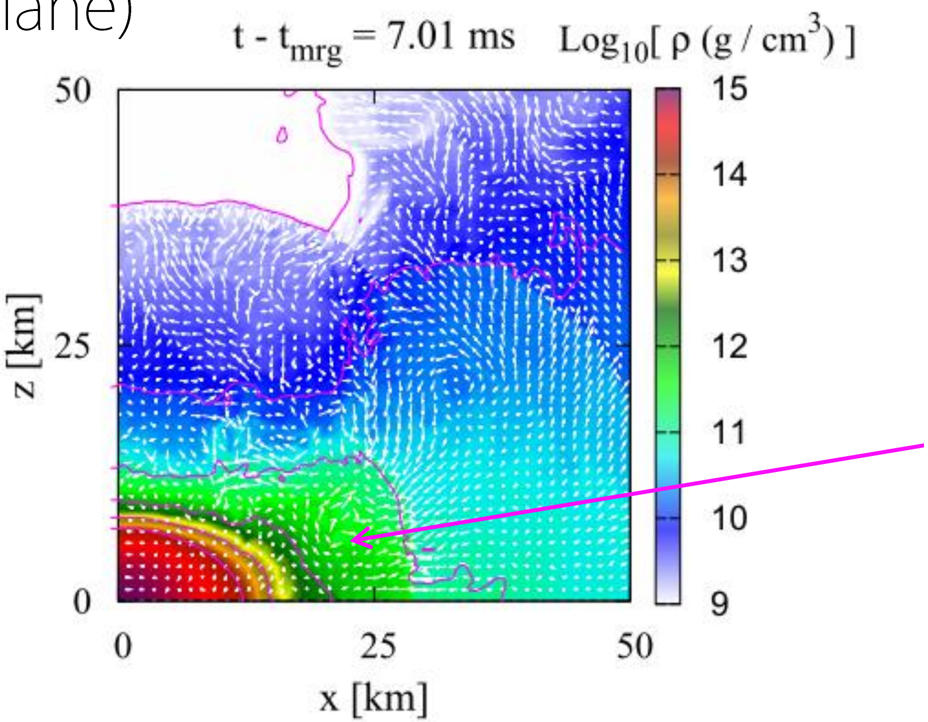
Field lines and density iso-contour inside HMNS



- ▶ Turbulent state inside HMNS
- ▶ HMNS is differentially rotating ⇒ Unstable against the Magneto Rotational Instability, $\nabla_R \Omega < 0$ (Balbus-Hawley 92)
- ▶ Magnetic winding works as well

B-field amplification inside HMNS

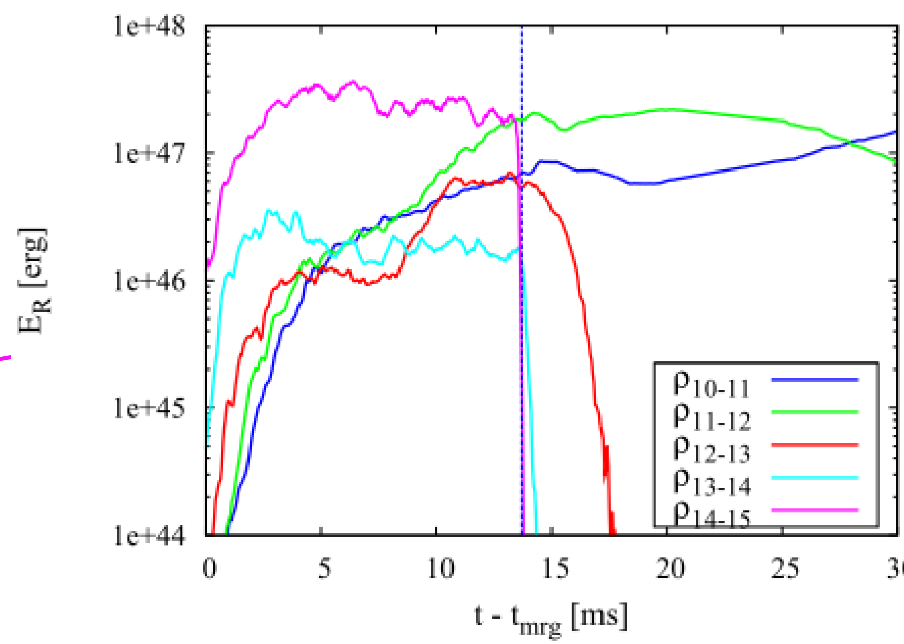
Density contour of HMNS (Meridional plane)



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

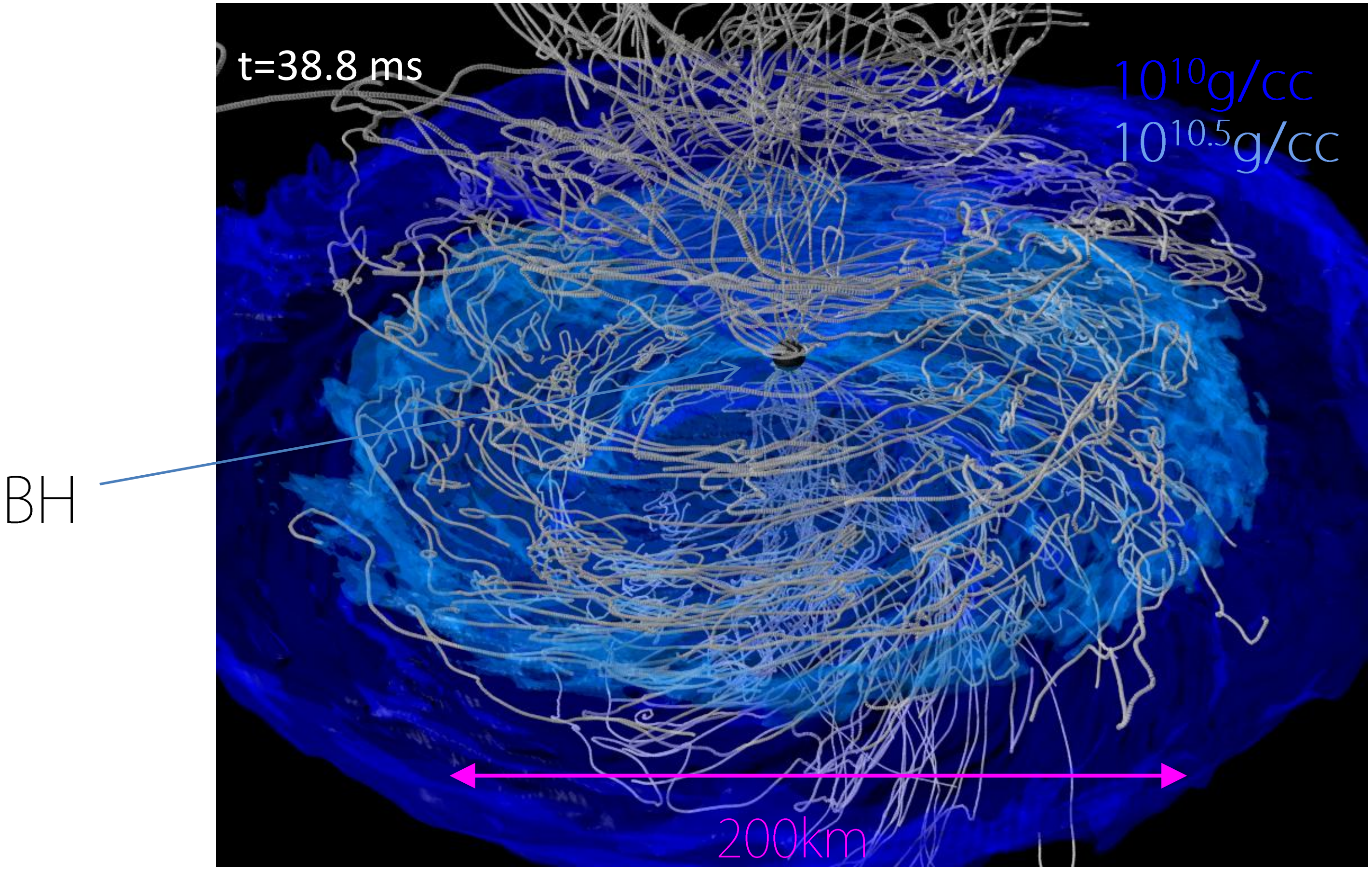
B-fields energy in 10^{a}g/cc ≤ ρ ≤ 10^{a+1}g/cc a=10-14 for high-res. run

BH BH BH



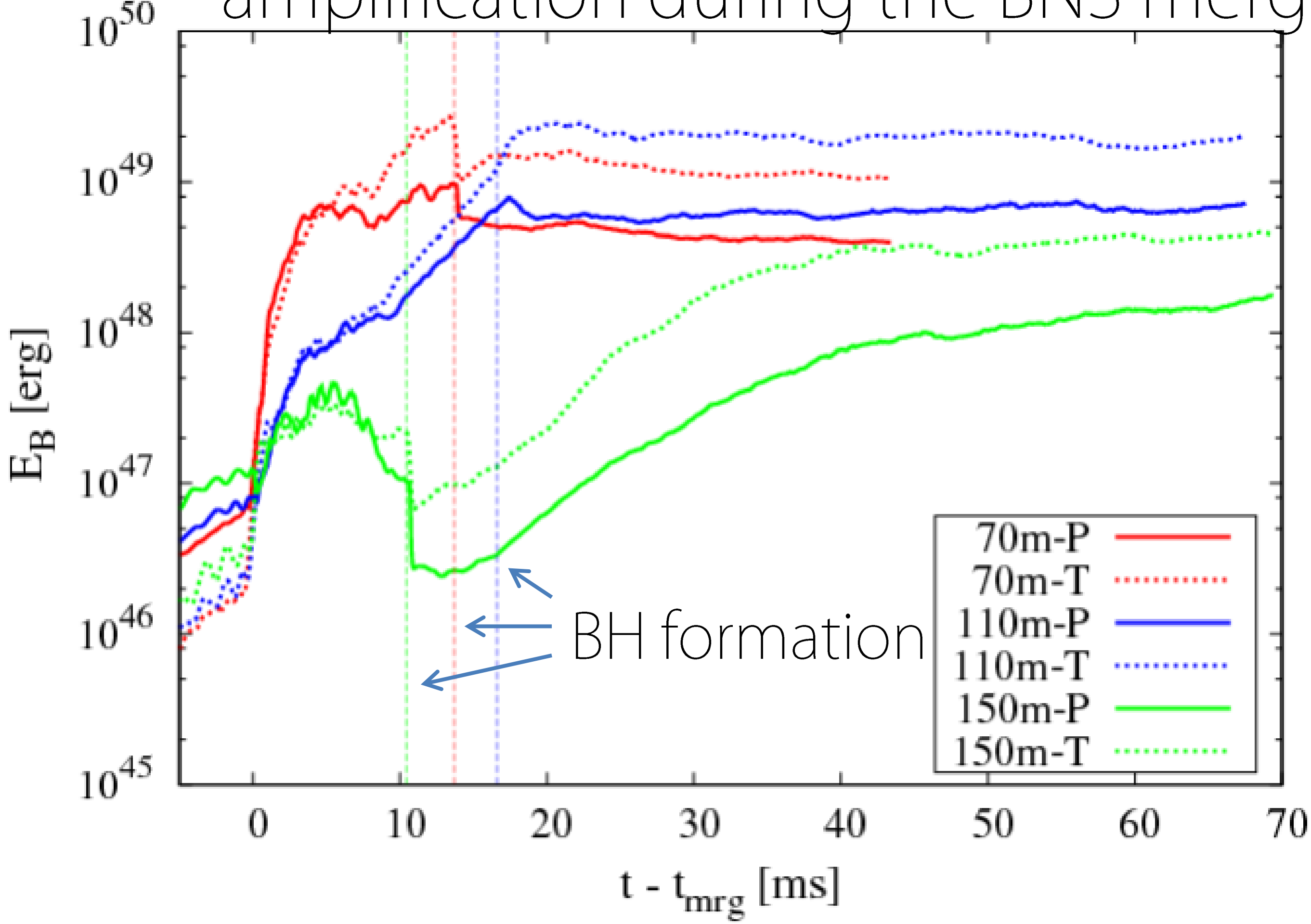
- $\lambda_{MRI} = B/(4\pi\rho)^{1/2}\, 2\pi/\Omega$
- The condition $\lambda_{MRI,\varphi}/\Delta x \gtrsim 10$ is satisfied for the high and medium run, but not in low run. B = Toroidal magnetic field
- Growth rate of B-fields for 8 - 14 ms ≈130-140Hz∼O(0.01)Ω
- B-field amplification is cause by the 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 $10^{14\text{-}15}$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

<u>Caveats</u>

If you start more "realistic" value of the magnetic fields, say 10^{11} G, you need more grid resolution. Otherwise, such a simulation will be nonsense.

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