磁場連星中性子星合体の高解像度シミュレーション

Kenta Kiuchi (YITP) XC-A, S

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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

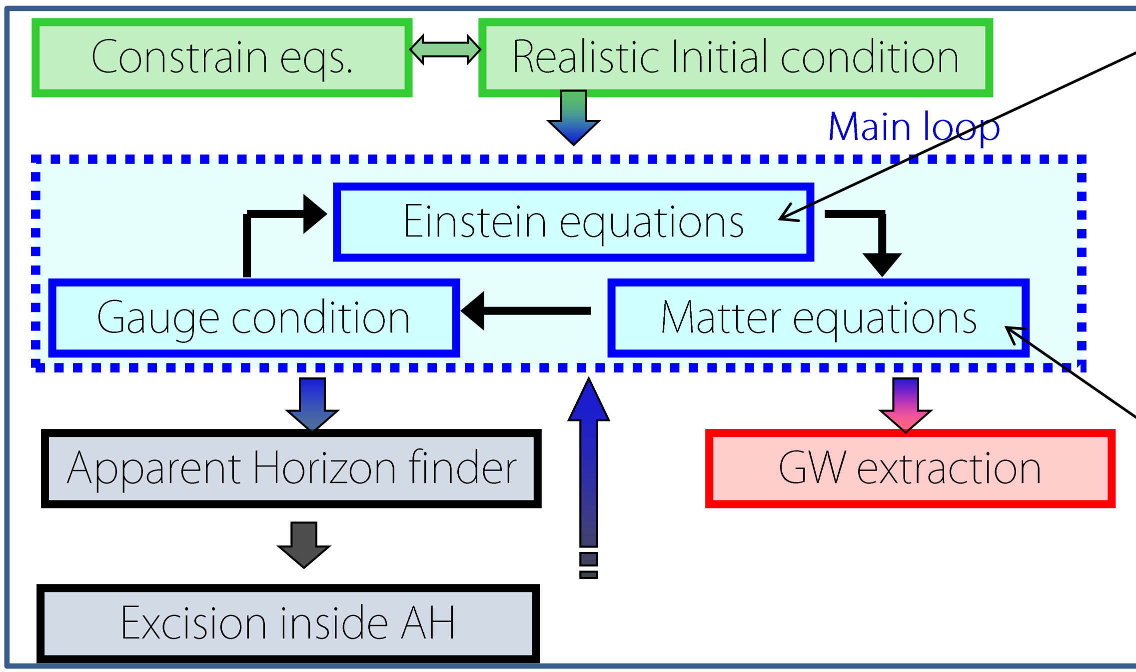
2. A possible site of the r-process synthesis

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)

Current status of Numerical Relativity



BSSN formulation
(Shibata & Nakamura 95, Baumgrte-Shapiro 99)
cf. Generalized harmonics formulation (Caltech-Cornell-CITA),
Fully constraint scheme (Meudon-Valencia)

- G R H D
- G R MHD
- G R R H D
- G R R M H D

Slide courtesy of Sekiguchi

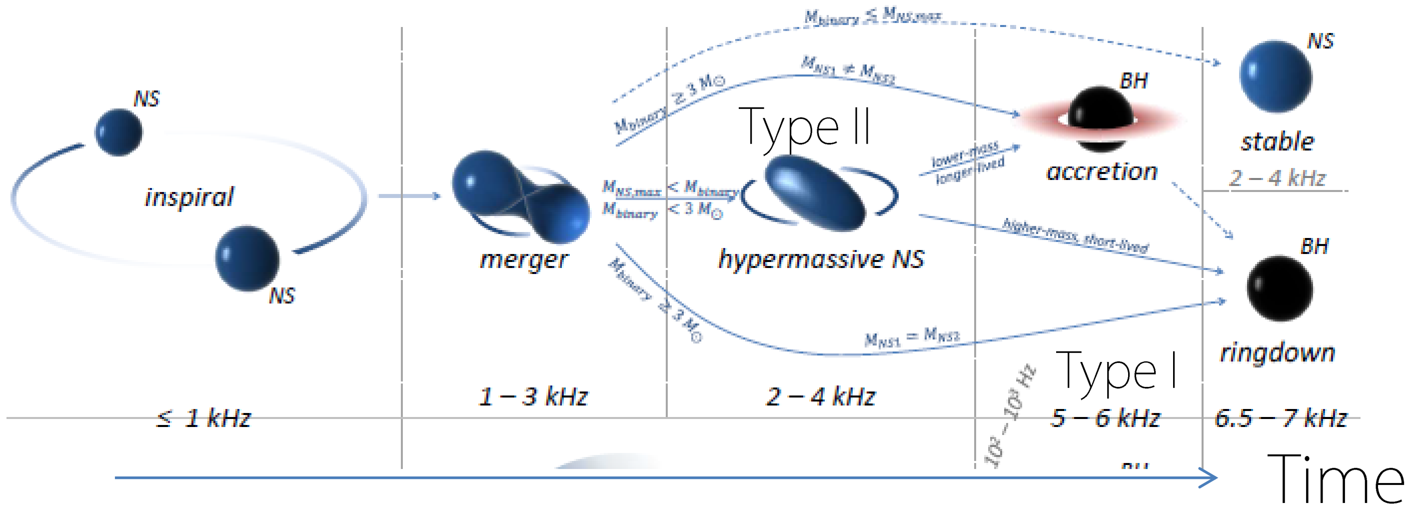
General Relativistic Magneo Hydro Dynamics (GRMHD)

- 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 binary neutron star merger (Bartos et al. 13)



Type I or Type II is determined by M and M_{max}

M: total mass, M_{max} : Maximum mass of spherical and cold NS (EOS dependent)

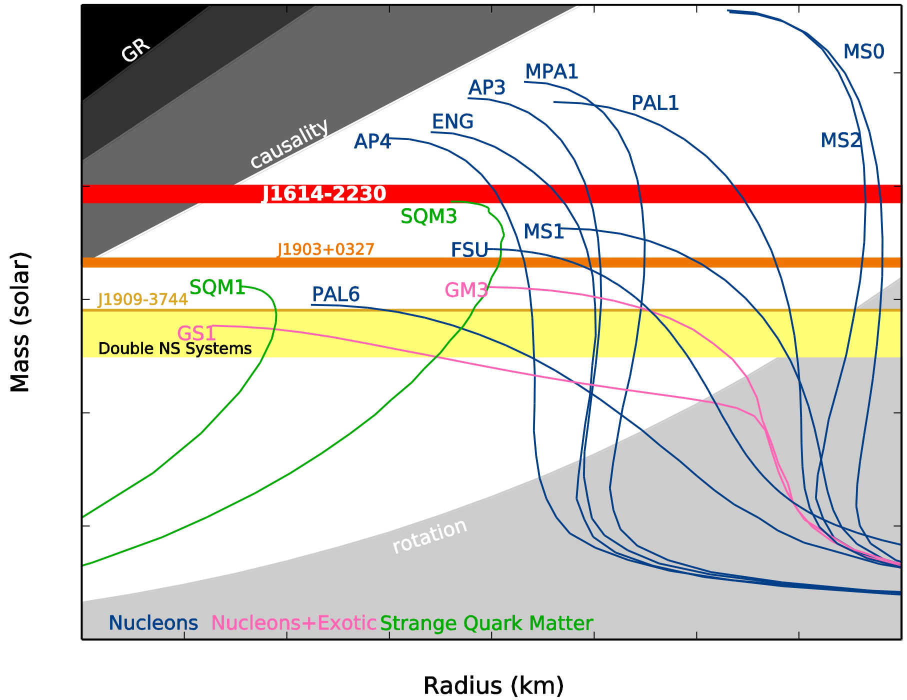
- $M > k\, M_{max}$ ⇨ Type I (Direct BH formation)
- $M < k\, M_{max}$ ⇨ Type II

$1.4 \lesssim k \lesssim 1.7$ (Hotokezaka+ 11)

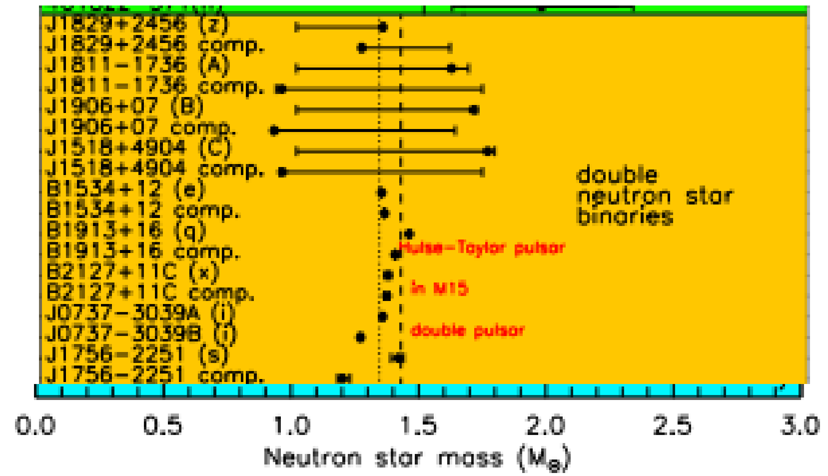
What's the origin of k greater than 1 ? ⇨ Rotation and thermal pressure (Shibata-Taniguchi 06, Sekiguchi et al. 11, Keplan et al. 14)

Observational evidence

M-R relation



Mass of observed NSs (Lattimer & Paraksh 06)



- Lower bound of maximum mass of NS is 2.01 $\pm$0.04 $M_\odot$

(Demorest et al. 10, Antoniadis et al.13)

- Canonical total mass = 2.6-2.8 $M_\odot$

The type II is likely to be "realistic".

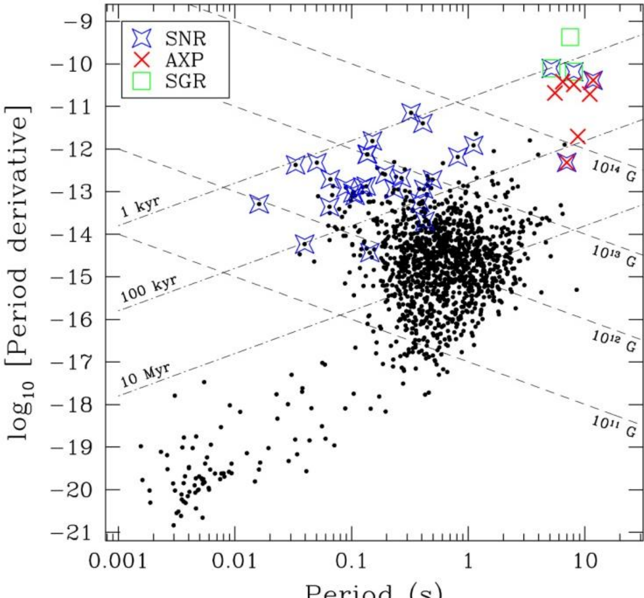
A step toward more physically reliable model of BNS mergers

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

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.

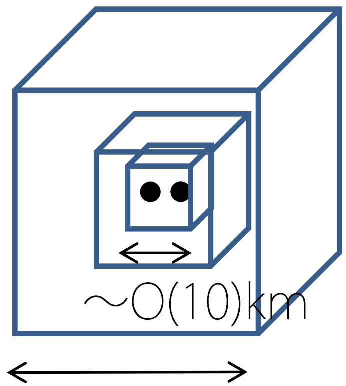
Japanese supercomputer K @ AICS

- 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.

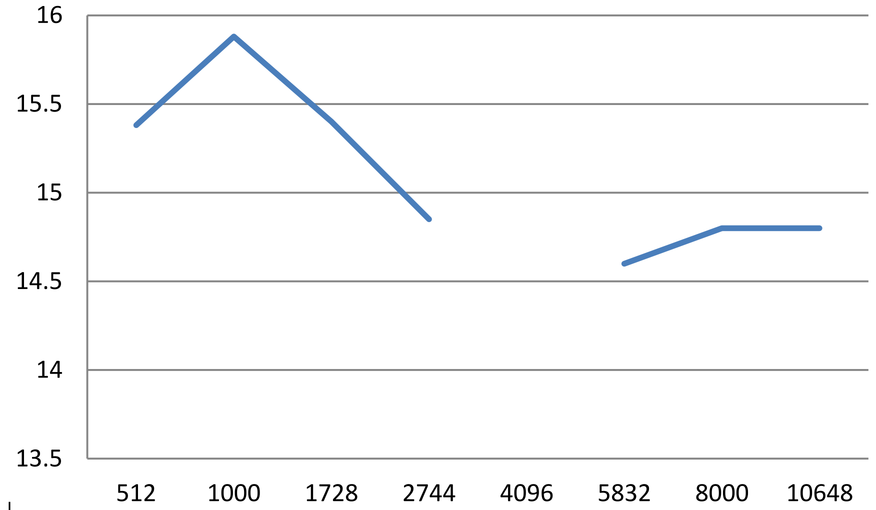
Outline of numerical relativity-MHD code

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

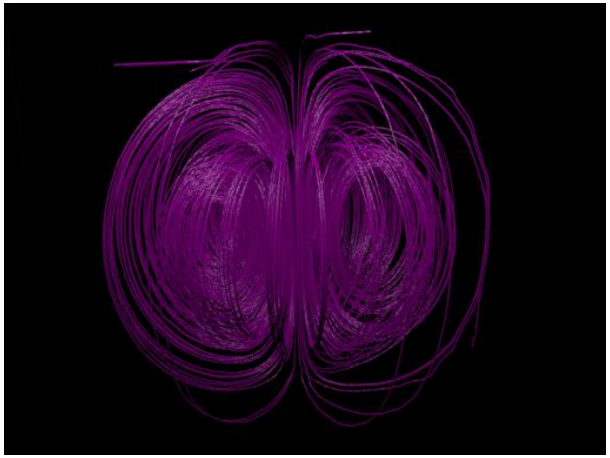
▶Good scaling up to about 80,000 cores

Numerical Relativity simulation of magnetized BNS mergers

▶High resolution $\Delta x=70m$ (16,384 cores on K)
▶Medium resolution $\Delta x=110m$ (XC30, 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)

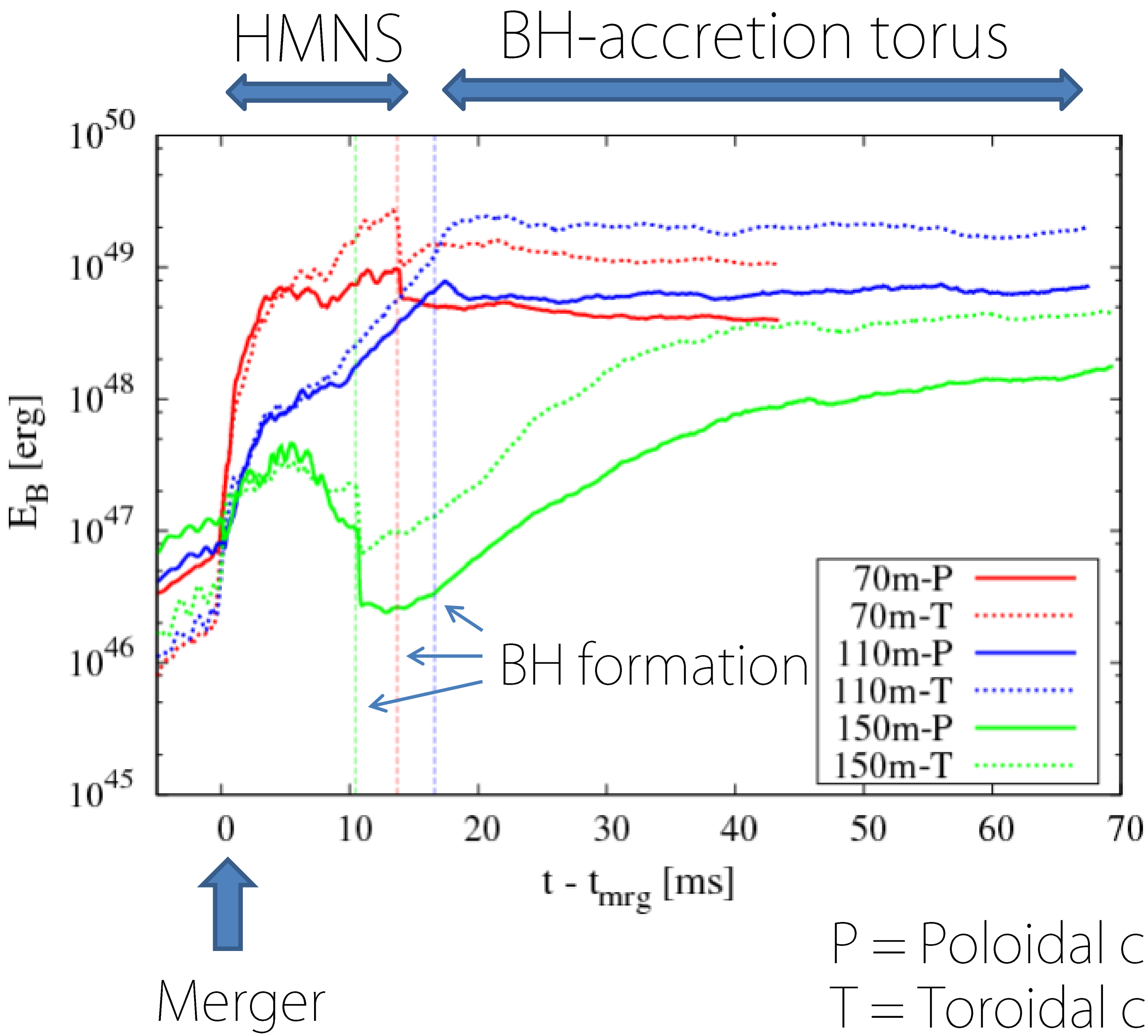
Nested grid ⇒ Finest box=$70km^3$, Coarserest grid =$4480km^3$ (N ～10^9) , a long term simulation of about 100 ms

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

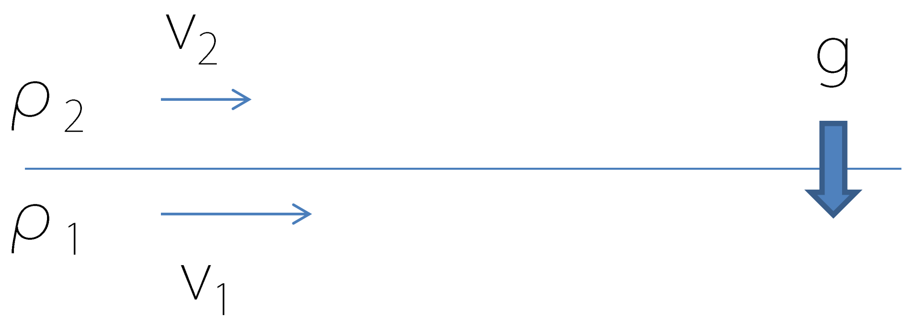
Evolution of the magnetic field energy



P = Poloidal comp.
T = Toroidal comp.

Amplification @ the merger (Rasio and Shapiro 99)

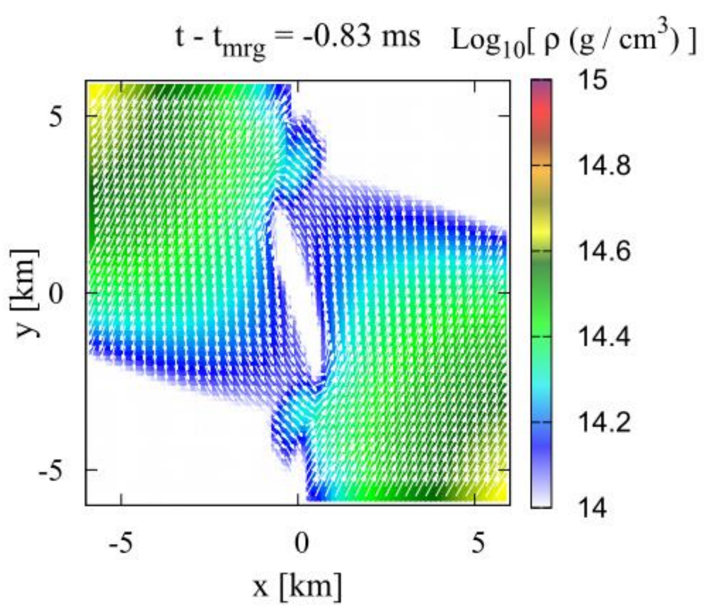
Kelvin Helmholtz instability

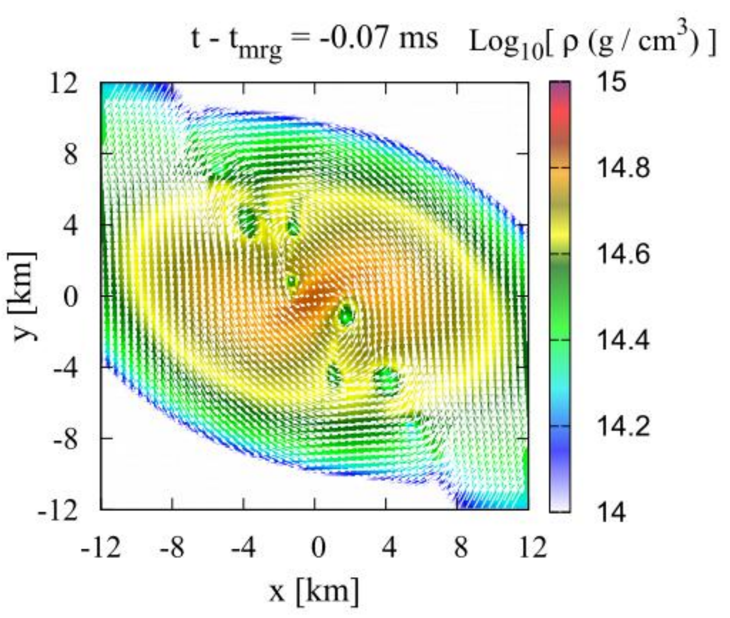


Minimum wave number of the unstable mode ;

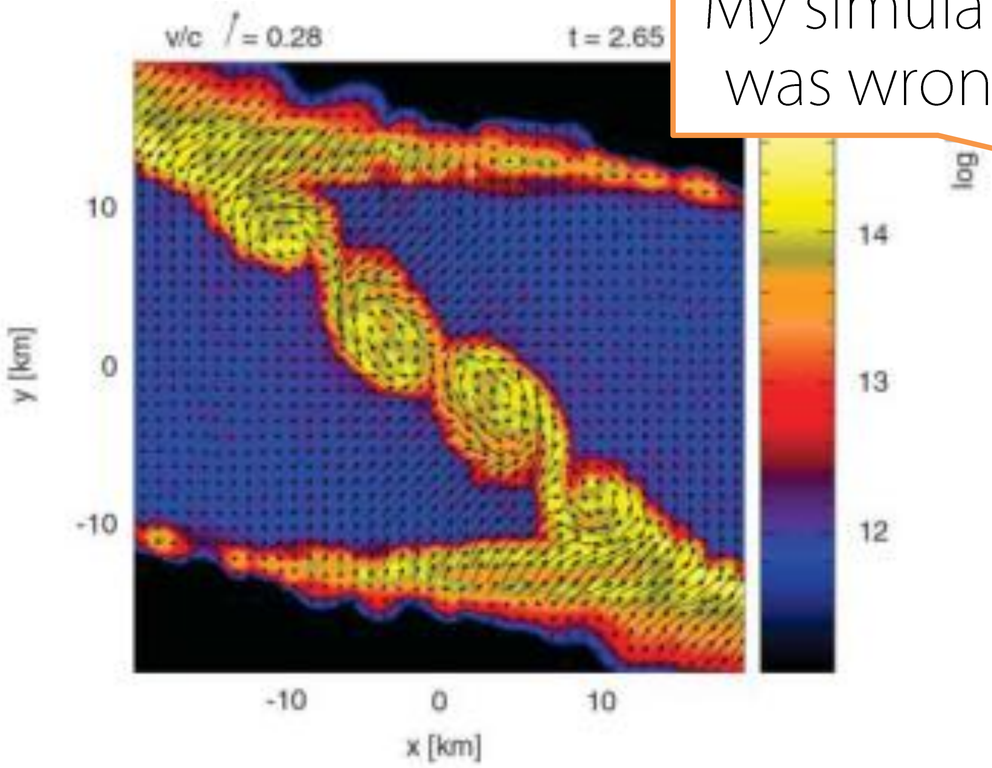
$k_{min} \propto g(\rho_1 - \rho_2)/(v_1 - v_2)^2$

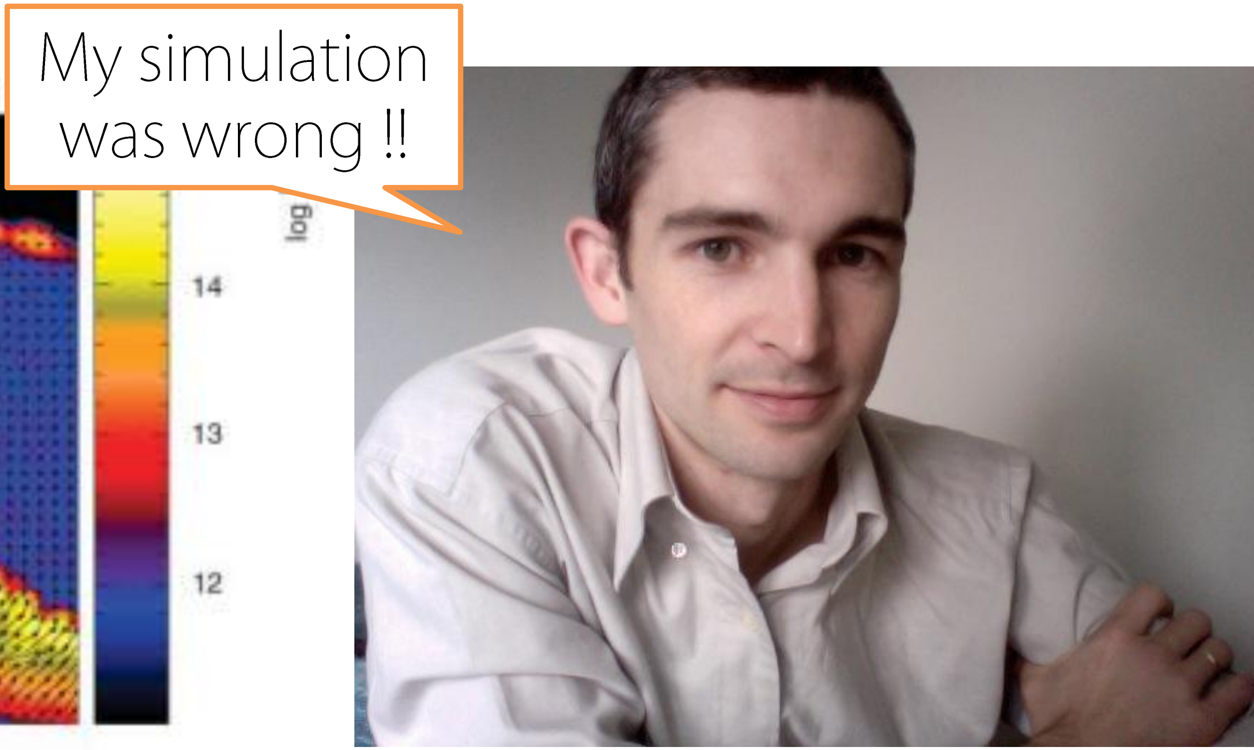
⇒ If g = 0, all the mode are unstable. Growth rate ∝ wave number



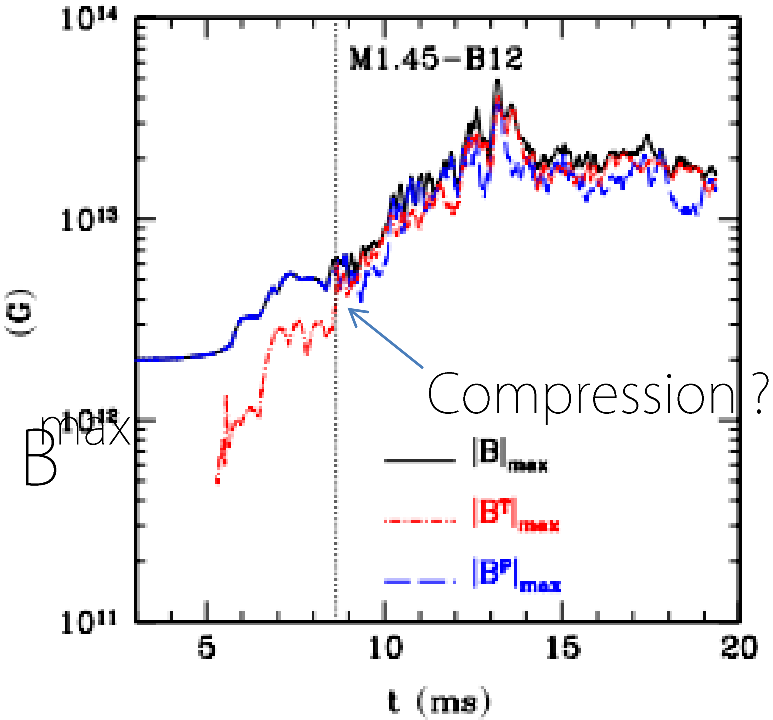


“Famous” study by Price-Rosswog (Price-Rosswog 06)



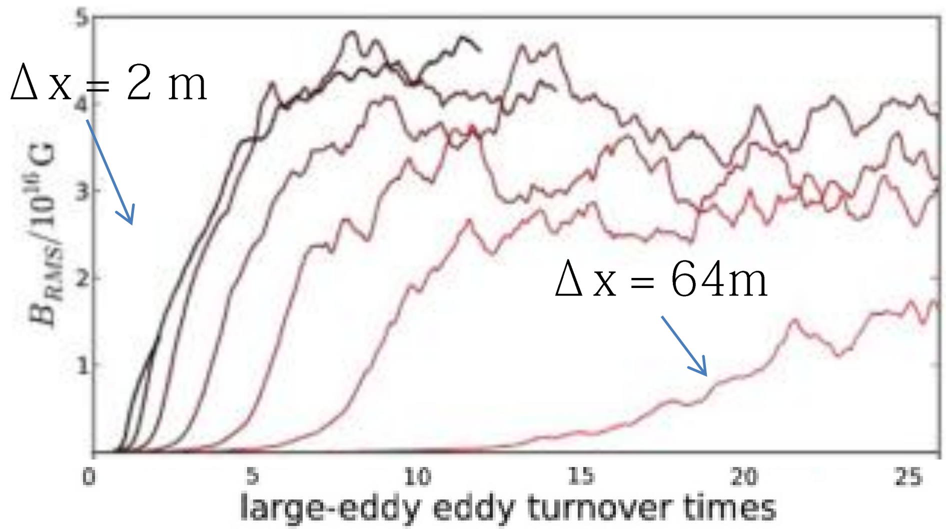


GRMHD by AEI (Giacomazzo et al. 11)



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

Time evolution of <B>

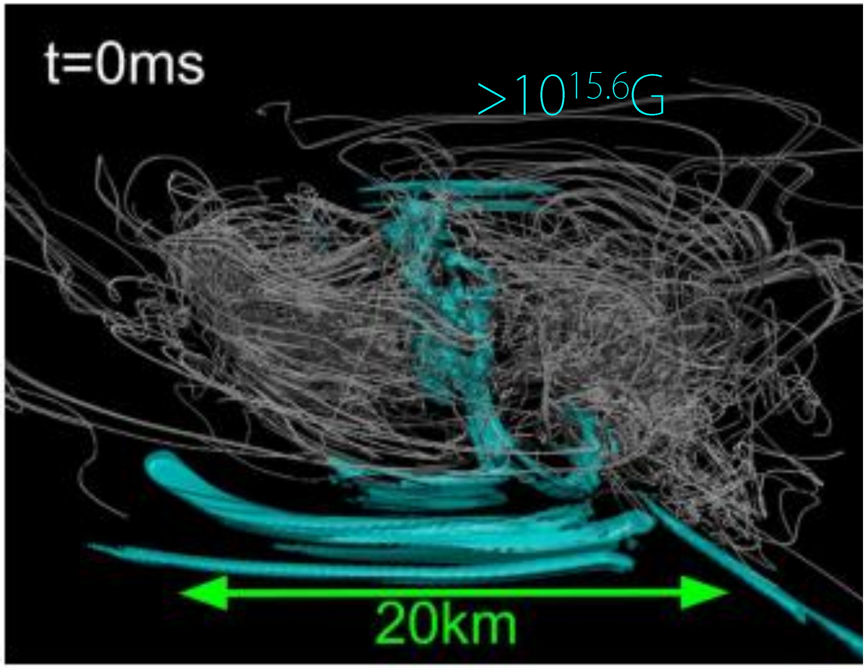


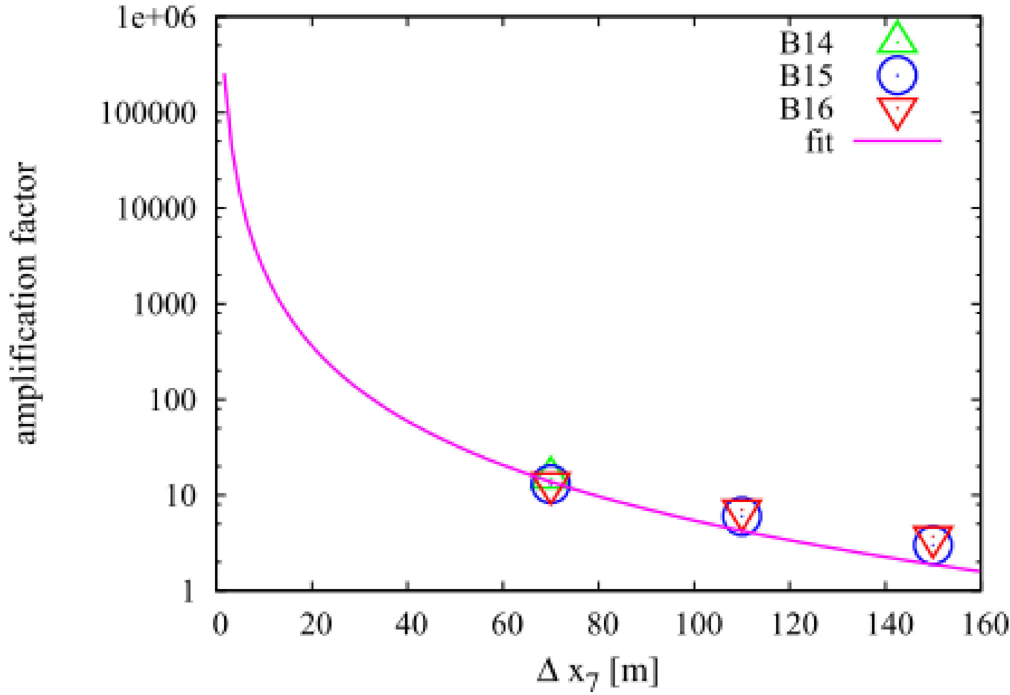
1=0.1ms

Can really the KH vortices amplify the B-fields ?

Yes !

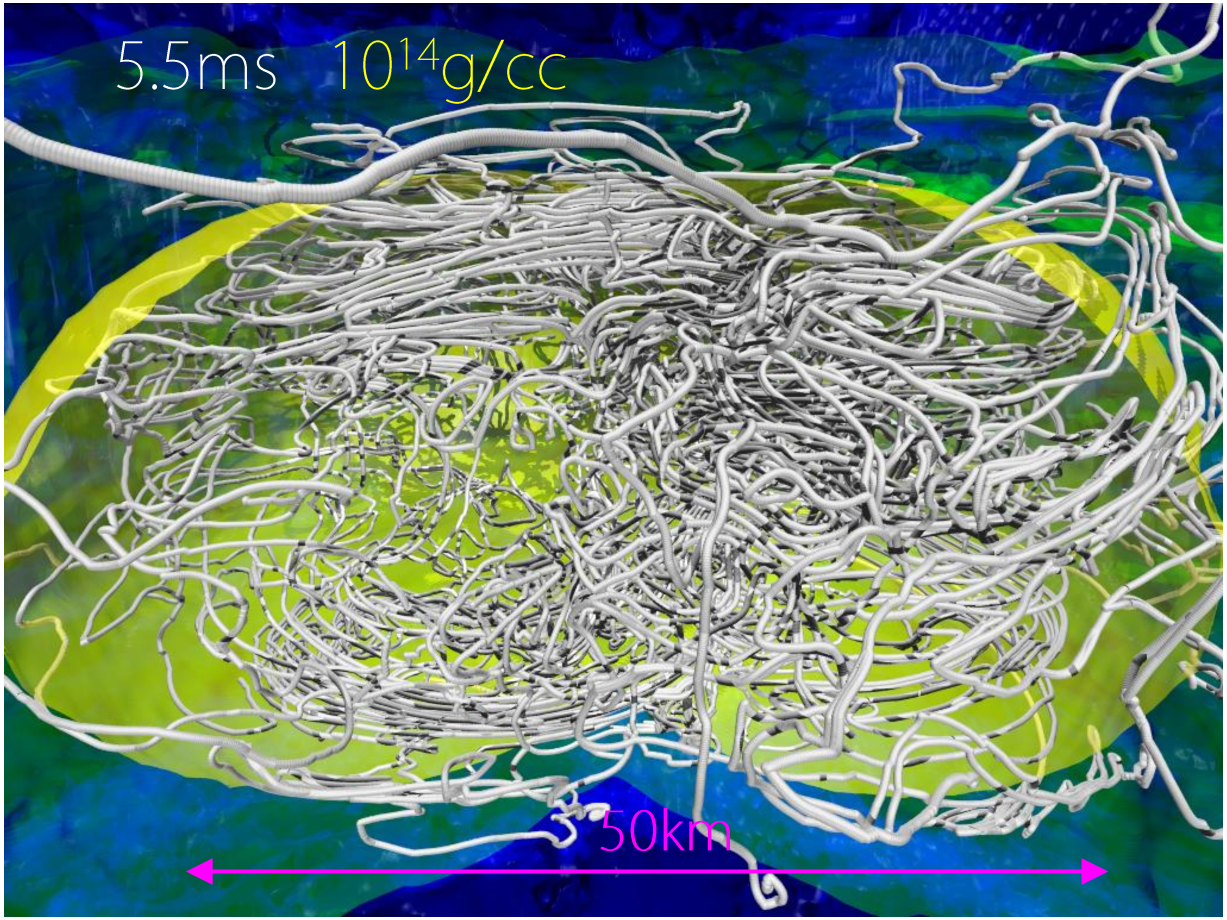
Field lines and strength @ merger　Amplification factor vs resolution





- 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



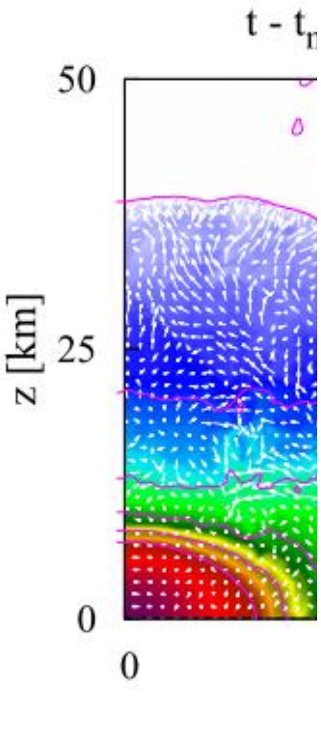
- ▶ Turbulent state inside HMNS
- ▶ HMNS is differentially rotating ⇒ Unstable against the Magneto Rotational Instability (Balbus-Hawley 92)
- ▶Magnetic winding works as well

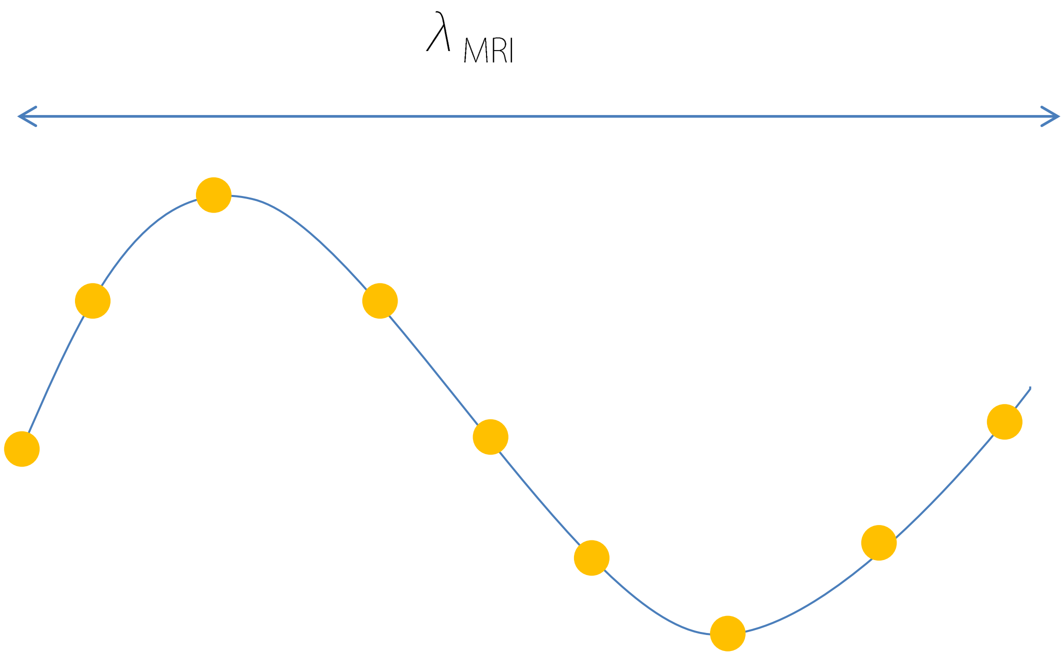
B-field amplification inside HMNS

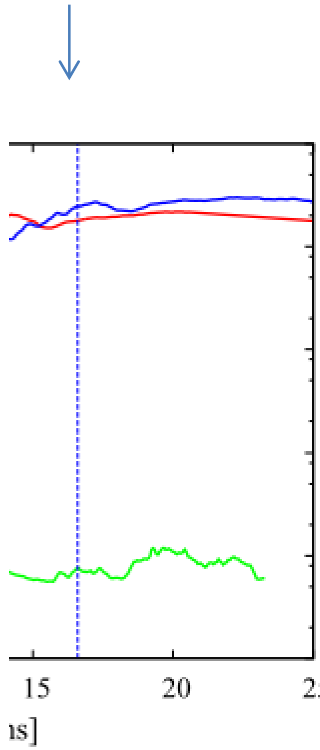
Density contour of HMNS (Meridional plane)

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

BH BH BH



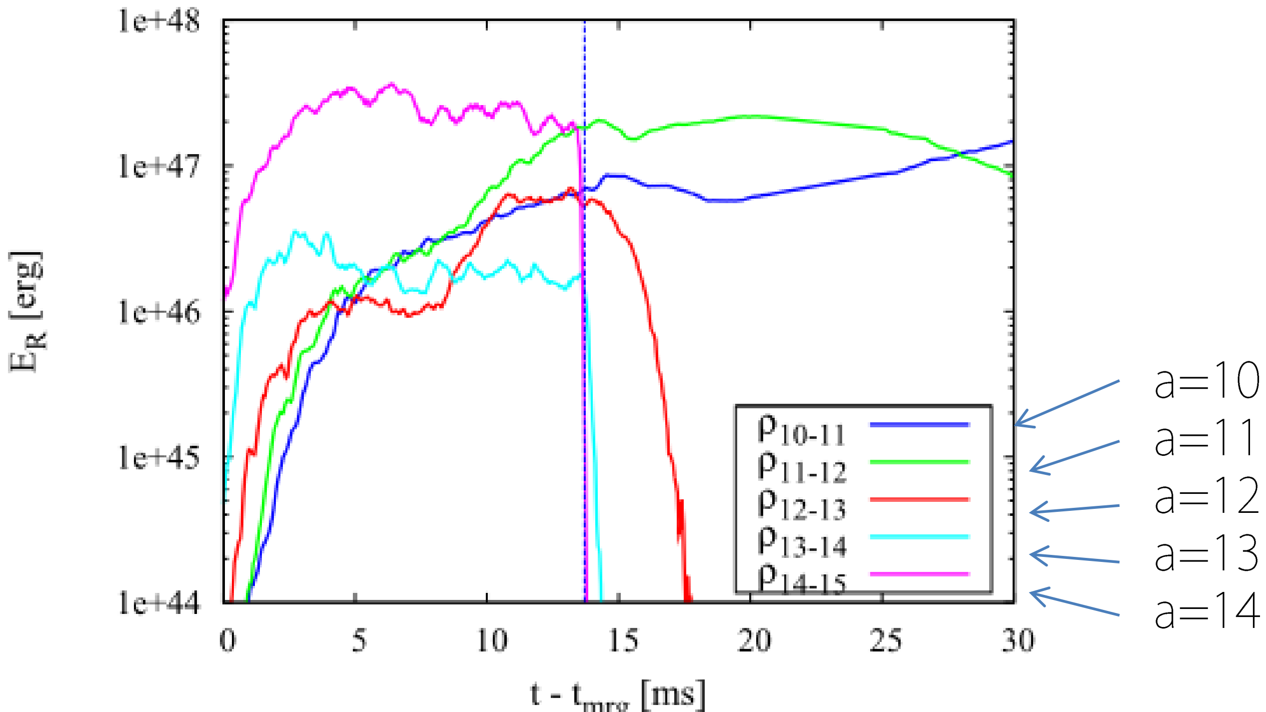




- $\lambda_{MRI} = B/(4\pi\rho)^{1/2}\, 2\pi/\Omega$
- The condition $\lambda_{MRI,\varphi}/\Delta x \gtrsim 10$ is satisfied for the high and medium run, but not in low run. B = Toroidal magnetic field
- Growth rate of B-fields for 8 - 14 ms ≈130-140Hz～O(0.01)Ω

B-field amplification inside HMNS

B-fields energy in10^ag/cc ≤ ρ ≤ 10^{a+1}g/cc   a=10-14 for high-res. run



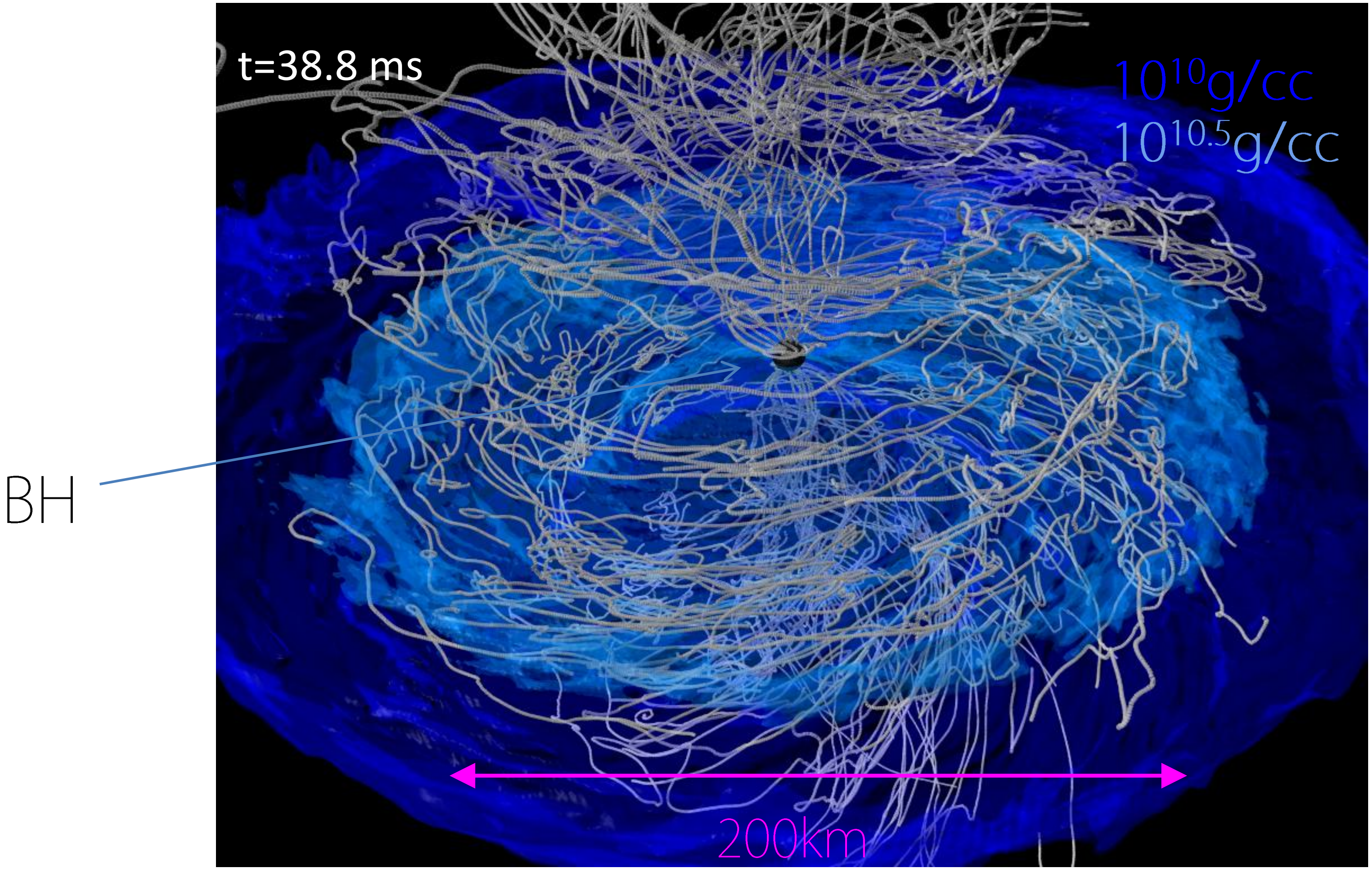
▶The high the density is, the high the growth rate is because of higher angular velocity

▶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

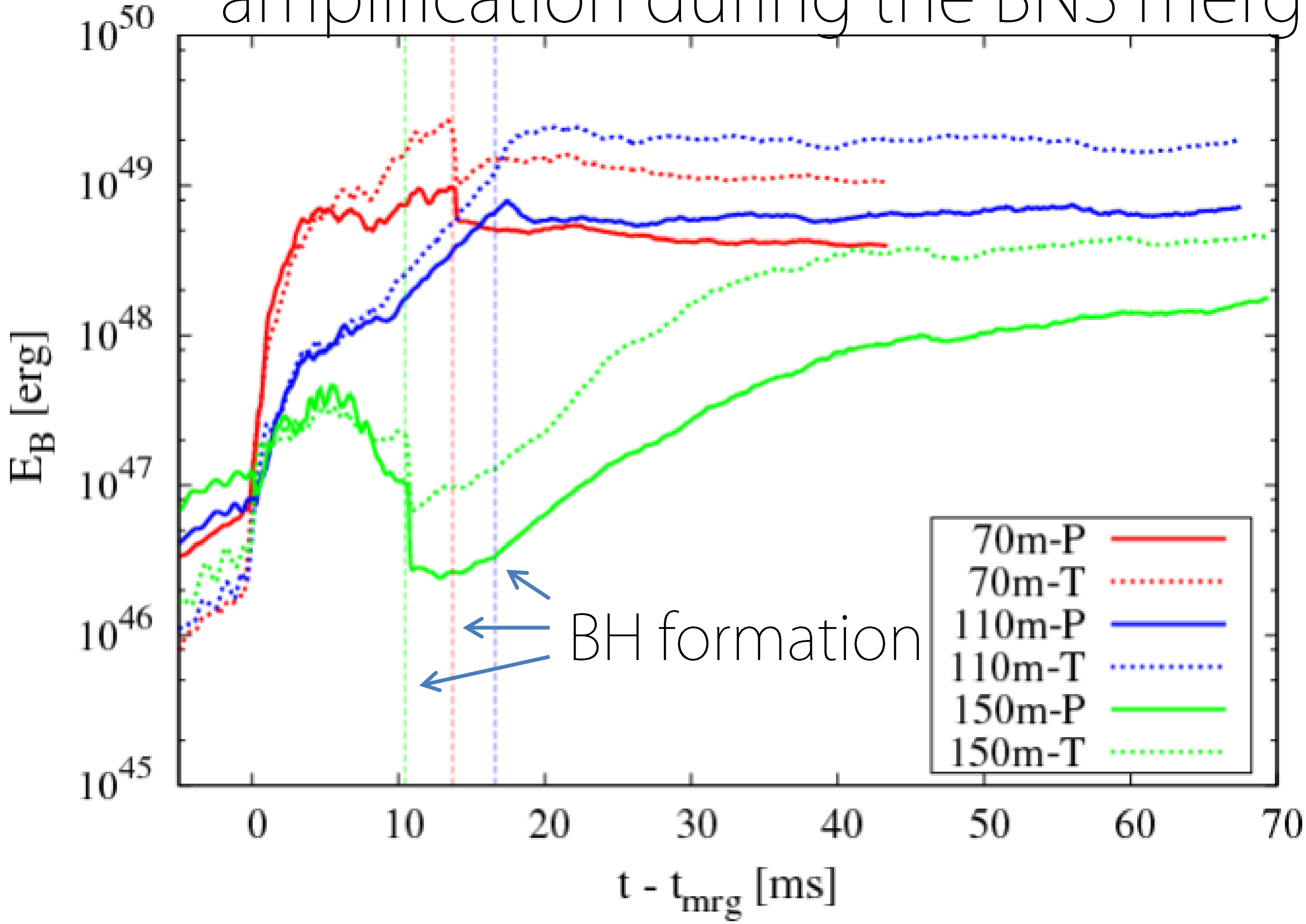
$B_\varphi \sim B_R\,\Omega\,t \sim 10^{16}G(B_R/10^{15}G)(\Omega/10^3 rad/s)(t/10ms)$

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)

Caveats

- Observation of the BNS ; $B_{dip} = 10^{12.2}$G
- We assume that B_{max} is 10^{15}G

The referee comment : the paper is certainly worth being published, the results are new, interesting and the work is very seriously done. The magnetic fields chosen, certainly for numerical reasons since the relevant wavelength increases with magnetic fields and lower field values would require still higher resolution, correspond to the highest magnetic fields observed for some magnetars. Therefore the present work is still a little academic.

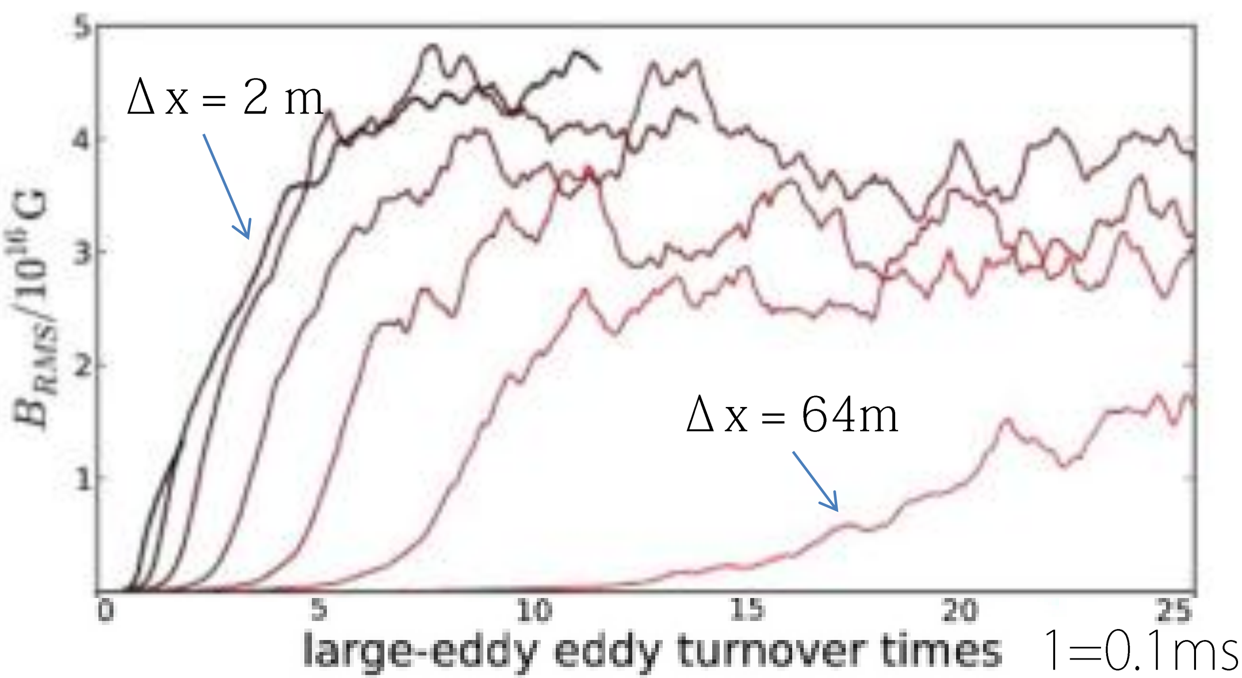
- We are not interested in the magnetar's merger.
- If you start more "realistic" value of the magnetic fields, say 10^{13} G, you need more grid resolution. Otherwise, such a simulation will be nonsense.

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

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

- $L \sim 1$ km
- SRMHD
- $\Delta x = 1, 2, 4, 8, 16, 32, 64$ m (N=1024^3, 512^3, 256^3, 128^3, 64^3, 32^3, 16^3)
- $B_0 = 10^{11}$G

Time evolution of <B>

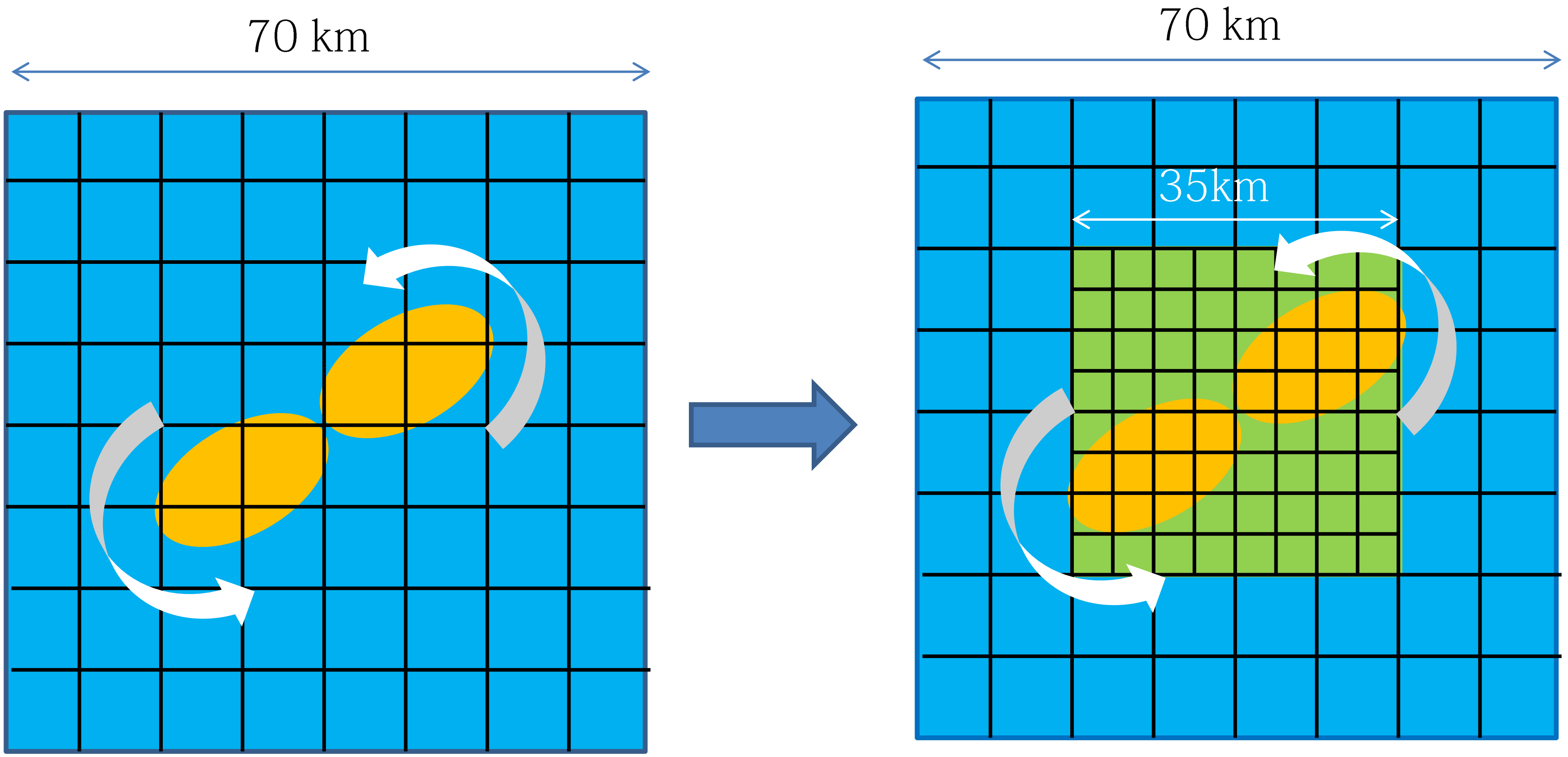


Amplification factor $\sim 10^5$, $E_B \approx 0.6 E_K$

But, this is the ideal setup

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.



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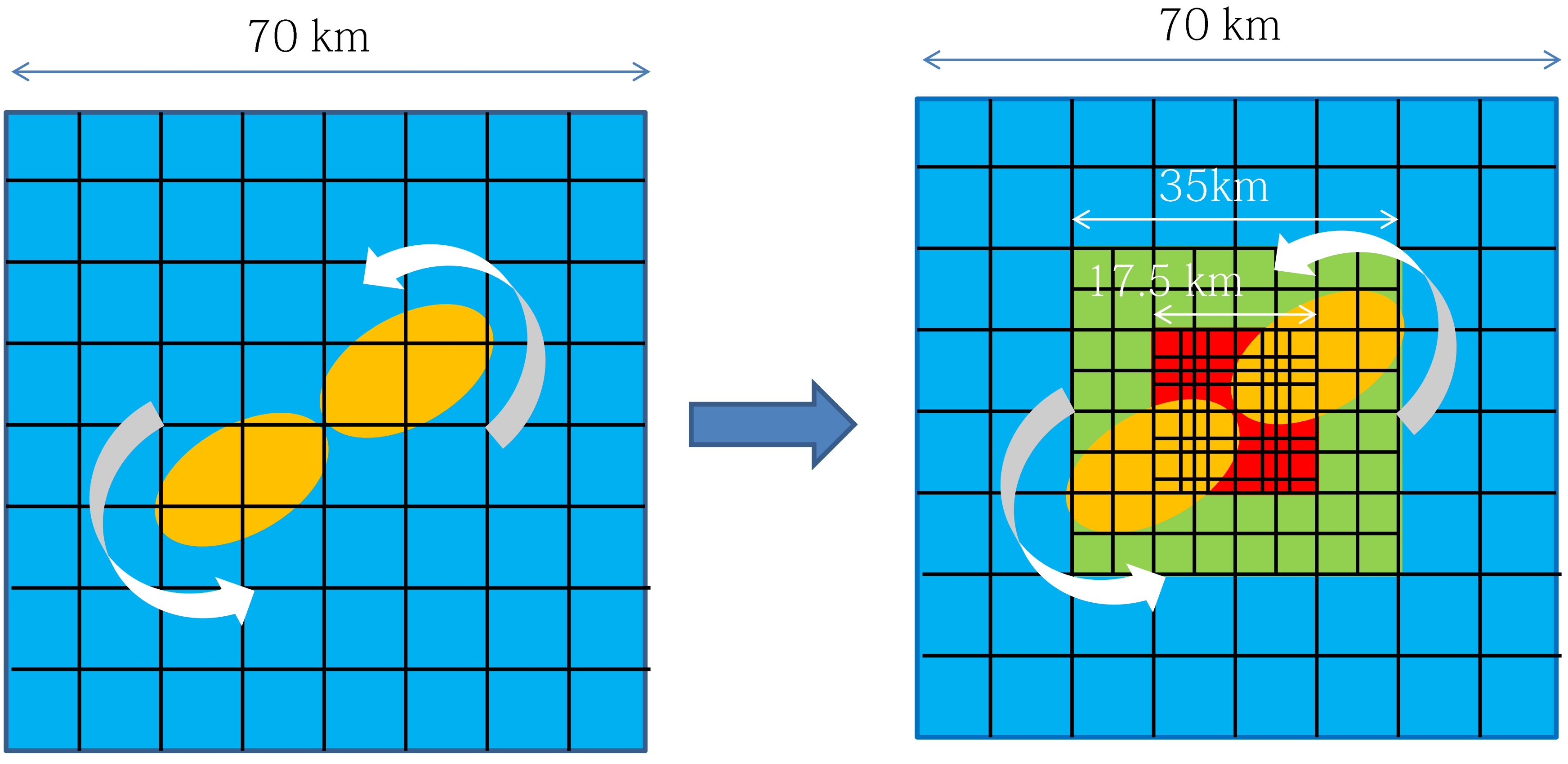


B-fields amplification via Kelvin-Helmholtz

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

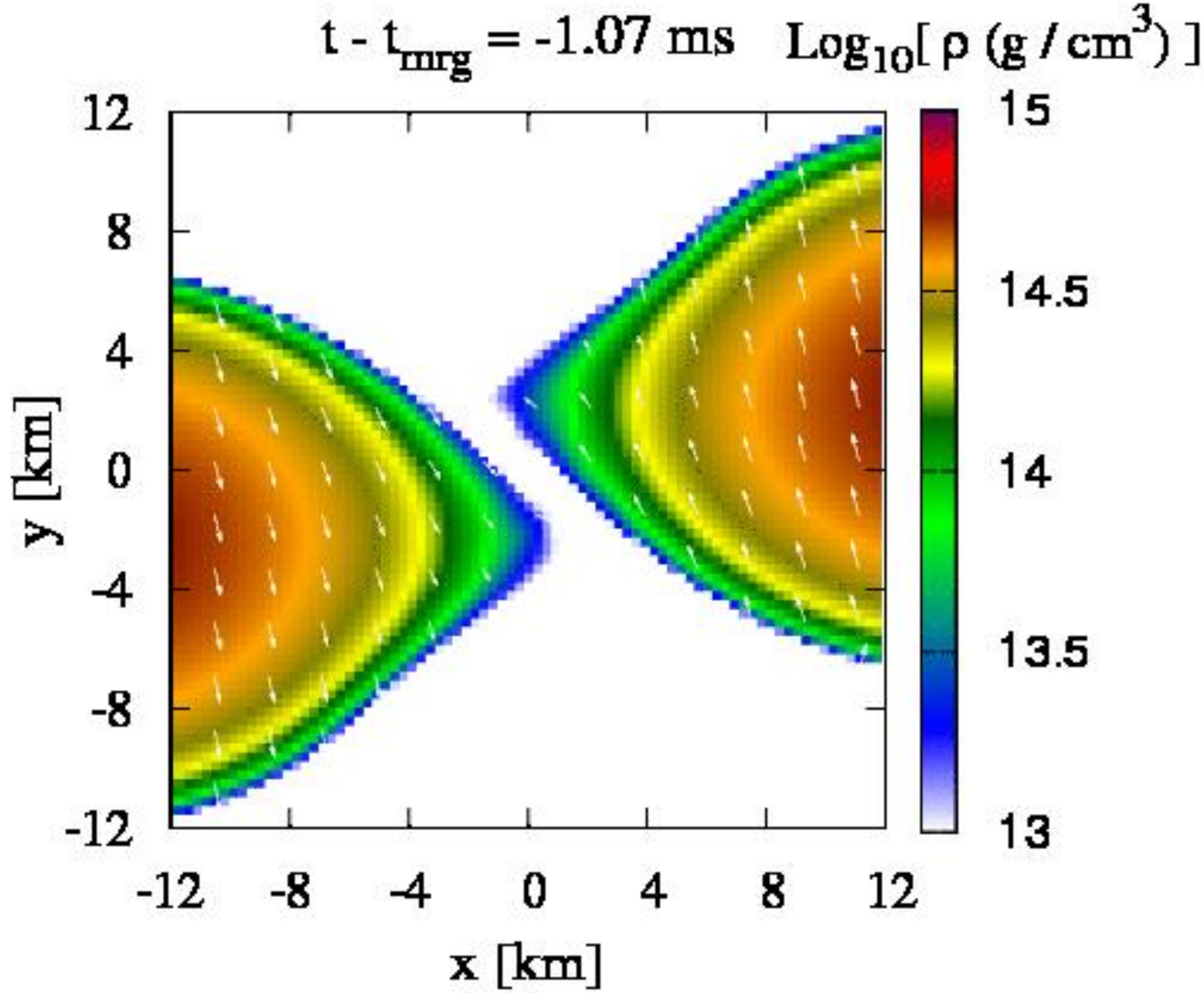
(ia) $\Delta x = 150$m ; no increase the FMR box
(ib) $\Delta x = 150$m $\Rightarrow$ 75m ; one FMR box is added
(ic) $\Delta x = 150$m $\Rightarrow$ 75m $\Rightarrow$ 37.5m ; two FMR boxes are added

(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

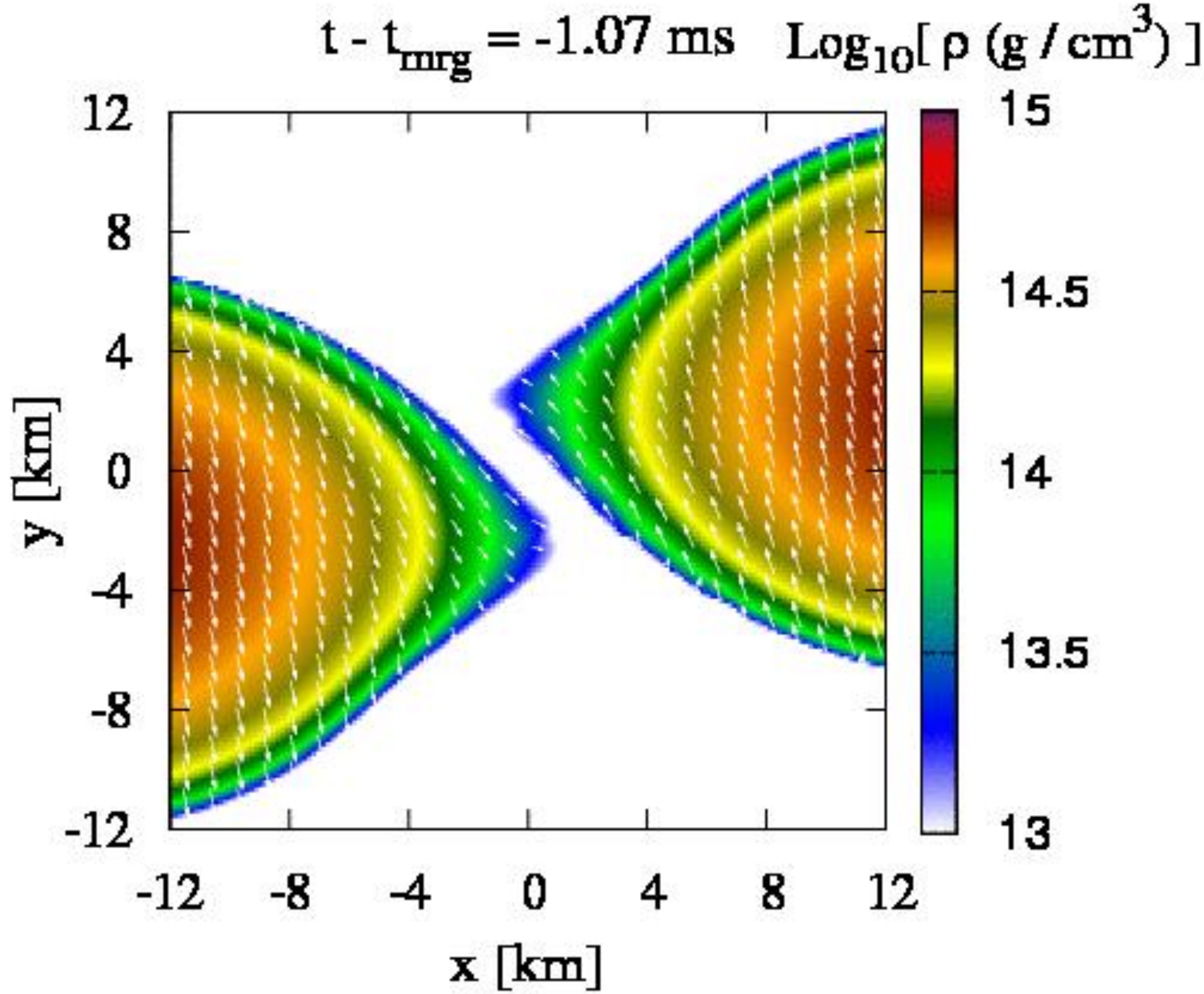
(iiia) $\Delta x = 70$m ; no increase the FMR box
(iiib) $\Delta x = 70$m $\Rightarrow$ 35m ; one FMR box is added
(iiic) $\Delta x = 70$m $\Rightarrow$ 35m $\Rightarrow$ 17.5m ; two FMR boxes are added

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

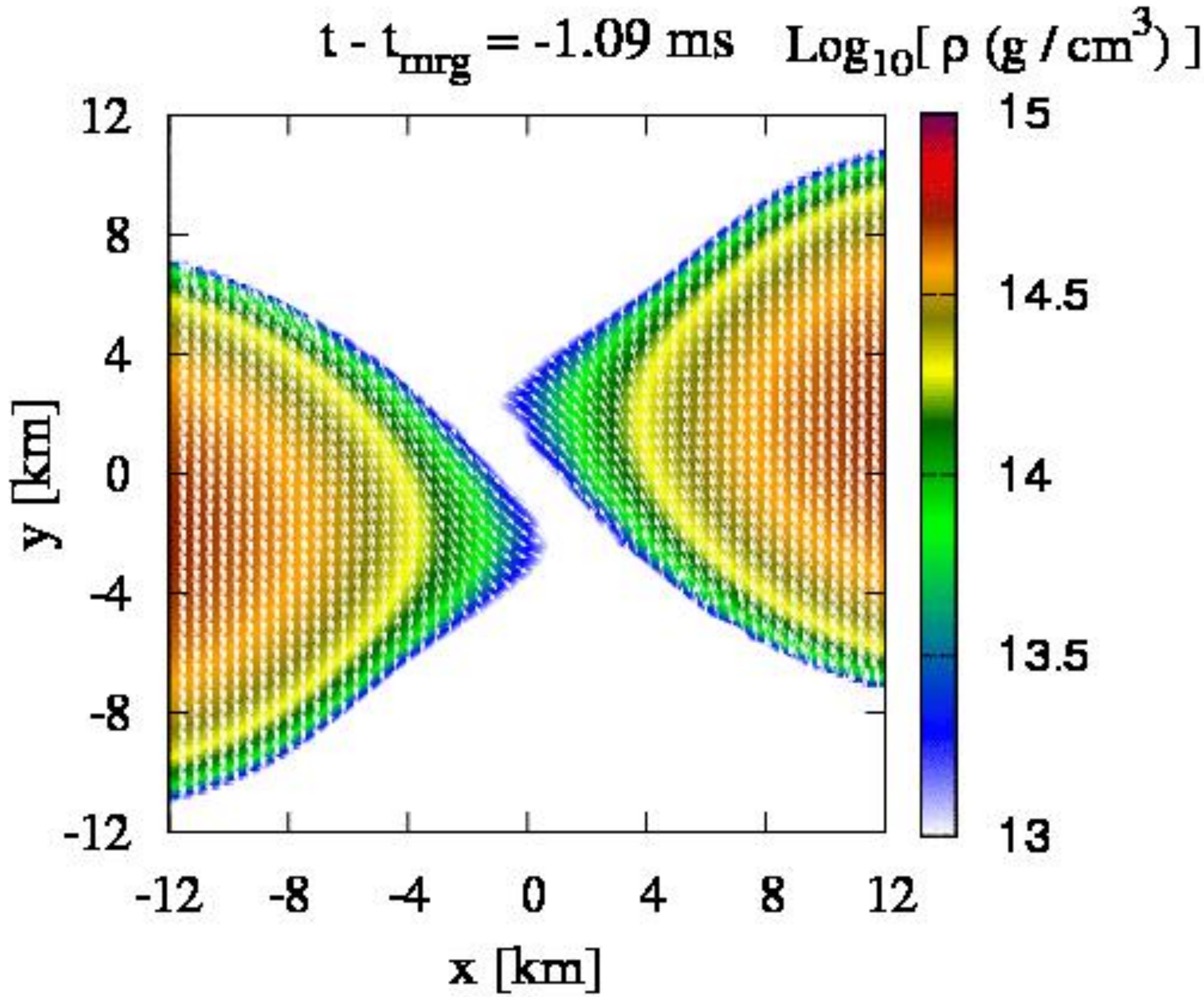
Density and vel. field on the orbital plane (Δx=150m)



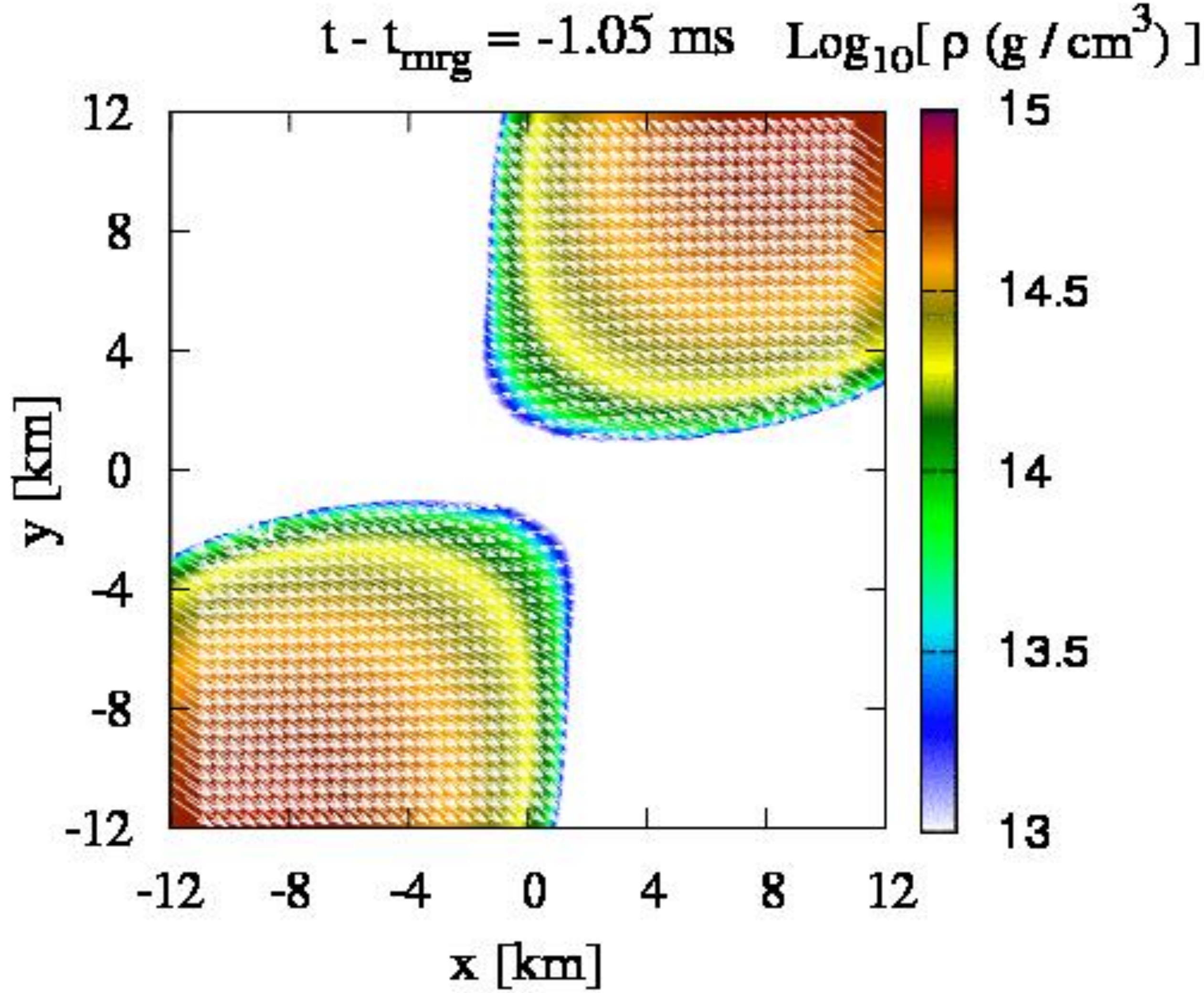
Density and vel. field on the orbital plane (Δx=150m→75m)



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

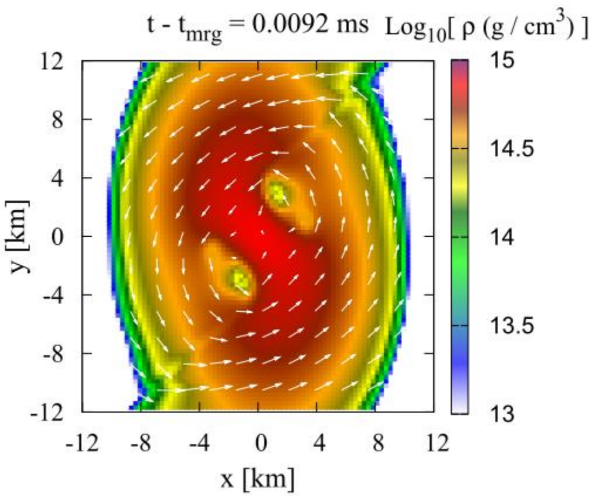


Density and vel. field on the orbital plane
(Δx=70m→35m→17.5m)

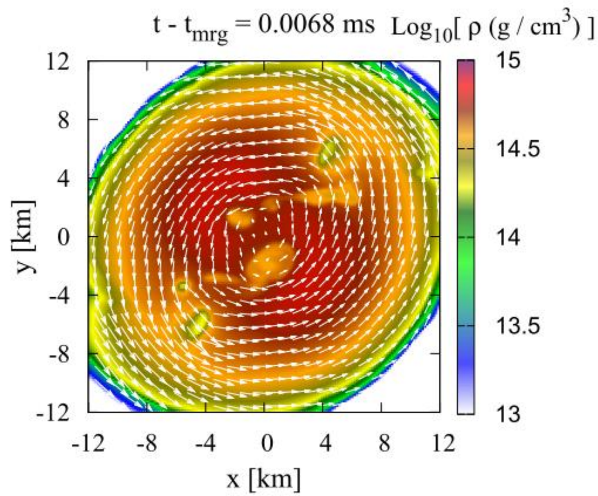


Density and vel. field on the orbital plane

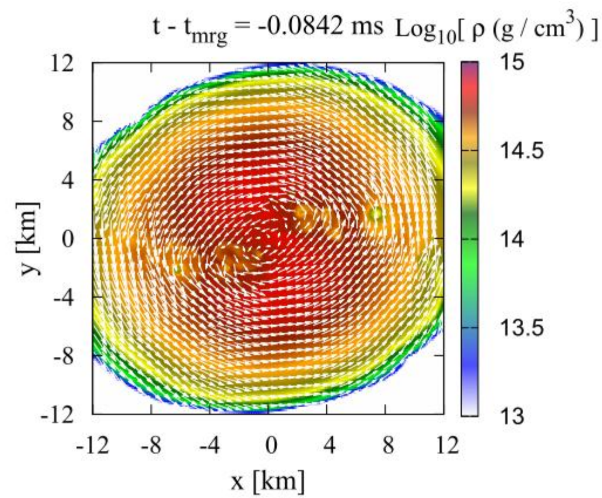
(Δx=150m)



(Δx=150m→75m)



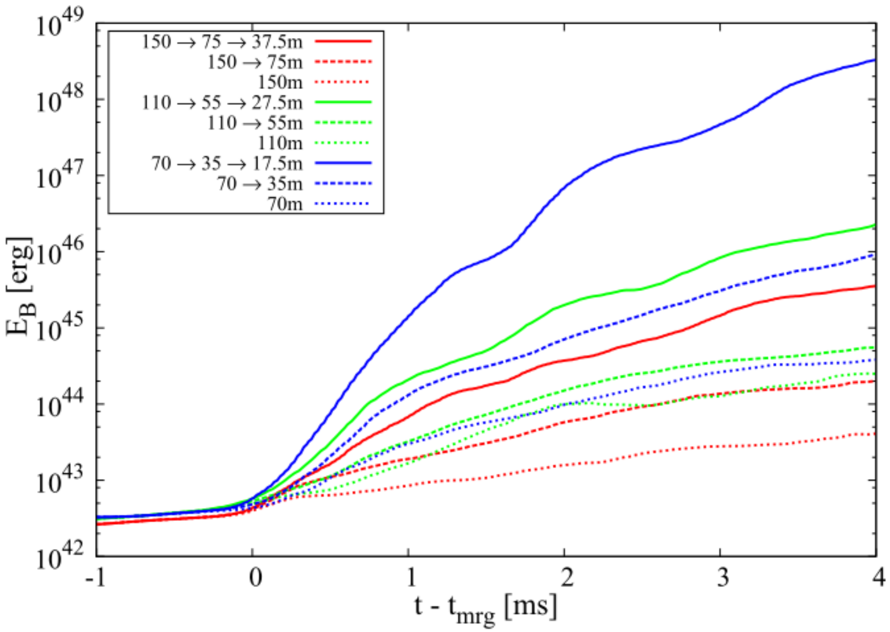
(Δx=150m→75m→37.5m)



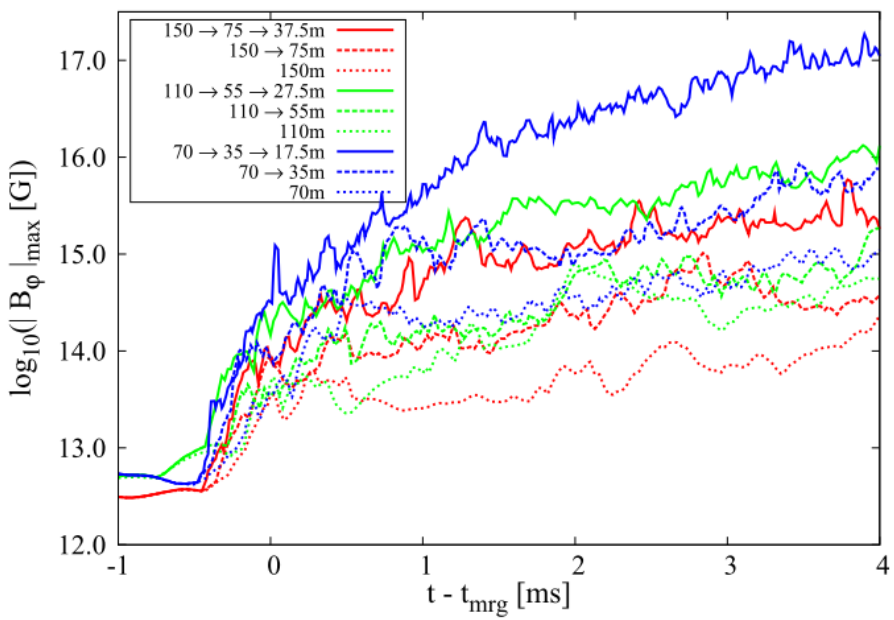
→ Real

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 ?

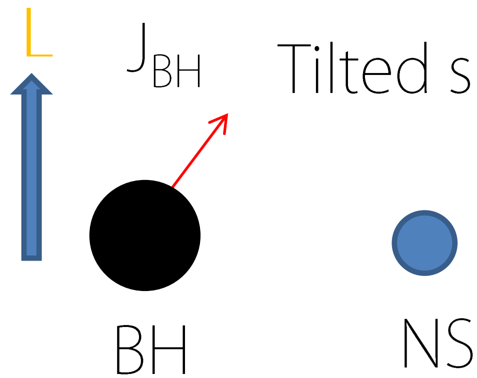
▶Angular momentum transport by Reynolds / Maxwell stress ?

▶What happens if the B-fields are dissipated ?

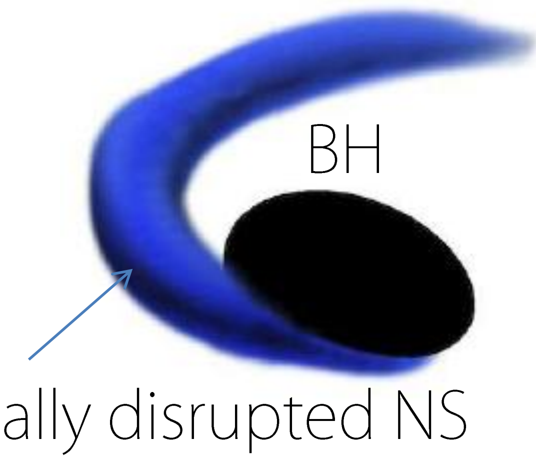
XC-S結果報告

▶ Simulation set up

BH – magnetized NS binary merger ; tilted BH spin case



Tilted spin



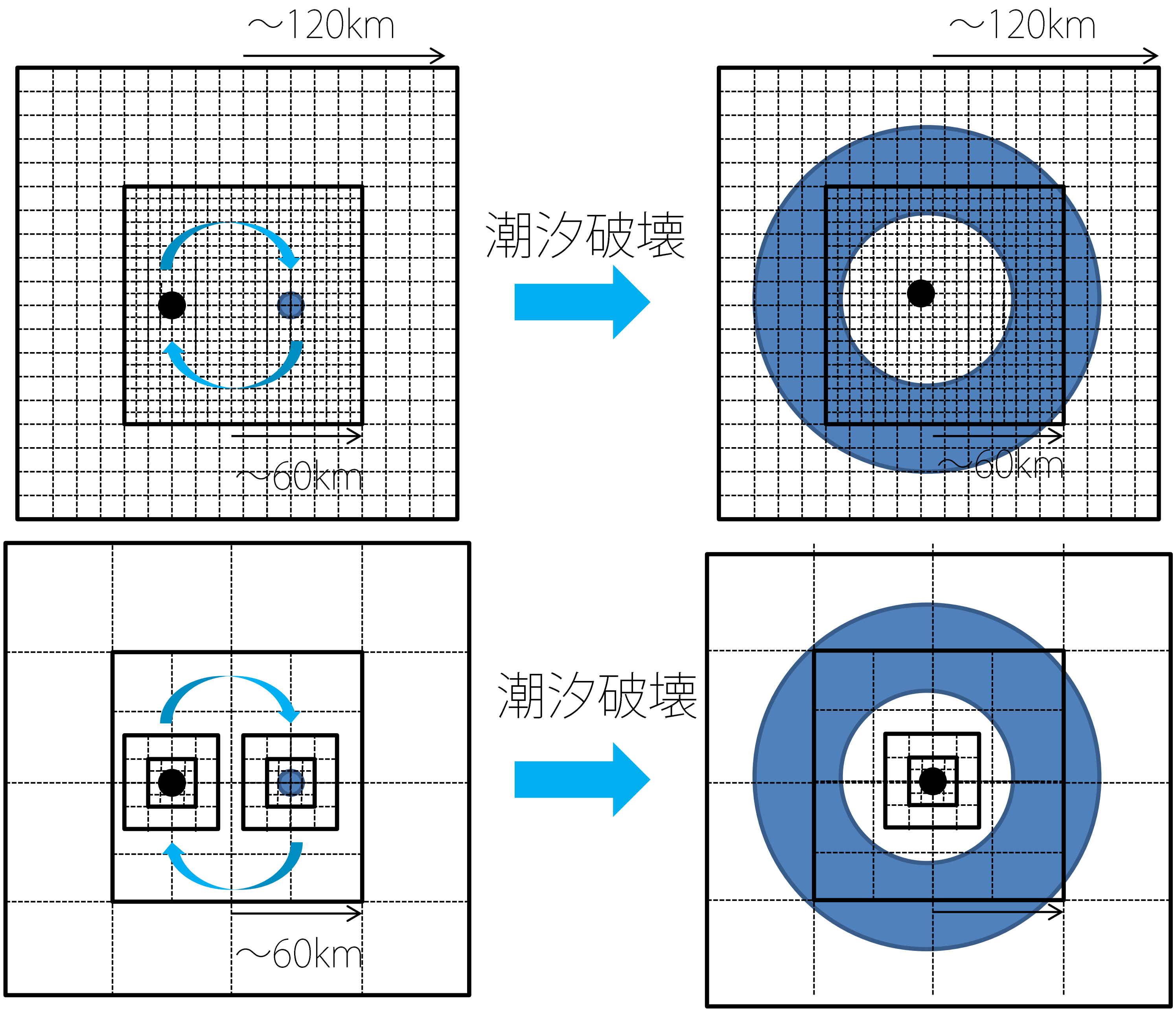
(Foucart+11,12)

▶ Simulation size

Nested grid structure ; N*level=$1{,}118^3$*10, Δx_{fine}=120m

（cf. 先行研究 N*level=100^3*10, Δx_{fine}=150m）

磁気流体計算は解像度が本質的



XC-S結果報告

▶ 1/7-1/8に大規模実行（→石津さん日程、調整ありがとうございました。）

▶ ノード使用数：1728 MPI process (20736 core)

*コードの仕様上、全ノード使用は出来ない

▶ 2823分実行　→　物理時間にして約9ミリ秒

▶ 実行効率

N	node	Einstein part (sec./ factor)	MHD part(sec./ factor)	Recovery part (sec./ factor)	Total(sec./ factor)	理論値（単ノード）
92	1728	0.089(1.08)	0.081(1.25)	0.064(1.31)	214.17(1.04)	2.12
82	512	0.063(1.52)	0.058(1.7)	0.045(1.85)	143.26(1.56)	3
82	512	0.096(1)	0.102(1)	0.084(1)	223.23(1)	1

*単体ノード性能：アテルイ（HASWELL）／アテルイ（Xeon）=3

*Nはグリッド数／ノード／方向

512ノード使用時とほぼ同じ効率～実行効率5-6%

科学的な結果を出すには時間が足りない。

Summary

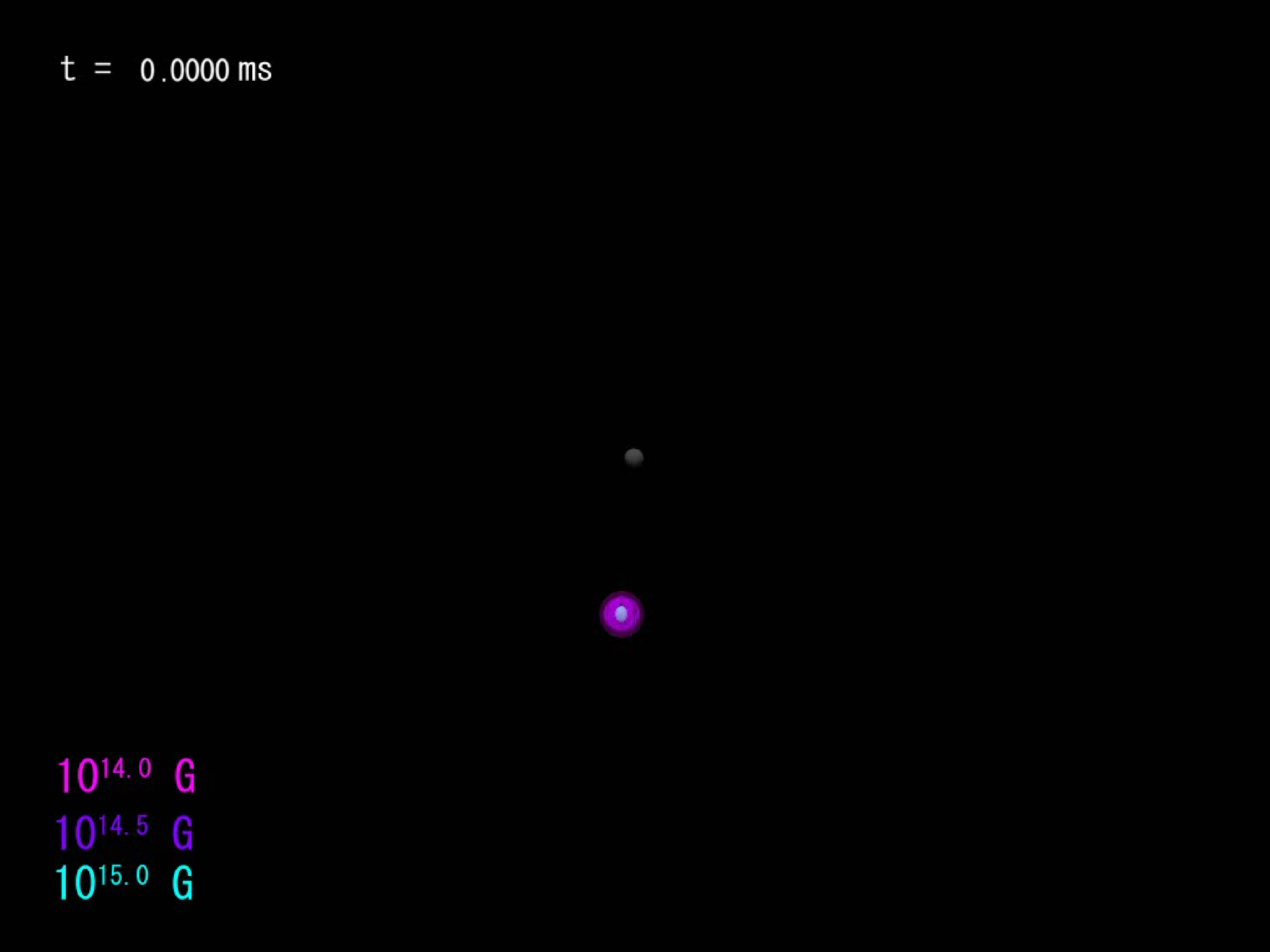
We are figuring out the physical process of BNS merger and constructing the physical modeling of BNS merger.

B-fields
▶ Kelvin-Helmholtz instability at the merger
▶ Non-axisymmetric MRI inside the HMNS
are key ingredients.

Necessity to launch an outflow to build a global poloidal magnetic field. => Magnetically driven wind ?

▶ KH instability amplifies the B-field whose strength is greater than the magnetar's field.


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