Recent progress of compact binary merger simulations in Kyoto numerical relativity group

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Ref.) PRD 90, 041502(R) (2014), Kiuchi et al. 15

YITP
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K computer

Talk plan

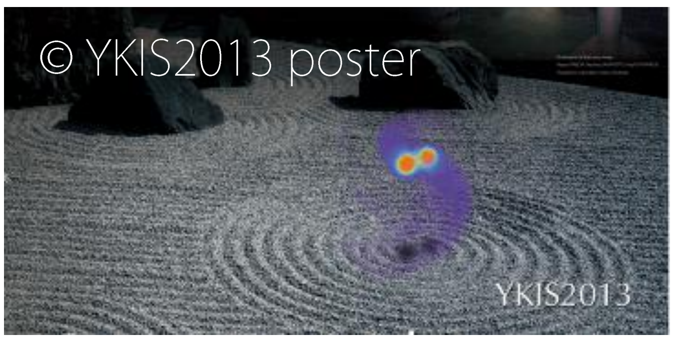
- ▶ Motivation ; why do we want to know compact binary mergers ?
- ▶ Neutron star (NS) – neutron star (NS) merger simulation ; Effect of the magnetic field
- ▶ Black hole (BH) – neutron star (NS) merger simulation ; Effect of the magnetic field
- ▶ Summary

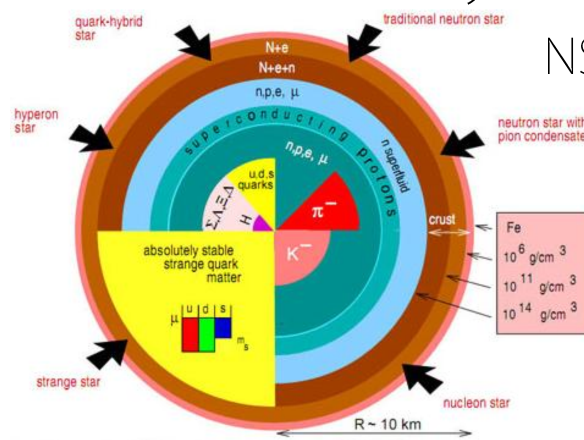
Motivation

Gravitational waves = Ripples of the spacetime

- Verification of GR
- The EOS of neutron star matter (Lattimer & Parakash 07)
- The central engine of short gamma-ray bursts (Narayan et al. 92)
- A possible site of the r-process synthesis (Lattimer & Schramm 74)

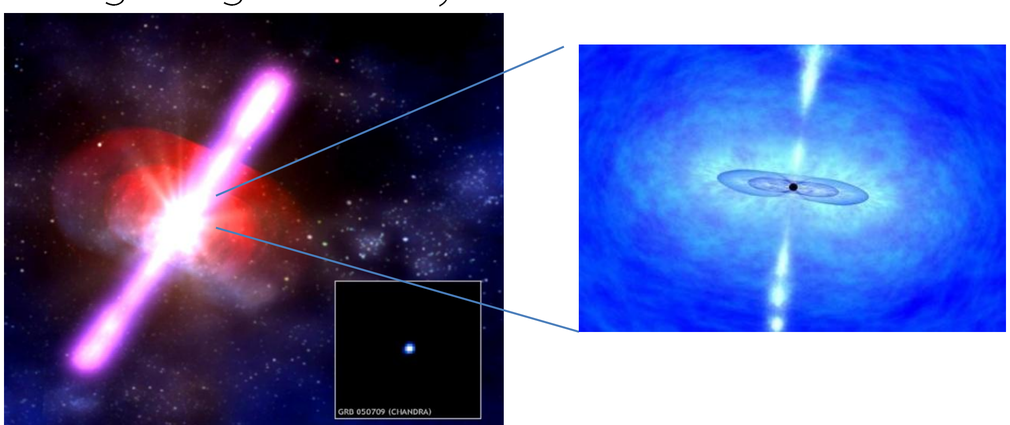
Advanced LIGO will observe ~10 events / yr.





NS interior

Image of gamma-ray burst



Colliding Neutron Stars Produce Gold ?

A step toward the physical modeling of compact binary 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

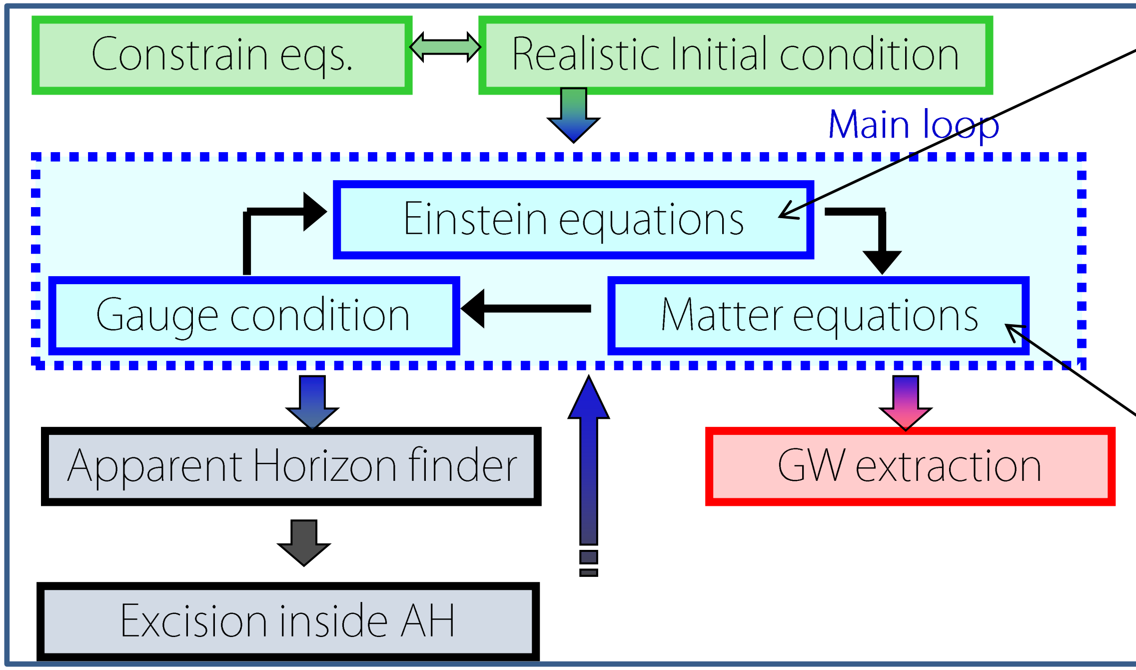
$$\nabla_\mu T^{\mu\nu} = 0, \quad T^{\mu\nu} = T^{\mu\nu}_{(\mathrm{fluid})} + T^{\mu\nu}_{(\mathrm{rad})} + T^{\mu\nu}_{(\mathrm{EM})}$$

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

Equation of state (Closure relation)

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

Current status of Numerical Relativity



Slide courtesy of Sekiguchi

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

General Relativistic Magneo Hydro Dynamics (GRMHD)

- Formulation by Shibata-Sekiguchi, and Duez et al. (Shibata & Sekiguchi 05, Duez et al. 05, Dionysopoulou et al. 13)

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)

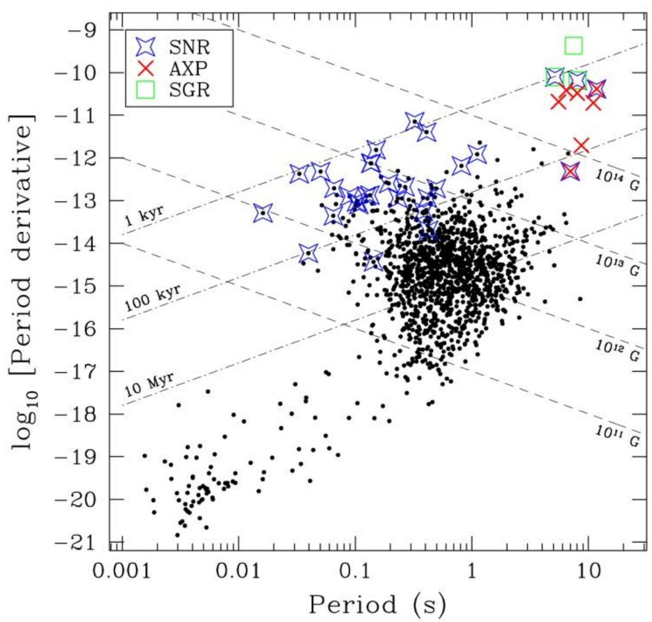
Kyoto NR group approaches from two directions;

- 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

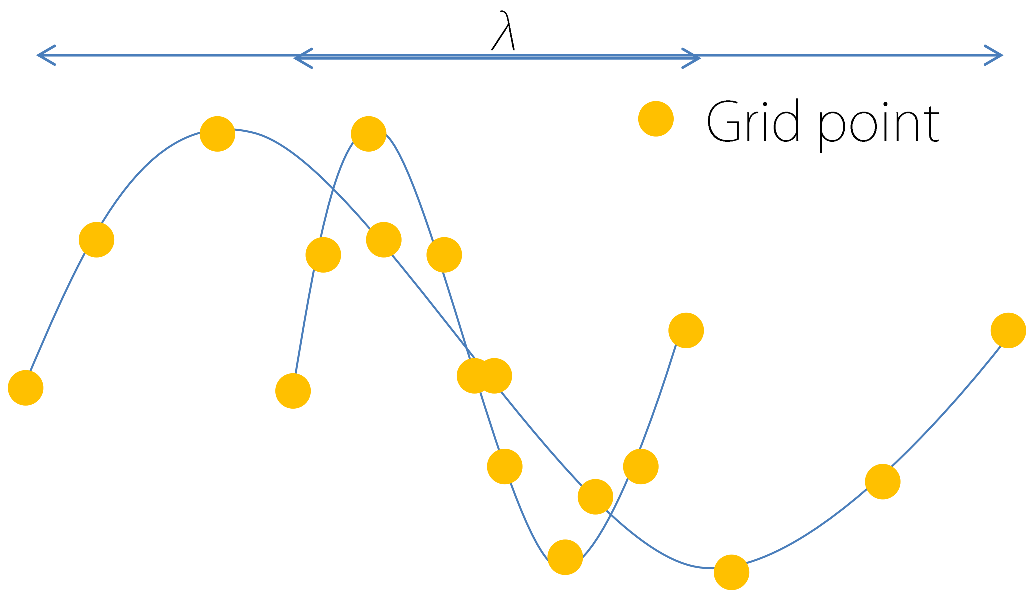
$P - \dot{P}$ Diagram



Difficulty in MHD simulations

- A short wavelength mode has a high growth rate.
- Turbulent eddies are killed by a numerical viscosity.

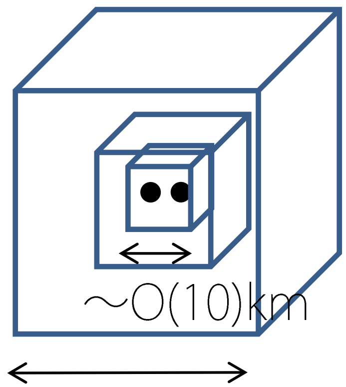
Mandatory to do an in-depth resolution study, which is lacking in a bunch of the simulations .



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

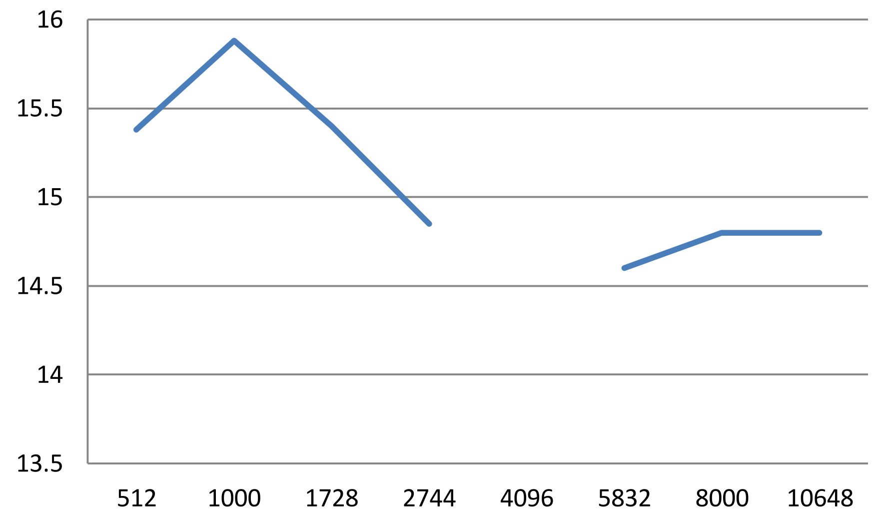
Kyoto NR-MHD code

Nested grid (KK et al12)



O(1000) km ≳ GW length～several 100 km

Execution performance (%) (Weak scale)



Node number (core ＝8×node)

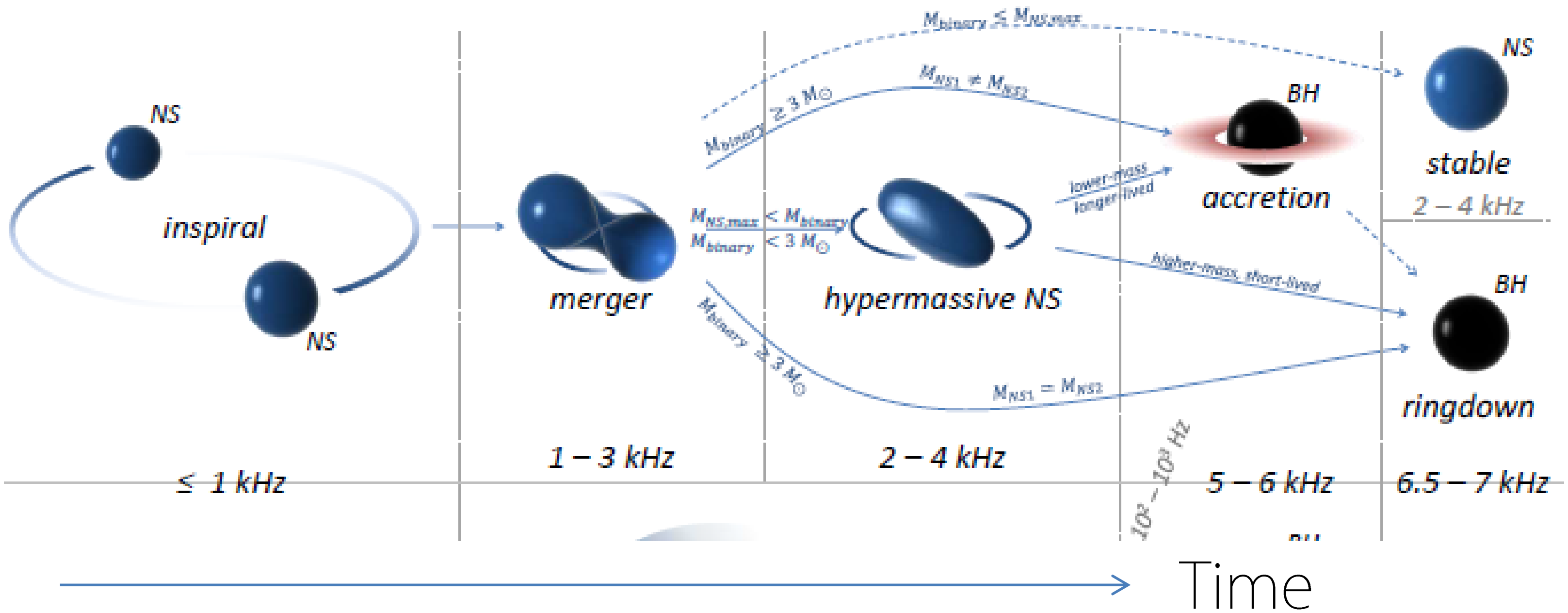
▶ Interpolation of B-fields on the refinement boundary is non-trivial：Flux conservation and Div B＝0 (KK et al 12, Balsara 01)

▶MPI communication rule is complicated, e.g., refinement boundary

▶Good scaling up to about 80k cores

Overview of NS-NS mergers

(Bartos et al. 13)



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

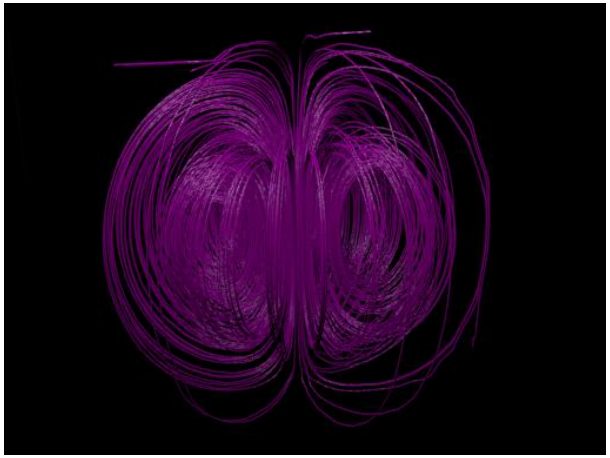
▶Observed mass of the binary NSs 2.6-2.8$M_\odot$ (Lattimer & Prakash 06)
⇒ It is a "realistic" path that a BH-torus is formed via hypermassive NS (HMNS) collapse.

Numerical Relativity simulation of magnetized binary NS 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, Coarsest grid =4480km^3 （N～10^9），a long term simulation of about 100 ms

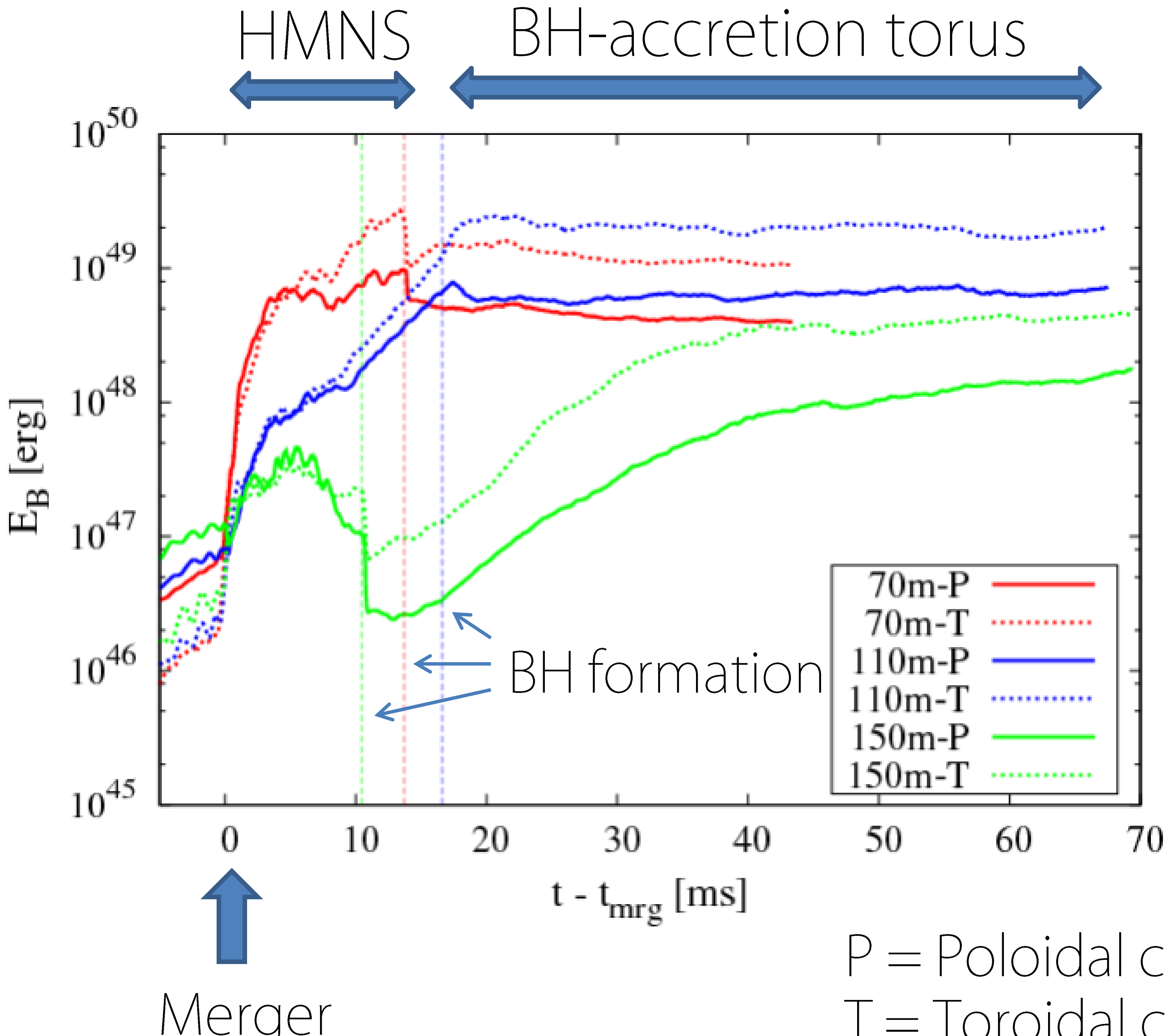
Magnetic field lines of NS



<u>Fiducial model</u>

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

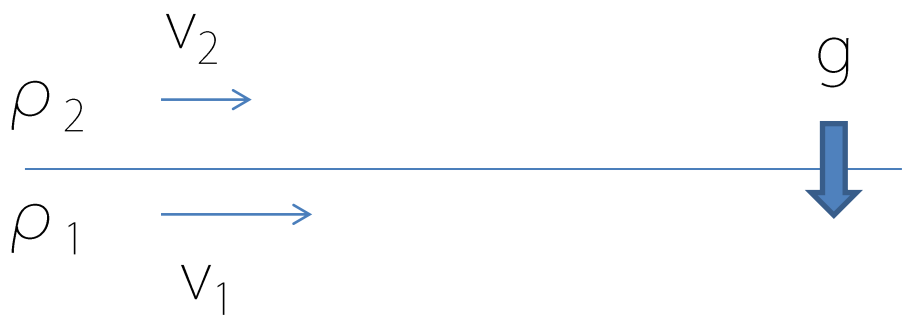
Evolution of the magnetic field energy



P = Poloidal comp.
T = Toroidal comp.

Amplification @ the merger (Rasio and Shapiro 99)

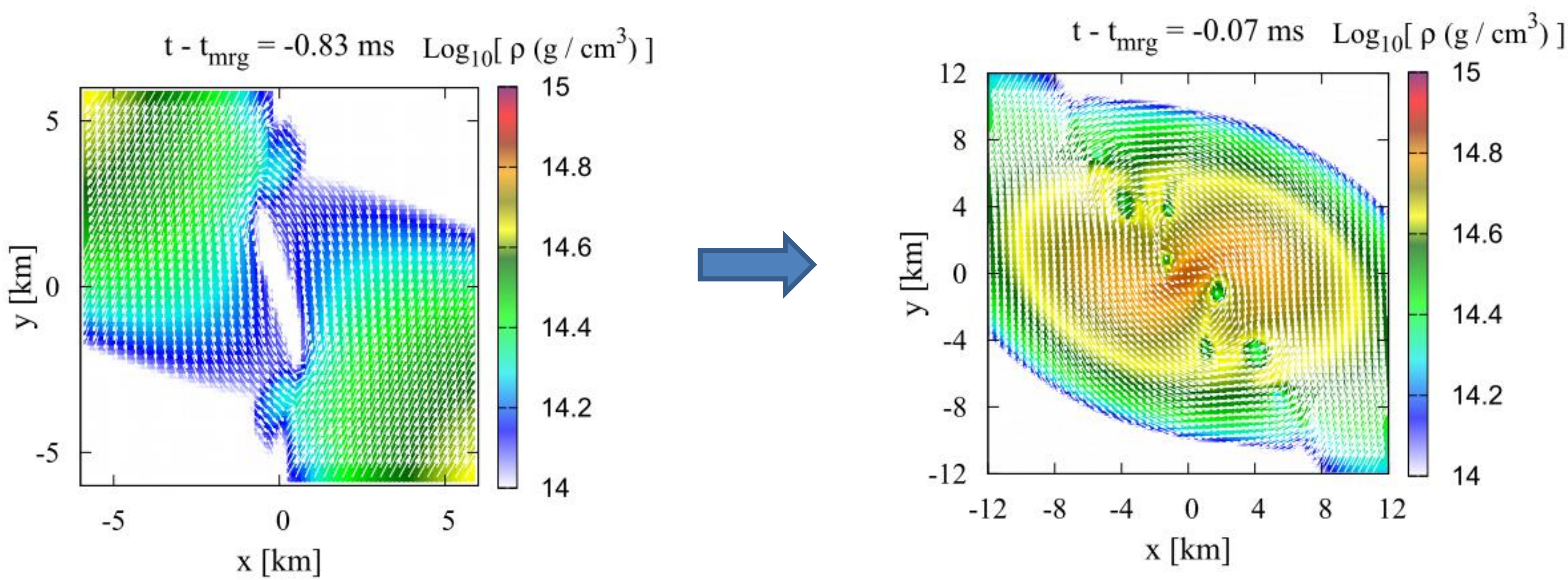
Kelvin Helmholtz instability



Minimum wave number of the unstable mode ;

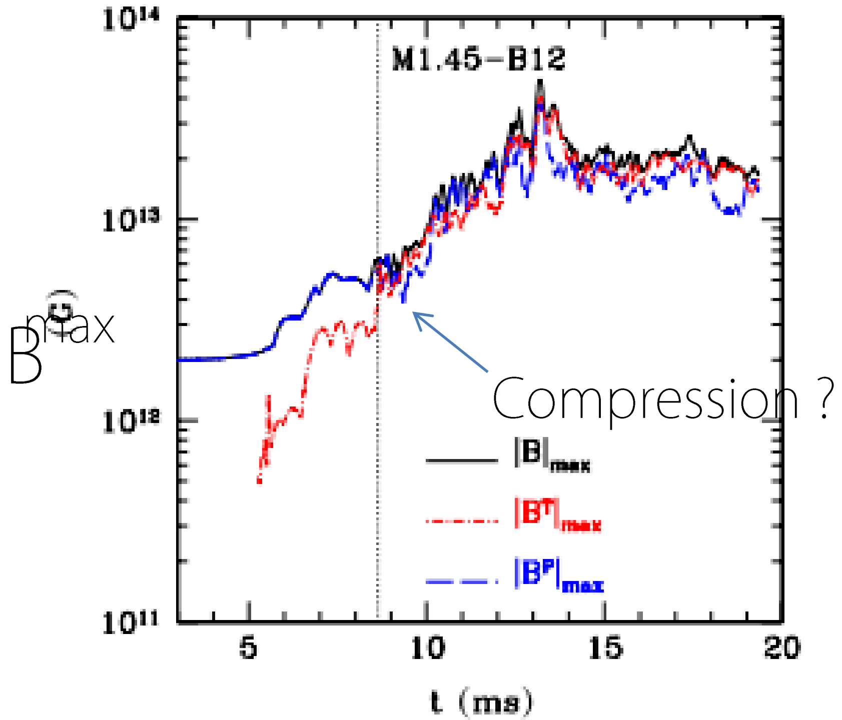
$k_{min} \propto g(\rho_1 - \rho_2)/(v_1 - v_2)^2$

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



Kelvin-Helmholtz instability (Rasio-Shapiro 99)

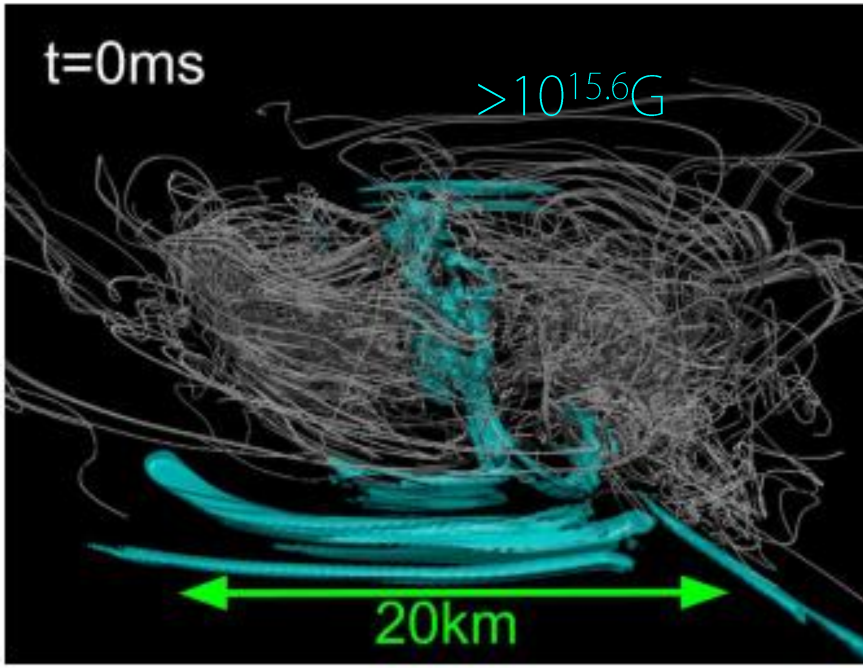
GRMHD by AEI (Giacomazzo et al. 11)

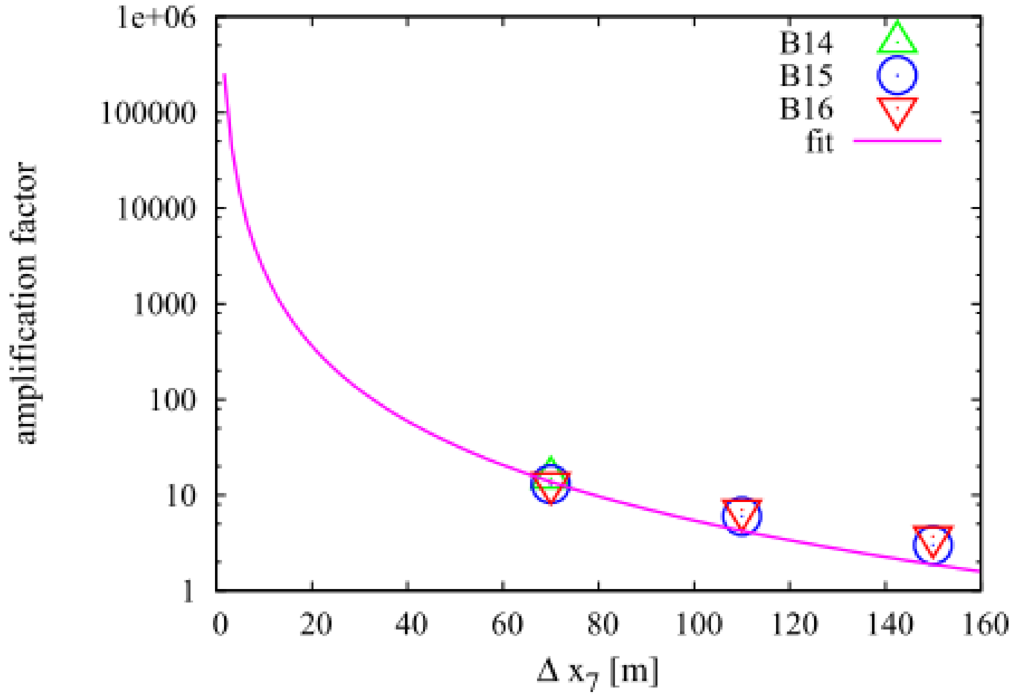


Can really the KH vortices amplify the B-fields ?

Yes !

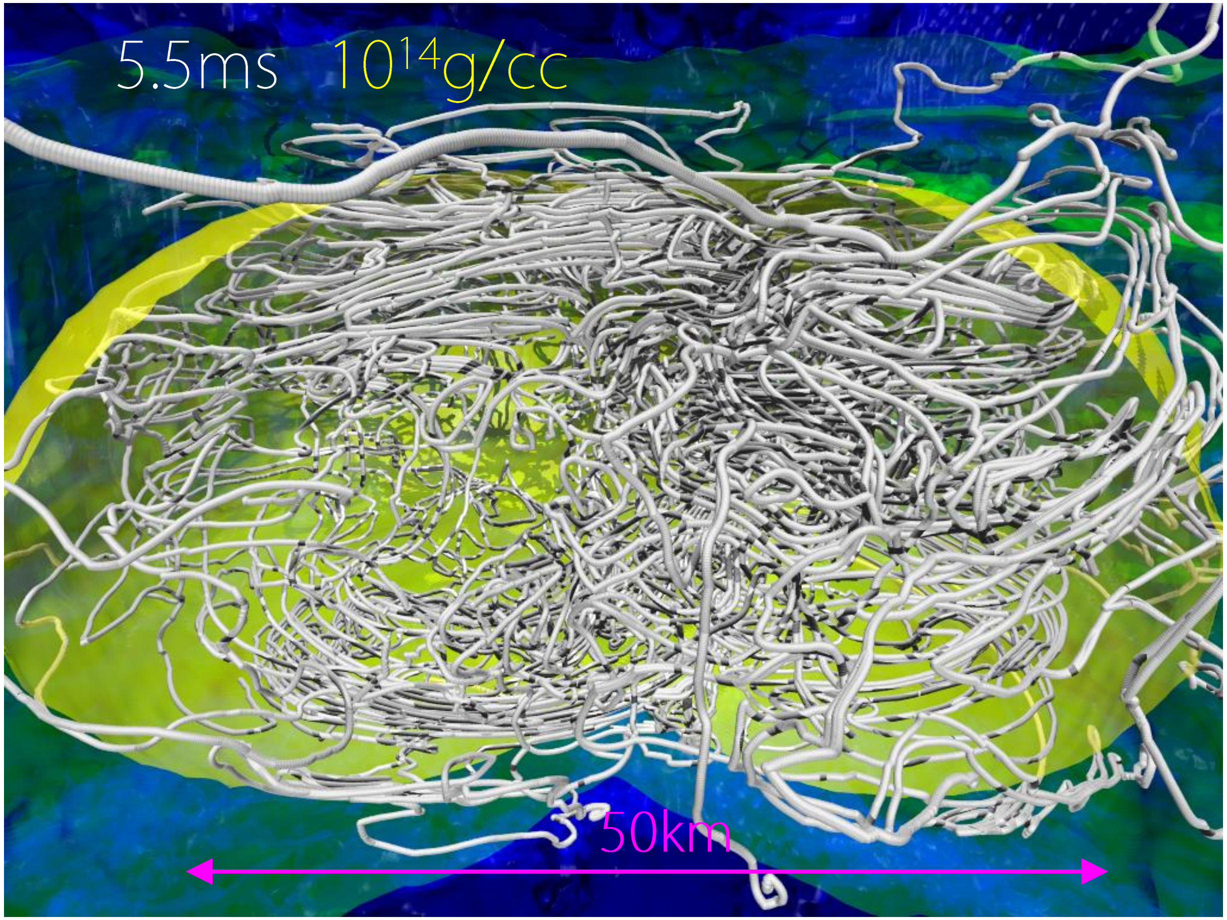
Field lines and strength @ merger   Amplification factor vs resolution





- 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)

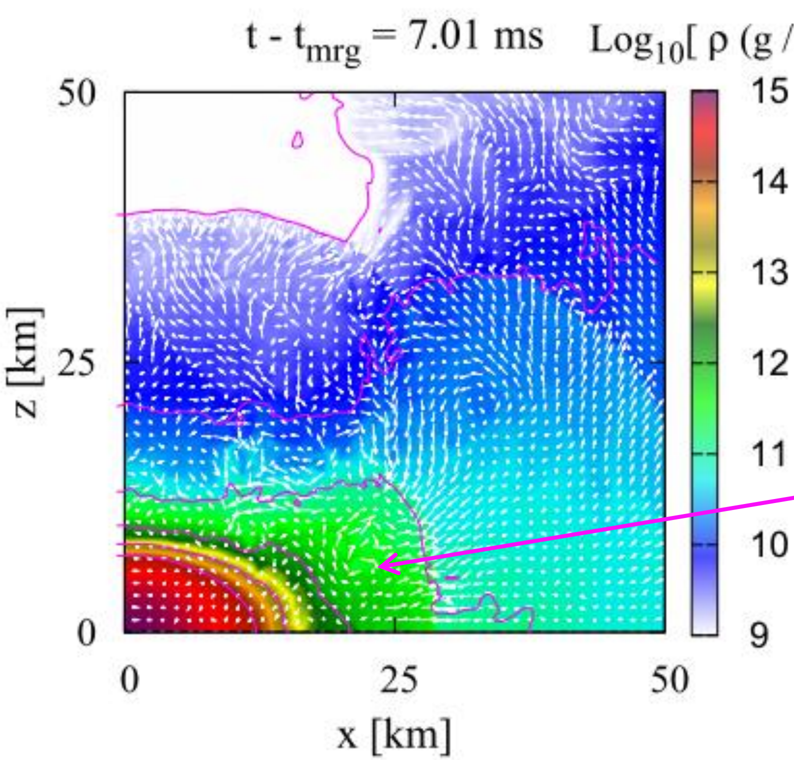
Field lines and density iso-contour inside HMNS



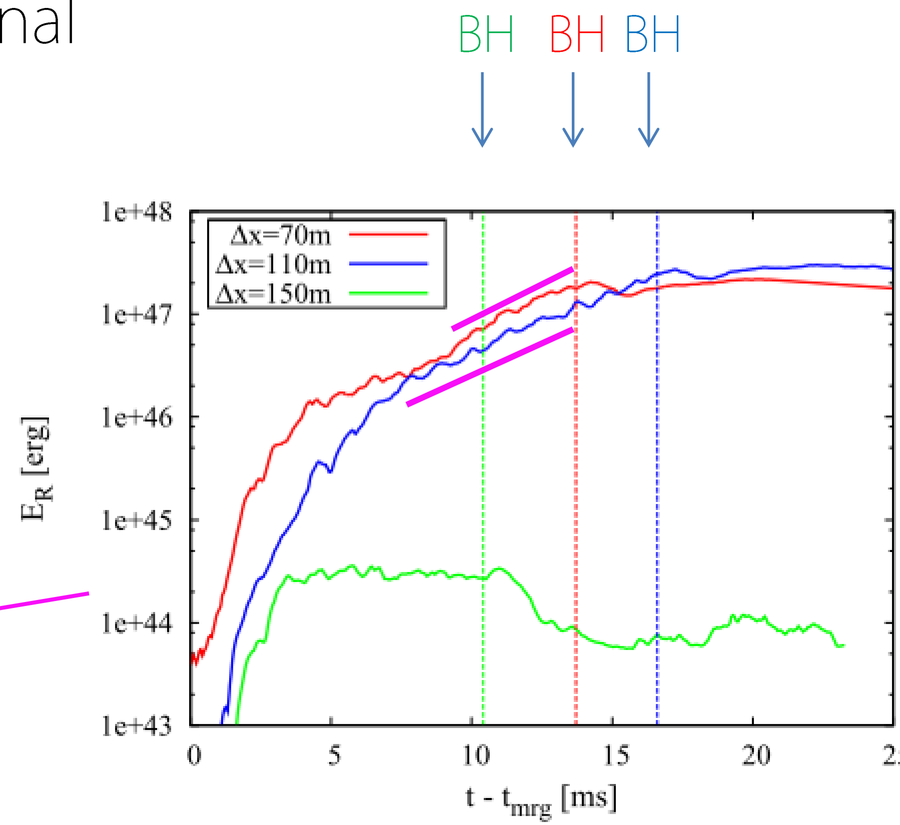
- Turbulent state inside HMNS
- HMNS is differentially rotating ⇒ Unstable against the Magneto Rotational Instability (Balbus-Hawley 92)
- Magnetic winding works as well

B-field amplification inside HMNS

Density contour of HMNS (Meridional plane)



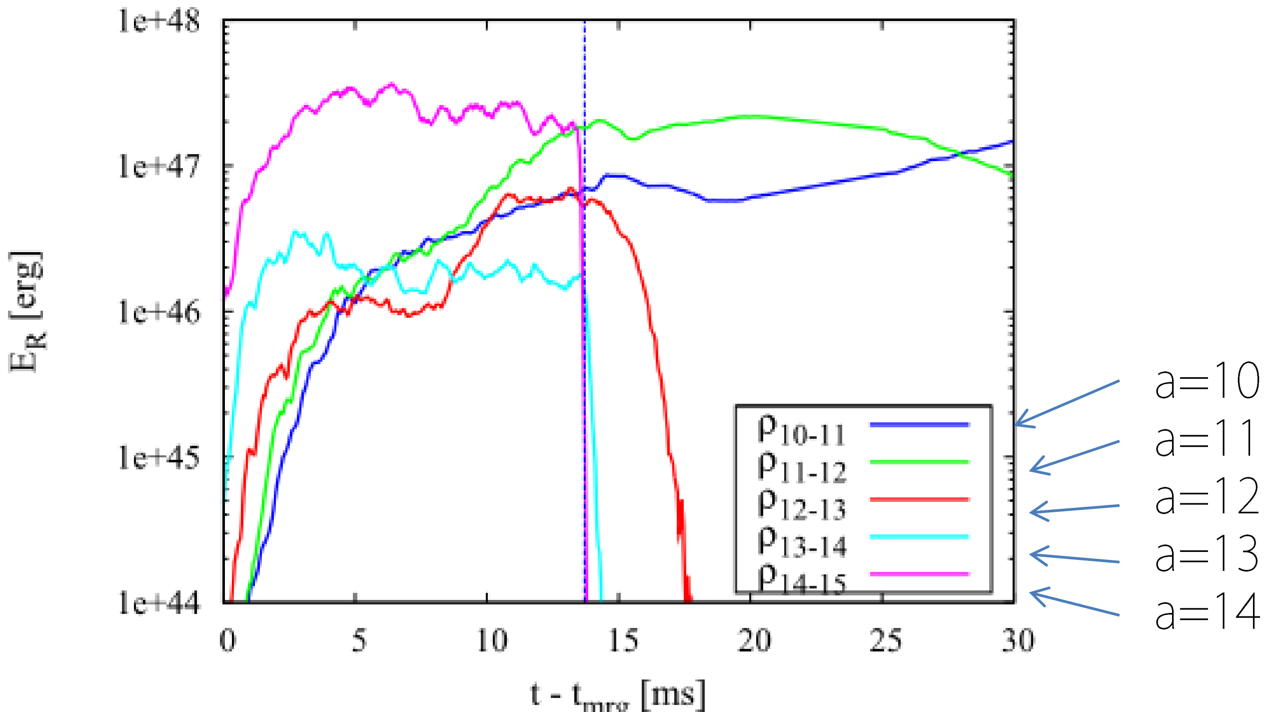
Magnetic field energy inside 10^{11}g/cc ≤ ρ ≤ 10^{12}g/cc



- $\lambda_{MRI} = B/(4\pi\rho)^{1/2}\, 2\pi/\Omega$
- 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^ag/cc ≤ ρ ≤ 10^{a+1}g/cc a=10-14 for high-res. run



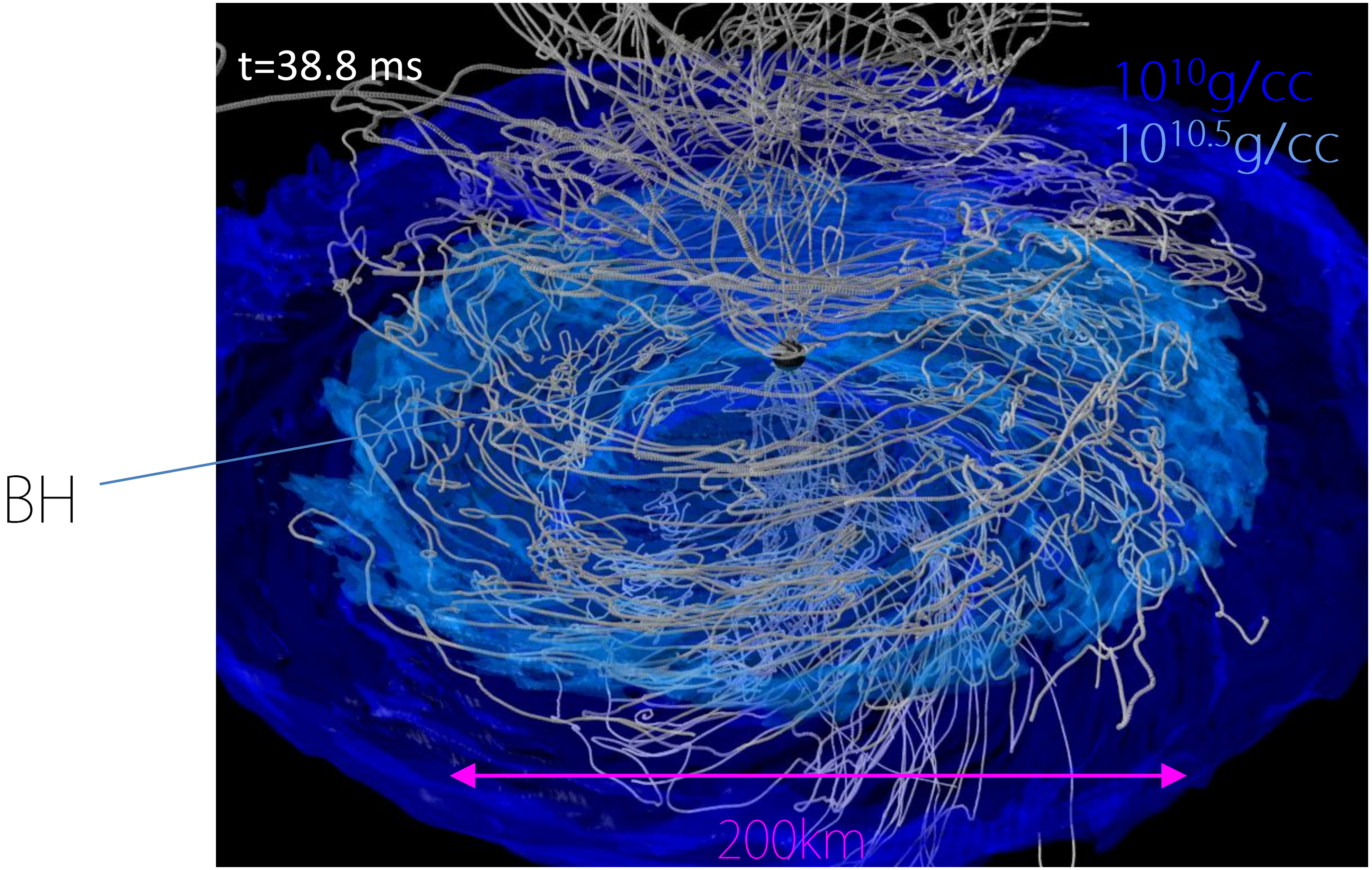
▶The high the density is, the high the growth rate is because of higher angular velocity

▶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

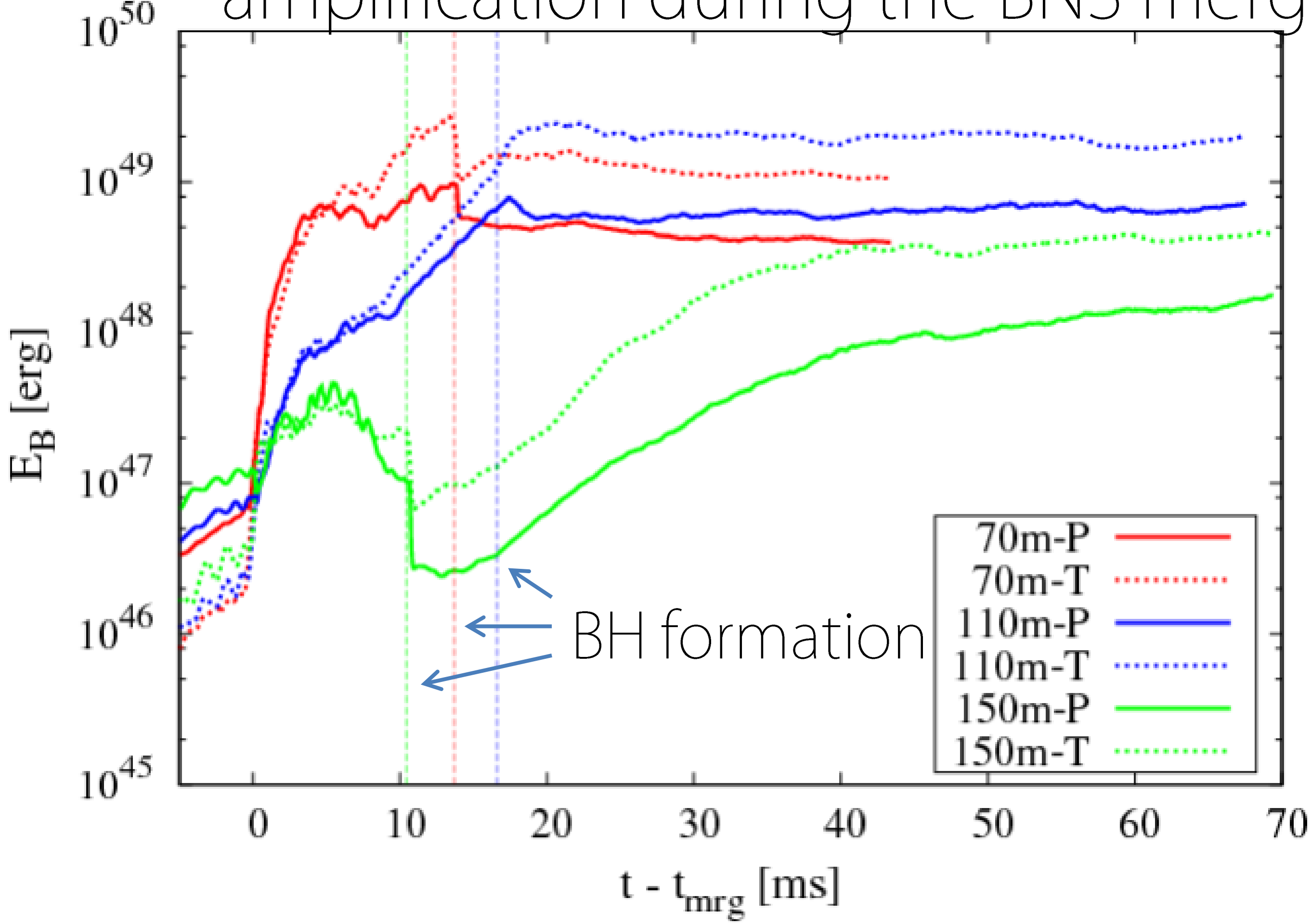
$B_\varphi \sim B_R \, \Omega \, t \sim 10^{16}\text{G}(B_R/10^{15}\text{G})(\Omega/10^3\text{rad/s})(t/10\text{ms})$

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

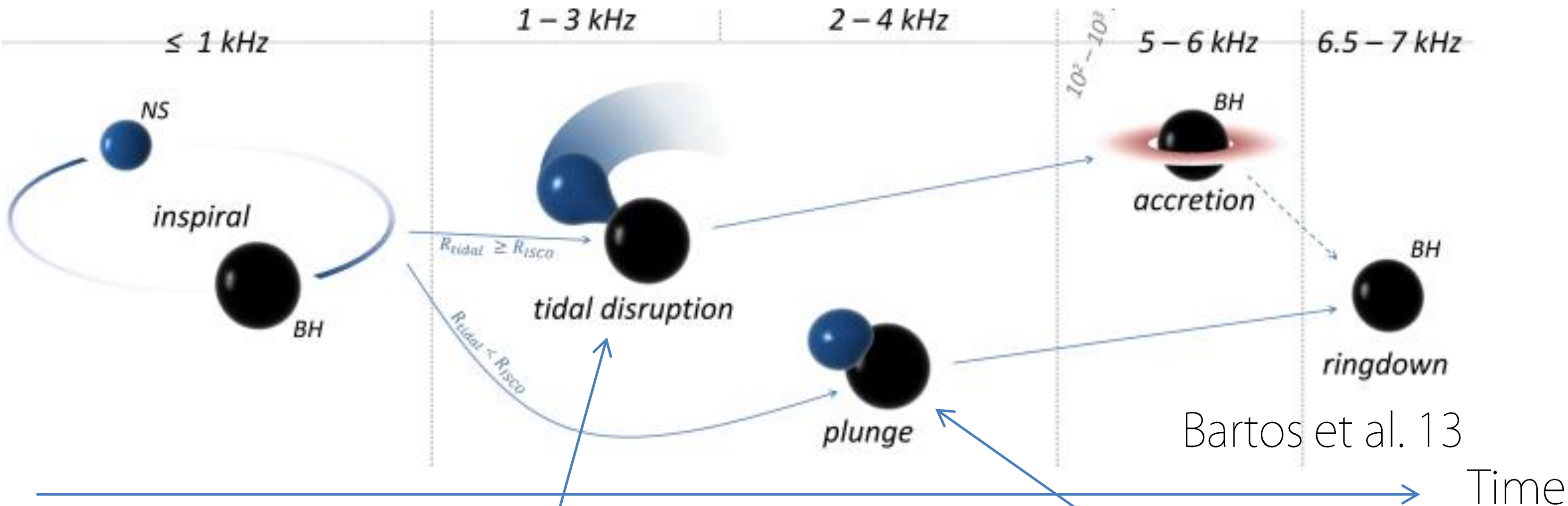


▶KH instability at the merger and MRI inside the HMNS ⇒ Significant amplification of B-fields

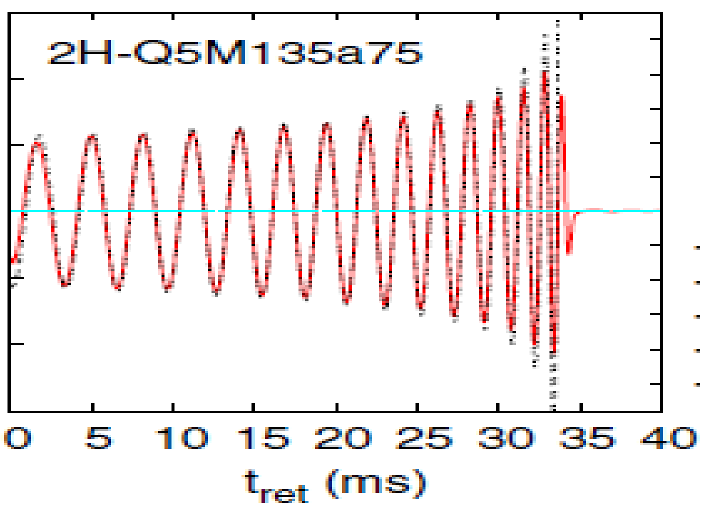
▶Low res. run cannot follow this picture ⇒ Amplification inside the BH-torus (picture drawn by the previous works)

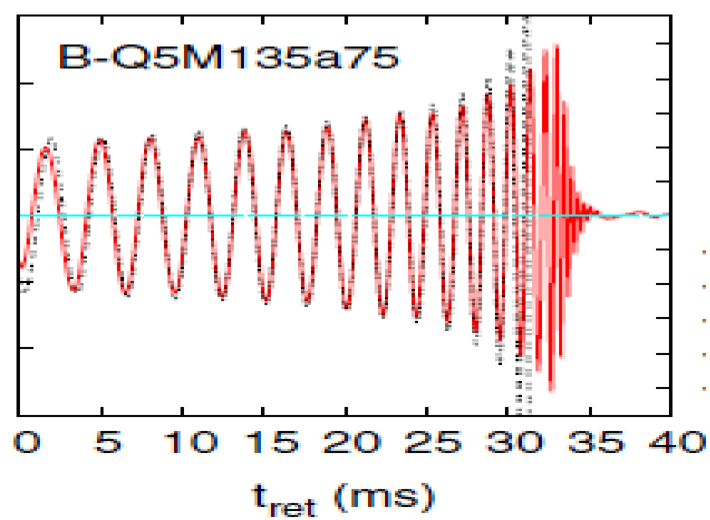
Overview of Black Hole (BH) – Neutron Star (NS) merger

Q: Tidal disruption or not ? (Mass ratio, BH spin, EOS of NS)



GW forms (Kyutoku et al. 11) *More detailed classification





BH – torus systems

A key ingredient = "viscosity"

EOM : $\partial_t(\rho R^2\Omega)+\partial_A(\rho R^2\Omega v_A-\eta R^2\partial_A\Omega) = 0$ (A=R, z)

ρ =density, Ω=angular velocity, η =dynamical viscosity

⇒ ▶ Angular momentum transfer by the viscous term.

▶ Energy dissipation due to the viscosity

Q. What is the "viscosity" in BH-torus systems ?

A. Magnetohydrodynamical turbulence ;

$q=q_{ave}+\delta q$ s.t. $<q> = q_{ave}$ and $<\delta q>=0$ where < ・ > denotes the time average.

EOM : $\partial_t<\rho R^2\Omega>+\partial_A(<\rho R^2\Omega v_A>+\rho R W_{A\varphi}) = 0$ (A=R, z)

$W_{A\varphi}=<\delta v_A \delta v_\varphi - B_A B_\varphi/4\pi\rho>$: Reynolds+Maxwell stress

Q. What produces the turbulence ?

A. Magnetohydrodynamical instability ; The magnetorotational intability (MRI) is a powerful amplification mechanism (Balbus & Hawley 91) . Unstable for $\nabla\Omega<0$ and growth rate $\propto\Omega$

Q & A cont. and what we have to do

Q. Does magnetic field exist in BH-NS binaries ?

A. Yes . The presence of the magnetic fields is one of the most characteristic properties of NSs.

Therefore, it is mandatory to perform BH-magnetized NS merger simulations.

Simulation set up

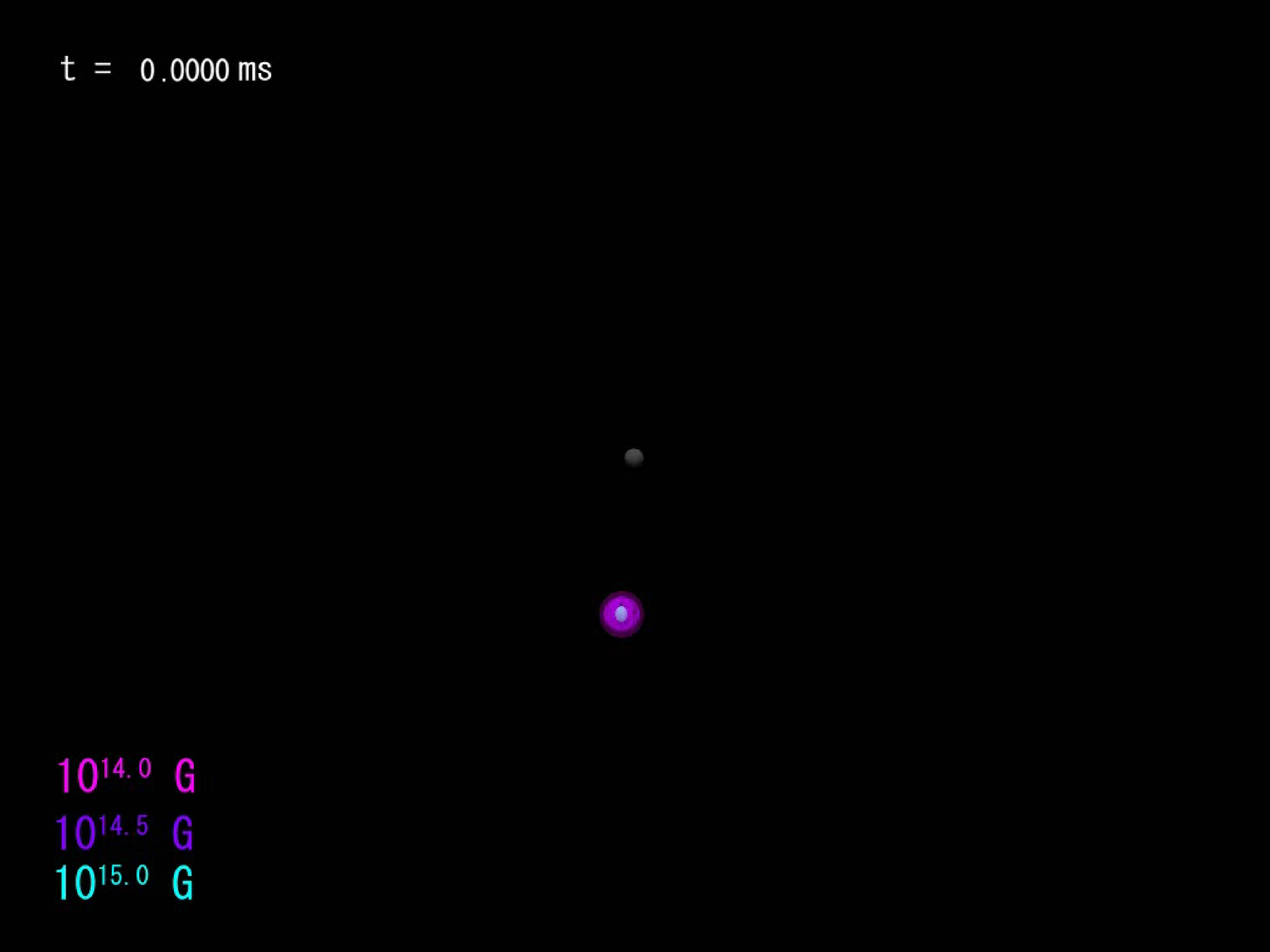
- High resolution ; Δx=120m, N=1028^3 (K ; 32,768 cores)
- Middle resolution ; Δx = 160m, N=756^3 (XC30 ; 4,096 cores)
- Normal resolution ; Δx = 202m, N=612^3 (XC30 ; 4,096 cores)
- Low resolution ; Δx = 270m, N=448^3 (FX10 ; 3,456 cores)

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

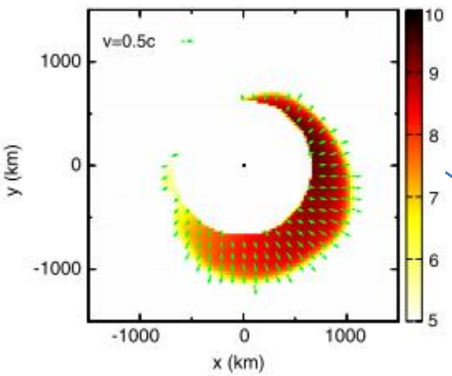

t = 0.2270 ms
10^{12} g/cm^3
10^{11} g/cm^3
10^{10} g/cm^3
10^{9} g/cm^3

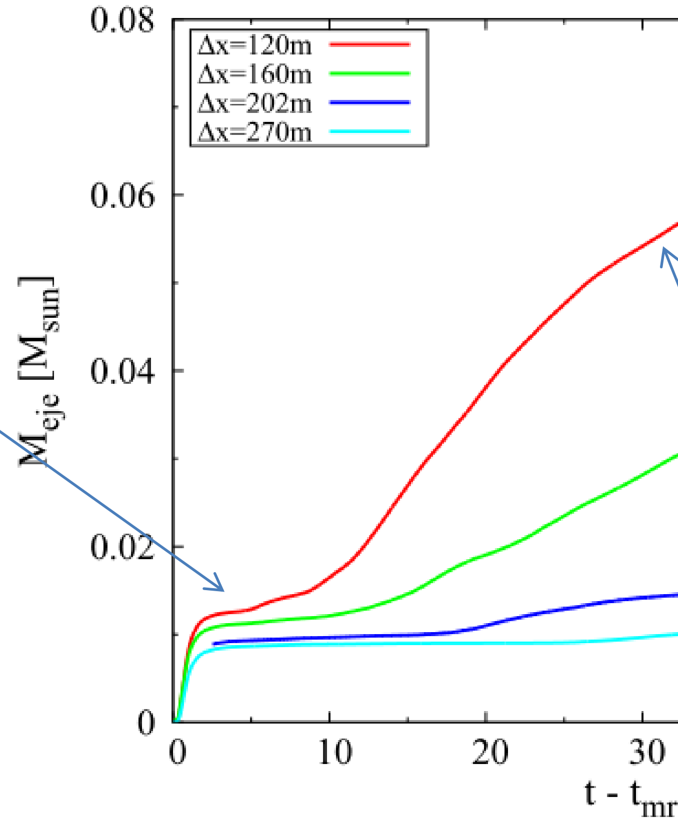

t = 0.0000 ms
$10^{14.0}$ G
$10^{14.5}$ G
$10^{15.0}$ G

Ejecta time evolution

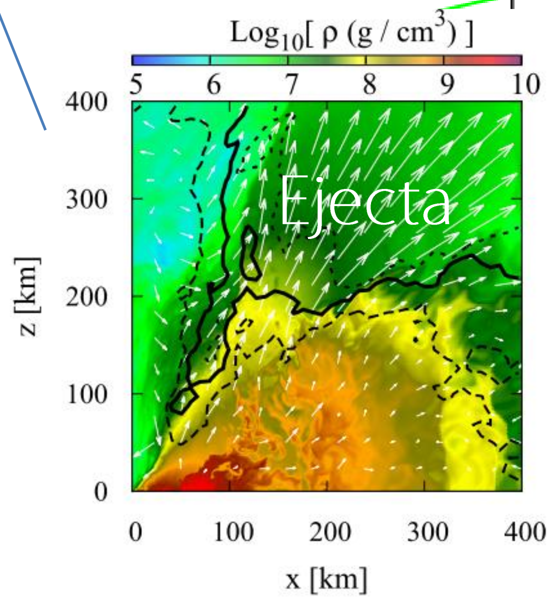
Ejecta $\stackrel{\text{def}}{=}$ Gravitationally unbounded fluid element

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



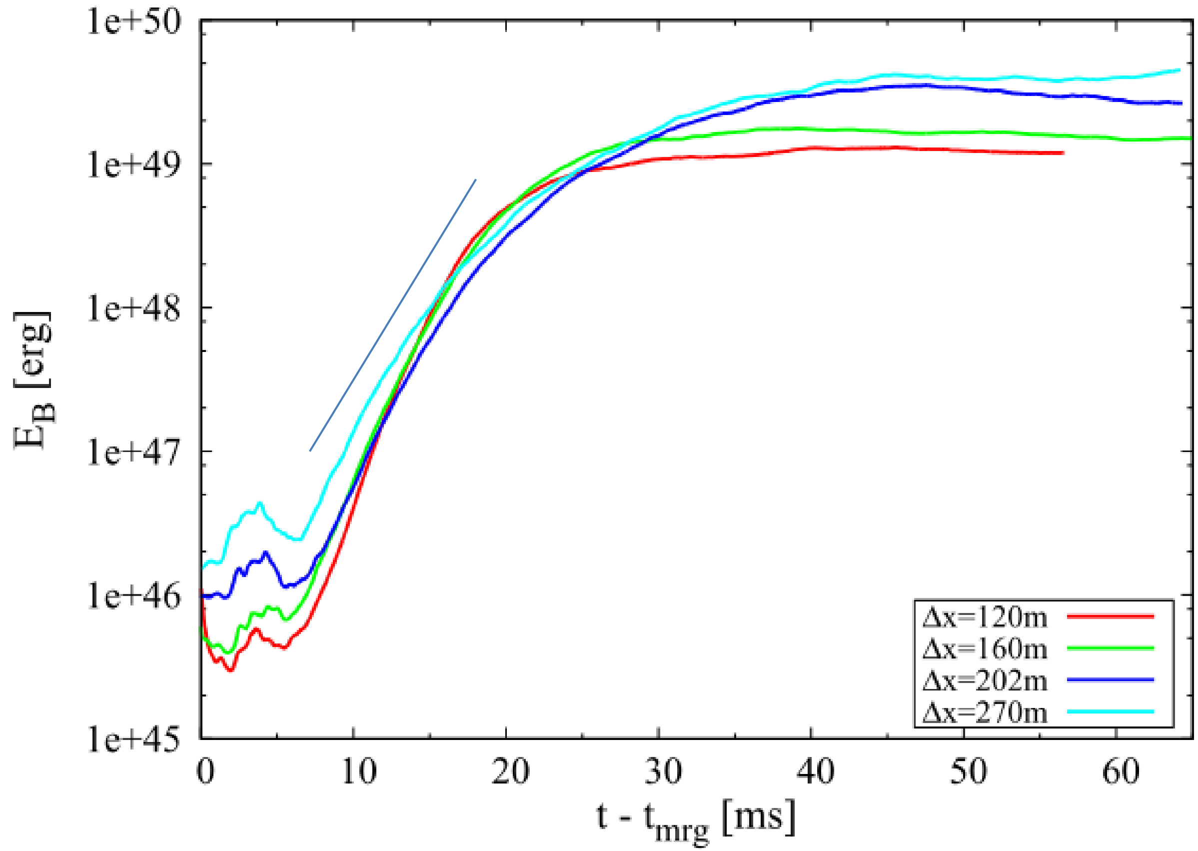


ρ on a meridional plane



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

Does the magetorotational instability switch on ?

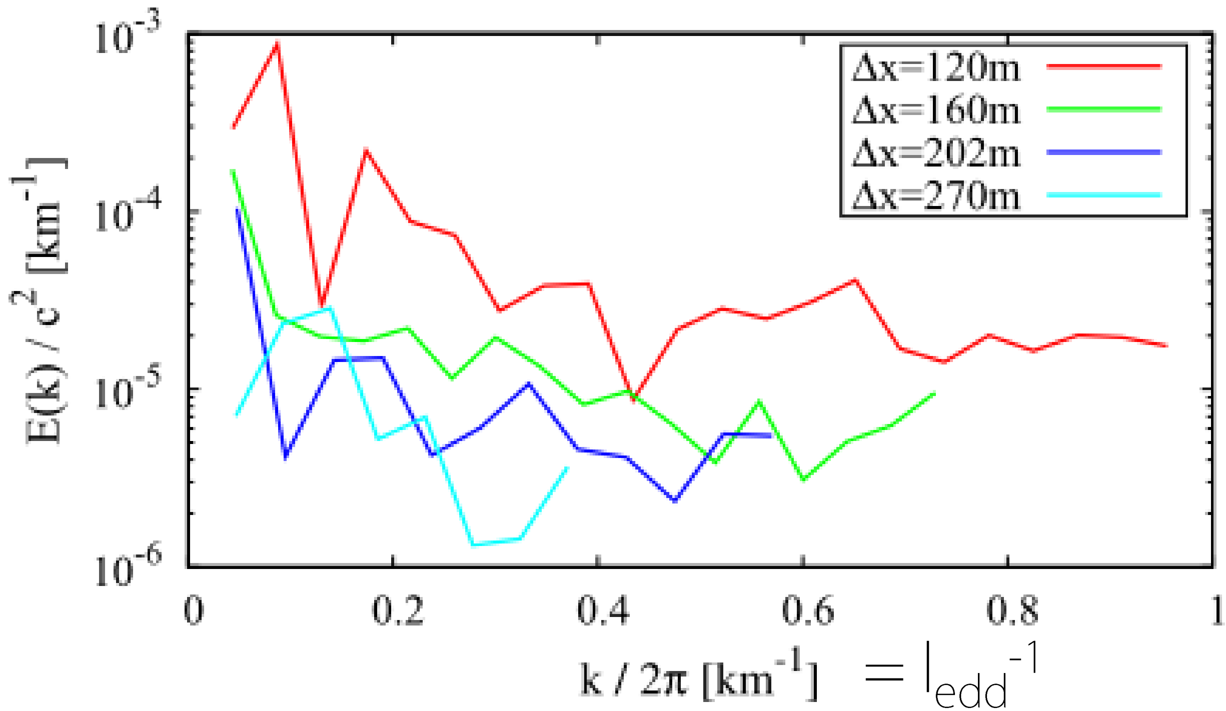


Yes. The magnetic-field energy is exponentially growing for 10 ms ≲ t ≲ 20 ms.

⇒ The growth rate agrees approximately with the linear perturbation (Balbus & Hawley 92) and the turbulent state is realized.

Is the effective turbulent viscosity really produced ?

Energy spectrum of the turbulence



▶The spectrum amplitude is higher in the higher-res. runs.

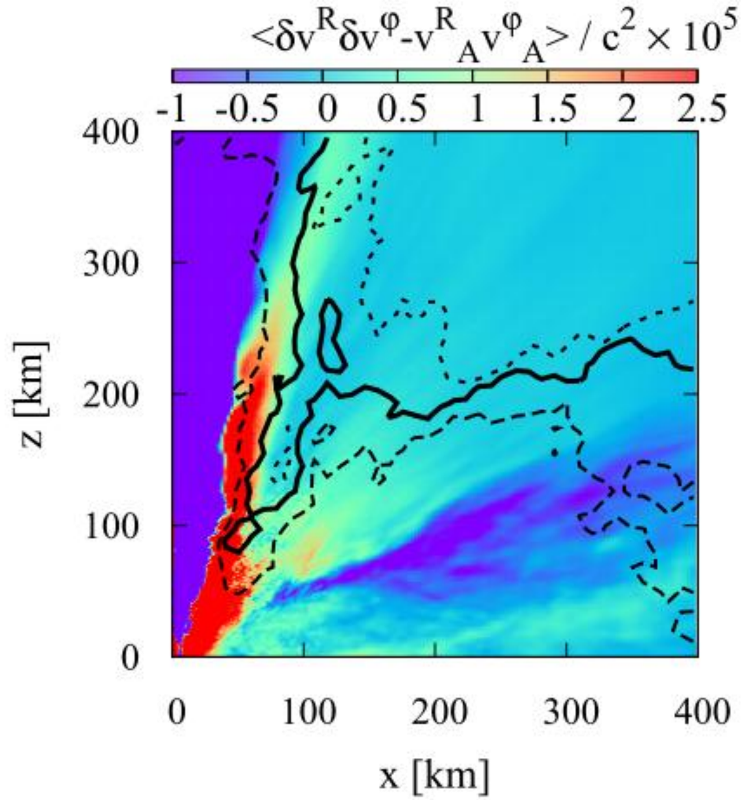
The effective turbulent viscosity is $\sim \delta v \cdot l_{edd}$ and $E(k) \propto \delta v^2$

$\Rightarrow$ For a given scale l_{edd}, the effective turbulent viscosity increases with increasing the resolution.

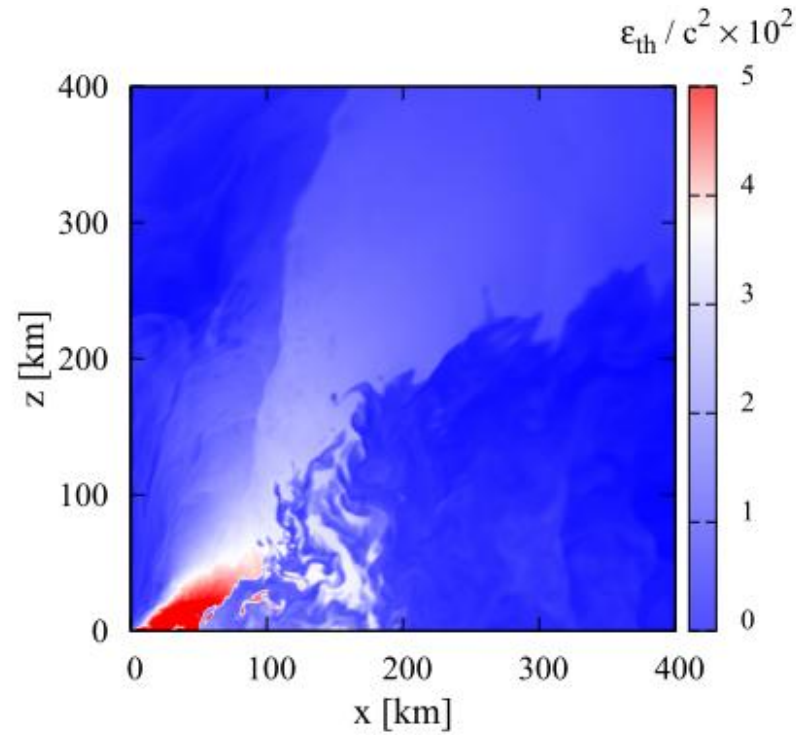
So, the answer is Yes.

Is the energy transferred outward and thermalized ?

Reynolds+Maxwell stress



Thermal component of
specific thermal energy



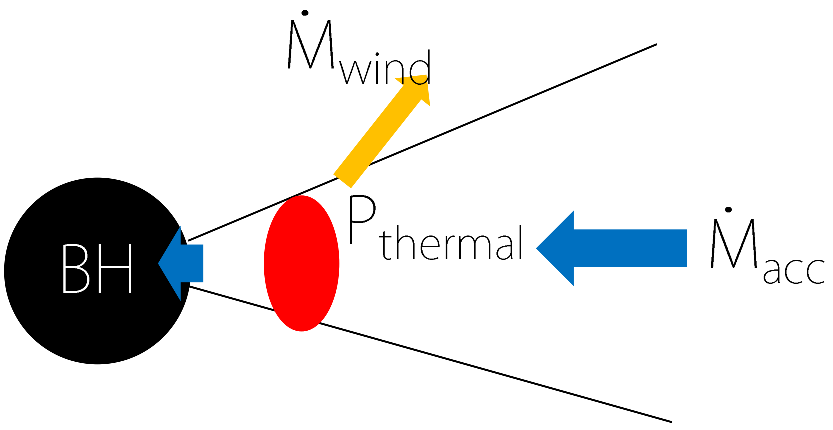
Yes.

▶The energy is transferred outward.

▶Efficient energy conversion to the thermal energy is realized in the vicinity of the inner edge of the torus.

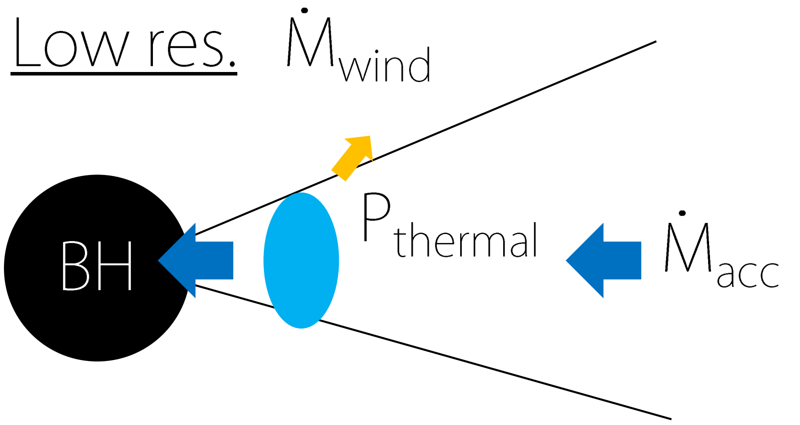
Mechanism of turbulence driven torus wind

▶The realistic high viscosity enhances the mass accretion inside the torus and converts the mass accretion energy to thermal energy efficiently.



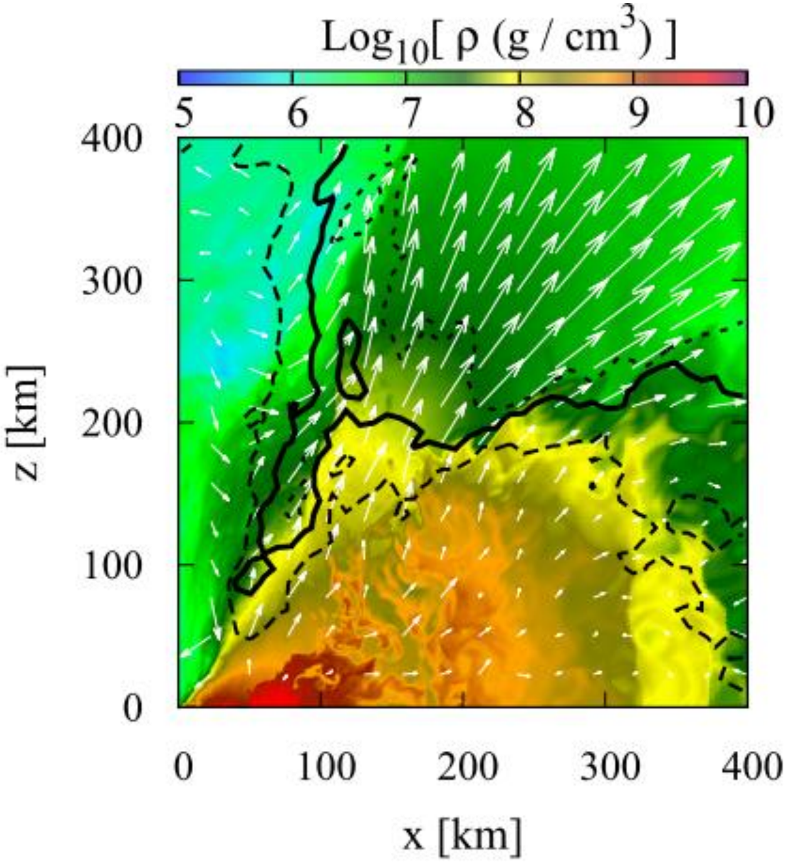
In the absence of the effective turbulent viscosity,

Low res.

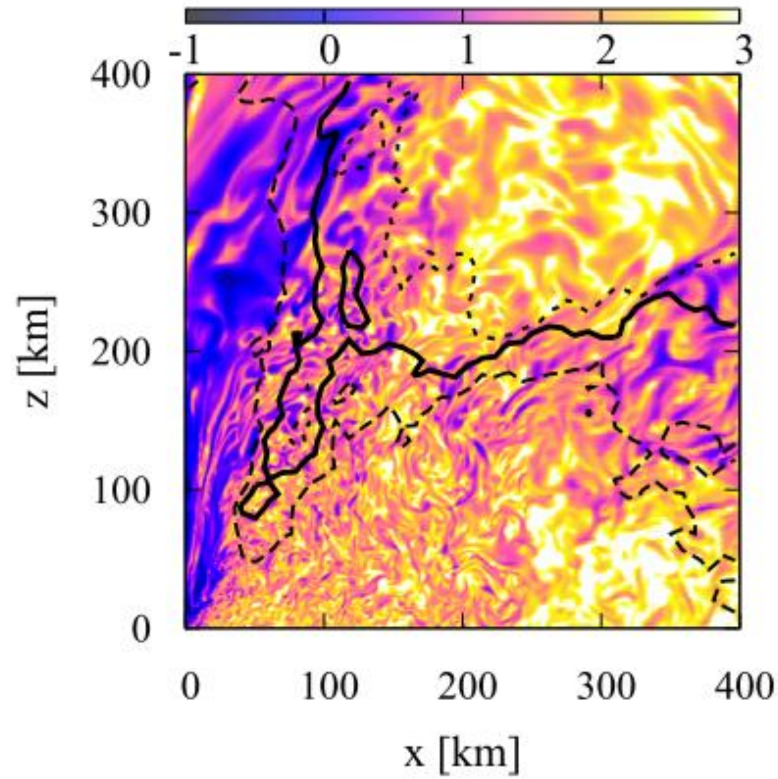


Natural consequence of the torus wind

Density



P / P_{mag}



- ▶ 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 ; $\approx 2 \times 10^{49}$ erg/s (Blandford-Znajek 77)

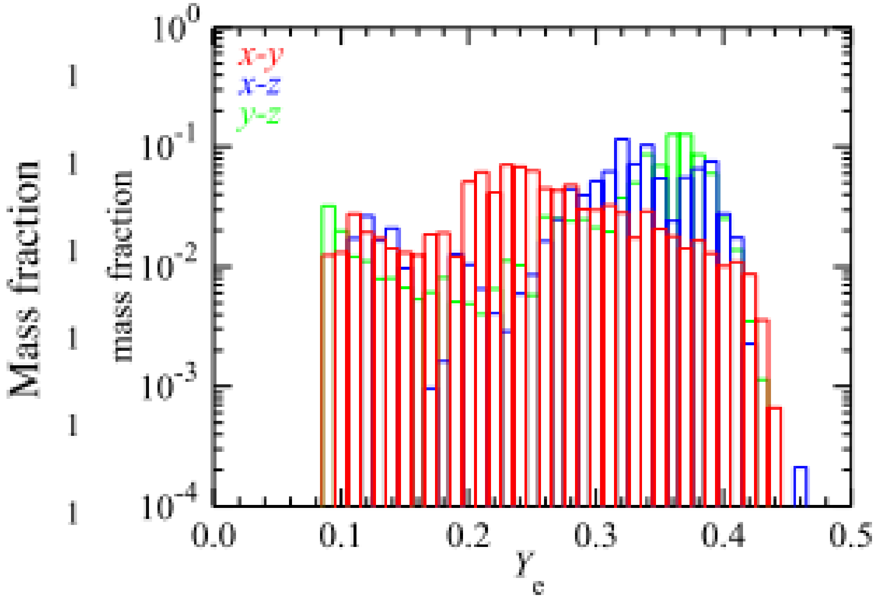
R-process nucleosynthesis in BH-NS merger

▶ Nucleosynthesis in the BH-NS merger

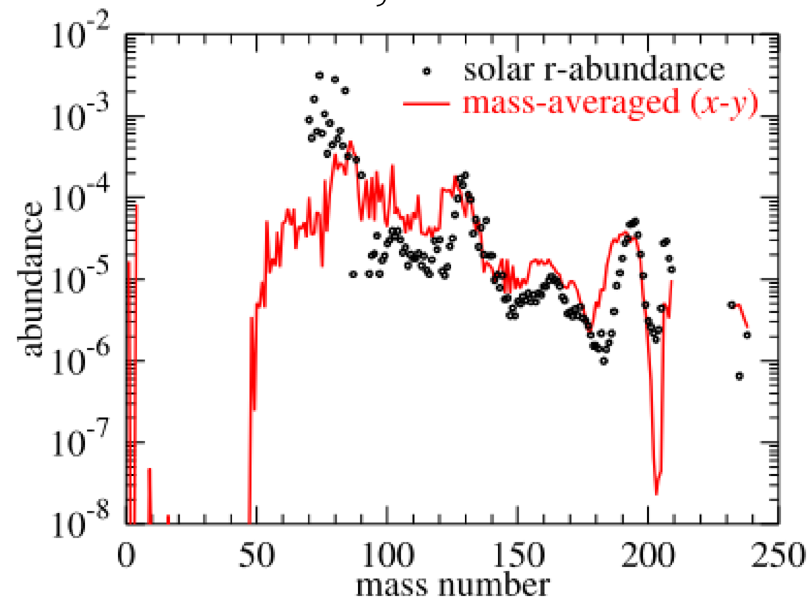
Electron fraction Y_e of the dynamical ejecta is $\lesssim 0.1$

⇒ 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, 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 performed high-resolution GRMHD simulations of a NS-NS and BH-NS merger on K.

- ▶ NS-NS : Kelvin-Helmholtz instability at the merger and non-axisymmetric MRI inside the hyper massive neutron star are key ingredients. The accretion torus is strongly magnetized at its birth. The picture is qualitatively different from that of the previous works.

- ▶ BH-NS : We self-consistently show a series of the processes composed of tidal disruption of the NS, accretion torus formation, the magnetic field amplification due to the non-axisymmetric MRI, thermal driven torus wind, subsequent formation of the funnel wall and BH magnetoshpere, and high Blandford-Znajek luminosity. Implication to a central engine of short gamma-ray bursts, r-process nucleosynthesis, and radioactively-powered electromagnetic emission.