ブラックホール一磁場中性子星連星合体の数値相対論シミュレーション

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Kiuchi et al. 15, submitted on last Monday

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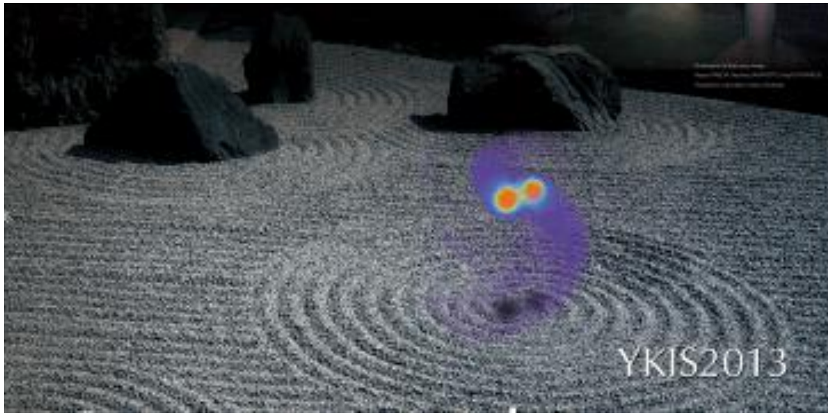
K computer

Motivation



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1. Gravitational waves = Ripples of the space-time

▶ Verification of GR

▶ The EOS of neutron star matter

▶ The central engine of Short Gamma Ray Burst

▶ ~10 events / yr for adv. LIGO (KAGRA will be in operation in 2018)

2. A possible site of the r-process synthesis

A significant amount of neutron star matter could be ejected from BH-NS mergers ; $M_{eje} \approx 10^{-6}$-$10^{-1} M_\odot$ (Kyutoku et al. 15)

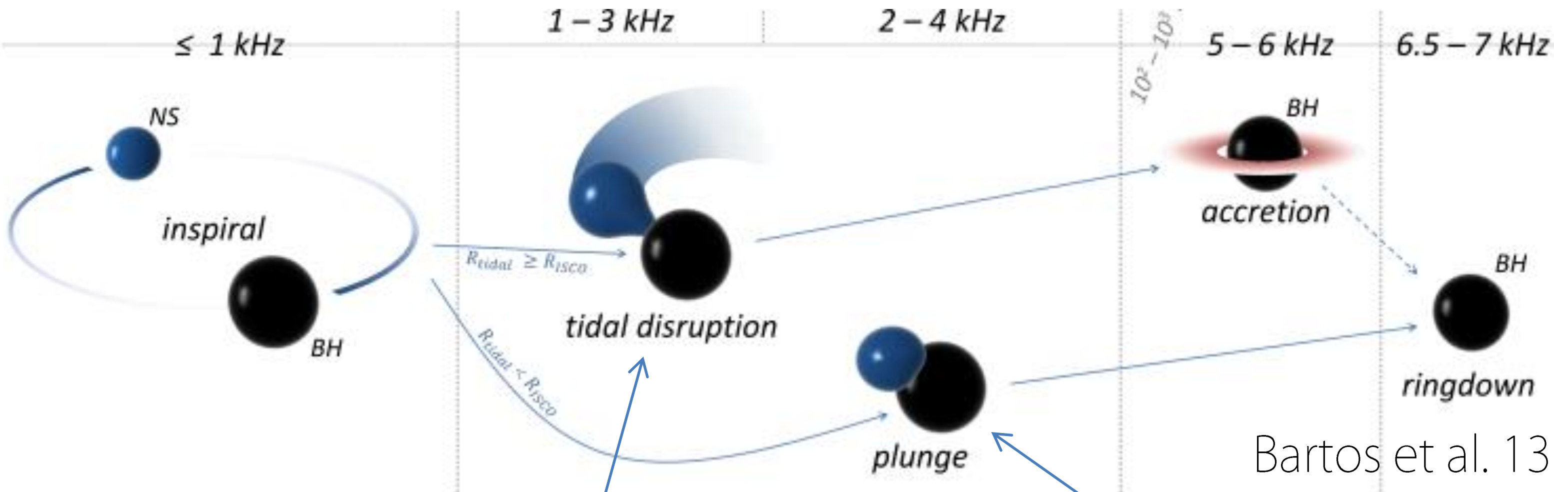
Nuclear synthesis in the ejecta (Lattimer & Schramm 74)

⇒ Radio active decay of the r-process elements (Li-Paczynski 98)

Electromagnetic counterpart = kilonova/macronova (Kulkarni 05, Metzger & Berger 12, Kasen et al. 13, Barnes & Kasen 13, Tanaka & Hotokezaka 13, Berger et al. 13, Tanvir et al. 13, Takami et al. 14, Kisaka et al. 15)

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

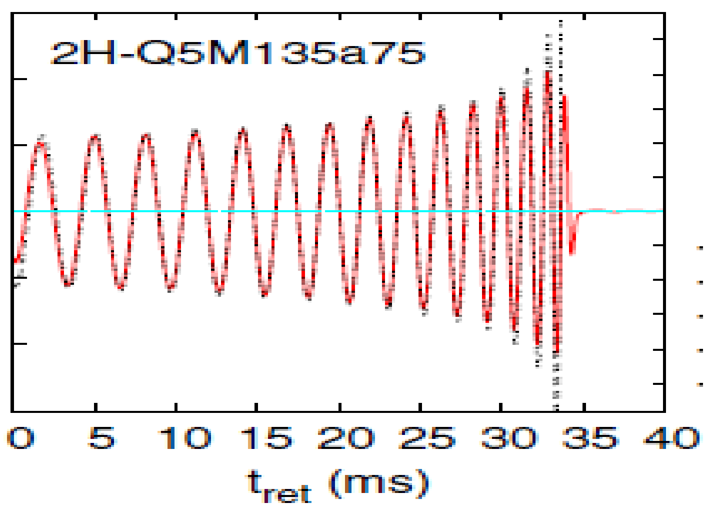
Q: Tidal disruption or not ? (Mass ratio, BH spin, EOS of NS)

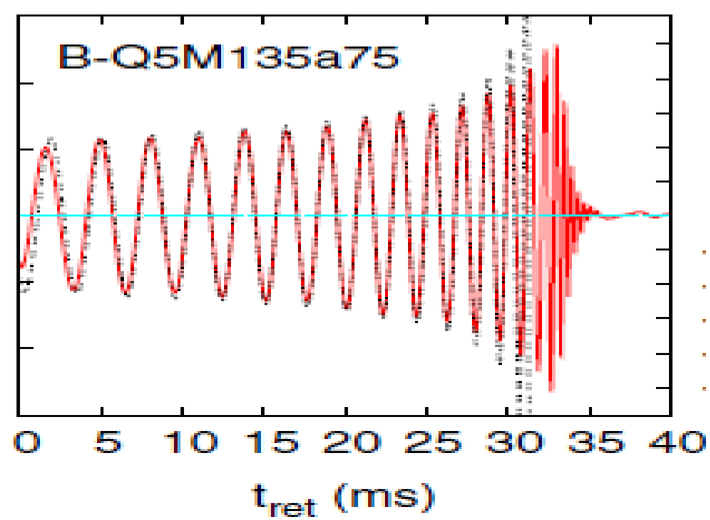


Bartos et al. 13

Time

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

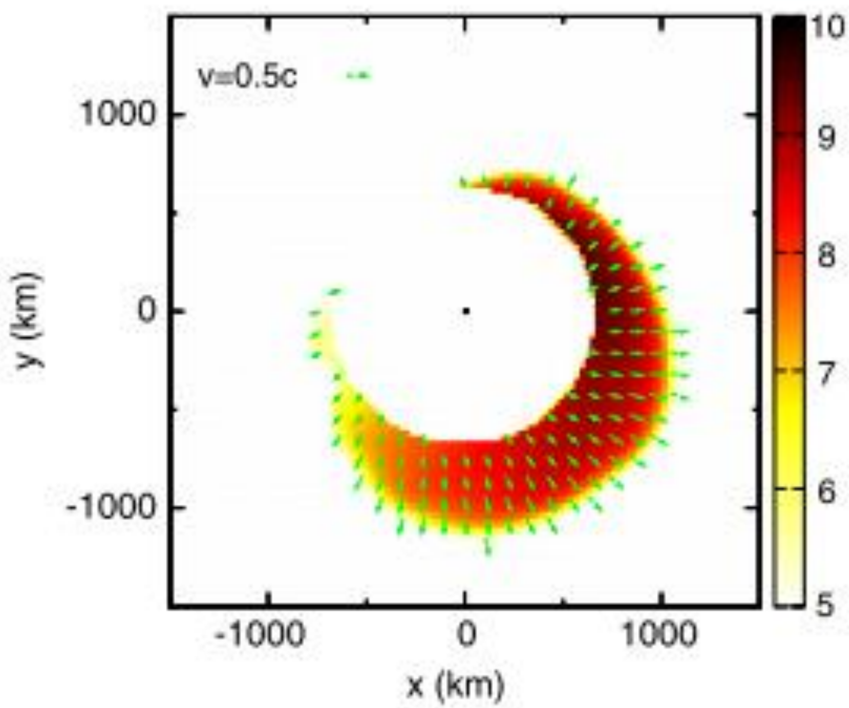




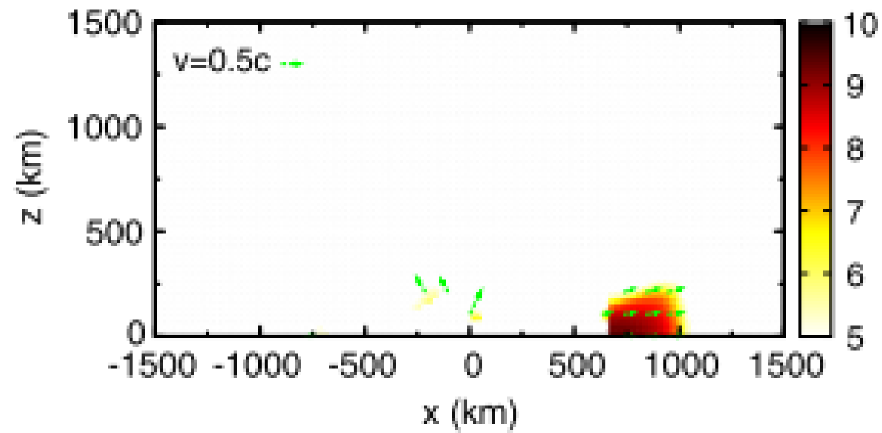
Mass ejection due to tidal torque (Kyutoku et al. 13, Kyutoku et al. 15)

A part of the tidal tail ⇒ Crescent like shape of the ejceta

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



ρ_{eje} on the meridional plane



This dynamical ejecta is a primary component in BH-NS mergers.

What's else ?

- Neutrino driven wind (Qian & Woosley 96)

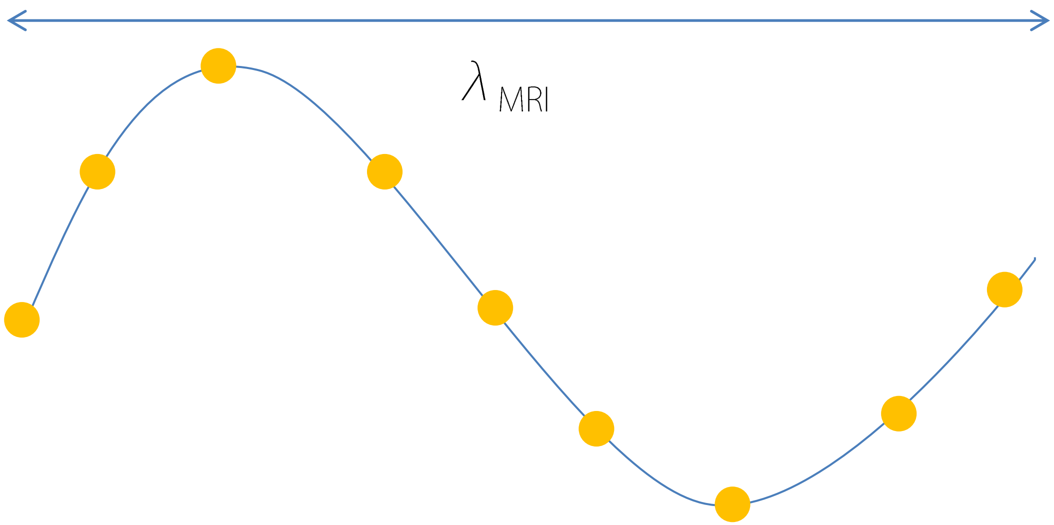
$$\dot{M} \approx 4.5 \times 10^{-3} L_{\bar{\nu}_e,53}^{5/3} \epsilon_{\bar{\nu}_e,10}^{10/3} R_6^{5/3} M_{2.7}^{-2} M_\odot/\mathrm{s},$$

- Disk wind due to the nuclear recombination/viscous heating (Fernandez & Metzger 13)

$M_{ej} \sim 0.1 M_{disk}$ for the viscous timescale (e.g., O(1)s)

- Magnetic-field effect (Liu et al. 08, Etienne et al. 12a, 12b, Paschalidis et al 14)

But, the role of the B-fields is still unclear during the merge. Why ? Because the wavelength of the unstable mode is too short.



What if you miss it ?
⇒ Turbulence is not developed .

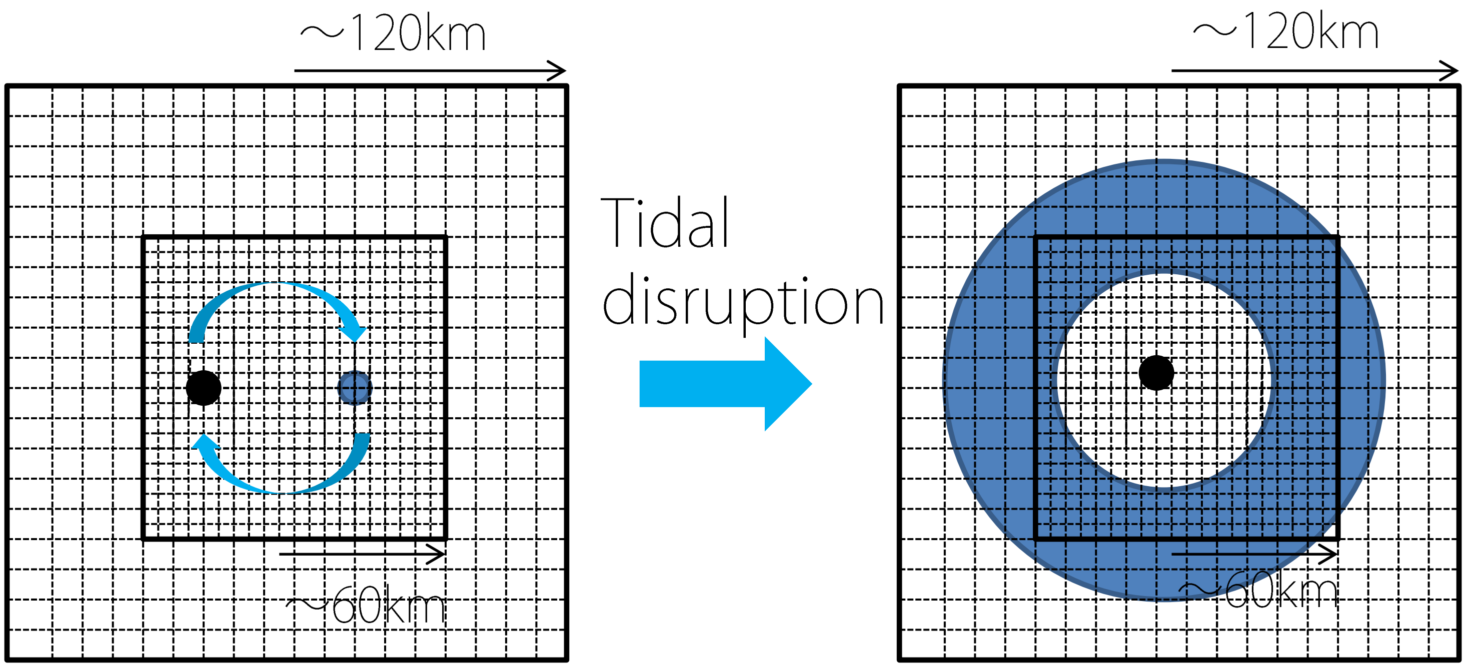
Difficulty in MHD simulation

▸ 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 .

▸ 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

<u>Fiducial model</u>
▸ EOS : APR4 ($M_{max} \approx 2.2M_\odot$), $M_{NS} = 1.35\ M_\odot$
▸ M_{BH}/M_{NS} : 4
▸ BH spin : 0.75
▸ B_{max} : 10^{15}G

Outline of numerical relativity-MHD code (Kiuchi et al. 12, 14)



▶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

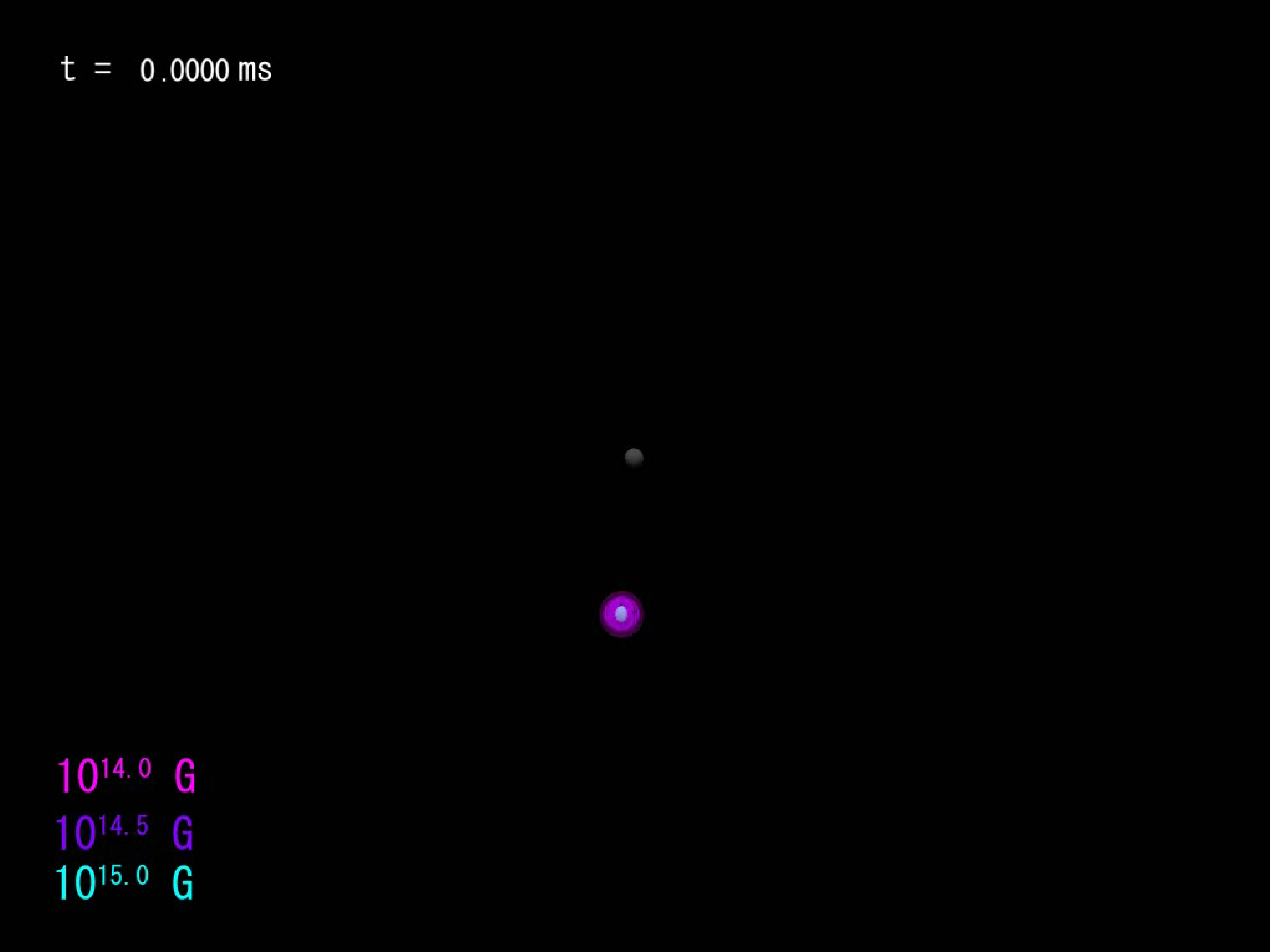
▶Good scaling up to about 80,000 cores (Execution performance 12-13%)

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.

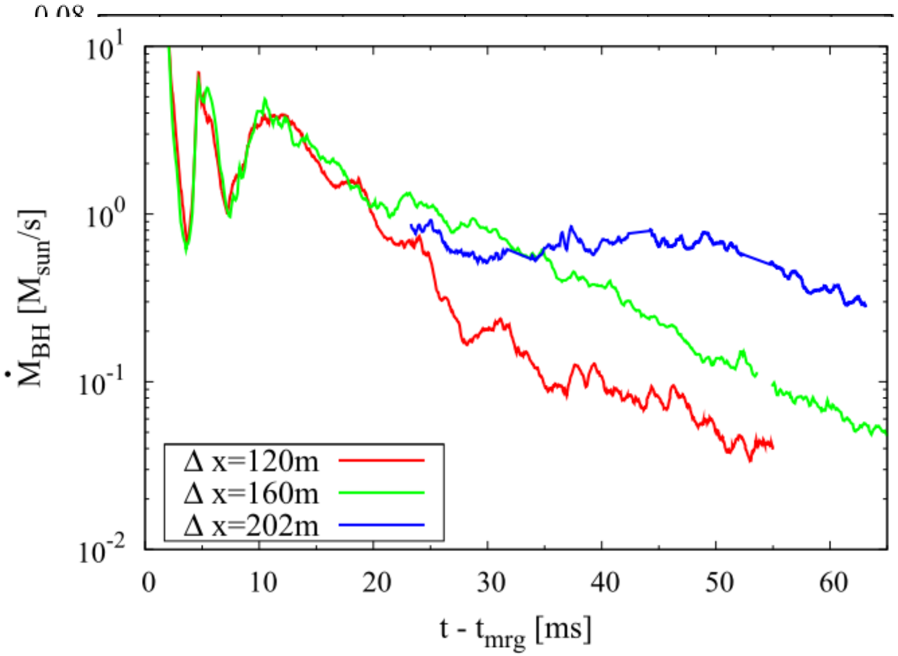

t = 0.2270 ms
10^{12} g/cm^3
10^{11} g/cm^3
10^{10} g/cm^3
10^{9} g/cm^3


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

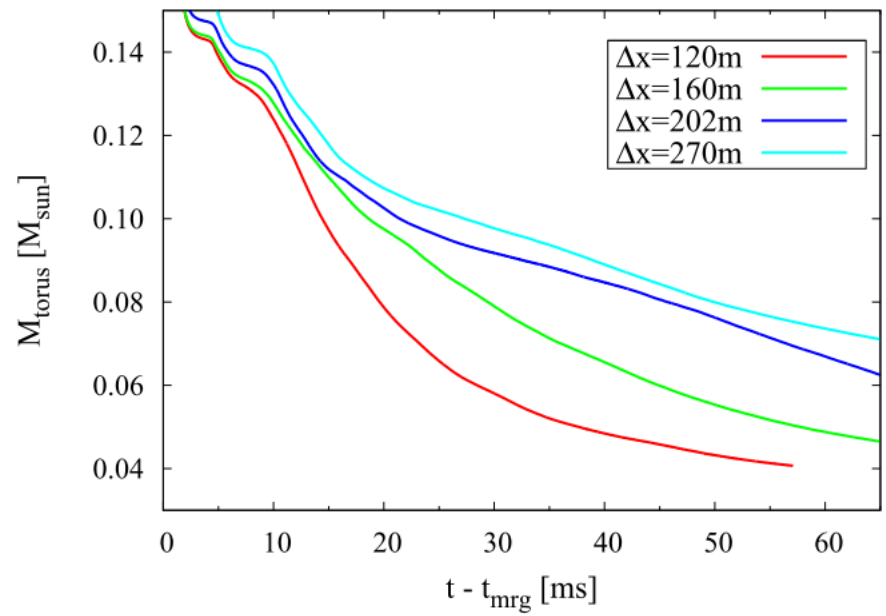
Mass ejection

Mass accretion rate onto the BH

Ejecta mass evolution



Torus mass evolution



- t ≲10ms ⇒ Dynamical mass ejection (Kyutoku et al. 15)
- 10ms ≲ t ⇒ New component = torus wind
- Mass accretion onto the BH for 10-20ms ⇒ ≈ 0.02$M_\odot$
- Disk mass decreases by ≈0.05$M_\odot$ for 10-20ms

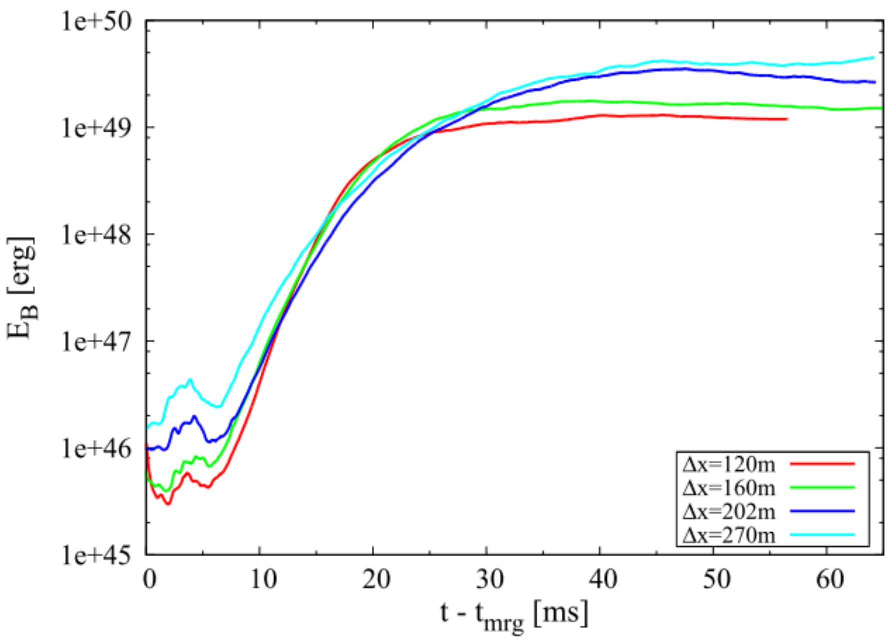
In the higher-resolution run,

- The launch time ⇒ earlier, The amount of the wind ⇒ larger,

The mass accretion rate ⇒ smaller in the higher-res. runs.

B-field amplification

Evolution of B-field energy



Magneto Rotational Instability (MRI) (Balbus & Hawley 91) ;
Powerful amplification mechanism of the B-fields.
If $d\Omega/dr<0$, it turns on and amplifies the B-fields exponentially.
→ Turbulent eddies are produced
→ Physical viscosity

▶ $t \lesssim 10$ms ⇒ highly dynamical phase (winding / stretching)
▶ $10\text{ms} \lesssim t$ ⇒ Magneto Rotational Instability activates($\lambda_{\text{MRI, fastest}} = B/(4\pi\rho)^{1/2} 2\pi/\Omega$)
▶ Linear growth rates are approximately converged; $0.07\text{-}0.08\Omega$ (Non-axisymetric MRI, $\lambda_{\text{MRI, fastest}}/\Delta x \gtrsim 10$)
▶Well-resolved turbulent eddies might play an important role.

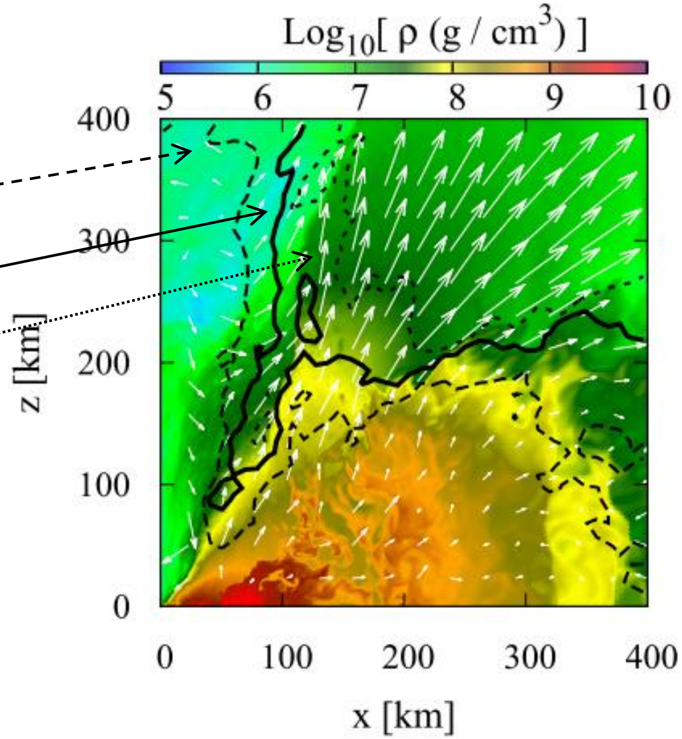
Structure of the torus wind

Density of a merdional plane at ≈50ms

u_t=-0.98

u_t=-1.00

u_t=-1.02



u_μ ; the four velocity

$u_t<-1 \Rightarrow$ unbound

▶ $u_t = -1$ is approximately parabolic in the vicinity of the z-axis

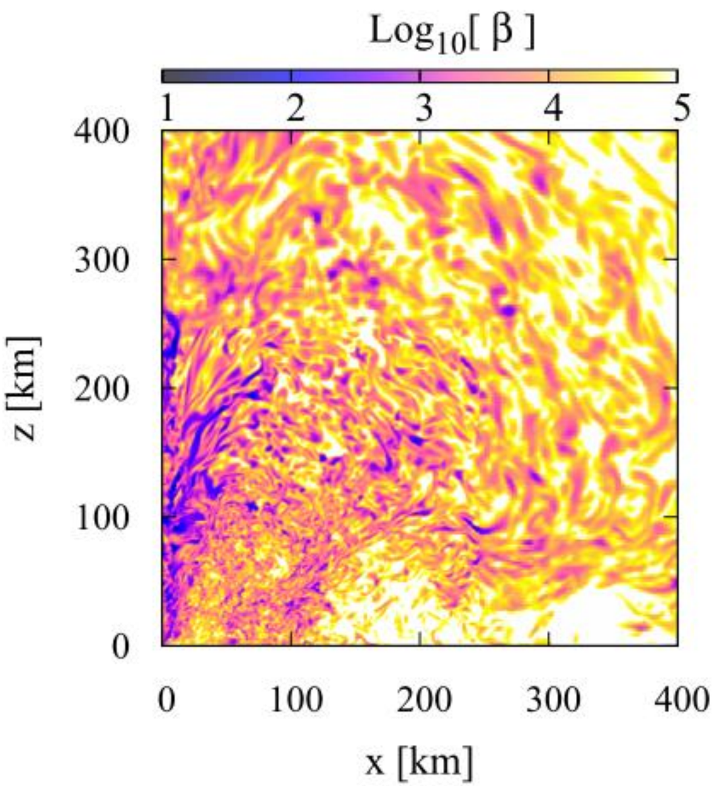
▶Effective potential : $\ln(-u_t) \rightarrow -GM_{BH}/(R^2+z^2)^{1/2} + l^2/2R^2$ (constant specific angular momentum l)

$\Rightarrow u_t=-1$ becomes parabolic (Hawley & Krolik 06, Blandford & Begelman 99)

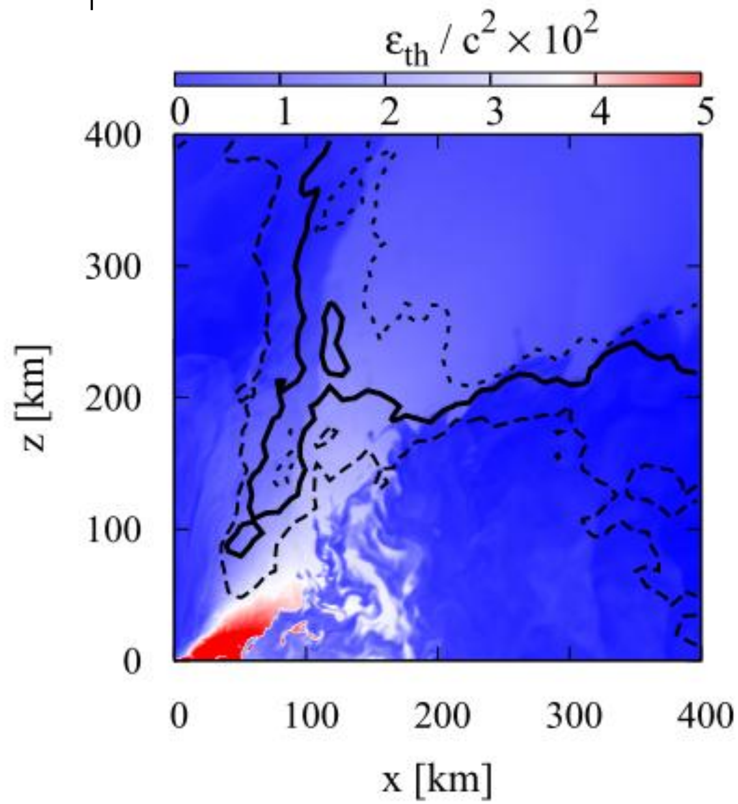
Formation of a region with $u_t<-1$ is natural consequence for the accretion torus formation in the BH-NS mergers.

Mechanism of the injection into a region with $u_t < -1$

P / P_{mag} on a merdional plane at ≈20ms



Thermal component of the internal energy on a merdional plane at ≈50ms



- ▶Magnetic pressure is not the main agent of the injection.
- ▶A hot region in the vicinity of the BH ⇒ Steep pressure gradient

The fluid elements are accelerated radially and become unbound.

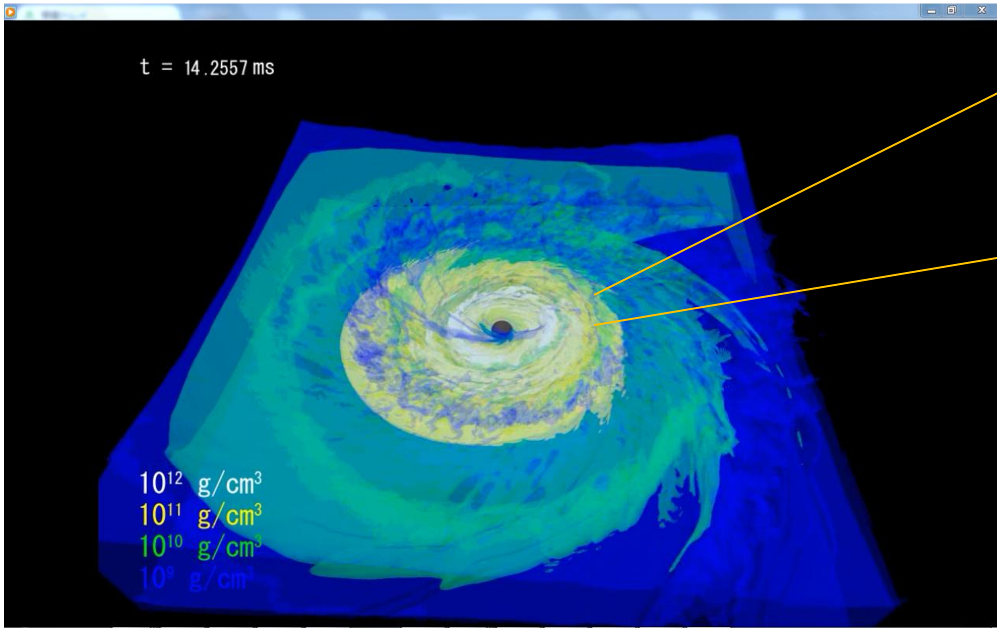
Mechanism of the injection into a region with $u_t < -1$

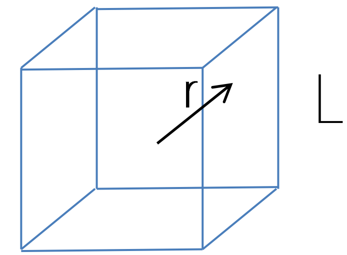
▶The high BH spin is a key ingredient as well.
▶Spin up χ : 0.75 ⇒≈ 0.90
▶Inner Stable Circular Orbit radius ≈ 2.32 GM_{BH}/c^2 ⇒ The accretion onto the BH is suppressed.
▶ The high BH spin prevents the fluid elements from being accreted onto the BH.
⇒ They tend to stay in the vicinity of the BH.
⇒ Steep pressure gradient (Shibata et al. 07)

The point : high BH spin is necessary for tidal disruption of realistic BH-NS binaries (mass ratio ≳ 7).

Mechanism to enhance the thermal pressure

Energy spectrum of the turbulent flow





Step 1. Choose a cubic region

Step 2. $\delta v^i = v^i - \langle v^i \rangle$

<> Time average

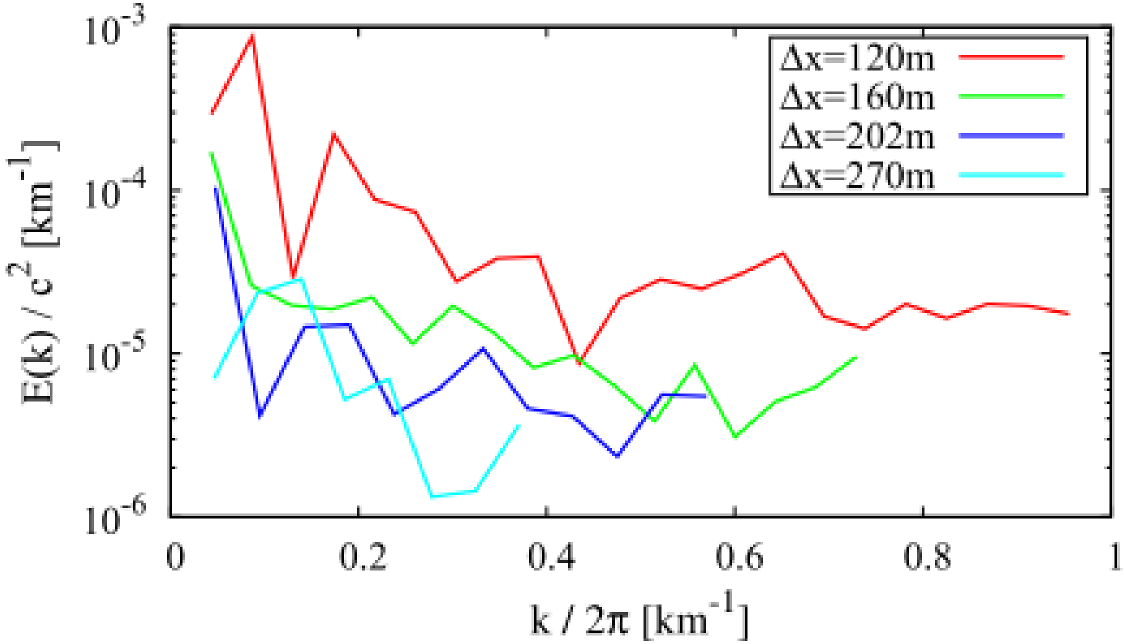
Step 3. $R_{ij}(\mathbf{r}) = \langle \delta v^i(\mathbf{x}+\mathbf{r})\, \delta v^i(\mathbf{x}) \rangle$

Step 4. $\varphi_{ij}(\mathbf{k}) = \iiint R_{ij}(\mathbf{r}) e^{-i\mathbf{k}\cdot\mathbf{r}} d\mathbf{r}$

Step 5. $E(k) = \iint \varphi_{ii}(\mathbf{k})\, d\Omega_k$

$k = |\mathbf{k}|$

Energy spectrum of the turbulent flow

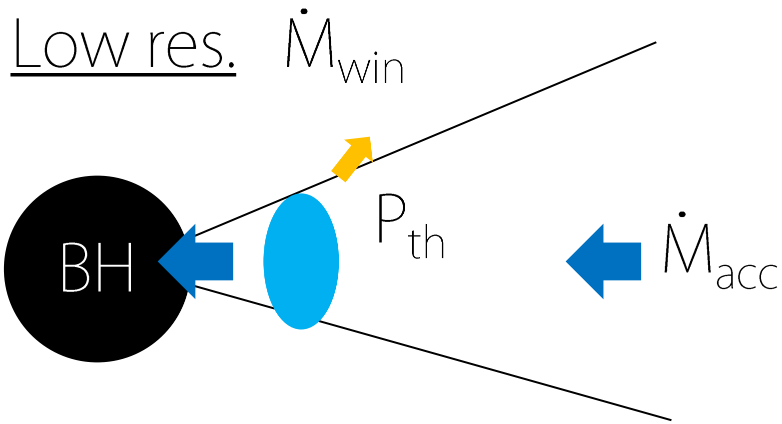


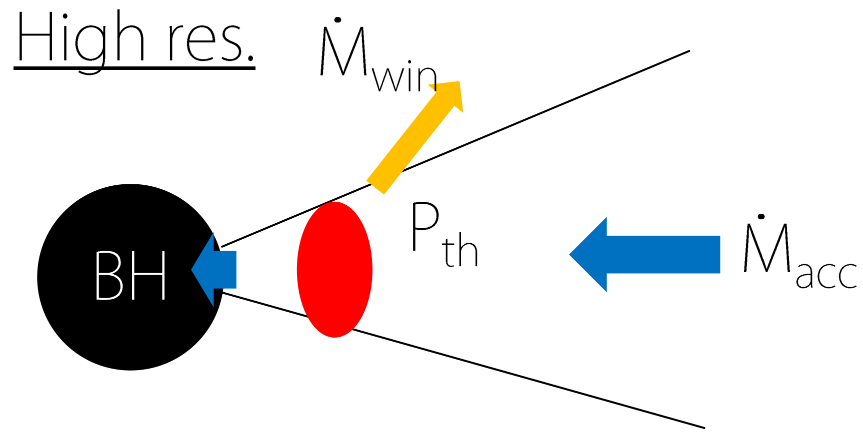
▶The spectrum extends to smaller scales in the higher-res. runs
⇒ The energy injection at a smaller scale where MRI develops.
▶The spectrum amplitude is higher in the higher-res. runs.

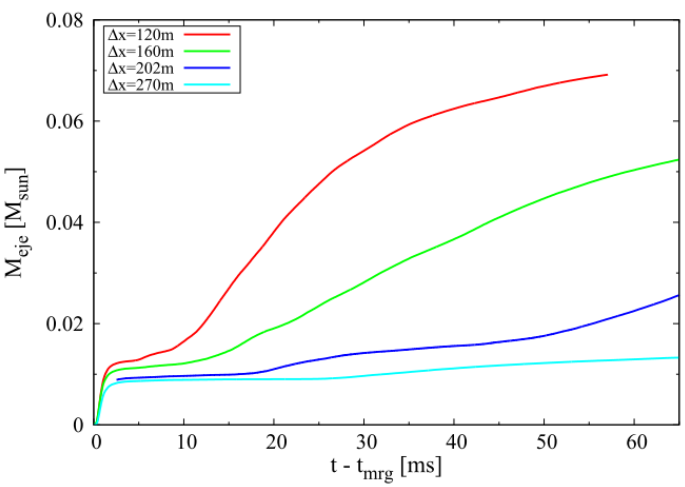
In the turbulent state, the energy dissipation rate is $\sim \delta v^3/l_{edd}$
⇒ Energy spectrum indicates the viscosity becomes higher in the higher-resolution runs.

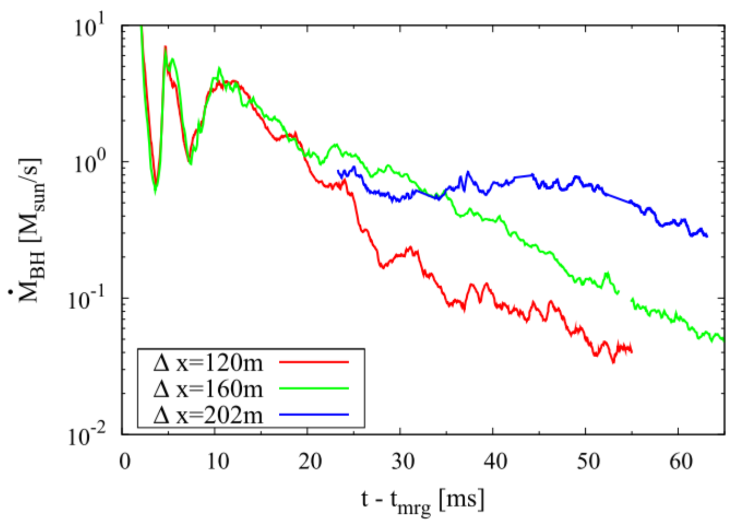
Mechanism to enhance the thermal pressure

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



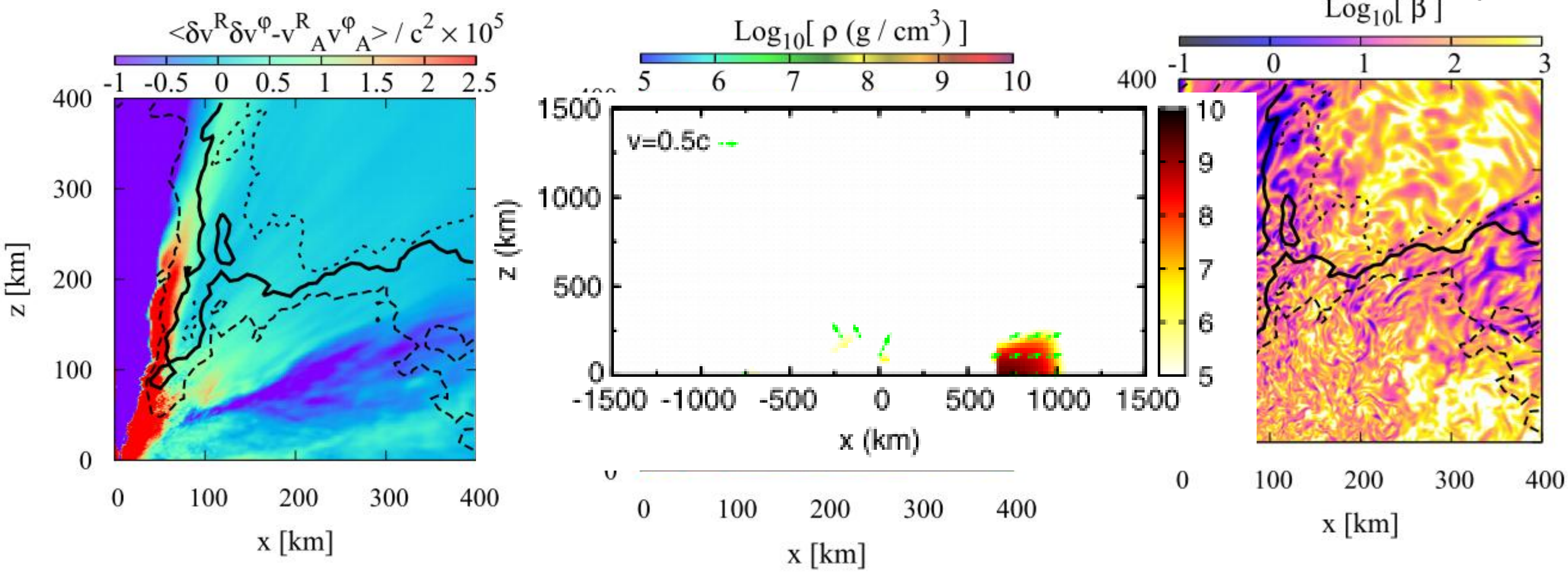






Formation of the funnel wall and magnetosphere

Reynolds+Maxwell stress　　Density　　P / P_{mag}

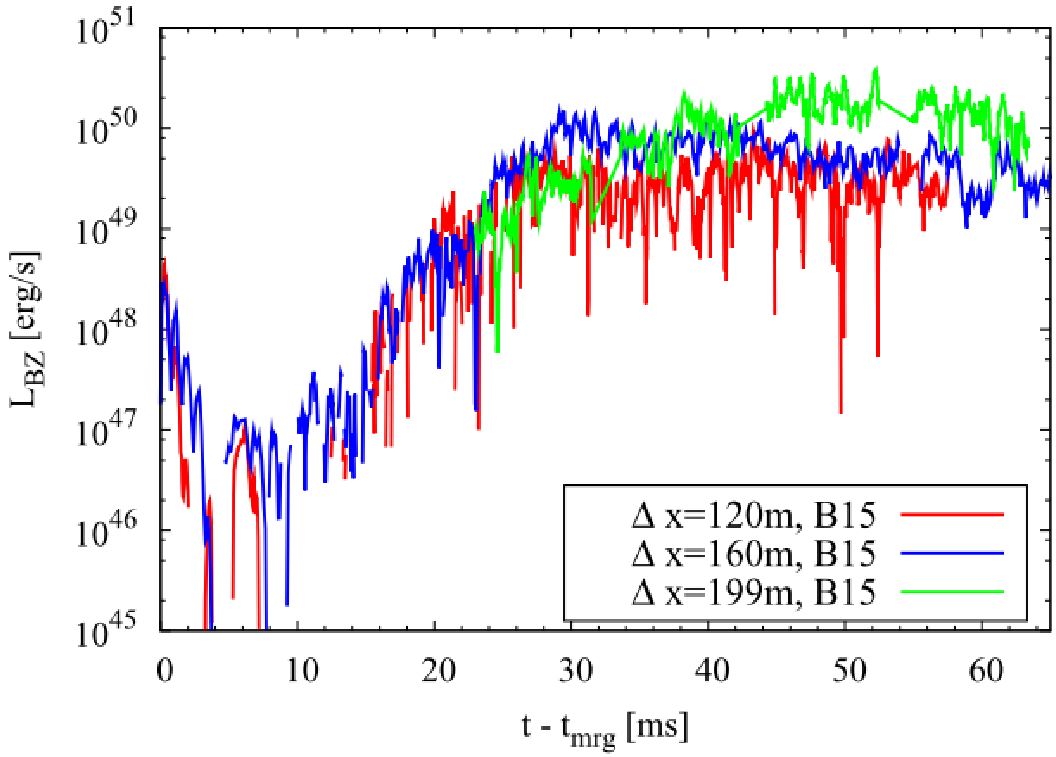


▶Energy is transported in a region with u_t<-1

▶Funnel wall formation by the torus wind

▶Torus wind ⇒ Coherent poloidal B-field ⇒ Formation of a low plasma beta region ⇒ Formation of the magnetosphere

Blandford–Znajek meshanism = Extraction of the BH rotational energy via B-fields



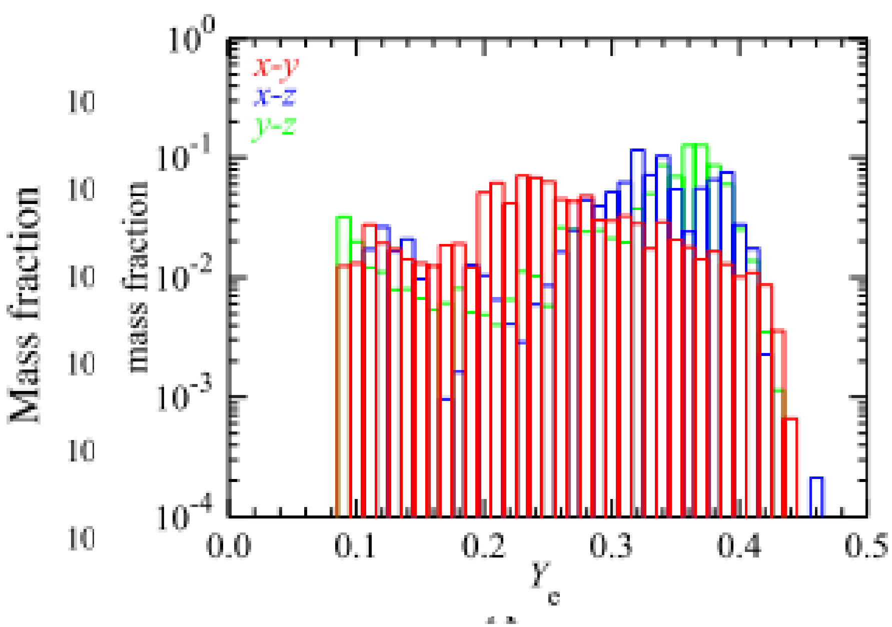
▶Outgoing Poynting flux is as high as ≈2×10^{49} erg/s
⇒ It could be a central engine for the SGRBs with low luminosity (Lee & Ramires-Ruiz 07)
▶Jet could be naturally collimated by the funnel wall once it launches.

Implications of the torus wind

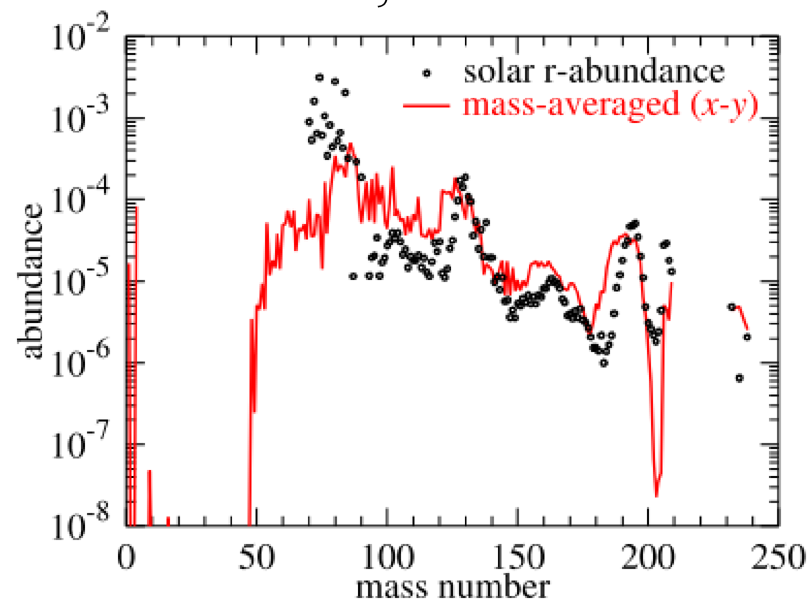
▶ Nucleosynthesis in the BH-NS merger

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

⇒ Reproduce the third peak of the solar abundance



Wanajo et al. 14



▶Torus wind is hot ⇒ Different Ye distribution from that for the dynamical component composed of the non-hot neutron rich matter.

▶ Broad distribution of the Ye could reproduce the solar abundance (BH-NS: Just et al. 15, NS-NS: Sekiguchi et al. 15, Wanajo et al. 14)

Implications of the torus wind

Macronova/kilonova model in the BH-NS merger (Li-Paczynski 98)

▶ Dynamical ejecta$\sim 10^{-6}$-$10^{-1} M_\odot$ (Hotokezaka et al. 13, Kyutoku et al. 15)

▶ Thermal driven torus wind $M_{ej} \sim 0.06 M_\odot$ ($\sim 0.5 M_{disk}$), but only one point in the parameter spaces

Systematic study should be done.

Caveat and summary

NR simulations of the BH-magnetized NS mergers on K

▶ Resolution study is essential.

▶ Tidal disruption ⇒ Accretion torus formation ⇒ Torus wind launch ⇒ Funnel wall formation ⇒ Magnetosphere formation in a self-consistent simulation

▶Turbulent eddies are the agent to drive the mass accretion and to convert the kinetic energy to thermal energy

Implications

▶ Central engine of the SGRBs

▶ The nucleosynthesis of the r-process elements

▶ The radioactively-powered transient emission