Magnetohydrodynamical simulations of black hole - neutron star mergers in numerical relativity

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Ref.) Kiuchi et al. 15

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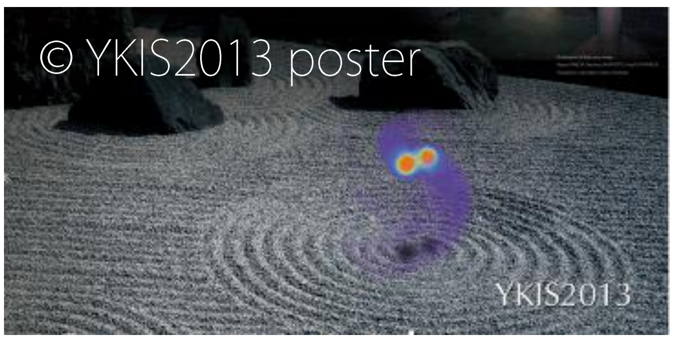
K computer

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

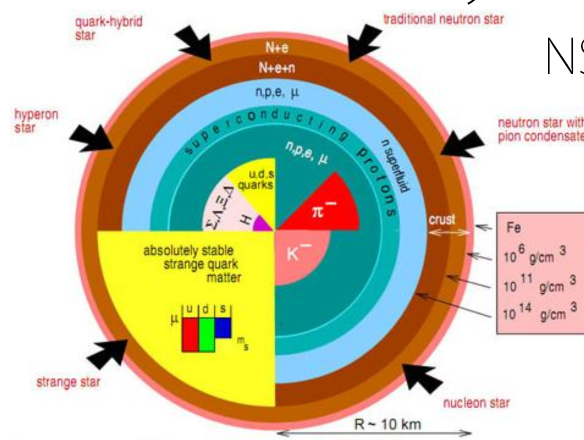
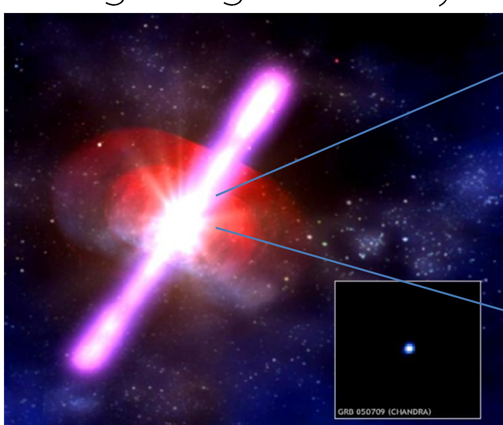
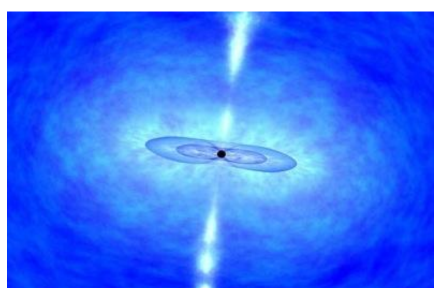


Image of gamma-ray burst

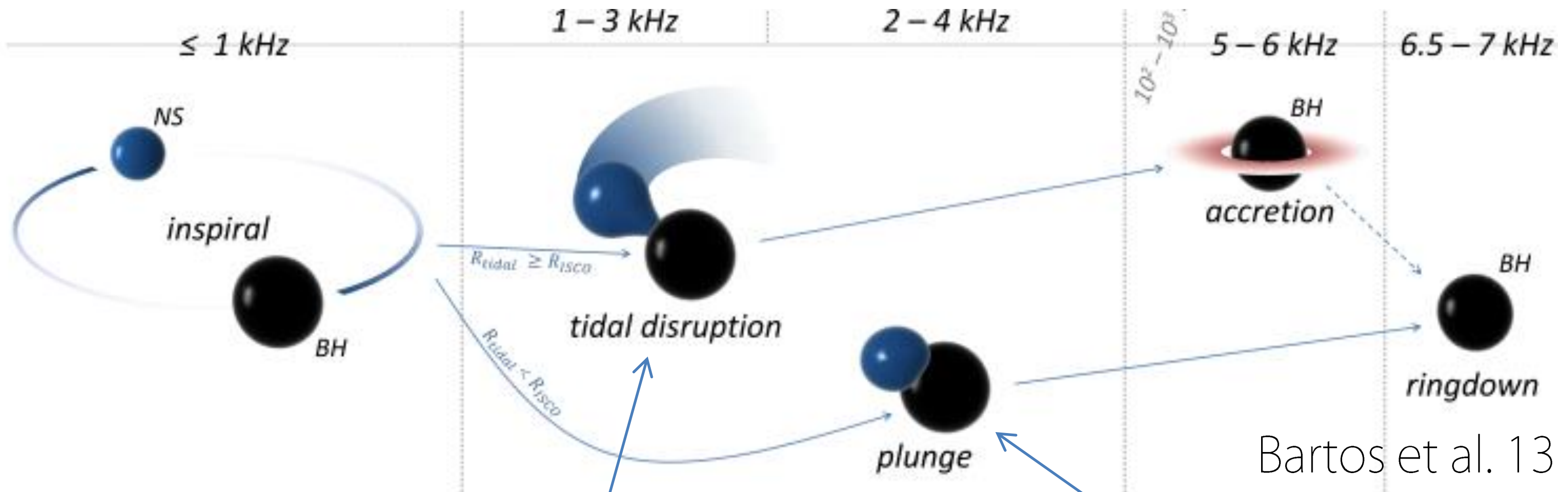




Colliding Neutron Stars Produce Gold ?

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

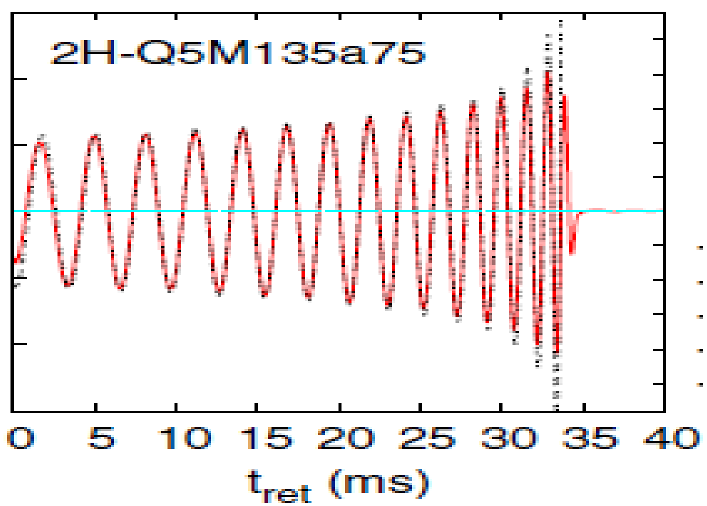
Q: Tidal disruption or not ? (Mass ratio, BH spin, EOS of NS)

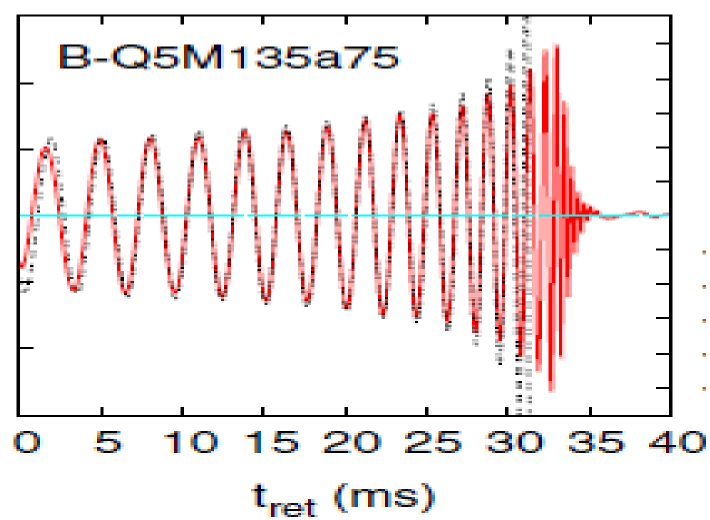


Bartos et al. 13

Time

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





BH – torus systems

<u>A key ingredient = "viscosity"</u>

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. $\langle q \rangle = q_{ave}$ and $\langle \delta q \rangle = 0$ where $\langle \cdot \rangle$ denotes the time average.

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

$W_{A\varphi} = \langle \delta v_A \delta v_\varphi - B_A B_\varphi / 4\pi\rho \rangle$ (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 $\propto \Omega$

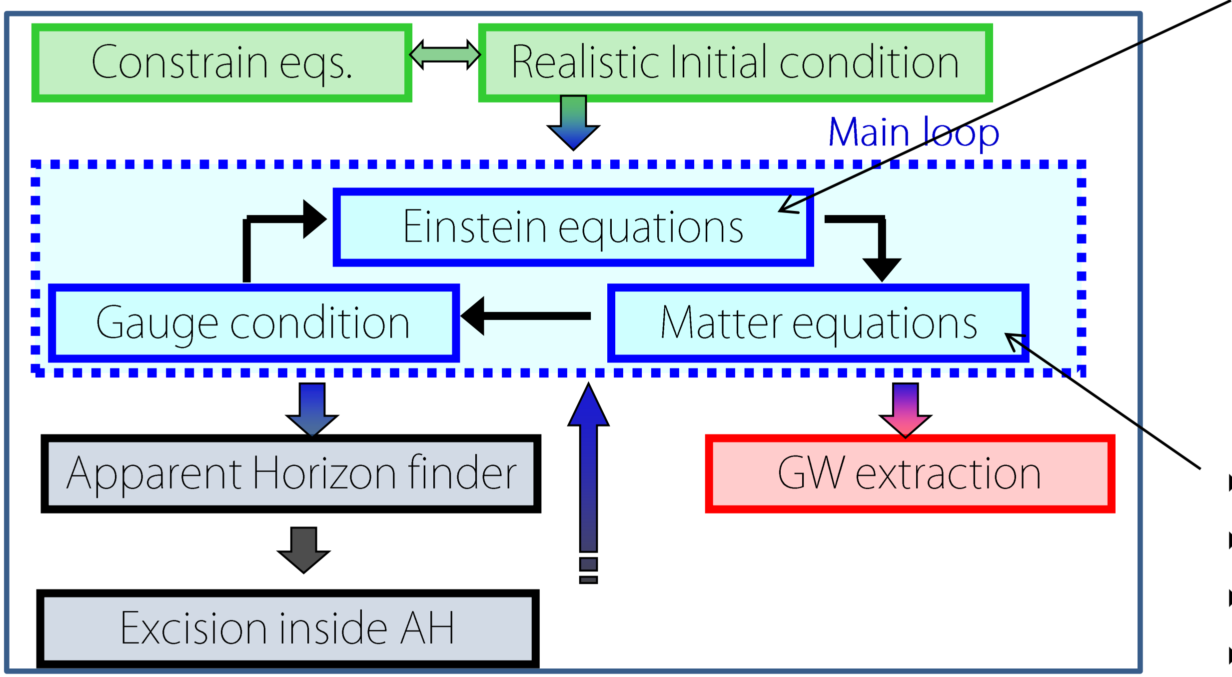
Q & A cont. and what we have to do

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.

Recipe of Numerical Relativity



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

- GR hydro.
- GR magneto hydro.
- GR radiation hydro.
- GR radiation magneto hydro.

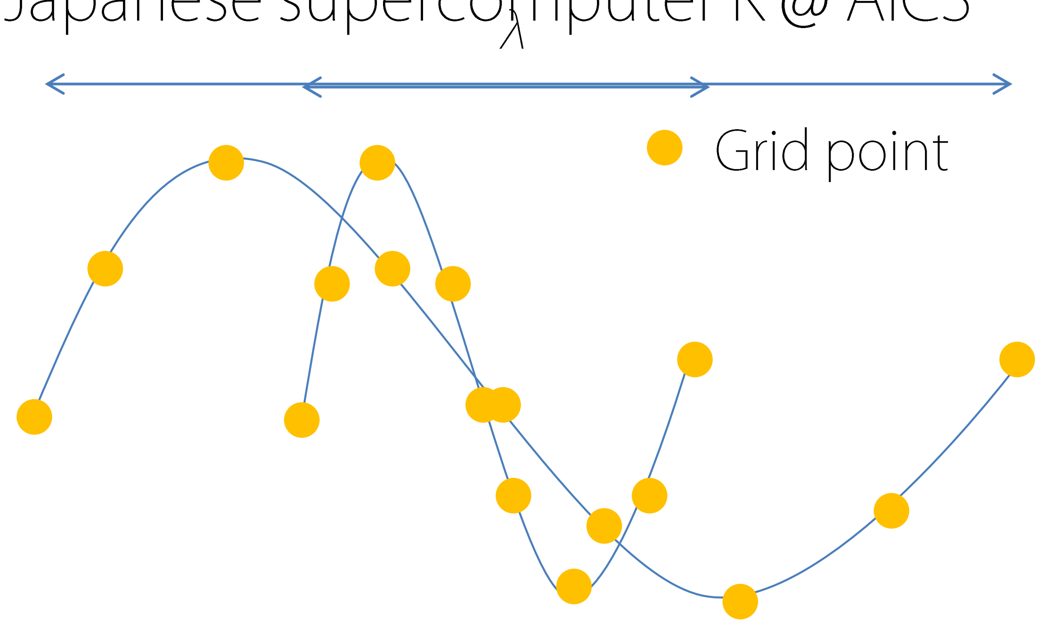
Slide courtesy of Sekiguchi

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 .

Japanese supercomputer K @ AICS



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

Simulation set-up

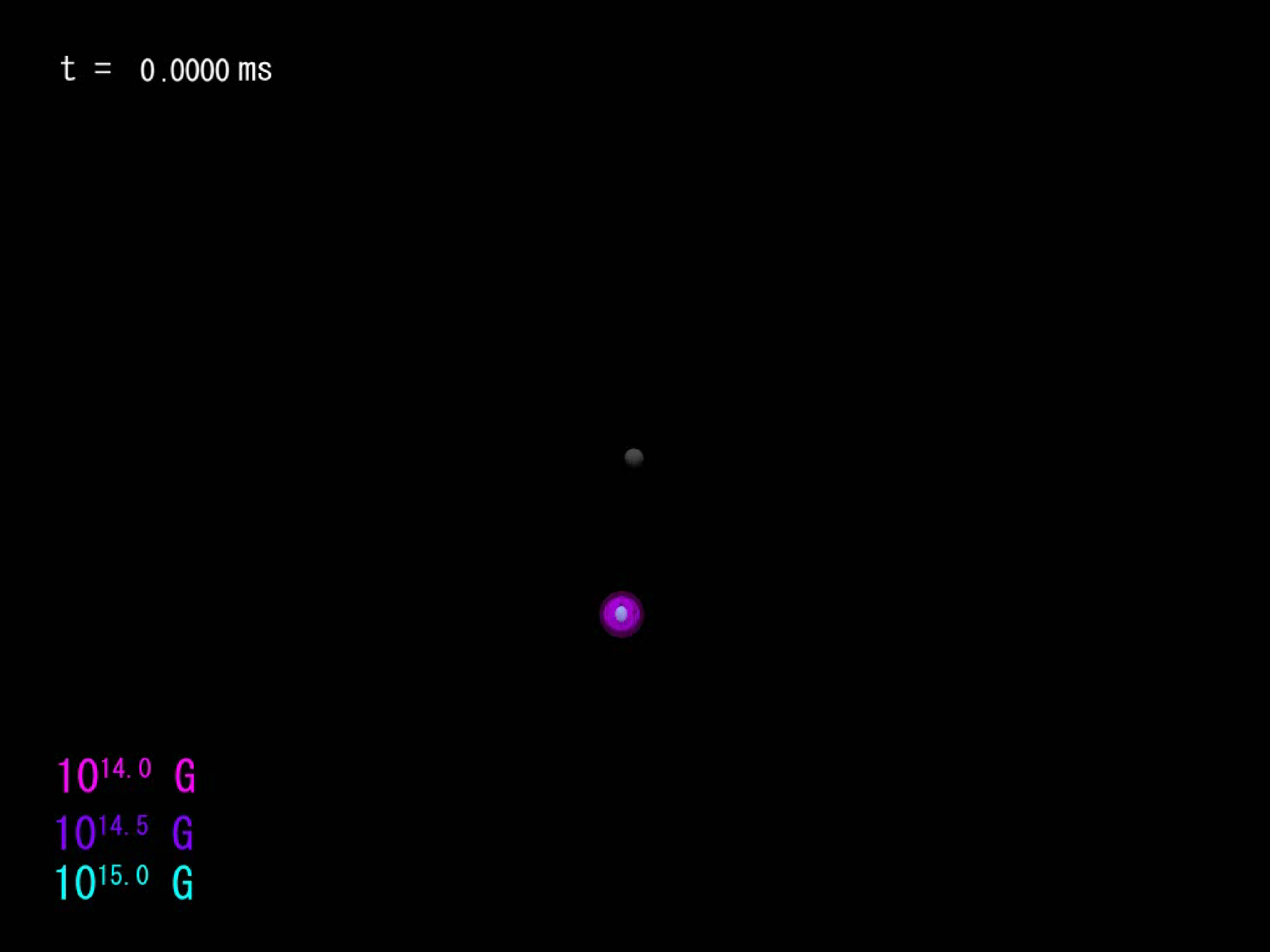
- High resolution ; Δx=120m, N=1028^3 (K ; 32,768 cores)
- Middle resolution ; Δx = 160m, N=756^3 (XC30 ; 4,096 cores)
- Normal resolution ; Δx = 202m, N=612^3 (XC30 ; 4,096 cores)
- Low resolution ; Δx = 270m, N=448^3 (FX10 ; 3,456 cores)

c.f. highest-res. in BH-magnetized NS simulation is $\Delta x \approx$260m, N =140^3

<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

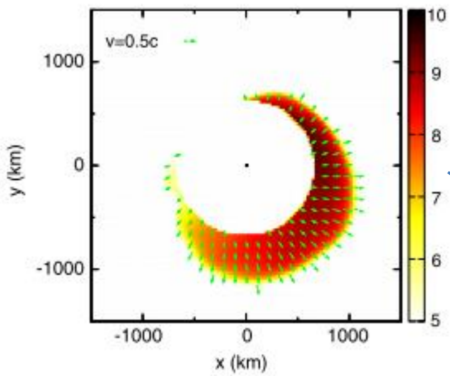

t = 0.2270 ms
10^{12} g/cm^3
10^{11} g/cm^3
10^{10} g/cm^3
10^{9} g/cm^3

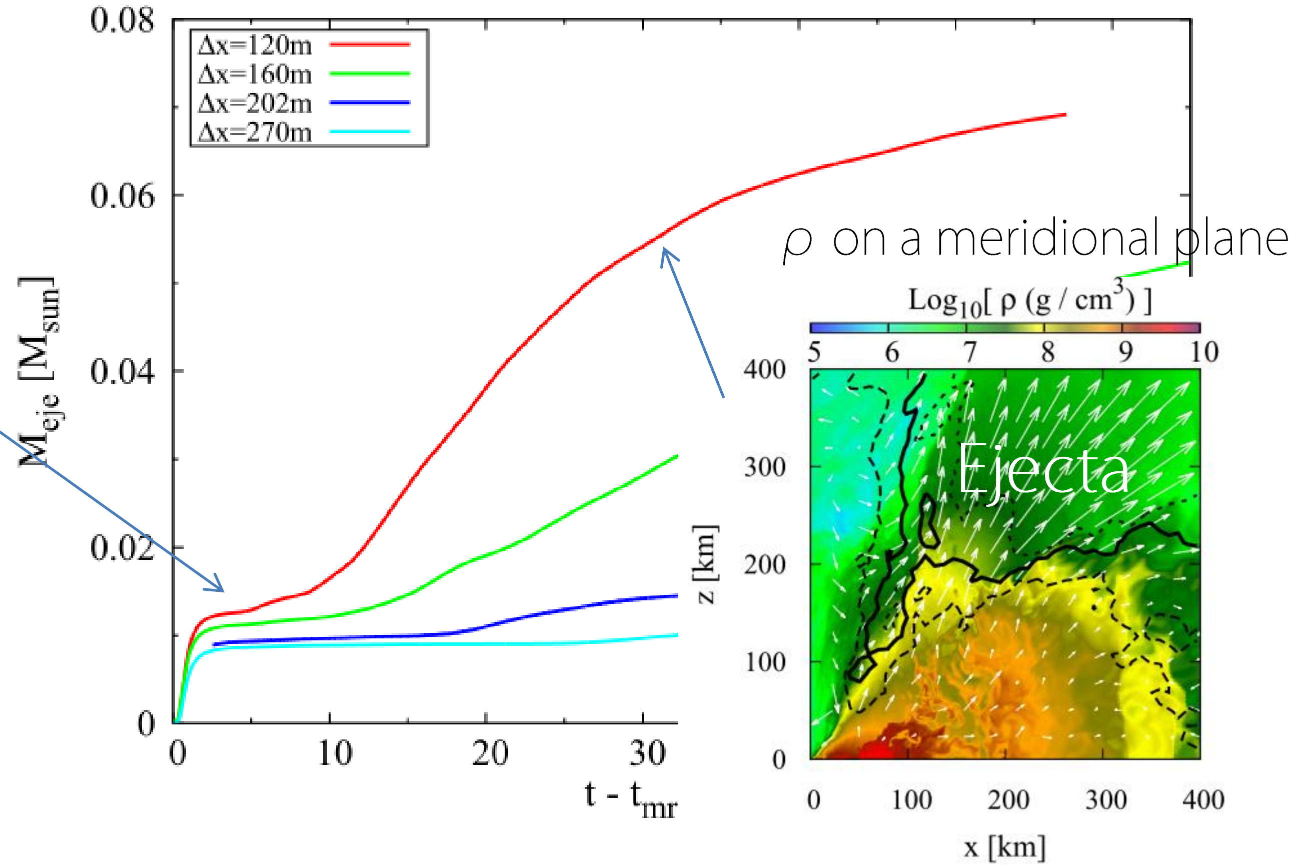

t = 0.0000 ms
$10^{14.0}$ G
$10^{14.5}$ G
$10^{15.0}$ G

Ejecta time evolution

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

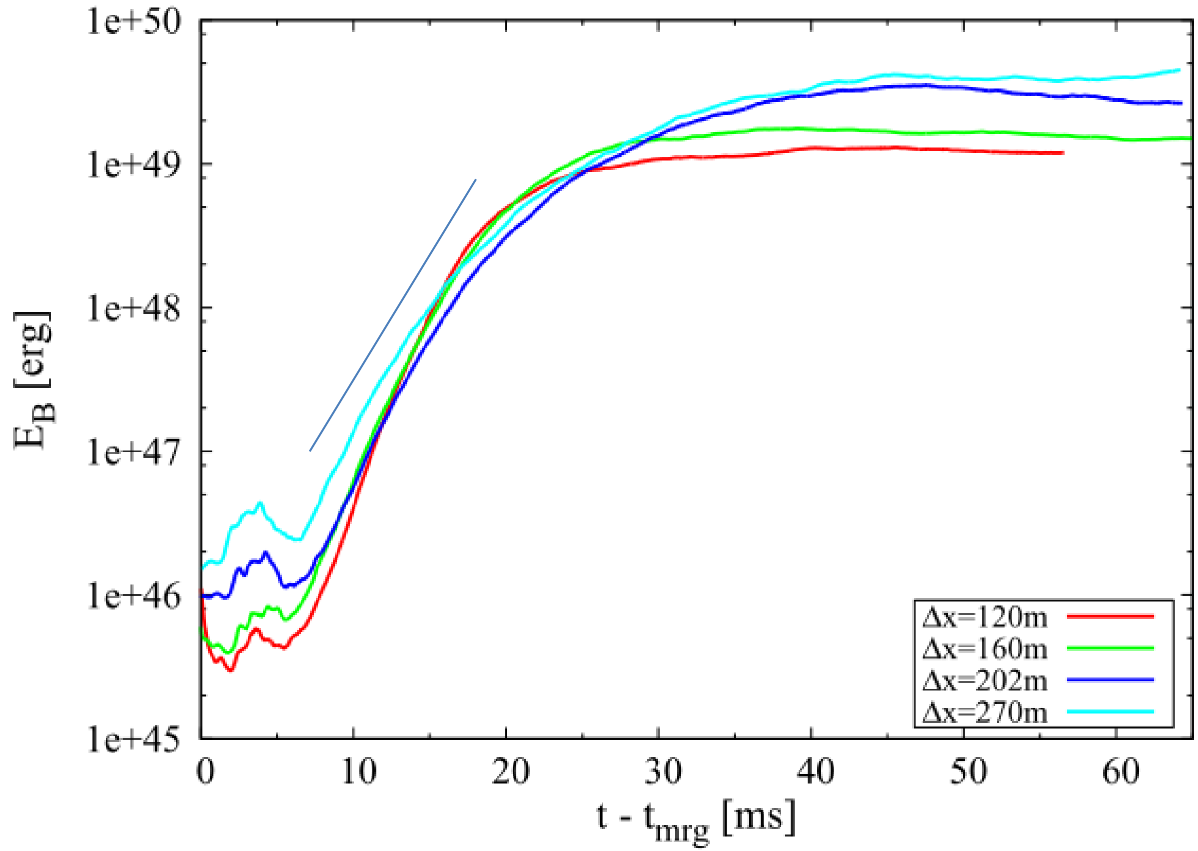
ρ_{eje} on the orbital plane (Log[ρ (g/cc)])





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

Does the magetorotational instability switch on ?

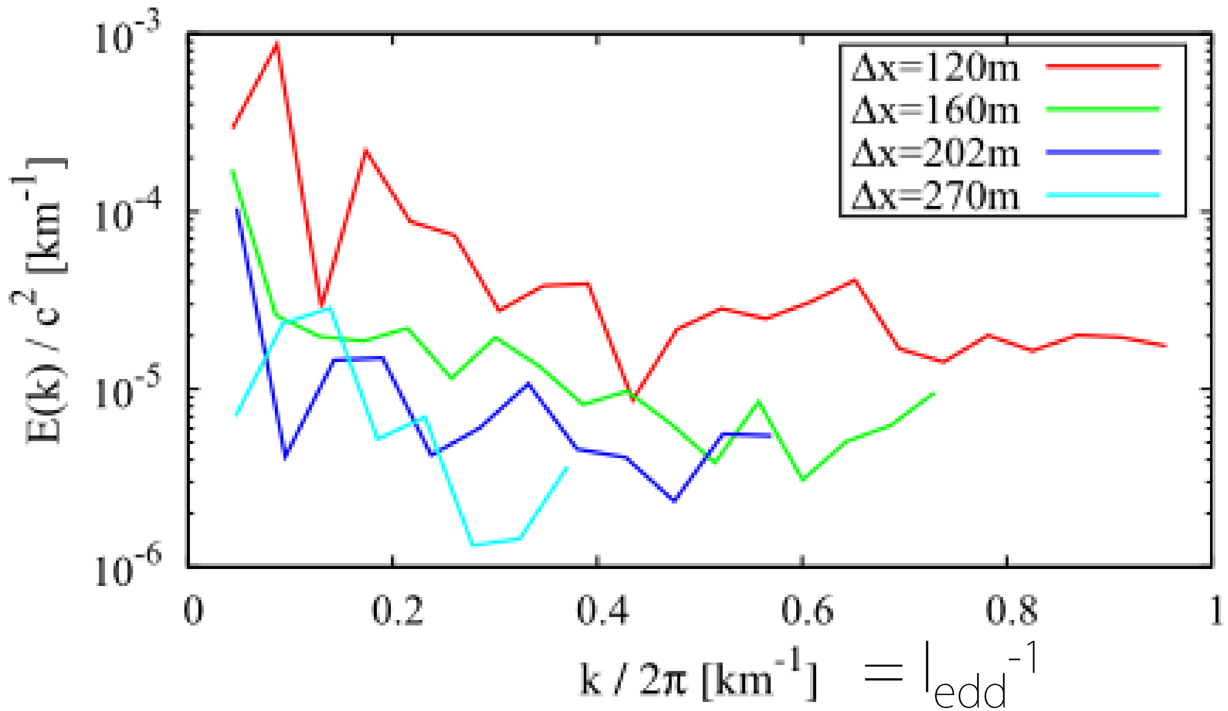


Yes. The magnetic-field energy is exponentially growing for 10 ms $\lesssim$ t $\lesssim$ 20 ms.

⇒ 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



$= l_{edd}^{-1}$

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

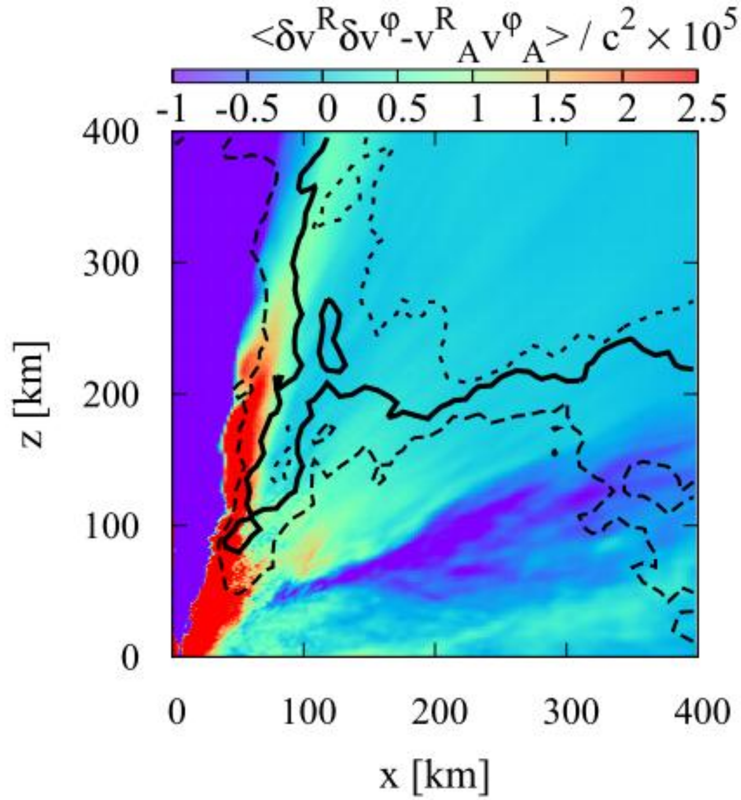
The effective turbulent viscosity is $\sim \delta v \, l_{edd}$ and $E(k) \propto \delta v^2$

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

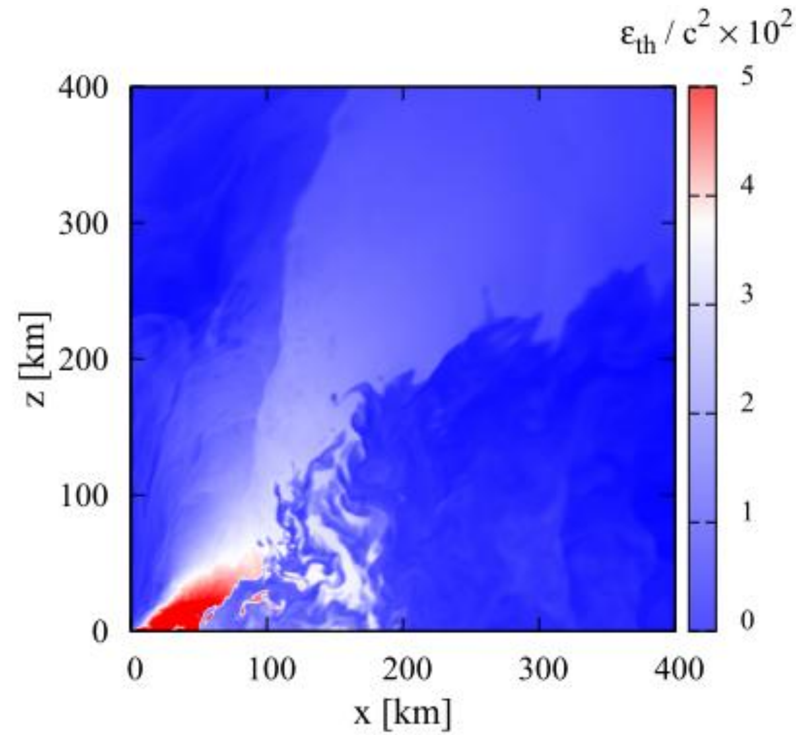
So, the answer is Yes.

Is the energy transferred outward and thermalized ?

Reynolds+Maxwell stress



Thermal component of specific thermal energy



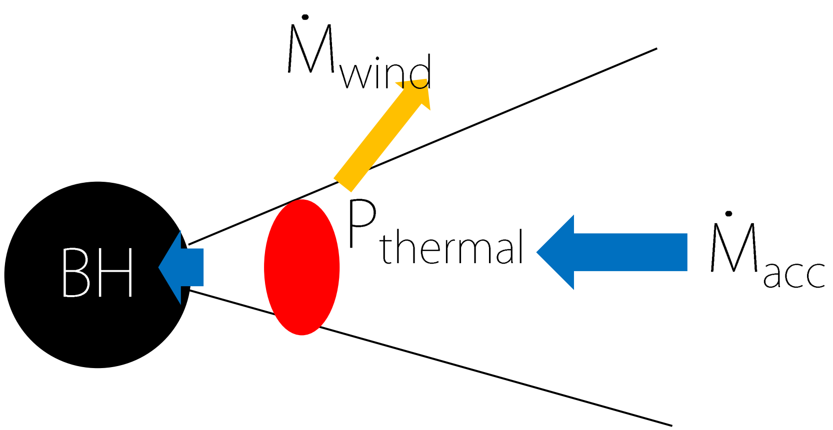
Yes.

▶The energy is transferred outward.

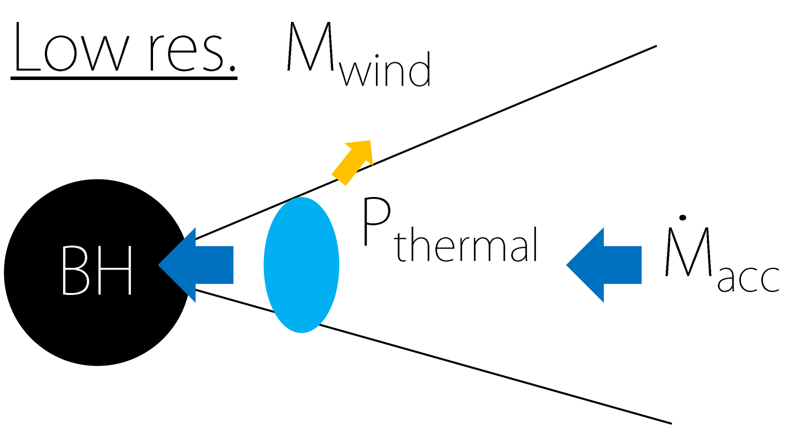
▶Efficient energy conversion to the thermal energy is realized in the vicinity of the inner edge of the torus.

Mechanism of turbulence driven torus wind

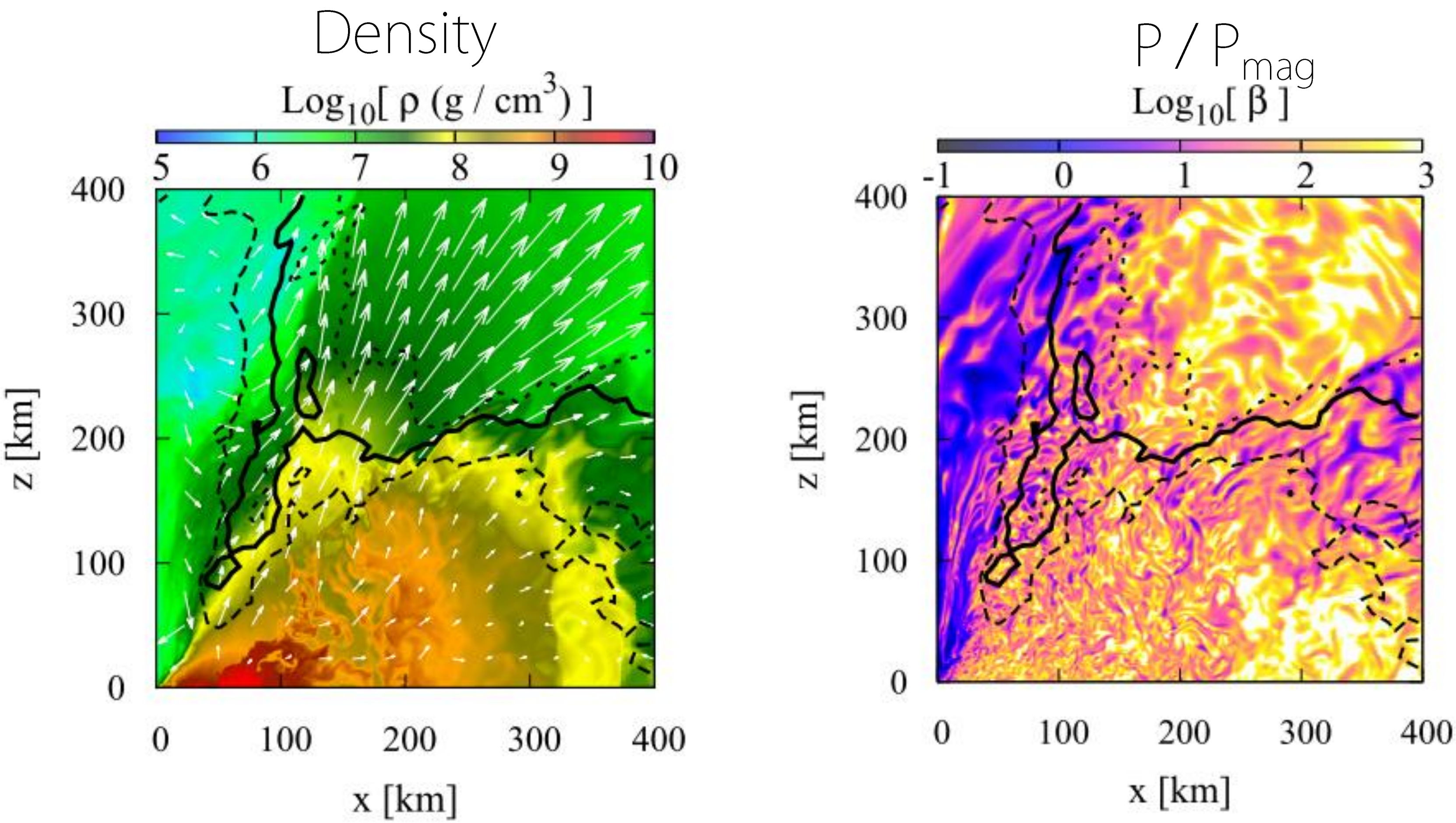
▶The realistic high viscosity enhances the mass accretion inside the torus and converts the mass accretion energy to thermal energy efficiently.



In the absence of the effective turbulent viscosity,



Natural consequence of the torus wind



▶ 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 (Blandford-Znajek 77)

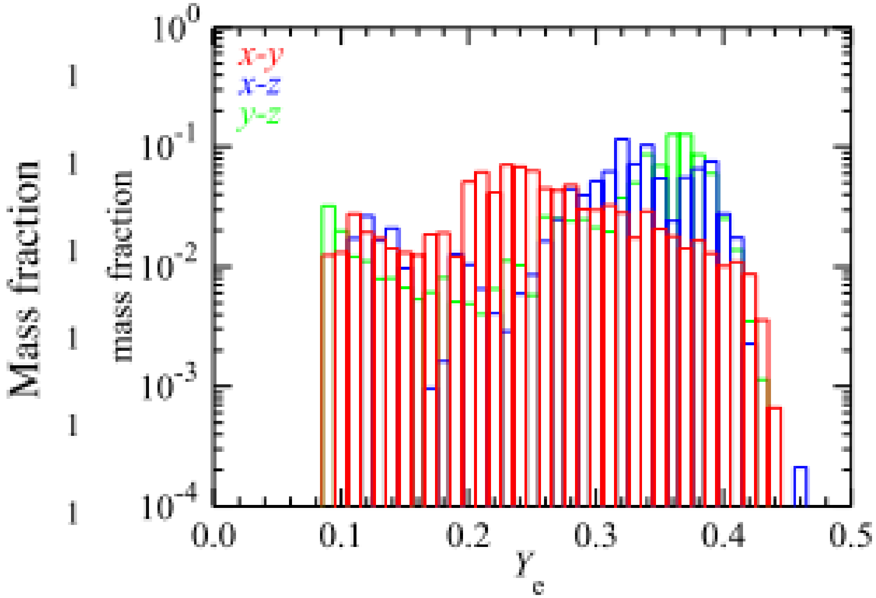
R-process nucleosynthesis in BH-NS merger

▶ Nucleosynthesis in the BH-NS merger

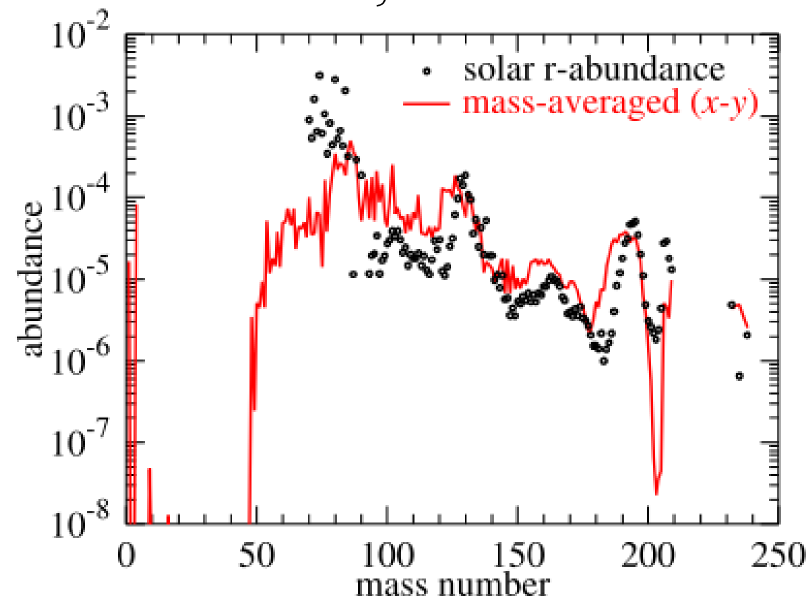
Electron fraction Y_e of the dynamical ejecta is $\lesssim 0.1$

$\Rightarrow$ Reproduce the third peak of the solar abundance

Bauswein et al. 14



Wanajo et al. 14



▶Torus wind is hot $\Rightarrow$ 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 radioacively-powered emission in BH-NS mergers.

Summary

▶ We performed high-resolution GRMHD simulations of a BH-NS merger on K.

▶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.

▶ We discussed the implications to a central engine of short gamma-ray bursts, r-process nucleosynthesis, and radioactively-powered electromagnetic emission.