ブラックホールー中性子星連星合体

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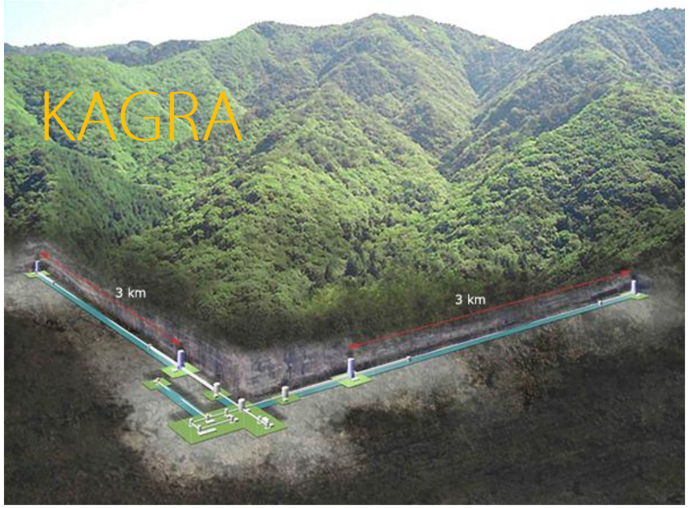
K computer

重力波天体の多様な観測による宇宙物理学の新展開
New development in astrophysics through multimessenger observations of gravitational wave sources

Motivation

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 advanced-LIGO (Abadie et al. 10)



Light curve of GRB

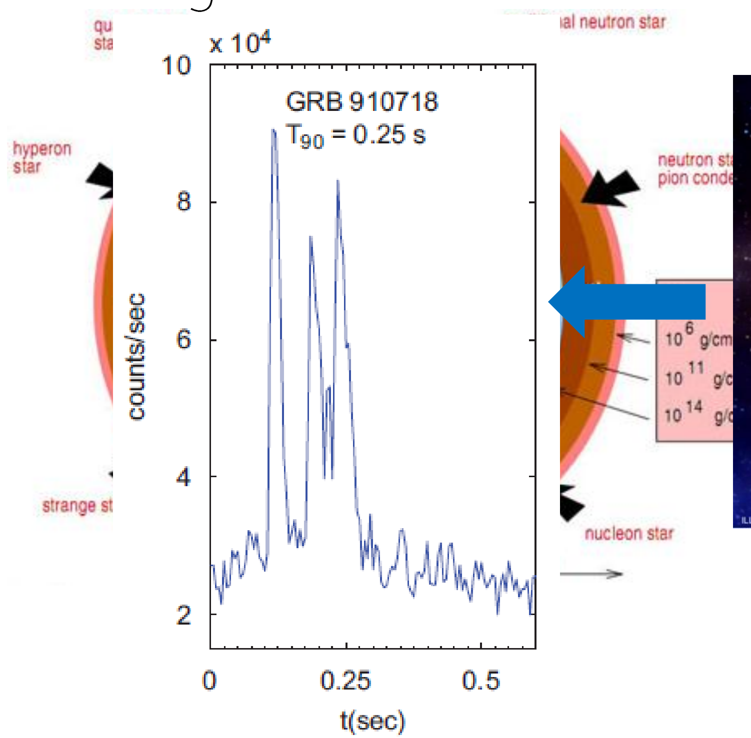
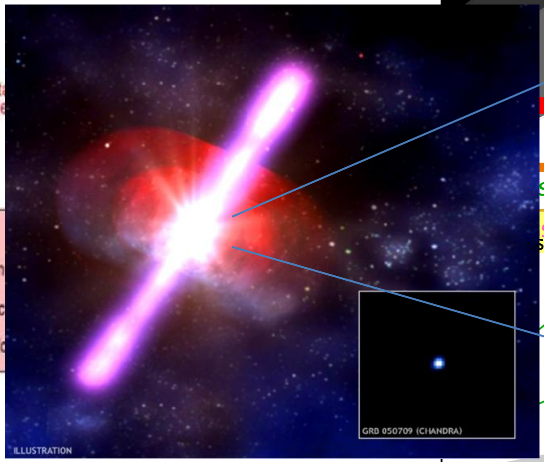
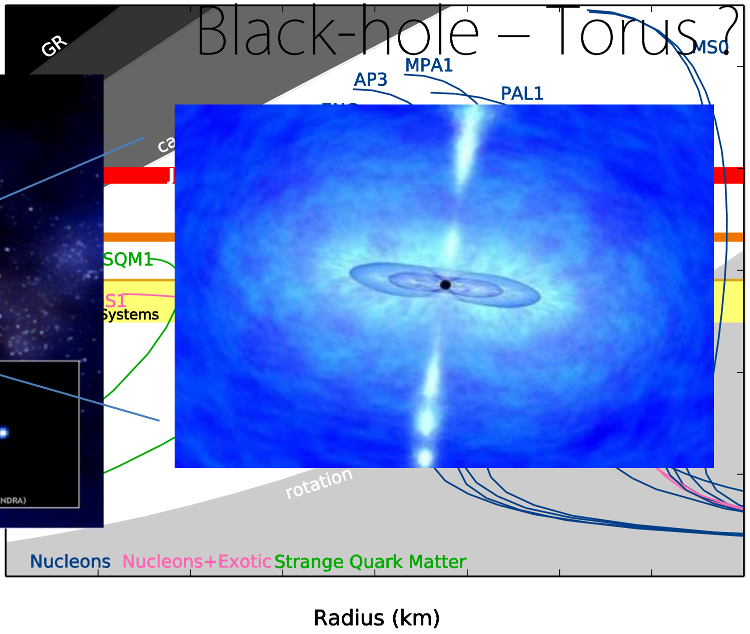


Image of GRB



Black-hole – Torus ?



2. A possible site of the r-process synthesis (Lattimer & Schramm 74)

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Significant amount of the ejected matter

▶ NS-NS : 10^{-4}-$10^{-2} M_\odot$ (Hotokezaka et al. 13, Sekiguchi et al. 15)

▶ BH-NS: 10^{-6}-$10^{-1} M_\odot$ (Kyutoku et al. 15)

⇒ Nucleosynthesis in the ejecta (Wanajo et al. 14, Korobkin et al. 12, Bauswein et al. 13, Wanajo san's talk)

3. Radioactively-powered emission (Li-Paczynski 98, Kulkarni 05, Metzger+10)

$t_{peak} \sim 10$ day $(v/0.2c)^{-1/2} (M_{eje}/10^{-2} M_\odot)^{1/2} (\kappa/10 cm^2/g)^{1/2}$

$L_{peak} \sim 10^{41}$ erg/s $(f/3\times10^{-6}) (v/0.2c)^{1/2} (M_{eje}/10^{-2} M_\odot)^{1/2} (\kappa/10 cm^2/g)^{-1/2}$

▶ A bunch of theoretical studies (Kasen et al. 13, Barnes-Kasen 13, Tanaka-Hotokezaka 13, Tanaka et al. 14, Metzger et al. 15, Kasen et al. 14, Metzger & Fernandez 14 Fernandez et al. 15, Tanaka kun's talk)

▶ Alternative models (Takami et al.14, Kisaka et al. 14)

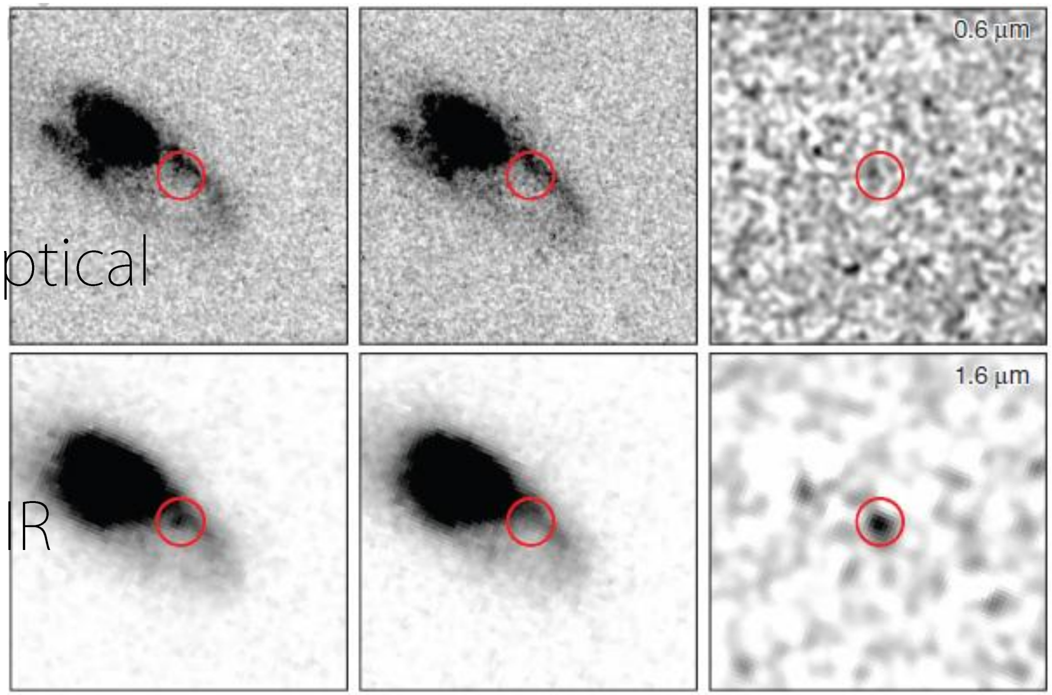
A macronova/kilonova candidate in GRB130603B
(Berger et al.13, Tanvir et al. 13)

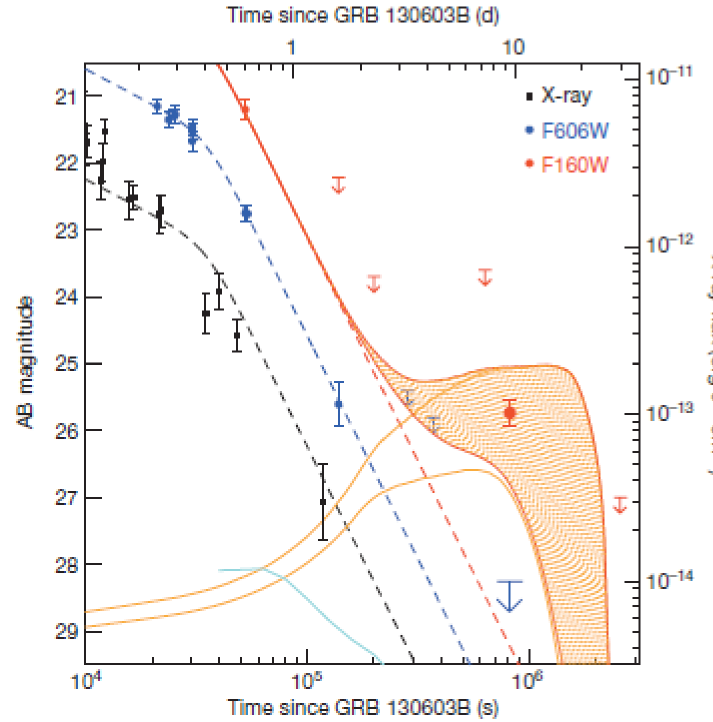
9 days after the burst

30 days after the burst

Optical

NIR





- Point source in NIR, not in optical band ⇒ An excess in NIR

Note T_{90} ≈ 0.18±0.02s, z ≈0.356

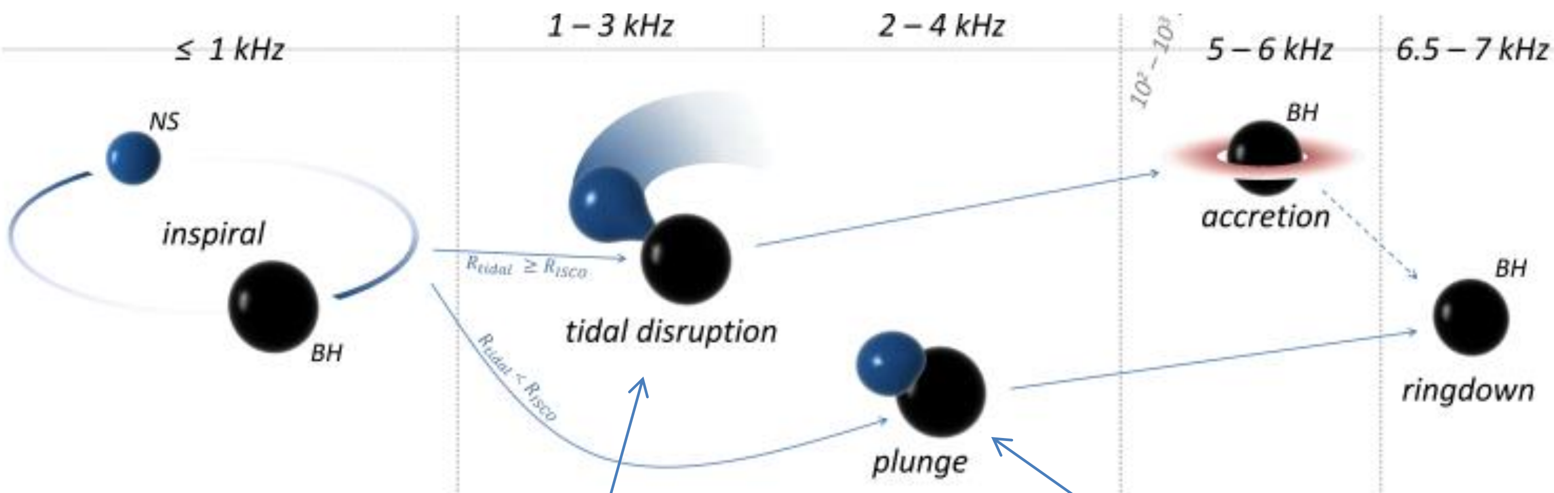
- Macronova model in the BH-NS mergers is a candidate

(Hotokezaka et al. 14)

Overview of Black Hole – Neutron Star

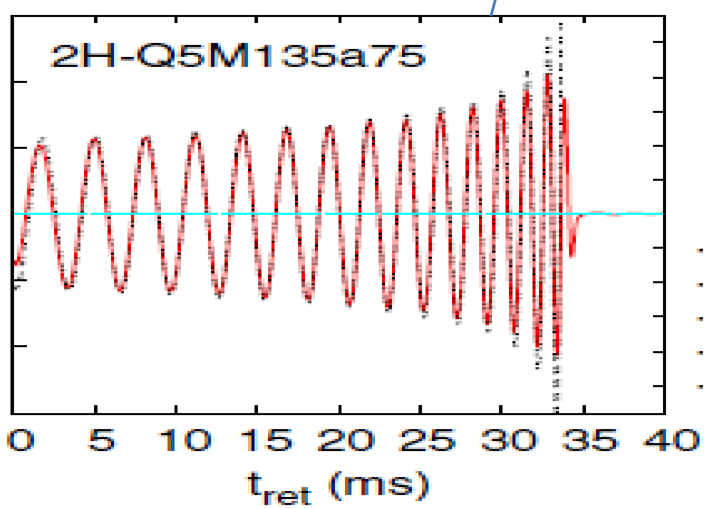
Q: Tidal disruption or not ?

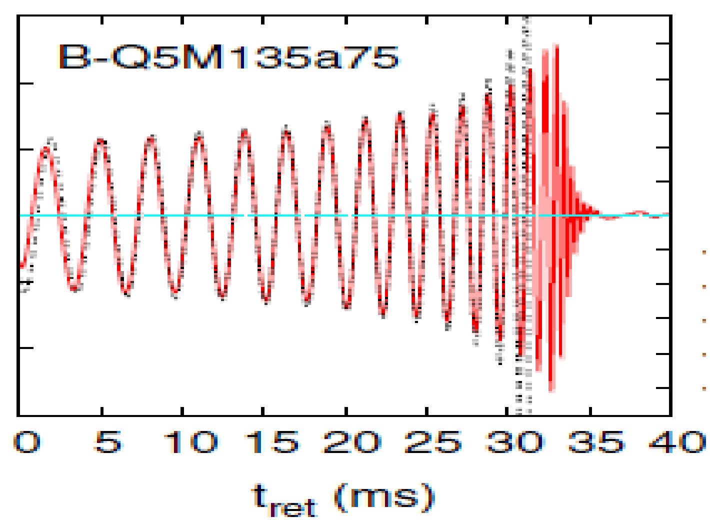
Bartos et al. 13



Time

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





Key ingredients for tidal disruption in BH-NS

Tidal force > NS self gravity

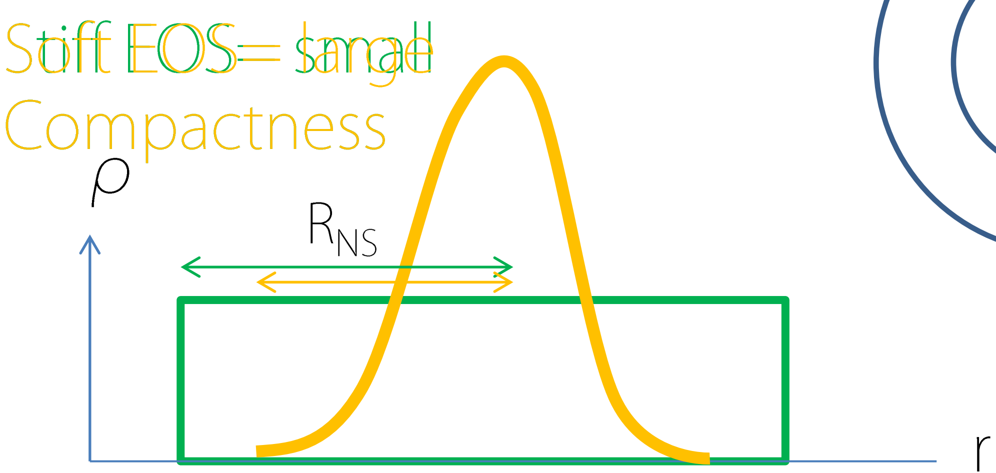
$\Rightarrow$ $r \lesssim (M_{BH}/M_{NS})^{-2/3} (M_{NS}/R_{NS})^{-1} M_{BH} \equiv r_{tidal}$

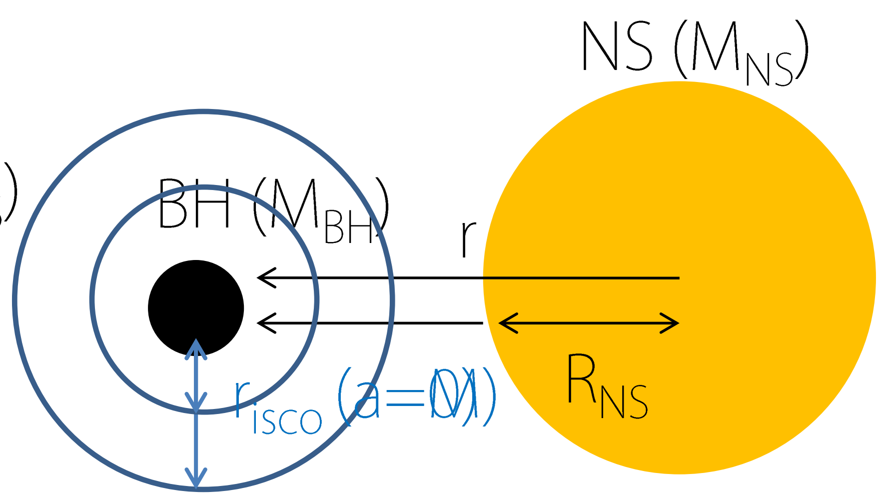
If $r_{tidal} > r_{isco}$ $\Rightarrow$ Tidal disruption

$r_{tidal} < r_{isco}$ $\Rightarrow$ No tidal disruption *ISCO = Inner Stable Circular Orbit

Key ingredients of the mass ejection in BH-NS are

- Spin of BH
- Mass ratio (M_{BH}/M_{NS})
- Compactness of NS (M_{NS}/R_{NS})

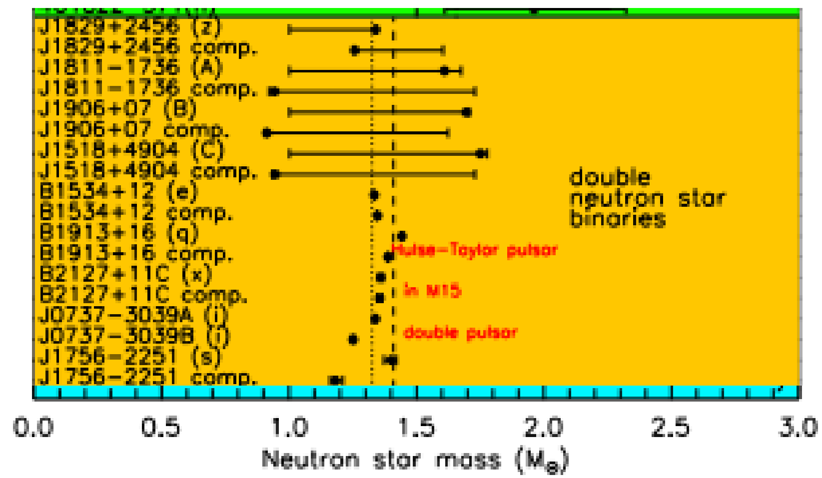




Key ingredients for tidal disruption

- NS mass $M_{NS} \Rightarrow 1.23\text{-}1.44 M_\odot$
- Mass ratio $\Rightarrow q \gtrsim 4\text{-}5$
- EOS ?
- BH spin ?

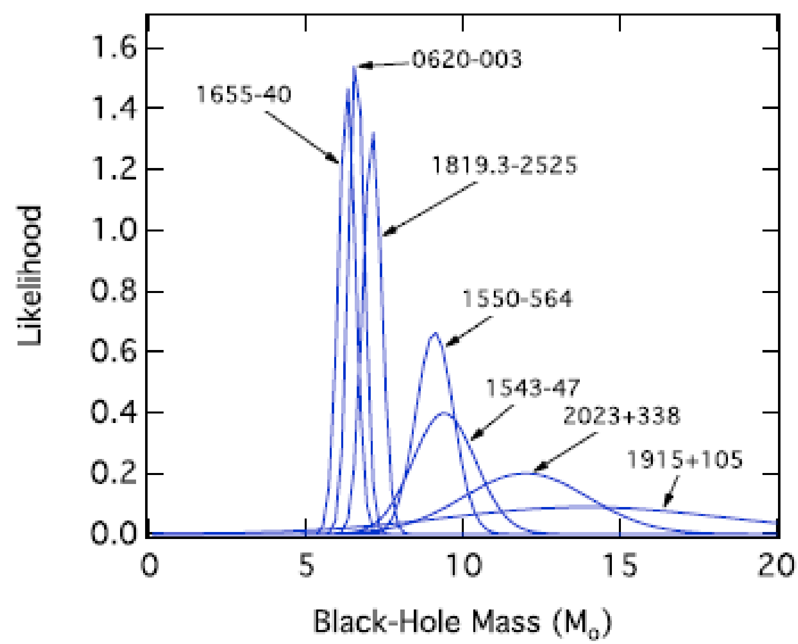
Lattimer & Prakash 06



<u>Systematic study in NR simulations</u>

$\Rightarrow$ Fitting formulae for the accretion torus (Foucart 12)

X-ray binary observation (Ozel+10)



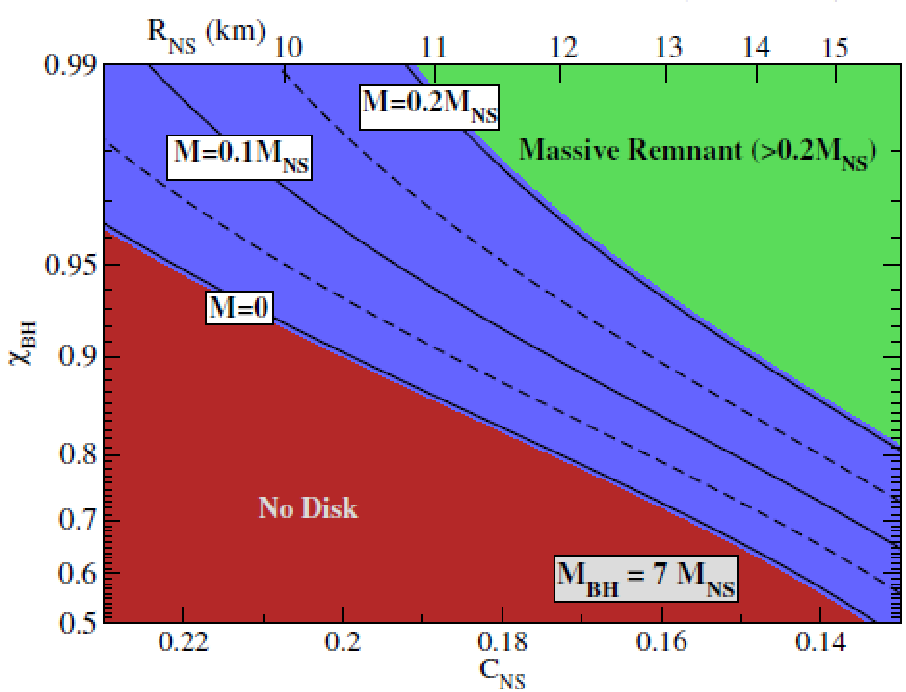
Disk Mass Prediction (Foucart 12)

Fitting formulae

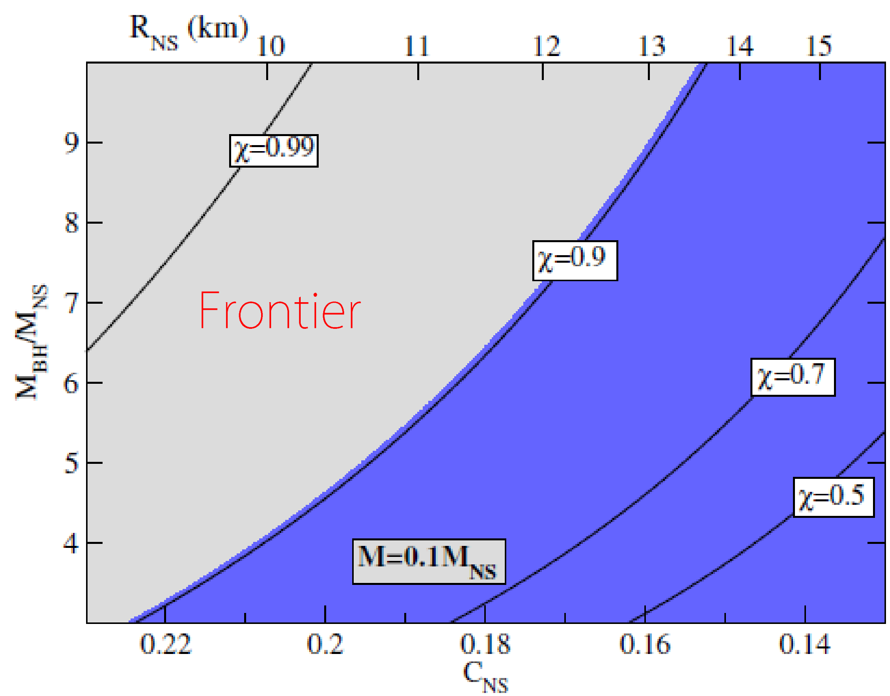
$$M_{disk}/M_{NS}\,(q, C_{NS}, \chi) = \alpha\,(3q)^{1/3}(1-2C_{NS}) - \beta\, r_{isco}/R_{NS}$$

▶31 NR simulations (28models by Kyutoku+11, 7models by Caltech-Cornel 4 models by UIUC

Disk mass contour with q=7



Spin contour with $M_{disk}=0.1M_{NS}$



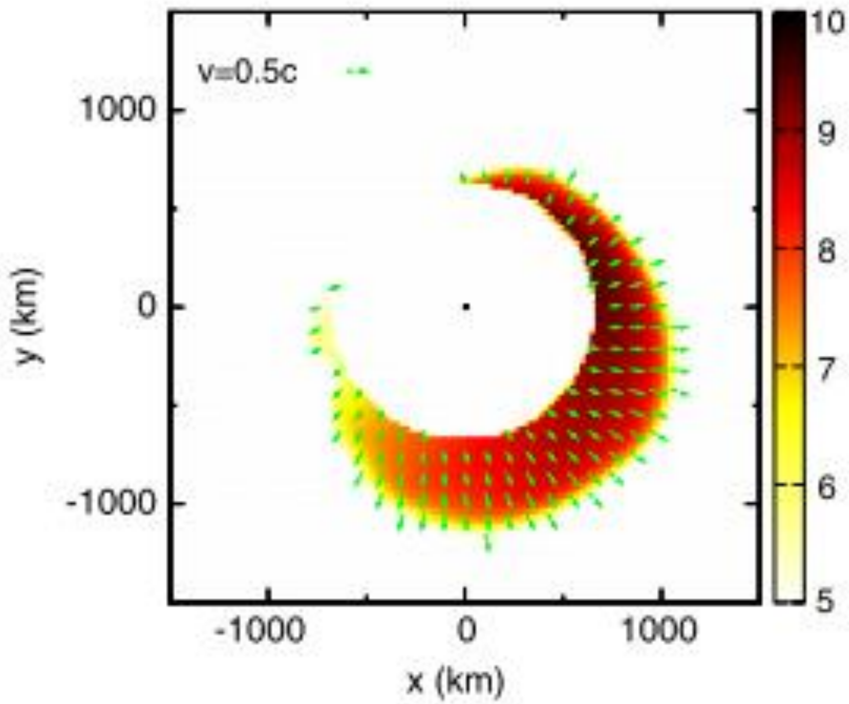
q=4-5, χ=0.75⇒Massive disk

Lovelace et al. q=3, C=0.144, χ=0.97, M_{disk}=0.6 M_{NS}

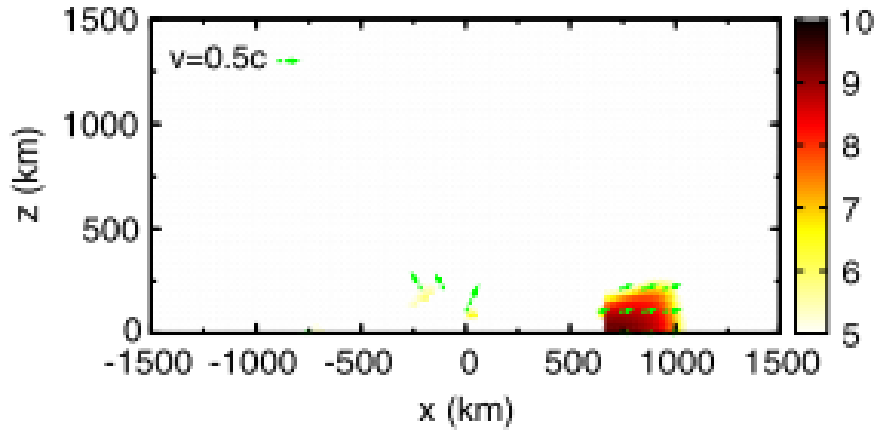
Mass ejection due to tidal torque (Kyutoku et al. 13, Kyutoku et al. 15)

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

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



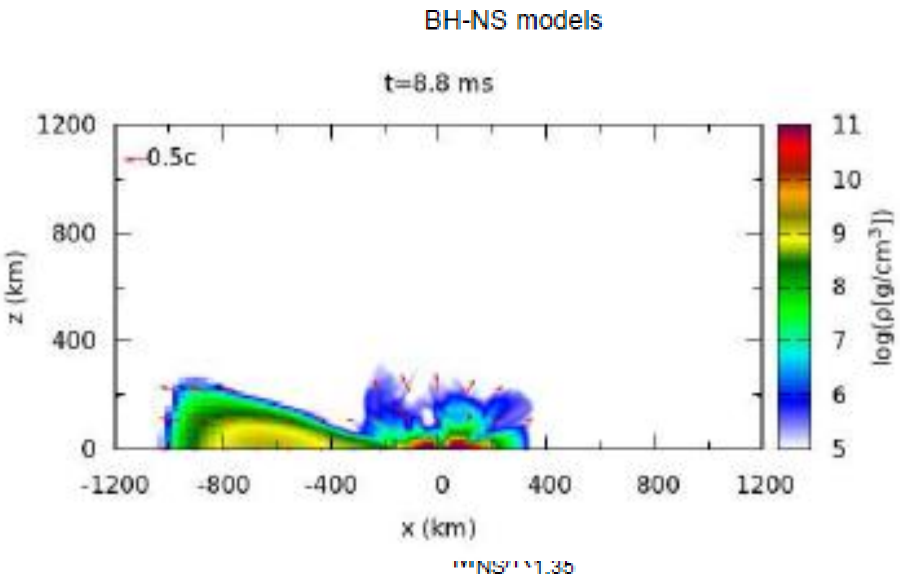
ρ_{eje} on the meridional plane

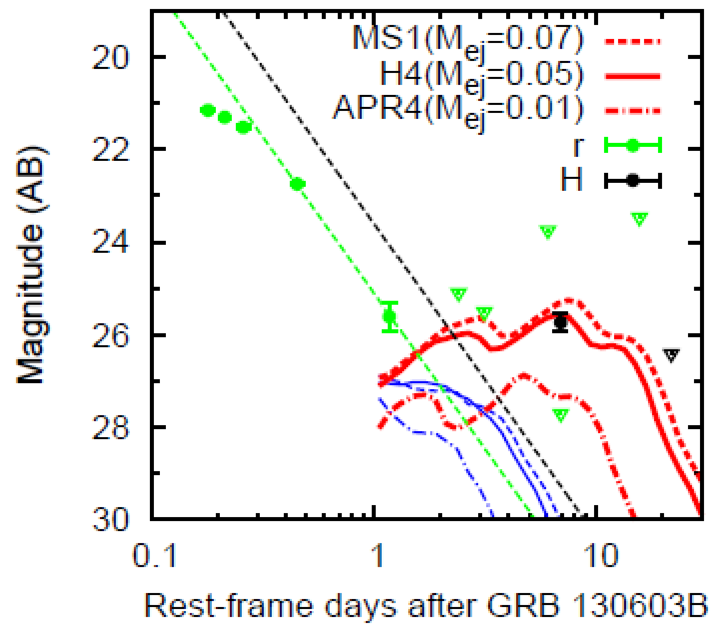


This dynamical ejecta is a primary component in BH-NS mergers (Tilted BH spin case ⇒ Kawaguchi kun's talk)

A macronova model of the BH-NS (Hotokezaka+13, Tanaka+13)

1st step : Numerical Relativity simulation of BH-NS merger => Amount and morphology of ejecta
2nd step : Photon radiation transfer in ejecta (heating due to the radioactive decay of the r-process element)





Hard ⟷ Soft

BH-NS merger models suggest $0.02\ M_\odot < M_{ej} < 0.07\ M_\odot$ is needed to reproduce the light curve of GRB130603B. => It favors a "hard" EOS. Note that you can see inverse trend in NS-NS case.

What's else ?

- Neutrino driven wind (Qian & Woosley 96)

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

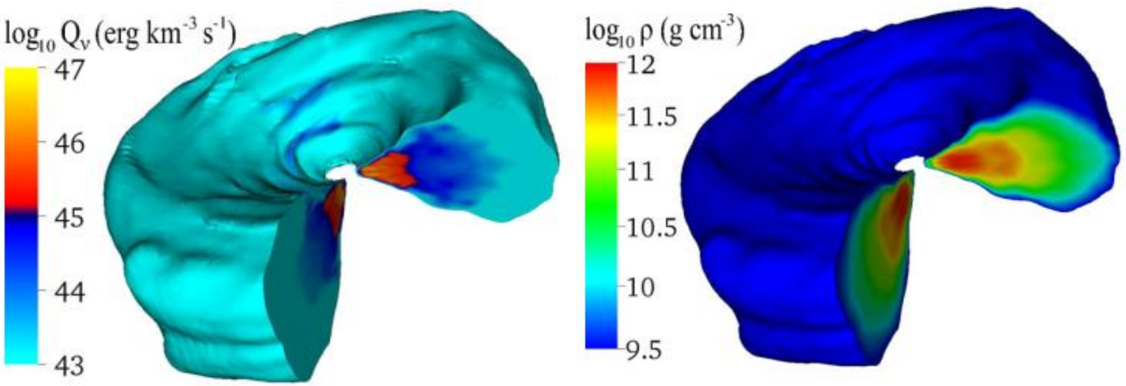
- Disk wind due to the nuclear recombination/viscous heating (Fernandez & Metzger 13)

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

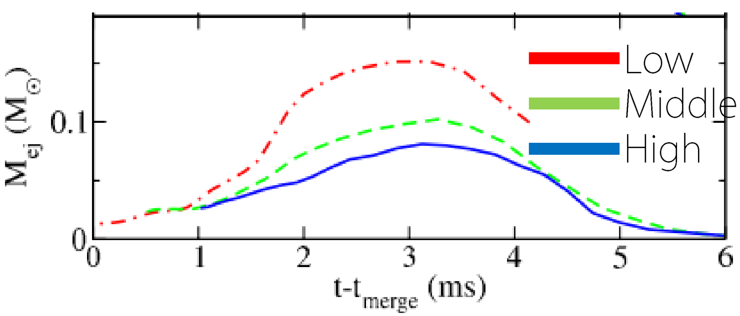
- Magnetic-field effect (e.g., Blandford & Payne 82)

<u>BH-NS merger simulations with microphysics</u>

(Deaton et al. 13, Fourcart et al. 14)



Ejecta mass evolution

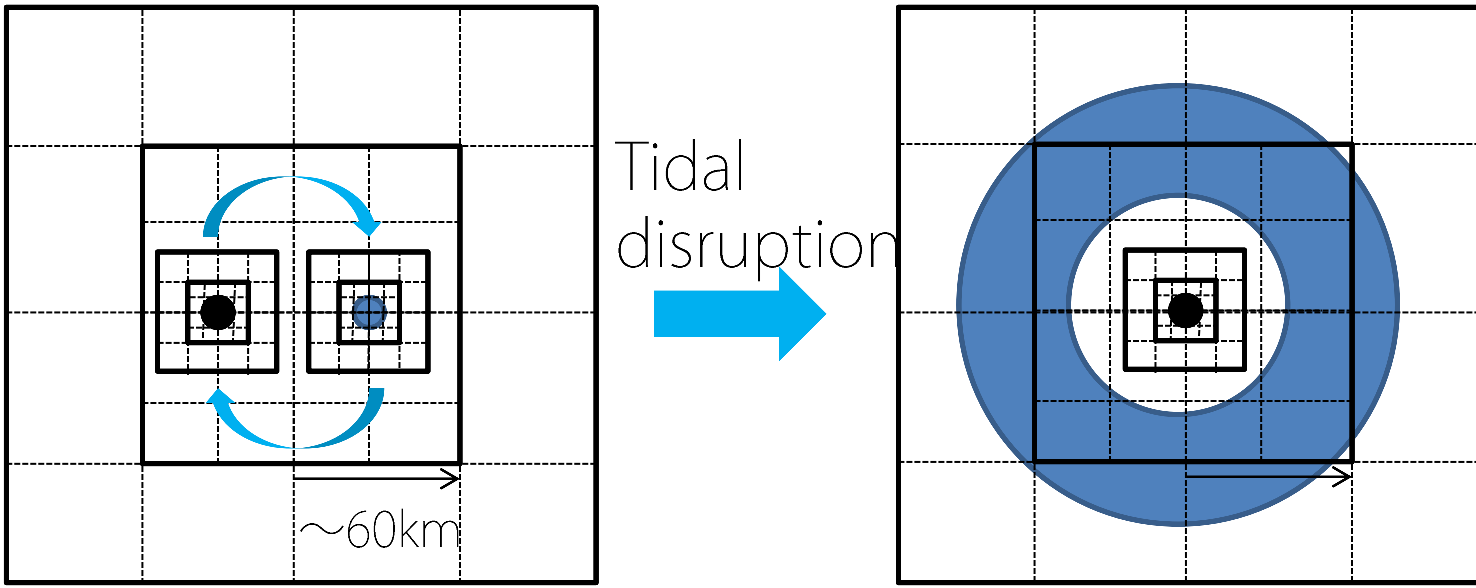


- Mentioning only the dynamical ejecta (no neutrino heating)
- $L_{\nu e} \sim 10^{53}$ erg/s

The BH-magnetized NS simulations by Illinois group

(Liu et al. 08, Etienne et al. 12a, 12b, Paschalidis et al 14)

- $q=3$, $M_{NS}/R_{NS}=0.145$, $\chi=0.75$
- AMR Algorithm, $\Delta x_{fin} \approx 260m$, $L_{fin} \approx 20km$

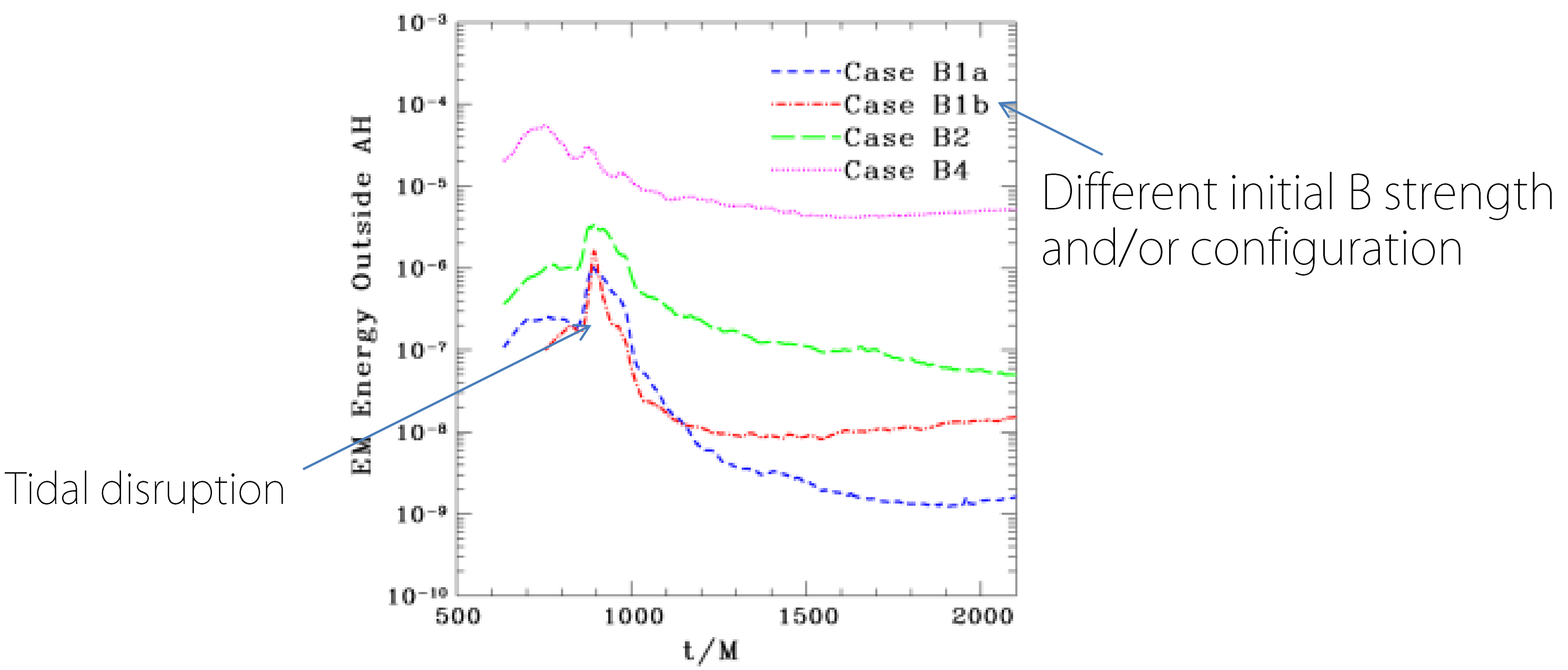


The BH-magnetized NS simulations by Illinois group

(Liu et al. 08, Etienne et al. 12a, 12b, Paschalidis et al 14)

Magnetic field evolution

Unit(Vertical axis) 9.3×10^{53}erg, (Horizontal) 26 μ s



- No magnetic field amplification inside the torus
- No discussion on the outflow except Paschalidis et al. 14

Difficulty in MHD simulation

- A short wavelength mode has a high growth rate
- Turbulence is killed by a numerical viscosity.

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

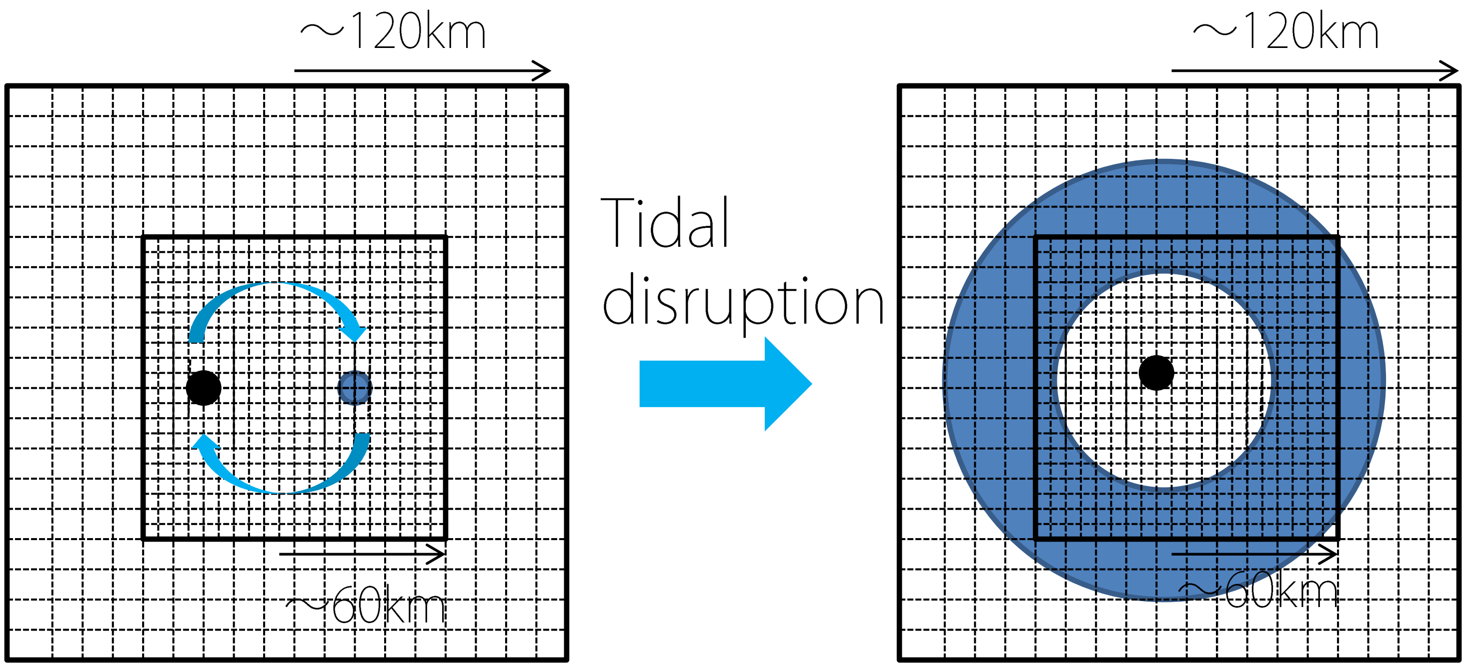
- High resolution ; Δx=120m, N=1024^3 (K ; 32,768 cores)
- Middle resolution ; Δx = 160m, N=756^3 (XC30 ; 4,096 cores)
- Normal resolution ; Δx = 202m, N=614^3 (XC30 ; 4,096 cores)
- Low resolution ; Δx = 270m, N=464^3 (FX10 ; 3,456 cores)

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

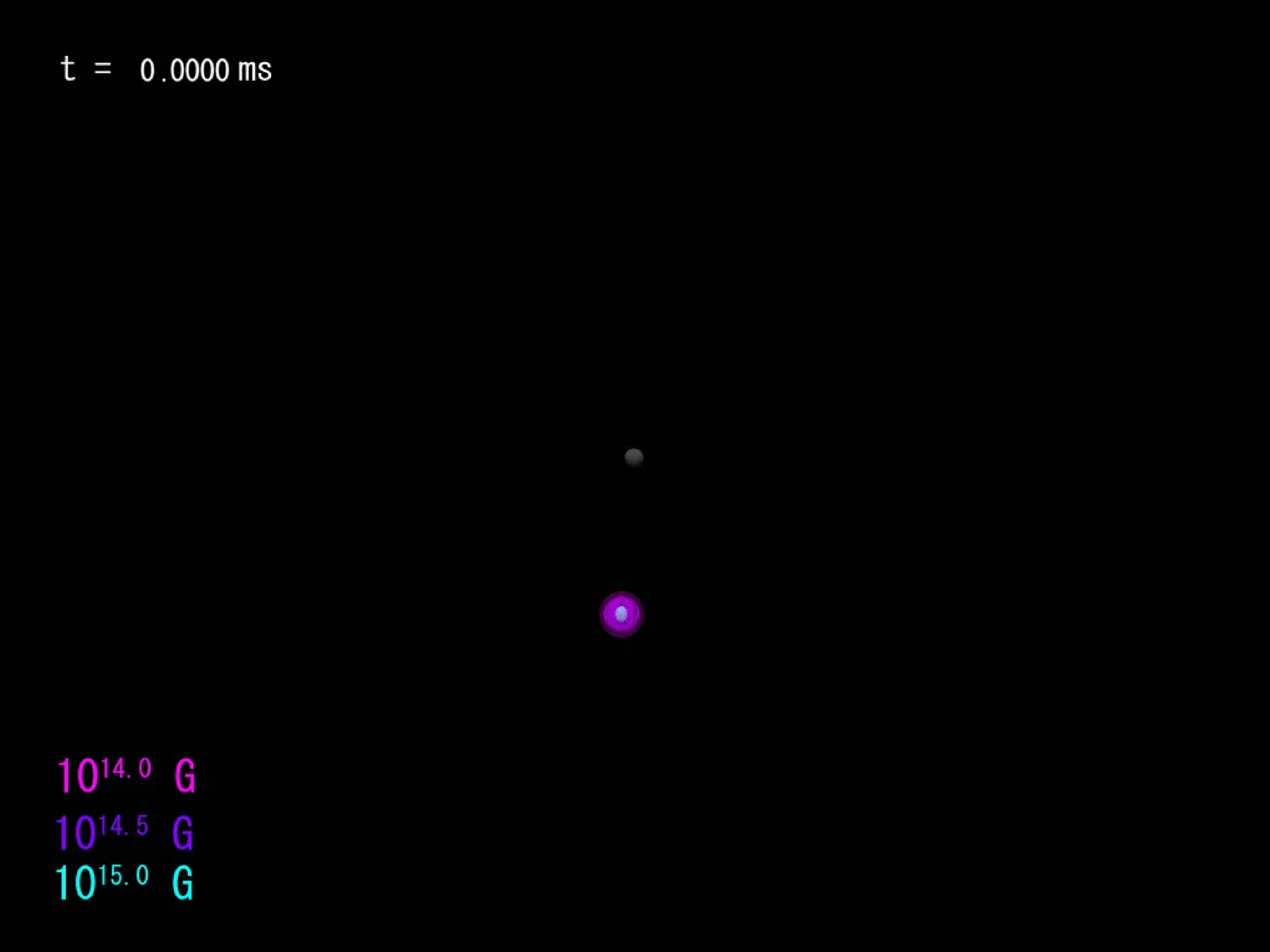
▶Good scaling up to about 80,000 cores (Execution performance 12-13%)

Japanese supercomputer K @ AICS

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

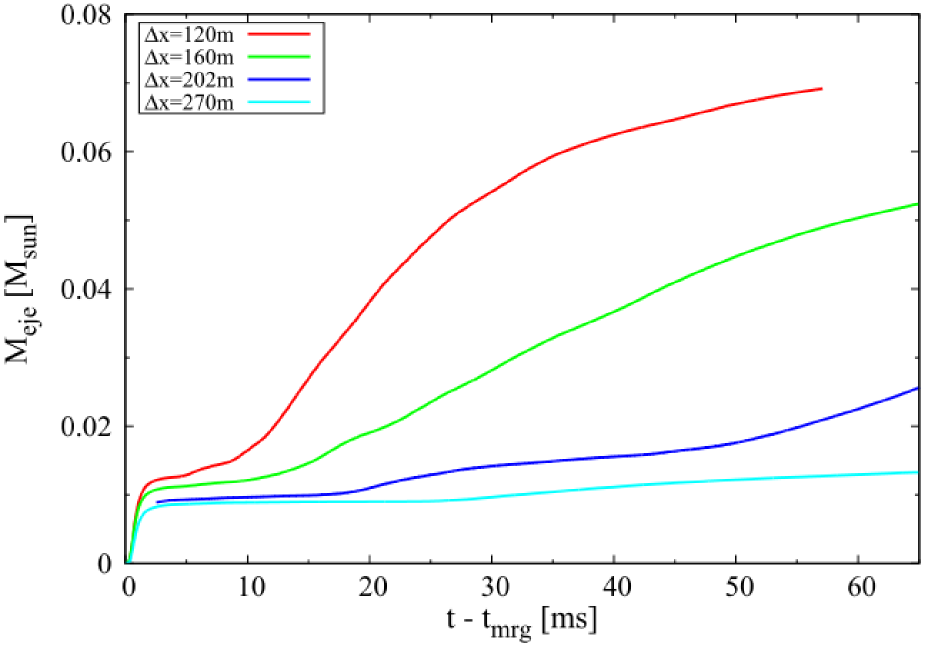
This study is one of the main subject of the HPCI strategic program field 5.


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

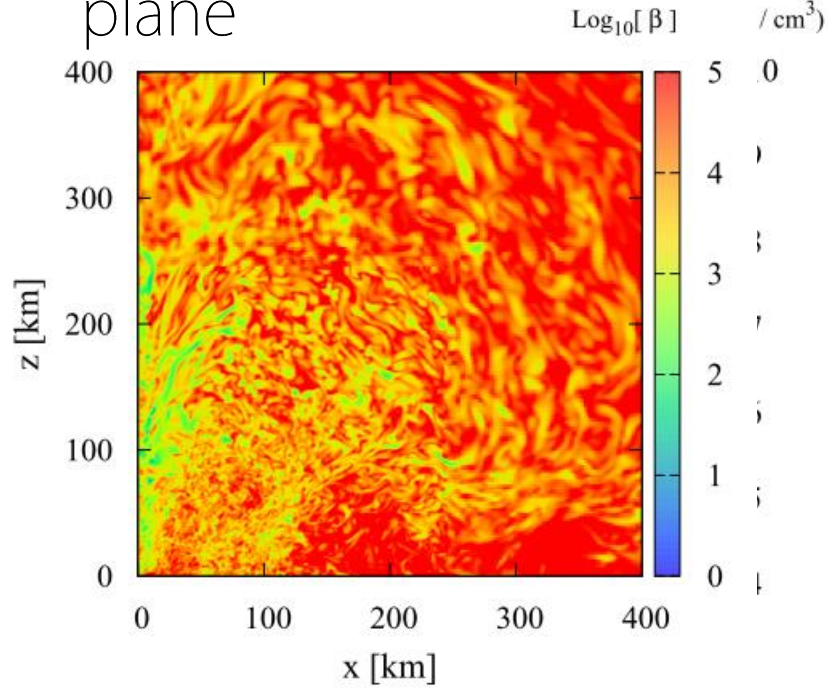

t = 0.0000 ms
10^14.0 G
10^14.5 G
10^15.0 G

Mass ejection

Ejecta mass evolution



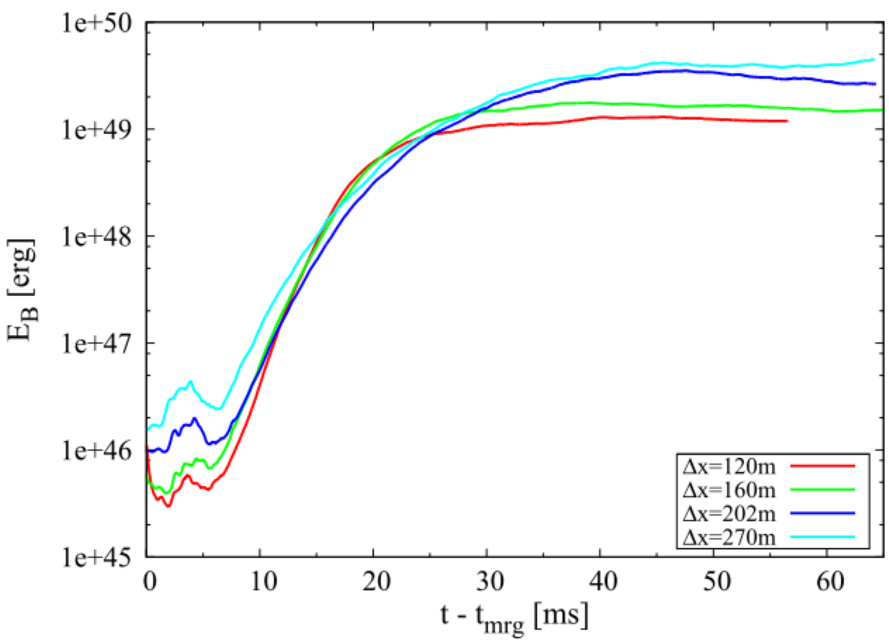
Ejecta density on meridional plane



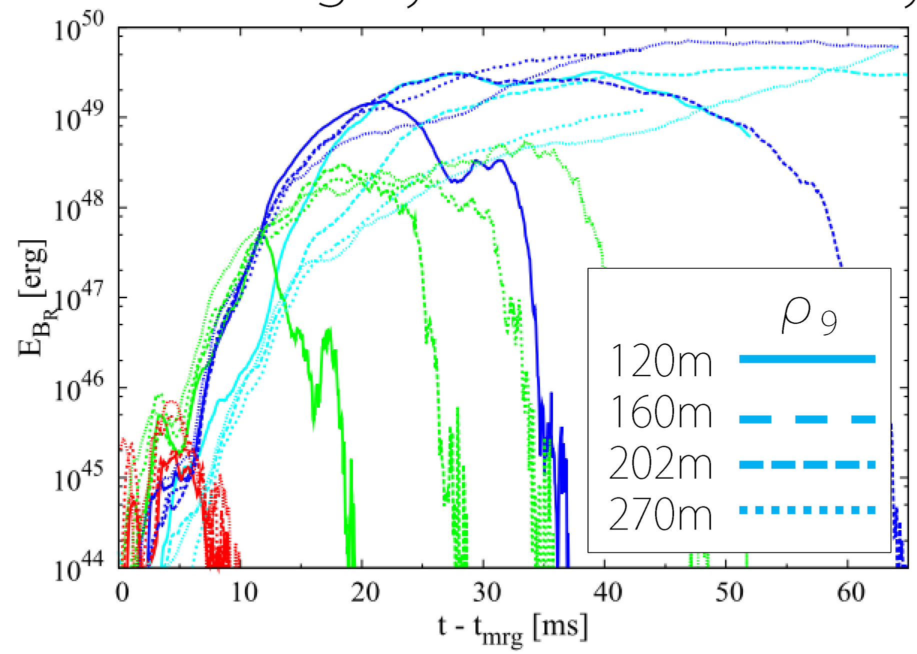
- t ≲10ms ⇒ Dynamical mass ejection (Kyutoku et al. 15)
- 10ms ≲ t ⇒ New component : Disk wind
- Magnetic pressure would not be a main agent
- The well resolved turbulent eddies are likely to play an important role

B-field amplification

Evolution of B-field energy



Evolution of B-field energy foliating by rest-mass density



▶ B-field energy increases and saturates at ≈2-5×10^{49} erg

▶ t ≲10ms ⇒ highly dynamical phase (winding / stretching)

▶ 10ms ≲ t ⇒ MRI activates($\lambda_{\mathrm{MRI,\ fastest}} = B/(4\pi\rho)^{1/2} 2\pi/\Omega$)

Calculate B-field energy in 10^a g/cm^3 ≤ ρ_a <10^{a+1} g/cm^3

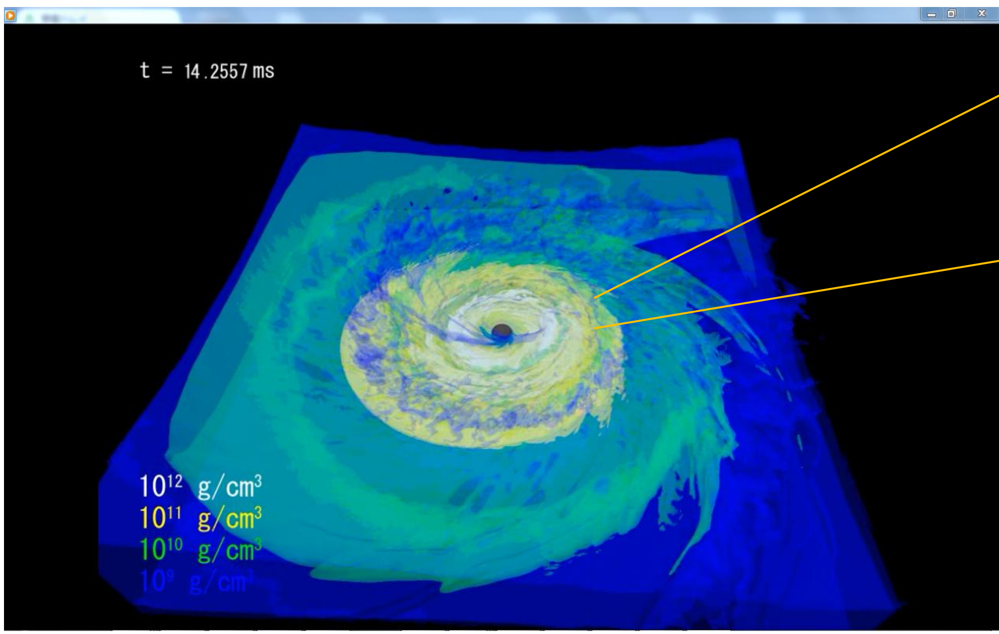
▶ Linear growth rates are approximately converged; 0.07-0.08Ω

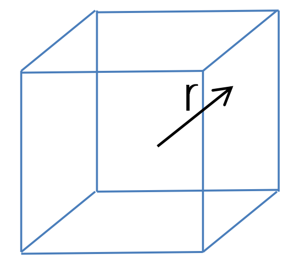
(Non-axisymetric MRI, $\lambda_{\mathrm{MRI,\ fastest}}/\Delta x \gtrsim 10$)

Energy of the turbulent flow

- Energy transport mechanism = MHD turbulent eddies (Reynolds+Maxwell stress)
- The higher the resolution is, the larger the amount of the disk wind

<u>Energy spectrum of the turbulent flow</u>





Step 1. Choose a cubic region

Step 2. $\delta v^i = v^i - <v^i>$

<> Time average

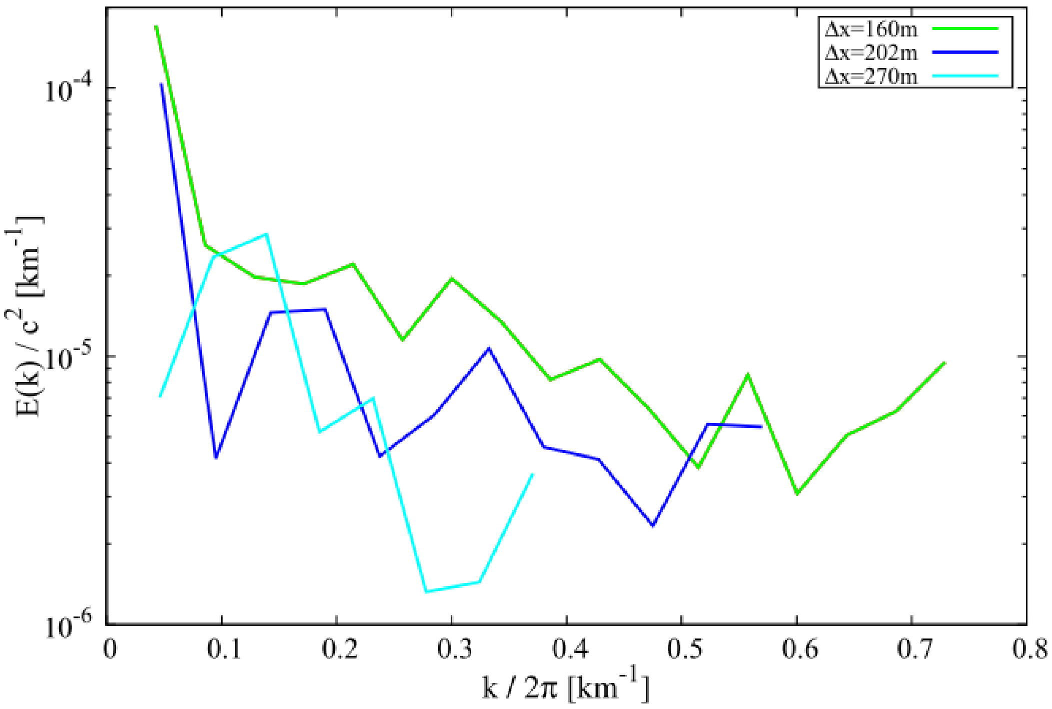
Step 3. $R_{ij}(\mathbf{r}) = <\delta v^i(\mathbf{x}+\mathbf{r})\, \delta v^i(\mathbf{x})>$

Step 4. $\varphi_{ij}(\mathbf{k}) = \iiint R_{ij}(\mathbf{r})\, d\mathbf{k}$

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

$k = |\mathbf{k}|$

Energy spectrum the turbulent flow



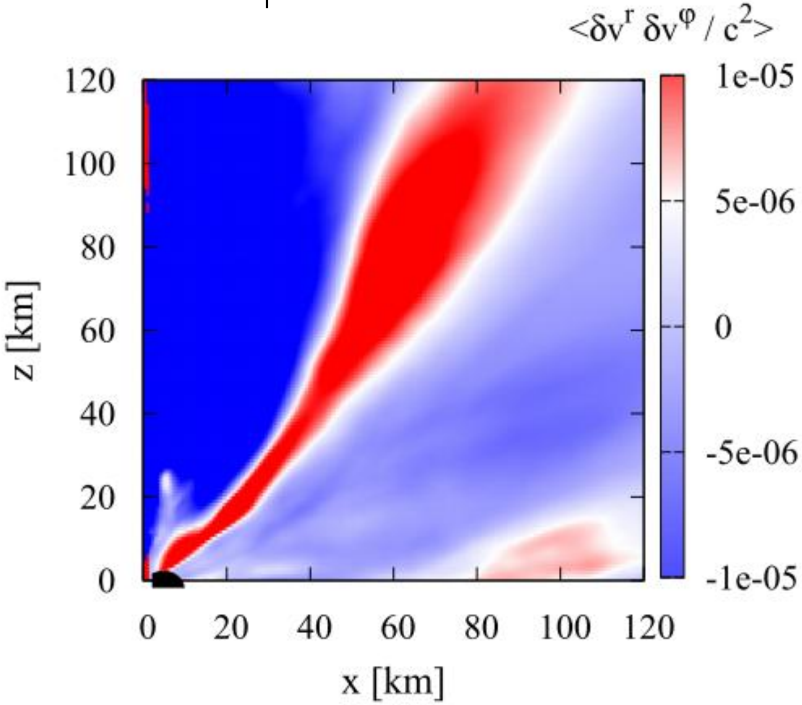
120m spectrum is calculating now….

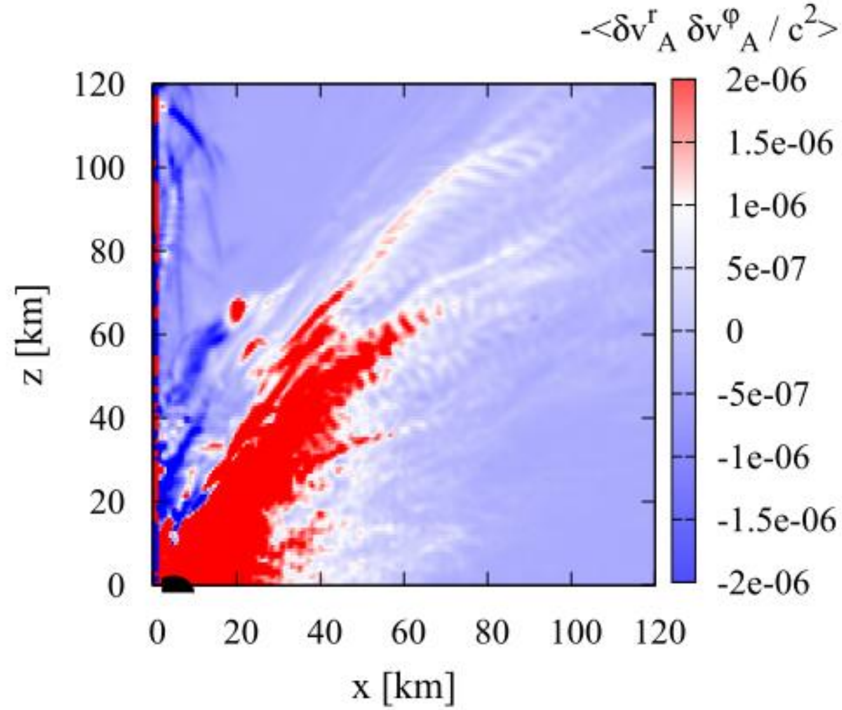
▶x ∊ [50km:70km], y ∊ [-10km:10km], z ∊ [-10km:10km], T=10-20ms

▶The turbulent energy is injected at a smaller scale for the higher resolution run.

▶The amplitude of the spectrum is higher in the higher resolution run ⇒ The turbulent eddies have a larger energy.

Reynolds-Maxwell stress (Energy, angular momentum transport)





▶ Energy and angular moment are transported outwardly by Reynolds-Maxwell stress.

Key ingredients for the disk wind

▶ High spin BH

BH is spun up to $\chi \approx 0.85$-0.9 after the merger

$R_{ISCO}(\chi=0.9) = 2.32M_{BH}$ cf. $R_{ISCO}(\chi=0.0) = 6M_{BH}$

If you consider the "realistic" value of the mass ratio $q \gtrsim 7$, the high spin is necessary for the tidal disruption as well.

▶ Energy source of the wind = Mass accretion energy

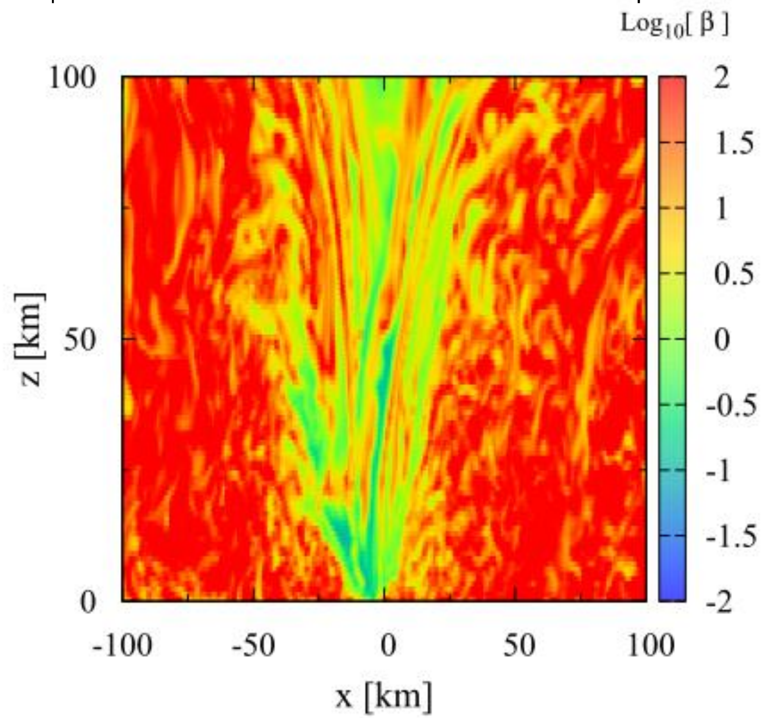
▶ Transport agent = Turbulent eddies

▶ ≈50% of the accretion torus at $t = 10$ms is ejected as the torus wind

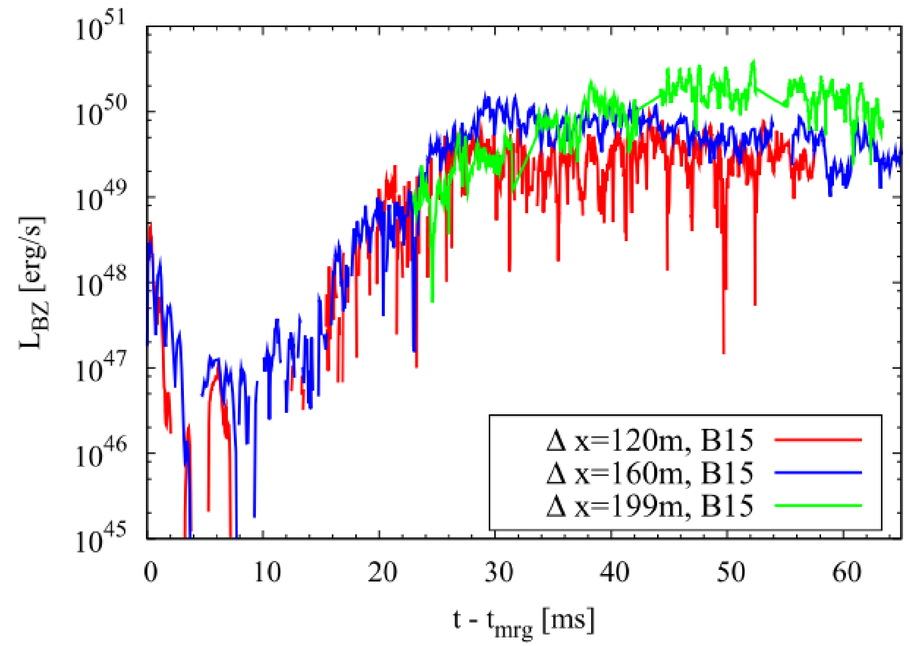
Implication of this new mass ejection (i)

▶ Formation of the low plasma beta region ($\beta \sim 10^{-2}$)
The wind facilitates the poloidal motion ⇒ Coherent poloildal magnetic field

β on the meriodinal plane



BZ luminosity evolution



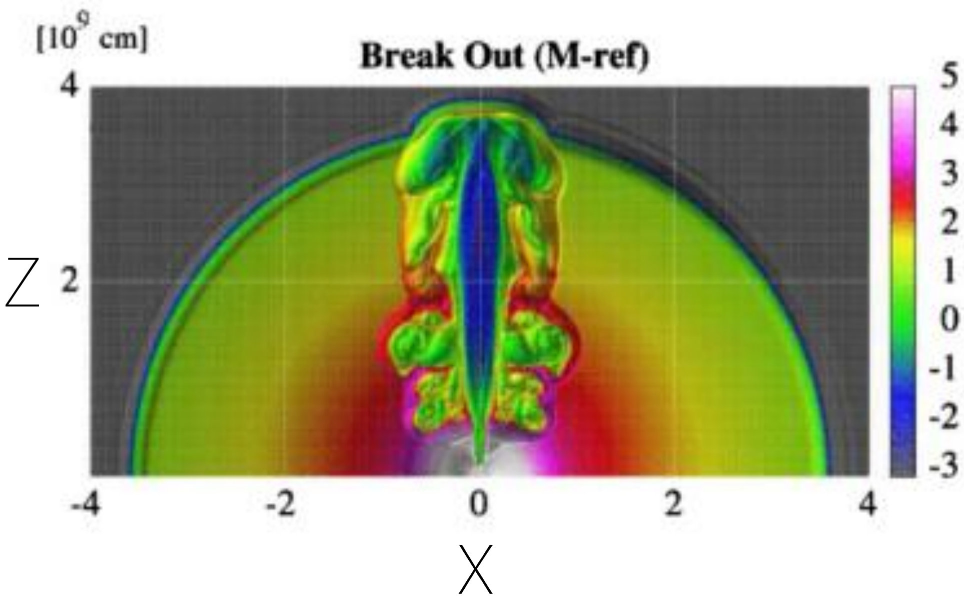
▶ Enhancement of the BZ luminosity (Brandford & Znajek 77)
$L_{BZ} \approx 2 \times 10^{49}$ erg/s ⇒ Central engine candidate of the SGRBs with low luminosity (Lee & Ramirez-Ruiz 07)

Implication of this new mass ejection (ii)

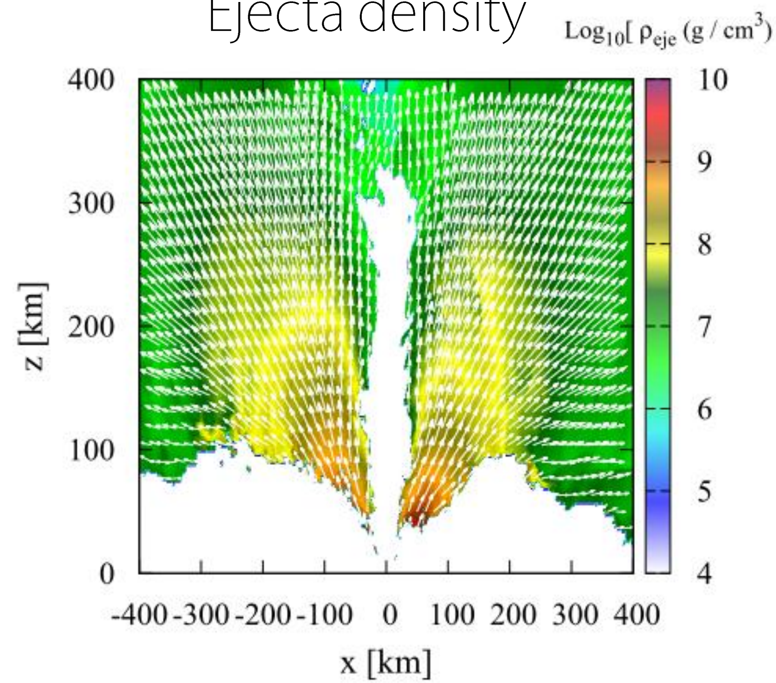
▶ Collimation of the relativistic jet

Dynamical ejecta is concentrated on the orbital plane.
On the other hand, for the NS-NS merger case ⇒ The ejecta expands quasi-spherically. (Hotokezaka et al. 13, Sekiguchi et al. 15)

Jet propagation simulation in the NS-NS ejecta (Nagakura et al. 14)



Ejecta density



▶Disk wind would help the collimation of the relativistic jet

Implication of this new mass ejection (iii)

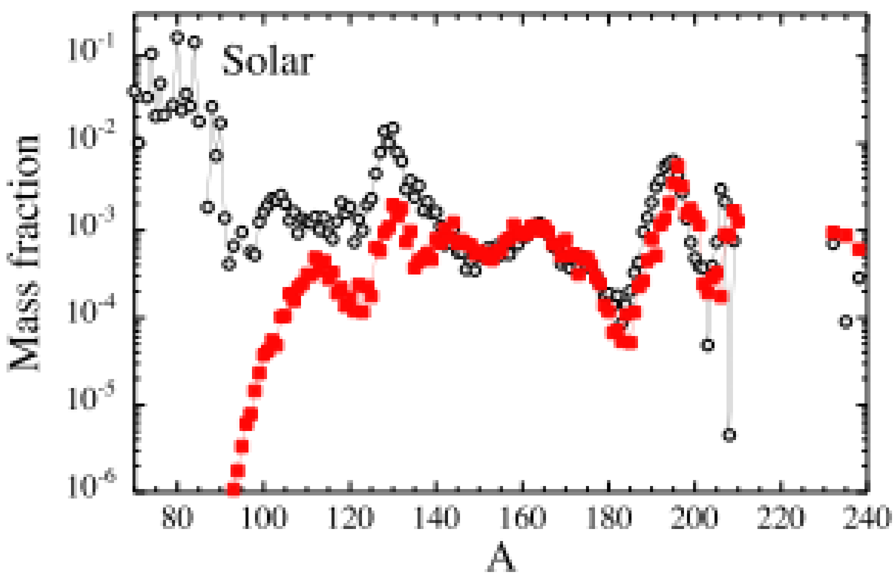
▶ Nucleosynthesis in the BH-NS merger

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

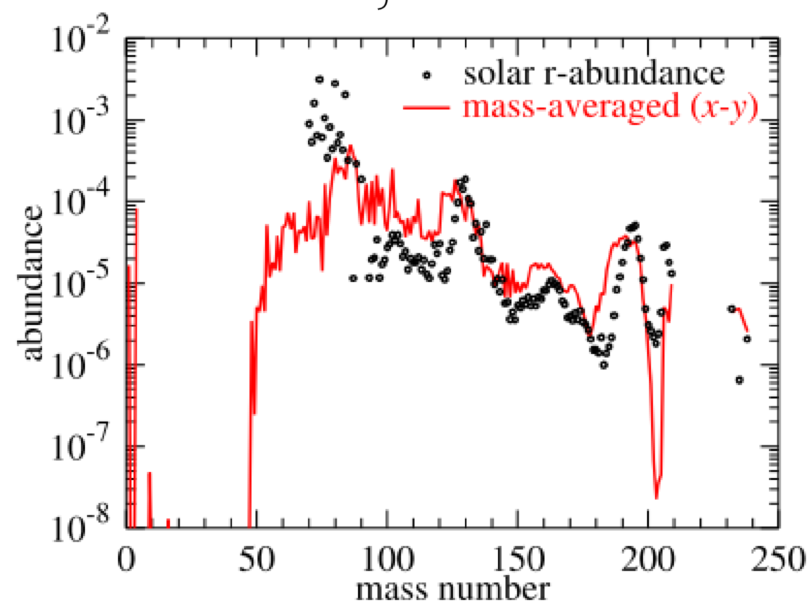
⇒ Reproduce the third peak of the solar abundance

On the other hand, for the NS-NS mergers, Ye of the ejecta has a broad distribution. (Sekiguchi et al. 15, Wanajo et al. 14)

Bauwsein et al. 14



Wanajo et al. 14



▶Disk wind launches in the vicinity of the torus surface.

The fluid elements experience shock heating. ⇒ Different Ye distribution from that for the dynamical component.

Implication of this new mass ejection (iv)

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)

▶ 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)

▶ Disk wind due to the MHD turbulence

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

Systematic studies have to be done.

Caveat and summary

▶ Self consistent modeling is important ; if you start from an equilibrium torus and BH, you cannot get a disk wind we found in this study.

▶ Resolution study is essential as well.

NR simulations of the BH-magnetized NS mergers on K.

▶ Disk wind driven by the MHD-turbulence

<u>Implications</u>

▶ Central engine of the SGRBs

▶ The nucleosynthesis of the r-process elements

▶ The radioactively-powered transient emission