連星中性子星（コンパクト連星）合体における磁場増幅機構

Kenta Kiuchi（YITP）

Ref.) PRD 90, 041502(R) (2014)

with Koutarou Kyutoku (UWM), Yuichiro Sekiguci (YITP), Masaru Shibata (YITP), Tomohide Wada (NAOJ)

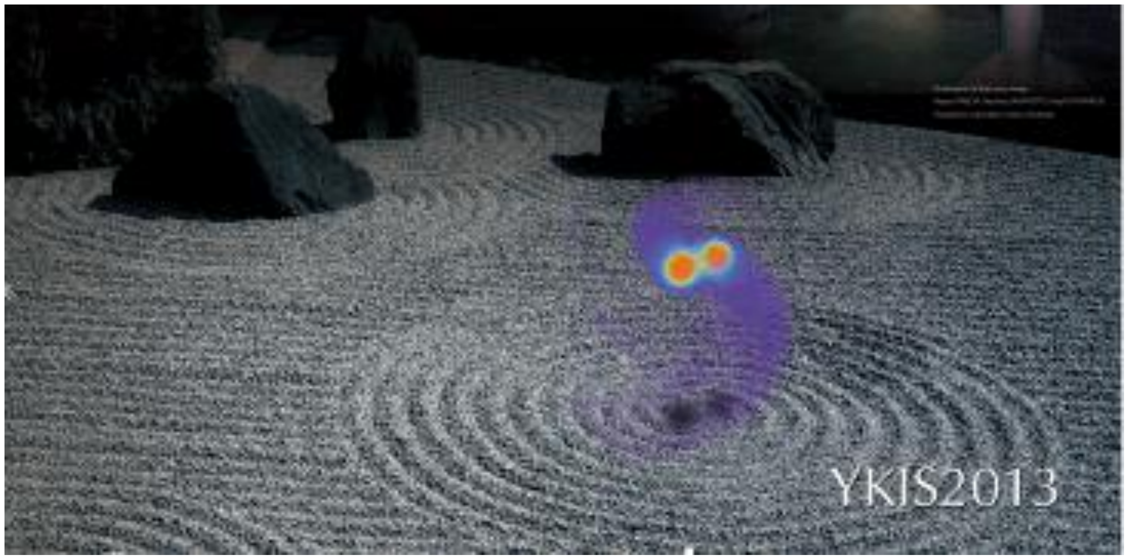
YITP
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

K computer

$= 10^{16}$
$= 10$ Peta

What are gravitational waves ?

Ripples of the spacetime predicted by Einstein almost 100 yr ago.



© YKIS2013 poster, the rock garden in a temple in Kyoto

They could see a region which is opaque for the EM signal.

Indirect evidence of GW

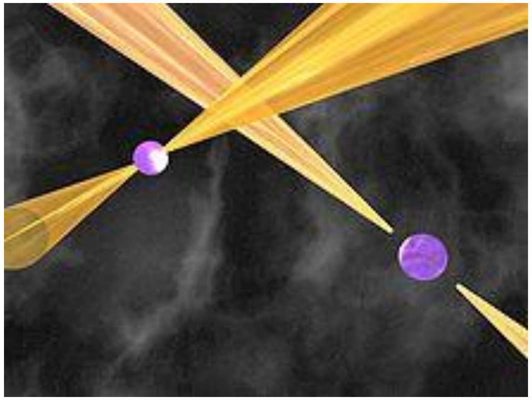


Image of the binary pulsar

Russell Alan Hulse 1950～　Joseph Hooton Taylor, Jr.、1941～

Hulse and Taylor have found the binary pulsar PSRB1913+16 in the Arecibo observatory.

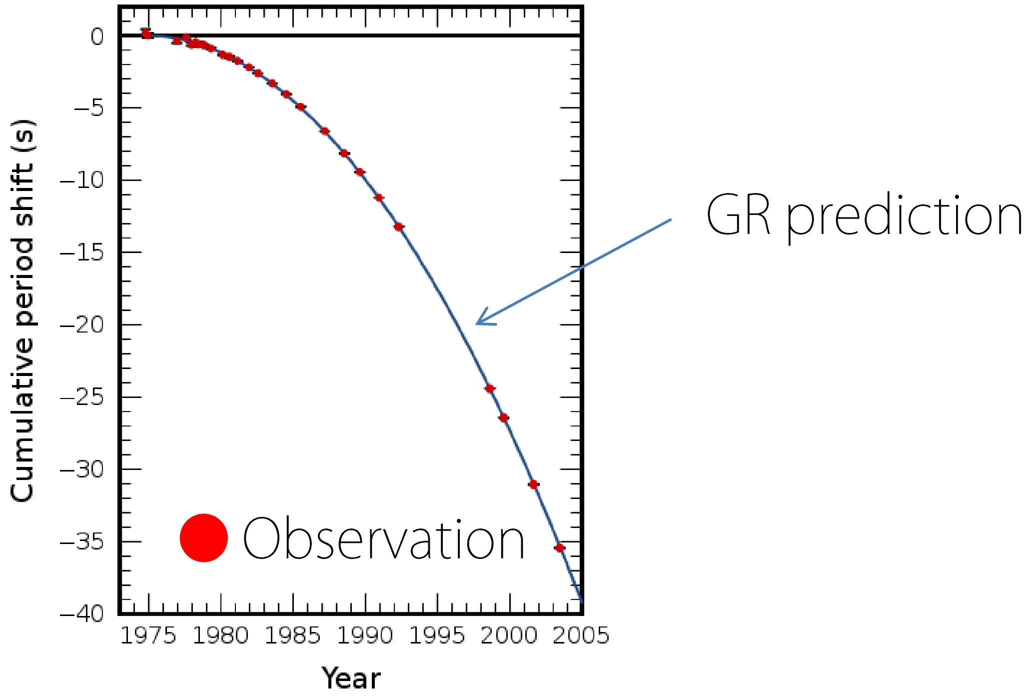
⇒ The orbital period gets shorter in time.

It implies the energy is radiated from the system.

Indirect evidence of GW

GR predicts the GW with which the energy is carries away.

The shift of the orbital period of 1913+16



The GR prediction agrees with the observation within 1 %.

⇒ Hulse and Taylor have gotten the Nobel Prize in 1993.

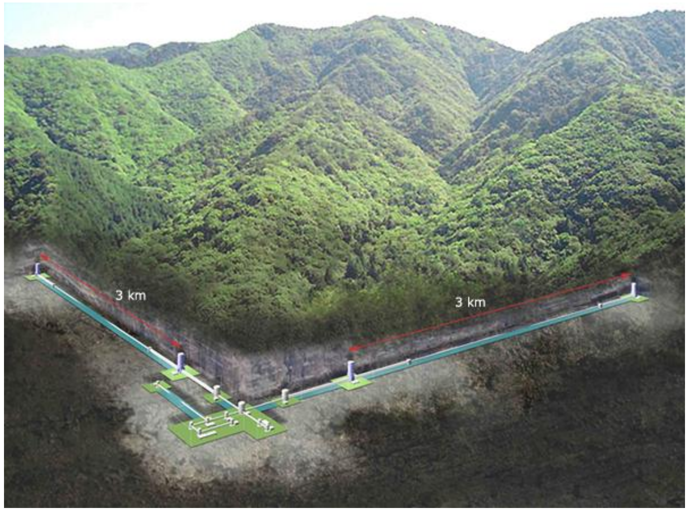
Their work is recognized as the indirect evidence of GW.

The direct observation is coming true.

$h_c \sim 10^{-22} \sim$ Size of H atom / The distance from Earth to Sun

The world map of the GW detectors

KAGRA (Kamioka mine)



KAGRA

▶ The project has been approved in 2010.

▶ The excavation of the tunnel has been finished in March 2014.

▶ It will be in operation in Dec. 2015 for one month (room temperature), then it will be updated.

▶ KAGRA will start the observation around 2018.

The targets of the ground-based GW detectors

- Binary neutron star merger ⇒ ~10 events / yr for KAGRA
- Neutron star – black hole merger ⇒ ~10 events /yr for adv. LIGO

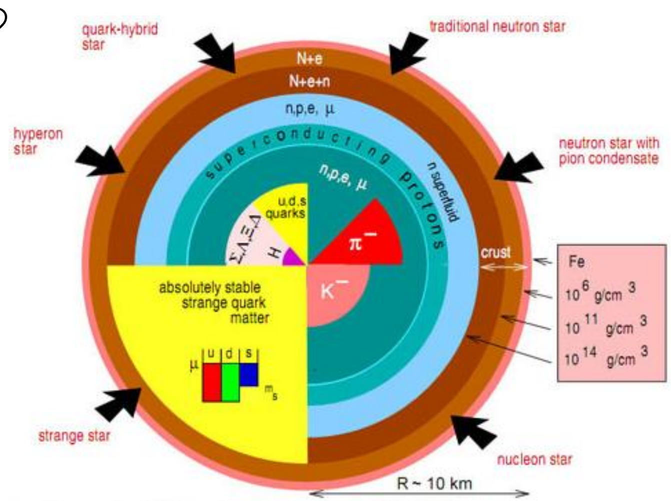
What will the GW tell us ?

- Validity of GR in a strong gravitational field
- The equation of state of neutron star matter

Mystery of high density matter

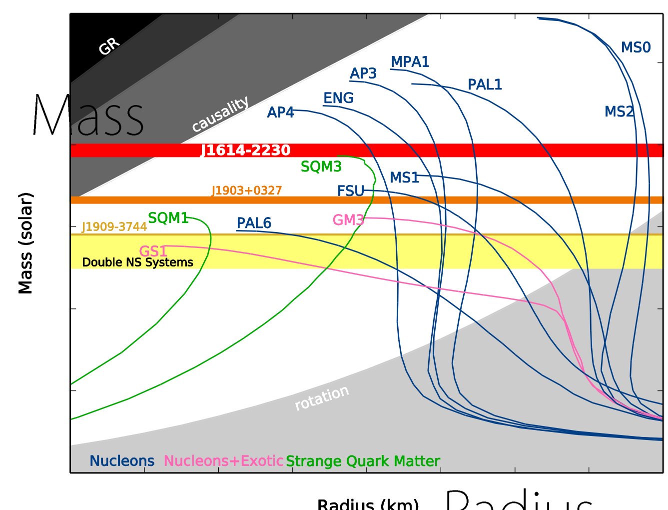
- ○ Hadronic matter, Pion condensation ? Kaon condensation ?
- ○ Hyperon ?
- ○ Quark ?
- ○ Strangeness ?

NS structure



Mass – radius relation

Mass



Radius

What will the GW tell us ?

- Central engine of short gamma ray bursts ?

- $E_{iso,\gamma} \sim 10^{49}$-$10^{51}$ erg, Duration ~ 0.1-2 s

They release the huge energy in a short time scale ⇒ A compact object could drive them.

Light curve of GRB

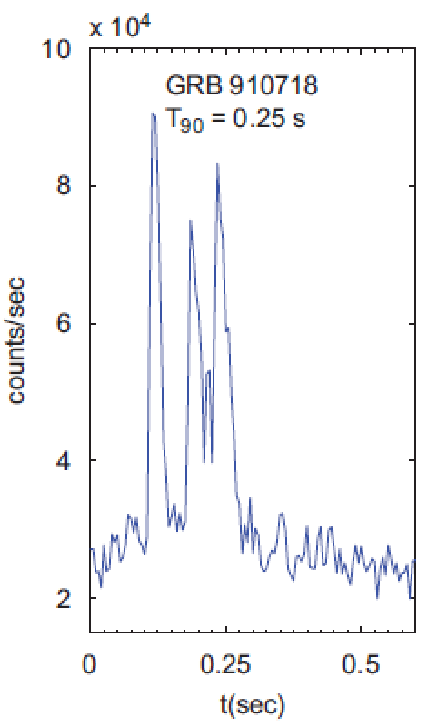
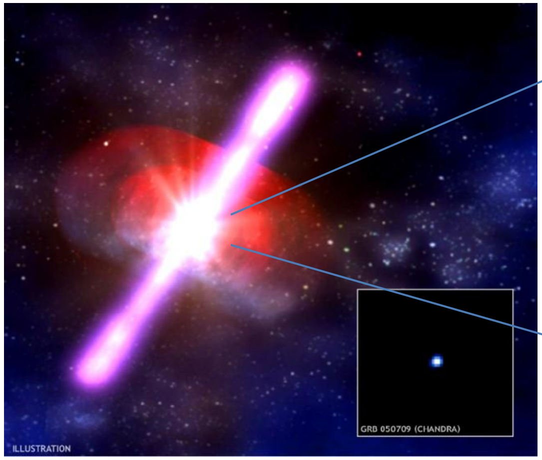
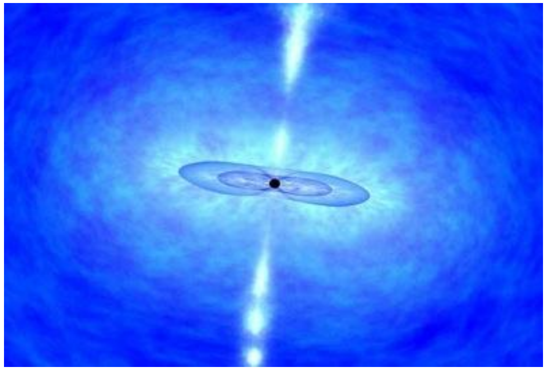


Image of GRB



Black-hole – Torus ?



BNS or BH-NS could drive the GRBs.

A possible site of the r-process synthesis

A common belief : heavy elements are synthesized in supernovae.

⇒ The state of art simulations suggest it is hard to synthesize them.

Compact binary merger as an alternative (Lattimer & Schramm 76)

- 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 due to the rapid process (Lattimer & Schramm 76)

Electromagnetic counterpart of BNS mergers

- Radio active decay of the r-process elements

Kilonova emission (Li-Paczynski 98, Kulkarni 05, Metzger+10, Kasen et al. 13, Barnes-Kasen 13, Tanaka-Hotokezaka 13)

It could increase the positioning accuracy of GW sources.

GRB130603B as a macronova/kilonova event ?

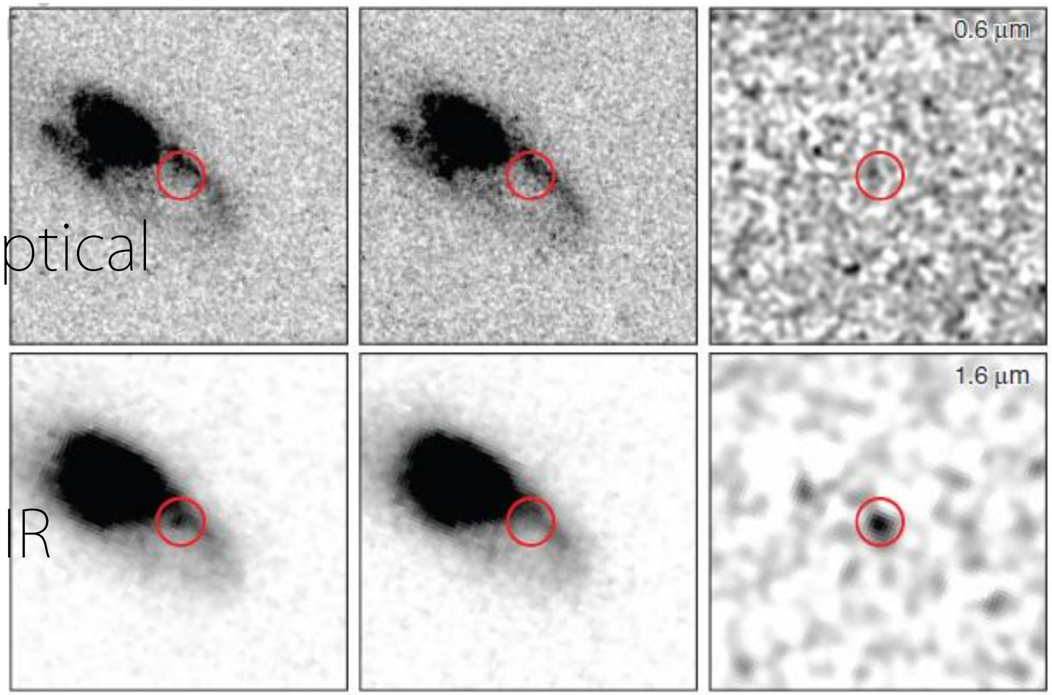
(Berger et al.13, Tanvir et al. 13)

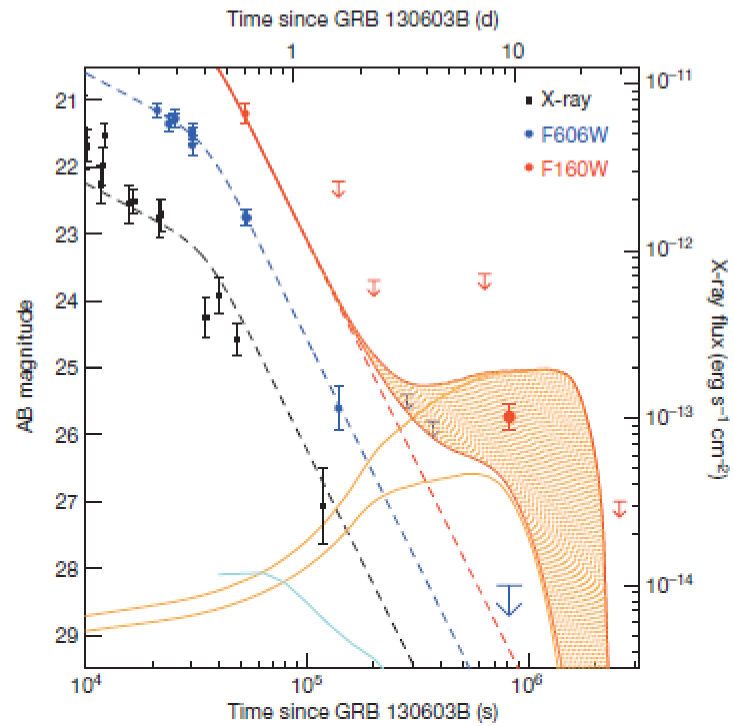
9 days after the burst

30 days after the burst

Optical

NIR





Point source in NIR, not in optical band ⇒ Transient point source in NIR

A step toward the physical modeling of BNS 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

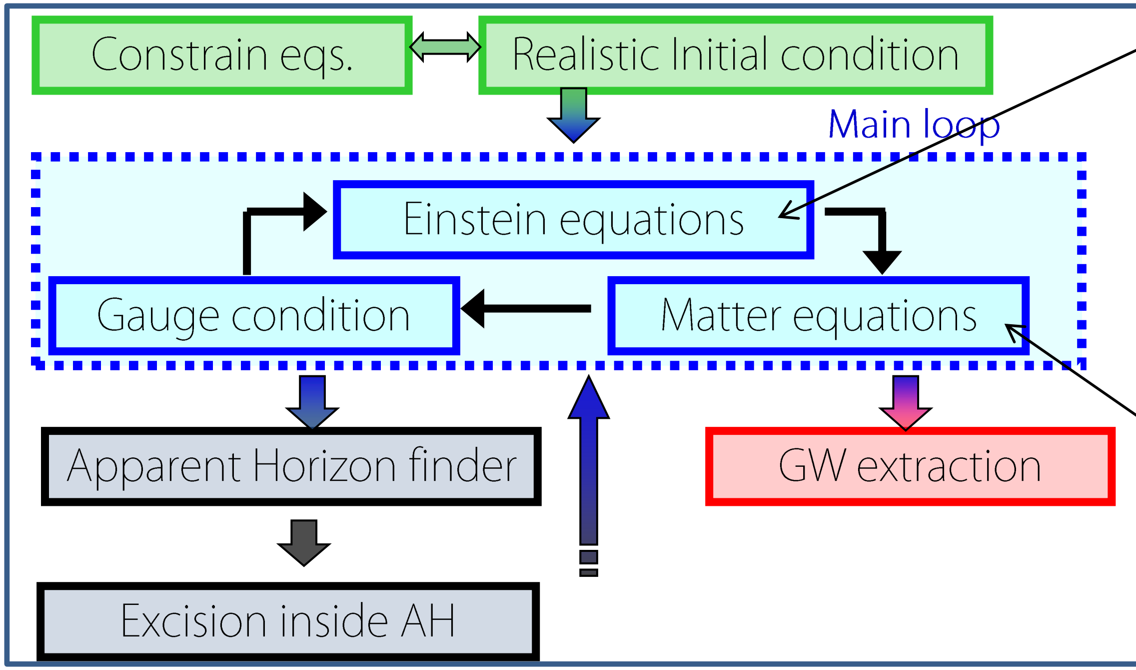
$$\nabla_\mu T^{\mu\nu} = 0, \quad T^{\mu\nu} = T^{\mu\nu}_{(\mathrm{fluid})} + T^{\mu\nu}_{(\mathrm{rad})} + T^{\mu\nu}_{(\mathrm{EM})}$$

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

Equation of state (Closure relation)

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

Current status of Numerical Relativity



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

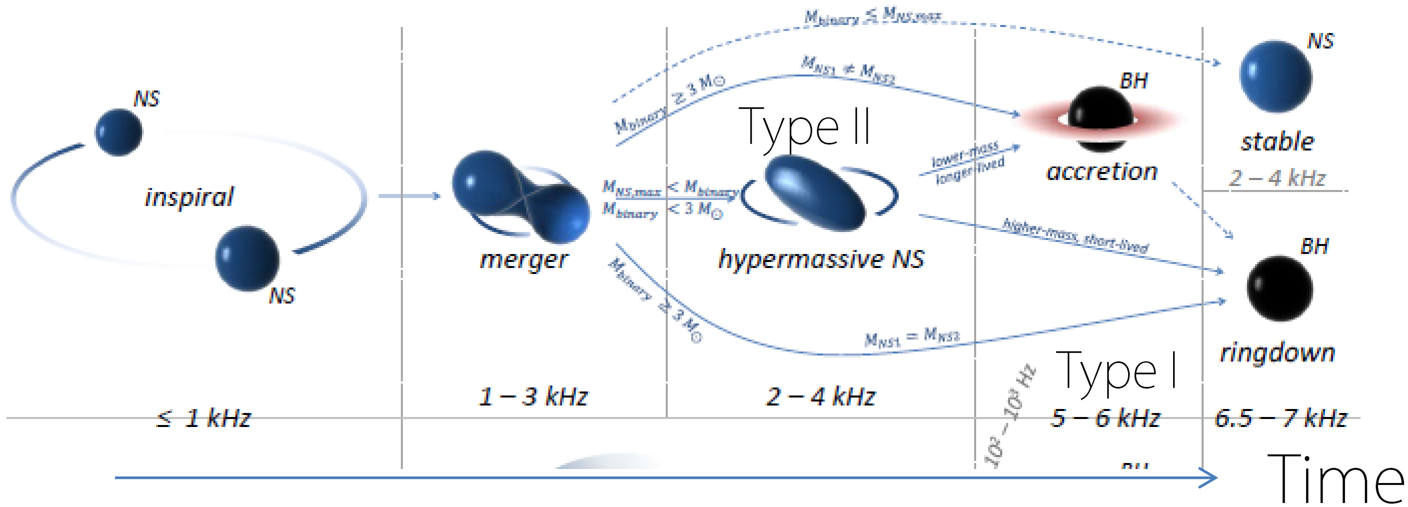
General Relativistic Magneo Hydro Dynamics (GRMHD)

- 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)

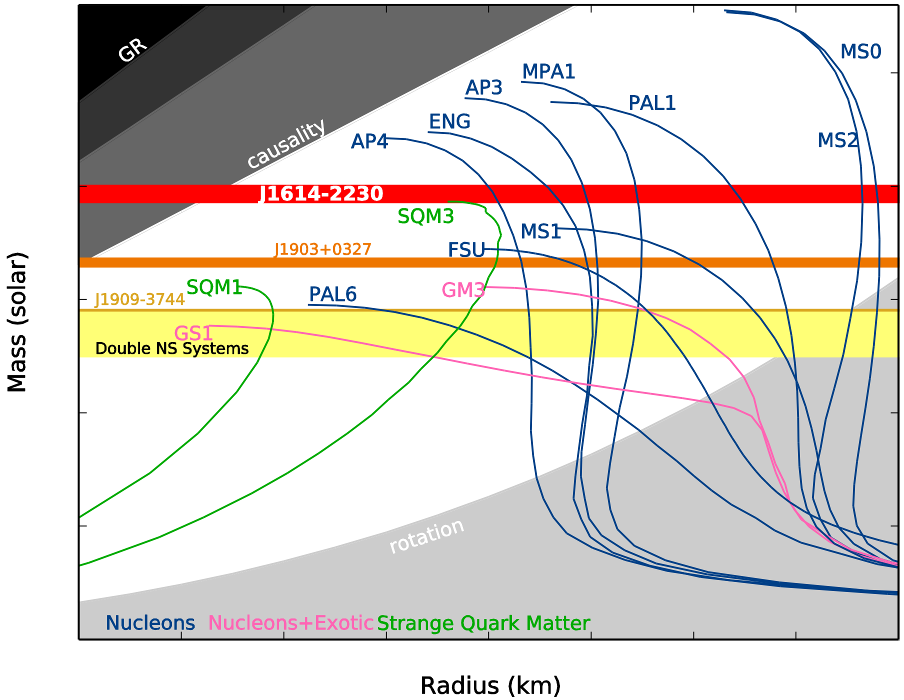
- $M > k\,M_{max}$ ⇨ Type I (Direct BH formation)
- $M < k\,M_{max}$ ⇨ Type II

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

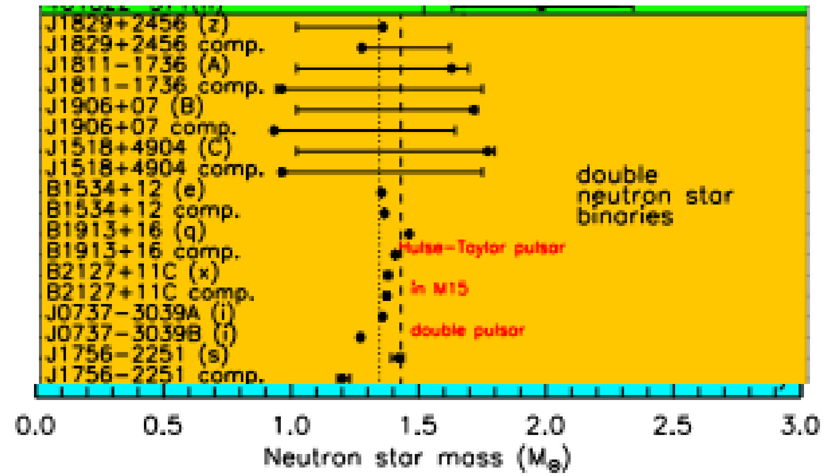
What's the origin of k greater than 1 ? ⇨ Rotation and thermal pressure (Shibata-Taniguchi 06, Sekiguchi et al. 11, Keplan et al. 14)

Observational evidence

M-R relation



Mass of observed NSs (Lattimer & Paraksh 06)



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

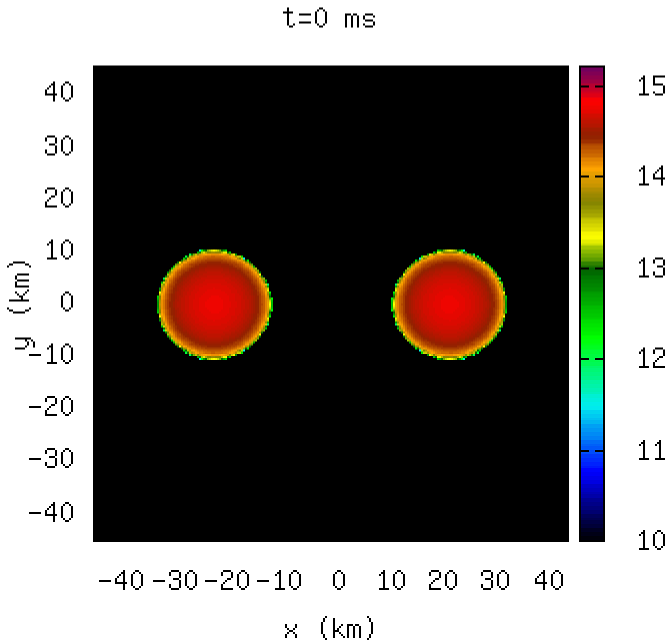
(Demorest et al. 10, Antoniadis et al.13)

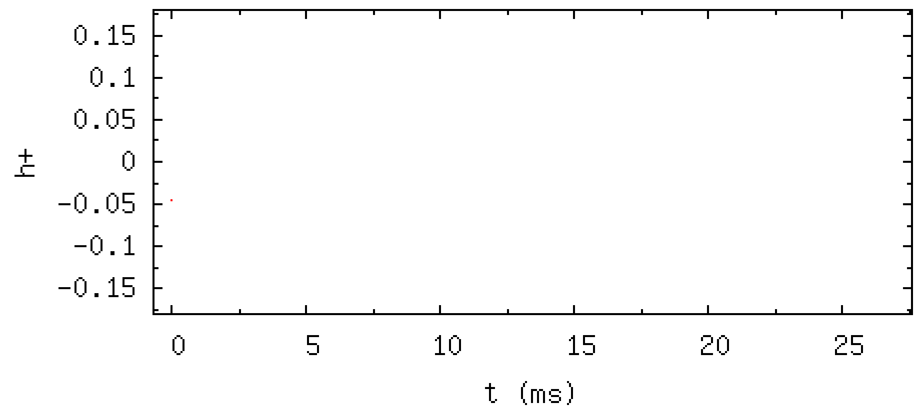
- Canonical total mass = 2.6-2.8 $M_\odot$

The type II is likely to be “realistic”.

Type II merger (Hotokezaka et al. 13)

Density contour on the orbital plane (EOS = H4, 1.4-1.4$M_\odot$)



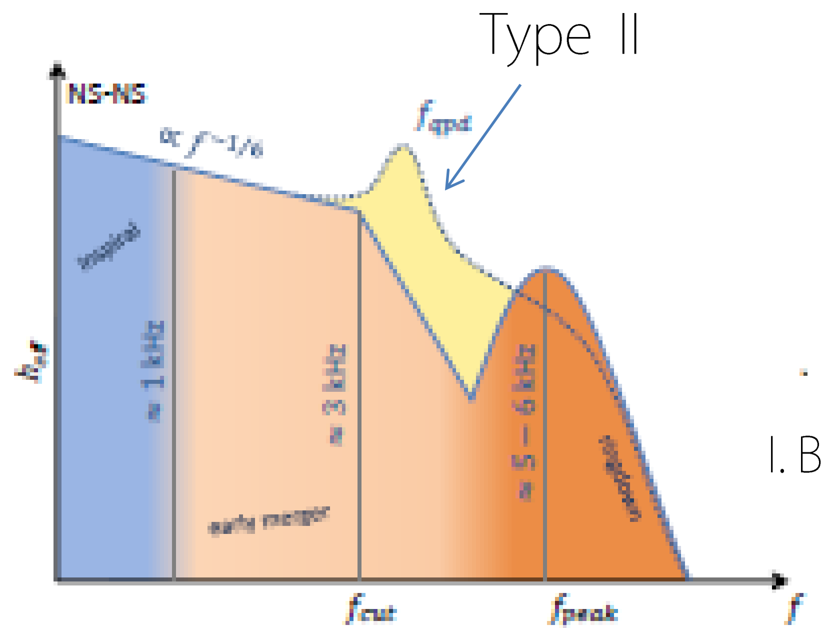


Animation by Hotokezaka

Hypermassive neutron star oscillations ⇨ sinusoidal GWs after the merger.

Type II merger (Hotokezaka et al. 13)

GW spectrum



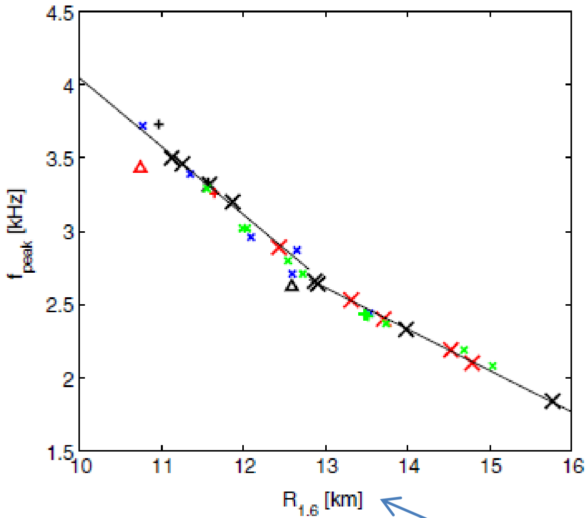
I. Bartos+ 13

Peak frequency of massive neutron star reflects a structure of NS
⇒ Measurement of f_{peak} constrains the EOS.

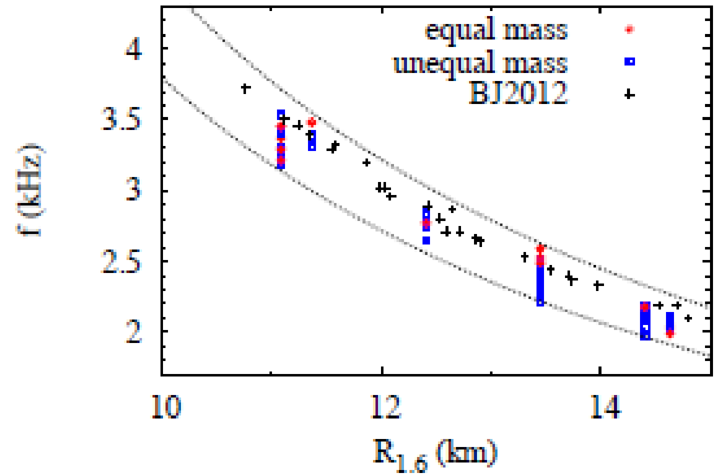
Type II merger (Hotokezaka et al. 13)

f_{peak} - R relation ($M_{tot} = 2.7M_\odot$)

Bauswein & Janka (2012)



Hotokezaka et al.13



Spherical NS radius of 1.6 $M_\odot$

NS radius of 1.6 $M_\odot$

- Strong correlation of f_{peak} and NS radius (small dispersion)
  If you could determine f_{peak}, you can infer $R_{1.6}$.

With an accuracy of $\Delta f = 40$ Hz, the error bar would be $\Delta R =$ 144 – 200m where the event rate for Adv. LIGO is 0.015-1.2/yr.
(see also Clark et al. 14)

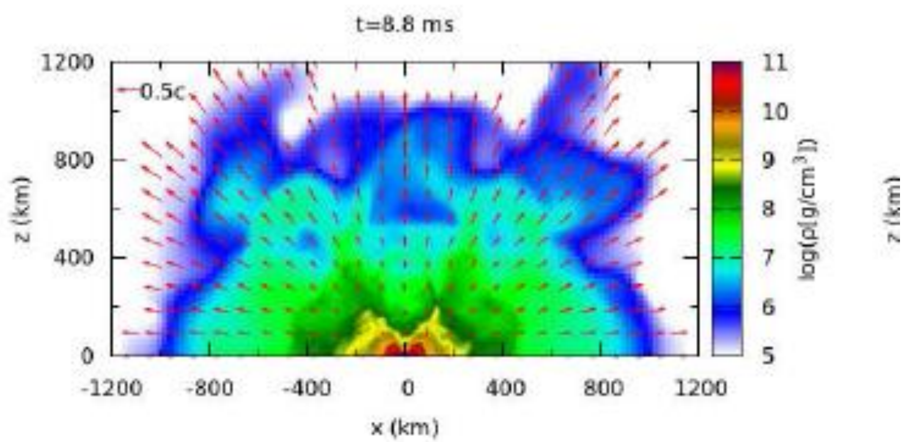
A kilonova or macronova model of GRB130603B (Hotokezaka et al. 13)

1st step

Dynamical ejecta of binary neutron star mergers

$$10^{-4} \lesssim M_{\rm ej}/M_\odot \lesssim 2\times 10^{-2} \quad \text{(soft EOSs)},$$
$$10^{-4} \lesssim M_{\rm ej}/M_\odot \lesssim 5\times 10^{-3} \quad \text{(stiff EOSs)}.$$

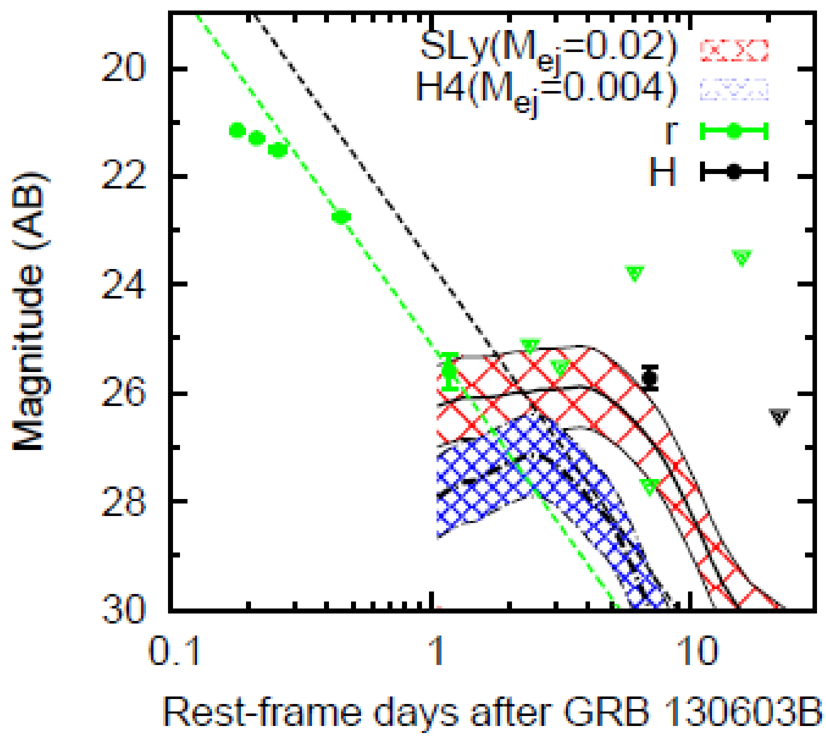
Ejecta morphology



2nd step.

Photon radiation transfer simulation with the decay of the r-process element by Masaomi Tanaka

A kilonova or macronova model of GRB130603B (Hotokezaka et al. 13)



The kilonova model of GRB130603 favors the “soft” EOS if its progenitors is BNS.
Note that the counter result for BHNS.

A step toward more physically reliable model of BNS mergers

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

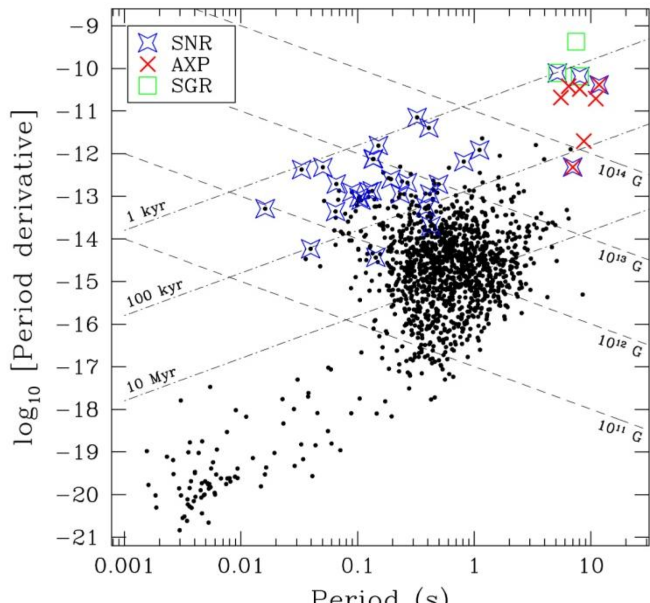
Why B-fields ?

- 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.



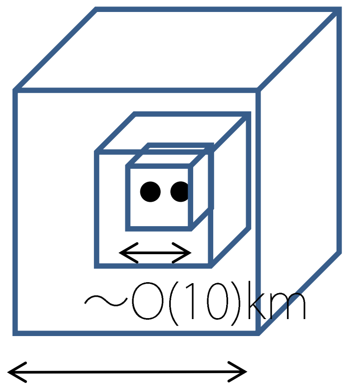
Japanese supercomputer K @ AICS

- 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.

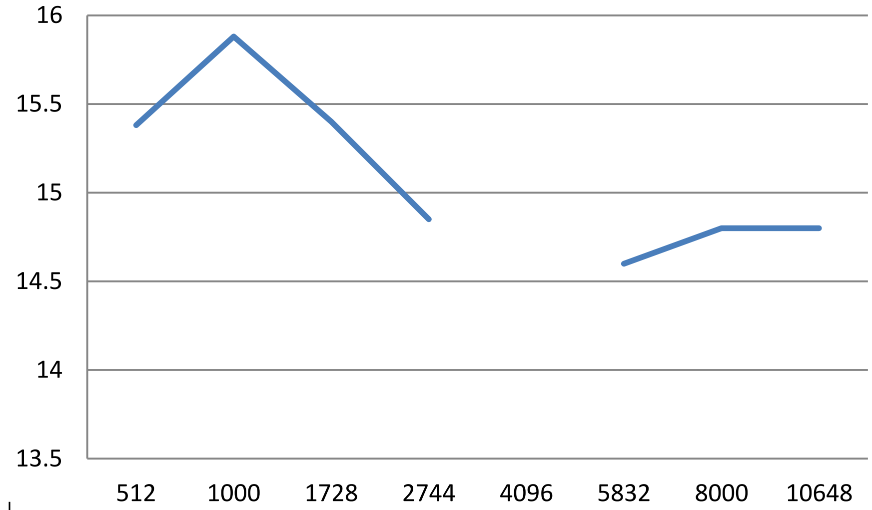
Outline of numerical relativity-MHD code

Nested grid (KK et al12)



O(1000) km ≳ GW length～several 100 km

Execution performance (%) (Weak scale)



Node number (core ＝8×node)

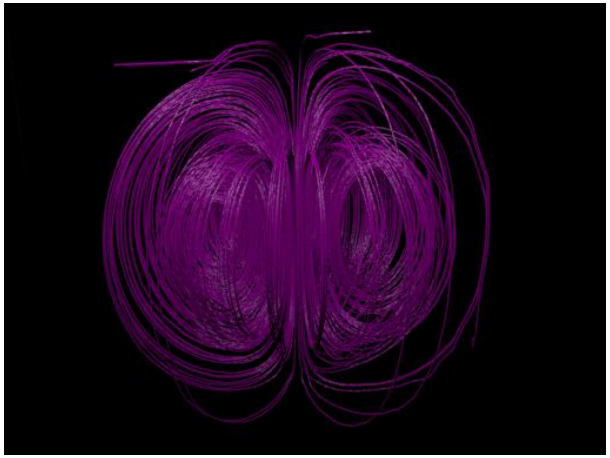
- ▶Time step is limited by the speed of light
- ▶ Interpolation of B-fields on the refinement boundary is non-trivial ： Flux conservation and Div B ＝ 0 (KK et al 12, Balsara 01)
- ▶ Larger B/F
- ▶MPI communication rule is complicated, e.g., refinement boundary
- ▶Good scaling up to about 80,000 cores

Numerical Relativity simulation of magnetized BNS mergers

▶High resolution 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)

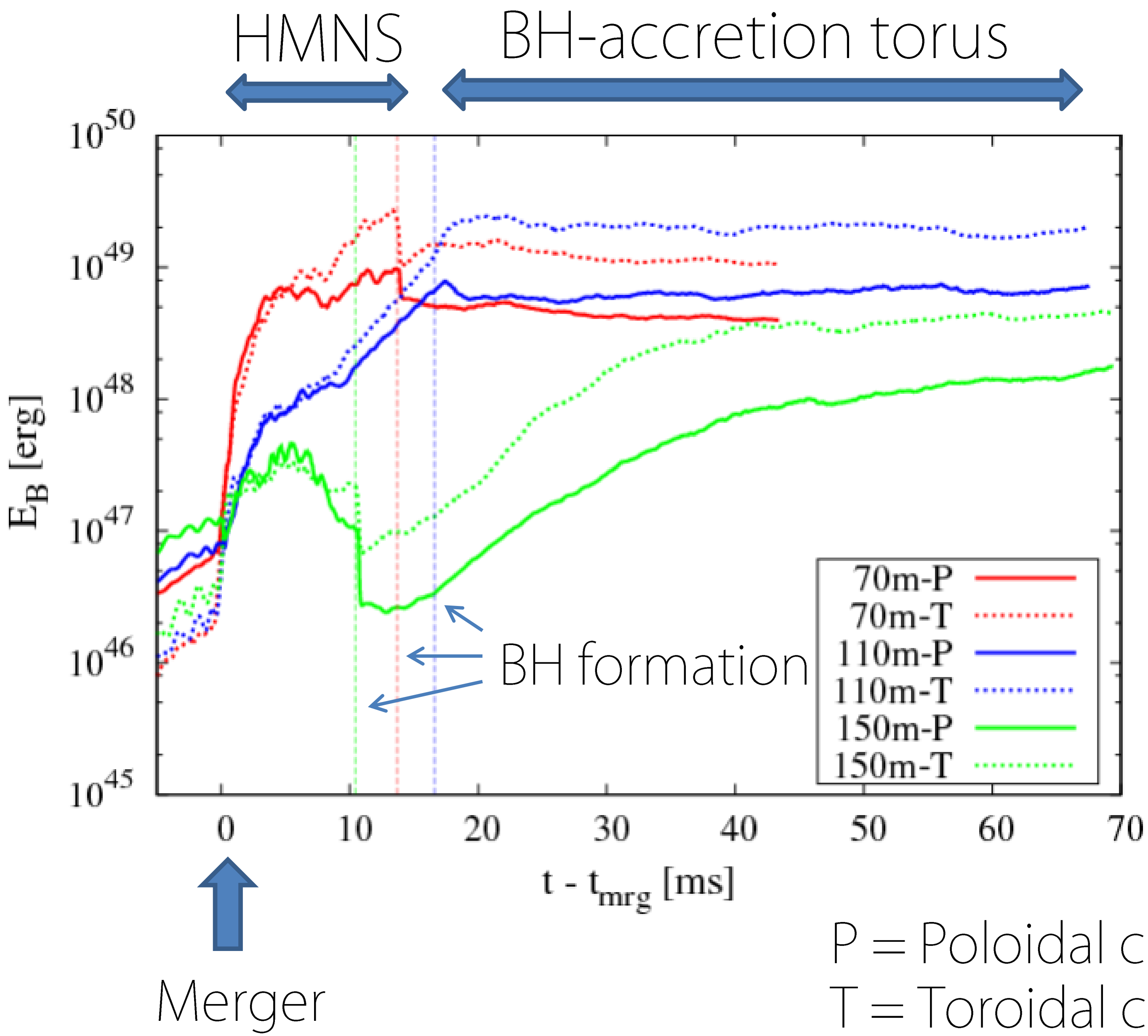
Nested grid ⇒ Finest box=$70km^3$, Coasarest grid =$4480km^3$ （N～10^9）, a long term simulation of about 100 ms

Magnetic field lines of NS



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

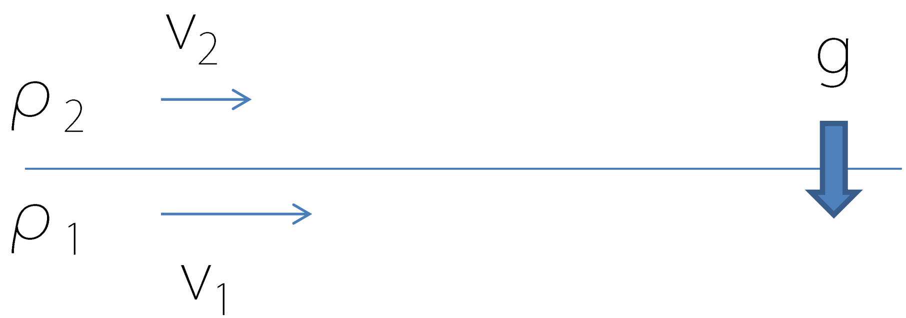
Evolution of the magnetic field energy



P = Poloidal comp.
T = Toroidal comp.

Amplification @ the merger (Rasio and Shapiro 99)

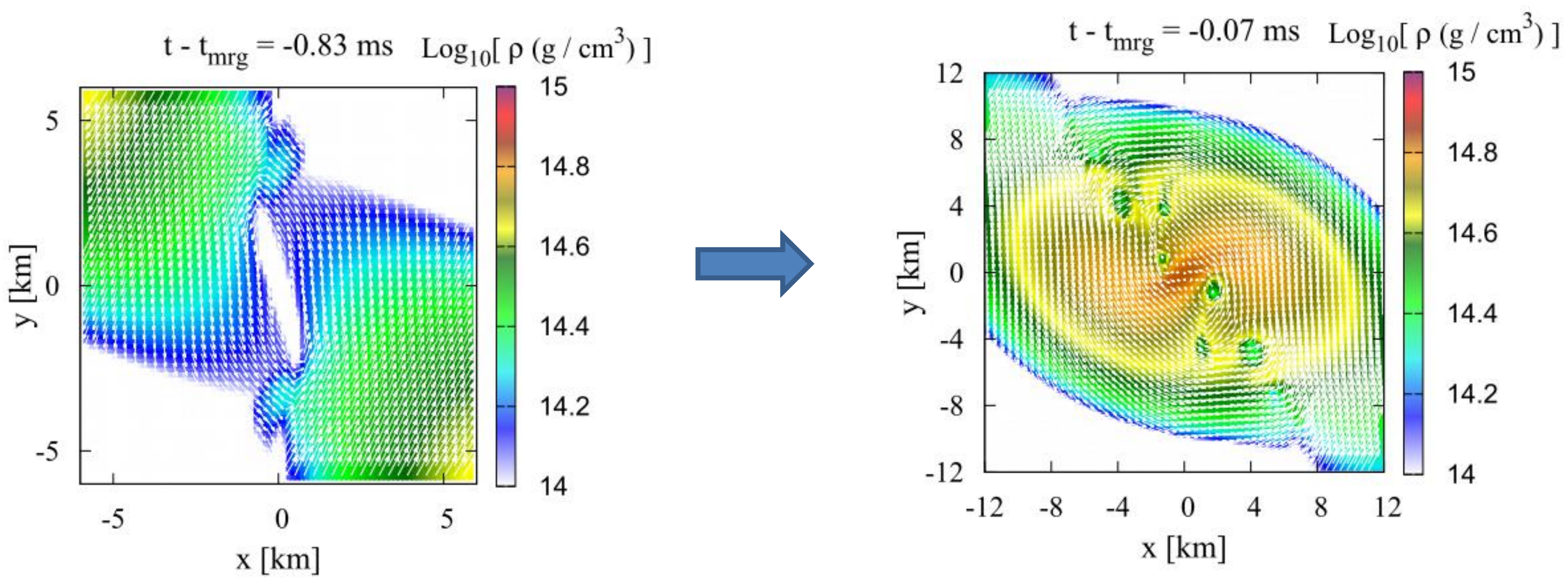
Kelvin Helmholtz instability



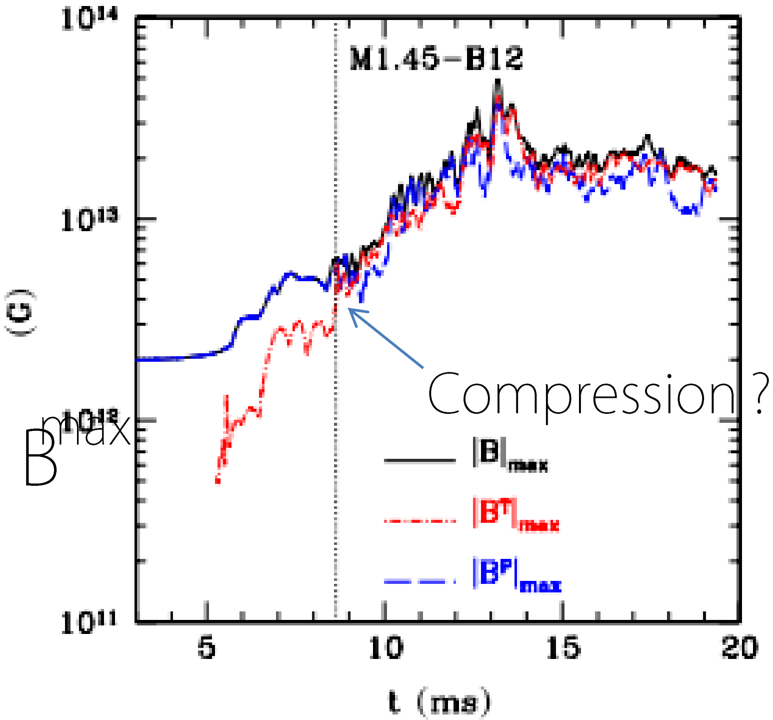
Minimum wave number of the unstable mode ;

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

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

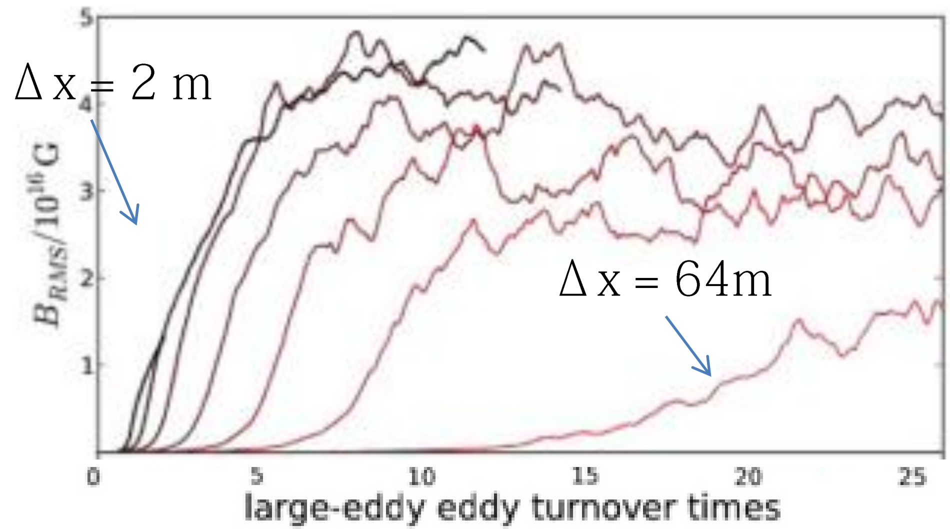


GRMHD by AEI (Giacomazzo et al. 11)



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

Time evolution of <B>

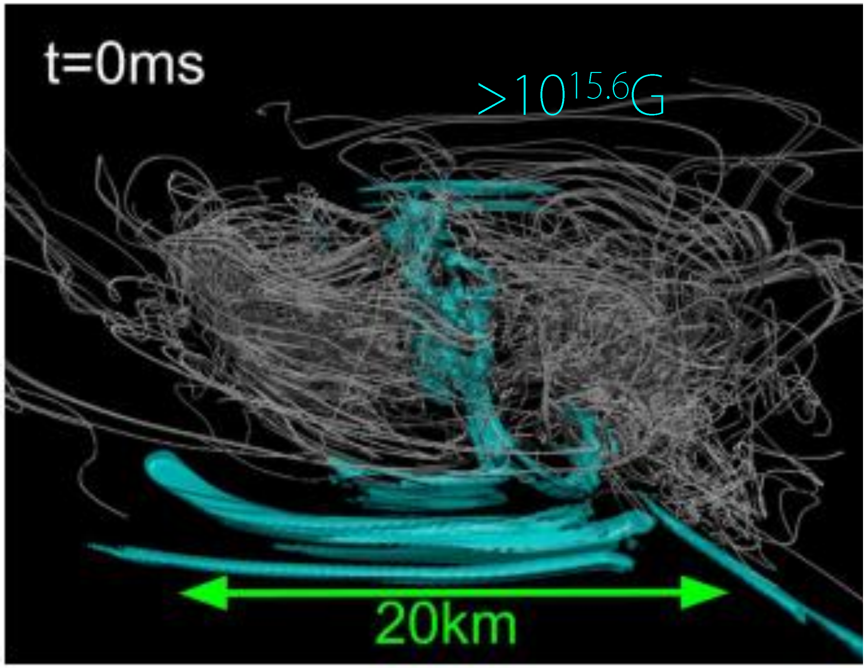


1=0.1ms

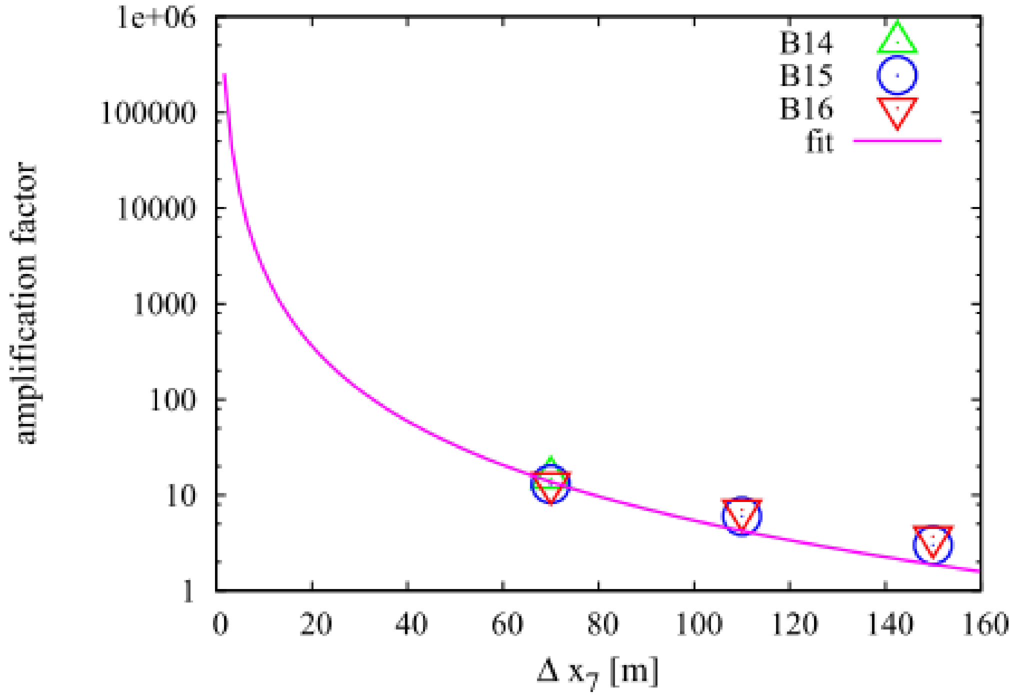
Can really the KH vortices amplify the B-fields ?

Yes !

Field lines and strength @ merger

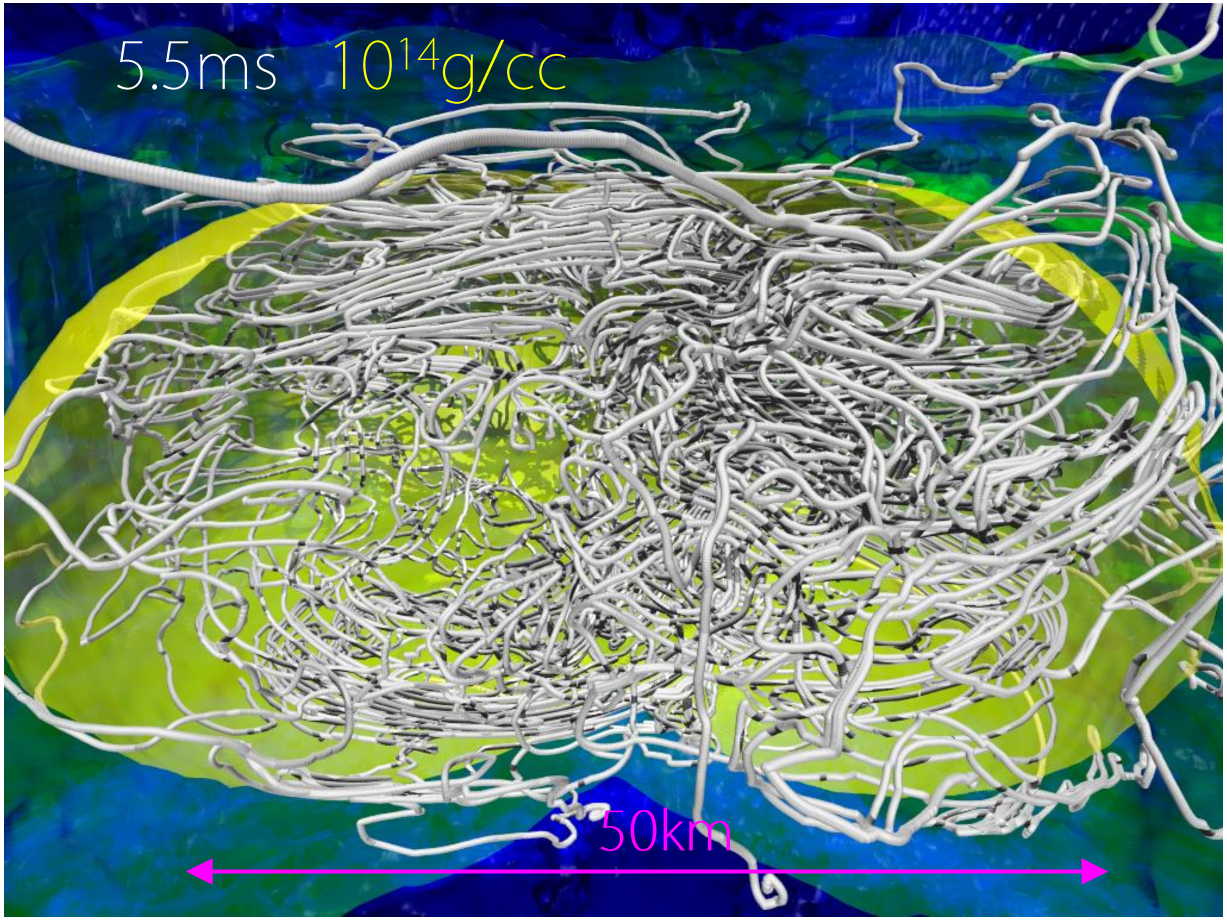


Amplification factor vs resolution



- 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)

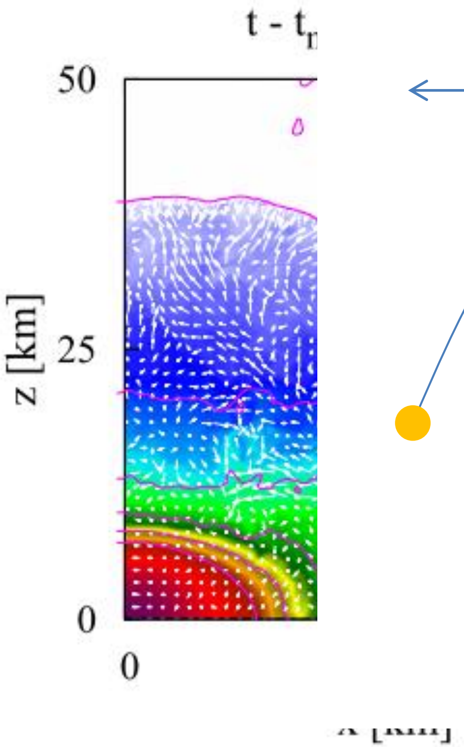
Field lines and density iso-contour inside HMNS

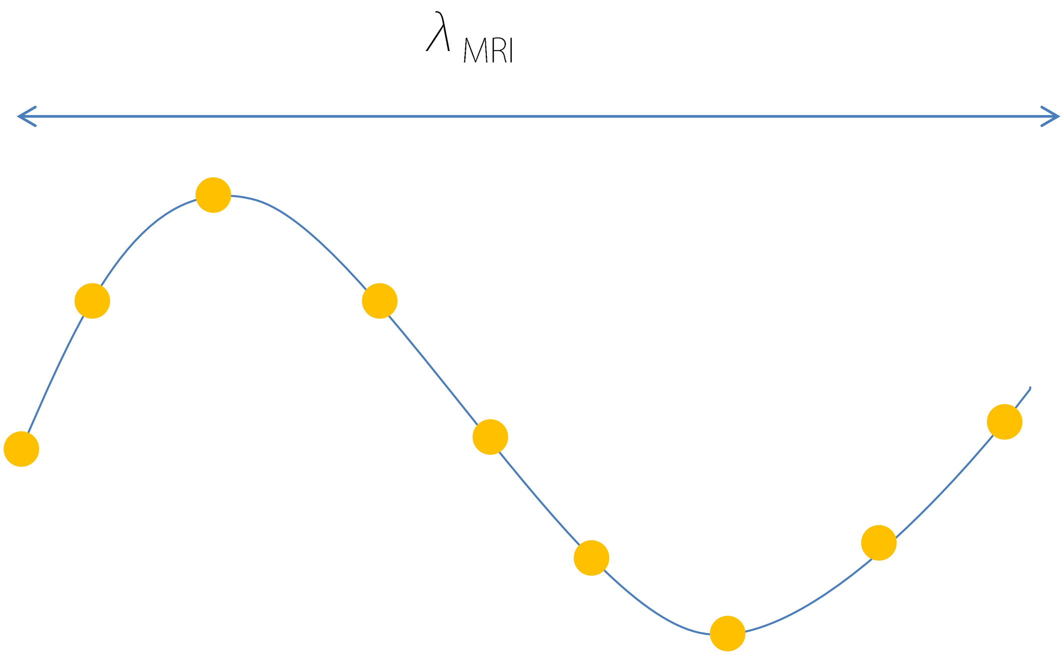


- Turbulent state inside HMNS
- HMNS is differentially rotating ⇒ Unstable against the Magneto Rotational Instability (Balbus-Hawley 92)
- Magnetic winding works as well

B-field amplification inside HMNS

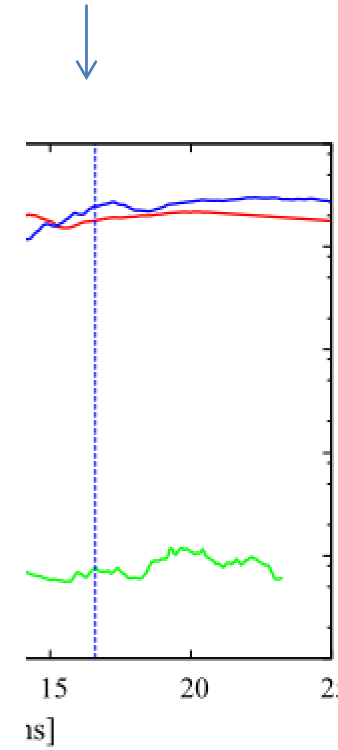
Density contour of HMNS (Meridional plane)





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

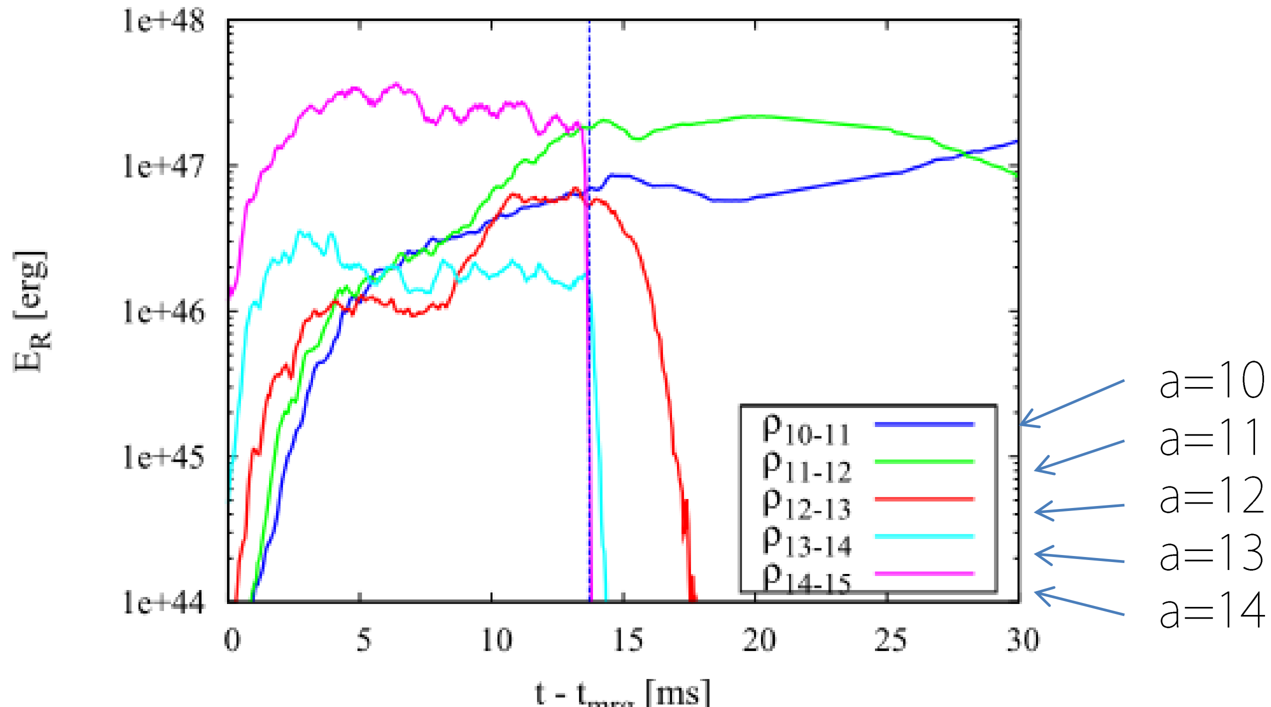
BH BH BH



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



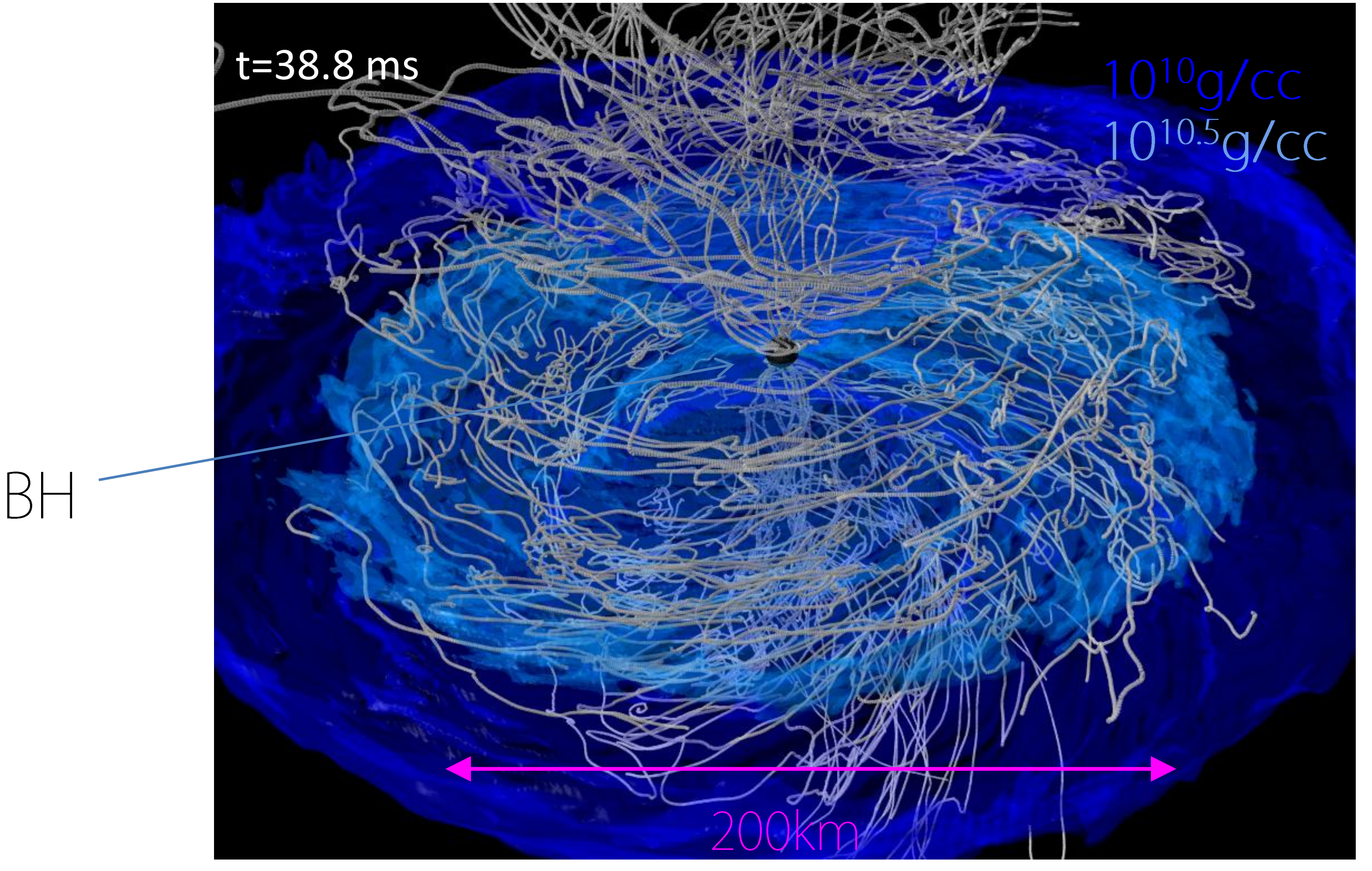
▶The high the density is, the high the growth rate is because of higher angular velocity

▶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

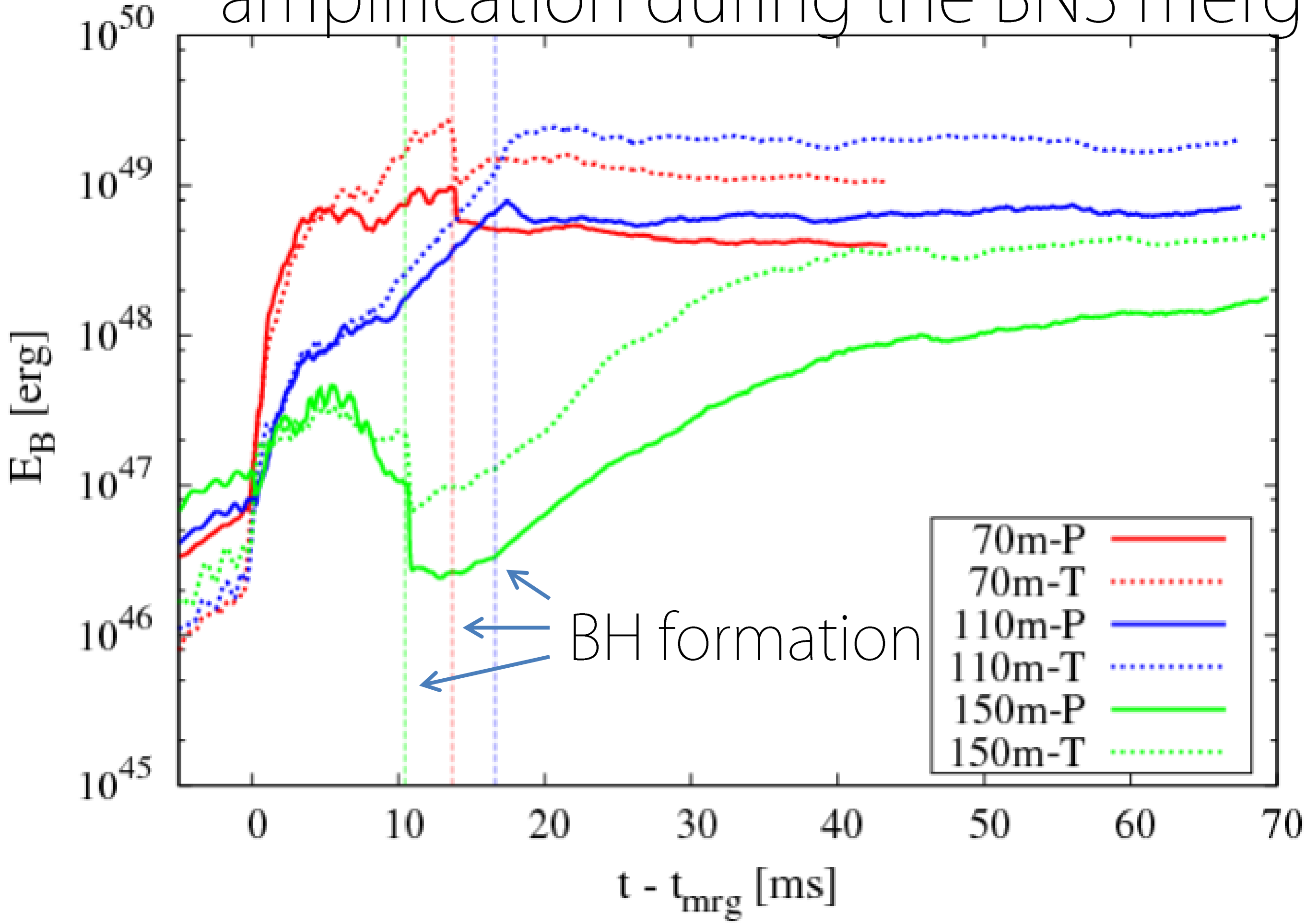
$B_\varphi \sim B_R\, \Omega\, t \sim 10^{16}$G($B_R$/$10^{15}$G)($\Omega$ /10^3rad/s)(t/10ms)

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

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.

Sub-grid scale model ? How do you justify it ?

What’s the final value of the amplified magnetic fields whose initial field value is $\sim 10^{13}$Gauss ?

Summary

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

<u>B-fields</u>

▶ 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 ?