General relativistic simulation of magnetized binary neutron star mergers

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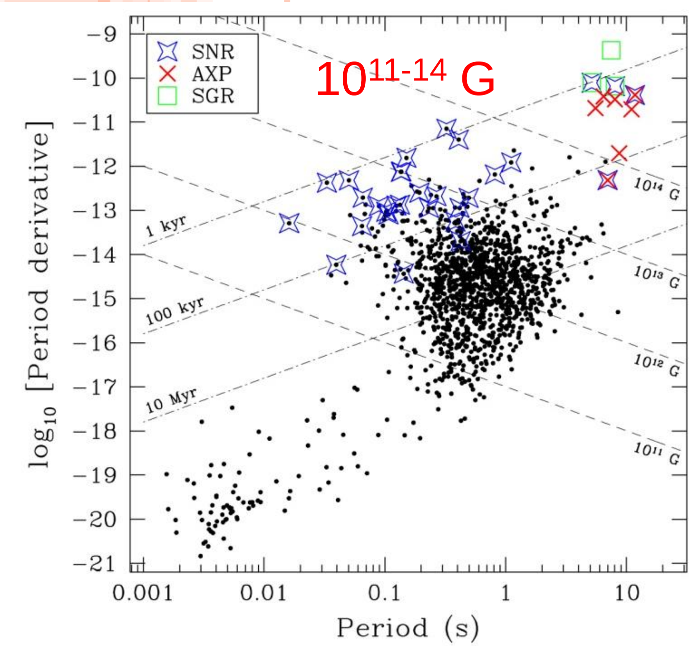
K computer

Magnetized Binary Neutron Star Mergers

Neutron stars have a magnetic field in general.

Magnetic Fields of NS（Manchester 04）

Period derivative



Spin period

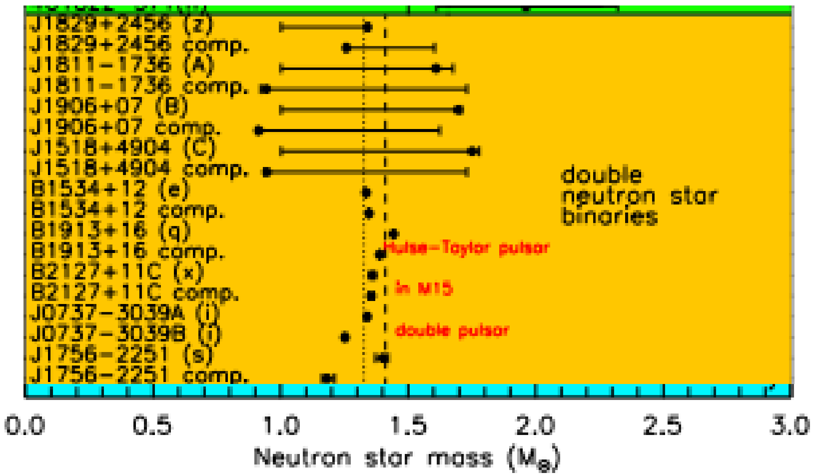
What about in binary neutron star mergers ?

<u>Possible amplification processes</u>

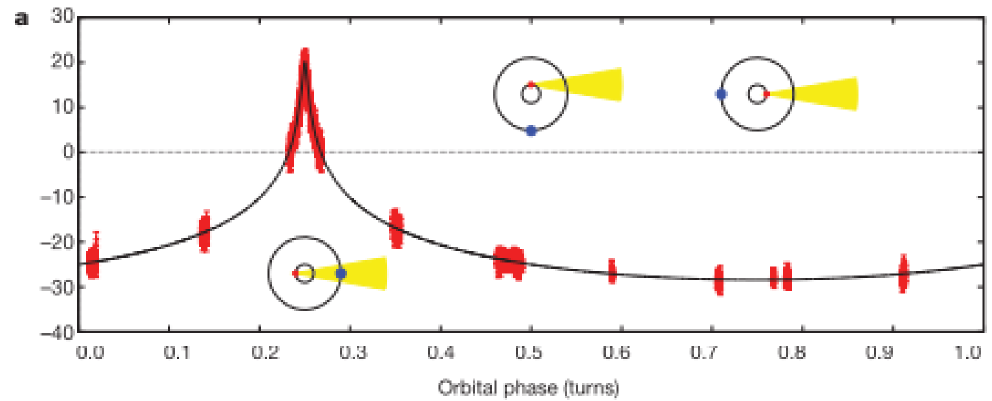
- Kelvin-Helmholtz instability (Price-Rosswog 06, Gaicomazzo+ 11)
- Magnetorotational instability (Balbus-Hawley 98, Rezzolla+ 11)
- Compression
- Magnetic winding

Outcome of binary neutron star mergers

Mass of observed NSs
(Lattimer & Paraksh 06)



Shapiro-Time delay of PSRJ1614-2230
(Demorest+ 10)



- Canonical mass of BNS = 2.7-2.8 $M_\odot$
- Maximum mass of spherical NS = 1.97 $\pm$0.04 $M_\odot$

Long-lived Hyper Massive Neutron Star (HMNS) would be formed after the merger

$\Rightarrow$ Magnetic fields would be an important player in binary neutron star mergers, e.g., angular momentum transport etc.

NR simulations for magnetized BNS mergers

✓Albert Einstein Institute (Giacomazzo+ 09, 11, Rezzolla+ 11)
- Γ-law EOS

✓Illinois University (Liu+ 08)
- Γ-law EOS

✓ Louisiana University+ (Anderson+ 08)
- Γ-law EOS

All the simulations have been done so far
- Relatively short duration $\lesssim$ 20 ms after merger or BH formation
- Applied only Γ-law EOS

Our motivation
- Long term simulation for exploring the magnetic amplification process
- Adopt the nuclear theory based EOS

GRMHD simulation of magnetized BNS mergers

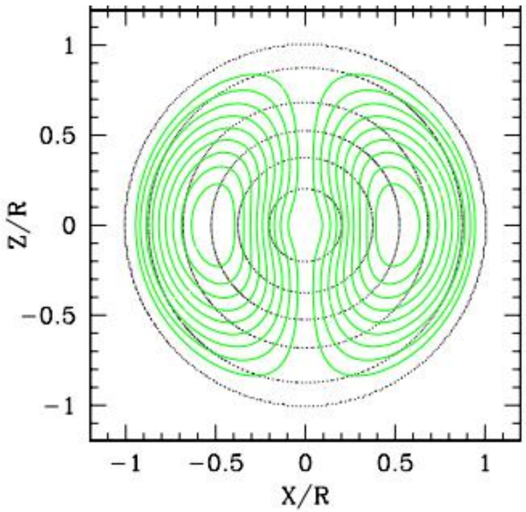
Set up

- Equation of State : H4 based on RMF (Gledenning & Moszkowski 91)

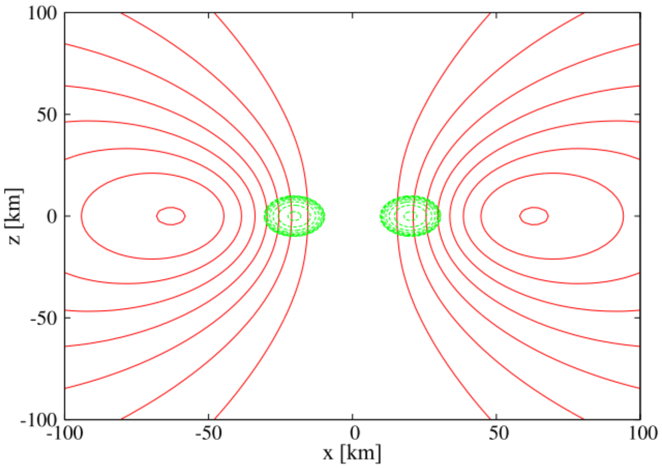
  $M_{max} \gtrsim 2.03\ M_\odot$ and Γ-law for thermal part (Γ_{th}=1.8)

  $P = P_{cold} + P_{th}$
- BNS mass : 2.7 $M_\odot$, 2.8 $M_\odot$ (Equal mass system)
- Magnetic fields configuration : Confined / Dipole field

Confined field line (Liu+08)



Dipole field line



GRMHD simulation of magnetized BNS mergers

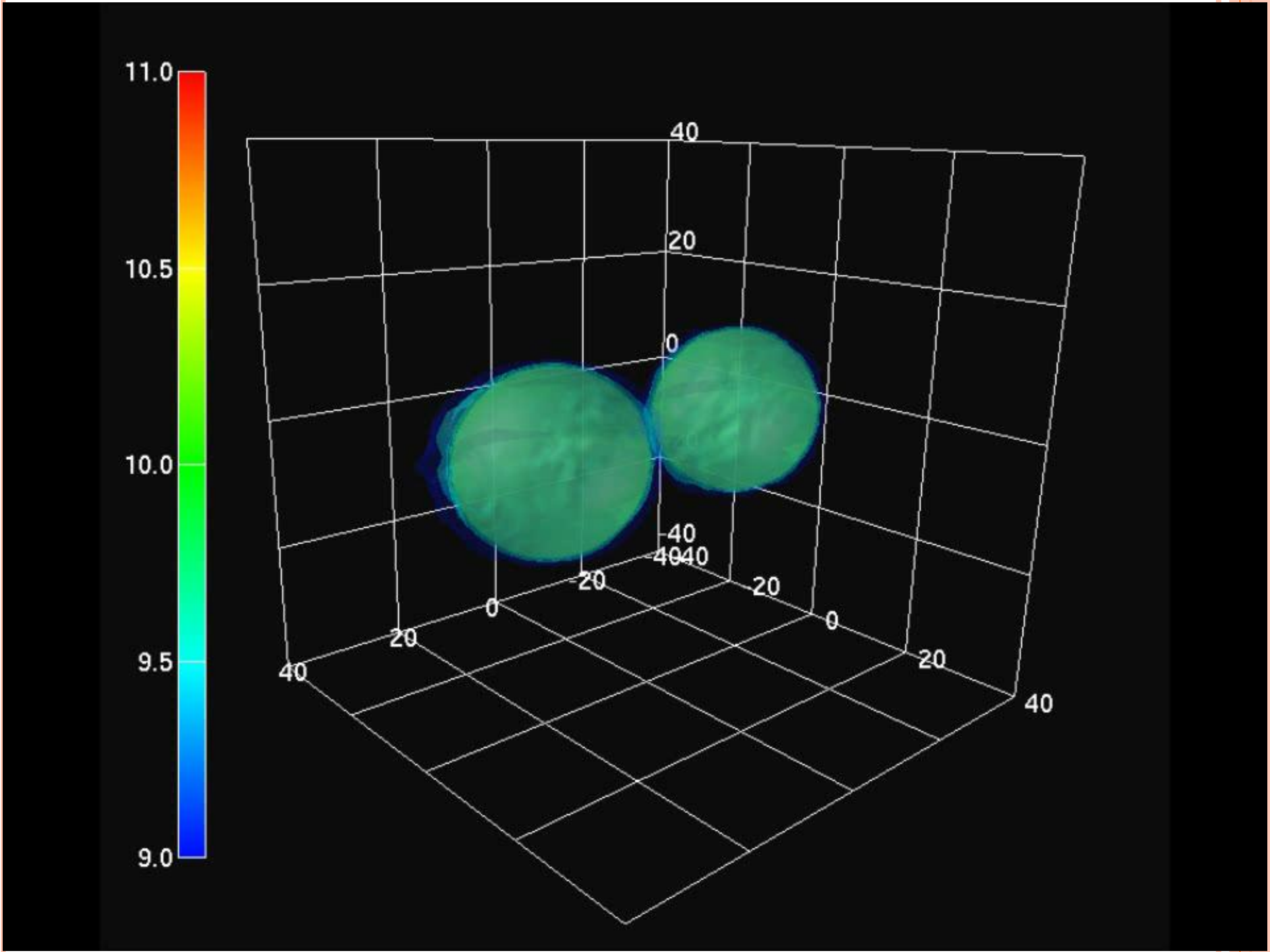
- Code description : FMR – GRMHD code based on Balsara's method preserving Div ·B = 0 as well as the magnetic flux conservation (KK+12 PRD in press)

Formulation and Numerical scheme

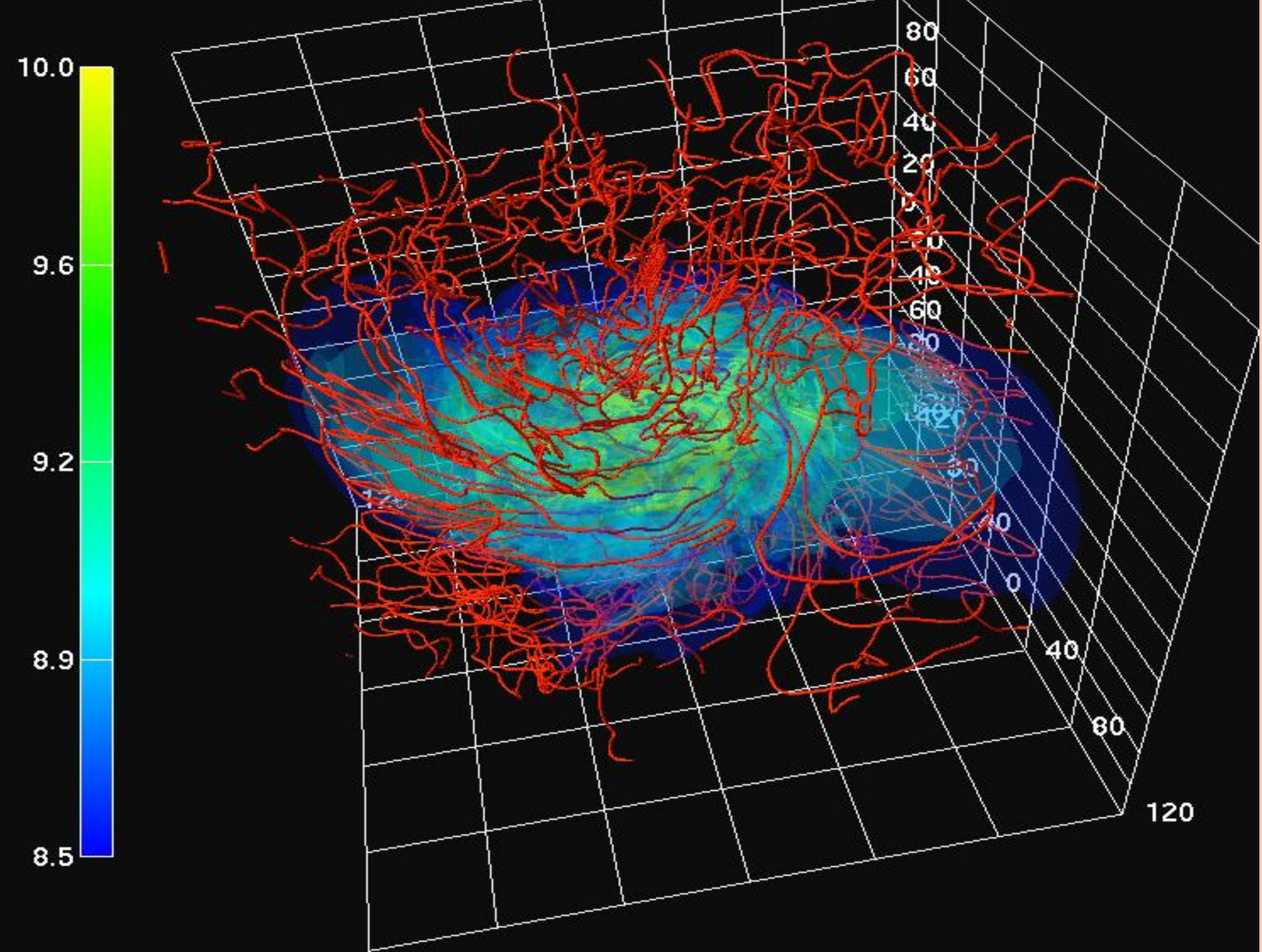
- Baumgarte-Shapiro-Shibata-Nakamura formulation (Shibata-Nakamura 95, Baumgarte-Shapiro 99)
- 4^{th}-order FD in space and time for the Einstein eqs.
- LLF flux and 3^{rd}-order reconstruction for MHD
- Weno5 for reconstruction in the refinement boundary

Resolution Study

- High resolution $\Delta x = 230$ m (NS covered by 100 grid points)
- Medium resolution $\Delta x = 288$ m (NS covered by 80 grid points)
- Low resolution $\Delta x = 384$ m (NS covered by 60 grid points)

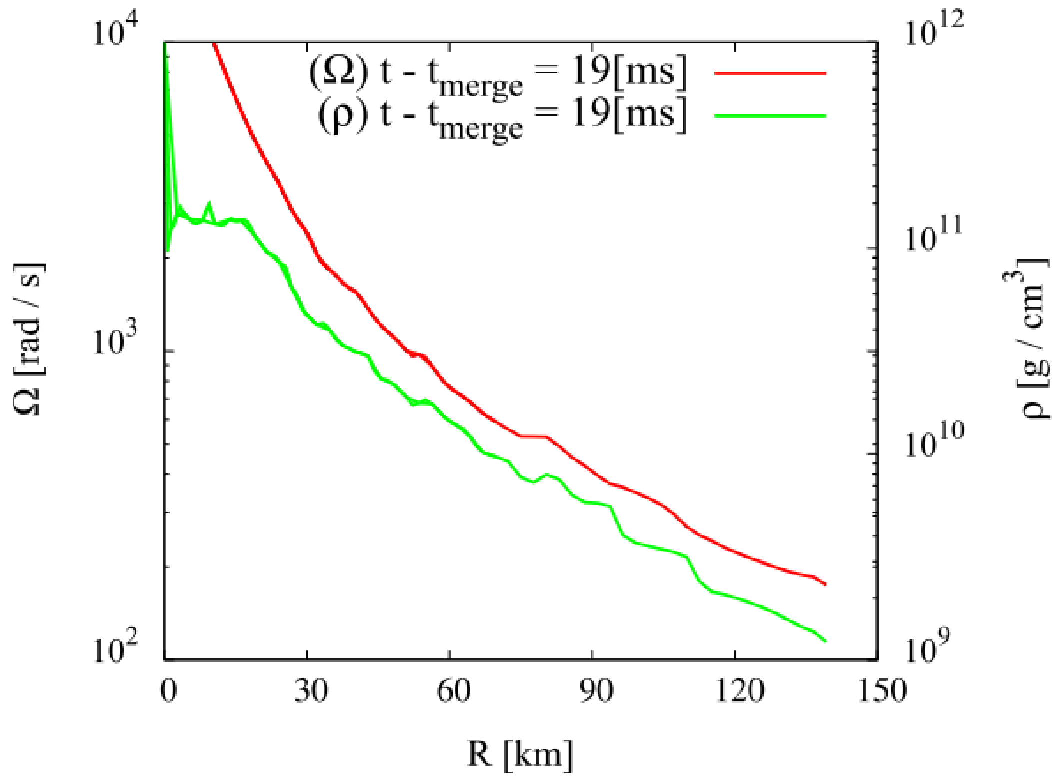


11.0
10.5
10.0
9.5
9.0
40
20
0
-40
-4040
-20
0
20
40
-20
0
20
40


10.0
9.6
9.2
8.9
8.5
80
60
40
60
40
80
120

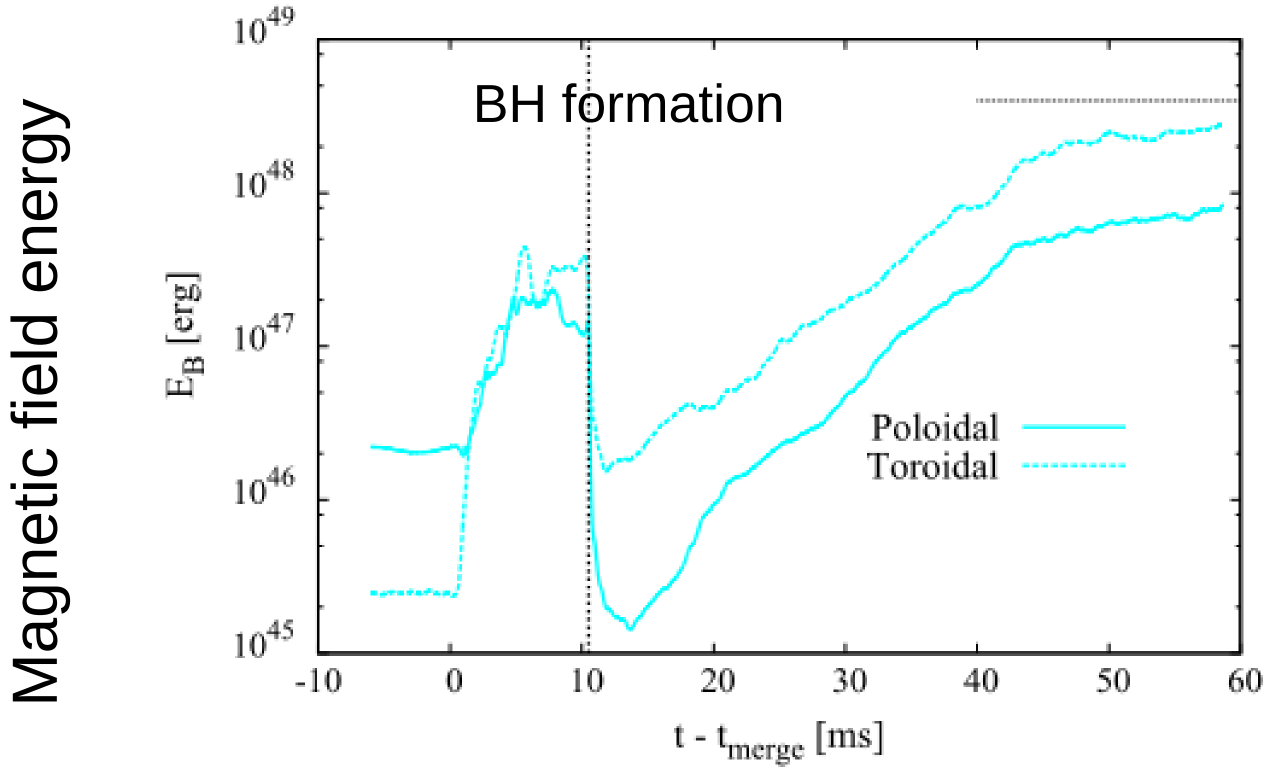
Property of BH and torus

Density and angular velocity profile along x-axis



- Mass of BH is 2.6-2.7 $M_\odot$ and spin of BH is ≈ 0.7
- Almost Keplerian profile ($\propto R^{-3/2}$)
- Torus mass ≈ 0.03-0.04 $M_\odot$ @ 30 ms after BH formation
- MRI wavelength would be larger compared to HMNS, e.g., $\rho \approx 10^{15}$ g / cm^3

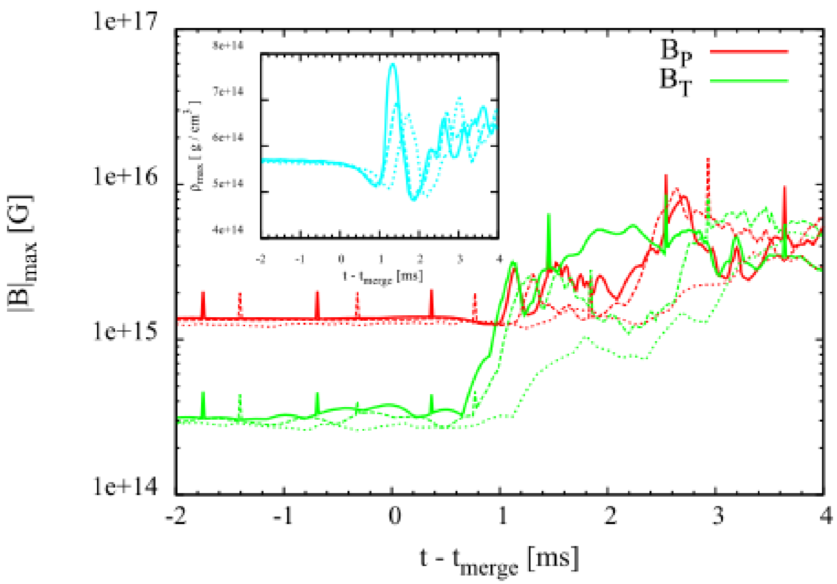
Magnetic field amplification (2.8 $M_\odot$ - confined model)



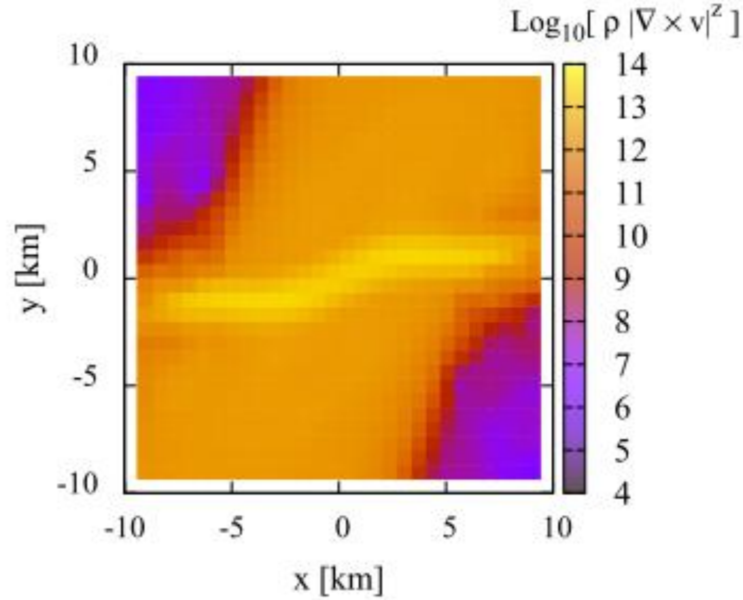
- Rapid increase at $t - t_{merge} \approx 0$ ms
- Slow increase in the HMNS phase
- Exponential growth after the BH formation (inside the torus)

Rapid increase at $t - t_{merge} \approx$ 0 ms

Magnetic field strength



Vorticity @ $t - t_{merge} \approx 0$ ms



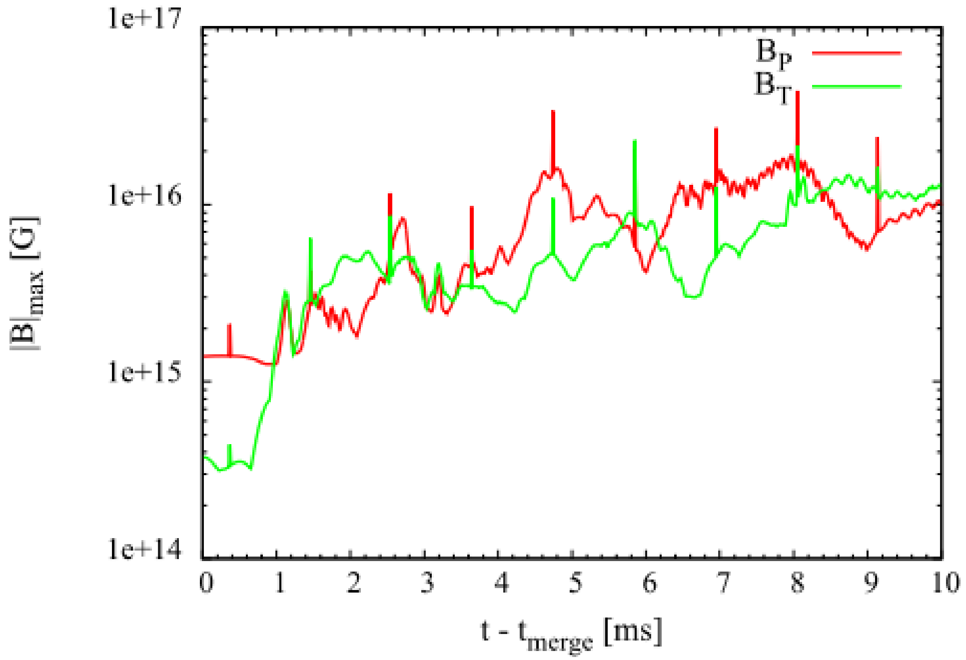
- Poloidal field increases by compression $\sim \rho^{2/3}$
- Toroidal field increases by the Kelvin-Helmholtz instability

(Price-Rosswog 06, Gaicomazzo+ 11)

- Vortexes appear in the shear layer forming the two stars come into contact.

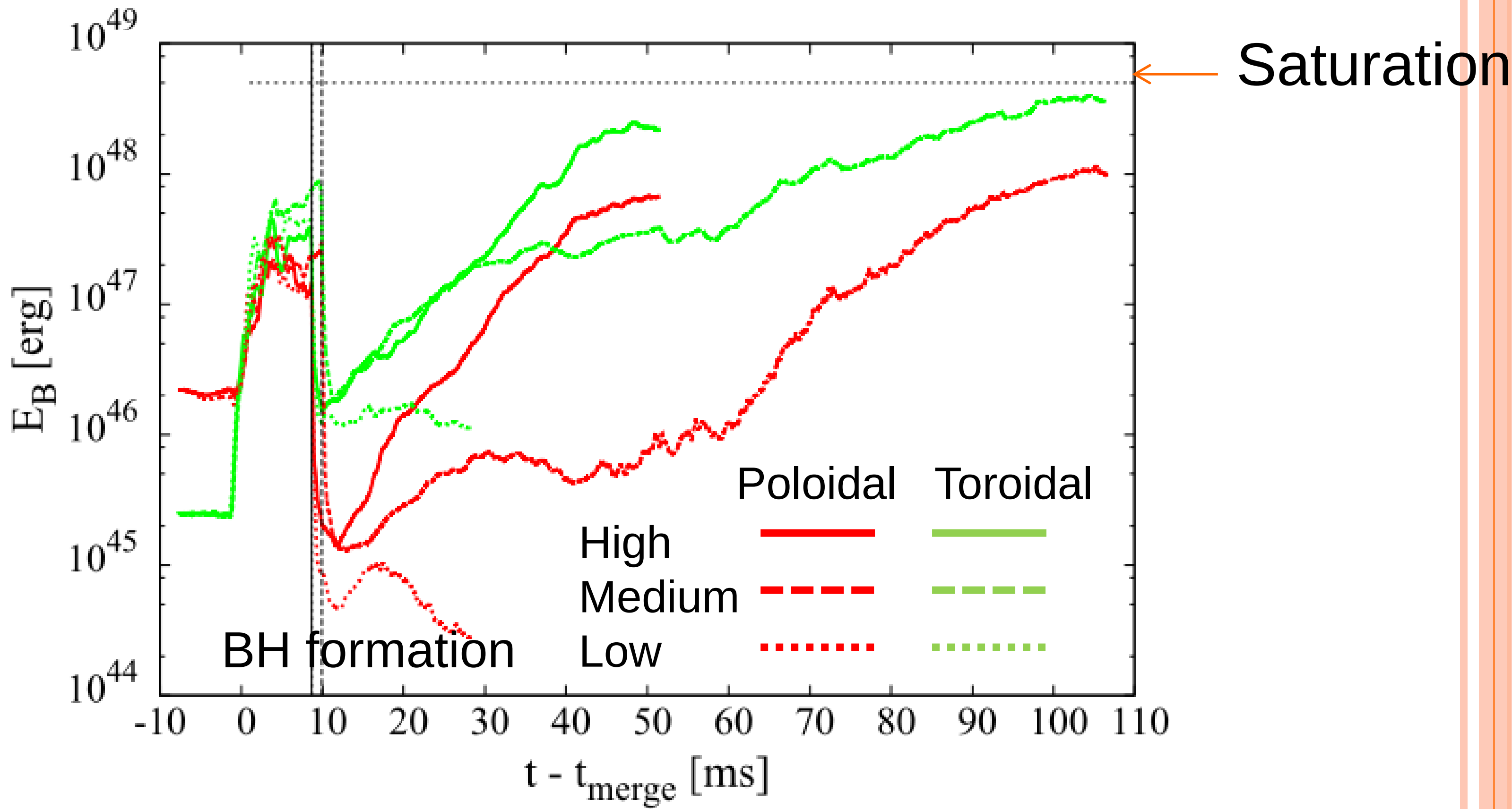
Slow increase in the HMNS phase

Magnetic field strength



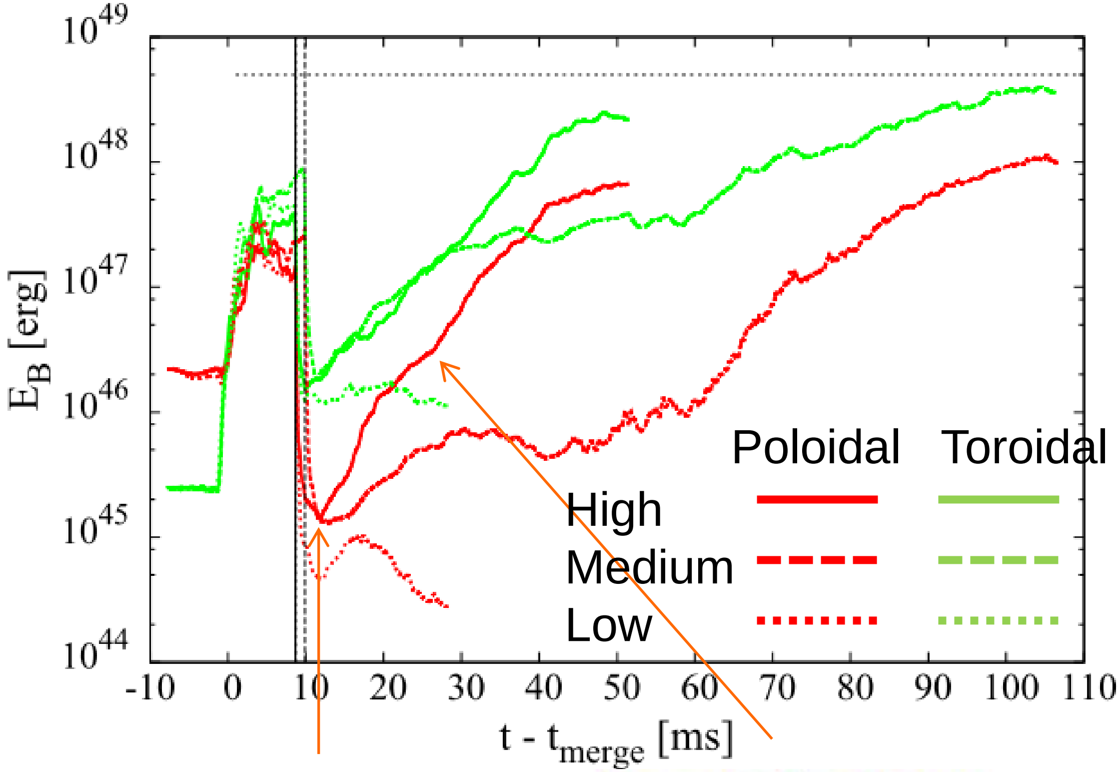
- Poloidal field increases due to the compression
- Toroidal field increases by the magnetic winding
- Very short MRI wavelength, i.e., $\rho \sim 10^{15}$ g / cm^3

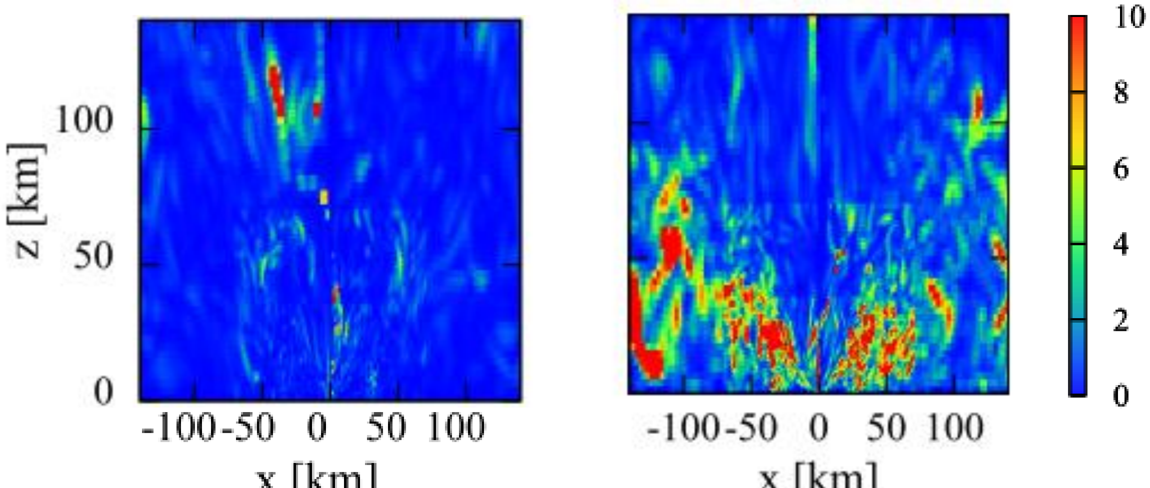
Exponential growth after the BH formation



- Exponential growth in the high resolution, not in the low resolution, after the BH formation
- e-folding time ≈ 6 ms (high resolution model)
- Saturation level ≈ 3-5 × 10^{48} erg (1-2 % of kinetic energy)

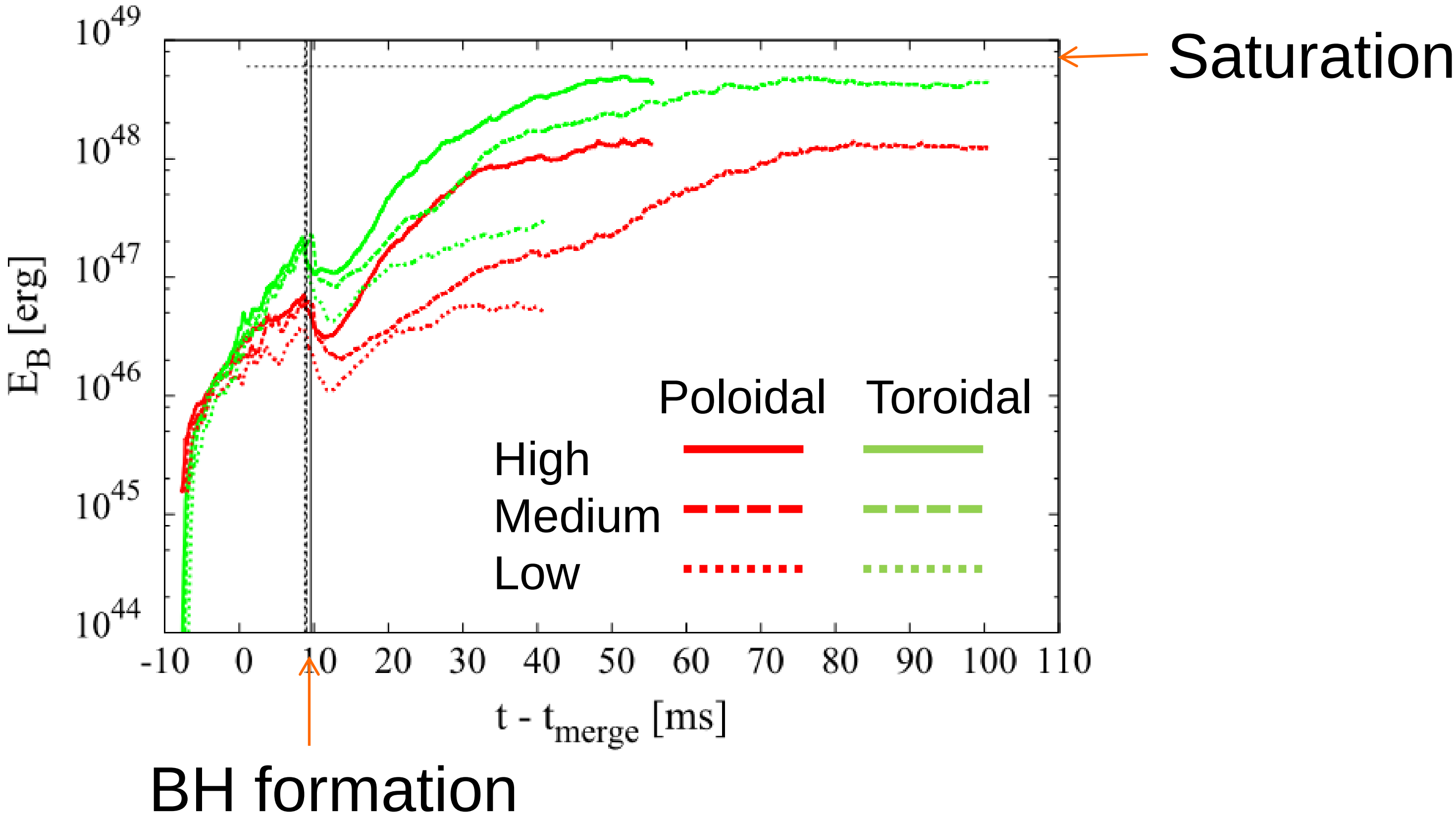
Grid resolution vs MRI wavelength





- Red region
= MRI wavelength is covered by more than 10 grid points

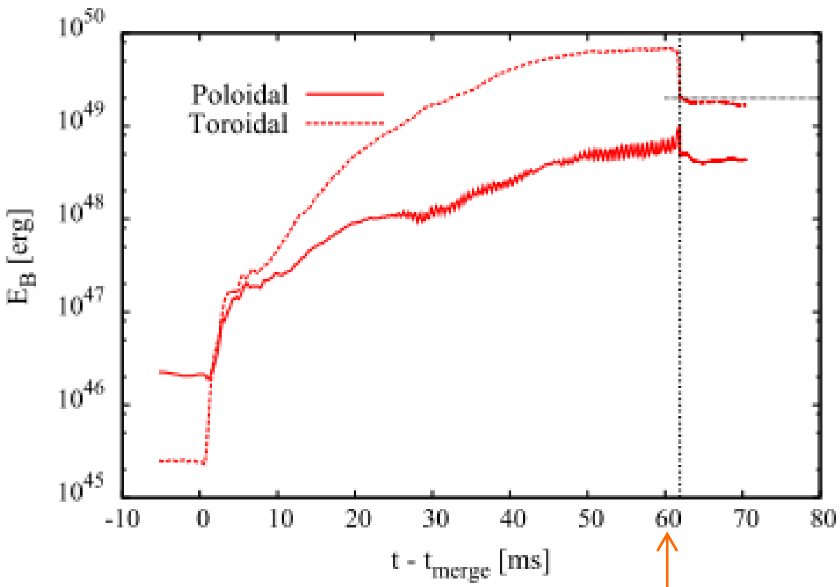
2.8 $M_\odot$ - Dipole model



- Exponential growth in the high and middle resolution, not in the low resolution after the BH formation
- e-folding time ≈ 6 ms (high resolution model)
- Saturation level ≈ 6-7 $\times 10^{48}$ erg (2-3 % of the kinetic energy)

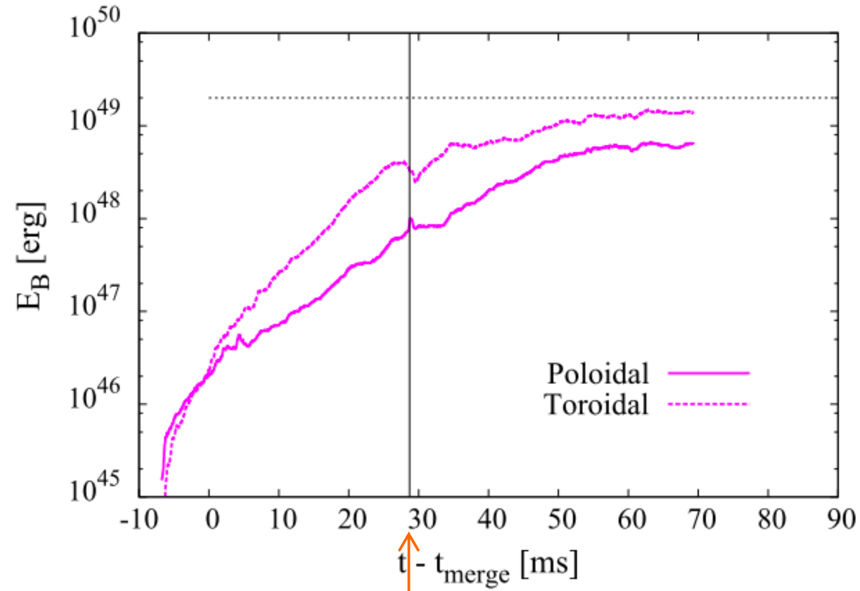
2.7 $M_\odot$ model

Confined model



BH formation

Dipole model



BH formation

- Life-time of HMNS depends on the magnetic field configurations
  - Strong magnetic pressure for the confined model
  - 2.7 $M_\odot$ model is marginally stable
- Saturation level ≈ 2×10^{49} erg (3-5 % of kinetic energy) for dipole model

Mass ejection

Mass ejection is important for the counter part of BNS mergers

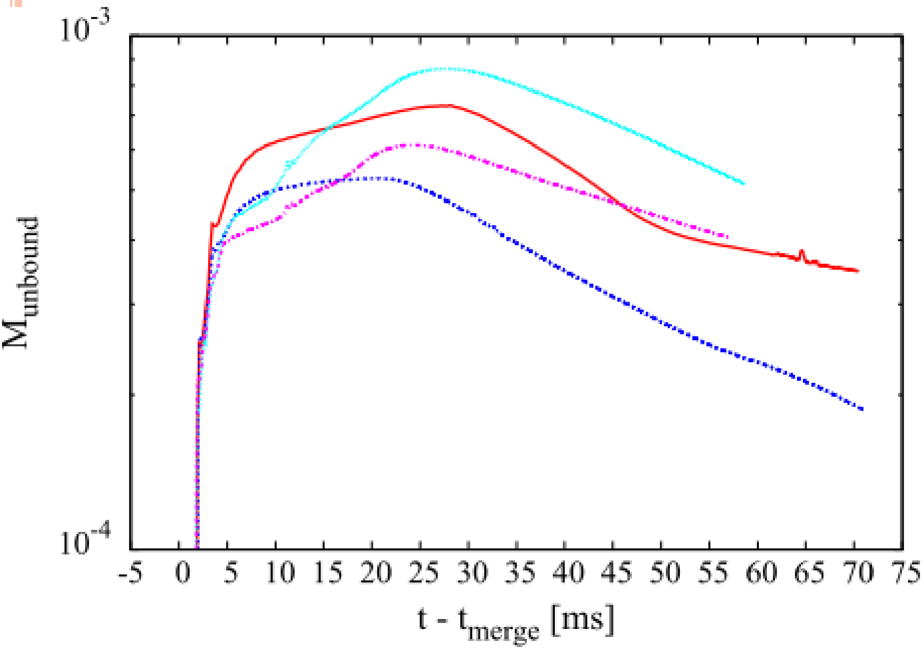
- synchrotron radiation (radio) (Nakar & Piran 11)

$\sim$ 2.5 mJy $(E_0/10^{49}\mathrm{erg})(n_0/1\mathrm{cm}^{-3})^{1/2}(\beta/0.2)^{-1}(D/300\mathrm{Mpc})^{-2}$

- r-process elements (optical) (Li-Paczynski 98, Metzger+10, 12)

$t_{peak} \sim 0.1\ \mathrm{day}\ (\beta/0.2)^{-1/2} (M_{eje}/10^{-3} M_\odot)^{1/2}$

$L_{peak} \sim 7 \times 10^{41}\ \mathrm{erg/s}\ (f/3\times10^{-6})(\beta/0.2)^{1/2}(M_{eje}/10^{-3} M_\odot)^{1/2}$



- 2.7 $M_\odot$ – confined B
- 2.7 $M_\odot$ – dipole B
- 2.8 $M_\odot$ – confined B
- 2.8 $M_\odot$ – dipole B

- Rapid rise due to the gravitational torque @ the merger
- $M_{eje} \approx$ several $\times 10^{-4} M_\odot$
- Kinetic energy $E_0 \approx 10^{49}$ erg

Summary for magnetized BNS mergers

- Torus around the BH is subject to the MRI

Long term and high-resolution simulation is essential

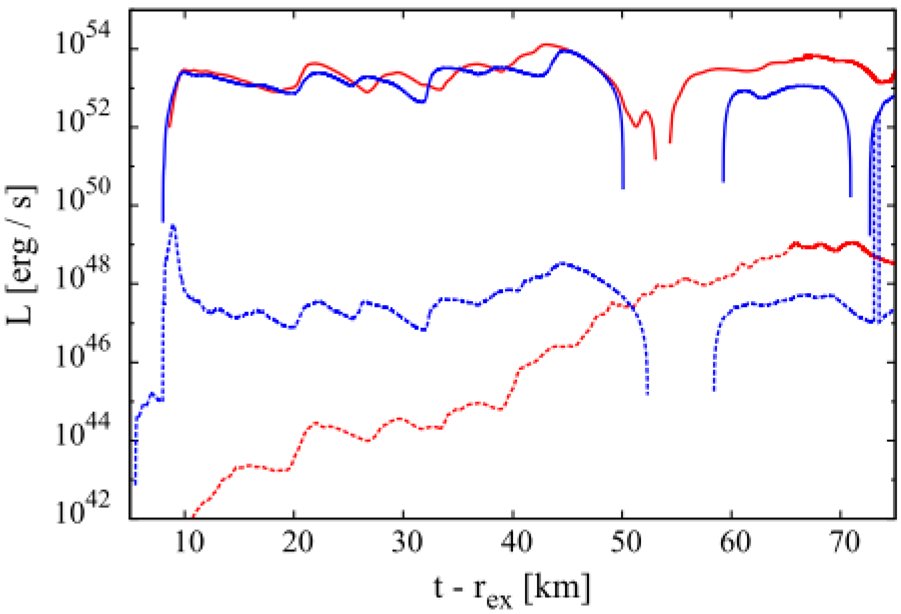
- Turbulent magnetic field develops inside the torus
- Saturation of MRI : magnetic energy ≈ 2-5 % of kinetic energy
- Initial magnetic configurations are important

Future work

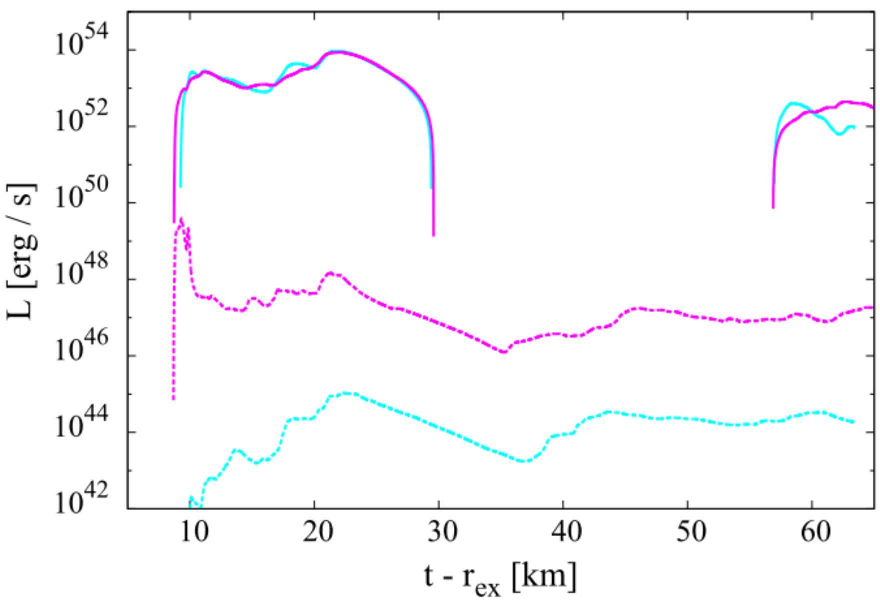
- Higher resolution simulation, ultimately $\Delta x \approx 100$ m
- Weak magnetic field, e.g., $10^{11\text{-}13}$ G for observed NSs
- Systematic study for EOS
- Equilibrium configuration of magnetized binary neutron stars as initial conditions

Luminosity

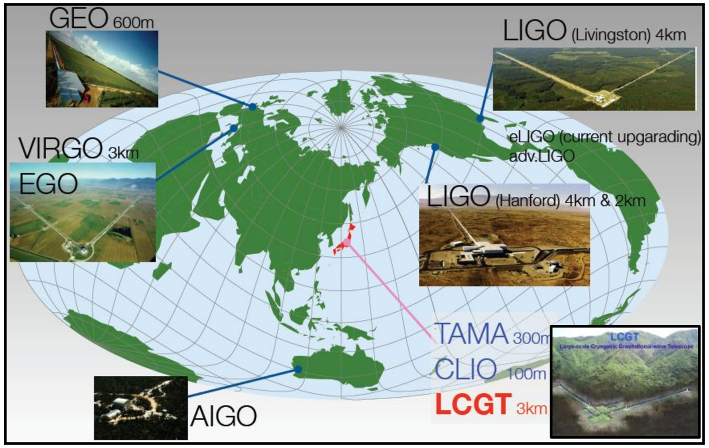
2.7 $M_\odot$ model



2.8 $M_\odot$ model



Gravitational wave astronomy and binary neutron star mergers



Gravitational waves

- Imprinting "raw" information of sources
- Extremely weak signal, $h_c \sim 10^{-22}$

Binary neutron star (BNS) mergers

- Promising source of GWs : 10 events / yr for KAGRA
- High-end laboratory for the nuclear theory : Reconstruction of Mass-Radius relation
- Theoretical candidate of Short-Gamma-Ray Burst (Narayan+ 92)

Numerical Relativity

BNS mergers

- Density $\sim 10^{15}$ g / cm^{3} (Strong interaction)
- Temperature $\sim 10^{11}$ K (Weak interaction)
- Strong gravity (Gravity)
- Magnetic field $\sim 10^{11\text{-}14}$ Gauss (Electromagnetic force)

Numerical Relativity : Simultaneously solving

- the Einstein equations
- Relativistic (magneto) hydrodynamics
- Radiation field for neutrino

Unique approach to explore phenomena in strong gravity