Magnetized binary neutron star merger

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K computer

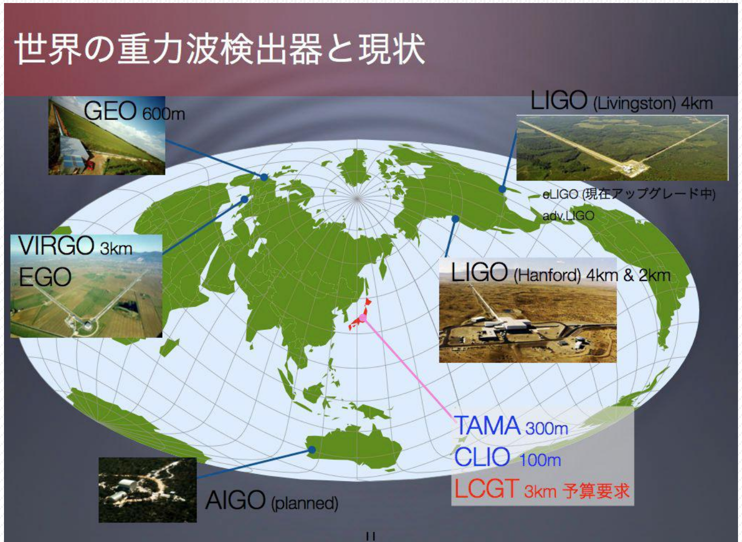
Introduction

High energy astrophysical phenomena
e.g., binary black hole (BH), neutron star (NS) merger,
Supernovae, gravitational stellar collapse

✓Density ~ 10^{15} g/cm^3 ⇒ Gravity, Strong interaction
✓Temperature ~ 10^{11}K ⇒ Weak interaction
✓Magnetic field ~ 10^{11-15}G ⇒ Electromagnetic interaction
✓Asymmetric and dynamical feature ⇒ Numerical Modeling

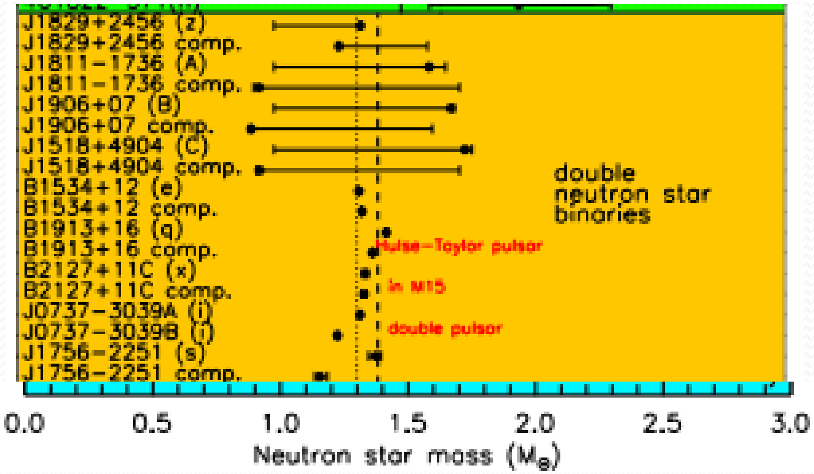
Numerical Relativity = Solving Einstein eqs. + (magneto) hydrodynamics + (radiation field) to explore extreme physics

✓ Experiments of high energy phenomena on computers
✓ Theoretical prediction of gravitational waves



Introduction

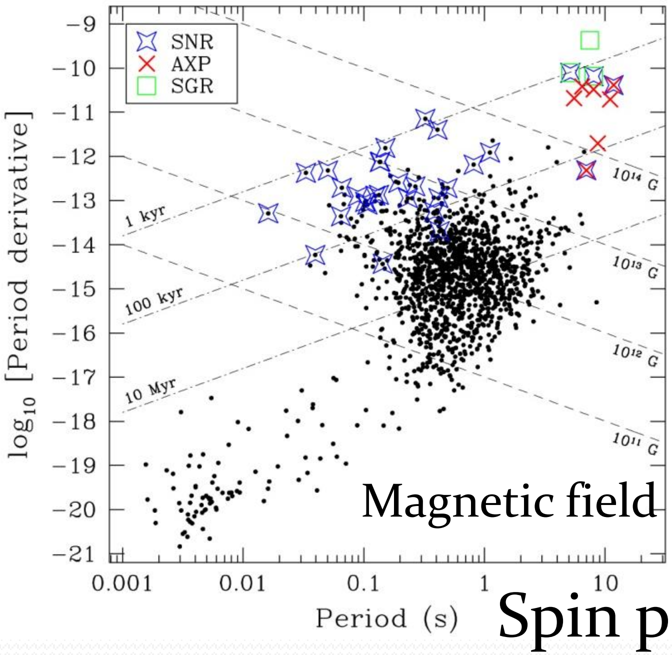
Observed binary NS (BNS)
(Lattimer & Paraksh 06)



Clustering around 1.35-1.4 $M_\odot$

Magnetic Fields of NS
(Manchester 04)

Period derivative



Magnetic field ~ $10^{11\text{-}15}$ G

Spin period

✓Canonical total mass of BNS ⇒ 2.7-2.8 $M_\odot$

✓Canonical magnetic field strength ⇒ $10^{11\text{-}13}$ G

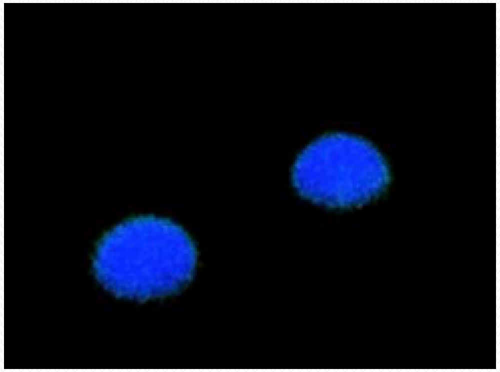
✓Maximum mass of NS ⇒ M_{max}= 1.97$\mp$0.04 $M_\odot$(PSR J1614-2230) (Demorest+ 10)

Introduction

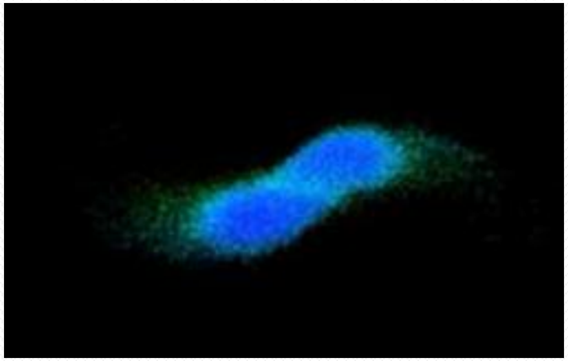
Overview of BNS merger

Animation by AEI & Koyamada lab.

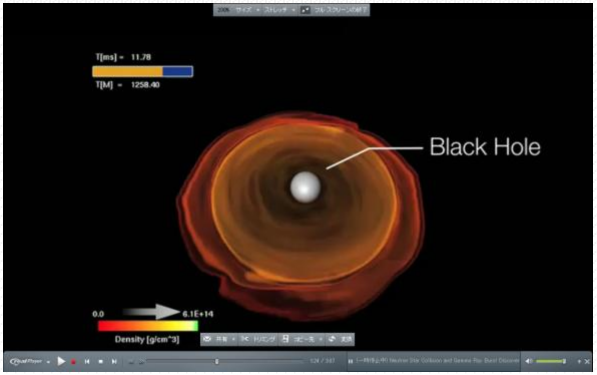
Inspiral



Merger



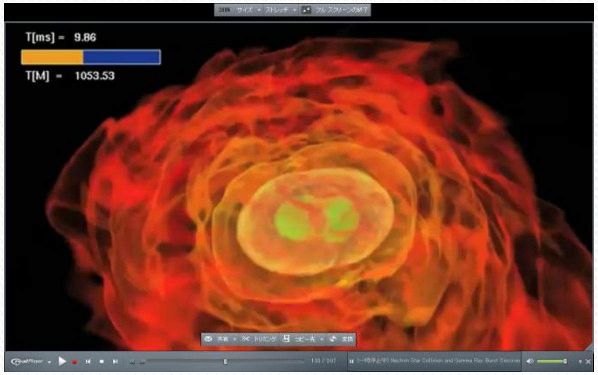
(B) Post merger (BH)



$M_{total} < M_{critical}$

$M_{total} > M_{critical}$

(A) Post merger
(Rapidly rotating NS)



BH formation ?

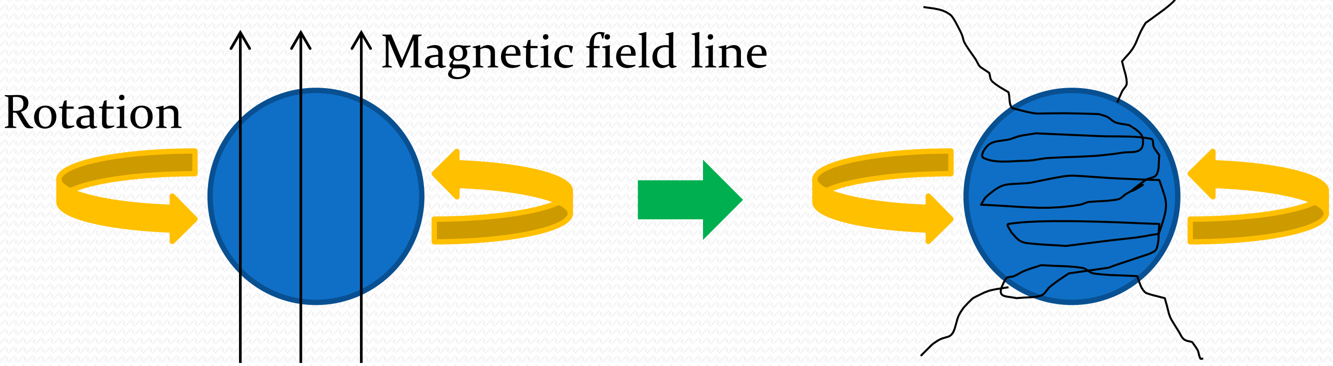
- ✓ $M_{critical} \simeq 1.3\text{-}1.7\ M_{max}$ (Hotokezaka+ 11)
- ✓ $M_{total} \sim 2.7\text{-}2.8\ M_{\odot}$
- ✓ $M_{max} = 1.97 \mp 0.04\ M_{\odot}$ ⇒ "Realistic" path is (A)

Introduction

Magnetic field amplification mechanism

✓ Magnetic winding

Differential rotation (Angular velocity $\Omega \neq$ const.) $\Rightarrow B \propto t^{\alpha}$

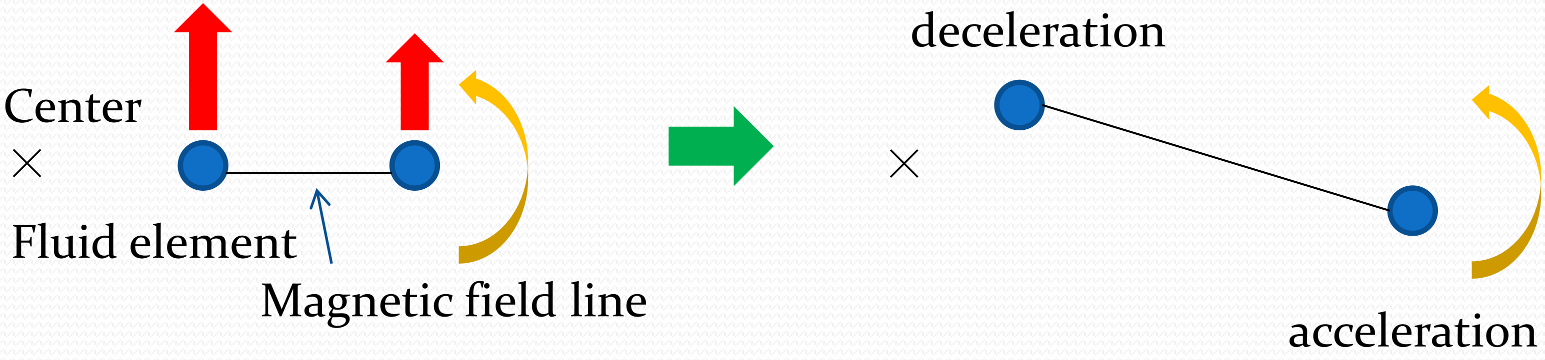


Magnetic field line

Rotation

✓ Magneto rotational instability (Balbus & Hawley 91)

Differential rotation ($\nabla\Omega < 0$) $\Rightarrow B \propto e^{\alpha t}$



deceleration

Center

×

Fluid element

Magnetic field line

acceleration

Motivation

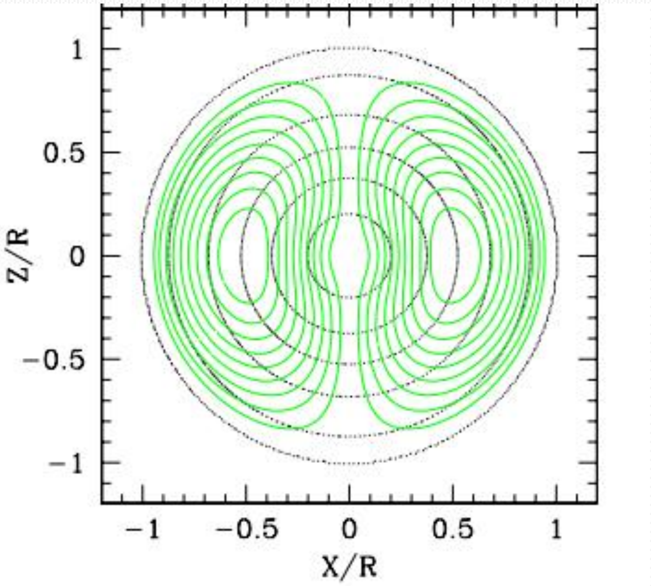
Points

✓Case for $M_{total}<M_{critical}$: Rapid rotating NS formation

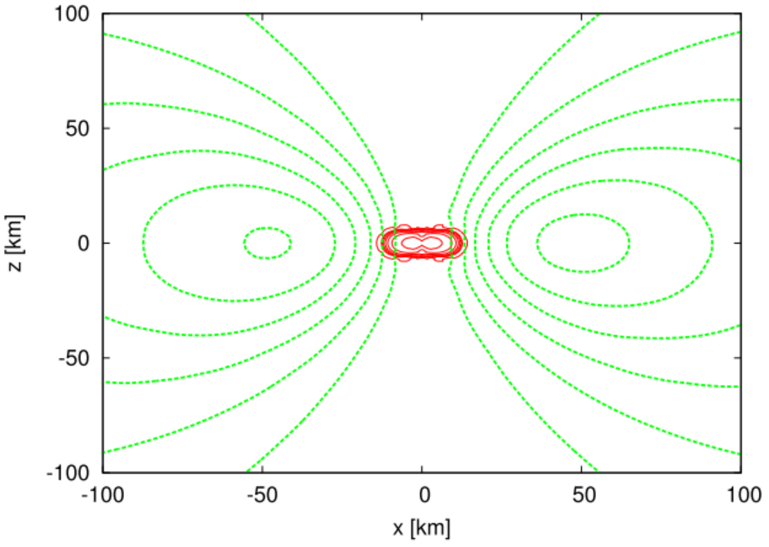
✓Case for $M_{total}>M_{critical}$: BH formation

✓ Initial magnetic field configuration（Previous works : Confined magnetic fields (see below))

Confined field line (Liu+08)



Dipole field line



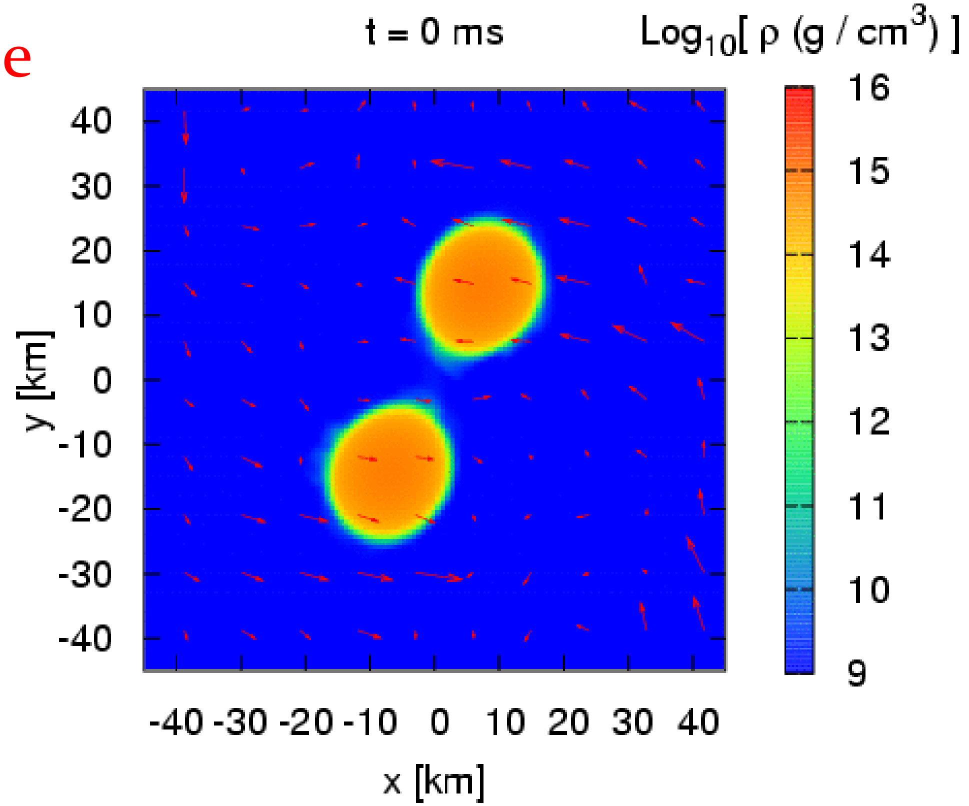
Set up

✓Total mass : 1.35-1.35 $M_\odot$ (NS formation)
or 1.45-1.45 $M_\odot$ (BH formation)
✓EOS ($P \propto \rho^{\Gamma(\rho)}$) ⇒ $M_{max} > 1.97 \mp 0.04\ M_\odot$
✓Dipole field (10^{13}G) or Confined field (10^{13}G)

Density on the orbital plane

NS formation case

Vector = velocity

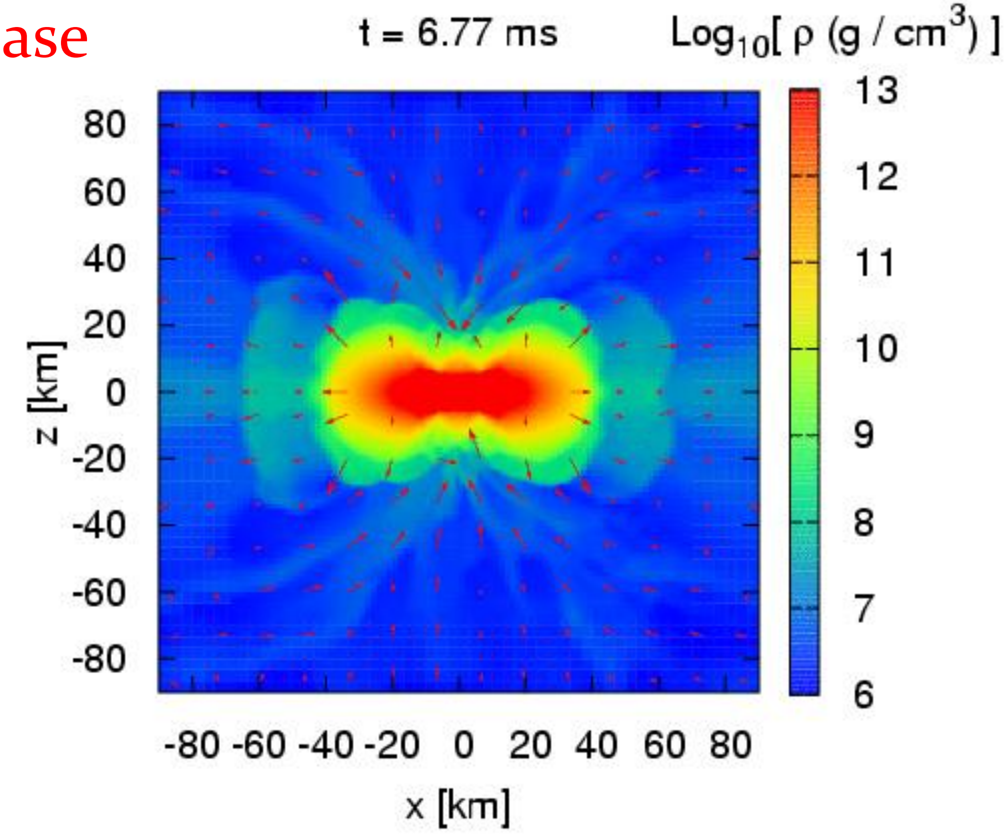


Magnetic field amplification inside NS

Numerical Results

Density on the merdional plane

BH formation case



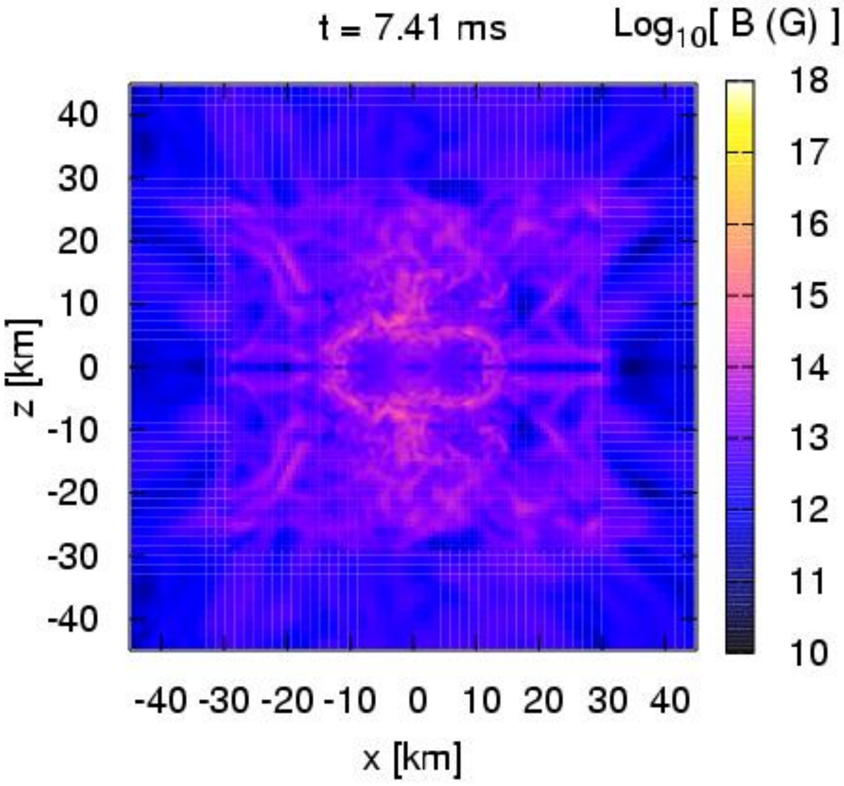
Magnetic field amplification inside the accretion disk around BH

Numerical Results

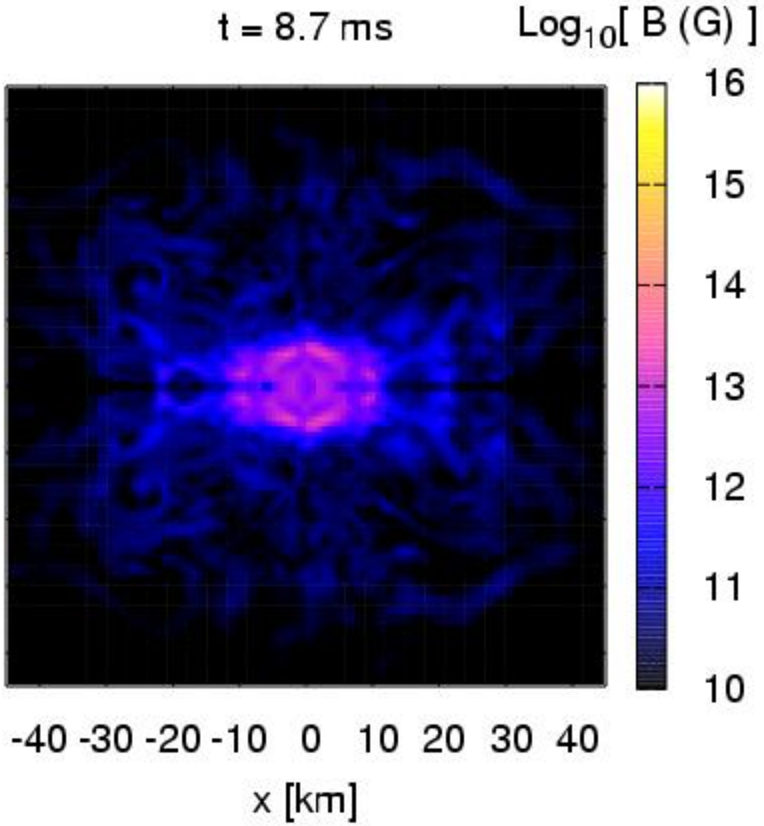
Magnetic filed on the meridional plane

NS formation case

Initial dipole field



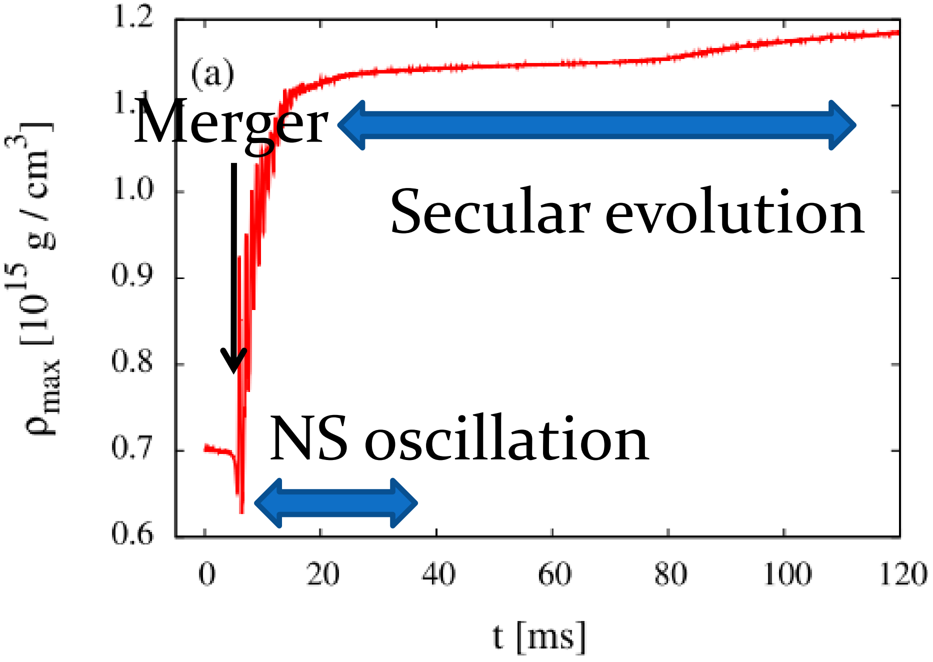
Initial confined field



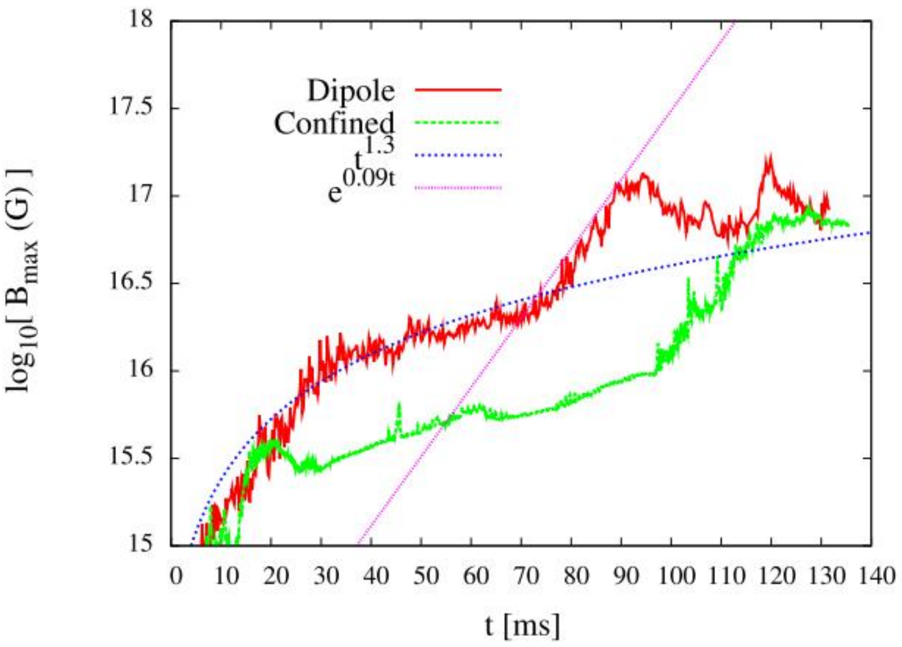
Initial fields are completely destroyed and amplified

Numerical Results

Central density



Maximum magnetic field

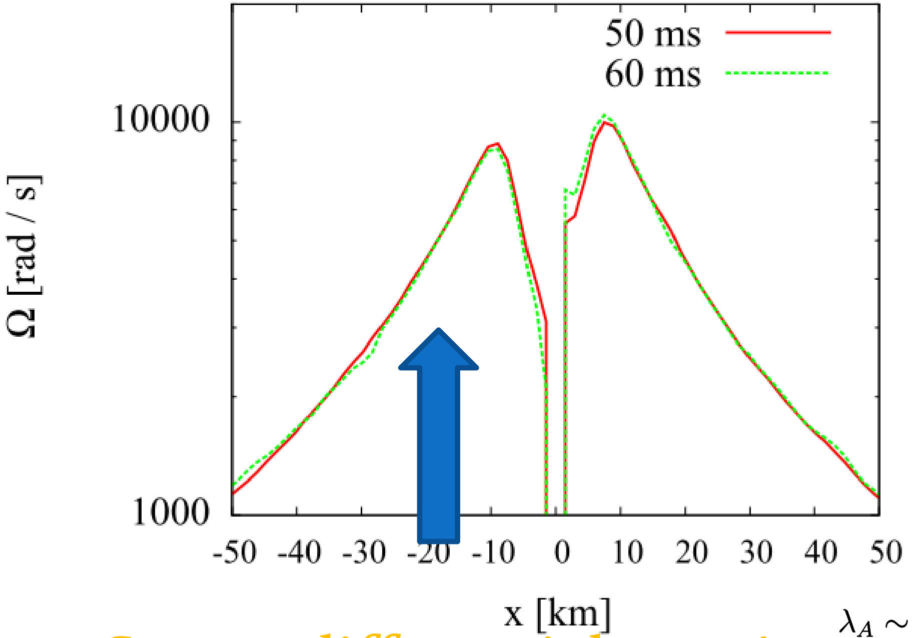


- ✓Dynamics does not depend on the magnetic field configuration
- ✓ Until ~70ms、 power law amplification ($B\propto t^{1.3}$)
- ✓For 70-90 ms, exponential growth ($B \propto e^{0.09t}$)
- ✓After 90ms、saturation
- ✓ Qualitatively same feature for the confined model

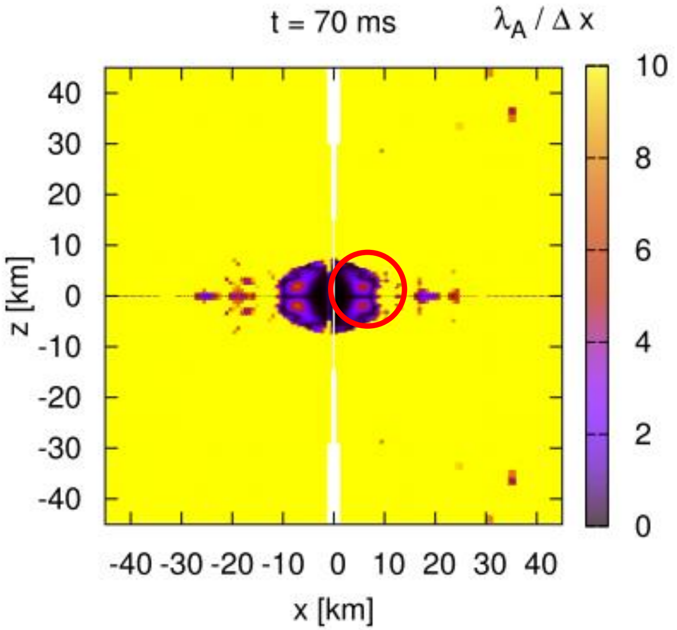
Numerical Results

- ✓ Power law amplification ($B \propto t^{1.3}$) ⇒ Magnetic winding
- ✓ Exponential growth ($B \propto e^{0.09t}$) ⇒ Magneto Rotational Instability
- ✓ Recall that the condition for winding and MRI is $\nabla \Omega < 0$

Angular velocity profile on the orbital plane



Wave length

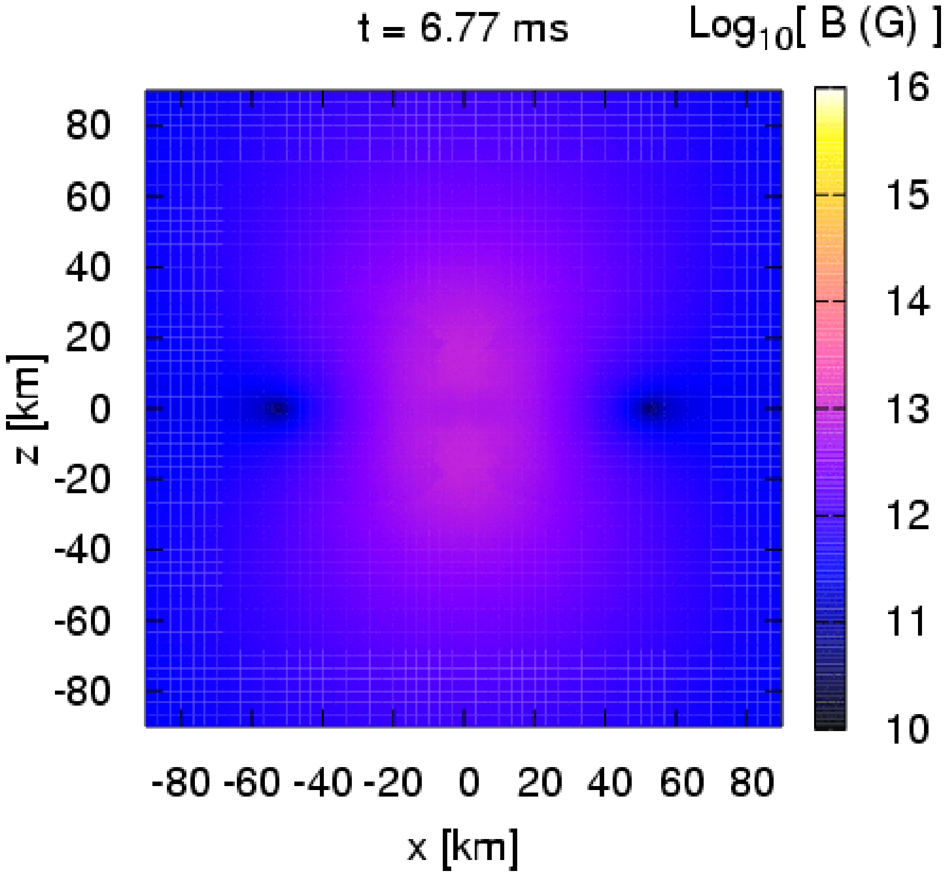


$$\lambda_A \sim v_A P \sim \frac{B}{\sqrt{4\pi\rho}} \frac{2\pi}{\Omega} \sim 500 - 600\mathrm{m} \left(\frac{B}{10^{16}\mathrm{G}}\right) \left(\frac{\rho}{10^{15}\mathrm{g/cm^3}}\right)^{-1/2} \left(\frac{\Omega}{10^{4}\mathrm{rad/s}}\right)^{-1}$$

Strong differential rotation

Numerical Results

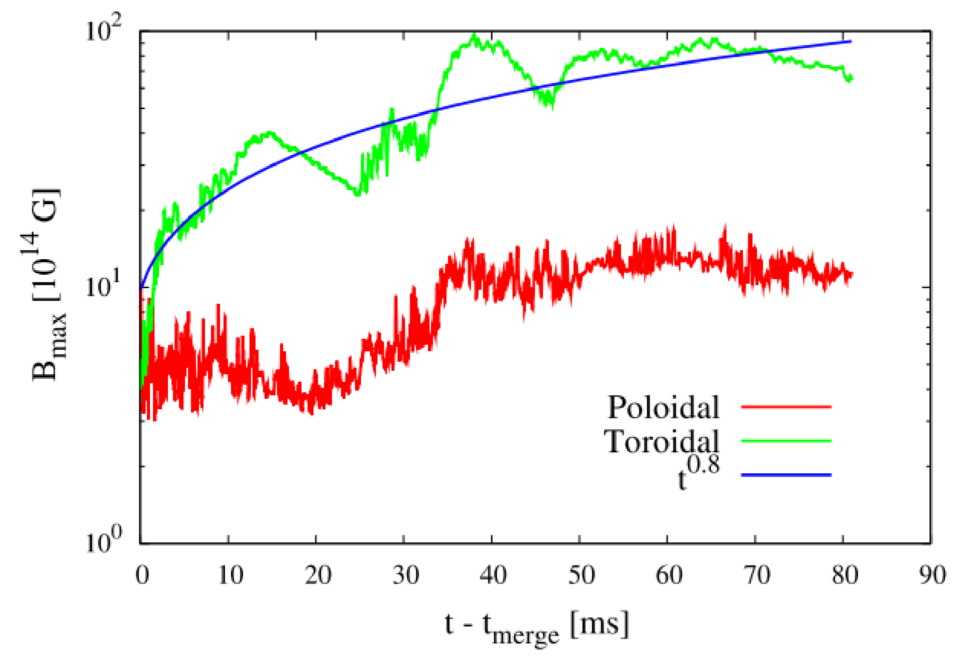
BH formation case



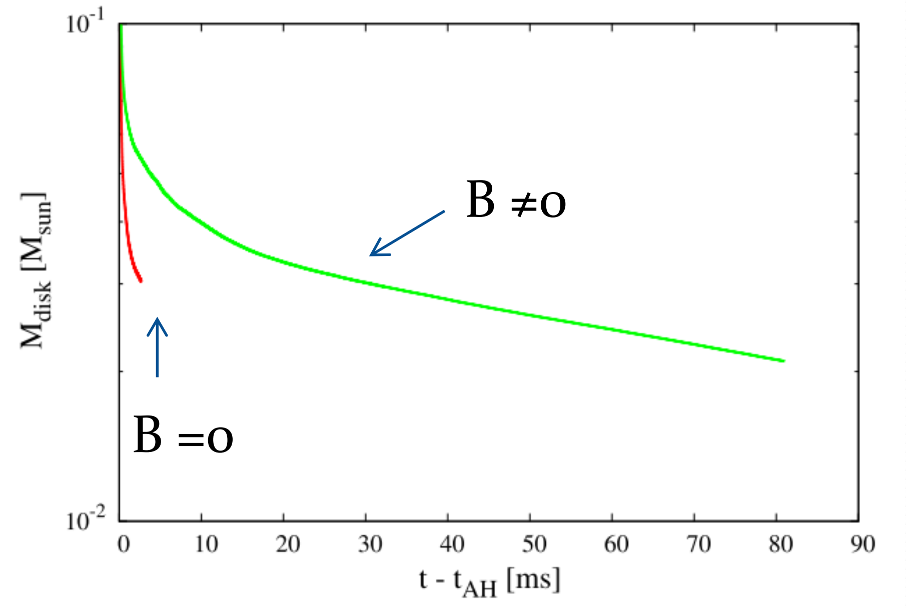
Magnetic field amplification inside the accretion disk

Numerical Results

Maximum magnetic field



Accretion disk mass



Angular momentum transport by magnetic field

✓Dominant toroidal field amplified by winding

✓Saturation at 10^{16}G

✓More massive disk for B ≠0 model ⇒ favored model for Gamma Ray Burst central engine

Summary

✓Numerical Relativity simulation for magnetized binary neutron star merger

✓ Long-lived massive NS (favored evolution path for observational constraint with PSR J1614-2230)

Magnetic winding ⇒ Magneto Rotational Instability ⇒ Saturation
But, need a careful resolution study because of $\lambda_{MRI} \propto B$

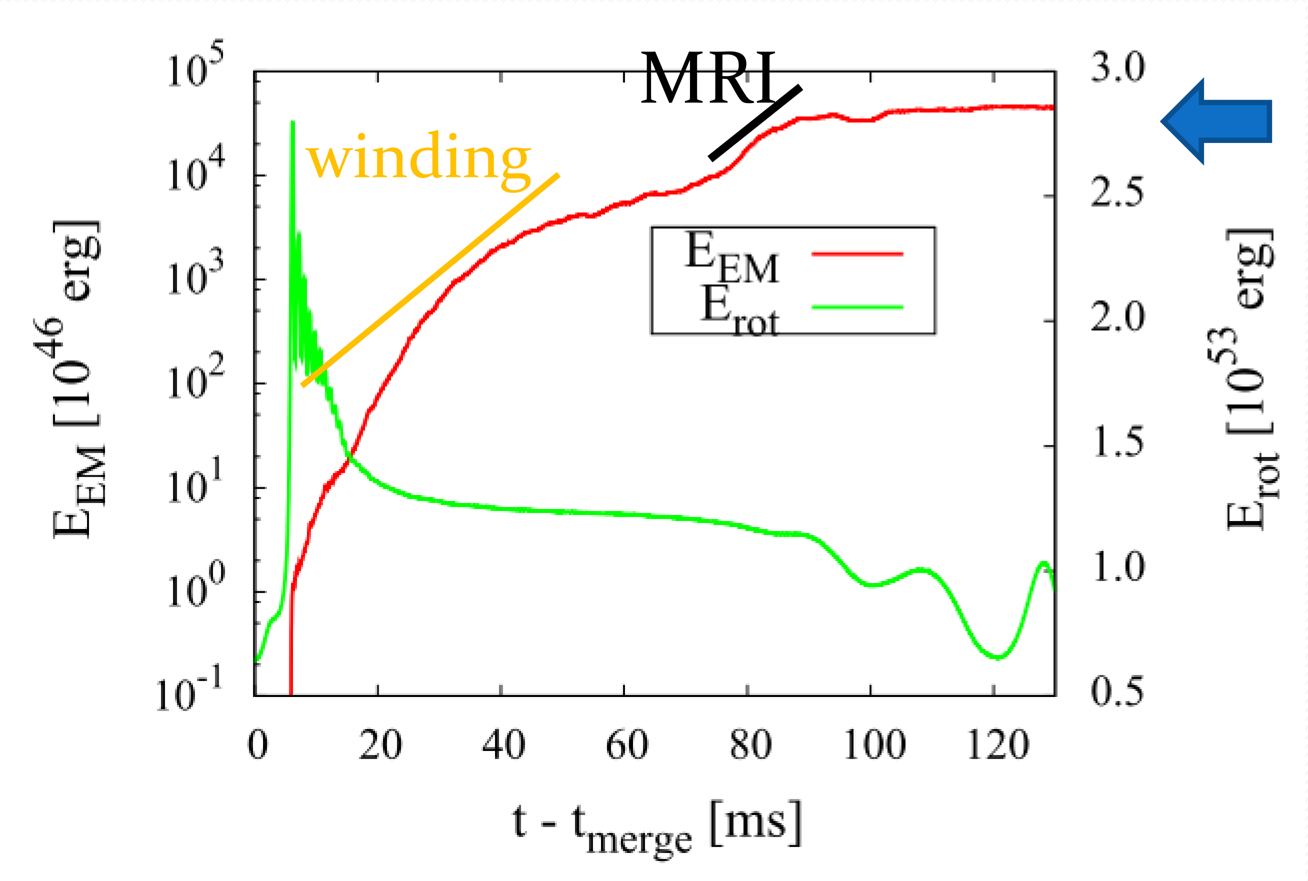
✓BH formation (disfavored evolution path ?)

Winding amplification up to 10^{16}G and massive disk

✓Utilizing the technique developed here, we'll explore the origin of NS magnetic fields in HPCI Strategic program field 5 (Supernova Explosion)

Numerical Results

Magnetic field energy vs rotational energy



~10^{51} erg

E_{mag} ~0.01 E_{rot}でsaturation