MHD simulation for merger of binary neutron stars in numerical relativity

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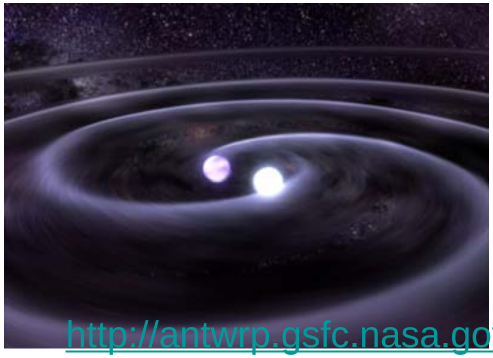
I Binary neutron stars

- Binary system composed of two neutron stars; 6 observed systems in our Galaxy which will merge in $\sim 10^{10}$ yrs
- Formed after two supernovae, and then evolve by gravitational wave emission
- Eventually merge

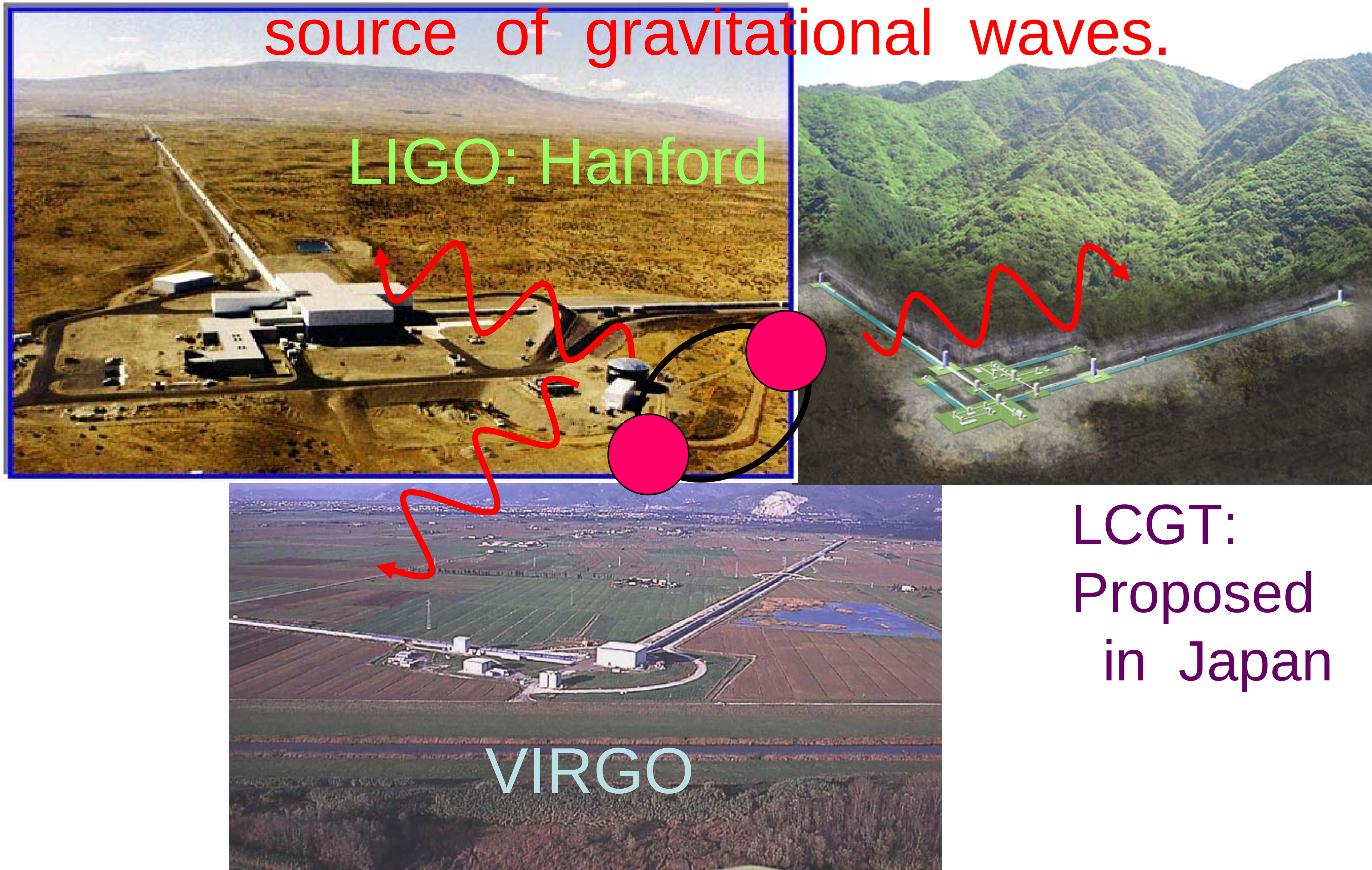


http://antwrp.gsfc.nasa.gov/apod/archivepix.html

- Neutron stars always have B-field → Merger is subject to GRMHD

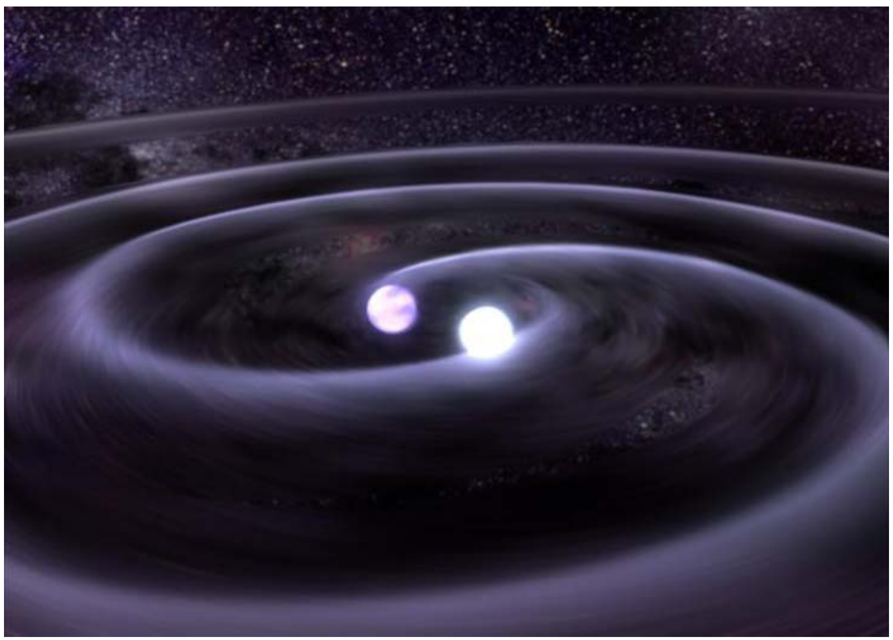
Why BNS is important ? 1

→ It is the most promising source of gravitational waves.

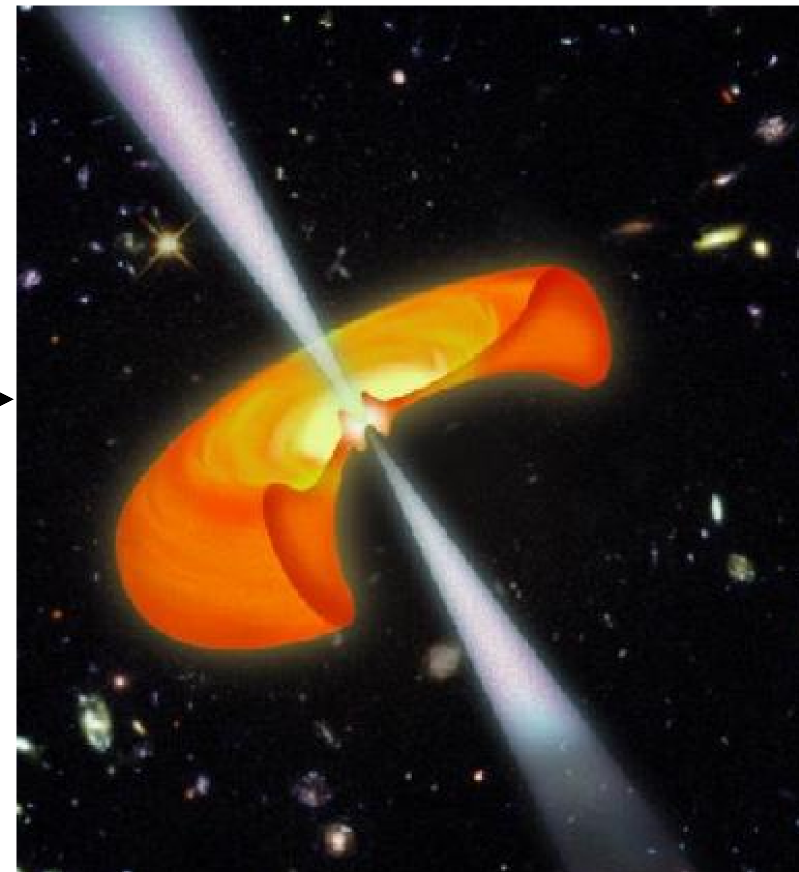


Why BNS is important ? 2

→ It may form central engine of short γ-ray burst



?



http://antwrp.gsfc.nasa.gov/apod/archivepix.html

How to study merger ?

- Neutron stars have strong, general relativistic gravity. Furthermore, black hole may be formed after merger
  → General relativistic study is necessary: The so-called numerical relativity is required

→ We solve Einstein equation & GRMHD equation in the ideal MHD approx.

II Basic equations

$$G_{\mu\nu} = 8\pi \frac{G}{c^4} T_{\mu\nu}$$ Einstein equation

$$\begin{Bmatrix} \nabla_\mu T^\mu_\nu = 0 \\ \nabla_\mu \left(\rho u^\mu \right) = 0 \end{Bmatrix}$$ GR Hydro

$$\nabla_\mu {}^* F^{\mu\nu} = 0$$ → Induction equation

- Einstein eqs. are solved by 3+1 BSSN formalism with 4th order finite difference.
- GR hydro by 3rd order central scheme (KT)
- Induction eq. by CT scheme.

Status of numerical relativity

- Einstein eqs. = Nonlinear hyperbolic eqs.
  → Nonlinearity induces high curvature
  (e.g. Black hole)
- For stable and accurate simulation, we need

1. Appropriate formulation
2. Appropriate coordinate conditions

After long research
for ~ 10 years

- Now, we have both and in principle, any globally hyperbolic spacetime can be evolved

III Evolution of BNS

At formation

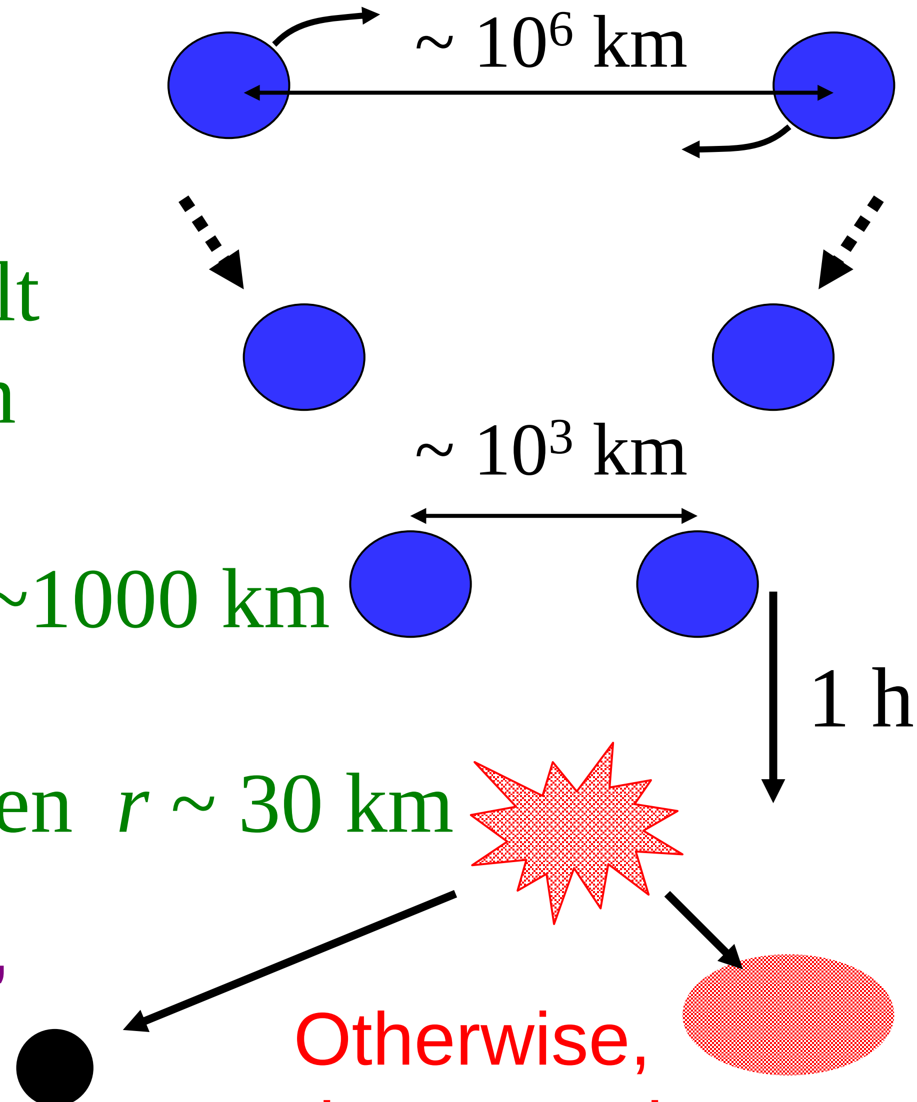
Evolve as a result of GW emission

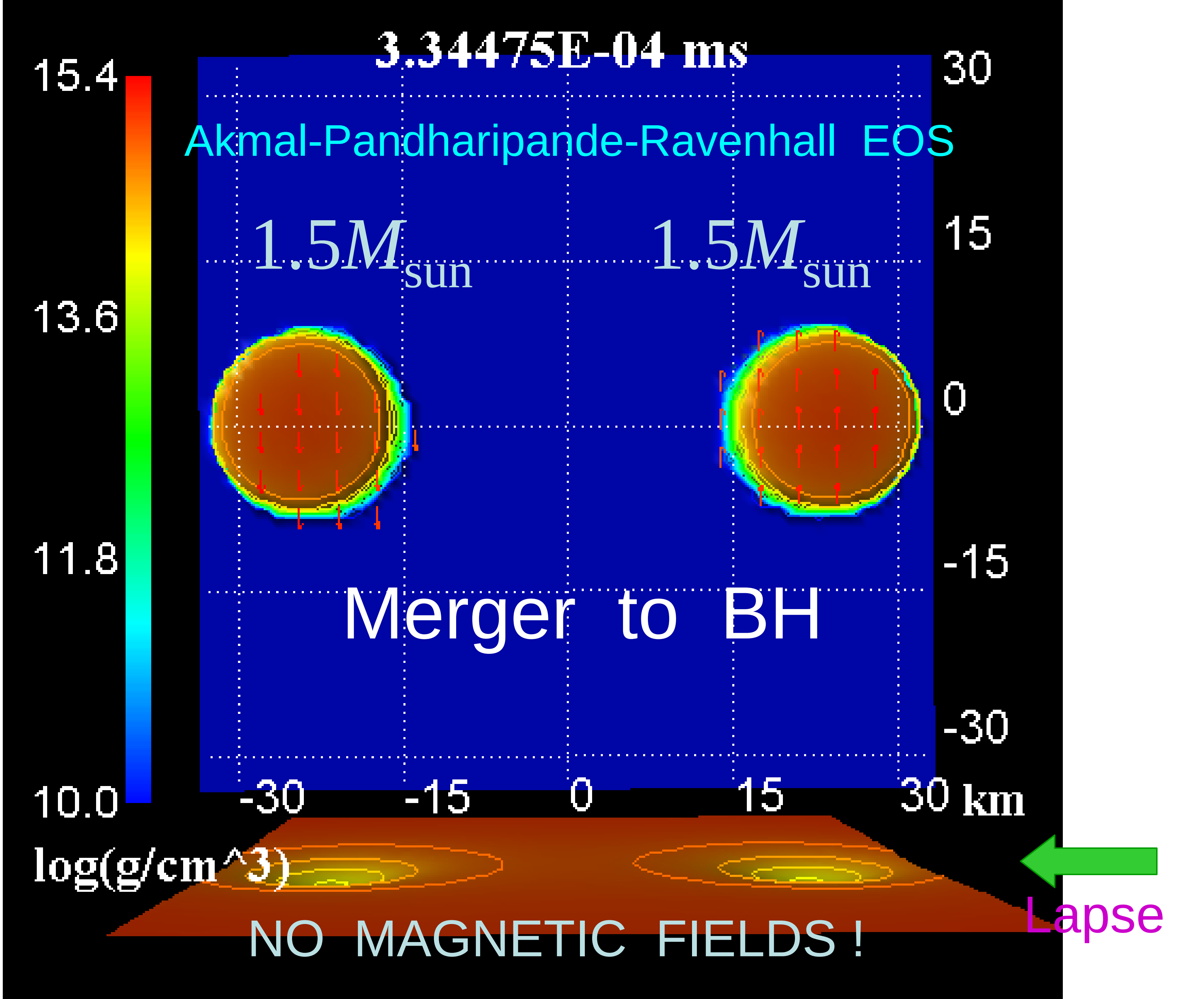
Last 1 hour at $r \sim 1000$ km

Merger starts when $r \sim 30$ km

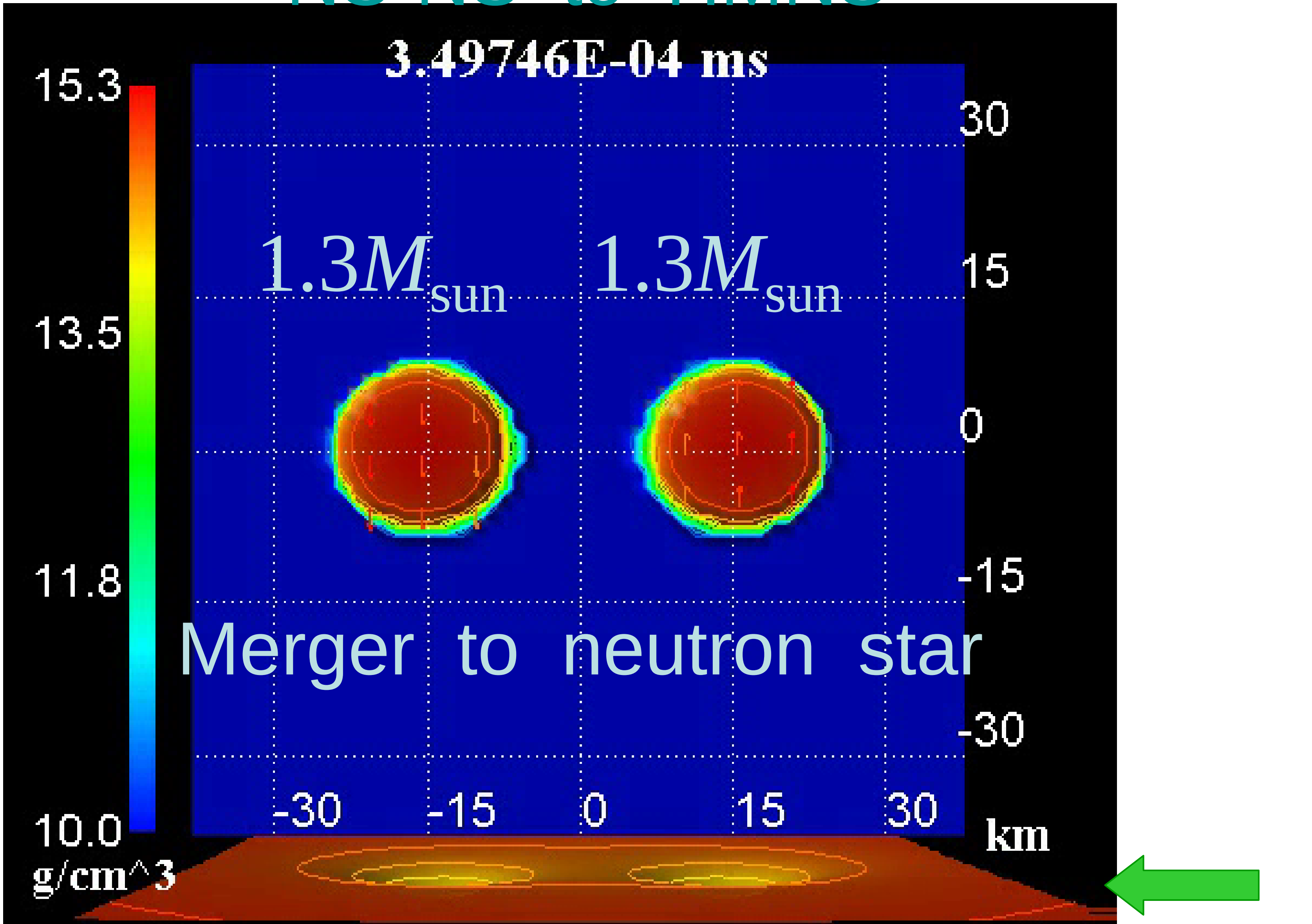
If mass is high enough, a black hole is formed

Otherwise, "hypermasive NS"




3.34475E-04 ms
Akmal-Pandharipande-Ravenhall EOS
1.5Msun
1.5Msun
Merger to BH
15.4
13.6
11.8
10.0
log(g/cm^3)
30
15
0
-15
-30
-30
-15
0
15
30 km
Lapse
NO MAGNETIC FIELDS !

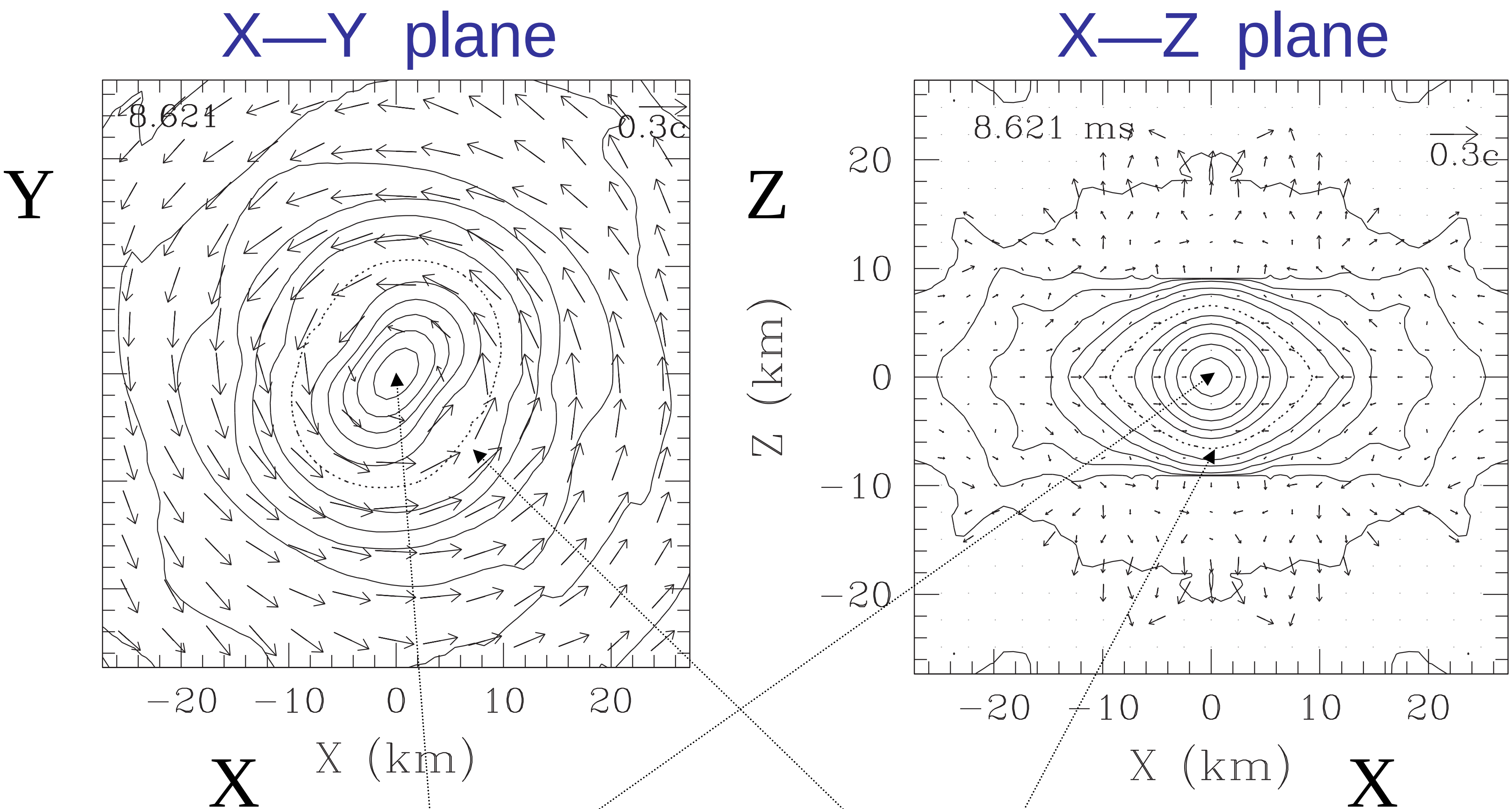
NS-NS to HMNS



NO MAGNETIC FIELDS !

Density contour plot

Massive ellipsoidal neutron star is formed

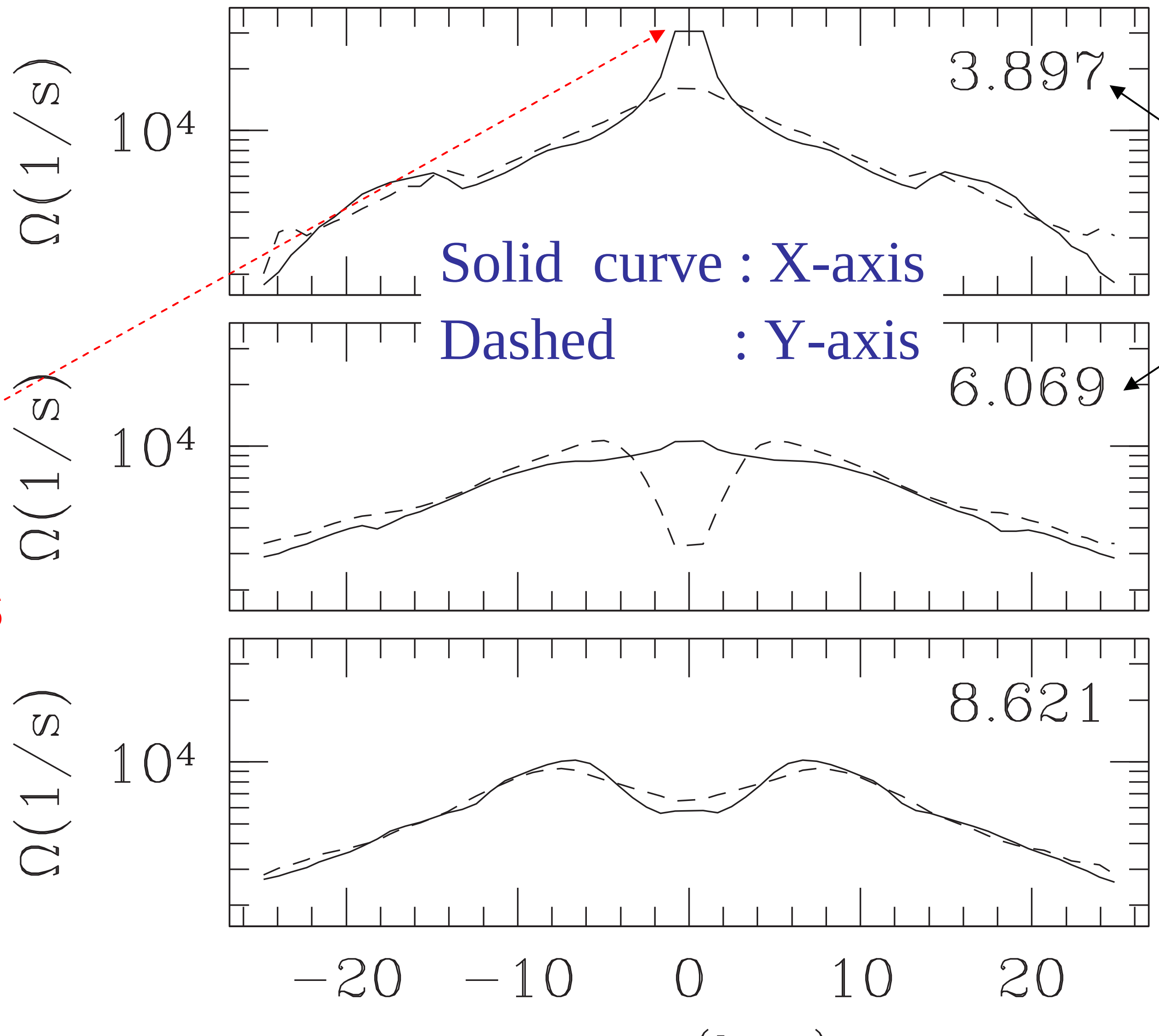


1.3e15 g/cc

Dotted curve=2e14 g/cc

Differentially and rapidly rotating

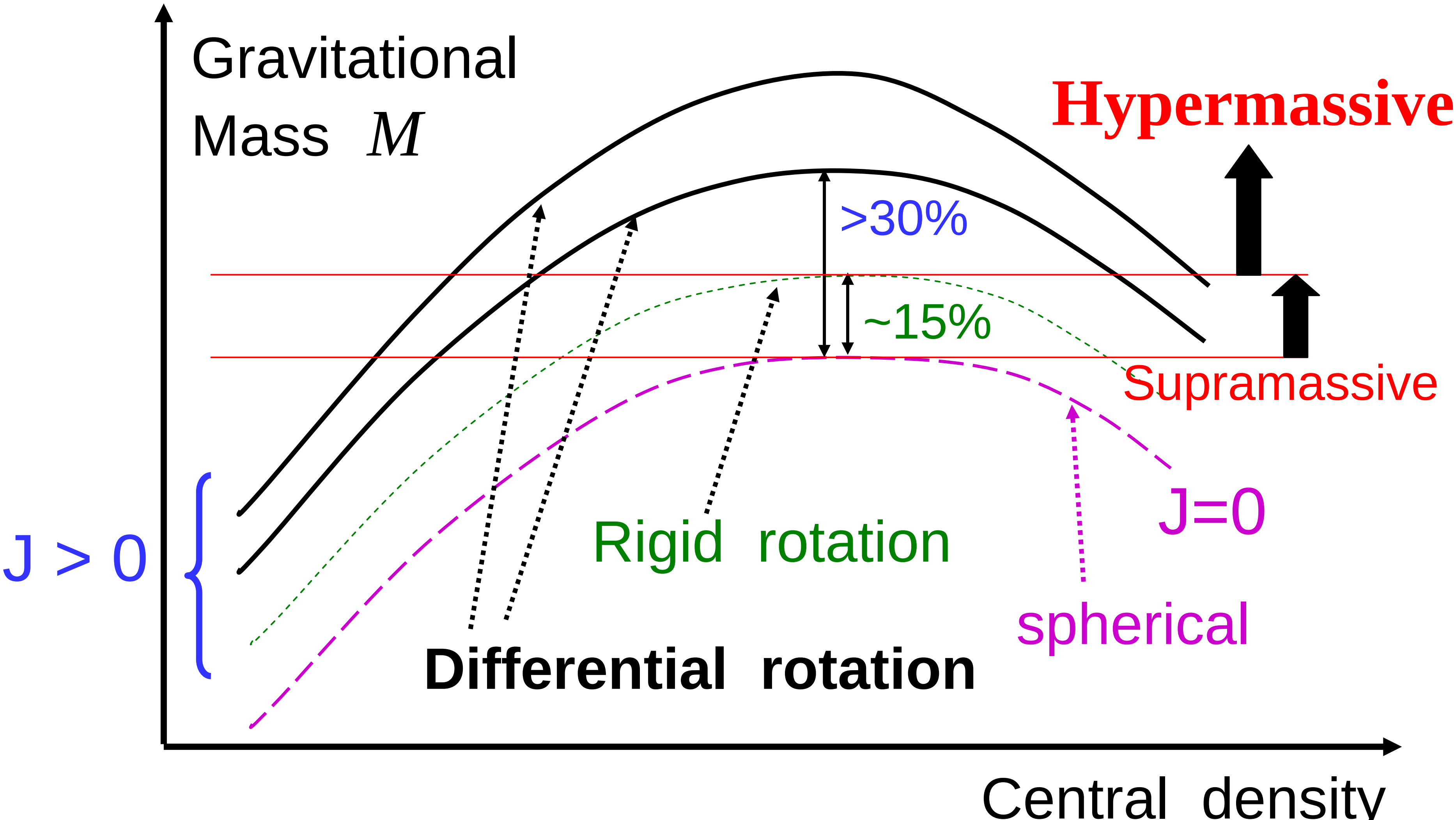
Angular velocity



msec

Rotation period ~ 0.2 ms

IV What is hypermassive neutron star ?



Possible fate of hypermassive stars (if no GW)

Differential rotation

→Angular momentum is redistributed by magnetic field (Winding and/or magnetorotational instability)

→Approaches to rigid rotation

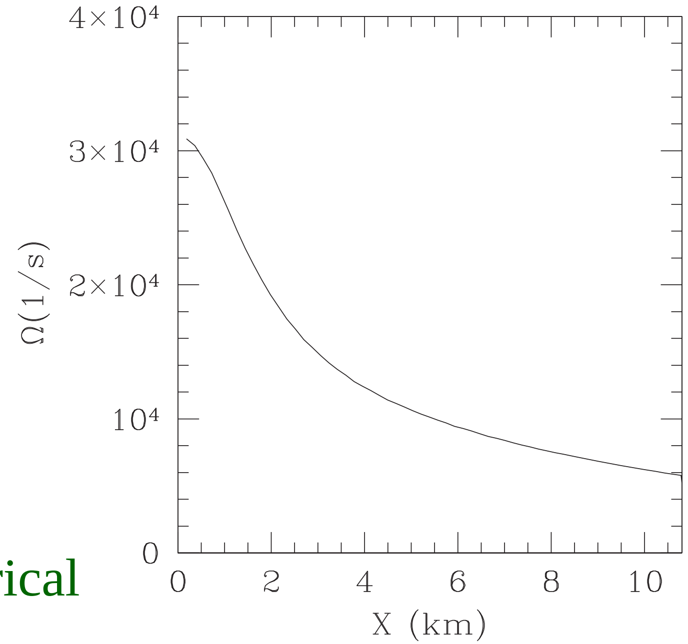
→ But, $M > M_{\mathrm{max,\ rigid\ rot}}$

→ Likely to collapse to a black hole

- HMNS may be even shorter lifetime in the presence of B-fields
- After collapse, BH + torus may form

Numerical simulation (PRL2006)

- EOS: Hybrid EOS → can mimic realistic EOS
- Differentially and rapidly rotating NS;
  $P_c \sim 0.2$ ms & $P_{surface} \sim 1$ ms

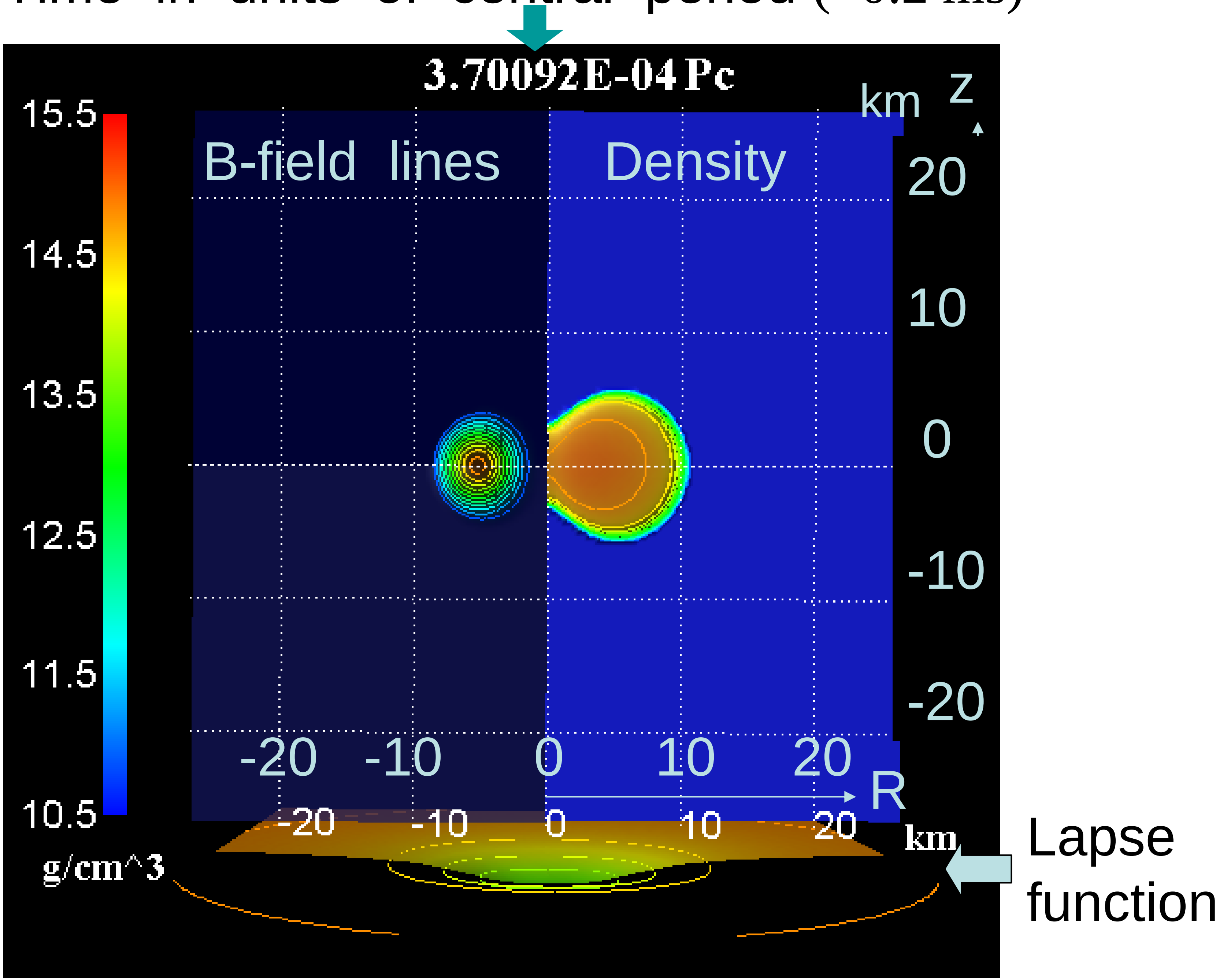


- Hypermassive:
  $M = 2.65M_{sun} >> 2M_{sun} = M_{spherical}$
- Seed poloidal Magnetic field
  confined to the NS ($P_{mag}/P \sim 0.3\%$ at $t = 0$)

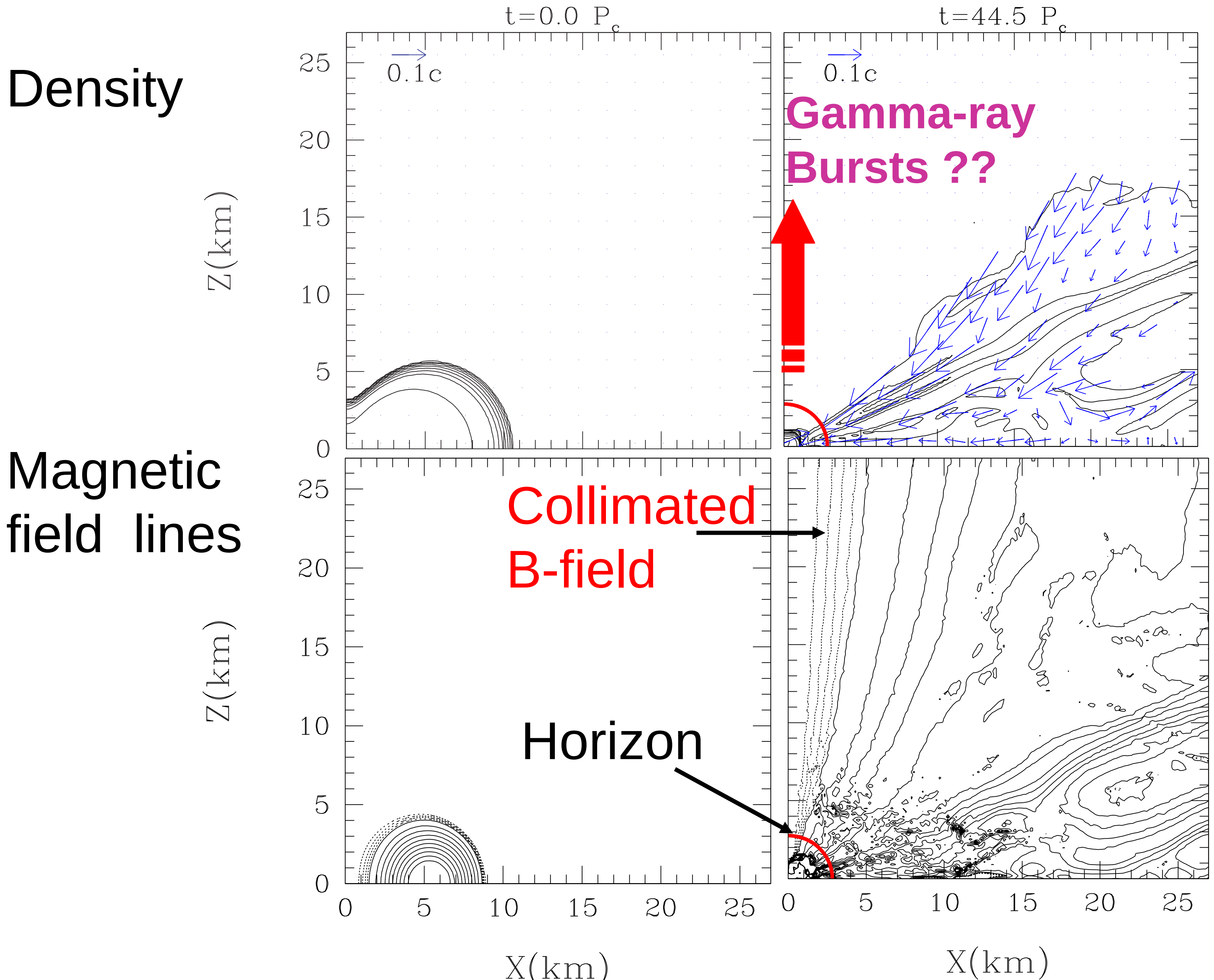
$$A_\varphi = \begin{cases} A\left(P - P_{cut}\right) & P > P_{cut} \\ 0 & P < P_{cut} \end{cases}$$

$$\lambda_{MRI} \sim 1\ \mathrm{km}$$

Time in units of central period (~0.2 ms)

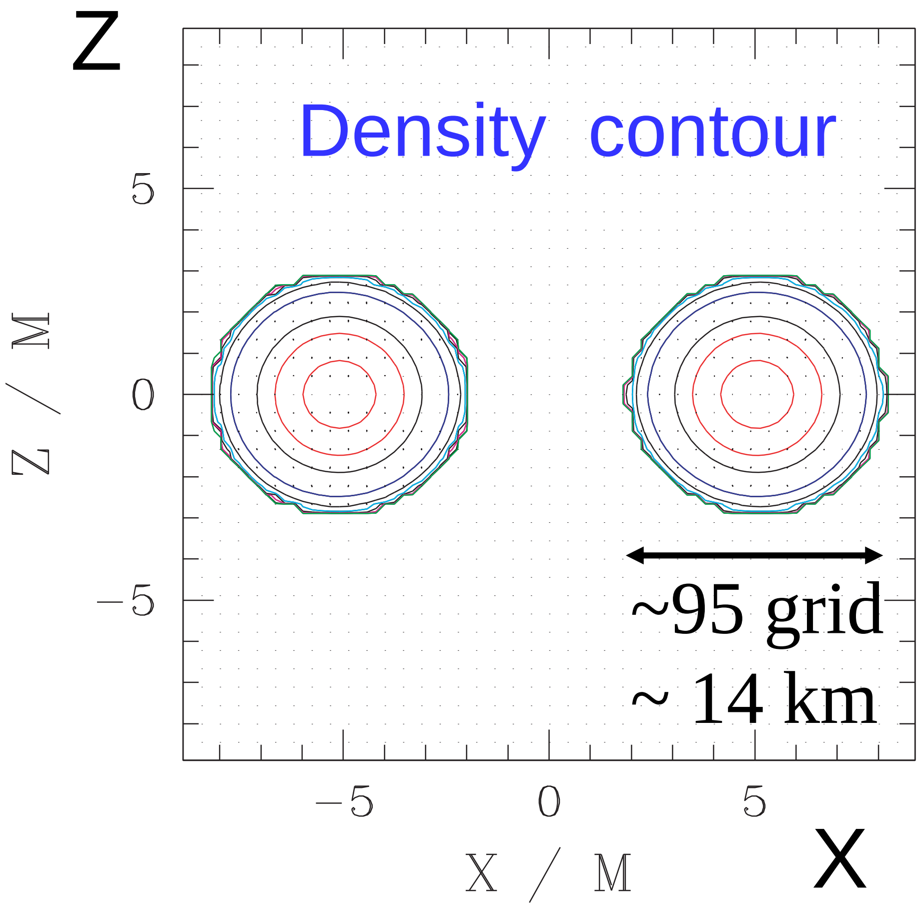


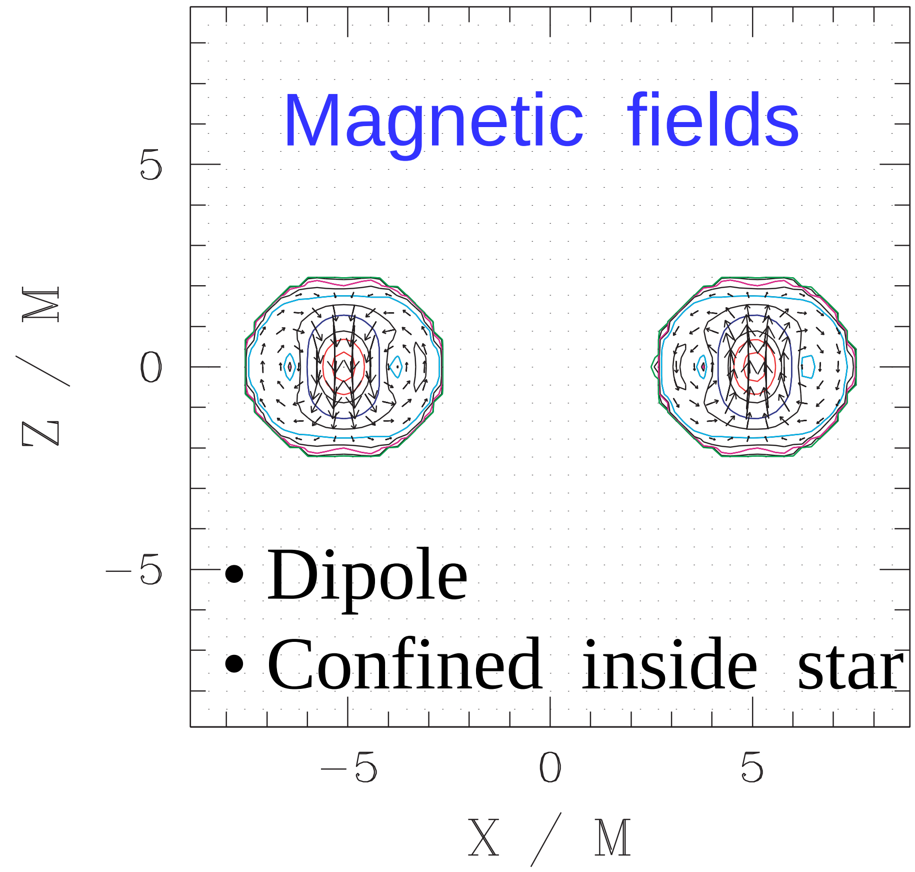
Axisymmetric simulation



Density
Magnetic field lines
t=0.0 P_c
t=44.5 P_c
0.1c
0.1c
Gamma-ray Bursts ??
Collimated B-field
Horizon
Z(km)
Z(km)
X(km)
X(km)

IV GRMHD simulation for binary neutron star (preliminary)

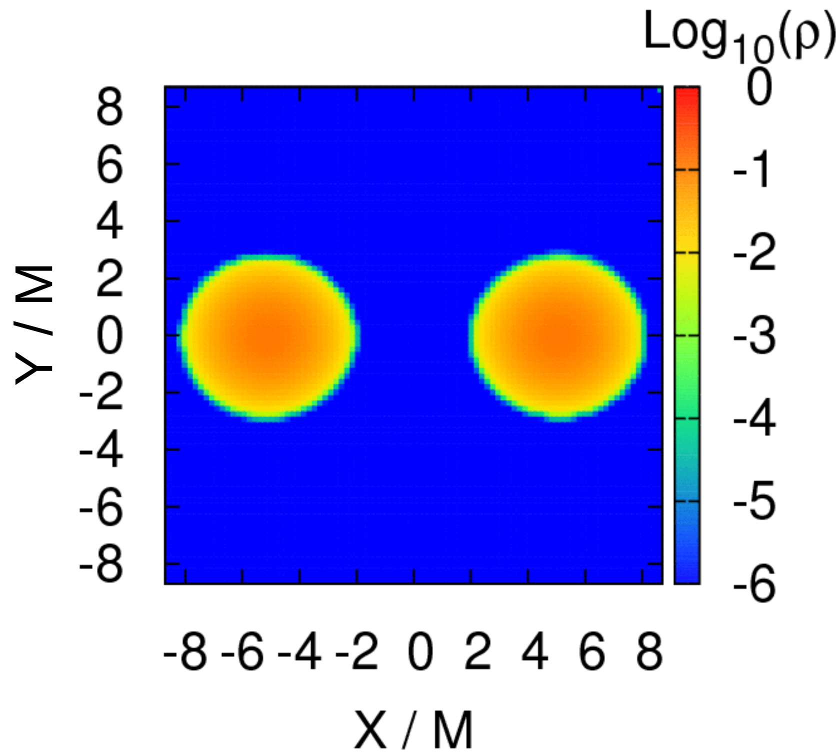




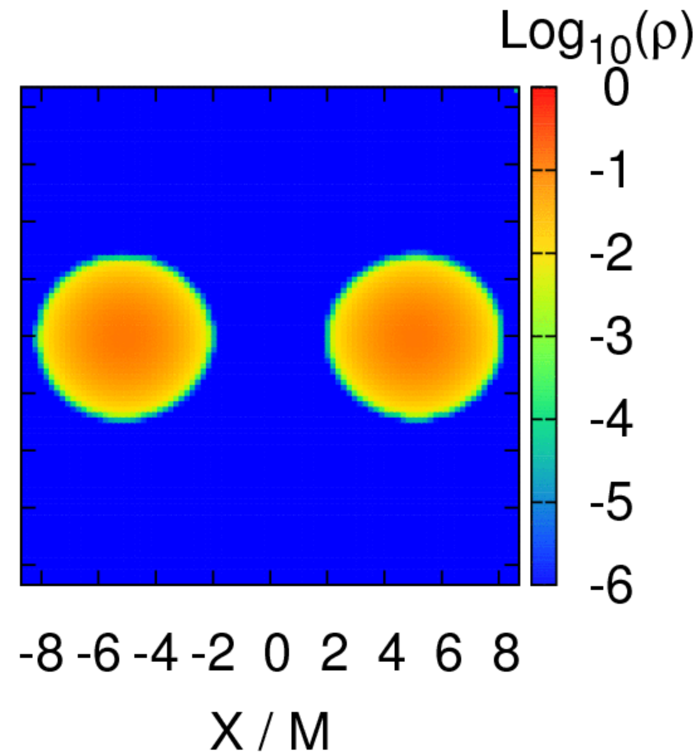
Averaged magnetic field strength ~ $5*10^{14}$ G

Max ~ 10^{16} G → λ_{MRI} ~ 1 km

Density on the equatorial plane



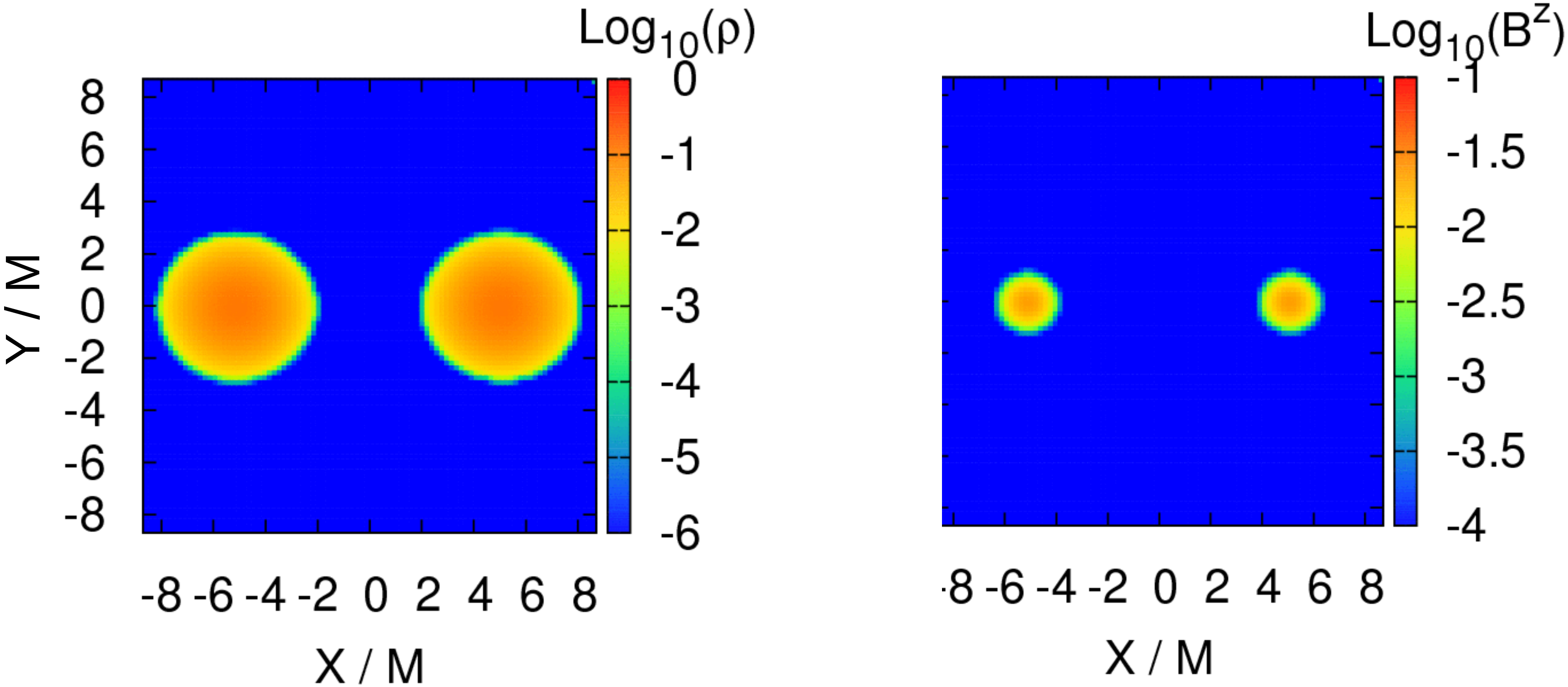
No B fields



With B fields

EOS: $P=(\Gamma-1)\rho\varepsilon$ for simplicity; $\Gamma=2$

Density & B field on the equatorial plane



Density

B^z

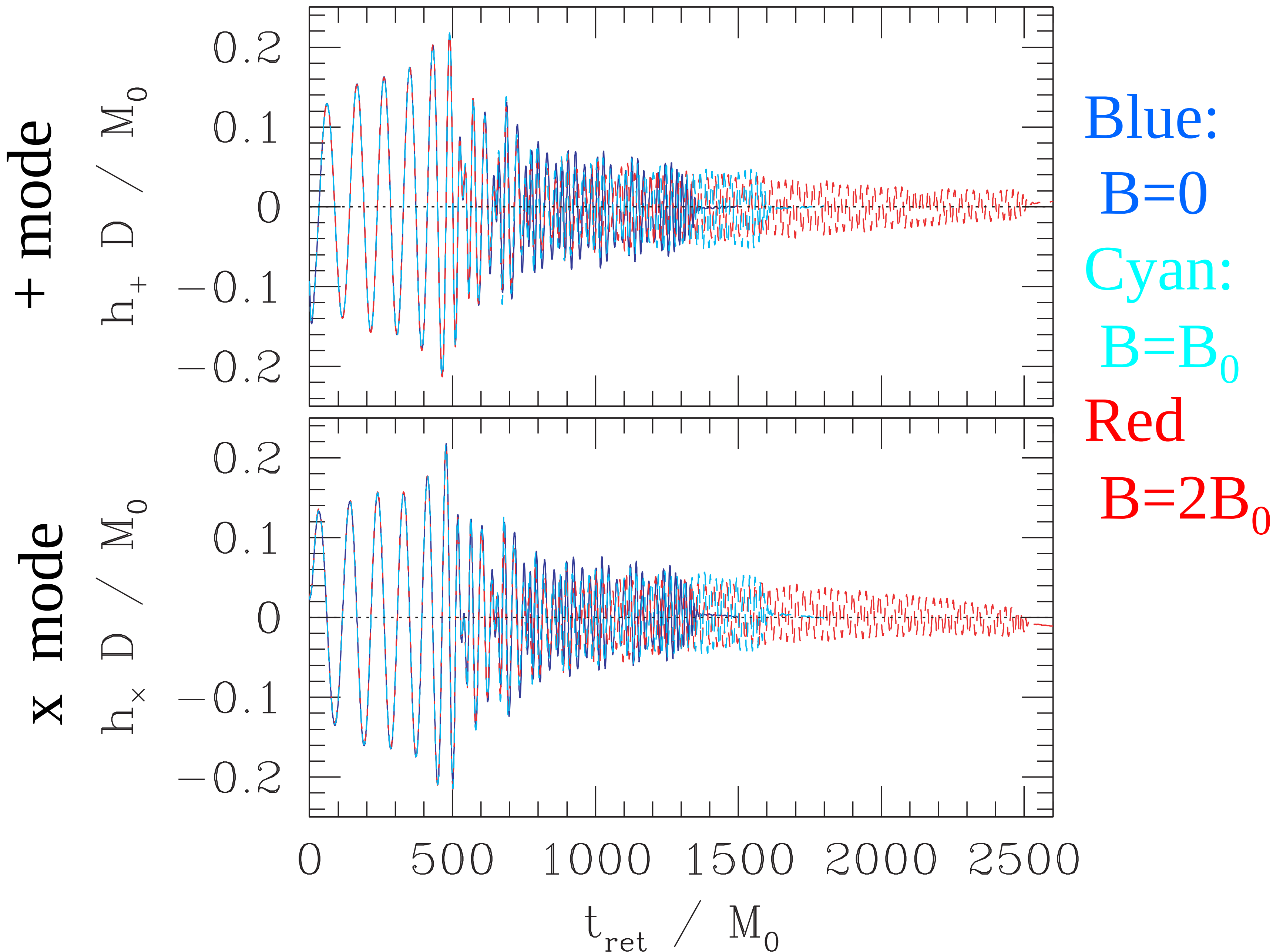
The reason

- HMNS, in this case, dissipates angular momentum primarily by gravitational radiation
- The emission rate is higher when HMNS is more nonaxisymmetrically deformed
- The deformation is larger for higher degree of differential rotation, but **magnetic field decreases this degree due to angular momentum transport**

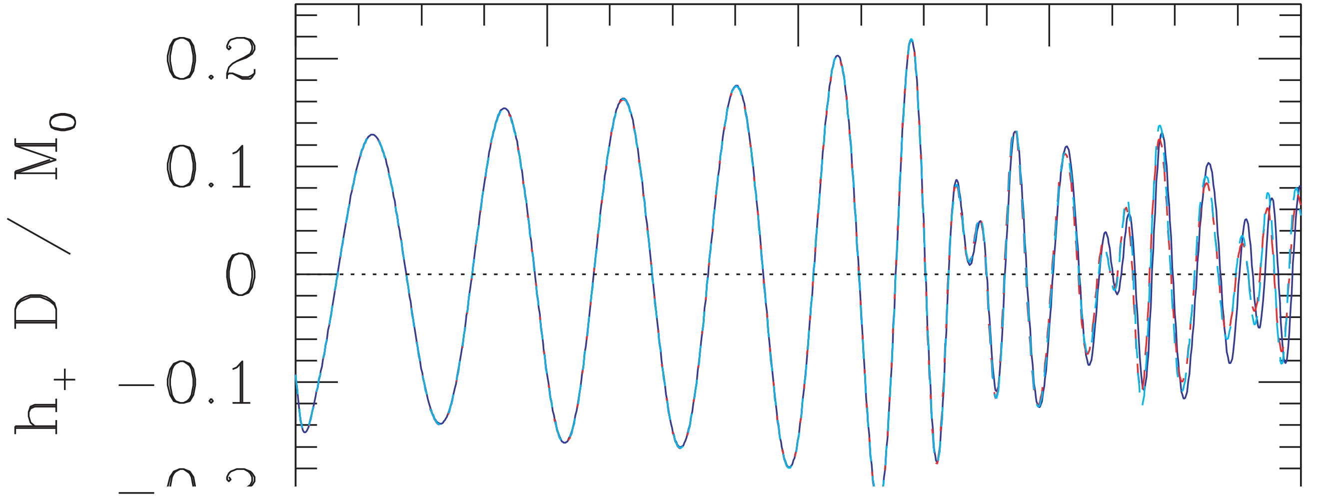
  → GW luminosity decreases

  → Life time increases

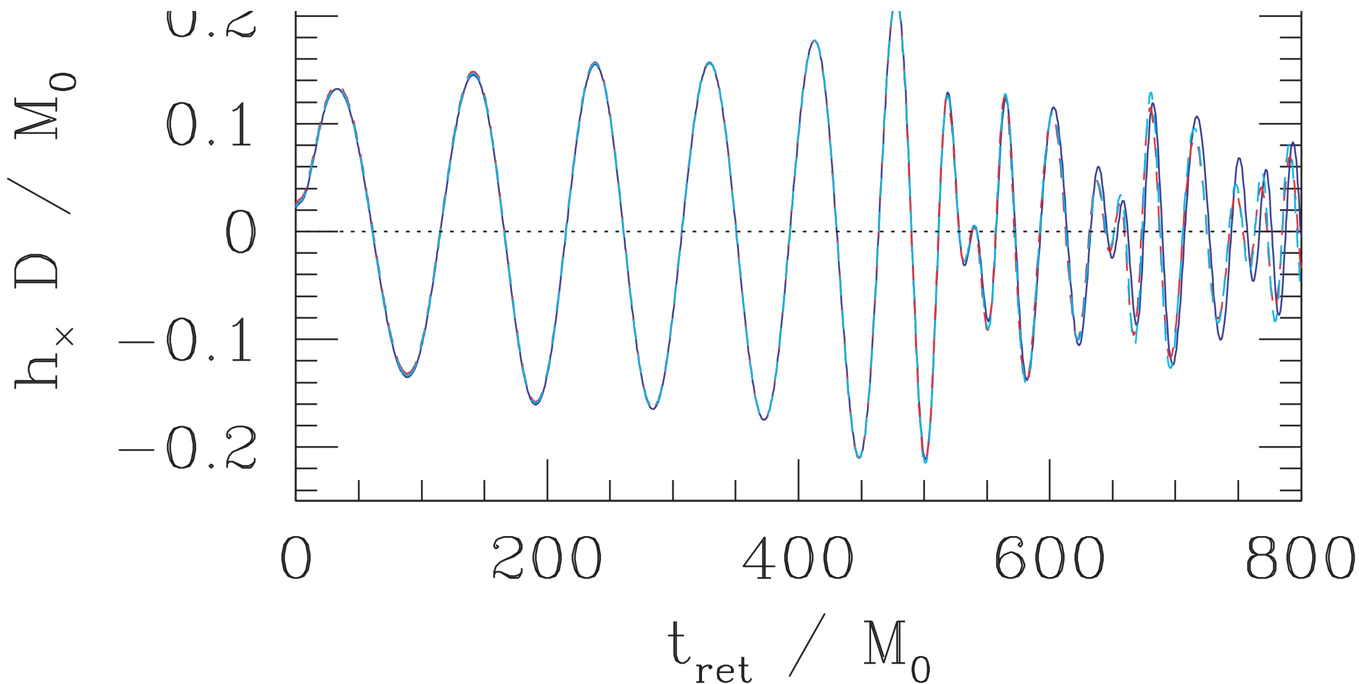
Gravitational waves



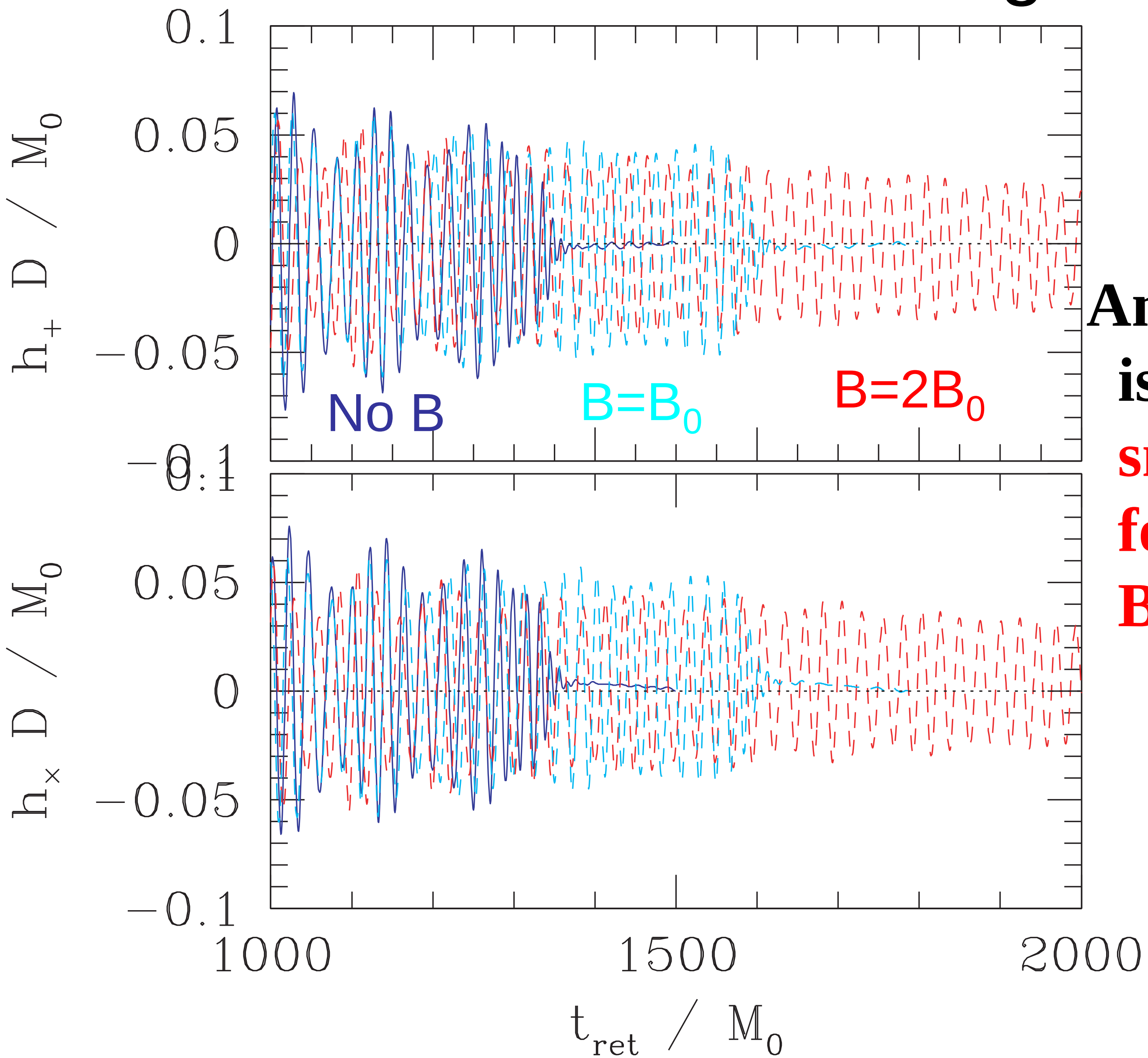
Gravitational waves: Inspiral



Approximately independent of B

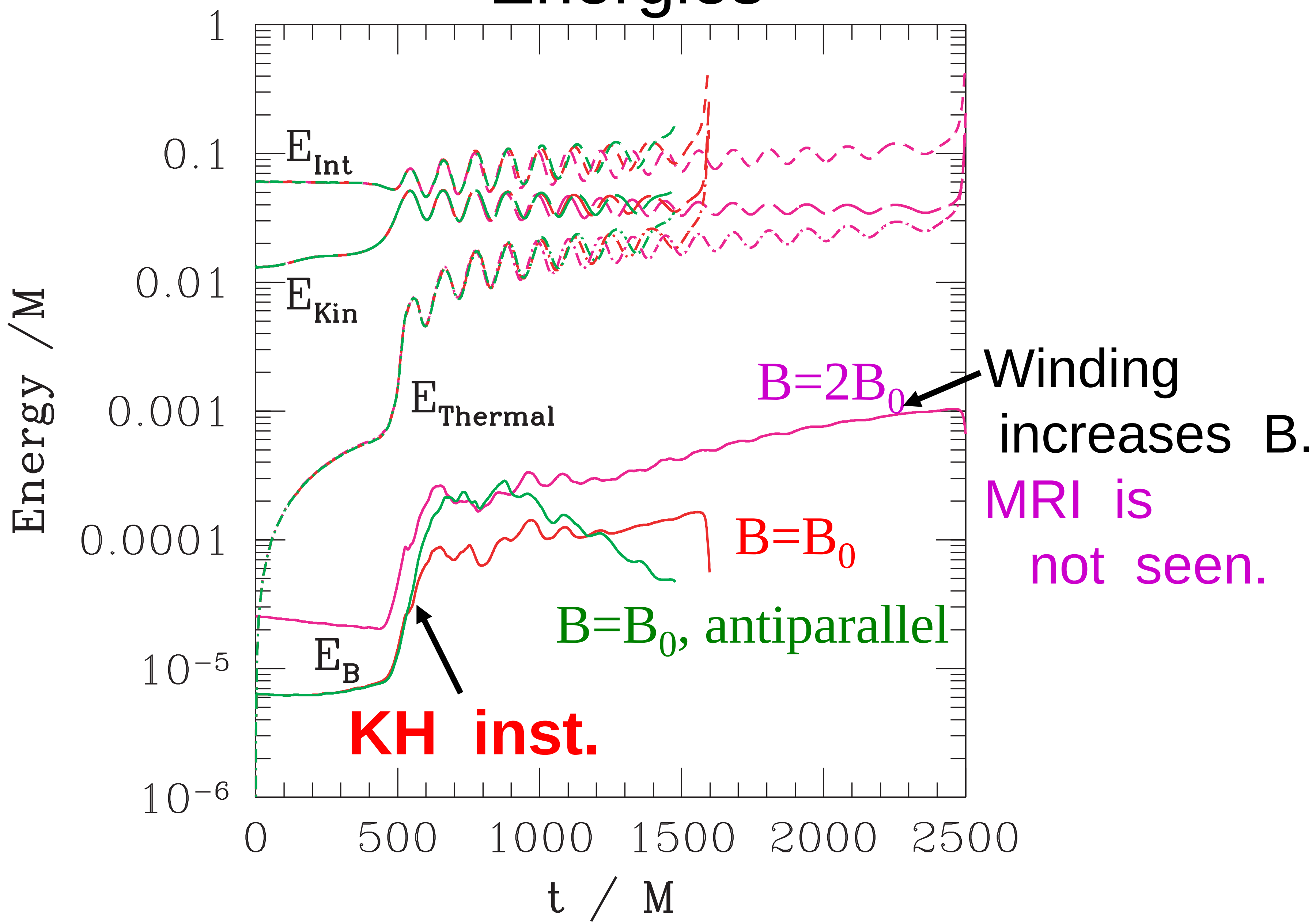


Gravitational waves after merger onsets



Amplitude is slightly smaller for larger B-Fields

Energies

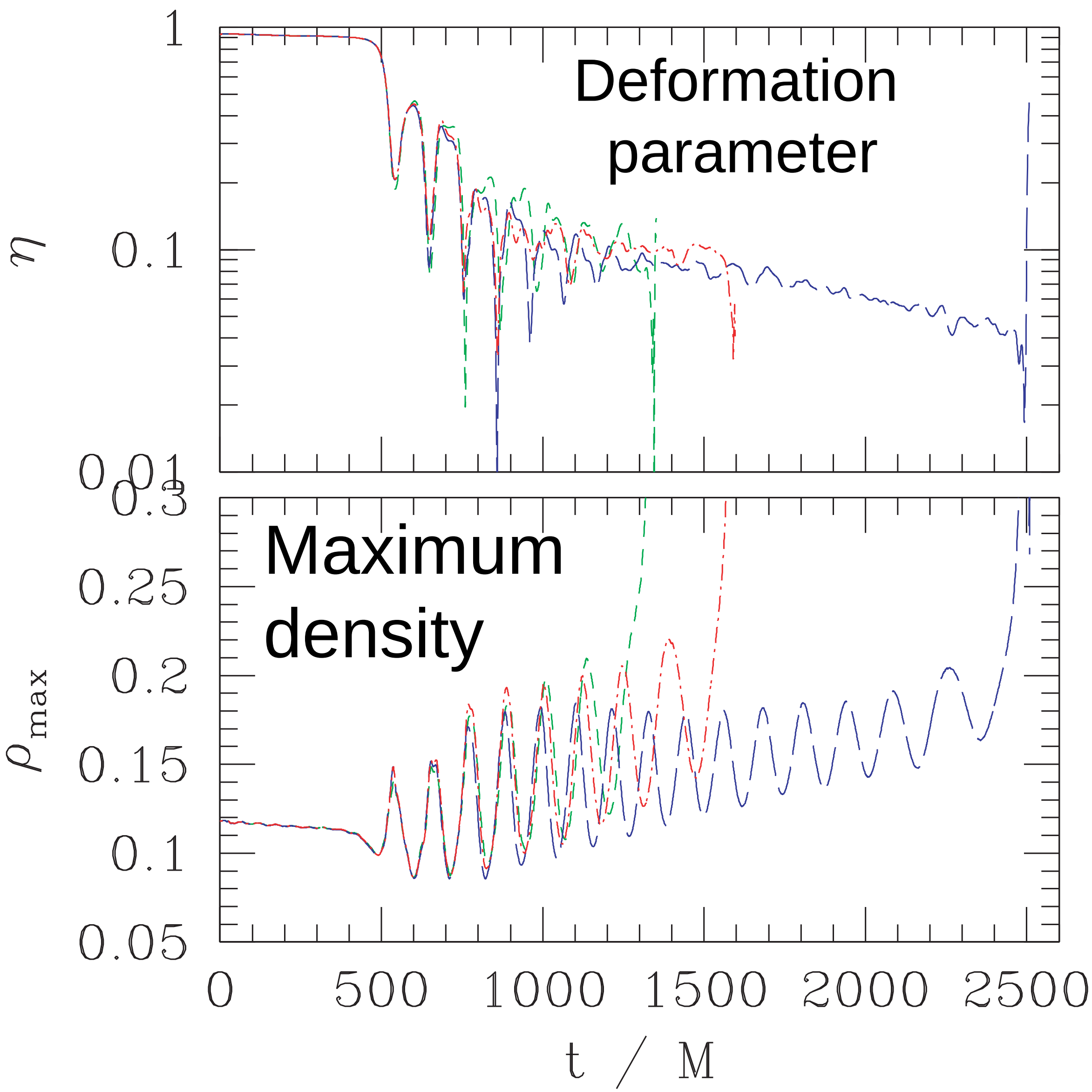


1
0.1
0.01
0.001
0.0001
10^{-5}
10^{-6}
Energy /M
0
500
1000
1500
2000
2500
t / M
E_{Int}
E_{Kin}
$E_{Thermal}$
E_B
$B=2B_0$
Winding increases B.
MRI is not seen.
$B=B_0$
$B=B_0$, antiparallel
KH inst.

V Summary

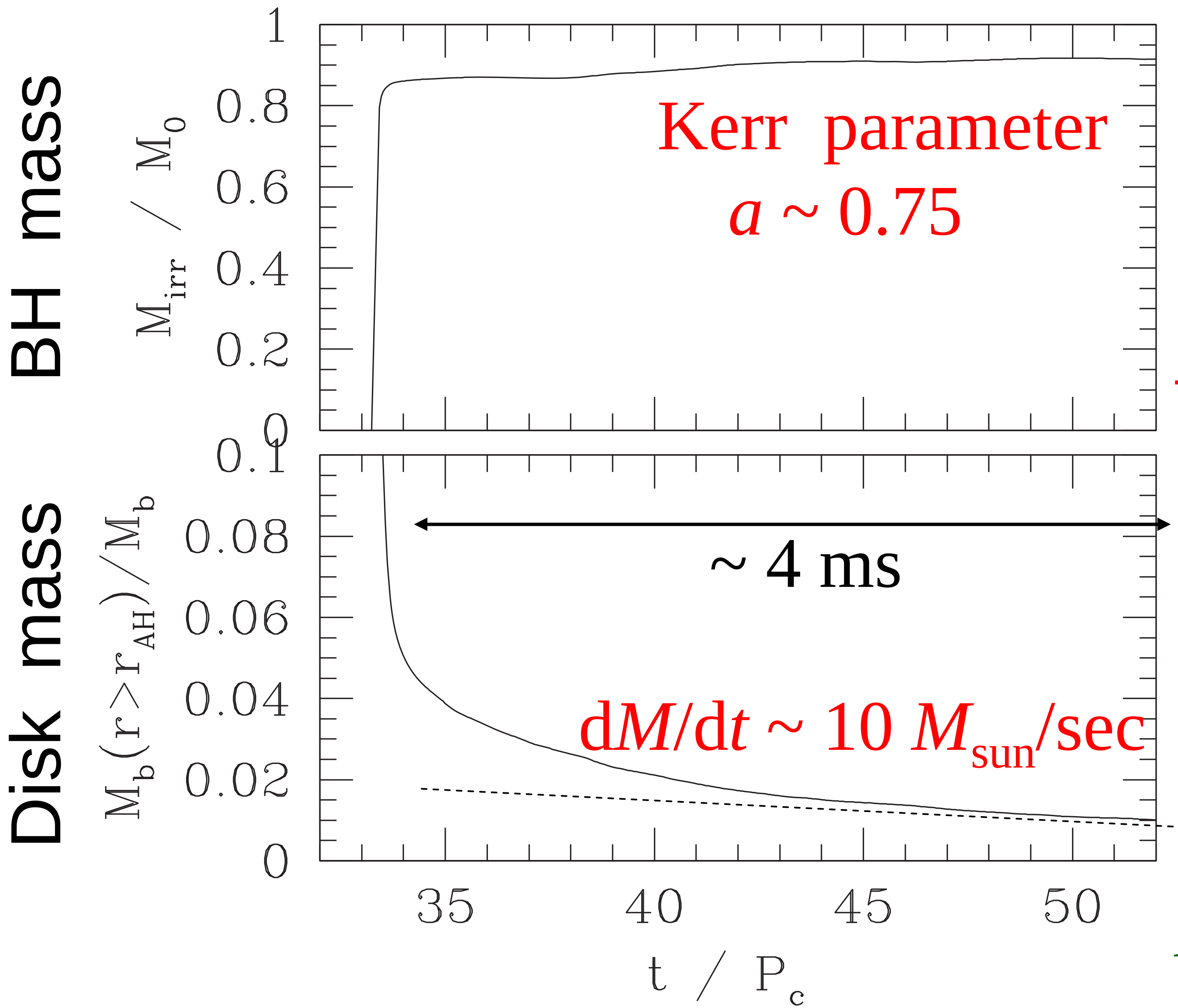
- Relatively low-mass binary neutron star will form a hypermassive neutron star
- It evolves by emission of gravitational waves as well as by magnetorotational effects
- Magnetic effects may NOT accelerate the collapse of HMNS to black hole
- 3D simulation for merger + subsequent evolution is done, but currently accurate simulation for it is not feasible due to limit of computational resources

B-field increases lifetime of HMNS !



Green:
No B-field
Red:
With B-field
Blue:
Factor 2 larger

Apparent horizon Mass & mass of torus



Lifetime of torus ~ 10 ms

$P_c \sim 0.2$ms