Fully General Relativistic Magneto HydroDynamics

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Refs. Shibata & Sekiguchi, PRD72 in press
(astroph/0507383; see formulations & equations)

1 Why is Fully GRMHD necessary ?

All differentially rotating stars cannot be in equilibrium in the presence of B-fields

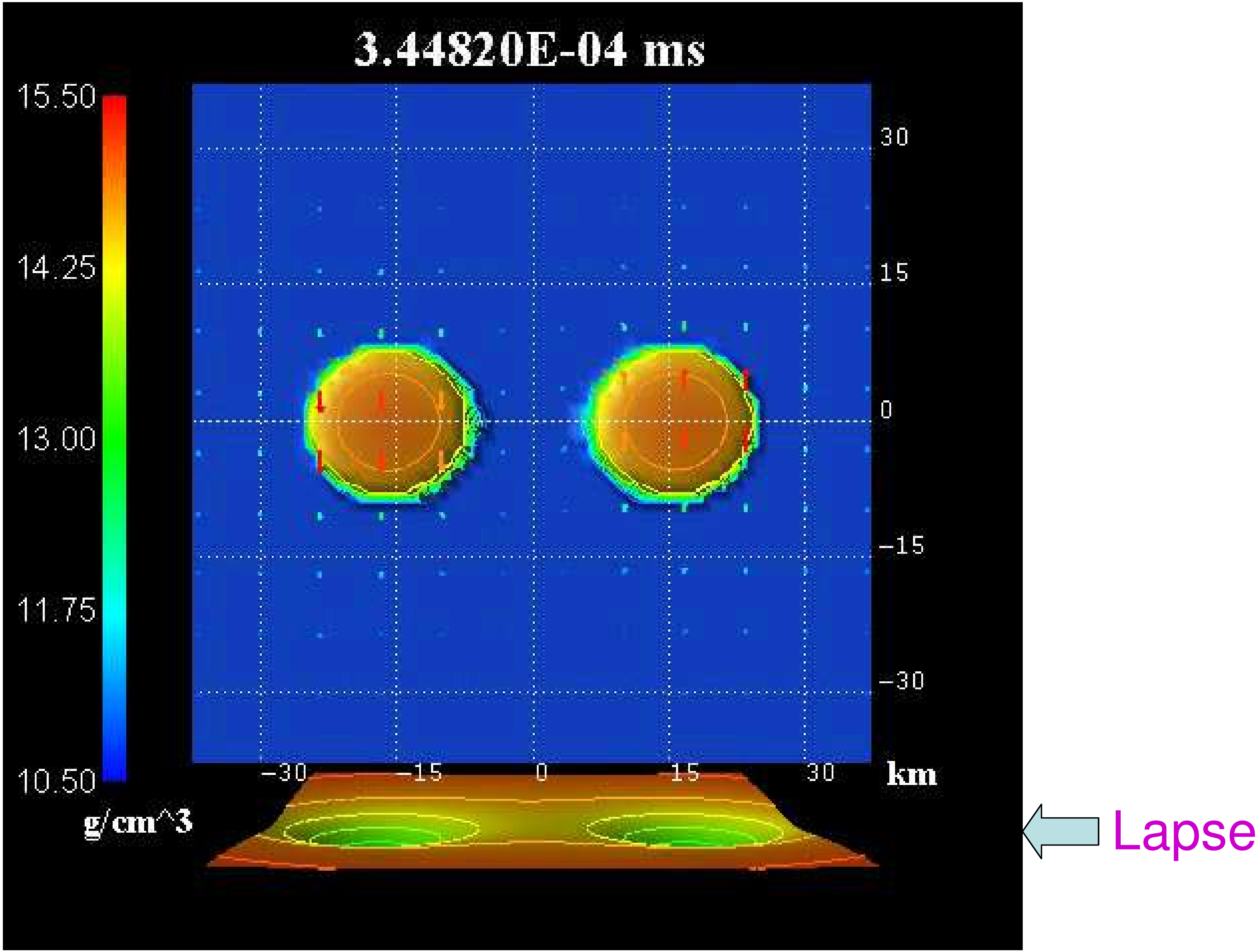
2. Differential rotation winds up B-fields and amplifies their magnitude
3. Magnetorotational Instability (MRI) always turns on.

Neutron stars alyways have B-field ↙
If they are differentially rotating, unstable.

2 What produces differentially rotating neutron stars ?

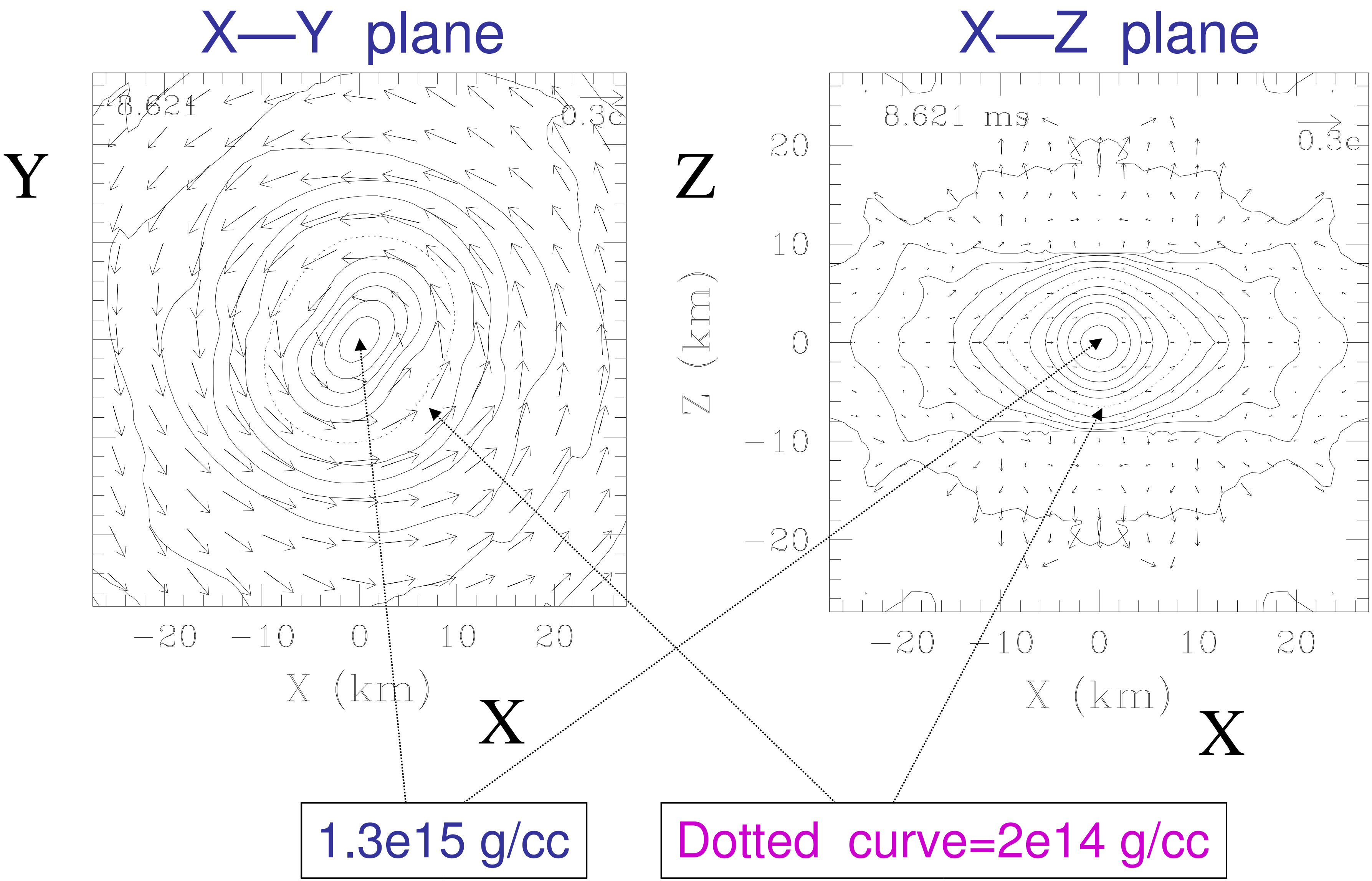
1. Stellar core collapse
   ↙ Differentially rotating protoneutron stars
2. Merger of binary neutron stars with relatively small mass
   ↙ Differentially rotating hypermassive neutron stars of M ~ 2.8M_sun

1.3-1.3M_sun : Density in the z=0



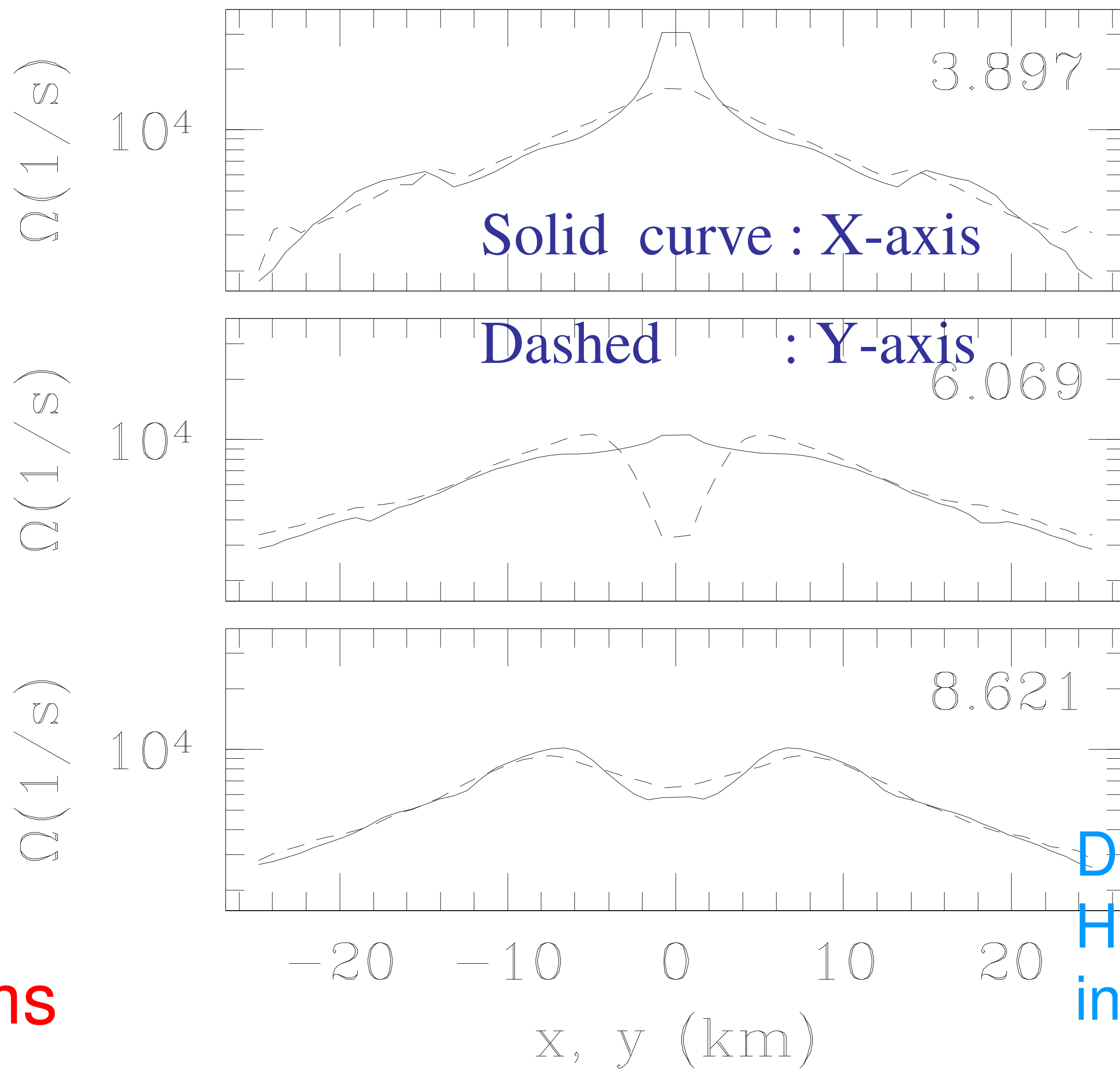
1.3 – 1.3 M_sun case : late-time snapshot

Massive ellipsoidal neutron star is formed



Formed Massive (2.6M_sun) toroidal NS is differentially and rapidly rotating

Angular velocity



msec

Due to GW Hydrodynamic interaction

Rotation period at center ~ 0.6 -1 ms

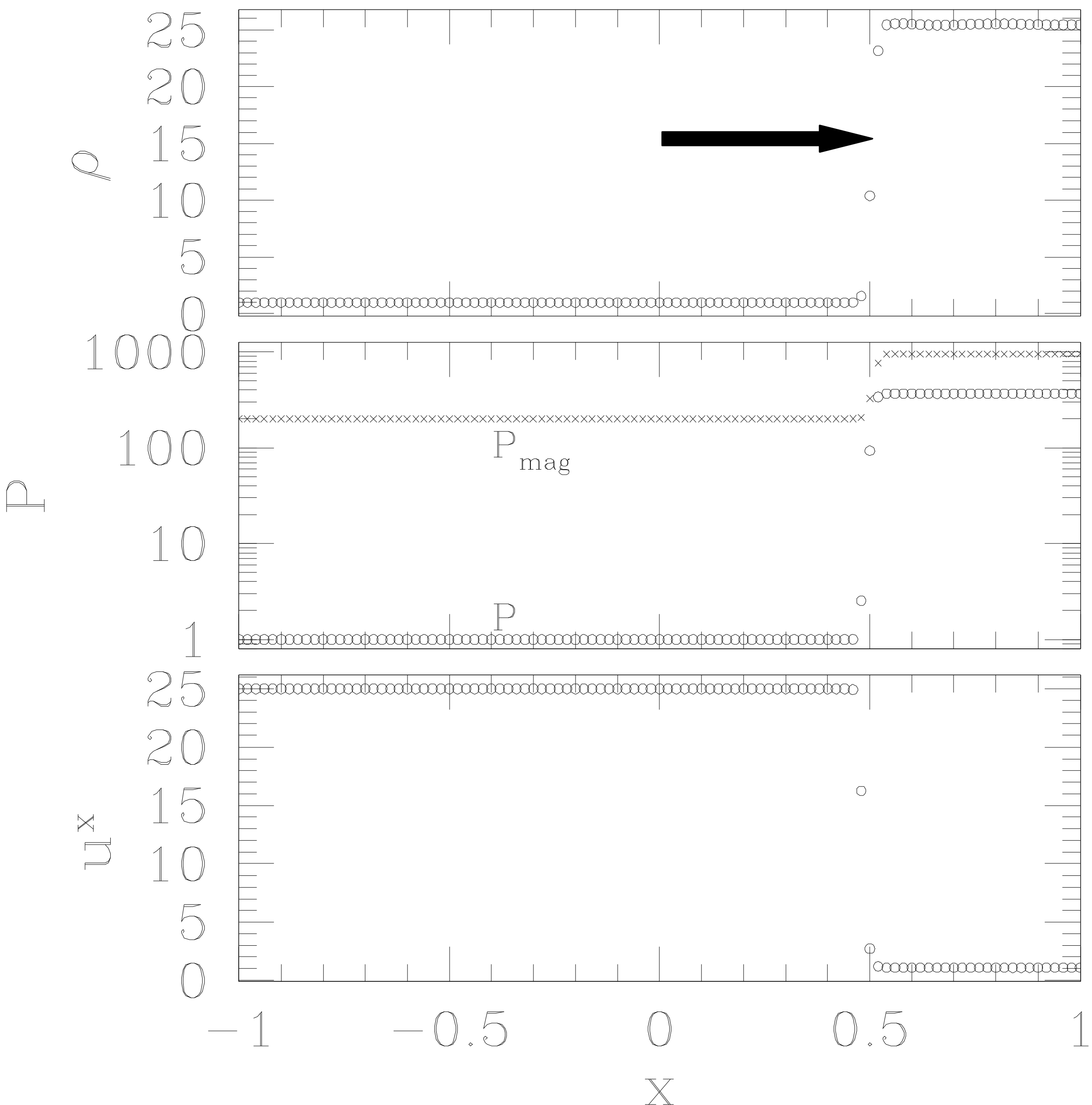
3 Our implementation

1. GR : Modified BSSN formalism (well established)
   ↗ Enable stable and longterm evolution for metric 2^{nd} order finite-differencing in space and time
2. Gauge : Dynamical lapse + Dynamical shift (well established)
3. Hydro : High-resolution central scheme
   Kurgonov-Tadmor Scheme (2000)
   + 3^{rd} order interpolation (Valencia 2004)
   ↗ As excellent as HRSC in SRHD; Also in GRHD (Shibata-Font 2005)
4. +constraint transport (similar to Del Zanna et al. 03)

Code tests for MHD

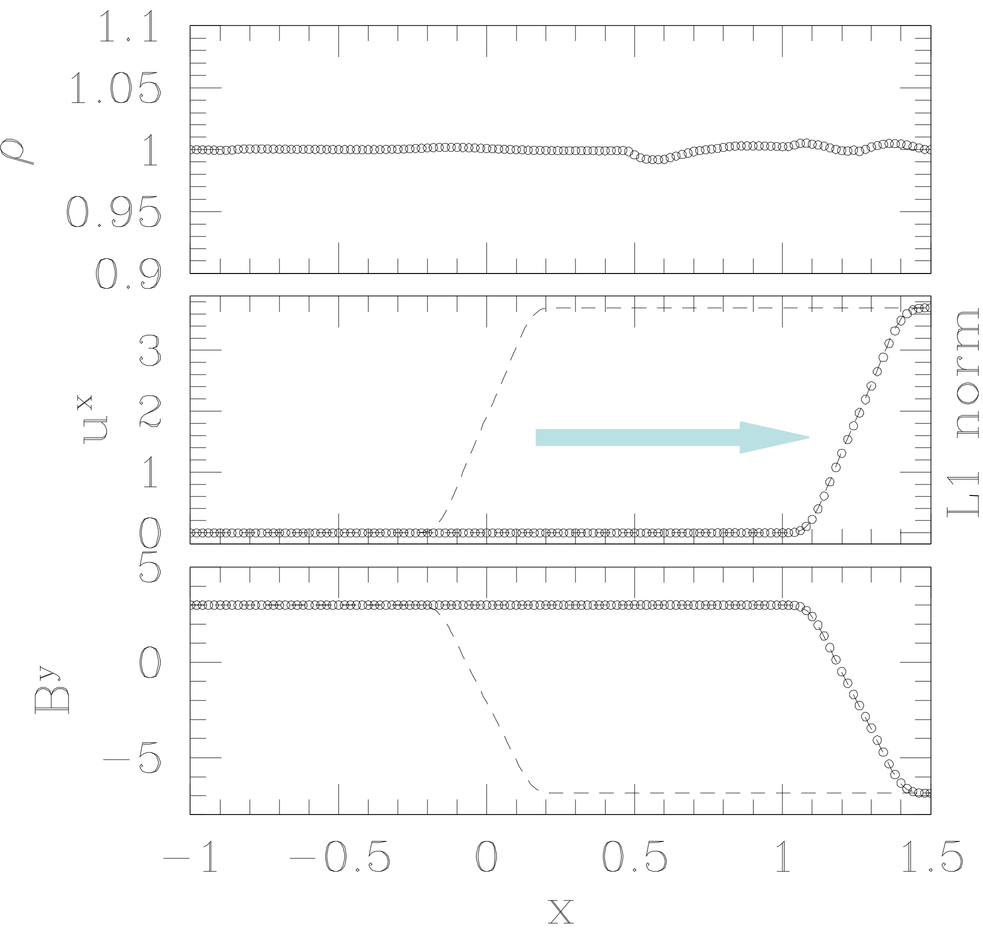
- 1D Shock tube with B-fields, Alfven wave propagation (e.g., Komissarov, 99 about test lists)
- 2D tests (Blast explosion, rotor, axisymm. jets; e.g., Del Zanna et al. 03)
- Magnetized Bondi flow in a fixed background (Hawley et al. 03, Gammie, …)
- NS + disk without and with B-fields in the disk (Full GRMHD simulation)
- Convergence tests

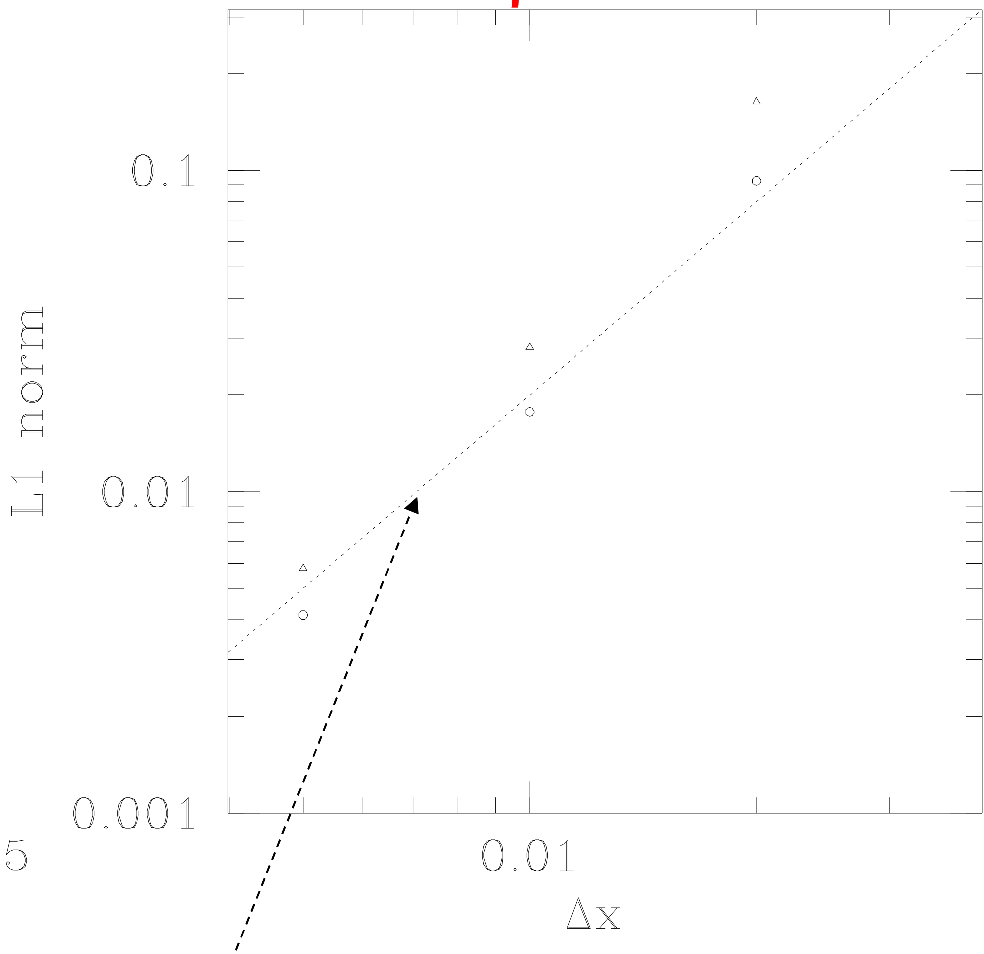
Propagation of shock with B fields



Propagation of Alfven wave

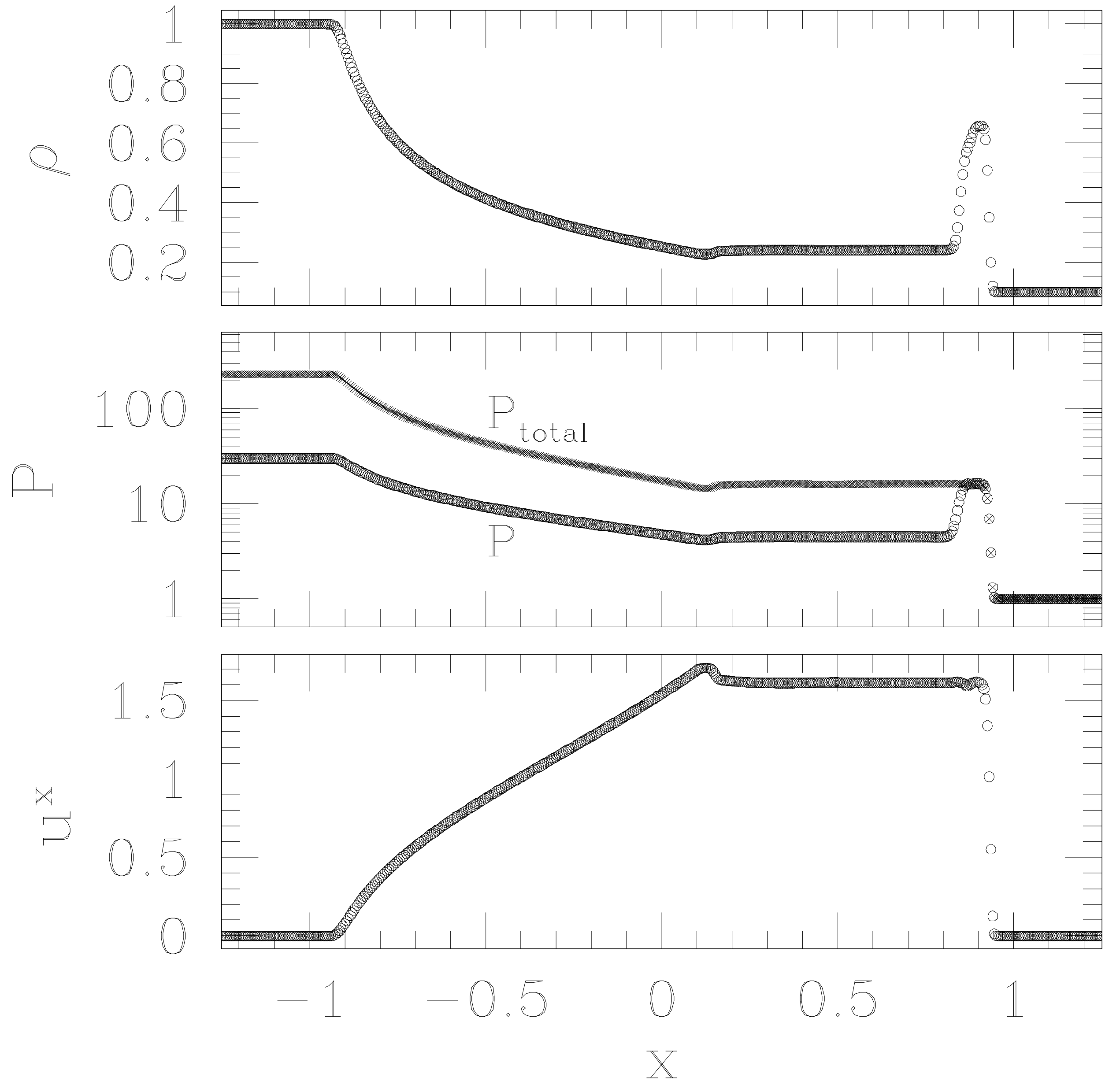
Convergence of errors in ρ & P





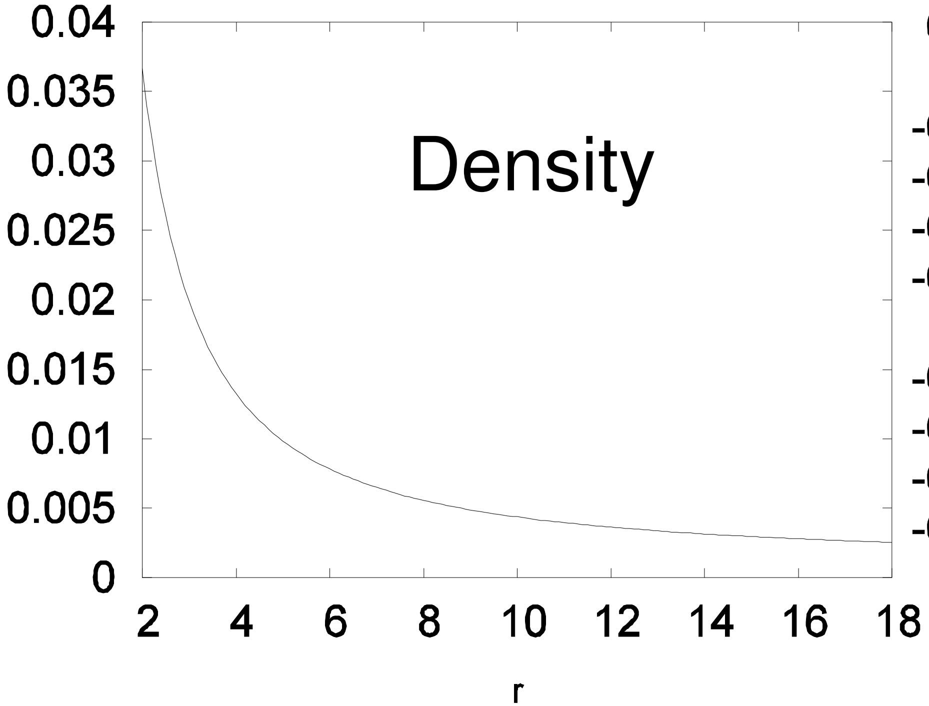
Approximately 2nd order convergent

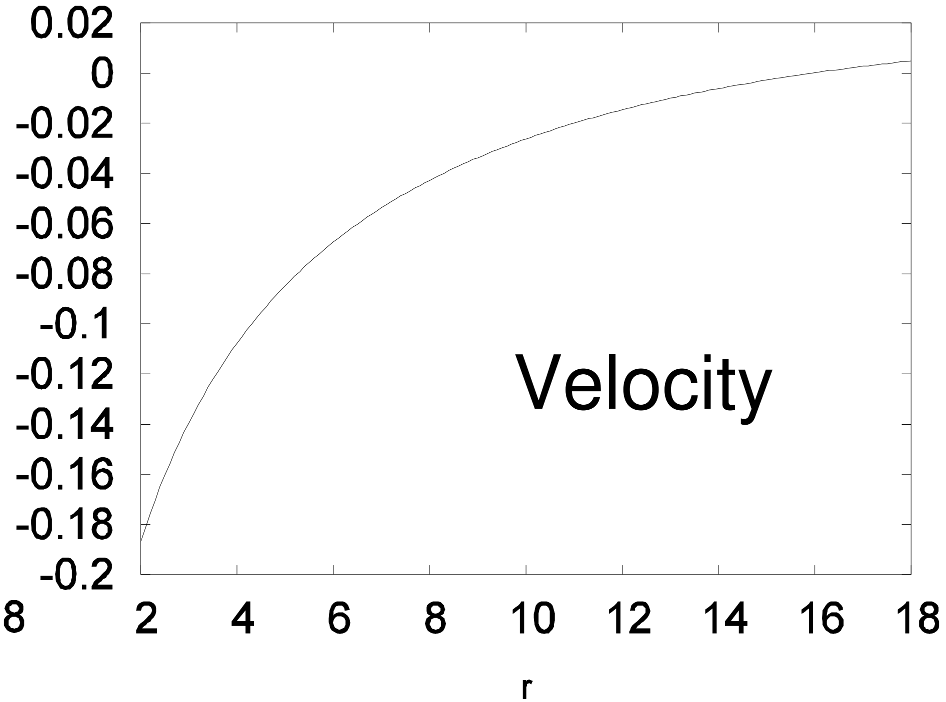
Shock tube test with B field



Bondi accretion test with radial magnetic field

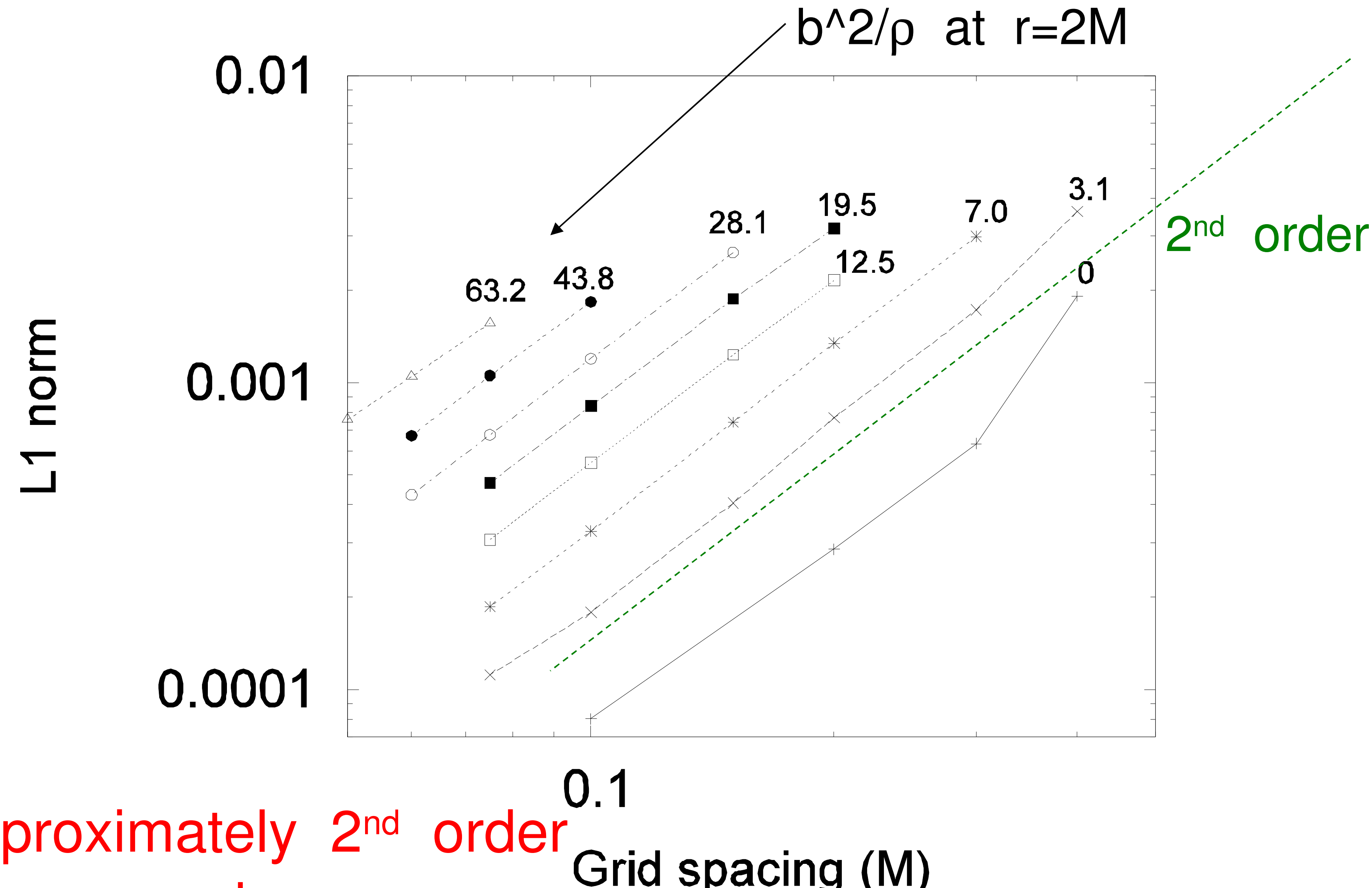
Exact solutions for r=8M sonic point





Kerr-Schild coordinates are used (but a=0)

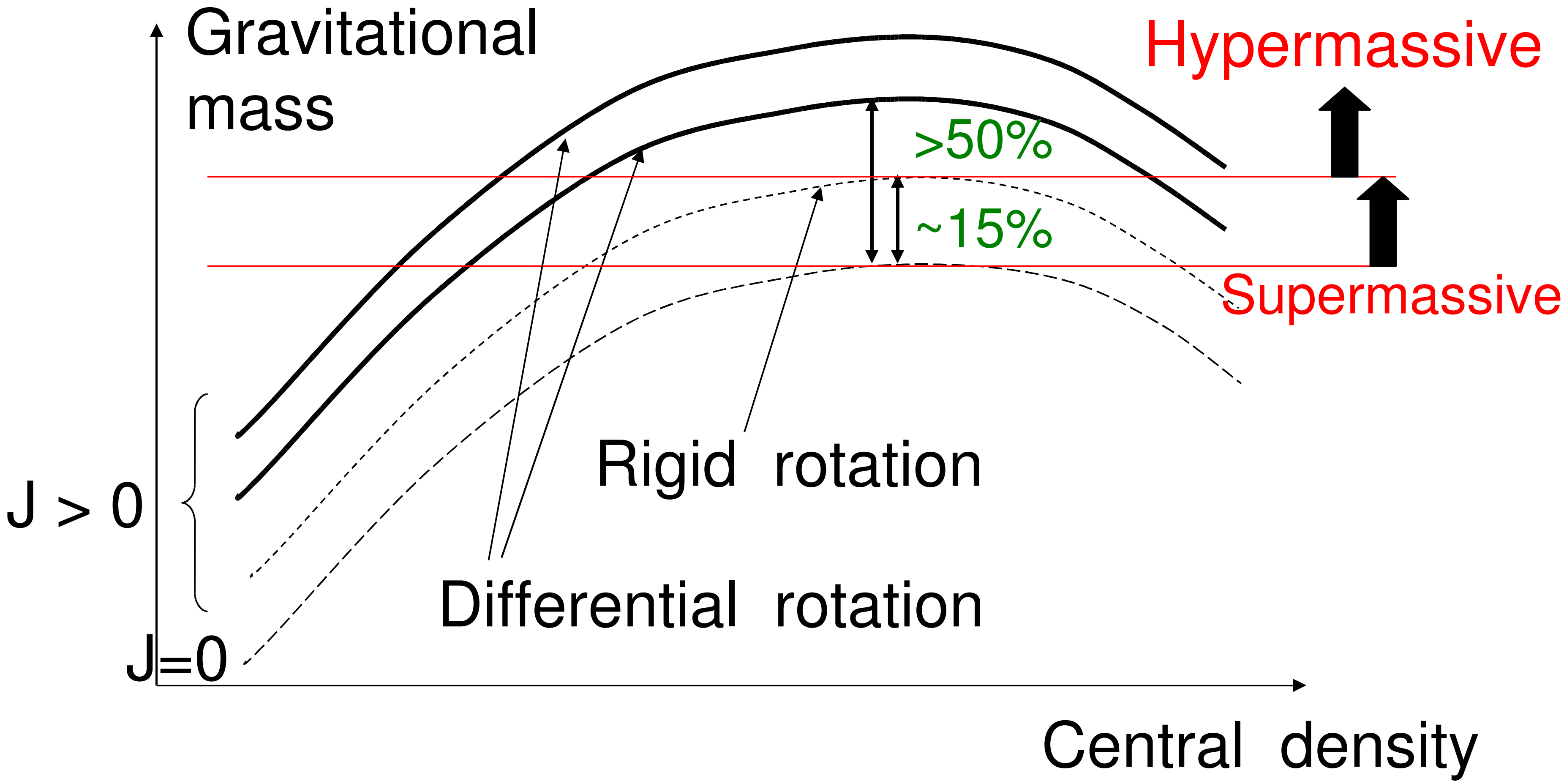
Convergence of error in ρ



Approximately 2nd order convergent

4 Simulation for differentially rotating hypermassive neutron star

- Hypermassive neutron star ?



Fate of hypermassive stars

Differential rotation

↙Angular momentum is redistributed by viscosity or magnetic field

↙Rigid rotation; M_max, rigid < M_max, dif

↙If M > M_max,rigid, then it is likely to collapse to a black hole

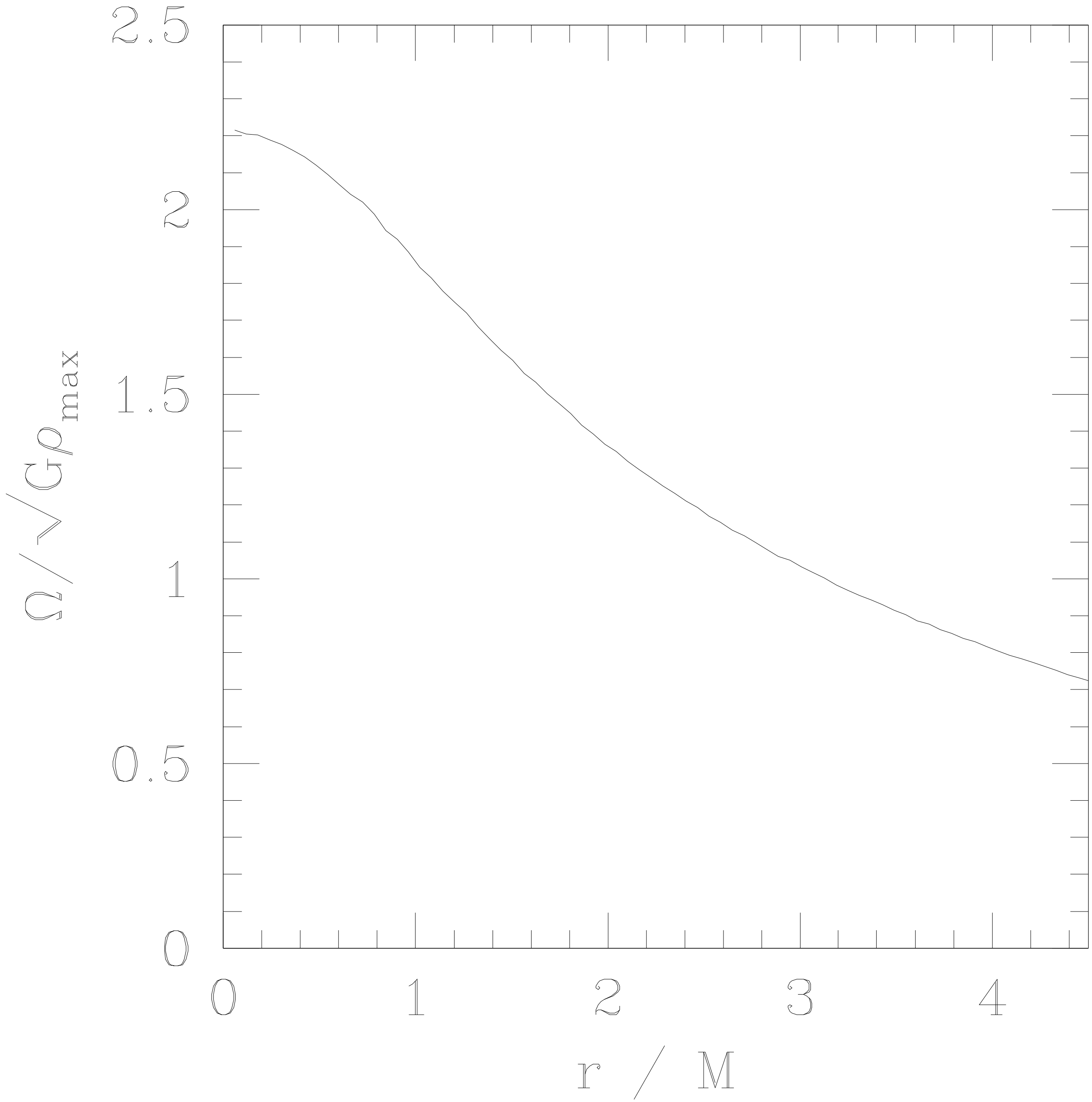
E.g.,
Neutron star formed after merger of 2 NSs
= hypermassive star ↙ Collapse eventually

Numerical result : Model

- EOS: $\Gamma=2$ polytropic EOS ($P=(\Gamma-1)\rho\varepsilon$)
- Differentially and rapidly rotating NS
- Hypermassive:
  Mass = 1.68 M_{0,max} = 1.46 M_{rig,max}
- Seed Magnetic field: Poloidal, confined to the NS (P_mag/P ~ 0.13% at t=0)

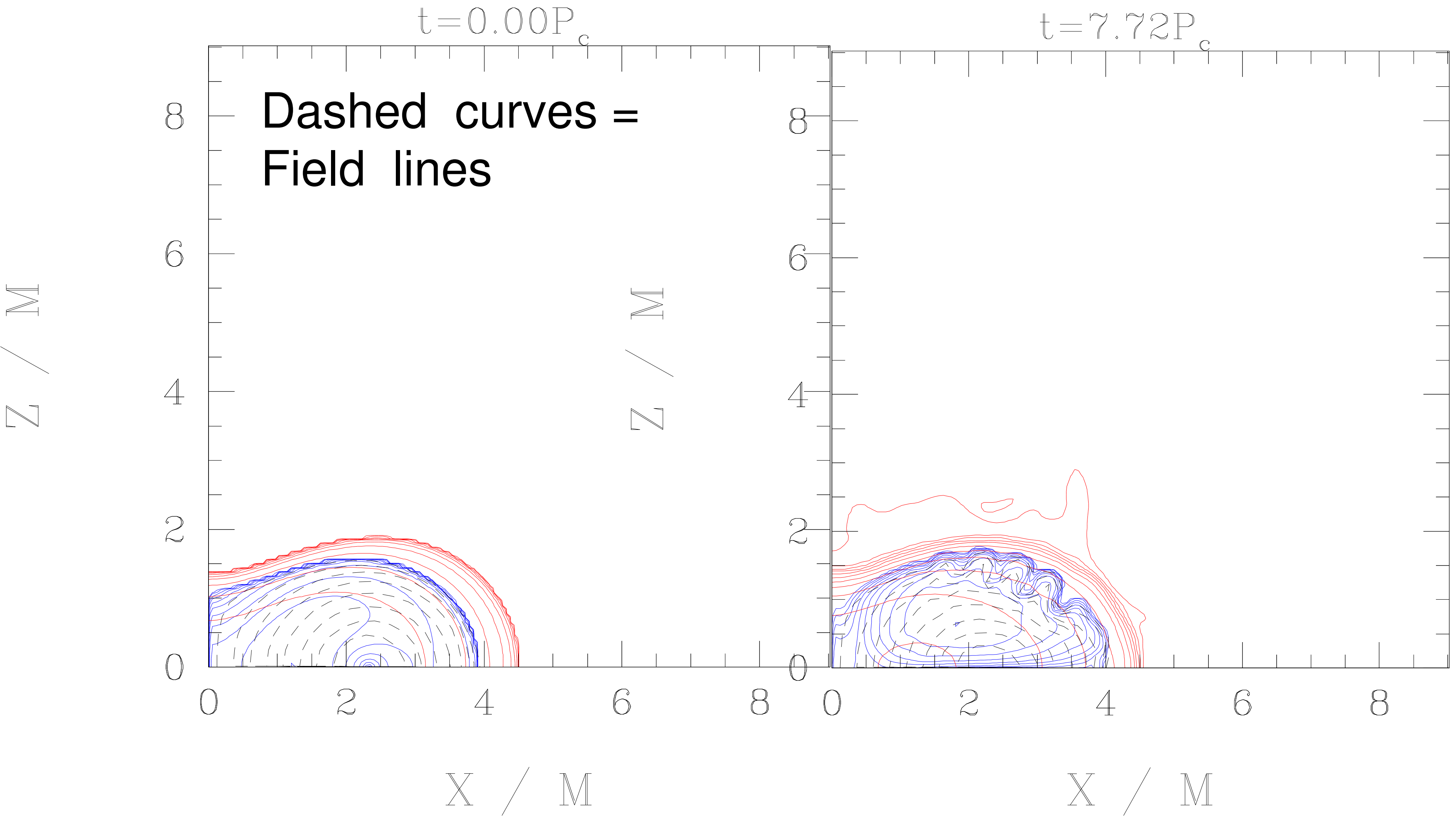
$$A_\varphi = \begin{cases} A\left(P - P_{\mathrm{cut}}\right) & P > P_{\mathrm{cut}} \\ 0 & P < P_{\mathrm{cut}} \end{cases}$$

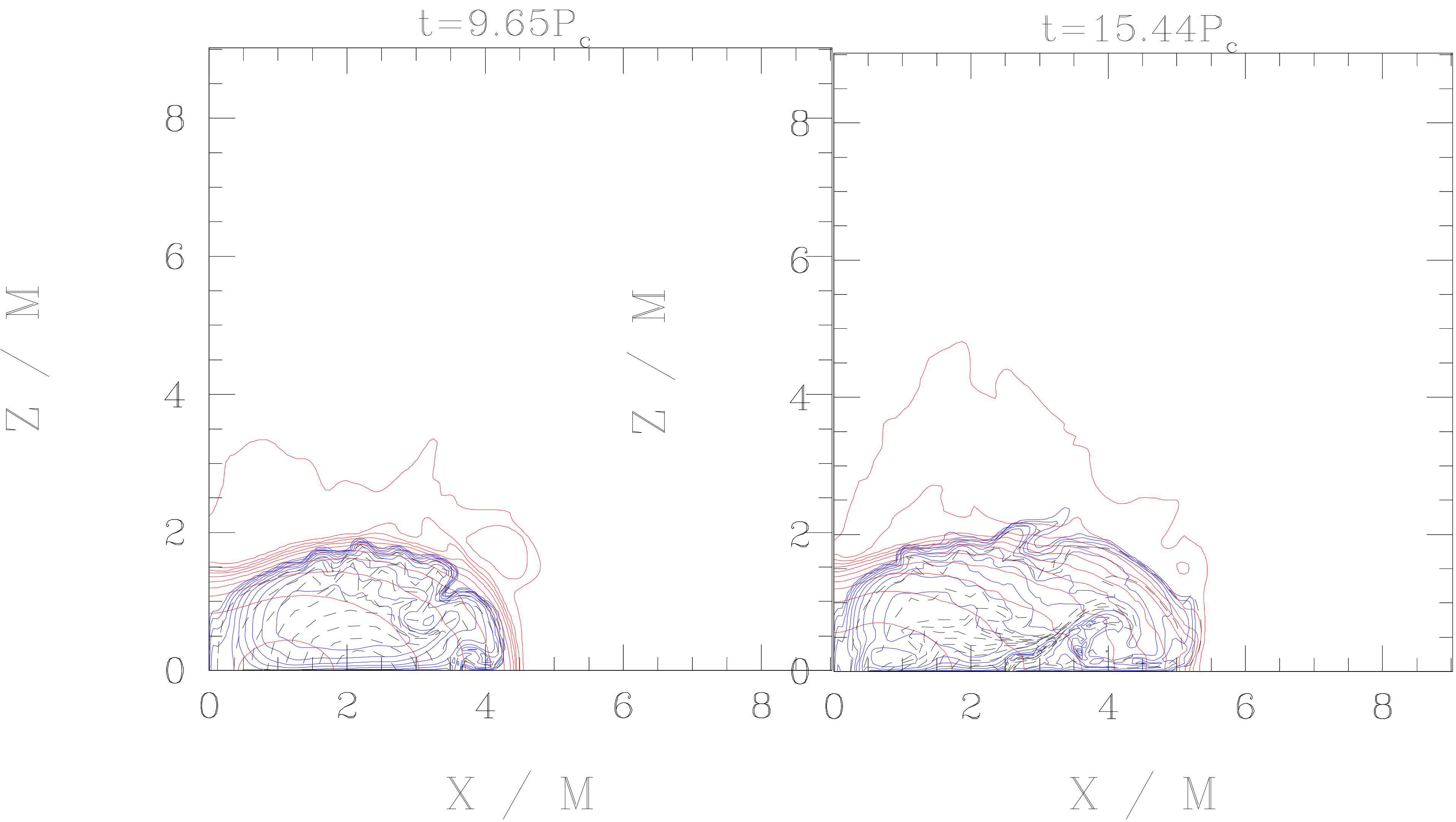
Angular velocity profile



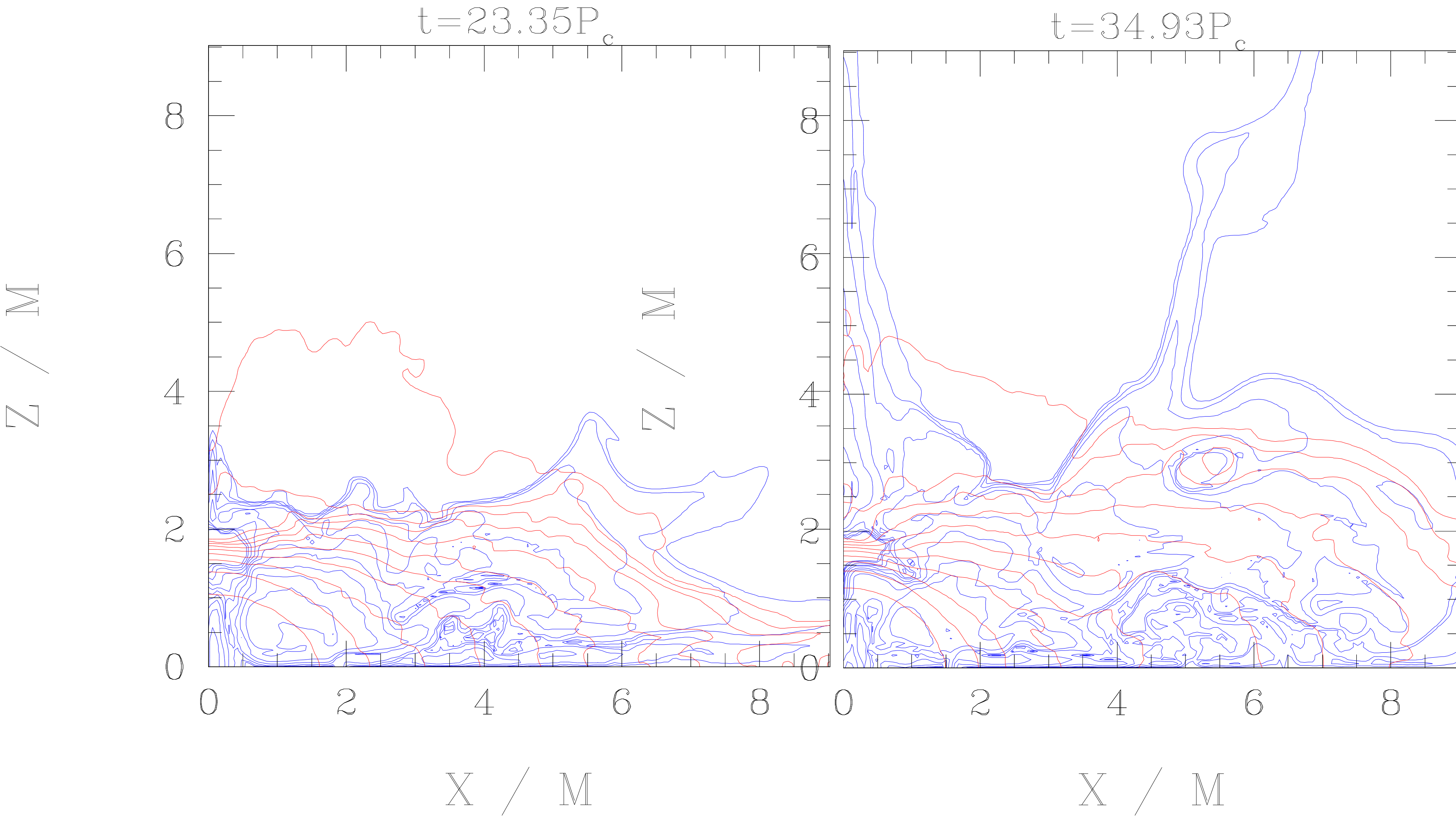
Red = density contour curves

Blue = magnetic pressure contour curves

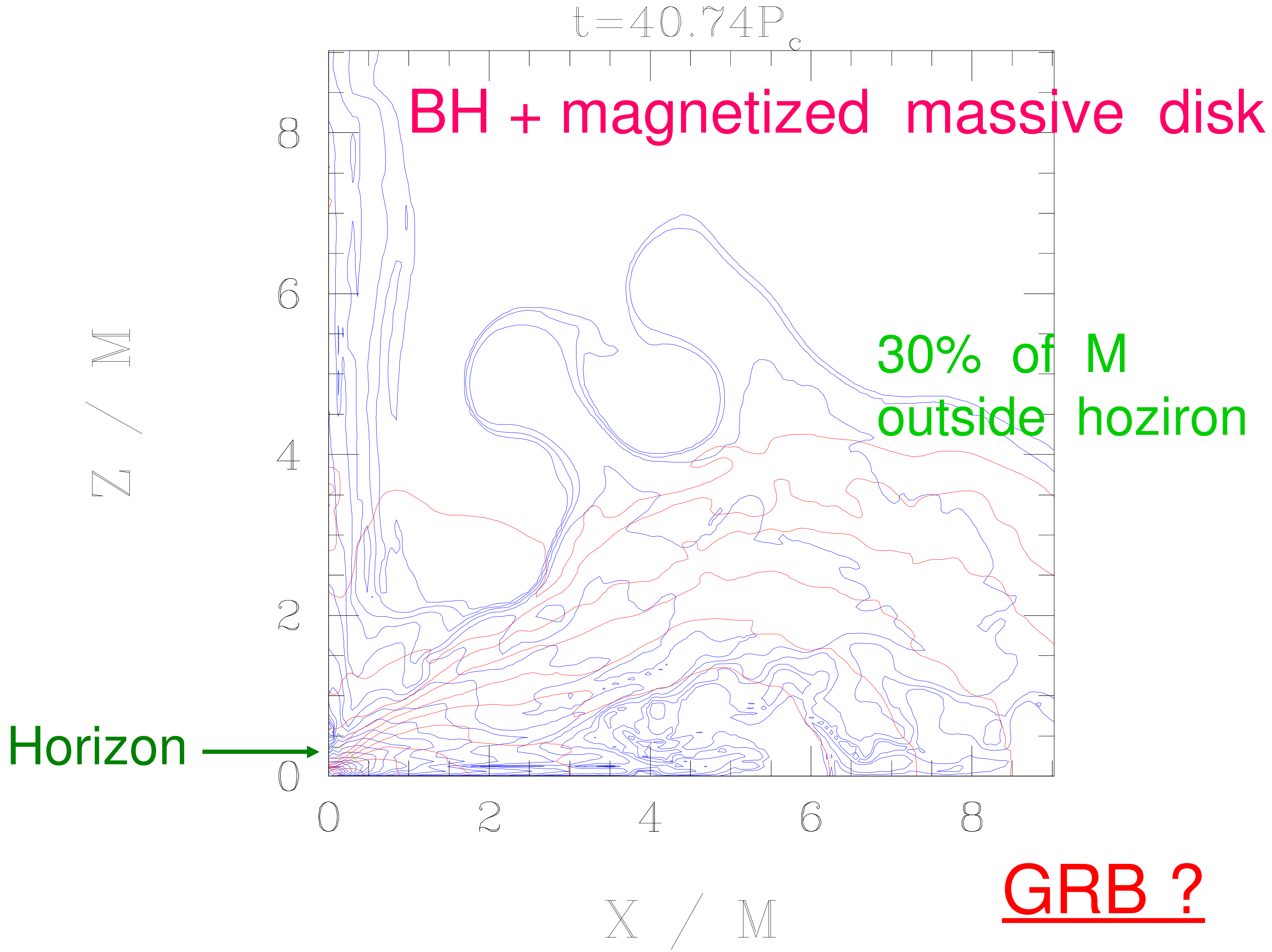




t=9.65P_c
t=15.44P_c
Z / M
Z / M
X / M
X / M
0
2
4
6
8

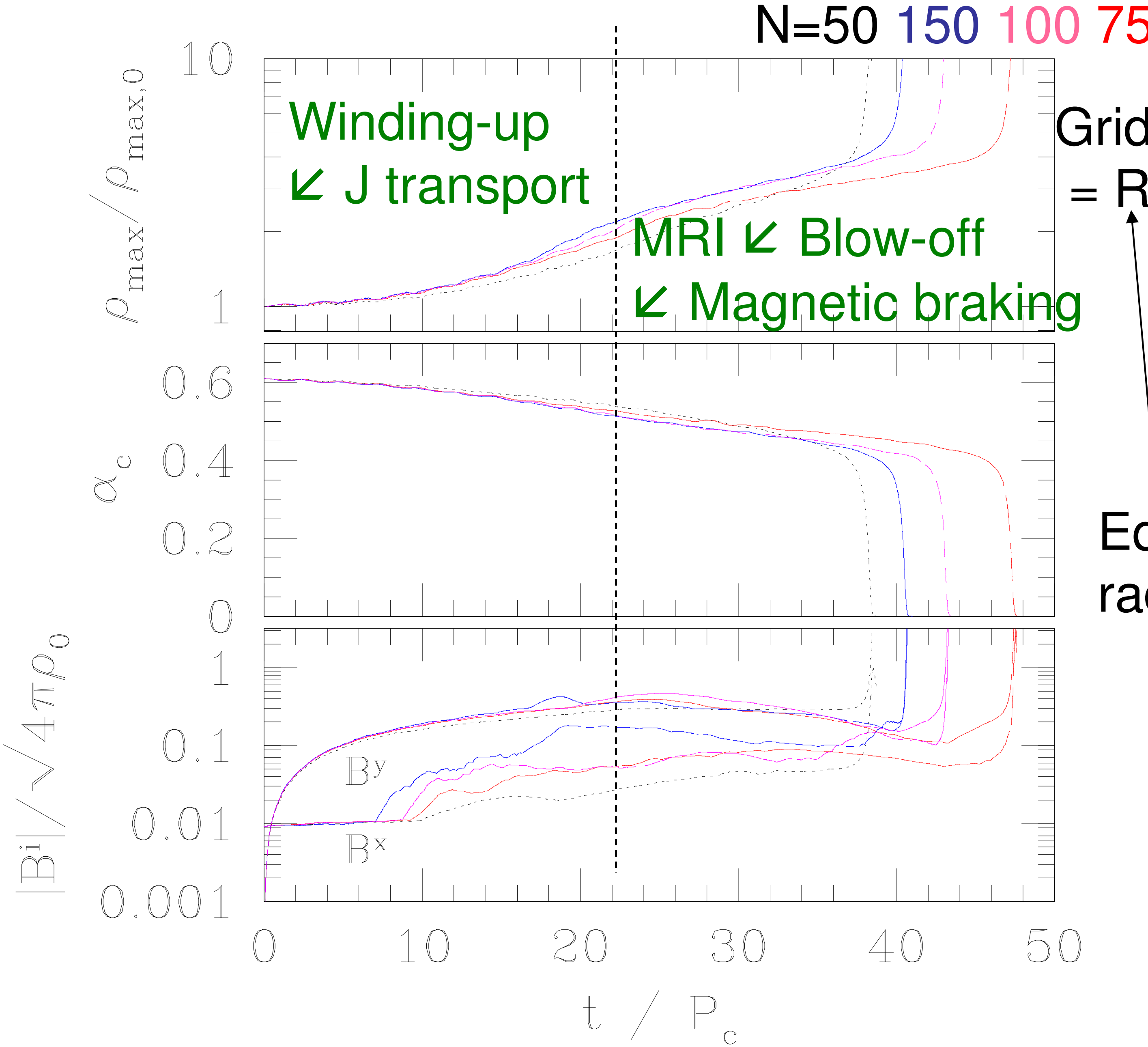


t=23.35P_c
t=34.93P_c
Z / M
X / M
0
2
4
6
8


t=40.74P_c
BH + magnetized massive disk
30% of M
outside hoziron
Horizon
Z / M
X / M
0
2
4
6
8

GRB ?

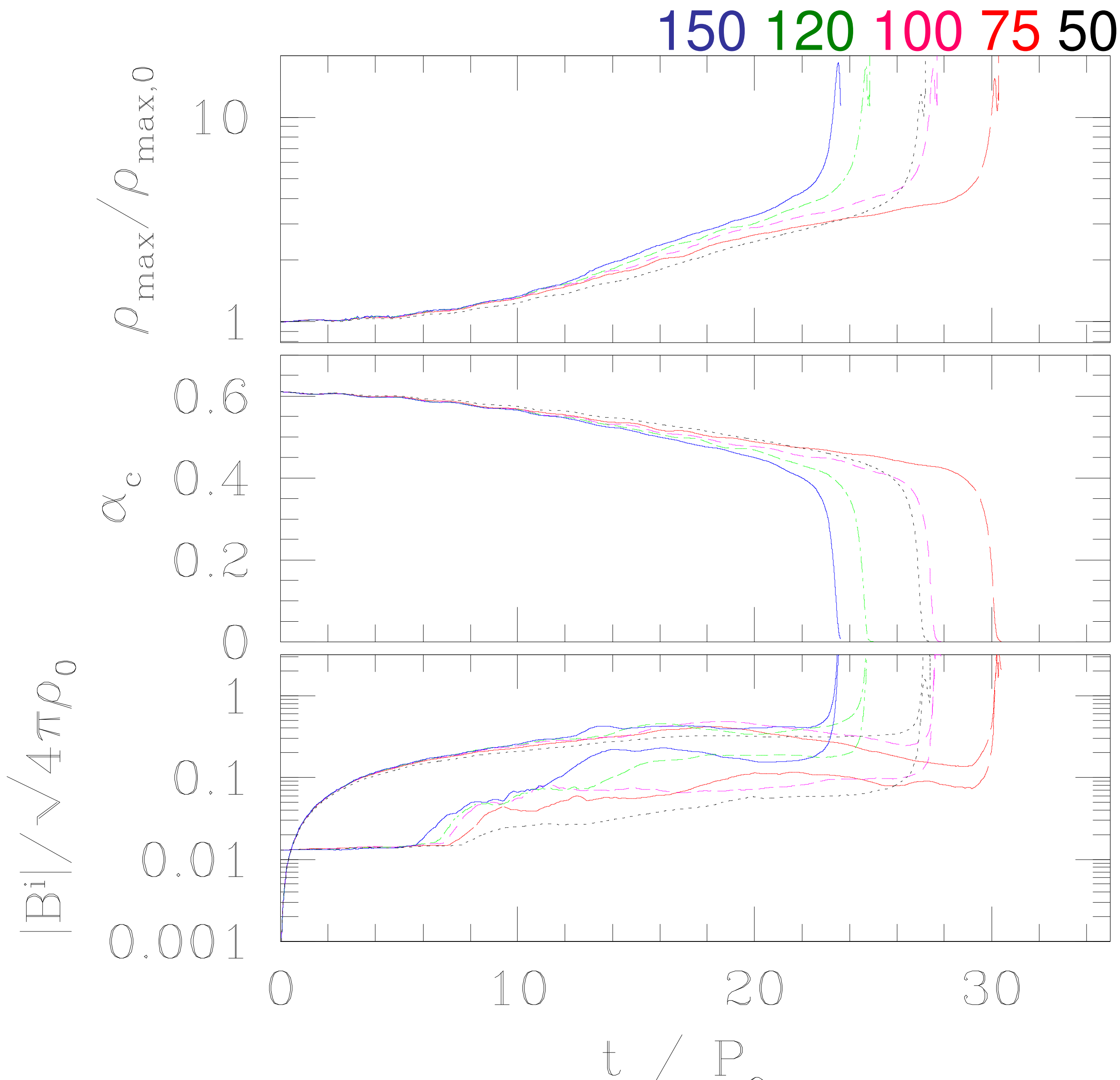
Implication & Convergence



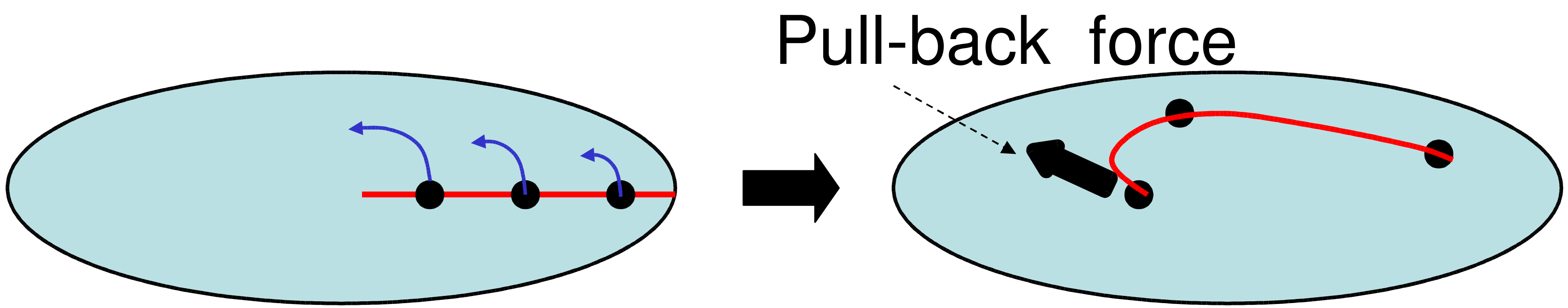
Grid spacing
= R / N

Equatorial
radius

B field: 1.4 times (Energy 2 times)



Winding of B-field and braking

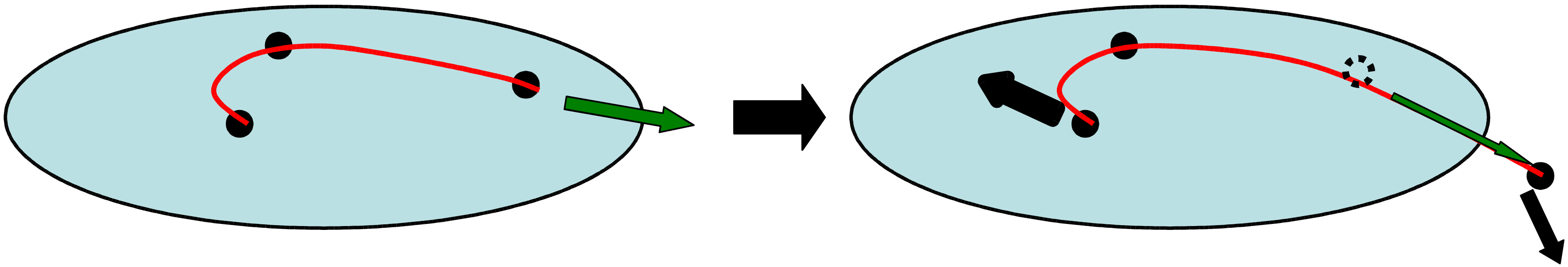


In the presence of R-component of B-field

- ↙ Amplify ϕ–component
- ↙ Eventual transport of angular momentum

B^ϕ grows approximately in proportional to $B^R * t$ until saturation

Rebraking by blown-off matter

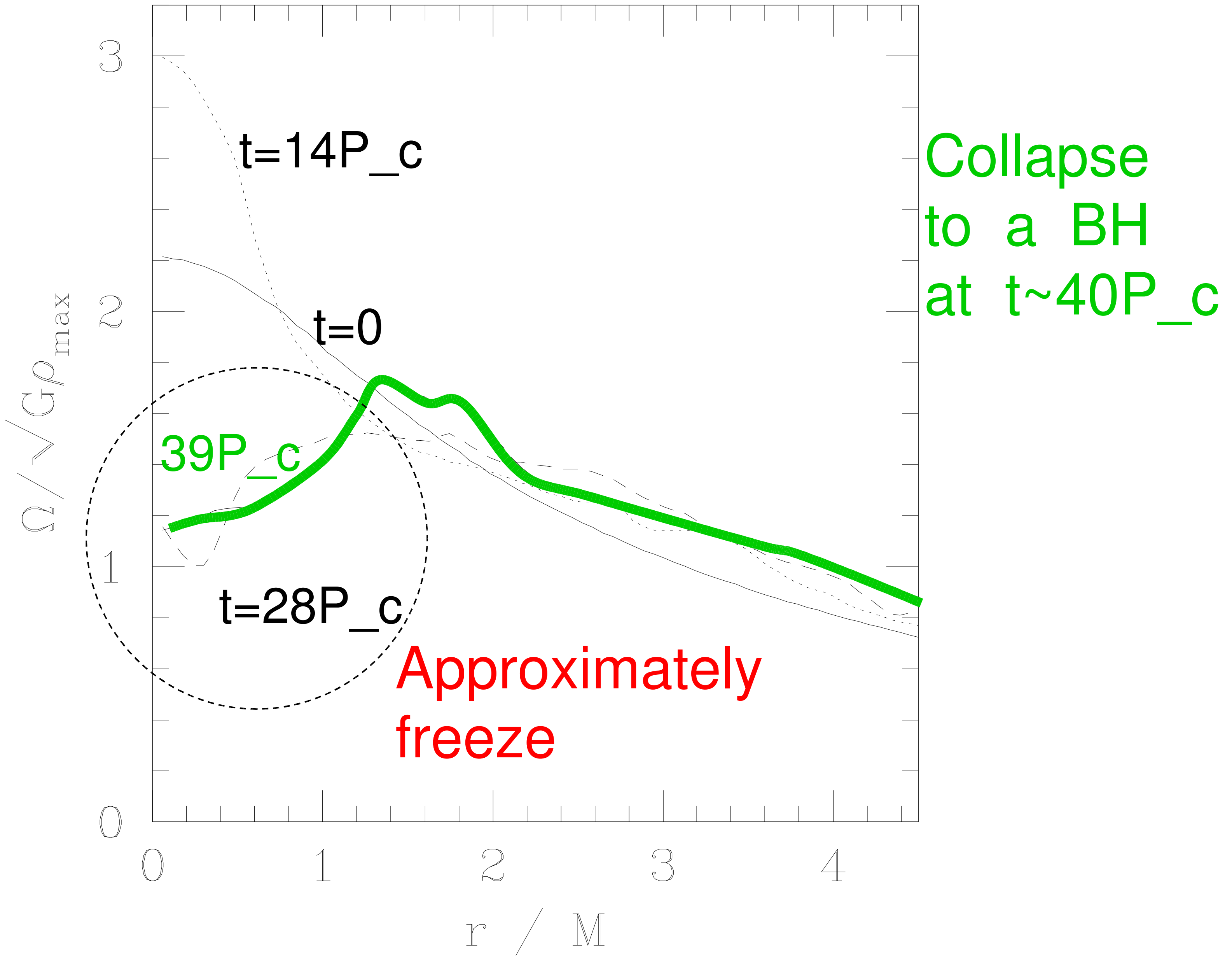


Matter blows off far from star

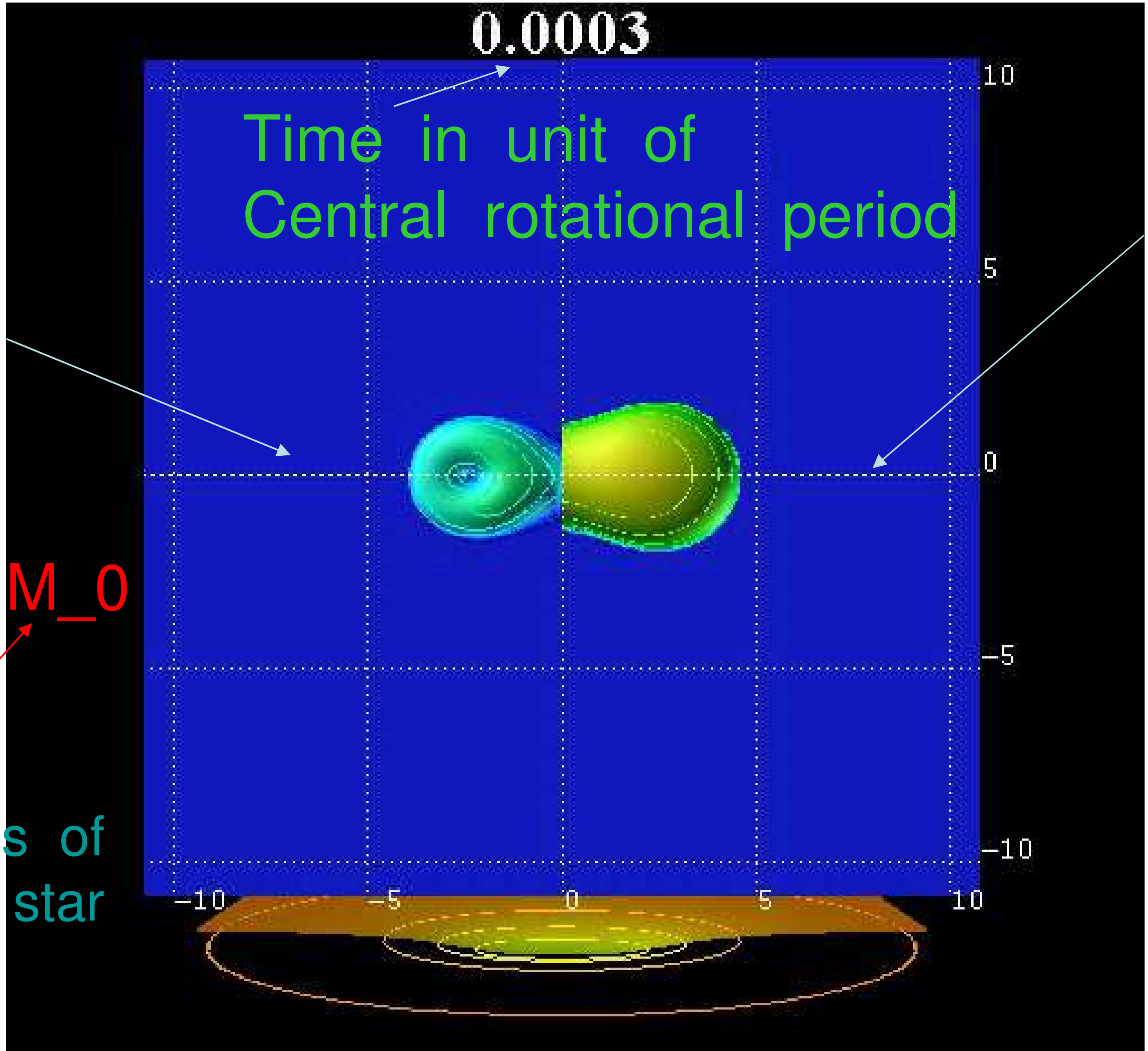
↙ Rotate more slowly (Ω decreases)

↙ Transport of angular momentum by magnetic stress to ejected matter

Evolution of Ω profile



Collapse of differentially rotating HMNS



5 Summary

- GRMHD code is ready
- First target = Evolution of HMNS

  (in collaboration with Shapiro and his colleague)

  ↙ BH + massive disk formed

  ↙ Source of short GRBs ?

- In future, we will carry out

4. Stellar core collapse to NS/BH
5. Merger of magnetized NSs
6. Nonaxisymmetric instabilities of rapidly rotating NS with B-fields

NS + disk in full GR

B-fields are confined in the disk