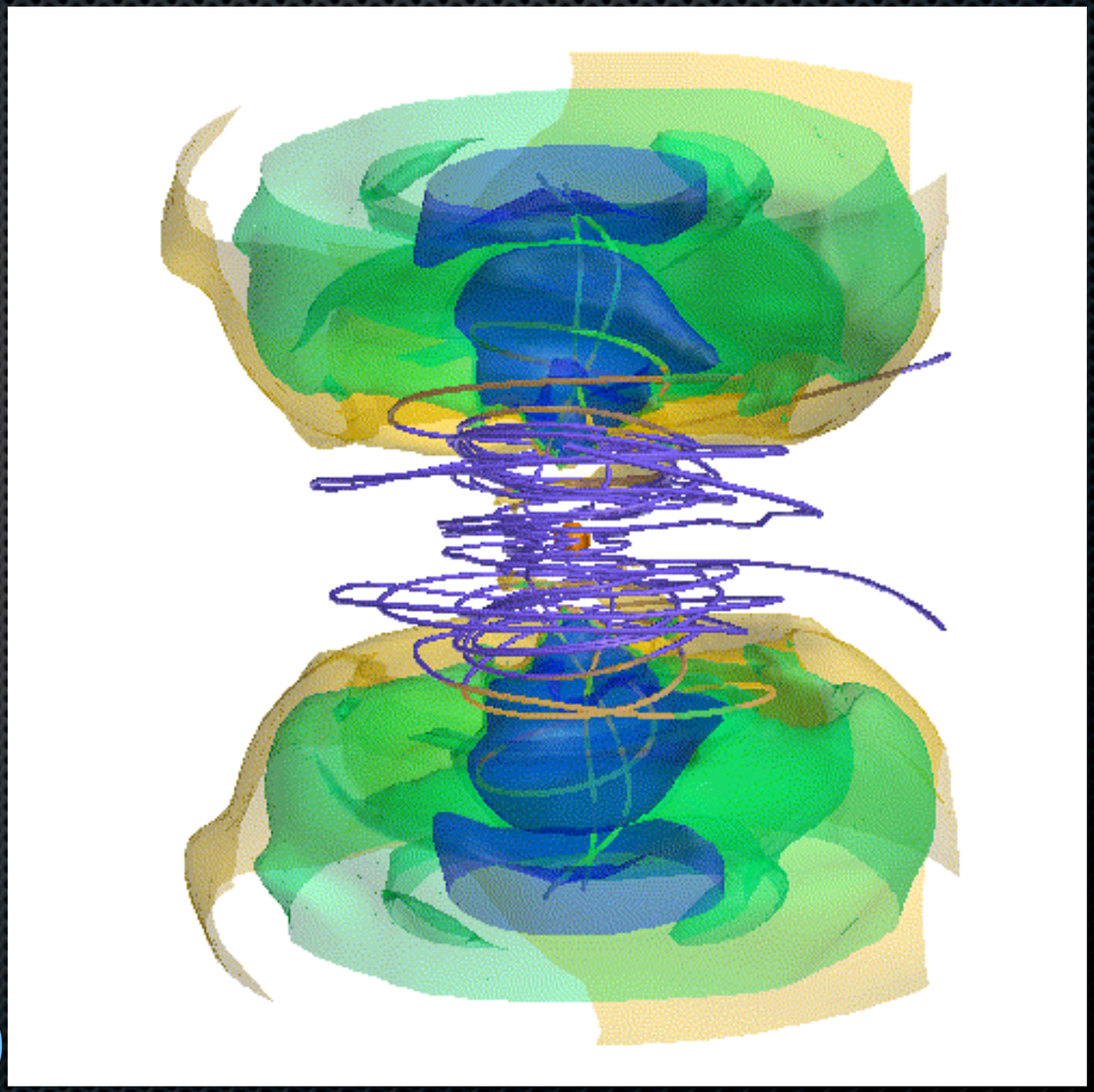
The 3D MHD Effects For A Core Collapse Supernova Explosion

Hayato MIKAMI
Chiba Univ.



coresearcher:
Y. Sato(Chiba Univ.)
T. Hanawa(Chiba Univ.)
T. Matsumoto(Hosei Univ.)

Outline

- The paper accepted by ApJ
  - Main result
  - Parameter dependenc
- Technical issues
  - Source term
  - Carbuncle instability
- 3D MHD simulation with Sfumato(AMR code)

Introduction

- Three-Dimensional Magnetohydrodynamical Simulations Of A Core-Collapse Supernova
  - accepted by ApJ
  - 2008 August 20.
  - You can get
    - astro-ph: 0804.3700
    - http://www.astro.phys.s.chiba-u.ac.jp/~mikami/research/

The Astrophysical Journal, 683:000–000, 2008 August 20

collapse

twist

bipoler jets

THREE-DIMENSIONAL MAGNETOHYDRODYNAMICAL SIMULATIONS OF A CORE-COLLAPSE SUPERNOVA

Hayato Mikami and Yuji Sato
Graduate School of Science, Chiba University, 1-33, Yayoi-cho, Inage-ku, Chiba 263-8522, Japan; mikami@p.s.chiba-u.ac.jp

Tomoaki Matsumoto
Faculty of Humanity and Environment, Hosei University, Fujimi, Chiyoda-ku, Tokyo 102-8160, Japan

and

Tomoyuki Hanawa
Center for Frontier Science, Chiba University, 1-33, Yayoi-cho, Inage-ku, Chiba 263-8522, Japan
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Model

- Ideal MHD Equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0$$

$$\frac{\partial v}{\partial t} + (v \cdot \nabla) v + \frac{1}{\rho}\left[\nabla P - \left(\frac{\nabla \times B}{4\pi}\right) \times B\right] - g = 0$$

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B)$$

$$g = -\nabla \Phi$$

- Self Gravity

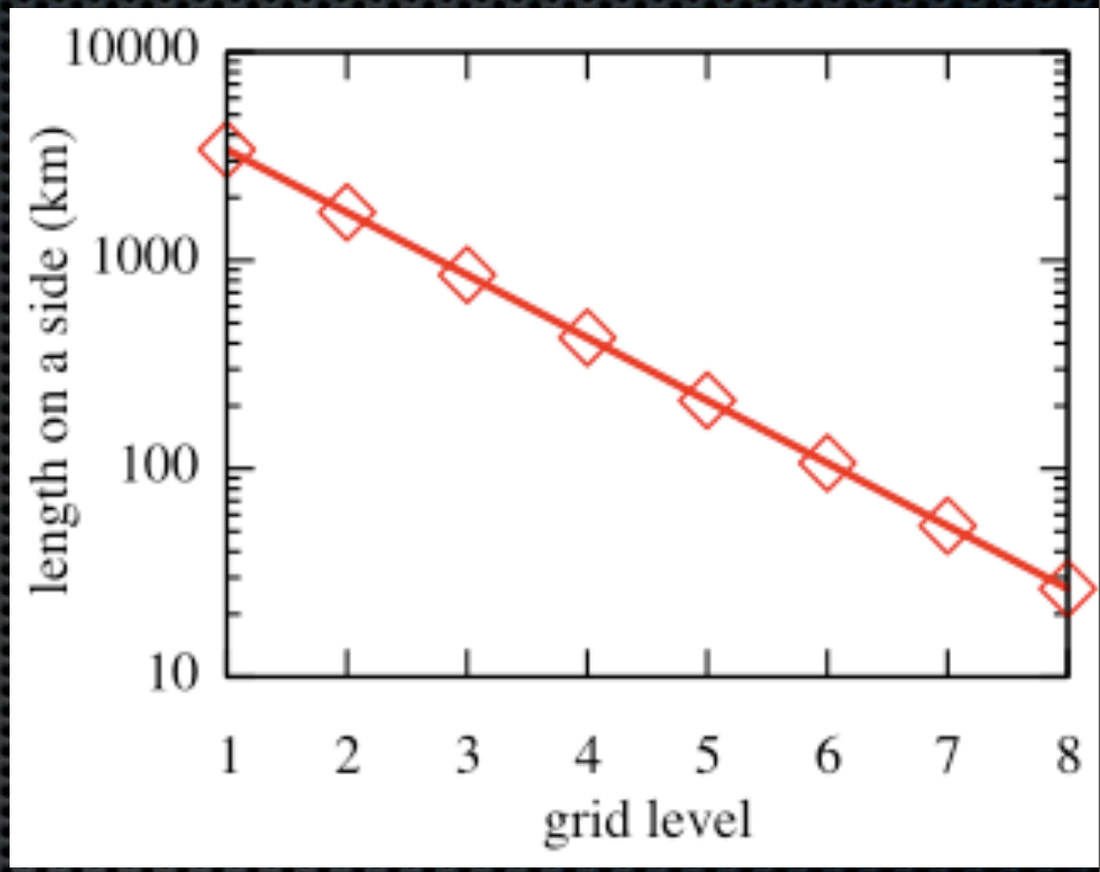
$$\Delta \Phi = 4\pi G \rho$$

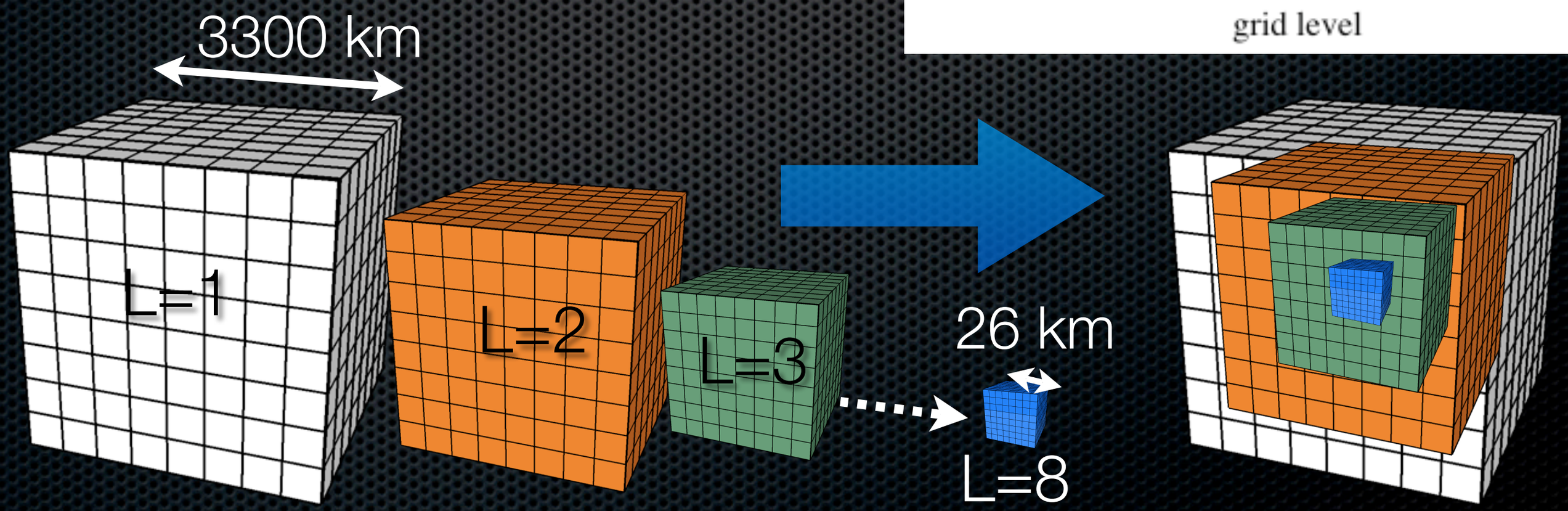
- EOS
  - Simplified
  - Takahara & Sato. 1984

$$\begin{aligned} P &= P_c + P_t \\ P_t &= \frac{\rho \varepsilon_t}{\gamma_t - 1} \\ P_c &= K_i \left(\frac{\rho}{\rho_i}\right)^{\gamma_i} \end{aligned}$$

Method

- Nested Grid Method
  - 8 concentric grids × 64^3 cells
  - Largest grid : 3300 km on a side
  - Finest resolution : 410 m
- Roe-type Scheme
  - A shock capturing scheme





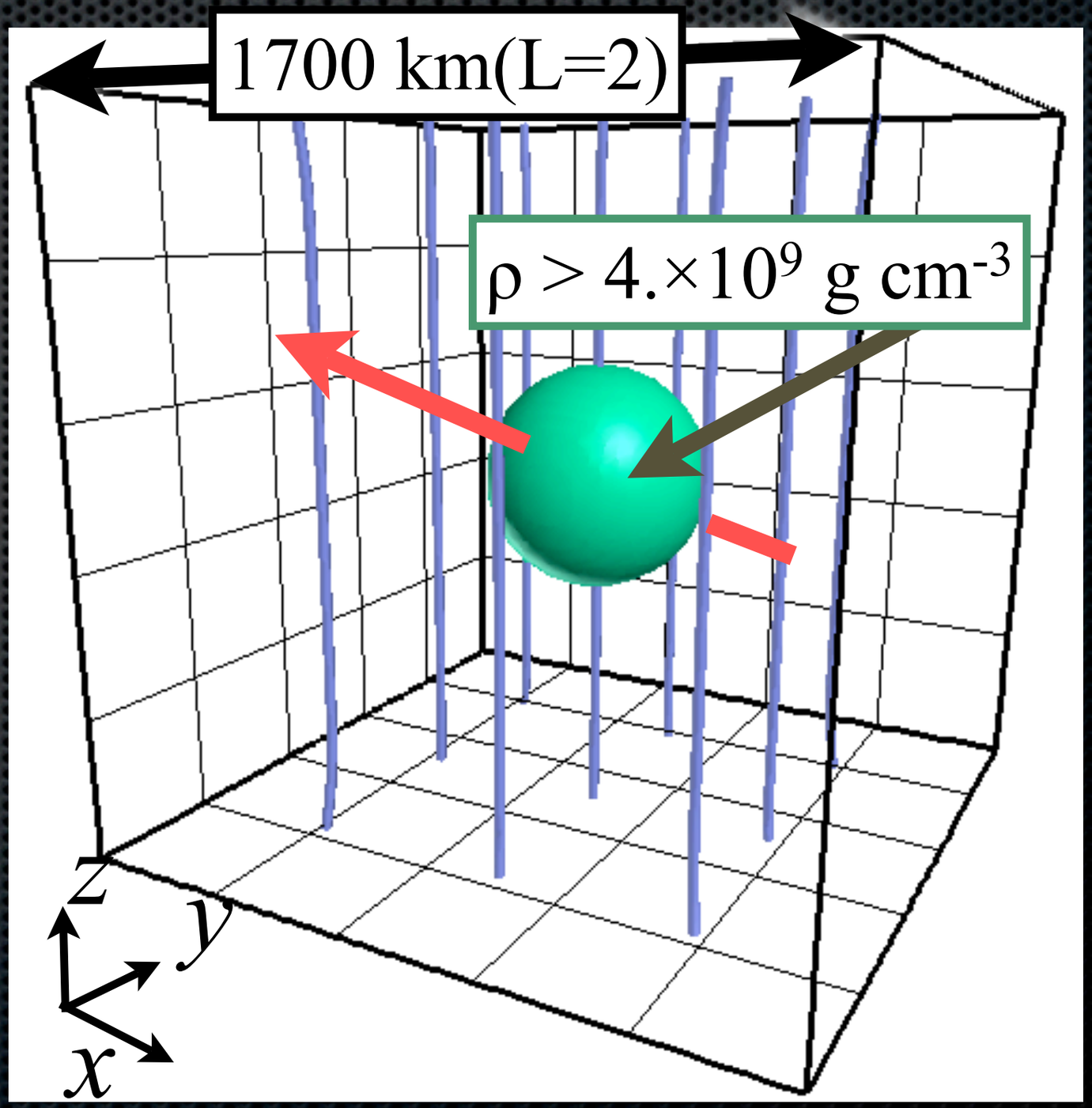
Inicial Condition

- 15 Mo star
  - Woosley et al. 2002
  - $\rho_0 = 6.8\times10^9$ g cm^{-3}
- B Field
  - Uniform
  - Dipole-like outside
  - $B_0 = 2. \times 10^{12}$ G
- Rotation
  - Differential rotation law

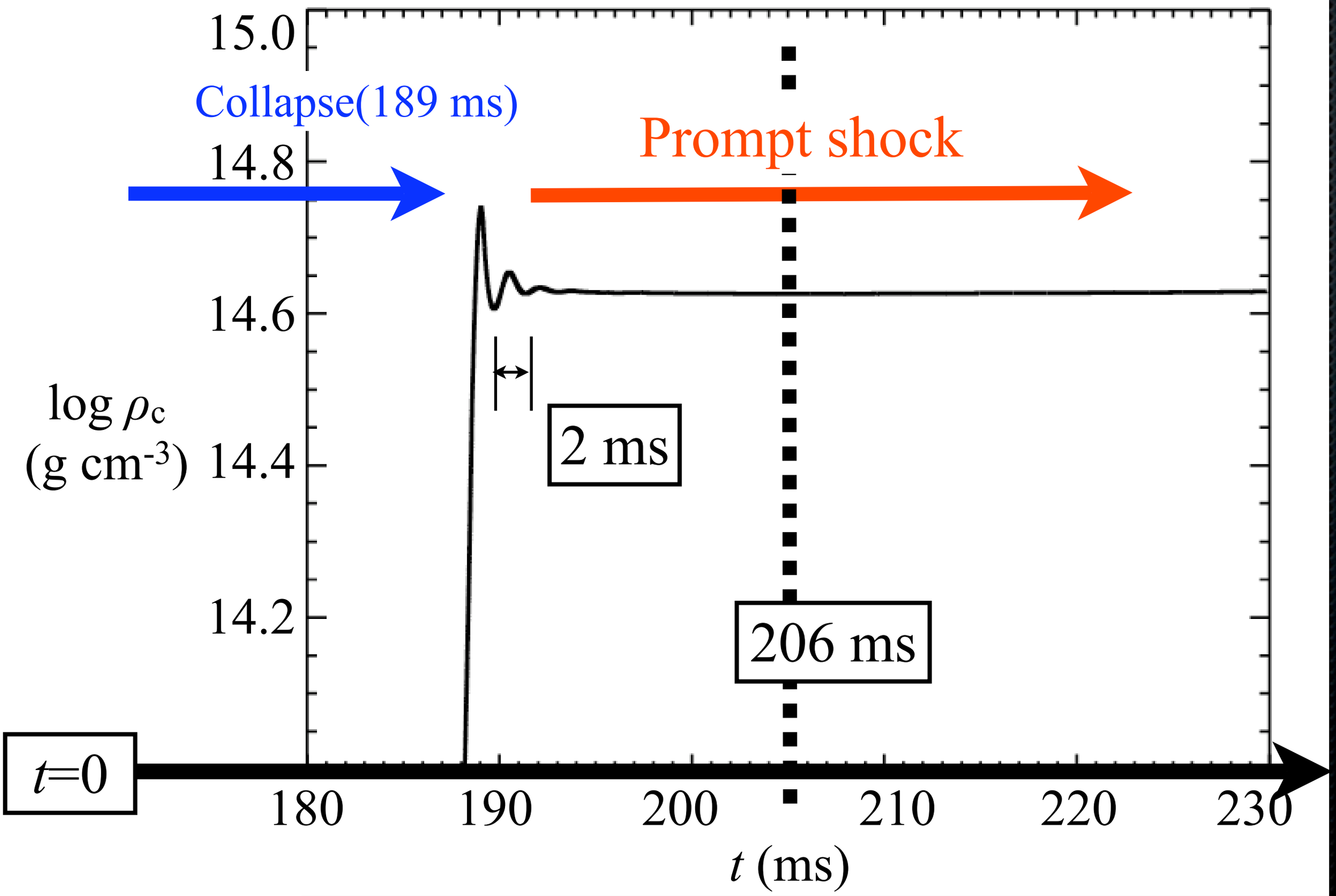
$$\Omega_0(r) = \frac{\Omega_c a^2}{r^2 + a^2}$$

  - $\Omega_c = 1.2$ s^{-1}
- Inclination angle
  - $\theta_\Omega = 60°$

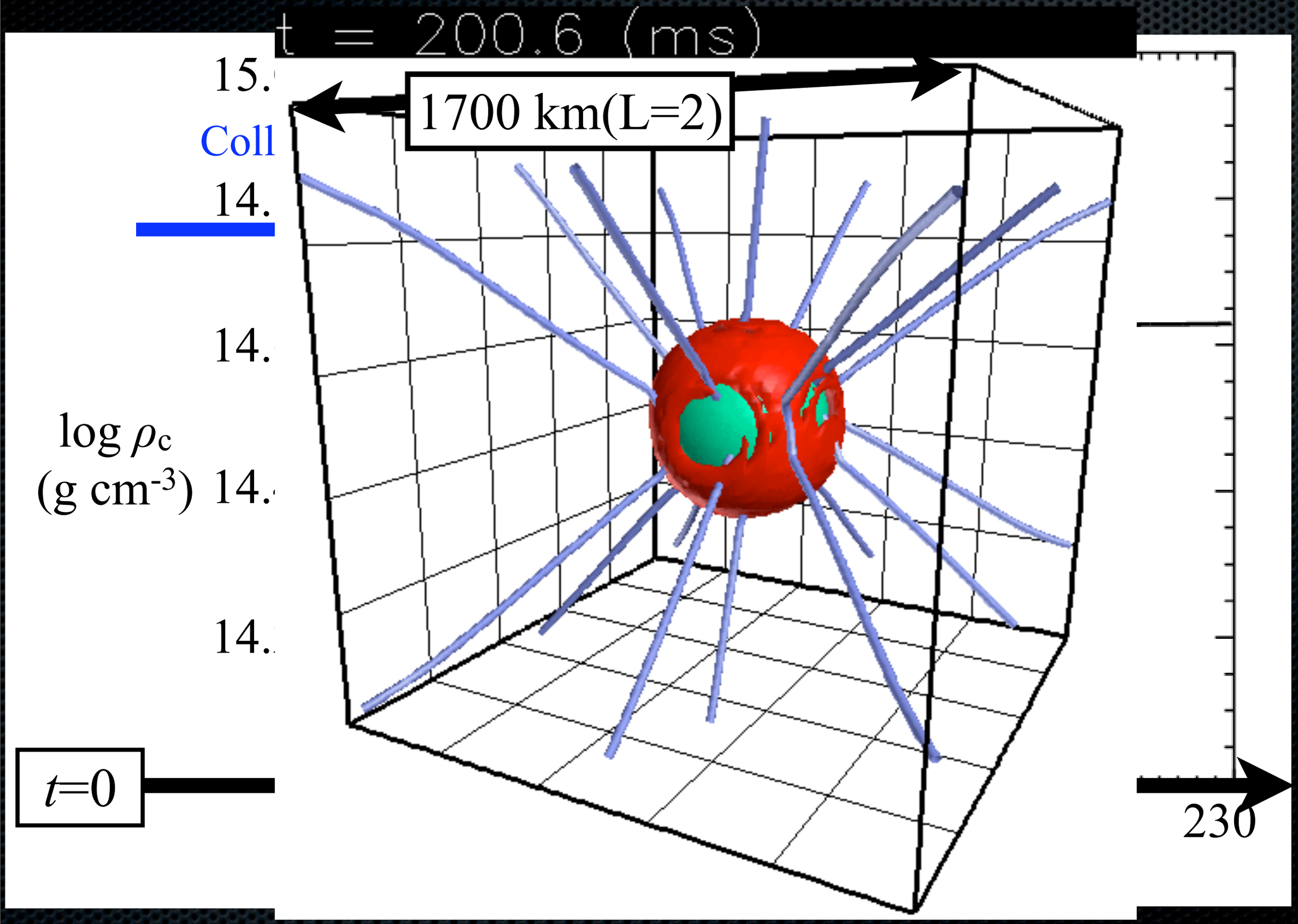
Code: No symmetry assumed
Initial : Point symmetry

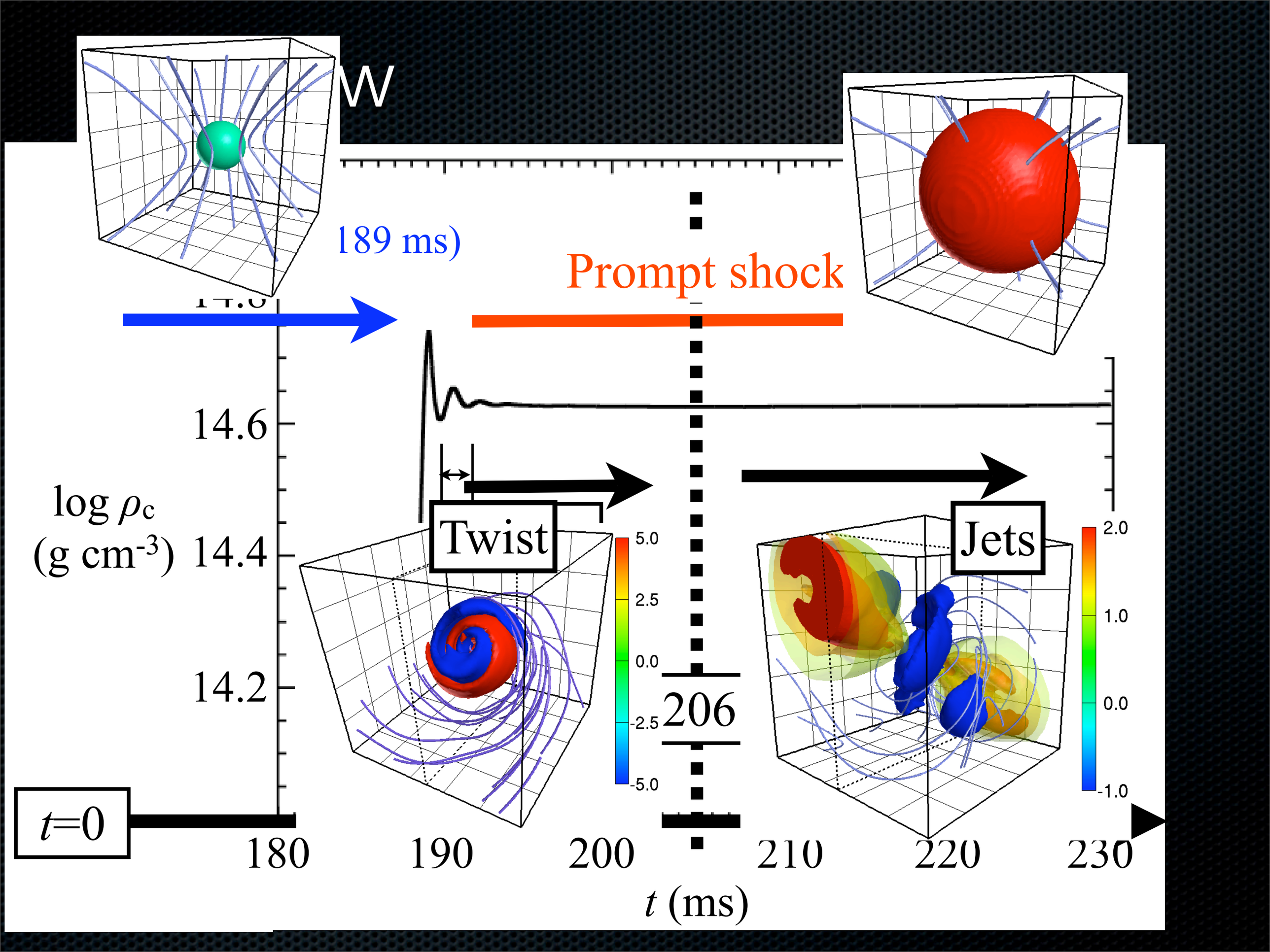


Overview

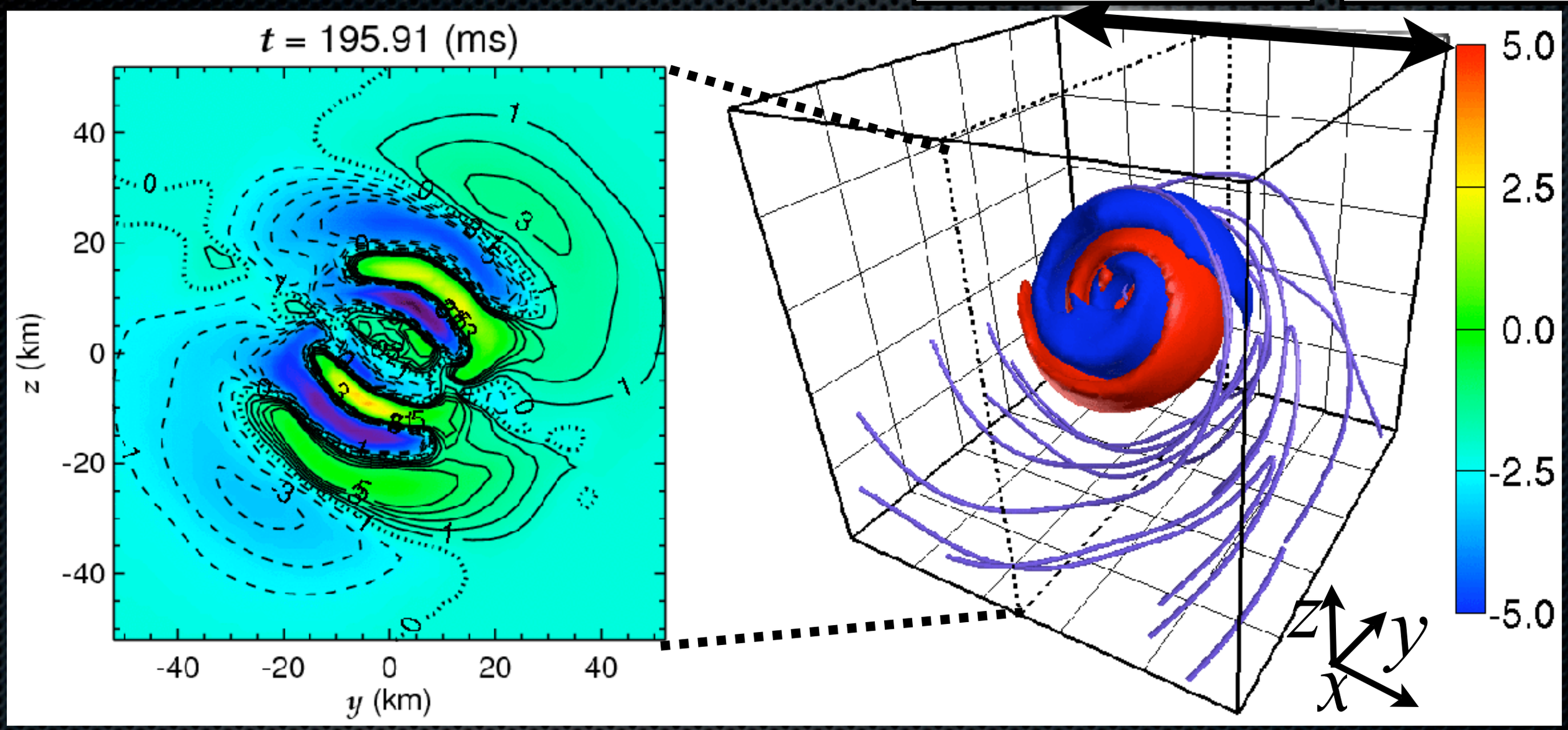

15.0
14.8
14.6
14.4
14.2
Collapse(189 ms)
Prompt shock
log ρ_c
(g cm^{-3})
2 ms
206 ms
t=0
180
190
200
210
220
230
t (ms)

Overview




W
189 ms)
Prompt shock
14.6
log ρ_c
(g cm^{-3})
14.4
14.2
Twist
5.0
2.5
0.0
-2.5
-5.0
206
Jets
2.0
1.0
0.0
-1.0
t=0
180
190
200
210
220
230
t (ms)

Twisted B Field

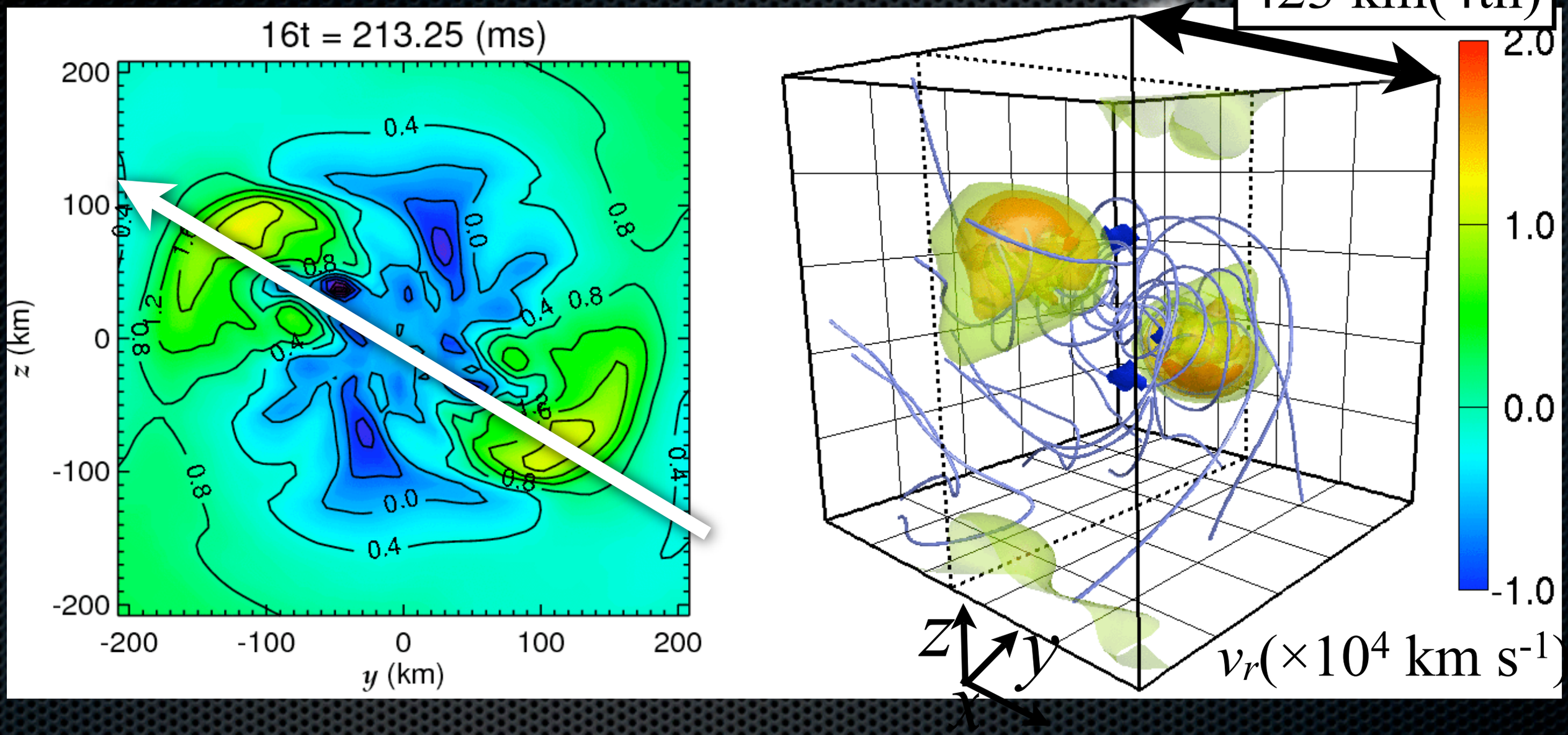


Uniform → Split monopole → Magnetic multi-layer

collapse period

twist period

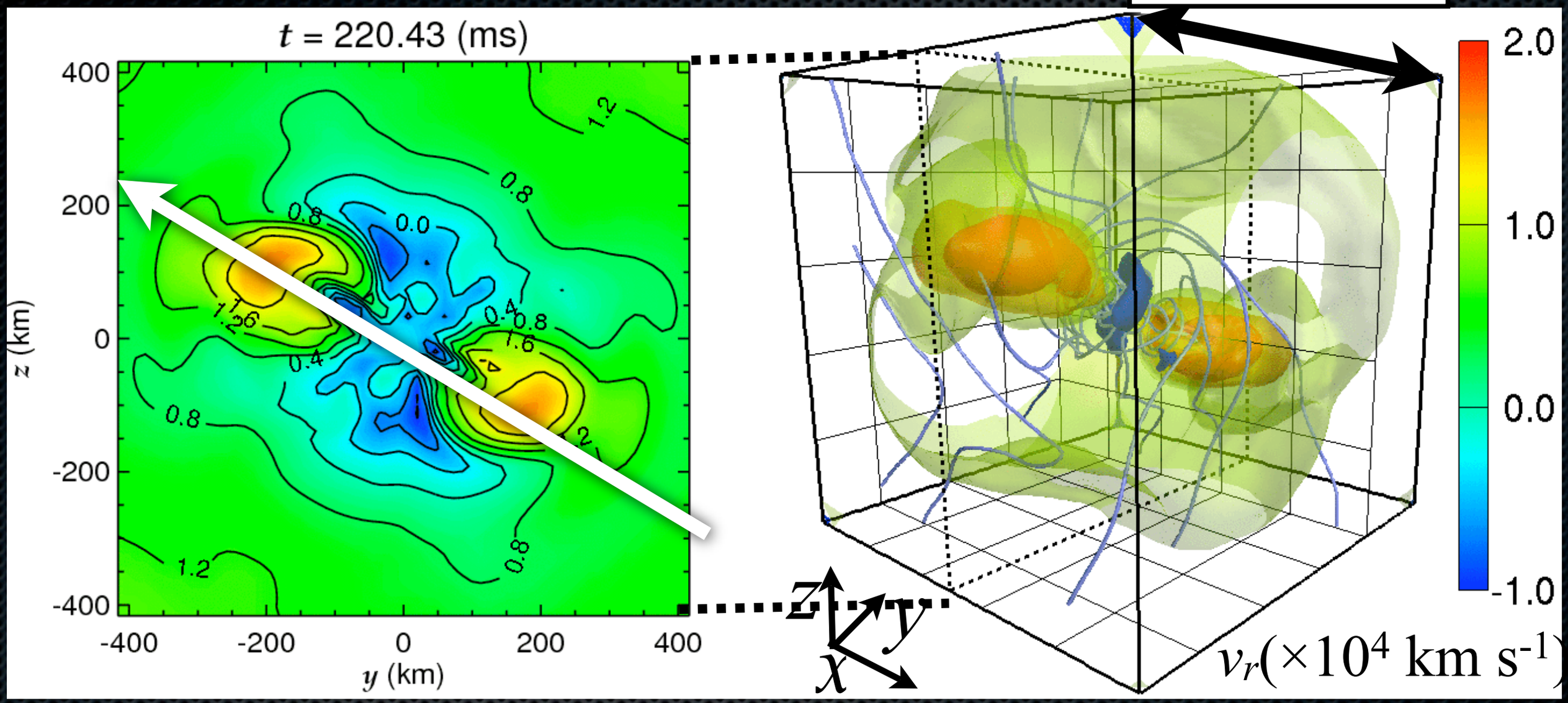
Bipolar Jets



Jets($2.\times10^4$ km s^{-1}) & downflow($1.\times10^4$ km s^{-1})

- The high velocity jets emerge from r ~ 60 km

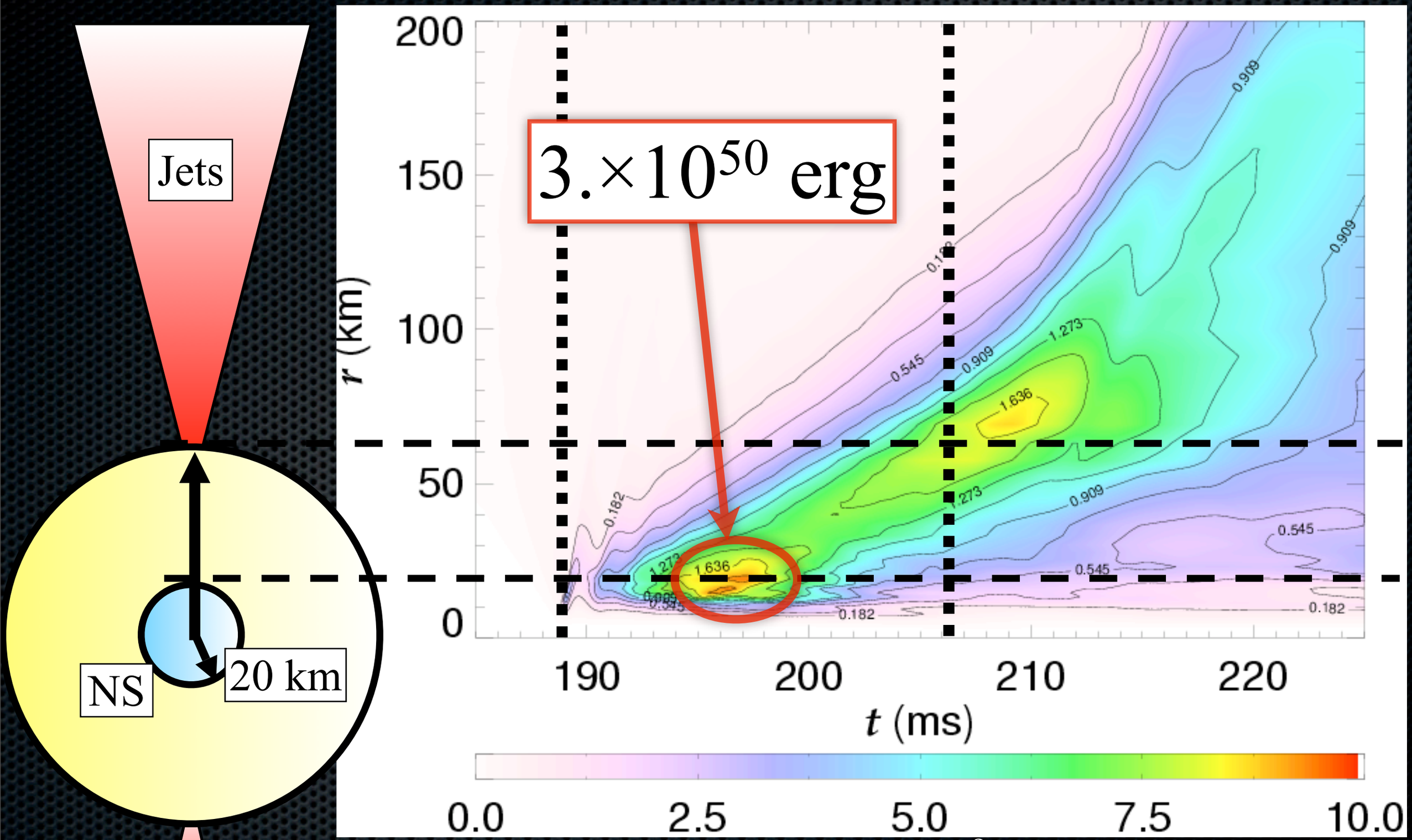
Bipolar Jets



Jets($2.\times 10^4$ km s^{-1}) & downflow($1.\times 10^4$ km s^{-1})

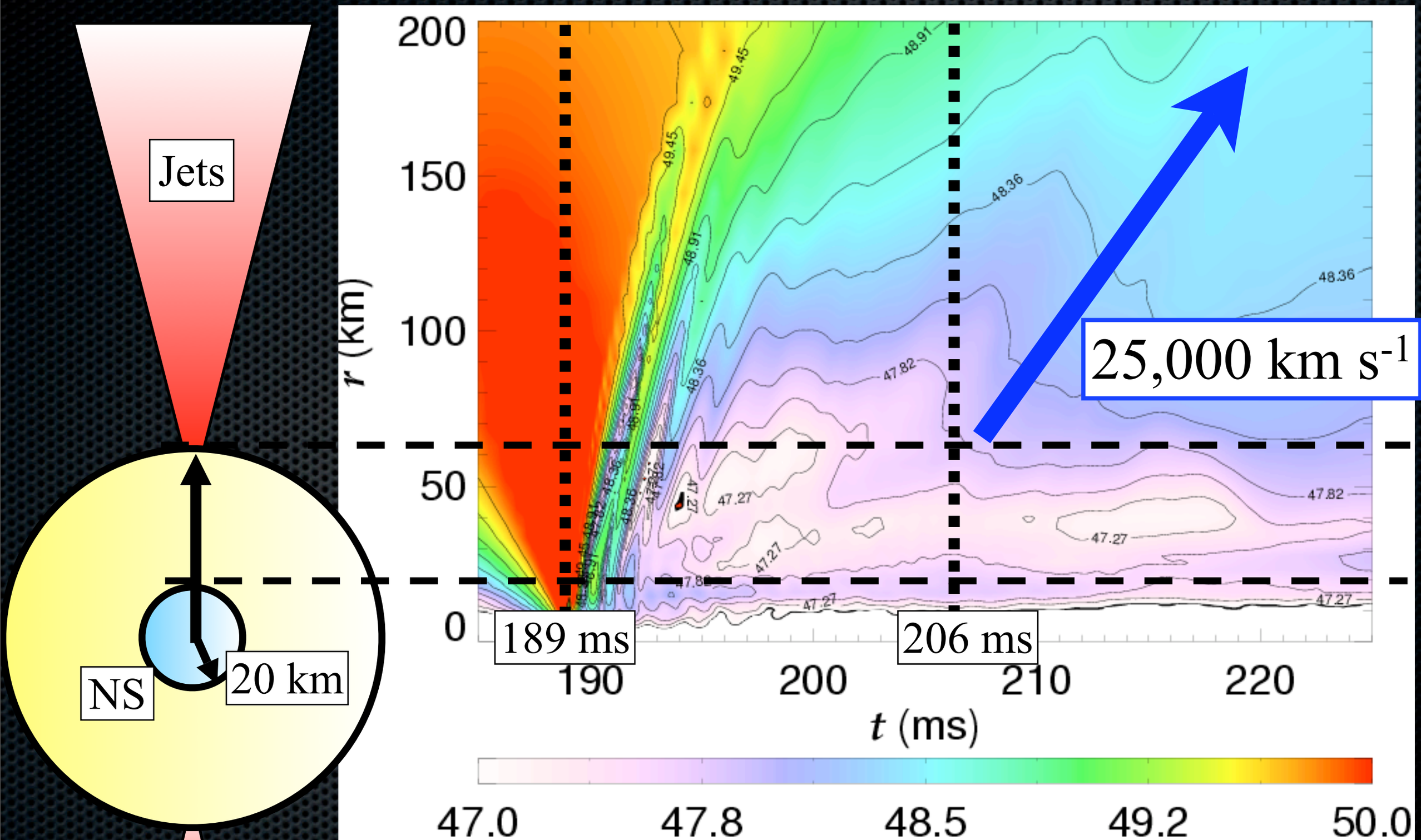
- The direction is along the initial rotation axis.

Evolution of *B* Energy



$$E_{\rm m} = \int \varepsilon_{\rm m}(r) d(\ln r), \quad \varepsilon_{\rm m}(r) = 4\pi r^3 \frac{B^2}{8\pi} \qquad \varepsilon_{\rm m}(r)/10^{49}\ [\rm erg]$$

Evolution of $K_{\rm rad}$ Energy



$$E_{v_{\rm r}} = \int \varepsilon_{v_{\rm r}}(r) d(\ln r), \quad \varepsilon_{v_{\rm r}}(r) = 4\pi r^3 \frac{\rho v_{\rm r}^2}{2} \qquad \log \varepsilon_{v_{\rm r}}(r)$$

Jet lag & Alfven transit time

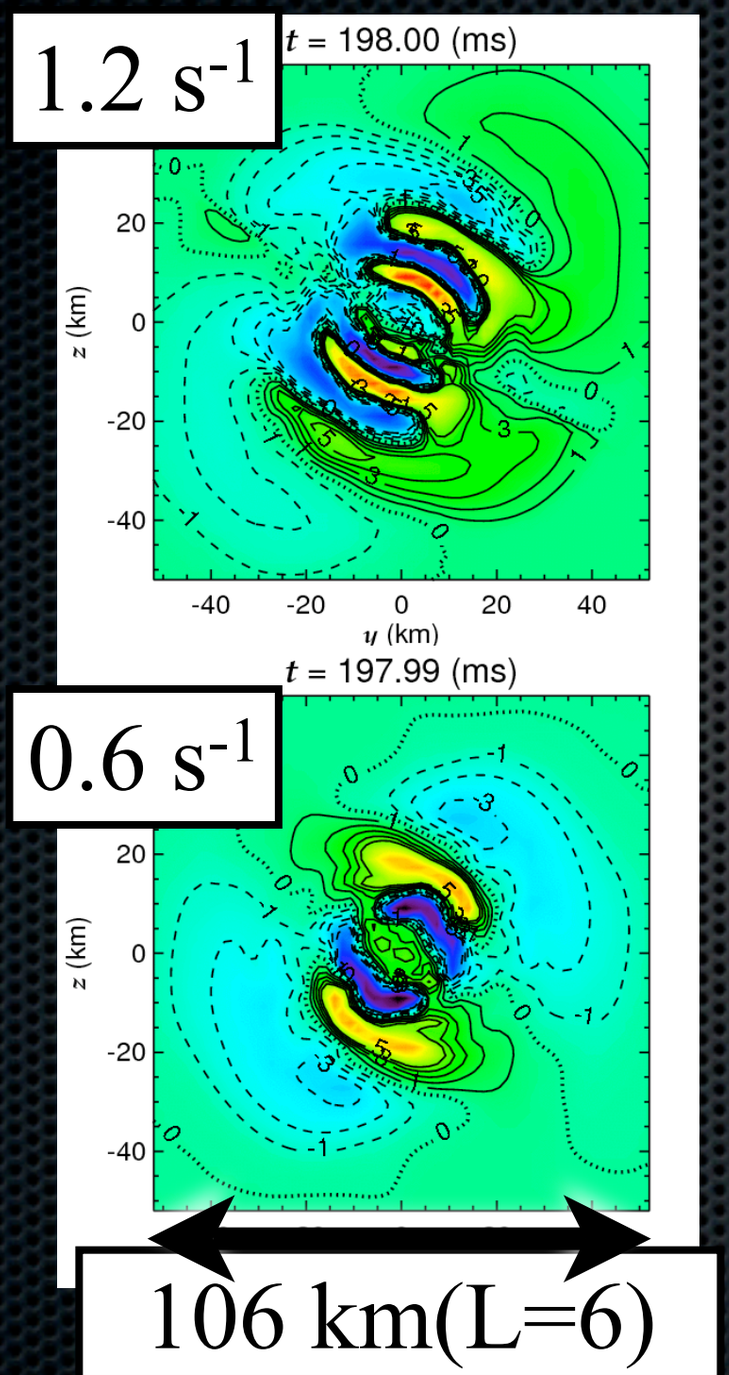
- The lag between the bounce and jet ejection is related to the Alfven transit time.

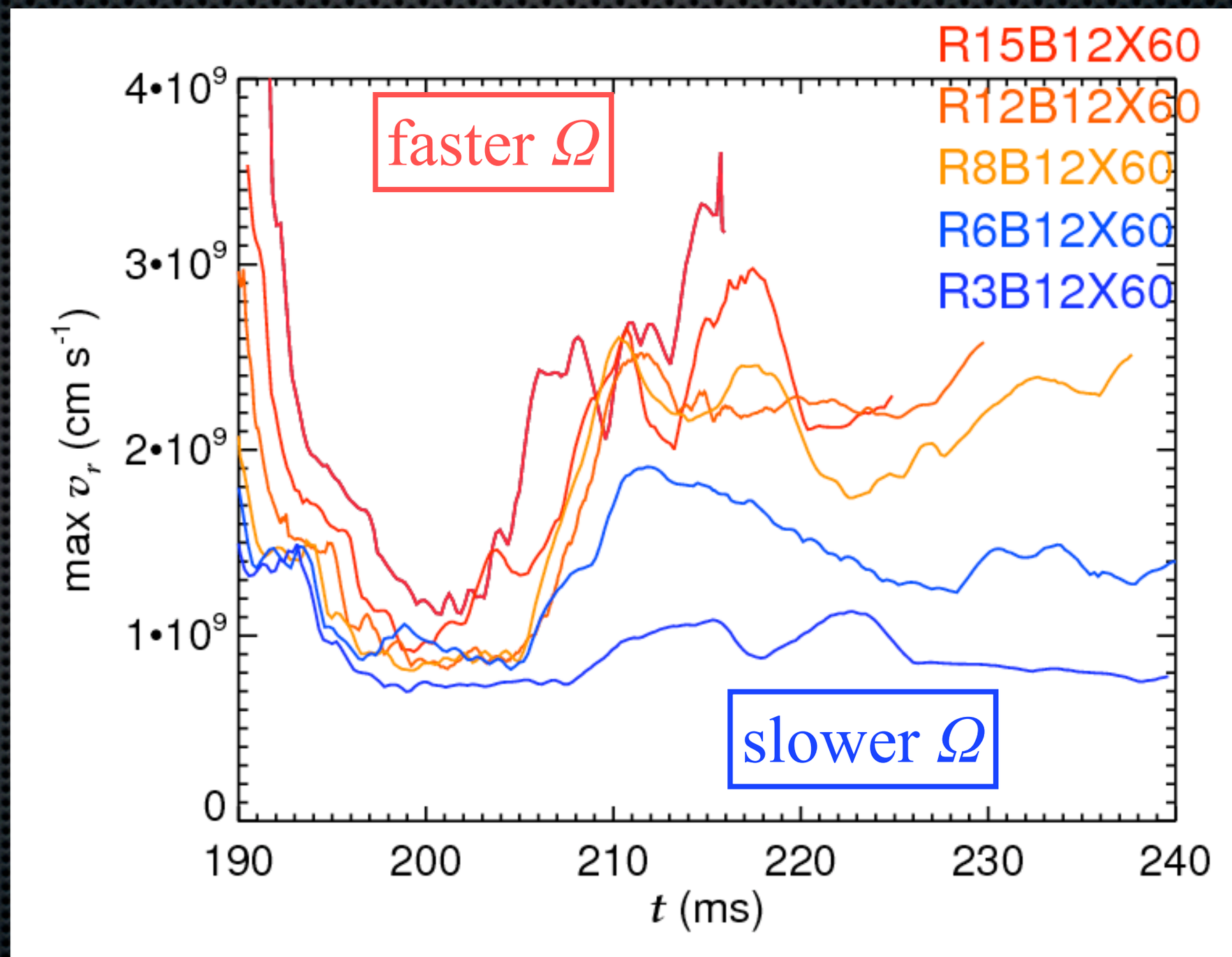
$$\tau_A \equiv \int^{r_j} \frac{1}{v_A} dr$$
$$= \int^{r_j} \frac{\sqrt{4\pi\rho}}{B_r} dr \quad \left(\frac{\sqrt{4\pi\rho}}{B_r} \propto \frac{1}{r} \right)$$
$$\sim 7.7 \text{ ms}$$

- the foot-point of the jets, r_j ~ 60 km
- If the B field is twisted in a deep interior of the PNS,
  - the lag → longer,
  - B energy → larger,
  - jets → stronger

Dependence on Rotation

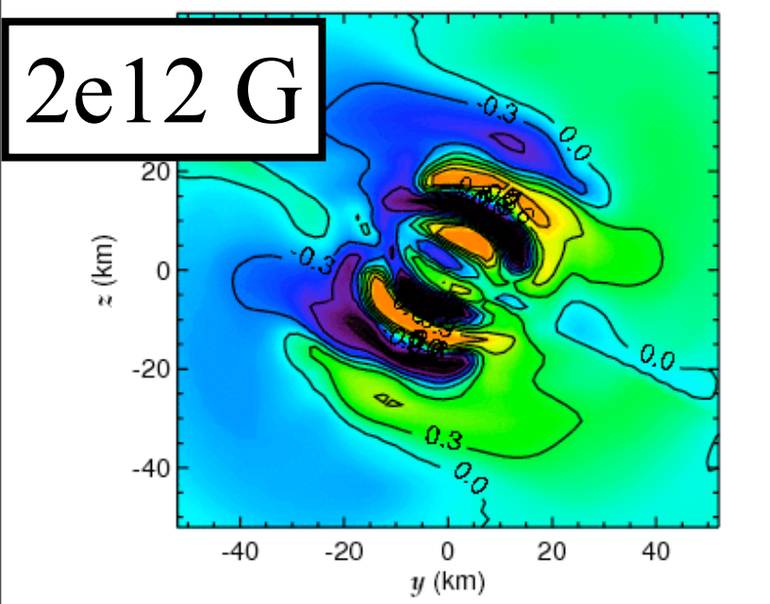
- When Ω_0 is faster, B field is more tightly twisted.
- When Ω_0 is faster, v_r rises earlier and stays at a high level.

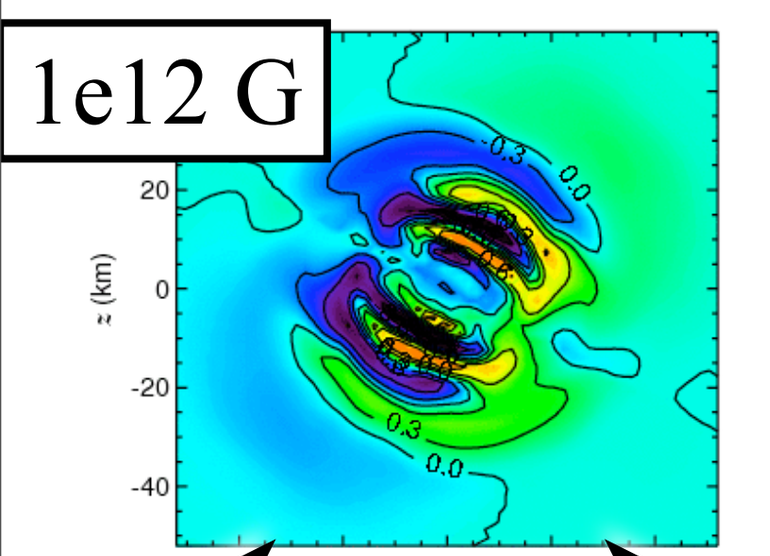




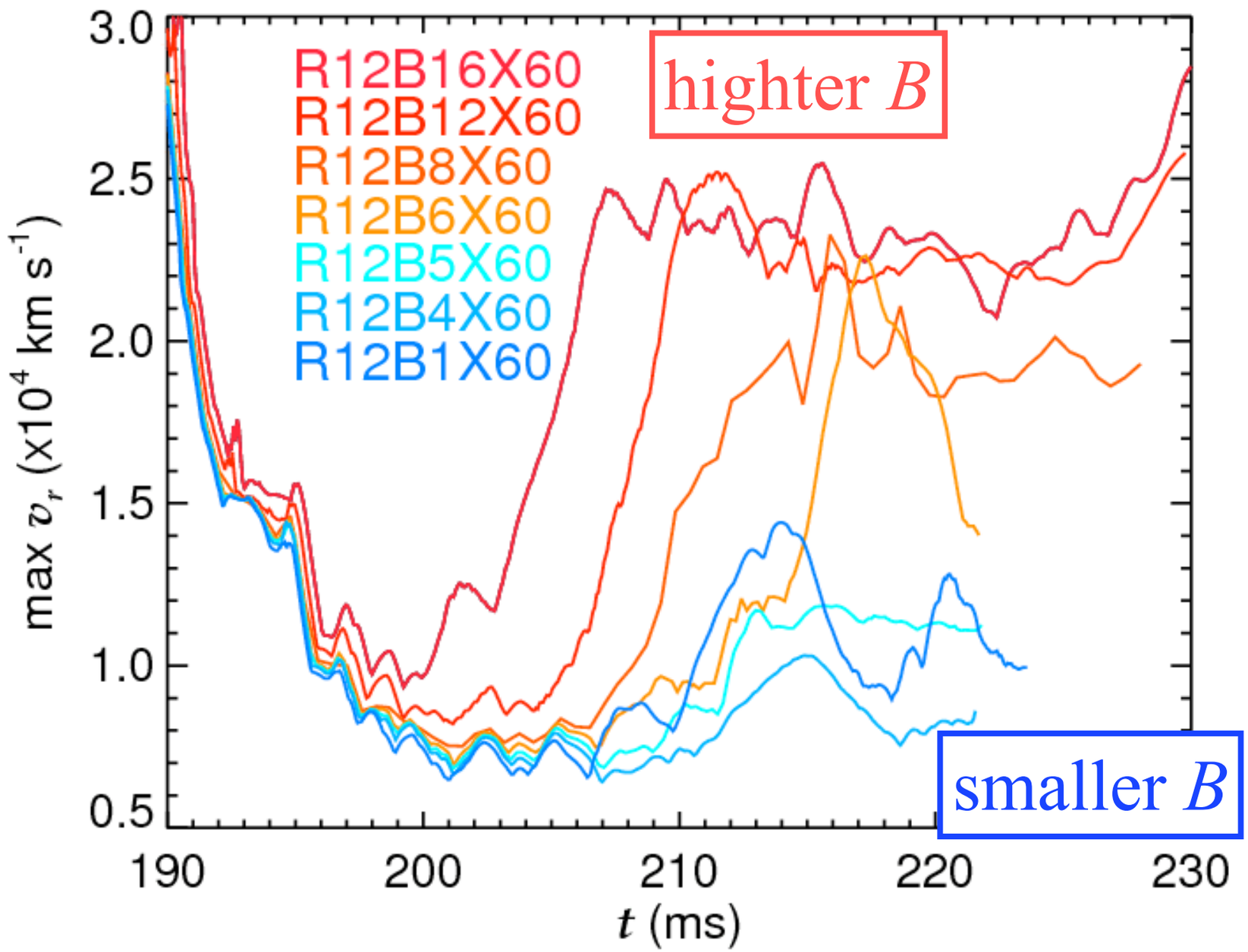
Dependence on B Field

- When B_0 is smaller, B field is more tightly twisted.
- When B_0 is larger, v_r rises earlier and stays at a high level.



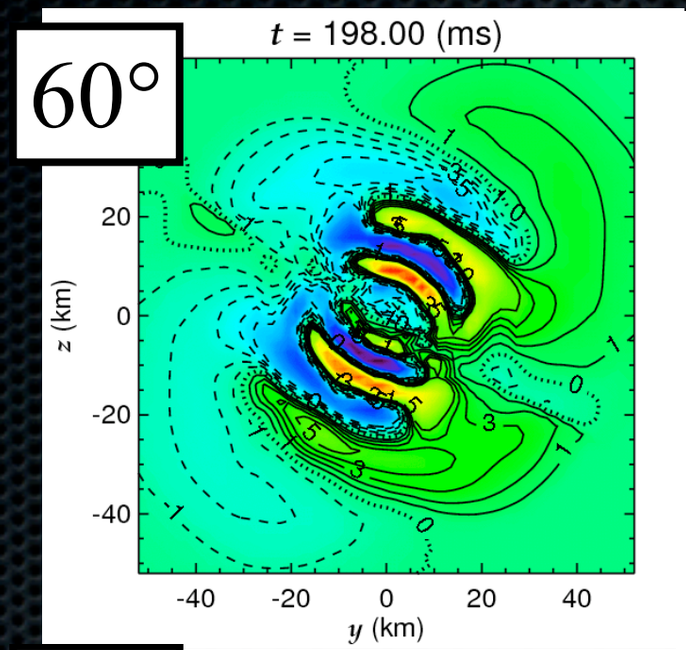


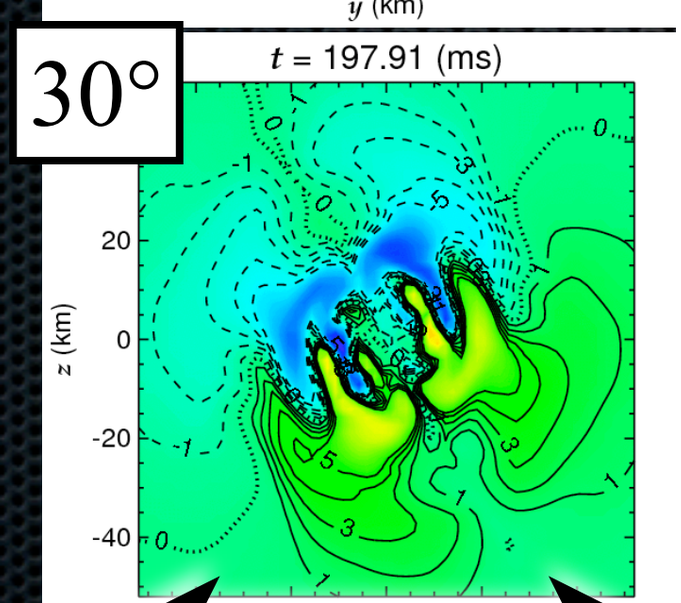
106 km(L=6)



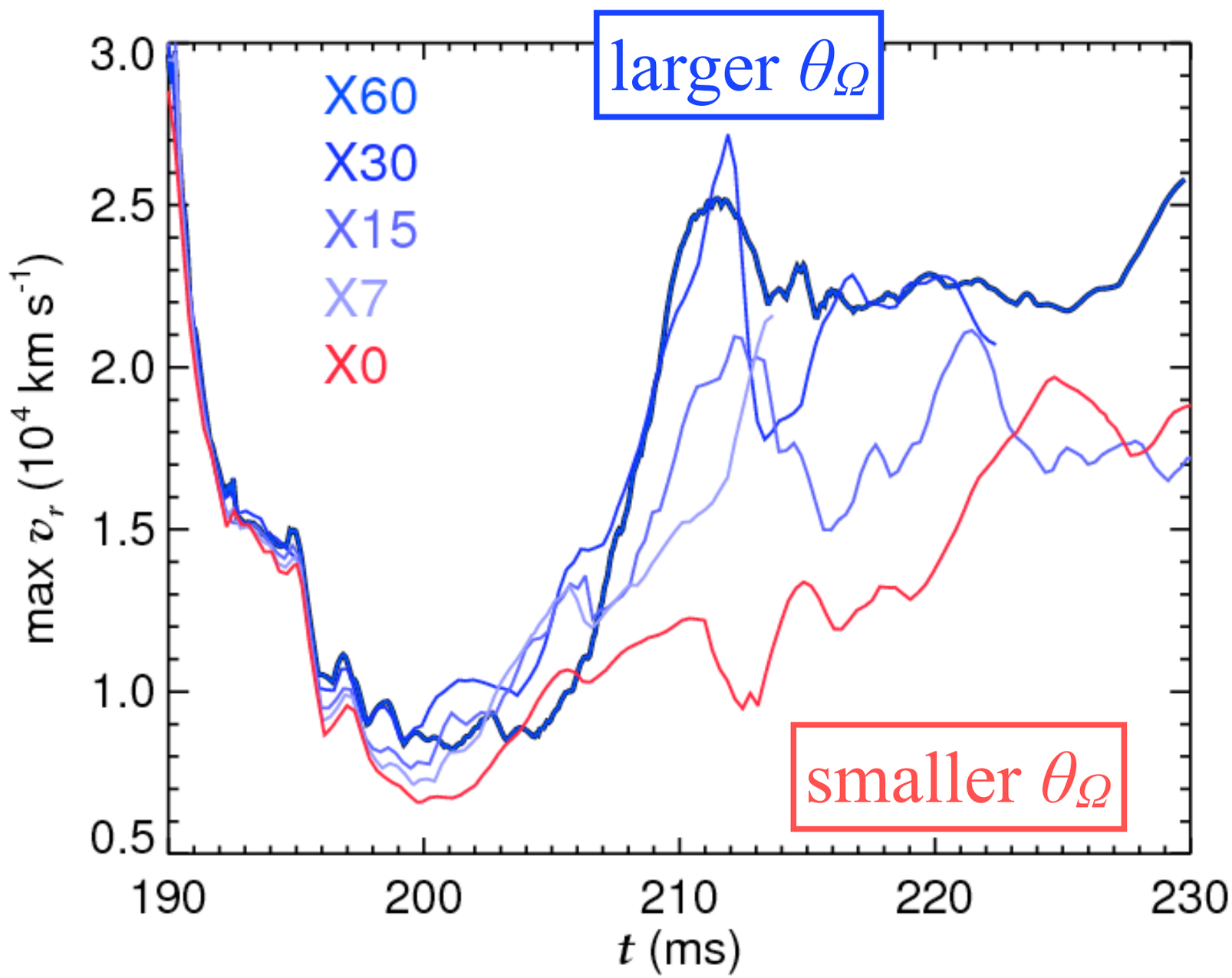
Dependence on inclination

- When θ_Ω is larger, magnetic multi-layers is taller.
- When θ_Ω is larger, vr rises earlier.





106 km(L=6)

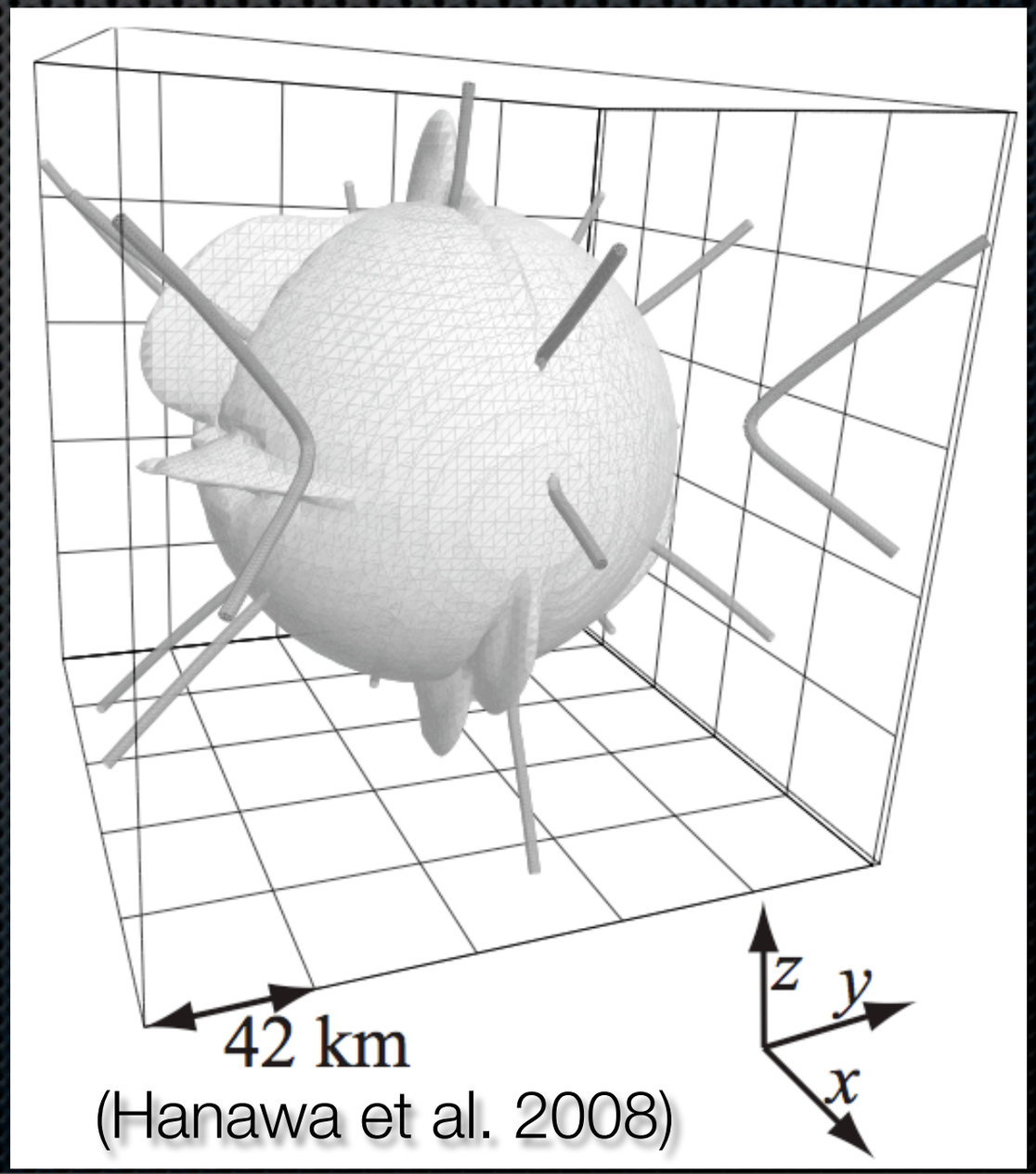


Technical Issues

- Source term of gravity
  - Cell center : spurious heating
  - Cell surface

$$\rho v_i g_i \rightarrow \frac{1}{2}\left(f_{i-1/2} + f_{i+1/2}\right) g_i$$

- Carbuncle Instability
  - additional viscosity : only in the regions where the characteristics of either fast or slow wave converges (Hanawa et al. 2008)



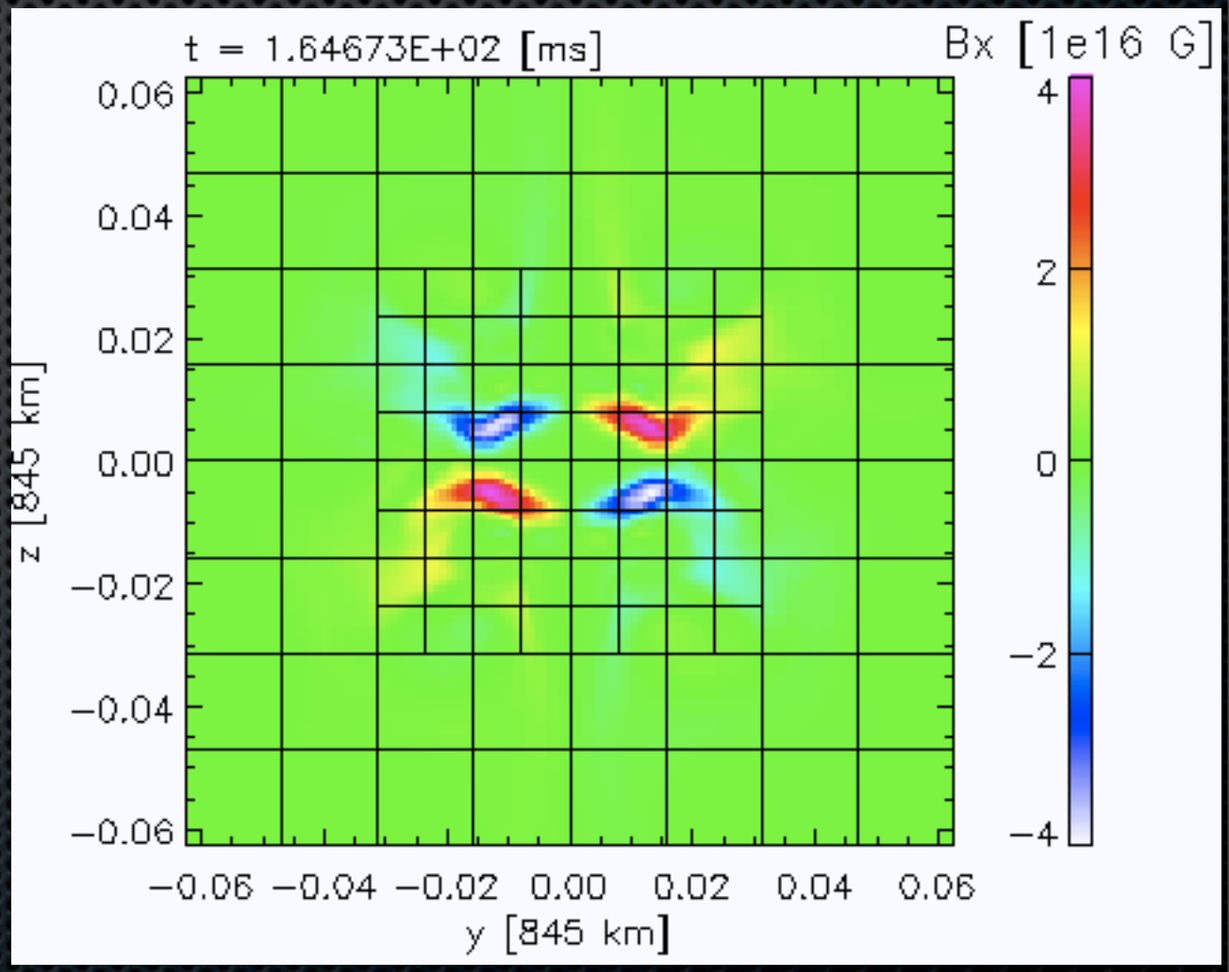
(Hanawa et al. 2008)

Next step

dissipated propagating outward for coarser grid

- Motivation
  - Jets structure
  - Magnetic multi-layer
  - MRI : observed with a spatial resolution of ~120 m (Etienne 2007).
- Sfumato (T. Matsumoto 2007)
  - AMR code for star formation
  - Roe type MHD scheme
  - Self gravity
  - Divergence cleaning
    - Dedner et al. 2002
- Performance
  - Cray XT4 : 64 PE
  - With a resolution of 100 m, 75 hours / 40 ms after core

$2\ ms^{-1}, 10^{15}\ G, 10^{14}\ g\ cm^{-3}$



Conclusions

- The new feature in 3D is B multi-layers. It is formed when the magnetic field is split monopole like and inclined with repect to the rotation axis.
  - B multi-layer more tightly when B0 ↓ or Ω0 ↑.

- MHD bipolar jets
  - Jets are ejected along the rotation axis.
  - B energy is stored on the sphere of r = 20 km and jets are launched from r = 60 km.
  - Jets emerge earlier when B0 ↑, Ω0 ↑, or θΩ ↑.

- Coming soon, the 3D MHD simulation for CCSN with AMR.