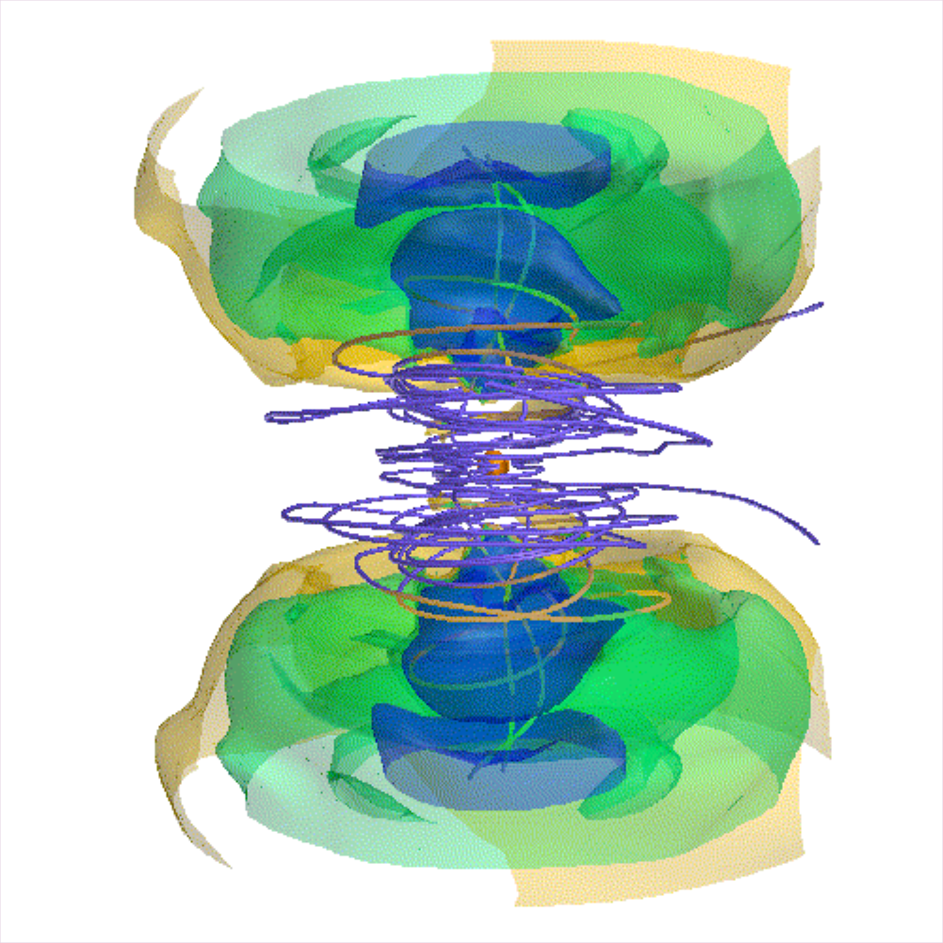
3D-MHD jets production in core-collapse supernovae explosions

Hayato Mikami
(Chiba Univ.)

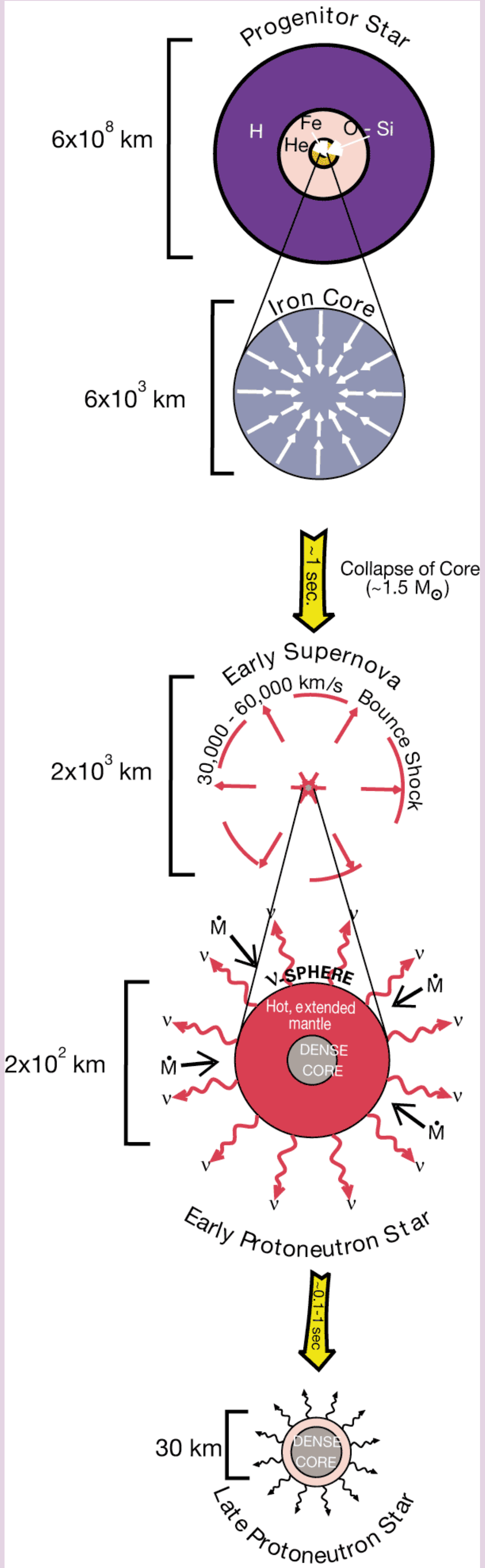


Tomoaki Matsumoto (Hosei Univ.)
Tomoyuki Hanawa (Chiba Univ.)

Introduction

- Core Collapse Supernova = Aspherical
  - Observation evidences
    ➡ Bipolar explosion
  - Earlier 2D MHD simulations
    ➡ Bipolar jet

- The 3D effect by the magnetic field inclined to the core rotation axis
  - What's new in 3D?
  - Which is the jet direction?
  - When is the jet ejected?
  - Where is the foot point of jets?



(Burrows, 2000)

Model

- Ideal MHD Equation

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

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

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

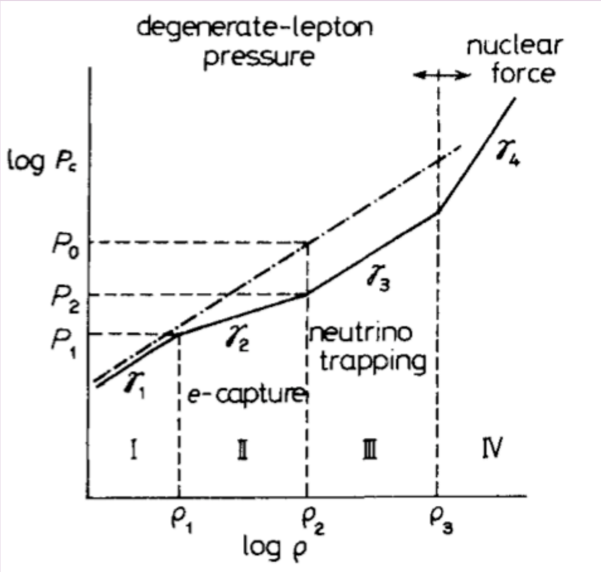
$$g = -\nabla \Phi$$

- Self Gravity

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

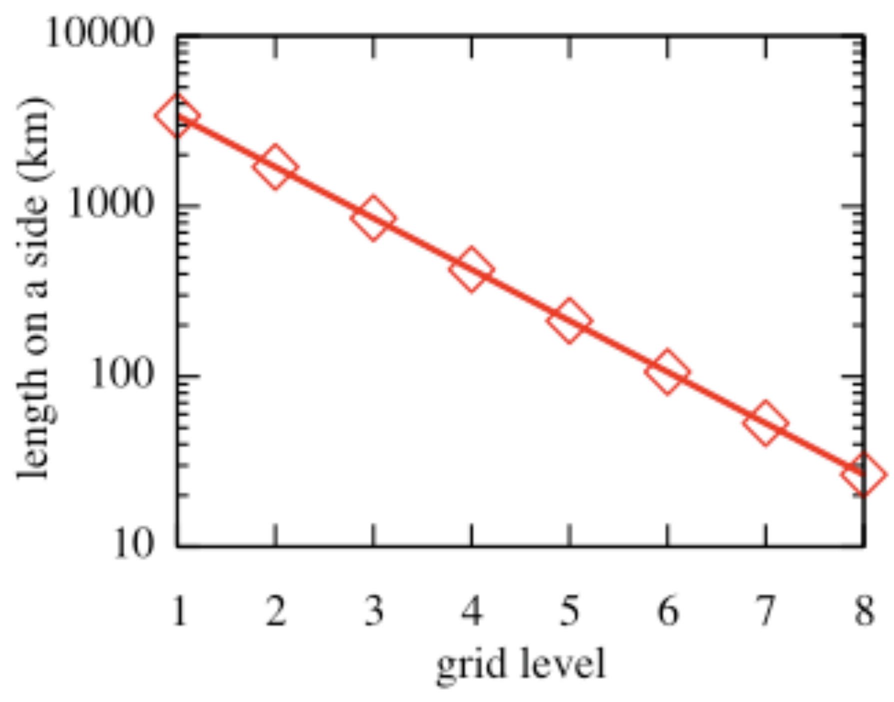
- EOS : simplified (Takahara & Sato. 1982)

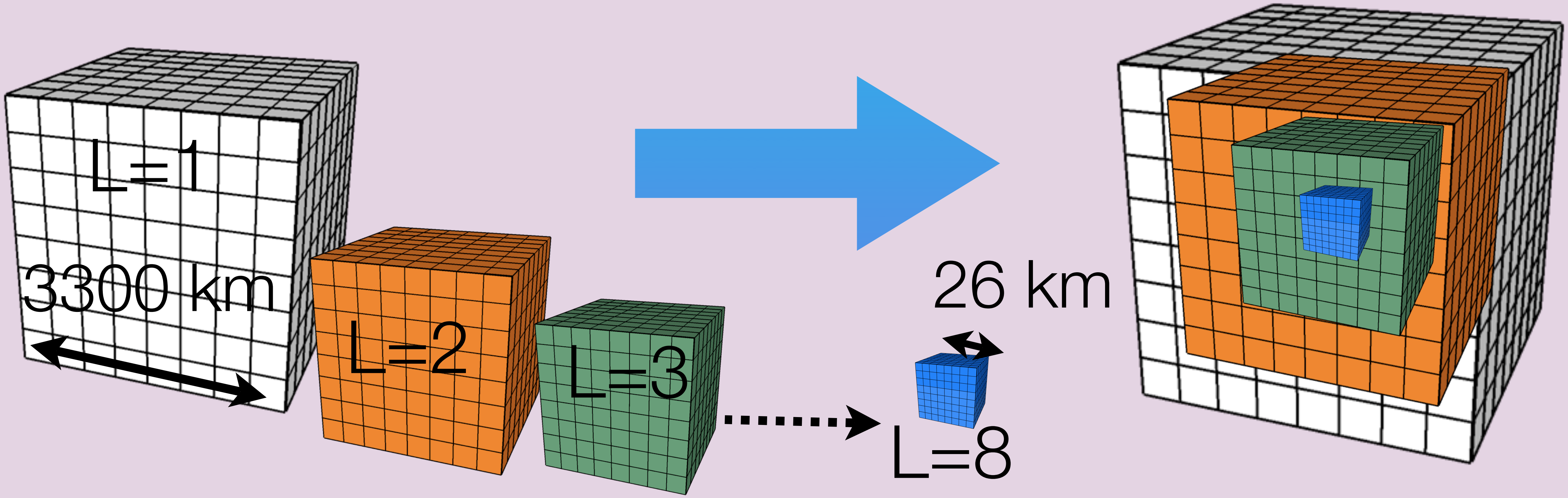
$$\begin{aligned} P &= P_c + P_t \\ P_t &= \frac{\rho \varepsilon_t}{\gamma_t - 1} \\ P_c &= K_i \left(\frac{\rho}{\rho_i}\right)^{\gamma_i} \end{aligned}$$



Method

- Nested Grid Method
  - 8 (concentric grids) × 64^3 cells
  - Largest grid : 3393 km on a side
  - Finest resolution : 413 m
- Roe-type Scheme
  - A shock capturing scheme
  - Care for carbuncle instability





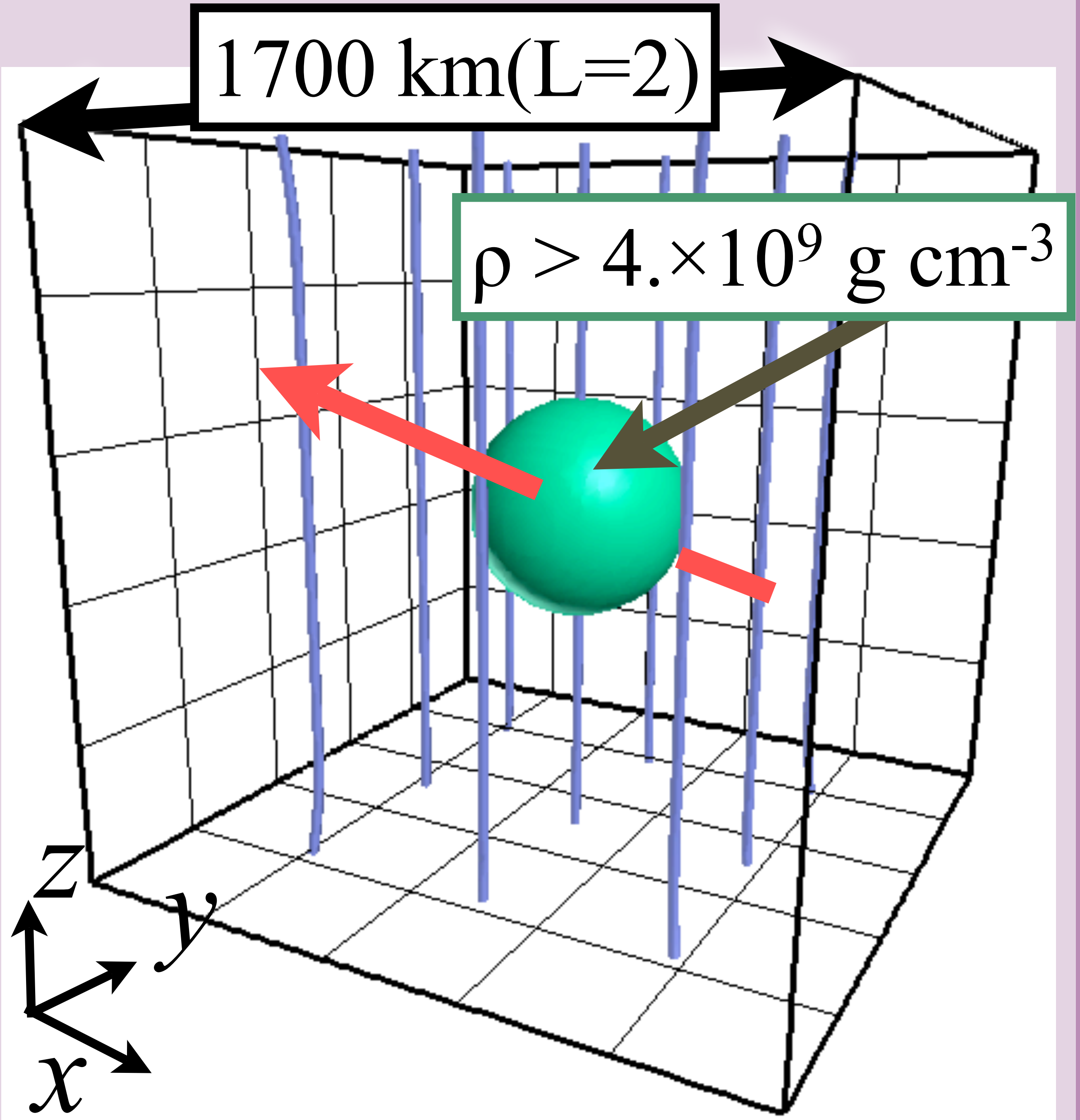
Initial Condition

- 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

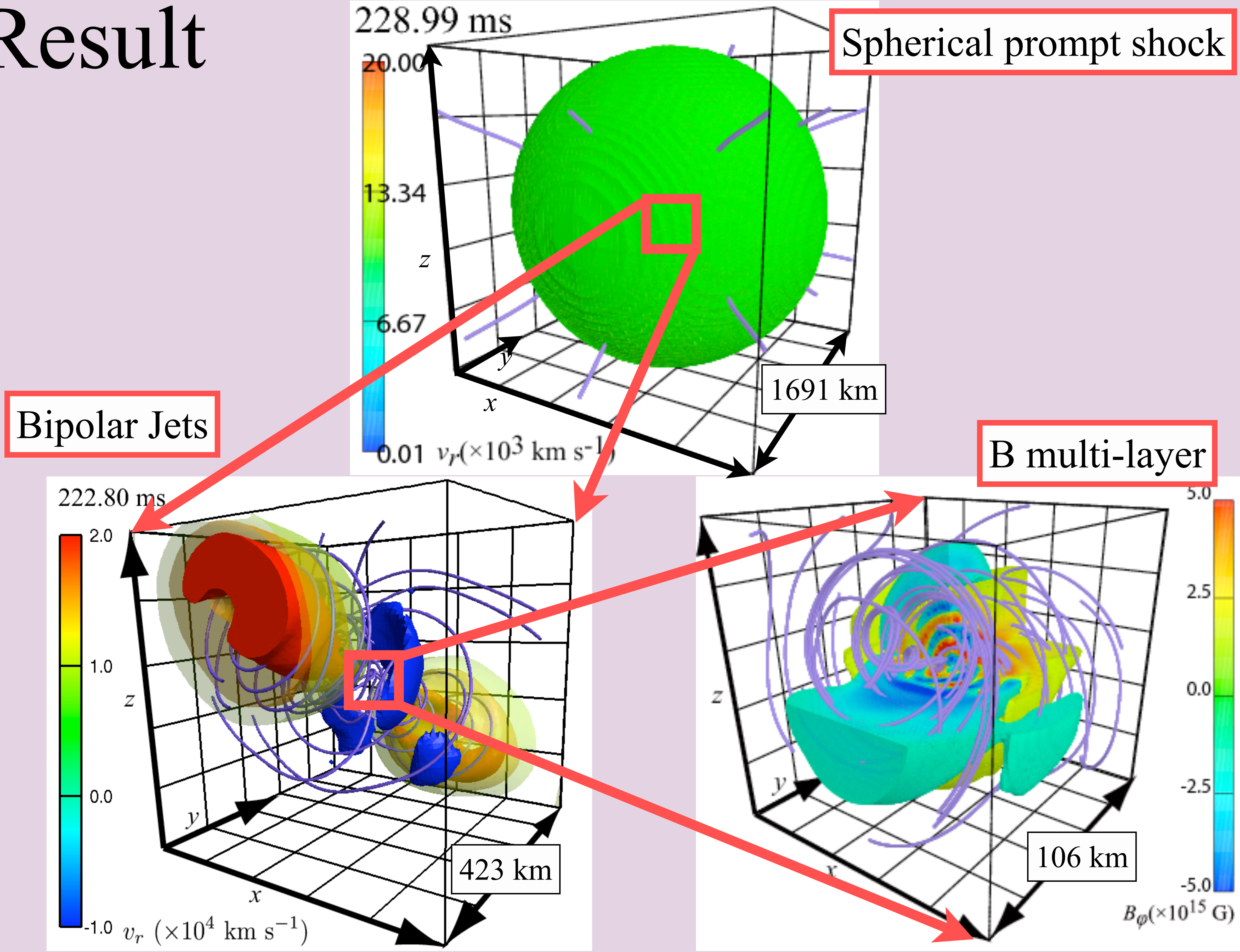
$$\Omega_0(r) = \frac{\Omega_c a^2}{r^2 + a^2}$$

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

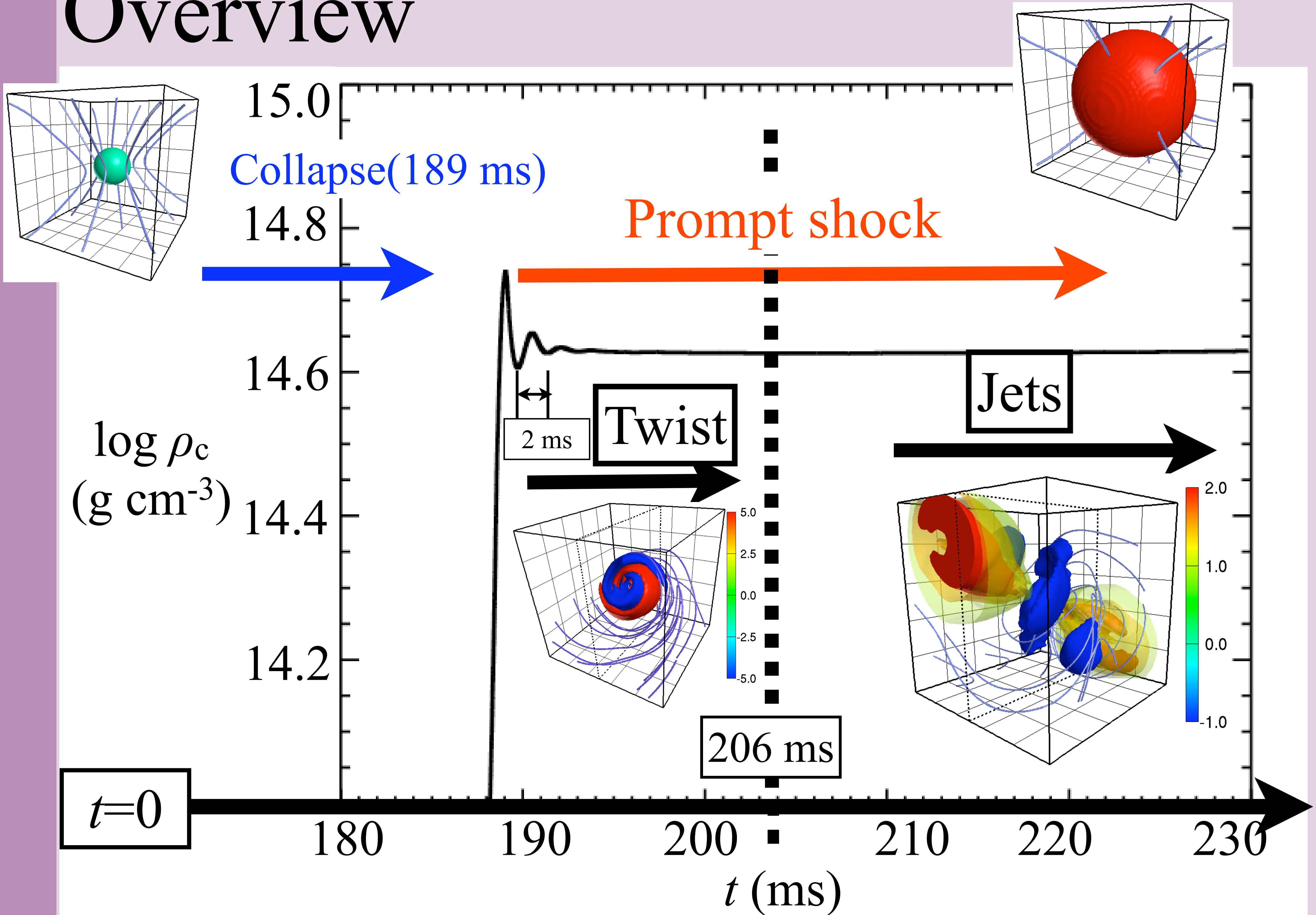
Code: No symmetry assumed
Initial : Point symmetry



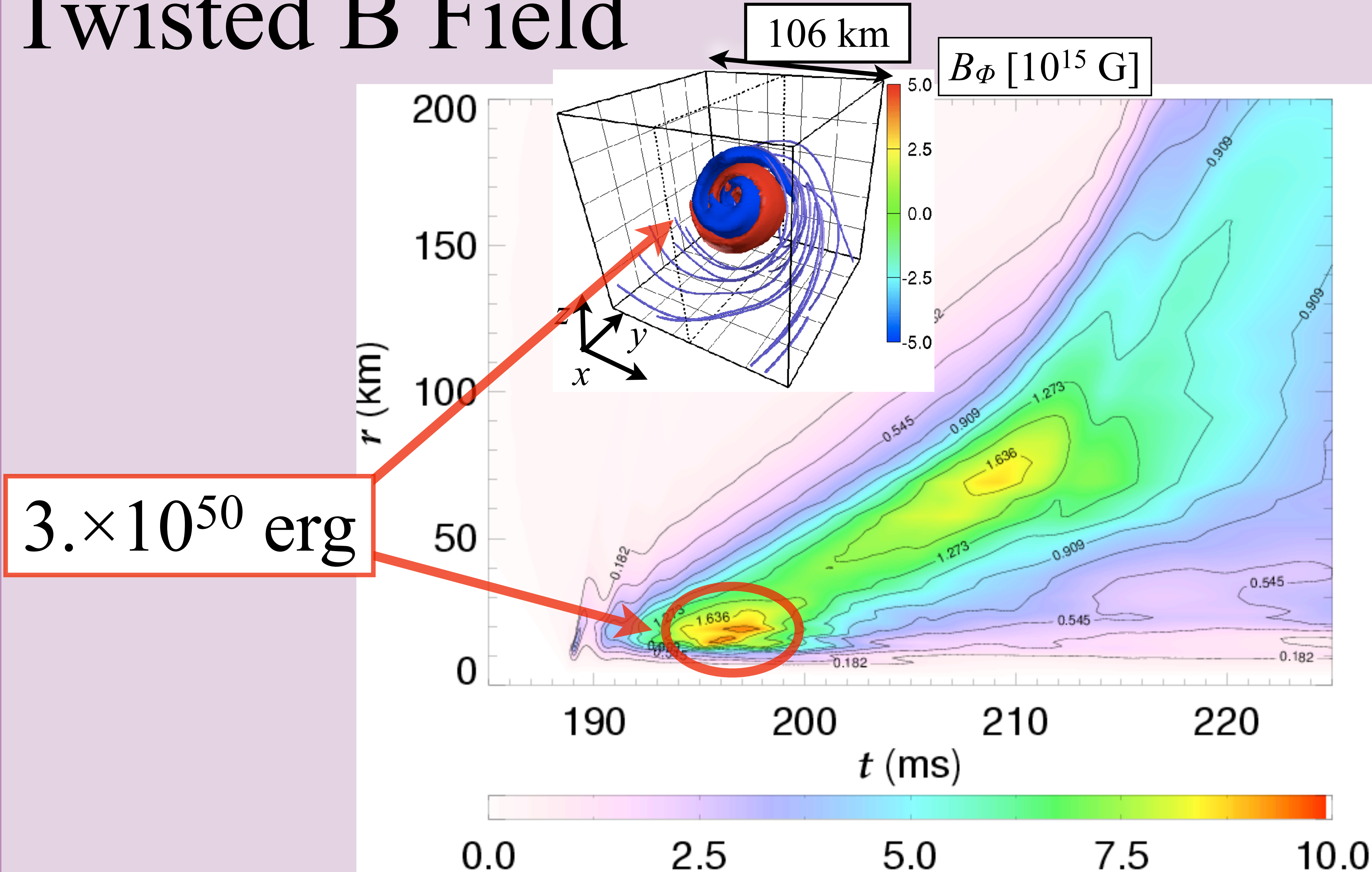
Result


228.99 ms
Spherical prompt shock
20.00
13.34
6.67
0.01 v_r(×10^3 km s^{-1})
1691 km
Bipolar Jets
B multi-layer
222.80 ms
2.0
1.0
0.0
-1.0 v_r (×10^4 km s^{-1})
423 km
5.0
2.5
0.0
-2.5
-5.0
B_φ(×10^{15} G)
106 km

Overview

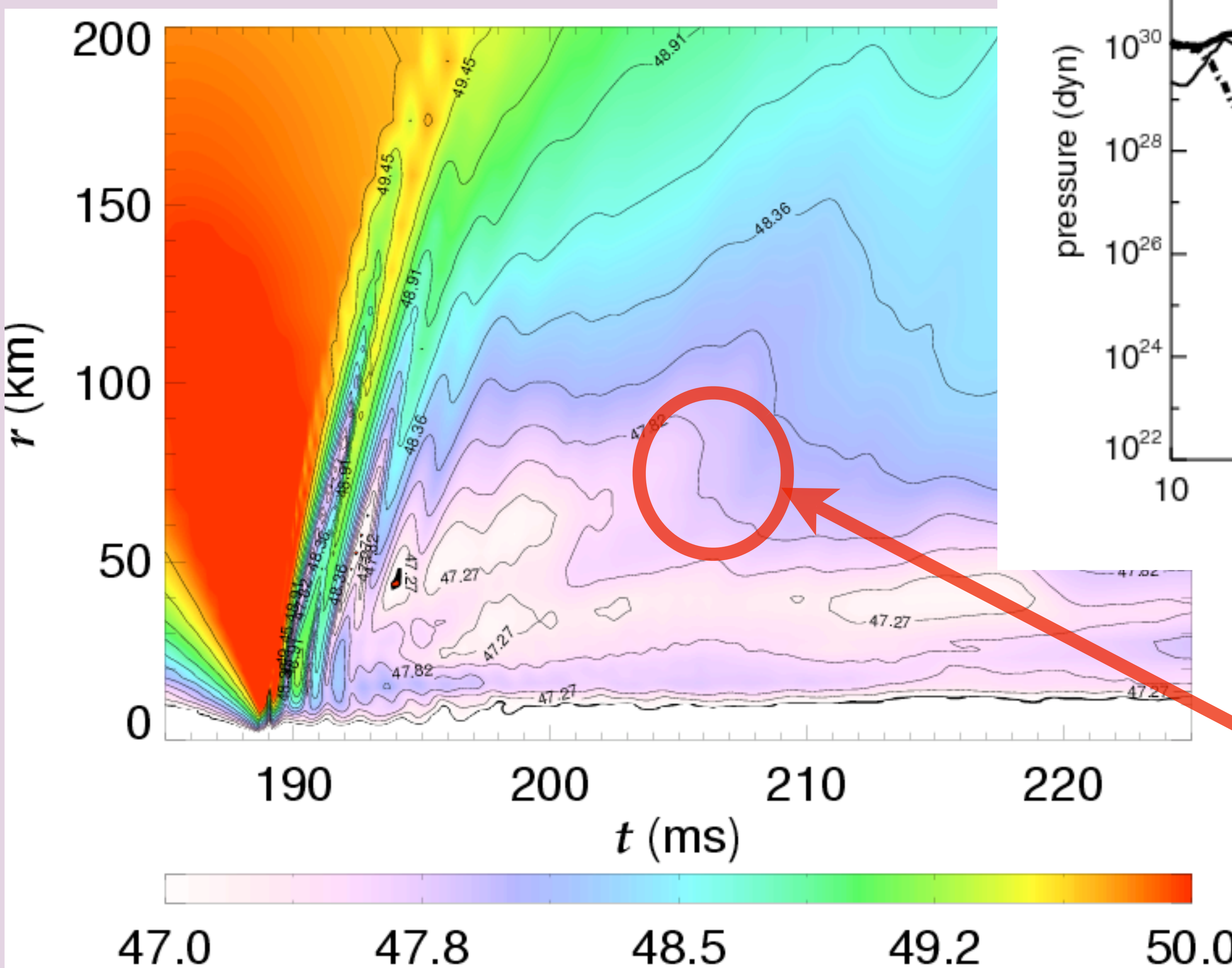

Collapse(189 ms)
Prompt shock
Twist
Jets
2 ms
206 ms
t=0
log ρc (g cm-3)
15.0
14.8
14.6
14.4
14.2
180
190
200
210
220
230
t (ms)
5.0
2.5
0.0
-2.5
-5.0
2.0
1.0
0.0
-1.0

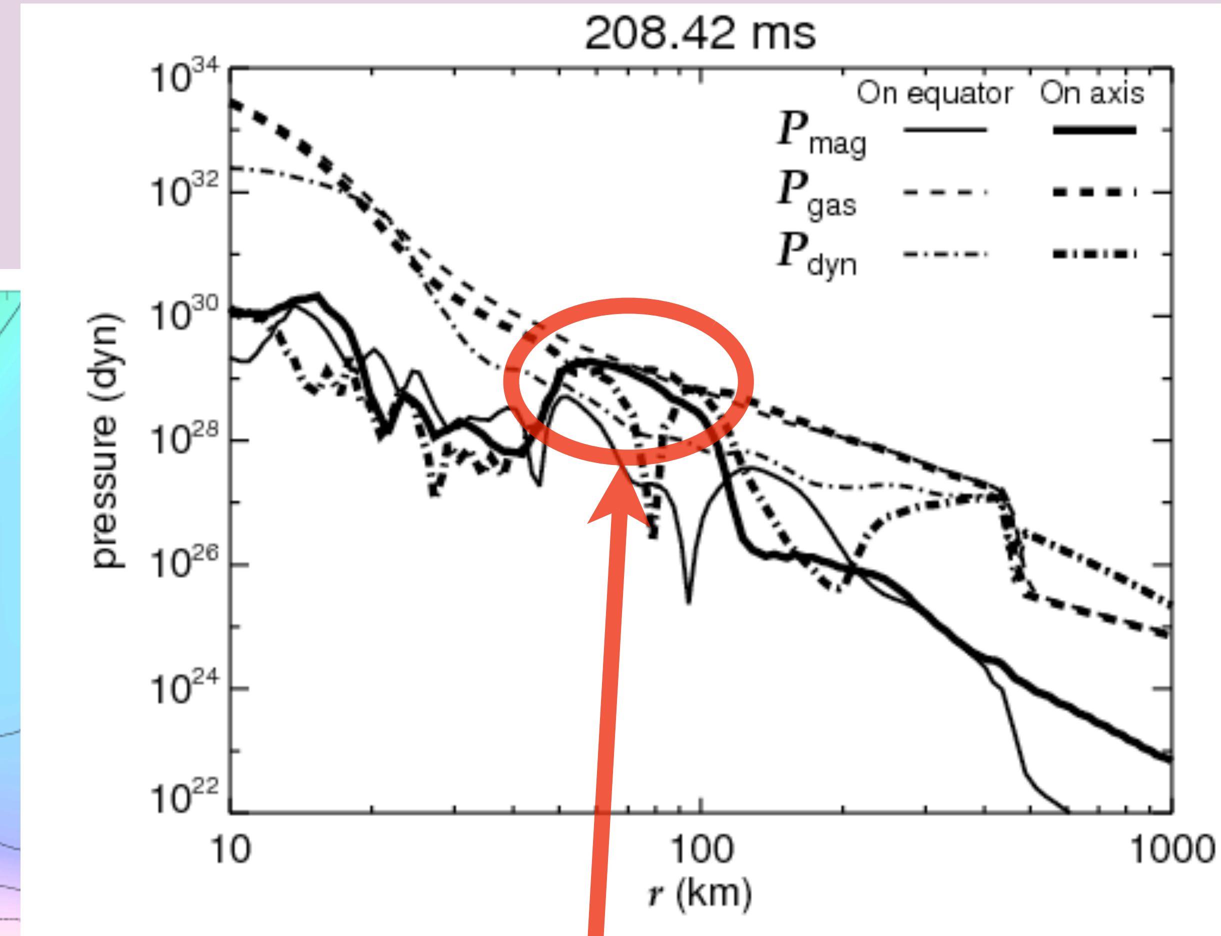
Twisted B Field



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

K_r & Pressure distribution





Magnetic pressure dominates.

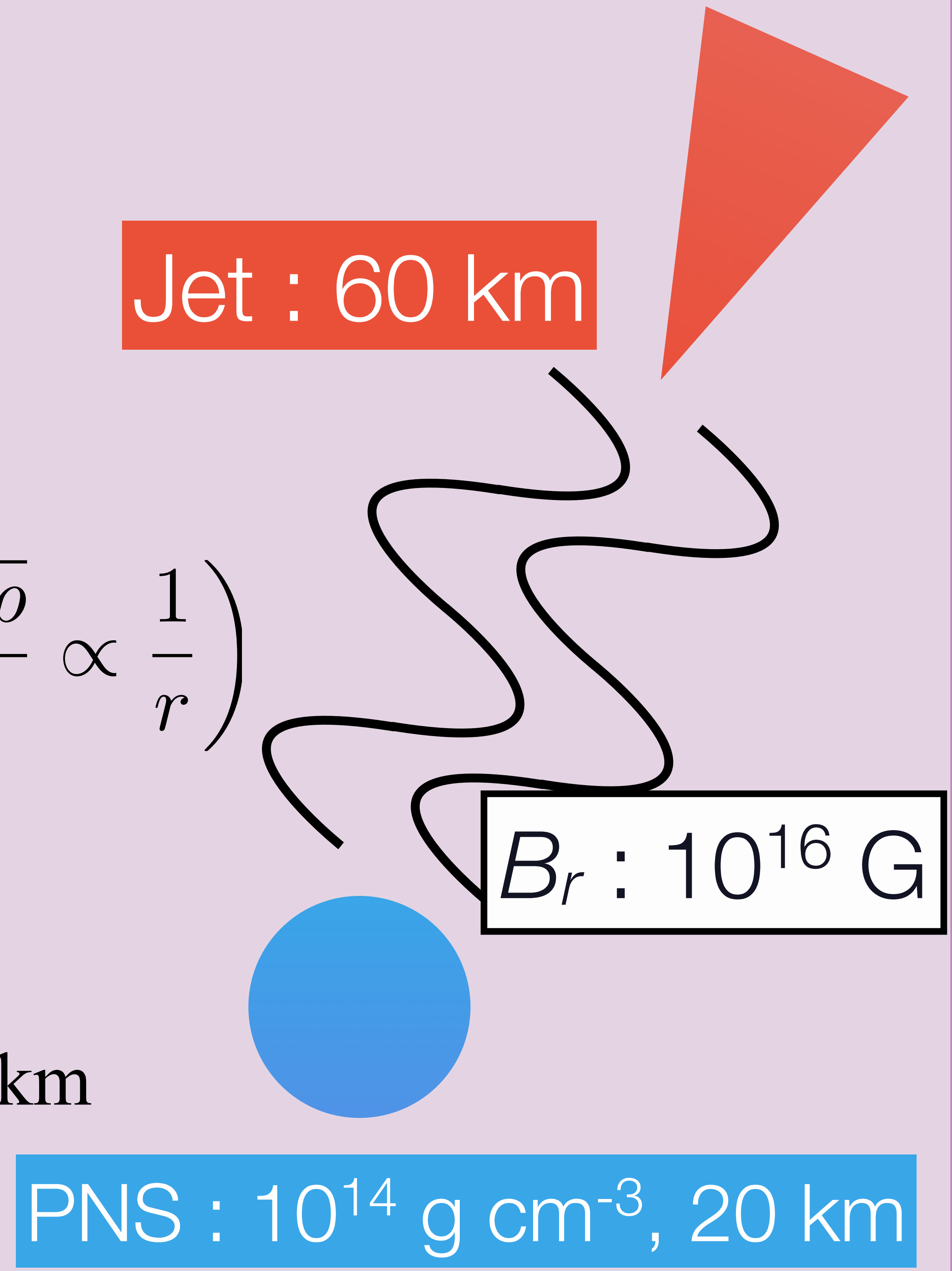
$$E_{v_r} = \int \varepsilon_{v_r}(r) d(\ln r), \quad \varepsilon_{v_r}(r) = 4\pi r^3 \frac{\rho v_r^2}{2} \quad \log \varepsilon_{v_r}(r)$$

Jet lag & Alfvén transit time

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

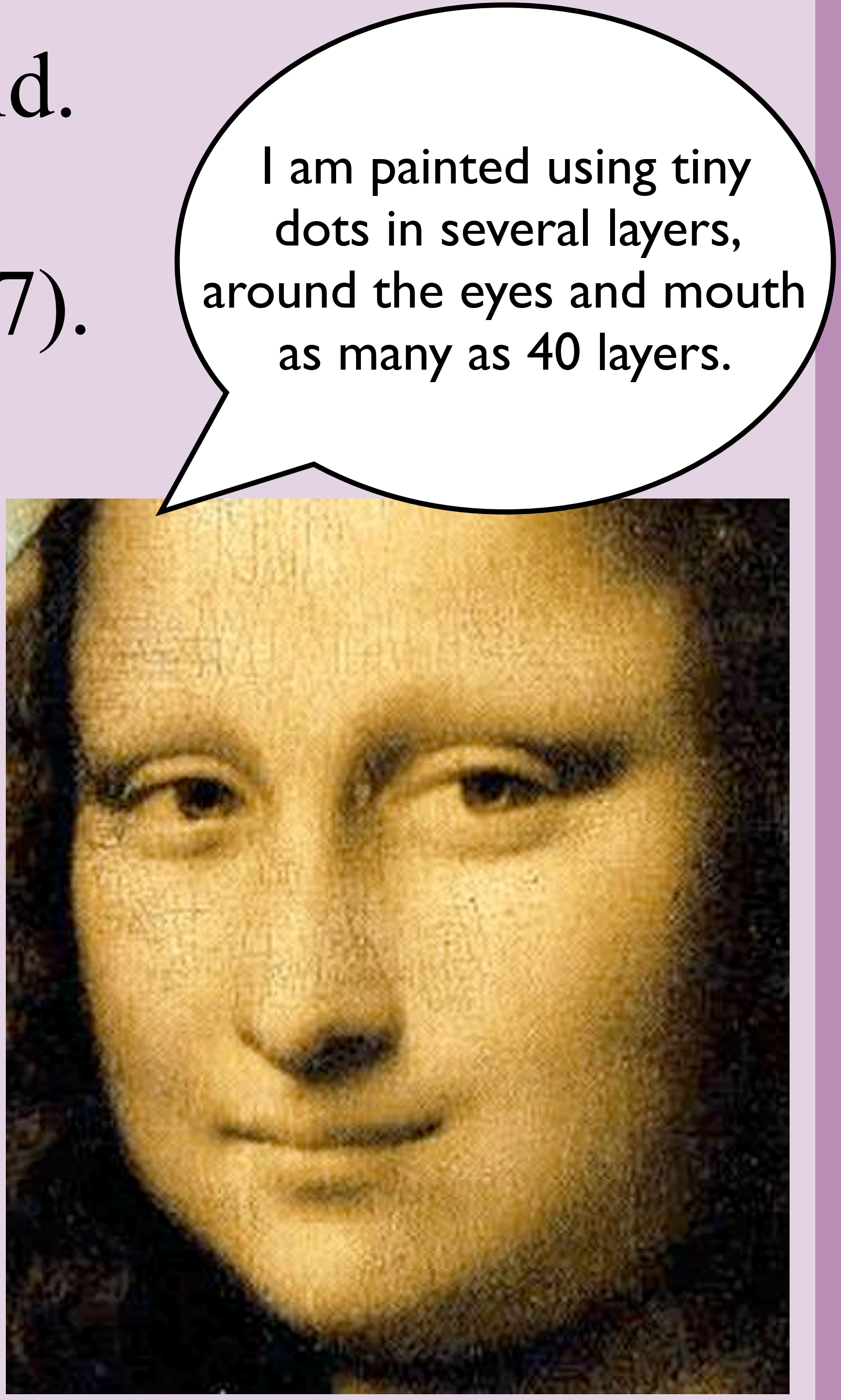
$$
\begin{aligned}
\tau_A &\equiv \int^{r_j} \frac{1}{v_A} dr \\
&= \int^{r_j} \frac{\sqrt{4\pi\rho}}{B_r} dr \quad \left(\frac{\sqrt{4\pi\rho}}{B_r} \propto \frac{1}{r} \right) \\
&\sim 7.7 \text{ ms}
\end{aligned}
$$

the foot point of the jets, $r_j \sim 60$ km

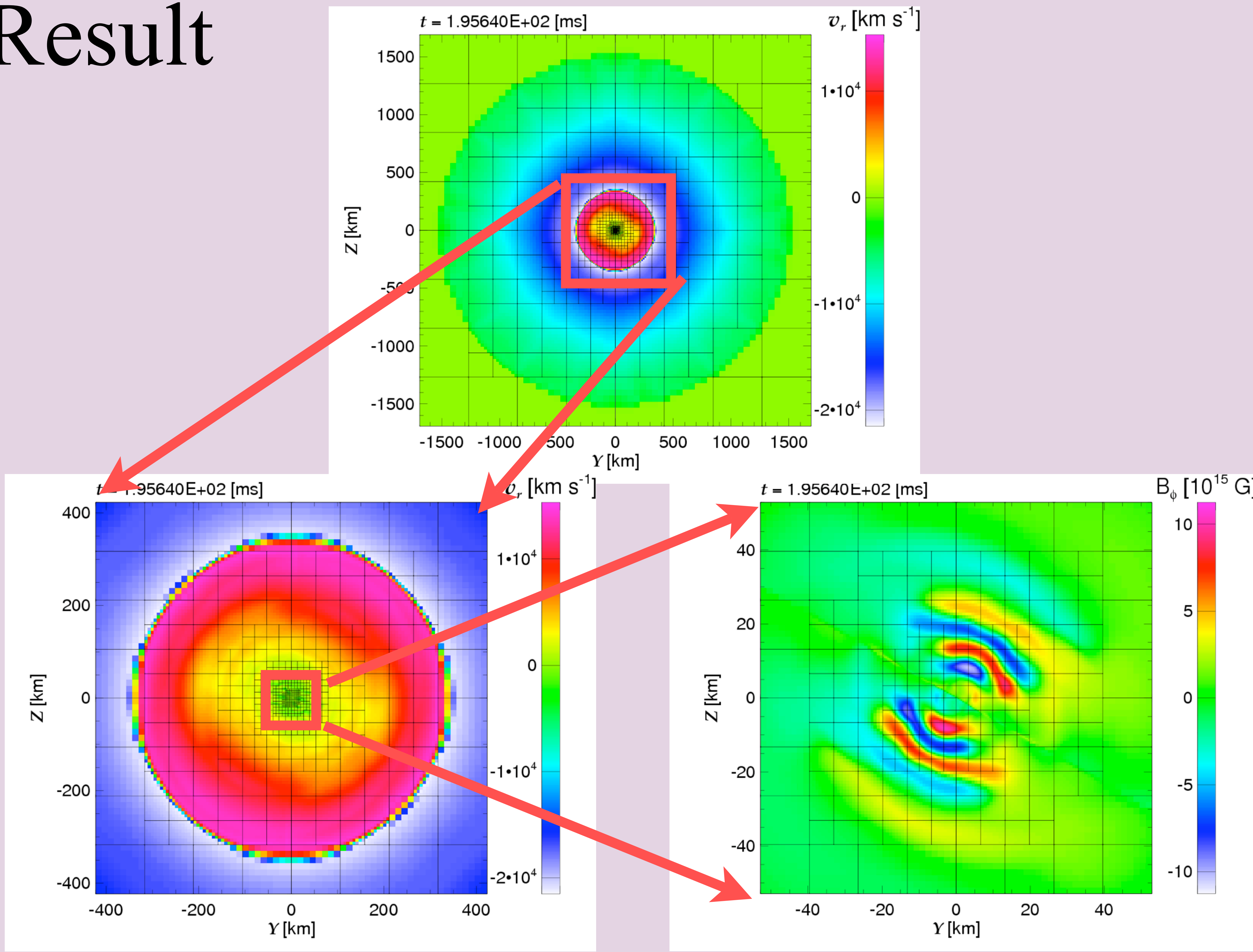


Next Step

- Motivation
  - Jets & B multi-layer : dissipated propagating outward for coarser grid.
  - 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)



Result



Hayato Mikami

Conclusion

- 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.
- MHD bipolar 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.