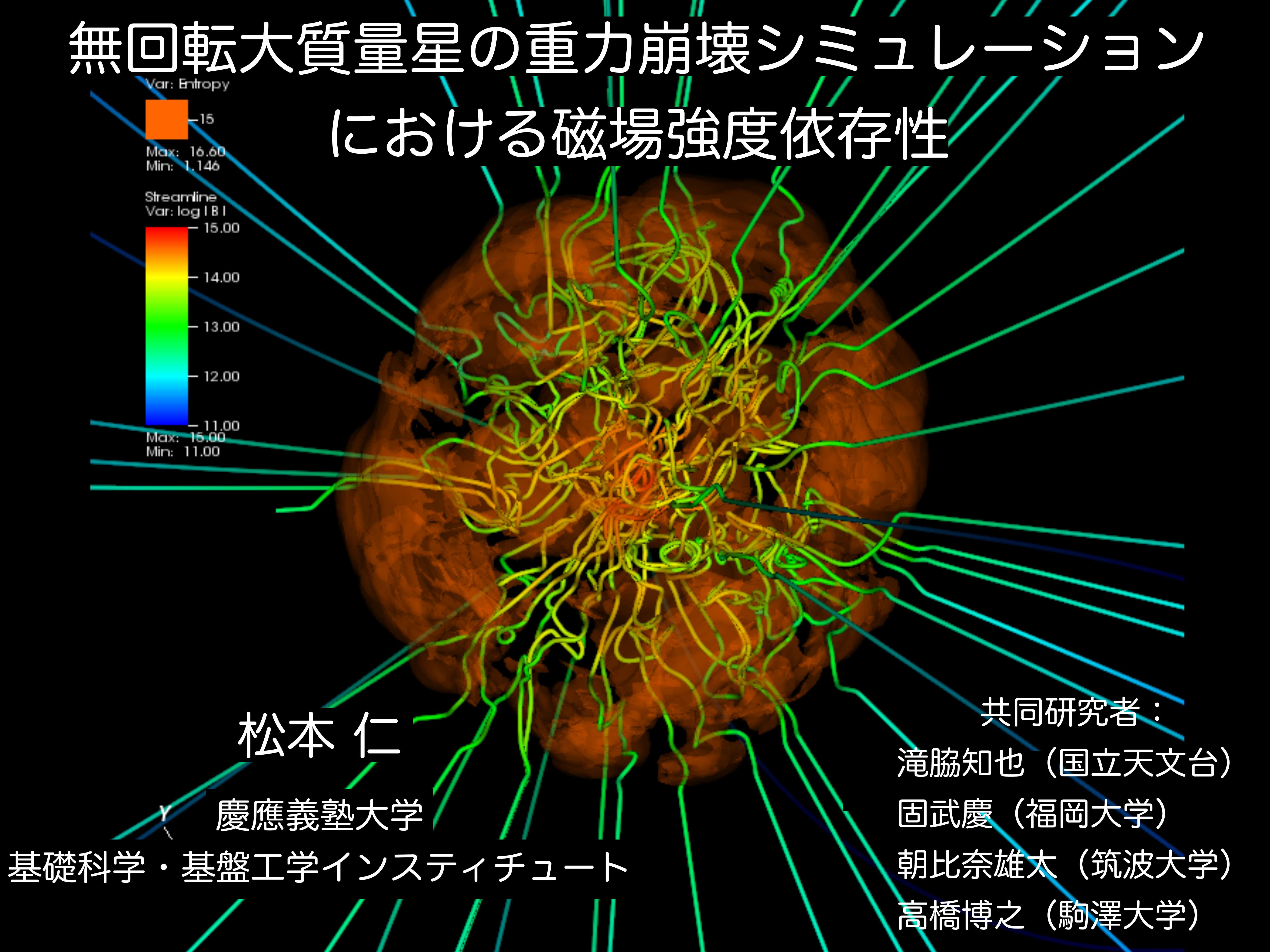
無回転大質量星の重力崩壊シミュレーションにおける磁場強度依存性



松本 仁

慶應義塾大学
基礎科学・基盤工学インスティテュート

共同研究者：
滝脇知也（国立天文台）
固武慶（福岡大学）
朝比奈雄太（筑波大学）
高橋博之（駒澤大学）

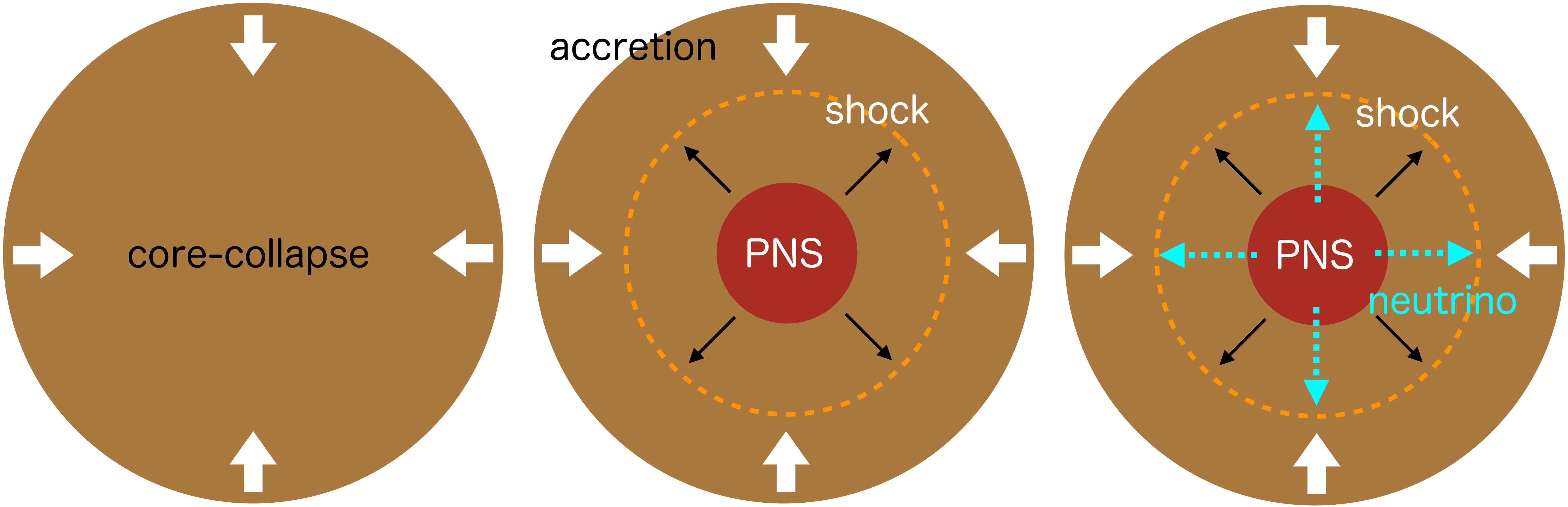
Neutrino-heating

- Core-collapse supernova (CCSN): massive star (> 8 solar mass)
- Explosion mechanism: neutrino-heating??

center of massive star
Fe core

shock after bounce

Explosion occurs when shock reaches to outer layer of core.



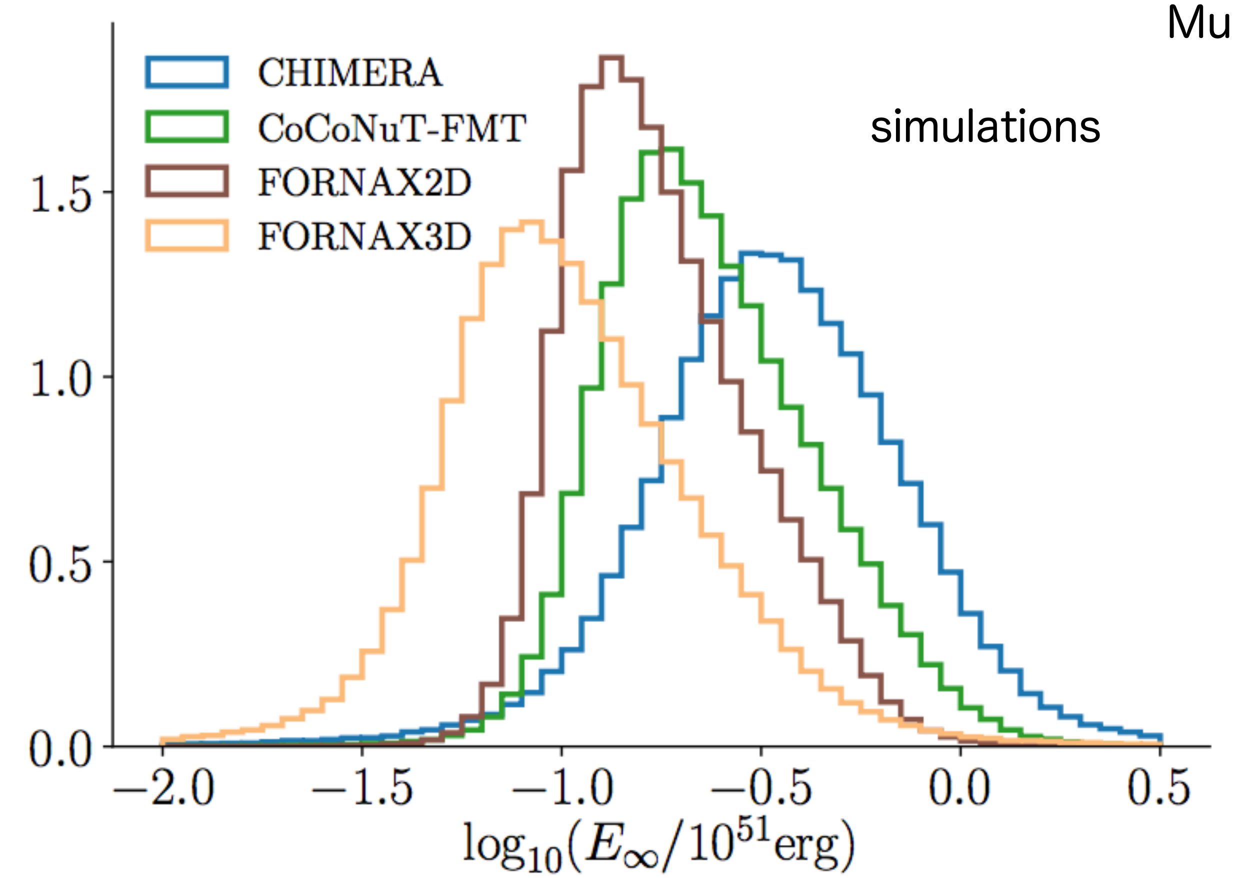
Extensive numerical simulations have been conducted.

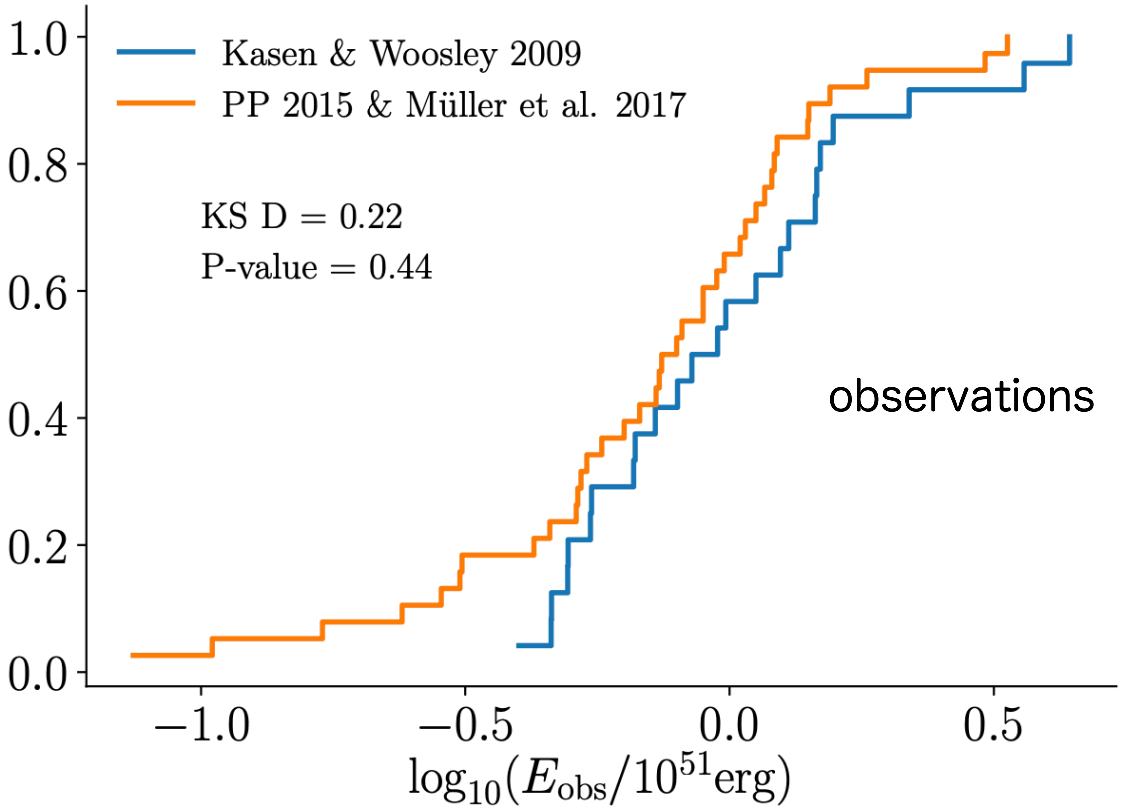
Neutrinos from PNS heat the material behind the stalled shock.

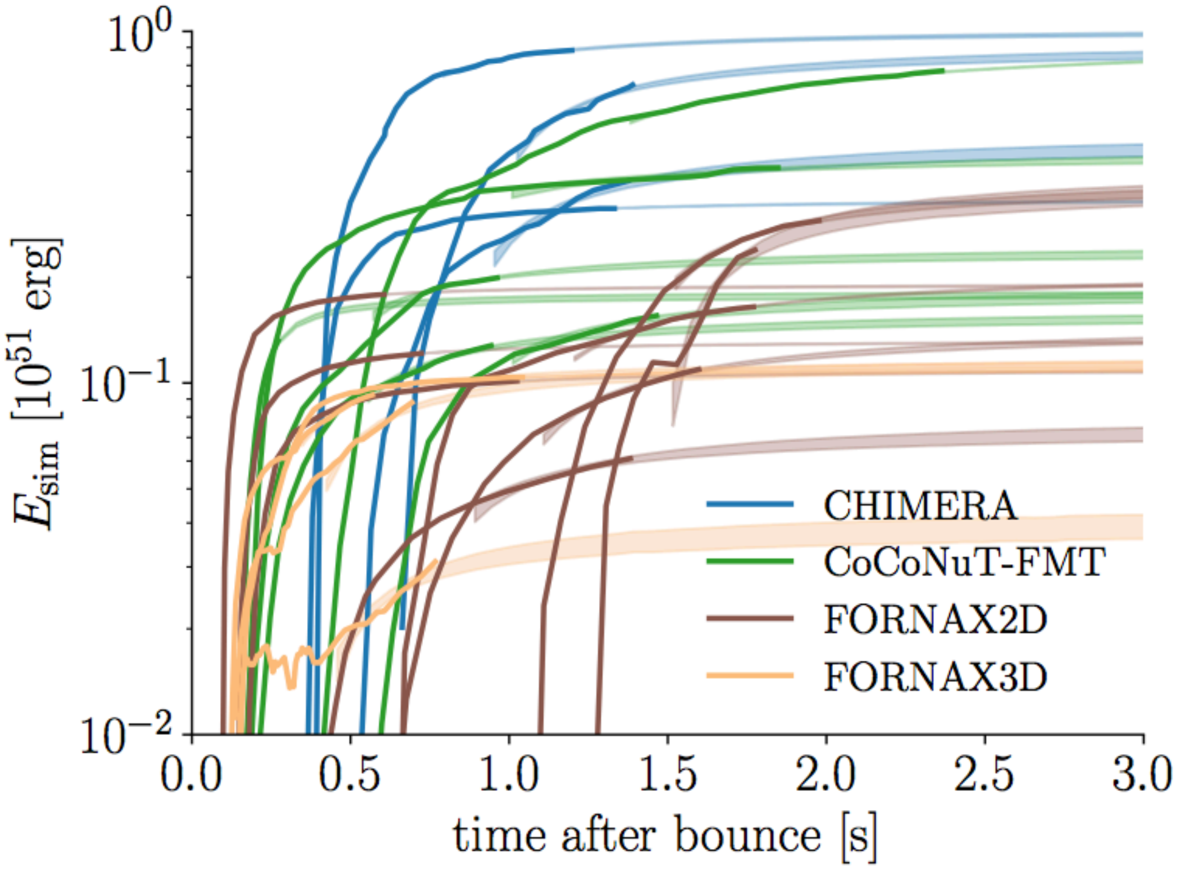
It is not easy to reproduce the canonical explosion energy of CCSNe.

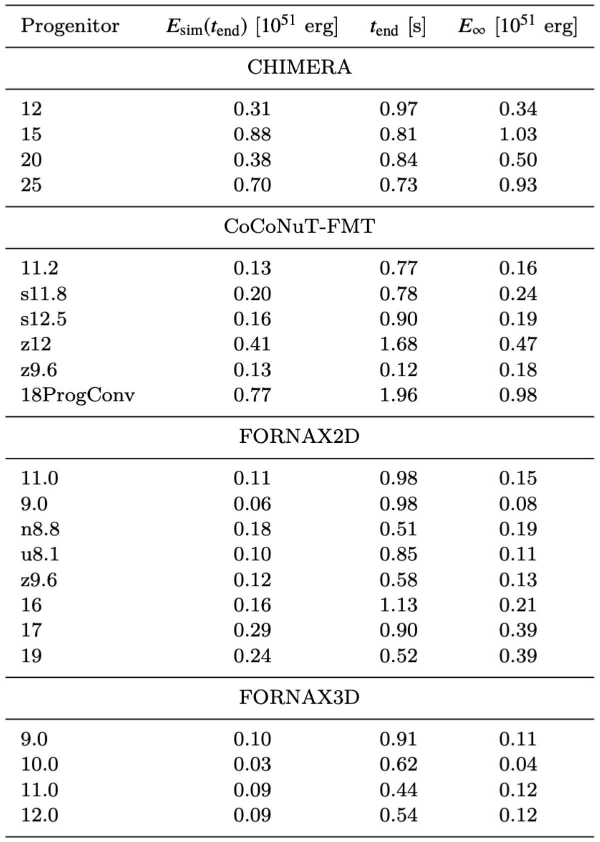
Simulation vs Observation

Murphy+19









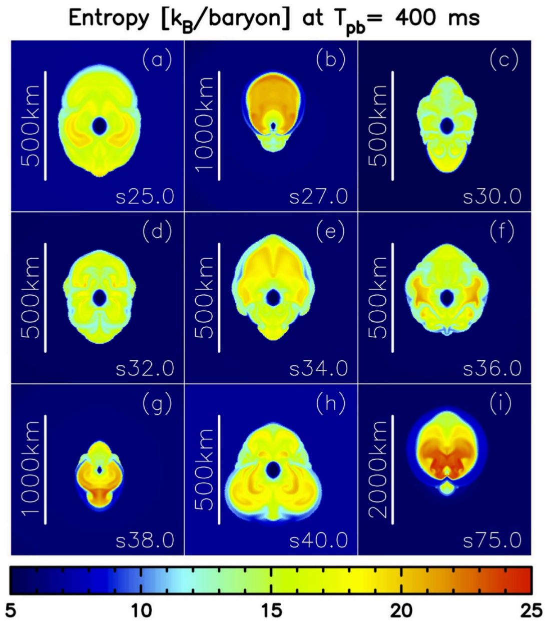
Progenitor	$E_{\mathrm{sim}}(t_{\mathrm{end}})$ $[10^{51}$ erg]	t_{end} [s]	E_∞ $[10^{51}$ erg]
CHIMERA			
12	0.31	0.97	0.34
15	0.88	0.81	1.03
20	0.38	0.84	0.50
25	0.70	0.73	0.93
CoCoNuT-FMT			
11.2	0.13	0.77	0.16
s11.8	0.20	0.78	0.24
s12.5	0.16	0.90	0.19
z12	0.41	1.68	0.47
z9.6	0.13	0.12	0.18
18ProgConv	0.77	1.96	0.98
FORNAX2D			
11.0	0.11	0.98	0.15
9.0	0.06	0.98	0.08
n8.8	0.18	0.51	0.19
u8.1	0.10	0.85	0.11
z9.6	0.12	0.58	0.13
16	0.16	1.13	0.21
17	0.29	0.90	0.39
19	0.24	0.52	0.39
FORNAX3D			
9.0	0.10	0.91	0.11
10.0	0.03	0.62	0.04
11.0	0.09	0.44	0.12
12.0	0.09	0.54	0.12

Inferred explosion energy of simulations is less than that of observations.

- massive star simulations: more energetic

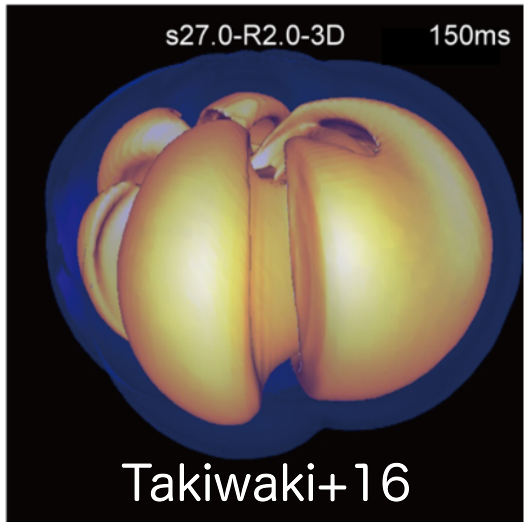
Approach to CCSNe

- sophisticated neutrino transport (e.g., Nagakura+19, Iwakami+20)
- difference of equation of state (e.g., Nagakura+18)
- dependence of progenitor (e.g., Nakamura+15)
- impact of rotation (e.g., Takiwaki+16)



Nakamura+15

rapid rotation



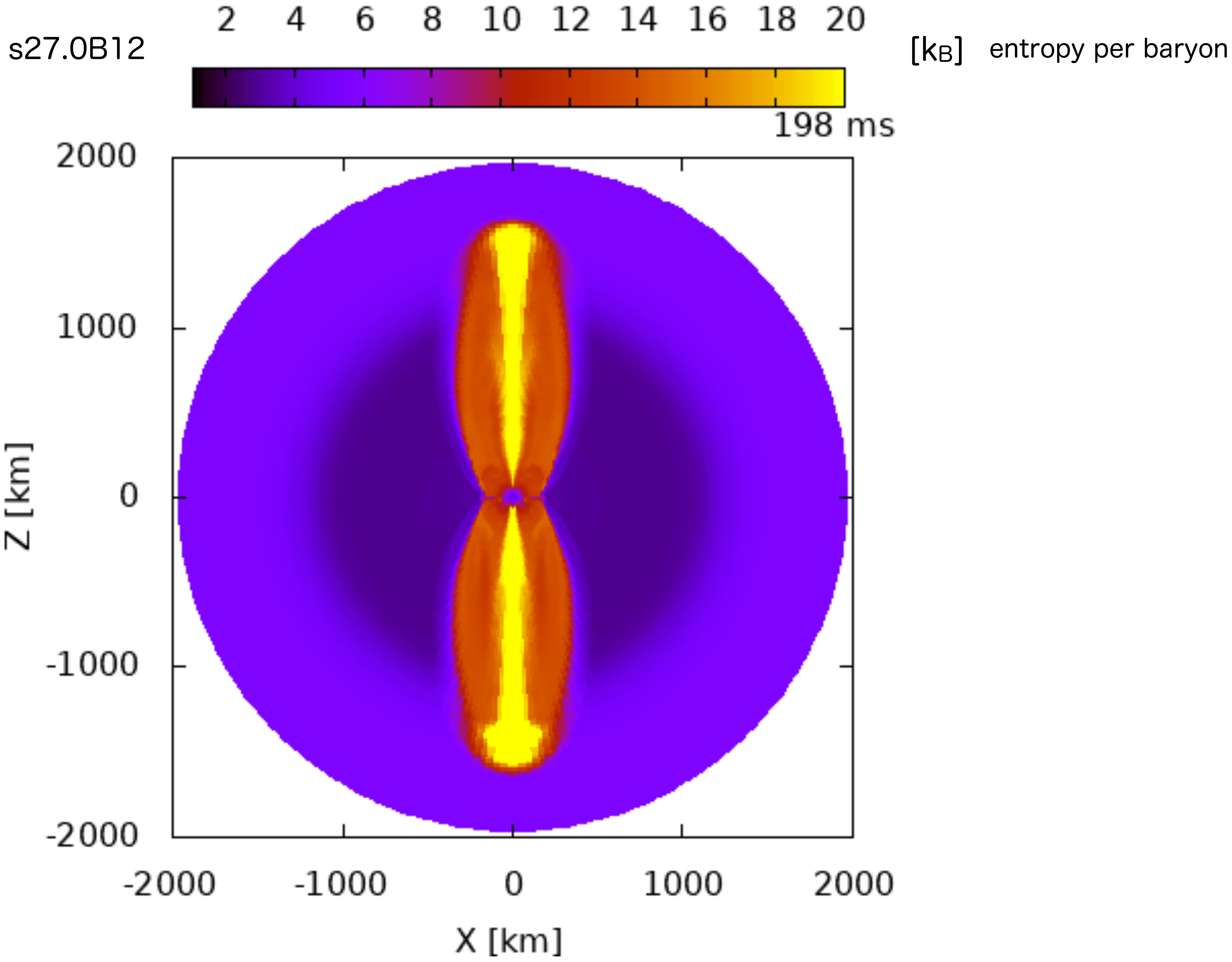
- impact of magnetic field
  - rotation (e.g., Yamada+04, Mosta+14, Bugli+20, Kuroda+20)
  - non-rotating (Endeve+10,12, Obergaulinger+14, Muller & Varma 20)

not so many, not fully understood

stellar evolution calculation:
majority of the magnetic core of the massive star is expected to be rotating slowly at the pre-collapse stage (Herger+05).

this work: revisits non-rotating progenitor with B-field

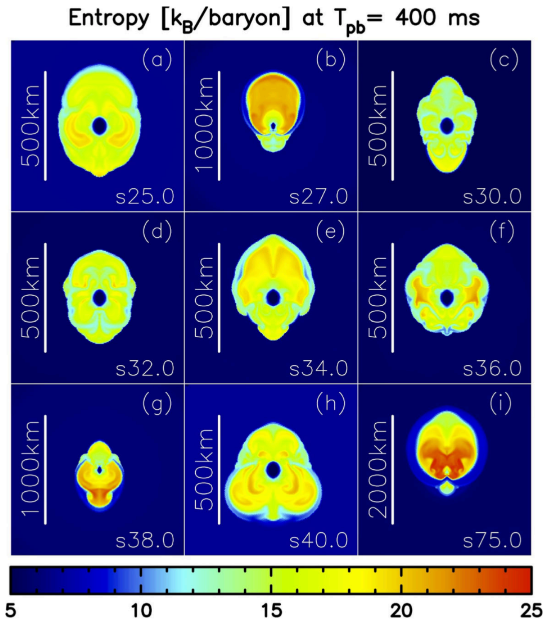
with rotation: ω=1rad/s



Increase of magnetic pressure due to magnetic field winding drives jet.

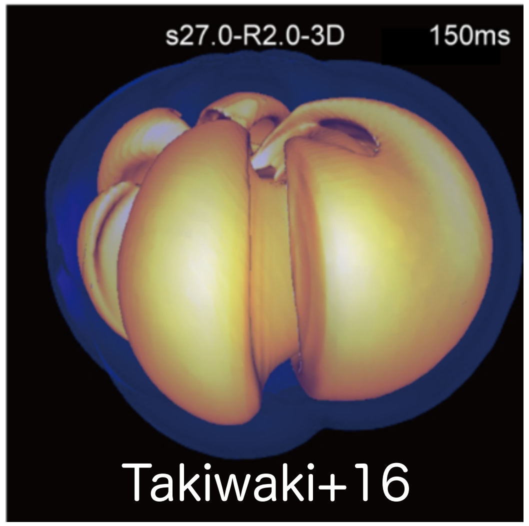
Approach to CCSNe

- sophisticated neutrino transport (e.g., Nagakura+19, Iwakami+20)
- difference of equation of state (e.g., Nagakura+18)
- dependence of progenitor (e.g., Nakamura+15)
- impact of rotation (e.g., Takiwaki+16)



Nakamura+15

rapid rotation



Takiwaki+16

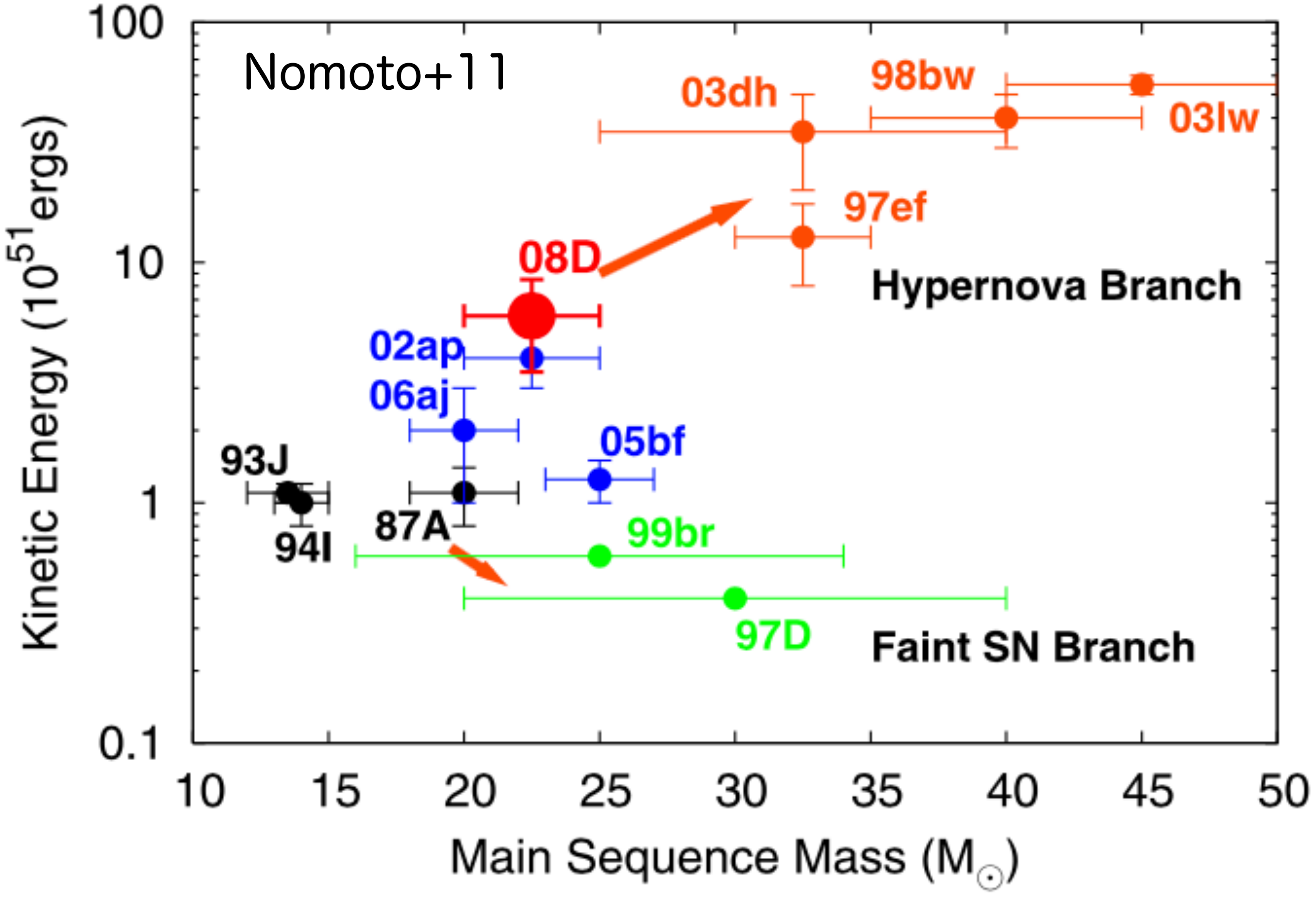
- impact of magnetic field
  - rotation (e.g., Yamada+04, Mosta+14, Bugli+20, Kuroda+20)
  - non-rotating (Endeve+10,12, Obergaulinger+14, Muller & Varma 20)

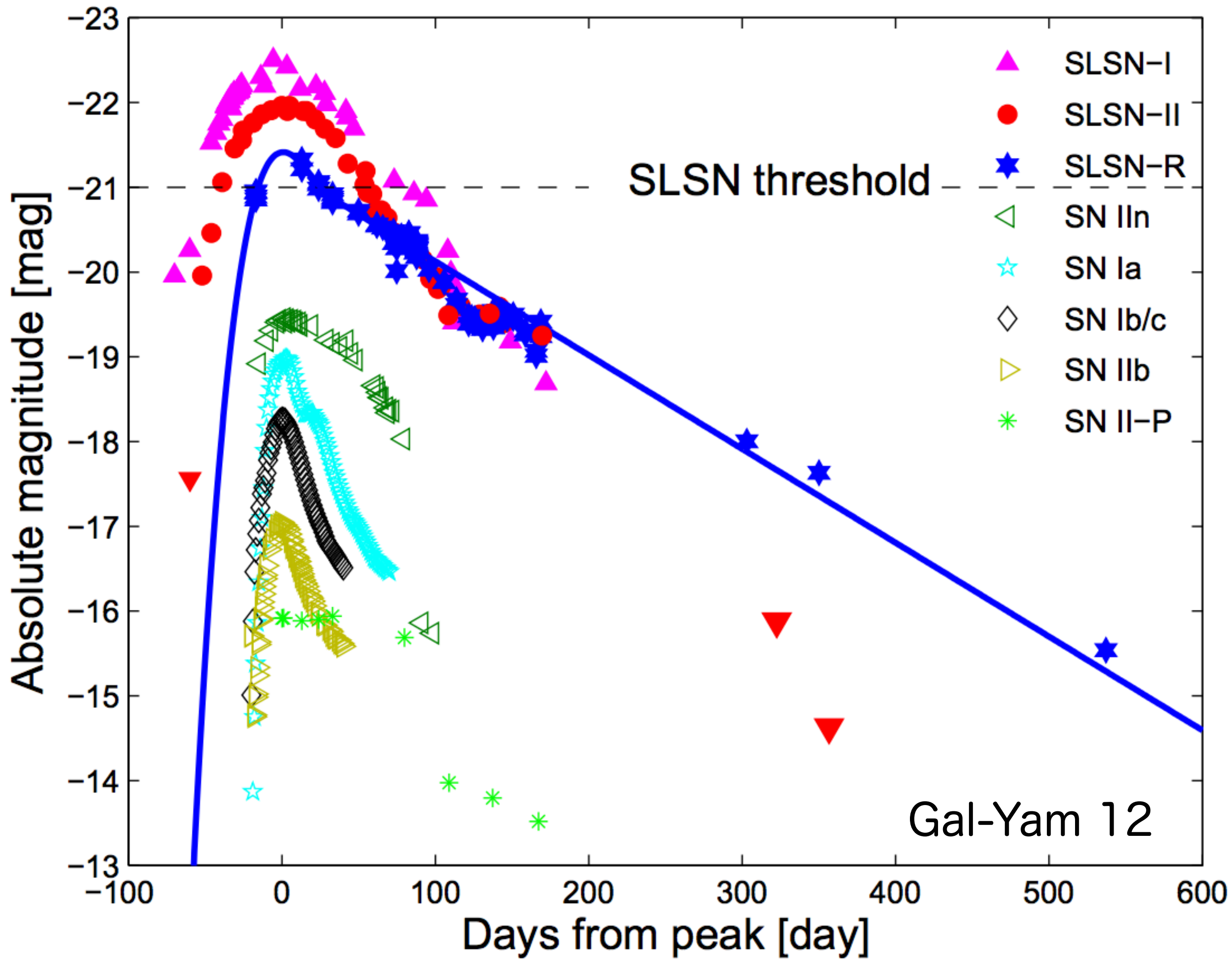
  not so many, not fully understood

  stellar evolution calculation:
  majority of the magnetic core of the massive star is expected to be rotating slowly at the pre-collapse stage (Herger+05).

this work: revisits non-rotating progenitor with B-field

Energetic subclasses of supernovae





hypernovae:

Kinetic energy is 10 times larger than that of canonical CCSNe.

superluminous SNe:

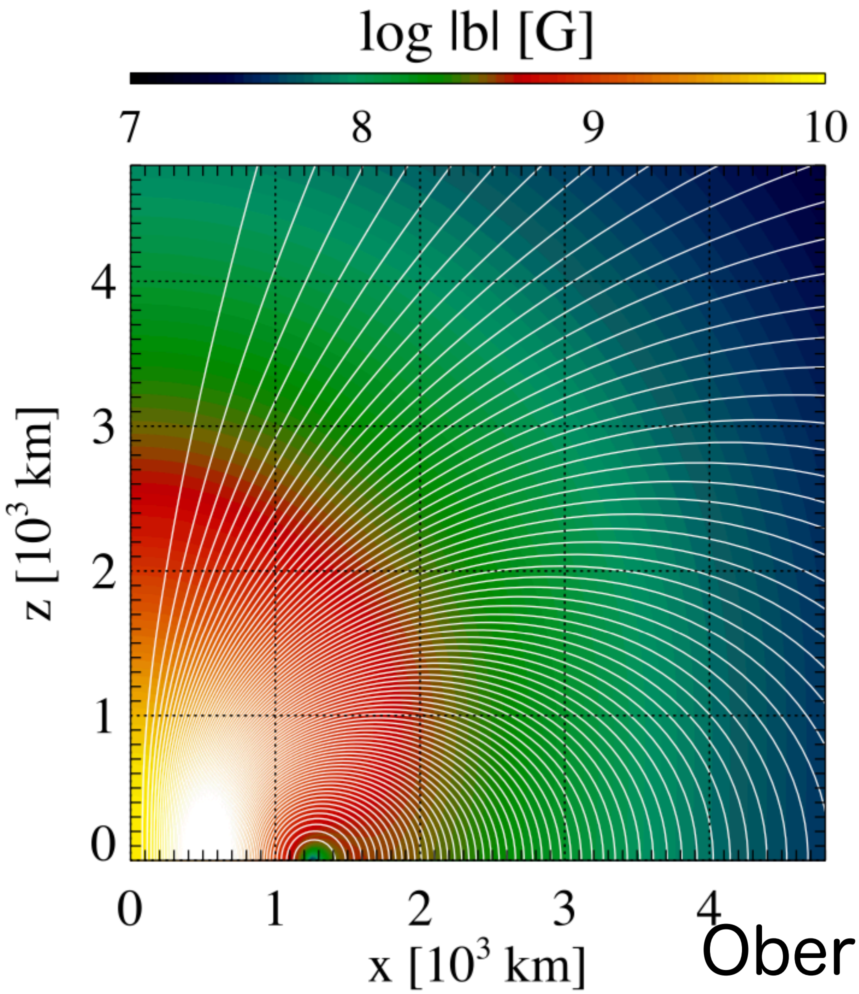
Luminosity is 10-100 times higher than that of the typical CCSNe.

Does B-field support Explosion?

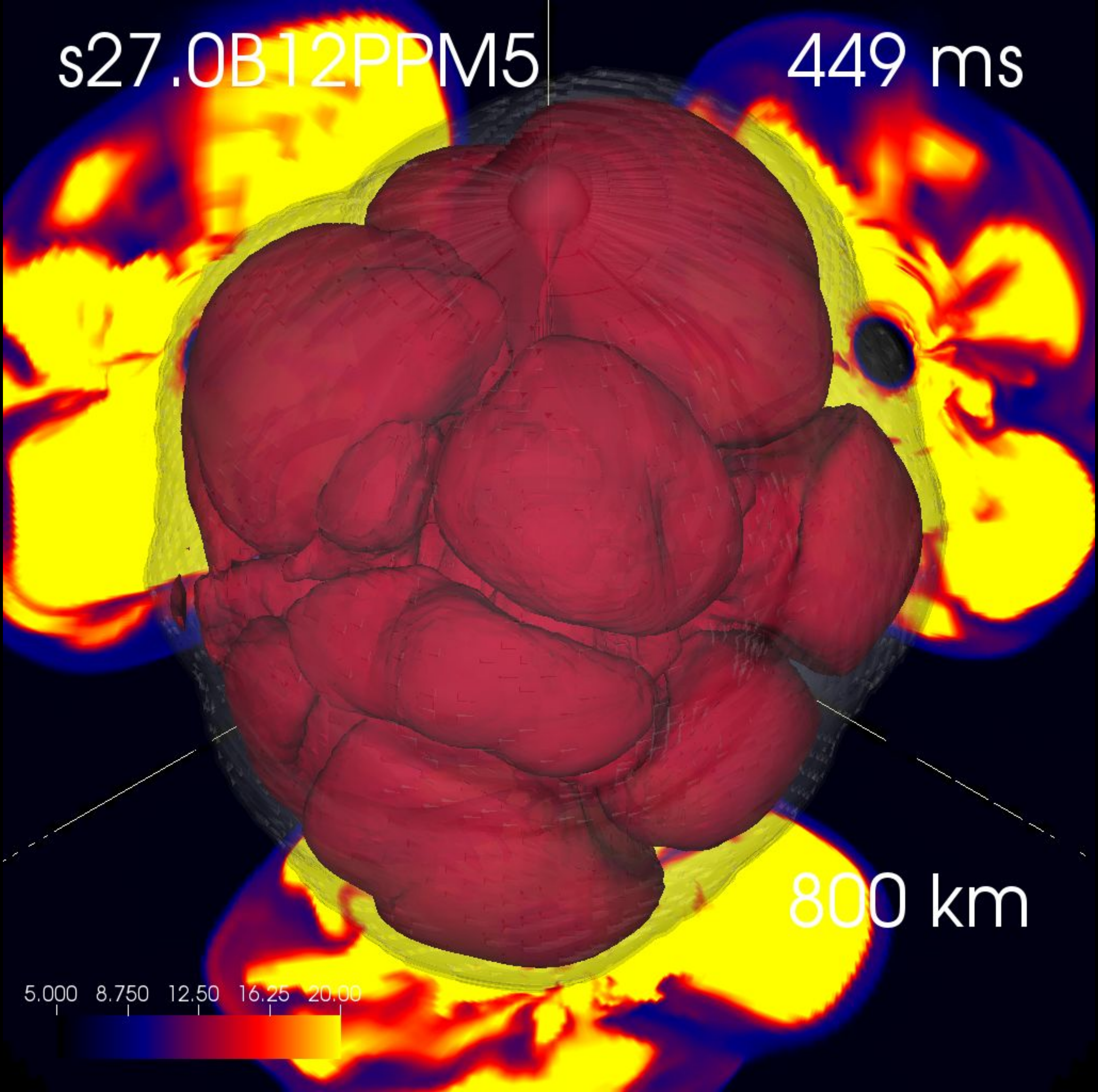
Settings

- 2D axisymmetric and 3D simulations
- 3DnSNe code (Takiwaki+16) updated to MHD (See Matsumoto+20)
- three-flavour neutrino transport based on Isotropic Diffusion Source Approximation (Kotake+18)
- EoS: Lattimer & Swesty (1991; incompressibility K=220 MeV)
- non-rotating progenitor : s15.0, s18.4, s20.0, s27.0 (Woosley+02)
- distribution of B-field: uniform (r < 1000km) + dipole (r > 1000km) (e.g., Suwa+07, Obergaulinger+14)
- Initial B-field: 10^{10}, 10^{11}, 10^{12} G
- vector potencial:

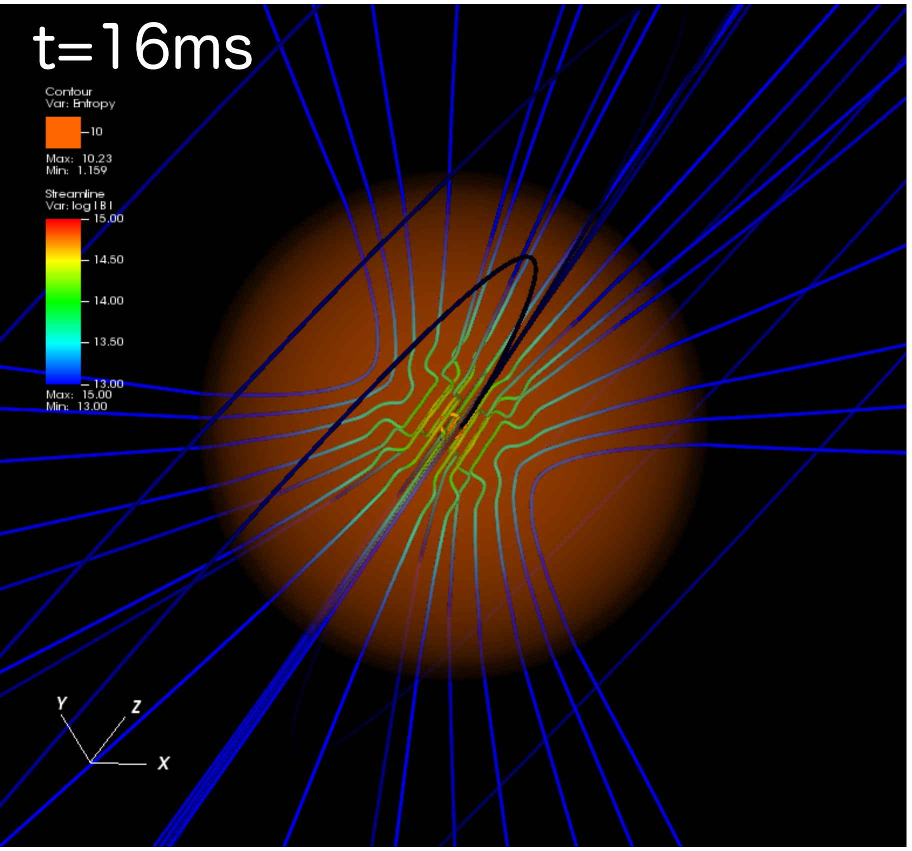
$$A_\phi = \frac{B_0}{2}\frac{r_0^3}{r^3 + r_0^3} r \sin\theta,$$

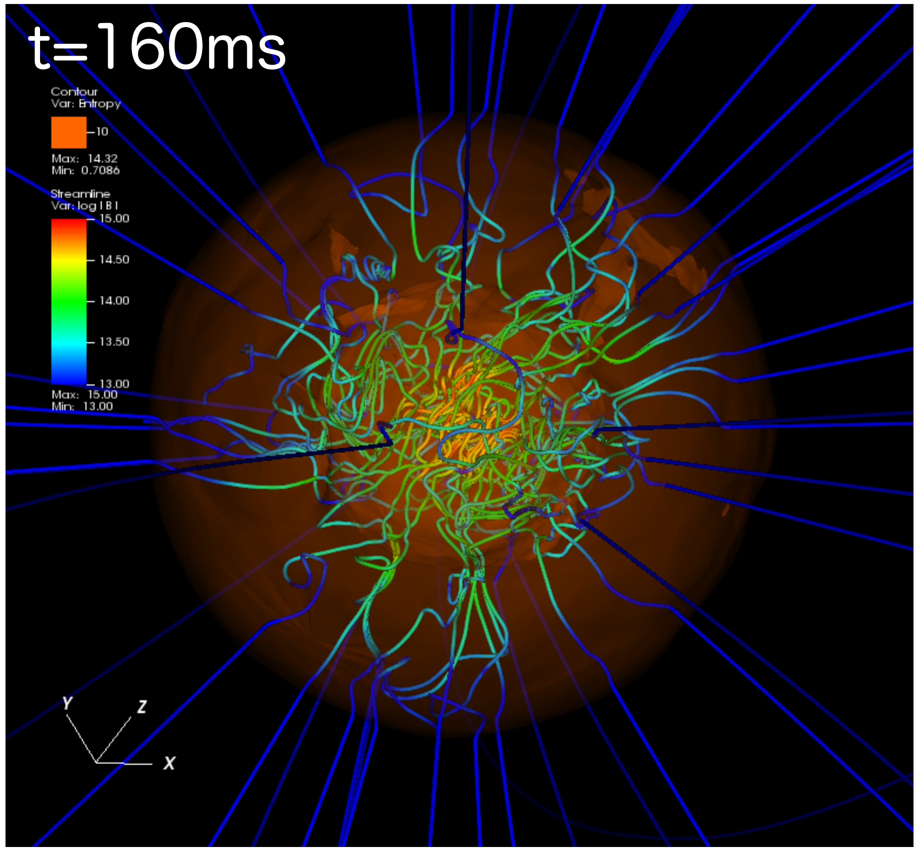


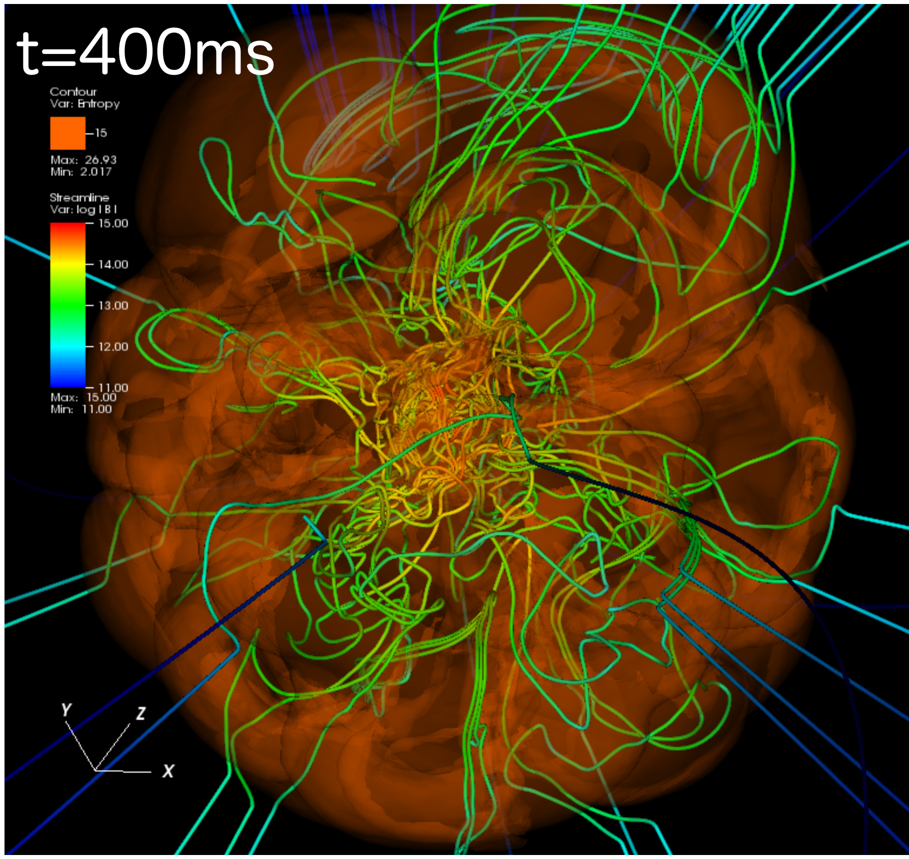
Obergaulinger+14


s27.0B12PPM5
449 ms
800 km
5.000
8.750
12.50
16.25
20.00

Overall evolution

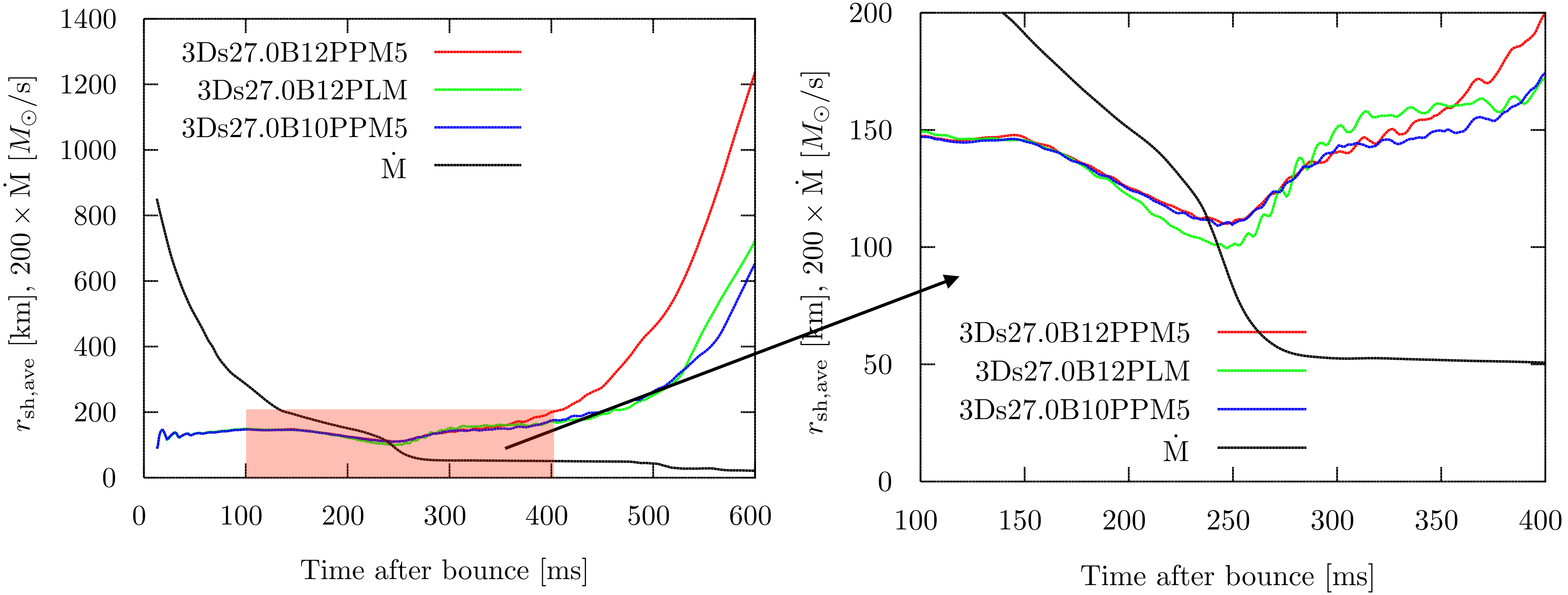






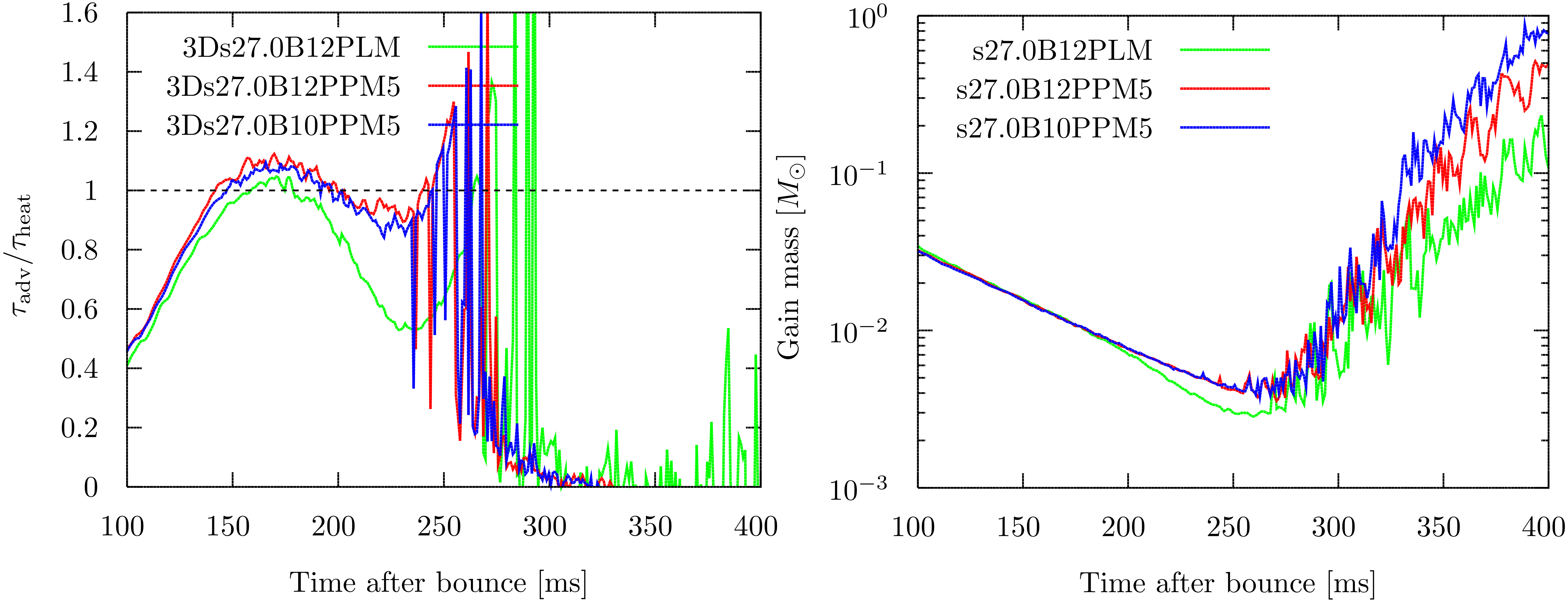
- magnetic field lines: a split monopole (t=16ms)
- Shock revival at around t=250ms
- field amplification in the post-shock region due to compression and stretching of the magnetic field
- neutrino-heating driven explosion

Time evolution of shock radius



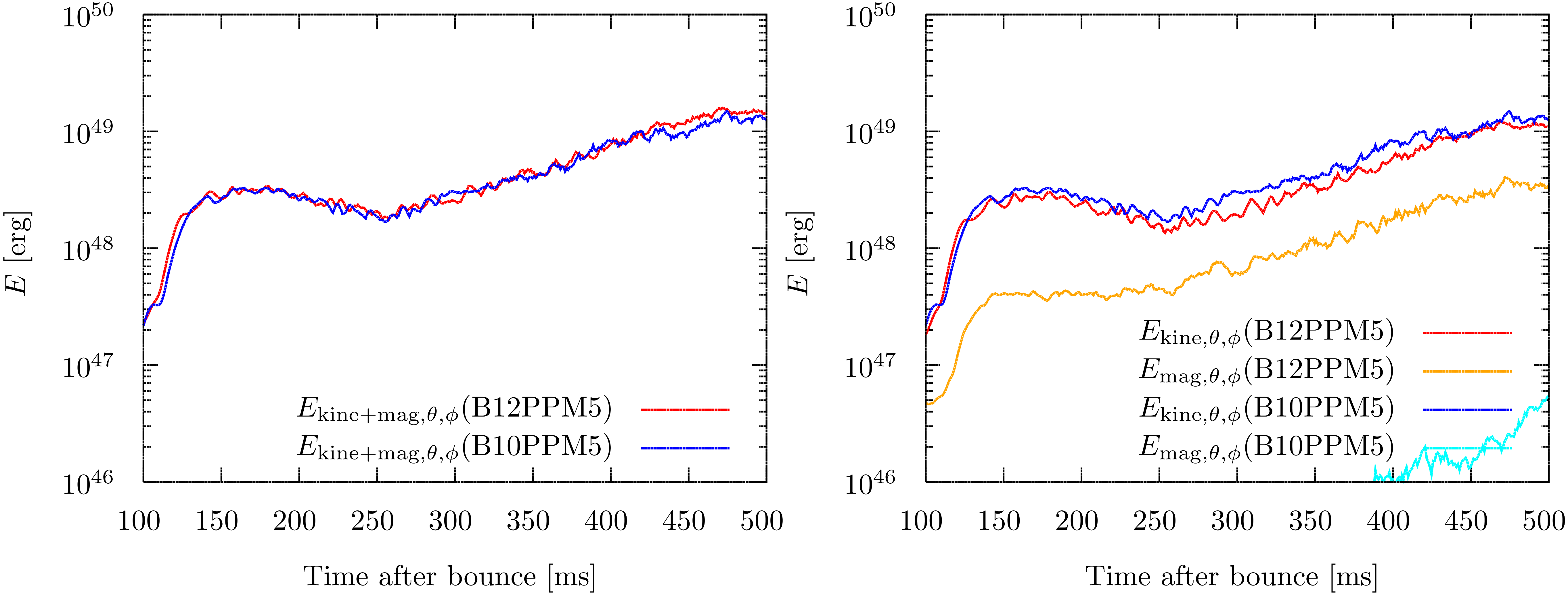
The shock wave evolves fast in the strong magnetic field model compared to the weak magnetic field model.

Shock revival by neutrino-heating



The mass enclosed in the gain layer (gain mass) of the strong magnetic field model is larger than that of the weak magnetic field model.

Time evolution of turbulent energy

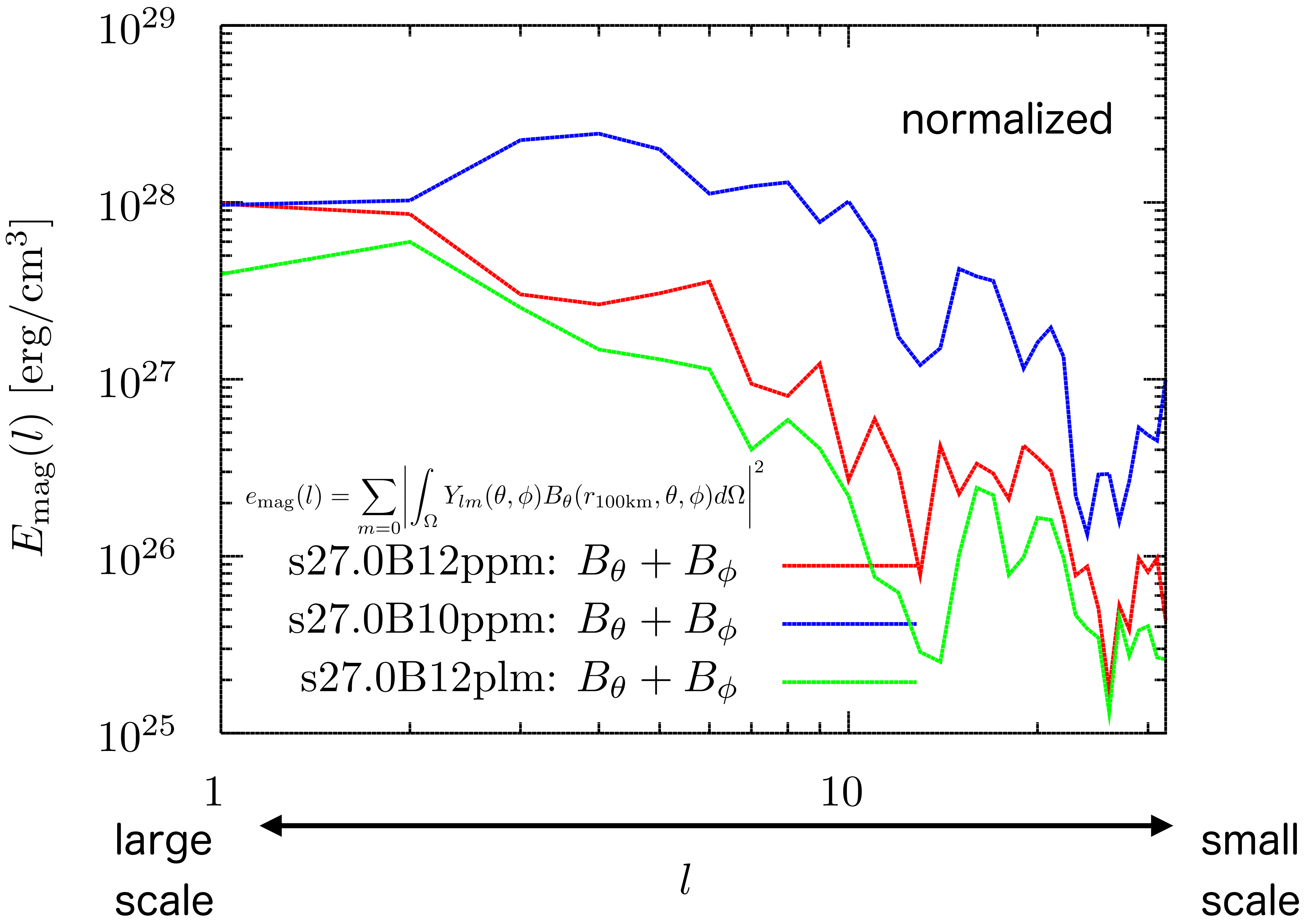


$E_{\mathrm{kine+mag},\theta,\phi}$ in the gain region:

Same level between different field strength models!!

However, $E_{\mathrm{mag},\theta,\phi}/E_{\mathrm{kine},\theta,\phi}$ is different between models.

Turbulent energy spectra

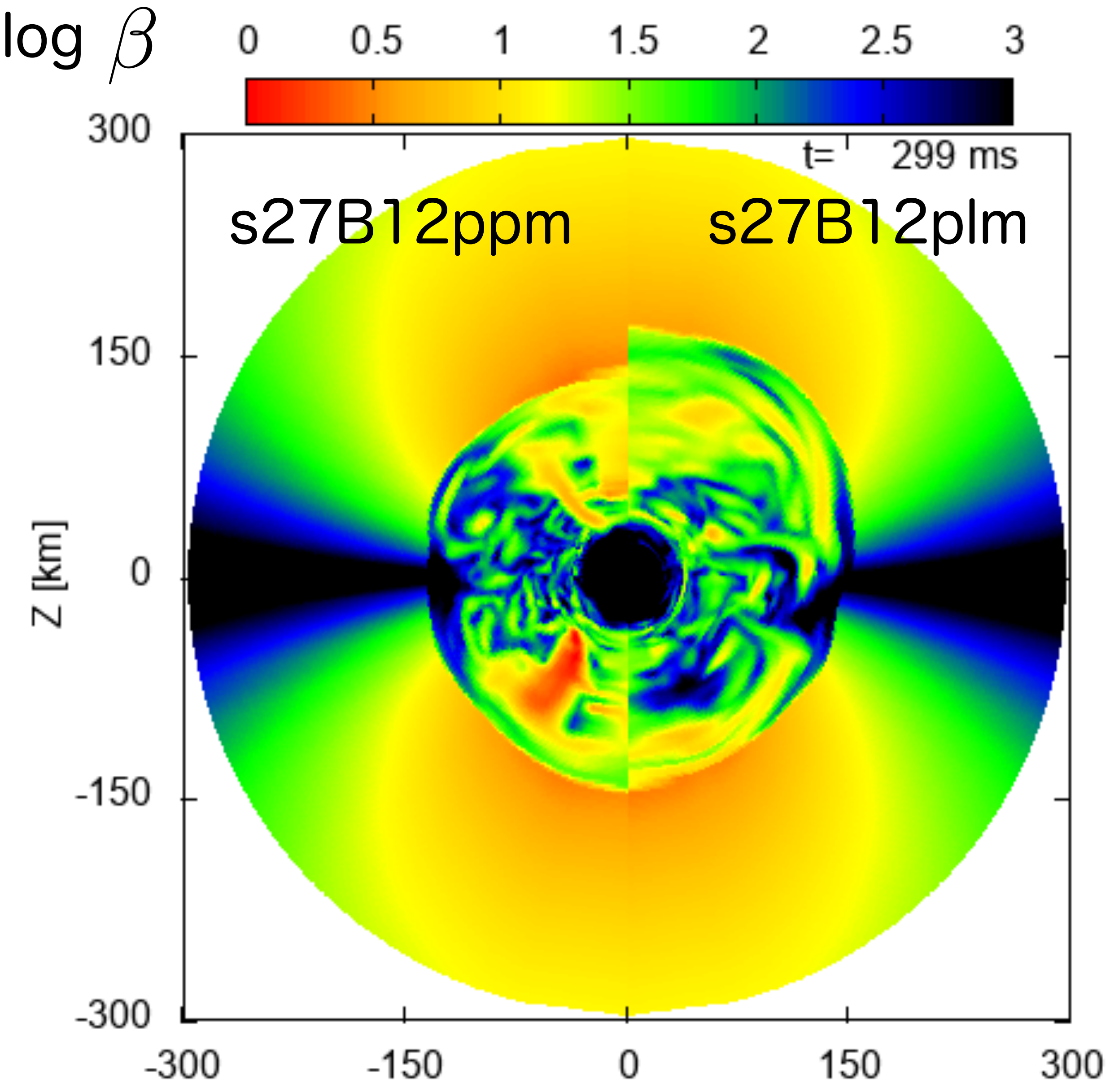


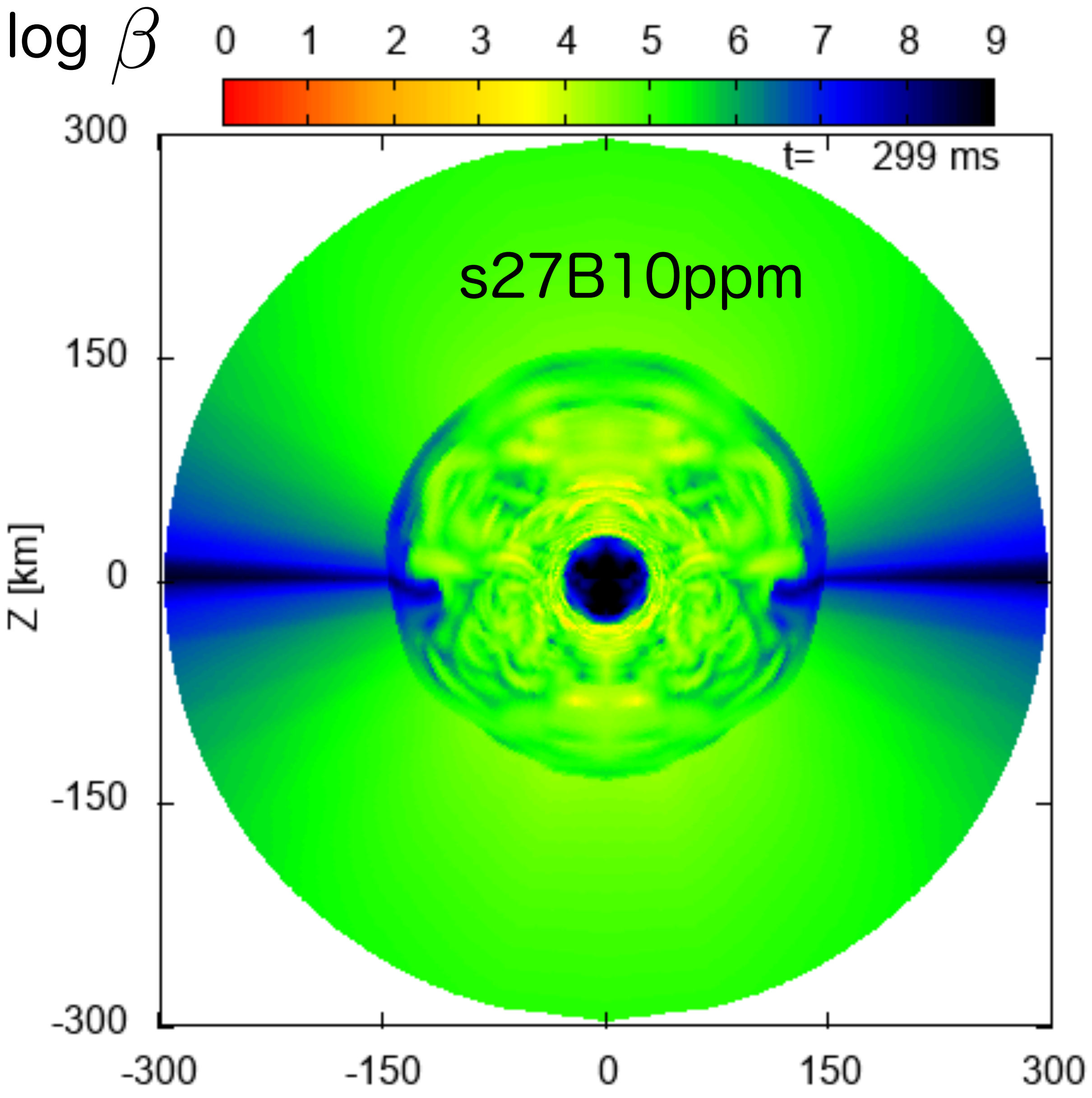
Strong magnetic field prevents the growth of the turbulent motions down to small scales (at larger l).

←<u>magnetic tension force</u>

(small curvature radius)

2D distribution of plasma beta





$$\beta = P_{\mathrm{gas}}/P_{\mathrm{mag}}$$

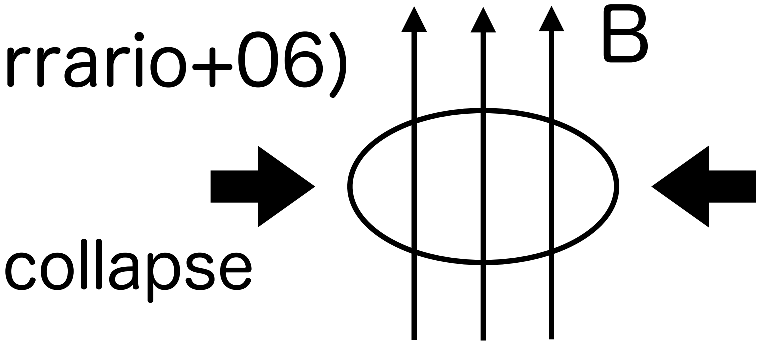
Magnetic pressure can partially contribute to the shock evolution in strong B-field model.

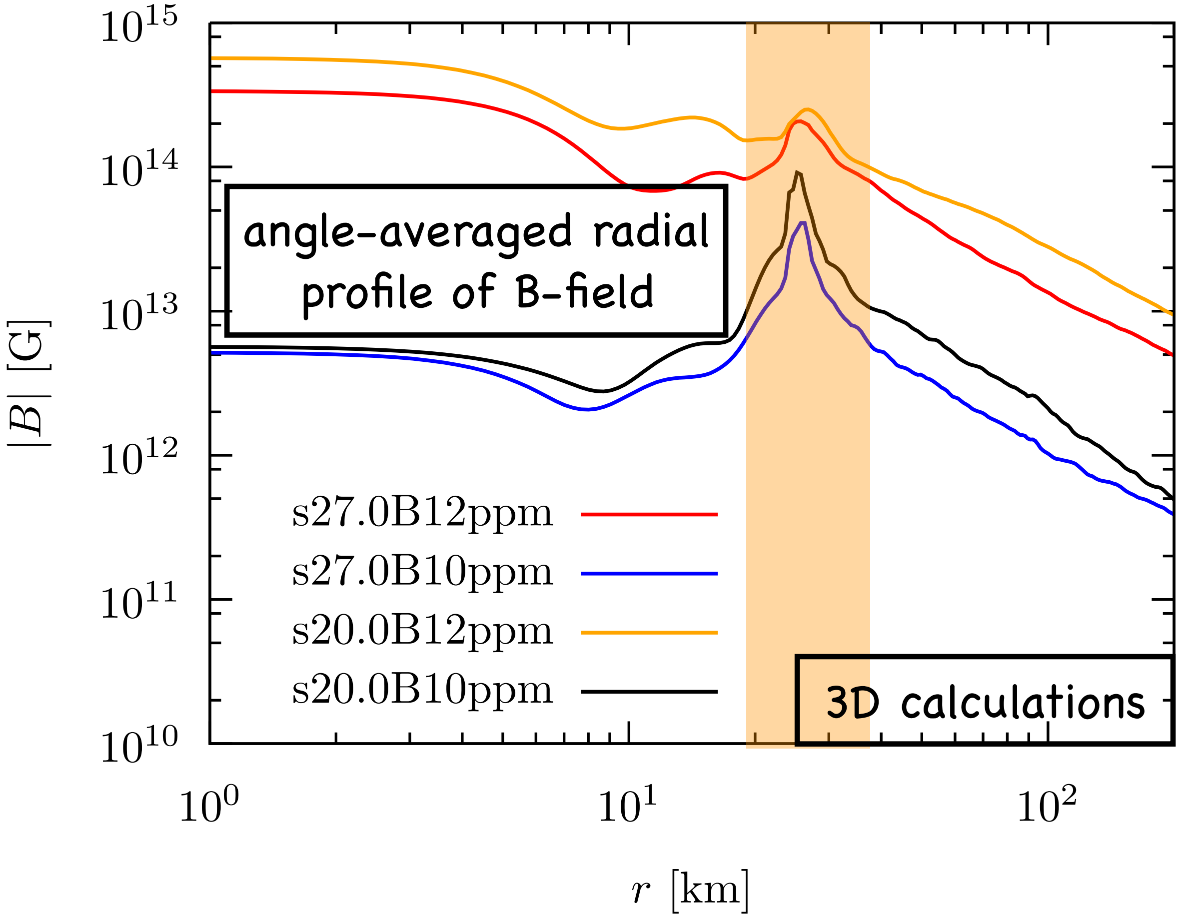
Speculation : magnetar formation

possible formation scenarios of magnetar

- turbulent dynamo amplification in a rapidly rotating PNS (Thompson+93)
- fossil field hypothesis (magnetic flux conservation) (Ferrario+06)

$$B_{\rm PNS} \sim 10^{15}{\rm G}\left(\frac{B_{0,r=1000{\rm km}}}{10^{12}{\rm G}}\right)\left(\frac{30{\rm km}}{r_{\rm PNS}}\right)^2$$





supernova remnants + magnetars in our galaxy

Kes 73 (AXP 1E 1841–045)

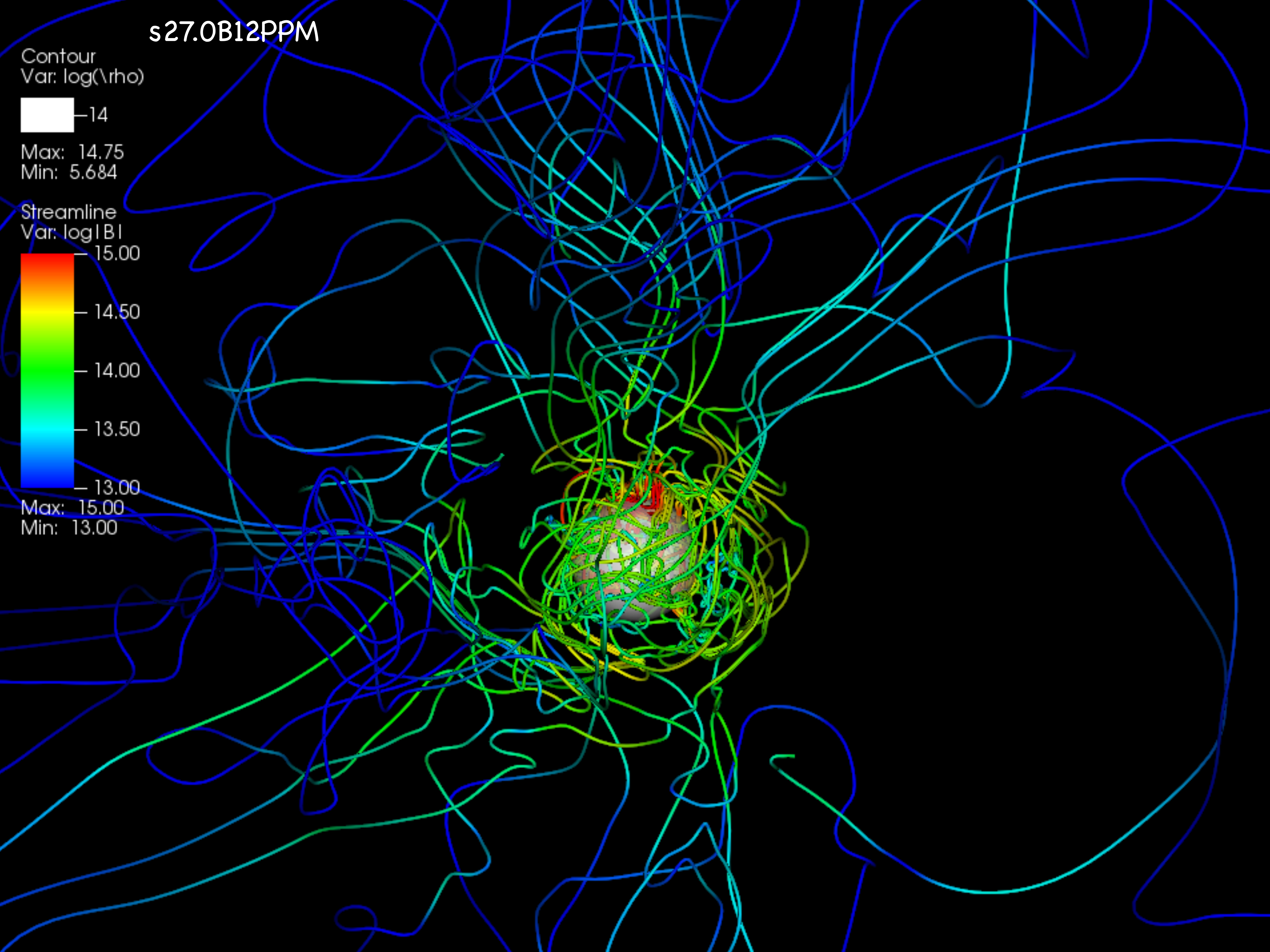
CTB 109 (AXP 1E2259+586)

N49 (SGR 0526–66)

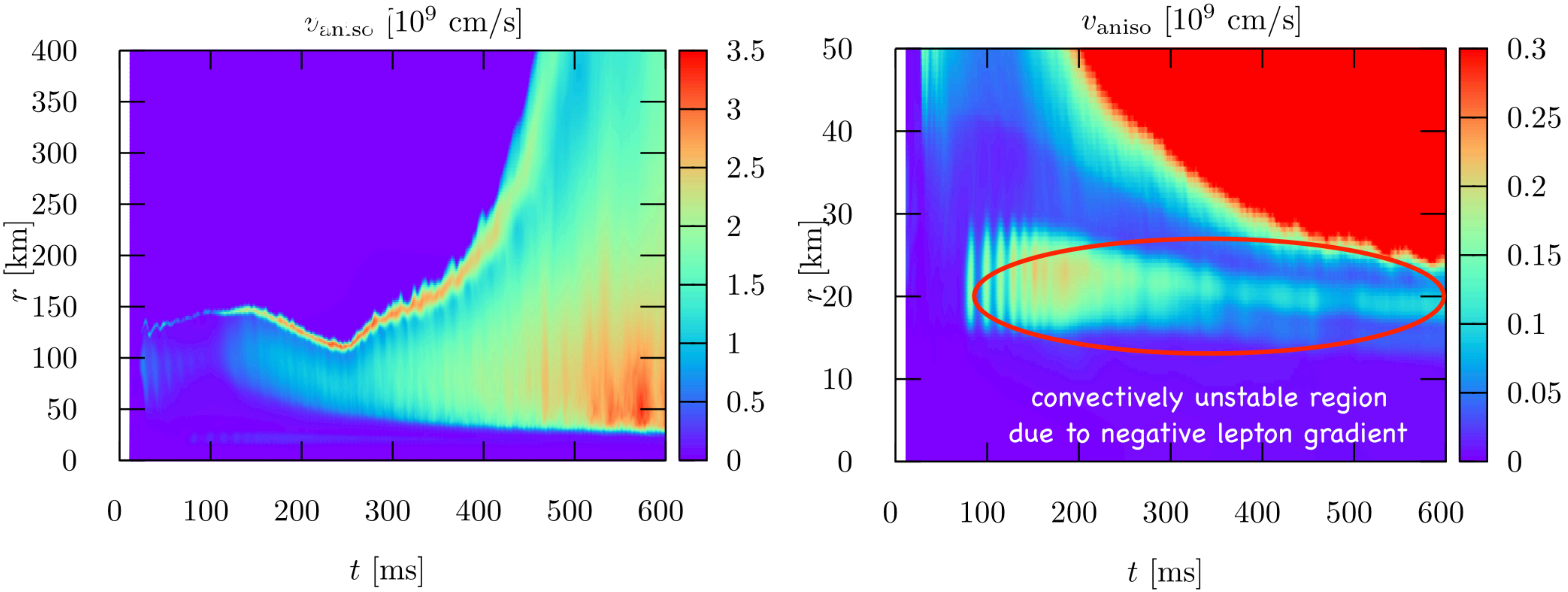
- typical explosion energy (10^{51}erg)
- slowly rotating

(Vink+06, Nakano+17)

Magnetars may not require rapid rotators with highly aspherical and energetic jets, but simply the normal neutrino- driven explosion as the central engine.


s27.0B12PPM
Contour
Var: log(\rho)
14
Max: 14.75
Min: 5.684
Streamline
Var: log|B|
15.00
14.50
14.00
13.50
13.00
Max: 15.00
Min: 13.00

Convection around PNS



convectively unstable region
due to negative lepton gradient

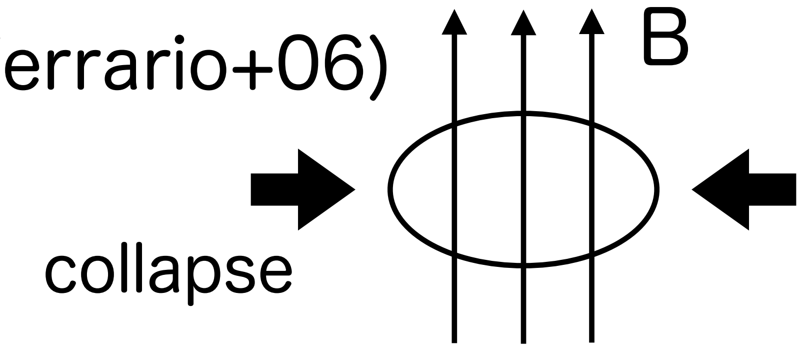
$$v_{\rm aniso} = \sqrt{\langle \rho \left((v_r - \langle v_r \rangle)^2 + v_\theta^2 + v_\phi^2 \right) \rangle / \langle \rho \rangle}.$$ (Takiwaki+12)

Can the convection around proto-neutron contribute to the magnetic field amplification?

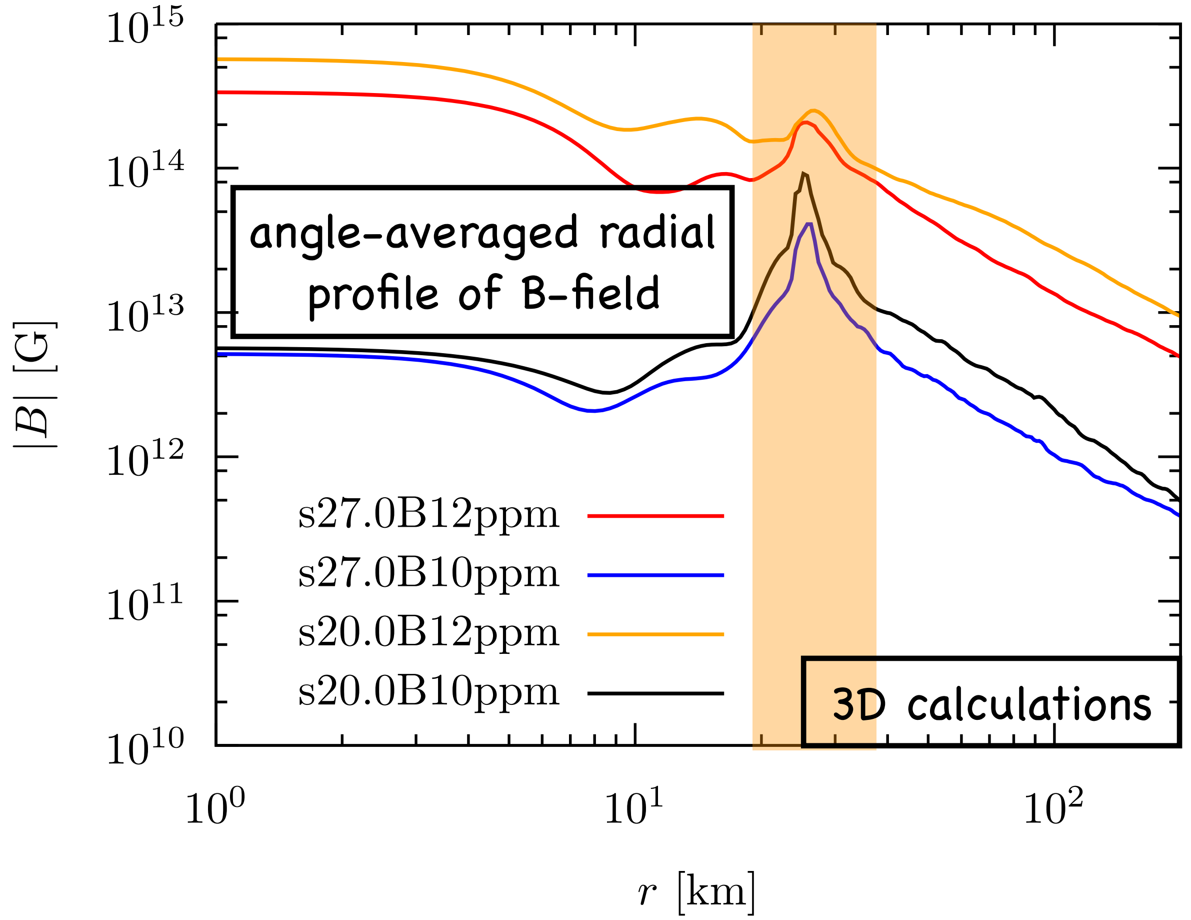
Speculation : magnetar formation

possible formation scenarios of magnetar

- turbulent dynamo amplification in a rapidly rotating PNS (Thompson+93)
- fossil field hypothesis (magnetic flux conservation) (Ferrario+06)



$$B_{\rm PNS} \sim 10^{15}{\rm G}\left(\frac{B_{0,r=1000{\rm km}}}{10^{12}{\rm G}}\right)\left(\frac{30{\rm km}}{r_{\rm PNS}}\right)^{2}$$



supernova remnants + magnetars in our galaxy

Kes 73 (AXP 1E 1841−045)

CTB 109 (AXP 1E2259+586)

N49 (SGR 0526−66)

- typical explosion energy (10^{51}erg)
- slowly rotating

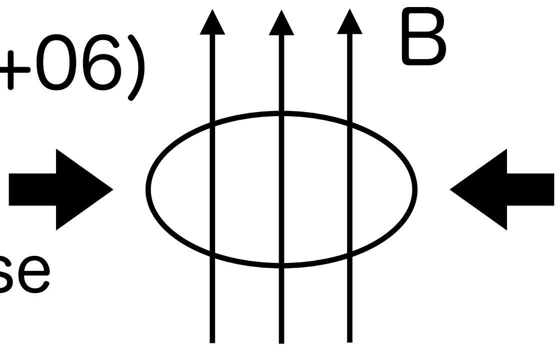
(Vink+06, Nakano+17)

Magnetars may not require rapid rotators with highly aspherical and energetic jets, but simply the normal neutrino- driven explosion as the central engine.

Speculation : magnetar formation

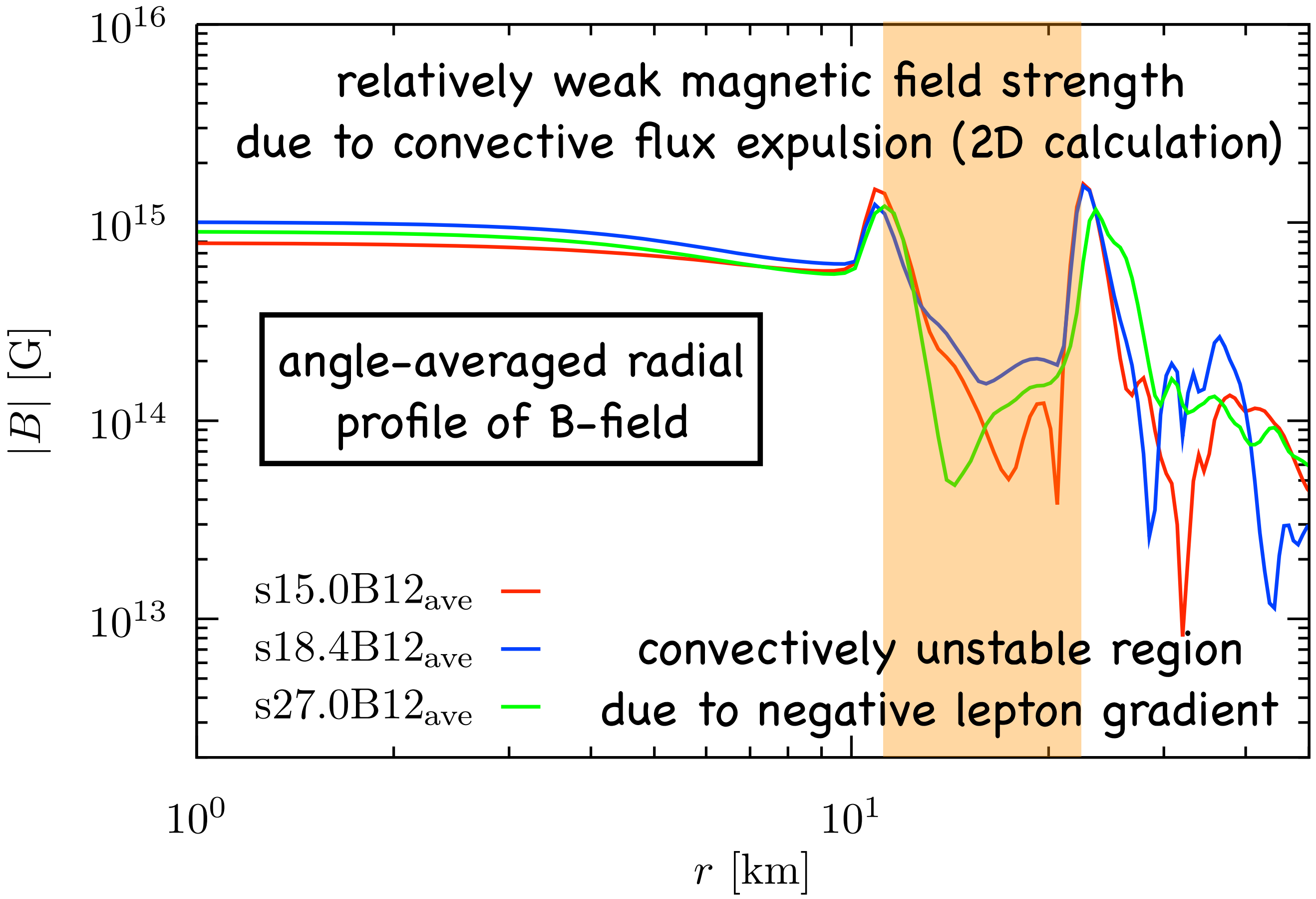
possible formation scenarios of magnetar

- turbulent dynamo amplification in a rapidly rotating PNS (Thompson+93)
- fossil field hypothesis (magnetic flux conservation) (Ferrario+06)



$$B_{\rm PNS} \sim 10^{15}{\rm G}\left(\frac{B_{0,r=1000{\rm km}}}{10^{12}{\rm G}}\right)\left(\frac{30{\rm km}}{r_{\rm PNS}}\right)^2$$

Matsumoto+20



supernova remnants + magnetars in our galaxy

Kes 73 (AXP 1E 1841–045)

CTB 109 (AXP 1E2259+586)

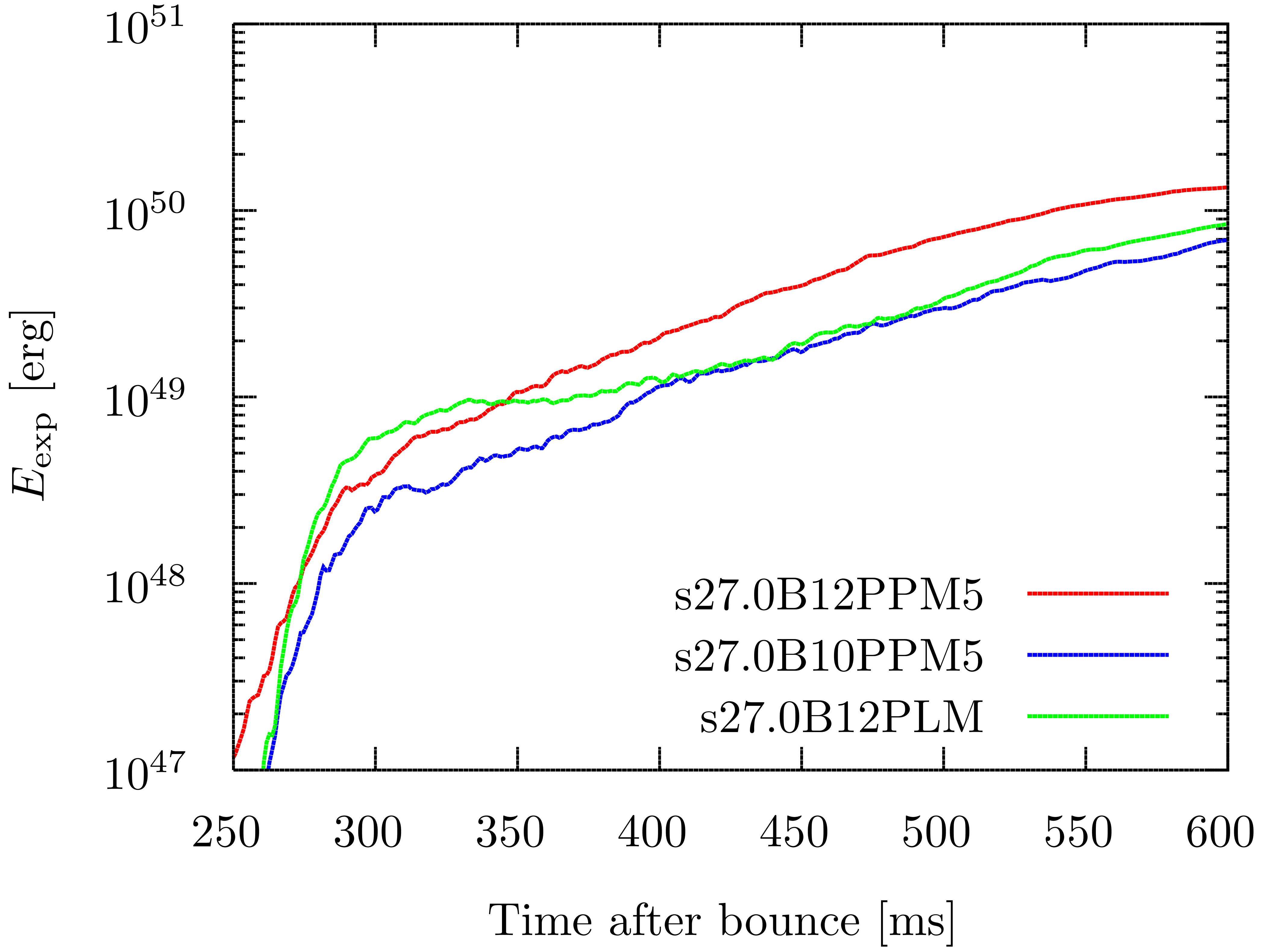
N49 (SGR 0526–66)

- typical explosion energy (10^{51}erg)
- slowly rotating

(Vink+06, Nakano+17)

Magnetars may not require rapid rotators with highly aspherical and energetic jets, but simply the normal neutrino- driven explosion as the central engine.

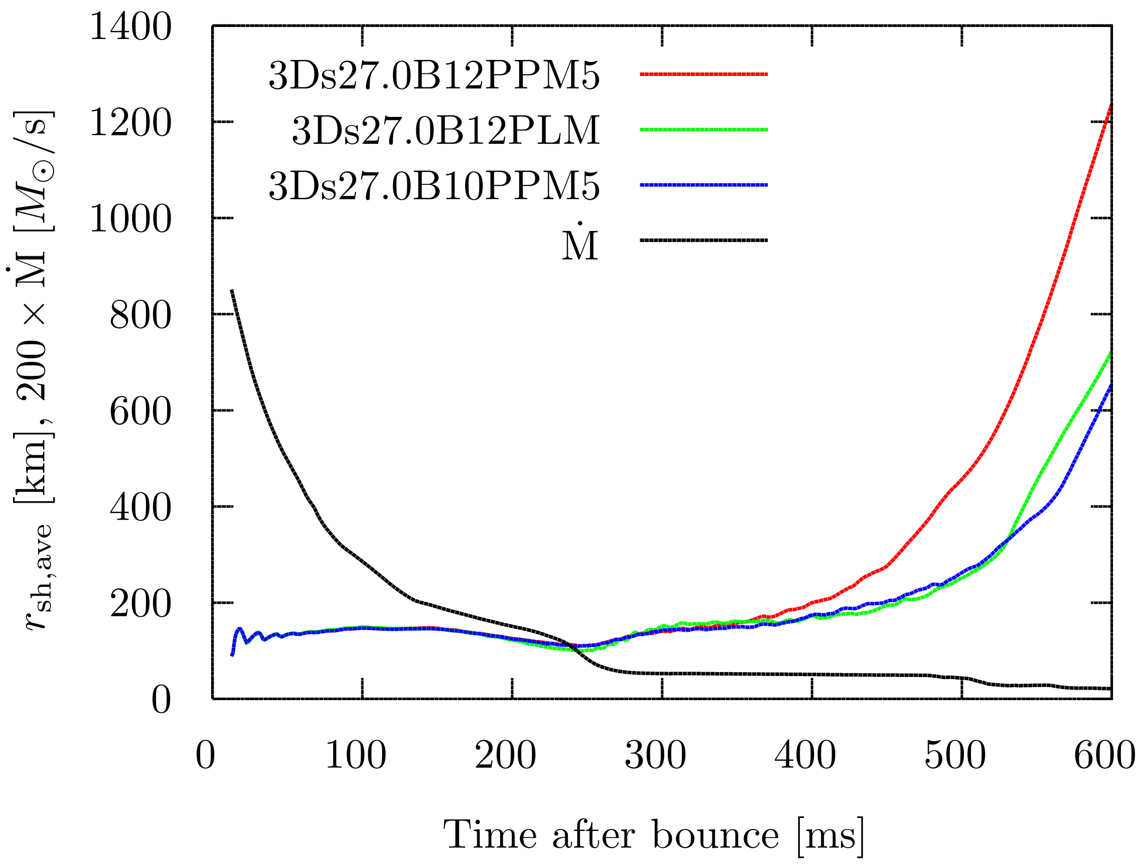
Explosion energy

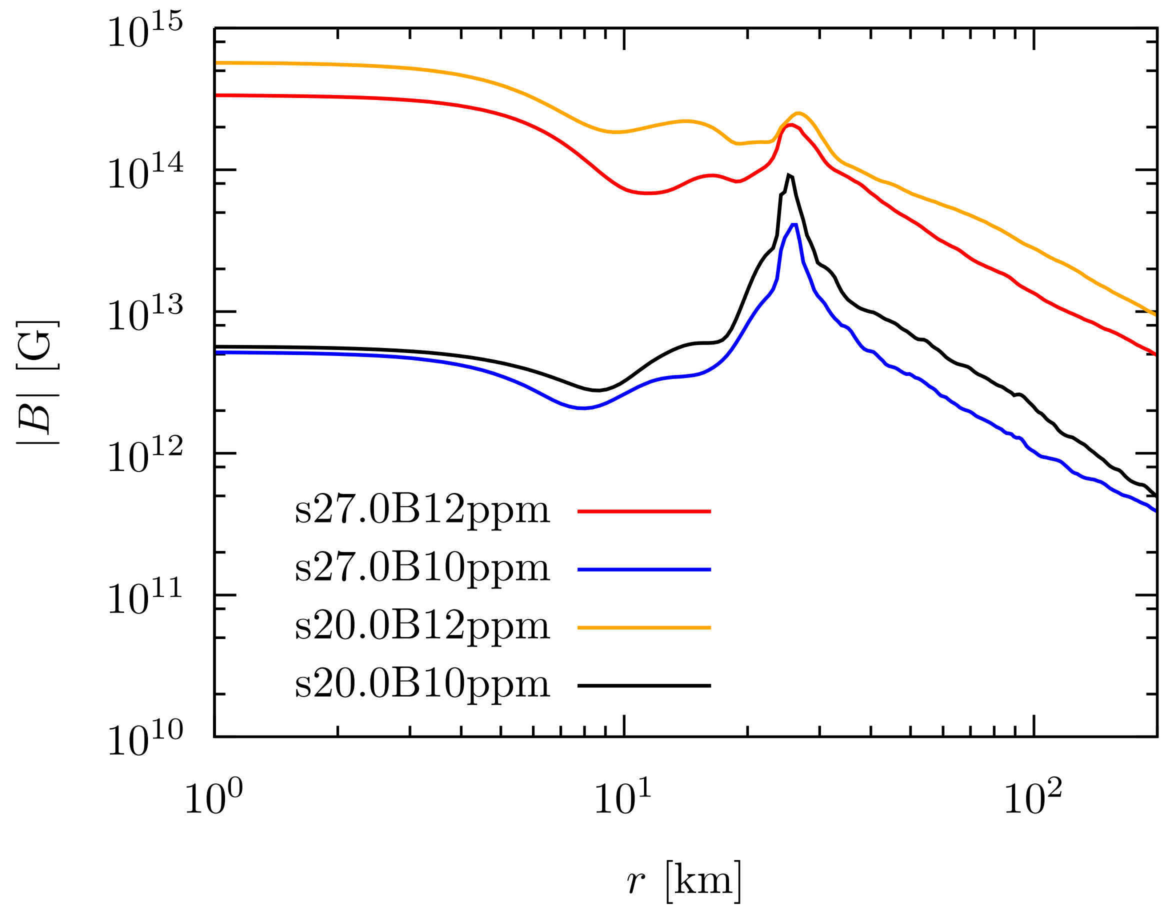


Explosion energy is smaller than ~10^{51} ergs during our calculation runs.

Summary

Impact of the magnetic field on the dynamics of non-rotating stellar cores through 3D MHD simulations：neutrino-driven core-collapse supernovae





Neutrino-driven explosion:

Strong B-field supports the explosion.

Magnetar formation:

Progenitor is slowly rotating?