On ^{56}Ni synthesis by the magnetar model for long gamma-ray bursts and hypernovae

Yudai Suwa (YITP, Kyoto Univ. & MPA, Garching)

with

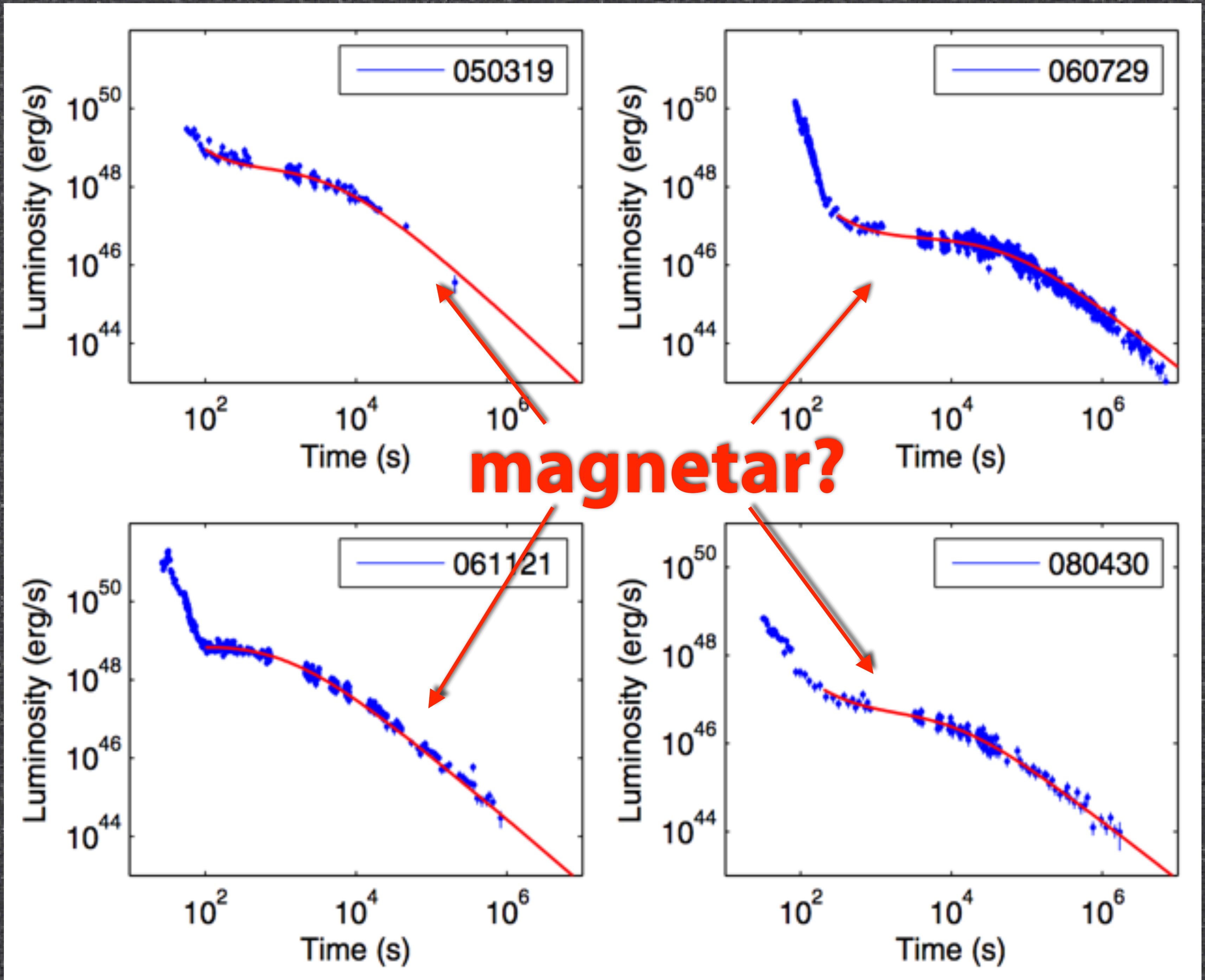
Nozomu Tominaga (Konan Univ. & Kavli IPMU)

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

YIPQS

YITP Kyoto

Late activity of GRBs

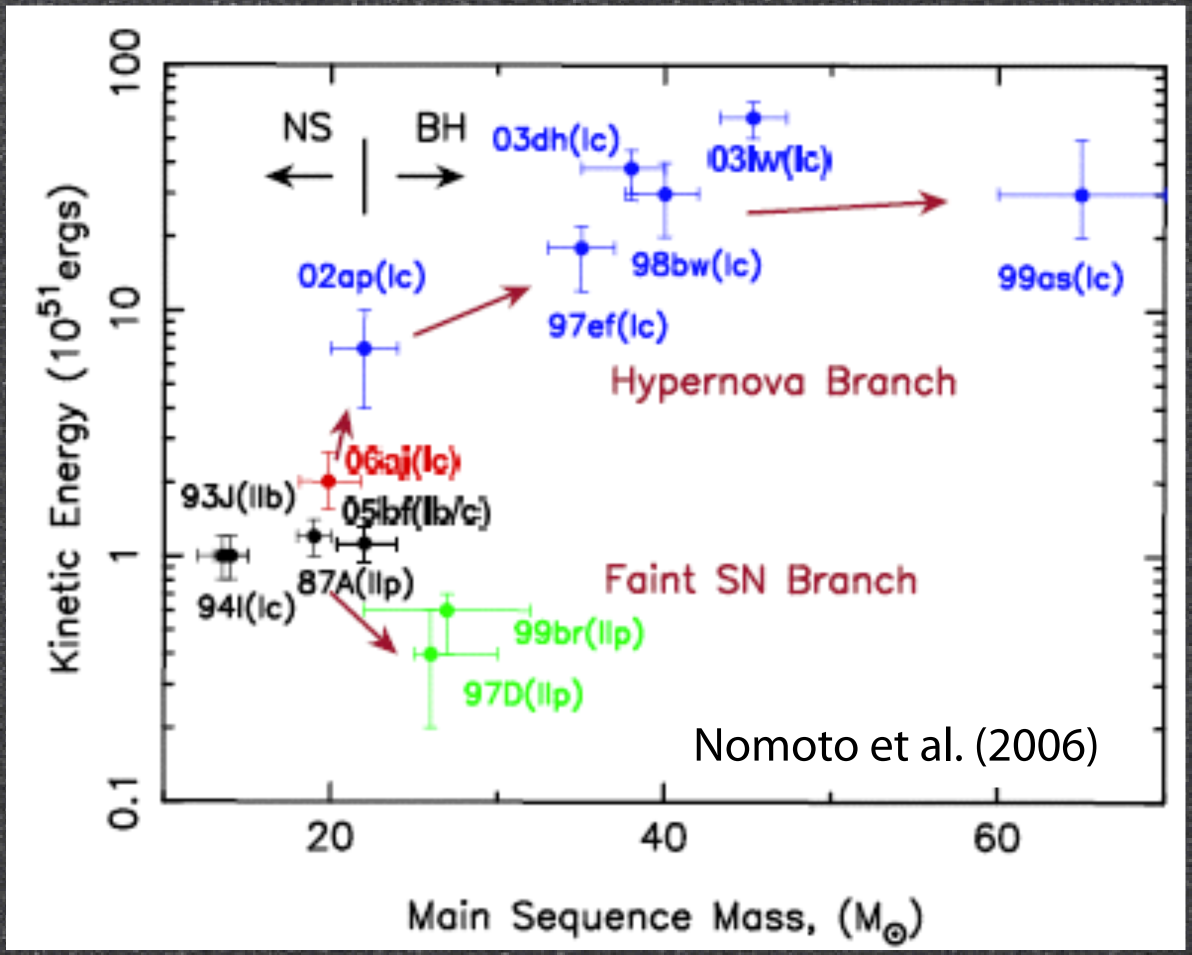


Dall'Osso+ 11

GRBs and HNe

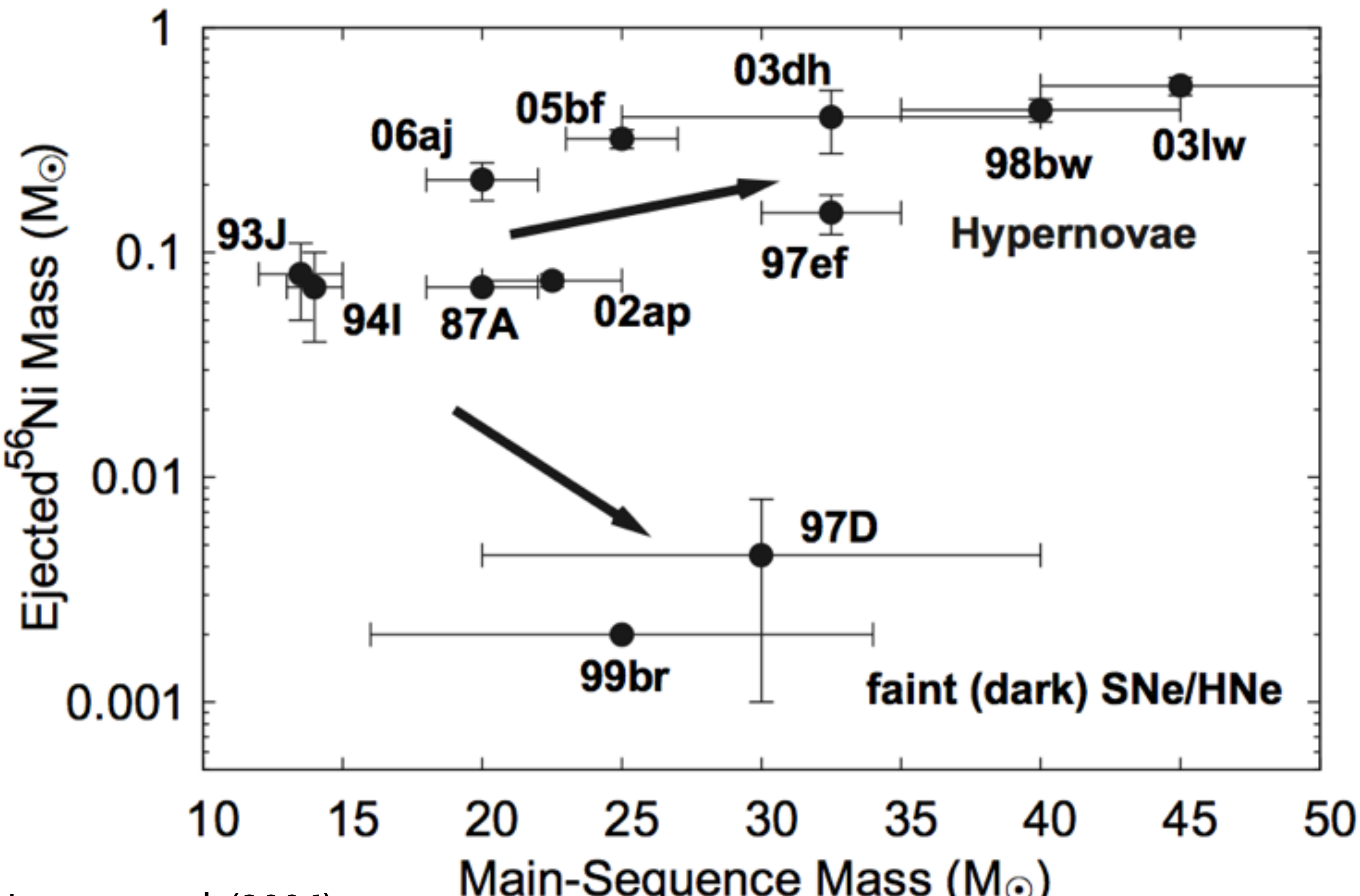
GRB ⇔ SN association

GRB 980425 / SN 1998bw (z=0.0085)
GRB 030329 / SN 2003dh (0.1687)
GRB 031203 / SN 2003lw (0.1055)
XRF 060218 / SN 2006aj (0.0335)
GRB 100316D/ SN 2010bh (0.0591)
GRB 130427A / SN 2013cq (0.3399) ...



- Observations of GRB suggest that some GRBs are connected with some kind of SNe.
- SNe which associate with GRB are "Hypernovae" (HNe) with explosion energy, **E_{exp}~10^{52} ergs.** (~10^{51} erg for canonical SNe)
- The central engine of GRBs is required to supply such an enormous explosion energy of GRBs/HNe.

^{56}Ni



Nomoto et al. (2006)

Central engine models

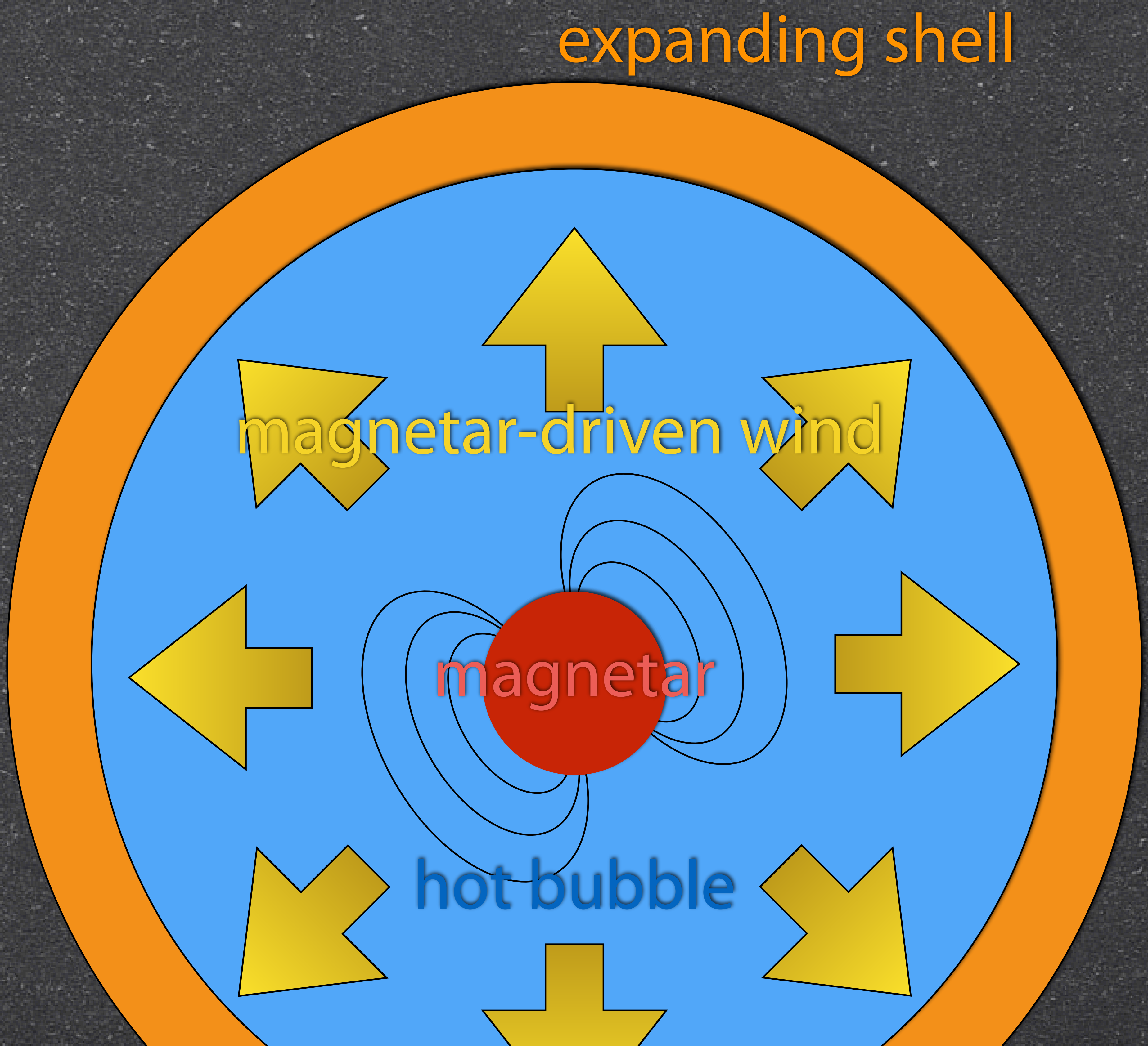
- **Collapsar scenario**;
  - consists of black hole (BH) and massive accretion disk as a end product of massive stars' death
  - relativistic jets are generated in the vicinity of BH (ν-driven? magnetic fields driven?)

- **Magnetar scenario**;
  - rapidly rotating neutron star with super strong magnetic fields
  - jets are driven by magnetic pressure or magneto-centrifugal force

Can magneters generate ^{56}Ni?

- to construct a self-consistent model for GRB/HN, ^{56}Ni should be considered seriously

Picture



Equations solved

- Magnetar evolution

$$L_w = 6.18 \times 10^{51} \mathrm{erg\ s^{-1}} \left(\frac{B_p}{10^{16}\ \mathrm{G}}\right)^2 \left(\frac{R}{10\ \mathrm{km}}\right)^6 \left(\frac{\Omega}{10^4\ \mathrm{rad\ s^{-1}}}\right)^4$$

$$\Omega(t) = \Omega_i \left(1 + \frac{t}{T_d}\right)^{-1/2}$$

$$T_d = 8.08\ \mathrm{s} \left(\frac{B_p}{10^{16}\ \mathrm{G}}\right)^{-2} \left(\frac{R}{10\ \mathrm{km}}\right)^{-6} \left(\frac{\Omega_i}{10^4\ \mathrm{rad\ s^{-1}}}\right)^{-2} \left(\frac{I}{10^{45}\ \mathrm{g\ cm^2}}\right)$$

$$E_{\mathrm{NS}} = \frac{1}{2} I \Omega_i^2 = 5 \times 10^{52}\ \mathrm{erg} \left(\frac{I}{10^{45}\ \mathrm{g\ cm^2}}\right) \left(\frac{\Omega_i}{10^4\ \mathrm{rad\ s^{-1}}}\right)^2$$

- shock evolution
  w/ thin shell approximation

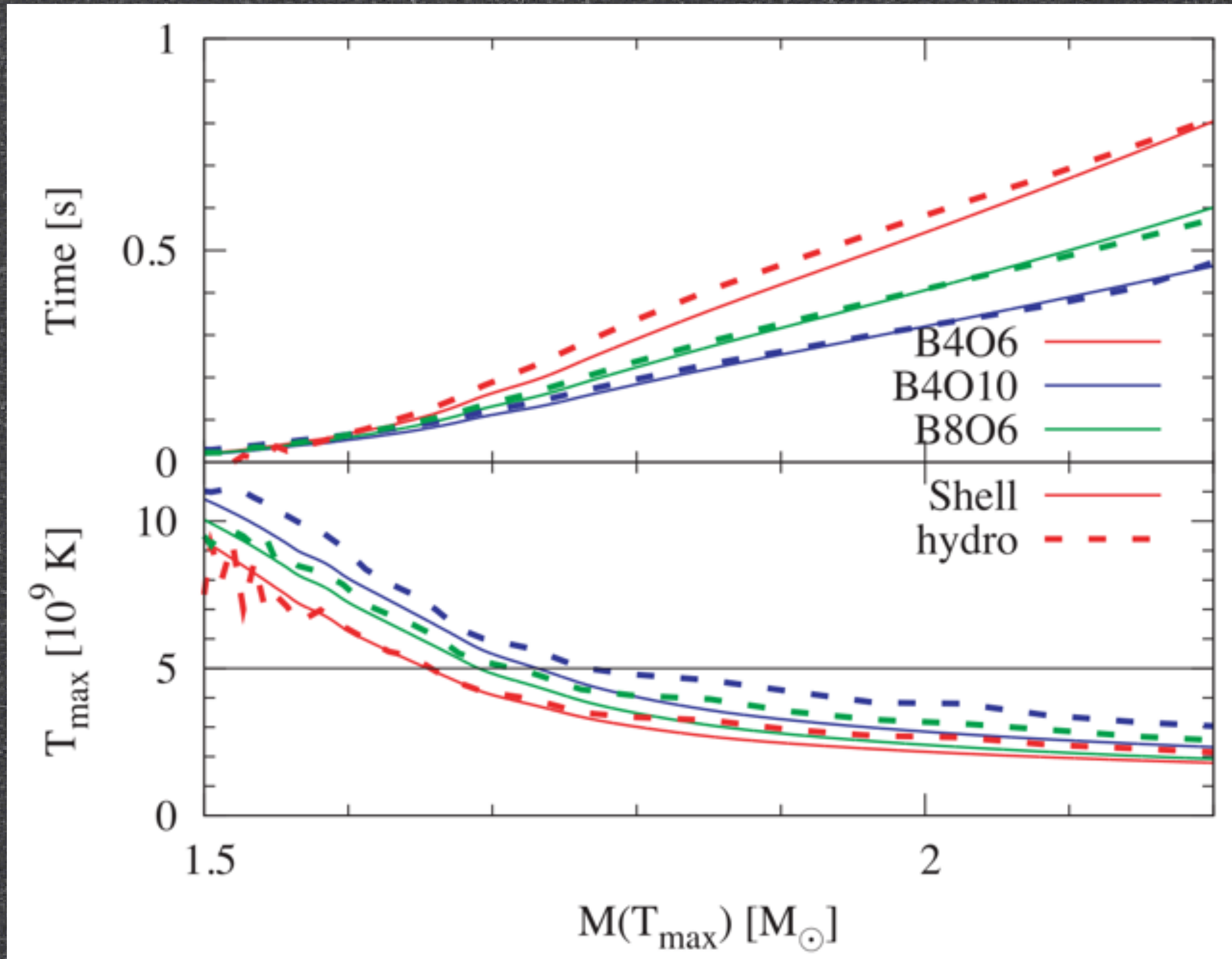
$$\frac{d}{dt}\left(M_s \dot{R}_s\right) = 4\pi R_s^2 p - F_g$$

$$\frac{d}{dt}\left(\frac{4\pi}{3} R_s^3 \frac{p}{\gamma - 1}\right) = L_w - p \frac{d}{dt}\left(\frac{4\pi}{3} R_s^3\right)$$

$$\begin{aligned}
&(3\gamma - 4) G M_s (2M_c + M_s) \dot{R}_s + 24\pi\gamma\rho_0 R_s^4 \dot{R}_s^3 \\
&+ 8\pi R_s^5 \dot{R}_s (\rho_0' \dot{R}_s^2 + 3\rho_0 \ddot{R}_s) \\
&- 2R_s^2 \left[3(\gamma - 1) L_w - (3\gamma - 2) M_s \dot{R}_s \ddot{R}_s\right] \\
&+ 2R_s^3 \left[4\pi G (M_c + M_s) \rho_0 \dot{R}_s + M_s \dddot{R}_s\right] = 0,
\end{aligned}$$

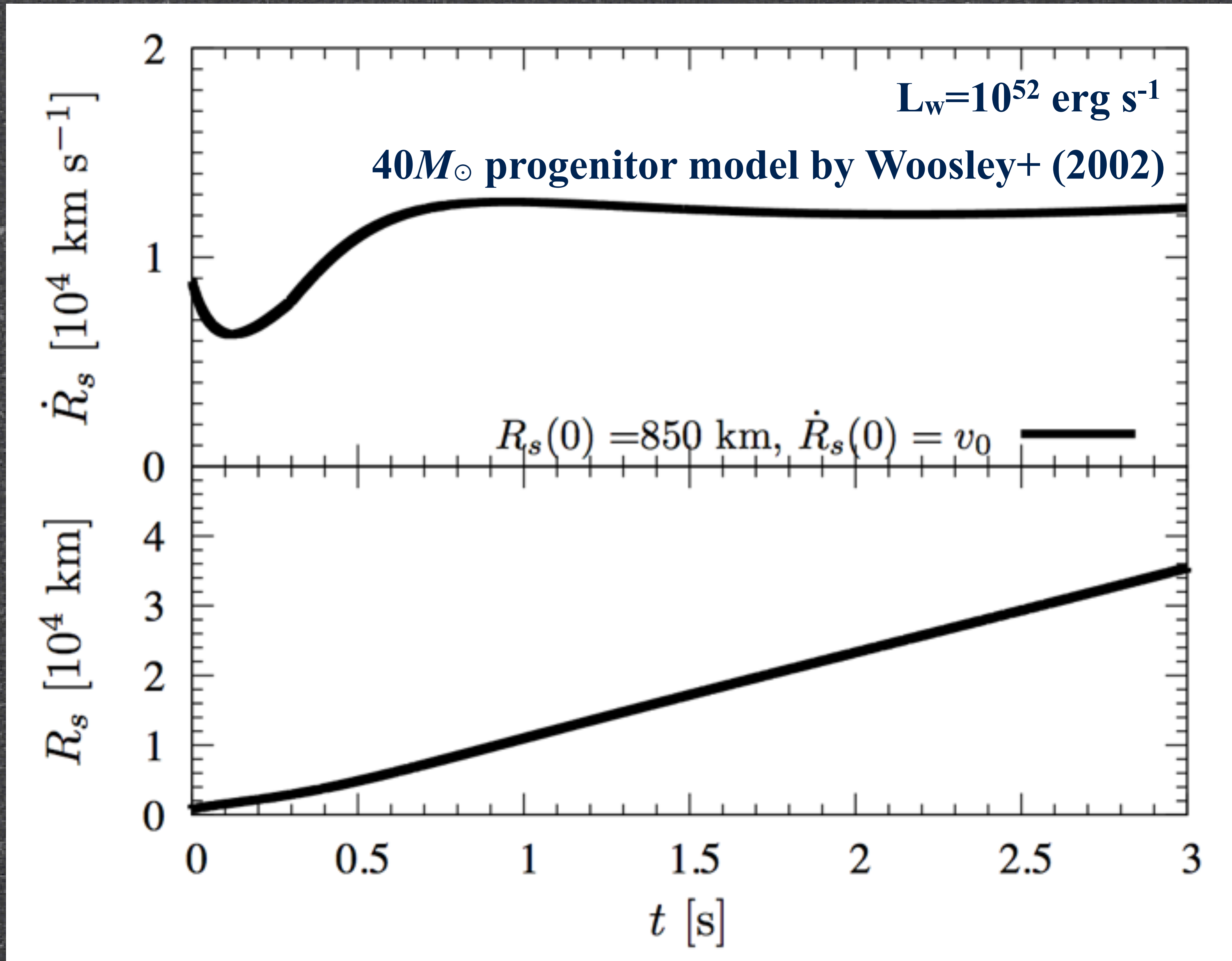
Suwa & Tominaga, MNRAS, 451, 4801 (2015)

Verification of model



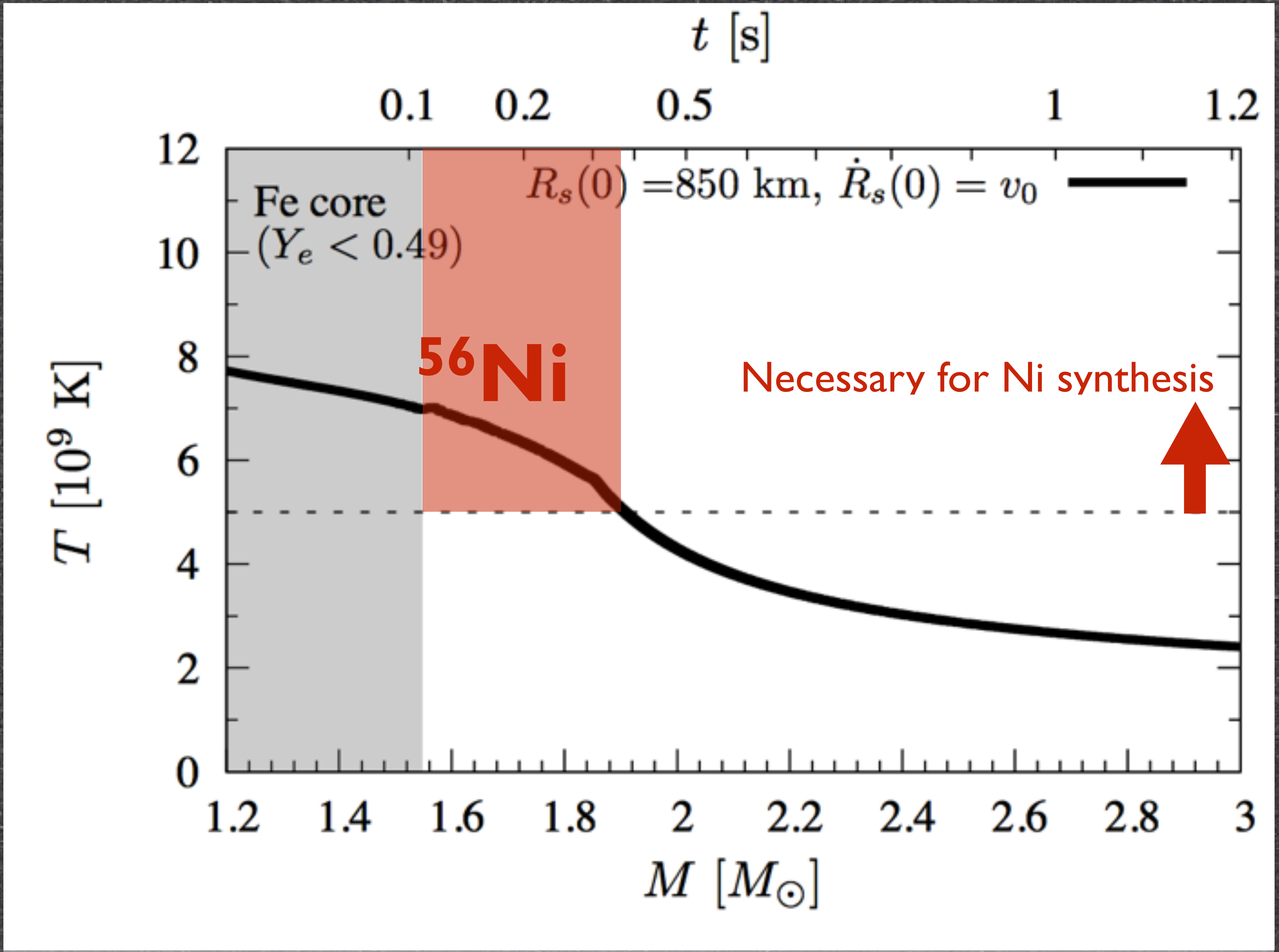
Suwa & Tominaga, MNRAS, 451, 4801 (2015)

Shock evolution



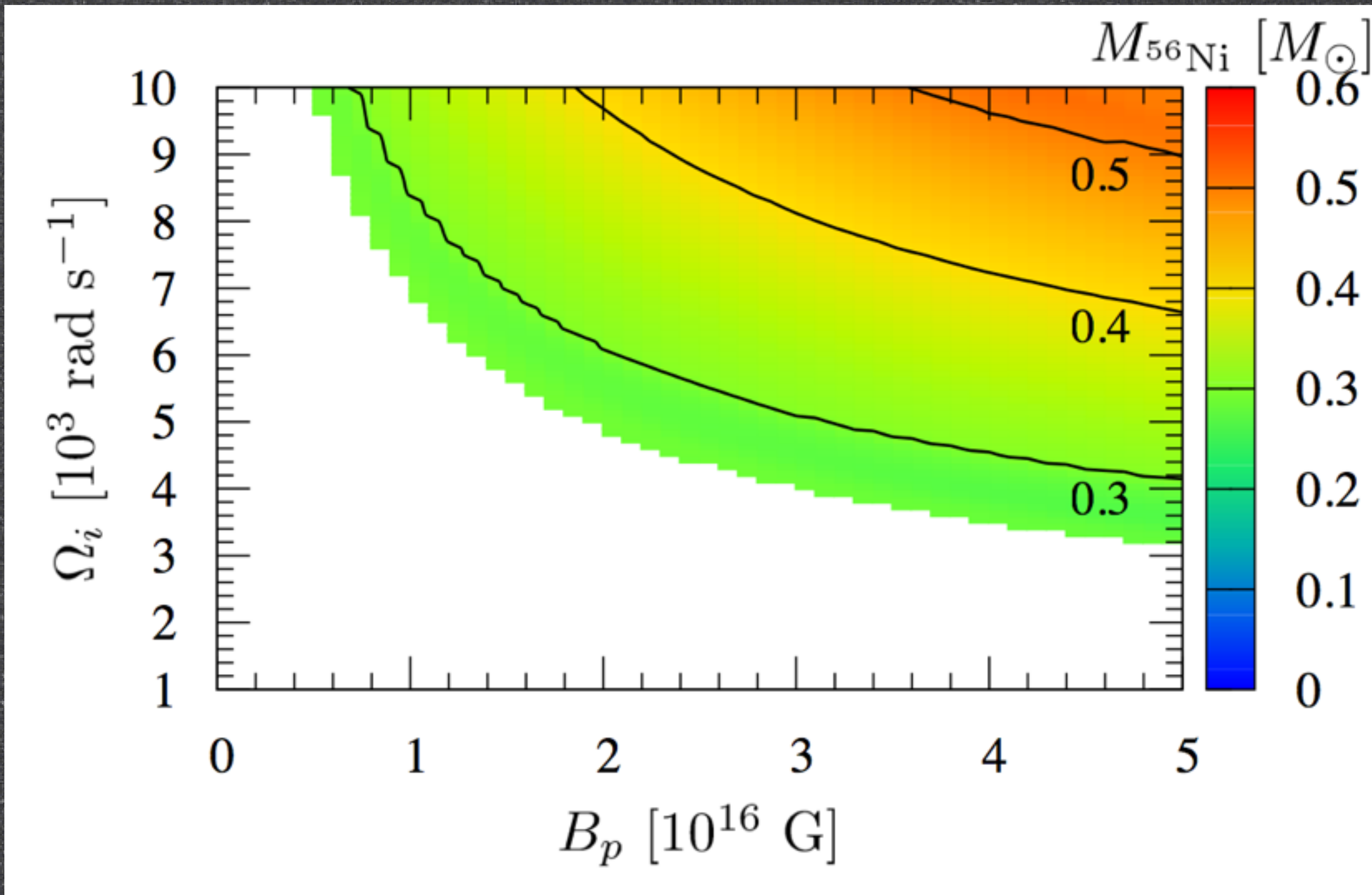
Suwa & Tominaga, MNRAS, 451, 4801 (2015)

Temperature evolution



Suwa & Tominaga, MNRAS, 451, 4801 (2015)

$M^{56}{}_{Ni}$



Suwa & Tominaga, MNRAS, 451, 4801 (2015)

Magnetars for ^{56}Ni

- necessary condition for $M_{^{56}\mathrm{Ni}} > 0.2 M_\odot$

$$\left(\frac{B_p}{10^{16}\mathrm{G}}\right)^{1/2}\left(\frac{\Omega_i}{10^4\ \mathrm{rad\ s^{-1}}}\right) \gtrsim 0.68$$

$P = 0.628$ ms

- extremely strong magnetic fields and (almost) breakup rotation are required to explain HNe
- doesn't match model parameters fitting GRB afterglows and SLSNe ($B \sim 10^{14}$G & $\Omega \sim O(10^3)$ rad s^{-1})
- we might need other mechanism (not dipole rad.) or other engine (BH wind?) to synthesize enough ^{56}Ni

Summary

- Q
  Can magnetar's dipole radiation produce enough amount of ^{56}Ni explaining hypernovae?
- A
  Seems difficult. We may need other mechanism to consistently explain hypernovae and GRBs with magnetar scenario