Evolution of magnetar-powered supernovae

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RIKEN-RESCEU joint meeting 2016/07/25-27

1. Neutron stars

- **Neutron Stars (NS)**
  - generated by core collapse supernovae
  - observed NS, a few hundreds

- **Power sources of them**
  - rotation energy
  - gravitational energy of accreting matters
  - thermal energy
  - magnetic field energy

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-> We focus on NS with strongest magnetic fields, “Magnetar”.

2. Magnetars

- NS with strong magnetic fields

$$P \sim 2-10 \text{ sec}, \ \dot{\mathrm{P}} \sim 10^{-13} \text{ s/s}$$

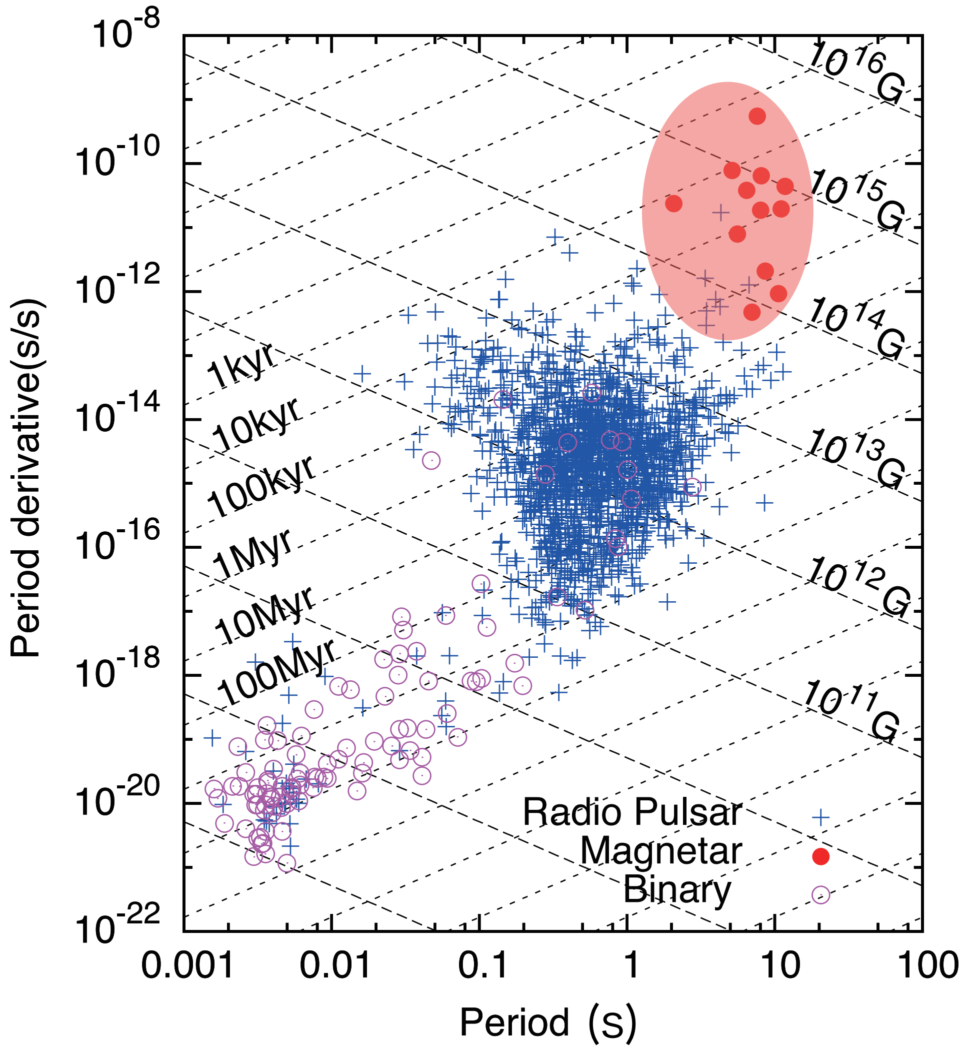
$$B \propto \sqrt{P\dot{P}} \sim 10^{14-15} \text{ G}$$

(typical neutron stars : $B \sim 10^{12}$ G)

- Spin down. Pdot > 0
- Radiate X-ray by using magnetic fields. $L_X \sim 10^{35}$ erg/s >> L_{spin}

-> **rapidly spin & Highly magnetize at their birth**.

-> The mechanism for growth of strong magnetic fields & what supernovae generate magnetars have not been well understood.

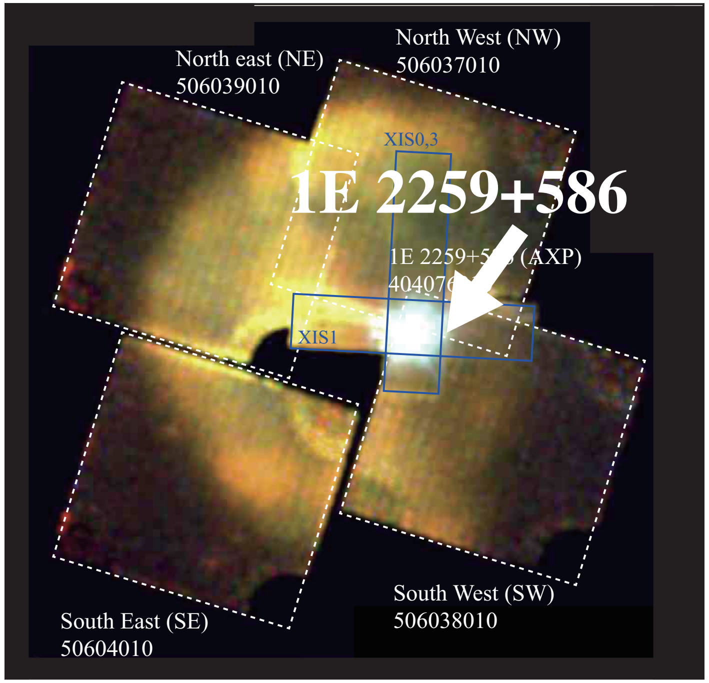


(ATNF pulsar catalog)

3. Previous works

- discovered magnetars : about 30
  (ATNF pulsar catalog)
- some associate with SNR
  (e.g. Kes 73, CTB 109)

- Observations of such SNR :
  - Progenitors are very massive (>30M$_\odot$)
    (e.g. Figer +05, Kumar +12)
  - **E_{SNR} ~ 10^{51} erg**
    (e.g. Vink & Kuiper 06)



Suzaku X-ray image,
CTB109 (SNR) & 1E2259+586 (magnetar)

- Theoretical prediction※ :
  - **E_{rot} ~ 10^{52} erg** are injected
    to stellar envelope by magnetic dipole radiation.

※ Magnetars have very short spin periods (P_0 < 3ms) and highly strong magnetic field (B_0 > 10^{15}G) at their birth (α-dynamo effect) (Duncan & Thompson 92).
Therefore they have E_{rot} ~ 10^{52} erg and inject its energy to stellar envelope.

4. Our work

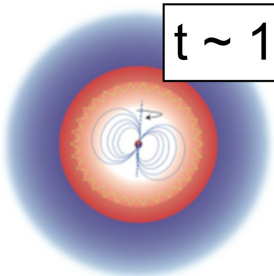
core collapse of massive star

t ~ 0 sec

R ~ 10^{10} cm

explosion

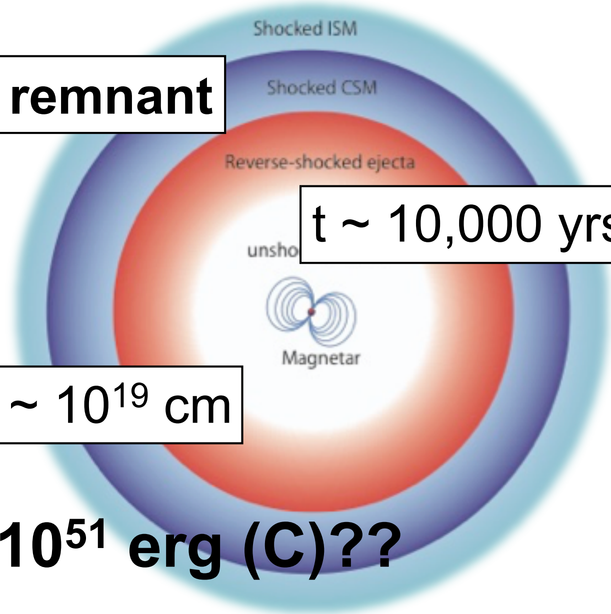
supernove



t ~ 100 days

expansion

supernove remnant



t ~ 10,000 yrs

R ~ 10^{19} cm

E_{rot} ~10^{52} erg (A)?? **(B)??** **E_{SNR} ~10^{51} erg (C)??**

(A). A mechanism without rapidly rotation amplify a magnetic field of magnetar. -> $E_{rot} < 10^{52}$ erg

(B). Most of rotation energy is used for something (e.g. GW, binding energy).

(C). Underestimate energy of SNR associated with magnetars. -> $E_{SNR} > 10^{51}$ erg

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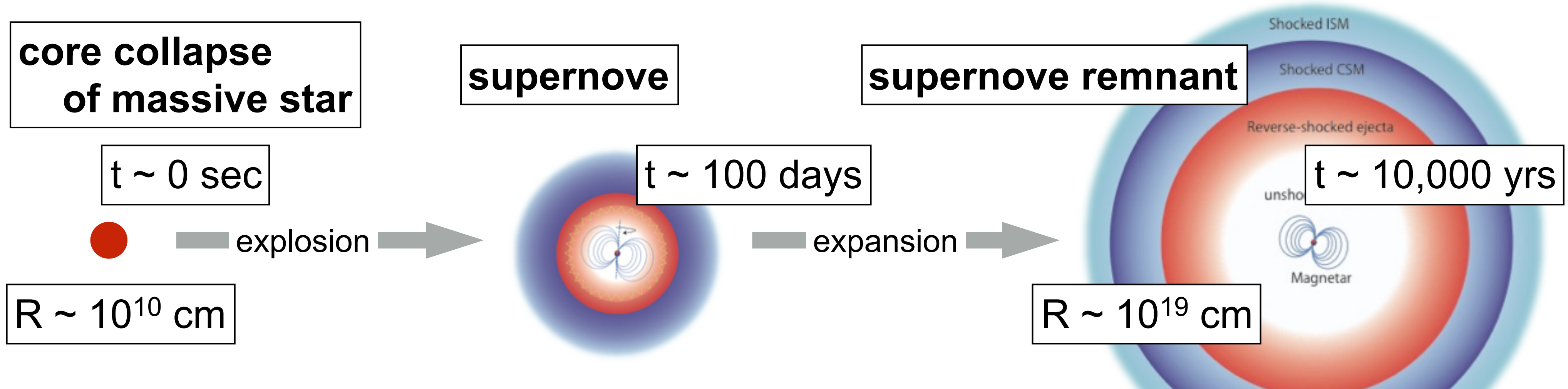

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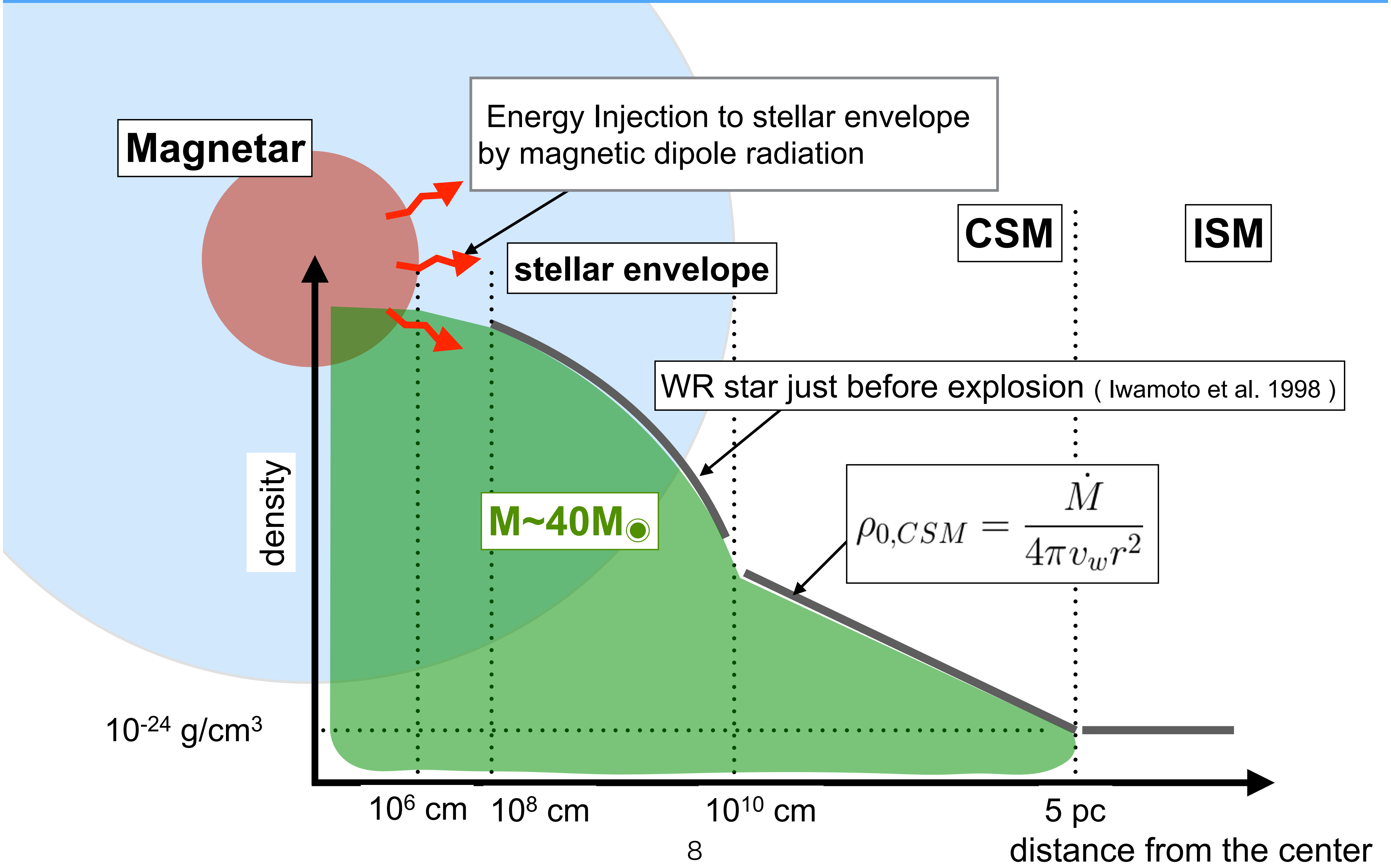
-> We perform 1D hydrodynamical simulations of evolutions of magnetars for 10,000 yrs to investigate the relation between E_{rot} and E_{SNR}.

5. Set up for simulations



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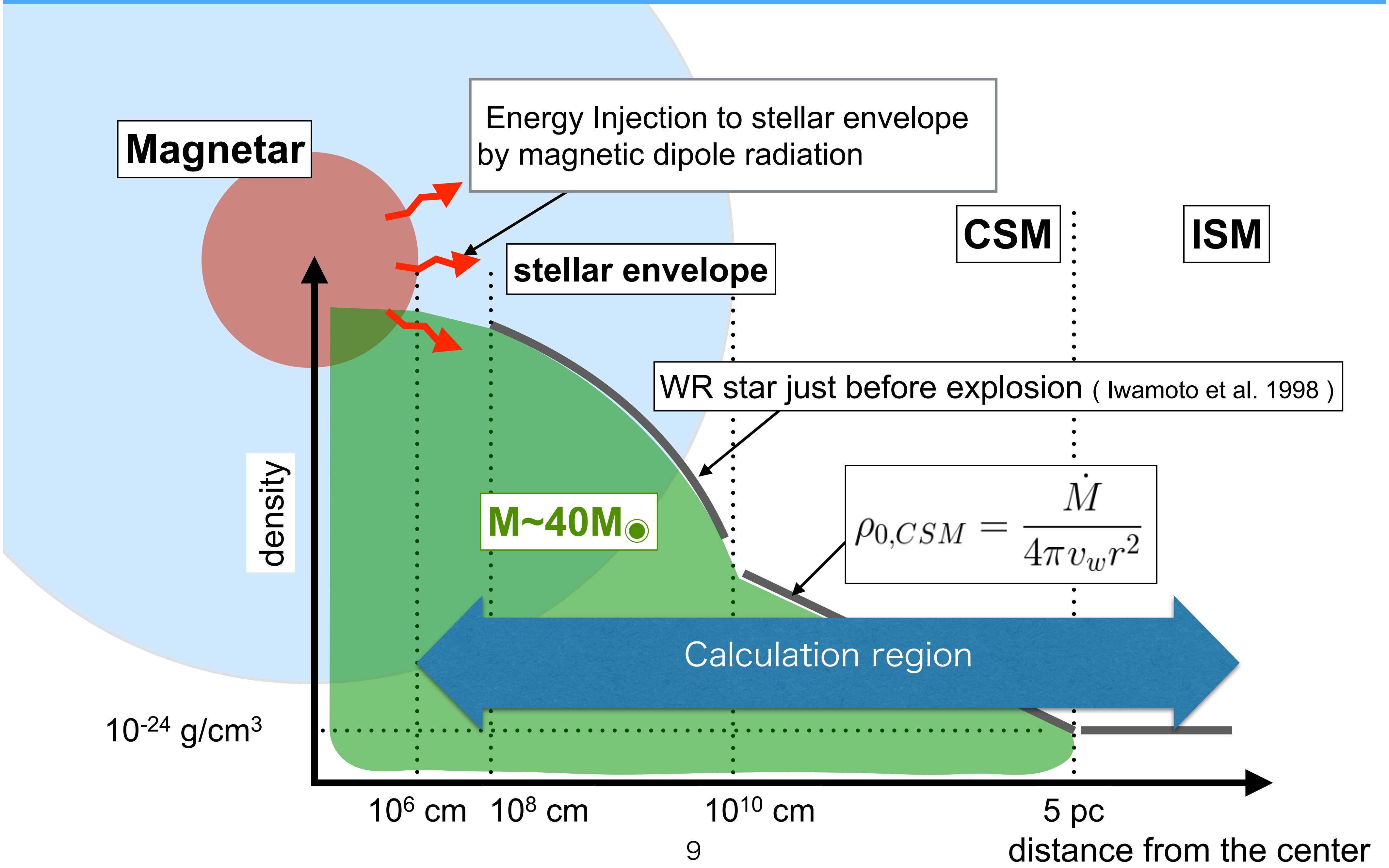

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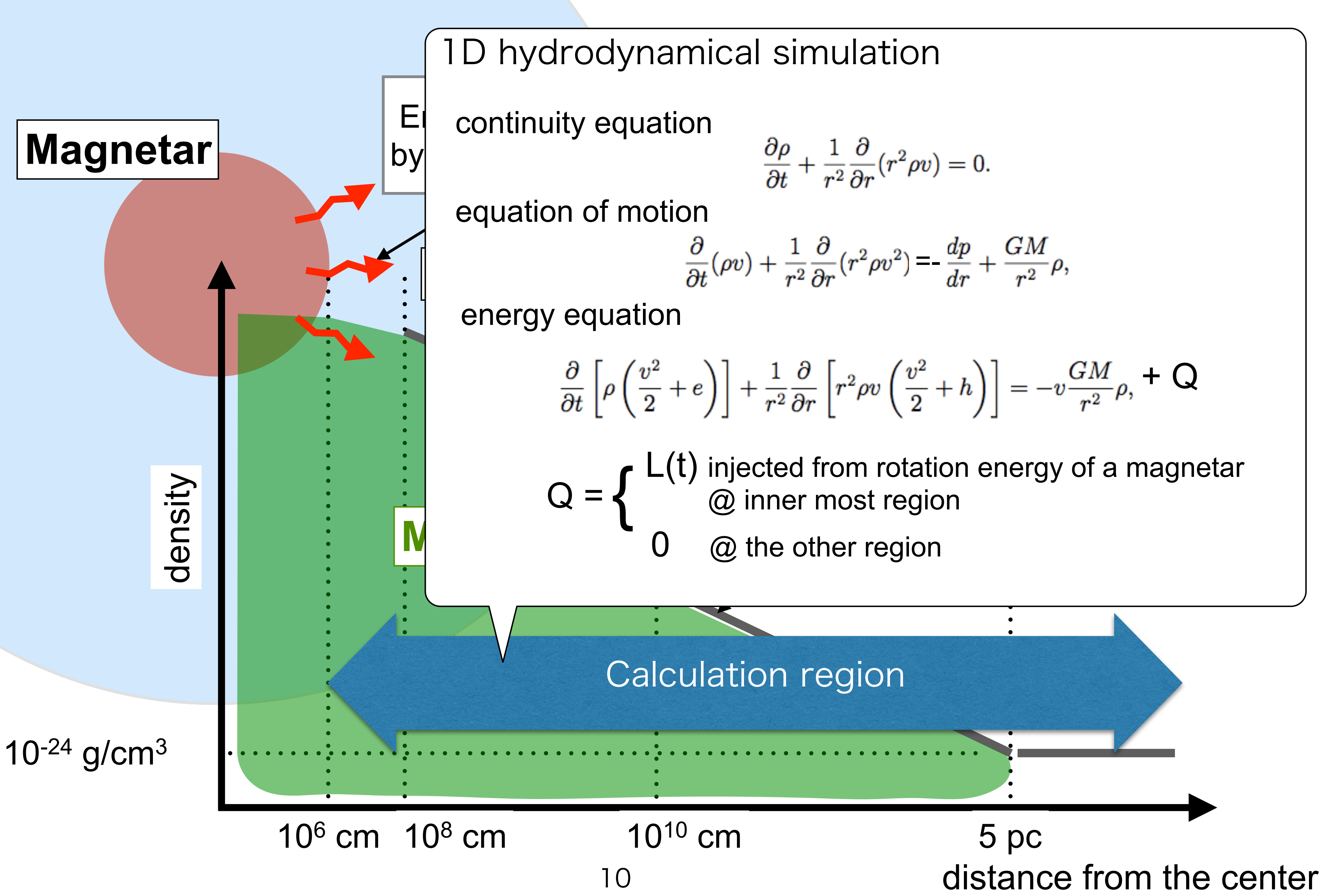


1D hydrodynamical simulation

continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho v) = 0.$$

equation of motion

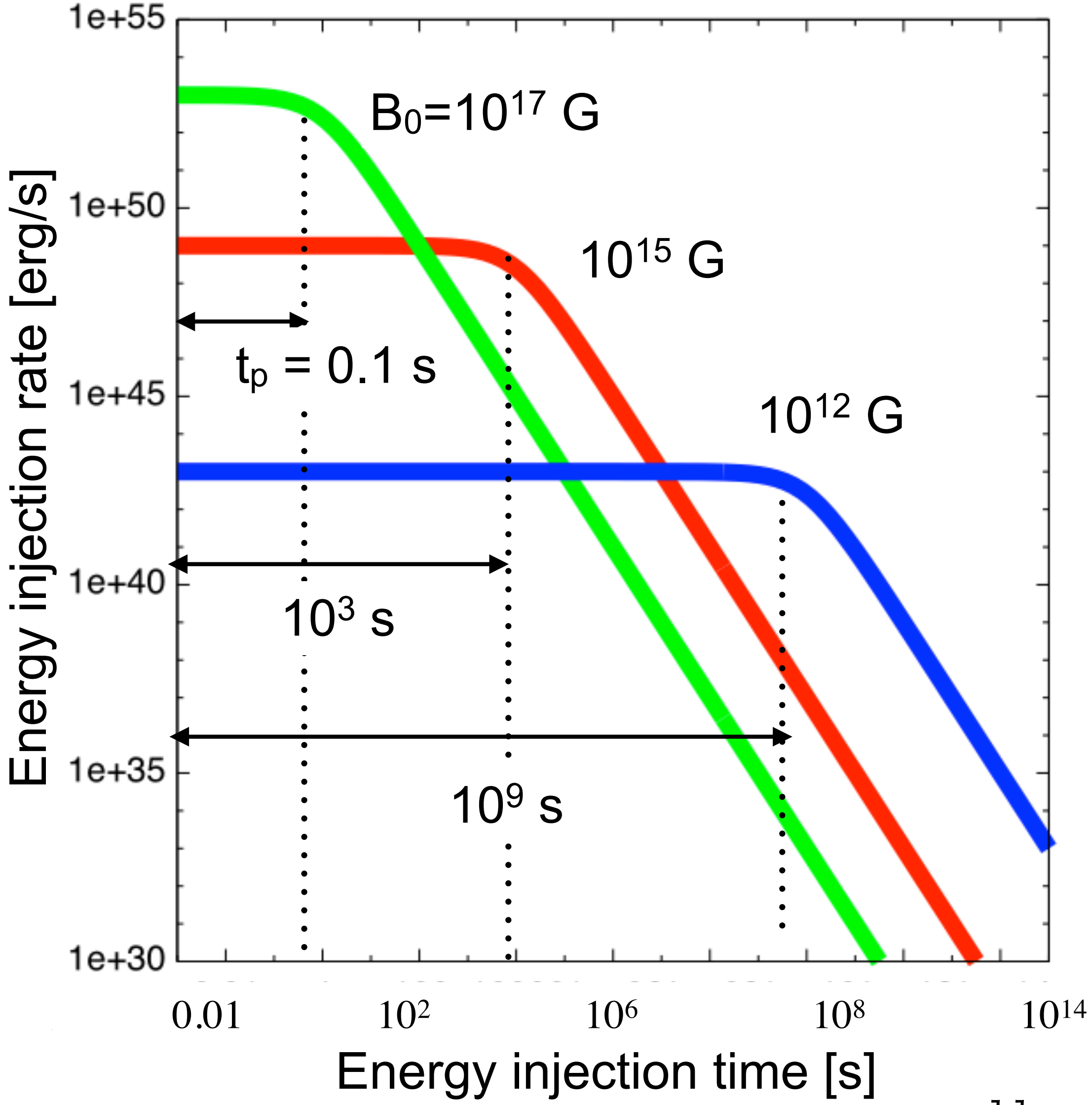
$$\frac{\partial}{\partial t}(\rho v) + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho v^2) = - \frac{dp}{dr} + \frac{GM}{r^2}\rho,$$

energy equation

$$\frac{\partial}{\partial t}\left[\rho\left(\frac{v^2}{2} + e\right)\right] + \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 \rho v \left(\frac{v^2}{2} + h\right)\right] = -v\frac{GM}{r^2}\rho, + Q$$

Q = { L(t) injected from rotation energy of a magnetar @ inner most region
0 @ the other region

6. Magnetars as a explosion engine



Magnetar

$$E_{rot} = 10^{52}\ \text{erg} \sim \frac{1}{2} I\omega^2$$

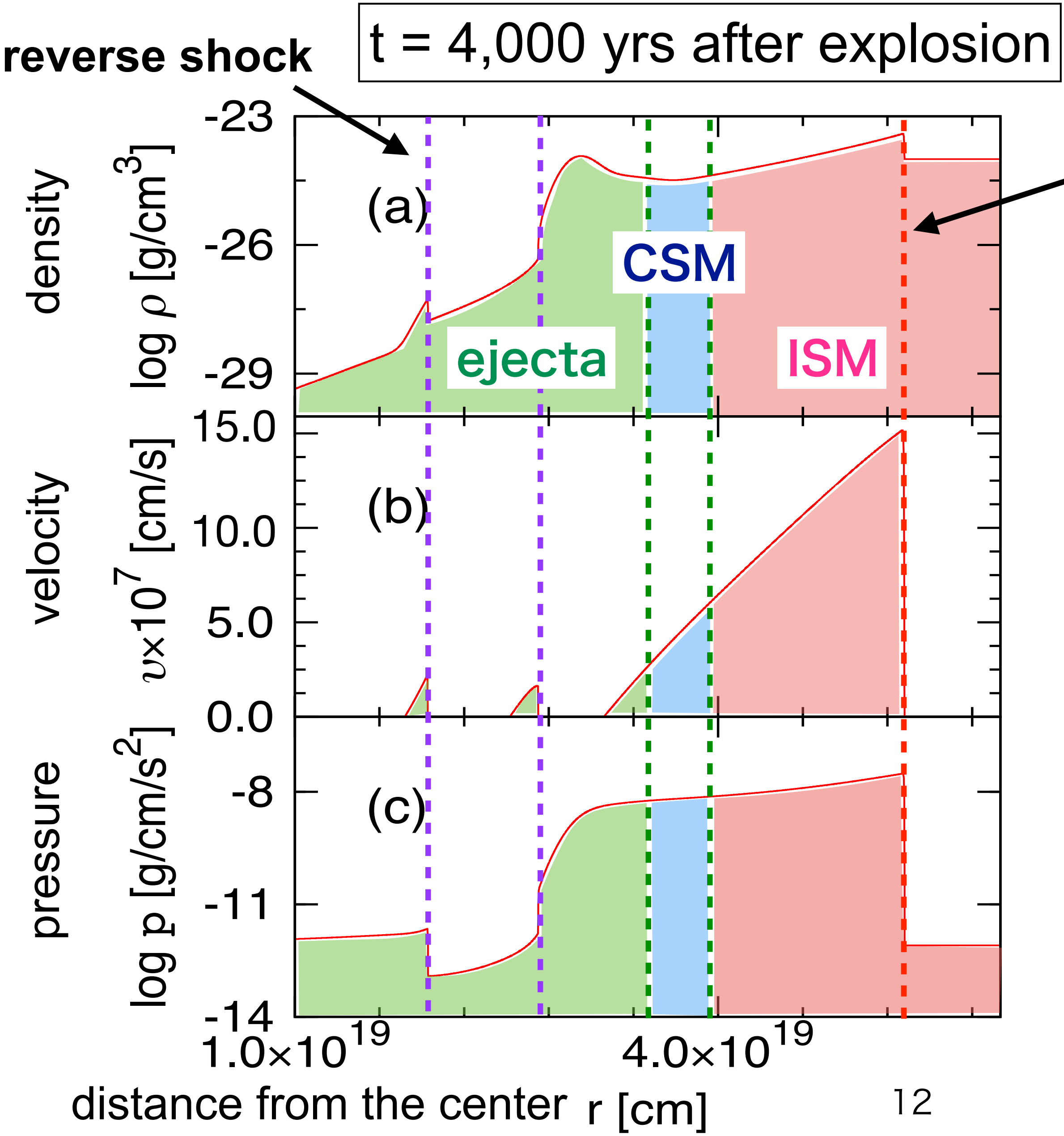
inject energy to stellar envelope by magnetic dipole radiation

$$\frac{dE}{dt} = \frac{E_{rot}}{t_p} \frac{1}{(1+\frac{t}{t_p})^2}$$

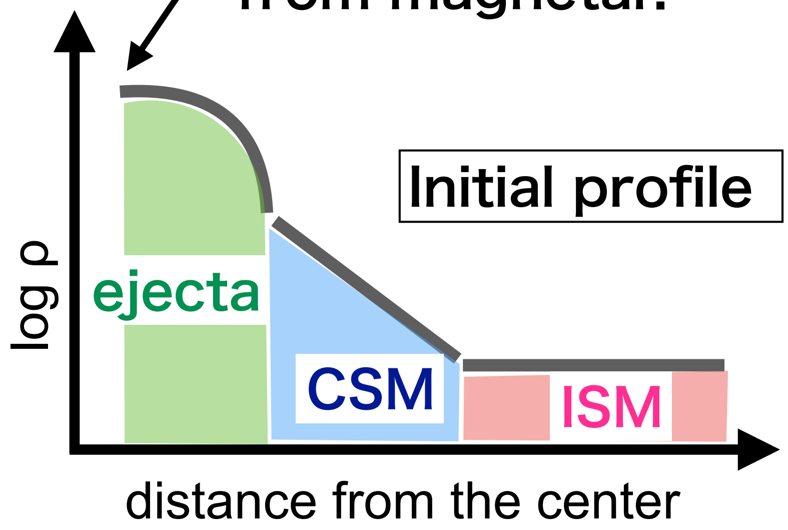
$$t_p = 10^3\ \text{sec} \left(\frac{P_0}{1\text{ms}}\right)^2 \left(\frac{B_0}{10^{15}\text{G}}\right)^{-2}$$

$$E_{rot} = \int \frac{dE}{dt} dt = 10^{52}\ \text{erg} \left(\frac{P_0}{1\text{ms}}\right)^{-2}$$

7. Time evolution of shock waves



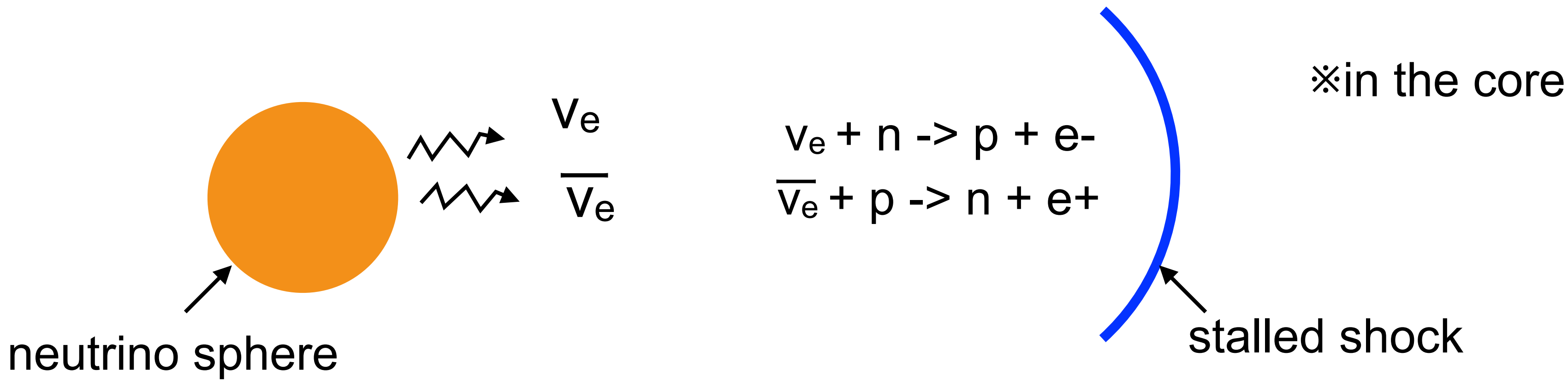
shock are formed by energy injection from magnetar.



8. Energy of neutrino-heating

- $E_{SNR} \sim E_{rot} + \mathbf{E_{\nu,heating}} + E_{nuc} + E_{bind}$

  -> The stalled shock is revived by depositing of a part of energy 10^{51} erg carried away by neutrino $\nu_e, \bar{\nu}_e$.

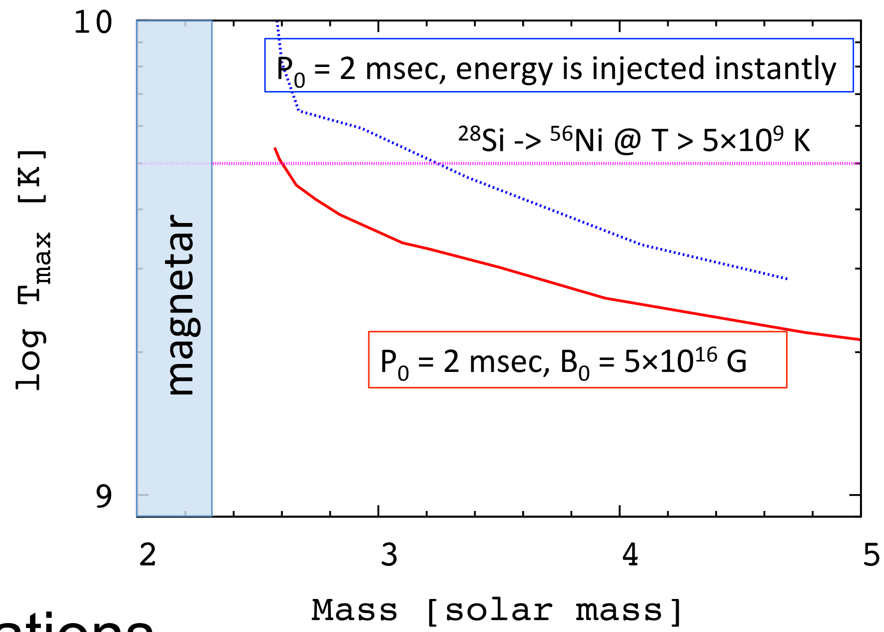


- $\mathbf{E_{\nu,heating}} \sim 10^{51}$ erg

9. Energy of nuclear reactions

- $E_{SNR} \sim E_{rot} + E_{\nu,heating} + \mathbf{E_{nuc}} + E_{bind}$
- rough estimation of nuclear energy under assumption that the matter which exceed T > 5×10^9 K will be ^{56}Ni.

-> $$E_{\rm nuc} = \frac{m_{^{28}{\rm Si}} \times 2 - m_{^{56}{\rm Ni}}}{m_{^{56}{\rm Ni}}} \times M_{^{56}{\rm Ni}} \times c^2$$
$$\sim 2.2 \times 10^{51}\ {\rm erg.}$$



- We should calculate hydrodynamical simulations including nuclear reactions and feedback to hydrodynamical simulations for magnetar-powered supernovae.

10. Gravitational binding energy

- $E_{SNR} \sim E_{rot} + E_{\nu,heating} + E_{nuc} + \mathbf{E_{bind}}$
- Progenitors of magnetars are considered to be massive stars.

(e.g. Safi-Harb & Kumar 2012)

Magnetar	Progenitor mass
1E 1048.1-5937 (Gaensler+ 2005)	30-40 $M_\odot$
CXO J164710.2-455216 (Muno+ 2006)	> 40 $M_\odot$
SGR1806-20 (Figer+ 2005)	~50 $M_\odot$
SGR 1900+14 (Davies+ 2009)	17 $M_\odot$
1E 1841–045 (Kumar+2014)	>> 20 $M_\odot$
SGR 0526–66 (Uchida+2015)	~26 $M_\odot$
1E 2259+586 (Nakano PhD thesis)	~40 $M_\odot$

- E_{bind} ~ **- 5 × 10^{51} erg** (just before explosion)

  in case that a progenitor mass is 40 $M_\odot$

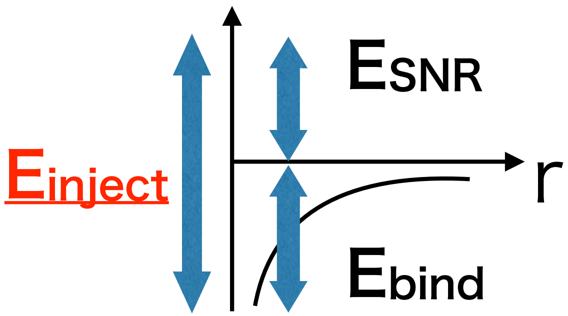
11. Time evolution of energy

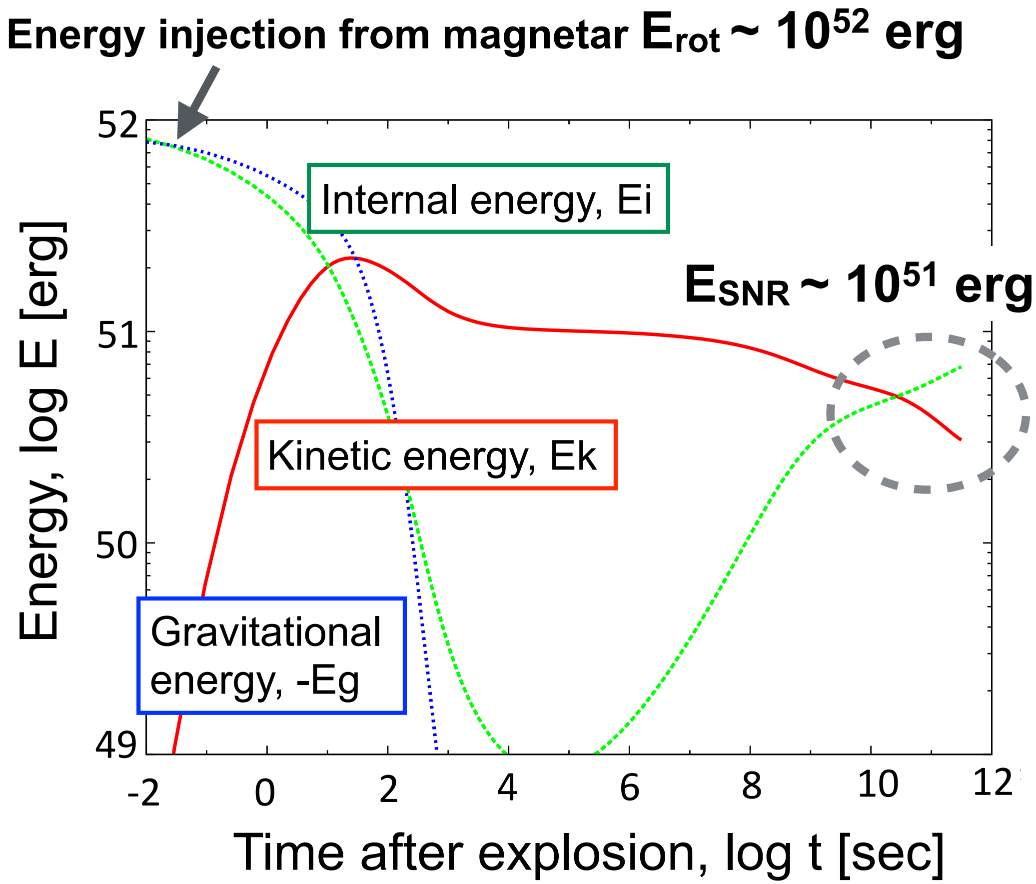
- $E_{SNR} \sim E_{rot} + E_{\nu,heating} + E_{nuc} + E_{bind}$

$$\sim 10^{52} + 10^{51} + 10^{51} - 5\times10^{51}$$

$$\sim 10^{51}\ \text{erg}$$

-> Most of the rotation energy 10^{52} erg is used to climb up the gravitational potential well of a massive star and the resultant SNR possesses the rest of the energy $E_{SNR} \sim 10^{51}$ erg.





12. Summary

- We perform 1D hydrodynamical simulations to investigate the relation between energy of magnetars at their birth E_{rot} and energy of supernova remnants associated with magnetars E_{SNR}.
- Most of the rotation energy is used to climb up the gravitational potential well of a massive star and the resultant supernova remnant possesses the rest of the energy $E_{SNR} \sim 10^{51}$ erg.
- We should carry out simulations including nuclear reactions and feedback to hydrodynamics.