Investigation of the formation mechanism of central compact objects with GR-MHD simulations

CCOにおける磁場の起源の解明：超新星フォールバック降着流の一般相対論的磁気流体力学シミュレーション

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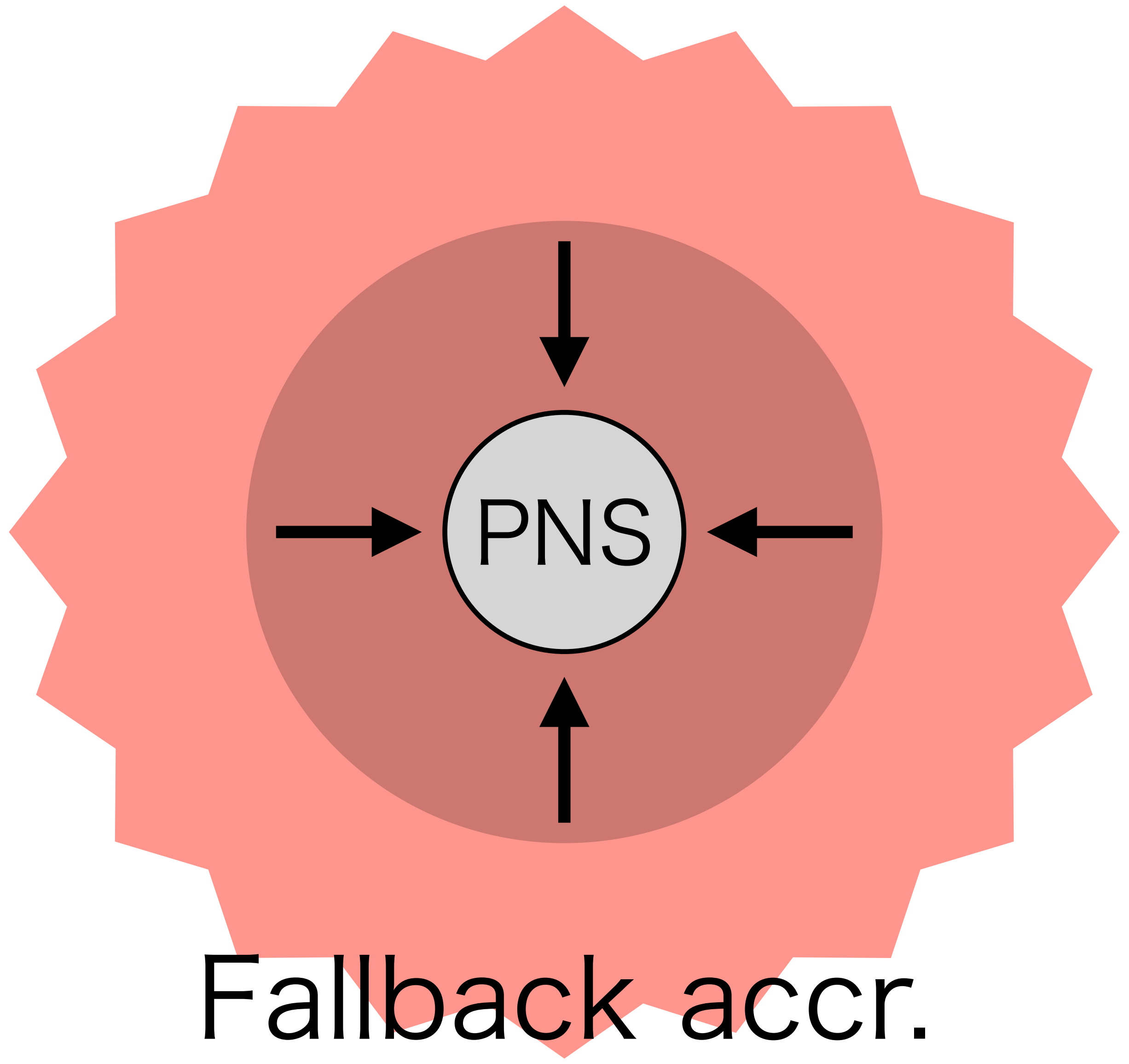
11th Supernova Neutrino Workshop (@ Univ. of Tokyo)

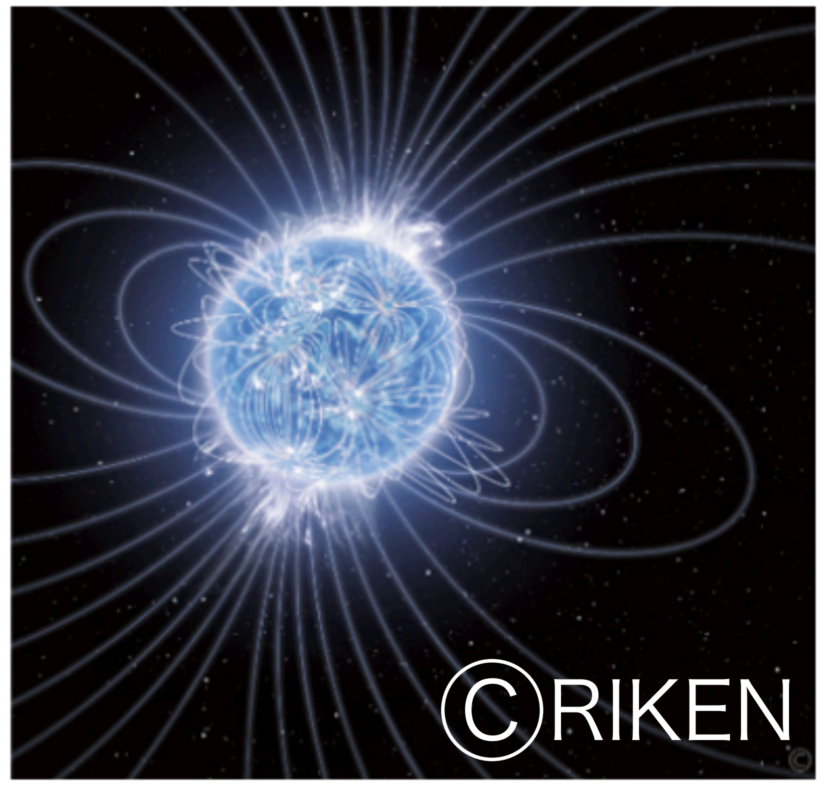
Diversity of young isolated neutron star

e.g.) Enoto+2019

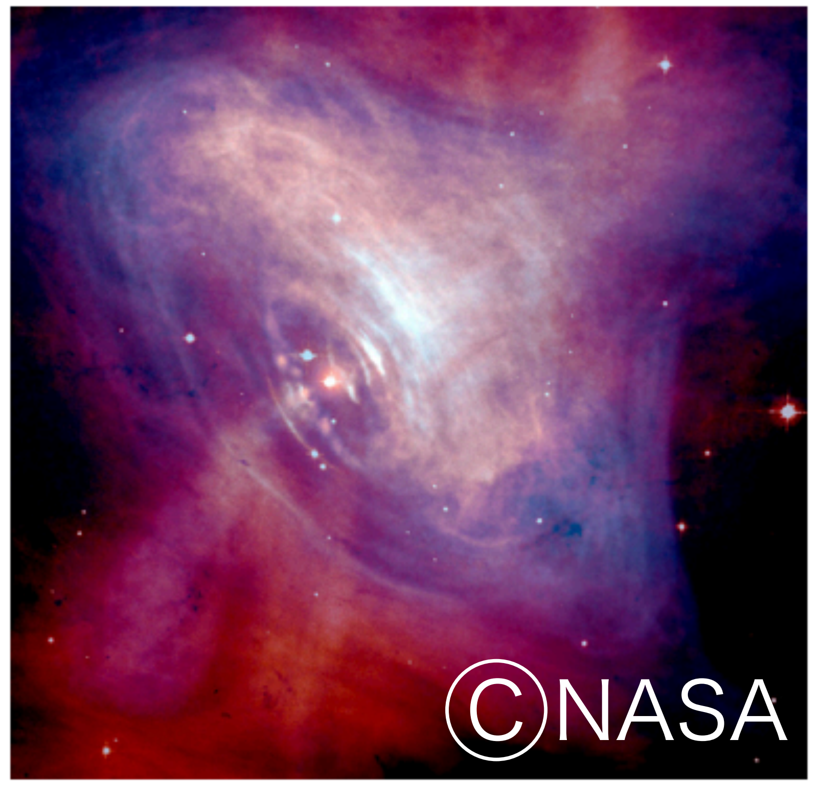


Diversity of the neutron star

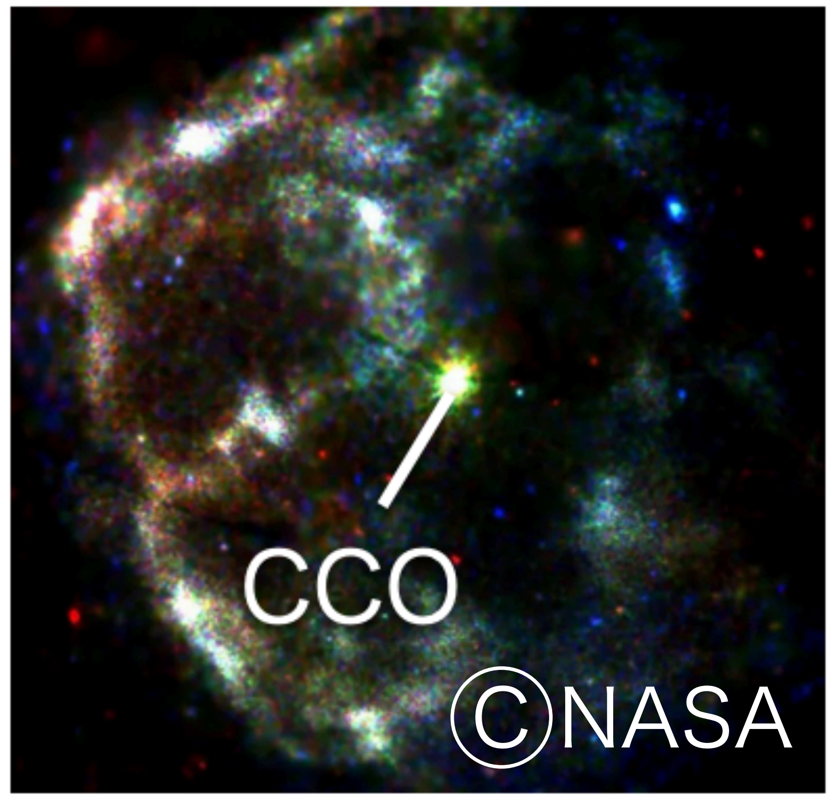
Magnetar
$B_{NS} \gtrsim 10^{14}$ G



Rotation-powered
$B_{NS} \sim 10^{11-13}$ G



Central Compact Object (CCO) $B_{NS} \lesssim 10^{11}$ G



Supernova mechanism or star's feature origin

This study will help us understand the supernova mechanism and the nature of their progenitors.

Supernova fallback

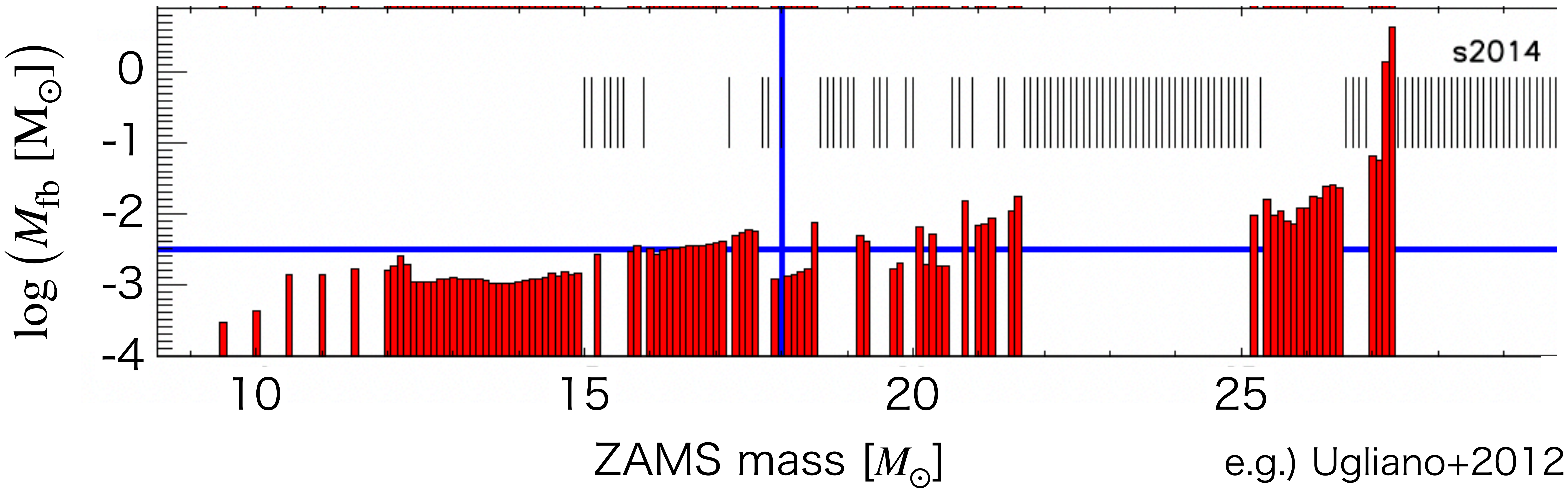
$M_{\rm fb}$: fallback mass

$t_{\rm fb}$: fallback time

The fallback accr. rate (Metzger+2018, Zhong+2021)

$$\dot{M}_{\rm fb} = \frac{2}{5}\frac{M_{\rm fb}}{t_{\rm fb}} \times \begin{cases} 1 & (t \leq t_{\rm fb}) \\ (t/t_{\rm fb})^{-5/3} & (t > t_{\rm fb}) \end{cases}$$

Michel 1988, Chevalier 1989



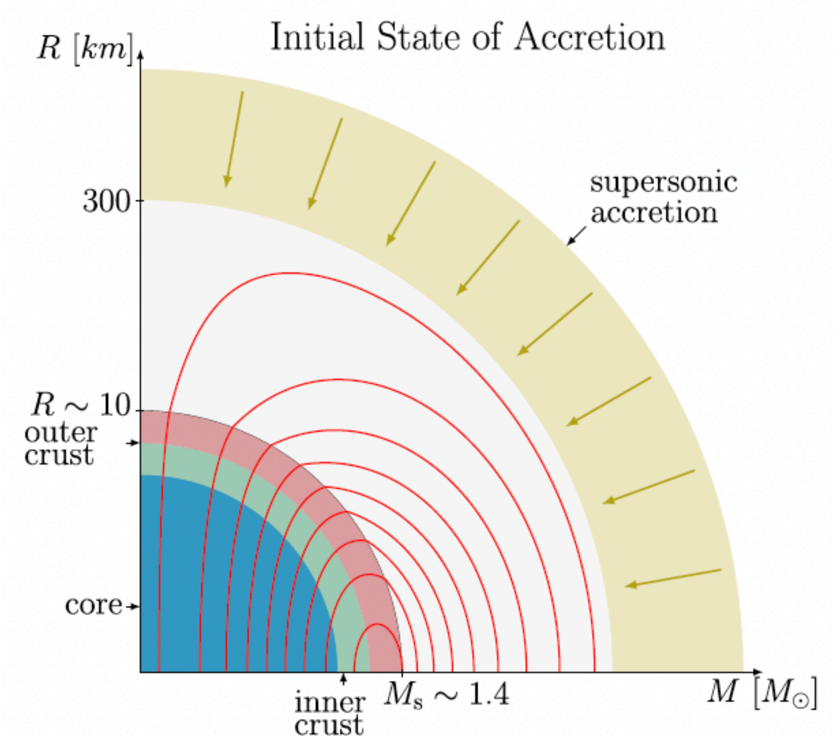
e.g.) Ugliano+2012, Ertl+2016

$M_{\rm fb}$ is sensitive to the progenitor structure and the supernova explosion mechanism, typically $\sim 10^{-(4-1)}$ M$_\odot$

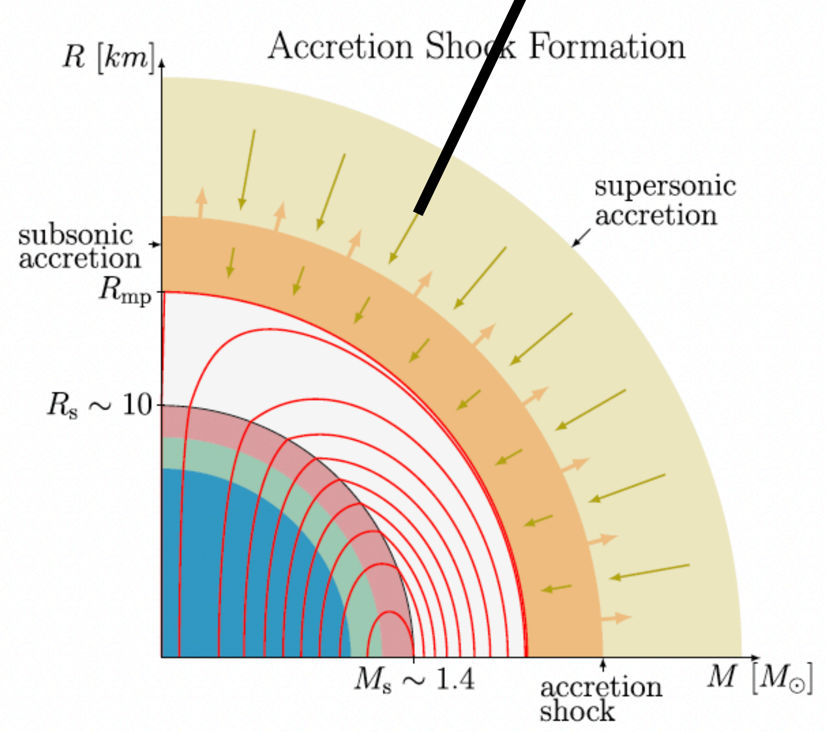
Neutrino cooling in fallback accretion

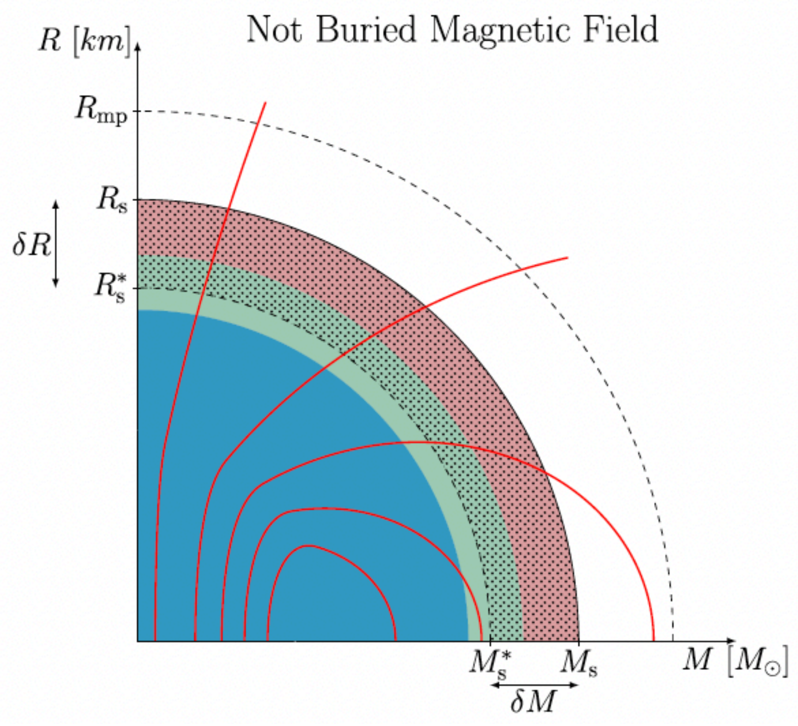
Chevalier+1989, Torres-Forné+2016, Shigeyama+2017

Strong $B_{\rm NS}$ or low $\dot{M}_{\rm fb}$



Fallback accr. flow





Strong $B_{\rm NS}$
(Magnetar or
rotation powers)

Weak $B_{\rm NS}$ or high $\dot{M}_{\rm fb}$

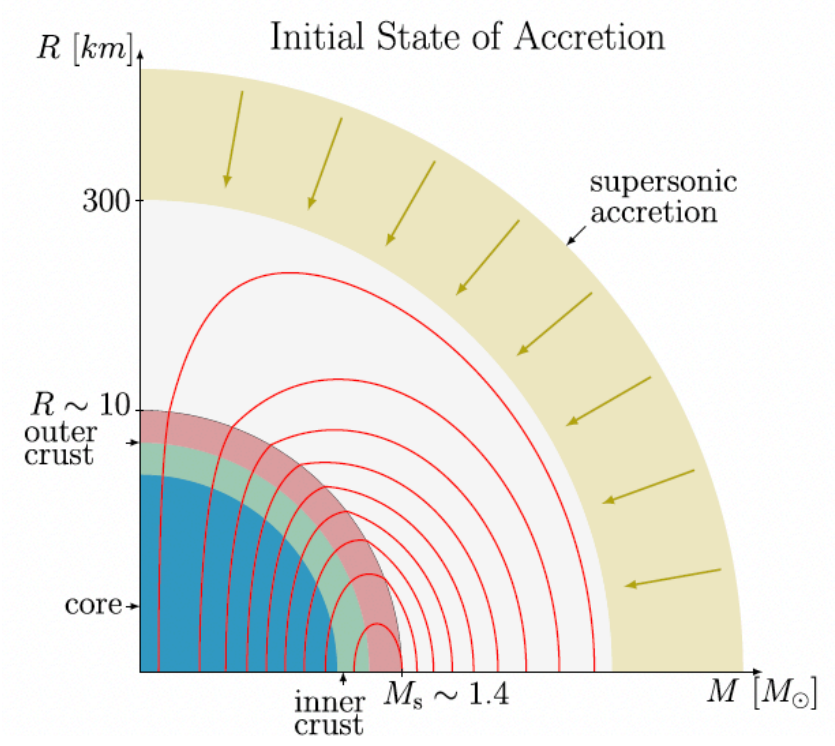
($\dot{M}_{\rm fb}$: fallback accr. rate)

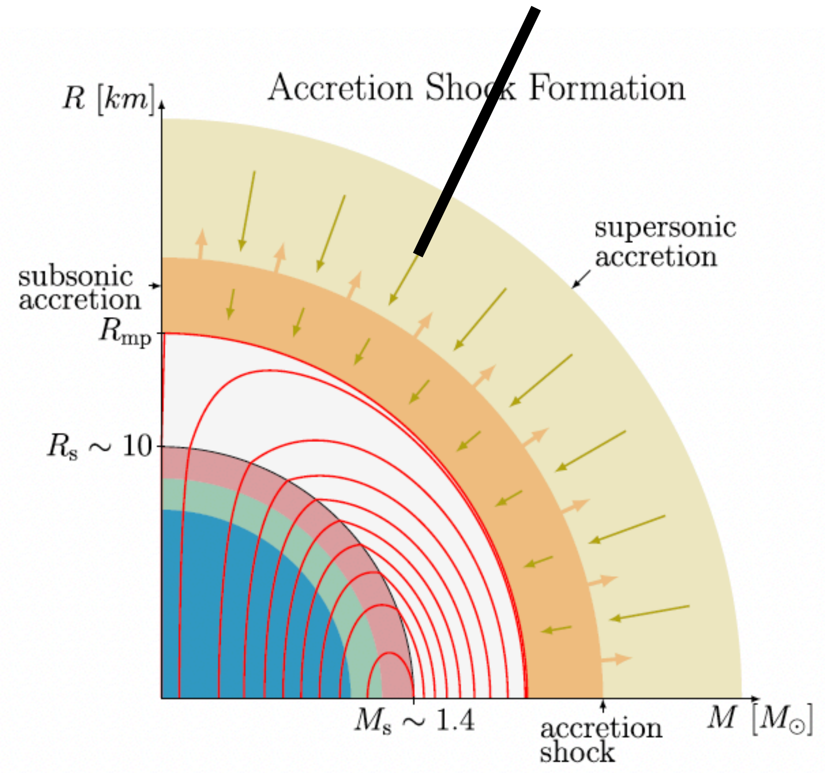
Neutrino cooling in fallback accretion

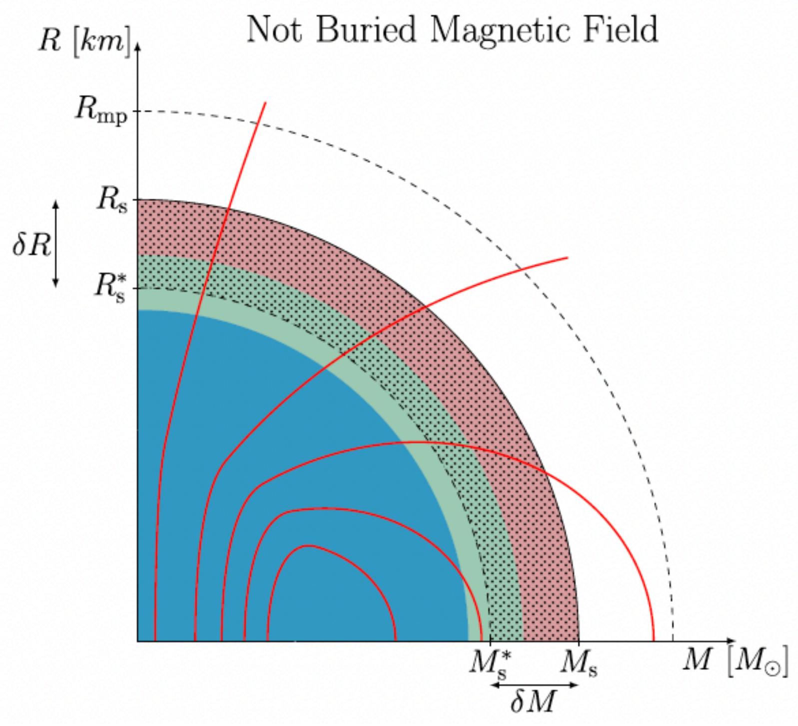
Chevalier+1989, Torres-Forné+2016, Shigeyama+2017

Fallback accr. flow

Strong $B_{\rm NS}$ or low $\dot{M}_{\rm fb}$

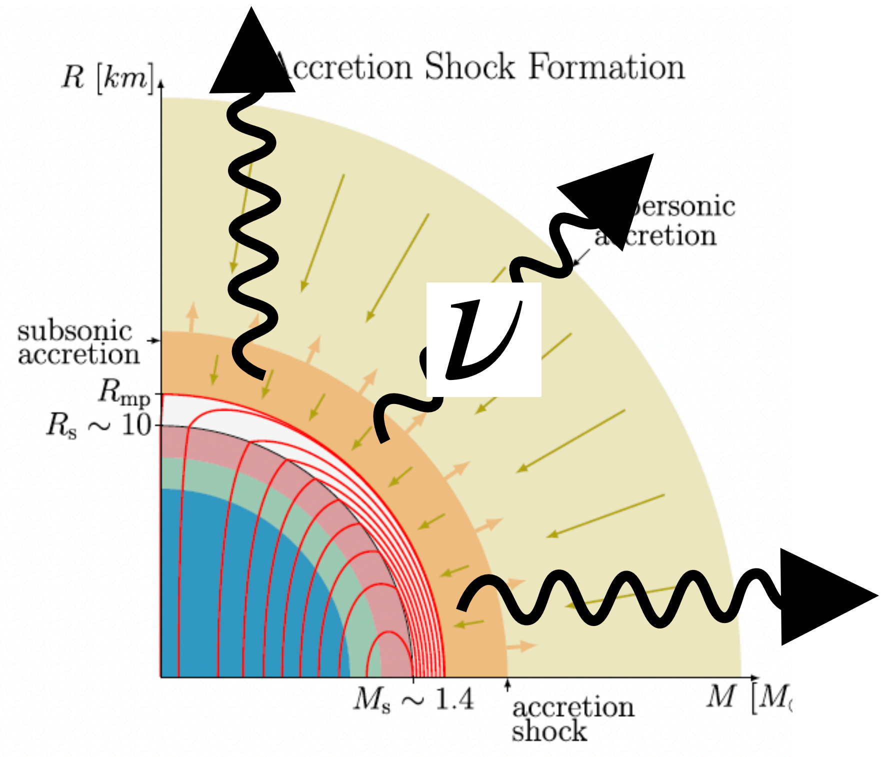


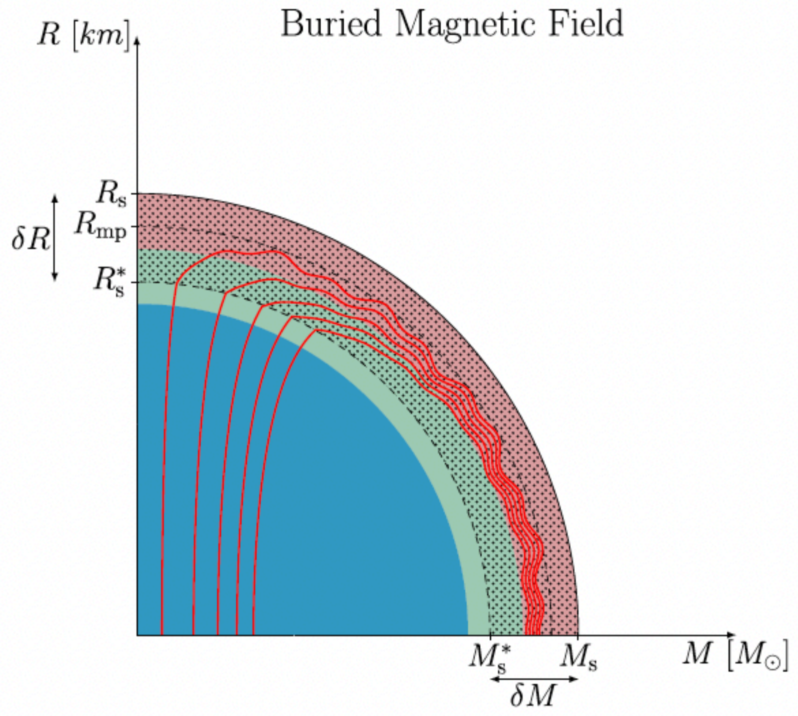




Strong $B_{\rm NS}$

(Magnetar or rotation powers)





Weak $B_{\rm NS}$

(CCO)

Weak $B_{\rm NS}$ or high $\dot{M}_{\rm fb}$

($\dot{M}_{\rm fb}$: fallback accr. rate)

Neutrino cooling

Outer crust formation

Purpose of this study

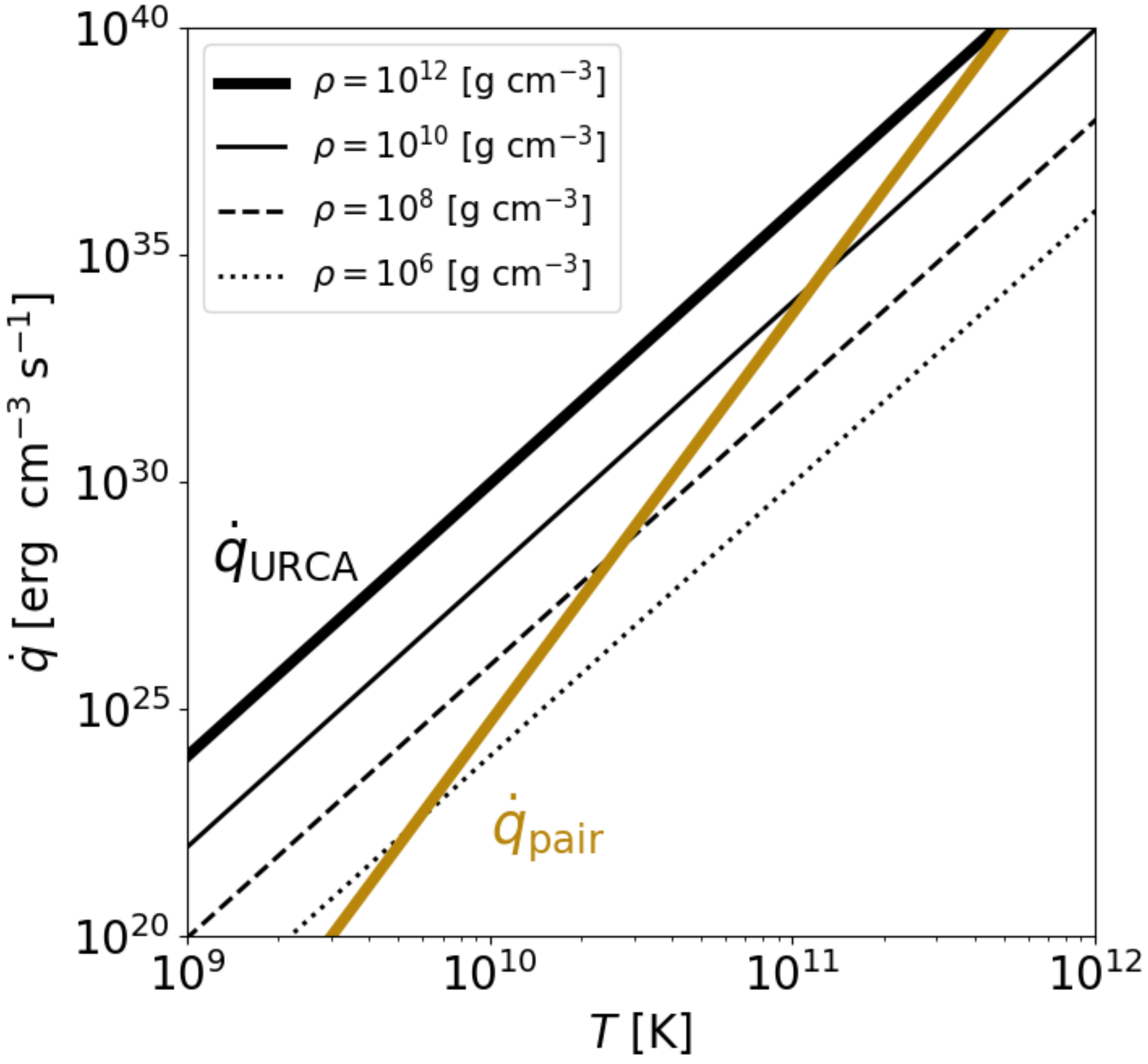
Question

- How does the neutrino cooling affect the accr. dynamics around a magnetized NS?
- Condition of the CCO formation?

Purpose of this study

- Investigate the fallback accr. through GR-MHD w/ neutrino cooling
- From the simulations, the criterion for CCO formation is derived

Neutrino cooling



<u>Neutrino cooling (Itoh et al.1989; Qian & Woosley 1996)</u>

Pair neutrino process $(e^+ + e^- \rightarrow \nu_e + \bar{\nu}_e)$

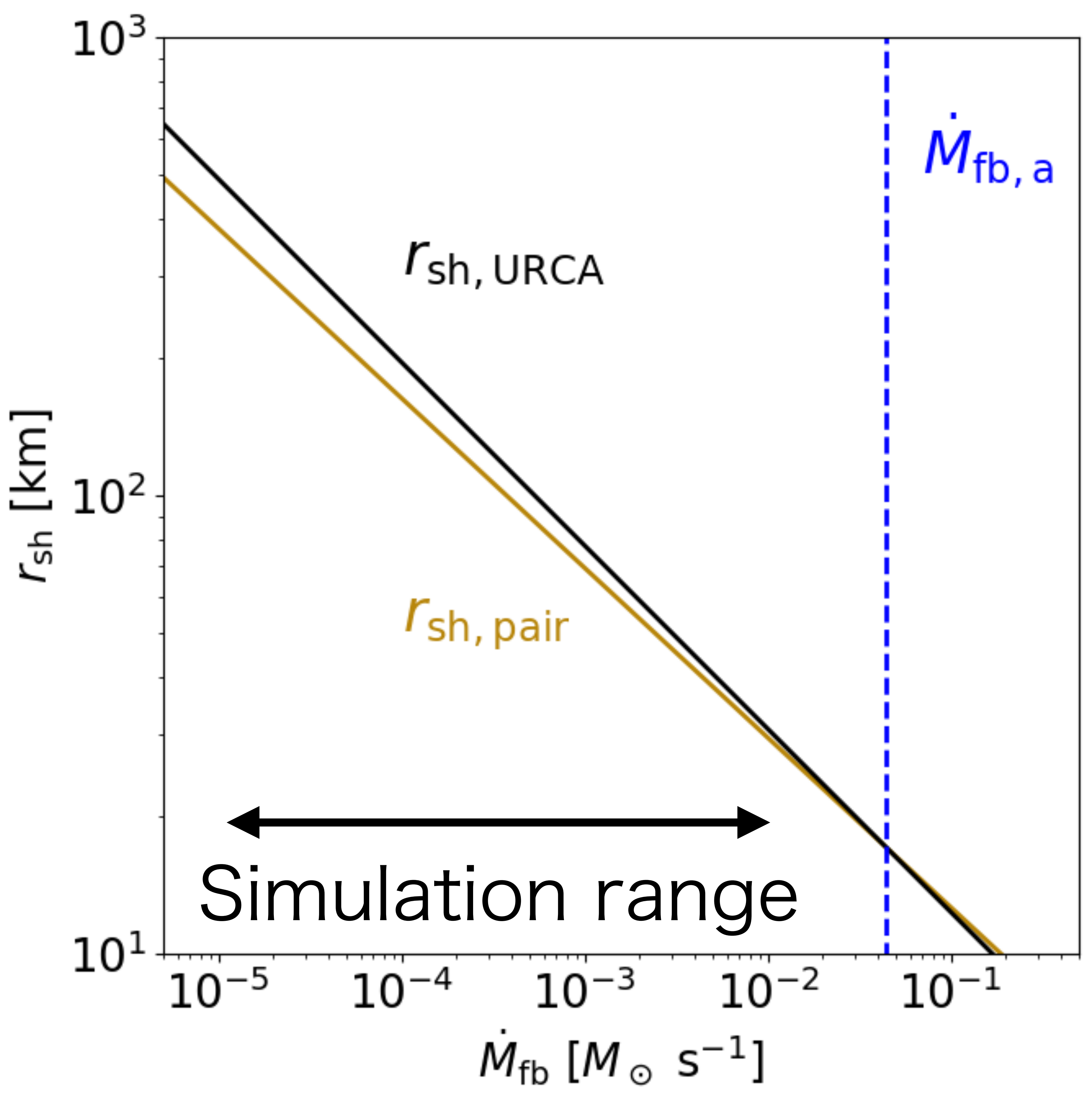
$$\dot{q}_{\rm pair} = 5 \times 10^{42}\ [\text{erg cm}^{-3}\ \text{s}^{-1}]\ \left(\frac{T}{10^{12}\ \text{K}}\right)^9$$

URCA process $(p + e^- \rightarrow n + \nu_e,\ n + e^+ \rightarrow p + \bar{\nu}_e)$

$$\dot{q}_{\rm URCA} = 9 \times 10^{29}\ [\text{erg cm}^{-3}\ \text{s}^{-1}]\ \left(\frac{\rho}{10^6\ \text{g cm}^{-3}}\right)\left(\frac{T}{10^{12}\ \text{K}}\right)^6$$

At high ρ, $\dot{q}_{\rm URCA}$ dominates $\dot{q}_{\rm pair}$

Steady solutions w/o magnetic field



Analytical solution (Chevalier 1989)

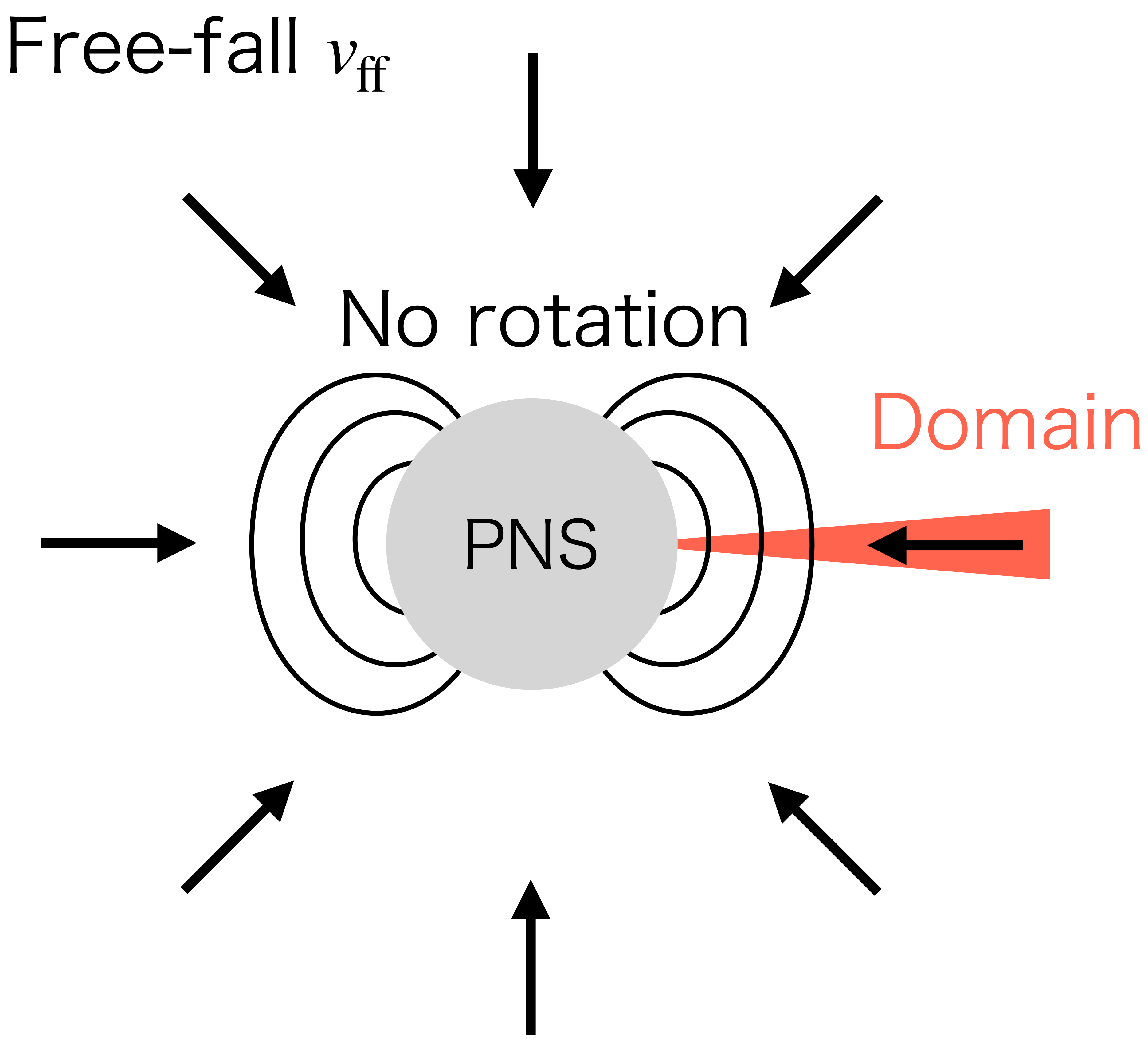
$$\frac{GM\dot{M}_{in}}{r_{NS}} = 4\pi r_{NS}^2 H\dot{q} \quad (H = r_{NS}^2 p_r / GM\rho \sim r_{NS}/4)$$

$$r_{sh,pair} = 3.4 \times 10^2 \text{ [km]} \times \left(\frac{r_{NS}}{10^6 \text{ cm}}\right)^{40/27} \left(\frac{M_{NS}}{1.4 \text{ M}_\odot}\right)^{-1/27} \left(\frac{\dot{M}_{fb}}{10^{-5} \text{ M}_\odot \text{ s}^{-1}}\right)^{-10/27}$$

$$r_{sh,URCA} = 5.0 \times 10^2 \text{ [km]} \times \left(\frac{r_{NS}}{10^6 \text{ cm}}\right)^{4/3} \left(\frac{M_{NS}}{1.4 \text{ M}_\odot}\right)^{1/5} \left(\frac{\dot{M}_{fb}}{10^{-5} \text{ M}_\odot \text{ s}^{-1}}\right)^{-2/5}$$

As $\dot{M}_{fb}$ increases, shock radius decreases

Simulation setup



GR-MHD simulations w/ neutrino cooling

Accr. rate : $\dot{M}_{in} \sim 10^{-(5-2)}$ $[M_{\odot}\ s^{-1}]$ (Ugliano+2012)

NS mag. : 0 G, 10^{13-15} G (dipole)

Adiabatic index : 4/3 (rad. press. ≫ gas press.)

Resolution & Domain

$10\ \mathrm{km} \leq r \leq 1000\ \mathrm{km}, \quad N_r = 16384\ (= 2^{14})$

Initial condition

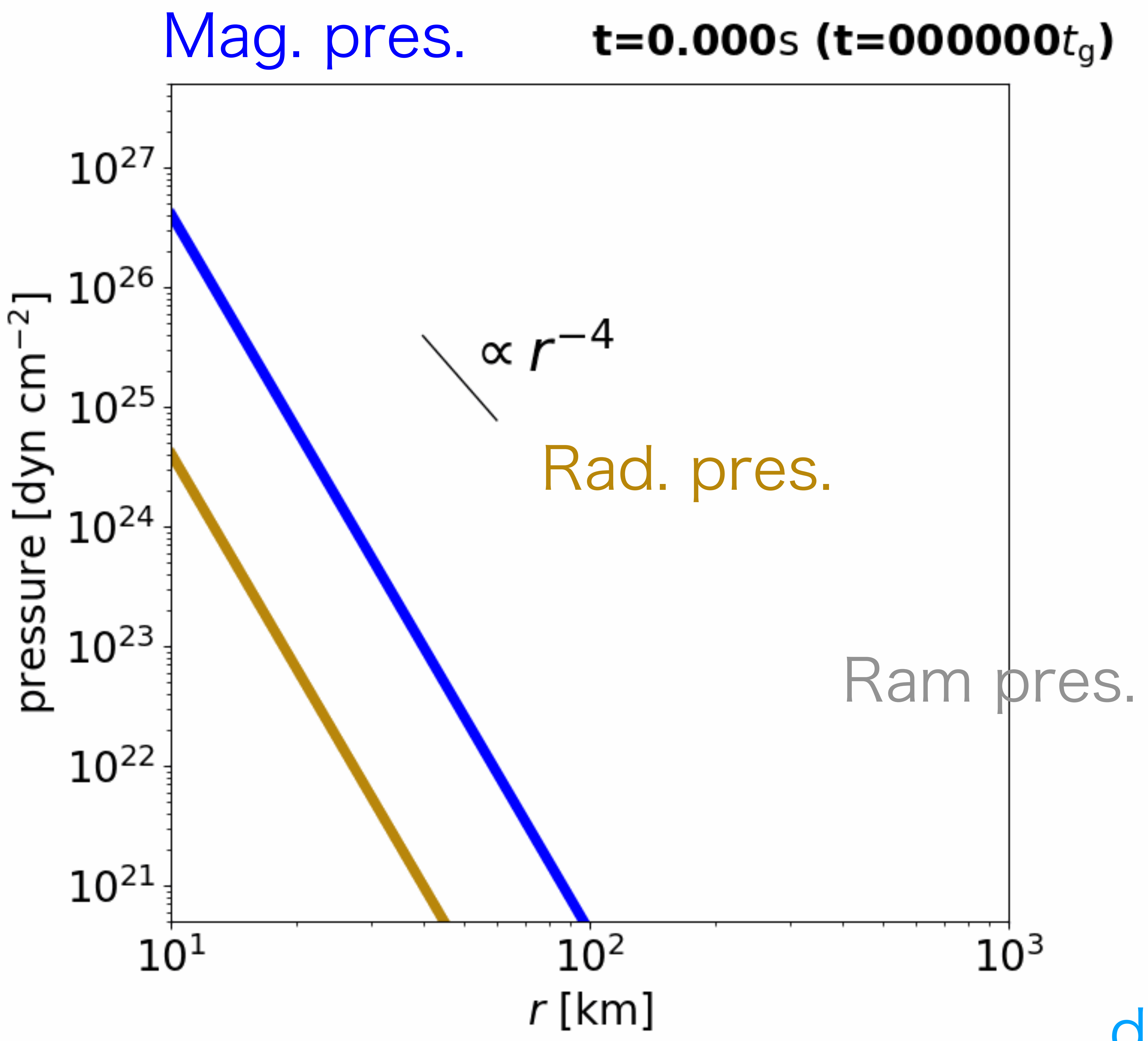
magnetic pressure supported hydrostatic atmosphere

NS surface : reflective boundary

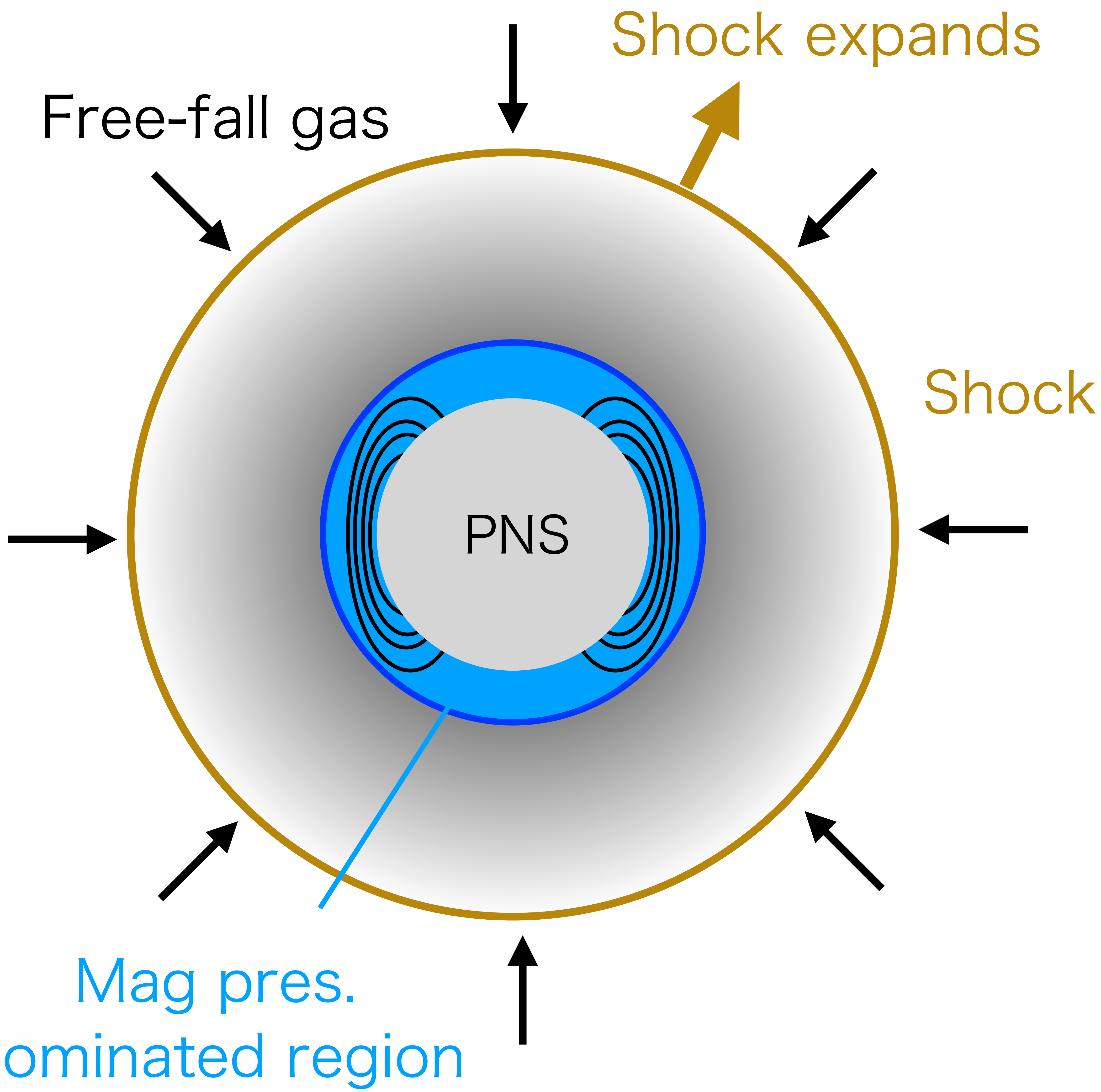
Numerical sheme

HLL, 2nd-order in space (van Leer 1977) and time

Overview

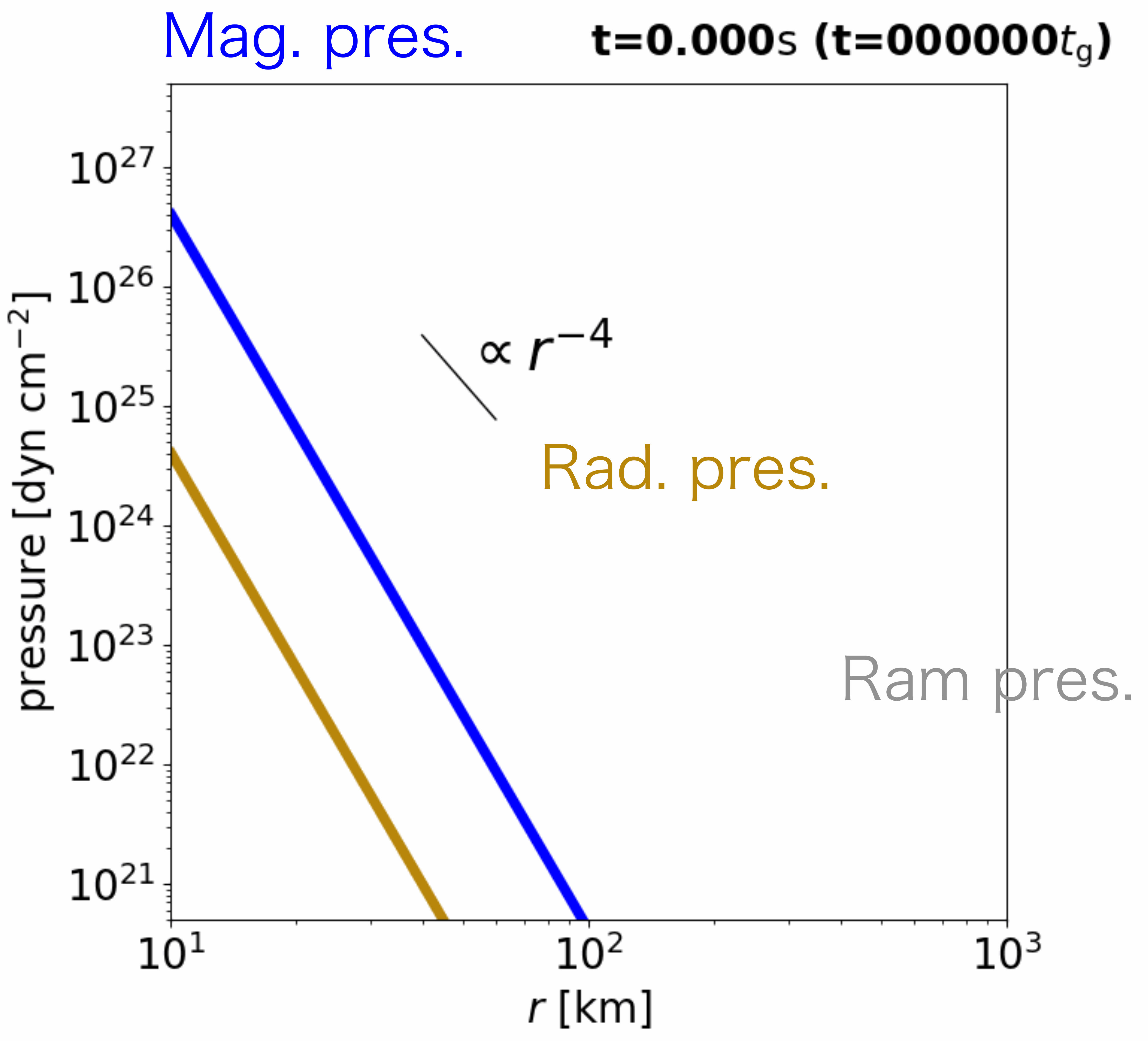


Mag. pres.
t=0.000s (t=000000t_g)
10^{27}
10^{26}
10^{25}
10^{24}
10^{23}
10^{22}
10^{21}
pressure [dyn cm^{-2}]
$\propto r^{-4}$
Rad. pres.
Ram pres.
10^1
10^2
10^3
r [km]

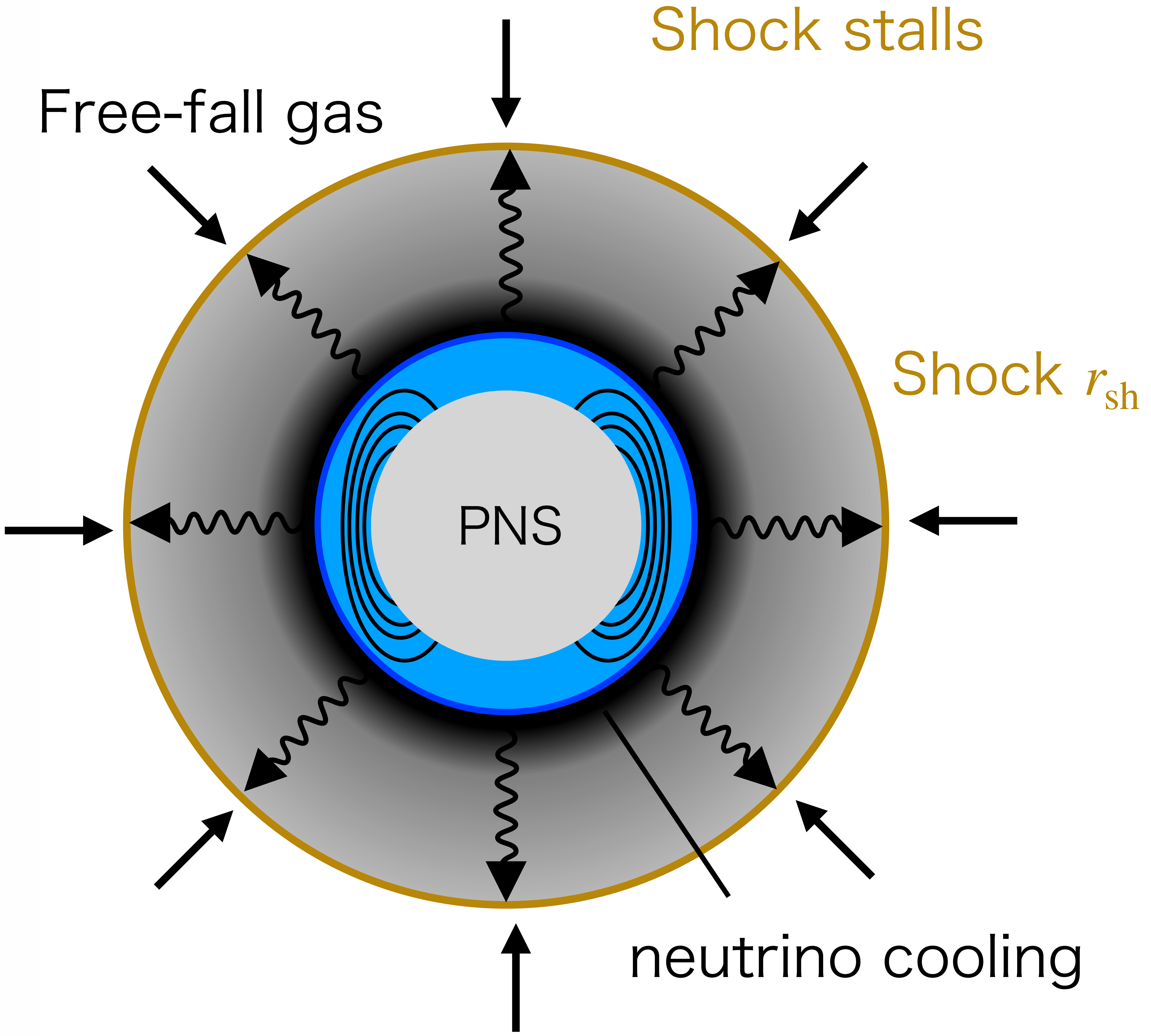


Shock expands
Free-fall gas
Shock
PNS
Mag pres.
dominated region

Overview

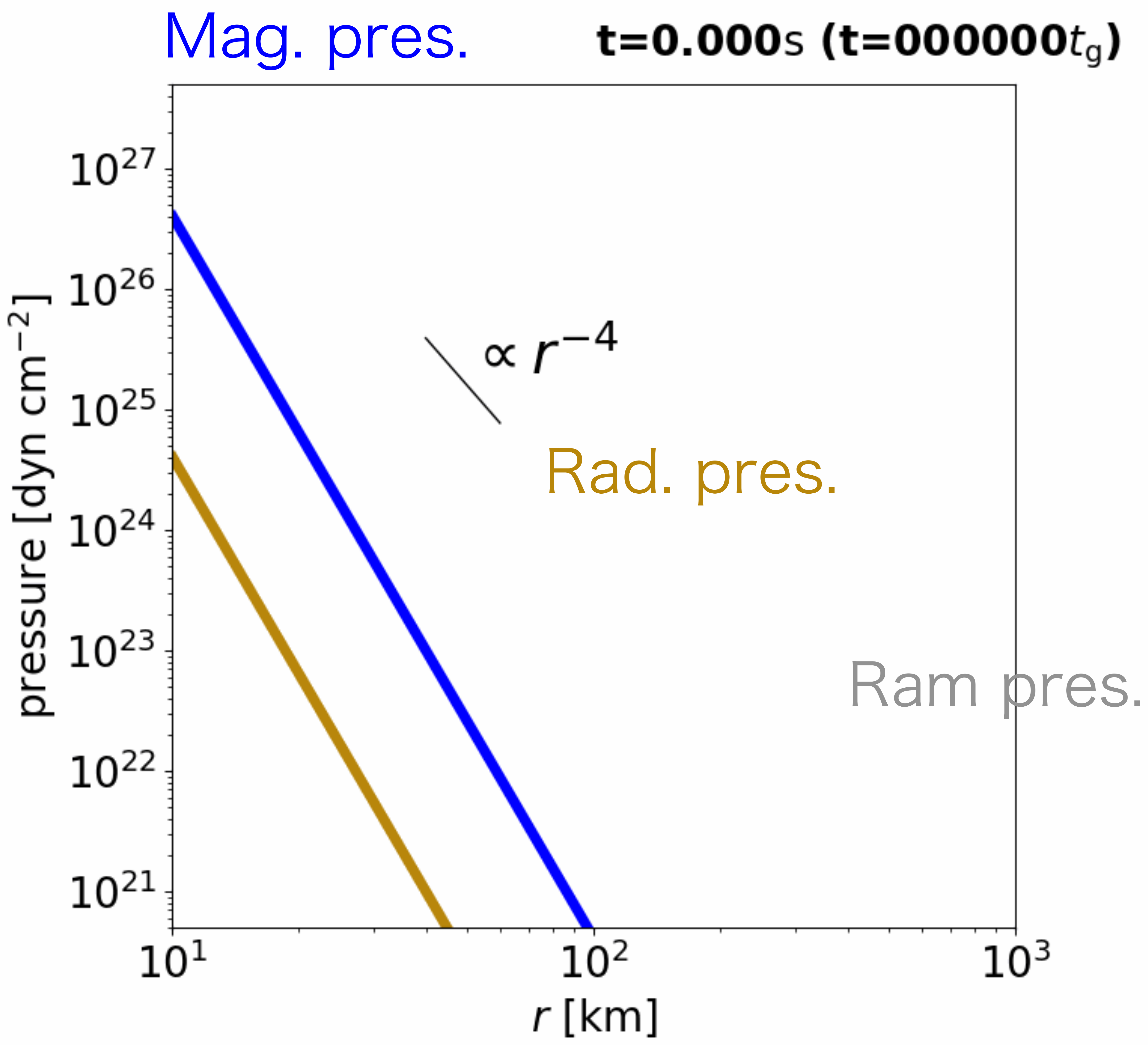


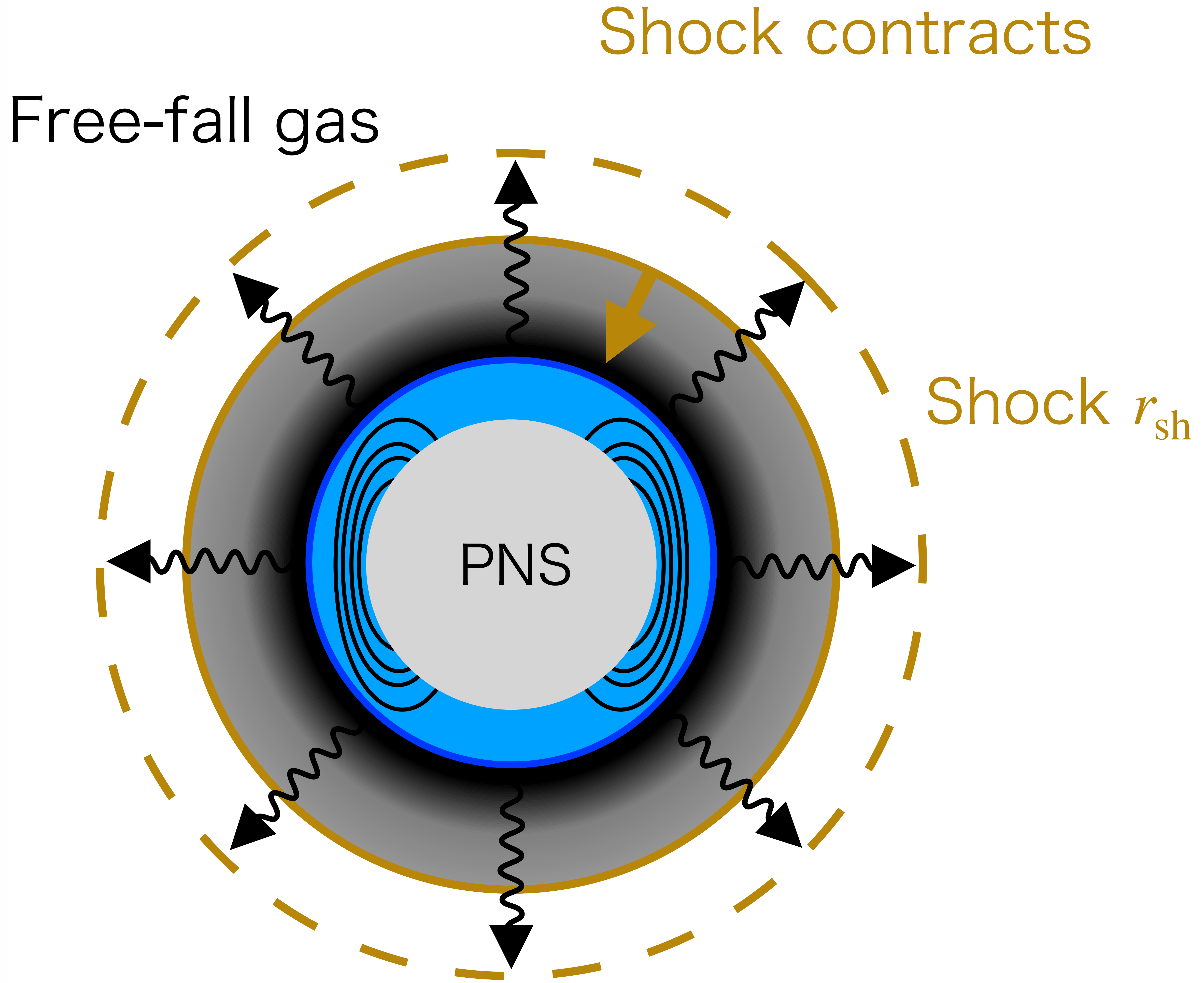
Mag. pres.
t=0.000s (t=000000t_g)
$\propto r^{-4}$
Rad. pres.
Ram pres.
pressure [dyn cm^{-2}]
10^{21}
10^{22}
10^{23}
10^{24}
10^{25}
10^{26}
10^{27}
10^1
10^2
10^3
r [km]



Shock stalls
Free-fall gas
Shock r_{sh}
PNS
neutrino cooling

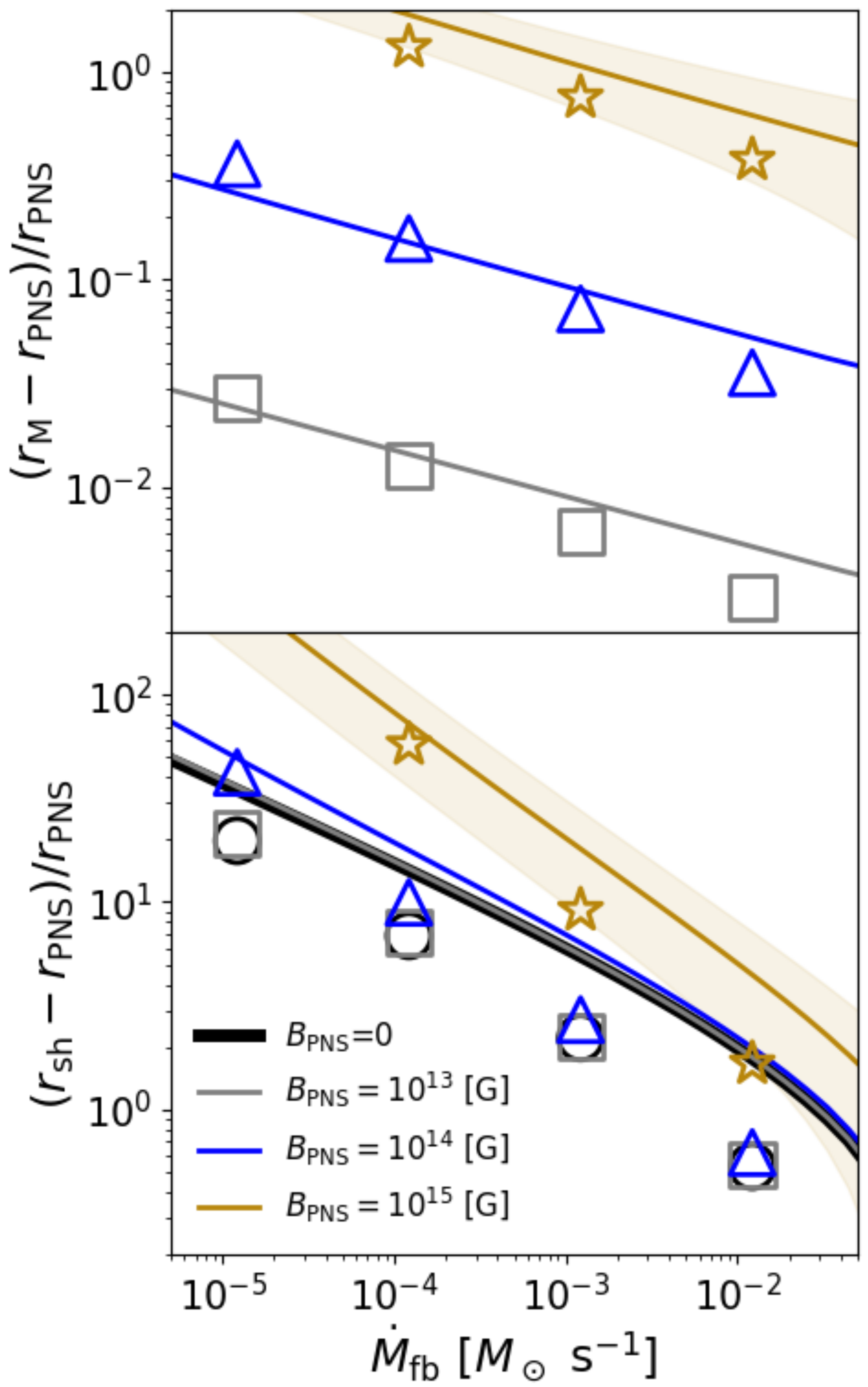
Overview





Density at r_M rapidly increases w/ time

Magnetospheric and shock radii when shock stalls



r_M and r_{sh} decrease w/ $\dot{M}_{fb}$ while increase w/ B_{PNS}.

Semi-analytic solutions (updated version of Chevalier 1989)

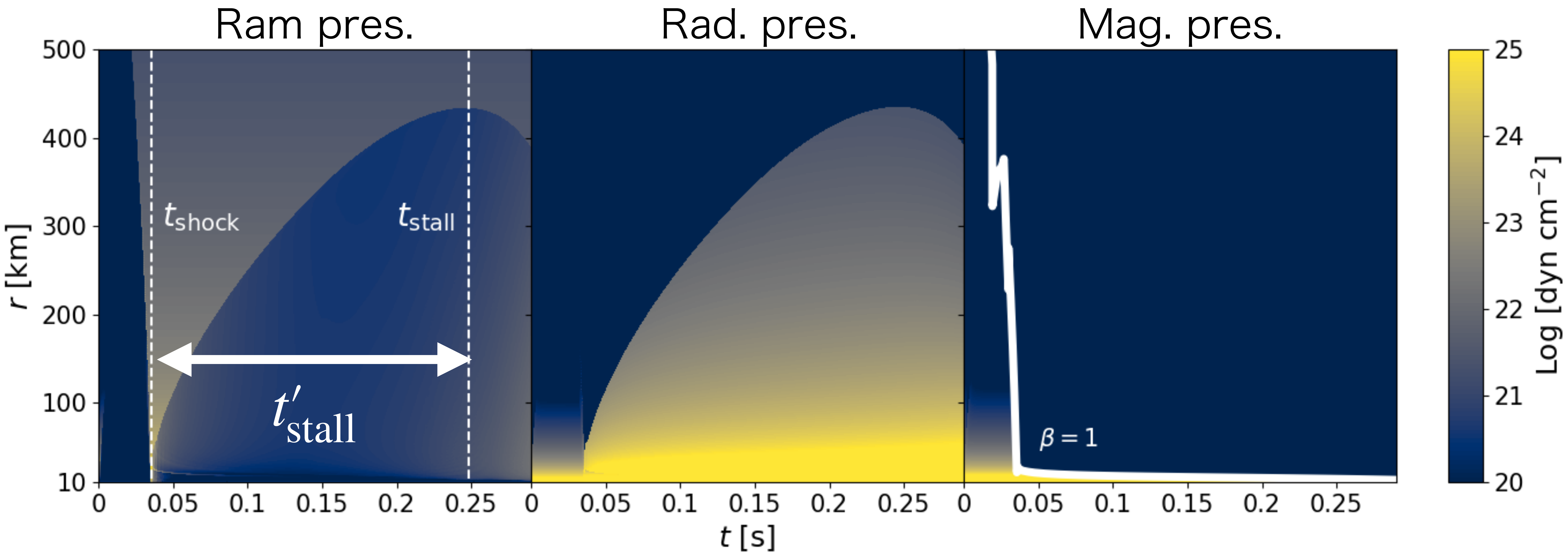
① : Pressure balance $p_{rad} = p_{mag}$

② : Energy equation

$$4\pi r_M^2 H_M \dot{q}(r_M, r_{sh}) = \frac{GM\dot{M}}{r_M} \quad \left(H_M = \frac{r_M{}^2 p_r(r_M, r_{sh})}{GM\rho(r_M, r_{sh})} = \frac{12}{49} r_M \right)$$

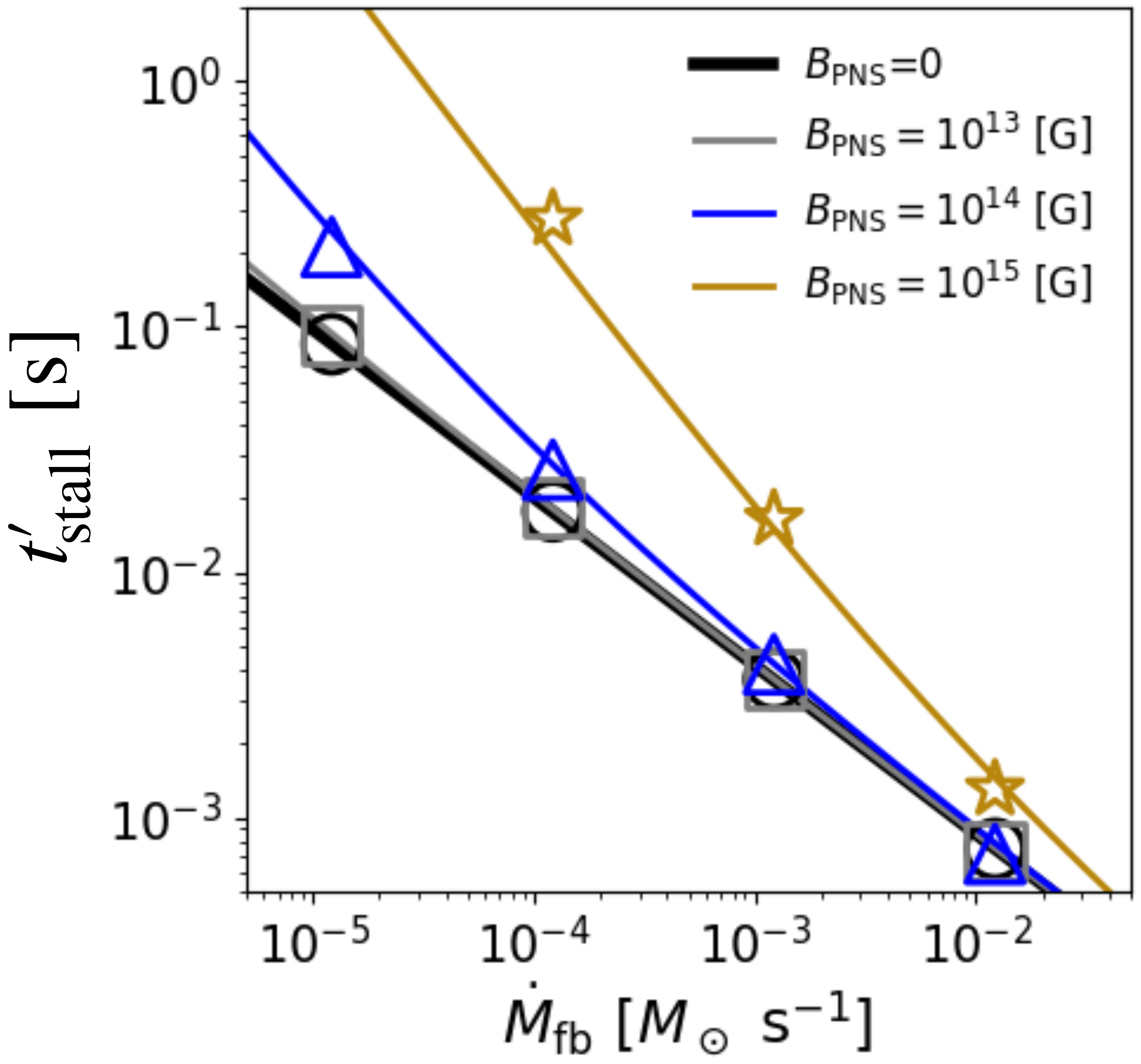
Simulation results can be reproduced by the semi-analytical solutions.

Time-sequenced images



We define the shock stalling timescale as $t'_{\rm stall} = t_{\rm stall} - t_{\rm shock}$

The dependence of $t'_{\rm stall}$ on $\dot{M}_{\rm fb}$ and $B_{\rm PNS}$



$t'_{\rm stall}$ decreases w/ $\dot{M}_{\rm fb}$ and increases w/ $B_{\rm PNS}$.

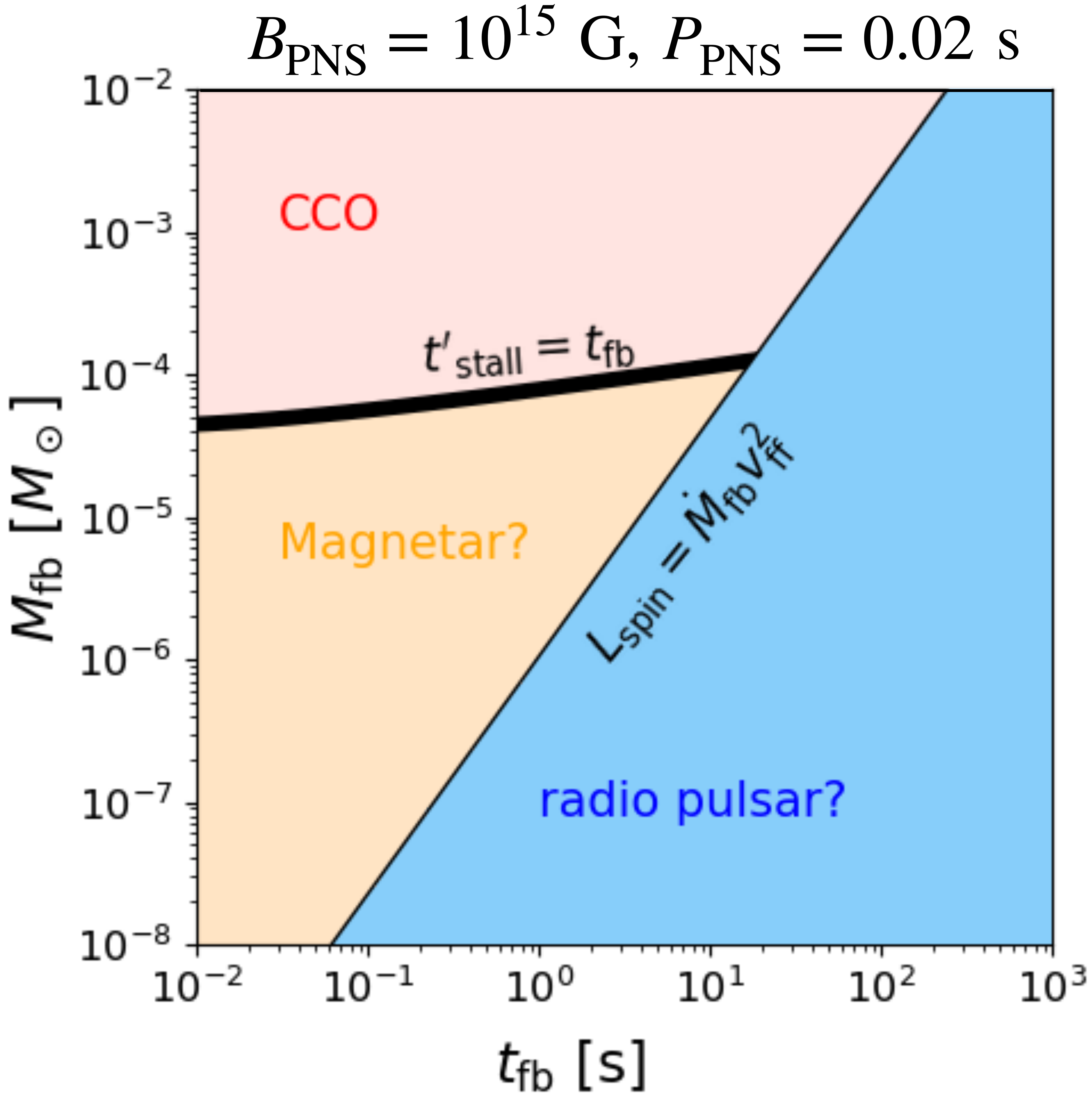
<u>Fitting result</u>

$$t'_{\rm stall} = 2.0 \times 10^{-1}\ [{\rm s}] \left(\frac{\dot{M}_{\rm fb}}{10^{-5}\ {\rm M_\odot\ s^{-1}}}\right)^{-1.2} \left(\frac{B_{\rm PNS}}{10^{14}\ {\rm G}}\right)^{1.3}$$

$$+ 9.8 \times 10^{-2}\ [{\rm s}] \left(\frac{\dot{M}_{\rm fb}}{10^{-5}\ {\rm M_\odot\ s^{-1}}}\right)^{-0.69}$$

If $t'_{\rm stall} < t_{\rm fb}$, a outer crust formation sets in.

Phase diagram: the diversity of the NS's B-field

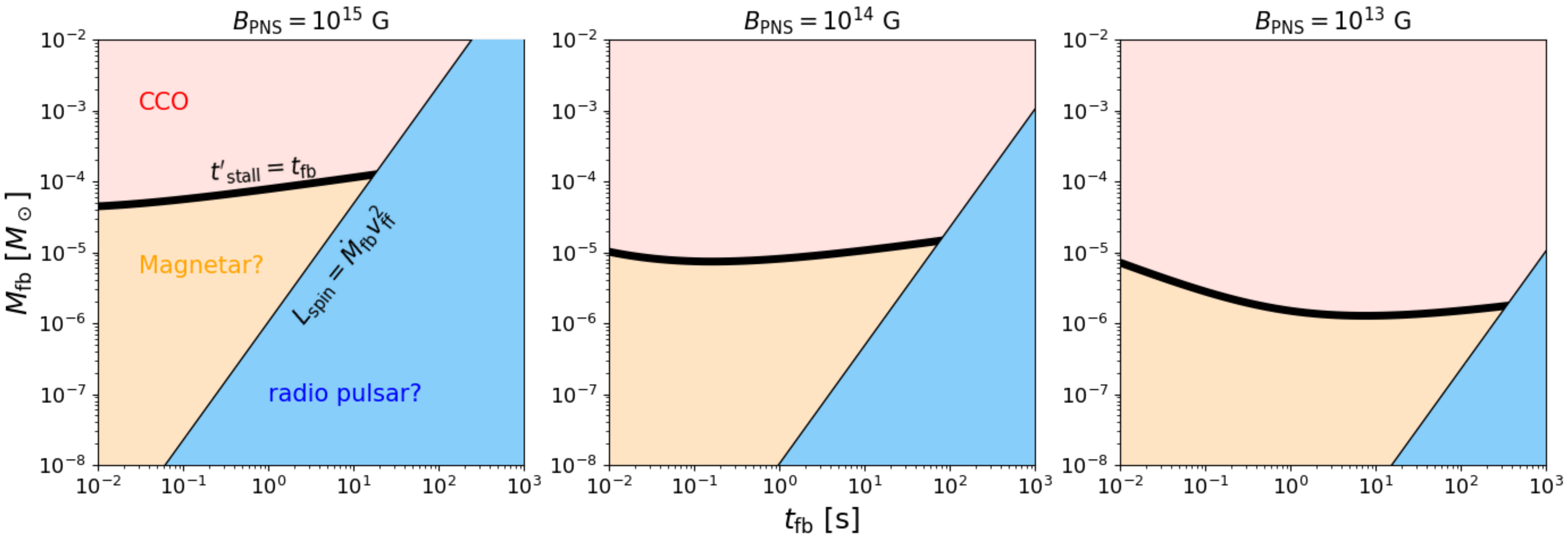


By assuming $\dot{M}_{\rm fb} = (2/5)(M_{\rm fb}/t_{\rm fb})$, we derive the phase diagram of the NS's B-field

CCO : $t'_{\rm stall} < t_{\rm fb}$, $L_{\rm spin} < \dot{M}_{\rm fb} v_{\rm ff}^2$
Magnetar : $t'_{\rm stall} > t_{\rm fb}$, $L_{\rm spin} < \dot{M}_{\rm fb} v_{\rm ff}^2$
Radio pulsar : $L_{\rm spin} > \dot{M}_{\rm fb} v_{\rm ff}^2$

In the case of $B_{\rm PNS} = 10^{15}$ G, $M_{\rm fb} > 10^{-4}$ $M_\odot$ is required for the CCO formation.

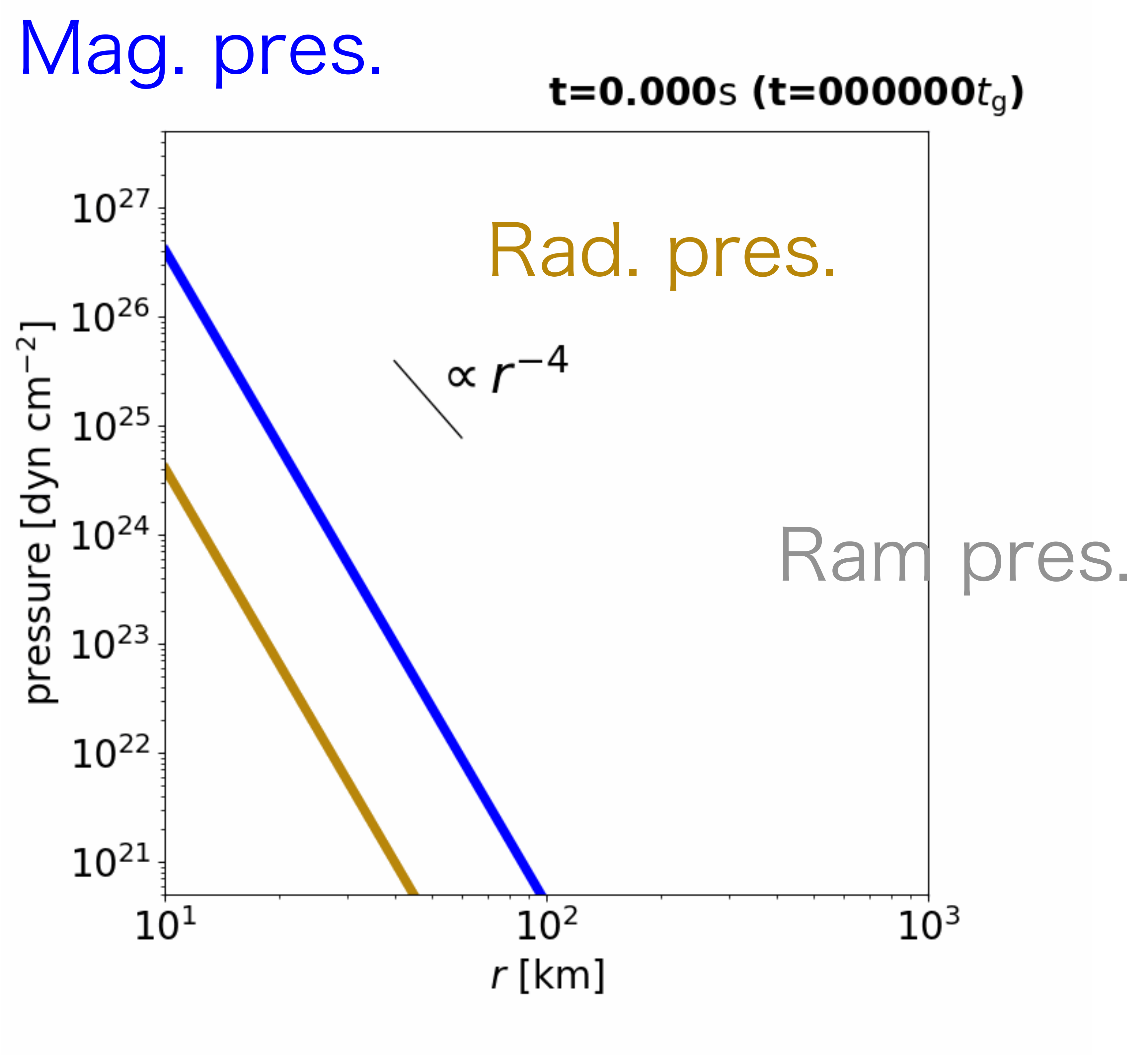
Phase diagram: the diversity of the NS's B-field

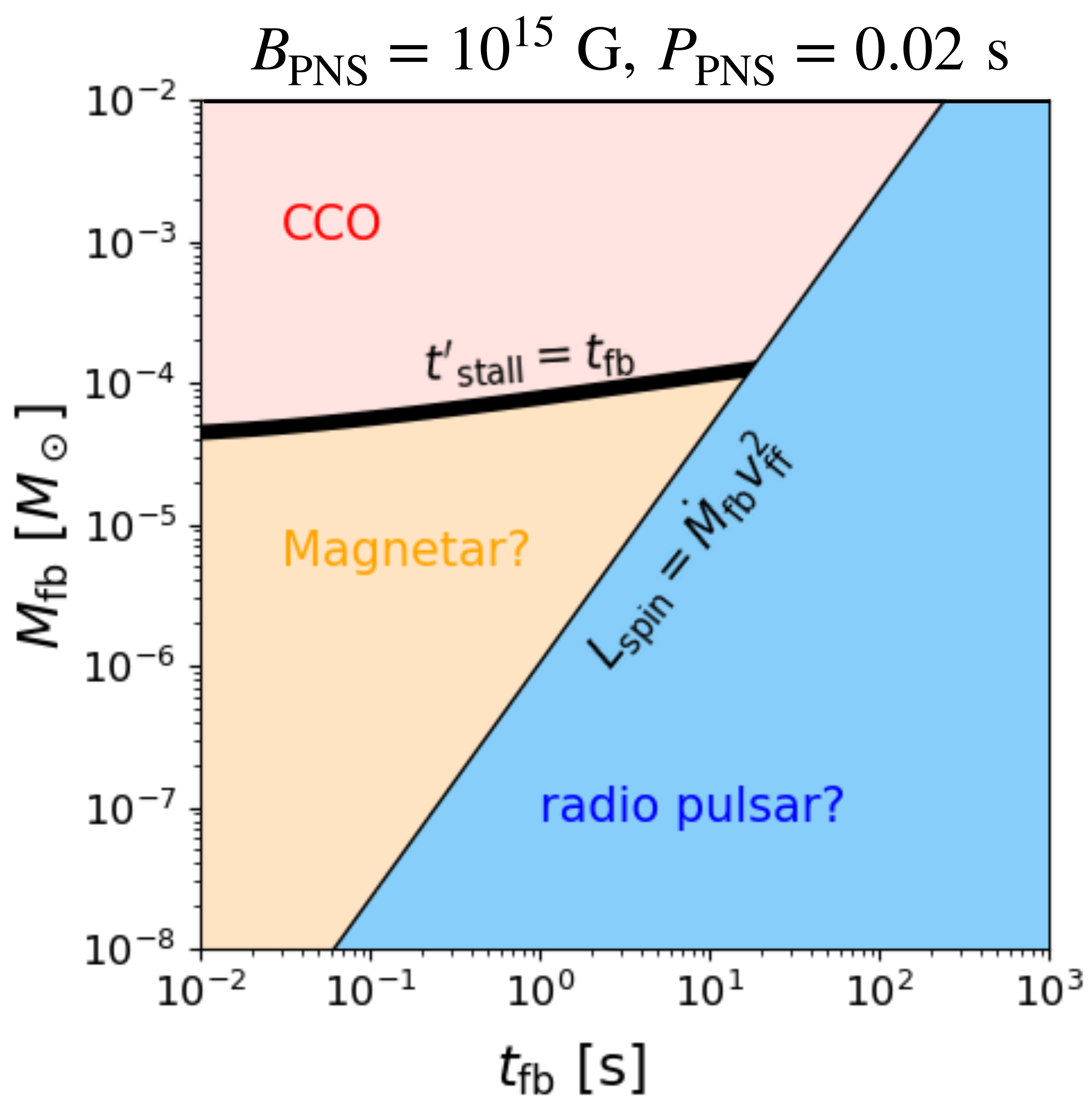


The region of radio pulsars seems to be rare …

(Crust formation time, Multi-dimensional effect, Pulsar wind amplified by the accr.?)

Conclusion





- In the early phase, the shock expands, but later, neutrino cooling causes it to stall and contract.
- $M_{fb} > 10^{-4}$ $M_\odot$ is required for the CCO formation for $B_{PNS} = 10^{15}$ G.