A diagnostic method for a proto-neutron star magnetic fields by supernova fallback
超新星フォールバック降着流による原始中性子星磁場の推定

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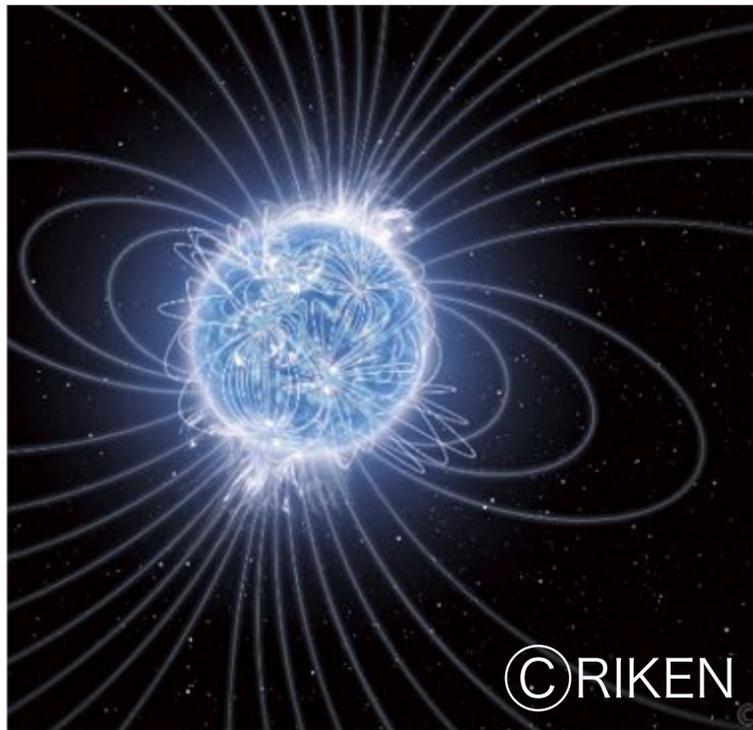
Summary

The proto-neutron star's magnetic field may be inferred from neutrinos associated with the supernova fallback

12th Supernova Neutrino Workshop

Diversity of young isolated neutron star

e.g.) Enoto+2019

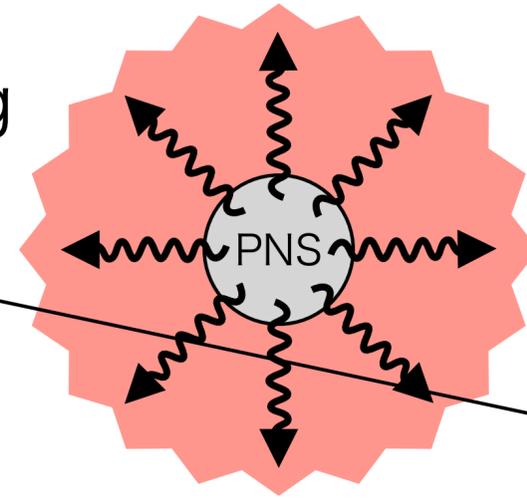| Magnetar	Rotation powered pulsar	Central Compact Object
$B_{\mathrm{NS}} \gtrsim 10^{14}$ G	$B_{\mathrm{NS}} \sim 10^{11-13}$ G	(CCO) $B_{\mathrm{NS}} \lesssim 10^{11}$ G

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CCO

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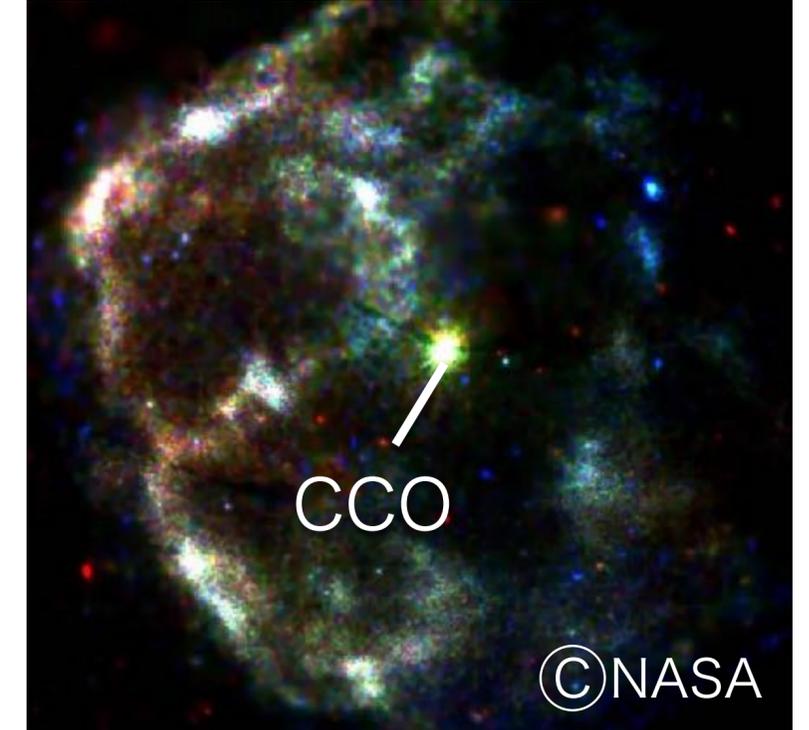
This study will help us understand supernova mechanism
and progenitor star's feature

Neutron star formation: core-collapse supernova

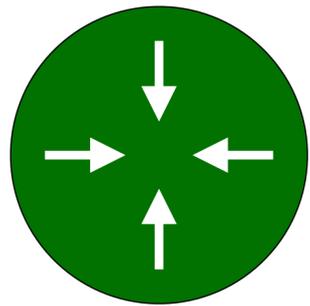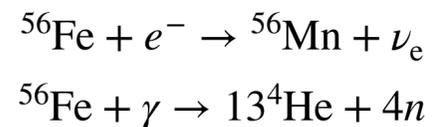Massive star
$\gtrsim 8M_\odot$
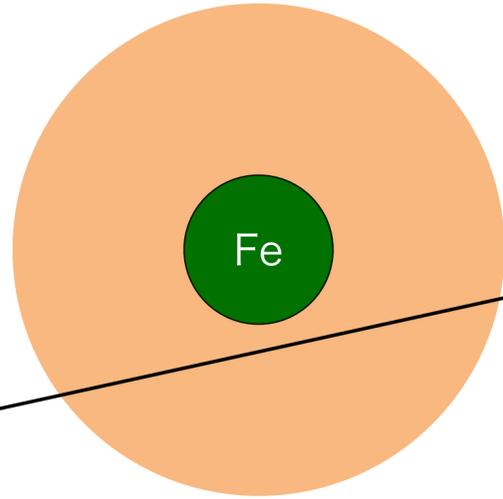
$\nu-$cooling

Core evolution

proto-neutron star
(PNS)

Grav. bound

Shock

Collapse

$^{56}\mathrm{Fe} + e^- \rightarrow {}^{56}\mathrm{Mn} + \nu_{\mathrm{e}}$
$^{56}\mathrm{Fe} + \gamma \rightarrow 13\,{}^4\mathrm{He} + 4n$
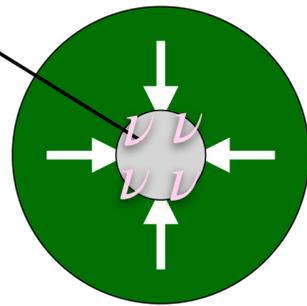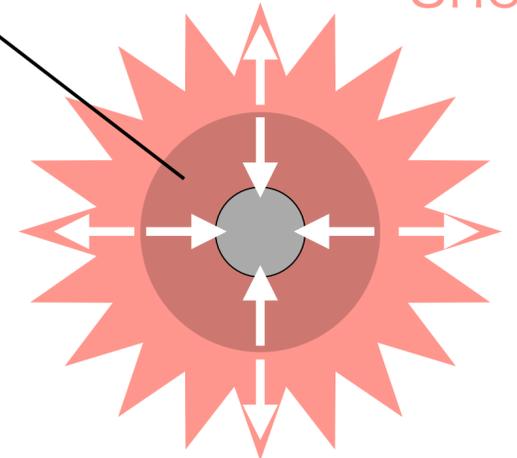
Core bounce
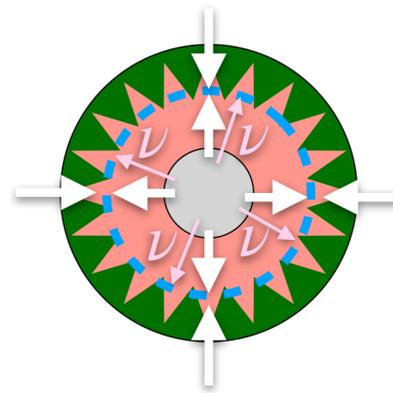
ν emission &
Shock expansion
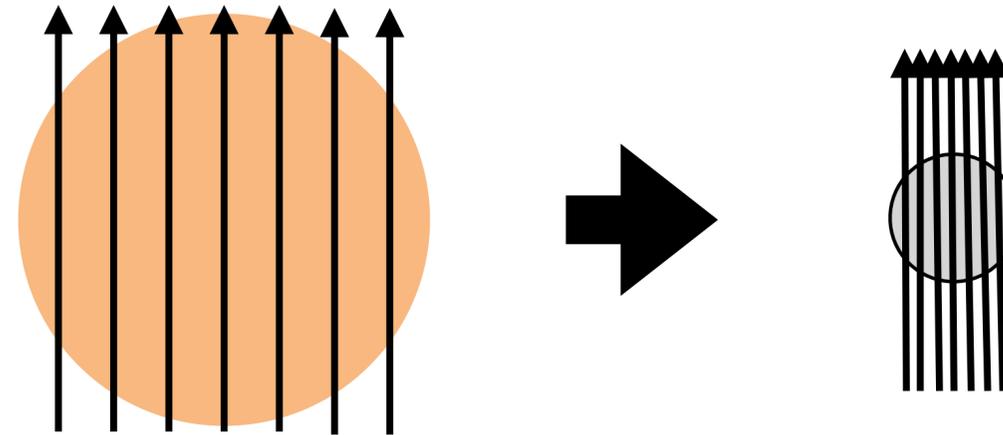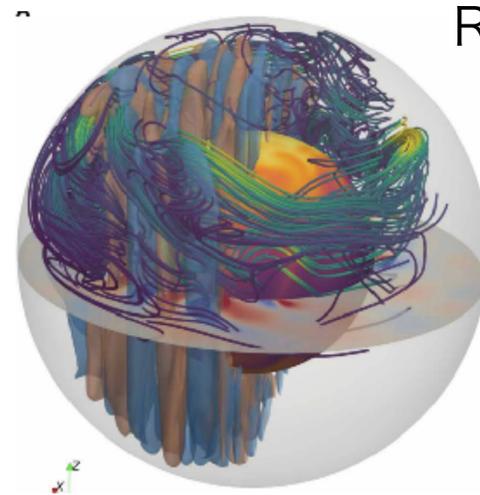
Explode &
Fallback accretion

What determines the NS magnetic field? (see e.g., Igoshev+2021)
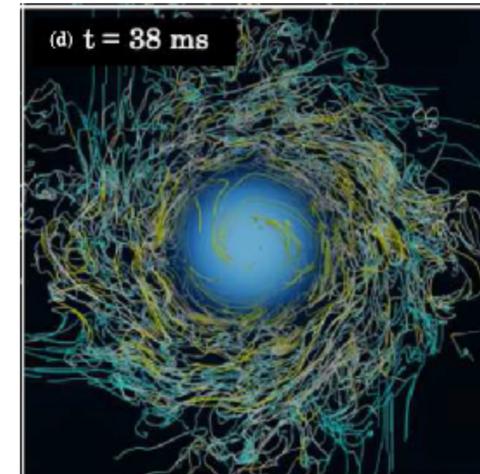
- Flux conservation
  (e.g., Woltjer 1964)

- Dynamo in the PNS phase
  (e.g., Duncan & Thompson 1992)

Raynaud+2020

Masada+2015

(d) t = 38 ms

- Supernova fallback
  (e.g., Shigeyama & Kashiyama 2018, Inoue+2026)

We need to measure the PNS magnetic field by observations!

Supernova fallback

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

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

Michel 1988, Chevalier 1989

e.g.) Ugliano+2012, Ertl+2016
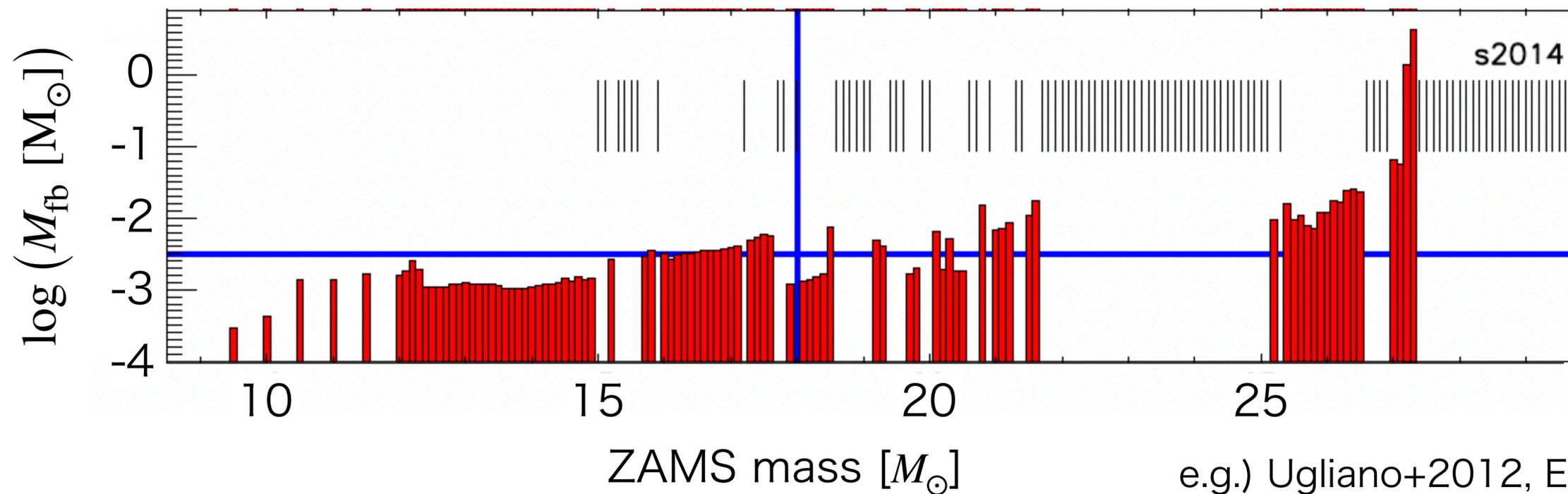
typically $M_{\rm fb} \sim 10^{-(4-1)}$ M$_\odot$ and $t_{\rm fb} \sim 10^{0-3}$ s $\rightarrow$ $\dot{M}_{\rm fb} \sim (10^{-7} - 10^{-1})$ M$_\odot$ s^{-1}

Highly uncertain (e.g., Janka+2021, Shinoda+2025)

Neutrinos from the supernova fallback

The neutrinos from a galactic supernova are detectable.

(Akaho et al. 2024)

Neutrinos associated
w/ the PNS cooling

Neutrinos associated w/
the supernova fallback

$10\ \mathrm{MeV} \lesssim E \lesssim 20\ \mathrm{MeV}$

Mean energy E [MeV]

Time

Neutrinos from the supernova fallback

The neutrinos from a galactic supernova are detectable.

(Akaho et al. 2024)

Neutrinos associated
w/ the PNS cooling

Neutrinos associated w/
the supernova fallback

$10 \text{ MeV} \lesssim E \lesssim 20 \text{ MeV}$

Strongly
magnetized case

(Inoue+2026)

Mean energy E [MeV]

Time
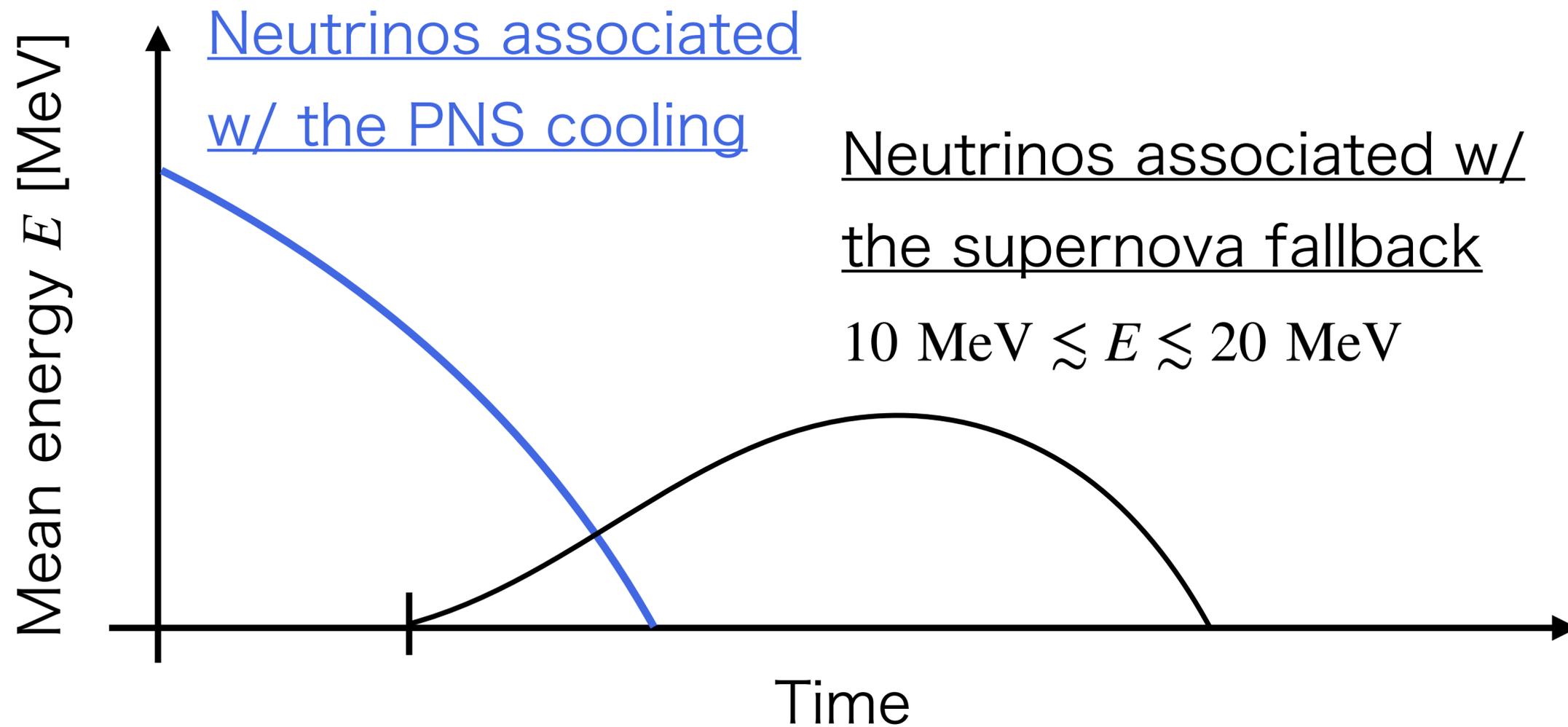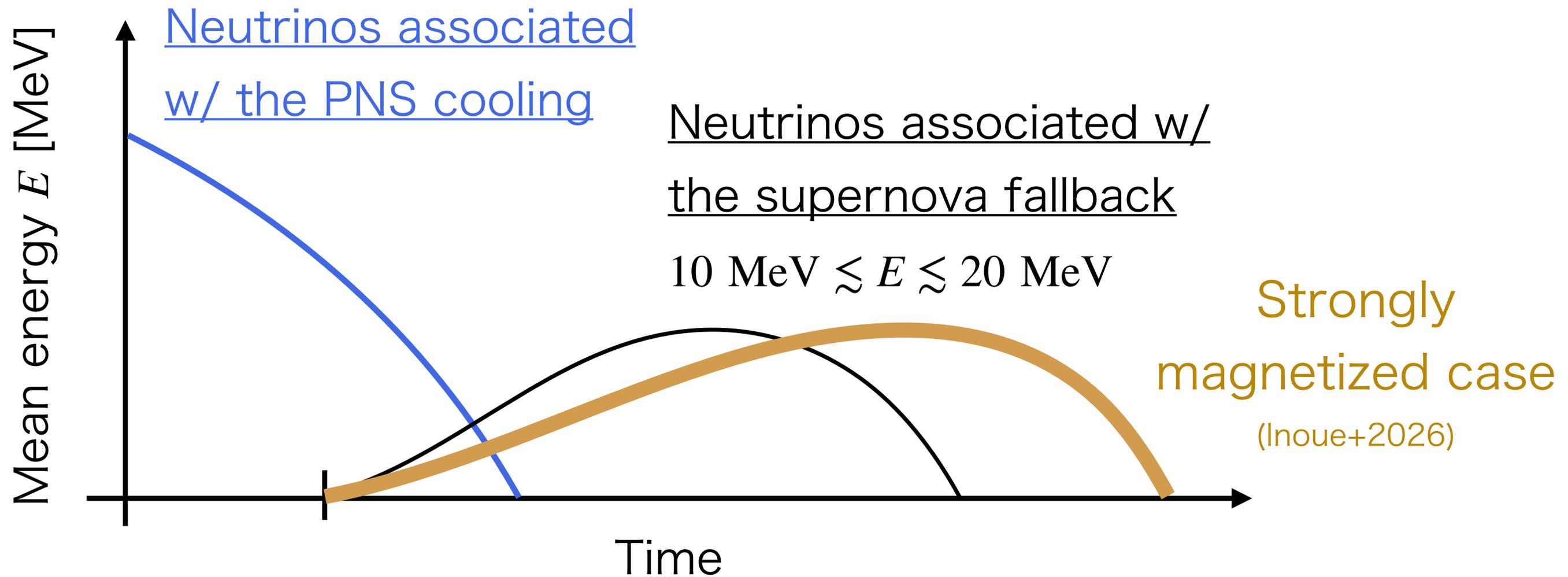
Dependences of the neutrinos on the PNS magnetic field and the fallback rate?
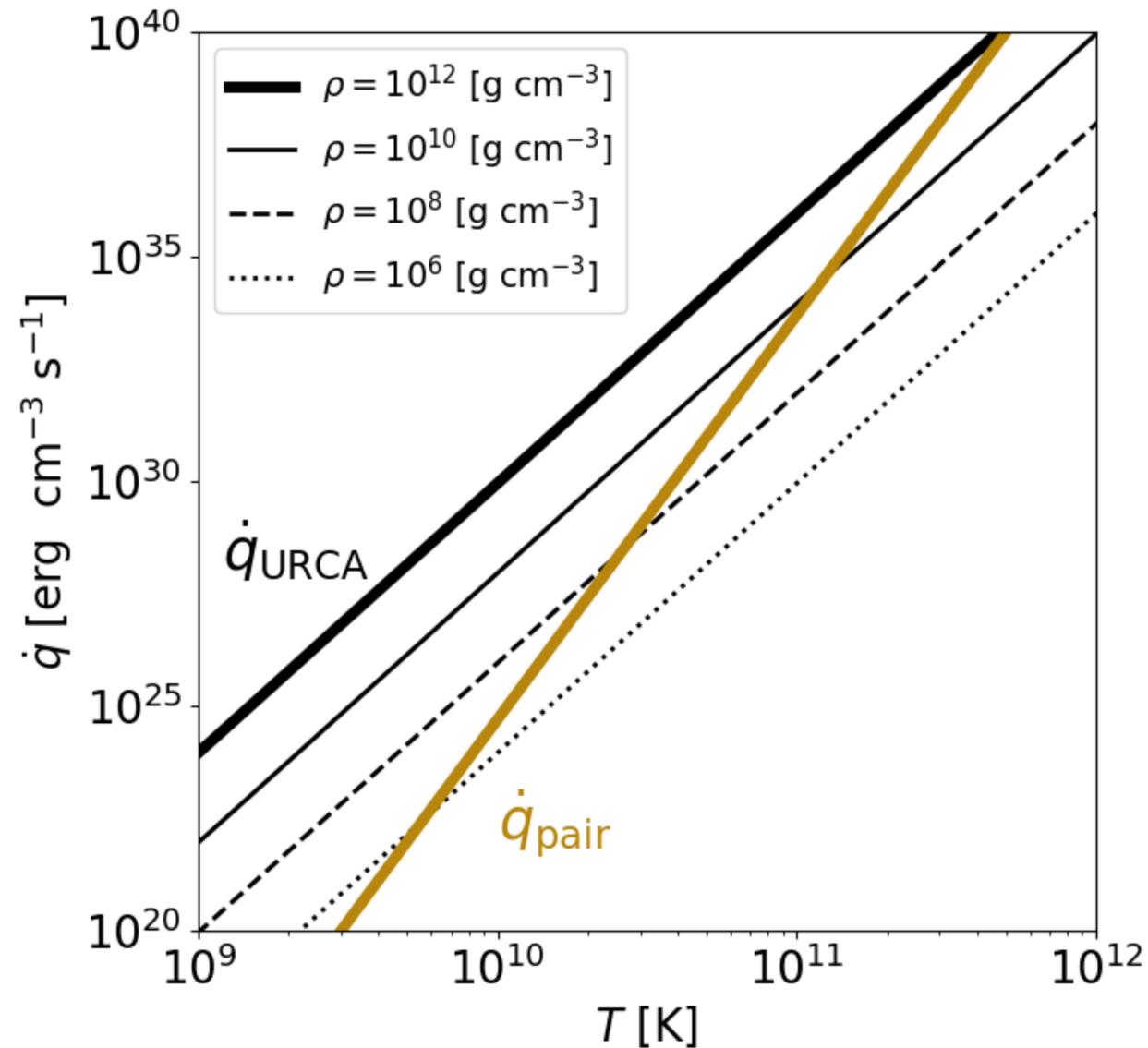
Purpose of this study

Motivation

- Diversity of the young isolated neutron star
- We need to measure the PNS magnetic field by observations

Purpose of this study

We aim to construct a diagnostic method for the PNS magnetic field

General relativistic MHD simulations of the supernova fallback

Neutrino cooling

Neutrino cooling (Itoh et al.1989; Qian & Woosley 1996)

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

$$\dot{q}_{\text{pair}} = 5 \times 10^{33} \text{ [erg cm}^{-3} \text{ s}^{-1}] \left(\frac{T}{10^{11} \text{ K}} \right)^9$$
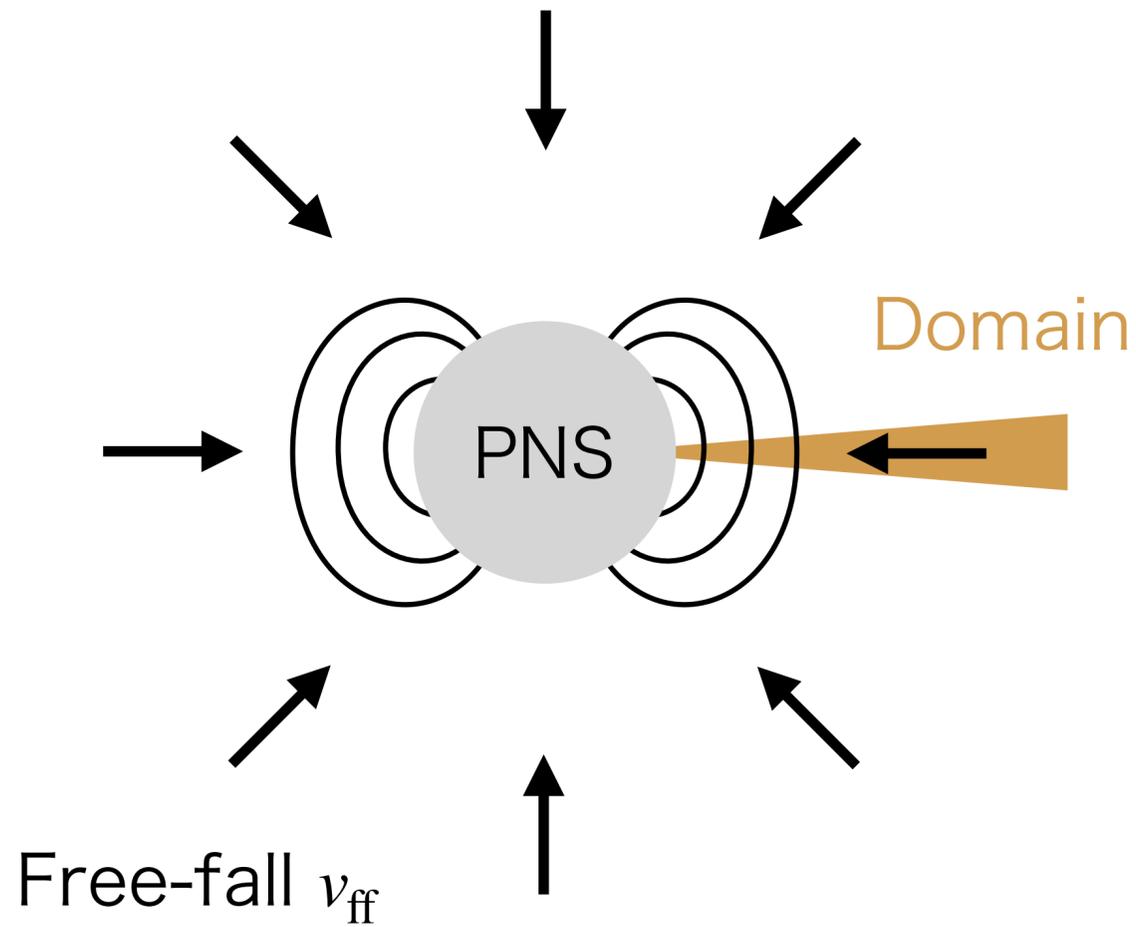
URCA process $(p + e^- \rightarrow n + \nu_e, \, n + e^+ \rightarrow p + \bar{\nu}_e)$

$$\dot{q}_{\text{URCA}} = 9 \times 10^{29} \text{ [erg cm}^{-3} \text{ s}^{-1}] \left(\frac{\rho}{10^6 \text{ g cm}^{-3}} \right) \left(\frac{T}{10^{11} \text{ K}} \right)^6$$

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

Numerical setup (UWABAMI code: Takahashi et al. 2016)

Non-rotating & magnetized PNS

(mass $M_{\rm PNS} = 1.4~{\rm M}_\odot$)

Domain

PNS

Free-fall $v_{\rm ff}$

General relativistic MHD simulations

Accr. rate (const.)　：$\dot{M}_{\rm fb} = 10^{-(3-2)}~[M_\odot~{\rm s}^{-1}]$

Mag. field strength：$B_{\rm 10km} = 0$ G, 10^{14-16} G (dipole $\propto r^{-3}$)

PNS radius　　　　：$r_{\rm PNS} = 10,~\cancel{13,~16,~20}$ km

EoS　　　　　　　：Helmholtz EoS

　　　$e^\pm$, radiation, free protons and neutrons ($Y_{\rm e} = 0.5$)

Resolution & Domain

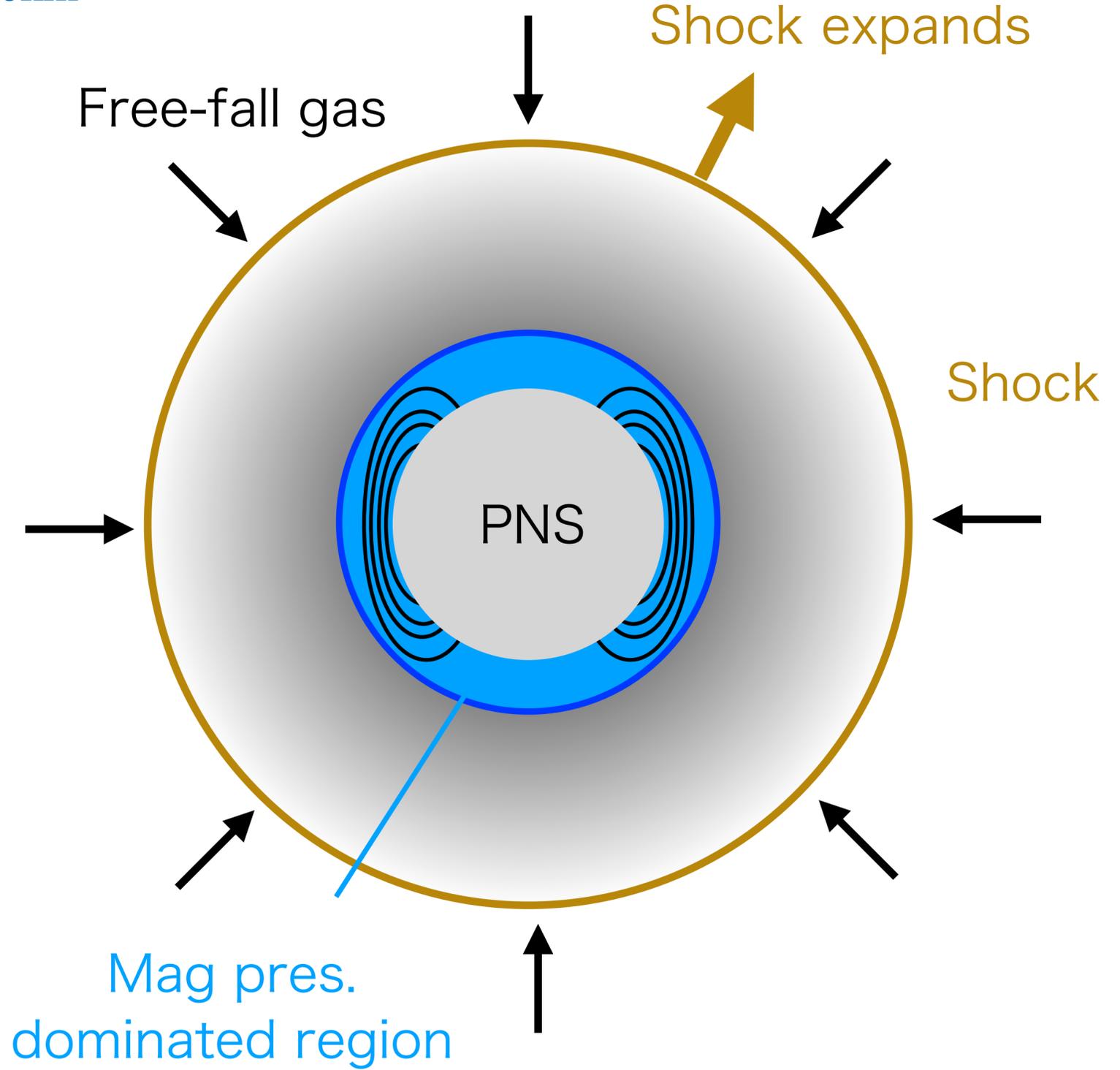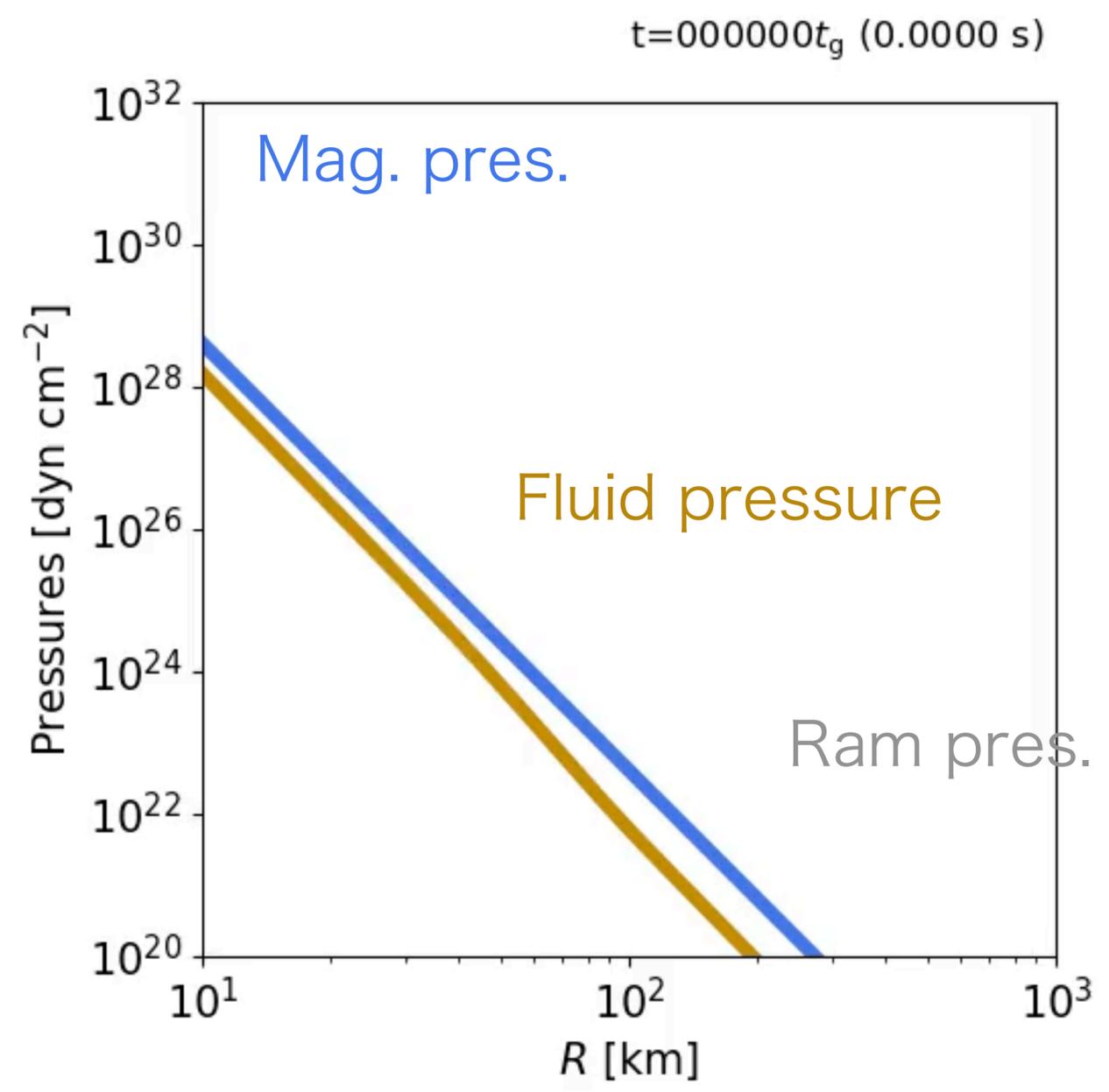10 km $\leq r \leq$ 1000 km,　$N_r = 16384~(=2^{14})$

Initial & boundary conditions

Mag. pressure supported hydrostatic atmosphere

Reflective boundary at the PNS surface

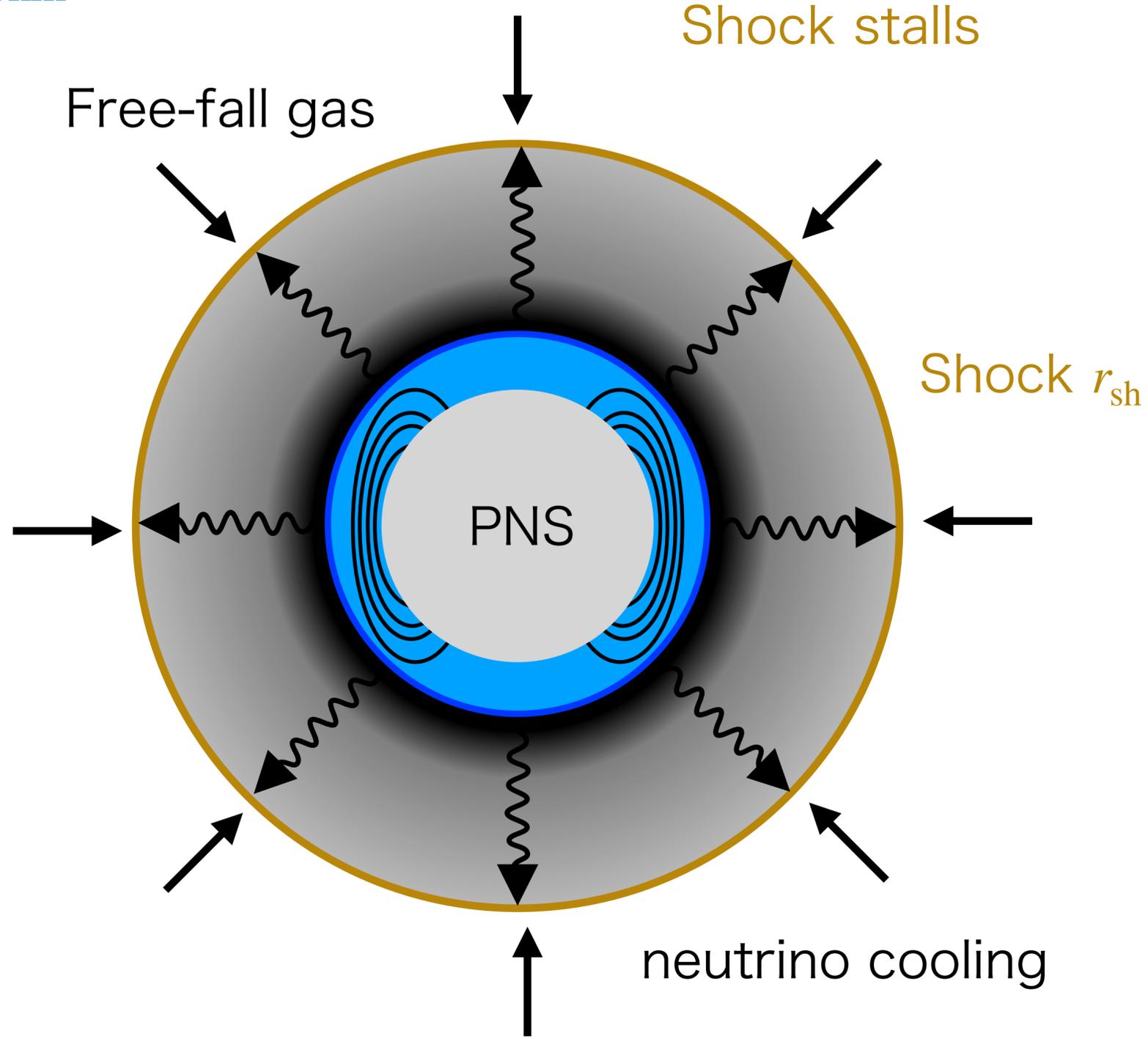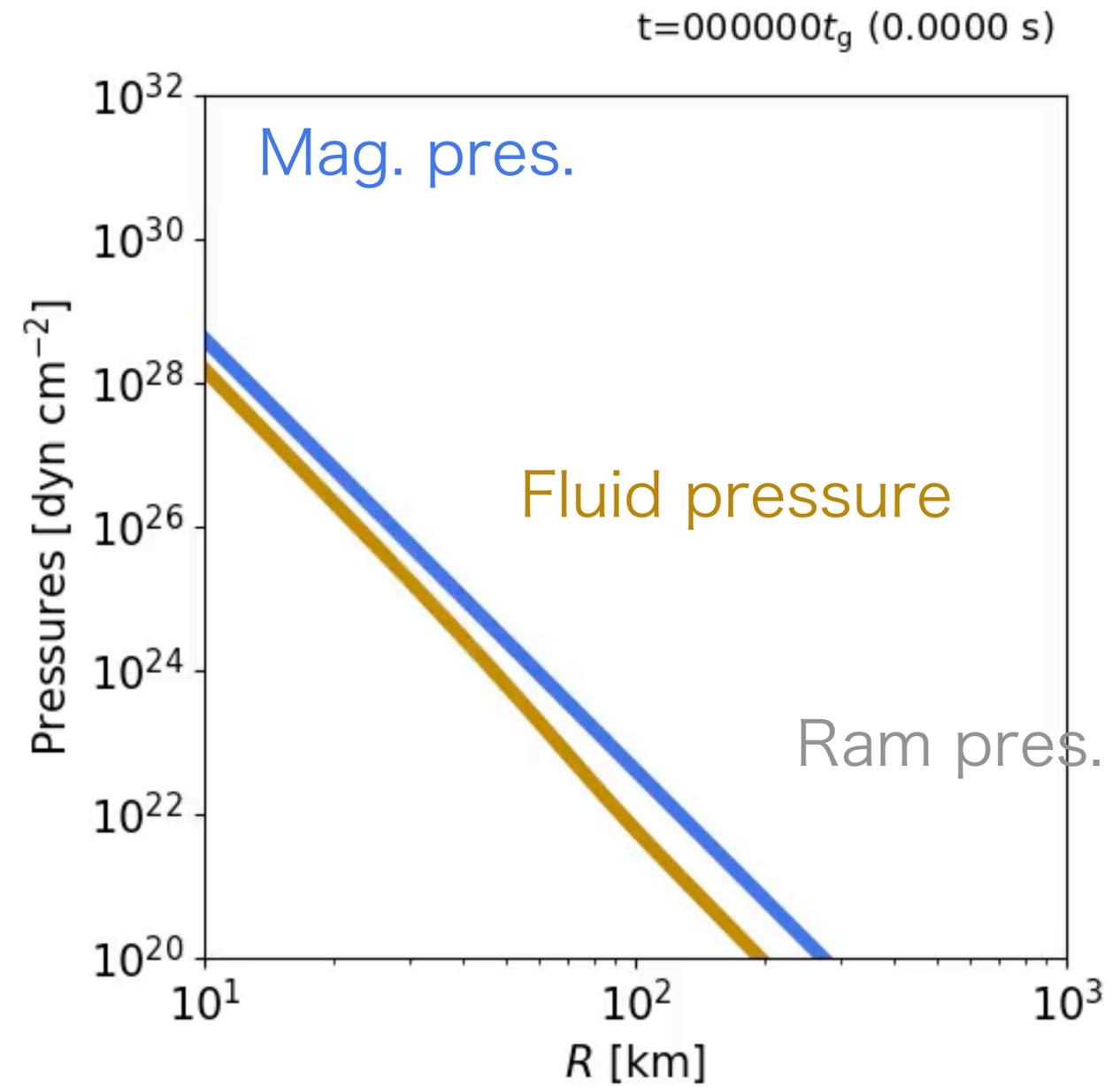# Overview $\dot{M}_{\rm fb} = 10^{-3}\ {\rm M}_\odot\ {\rm s}^{-1}, B_{\rm 10km} = 10^{15}\ {\rm G}$

t=000000$t_{\rm g}$ (0.0000 s)

Mag. pres.

Fluid pressure

Ram pres.

Pressures [dyn cm^{-2}]

R [km]

Free-fall gas

Shock expands

Shock

PNS

Mag pres.
dominated region

Overview $\dot{M}_{\rm fb} = 10^{-3}~{\rm M}_\odot~{\rm s}^{-1},~B_{\rm 10km} = 10^{15}~{\rm G}$

t=000000$t_{\rm g}$ (0.0000 s)

Mag. pres.

Fluid pressure

Ram pres.

Pressures [dyn cm^{-2}]

R [km]

Shock stalls

Free-fall gas

Shock $r_{\rm sh}$

PNS

neutrino cooling

Overview $\dot{M}_{\mathrm{fb}} = 10^{-3}\ \mathrm{M}_{\odot}\ \mathrm{s}^{-1},\ B_{10\mathrm{km}} = 10^{15}\ \mathrm{G}$

t=000000t_{g} (0.0000 s)

Mag. pres.

Fluid pressure

Ram pres.

Pressures [dyn cm^{-2}]

R [km]

Free-fall gas

Shock recedes

Shock r_{sh}

PNS
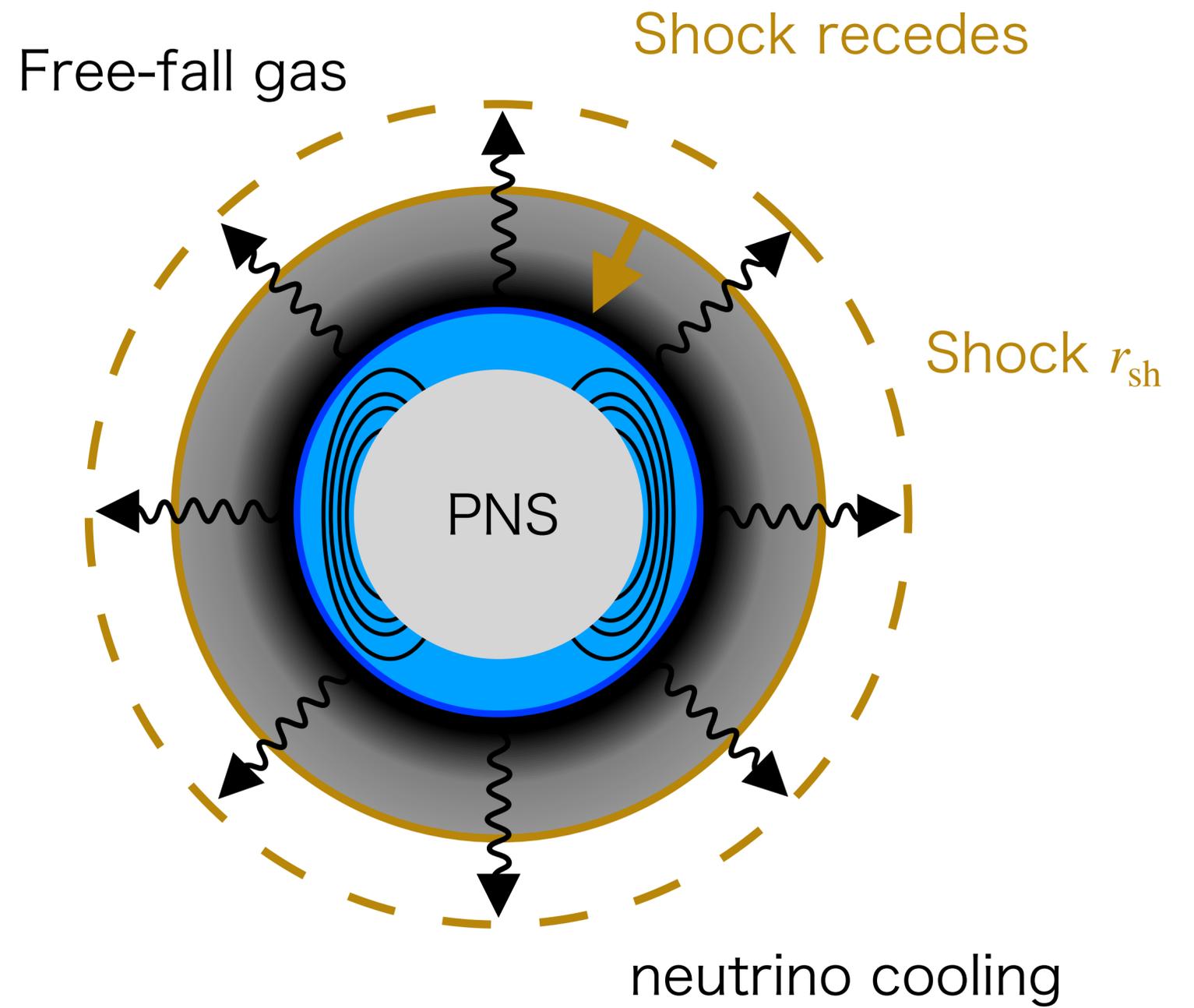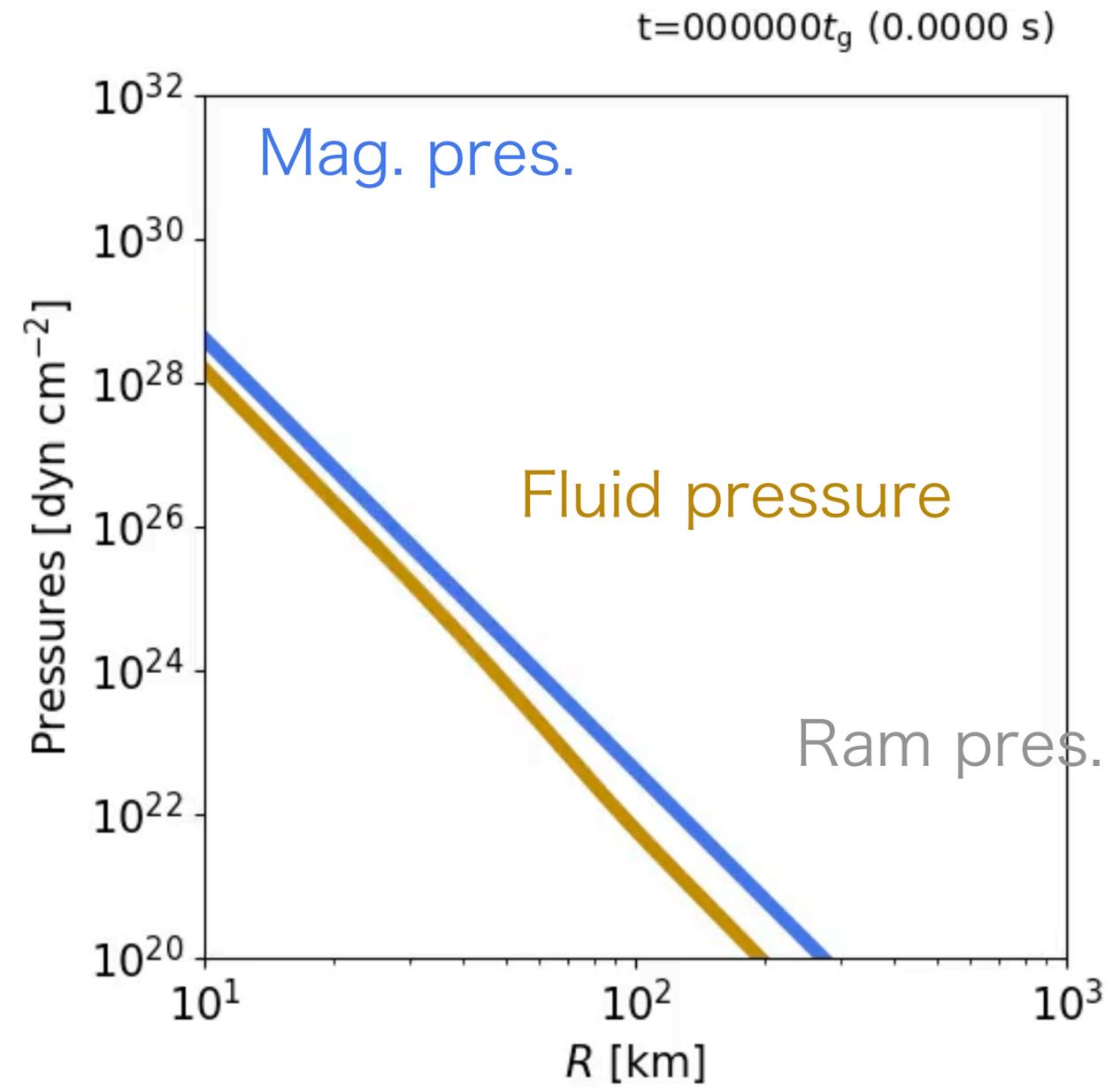
neutrino cooling

Neutrino light curve

$B_{10km} = 10^{15}$ G

$\dot{M}_{fb} = 10^{-3}$ $M_\odot$ s^{-1}
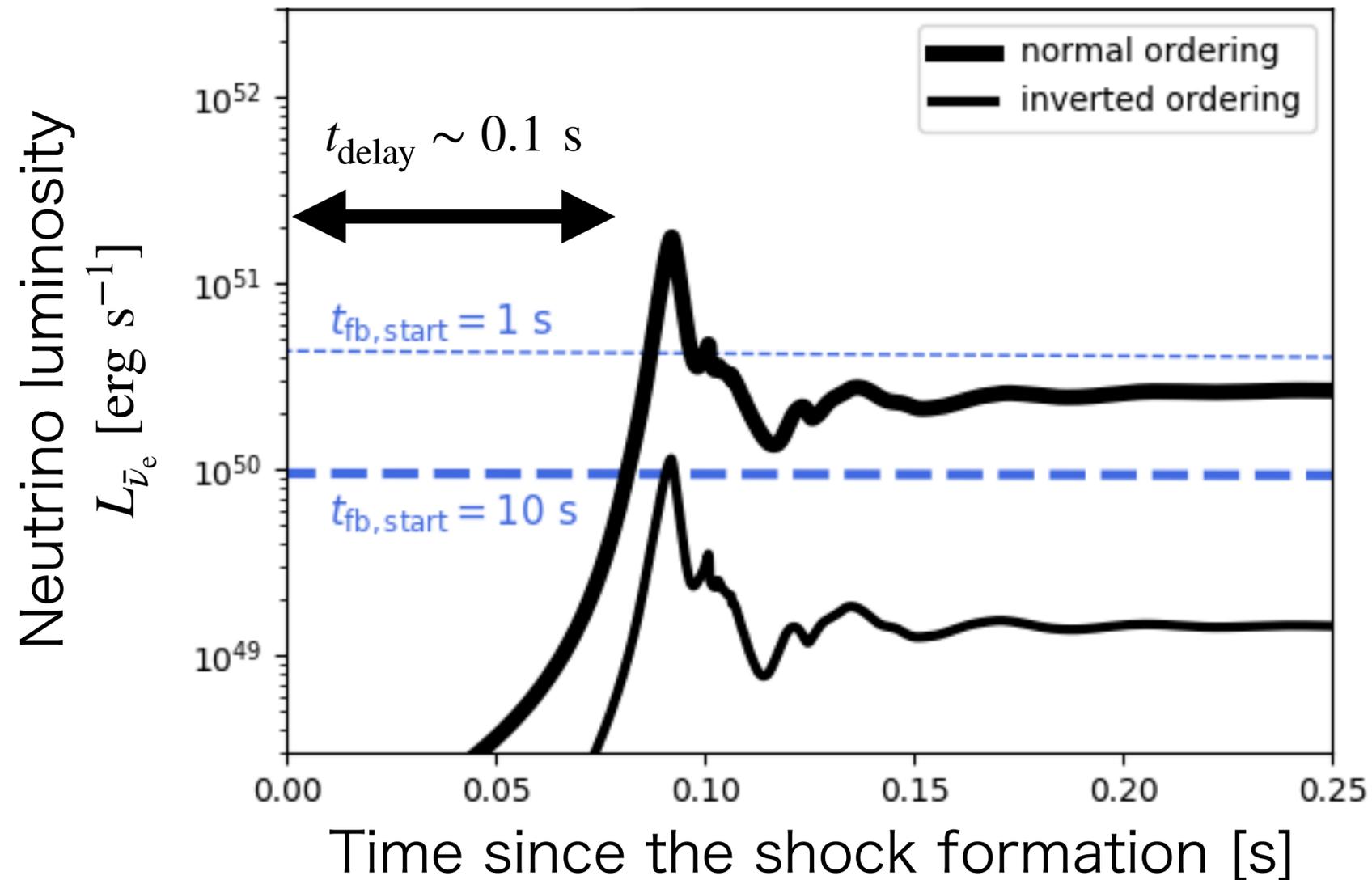
There is a time delay between the shock formation and the neutrino emission.
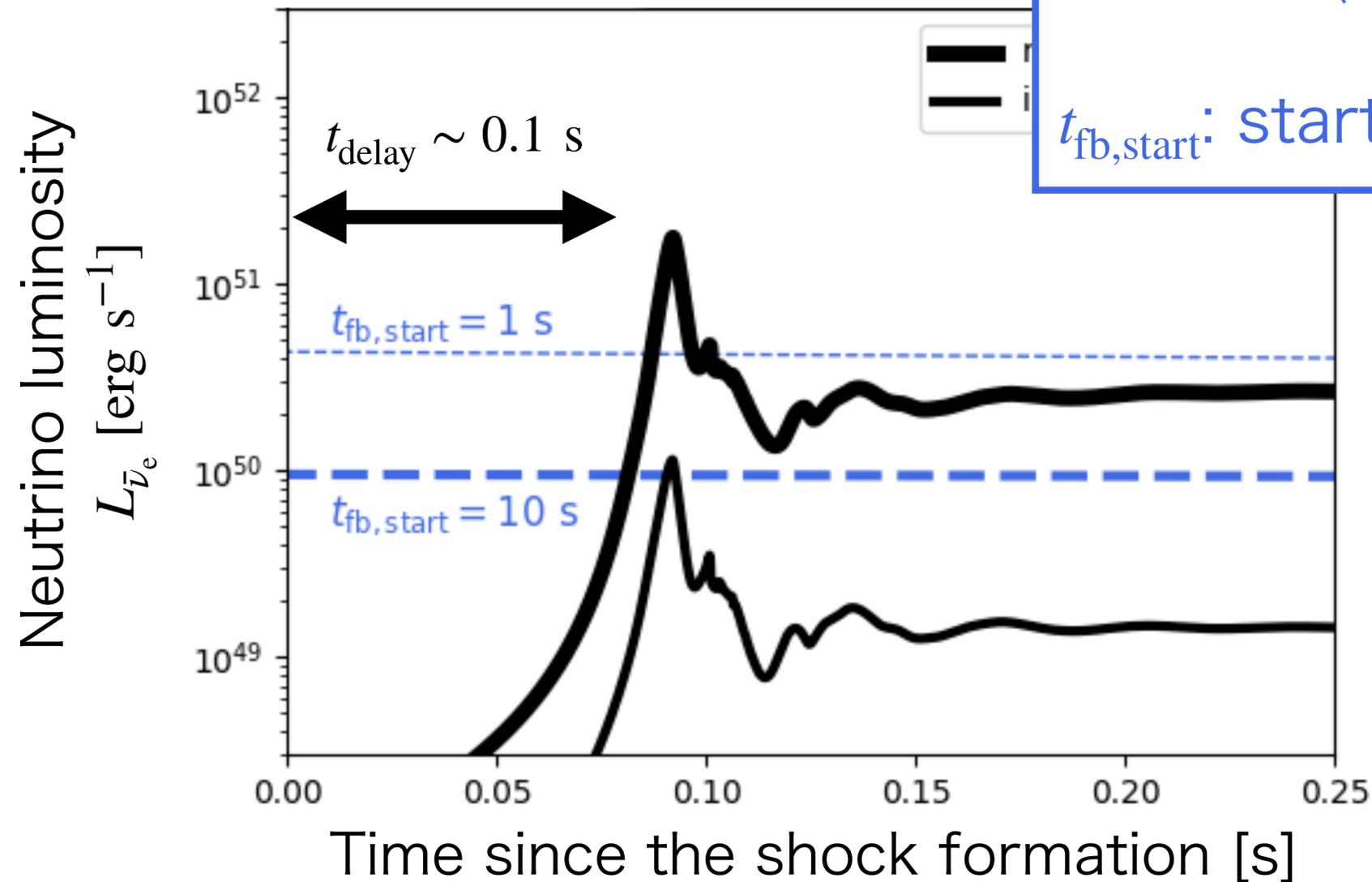
We investigate its parameter dependence

Fallback .vs. PNS cooling

$B_{10\mathrm{km}} = 10^{15}$ G

$\dot{M}_{\mathrm{fb}} = 10^{-3}$ M$_\odot$ s^{-1}
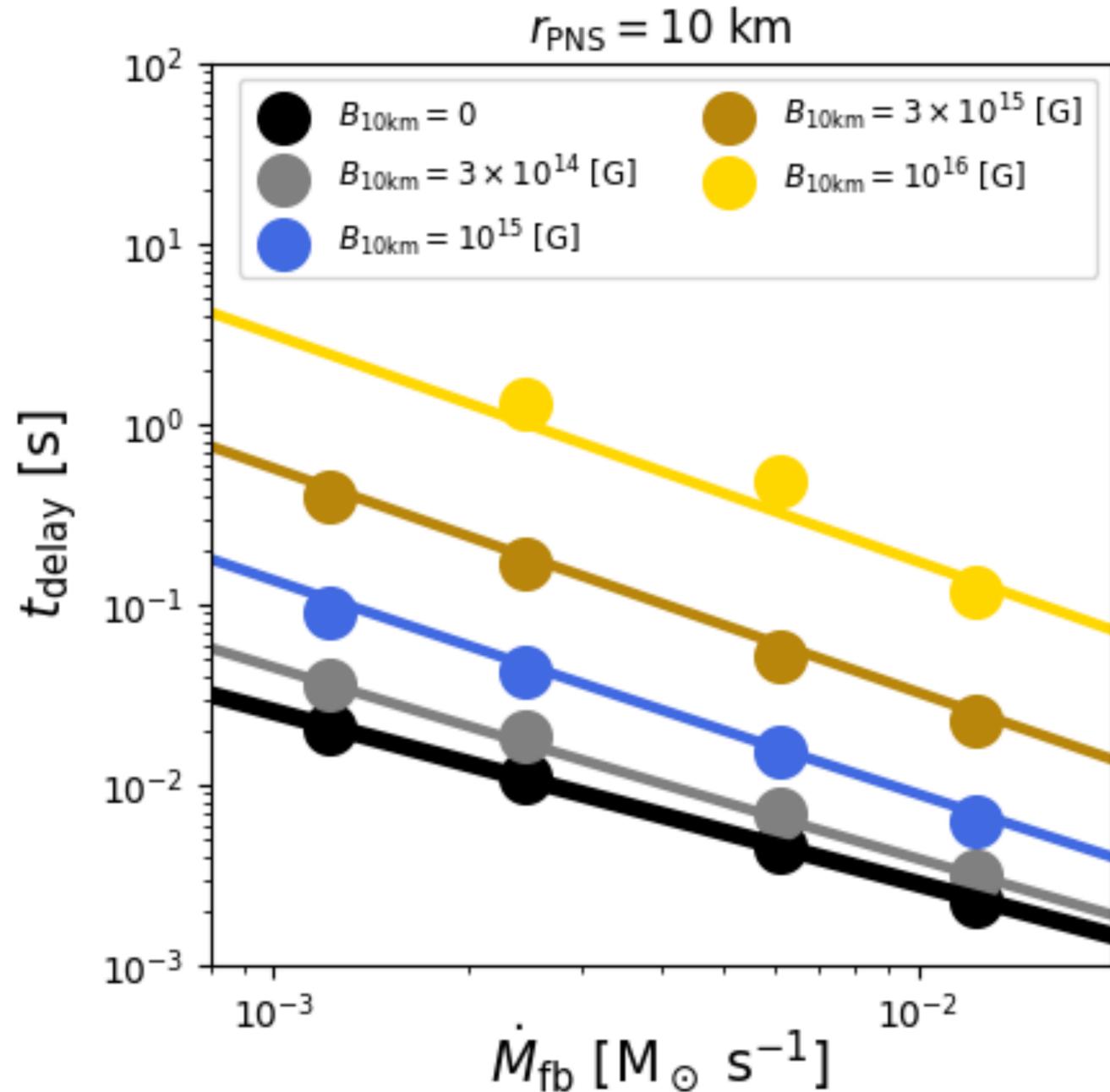
$t_{\mathrm{fb,start}}$: start time of the fallback

The resulting luminosity is comparable to the PNS luminosity for $t_{\mathrm{fb,start}} < 10$ s.
We also investigate the neutrino spectra as an additional diagnostic.
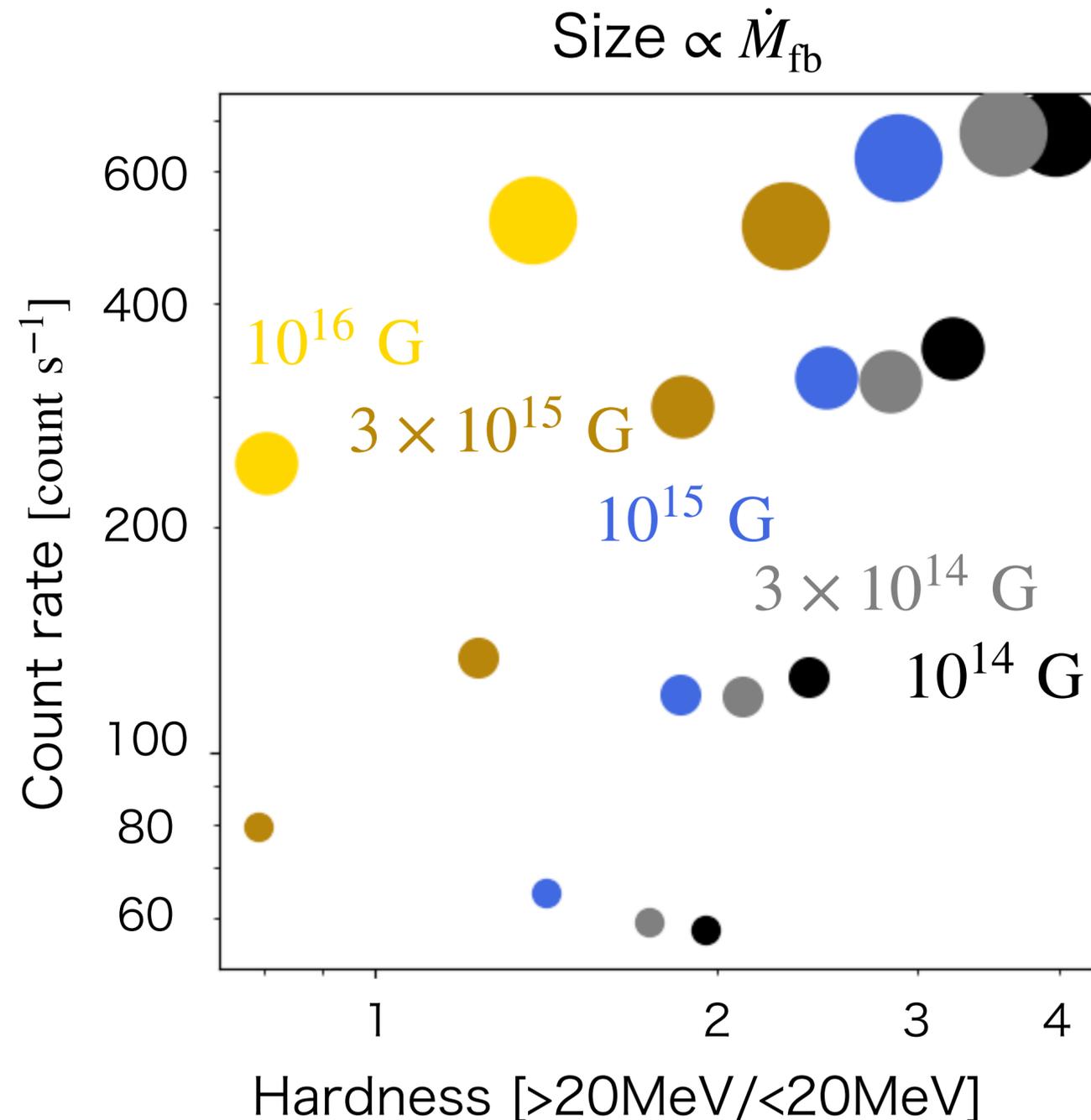
Parameter dependence of the delay

$r_{\rm PNS} = 10$ km

- $B_{\rm 10km} = 0$
- $B_{\rm 10km} = 3 \times 10^{14}$ [G]
- $B_{\rm 10km} = 10^{15}$ [G]
- $B_{\rm 10km} = 3 \times 10^{15}$ [G]
- $B_{\rm 10km} = 10^{16}$ [G]

The delay is an increasing function of $B_{\rm 10km}$, while it is a decreasing function of $\dot{M}_{\rm fb}$.

Fitting formula

$$t_{\rm delay} \approx 0.11 \ [{\rm s}] \left(\frac{\dot{M}}{10^{-3} \ M_{\odot} \ {\rm s}^{-1}} \right)^{-1.26} \left(\frac{B_{\rm PNS}}{10^{15} \ {\rm G}} \right)^{1.45}$$

$$+ 0.025 \ [{\rm s}] \left(\frac{\dot{M}}{10^{-3} \ M_{\odot} \ {\rm s}^{-1}} \right)^{-0.95}$$

Neutrino spectra: Hardness Intensity diagram

Size $\propto \dot{M}_{\rm fb}$

Count rate [count s^{-1}]

10^{16} G

3×10^{15} G

10^{15} G

3×10^{14} G
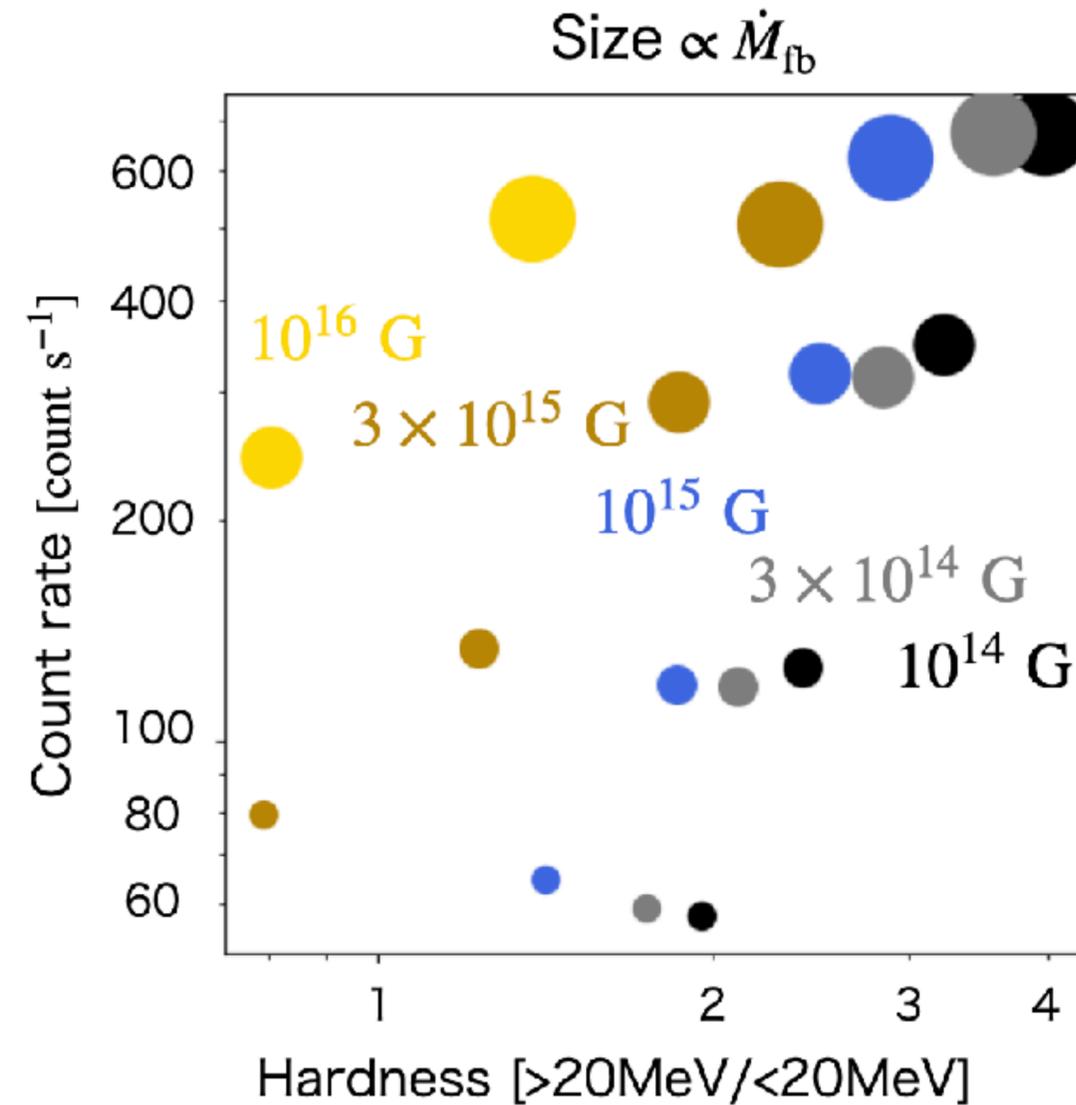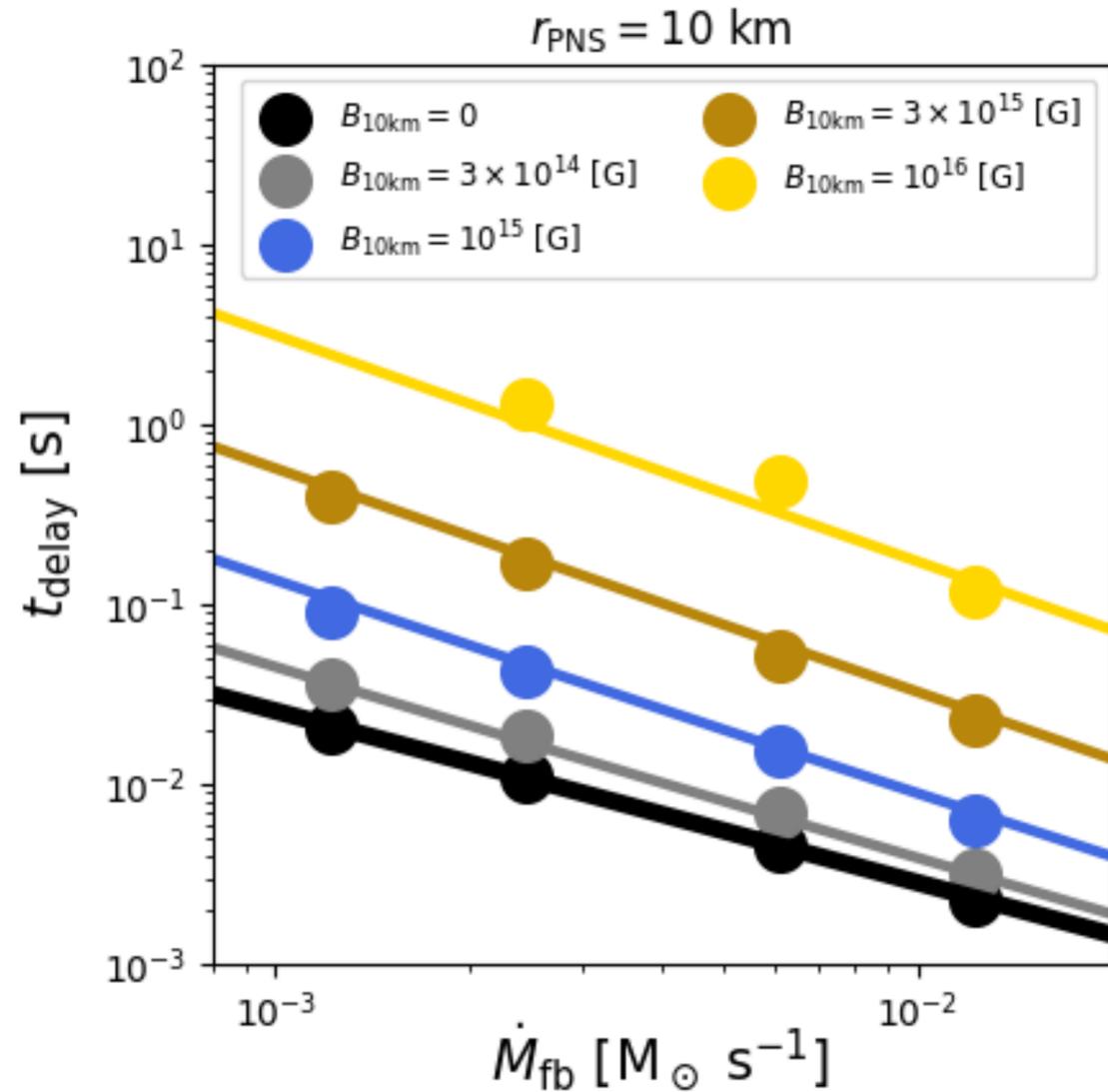
10^{14} G

Hardness [>20MeV/<20MeV]

We assumed the Fermi-Dirac distribution

Count rate for Super-Kamiokande (normal ordering)

・ A higher $\dot{M}_{\rm fb}$, higher count rates

・ A stronger $B_{\rm 10km}$, softer spectra

This diagram may be used for estimating the PNS magnetic field

Summary

· We performed general relativistic MHD simulations of the supernova fallback

· The time delay and the hardness ratio may be used to infer the PNS magnetic field