超新星フォールバックの数値流体シミュレーション

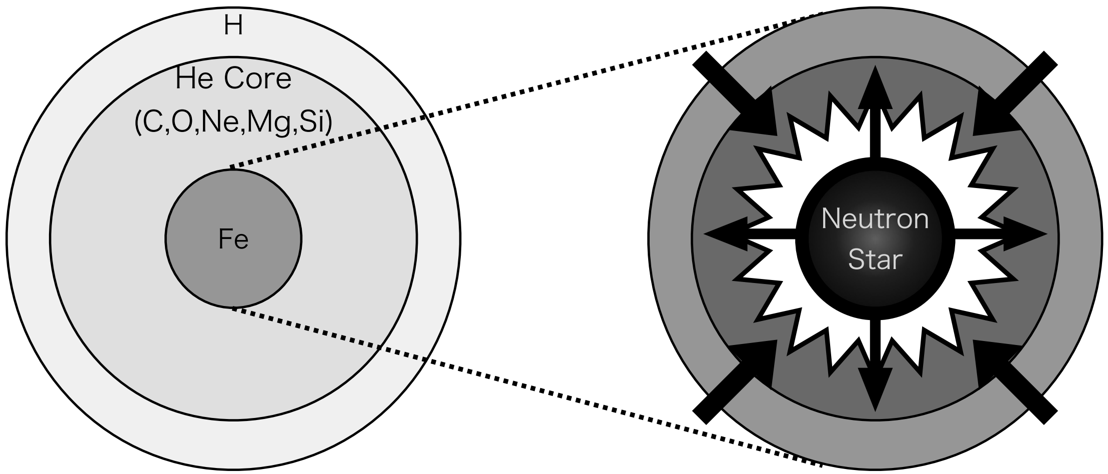
Kengo Shinoda (University of Tokyo)

Co-researcher :

Ryo Sawada, Yudai Suwa, Takeru Suzuki (University of Tokyo), Ryosuke Hirai (Monash University), Kazunari Iwasaki (NAOJ), Kengo Tomida(Tohoku University)

2025/03/04 第１１回超新星ニュートリノ研究会@東京大学 駒場キャンパス

Core Collapse Supernova (CCSN) Mechanism



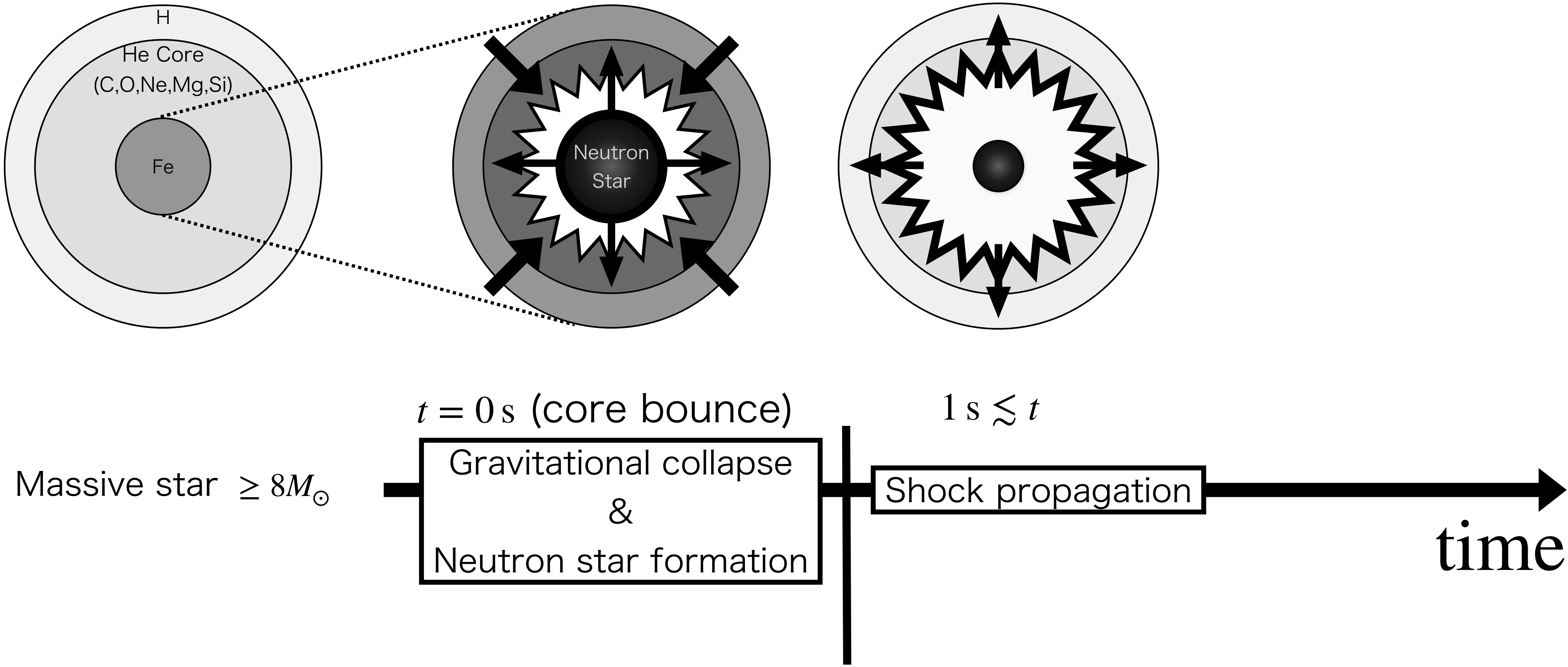
$t = 0\,\mathrm{s}$ (core bounce)

Massive star $\geq 8 M_{\odot}$

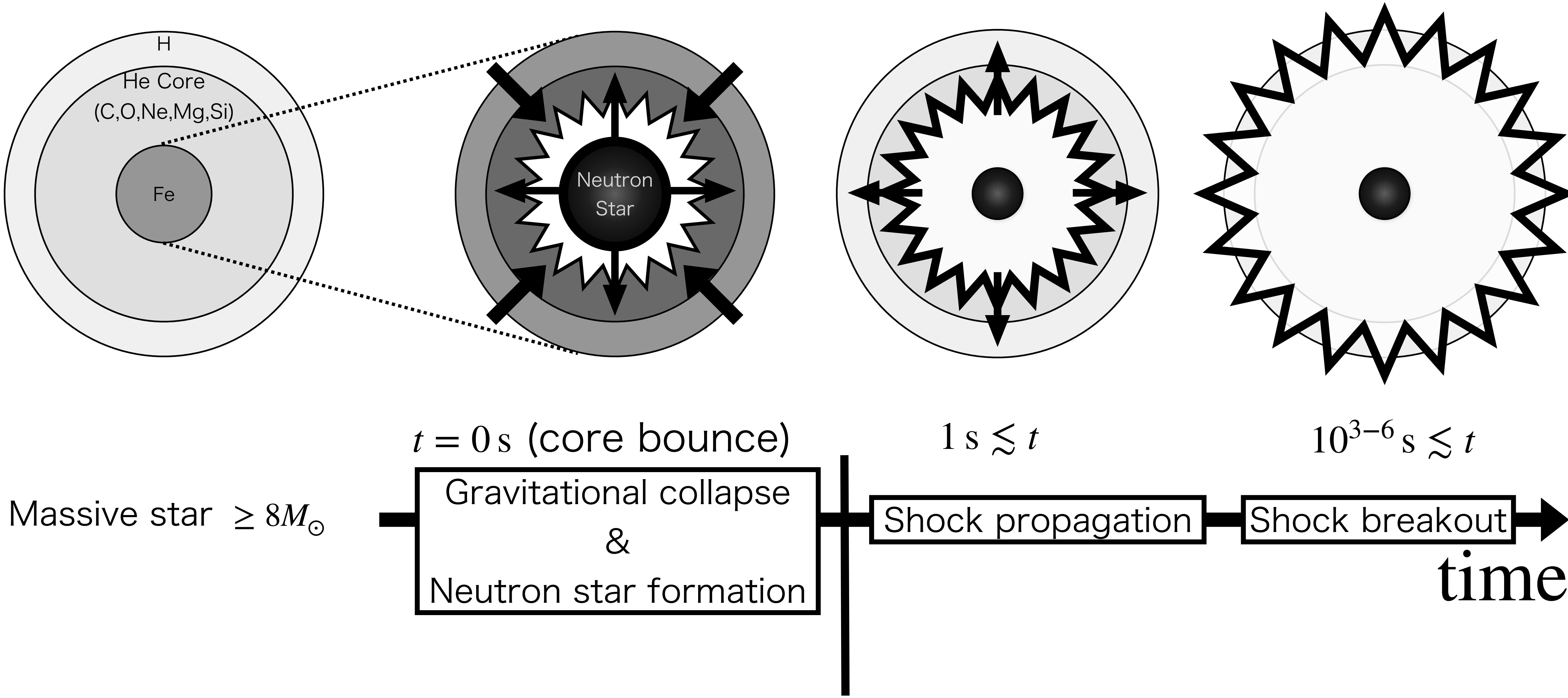
Gravitational collapse
&
Neutron star formation

time

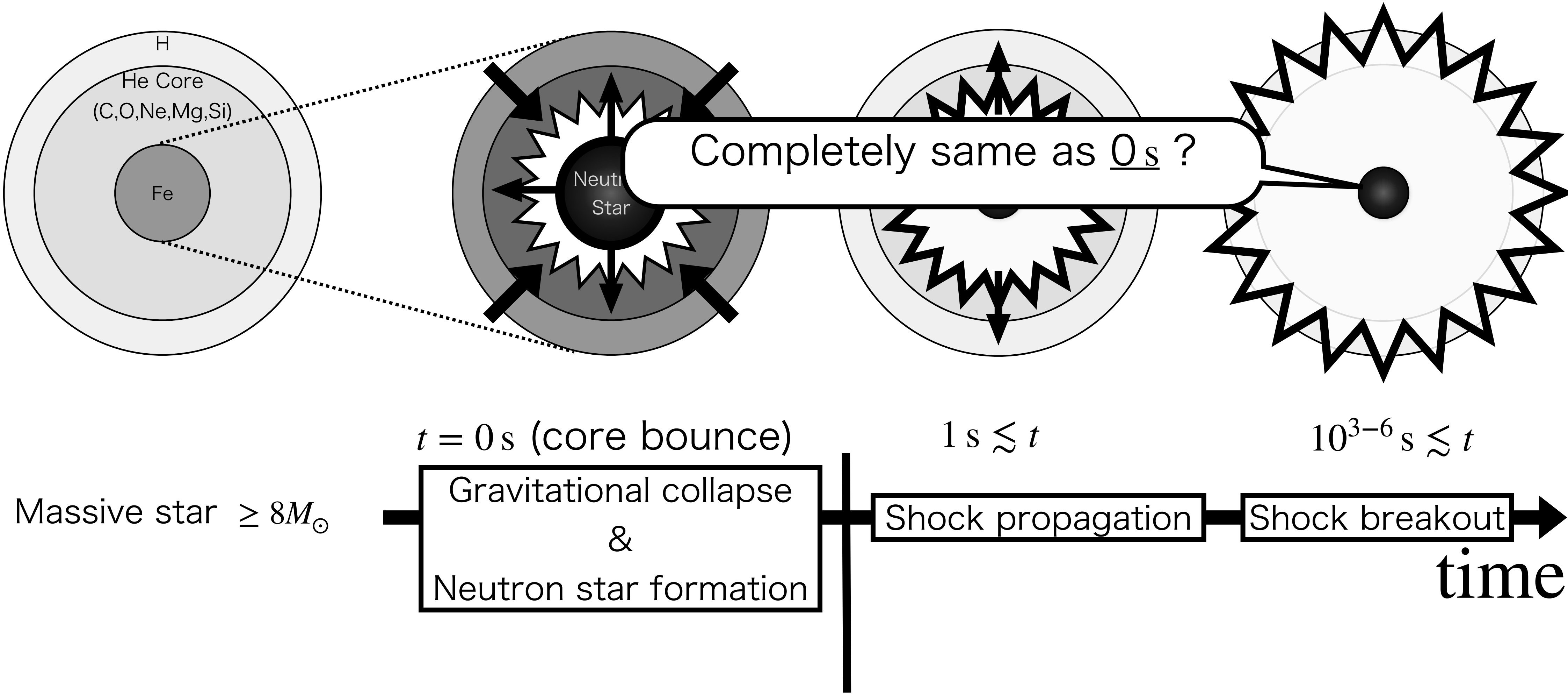
Core Collapse Supernova (CCSN) Mechanism



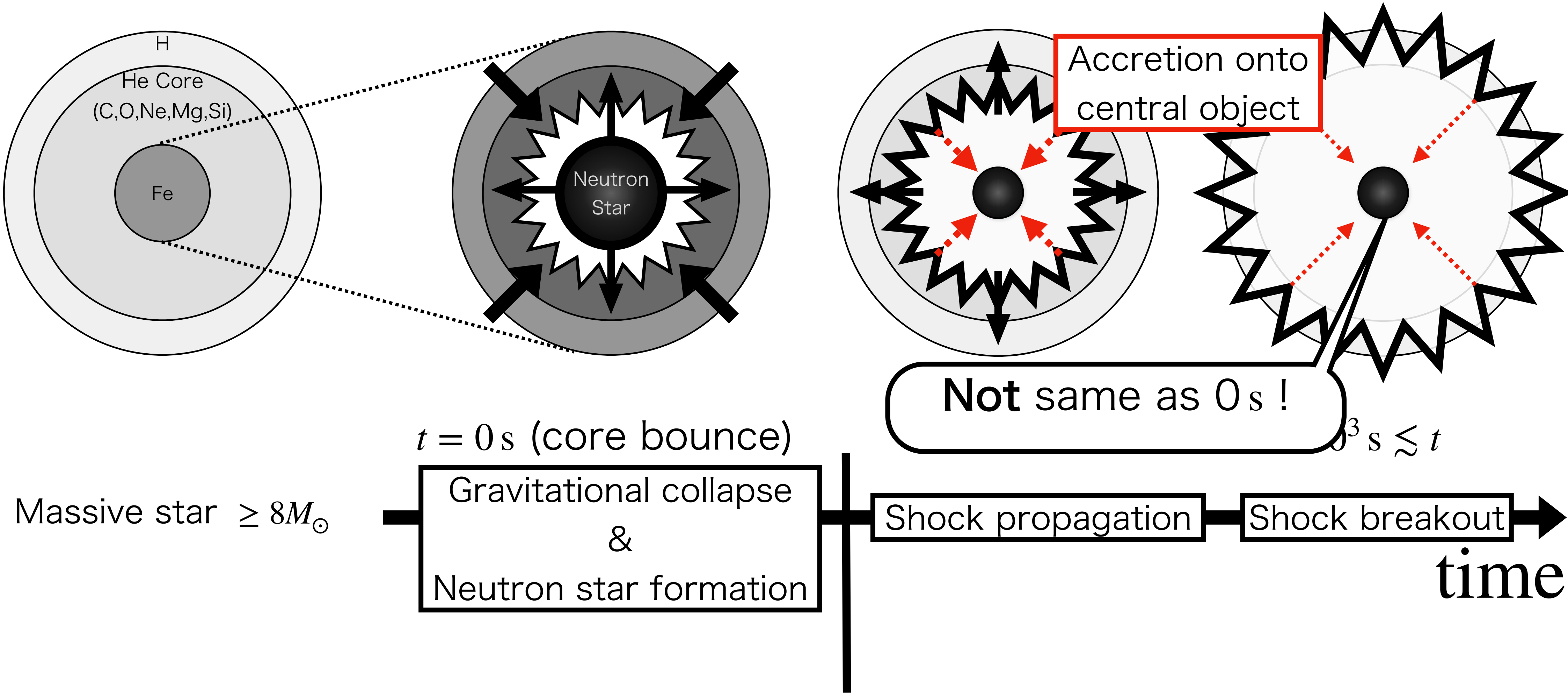
Core Collapse Supernova (CCSN) Mechanism



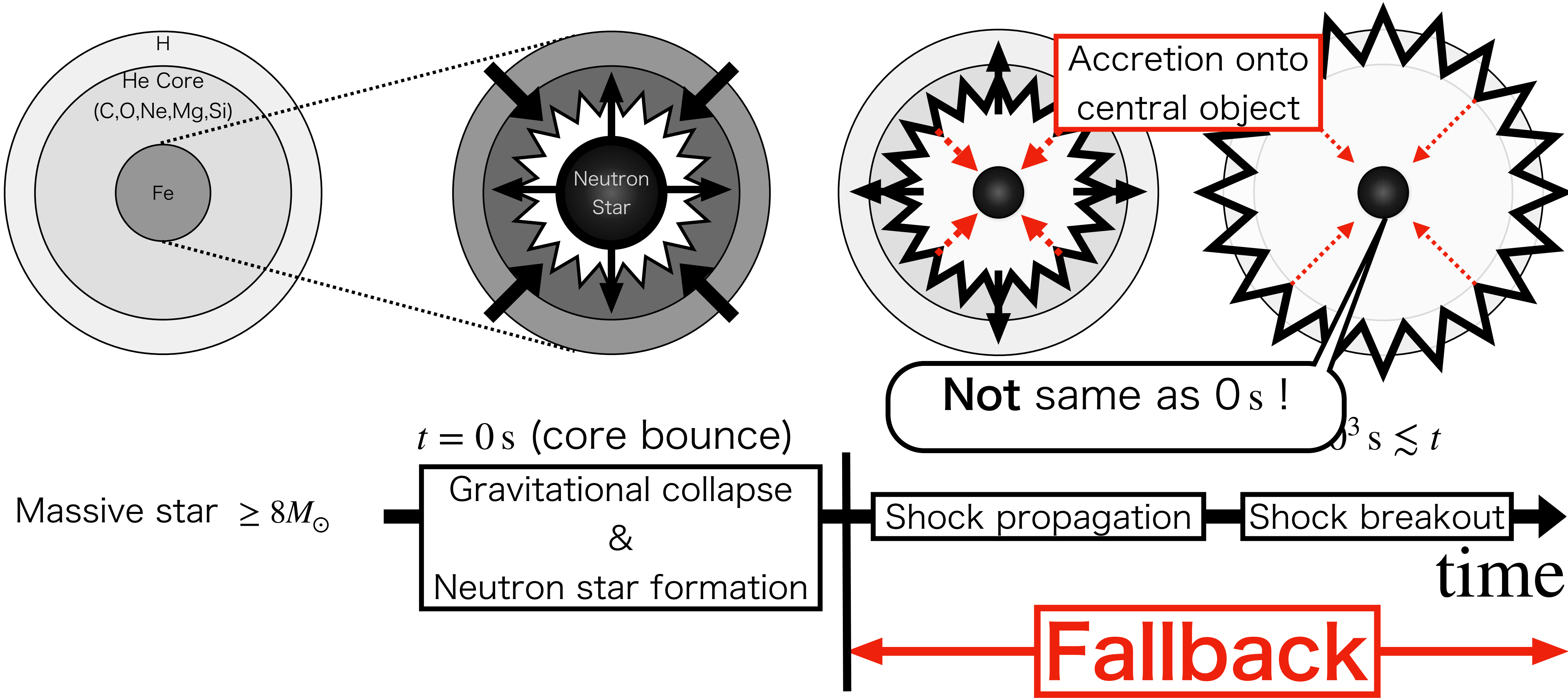
Core Collapse Supernova (CCSN) Mechanism



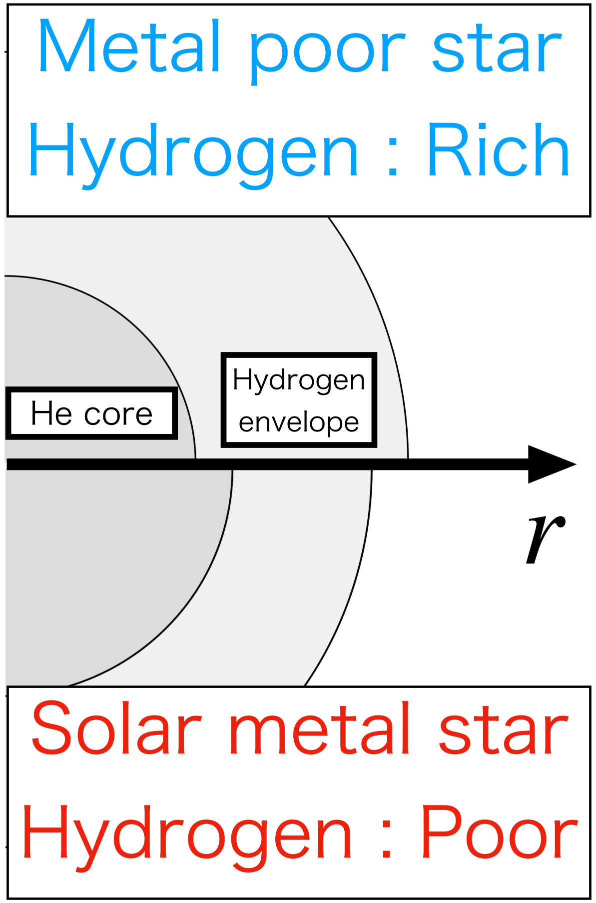
Core Collapse Supernova (CCSN) Mechanism

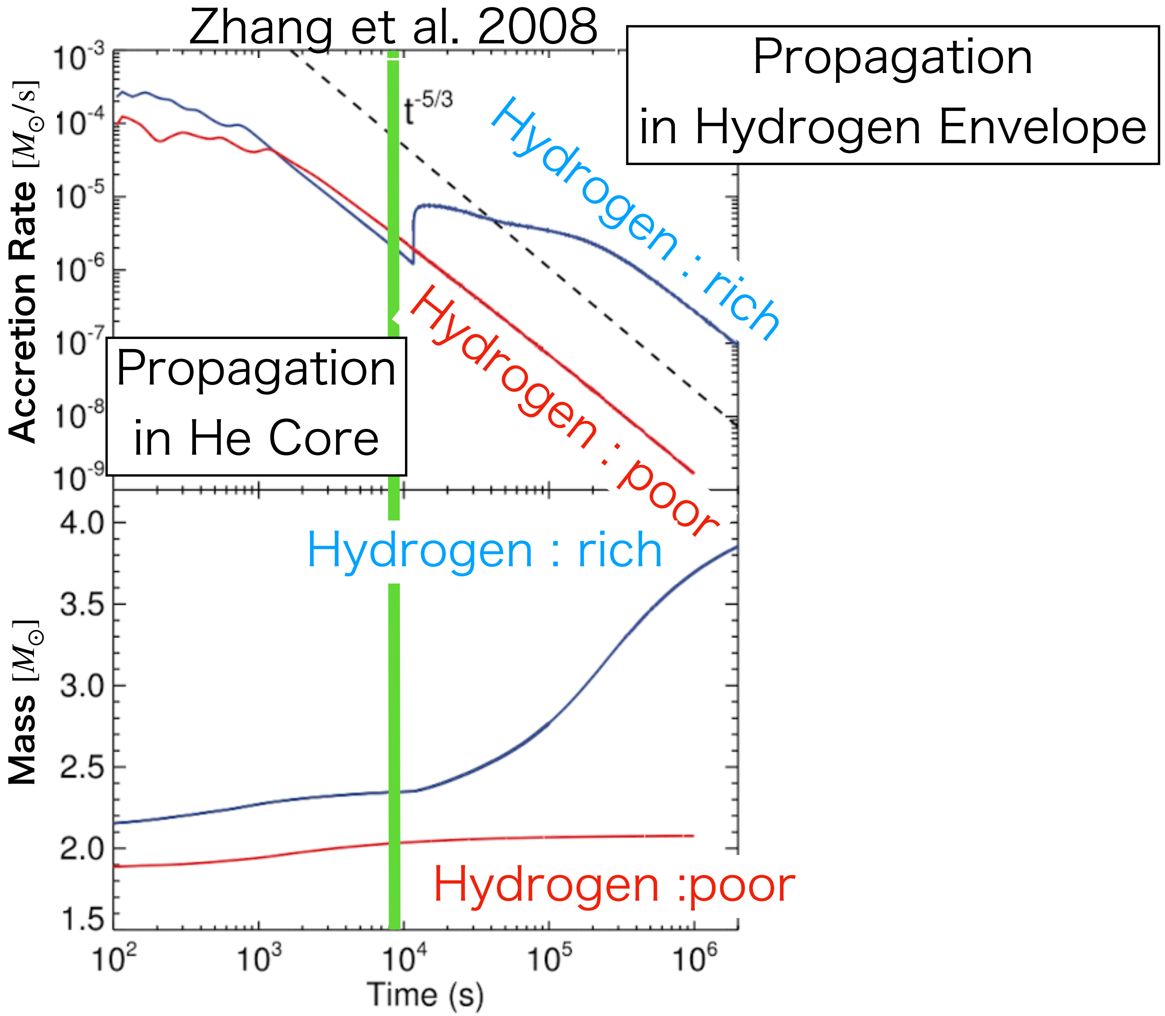


Core Collapse Supernova (CCSN) Mechanism

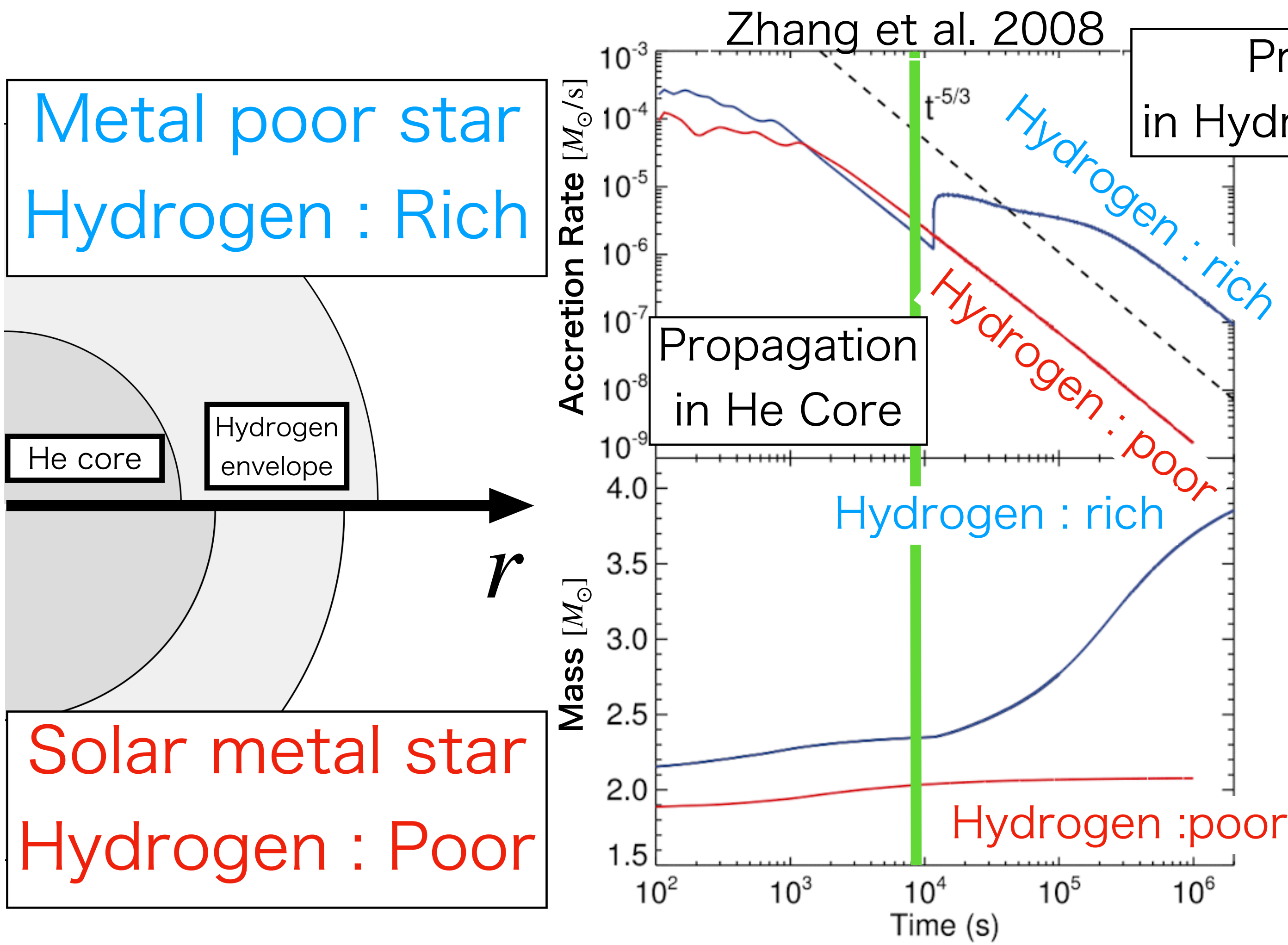


Effects of Fallback by Hydrogen Envelope?





Effects of Fallback by Hydrogen Envelope?



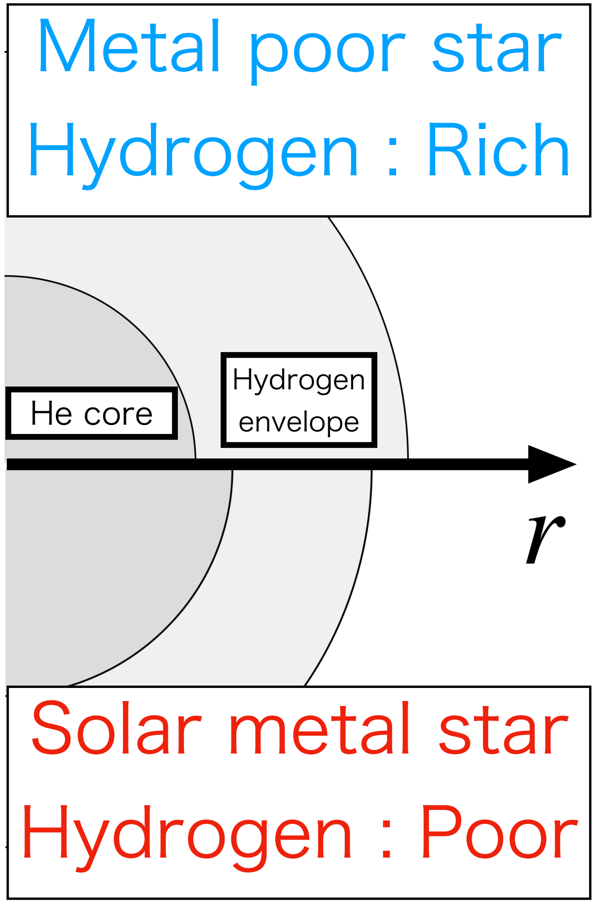
: Metal-free star

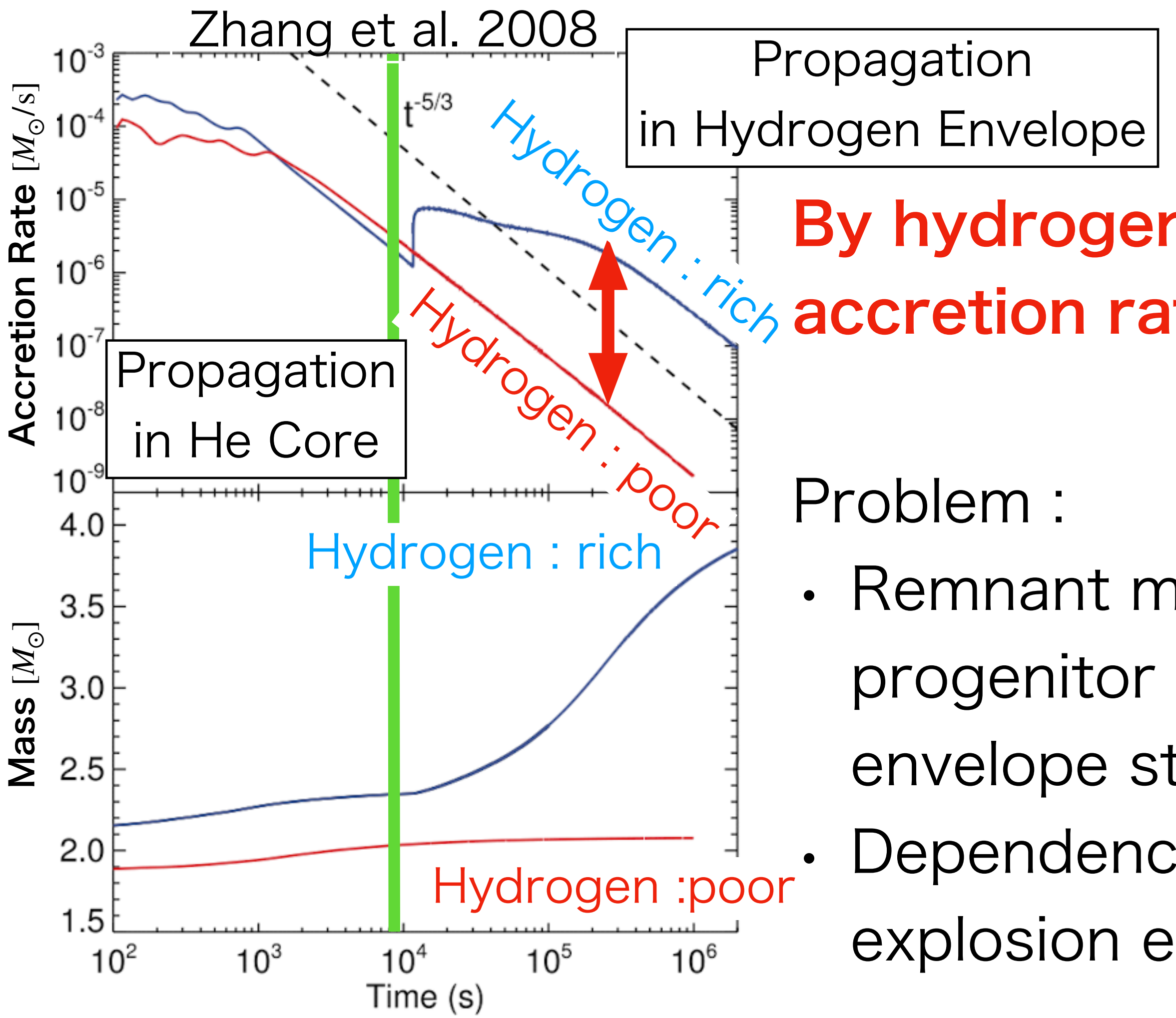
: Solar metal star

Metal-free star :
Higher fallback accretion rate, heavier remant mass

Solar metal star :
Lower fallback accretion rate, lower remnant mass

Effects of Fallback by Hydrogen Envelope?





By hydrogen envelope, accretion rate increases

Problem :

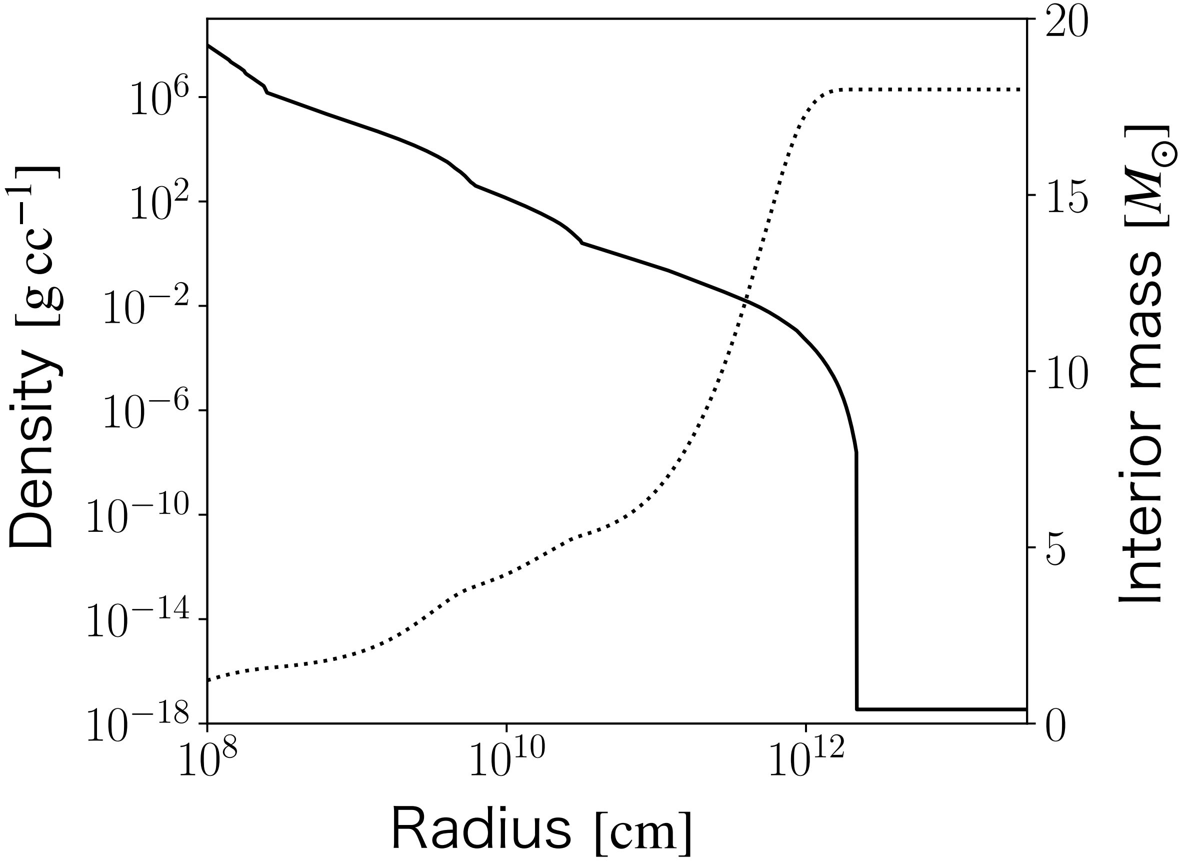
- Remnant mass by progenitor hydrogen envelope structure?
- Dependence of explosion energy? …

Motivation How does the hydrogen envelope affect fallback?

Simulation **Calculation of spherically symmetric 1D fluid in progenitors with "only" different hydrogen envelope**

Motivation How does the hydrogen envelope affect fallback?

Simulation **Calculation of spherically symmetric 1D fluid in progenitors with "only" different hydrogen envelope**



Initial Condition

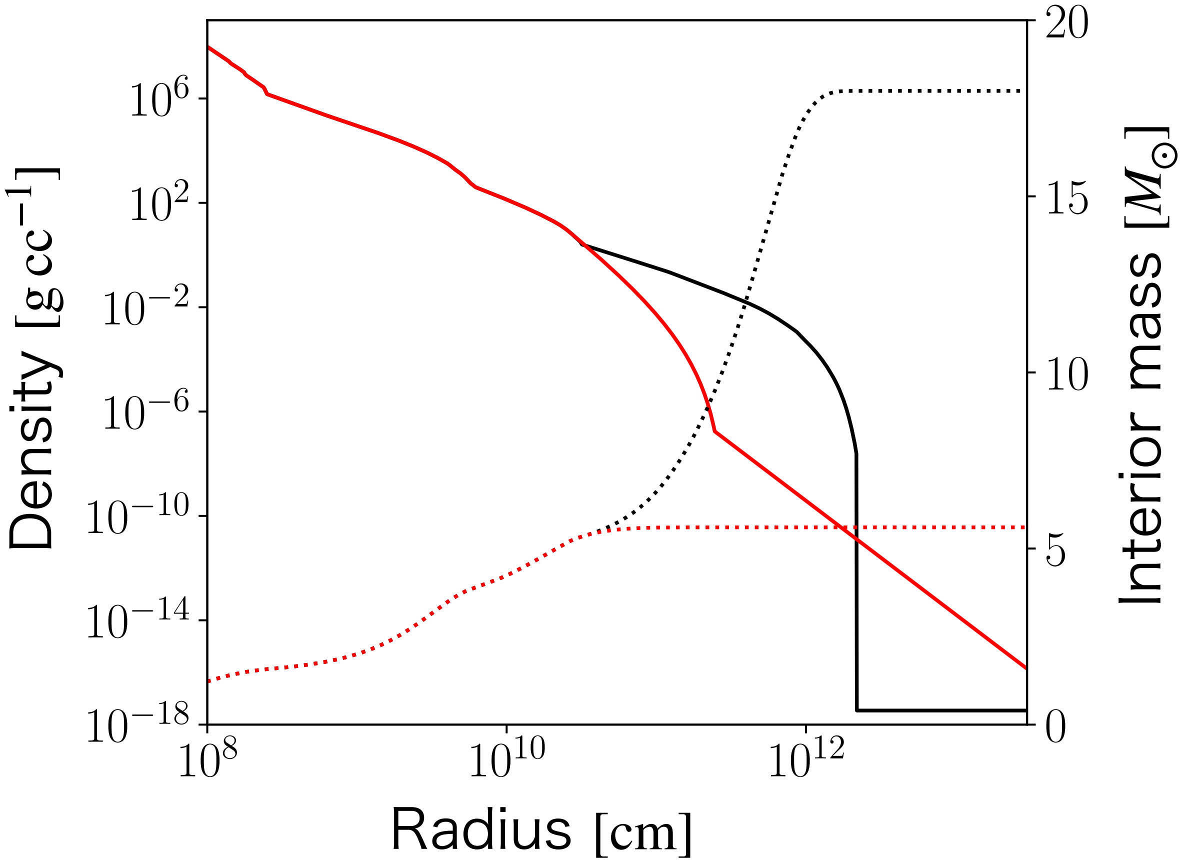
Black: type II (Hydrogen: Rich)

$Z = 10^{-4} Z_\odot$, $M_{\rm ZAMS} = 18 M_\odot$

Woosley+02

Motivation How does the hydrogen envelope affect fallback?

Simulation **Calculation of spherically symmetric 1D fluid in progenitors with "only" different hydrogen envelope**



Initial Condition

Black: type II (Hydrogen: Rich)

$Z = 10^{-4} Z_\odot$, $M_{\rm ZAMS} = 18 M_\odot$

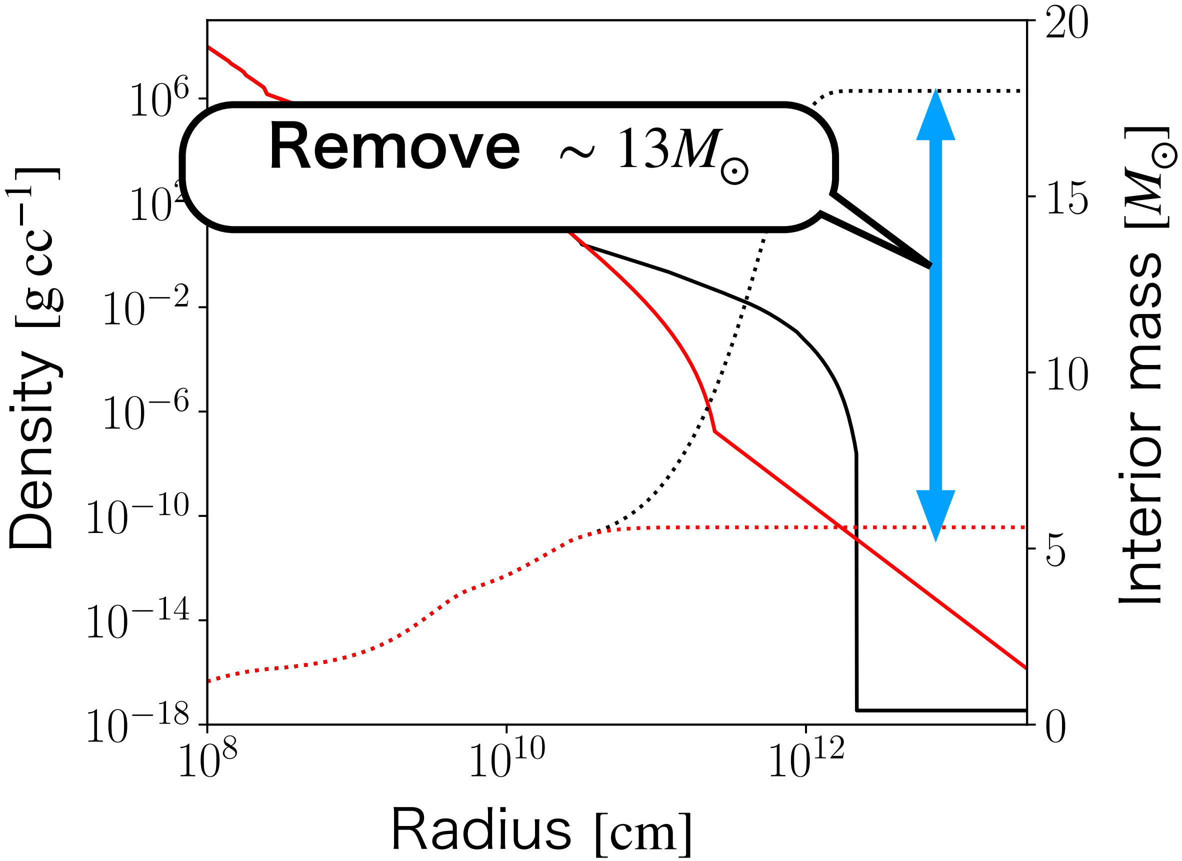
Woosley+02

Red: type IIb (Hydrogen: Poor)

Remove hydrogen envelope from type II progenitor (Method: Matzner+99)

Motivation How does the hydrogen envelope affect fallback?

Simulation **Calculation of spherically symmetric 1D fluid in progenitors with "only" different hydrogen envelope**



Initial Condition

Black: type II (Hydrogen: Rich)

$Z = 10^{-4}Z_{\odot}$, $M_{\mathrm{ZAMS}} = 18M_{\odot}$

Woosley+02

Red: type IIb (Hydrogen: Poor)

Remove hydrogen envelope from type II progenitor (Method: Matzner+99)

Motivation How does the hydrogen envelope affect fallback?

Simulation **1D explosion calculation for progenitors with hydrogen envelope**

Code: Athena++ (Stone+20)

Equations: pure hydro + self-gravity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u} + P^{*}) = \rho \mathbf{g}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \{\mathbf{u}(e + p)\} = \rho \mathbf{u} \cdot \mathbf{g}$$

$$p = \epsilon(\gamma - 1), \gamma = 5/3$$

Motivation How does the hydrogen envelope affect fallback?

Simulation **1D explosion calculation for progenitors with hydrogen envelope**

Code: Athena++ (Stone+20)

Equations: pure hydro + self-gravity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u} + P^*) = \rho \mathbf{g}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \{\mathbf{u}(e+p)\} = \rho \mathbf{u} \cdot \mathbf{g}$$

$$p = \epsilon(\gamma - 1), \gamma = 5/3$$

Explosions: Thermal bomb

Inject internal energy ($E_{\rm inj}$) at 10^7cm

⟹Calcurate total energy of ejecta as explosion energy ($E_{\rm exp}$)

Put $E_{\rm inj}$ to reproduce $E_{\rm exp} \simeq 10^{49-52}$erg

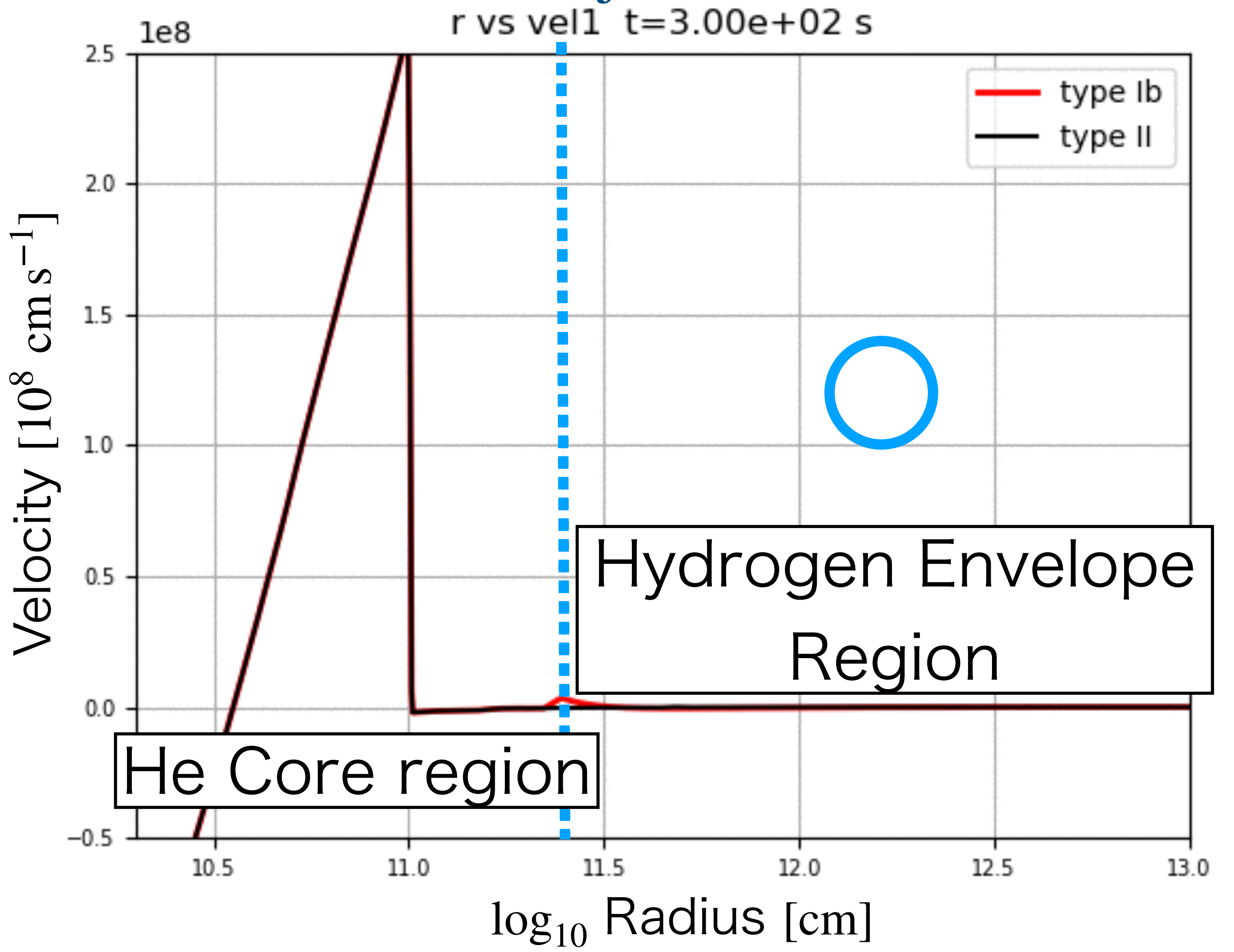
Results : Shock evolution $(E_{\rm inj} = 8 \times 10^{50} {\rm erg})$

▬ : Hydrogen **Rich**
type II

▬ : Hydrogen **Poor**
type IIb

Before run in Envelope
⇒**Same**

After run in Envelope
⇒**Change**



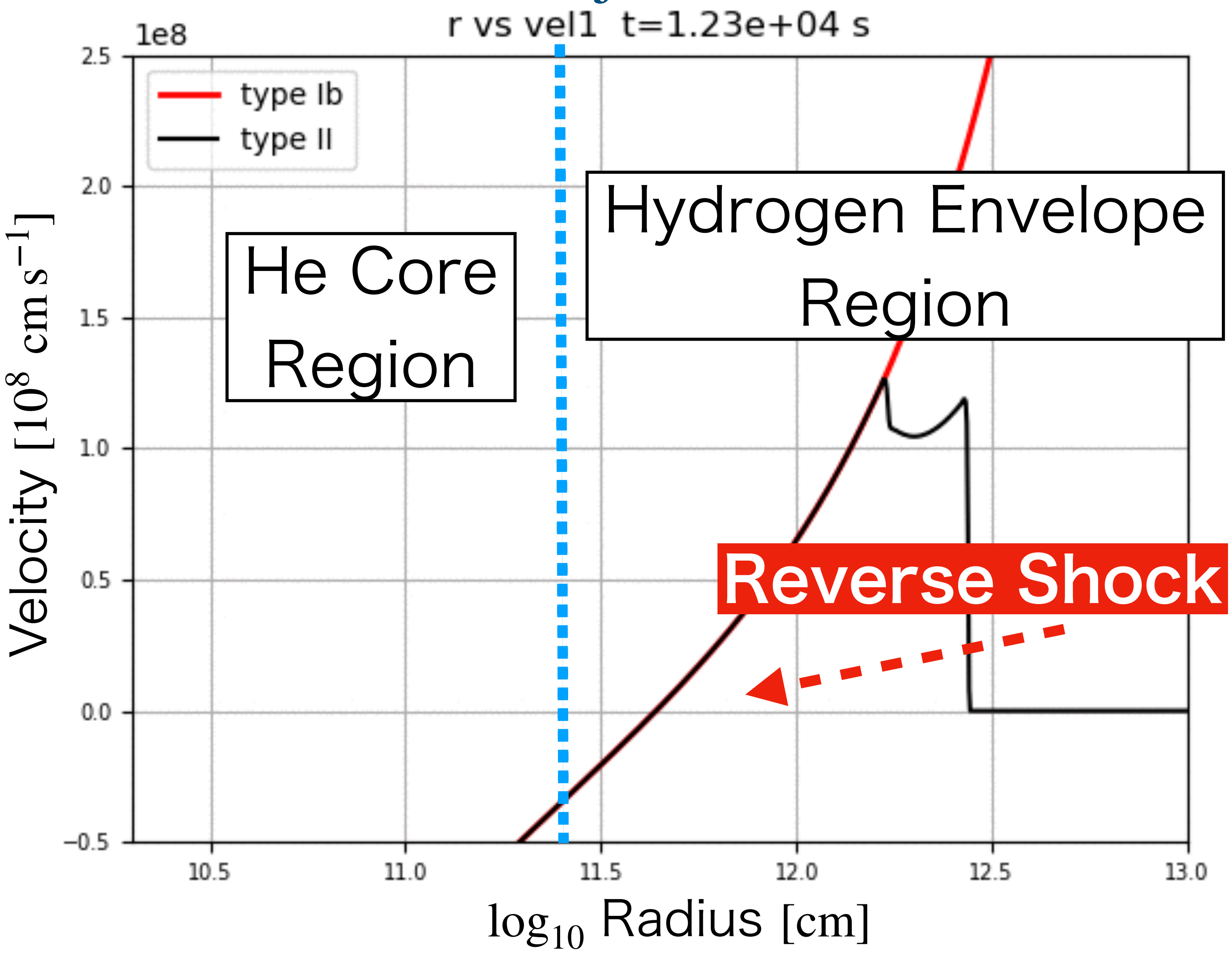
Results : Shock evolution $(E_{inj} = 8 \times 10^{50} \mathrm{erg})$

— : Hydrogen **Rich**
type II

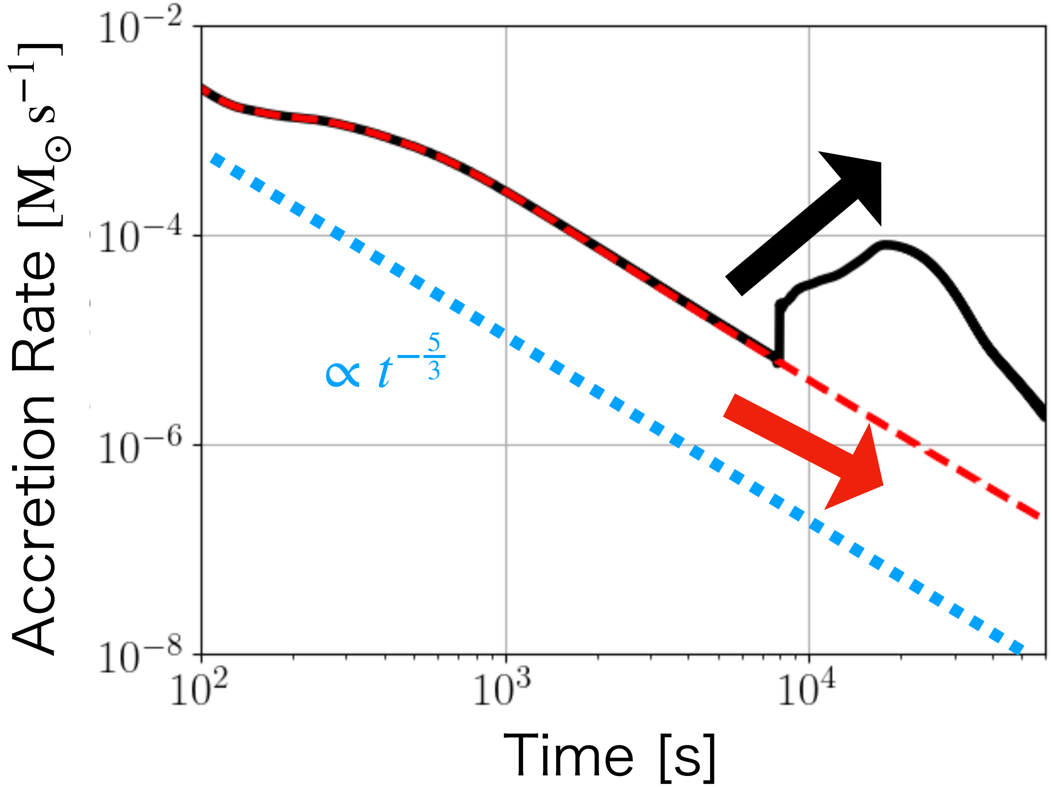
— : Hydrogen **Poor**
type IIb

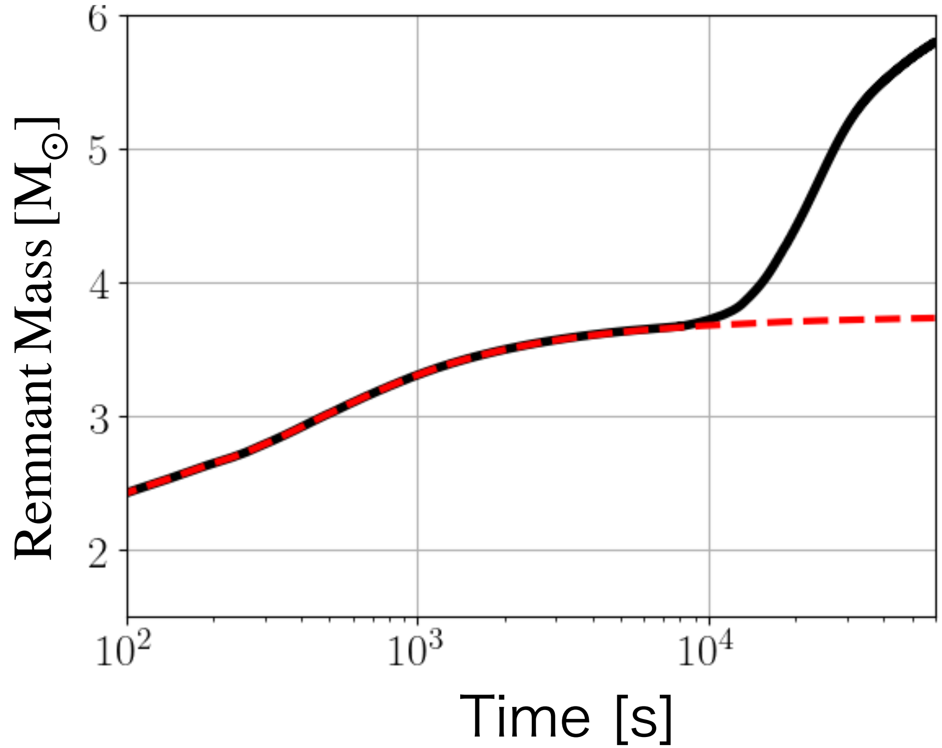
Before run in Envelope
⇒**Same**

After run in Envelope
⇒**Change**



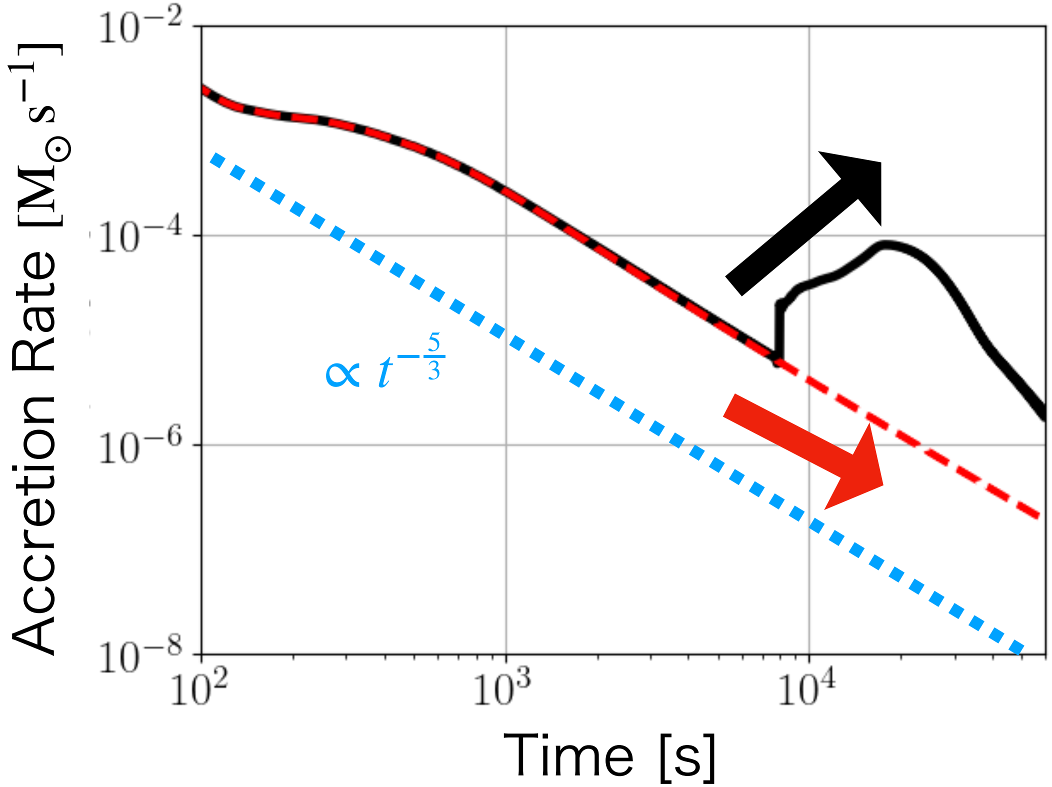
Results : Weak Explosion $(E_{\rm inj} = 7 \times 10^{50}{\rm erg})$

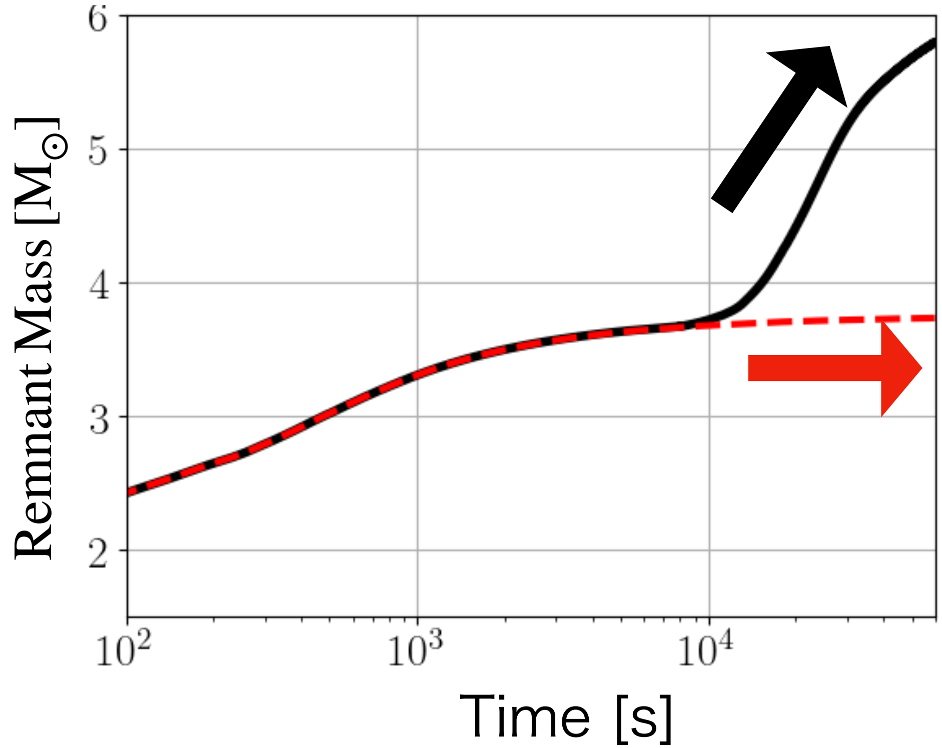




Left panel: **Strong** fallback due to the reverse shock!

Results : Weak Explosion $(E_{\rm inj} = 7 \times 10^{50}{\rm erg})$

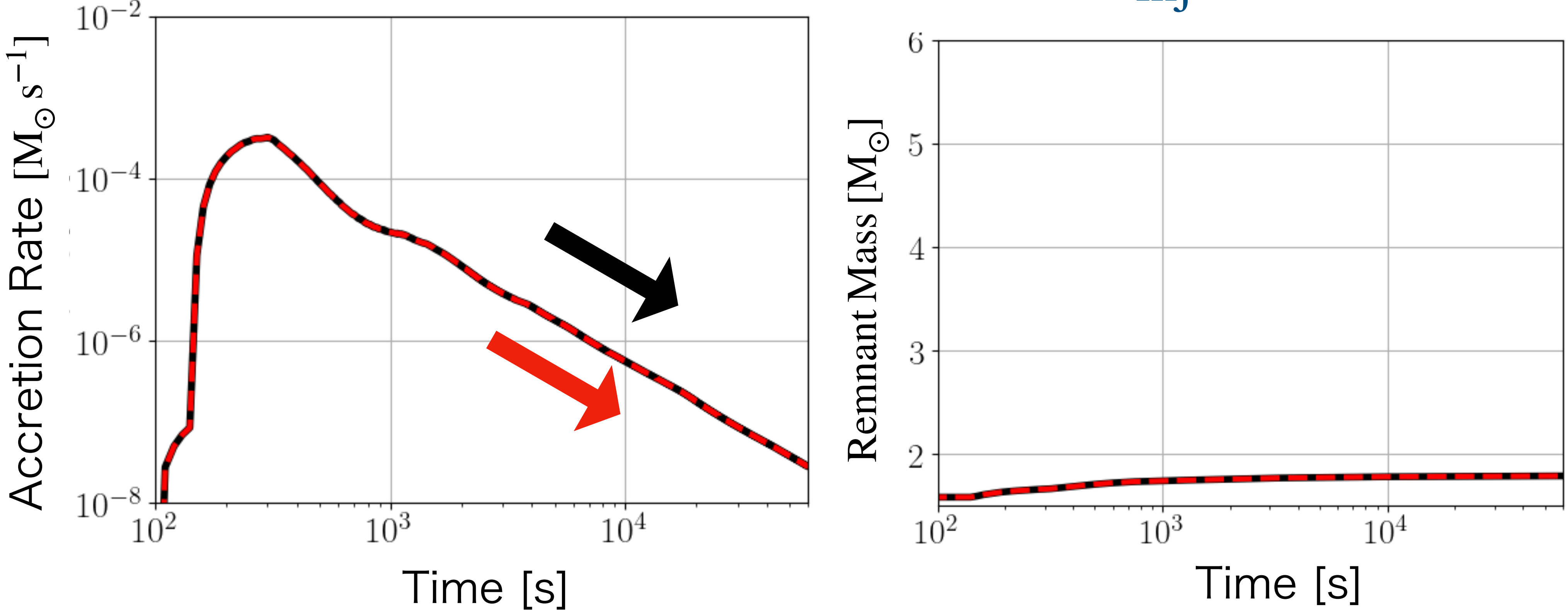




Left panel: **Strong** fallback due to the reverse shock!

Right panel: The final remnant mass is $\sim 5.8 M_\odot$, $\sim 3.8 M_\odot$

Results : Strong Explosion $(E_{\rm inj} = 2 \times 10^{51} {\rm erg})$



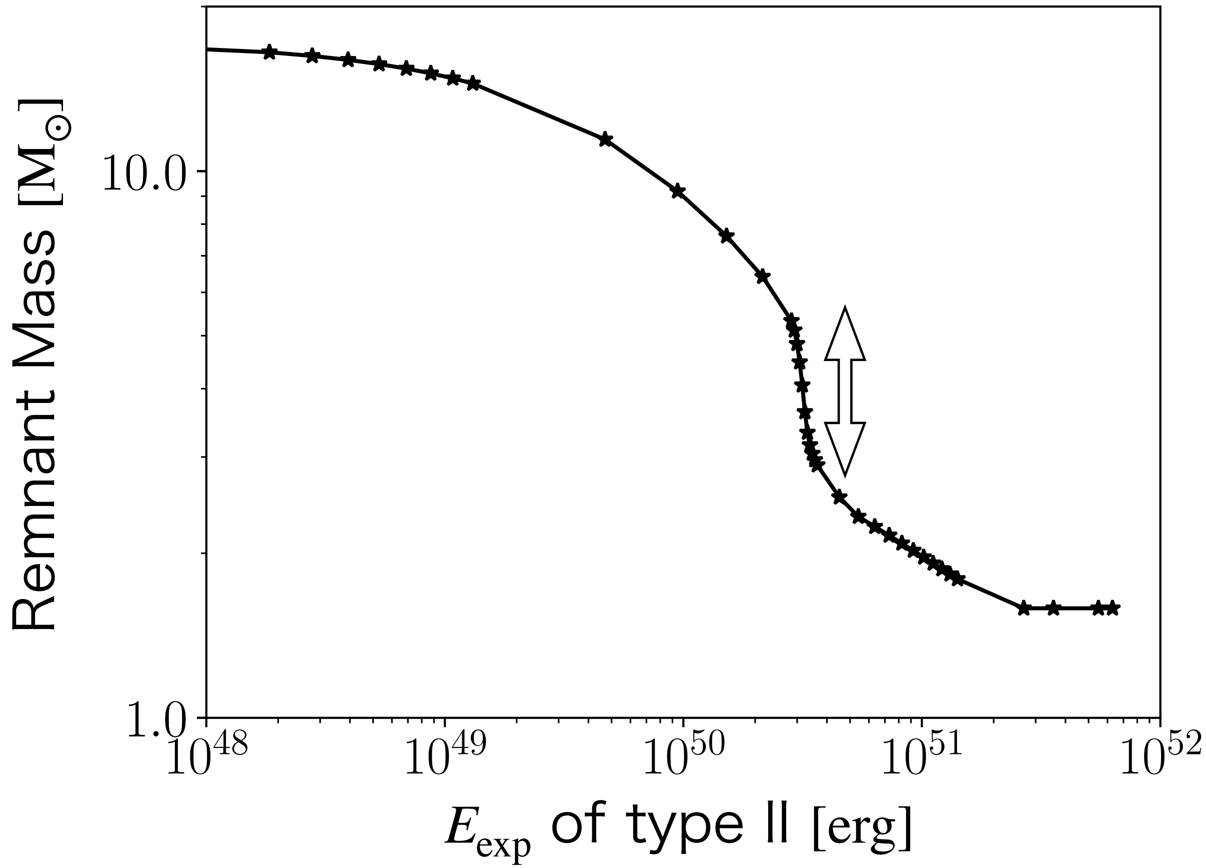
Left panel: **Weak** fallback!

Right panel: The final remnant mass is $\sim 1.8 M_\odot$, $\sim 1.8 M_\odot$

Result: Explosion energy and the remnant mass

Explosion energy ($E_{\rm exp}$) : the total energy of ejecta

$E_{\rm exp} \sim$ total energy of progenitor $+ E_{\rm inj}$



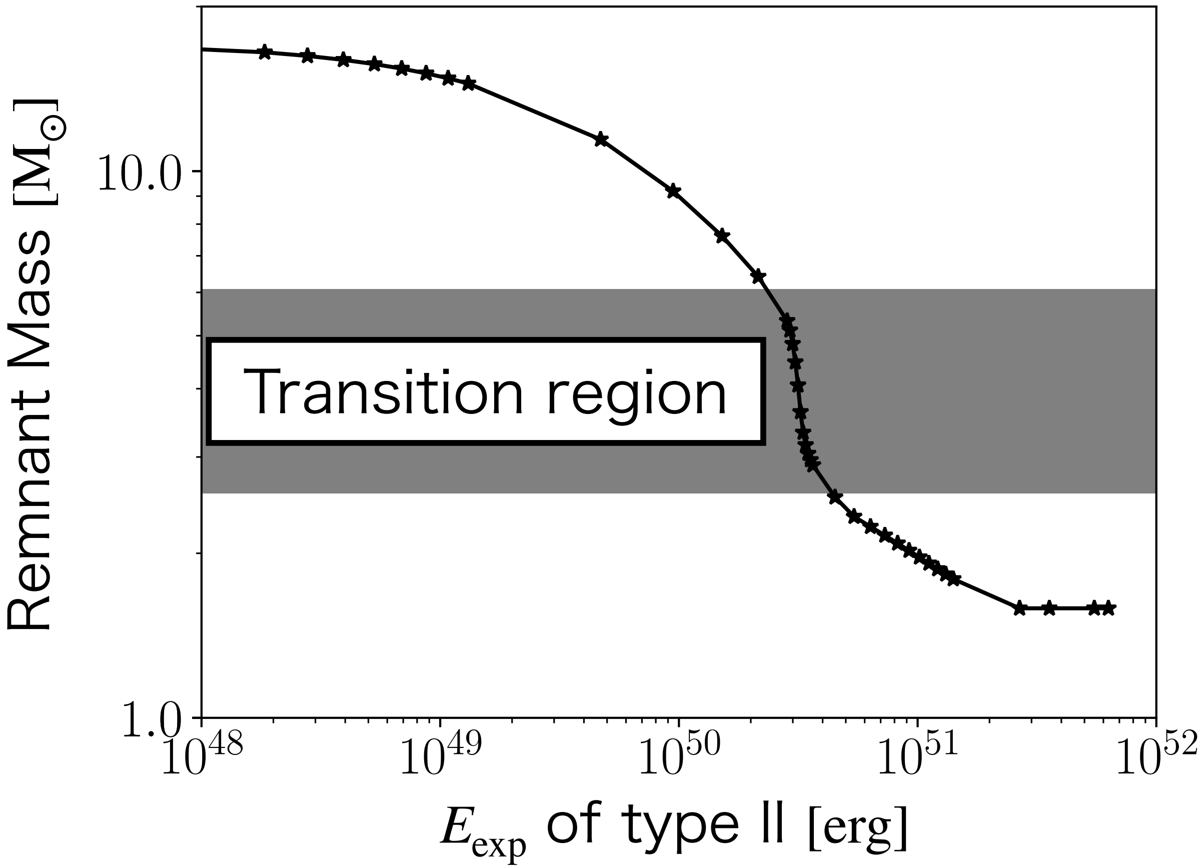
Black: type II (Hydrogen: Rich)

Increases $\sim 3M_\odot$ by the reverse shock immediately

Result: Explosion energy and the remnant mass

Explosion energy (E_{exp}) : the total energy of ejecta

$E_{exp} \sim$ total energy of progenitor $+ E_{inj}$



Black: type II (Hydrogen: Rich)

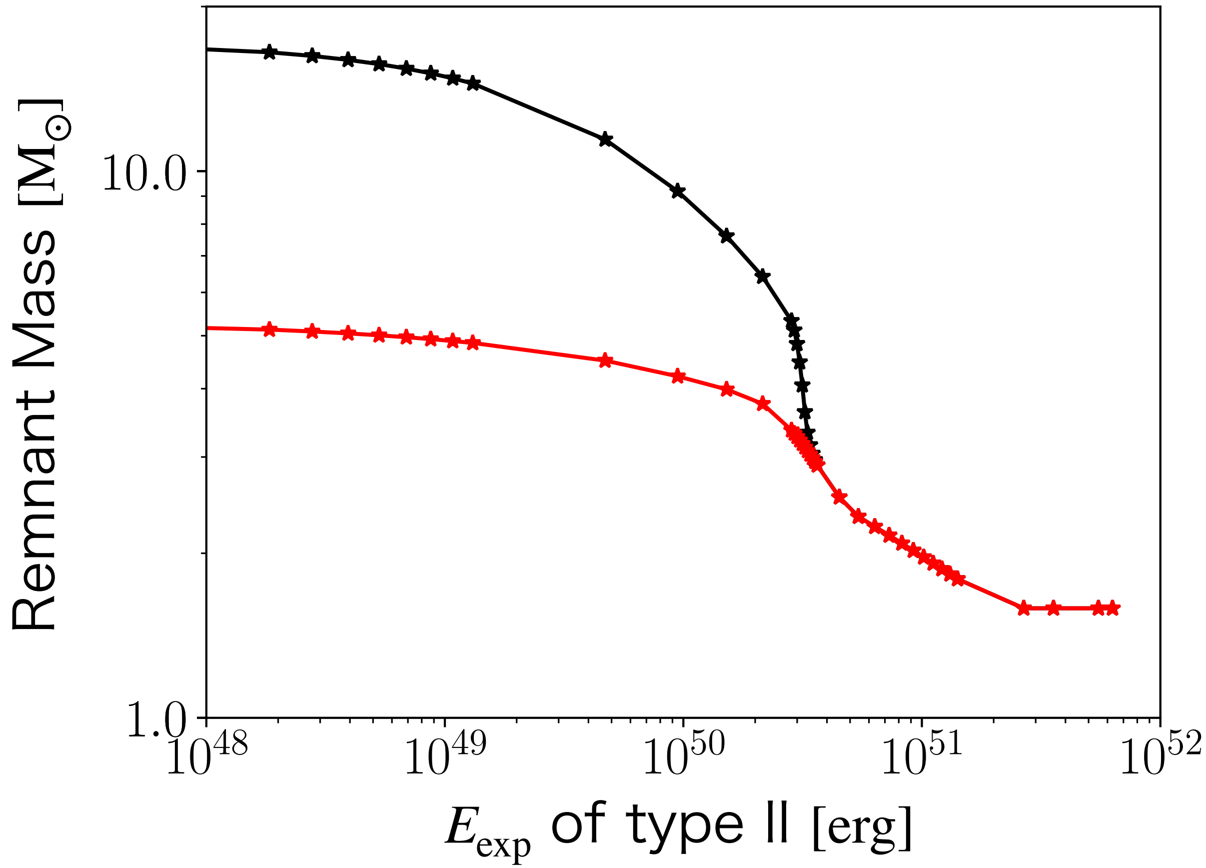
Increases $\sim 3M_\odot$ by the reverse shock immediately

Transition region: 2.5 - $6M_\odot$

Result: Explosion energy and the remnant mass

Explosion energy (E_{exp}) : the total energy of ejecta

$E_{exp} \sim$ total energy of progenitor $+ E_{inj}$



Black: type II (Hydrogen: Rich)

Increases $\sim 3M_\odot$ by the reverse shock immediately

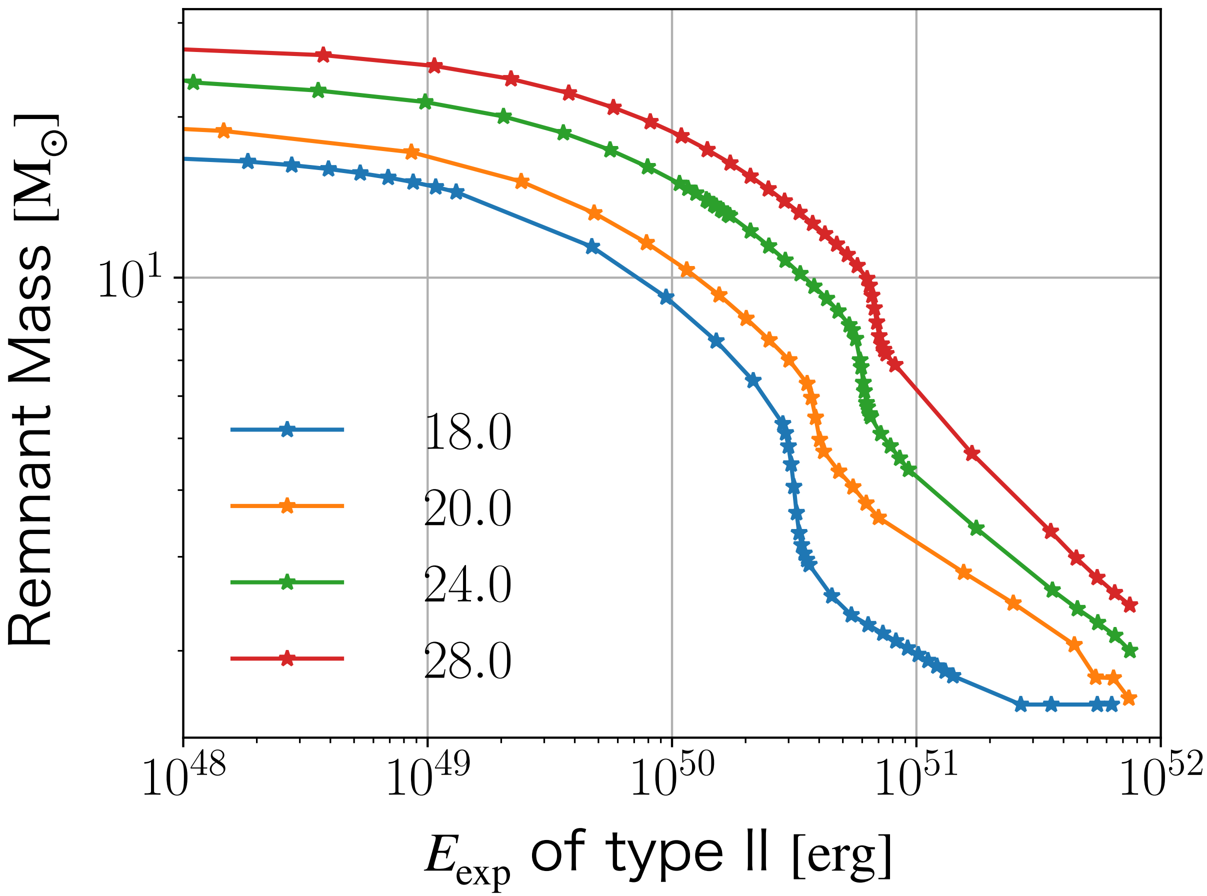
Transition region: 2.5 - 6$M_\odot$

Red: type IIb (Hydrogen: Poor)

Smaller power than type II

The remnant mass is the same at $E_{exp} \gtrsim 4 \times 10^{50}$ erg

Result: Explosion energy and the remnant mass

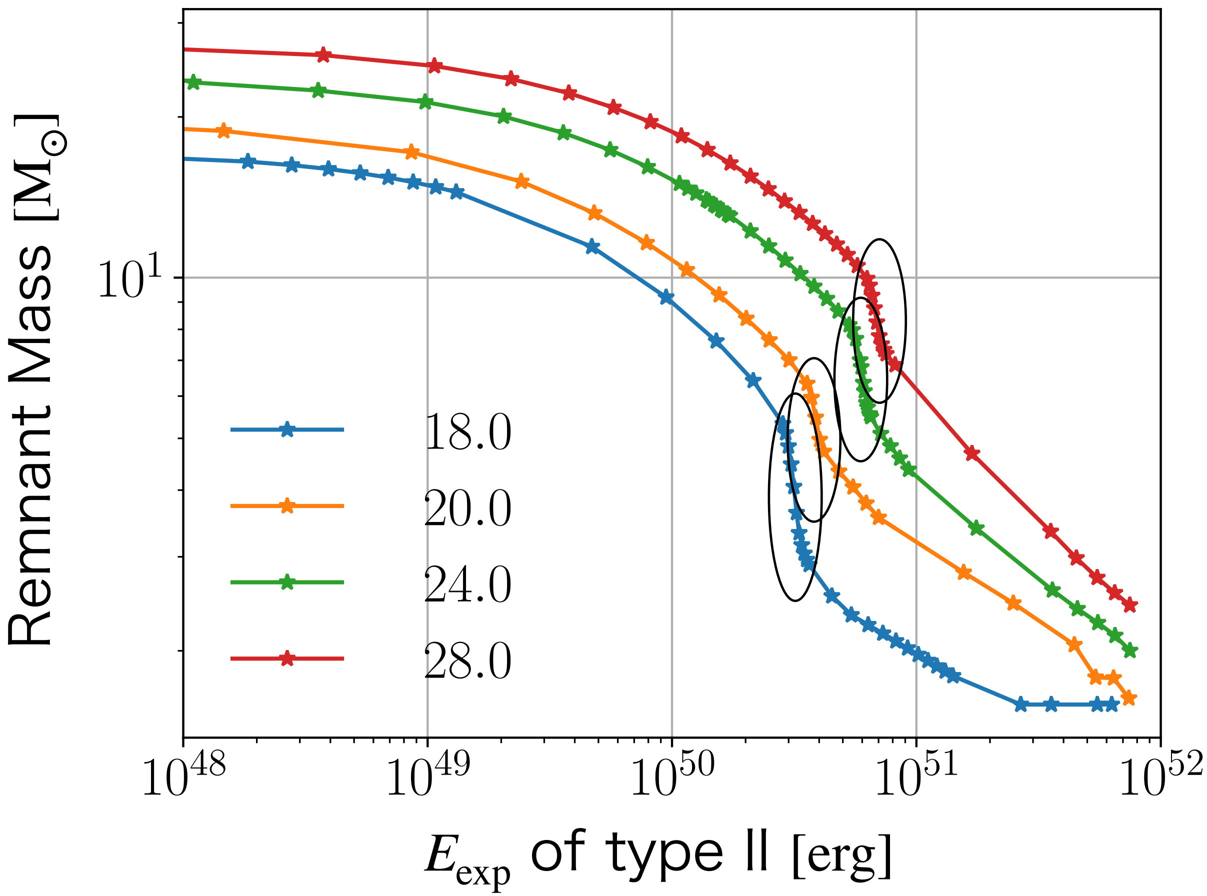


Parameter search:

$M_{\rm ZAMS} = 18,20,24,28 M_\odot$

$Z = 10^{-4} Z_\odot$

Result: Explosion energy and the remnant mass



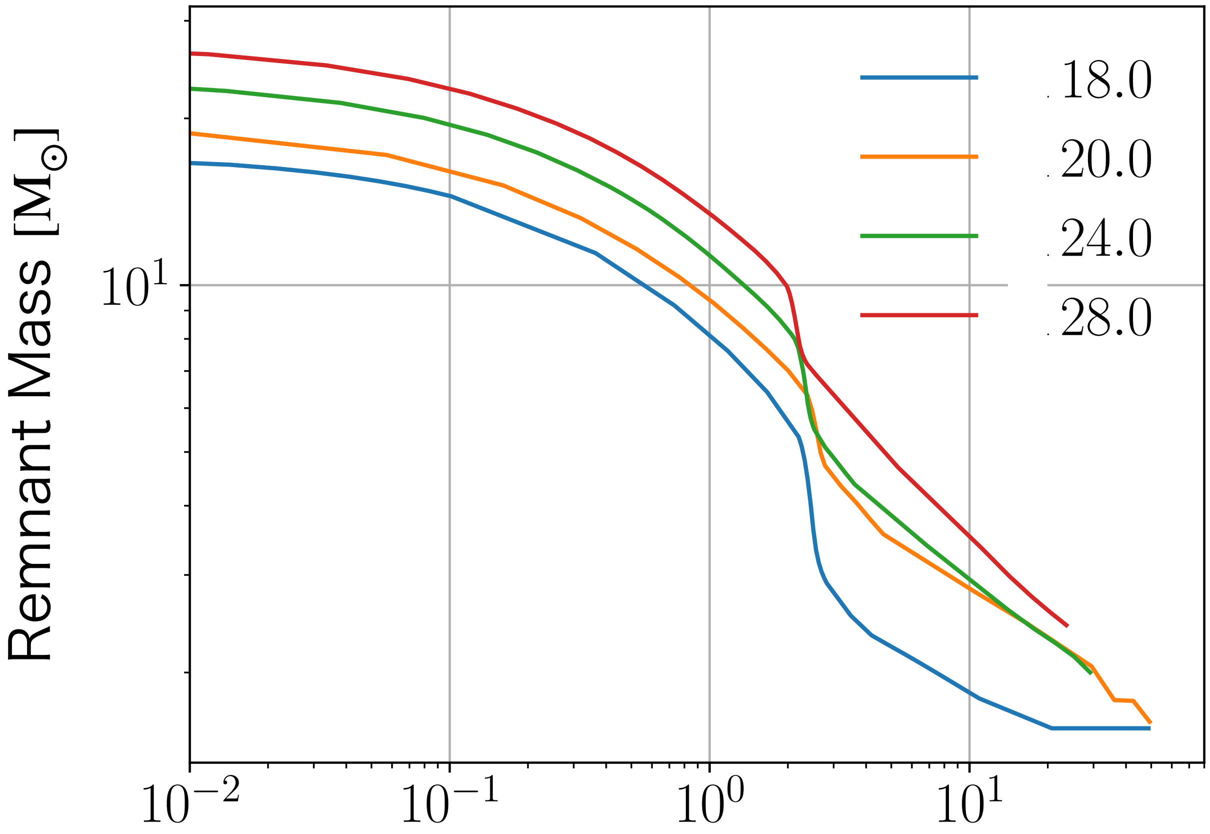
Parameter search:

$M_{\rm ZAMS} = 18,20,24,28 M_\odot$

$Z = 10^{-4} Z_\odot$

All models have transition regions!

Result: Explosion energy and the remnant mass



E_{exp} of type II / Binding energy of hydrogen envelope ($E_{\mathrm{grav,Hyd}}$)

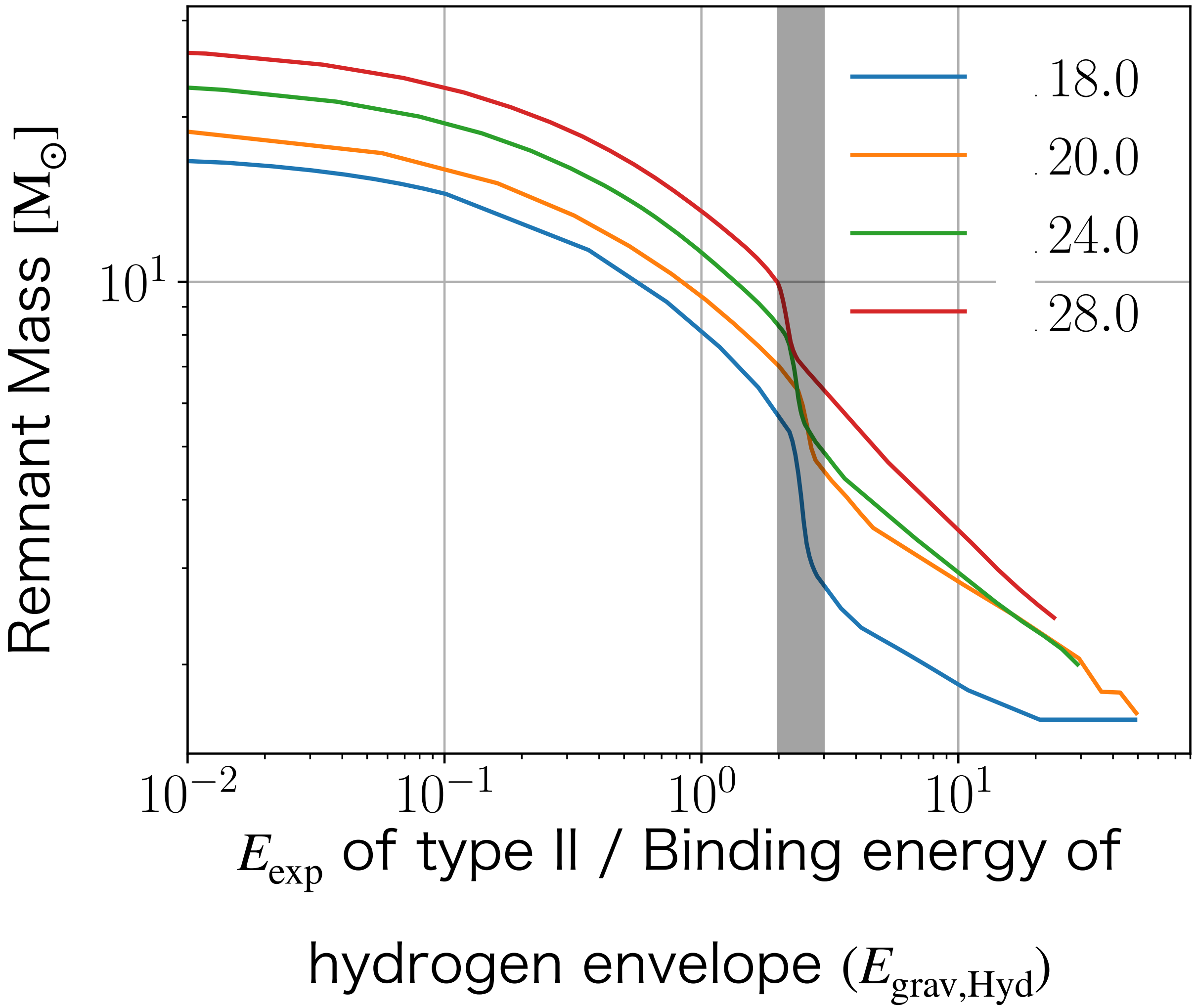
Parameter search:

$M_{\mathrm{ZAMS}} = 18,20,24,28 M_{\odot}$

$Z = 10^{-4} Z_{\odot}$

All models have transition regions!

Result: Explosion energy and the remnant mass



Parameter search:

$M_{\rm ZAMS} = 18,20,24,28 M_\odot$

$Z = 10^{-4} Z_\odot$

All models have transition regions!

Transition region:
Factor 2-3 of $E_{\rm grav,Hyd}$

Summary

Simulation

Calculation of spherically symmetric 1D fluid in progenitors with **"only"** different hydrogen envelope

Result

- Reverse shock makes Transition region
- High-power region mass range is $2.5M_{\odot}$ to $6M_{\odot}$ at $M_{ZAMS} = 18M_{\odot}, Z = 10^{-4}Z_{\odot}$
- High-power region : $2-3\times E_{\rm grav,Hyd}$

Future Task

- What is the factor of 2-3?
- The effect of changing $M_{\rm ZAMS}$ and Z ?
- Multi-dimensional effect?