The Correlation Between Supernova Fallback and Progenitor's Hydrogen Envelope

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Co-researcher :

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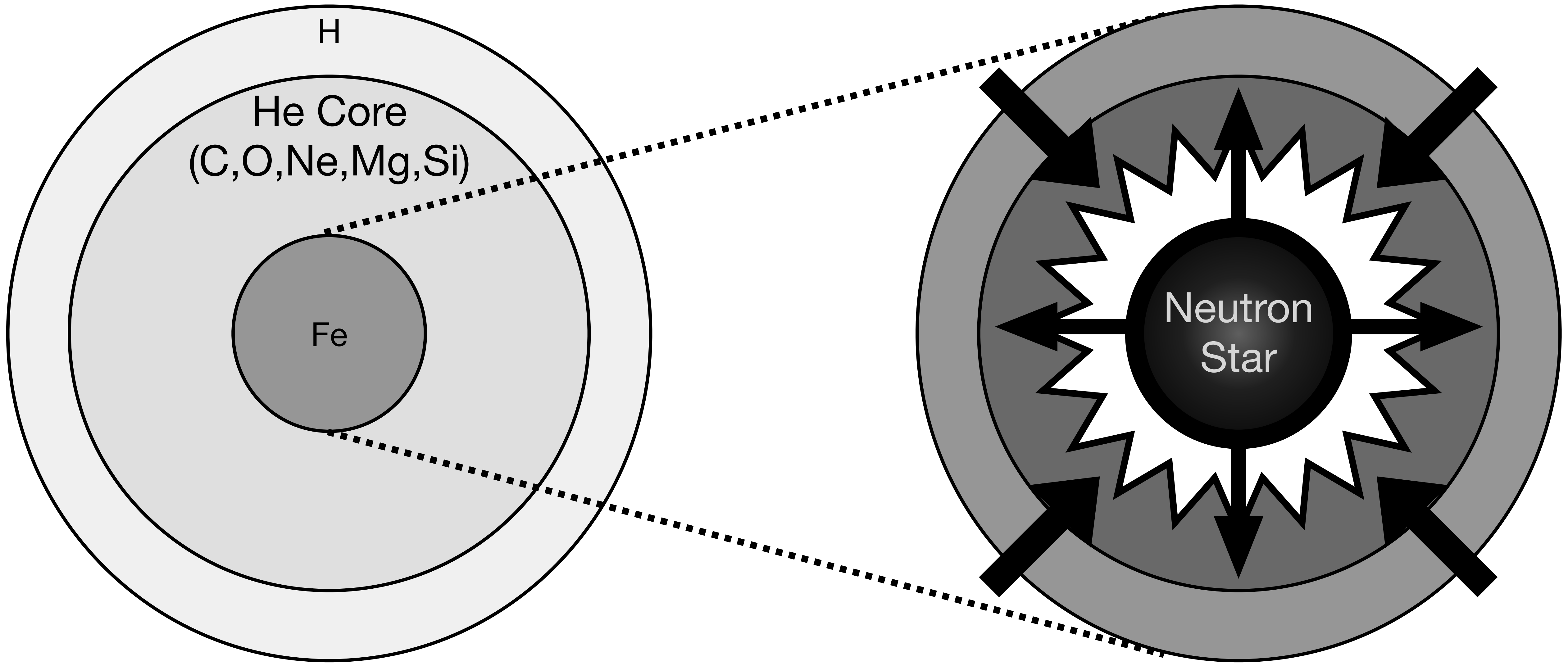
14:20/24/07/2025 SN2025GW in University of Warsaw

Core Collapse Supernova (CCSN) Mechanism



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

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

Gravitational collapse
&
Neutron star formation

time

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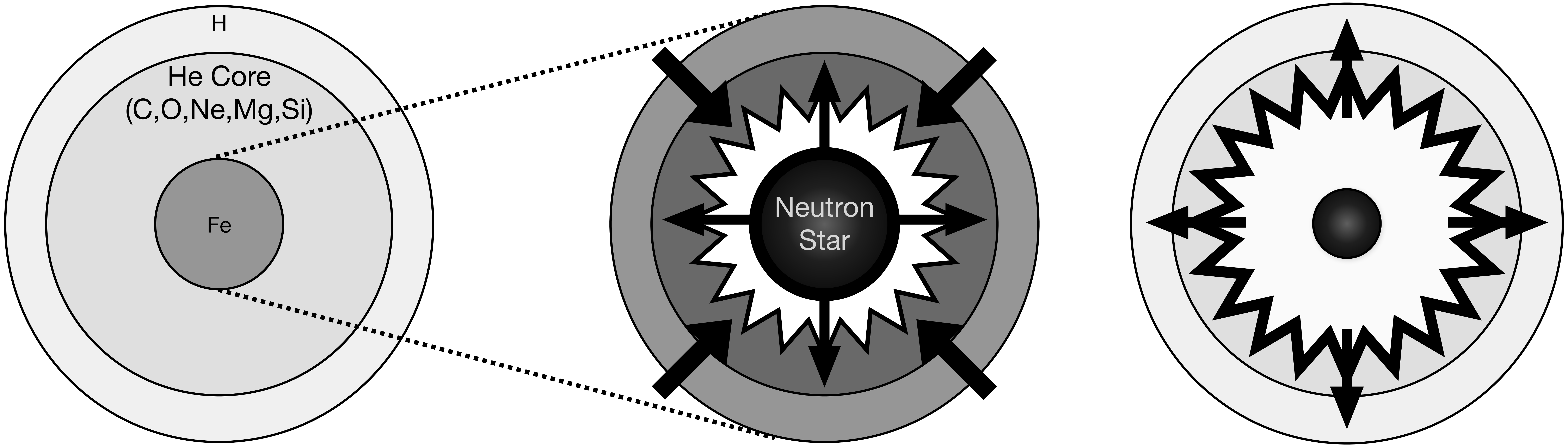

$t = 0\,\mathrm{s}$ (core bounce)

$1\,\mathrm{s} \lesssim t$

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

Gravitational collapse
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Shock propagation

time

Core Collapse Supernova (CCSN) Mechanism

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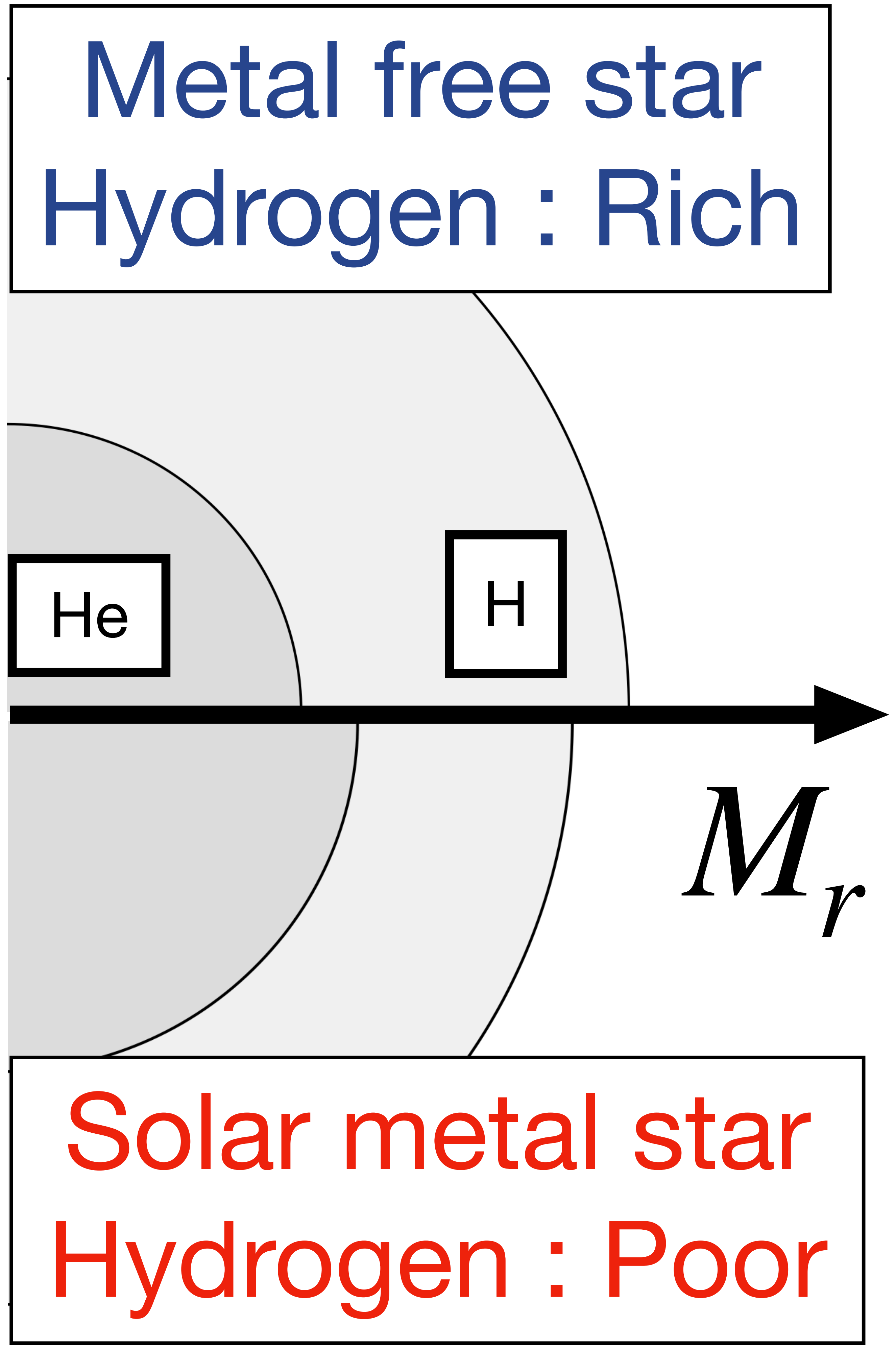
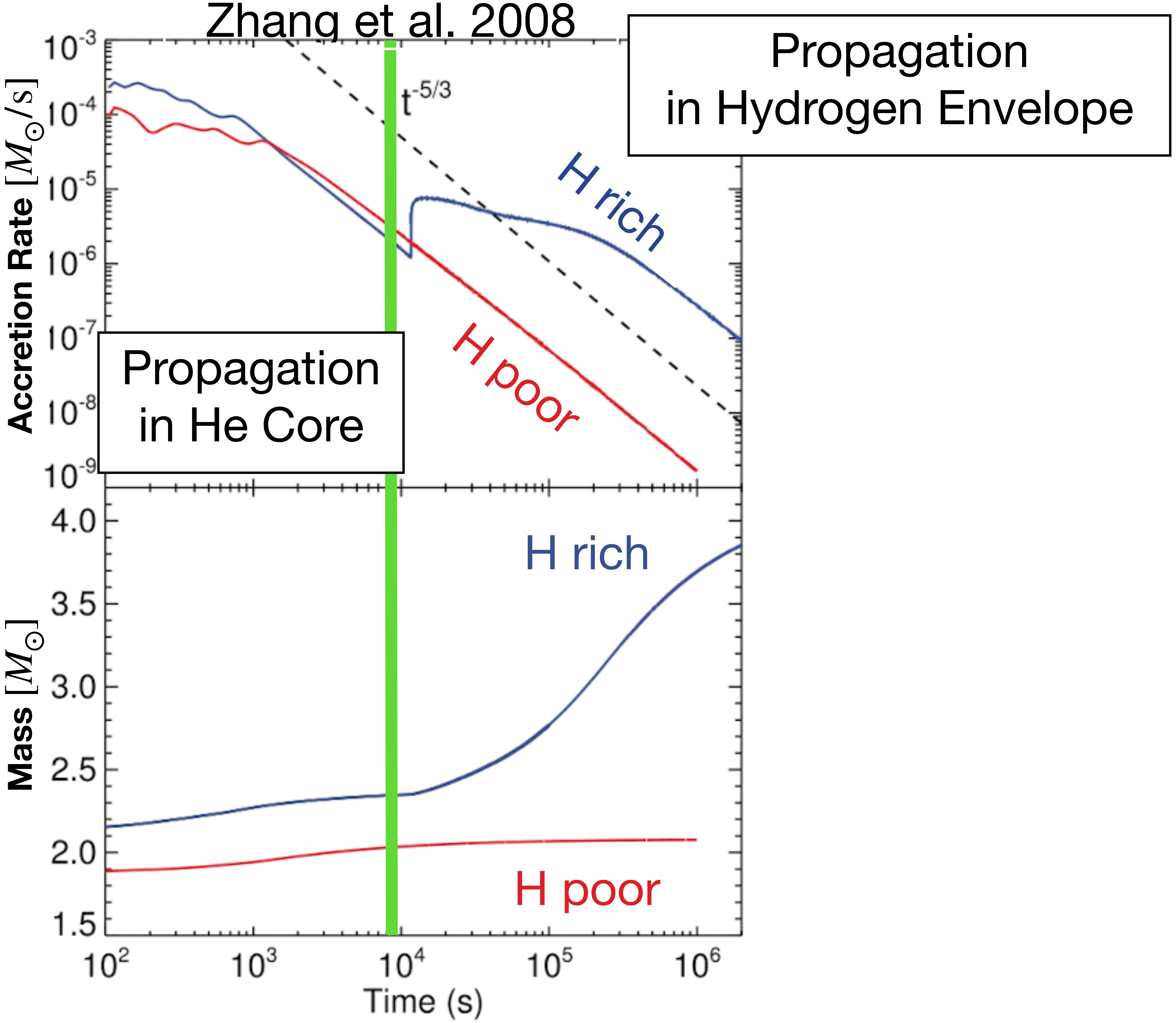
Effects of Fallback by Hydrogen Envelope?



Zhang et al. 2008



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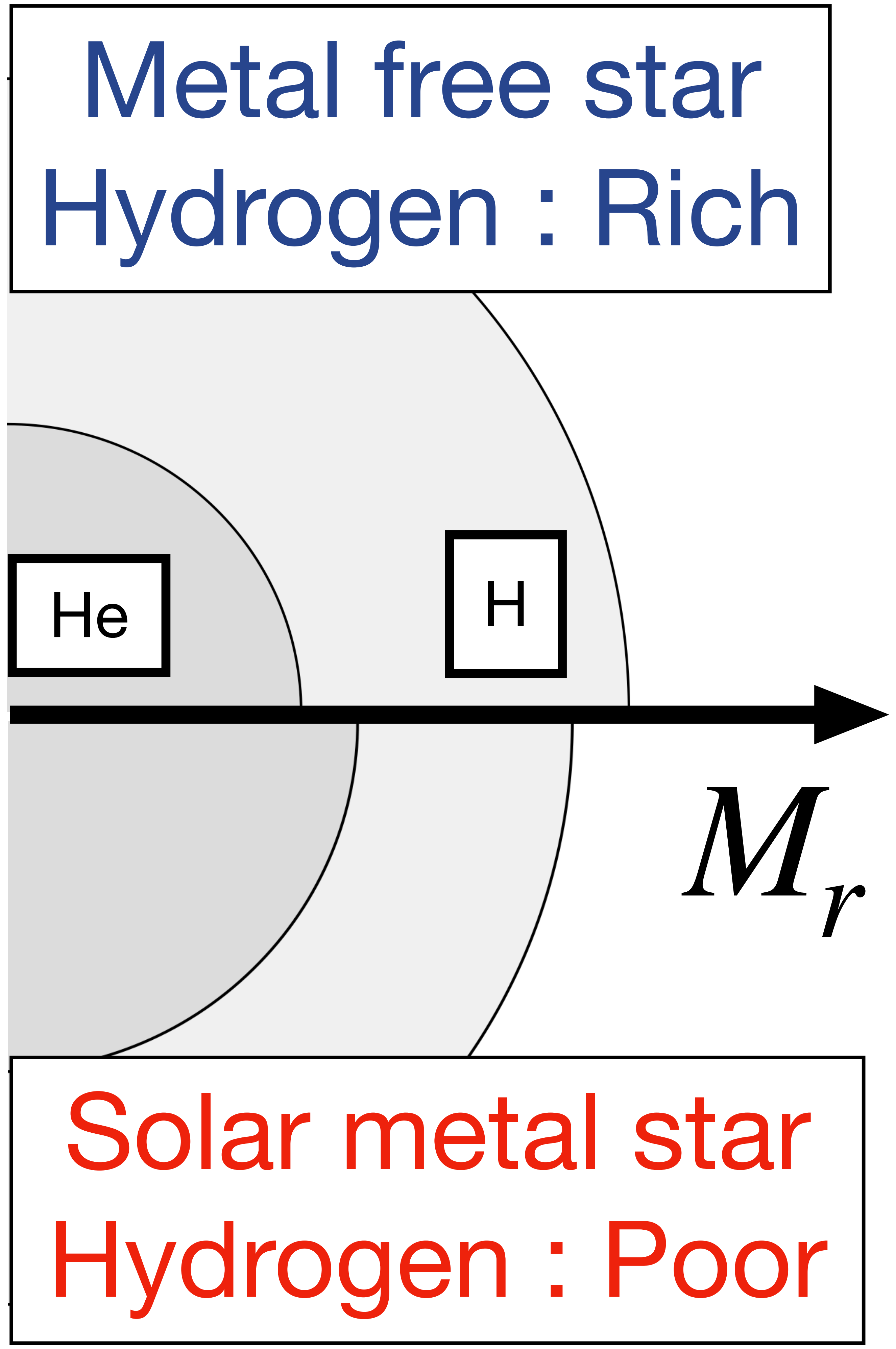
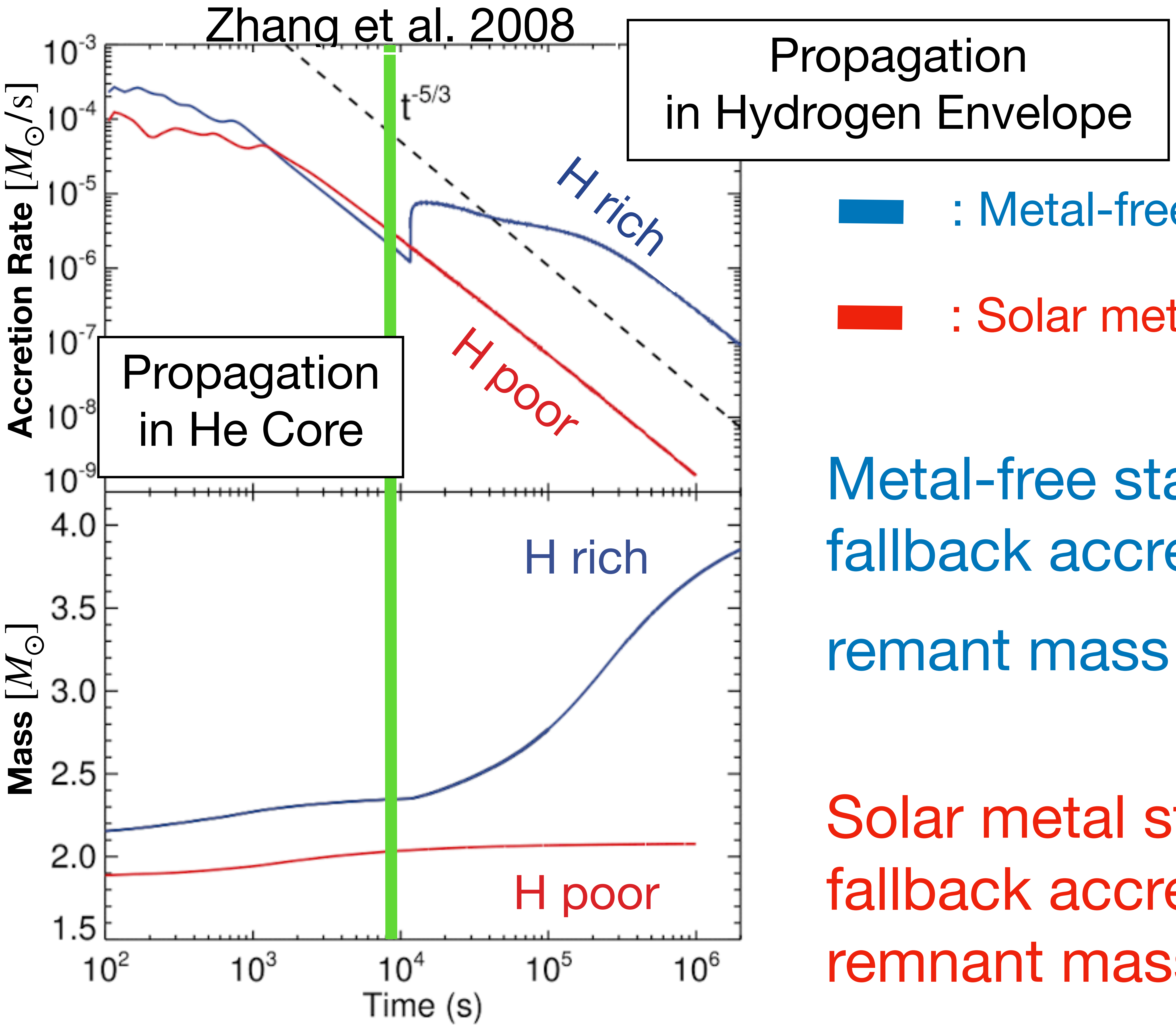




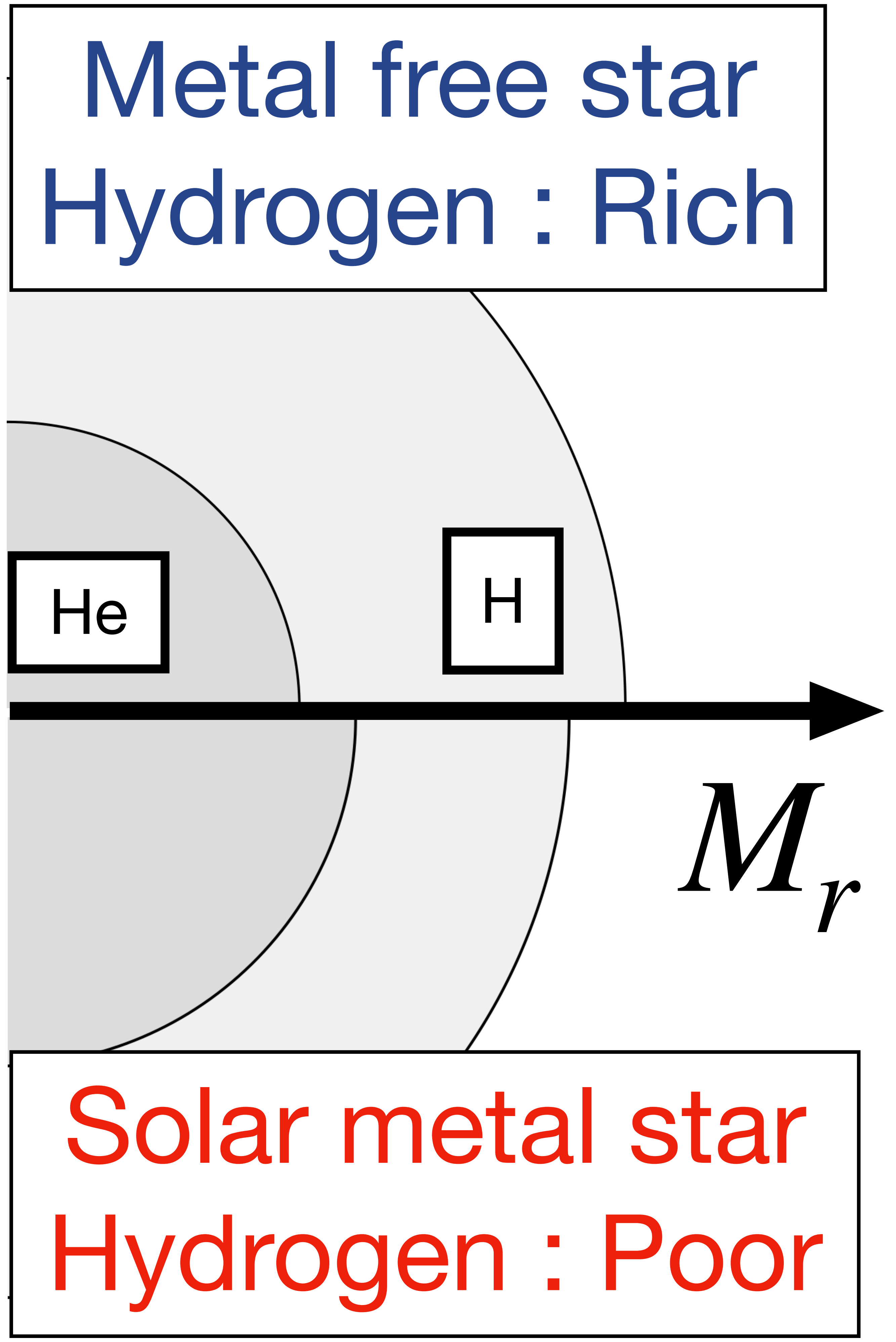
: Metal-free star

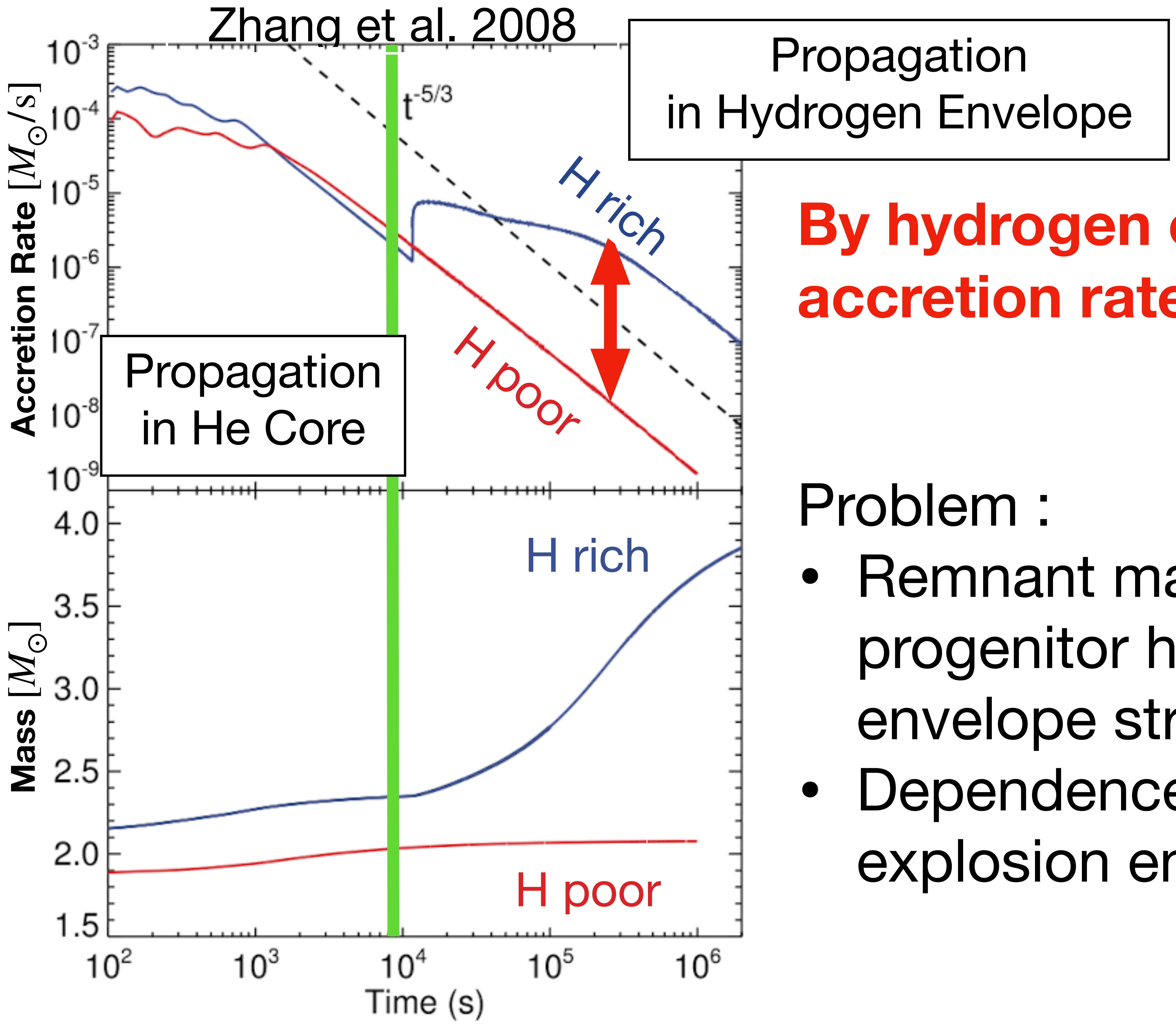
: Solar metal star

Metal-free star :
fallback accretion rate ↗
remant mass ↗

Solar metal star :
fallback accretion ↘
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**

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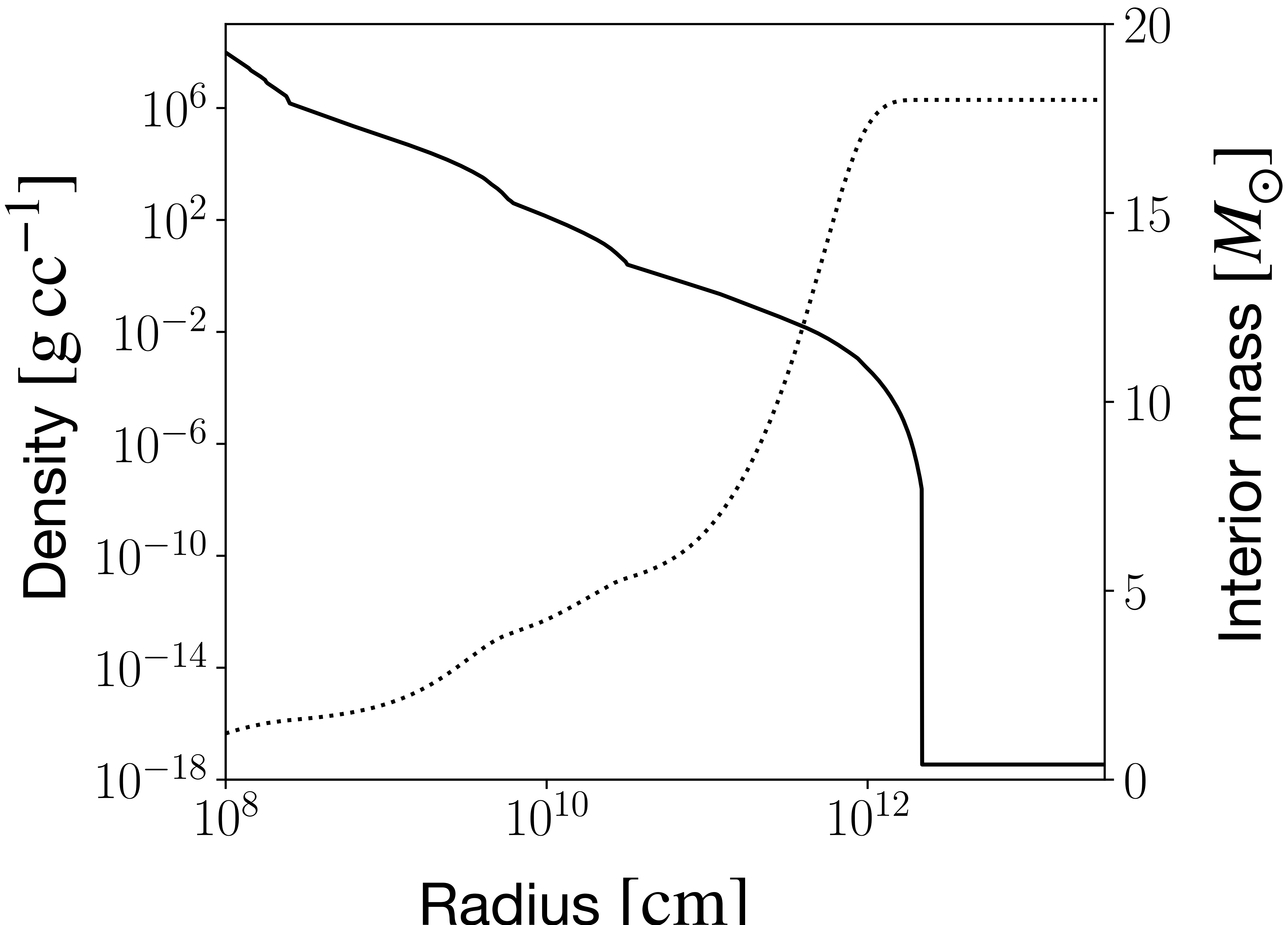

Initial Condition

Black: type II (Hydrogen: Rich)

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

Woosley+02

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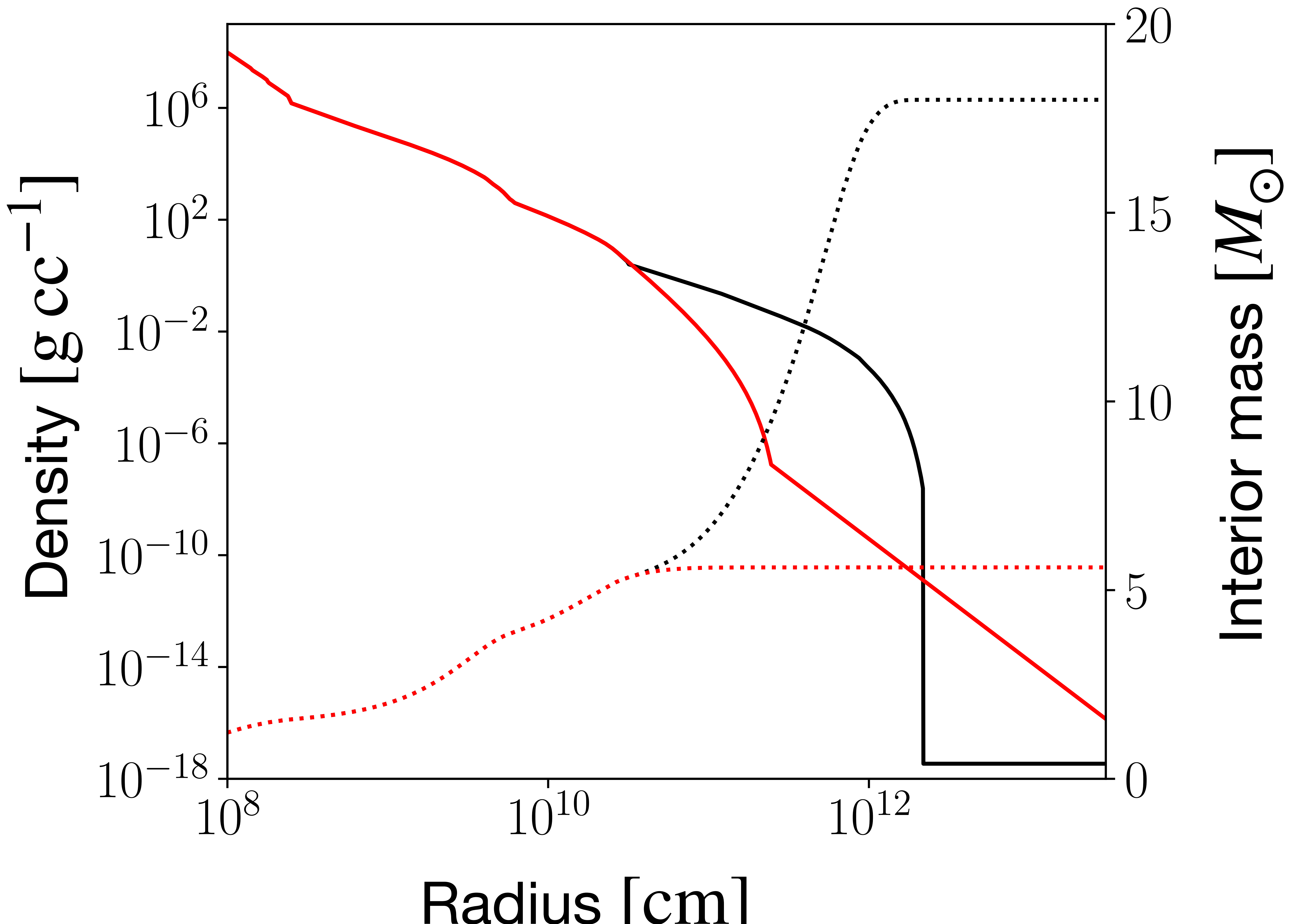

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Red: type IIb (Hydrogen: Poor)

Remove hydrogen envelope from type II progenitor

(Method: Matzner+99)

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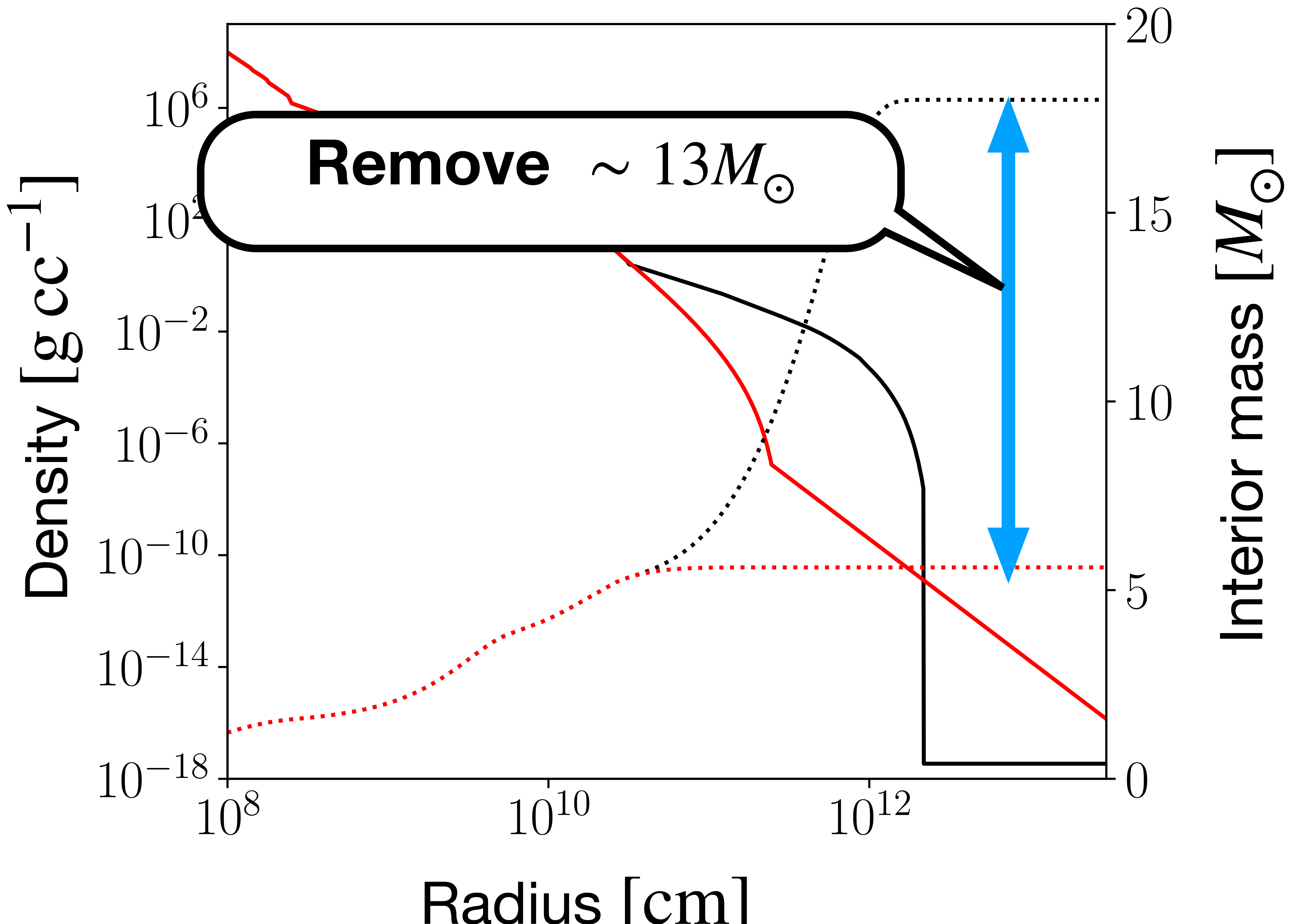

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Code: Athena++ (Stone+20)

Equations: pure hydro + self-gravity

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

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

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

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

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Explosions: Thermal bomb

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

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

Put $E_{\rm inj}$ to reproduce $E_{\rm exp} \simeq 10^{48-52} {\rm erg}$

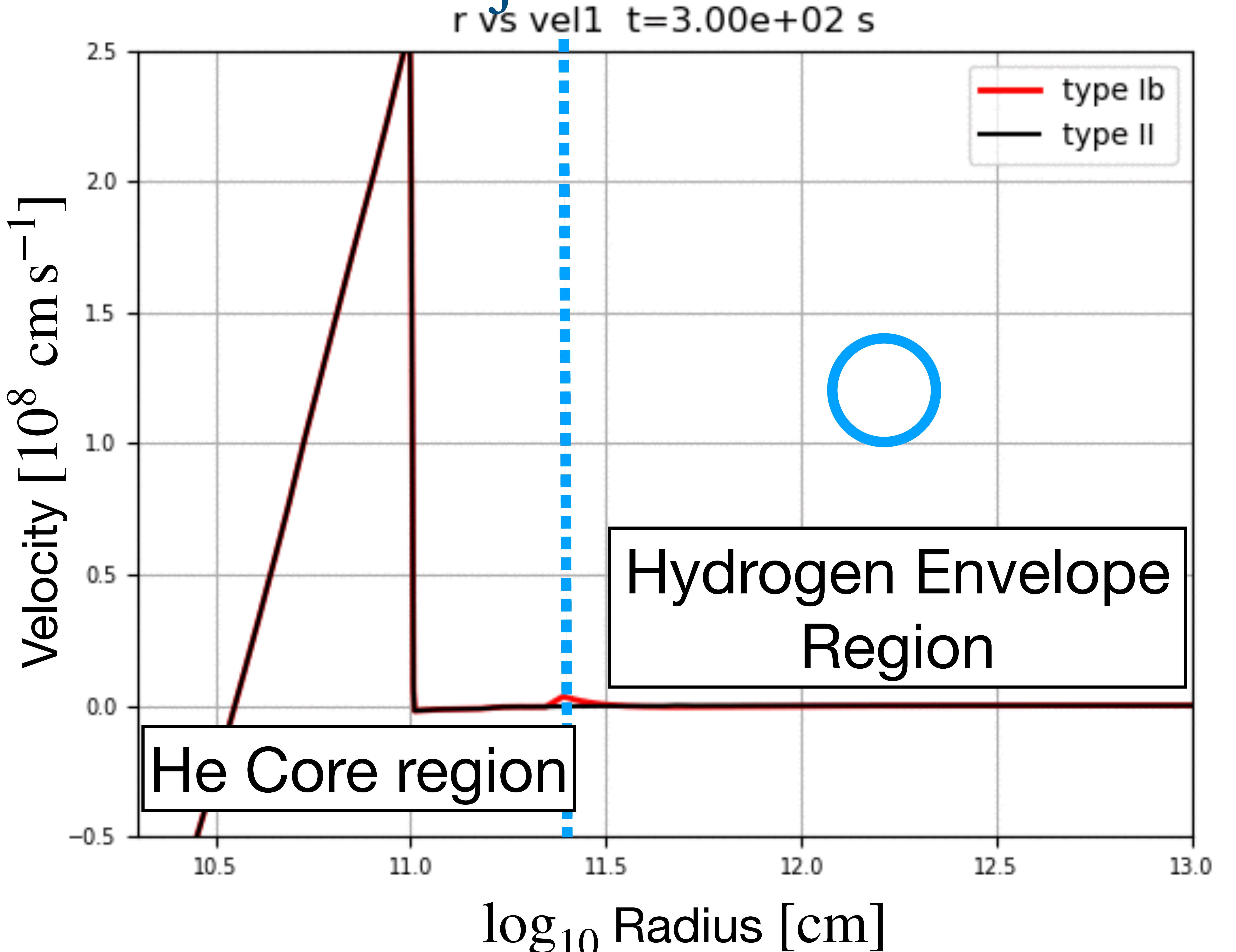
Results : Shock evolution $(E_{\rm inj} = 8 \times 10^{50} {\rm erg})$

: Hydrogen **Rich**
type II

: Hydrogen **Poor**
type IIb

Before run in Envelope
⇒**Same**

After run in Envelope
⇒**Change**



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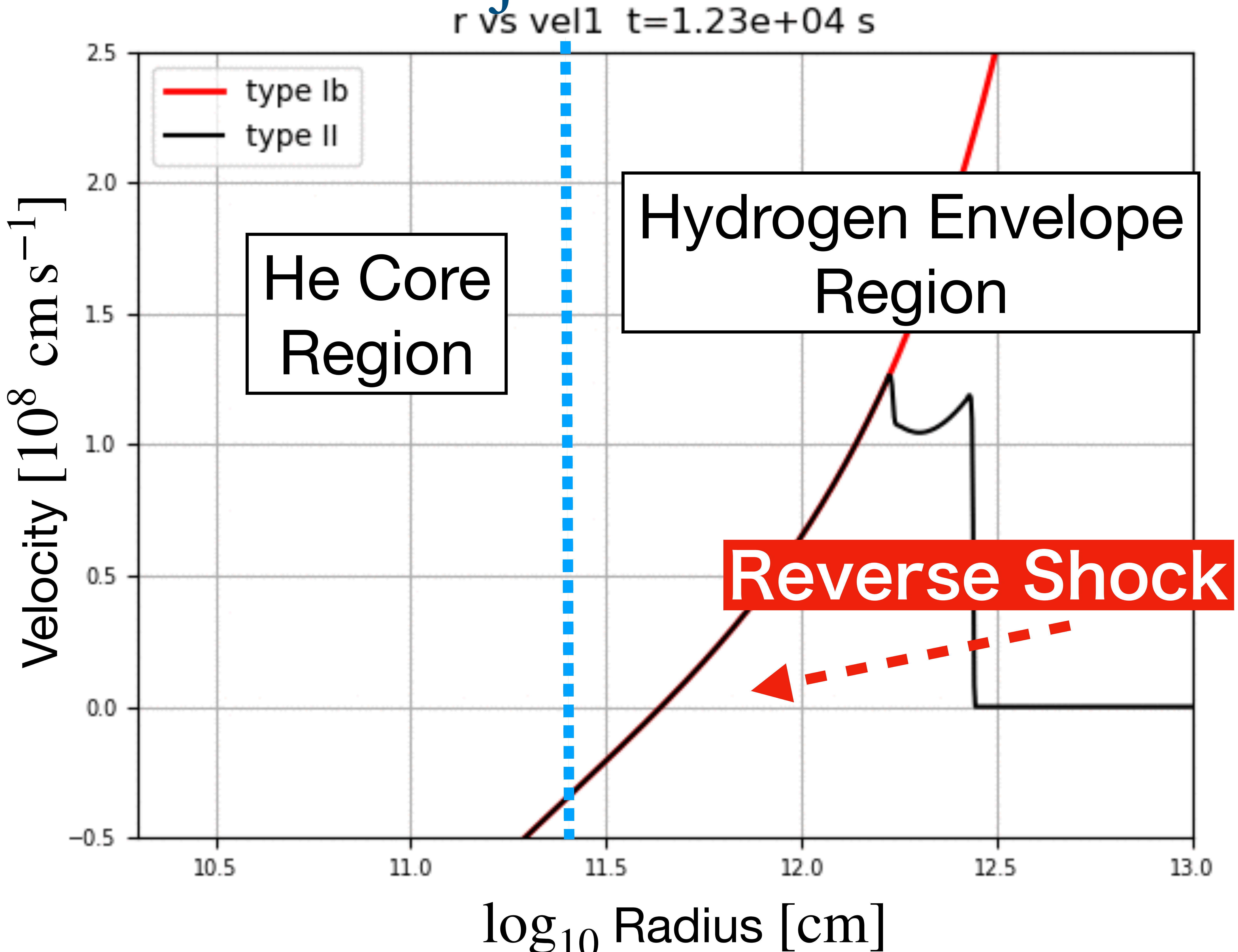
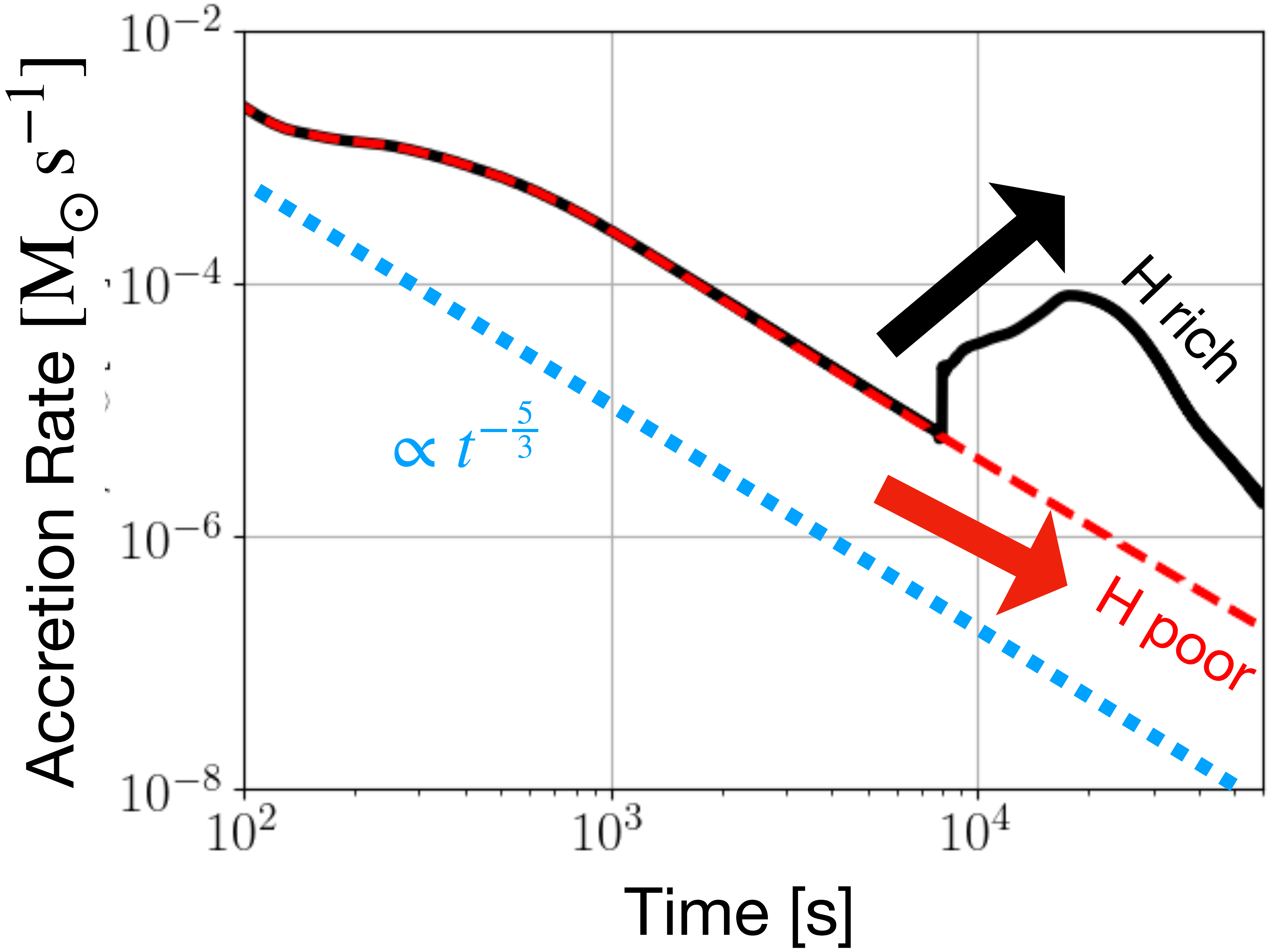
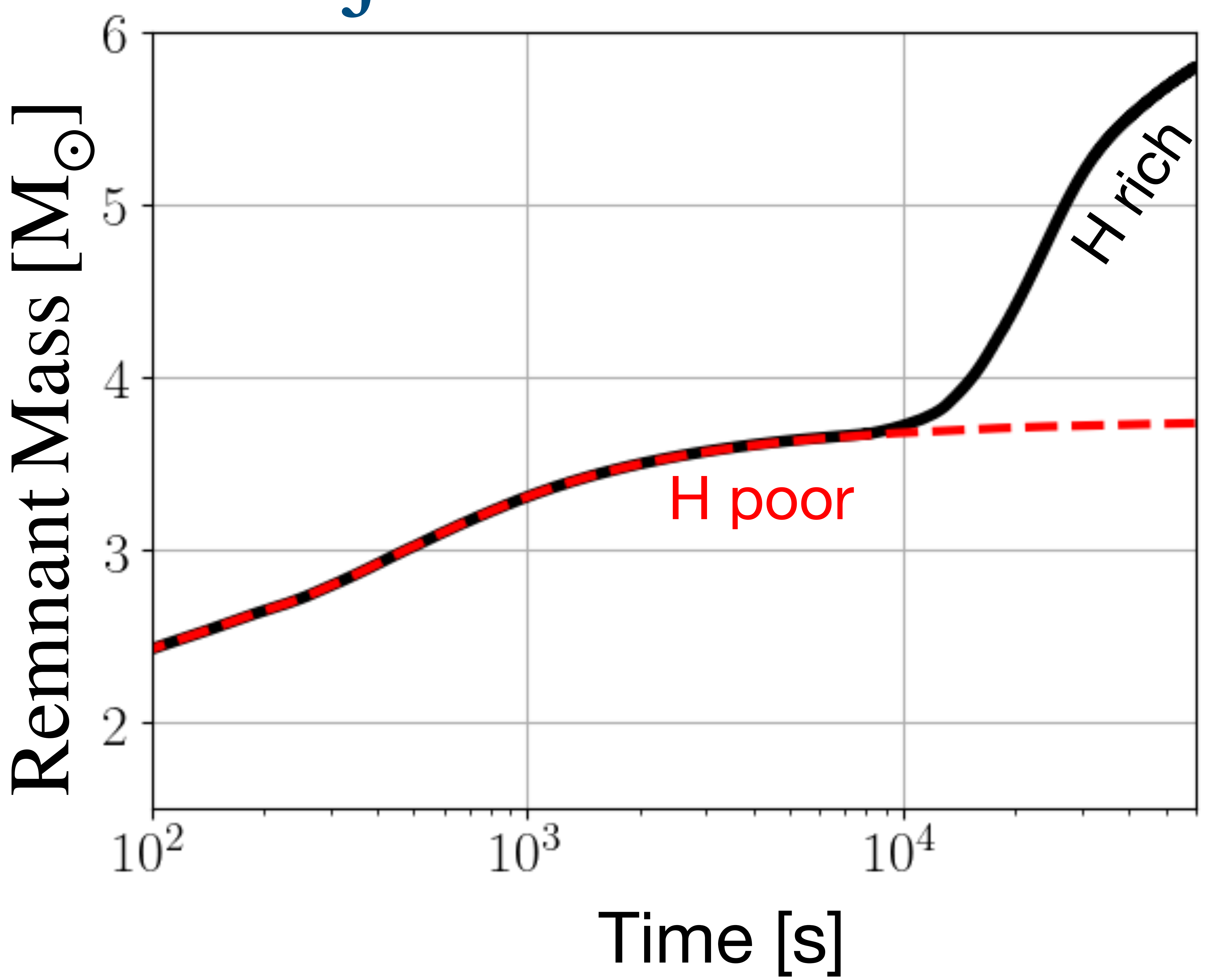


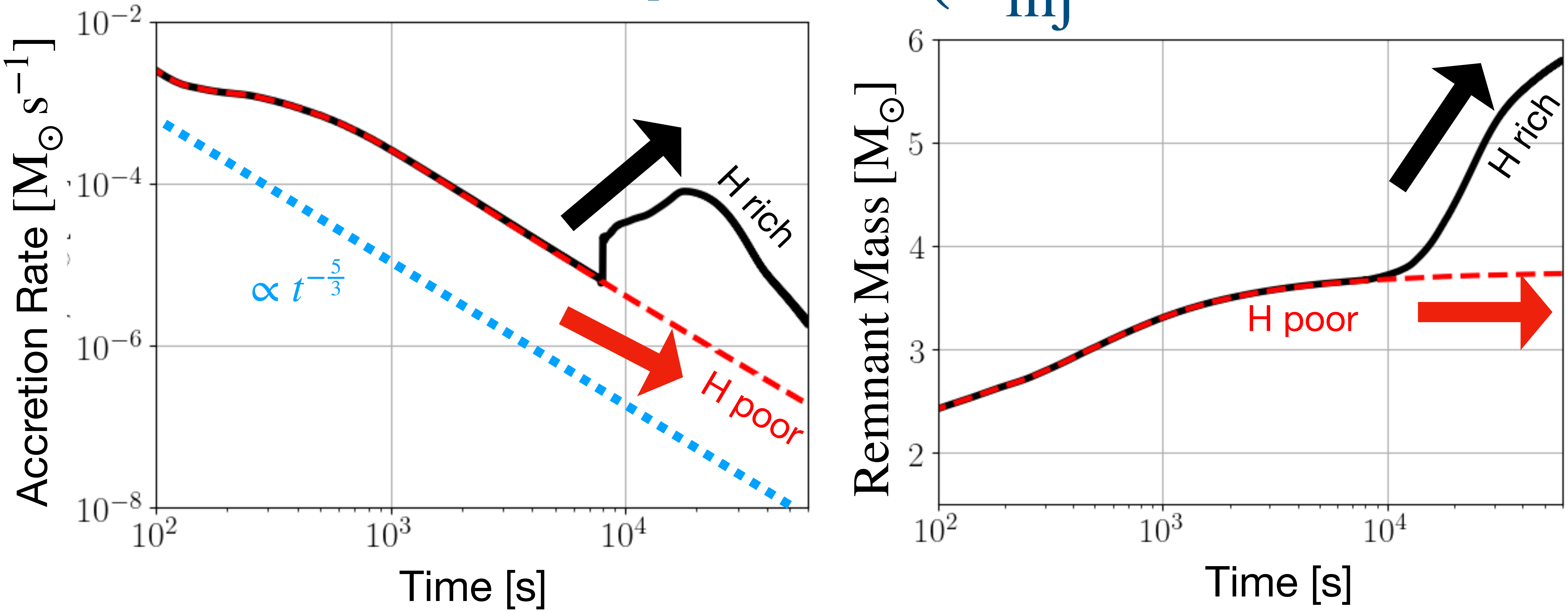
Results : Weak Explosion $(E_{\rm inj} = 7 \times 10^{50} {\rm erg})$





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

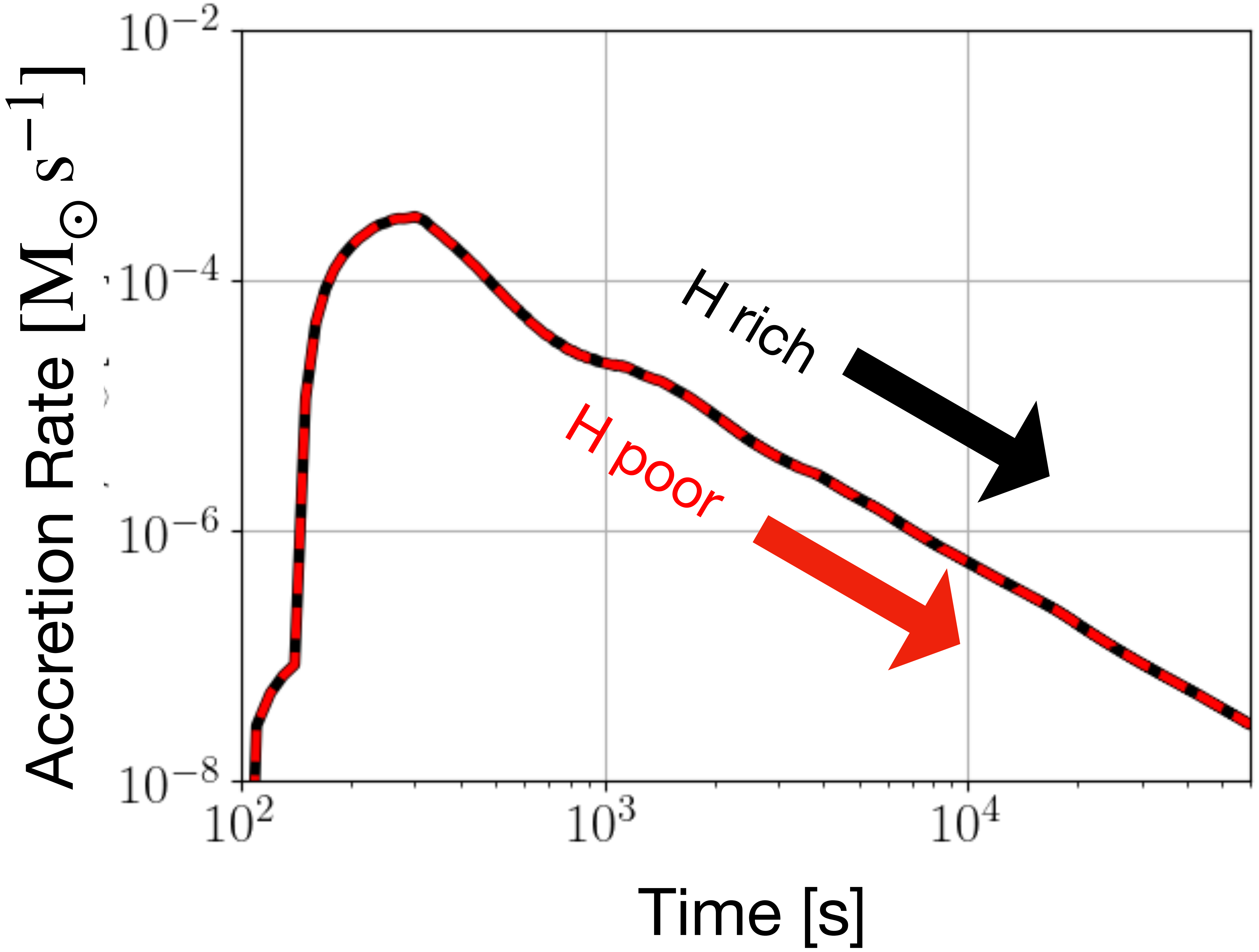
Results : Weak Explosion $(E_{\rm inj} = 7 \times 10^{50}{\rm erg})$

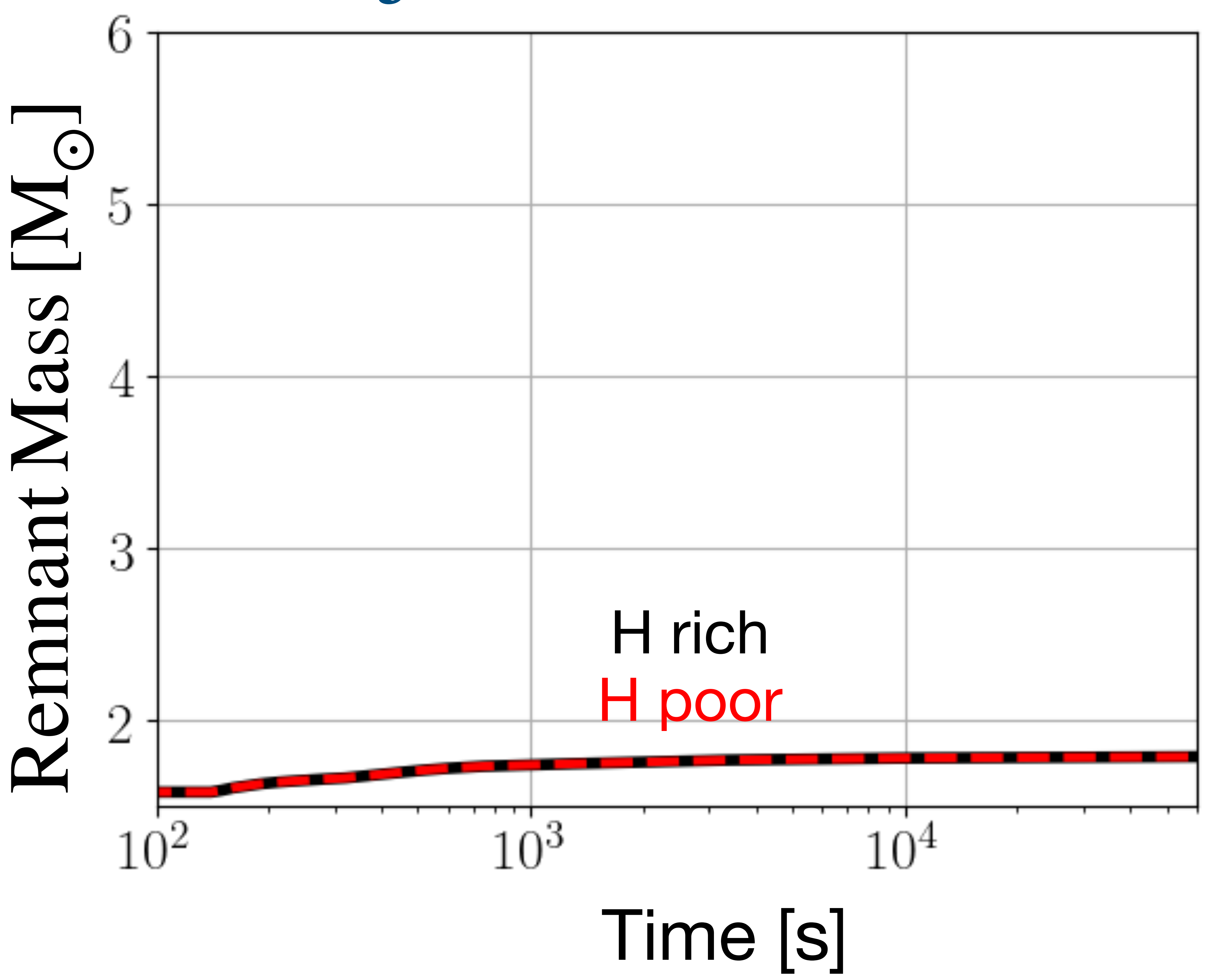


Left panel: **Strong** fallback due to the reverse shock!

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

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





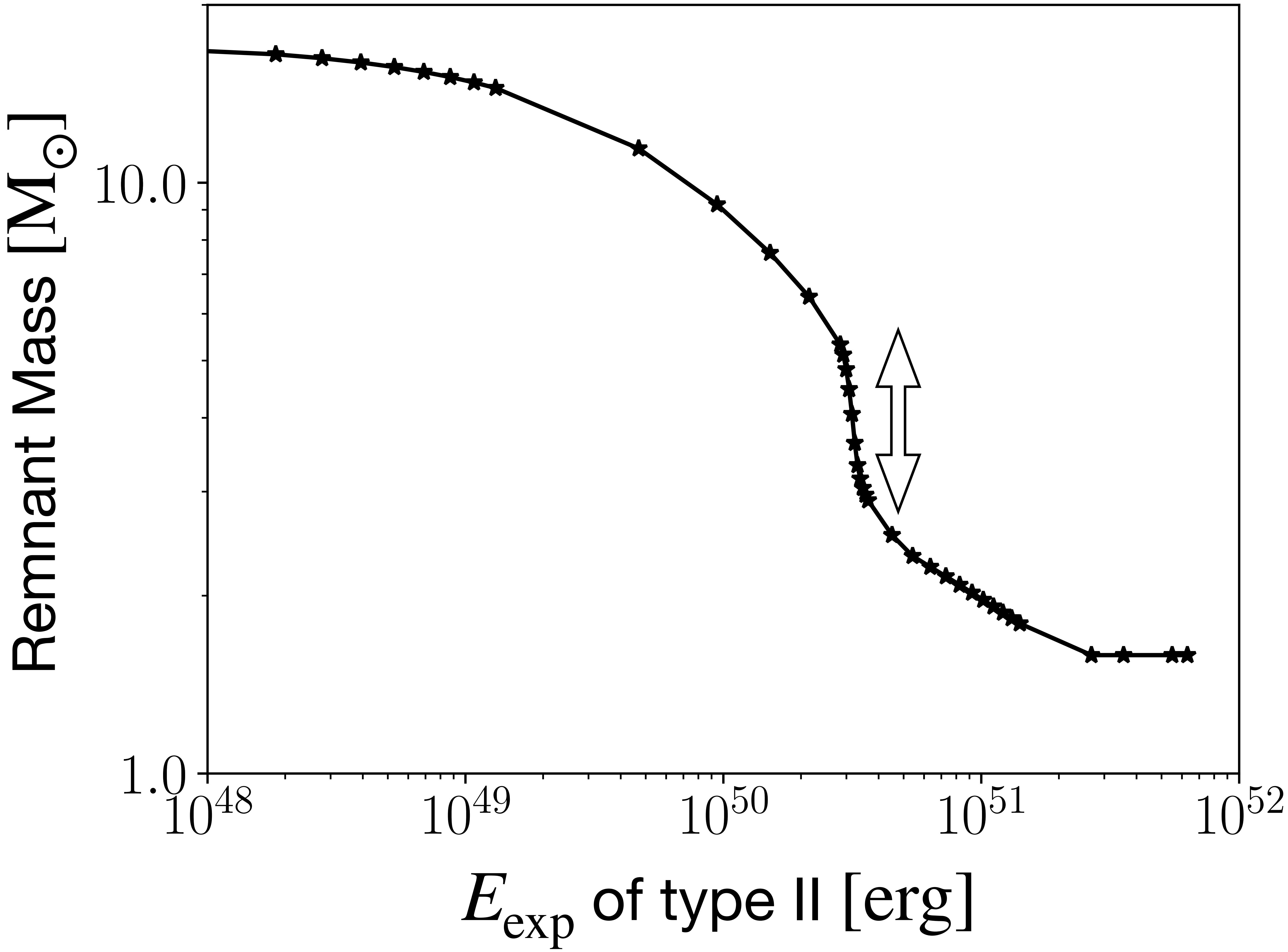
Left panel: **Weak** fallback!

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

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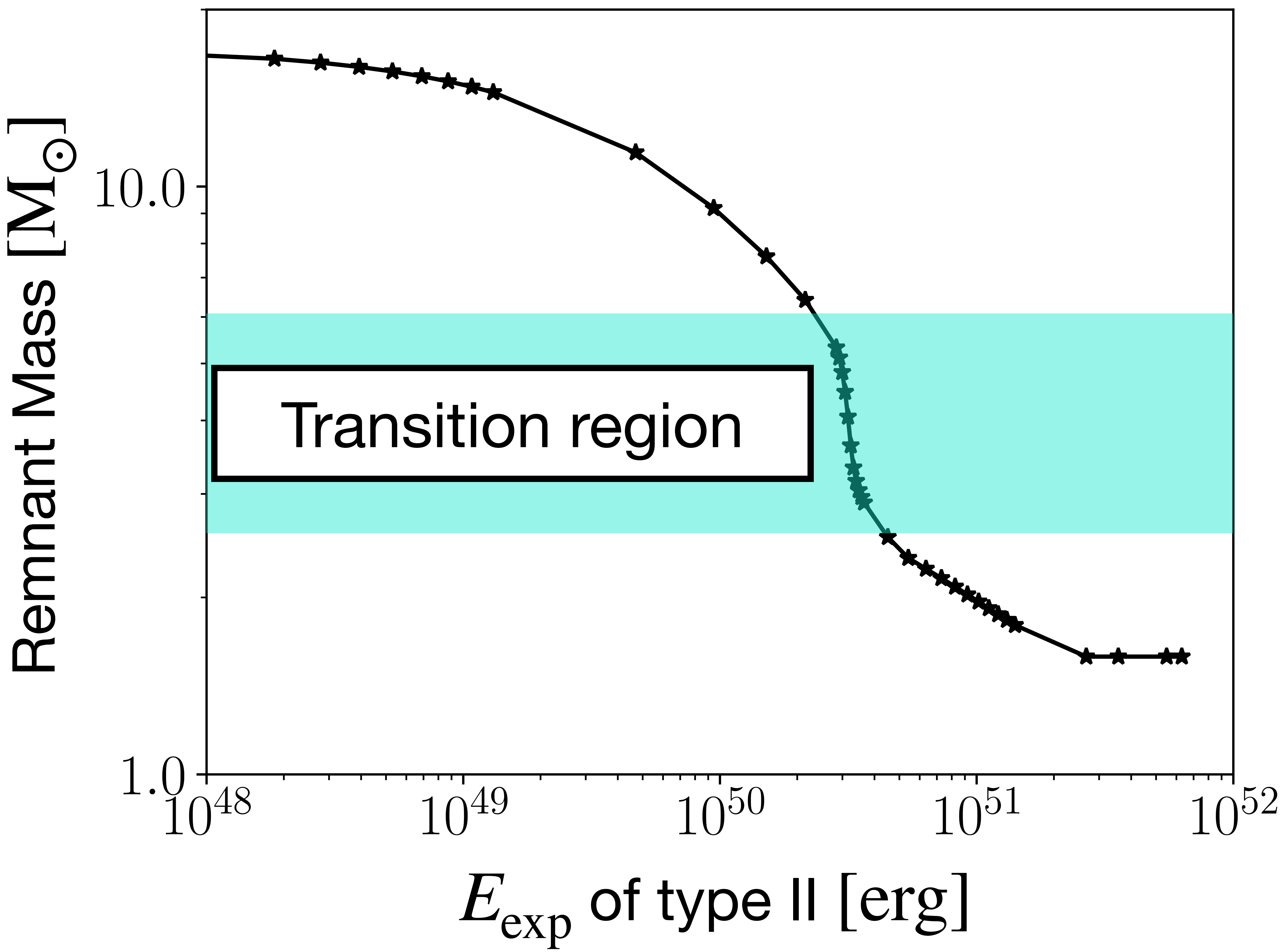

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Increases $\sim 3M_\odot$ by the reverse shock immediately

Transition region: ~2.5 - ~6$M_\odot$

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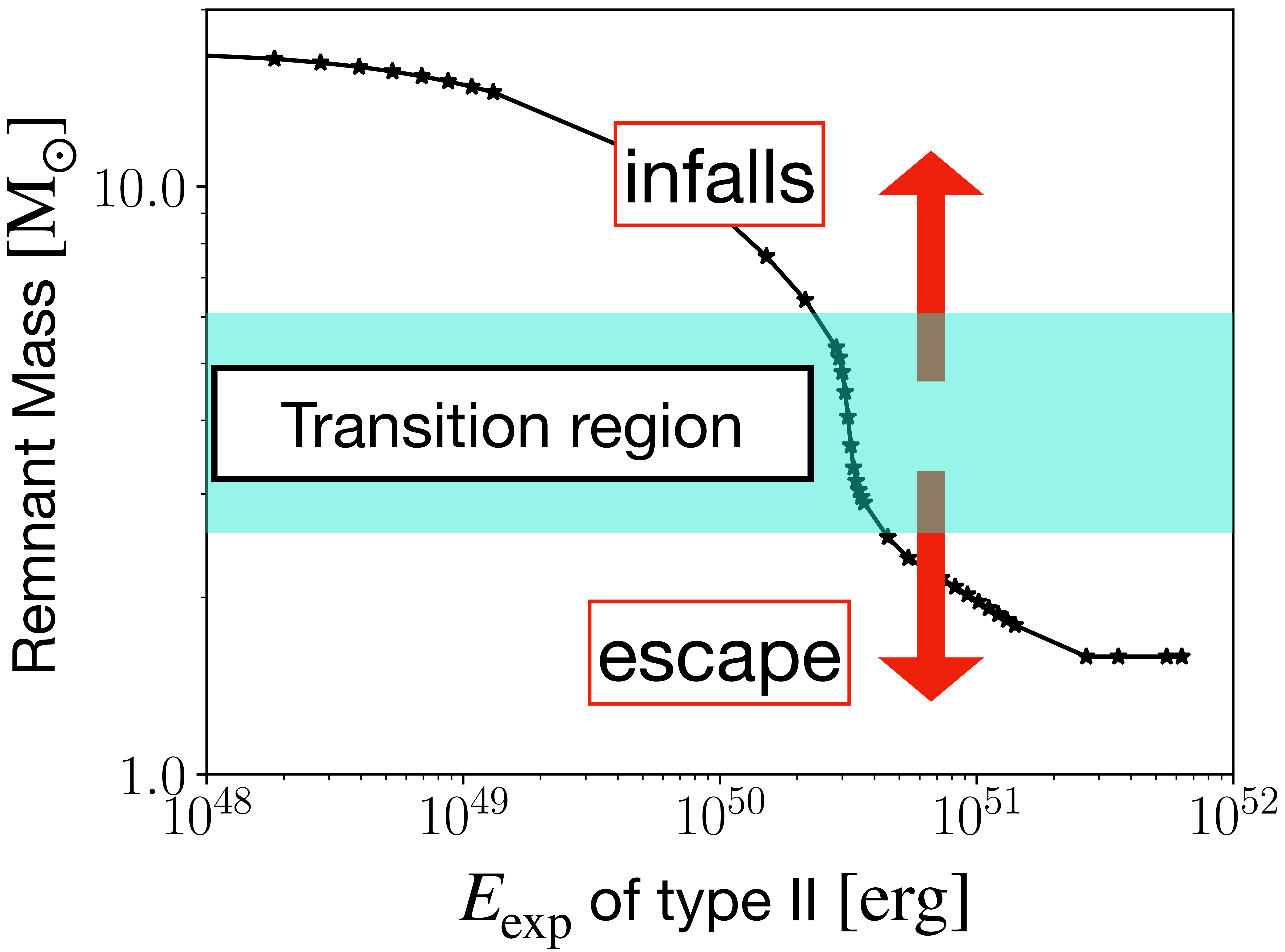

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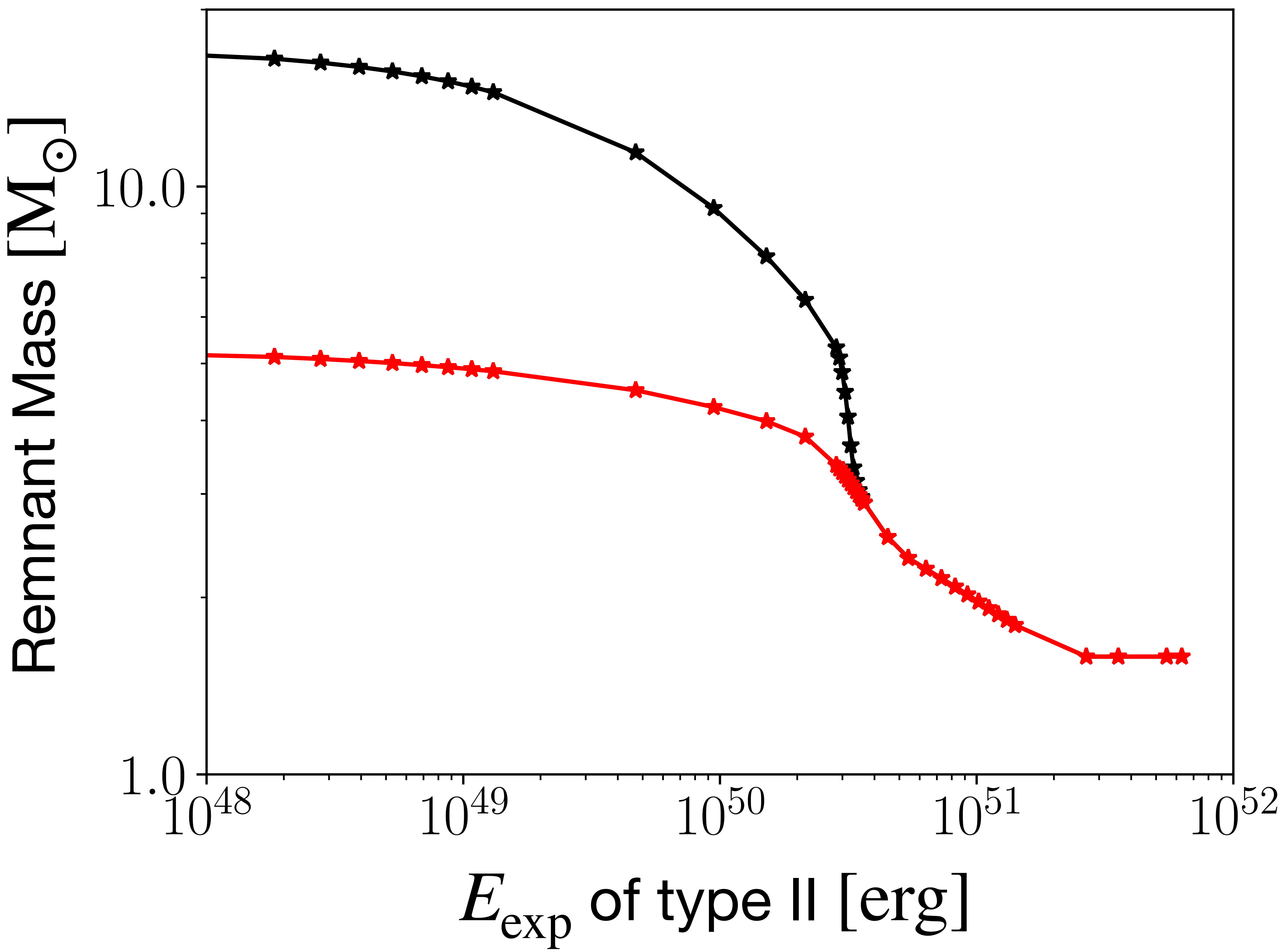

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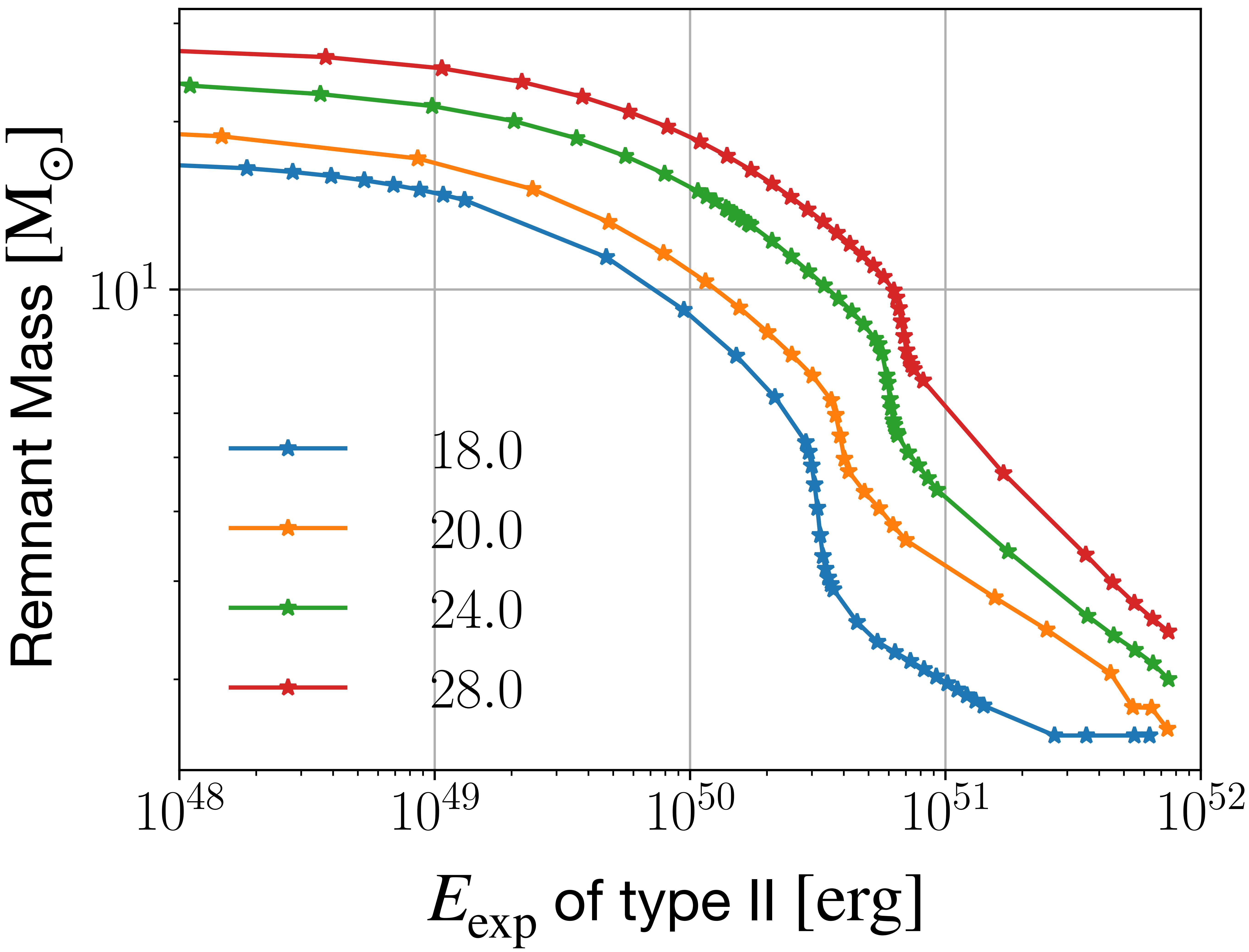
<u>Red: type IIb (Hydrogen: Poor)</u>

Shallow than type II

The remnant mass is the same at $E_{\rm exp} \gtrsim 4\times10^{50}\,{\rm erg}$

Result: Explosion energy and the remnant mass

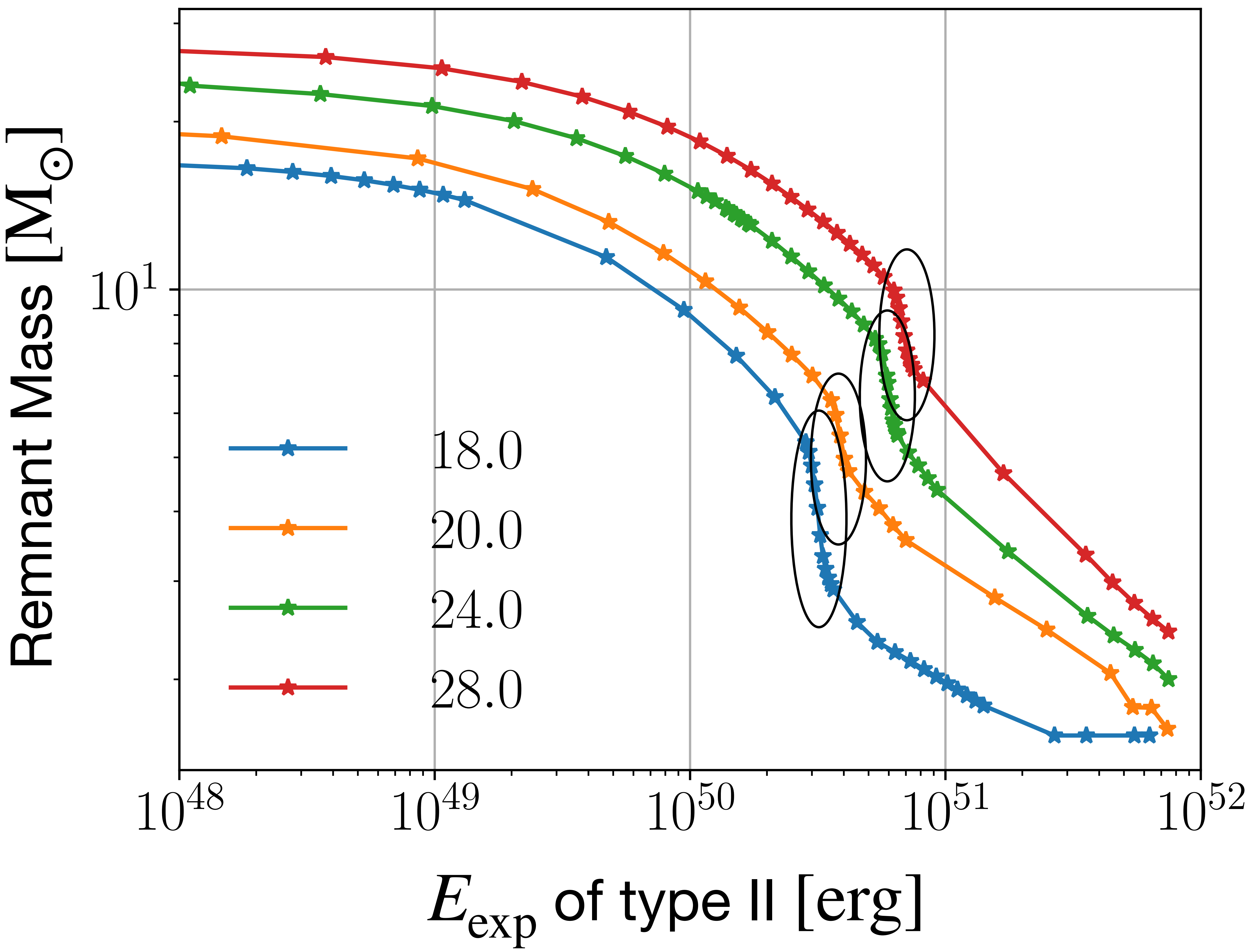


Parameter search:

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

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

Result: Explosion energy and the remnant mass



Parameter search:

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

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All models have Transition regions!

Transition region:

Factor 2-3 of heydrogen envelope's binding energy

Summary

Simulation

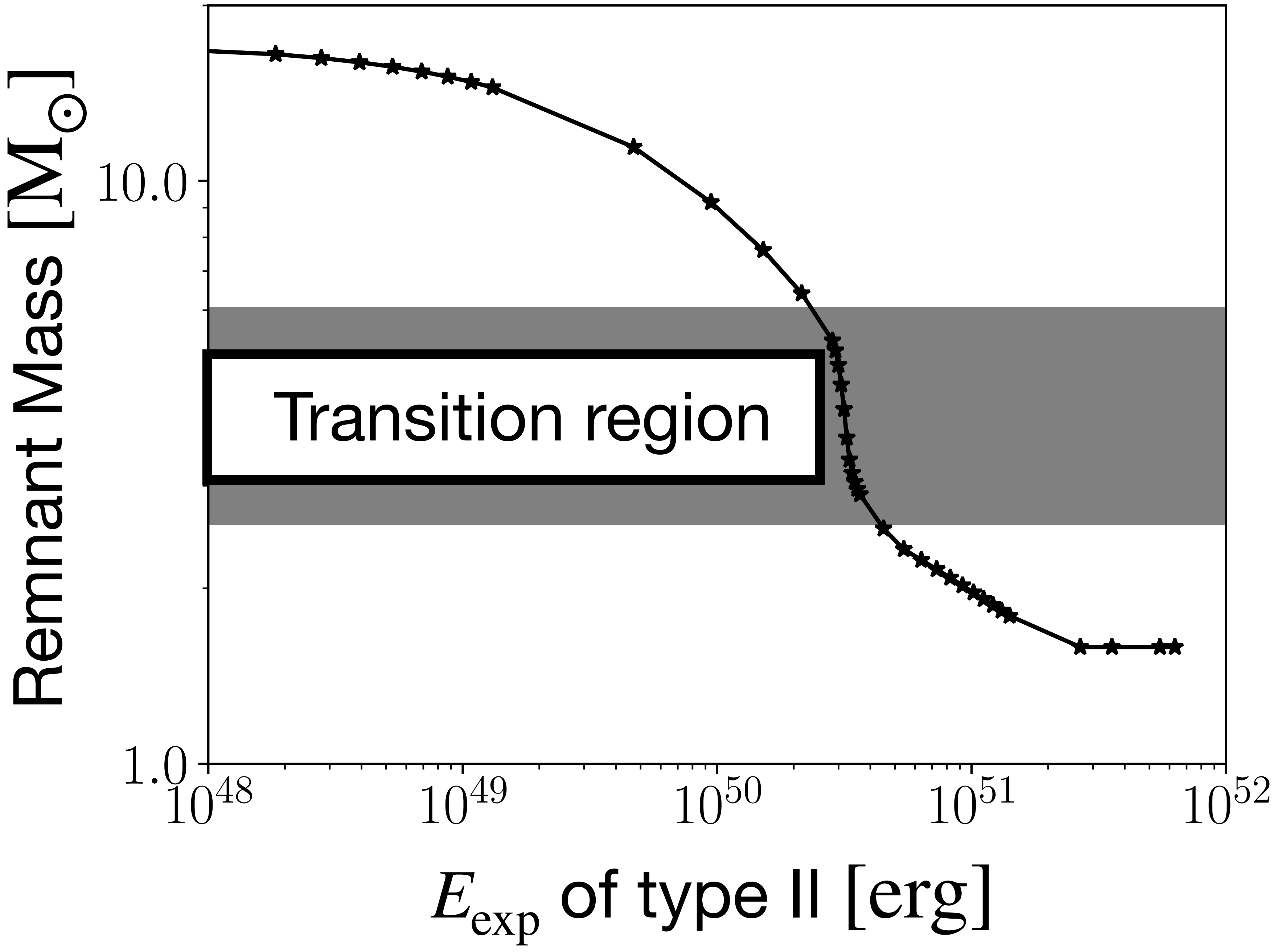
Calculation of spherically symmetric 1D fluid in progenitors with **"only"** different hydrogen envelope

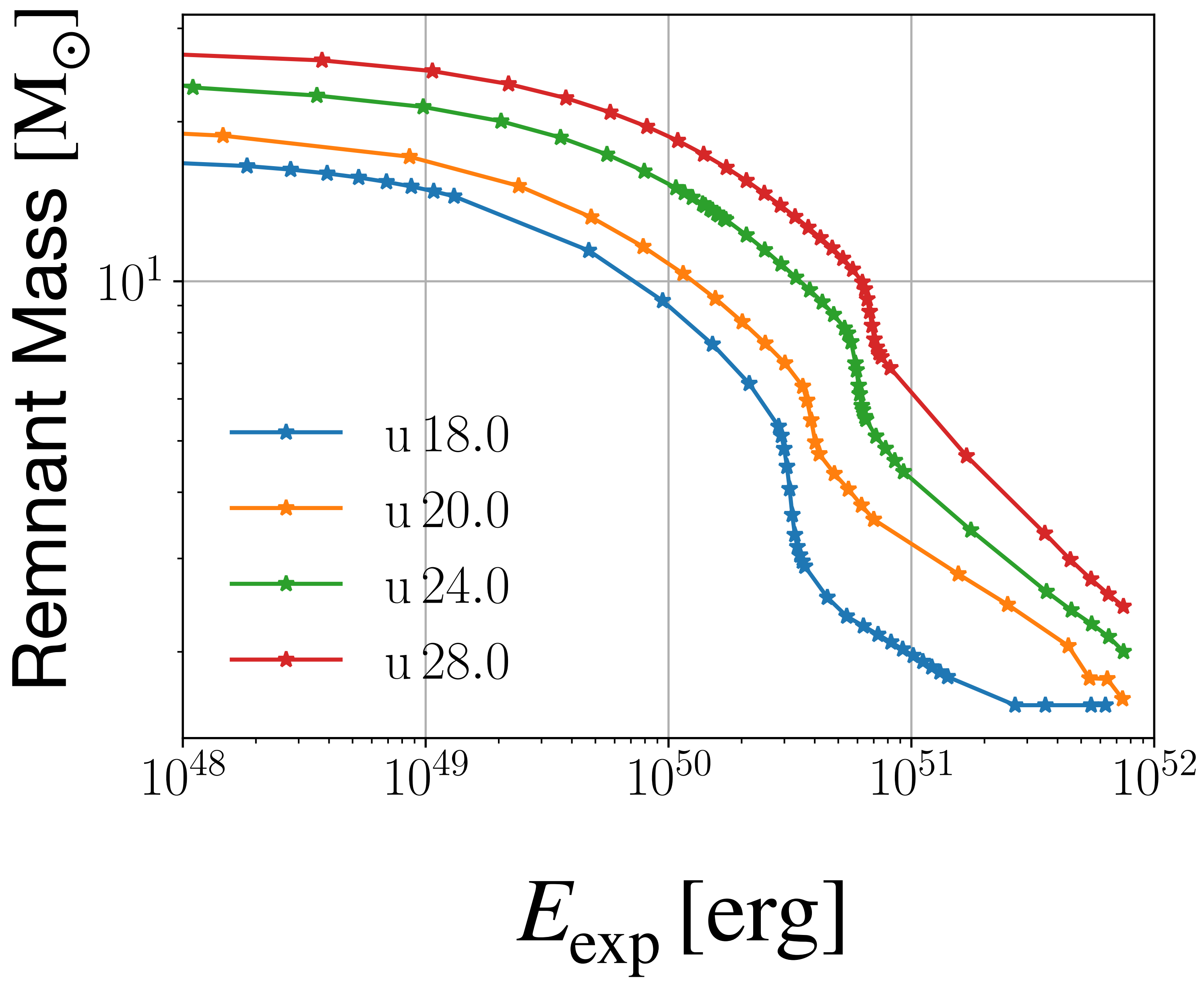
Result

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

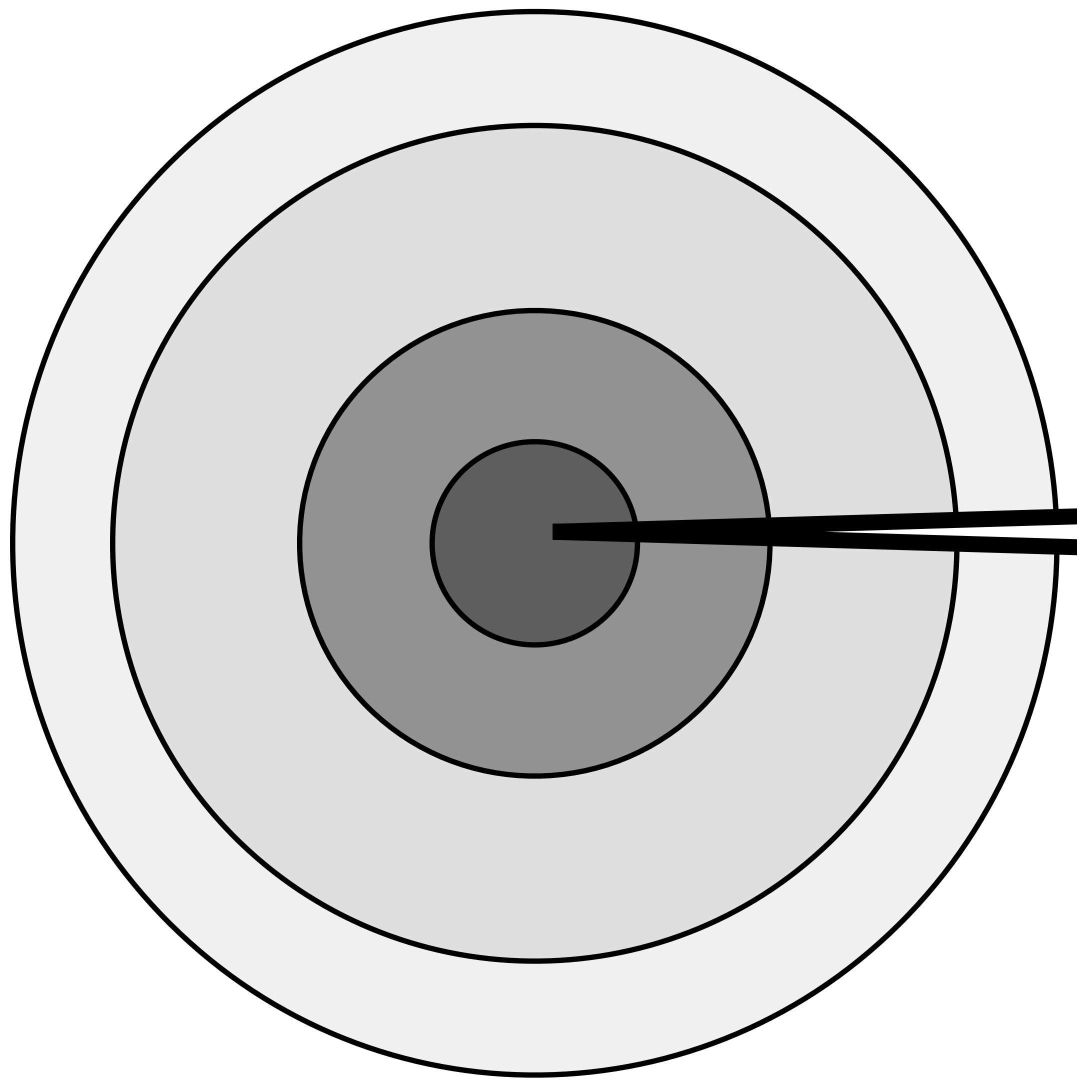
Future Task

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





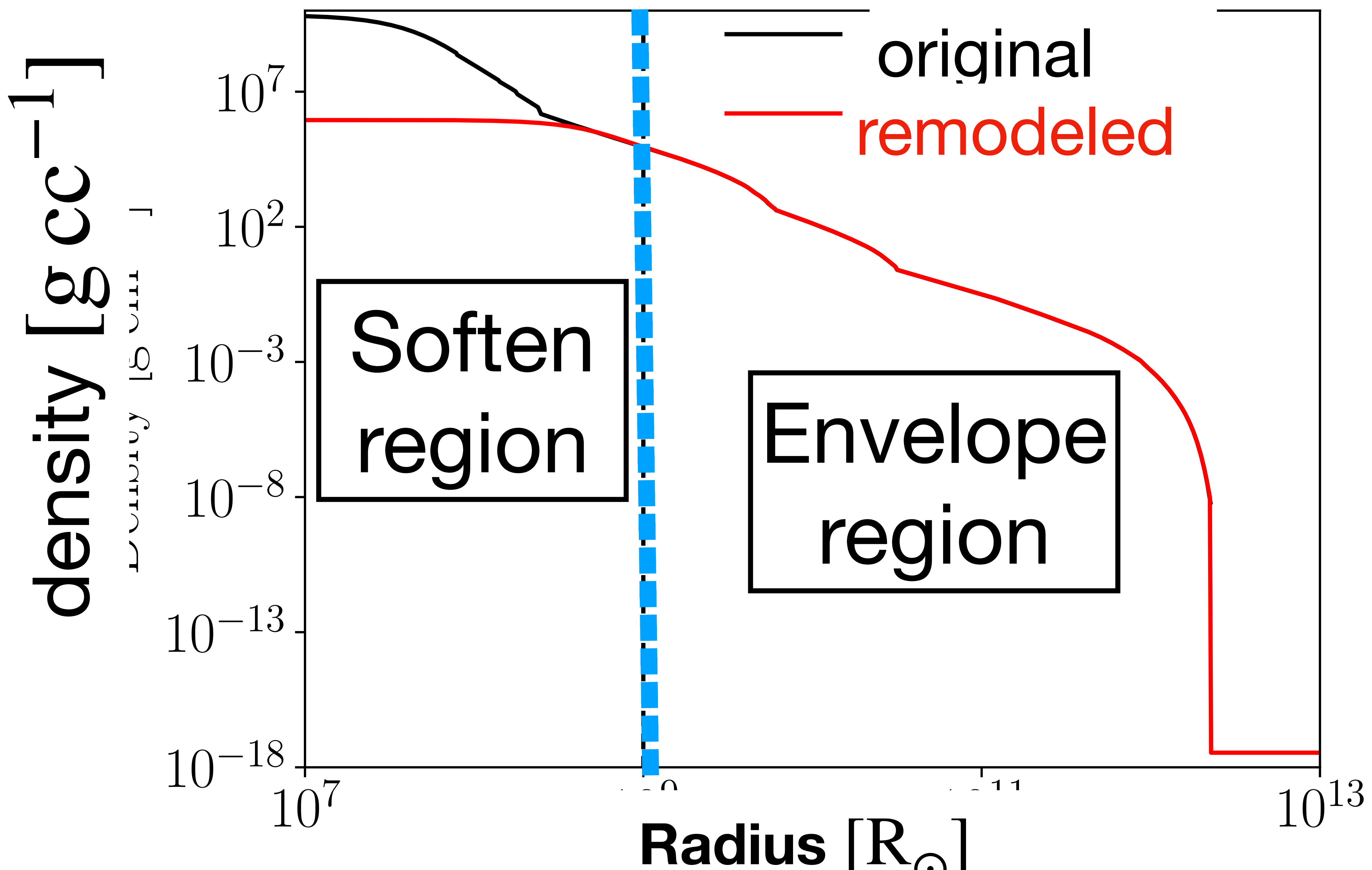
Approximation of Core region



Core center
NS

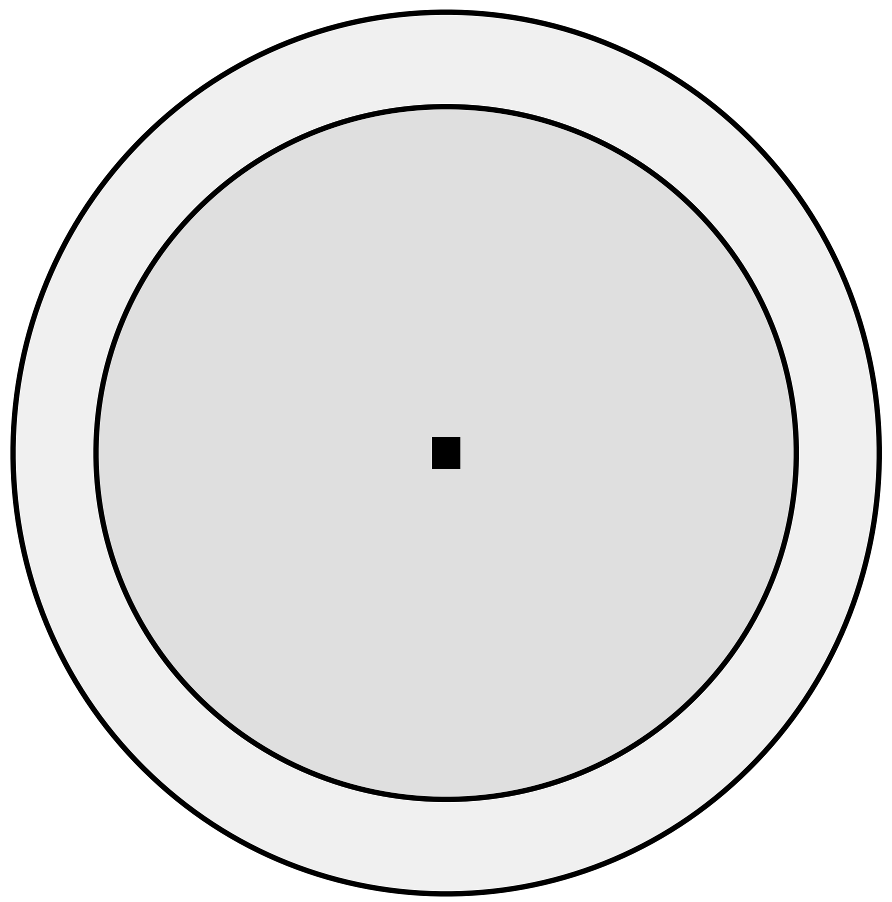
- density scale height $\Delta z \propto \dfrac{\rho}{\nabla \rho}$
- CFL condition $\Delta t \propto \dfrac{\Delta z}{c_s}$

➡ **High cost**



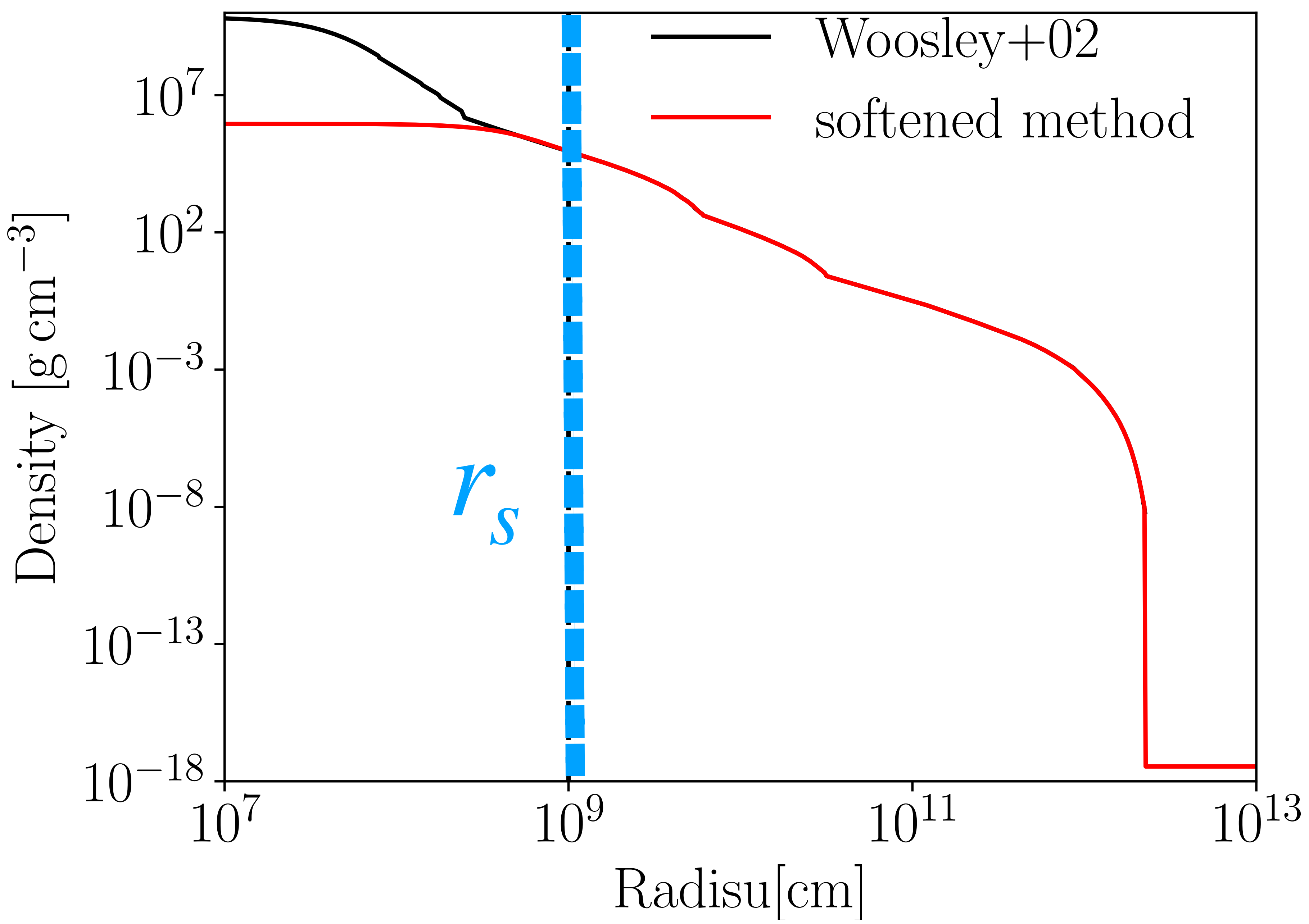
Envelope ⇒ **Same as original**

Core, NS ⇒ **point mass + thin matter**



➡**Low cost**

How to make inner region



Self-gravity of thin matter pointmass

$$\nabla p_{\mathrm{m}}(r) + G\rho_{\mathrm{m}}(r)\left(\boxed{\frac{m_{\mathrm{m}}(r)}{r^2}} + \boxed{M_{\mathrm{pt}}\nabla\phi'_{\mathrm{pt}}(r, r_{\mathrm{s}})}\right) = 0, \tag{B1}$$

$$p_{\mathrm{m}}(r_{\mathrm{s}}) = p(r_{\mathrm{s}}), \tag{B2}$$

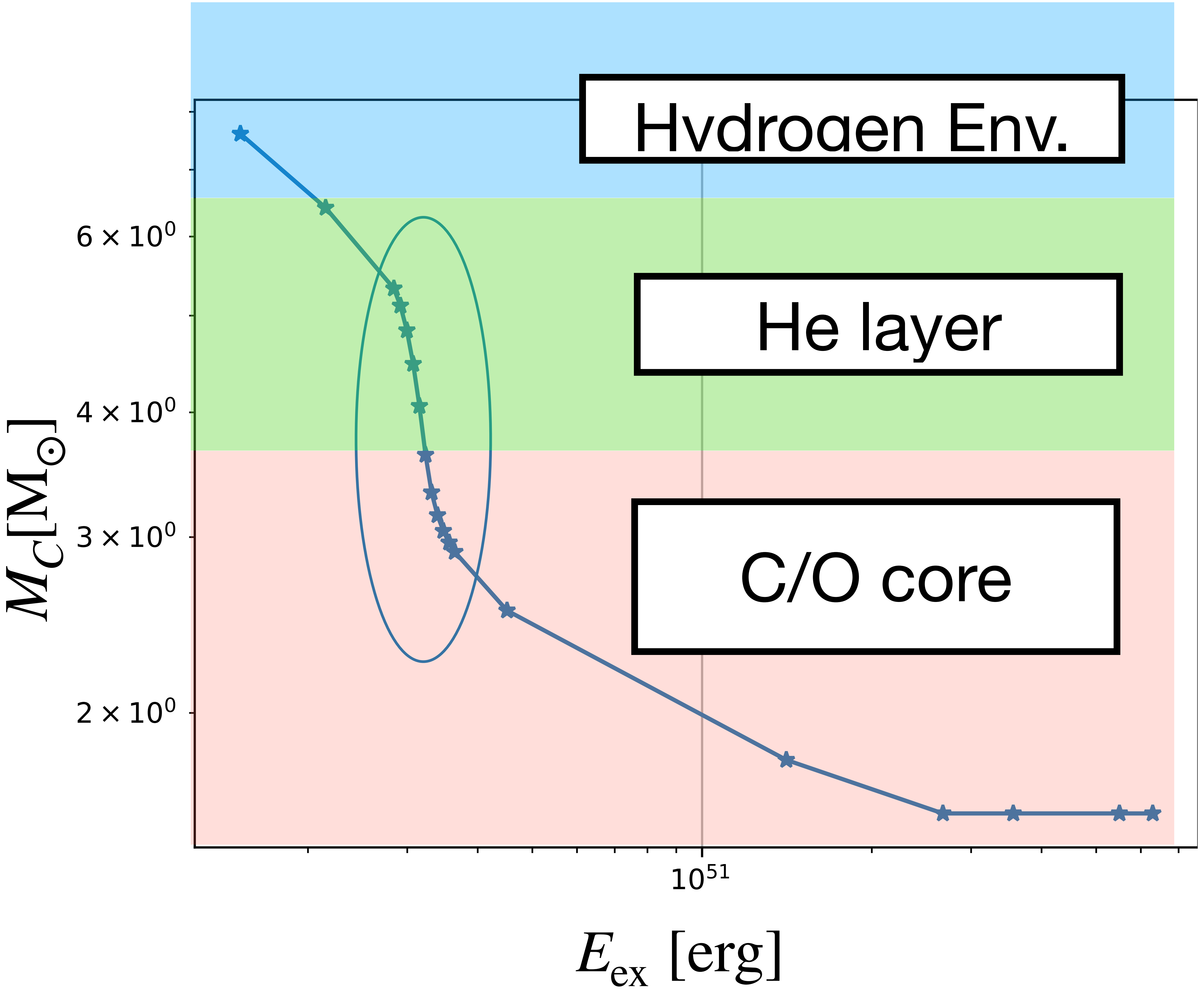
$$\nabla p_{\mathrm{m}}(r_{\mathrm{s}}) = \nabla p(r_{\mathrm{s}}), \tag{B3}$$

$$M_{\mathrm{pt}} + m_{\mathrm{m}}(r_{\mathrm{s}}) = m(r_{\mathrm{s}}). \tag{B4}$$

$$\phi'(r, r_s) = \begin{cases} 1/h^2\left(\frac{4}{3}q - \frac{6}{5}q^3 + \frac{1}{2}q^4\right), & 0 \leqslant q < 1; \\ 1/h^2\left(\frac{8}{3}q - 3q^2 + \frac{6}{5}q^3 - \frac{1}{6}q^4 - \frac{1}{15q^2}\right), & 1 \leqslant q < 2; \\ 1/r^2 & q \geqslant 2, \end{cases} \qquad q = r/r_s$$

Result : Explosion energy and M_C

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



Result : Normalized Explosion energy and M_C

$$x = \frac{E_{\rm ex}}{E_{\rm g,H}}, y = \frac{M_C - M_{\rm pt}}{M_* - M_{\rm pt}}$$

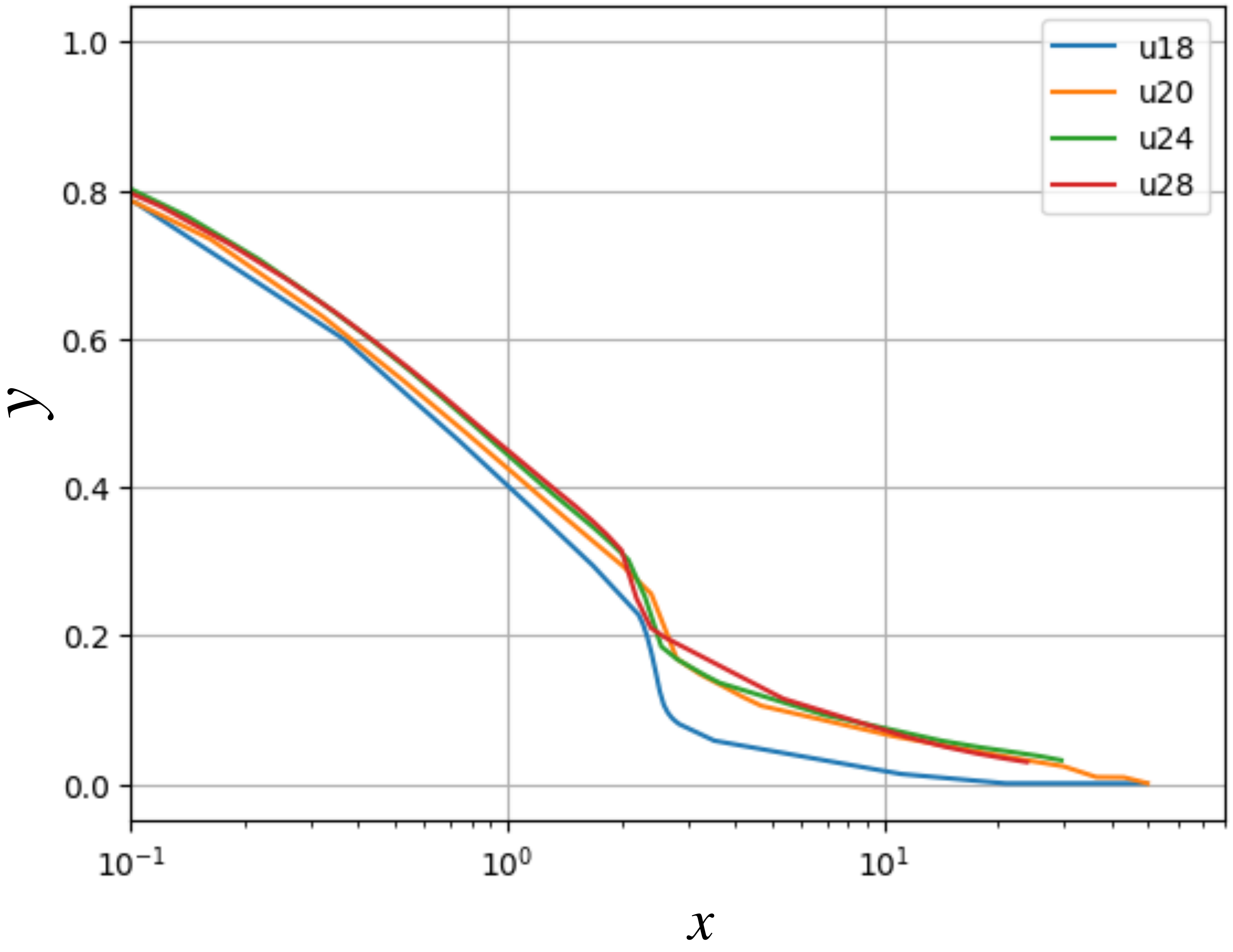
$y = 0 : M_{\rm C} = M_{\rm pt}$ no accretion

$y = 1 : M_* = M_C$ Full collapse

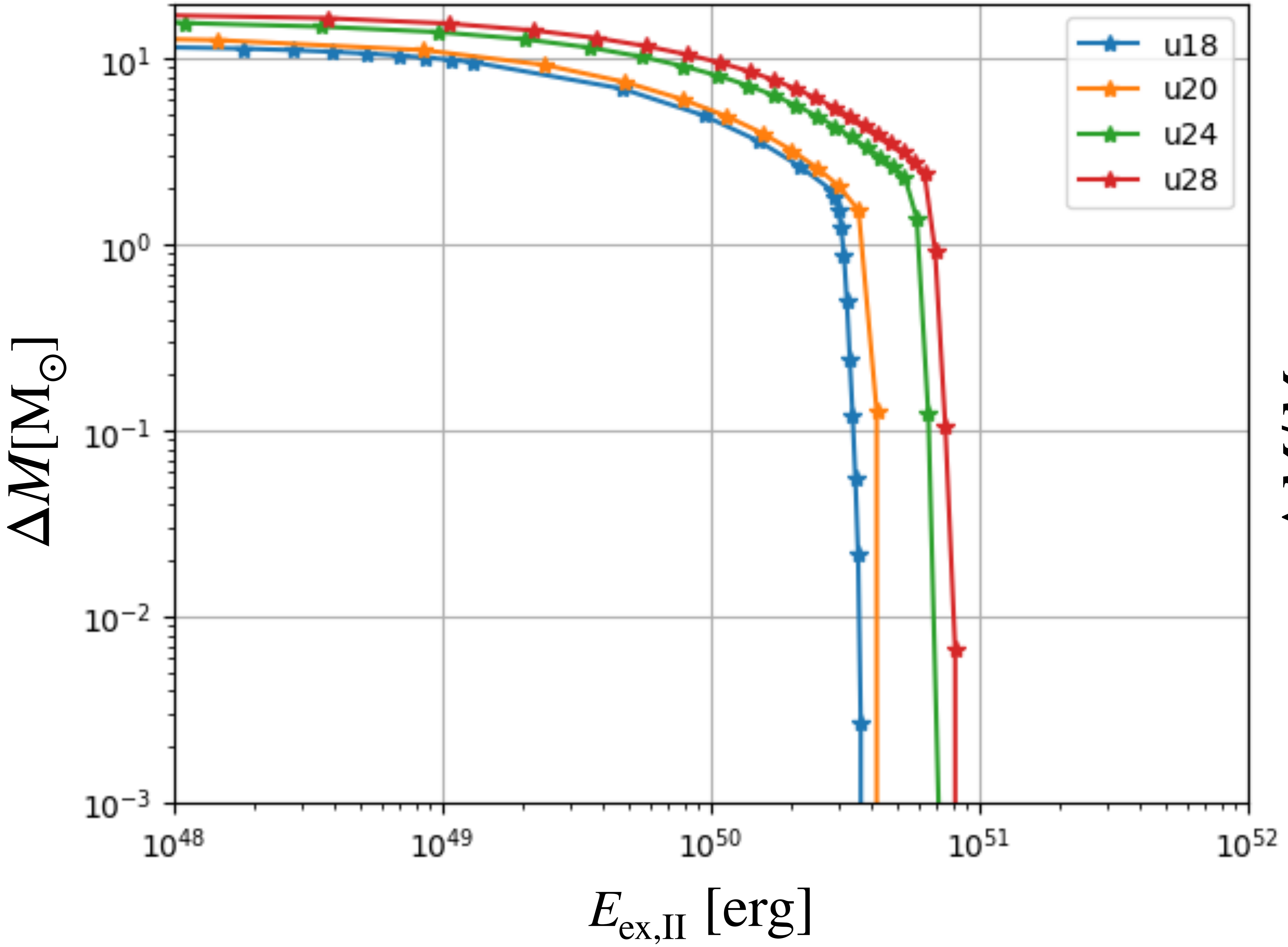
cutoff : $x \sim 2 - 3$

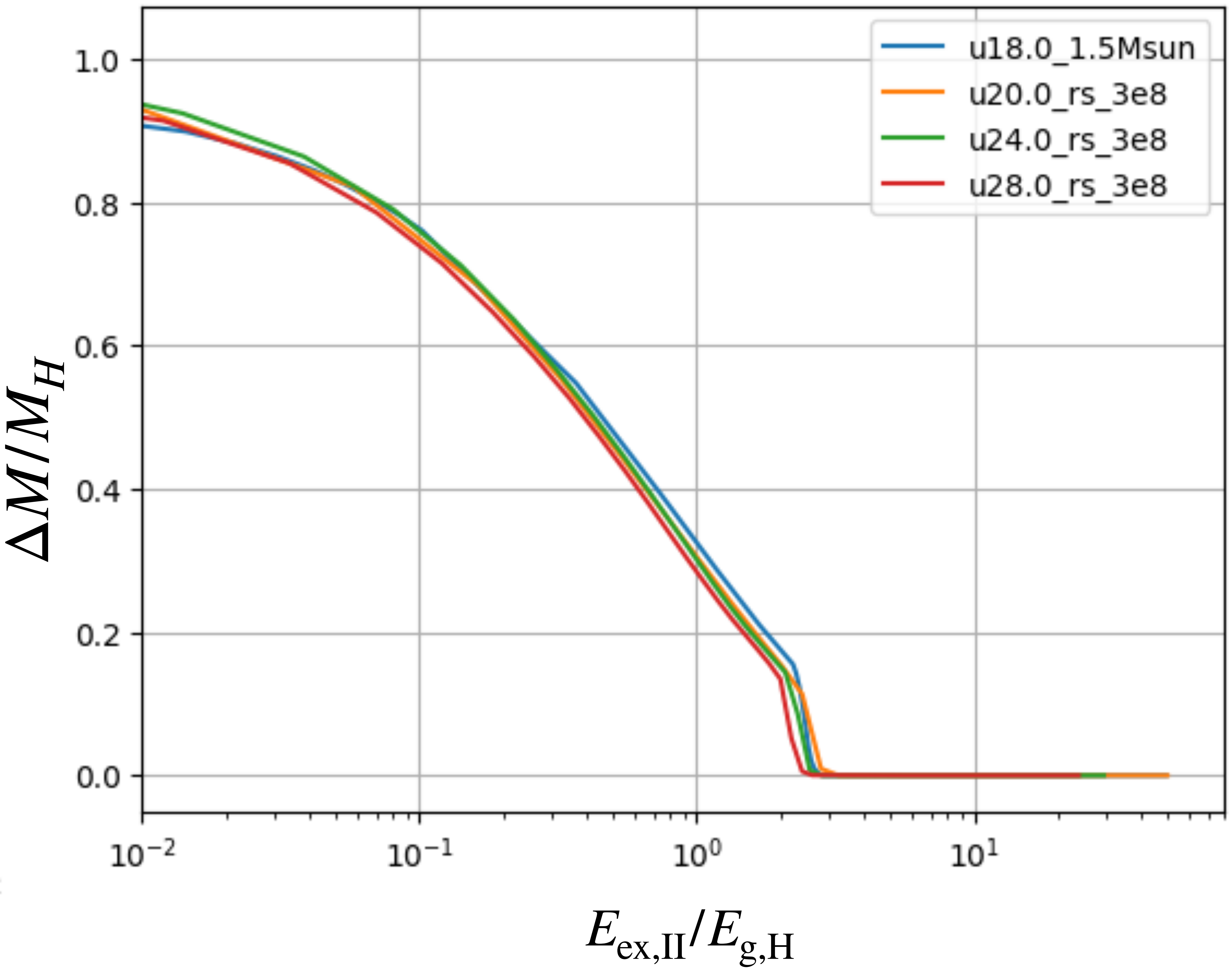
$x = 10^{-1}$: all lines have $y \simeq 0.8$

$x \gtrsim 3$: only u18 is different ?



Discussion : Hydrogen Envelope Value vs M_C





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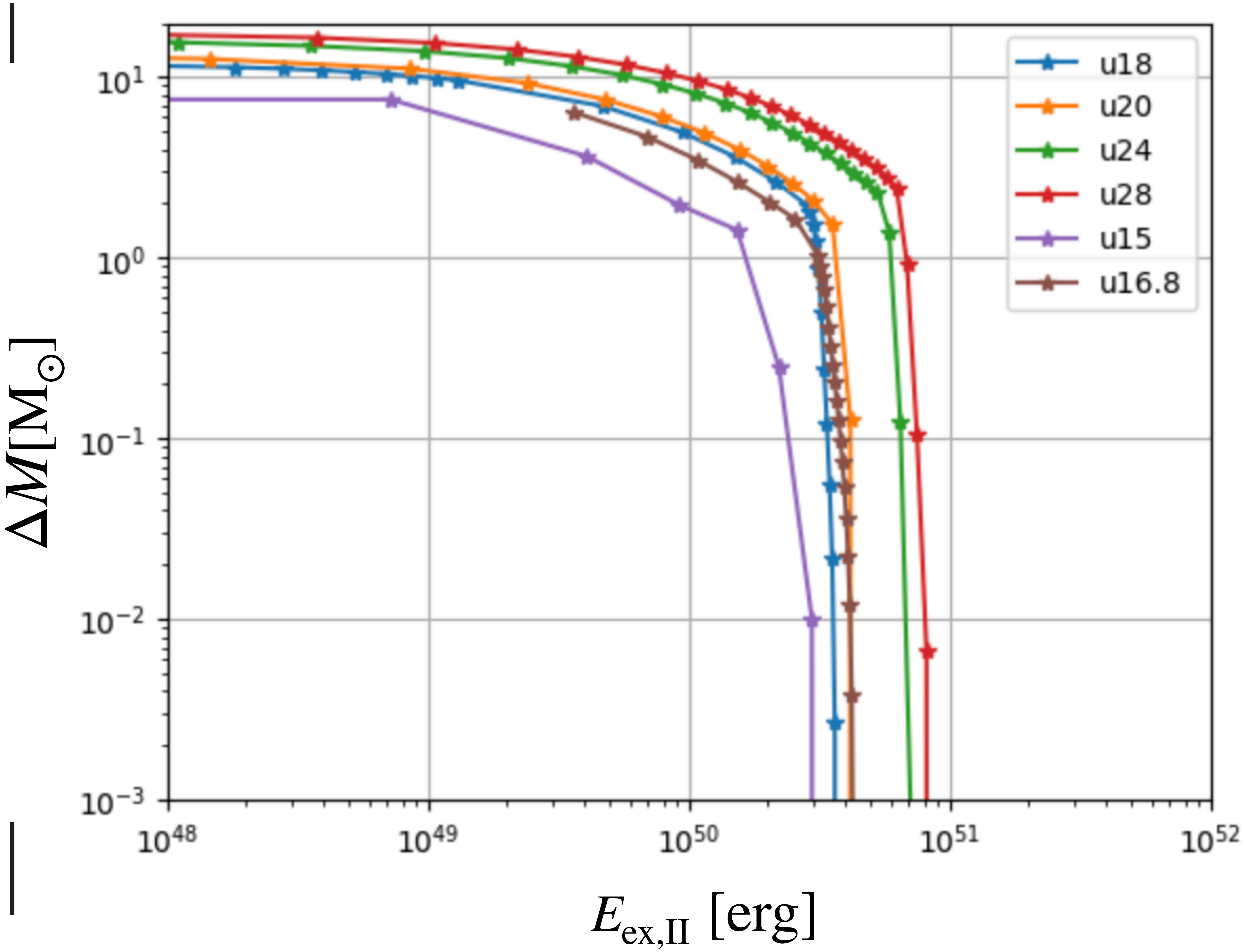

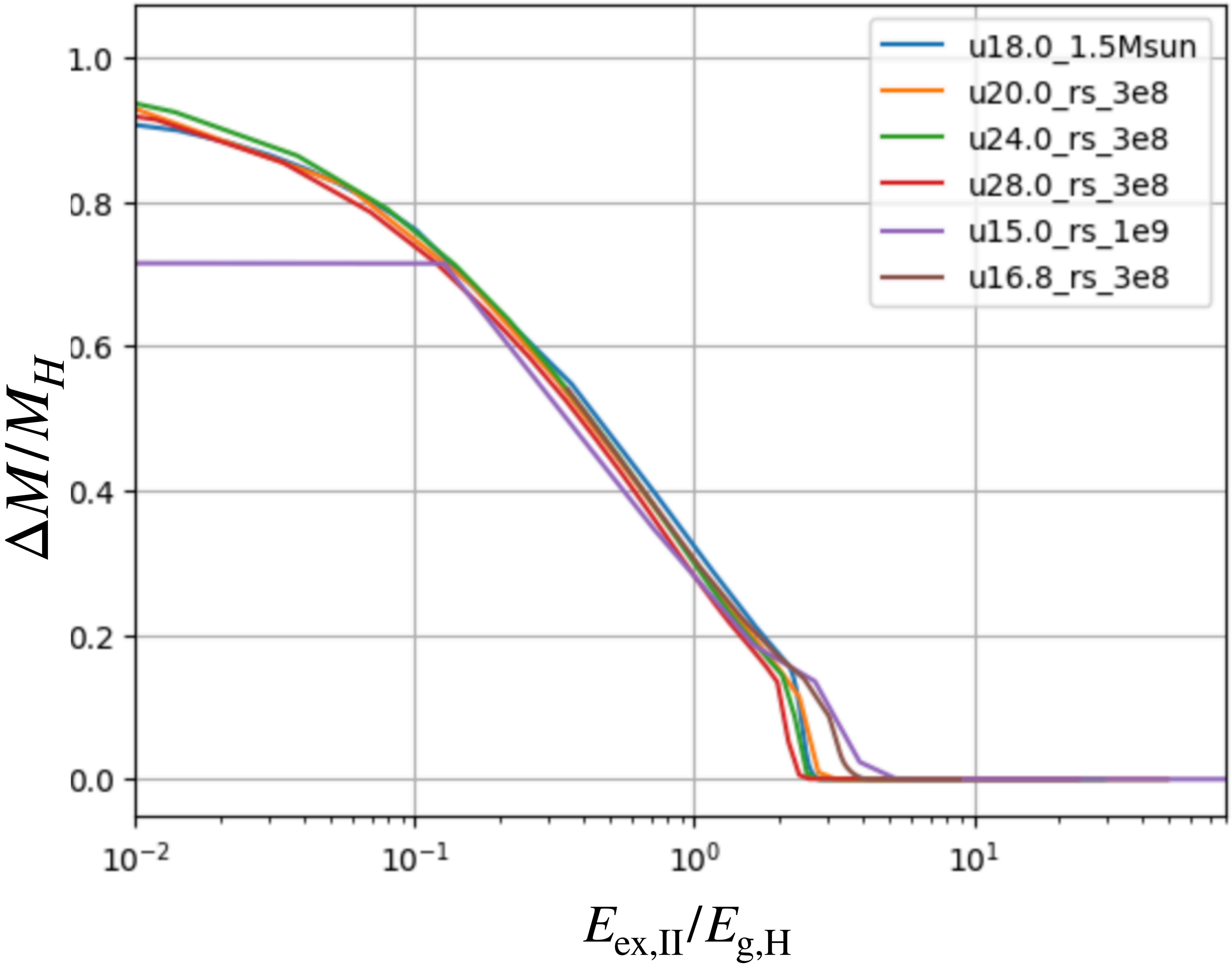

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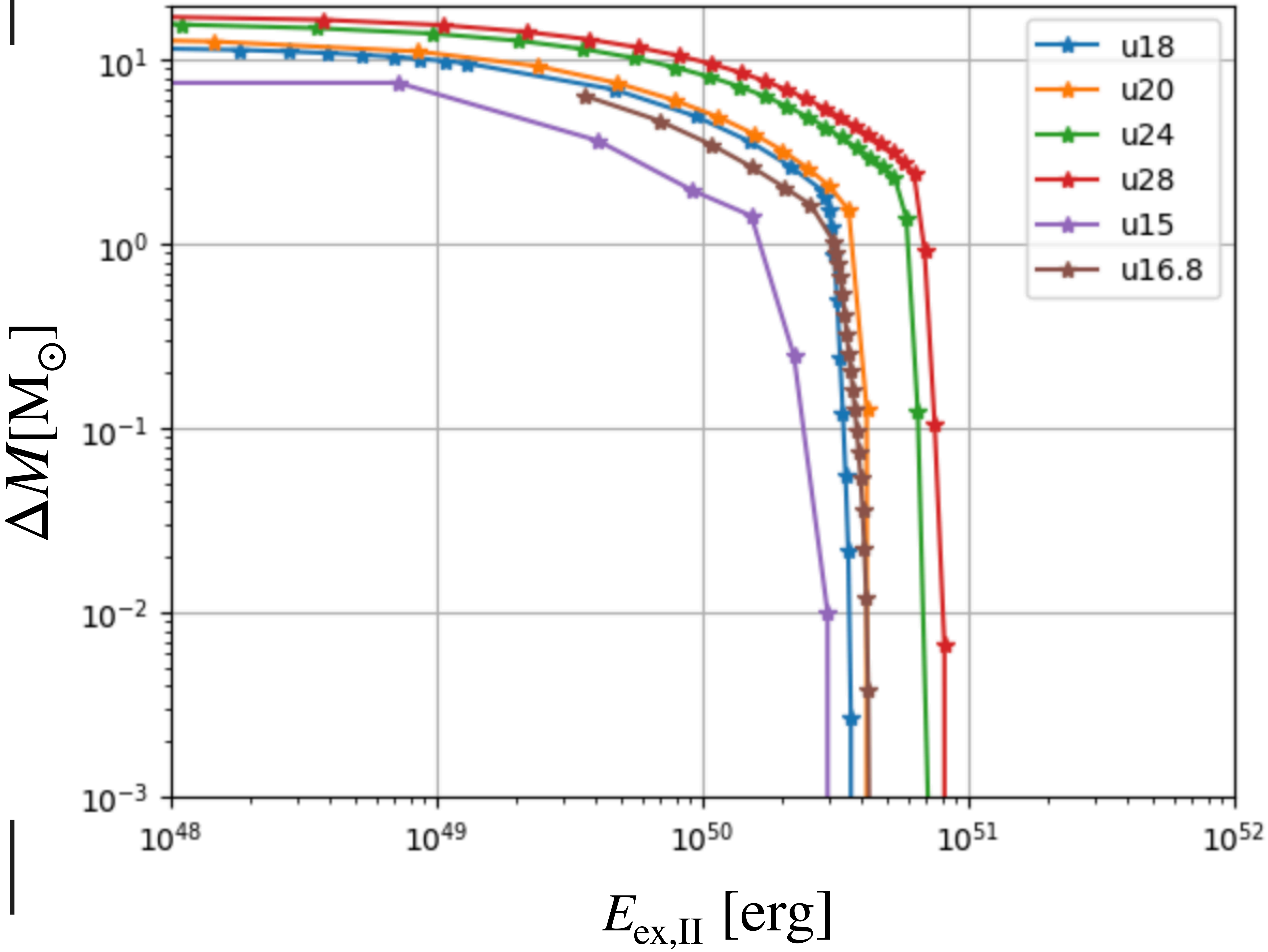

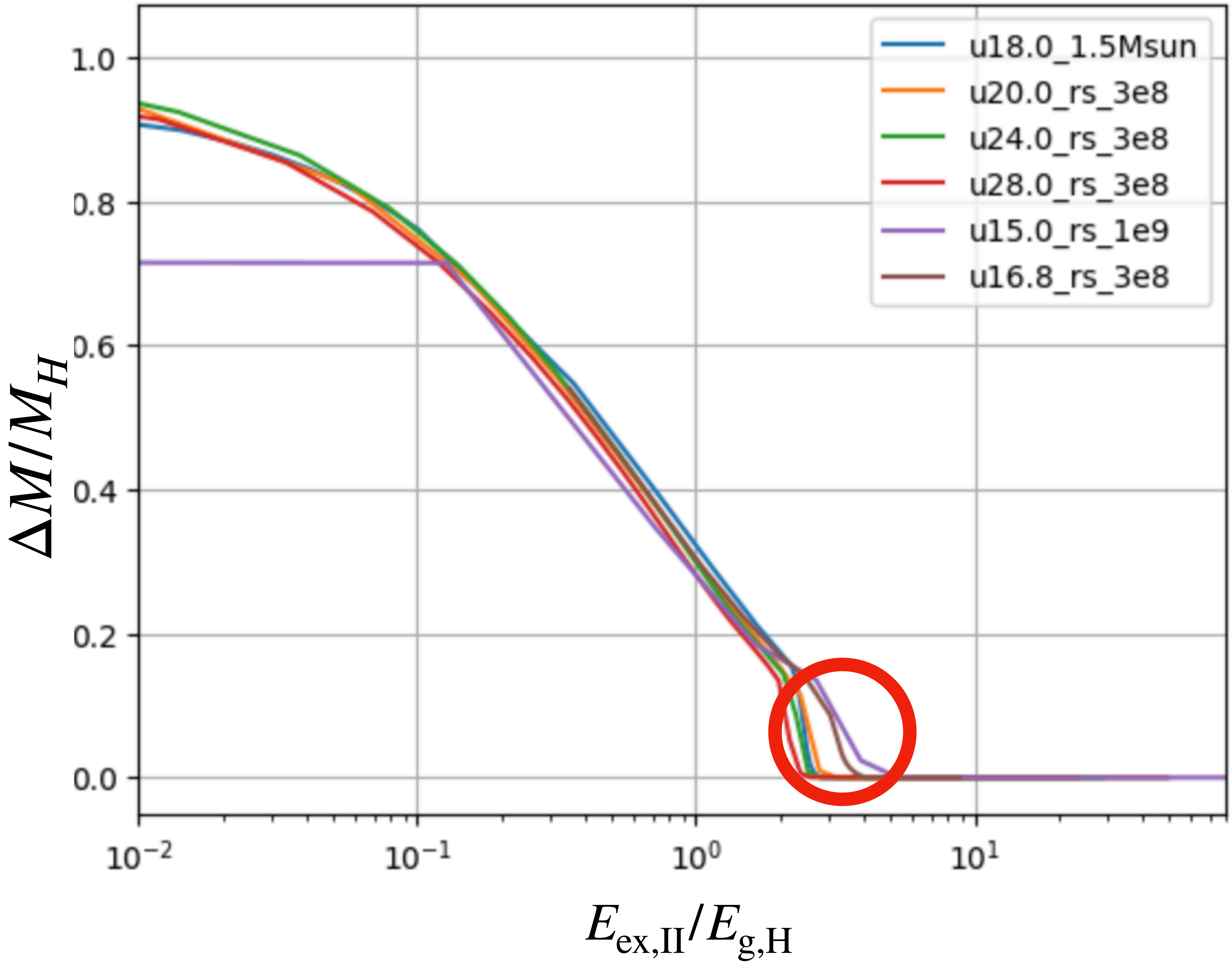

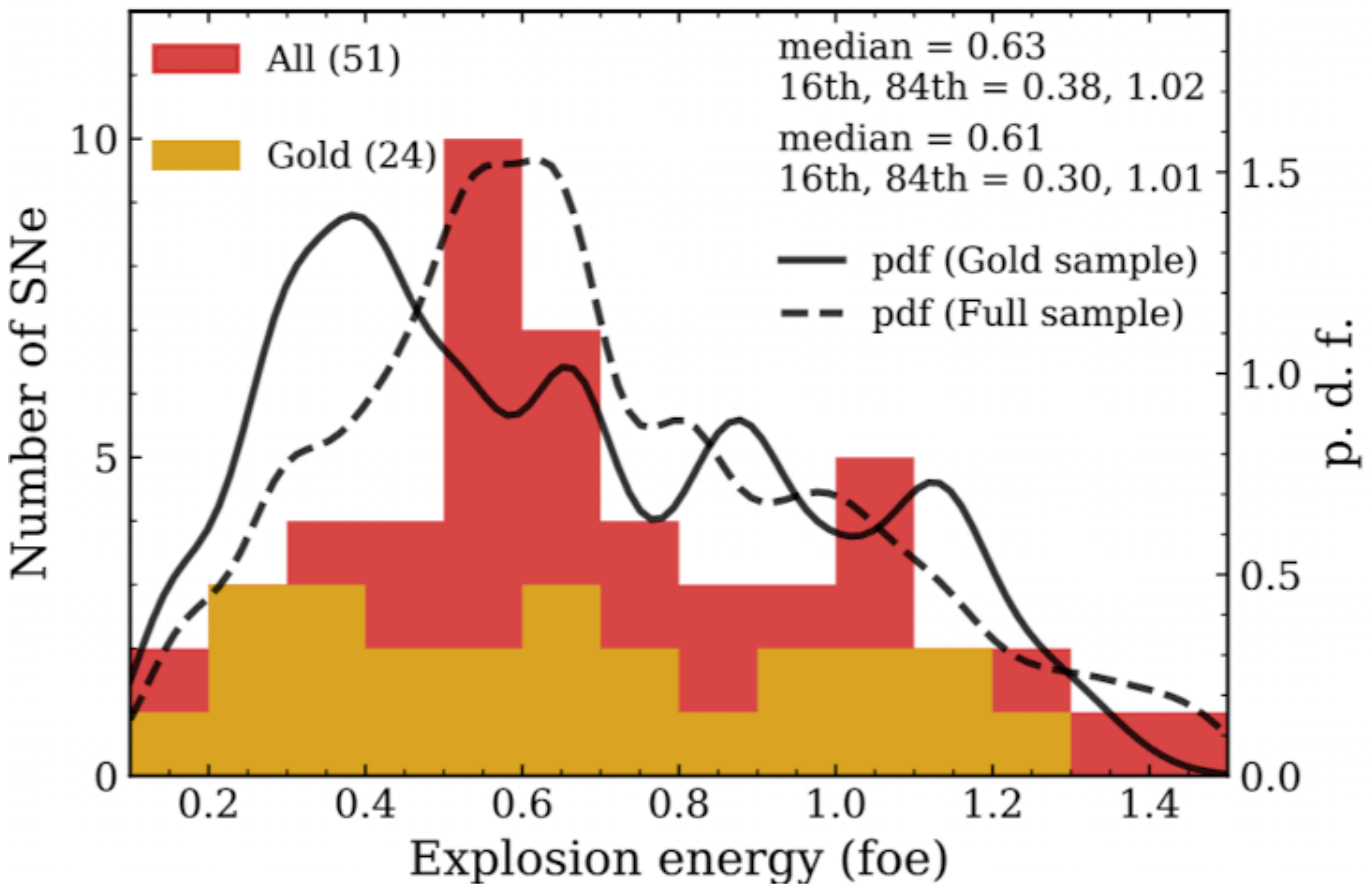
All (51)
Gold (24)
median = 0.63
16th, 84th = 0.38, 1.02
median = 0.61
16th, 84th = 0.30, 1.01
pdf (Gold sample)
pdf (Full sample)
Number of SNe
p. d. f.
Explosion energy (foe)
0
5
10
0.0
0.5
1.0
1.5
0.2
0.4
0.6
0.8
1.0
1.2
1.4