Progenitors of lowest mass Fe core collapse supernova explosions

(Umeda & Ishiguro 2025 to be submitted)

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Lowest Mass CCSN: What is … ?

the mass ?

the neutron star mass for it ?

the explosion energy ?

^{56}Ni mass (brightness of the SN) ?

the nucleosynthesis ?

the observed properties of light curves (different from ECSN) ?

If it can explode in 1D simulation (as an ECSN)?

Lowest Mass CCSN: Previous works

Sukhbold et al 2016, ApJ : 9 to 120 $M_\odot$ CCSN

They exploded progenitor models in 1D using "calibrated central engines".

For loweset mass models , they used the engine calibrated for electron capture like Supernovae.

For the lowest mass

9$M_\odot$, 0.006 $M_\odot$ (^{56}Ni mass), 0.11 B (explosion energy), 1.35 $M_\odot$ (remnant mass),

cf. (since Muller et al 2024 found the lowest remnant mass for 9.9$M_\odot$ model)

10$M_\odot$, 0.031 $M_\odot$ (^{56}Ni mass), 0.60 B (explosion energy), 1.45 $M_\odot$ (remnant mass),

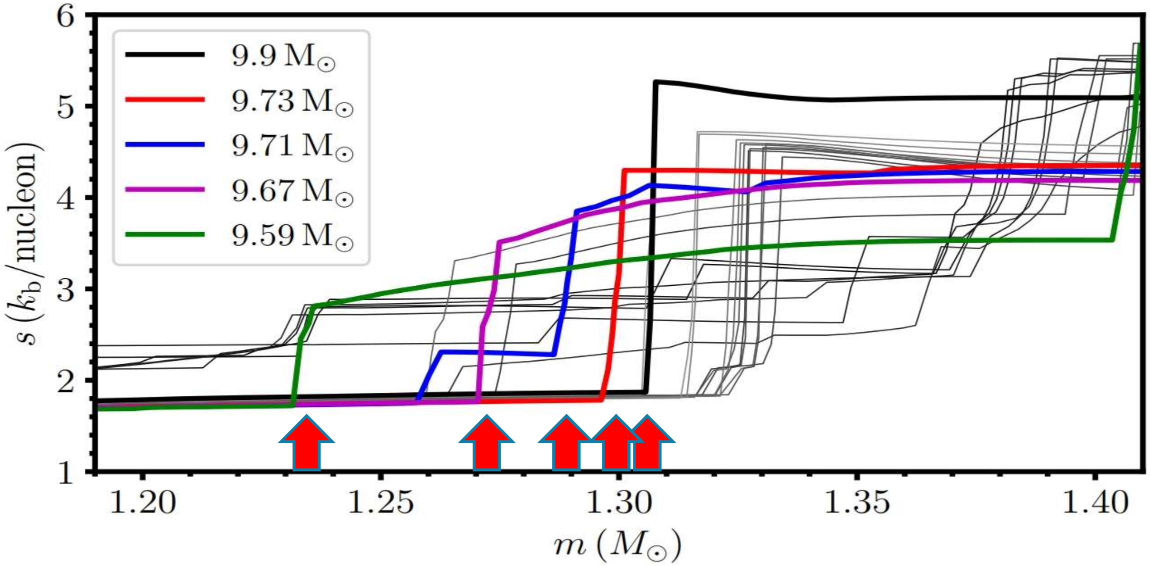
Lowest Mass CCSN: Previous works

Müller et al 2024, arXiv:2407.08407 : The minimum NS mass in neutrino-driven SN

Using similar progenitor models as Sukhbold et al 2016, they exploded in 3D

Entropy profiles of progenitors →

⬆ roughly represent Mass coordinates of "Fe" cores

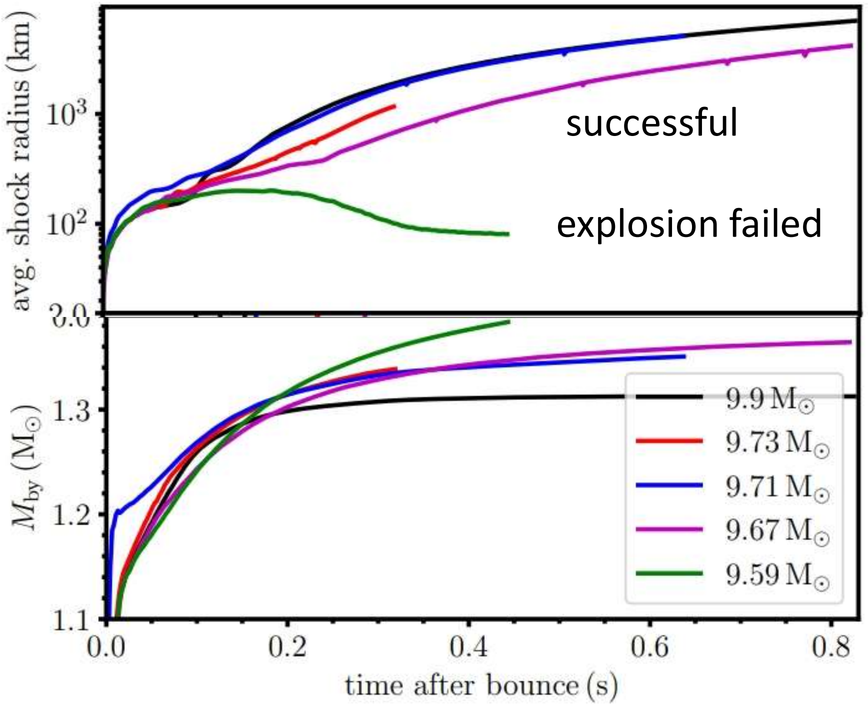


Lowest Mass CCSN: Müller et al. 2024

Smaller initial mass usually leads smaller "Fe"-core, however, it is not necessary true that smaller mass leads smaller Neutron star (remnant) mass,

because the remnant mass depends

on explosion.



Remnant baryon mass (time evolution) →

9.9 $M_\odot$ model has the lowest neutron star mass (M_{by})

Lowest Mass CCSN: Müller et al. 2024 (summary)

Lowest mass for explosion: 9.67$M_\odot$ model , 0.047 B, $M_{by} > 1.36M_\odot$

Lowest neutron star mass : 9.90$M_\odot$ model , 0.15 B, $M_{by} = 1.313M_\odot$

(NS gravitational mass, $M_g = 1.192\ M_\odot$)

(their motivation was to fit a value for J0453+1559, $M_g = 1.174\ M_\odot$)

c.f. Sukhbold et al 2016

9$M_\odot$, 0.006 $M_\odot$ (^{56}Ni mass), 0.11 B (explosion energy), 1.35 $M_\odot$ (remnant mass)

10$M_\odot$, 0.031 $M_\odot$ (^{56}Ni mass), 0.60 B (explosion energy), 1.45 $M_\odot$ (remnant mass)

We should note that the SN explosion simulations have still uncertainties.

Lowest Mass CCSN: Our previous works

We have been working on CCSN progenitor models (e.g., Umeda & Nomoto 2002, 2008)

Main purpose for these works were nucleosynthesis, thus only M > 13$M_\odot$ were considered (e.g., Tominaga et al, 2007; Nomoto et al. 2013)

In Umeda et al. 2012, PTEP, we considered lower mass models up to 10.0 $M_\odot$,

We showed that the remnant mass for the model was 1.29 $M_\odot$ (baryon mass)

and 1.18 $M_\odot$ (gravitational mass).

However, the results may not be realistic, for the low mass end of CCSNe,

since we exploded the stars by assuming 1B energy and the mass cut is determined artificially by setting the ejected ^{56}Ni mass to be 0.07$M_\odot$.

In this talk, I show our updated results for the lowest mass CCSNe.

Method

We calculate progenitor models using the HOSHI code (Takahashi, Yoshida, Umeda 2018) --- Heney type stellar evolution code with rotation effects

In this work, we use 300 isotope nuclear reaction network.

Supernova explosion is simulated by a 1D PPM code with a thermal bomb

method (this is same as our previous work).

However, Mass cut is determined gravitationally, i.e., self-consistently, by inserting explosion energy deeper inside than before.

This is different. Previously we had two parameters (explosion energy and mass cut), but in this work just one parameter (explosion energy).

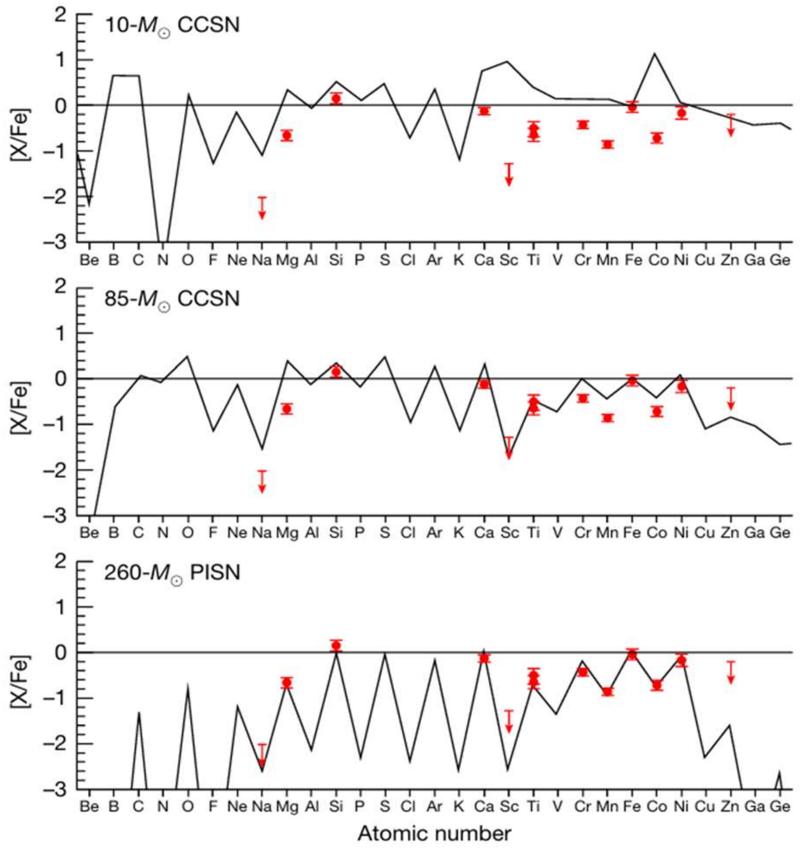
Method

We constrain explosion energy by neutron star mass, and nucleosynthesis, assuming that the abundance ratios of ejected matter (e.g., Si/Fe, Mg/Fe shouldn’t be far from the solar ratios.

Also, the abundance pattern of a metal poor star J1010+2358 is used to constrain the explosion, since this star might have an abundance pattern of the lowest mass CCSN.

Xing et al.(2023), Nature

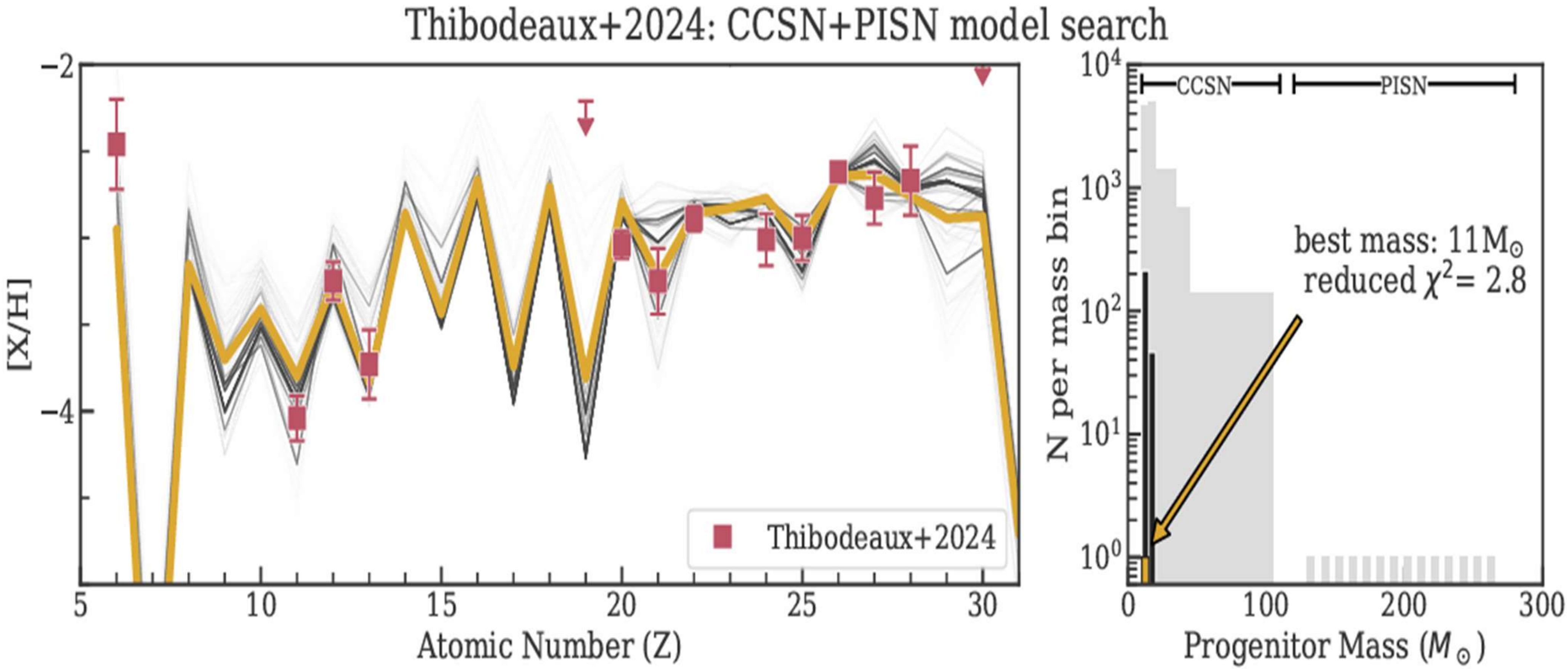
The Galactic halo star J1010+2358 with [Fe/H] = - 2.42 may have abundance pattern of Pair Instability Supernovae (PISNe)



Abundance pattern was obtained by an LTE model

The abundance pattern is quite unusual for CCSNe because of relatively small
Mg, Si, Ca, Ti/Fe and
non-detection of Zn.

Thibodeaux et al.(2024) ⇒ new observation with a **non-LTE model to get abundance**



⇒The lowest mass CCSN model fits best to J1010+2358.

Results: The lowest mass for CCSNe

We consider two sets of models with the solar metallicity ($Z_\odot$) and 10^{-3} $Z_\odot$.

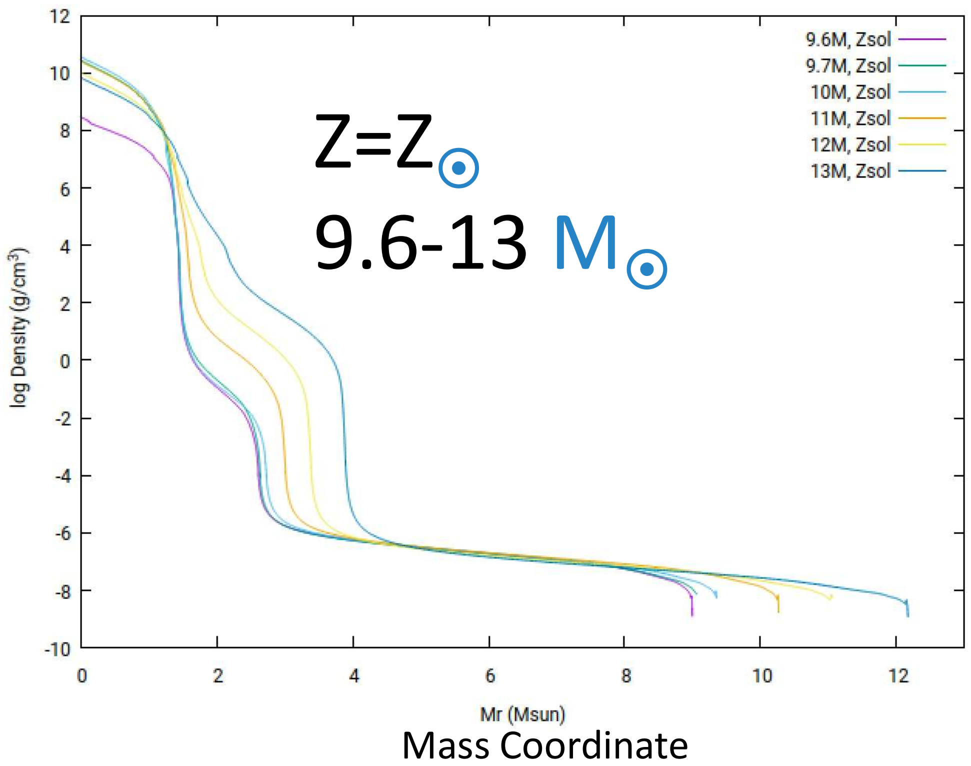
The reason to consider the 10^{-3} $Z_\odot$ is because we would like to compare with a metal poor star J1010+2358.

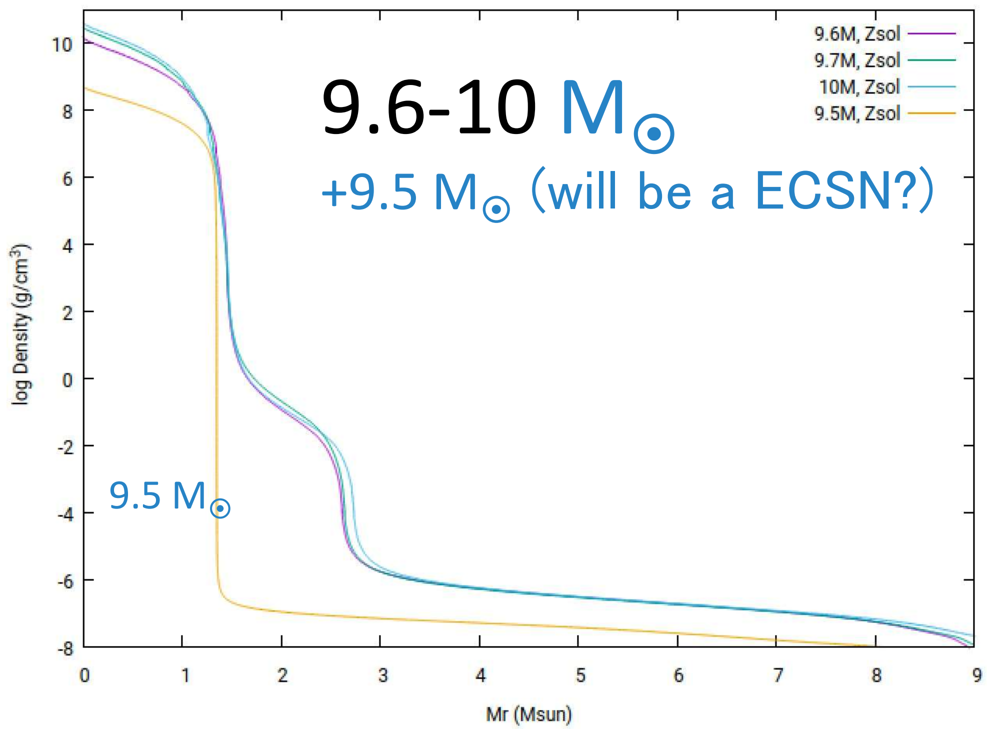
The lowest mass for CCSNe

$Z_\odot$ model : $9.7M_\odot$ （$9.6M_\odot$ forms a "small Fe" core ＞ Fe core collapse（done yesterday）

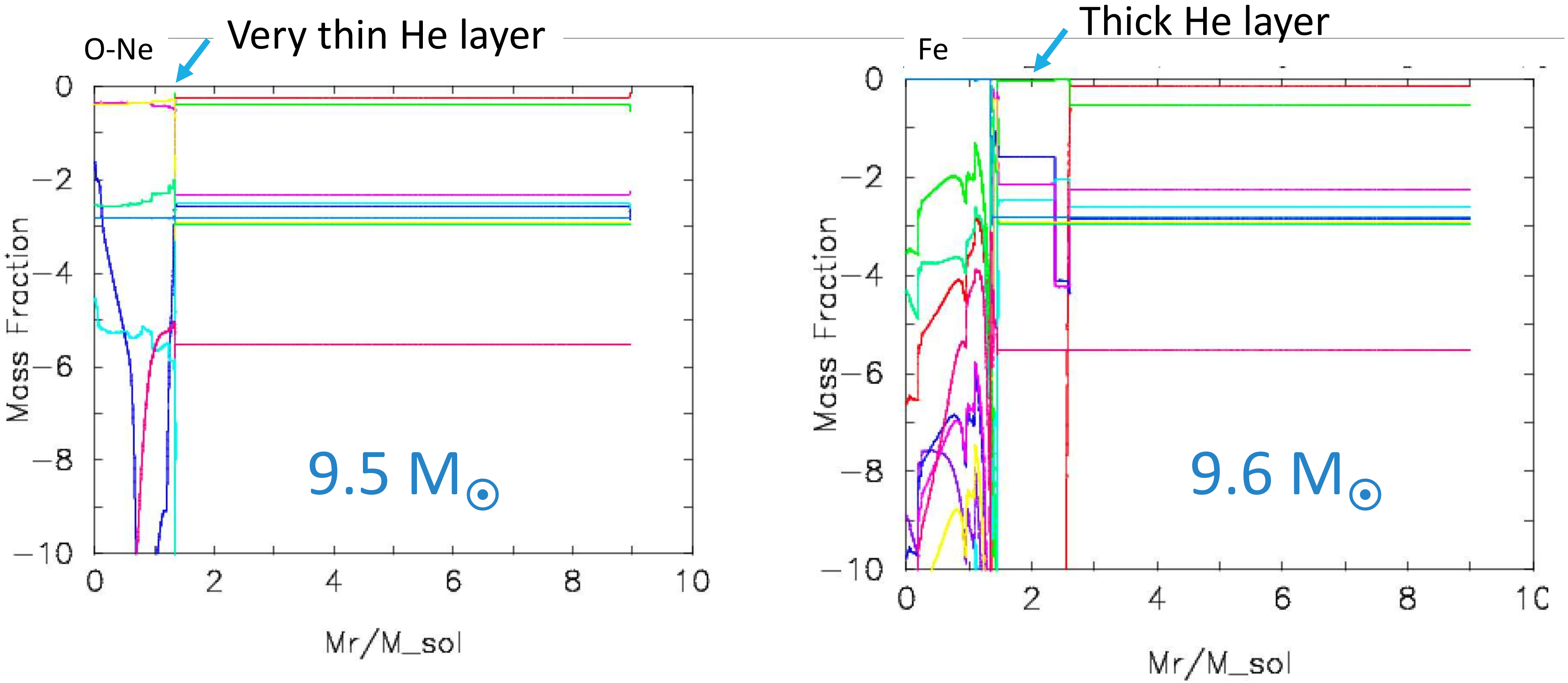
10^{-3} $Z_\odot$ model : $10.1M_\odot$ （$10.0M_\odot$ forms a "small Fe" core ＞ will collapse

Results: Density Structure (Log ρ vs M_r)

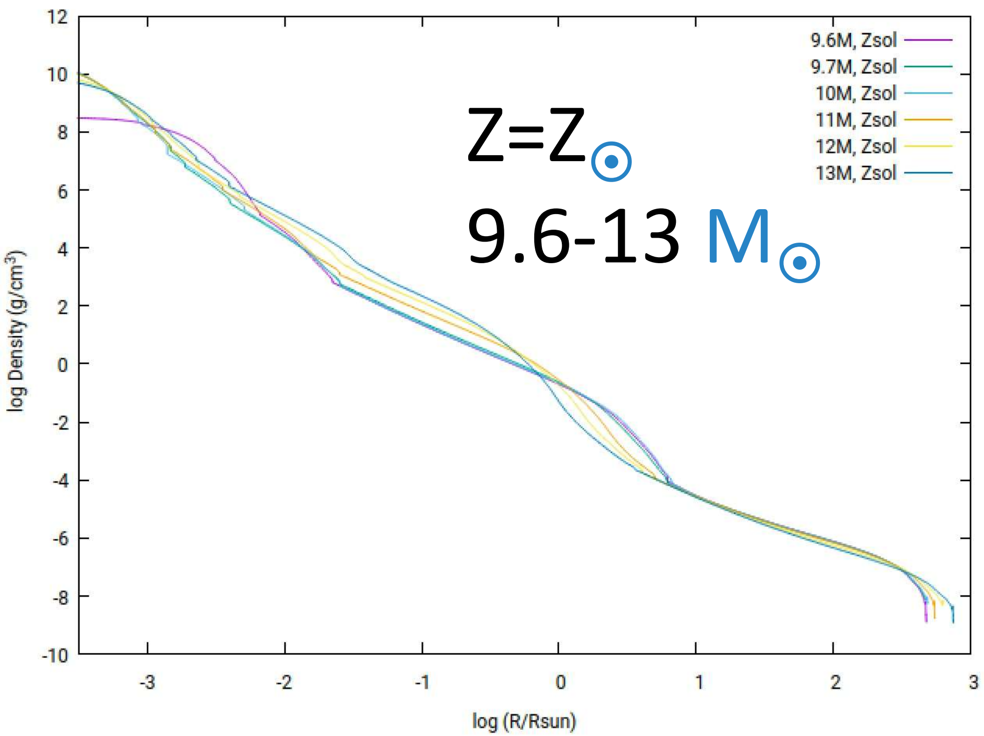




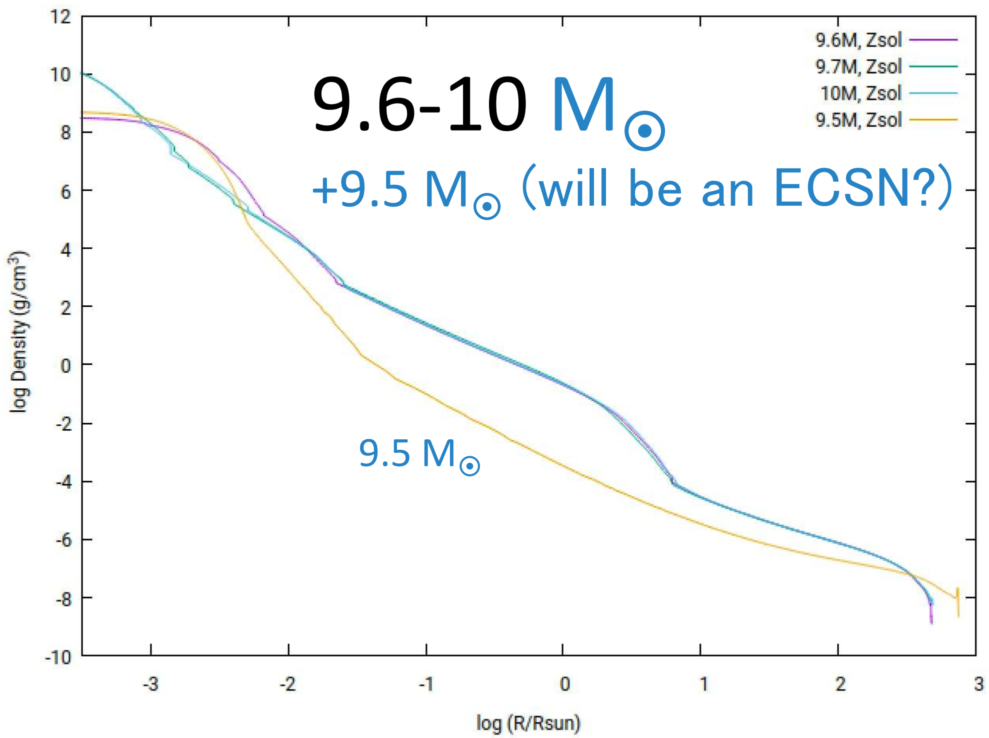
Results: Abundance Distribution (9.5, 9.6 $M_\odot$)



Results: Density Structure (Log ρ vs Log r/R⊙)



Radius



Results: Explosion energy and NS mass for the lowest mass models

	E_{ex} (B)	NS mass ($M_\odot$)	
$Z_\odot$, 9.7$M_\odot$:	0.058	1.447	
	0.068	1.379	
	0.083	1.369	Explosion energy should be smaller than 0.115B
	0.115	<1.289	
$10^{-3} Z_\odot$, 10.1$M_\odot$:	0.089	1.482	
	0.15	1.350	
	0.176	1.330	
	0.20	1.328	Explosion energy should be smaller than 0.22B
	0.22	< 1.29	

Results: Upper limit of Explosion energy

Similary, if we assume that the baryon mass of a NS should be larger than $1.3M_{\odot}$, our models suggest the upper limit of E_{ex} for each model.

$Z_{\odot}$ model (mass)	Upper limit of E_{ex} (B)
9.7	0.115
10.0	0.62
12.0	0.43
13.0	0.69
15.0	0.77
18.0	--- (>1.04)

These numbers seems to be smaller than the typical CCSN explosion energy Eex ~ 1, mentioned in the literature.

Results: Lowest mass models, ^{56}Ni ejection mass

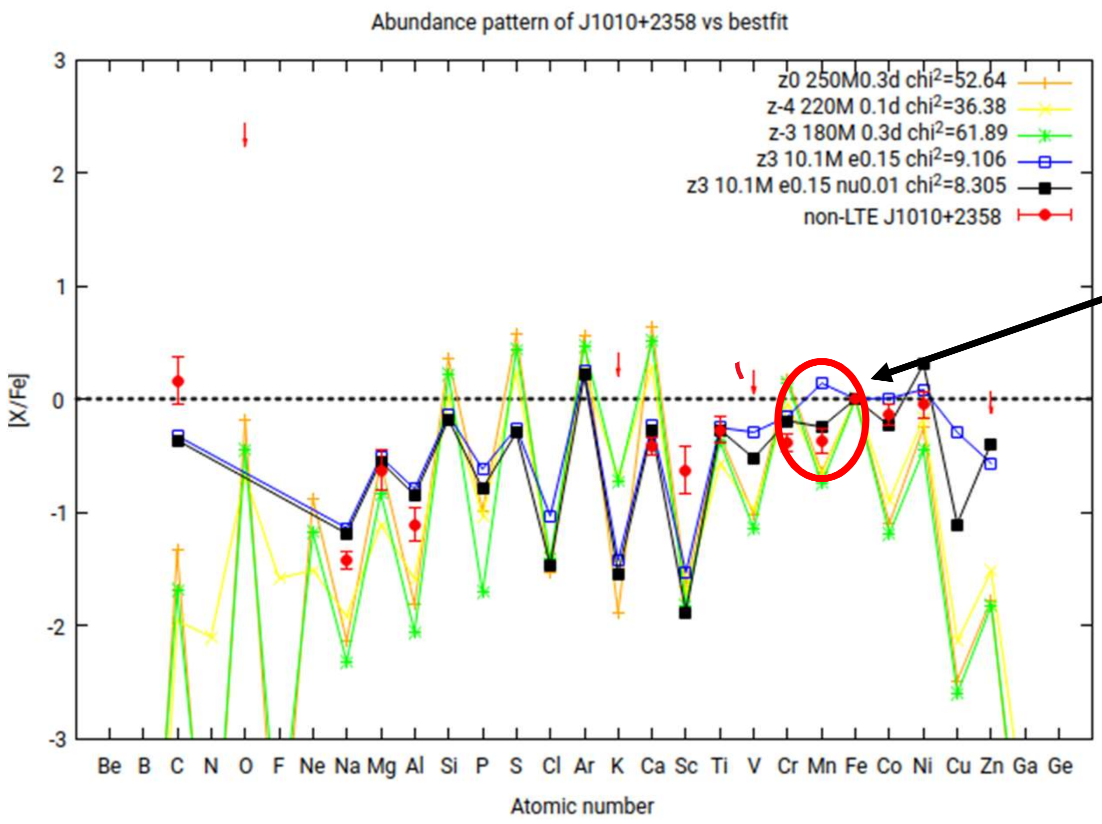
10^{-3} $Z_{\odot}$ model (mass)	E_{ex} (B)	M_{cut}(remnant mass)	ejected ^{56}Ni mass ($M_{\odot}$)
10.1	0.082	1.482	0
		1.36	0.01
	0.15	1.350	0.023
	0.22	1.29	0.025
		1.35	0.0017

Red : Mcut = self consistent value obtained from the 1D simulation

Black : Mcut is changed to see the effects of changing Mcut

From this result, we may conclude that the lowest mass CCSN should not be a bright SN

Comparison with J1010+2358 Ishiguro Master's thesis (2025)



PISN models are also shown

Mn ↓ ⇒ χ^2 ↓

(reason)

Mn is produced through neutrino process.

⬇

neutrino ↑ ⇒ Mn ↑

Fitting and χ^2 values: Here Mcut is also used as a fitting parameter

(Ishiguro Mater's thesis 2025)

RED: Best Fit

PISN

Metallicity	Best fit model	χ^2
0	$250M_\odot$ 0.3d	52.64
$10^{-4}Z_\odot$	$220M_\odot$ 0.1d	36.38
$10^{-3}Z_\odot$	$180M_\odot$ 0.3d	61.89

・We also take the strength of neutrino nucleosynthesis process as a parameter,

1: relatively strong

0.01: basically off

CCSN($Z = 10^{-3}Z_\odot$)

Ejected ^{56}Ni mass

Model	Mass cut for best fit[$M_\odot$]	χ^2
$10.1M_\odot$ e0.089 nu=1	1.3229	13.02
$10.1M_\odot$ e0.089 nu=0.01	1.3114	10.71
$10.1M_\odot$ e0.15 nu=1	1.3229 (0.044)	9.106
$10.1M_\odot$ e0.15 nu=0.01	1.3157 (0.048)	8.305
$10.1M_\odot$ e0.22 nu=0.01	1.2370	38.14
$11M_\odot$ e0.092 nu=1	1.0942	41.22
$11M_\odot$ e0.092 nu=0.01	1.0942	27.92
$11M_\odot$ e0.17 nu=1	1.0942	36.83
$11M_\odot$ e1.07 nu=1	1.2026	17.20
$13M_\odot$ e0.34 nu=1	1.4288	15.22

・The smaller the neutrino irradiation, the smaller the value of χ^2.

Discussion: Best fit model for J1010+2358

10.1$M_\odot$, 0.15 B, NS mass 1.3157$M_\odot$, ^{56}Ni 0.048$M_\odot$

The NS mass is smaller and **^{56}Ni mass** is larger than the "self-consistent" model,

M_{rem} = 1.350 and **^{56}Ni = 0.023$M_\odot$** (slide 14)

This means that the explosion energy should be slightly larger.

For this best fit-model, the baryon mass **1.3157$M_\odot$** corresponds to the gravitational mass **1.196$M_\odot$**, which is close to the possible observational lower limit M_g = 1.174 $M_\odot$ for J0453+1559.

We plan to apply this model to 2D and 3D explosion simulations.

(started work with Nakamura (Fukuoka U.) about 2D)