Properties of the lowest mass Fe-core collapse supernovae

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We calculate progenitors for Fe-core collapse SNe in a fine grid to investigate properties of low mass CCSNe. Treating the explosion energy as a free parameter, we attempt to constrain both the explosion energy and the ejected ^{56}Ni mass using observational constraints on neutron star mass and on chemical abundances in metal-poor stars.

Lowest Mass CCSN: What is … ?

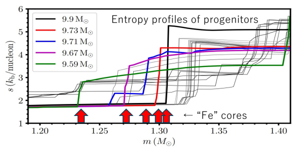
the mass ? the neutron star mass for it ? the explosion energy ?
^{56}Ni mass (brightness of the SN) ? the nucleosynthesis ?
the observed properties of light curves (different from ECSN) ?
If it can explode in 1D simulation (as an ECSN)?

Previous work 1

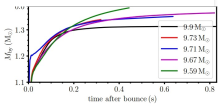
Sukhbold et al 2016, ApJ : 9 to 120 $M_\odot$ CCSN
Exploded in 1D using "calibrated central engines"
For the lowest mass models, an engine for ECSNe is used
The lowest mass
9$M_\odot$, 0.006 $M_\odot$ (^{56}Ni mass), 0.11 B (explosion energy), 1.35 $M_\odot$ (remnant mass),
cf. (since Muller et al 2024 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),

Previous work 2 Müller et al 2025, PhRvL : The minimum NS mass in neutrino-driven SN

Similar progenitor models as Sukhbold et al 2016



exploded in 3D
Remnant baryon mass (time evolution)



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

Lowest neutron star mass : 9.90$M_\odot$ model , 0.15 B, M_{by} = 1.313$M_\odot$ (M_g = 1.192 $M_\odot$)

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

Method

We use the HOSHI stellar evolution code (Takahashi, Yoshida, Umeda 2018)
Explosion: 1D PPM code with a thermal bomb(same as our previous work)

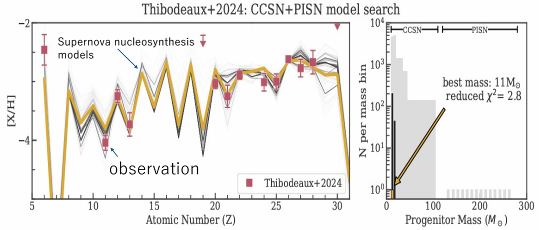
However, Mass cut is determined gravitationally, i.e., self-consistently, by inserting explosion energy deeper inside than before.

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

We constrain explosion energy by neutron star mass, and nucleosynthesis

For example, the abundance pattern of a metal poor star J1010+2358 is used, since this star might have an abundance pattern of the lowest mass CCSN.

Thibodeaux et al.(2024) ⇒ new abundance with **non-LTE abundance**



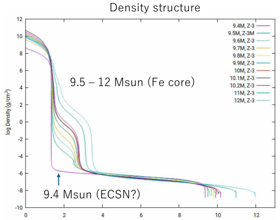
⇒The lowest mass CCSN model fits best to J1010+2358.

Our progenitor models

We consider 10^{-3} $Z_\odot$ models because we would like to compare with a metal poor star J1010+2358.
The lowest mass for Fe-core collapse : 9.5$M_\odot$ (9.4$M_\odot$ forms an ONeMg core)

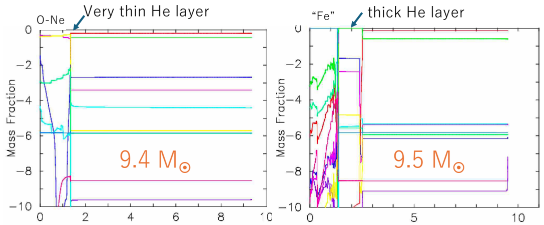
c.f., $Z_\odot$ model : 9.6$M_\odot$ (lowest)
(9.5$M_\odot$ forms an ONeMg core)

Density structure



Mass coordinate (Mr/Msun)

Our progenitor models (Internal abundance)



Results: Explosion energy and NS mass for the exploding lowest mass model

10^{-3} $Z_\odot$, 10.1$M_\odot$:	Eex(B)	Mns (baryon mass)	ejected ^{56}Ni mass ($M_\odot$)
	0.089	1.482	0
	0.15	1.350	0.023
	0.176	1.330	0.040
	0.20	1.328	0.043
	0.22	< 1.29	

Explosion energy should be smaller than 0.22B for Mns > 1.3Msun to avoid very small NS small

E_{ex} (B)	M_{cut}(remnant mass)	ejected ^{56}Ni mass
0.089	1.482	0
	1.36	0.01
0.15	1.350	0.023
0.22	1.29	0.025
	1.35	0.0017

Artificially set mass-cut and ejected 56Ni mass

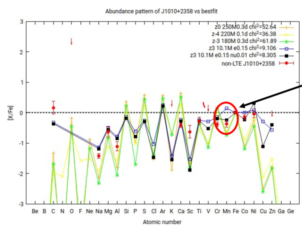
M ~< 10.0 Msun models require small explosion energies Eex < 0.1 B,
(which is consistent with Muller's 3D simulation results)
and difficult to eject significant amount of 56Ni
to explain J1010+2358 abundance (though they may exist in nature)

Summary and references

■Best fit to a VMP star J1010+2358 is obtained for a metal poor CCSN model with initial mass 10.1$M_\odot$, E_{exp}=0.15B, M(^{56}Ni)=0.048$M_\odot$, and weak neutrino process.
■Low mass CCSNe have small E_{exp} and ^{56}Ni ejection.
■~9.5-10.0$M_\odot$ can be dark SNe II with small E_{exp} <0.1B without ^{56}Ni ejection.
■It will be interesting to study these models further (nucleosynthesis and light curves) with detailed 2D & 3D simulations.

- This work (to be submitted)
- Sukhbold et al. 2016, ApJ 821, 38
- Müller et al. 2025, PhRvL 134, 1403
- Takahashi et al. 2018, ApJ, 857, 111
- Thibodeaux et al. 2024, OJAp 7, id66

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 process stronger ↑
⇒ Mn ↑

Fitting and χ^2 values: (Ishiguro Mater's thesis 2025)

Here Mcut is also used as a fitting parameter

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

nu=1: relatively strong
nu=0.01: basically off

RED: Best Fit

Model	Best fit : Mass cut and (ejected ^{56}Ni mass) [$M_\odot$]	χ^2
10.1$M_\odot$ e0.089 nu=1	1.3229	13.02
10.1$M_\odot$ e0.089 nu=0.01	1.3114	10.71
10.1$M_\odot$ e0.15 nu=1	1.3229 (0.044)	9.106
10.1$M_\odot$ e0.15 nu=0.01	1.3157 (0.048)	8.305
10.1$M_\odot$ e0.22 nu=0.01	1.2370	38.14
11$M_\odot$ e0.092 nu=1	1.0942	41.22
11$M_\odot$ e0.092 nu=0.01	1.0942	27.92
11$M_\odot$ e0.17 nu=1	1.0942	36.83
11$M_\odot$ e1.07 nu=1	1.2026	17.20
13$M_\odot$ e0.34 nu=1	1.4288	15.22

Discussions:

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 $M_\odot$
- This suggests that the explosion energy should be slightly larger than 0.15B.
- 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 observational lower limit M_g = 1.174 $M_\odot$ for J0453+1559 (though this particular NS may need binary interaction model to explain).
- We plan to apply these low mass progenitor models to 2D and 3D explosion simulations (just started).

Upper limit of Explosion energy

$Z_\odot$ model (mass)	Upper 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)

This energy seems to be smaller than conventional wisdom

~E_{ex} of typical SN II should be around 1B