Progenitor Mass Distribution of Core-Collapse Supernova Remnants in Our Galaxy and Magellanic Clouds

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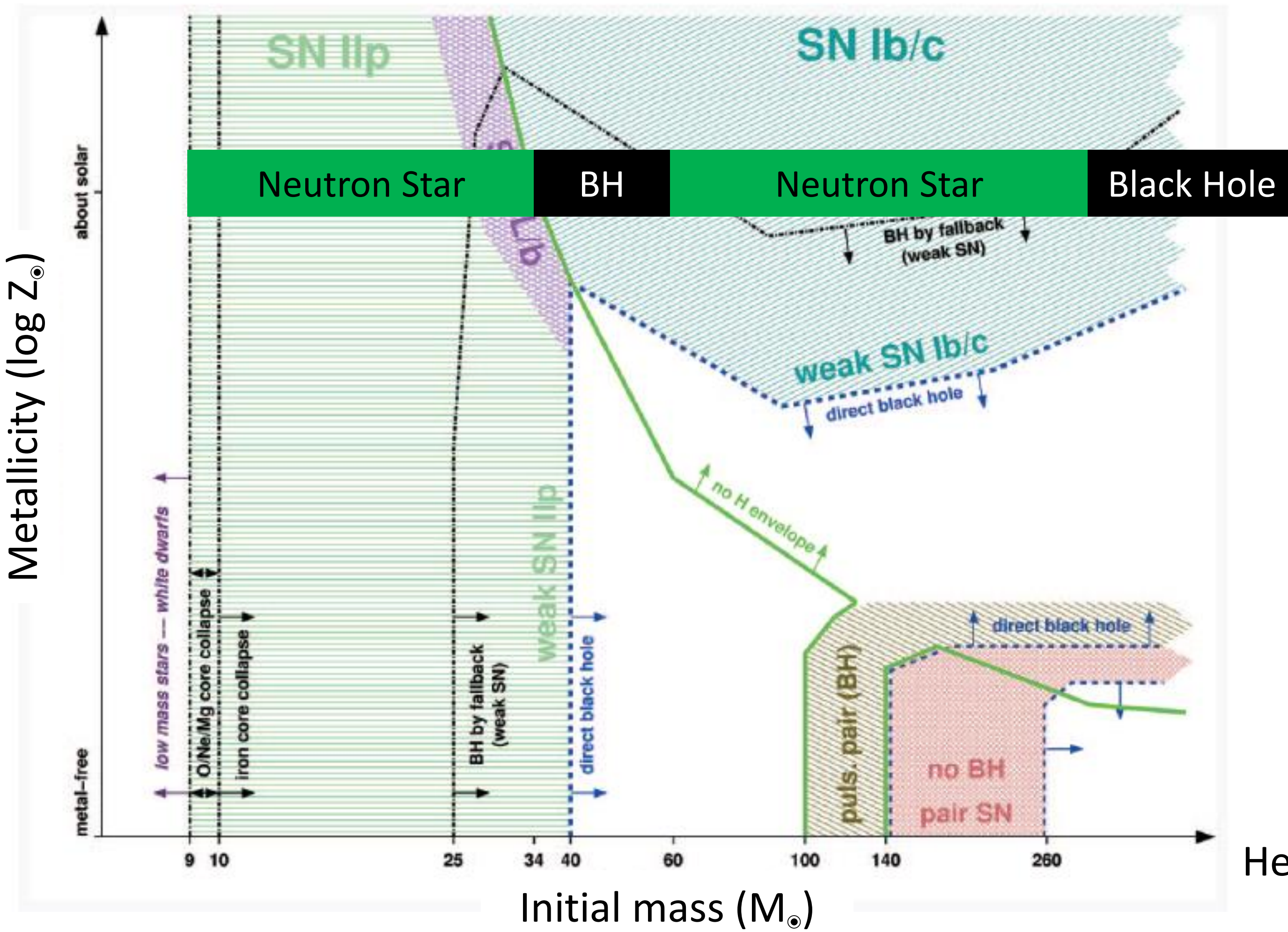
Initial Masses (M_{ZAMS}) of Massive Stars Are Sensitive to Final Fates of Massive Stars

- M_{ZAMS} vs. successful or failed supernovae
- M_{ZAMS} vs. supernovae types (Type IIp, IIL, IIn, Ibc, …)



@ solar metallicity

Heger et al. (2003)

Observational Status on Explodability

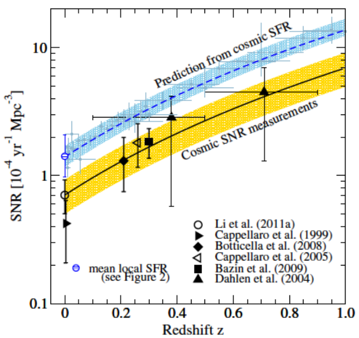
1) Observational implications on SN explodability

(a) SN rate vs. SF rate
→10—30%

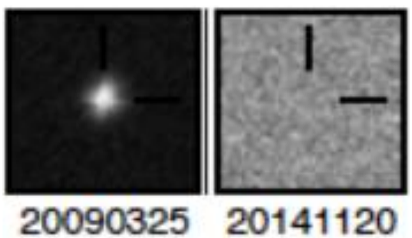
(b) Fading massive stars
10—40%

(c) BH masses
20—30%

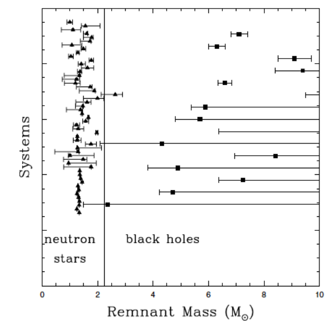
(d) Nucleosynthetic constraints
0% failed SNe



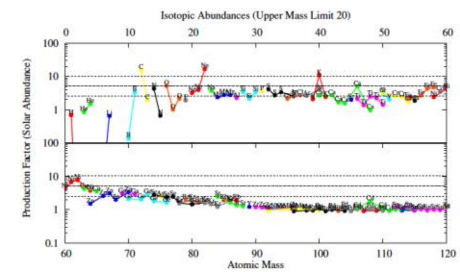
Horiuchi et al. (2011)



Gerke et al. (2015)



Kochanek et al. (2014)



Brown & Woosley (2013)

2) M_{ZAMS} of exploding stars

a) Direct imaging of progenitor stars for SNe → M_{ZAMS} distribution

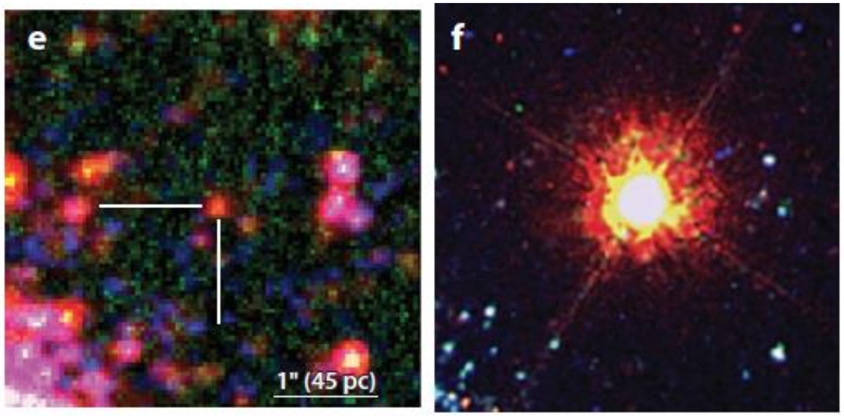
b) Age dating of stellar population around SNRs → M_{ZAMS} distribution

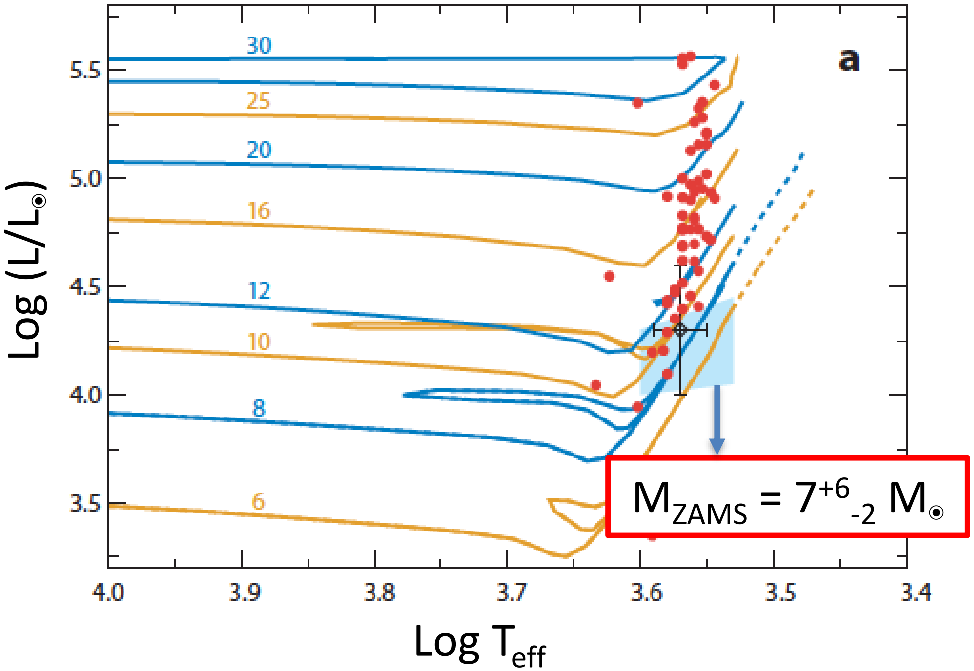
Direct Imaging of Progenitors

Pre-explosion

Post-explosion

SN 2003gd

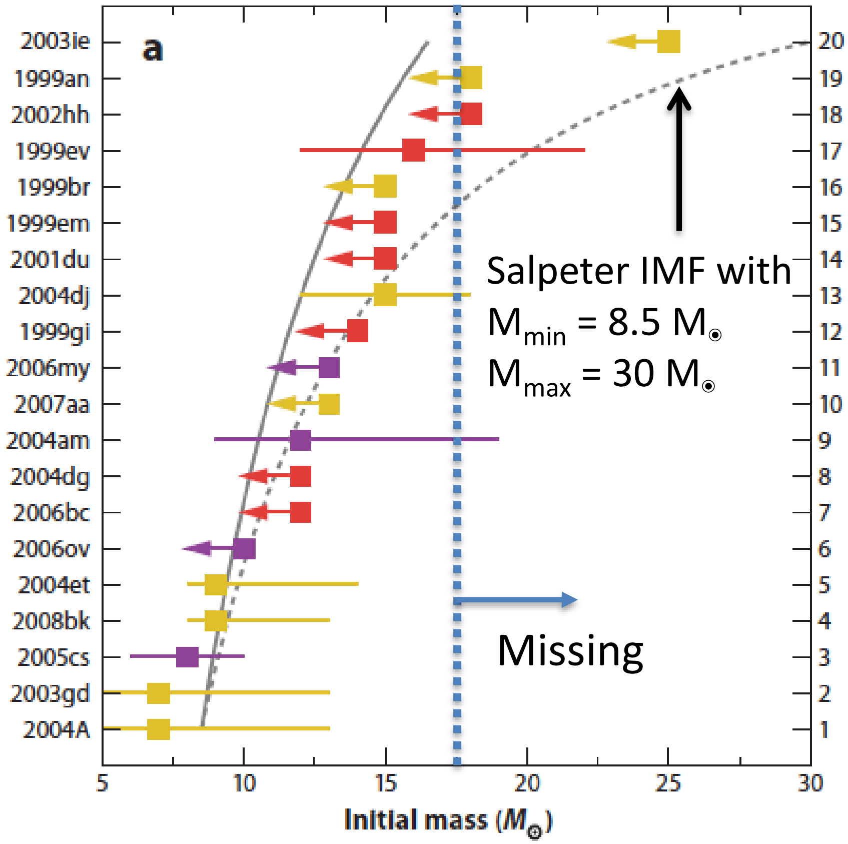




So far, ~30 detections of precursor objects (Van Dyk 2017).

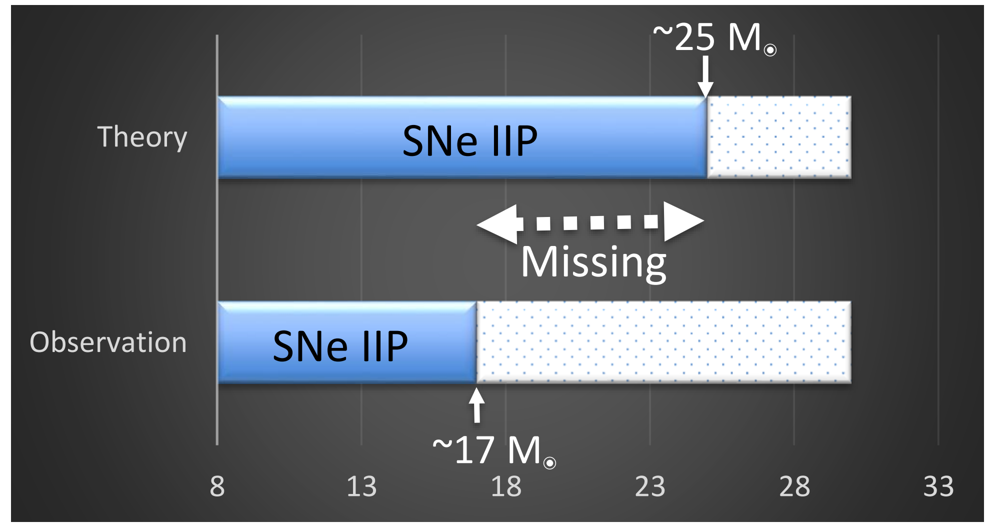
Red Supergiant Problem

M_{ZAMS} for Type IIP SNe



Smartt (2009)

The RSG problem

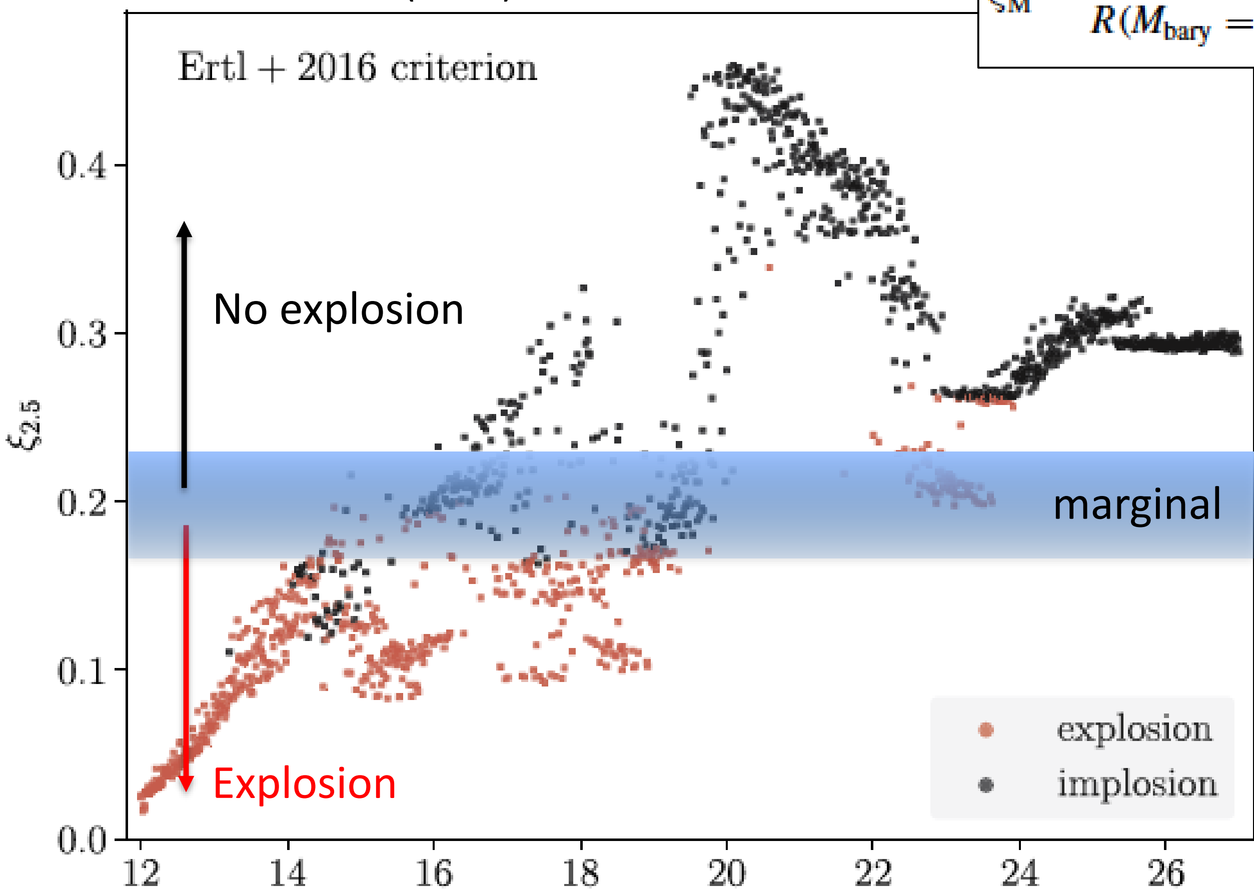


Progenitor mass, M_{ZAMS} ($M_\odot$)

Explodability and Compactness ($\xi_{2.5}$)

$$\xi_M = \frac{M/M_\odot}{R(M_{bary} = M)/1000\ \mathrm{km}}\Bigg|_{t_{bounce}}$$

Sukhbold et al. (2018)



Critical $\xi_{2.5}$ ~ 0.2 for 1D simulations

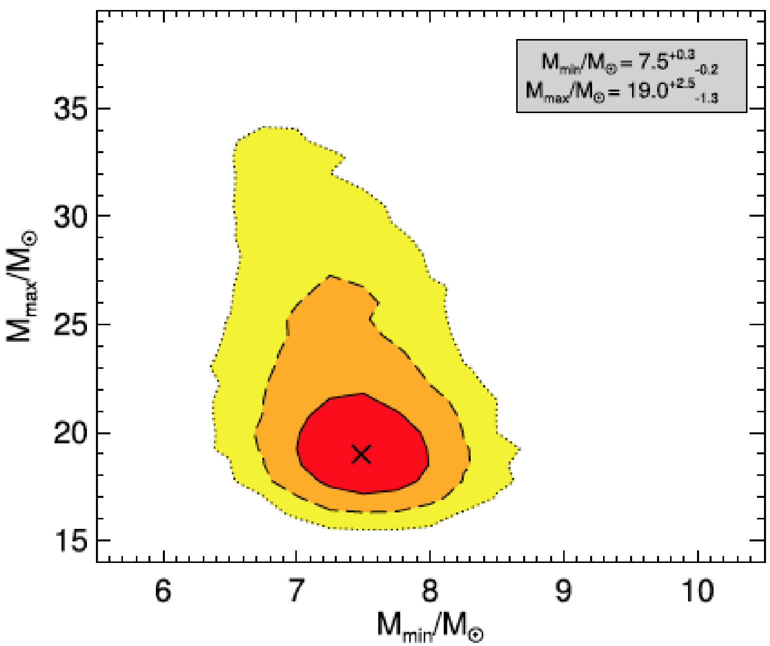
No explosion

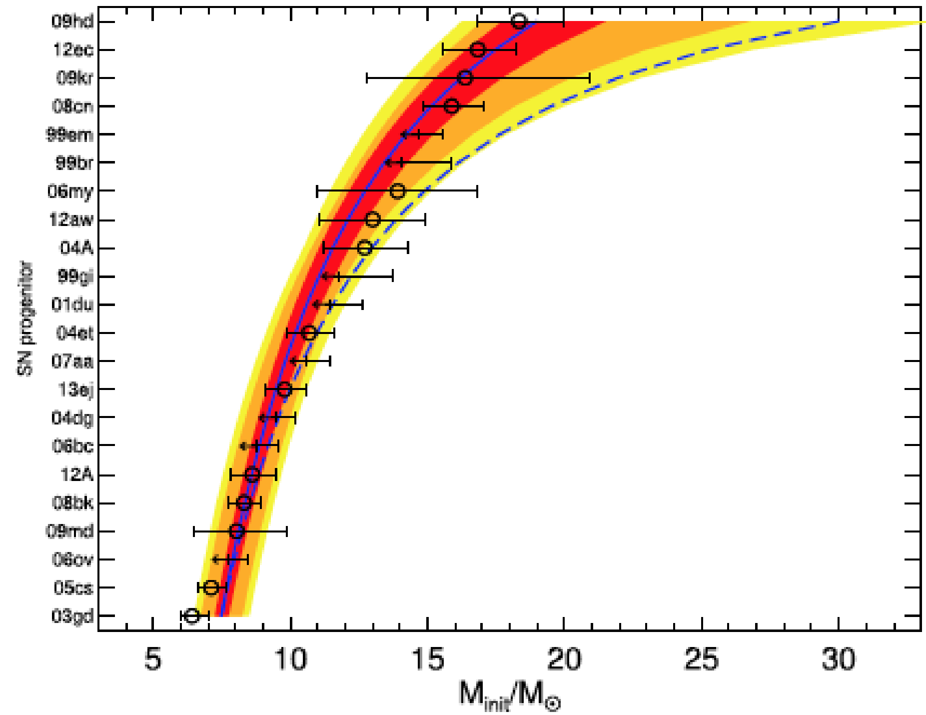
But Still Debated…

A systematic error: RSGs evolve to later spectral type as they approach SNe, resulting in underestimates of a star's luminosity (and its mass) if this effect is ignored.

Reappraisal increased the high-mass cutoff to be $19.0^{+2.5}_{-1.3}$ $M_\odot$ → could be even higher up to 25 $M_\odot$ by considering other systematic errors.

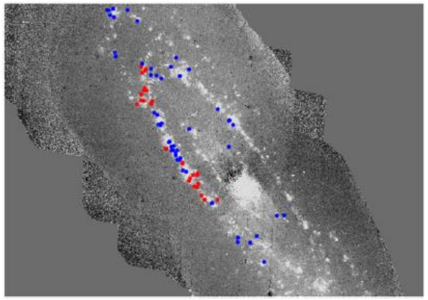
Davies & Beasor (2018)



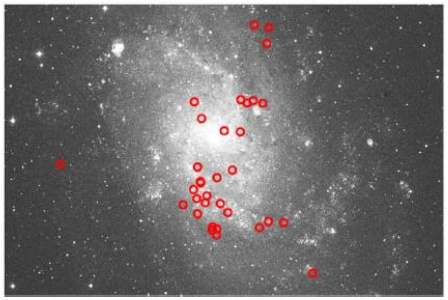


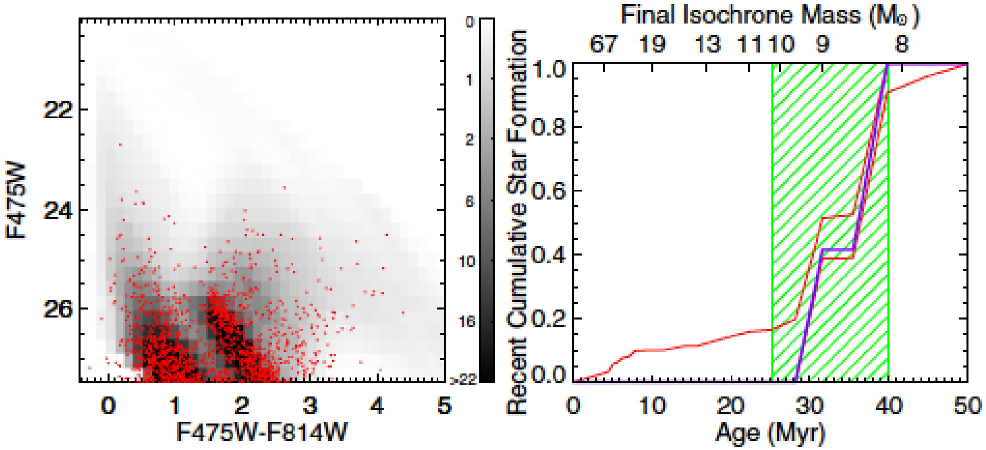
Age Dating of Stellar Population around Supernova Remnants

M31

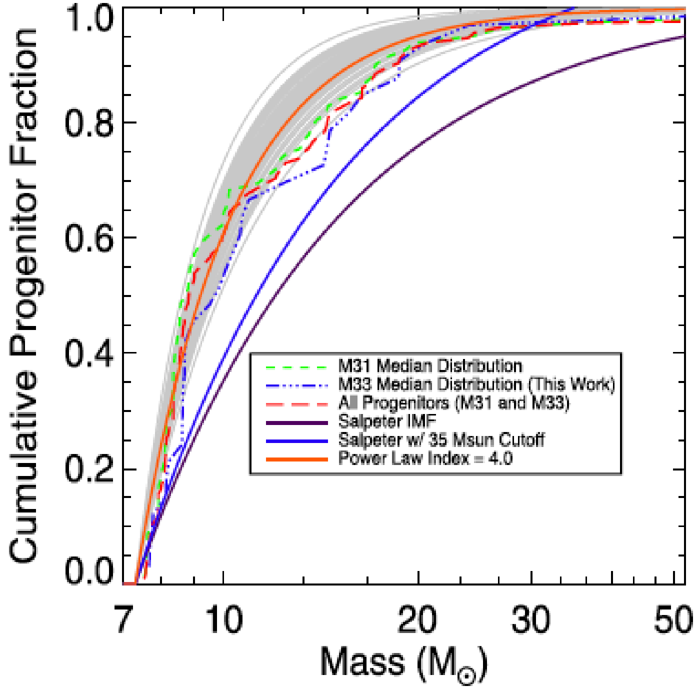


M33





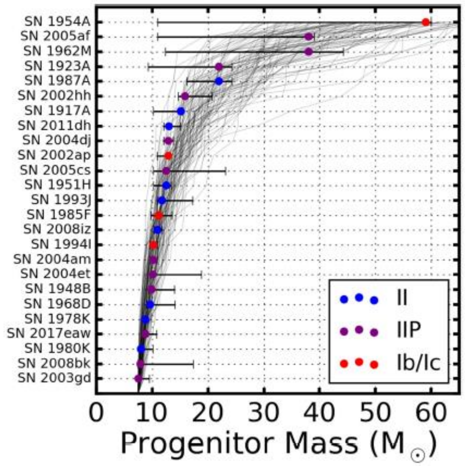
Jennings et al. (2012; 2014)



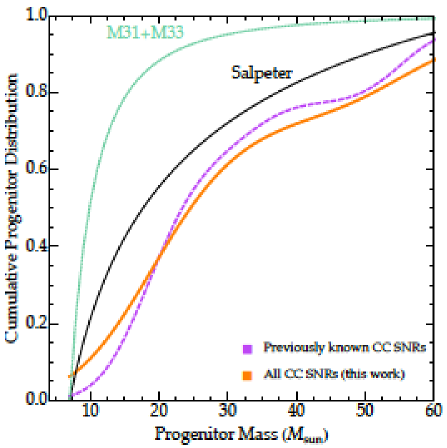
→ Steeper-than-Salpeter distribution, confirming the RSG problem (i.e., the most massive stars are missing).

But Still Debated...

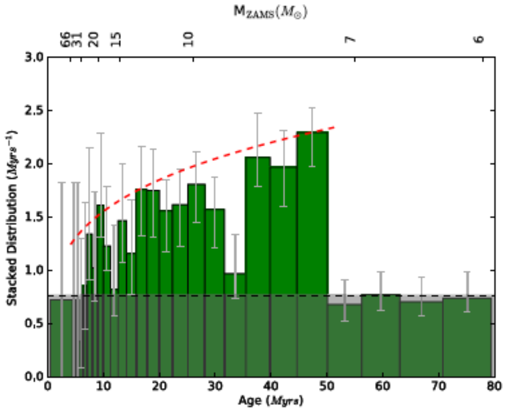
- Stellar population analyses for
  - Nearby historical SNe → standard Salpeter IMF
  - 23 SNRs in the SMC → standard Salpeter IMF
  - 94 SNRs in M31 & M33 → slightly steeper-than-Salpeter IMF



Williams et al. (2018)



Auchettl et al. (2018)

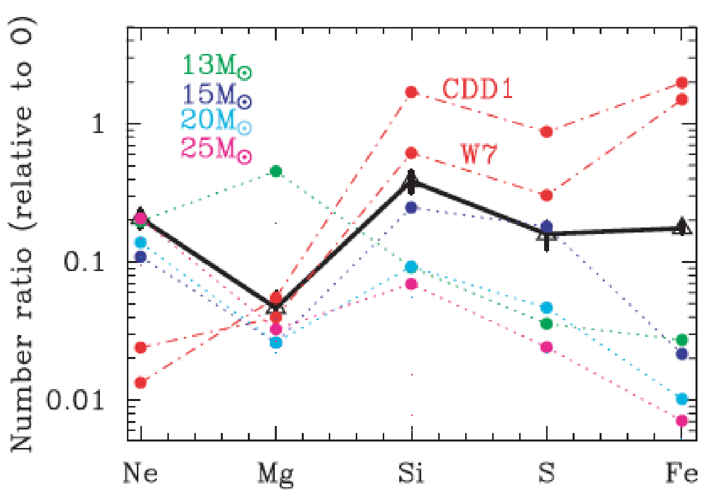


Diaz-Rodriguez et al. (2018)

Our Aim: M_{ZAMS} for Galactic & MC SNRs

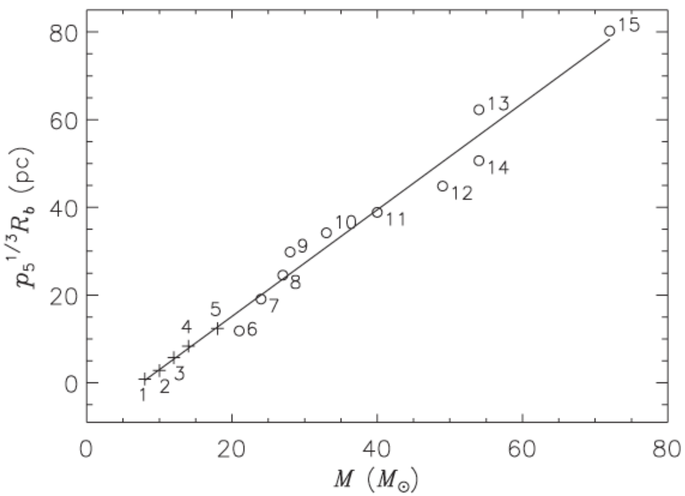
- A lot of estimates have been performed for individual SNRs, but these data were not summarized yet.
- Two kinds of measurements:

1) Elemental abundances of the SN ejecta



Tsunemi, SK, Nemes, & Miller (2007)

2) The size of stellar-wind bubble



Chen et al. (2013)

Progenitor Masses in the Literature

SNR	Age (years)	M_{ZAMS} ($M_{\odot}$)
*** Galactic SNRs ***		
Cassiopeia A	~340 (1)	15–20 (2)
Kes 73	~750 (4)	20–30 (5)
G350.1-0.3	~900 (6)	15–25 (7)
RX J1713.7-3946	~1600 (8)	$\lesssim$15 (9)
MSH 15-52	~1700 (10)	N.A.
G292.2-0.5	~1900 (12)	25–30 (13)
RCW103	~2000 (14)	18–20 (15)
G349.7+0.2	~2800 (16)	35–40 (7)
G292.0+1.8	~3000 (17)	30–35 (18)
Puppis A	~4500	15–25 (19)
Kes 79	4400–6700 (21)	30–40 (22)
Cygnus Loop	~10000 (23)	$\lesssim$15 (24)
Sgr A East	~10000 (26)	13–20 (26,27)
MSH 15-56	~11000 (29)	N.A.
IC443	3000–30000 (31,32)	~25 (33)
G290.1-0.8	10000–20000 (35)	20–25 (36)
3C391	~19000 (37)	~15 (38)
W44	20000 (39)	8–15 (40)
G284.3-1.8	~21000 (42)	>25 (43)
G156.2+5.7	20000–30000 (44)	$\lesssim$15 (45)
3C400.2	~100000 (47)	N.A.
3C396	~3000 (49)	13–15 (49)
G15.9+0.2	2000–6000 (50)	20–25 (50)
Kes 17	2000–40000 (51)	25–30 (52)
CTB109	~14000 (53)	30–40 (54)
G116.9+0.2 (CTB1)	~16000 (55)	13–15 (56)
G296.1-0.5	~28000 (57)	25–30 (57)
W51C	~30000 (58)	$\gtrsim$20 (59)
*** LMC SNRs ***		
N132D	~2500 (60)	~50 (61)
N63A	2000–5000 (63)	N.A.
N23	~4000 (65)	N.A.
N49	~4800 (67)	N.A.
N49B	~10000 (63)	>25 (68,69)
B0453-68.5	12000–15000 (70)	N.A.
30 Dor C	4000–20000 (71)	N.A.
Honeycomb	N.A.	N.A.
*** SMC SNRs ***		
1E0102.2-7219	~2050 (72)	25–35 (73)
IKT2	N.A.	N.A.
DEM S32	N.A.	N.A.
IKT6	~14000 (76)	13–15 (77)
IKT23	~18000 (79)	~18 (79)

Fractions of massive stars

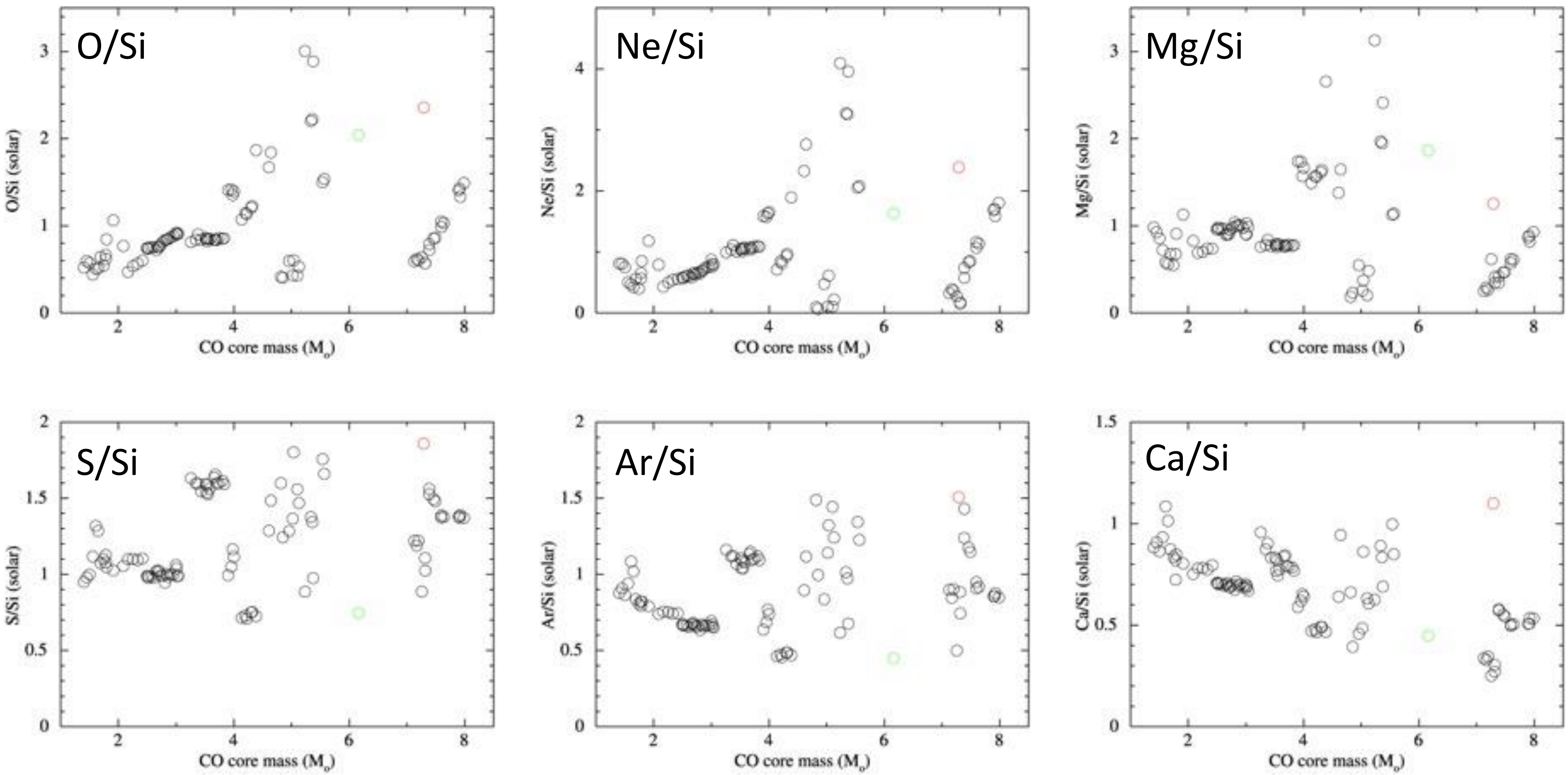
f ($M<15M_{\odot}$)	f ($15–22.5M_{\odot}$)	f ($M>22.5M_{\odot}$)
0.27	0.27	0.46

Top-heavy mass distribution?!
→ Is this correct??

Problem with Previous Measurements

- Previous mass estimates used several elements such as Ne/Si, Mg/Si, Ar/Si, or Fe/Si.
- However, these abundance ratios except for Si/Fe are never sensitive to the progenitor masses (see, the next two slides).
- Only Si/Fe is sensitive to CO core masses of progenitor stars.
- Therefore, we re-estimated progenitor masses based on Si/Fe ratio from a recent nucleosynthesis model (Sukhbold et al. 2016).

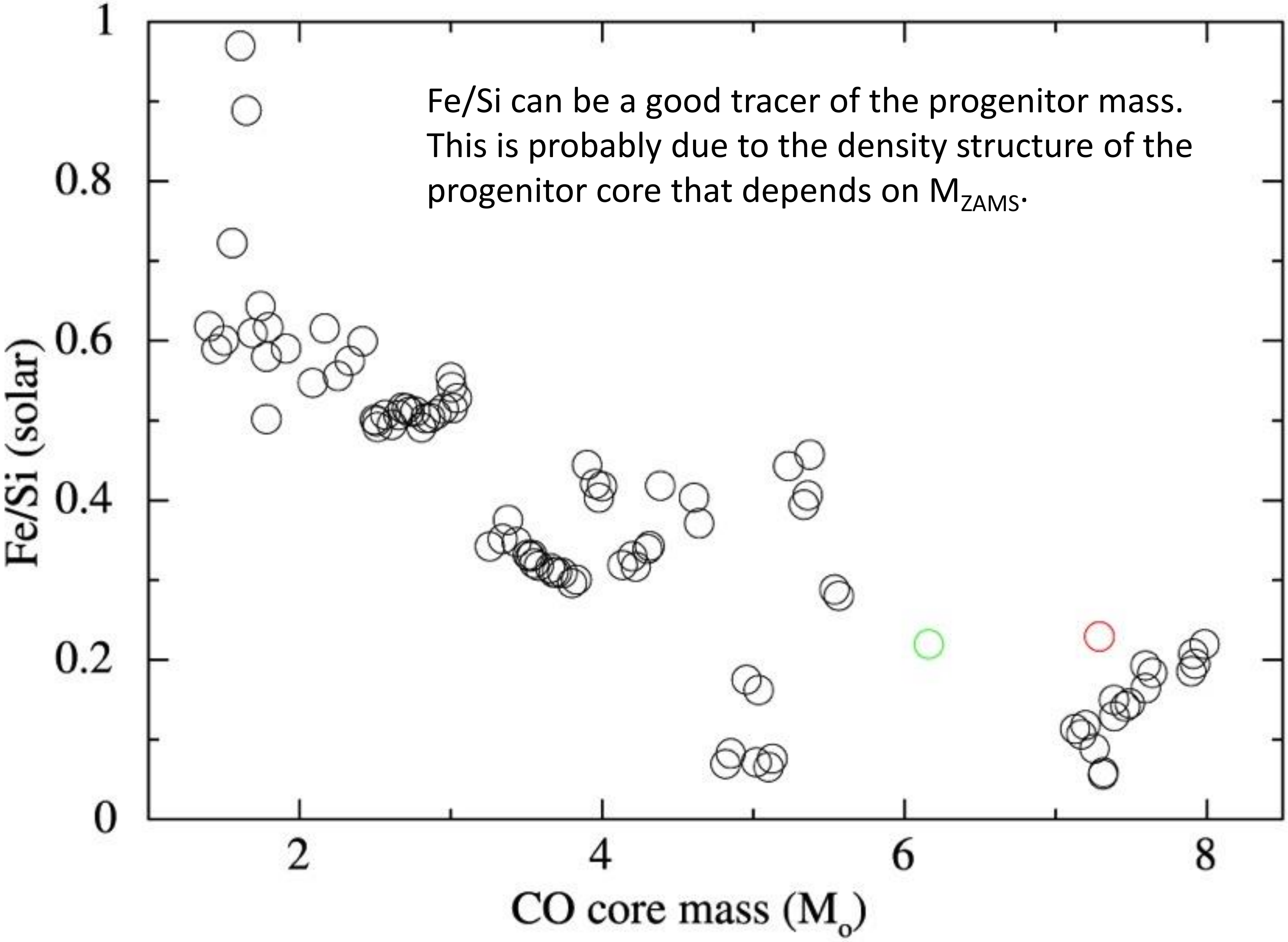
X/Si vs. CO Core Mass (Sukhbold+2016)



Black: ZAMS = 9.0--28 $M_\odot$; Red: ZAMS = 60 $M_\odot$; Green: ZAMS = 120 $M_\odot$

→ These abundance ratios are never sensitive to the progenitor masses (or core masses).

Fe/Si vs. CO Core Mass (Sukhbold+2016)

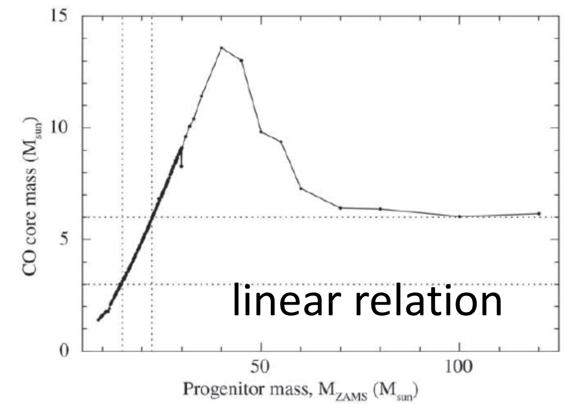


The Progenitor Mass Distribution Revised

CO core — ZAMS

SNR	Age (years)	M_{ZAMS} ($M_\odot$)	$(Fe/Si)/(Fe/Si)_\odot$	Revised M_{COcore} ($M_\odot$)	Revised M_{ZAMS} ($M_\odot$)[a]
*** Galactic SNRs ***					
Cassiopeia A	~340 (1)	15–20 (2)	1.0 ± 0.1 (3)	<3	<15
Kes 73	~750 (4)	20–30 (5)	$0.8^{+1.0}_{-0.3}$ (5)	<3	<15[m1]
G350.1-0.3	~900 (6)	15–25 (7)	0.35 ± 0.05 (7)	3–6	15–22.5 [m1]
RX J1713.7-3946	~1600 (8)	≲15 (9)	<0.03 (9)	>6	>22.5
MSH 15-52	~1700 (10)	N.A.	0.78 ± 0.09 (11)	<3	<15
G292.2-0.5	~1900 (12)	25–30 (13)	$0.59^{+0.62}_{-0.48}$ (13)	<3	<15[m1,m2]
RCW103	~2000 (14)	18–20 (15)	$1.33^{+0.27}_{-0.14}$ (15)	<3	<15
G349.7+0.2	~2800 (16)	35–40 (7)	$0.56^{+0.09}_{-0.10}$ (7)	<3	<15[m1]
G292.0+1.8	~3000 (17)	30–35 (18)	0.55 ± 0.24 (18)	<3	<15[m1,m2]
Puppis A	~4500	15–25 (19)	0.63 ± 0.05 (20)	<3	<15
Kes 79	4400–6700 (21)	30–40 (22)	$0.35^{+0.04}_{-0.05}$ (22)	3–6	15–22.5 [m1]
Cygnus Loop	~10000 (23)	≲15 (24)	0.7 ± 0.1 (25)	<3	<15
Sgr A East	~10000 (26)	13–20 (26,27)	$0.26^{+0.12}_{-0.06}$ (28)	3–6	15–22.5 [m1,m2]
MSH 15-56	~11000 (29)	N.A.	0.37 ± 0.11 (30)	3–6	15–22.5 [m1]
IC443	3000–30000 (31,32)	~25 (33)	0.25 ± 0.10 (34)	3–6	15–22.5 [m1,m2]
G290.1-0.8	10000–20000 (35)	20–25 (36)	0.11 ± 0.06 (36)	>6	>22.5
3C391	~19000 (37)	~15 (38)	<0.06 (38)	>6	>22.5
W44	20000 (39)	8–15 (40)	0.03 ± 0.01 (41)	>6	>22.5[m2]
G284.3-1.8	~21000 (42)	>25 (43)	$0.59^{+1.59}_{-0.36}$ (43)	<3	<15[m1,m2]
G156.2+5.7	20000–30000 (44)	≲15 (45)	0.37 ± 0.1 (45,46)	3–6	15–22.5 [m1]
3C400.2	~100000 (47)	N.A.	$5.3^{+3.1}_{-2.1}$ (48)	<3	<15
3C396	~3000 (49)	13–15 (49)	N.A.	N.A.	N.A.
G15.9+0.2	2000–6000 (50)	20–25 (50)	N.A.	N.A.	N.A.
Kes 17	2000–40000 (51)	25–30 (52)	N.A.	N.A.	N.A.
CTB109	~14000 (53)	30–40 (54)	N.A.	N.A.	N.A.
G116.9+0.2 (CTB1)	~16000 (55)	13–15 (56)	N.A.	N.A.	N.A.
G296.1-0.5	~28000 (57)	25–30 (57)	N.A.	N.A.	N.A.
W51C	~30000 (58)	≳20 (59)	N.A.	N.A.	N.A.
*** LMC SNRs ***					
N132D	~2500 (60)	~50 (61)	$0.48^{+0.14}_{-0.15}$ (62)	<3	<15[m1]
N63A	2000–5000 (63)	N.A.	0.87 ± 0.13 (64)	<3	<15
N23	~4000 (65)	N.A.	0.38 ± 0.13 (66)	3–6	15–22.5 [m1]
N49	~4800 (67)	N.A.	0.18 ± 0.01 (66)	>6	>22.5[m2]
N49B	~10000 (63)	>25 (68,69)	1.03 ± 0.07 (66)	<3	<15
B0453-68.5	12000–15000 (70)	N.A.	$0.42^{+0.17}_{-0.16}$ (64)	3–6	15–22.5 [m1,m2]
30 Dor C	4000–20000 (71)	N.A.	$0.08^{+0.20}_{-0.06}$ (71)	>6	>22.5[m2]
Honeycomb	N.A.	N.A.	$0.17^{+0.13}_{-0.10}$ (64)	>6	>22.5[m2]
*** SMC SNRs ***					
1E0102.2-7219	~2050 (72)	25–35 (73)	$0.63^{+0.26}_{-0.20}$ (74)	<3	<15[m1]
IKT2	N.A.	N.A.	0.32 ± 0.24 (75)	3–6	15–22.5 [m1,m2]
DEM S32	N.A.	N.A.	0.28 ± 0.26 (75)	3–6	15–22.5 [m1,m2]
IKT6	~14000 (76)	13–15 (77)	$0.26^{+0.16}_{-0.07}$ (78)	3–6	15–22.5 [m1,m2]
IKT23	~18000 (79)	~18 (79)	$0.48^{+0.14}_{-0.25}$ (78)	<3	<15[m1,m2]

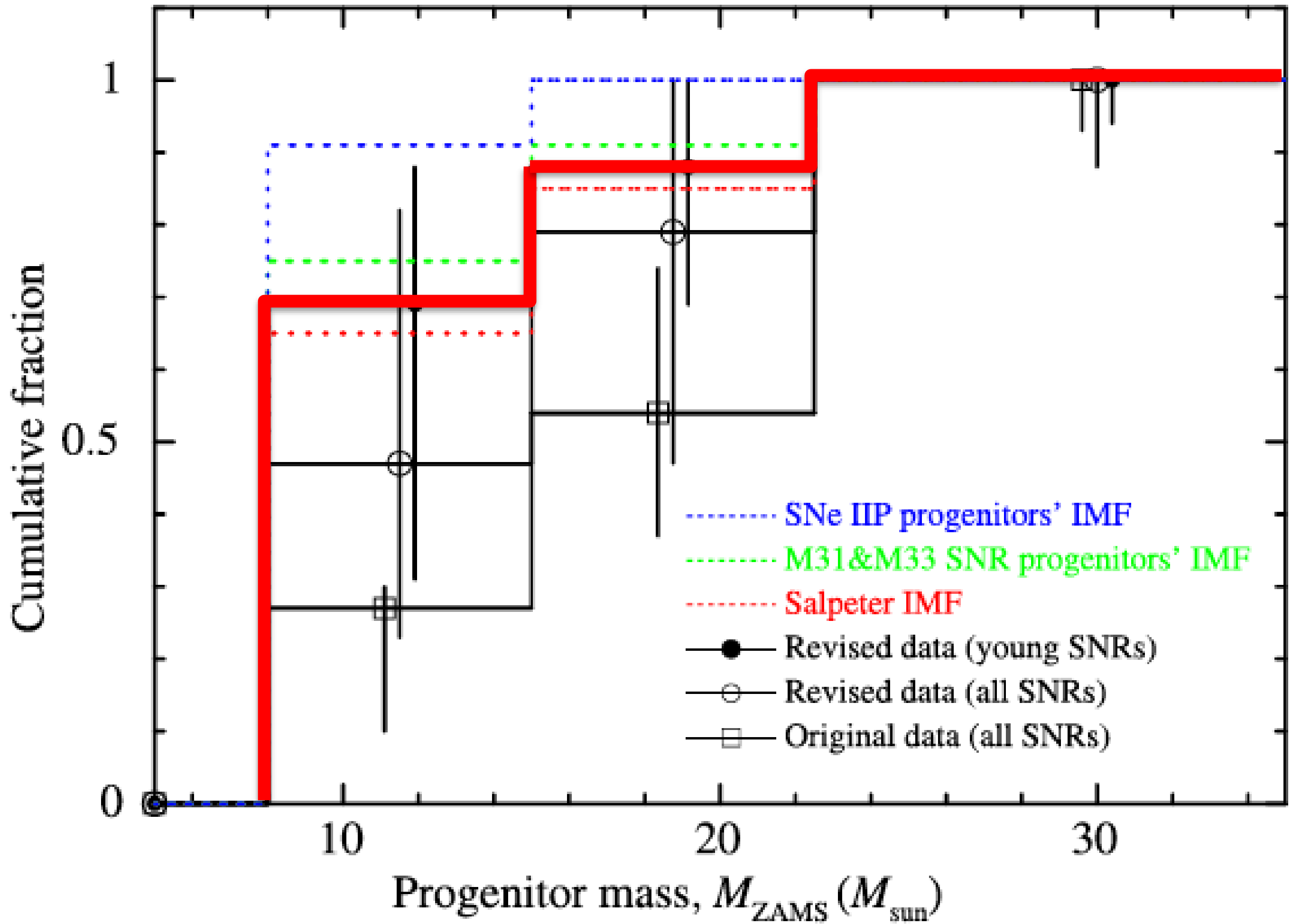
M_{COcore} → M_{ZAMS} conversion



M_{COcore} ($M_\odot$)	↔	M_{ZAMS} ($M_\odot$)
< 3	↔	< 15
3 – 6	↔	15 – 22.5
> 6	↔	> 22.5

for single star systems

Progenitor Mass Distribution



The revised progenitor mass distribution is consistent with a standard Salpeter IMF!

Summary

- We have derived a progenitor mass distribution based on elemental abundances for core-collapse SNRs in our Galaxy and Magellanic Clouds, for the first time.
- A simple compilation of the progenitor masses in the literature gave a top-heavy mass distribution.
- We realized, however, that only the Fe/Si ratio is sensitive to the progenitor mass (CO core mass), and revised all the previous mass estimates.
- As a result, we found the mass distribution is consistent with a Salpeter IMF.
- It should be noted that the mass distribution could be affected by binary evolution, which is not taken into account in our study. Even if we ignore binary effects, we can argue that progenitors with massive CO cores do explode.
- In the era of XRISM (to be launched in 2022), Fe/O ratios will be another good probe to infer the progenitor masses.

The Astrophysical Journal (2018), 863, 127

M_{ZAMS}: Also Important to SN Types

$$80\ M_\odot < M < 150\ M_\odot:\ \mathrm{O} \rightarrow \mathrm{LBV} \rightarrow \mathrm{SN\ IIn(?)}, \quad (1)$$

$$40 M_\odot < M < 80 M_\odot:\ \mathrm{O} \rightarrow \mathrm{LBV} \rightarrow \mathrm{WN} \rightarrow \mathrm{WC/WO} \rightarrow \mathrm{SN\ Ic}, \quad (2)$$

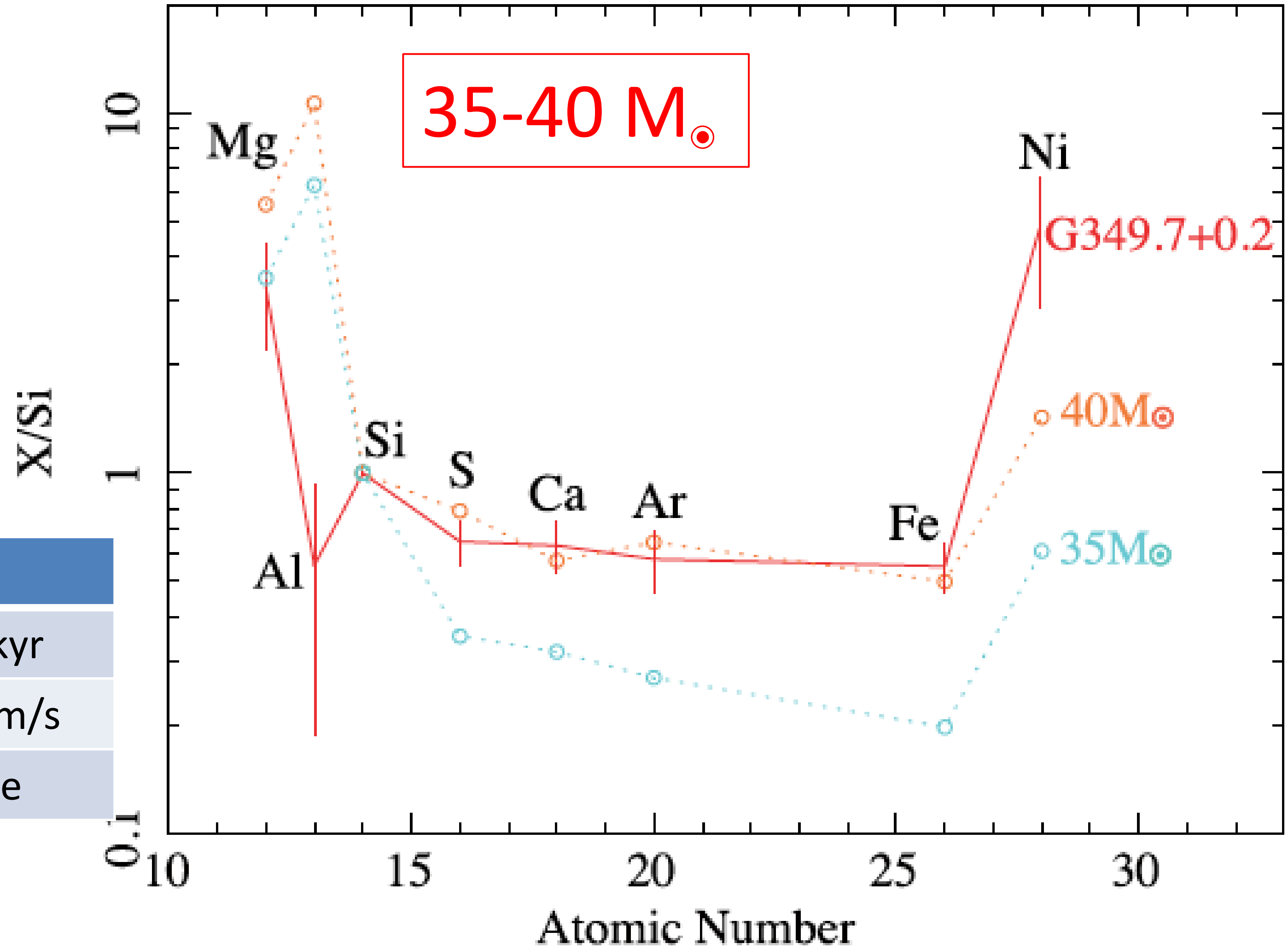
$$25\ M_\odot < M < 40\ M_\odot:\ \mathrm{O} \rightarrow \mathrm{LBV} \rightarrow \mathrm{(early)WN} \rightarrow \mathrm{SN\ Ib}, \quad (3)$$

$$15\ M_\odot < M < 25\ M_\odot:\ \mathrm{O} \rightarrow \mathrm{RSG} \rightarrow \mathrm{(late)WN} \rightarrow \mathrm{SN\ II-L/IIb}, \quad (4)$$

$$8\ M_\odot < M < 15\ M_\odot:\ \mathrm{B/O} \rightarrow \mathrm{RSG} \rightarrow \mathrm{SN\ II-P}. \quad (5)$$

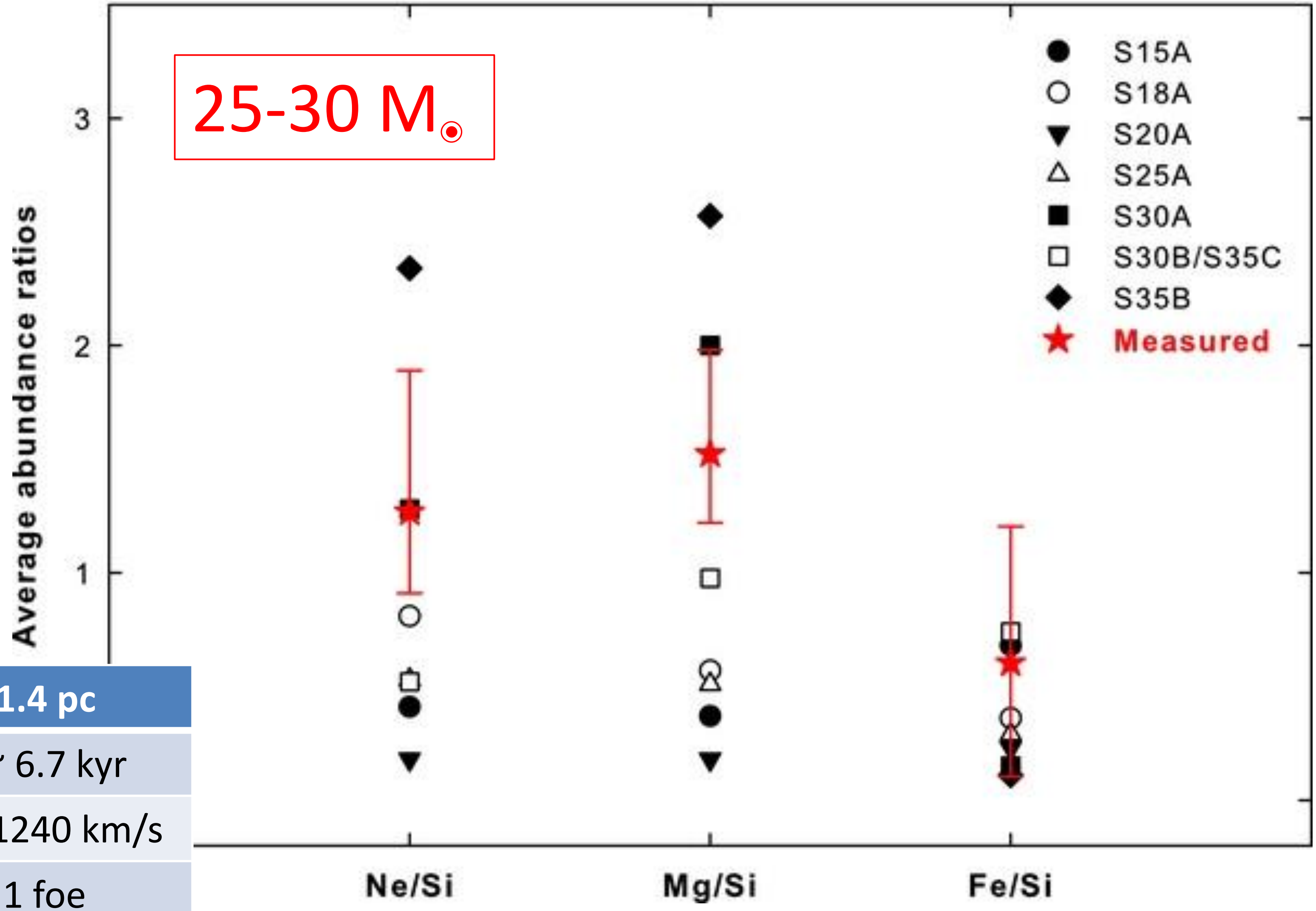
From Gal-Yam et al. (2007)

G349.7+0.2 (Yasumi+14)



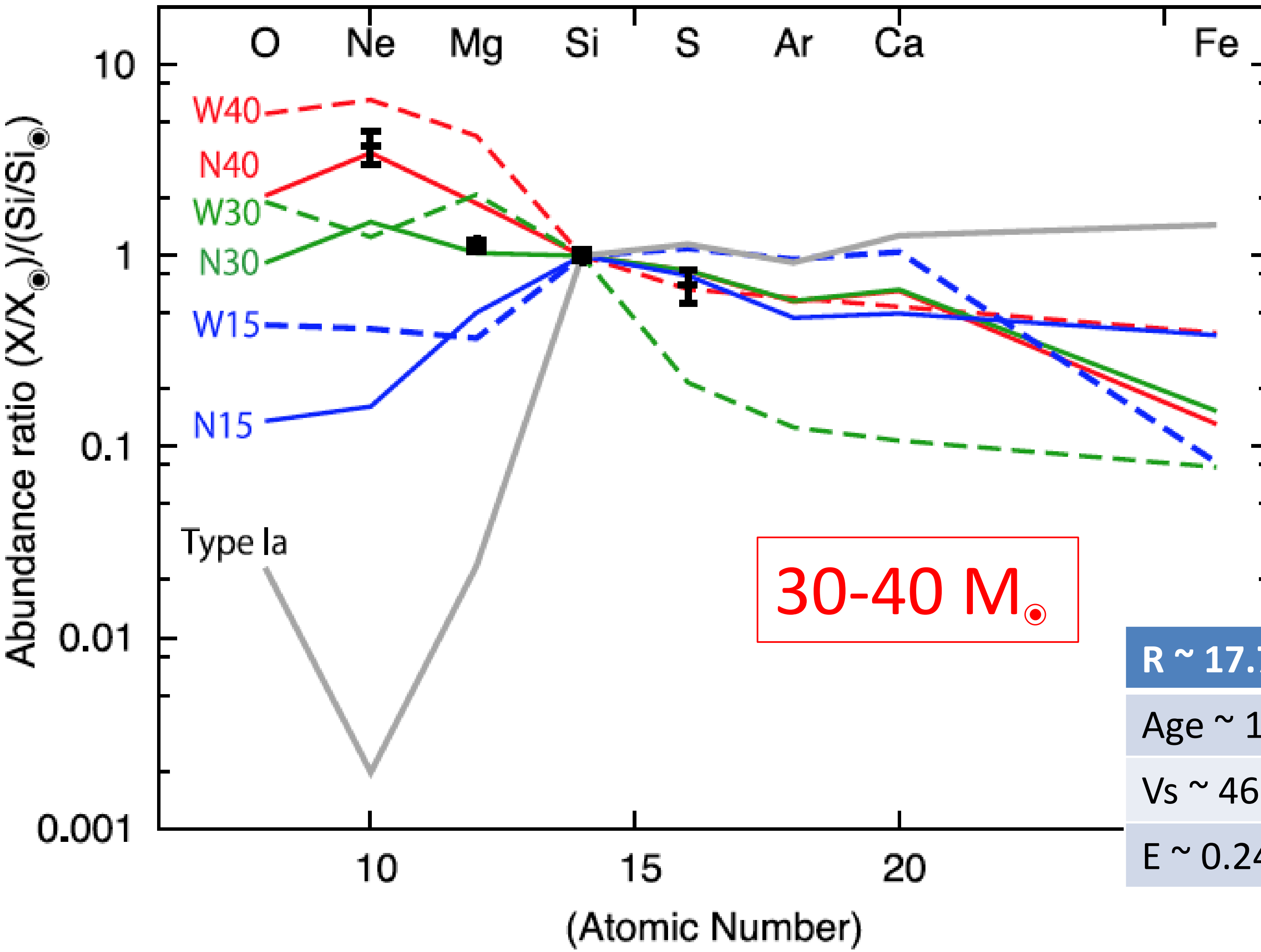
R ~ 8.3 pc
Age ~ 4.6 kyr
Vs ~ 720 km/s
E ~ 0.06 foe

G292.2-0.5 (Kumar+12)



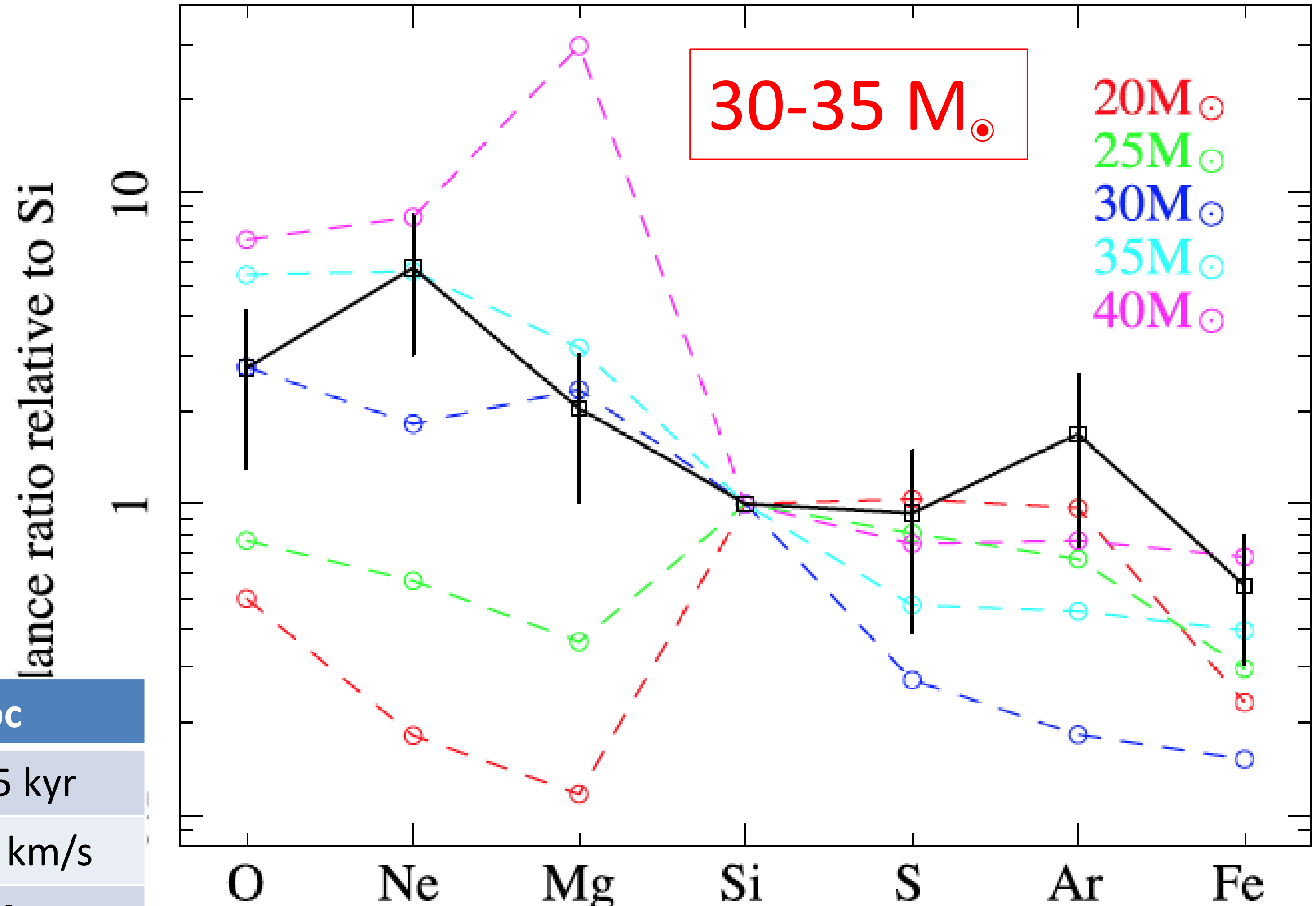
R ~ 21.4 pc
Age ~ 6.7 kyr
Vs ~ 1240 km/s
E ~ 3.1 foe

CTB 109 (Nakano+17)



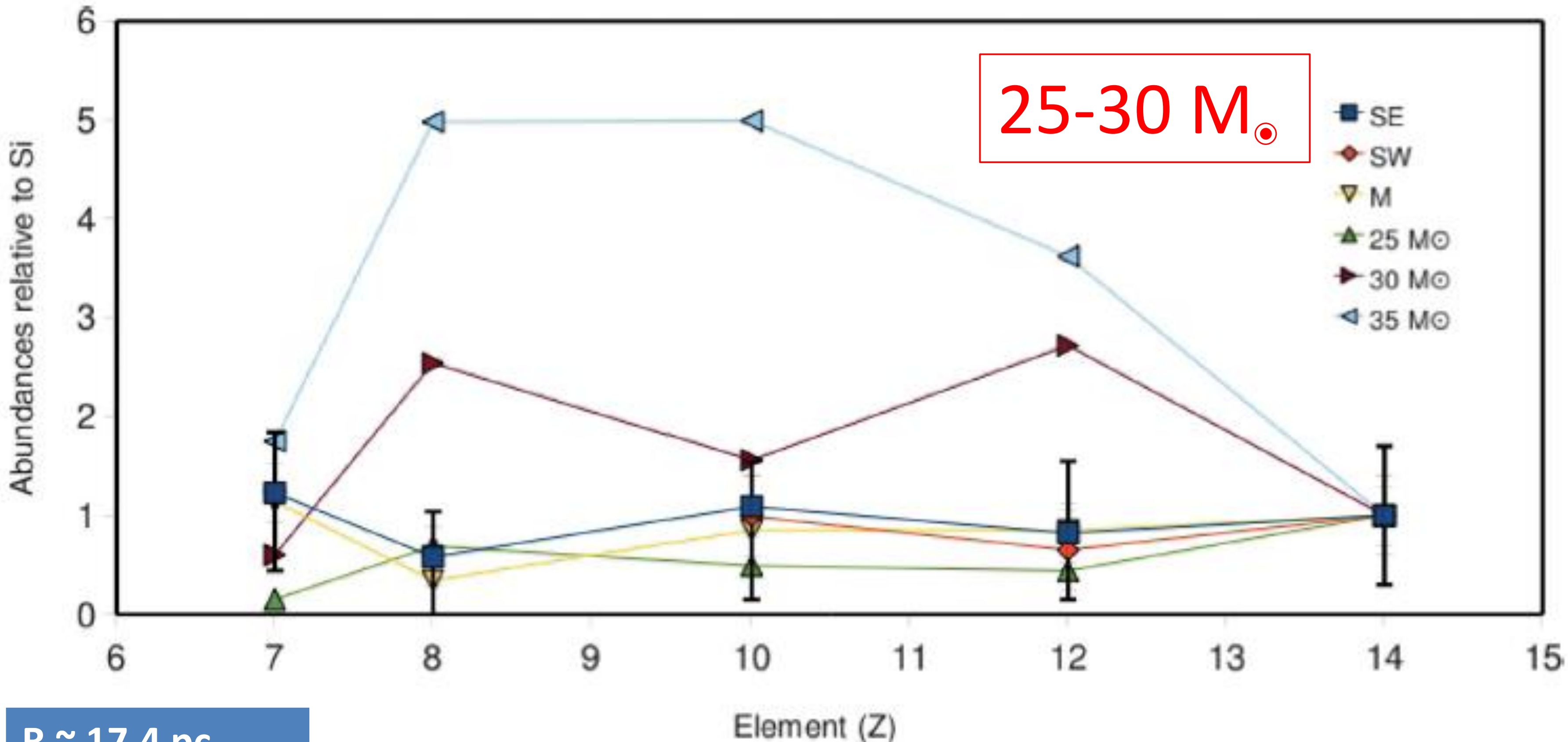
R ~ 17.7 pc
Age ~ 15.1 kyr
Vs ~ 460 km/s
E ~ 0.24 foe

G292.0+1.8 (Kamitsukasa+14)



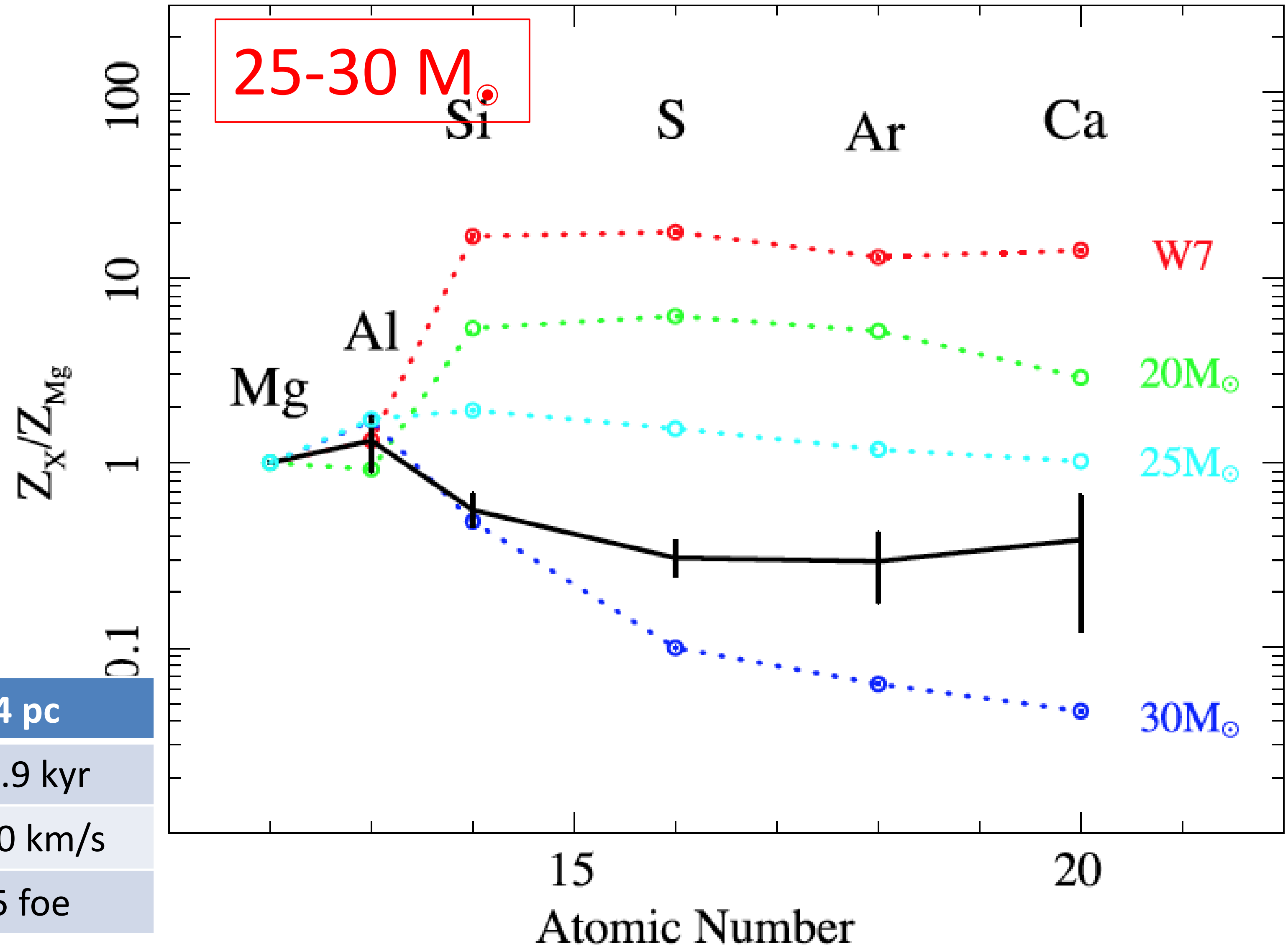
R ~ 7.5 pc
Age ~ 3.5 kyr
Vs ~ 830 km/s
E ~ 0.06 foe

G296.1-0.5 (Gok&Sezer12)



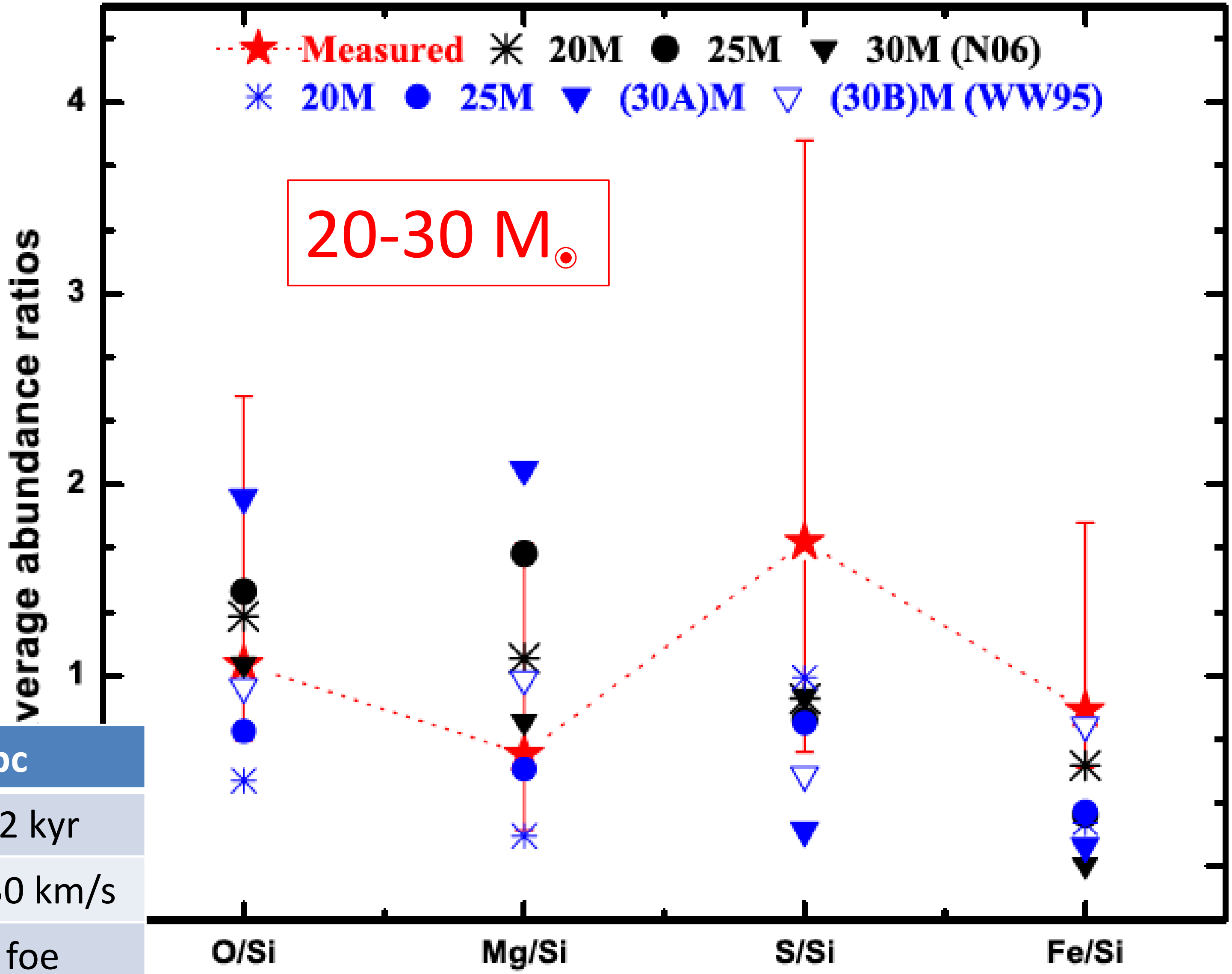
R ~ 17.4 pc
Age ~ 10.5 kyr
Vs ~ 650 km/s
E ~ 0.47 foe

Kes 17 (Washino+16)



R ~ 17.4 pc
Age ~ 8.9 kyr
Vs ~ 770 km/s
E ~ 0.65 foe

Kes 73 (Kumar+14)



R ~ 6.2 pc
Age ~ 2.2 kyr
Vs ~ 1130 km/s
E ~ 0.06 foe

G284.3-1.8 (Williams+15)

- Mg/O ~ 4.5 solar → Very massive (>25$M_\odot$) star

R ~ 15.7 pc
Age ~ 8.0 kyr
Vs ~ 770 km/s
E ~ 0.48 foe

W51C (Sasaki+14)

- M_{Ne} ~ 2.9 $M_\odot$
- M_{Mg} ~ 0.3 $M_\odot$

} >20 $M_\odot$

R ~ 52.3 pc
Age ~ 26.7 kyr
Vs ~ 770 km/s
E ~ 17.7 foe

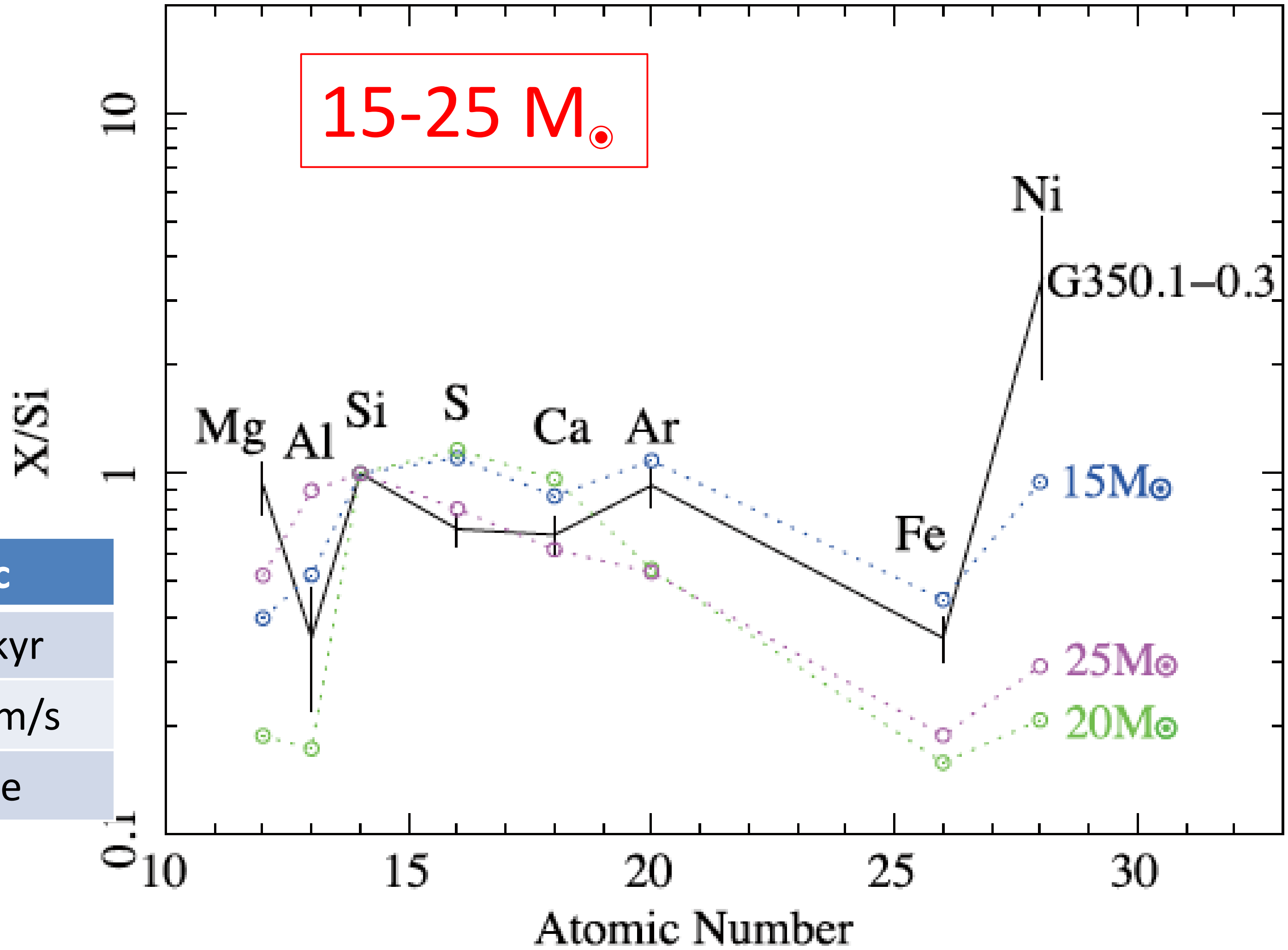
IC 443 (Troja+08)

- Mg/Si: 2.1 +1.4 -0.7
- S/Si: 1.0 +/- 0.4
- Fe/Si: < 0.018

} 25 $M_{\odot}$

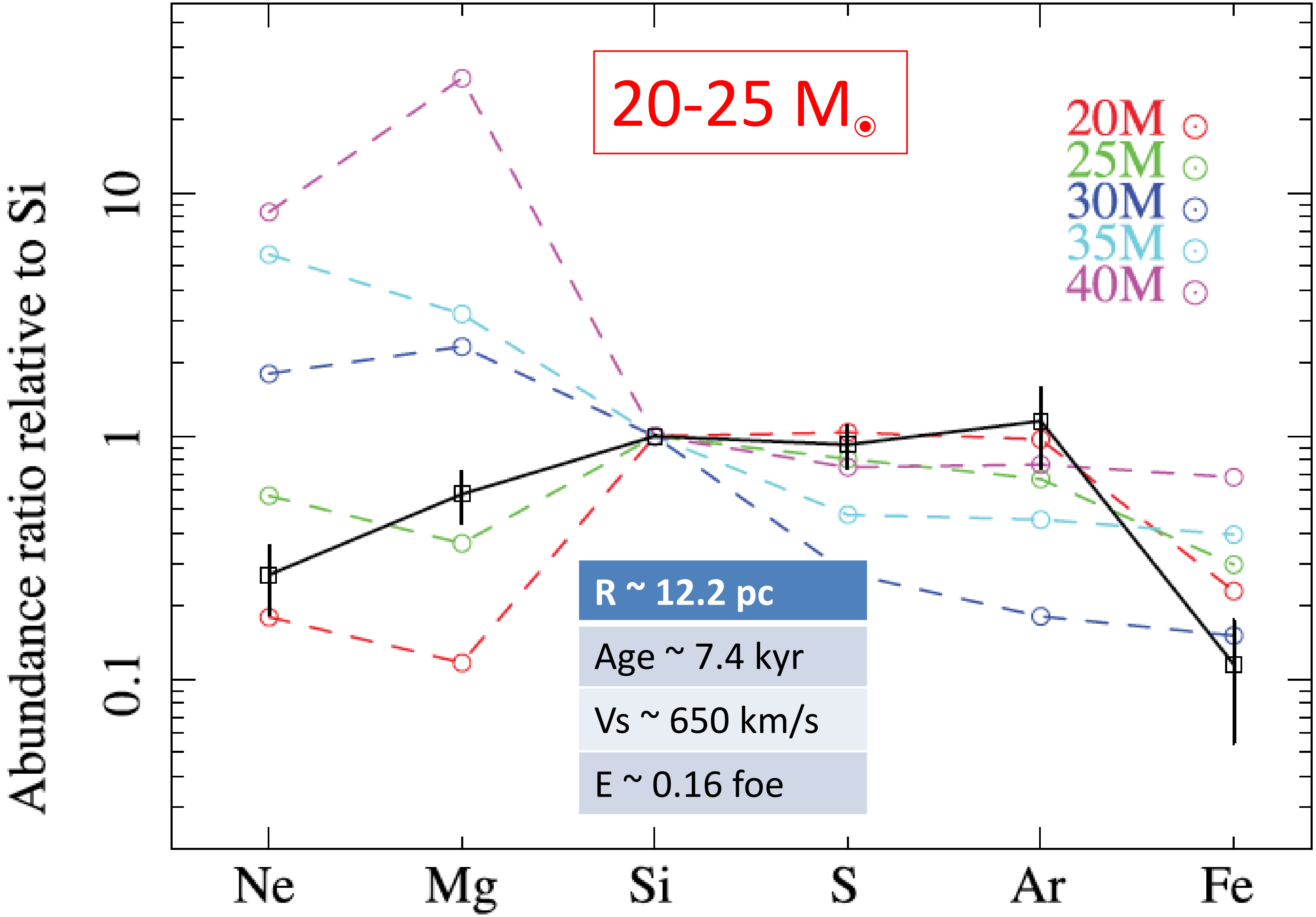
R ~ 15.3 pc
Age ~ 8.4 kyr
Vs ~ 720 km/s
E ~ 0.38 foe

350.1-0.3 (Yasumi+14)

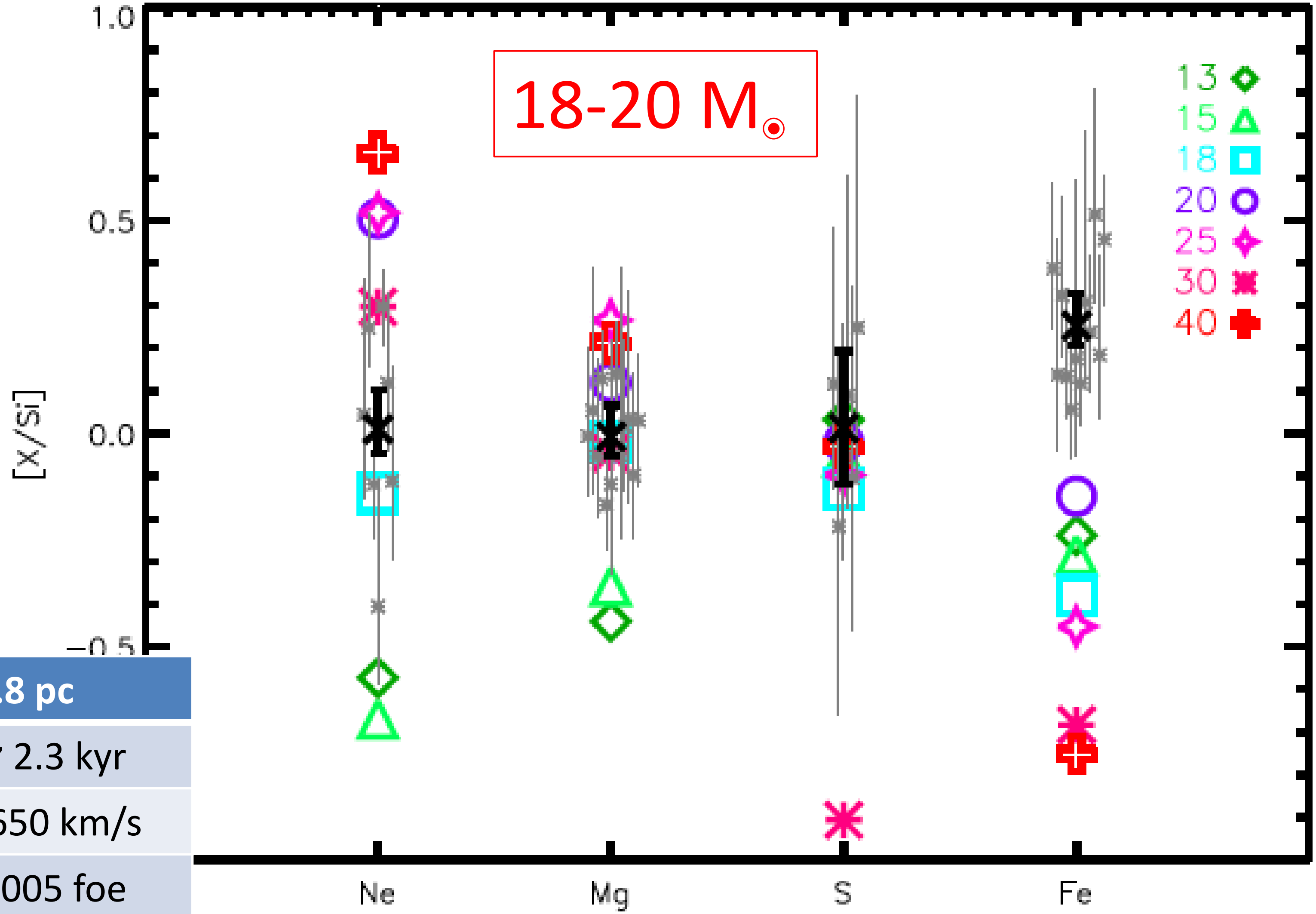


R ~ 10.5 pc
Age ~ 6.4 kyr
Vs ~ 640 km/s
E ~ 0.10 foe

G290.1-0.8 (Kamitsukasa+15)

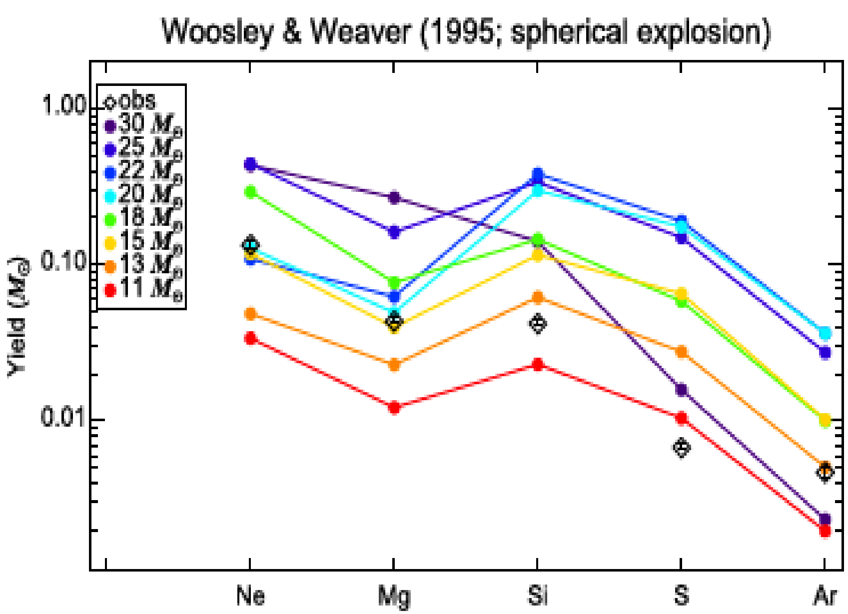


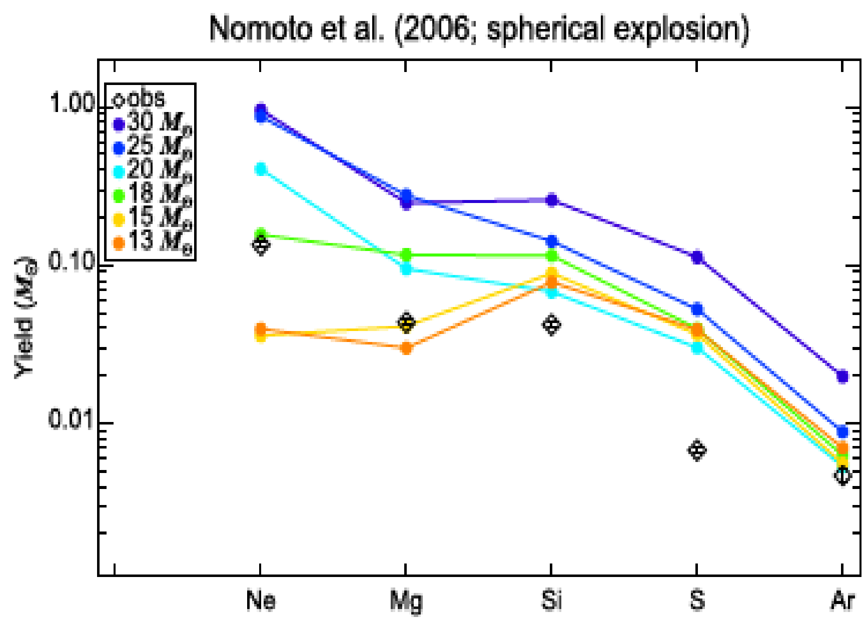
RCW 103 (Frank+15)



R ~ 3.8 pc
Age ~ 2.3 kyr
Vs ~ 650 km/s
E ~ 0.005 foe

Kes 79 (Zhou+16)

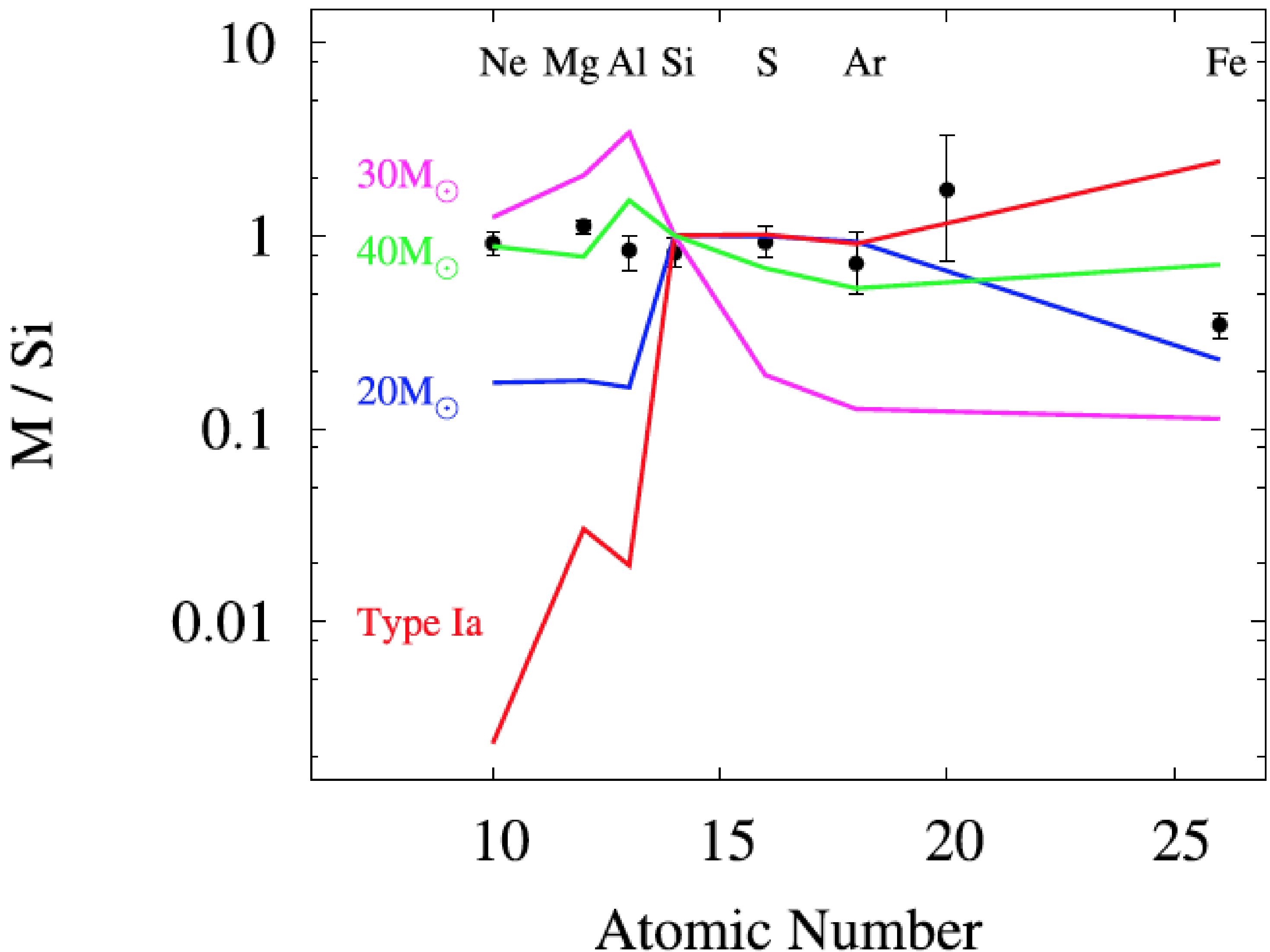




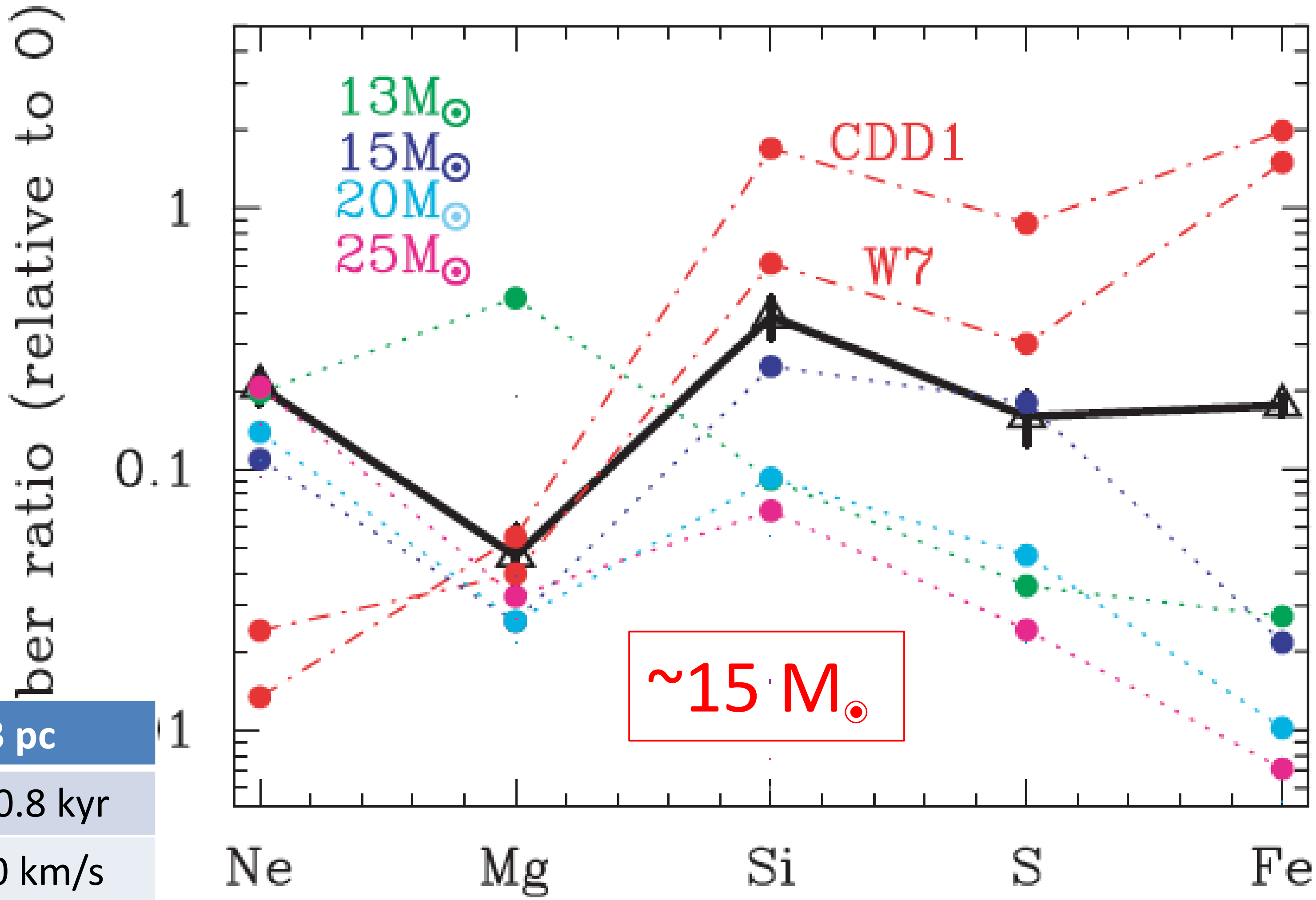
R ~ 8.3 pc
Age ~ 4.6 kyr
Vs ~ 720 km/s
E ~ 0.06 foe

15-20 $M_\odot$

Kes 79 (Sato+16)

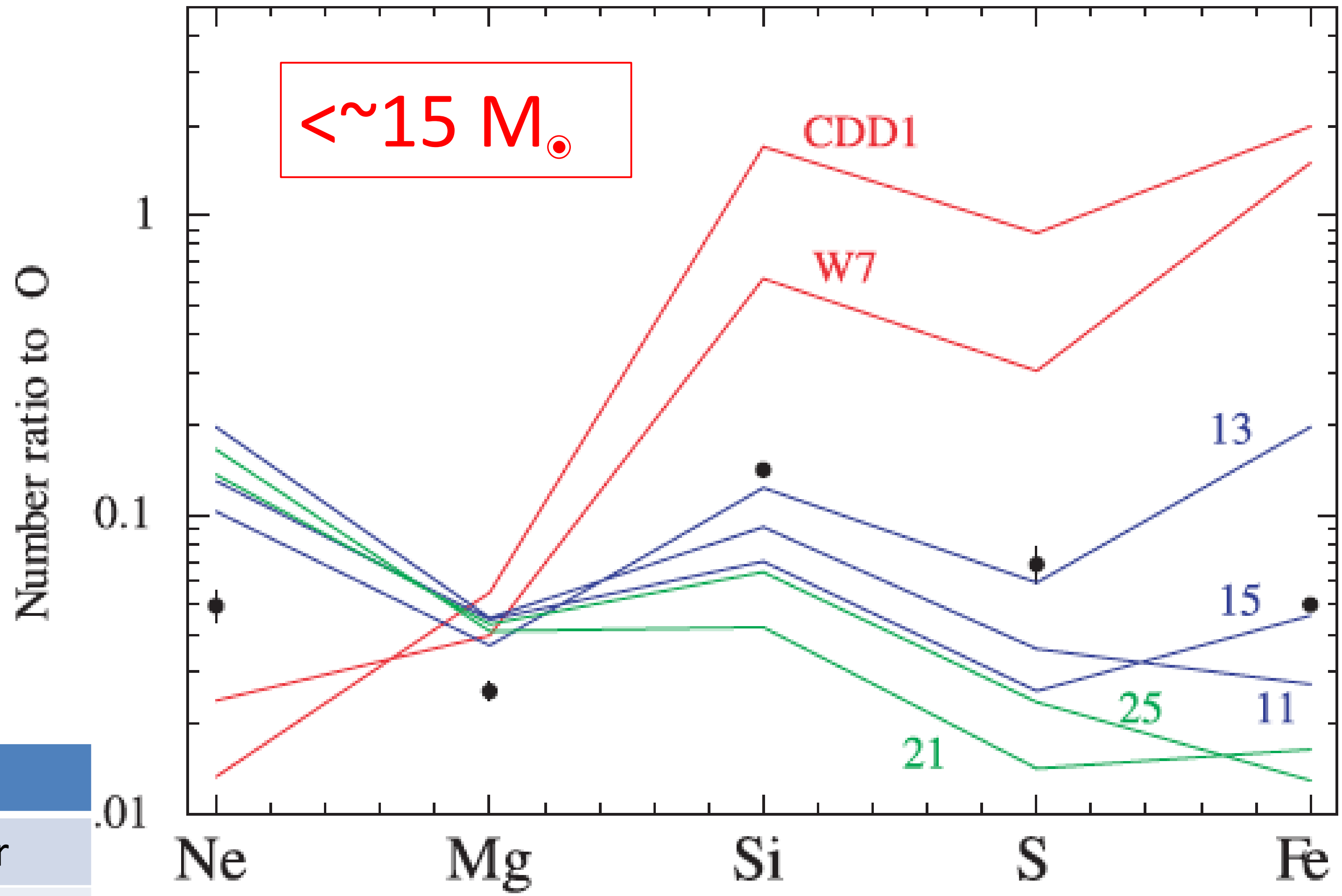


Cygnus Loop (Tsunemi+07)



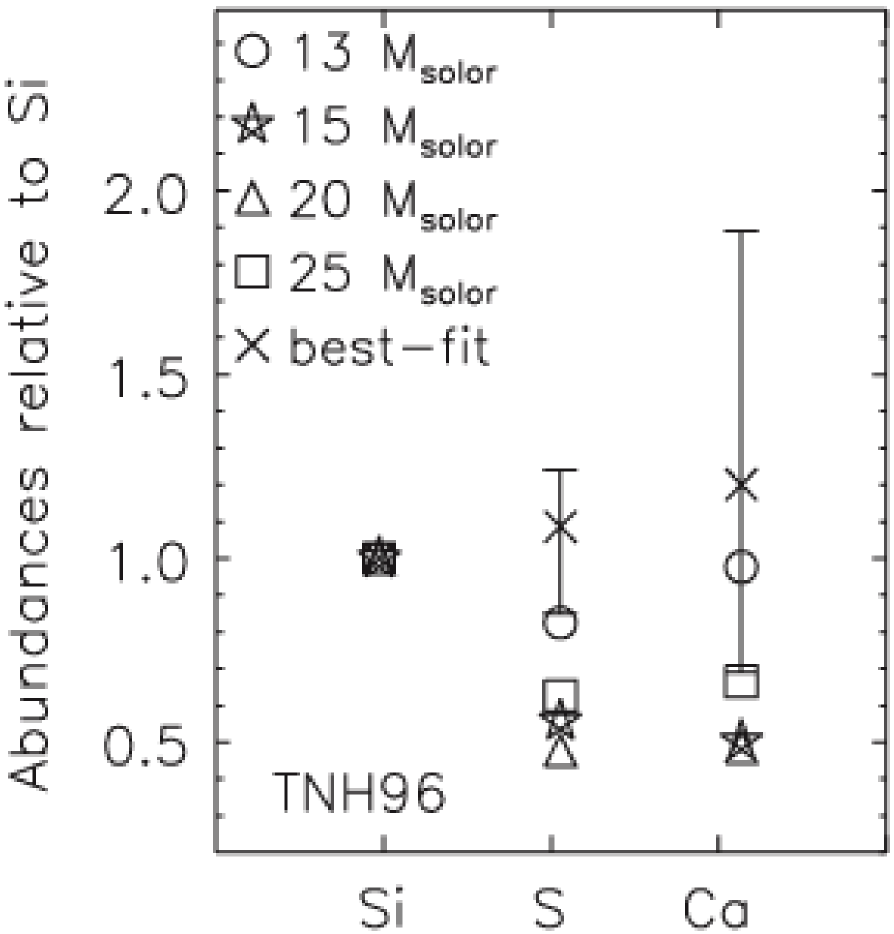
R ~ 11.3 pc
Age ~ 10.8 kyr
Vs ~ 400 km/s
E ~ 0.05 foe

G156.2+5.7 (Katsuda+09)



R ~ 47.1 pc
Age ~ 37 kyr
Vs ~ 500 km/s
E ~ 5.5 foe

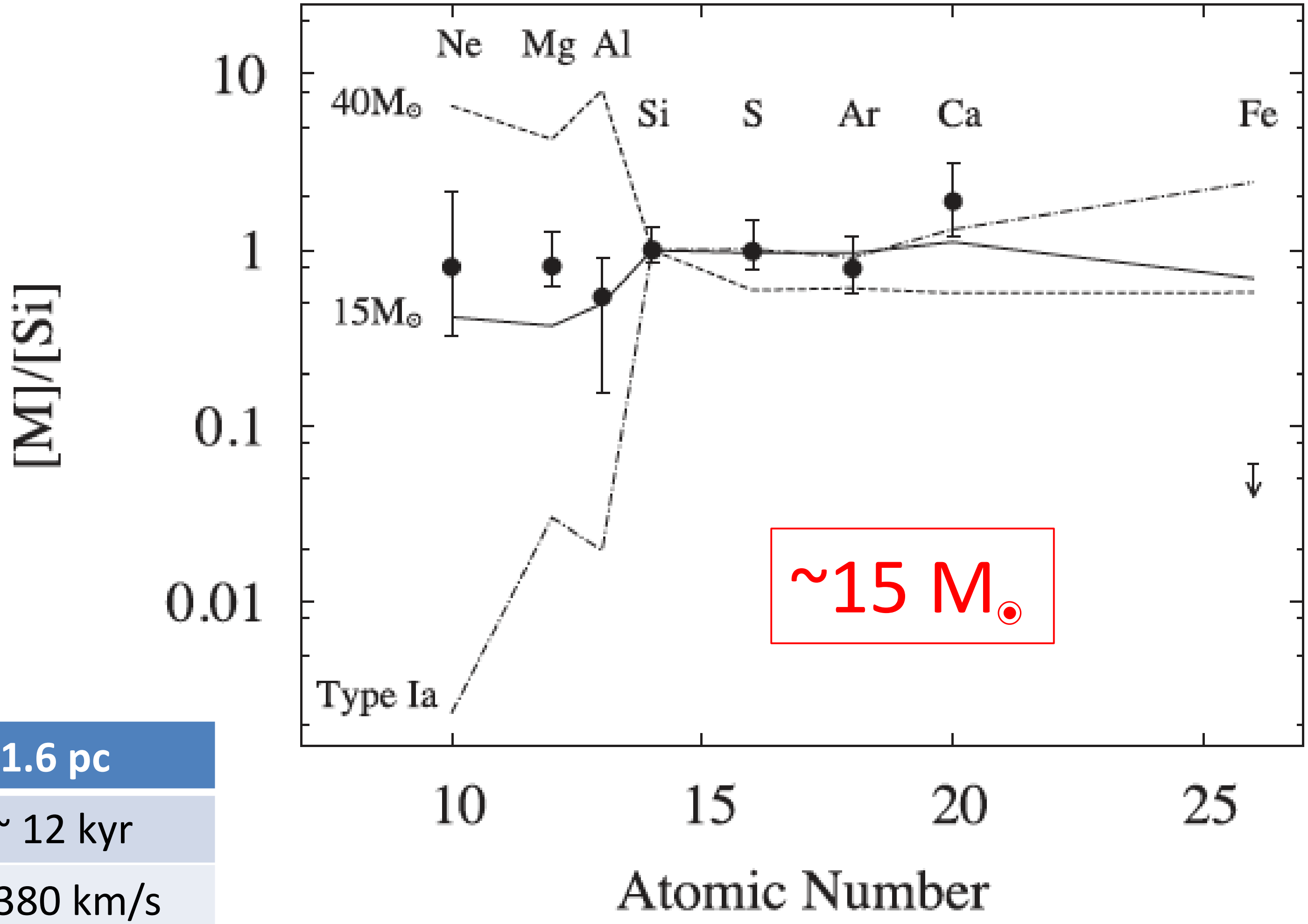
3C396 (Su+11)



13-15 $M_\odot$

R ~ 7.0 pc
Age ~ 3.2 kyr
Vs ~ 880 km/s
E ~ 0.06 foe

3C391 (Sato+14)



R ~ 11.6 pc
Age ~ 12 kyr
Vs ~ 380 km/s
E ~ 0.05 foe

RXJ1713 (Katsuda+15)

Parameter	Observation	Model	13 $M_\odot$	15 $M_\odot$	17/18 $M_\odot$[a]	20 $M_\odot$	25 $M_\odot$	30 $M_\odot$	40 $M_\odot$
Mg/Ne (solar)	2.0–2.6	Umeda—Original	1.9	2.7	2.1	0.7	0.9	0.7	0.6
		Umeda—CO core	2.7	5.5	2.3	0.7	1.4	0.7	1.1
		Limongi—Original	1.4	0.7	0.6	0.5	0.5	0.6	1.0
		Limongi—CO core	1.8	2.2	0.7	1.0	1.7	2.1	1.0
Si/Ne (solar)	1.5–2.0	Umeda—Original	1.5	3.5	1.5	0.6	0.5	0.9	0.4
		Umeda—CO core	1.6	7.7	1.3	0.5	0.2	0.8	0.1
		Limongi—Original	1.9	1.6	1.2	0.5	0.5	0.7	0.1
		Limongi—CO core	1.7	1.5	0.4	0.1	0.1	0.1	0.1
Fe/Ne (solar)	<0.05	Umeda—Original	0.43	0.54	0.15	0.07	0.04	0.05	0.05
		Umeda—CO core	0.006	0.005	0.009	0.018	0.047	0.026	0.010
		Limongi—Original	0.37	0.13	0.07	0.04	0.03	0.03	0.05
		Limongi—CO core	0.023	0.012	0.005	0.069	0.064	0.061	0.054
Mass integrated ($M_\odot$)	~0.7[b]	Umeda—Original	10.9	12.4	15.0	16.7	19.9	22.4	19.5
		Umeda—CO core	0.10	0.11	1.03	1.74	0.07	4.89	0.03
		Limongi—Original	10.1	11.5	13.0	14.6	14.5	11.0	3.9
		Limongi—CO core	0.4	1.0	1.6	0.5	0.5	0.5	3.9

Notes.
[a] 17 $M_\odot$ and 18 $M_\odot$ are responsible for Limongi's and Umeda's model, respectively.
[b] Based on a simple area scaling from the circular region of our interest to the entire remnant. The abundances are integrated from the outermost envelope to the mass
een the data and the model minimizes. The results are based on nucleosynthetic models with solar-metallicity progenitor and explosion
gi & Chieffi (2006), Umeda & Nomoto (2005), Tominaga et al. (2007), Nomoto et al. (2013).

R ~ 8.7 pc
Age ~ 1.2 kyr
Vs ~ 3000 km/s
E ~ 1.2 foe

~15 $M_\odot$

Puppis A (Katsuda+10; Hwang+08)

- Ne/O ~ 2 solar
- Mg/O ~ 2 solar
- Si/O ~ 0.5 solar
- Fe/O ~ 0.5 solar

<~ 25 $M_\odot$

R ~ 16 pc
Age ~ 12 kyr
Vs ~ 500 km/s
E ~ 0.2 foe

CTB1 (Pannuti+2010)

- O/Fe ~ 4.3 (+10.2 -2.5) solar
- Ne/Fe ~ 4.0 (+8.0 -2.2) solar

} 13-15 $M_{\odot}$

R ~ 15.3 pc
Age ~ 11.9 kyr
Vs ~ 500 km/s
E ~ 0.19 foe

Sagrittarius A East (Sakano+04)

- S/Si ~ 0.38 solar
- Ar/Si ~ 0.24 solar
- Ca/Si ~ 0.5 solar
- Fe/Si ~ 0.26 solar

} 13-20 $M_\odot$

R ~ 3.2 pc
Age ~ 1.4 kyr
Vs ~ 920 km/s
E ~ 0.006 foe

W44 (Rho+94)

- Mg: 0.14 $M_\odot$
- Si: 0.17 $M_\odot$
- S: 0.1 $M_\odot$
- Fe: 0.414 $M_\odot$

} 8-15 $M_\odot$

R ~ 15.7 pc
Age ~ 9.5 kyr
Vs ~ 650 km/s
E ~ 0.34 foe

Wind Blown Bubble

- 3C58: 20-30 $M_\odot$ (Kothes+13)
- Kes78: 21+/-2 (Chen+13)
- Kes69: 18+/-2 (Chen+13) -- abundance(?)
- Kes75: 12+/-2 (Chen+13)
- 3C396: 13+/-2 (Chen+13) -- abundance
- Vela: 21+/-3 (Chen+13) -- abundance(?)
- RX J1713: 15+/-2 (Chen+13) -- abundance
- DA 530: 10+/-2 (Jiang+07)

IR Dust Composition

- G54.1+0.3: 16-27 $M_{\odot}$ (Temim+17)

R ~ 10.5 pc
Age ~ 3.2 kyr
Vs ~ 1300 km/s
E ~ 0.4 foe

OB Association

- S147: ~13-20 $M_{\odot}$ (Dincel+15)

R ~ 37.8 pc
Age ~ 29.4 kyr
Vs ~ 500 km/s
E ~ 2.9 foe

Some Others

- Crab: 10+/-1

R ~ 1.7 pc
Age ~ 0.4 kyr
Vs ~ 1750 km/s
E ~ 0.003 foe

- Cas A: 15-20

R ~ 2.5 pc
Age ~ 0.2 kyr
Vs ~ 5000 km/s
E ~ 0.08 foe