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

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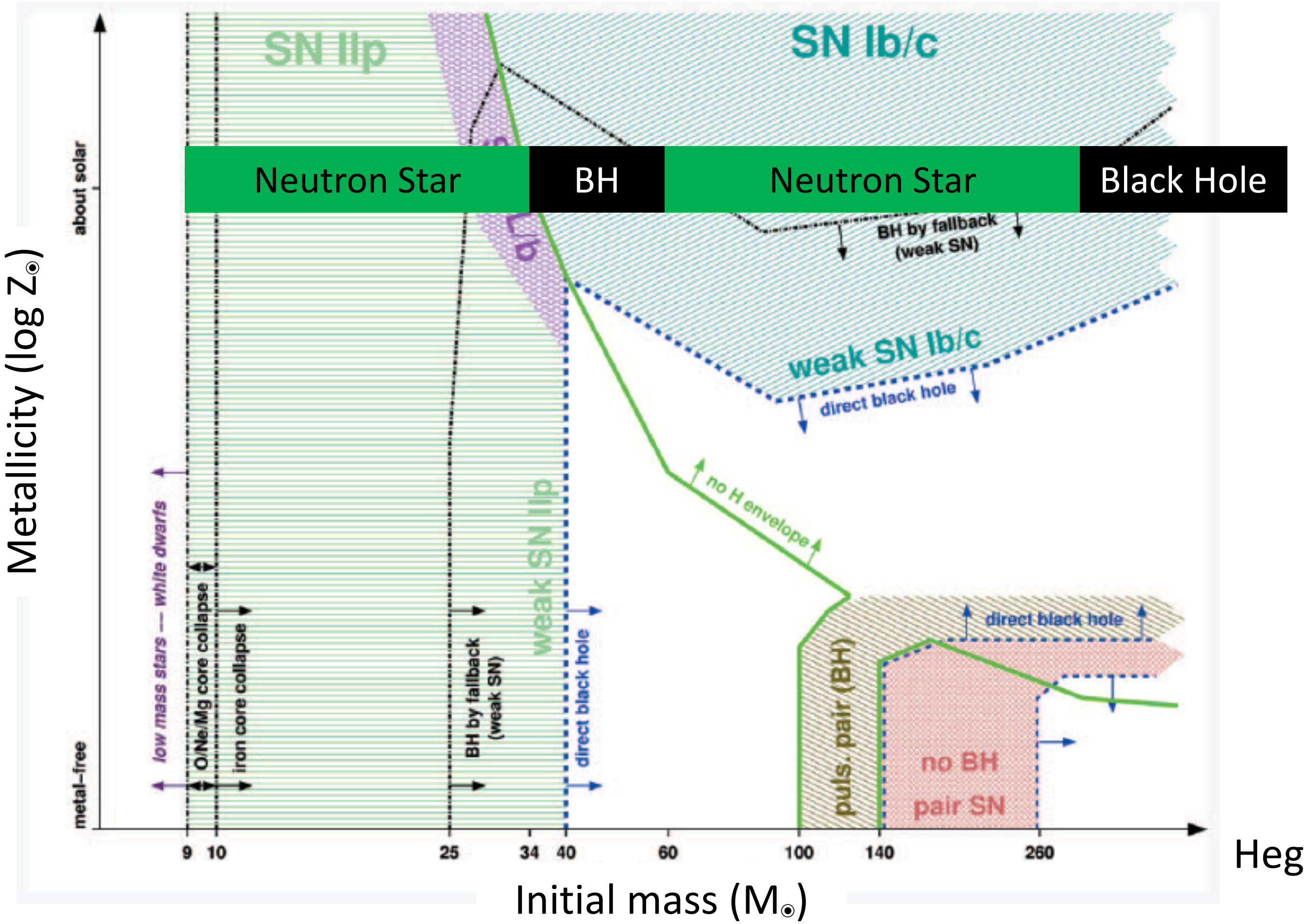
The Astrophysical Journal, 863, 127 (2018)

Initial Masses (M_{ZAMS}) of Massive Stars ←→ Final Fates of Massive Stars

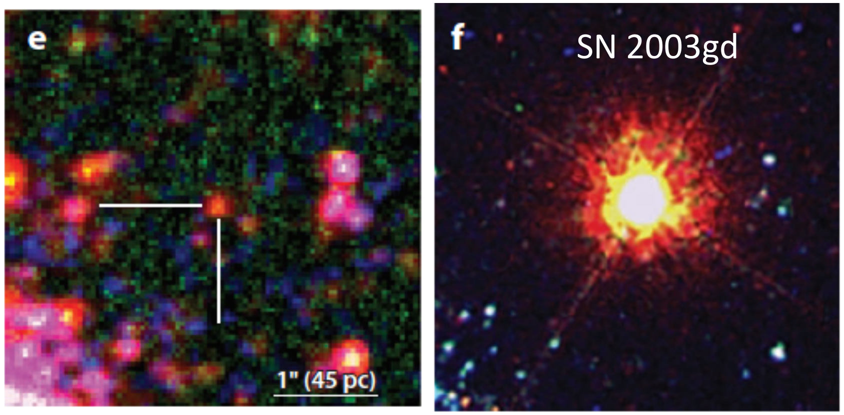
- Which M_{ZAMS} produces successful or failed supernovae? – Explodability
- Which M_{ZAMS} produces which supernovae types (Type IIp, IIL, IIn, Ibc, …)?



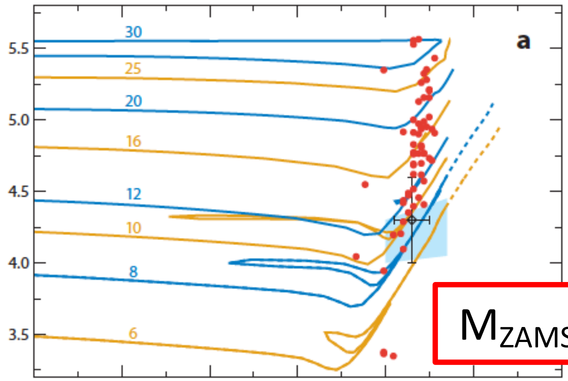
@ solar metallicity

Heger et al. (2003)

M_{ZAMS} by Direct Imaging of Progenitors


Pre-explosion

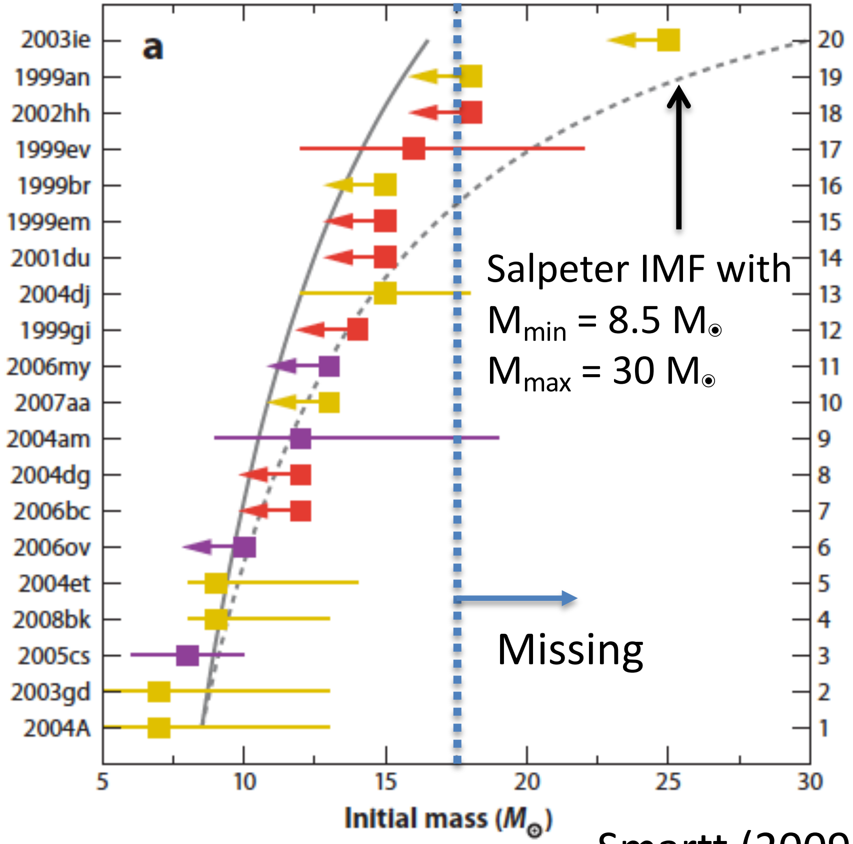
Post-explosion



$M_{ZAMS} = 7^{+6}_{-2}\ M_{\odot}$

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

The most massive progenitors for Type IIP SNe are missing. → Red supergiant problem.



Salpeter IMF with
$M_{min} = 8.5\ M_{\odot}$
$M_{max} = 30\ M_{\odot}$

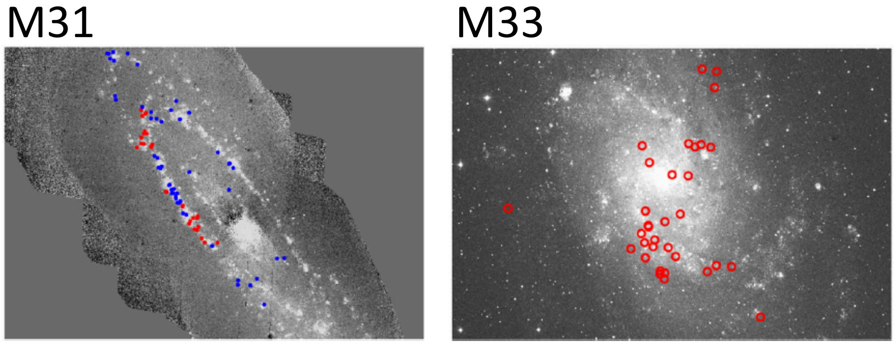
Missing

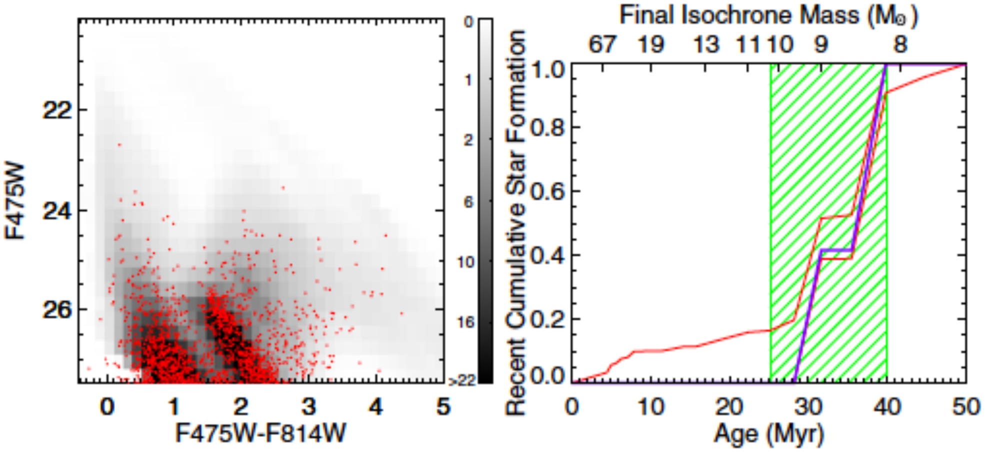
Smartt (2009)

But, still debated (e.g., Davies & Beasor 2018)

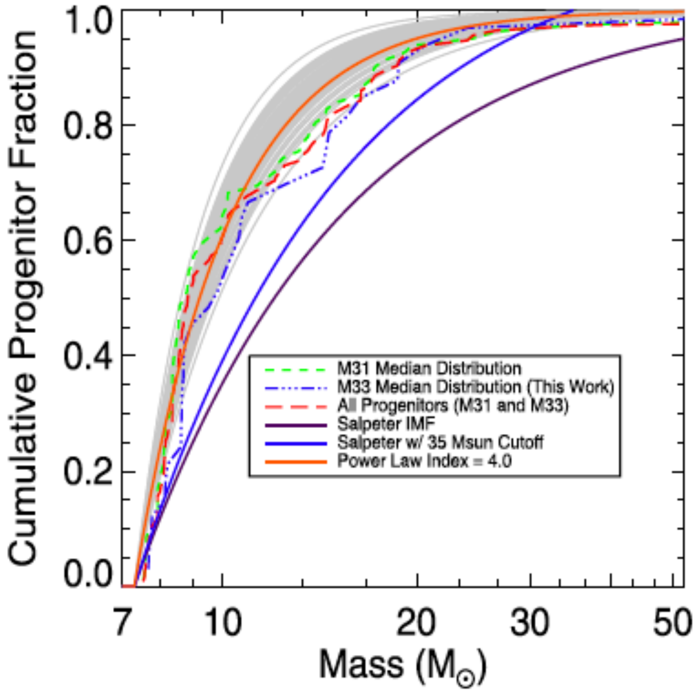
M_{ZAMS} by Age Dating of Stellar Population around Supernova Remnants

M31 M33





Jennings et al. (2012; 2014)



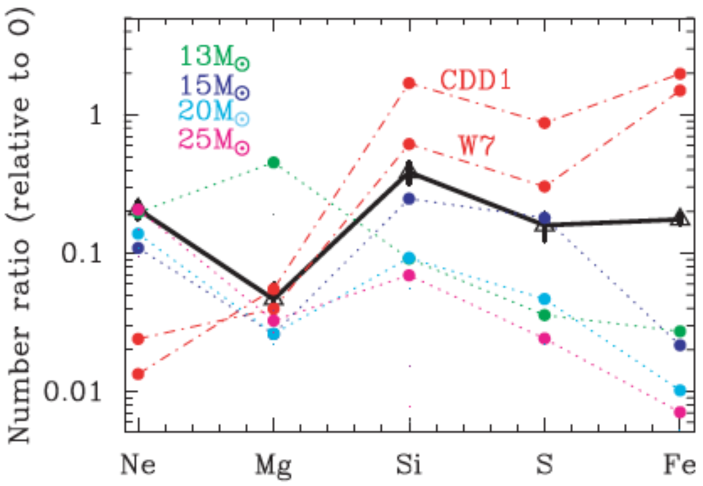
→ Steeper than Salpeter distribution, confirming the RSG problem.

→ But, this result is also still debated (Williams+2018; Auchettl+2018; Diaz-Rodriguez+2018).

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

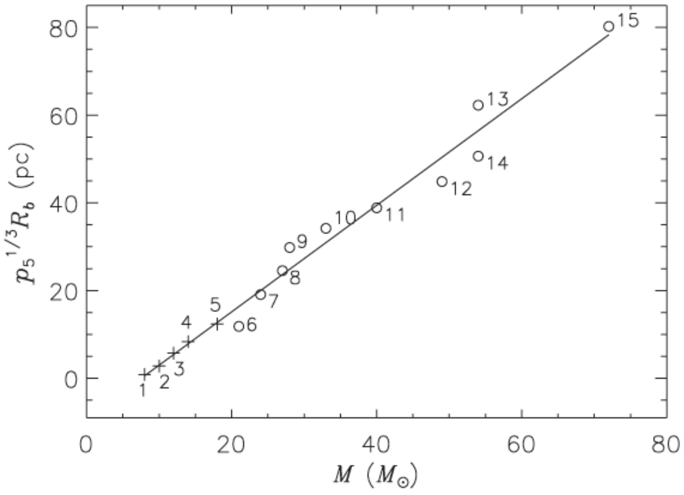
- A lot of estimates for individual SNRs, but these data were not summarized yet.
- Two kinds of measurements:

1) Elemental abundances of the SN ejecta



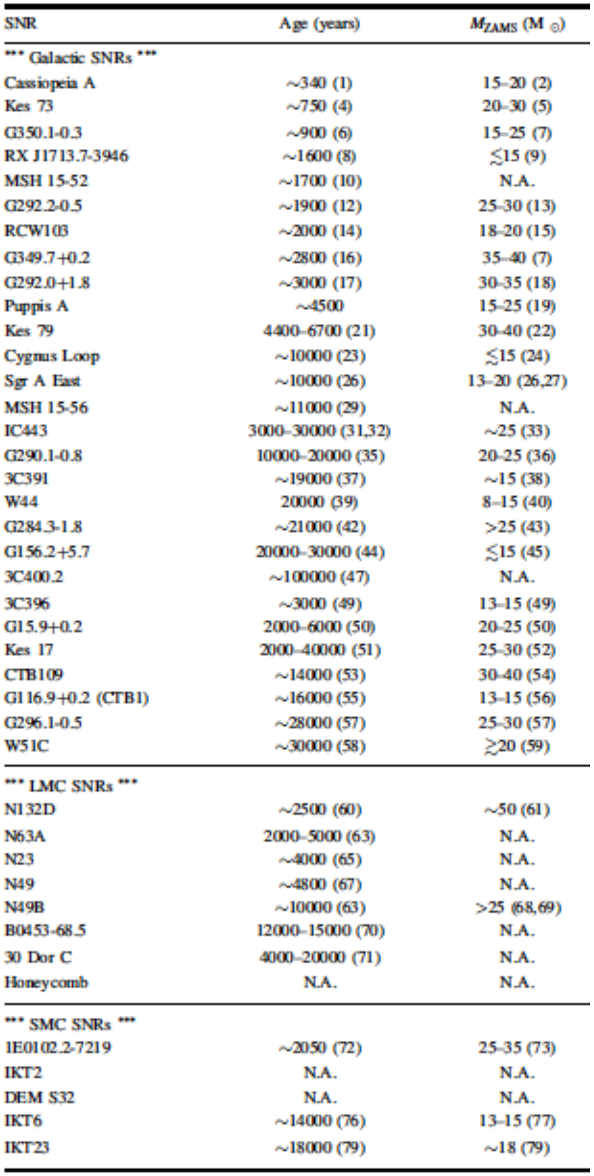
Tsunemi, SK, Nemes, & Miller (2007)

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)	≲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)	≲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)	≲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)	≳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

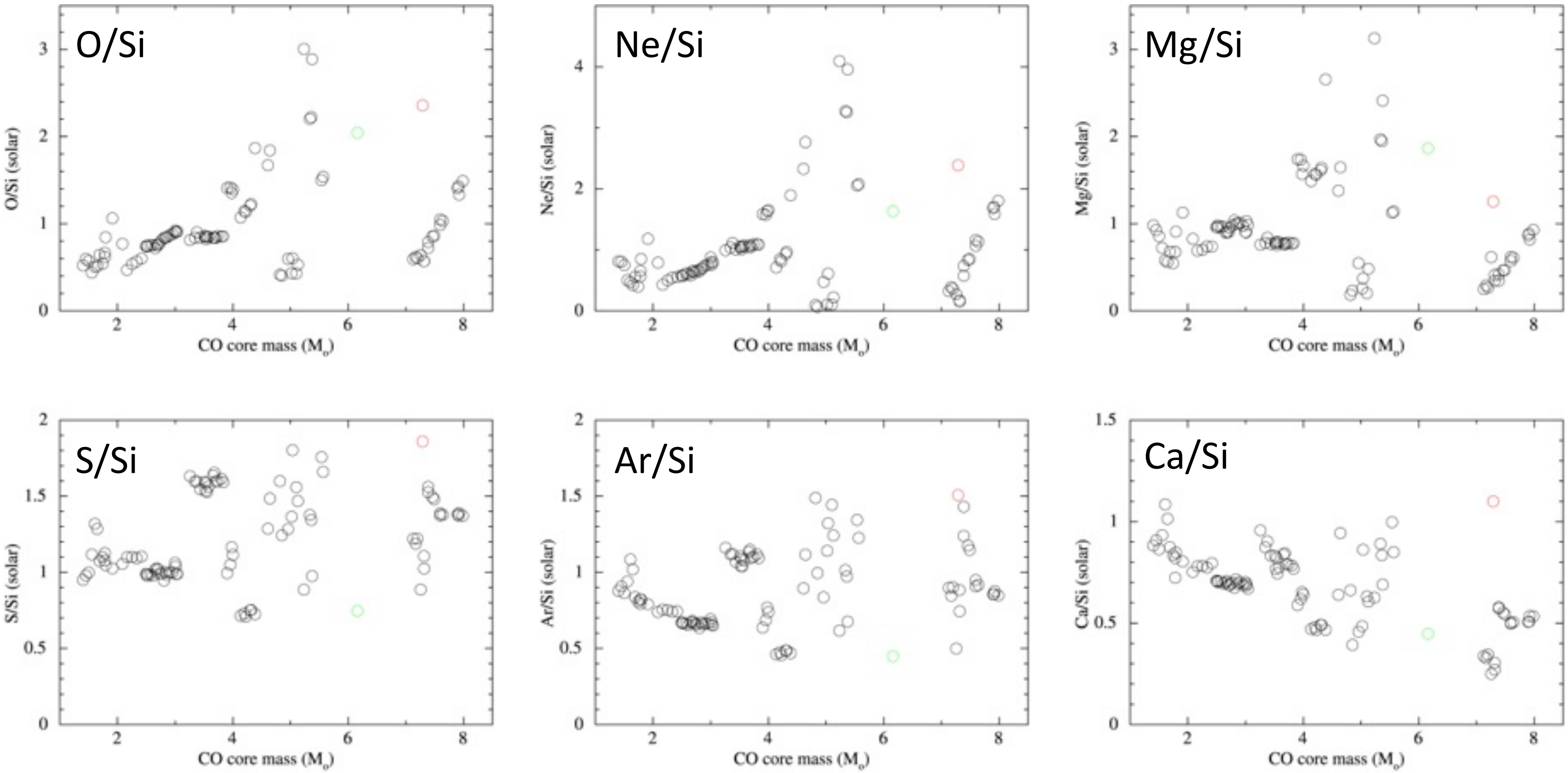
Top-heavy mass distribution?!

→ 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
  → Next slide.
- Only Si/Fe is sensitive to CO core masses of progenitor stars.
  → Next-next slide.
- Therefore, we re-estimated progenitor masses based on Si/Fe ratio taken from a recent nucleosynthesis model (Sukhbold et al. 2016).
  → Next—next-next slide

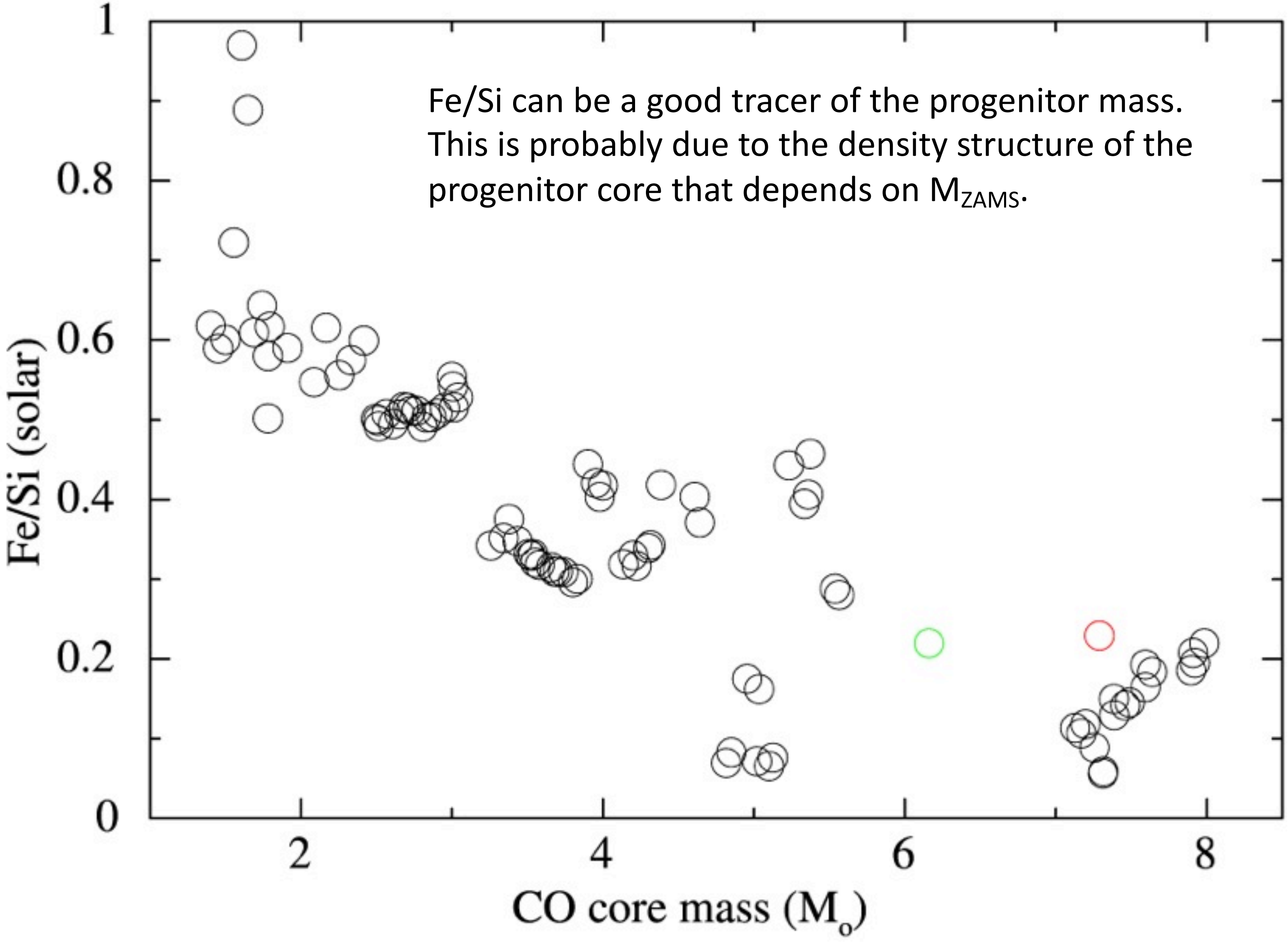
X/Si vs. CO Core Mass (Sukhbold+2016)



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)

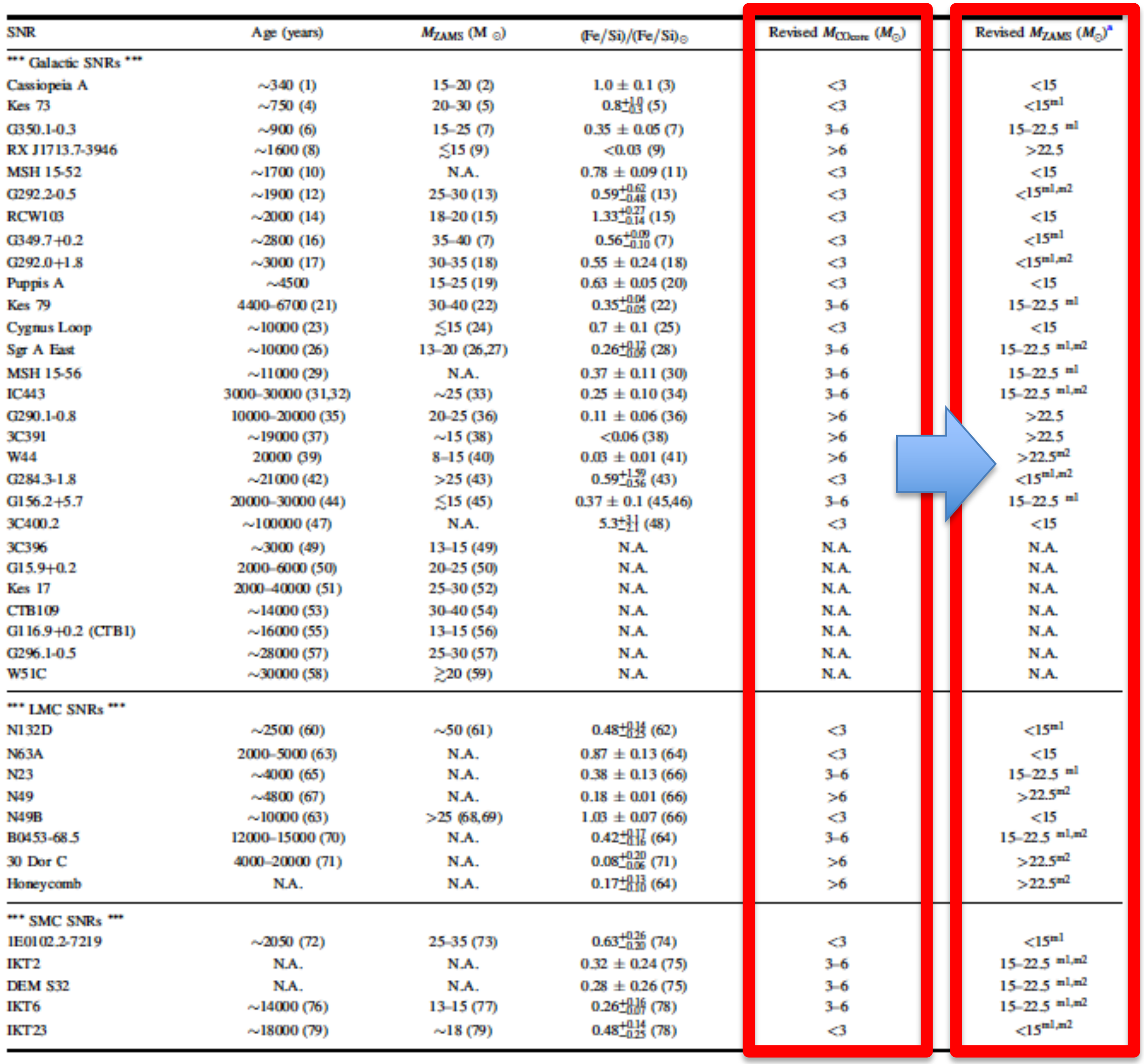


Fe/Si can be a good tracer of the progenitor mass. This is probably due to the density structure of the progenitor core that depends on M_{ZAMS}.

The Progenitor Mass Distribution Revised

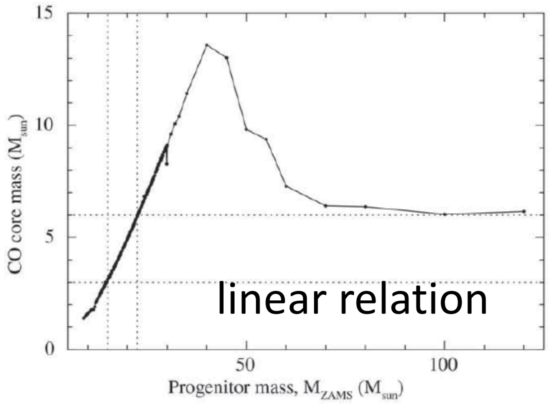
CO core

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)	$\lesssim$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)	$\lesssim$15 (24)	0.7 ± 0.1 (25)	<3	<15
Sgr A East	~10000 (26)	13–20 (26,27)	$0.26^{+0.12}_{-0.09}$ (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)	$0.59^{+1.59}_{-0.56}$ (43)	<3	$<15^{m1,m2}$
G156.2+5.7	20000–30000 (44)	$\lesssim$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)	$\gtrsim$20 (59)	N.A.	N.A.	N.A.
*** LMC SNRs ***					
N132D	~2500 (60)	~50 (61)	$0.48^{+0.14}_{-0.25}$ (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	$<15^{m1,m2}$

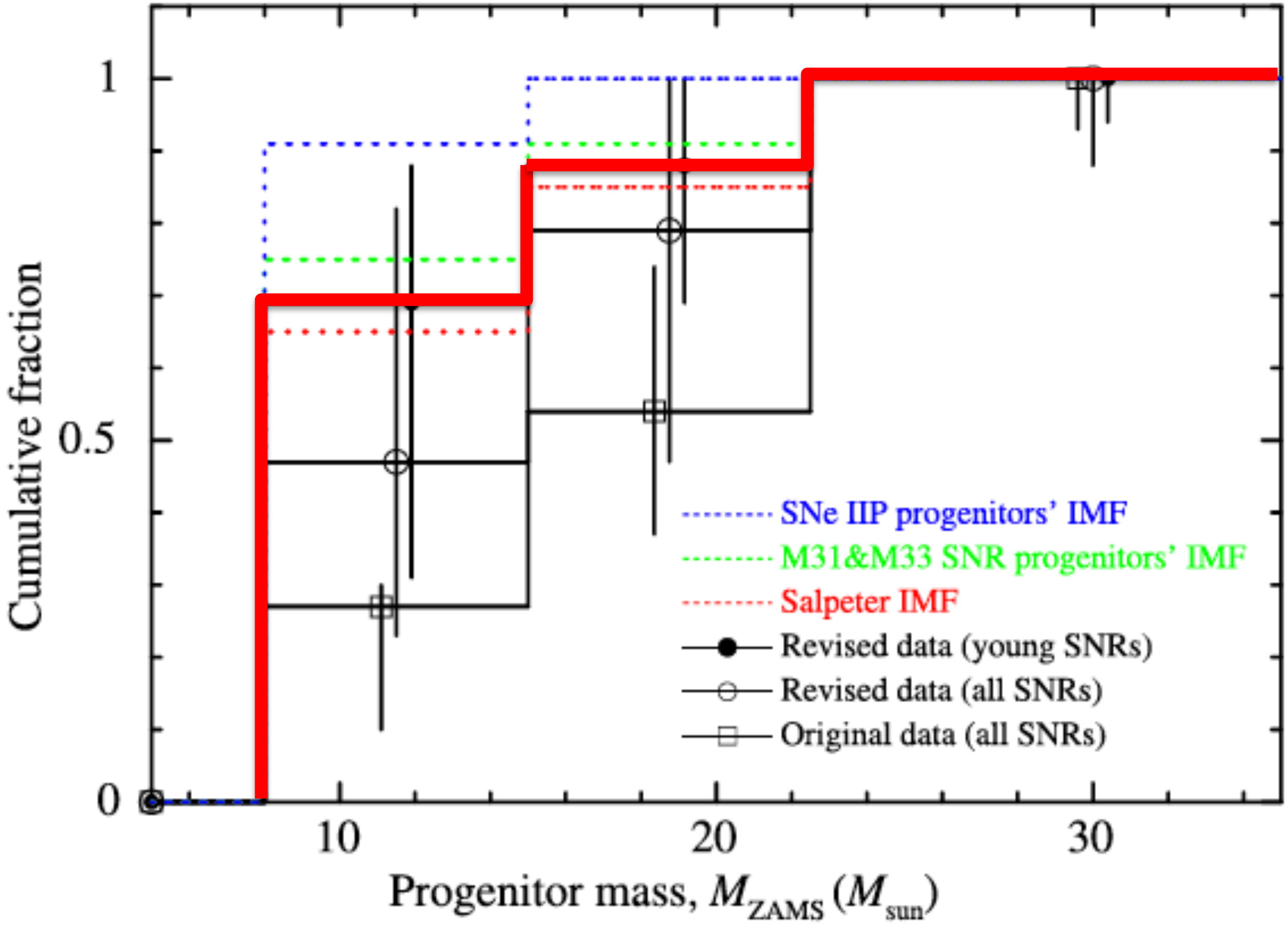
M_{COcore} → M_{ZAMS} conversion



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, requiring no high-mass cutoff.
- 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, 863, 127 (2018)