Following - Epstein, Colgate and Haxton, “Neutrino-induced r-process nucleosynthesis” PRL, 61, 2038 (1988)

## Supernova neutrinos, neutral currents and the origin of fluorine

Show affiliations

Woosley, S. E.; Haxton, W. C.

As the detection[1,2] of a neutrino burst from supernova 1987A one year ago has dramatically illustrated, the flux of neutrinos generated by the collapse of the core of a massive star is truly prodigious. Common lore has it that these neutrinos, because of their weak coupling to matter, pass through all but the iron core and inner silicon shell of the collapsing star with negligible interaction. So far as energy deposition and the explosion mechanism go, this is true but for the nuclear chemistry of the star, we argue that it is not. We draw particular attention to the synthesis of an element whose origin has hitherto been obscure - fluorine - and show that its solar abundance constrains the temperature of muon and tauon neutrinos to values near what is expected from the standard model (8-10 MeV).

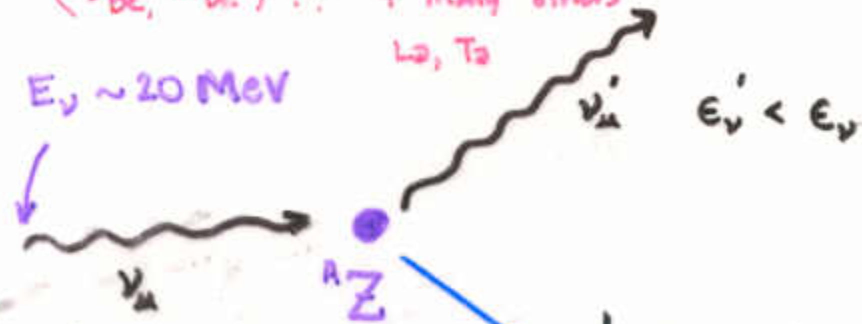
**Publication:** Nature, Volume 334, Issue 6177, pp. 45-47 (1988).

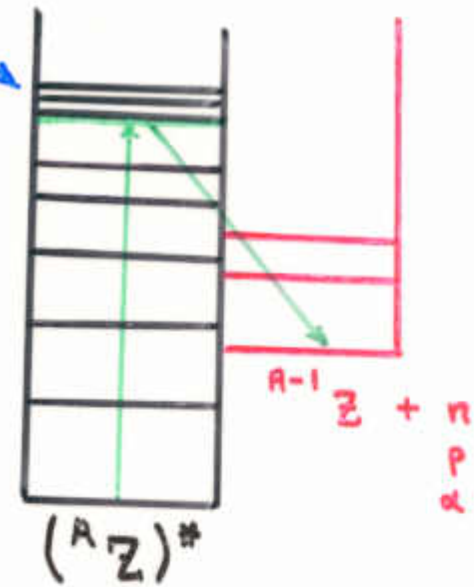
**Pub Date:** July 1988

Also numerous earlier papers on neutrino nucleosynthesis in supernovae by Dimitrij Nadyozhin in the late 70’s and early 80’s of which we were unaware. Also those were by charged current reactions.

Woosley, Hartmann, Hoffman, + Haxton (1990)

Responsible for (some) $^7Li$, $^{11}B$, $^{19}F$ (${}^9Be$, ${}^{10}Be$) ?? contributions to + many others La, Ta




**Examples:**

$^{12}C(\nu,\nu'p)\,^{11}B$ [$^{10}B$, $^9Be$??]

$^{12}C(\nu,\nu'n)\,^{11}C(e^+\nu)\,^{11}B$

$^{20}Ne(\nu,\nu'p)\,^{19}F$

$^{20}Ne(\nu,\nu'n)\,^{19}Ne(e^+\nu)\,^{19}F$

$^4He(\nu,\nu'n)\,^3He(\alpha,\gamma)\,^7Be$

+ secondary reactions

*Production factor relative to solar normalized to $^{16}O$ production as a function of $\mu$ and $\tau$ neutrino temperature (neutral current) and using 4 MeV for the electron (anti-)neutrinos (for charged current only). 6 MeV is now considered a more likely value for $T_{\mu\tau}$*

| **Product** | $15\ M_\odot$ | | | | $25\ M_\odot$ | | | |
|---|---|---|---|---|---|---|---|---|
| | **6 MeV** | | **8 MeV** | | **6 MeV** | | **8 MeV** | |
| | **WW95** | **This work** | **WW95** | **This work** | **WW95** | **This work** | **WW95** | **This work** |
| $^{11}B$ | 1.65 | 1.88 | 3.26 | 3.99 | 0.95 | 1.18 | 1.36 | 1.85 |
| $^{19}F$ | 0.83 | 0.60 | 1.28 | 0.80 | 0.56 | 0.32 | 1.03 | 0.53 |
| $^{15}N$ | 0.46 | 0.49 | 0.54 | 0.58 | 0.09 | 0.12 | 0.15 | 0.19 |
| $^{138}La$ | | 0.97 | | 1.10 | | 0.90 | | 1.03 |
| $^{180}Ta$ | | 2.75 | | 3.07 | | 4.24 | | 5.25 |

*Heger et al,, 2005, Phys Lettr B, **606**, 258*

Sieverding et al ApJ, 865, 143, (2018)


13 – 30 solar masses, 1.2 x $10^{51}$ erg piston induced explosions

| Nucleus | No $\nu$ | Low Energies[a] | | |
|---|---|---|---|---|
| | | With $\nu$ | Only Charged Current | Only Neutral Current |
| $^{7}$Li | 0.002 | 0.04 | 0.01 | 0.03 |
| $^{11}$B | 0.01 | 0.31 | 0.17 | 0.21 |
| $^{15}$N | 0.06 | 0.09 | 0.08 | 0.08 |
| $^{19}$F | 0.13 | 0.18 | 0.14 | 0.16 |
| $^{138}$La | 0.16 | 0.46 | 0.44 | 0.18 |
| $^{180}$Ta[c] | 0.20 | 0.49 | 0.48 | 0.24 |

$$T_{\nu_e} = 2.8\ \text{MeV};\ T_{\bar{\nu}_e,\nu_\mu,\nu_\tau} = 4.0\ \text{MeV}$$

Much cooler, also cross sections smaller especially F.

Sieverding et al (including spectrum from Janka) 27 solar mass model only.

**Table 3**

Production Factors

| Nucleus | Appr. 1a $\alpha = \alpha(t)$ | Appr. 1b $\alpha = 2.3$ | Appr. 2 $\alpha = 2.3$ | Appr. 3 $\alpha = 2.3$ | Literature FD |
|---|---|---|---|---|---|
| $^{7}$Li | 0.04 | 0.04 | 0.03 | 0.02 | 0.02 |
| $^{11}$B | 0.30 | 0.31 | 0.28 | 0.18 | 0.13 |
| $^{15}$N | 0.06 | 0.05 | 0.05 | 0.04 | 0.04 |
| $^{19}$F | 0.12 | 0.12 | 0.11 | 0.10 | 0.10 |
| $^{138}$La | 0.69 | 0.74 | 0.66 | 0.41 | 0.44 |
| $^{180}$Ta$^{m}$ | 1.32 | 1.33 | 1.27 | 1.09 | 1.11 |

Sieverding et al (2019) - time dependent neutrino flux histories from models including break out slightly increase yields, especially of boron. This is the low temperature case from the previous slide.

*So should multiply B yield on previous slide by 2.5. B probably mostly due to neutrino process (my view). Can be used to constrain $\nu$−spectrum*

# THE DEATHS OF MASSIVE STARS AND THE BIRTH OF BLACK HOLES

*Stan Woosley (UCSC)*

*with Tuguldur Sukhbold (Ohio)*
*Thomas Ertl (MPI), and*
*Thomas Janka (MPI)*

# Surveys For the Impatient

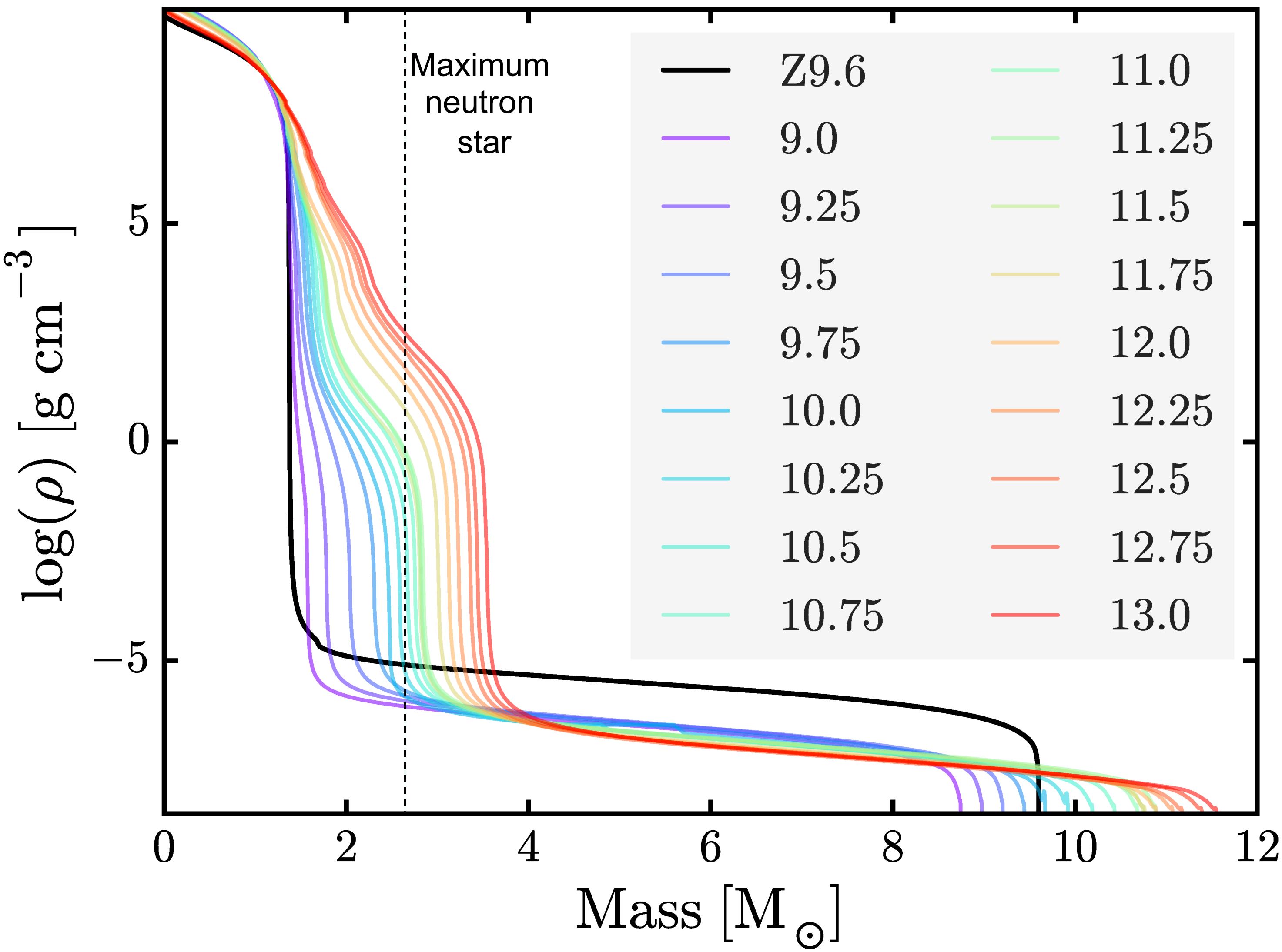
- For over 50 years (Colgate and White 1966) theorists have struggled to produce supernovae powered by neutrino transport that agree with observations. A lot of progress has been made.  Really.

- Several groups now routinely get low energy explosions of low mass progenitors, roughly 8 to 11 solar masses. These may account for the Crab, in particular, and maybe half of all supernovae. Heavier stars occasionally explode on the computer, but with low energy – few x $10^{50}$ erg

- Heavier stars are needed for nucleosynthesis, light curves, explosion energies above $\sim 10^{51}$ erg, and remnant mass distributions, but it may be that most stars over 20 solar masses (helium cores about 6 solar masses) usually fail to explode. This is (maybe barely) consistent with observations

- Missing pieces may involve presupernova turbulence, mild rotation, modifications to the EOS, and/or new physics (flavor mixing?).

# Presupernova Density Distributions

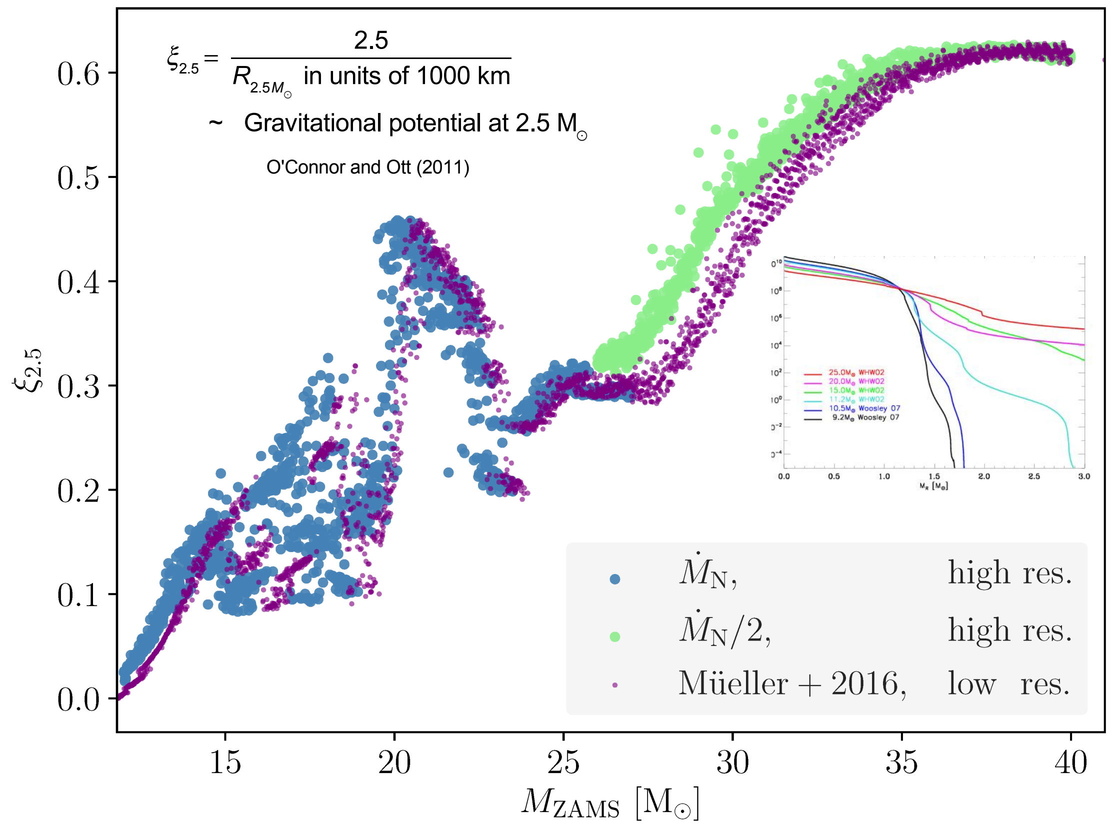



Stars below 12 $M_{O}$ (He core 3.5 $M_{O}$) are comparatively easy to explode with neutrino transport and account for about half of observed supernovae. *It is very likely that they all make neutron stars.*

The “supernova problem” has three pieces: preSN models, explosion models, and observation. Presently in terms of quality of data:

Observations >> PreSN models >> Explosion models

The preSN models show a great deal of systematics that will certainly affect the outcome. We’d like to explore those systematics now, especially in an era of GW observations

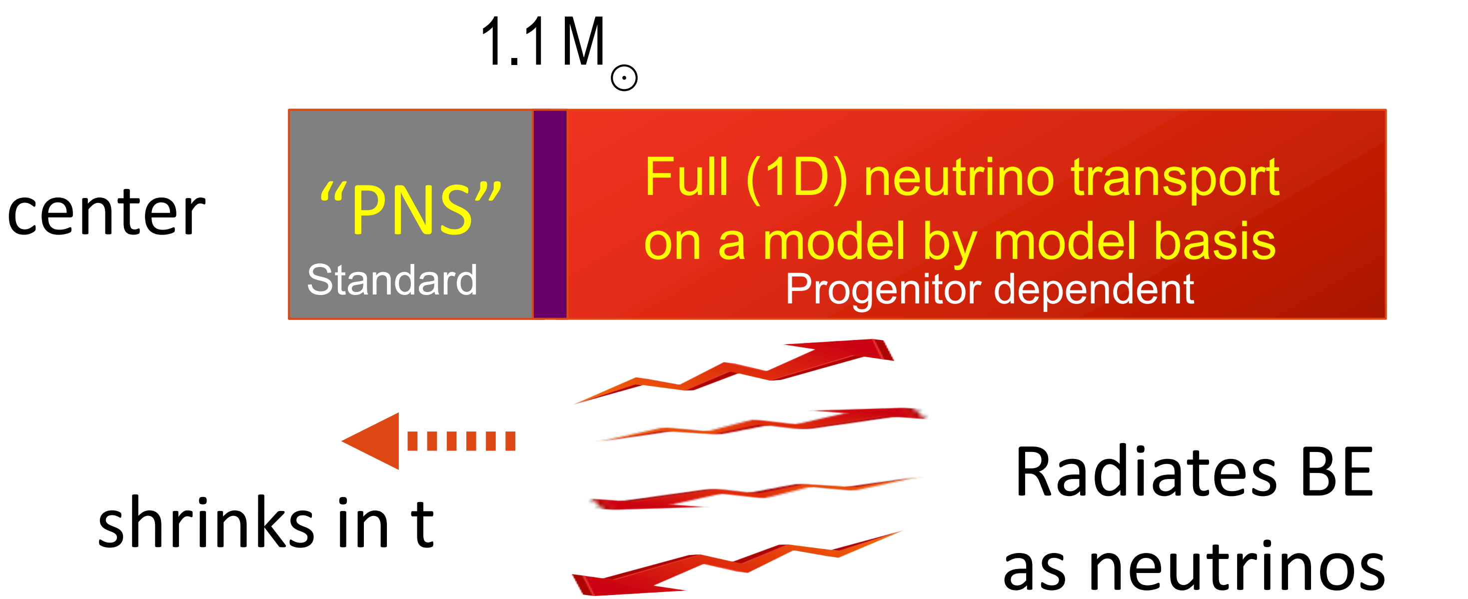



Hard to Explode

Easy

# Beyond Pistons

## 1D Neutrino-Transport Calculation with a standard central 1.1 $M_{\odot}$ core




*Sukhbold, Ertl, Woosley, Brown, and Janka (2016)*

see Ugliano, Janka, Marek, and Arcones (2012)
[*ApJ*, **757**, 60]

Central engine varied – 5 models for 87A; 1 for the Crab

Star not forced to explode

$$L_{\nu,tot} = \frac{1}{3(\Gamma - 1)}\left[(3\Gamma - 4)(E_g + S)\frac{\dot{R}_c}{R_c} + S\frac{\dot{m}_{acc}}{m_{acc}}\right]$$

$$E_g + S = -\frac{2}{5}\frac{GM_c}{R_c}\left(M_c + \frac{5}{2}\varsigma m_{acc}\right)$$

$$S = -\varsigma\frac{GM_c m_{acc}}{R_c}$$

$$R_c(t) = R_{c,f} + \frac{R_{c,i} - R_{c,f}}{(1+t)^n}$$

*$M_c$ = 1.1 solar masses*
*$R_{c,i}$ from preSN model*
*EOS Lattimer Swesty 220 MeV*

*Neutrinos launched from edge of core with thermal distributions and the local temperature. 1D transport after that.*

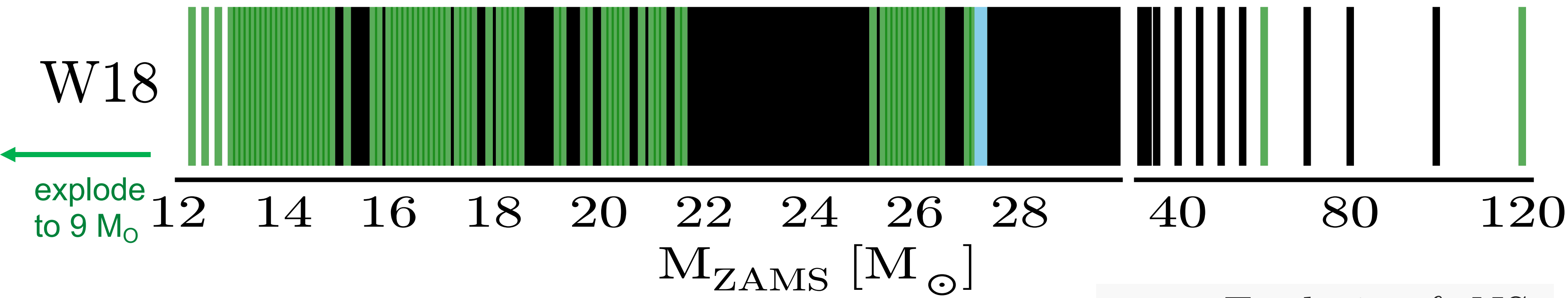
TABLE 3. PNS CORE-MODEL PARAMETERS IN P-HOTB

| | Model | $R_{c,f}$ [km] | $\Gamma$ | $\zeta$ | $n$ | $E_{51}$ | M($^{56}$Ni+ 1/2 Tr) | |
|---|---|---|---|---|---|---|---|---|
| | Z9.6 | 7.0 | 3.0 | 0.65 | 1.55 | 0.16 | 0.0087 | Crab |
| | S19.8 | 6.5 | 3.0 | 0.90 | 2.96 | 1.30 | 0.089 | |
| | W15 | 6.0 | 3.0 | 0.60 | 3.10 | 1.41 | 0.068 | |
| standard * | W18 | 6.0 | 3.0 | 0.65 | 3.06 | 1.25 | 0.074 | 87A |
| | W20 | 6.0 | 3.0 | 0.70 | 2.84 | 1.24 | 0.076 | |
| | N20 | 6.0 | 3.0 | 0.60 | 3.23 | 1.49 | 0.062 | |

Central engine varied – 5 models for 87A; 1 for the Crab

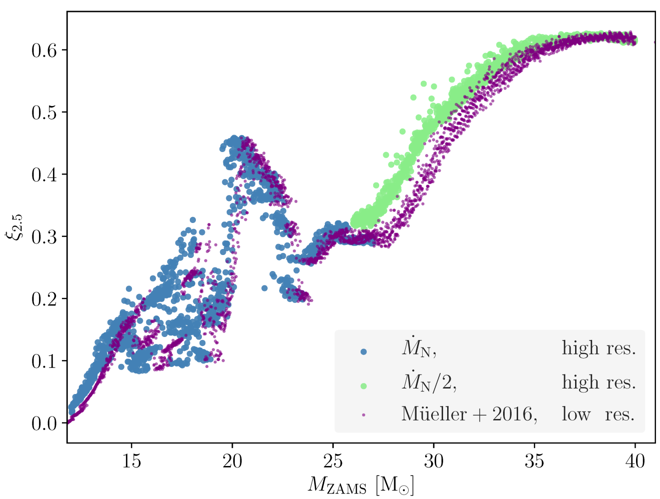
Star not forced to explode

# Explosion highly correlated with compactness
(about 200 preSN models explored; 5 explosions each)




Sukhbold et al (ApJ, *821*, **38**, 2016) **12 – 70 $M_\odot$**

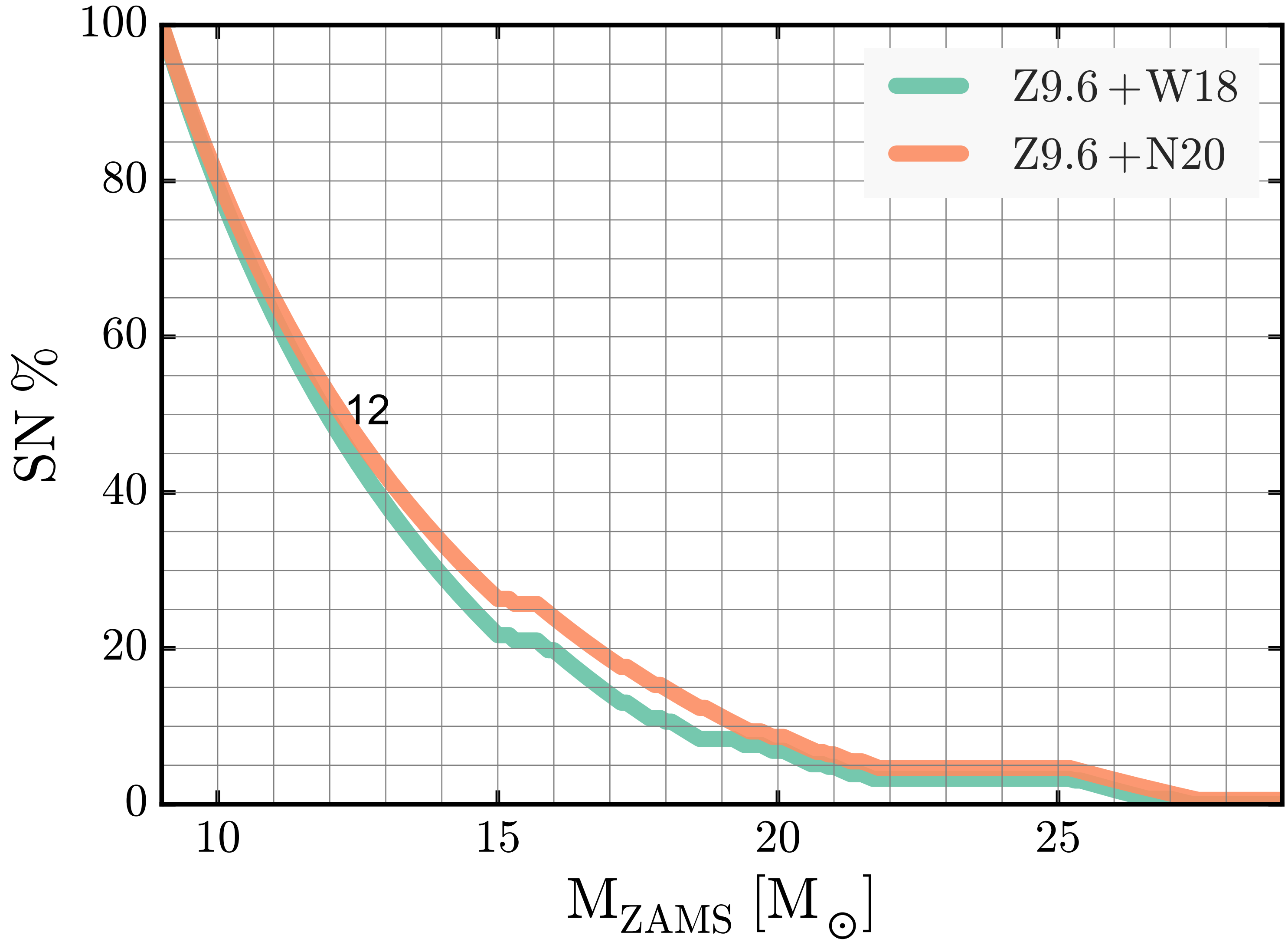
WR mass loss from Welstein and Langer (1999)
[large




## Single stars

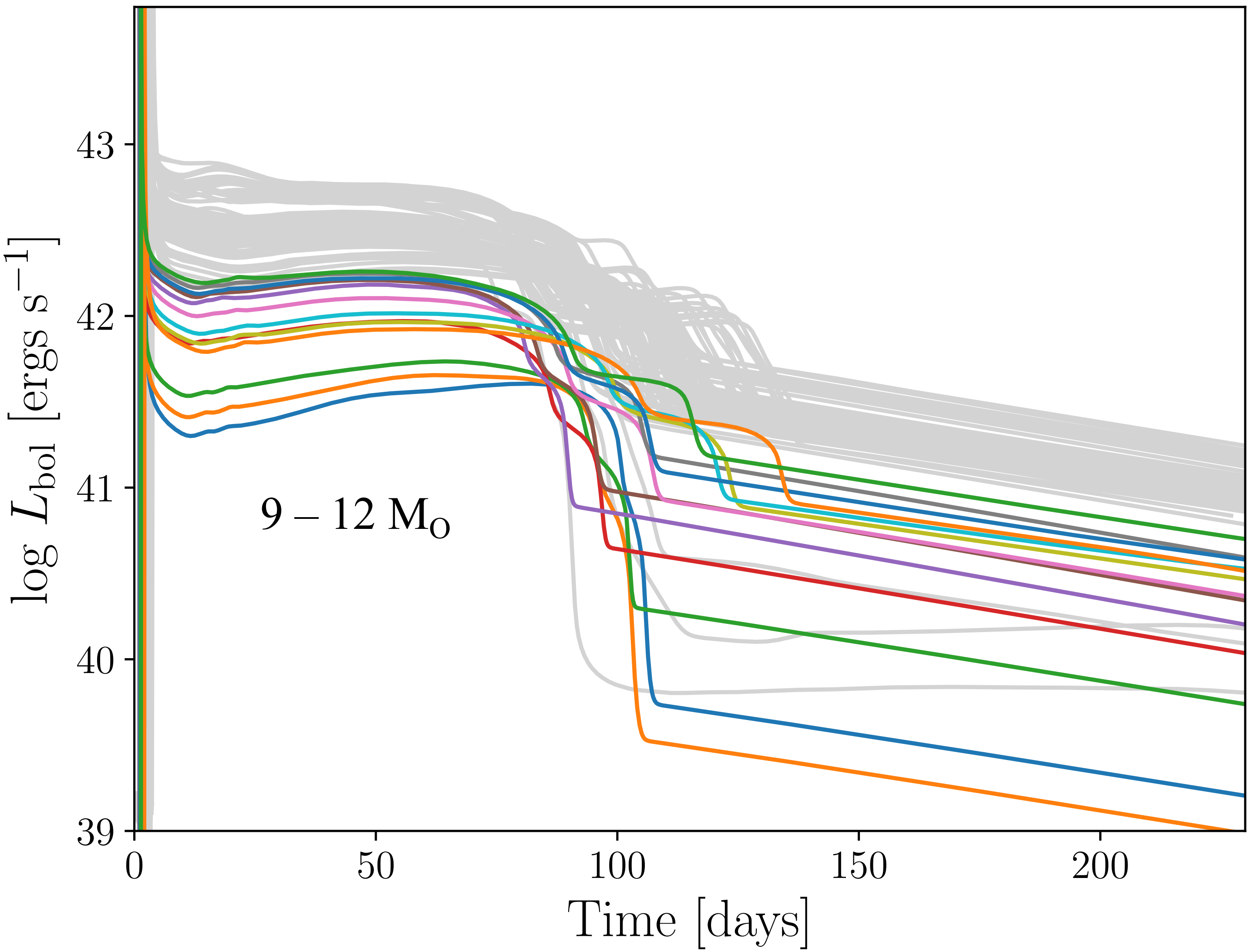
| | |
|---|---|
| Average explosion energy | 6 - 8 x $10^{50}$ erg |
| Average $^{56}$Ni mass | 0.04 – 0.06 $M_\odot$ |
| Supernovae > 20 $M_\odot$ | 5% |
| Fraction SN that make BH | 26 – 45% |

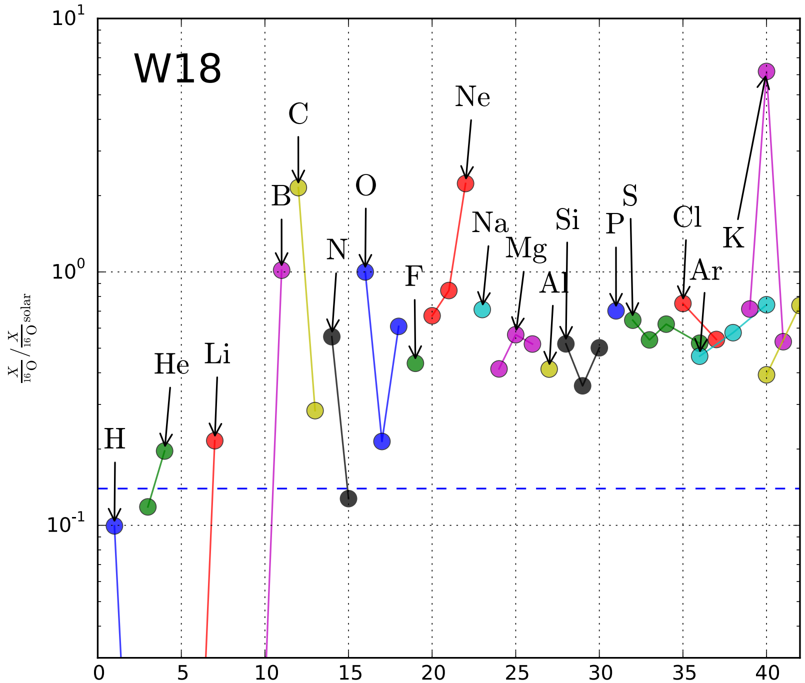
50% of SN below 12 $M_\odot$ ; Very few above 20 $M_\odot$

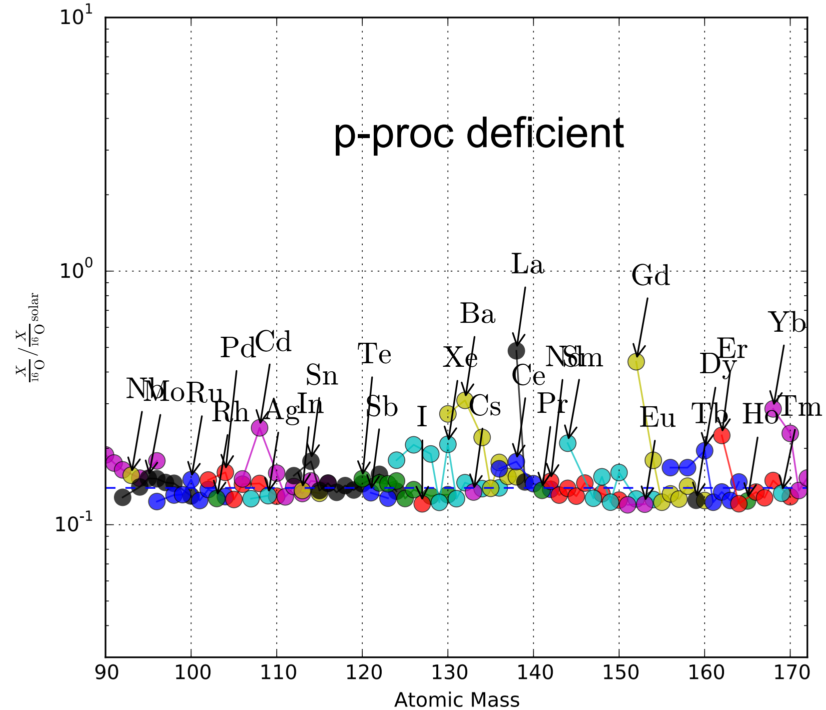


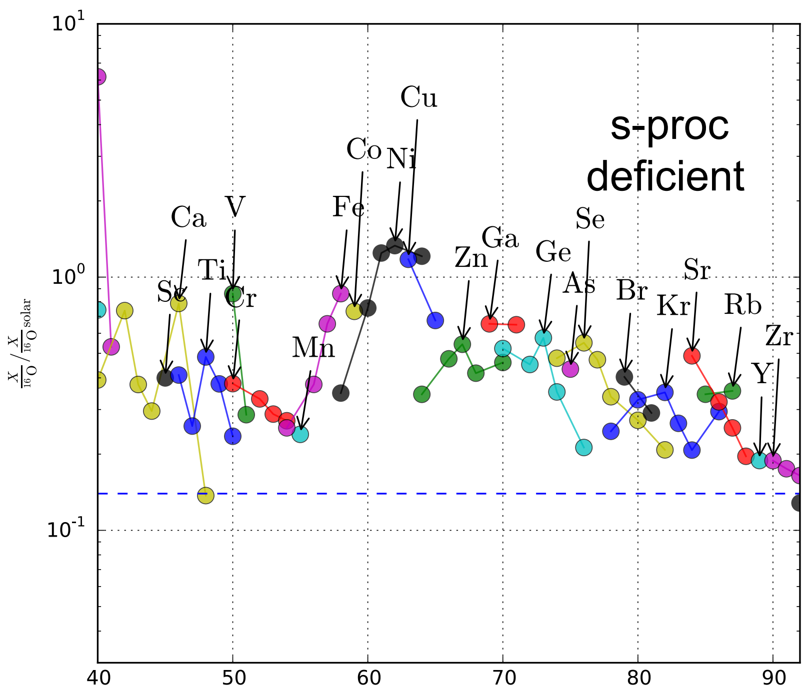

Sukhbold et al (2016)

Prediction : The light curves and tails of SN below 12 $M_\odot$ are typically fainter. There should be a correlation between preSN brightness and SN brightness.



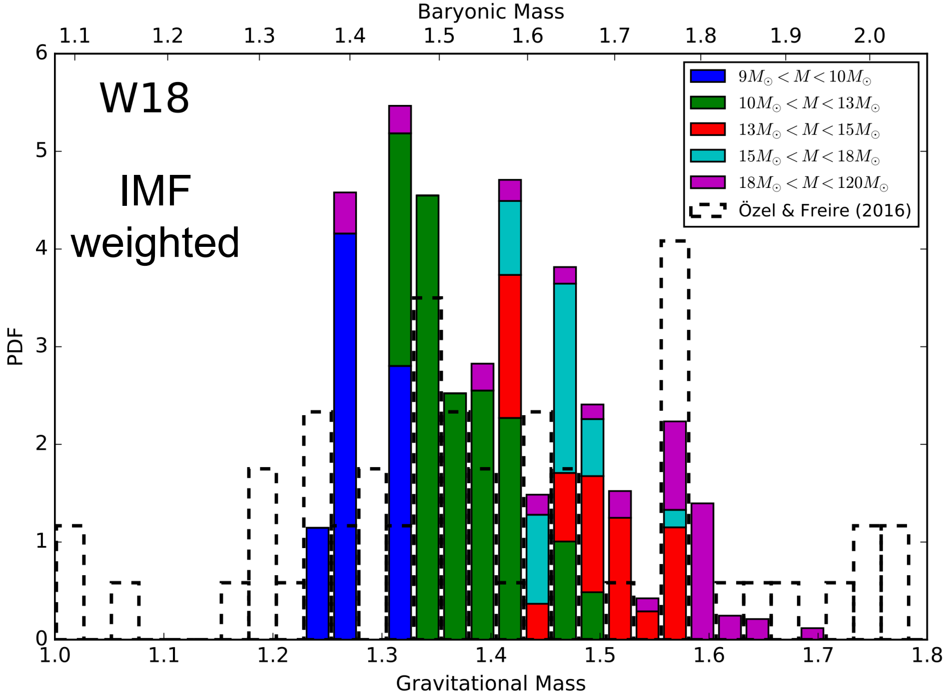



IMF averaged nucleosynthesis is reasonably good but a deficiency of s- and p-process. Need larger $^{22}$Ne($\alpha$,n)$^{25}$Mg rate or more massive stars to explode. B and F are mostly $\nu$-process here but used a large $T_{\mu\tau}$

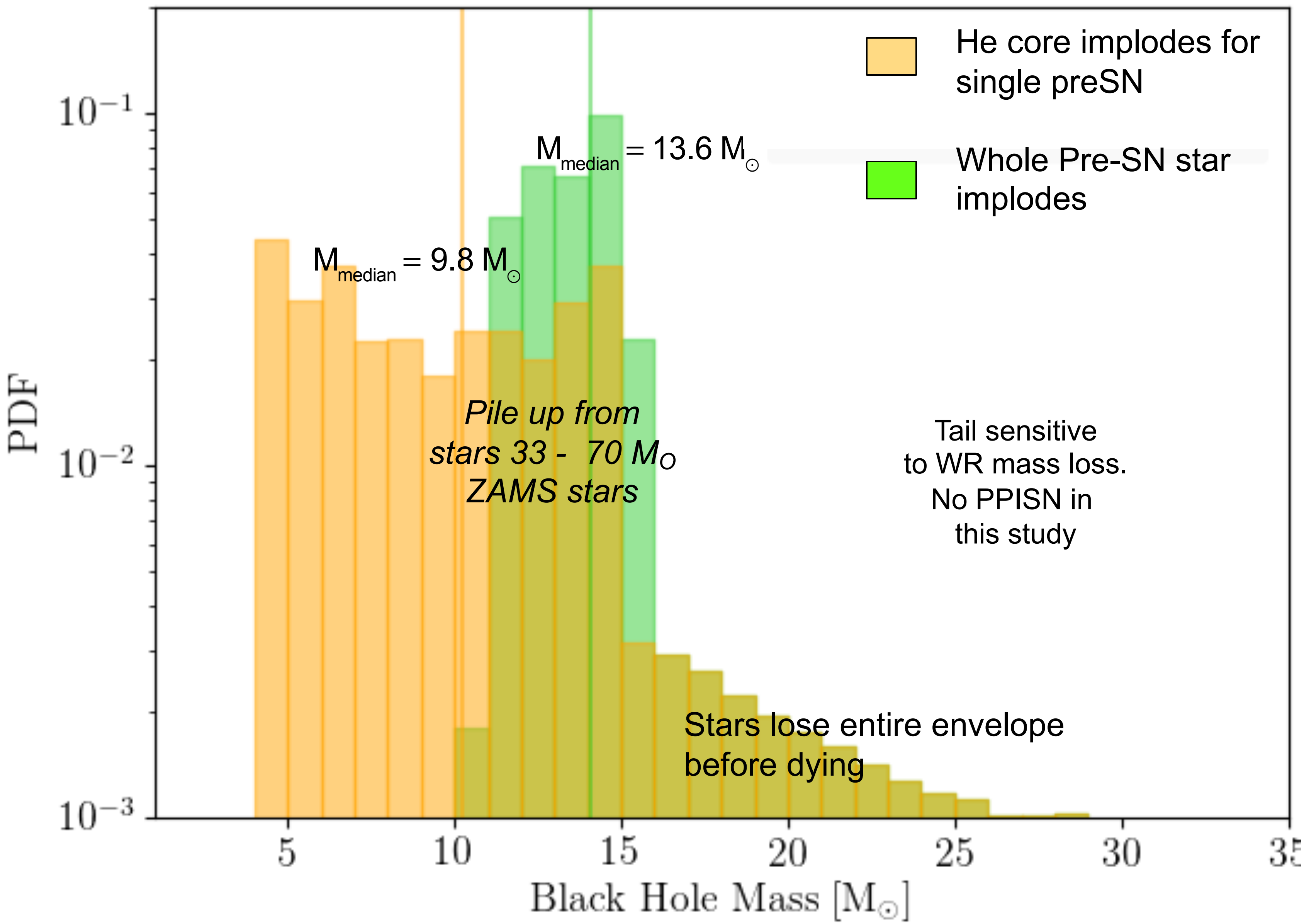
# Neutron Star Masses




Average mass = 1.37 $M_\odot$

Range = 1.3 $M_\odot$ to 1.9 $M_\odot$

# Black hole mass distribution
## Solar Metallicity; "Normal" Mass Loss, Single stars



# Survey - Binaries

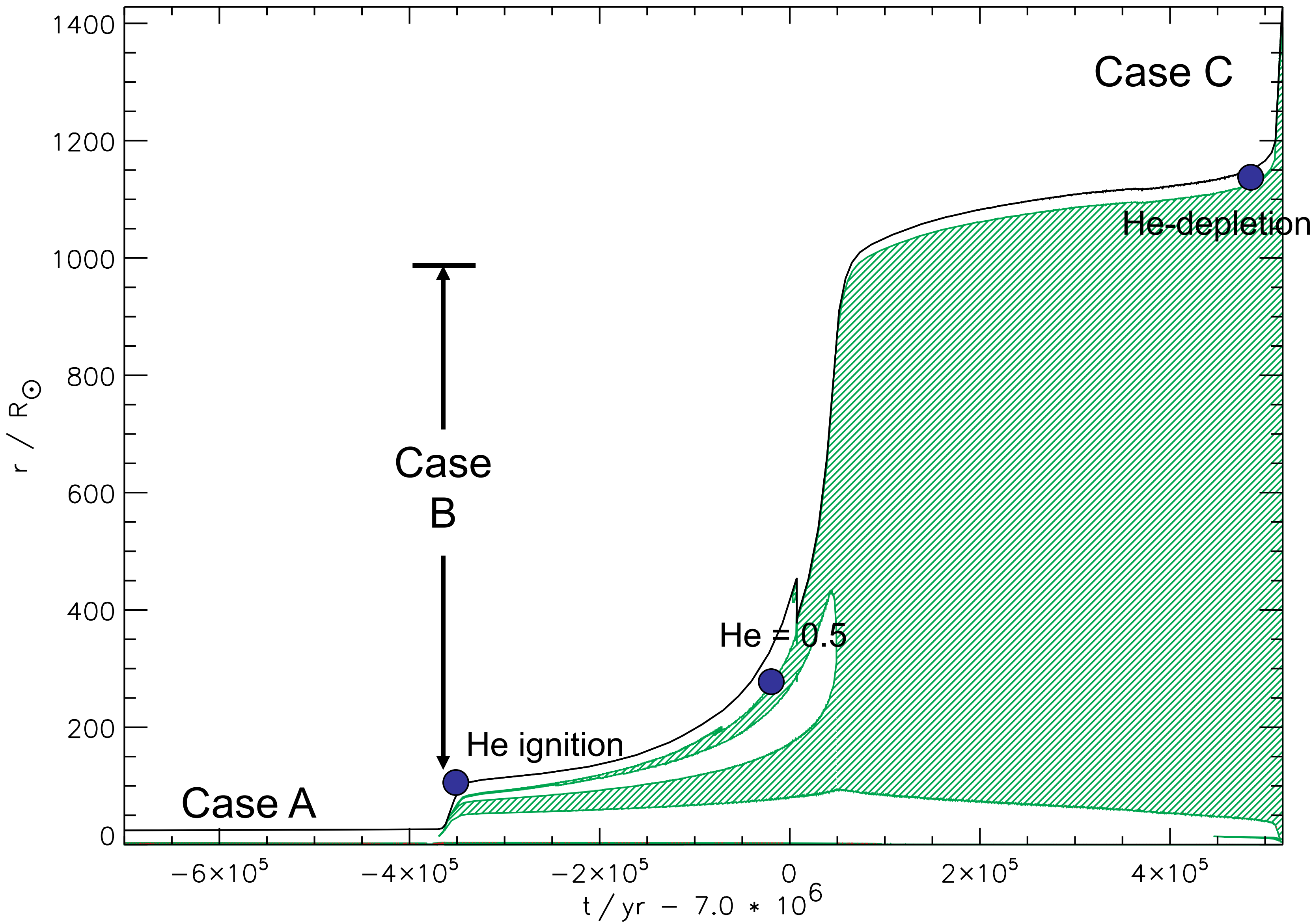
Woosley (2019, ApJ)

Half or more of massive stars are found in binaries with such close separations that the stars will interact when one of them becomes a supergiant (Sana & Evans 2011; Sana et al. 2012).

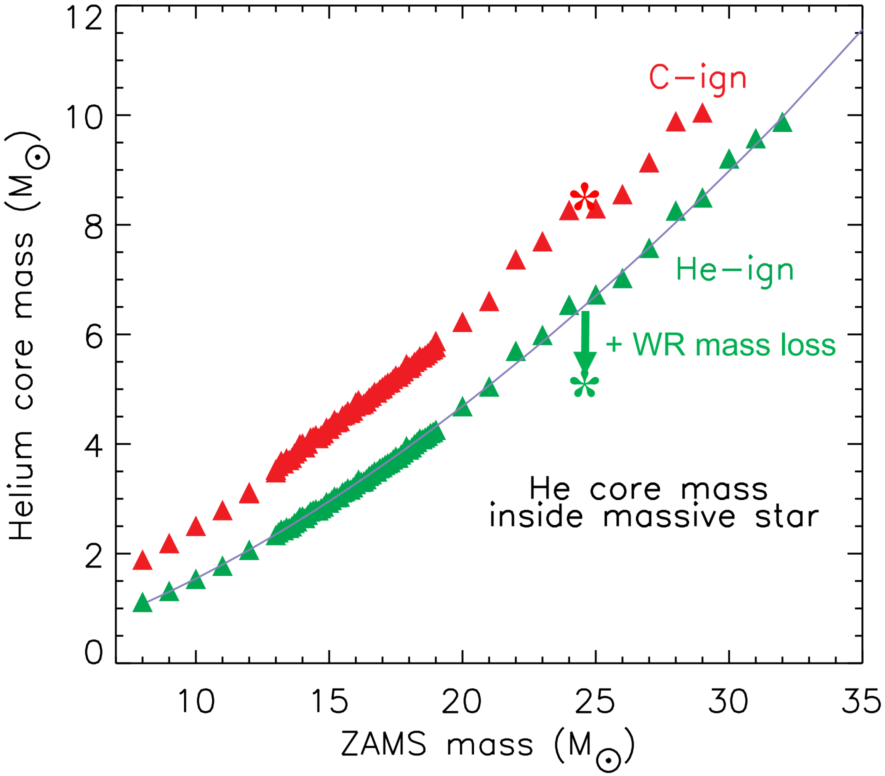
Most measurements of stellar remnant masses come from close binaries that will have interacted during their evolution.

Most often mass transfer occurs during or near the onset of core helium burning (Case B mass transfer),

# 25 $M_O$ Radius History



# The outcome of presupernova evolution is different in binaries




The size of the helium core in a massive star grows during He burning if the star retains an envelope. But suppose the envelope is lost to a companion at the beginning of helium burning (Case B). Its initial mass would be the green points.

Had the star kept its envelope until the end, its mass would be the red points. A 25 $M_O$ star in a bianry ends up as a 5 $M_O$ progenitor instead of a RSG with an 8.4 $M_O$ core.

The exposed helium core then loses mass as a WR-star. It's mass shrinks further.

$$\log \dot{M}_{CO} = -9.2 + 0.85 \log\left(\frac{L}{L_\odot}\right) + 0.44 \log Y_s + 0.25 \log\left(\frac{X_{Fe}}{X_{Fe\odot}}\right)$$

Yoon (2018)

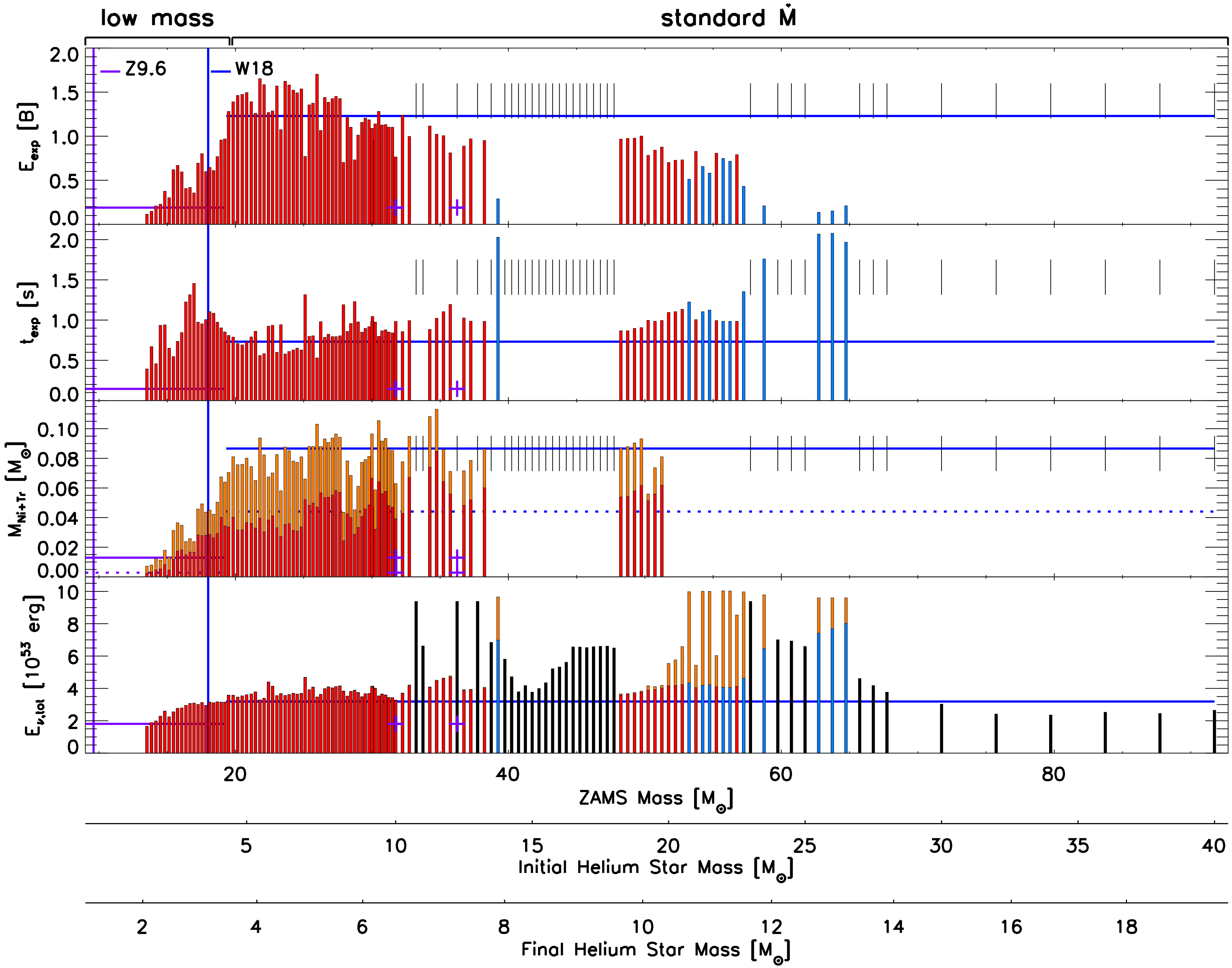
$$\log \dot{M}_{WNE} = -11.32 + 1.18 \log\left(\frac{L}{L_\odot}\right) + 0.6 \log\left(\frac{X_{Fe}}{X_{Fe\odot}}\right)$$

- Use same approach to modeling the explosion as before. – central 1.1 $M_O$ of proto-neutron star evolves as before in models calibrated to SN 1987A; 1D neutrino transport outside.

- Again study hundreds of models, but this time start with bare helium stars and allow them to lose mass according to several current mass loss prescriptions. Essentially we assume that the effect of binary membership is to remove the hydrogen envelope at helium ignition.

- Explode using P-HOTB, postprocess with KEPLER. Check for consistent energy, remnant mass, and especially $^{56}$Ni production.

Ertl, Woosley. Sukhbold and Janka (2019)

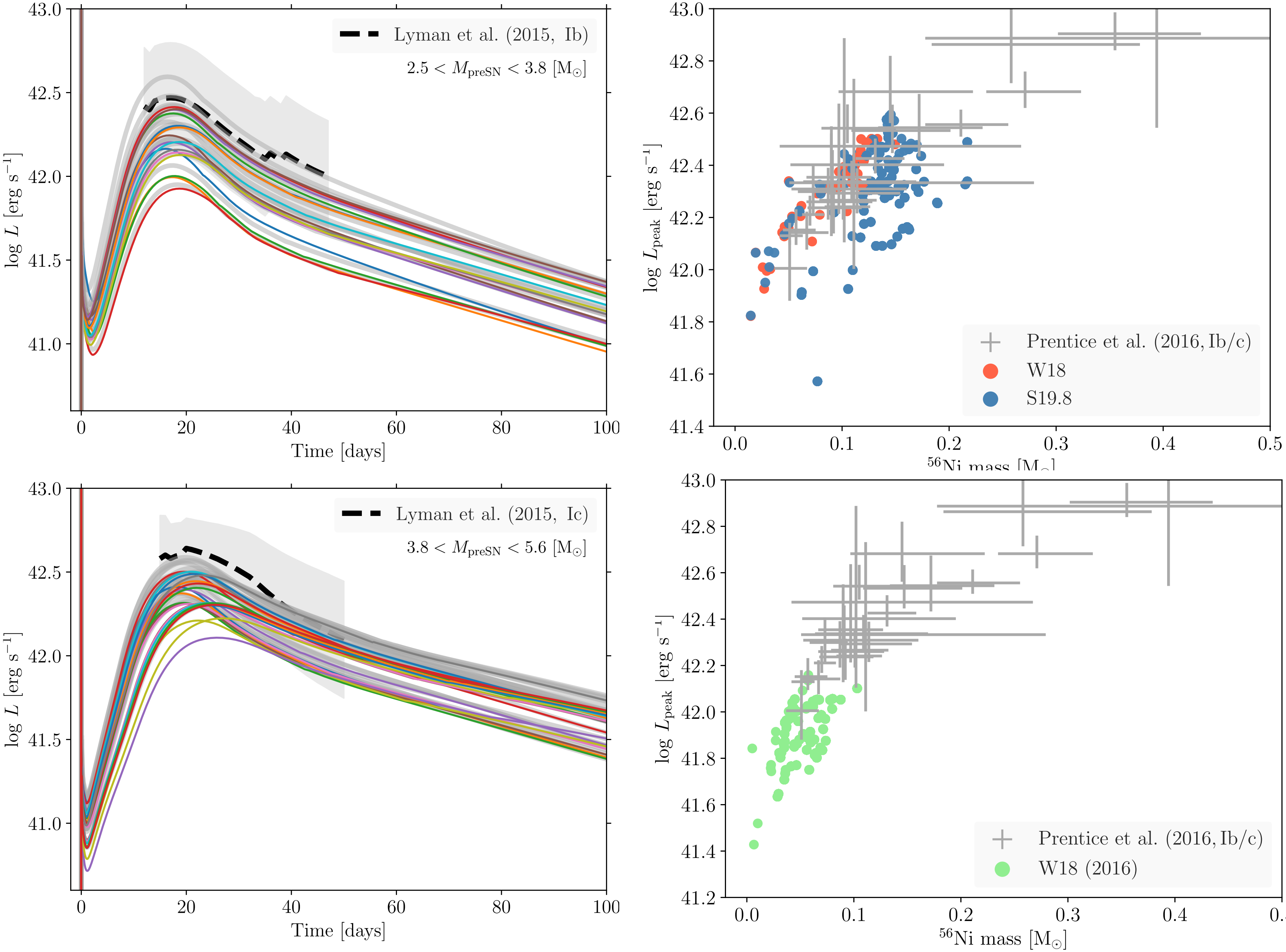


low mass
standard $\dot{M}$
Z9.6
W18
$E_{exp}$ [B]
$t_{exp}$ [s]
$M_{Ni+Tr}$ [$M_\odot$]
$E_{\nu,tot}$ [$10^{53}$ erg]
ZAMS Mass [$M_\odot$]
Initial Helium Star Mass [$M_\odot$]
Final Helium Star Mass [$M_\odot$]

| | | $E_{\mathrm{exp}}$ [B] | $\mathrm{Ni}_{\mathrm{min}}$ [$\mathrm{M}_{\odot}$] | Ni + Tr/2 [$\mathrm{M}_{\odot}$] | Ni + Tr [$\mathrm{M}_{\odot}$] | $\mathrm{Ni}_{\mathrm{max}}$ [$\mathrm{M}_{\odot}$] | Ni (2016) [$\mathrm{M}_{\odot}$] |
|---|---|---|---|---|---|---|---|
| | | | | | overall | | |
| W18 | median | 0.753 | 0.028 | 0.042 | 0.054 | 0.069 | 0.036 |
| | mean | 0.832 | 0.029 | 0.041 | 0.053 | 0.073 | 0.035 |
| S19.8 | median | 0.966 | 0.031 | 0.051 | 0.070 | 0.097 | |
| | mean | 1.015 | 0.036 | 0.052 | 0.068 | 0.090 | |
| | | | | | $5 > M_{\mathrm{He,i}} \geq 3$ | | |
| W18 | median | 0.628 | 0.026 | 0.034 | 0.042 | 0.059 | 0.036 |
| | mean | 0.738 | 0.023 | 0.034 | 0.044 | 0.064 | 0.032 |
| S19.8 | median | 0.680 | 0.025 | 0.032 | 0.041 | 0.059 | |
| | mean | 0.833 | 0.025 | 0.037 | 0.049 | 0.071 | |
| | | | | | $8 > M_{\mathrm{He,i}} \geq 5$ | | |
| W18 | median | 1.429 | 0.037 | 0.058 | 0.081 | 0.113 | 0.042 |
| | mean | 1.408 | 0.040 | 0.061 | 0.081 | 0.110 | 0.045 |
| S19.8 | median | 1.782 | 0.038 | 0.069 | 0.100 | 0.136 | |
| | mean | 1.719 | 0.045 | 0.071 | 0.097 | 0.130 | |

$\mathrm{Ni}_{\mathrm{max}}$ = 0.75*(Ni+Tr+$\alpha$) starts to violate fundamental constraints

# These explosions produce Type Ib and Ic supernovae




Ertl et al (2019)

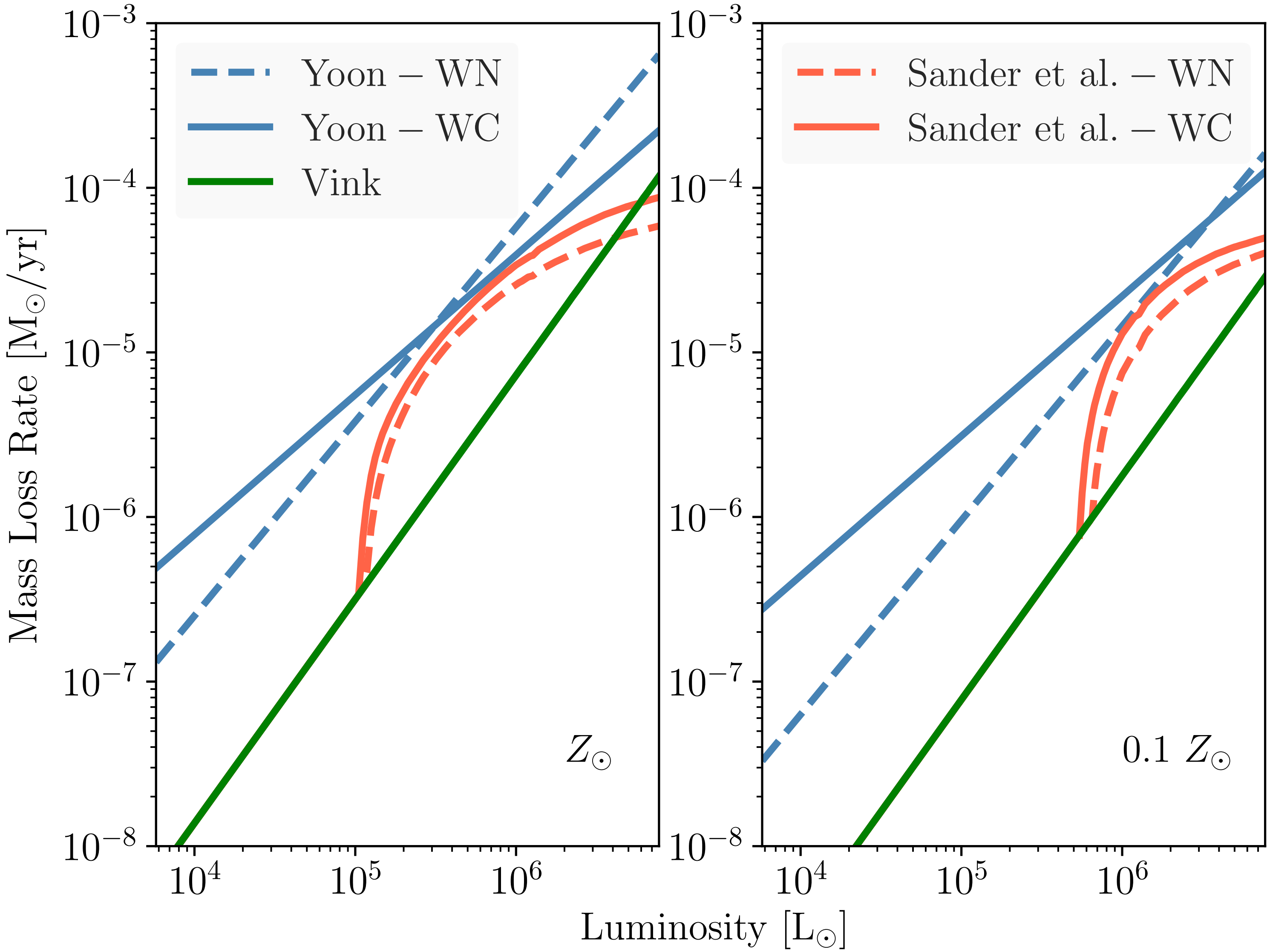
*The rise times, widths, velocities, and temperatures of the models are consistent with observations. However, it only proves possible to produce the peak luminosity of about half the observations.*

*The models predict a maximum bolometric luminosity of $10^{42.5}$ erg $s^{-1}$ and a maximum $^{56}$Ni mass near 0.15 $M_O$. Median luminosities and Ni masses were between $10^{41.15}$ and $10^{42.23}$ erg $s^{-1}$ and 0.05 to 0.07 $M_O$*

## Possibilities

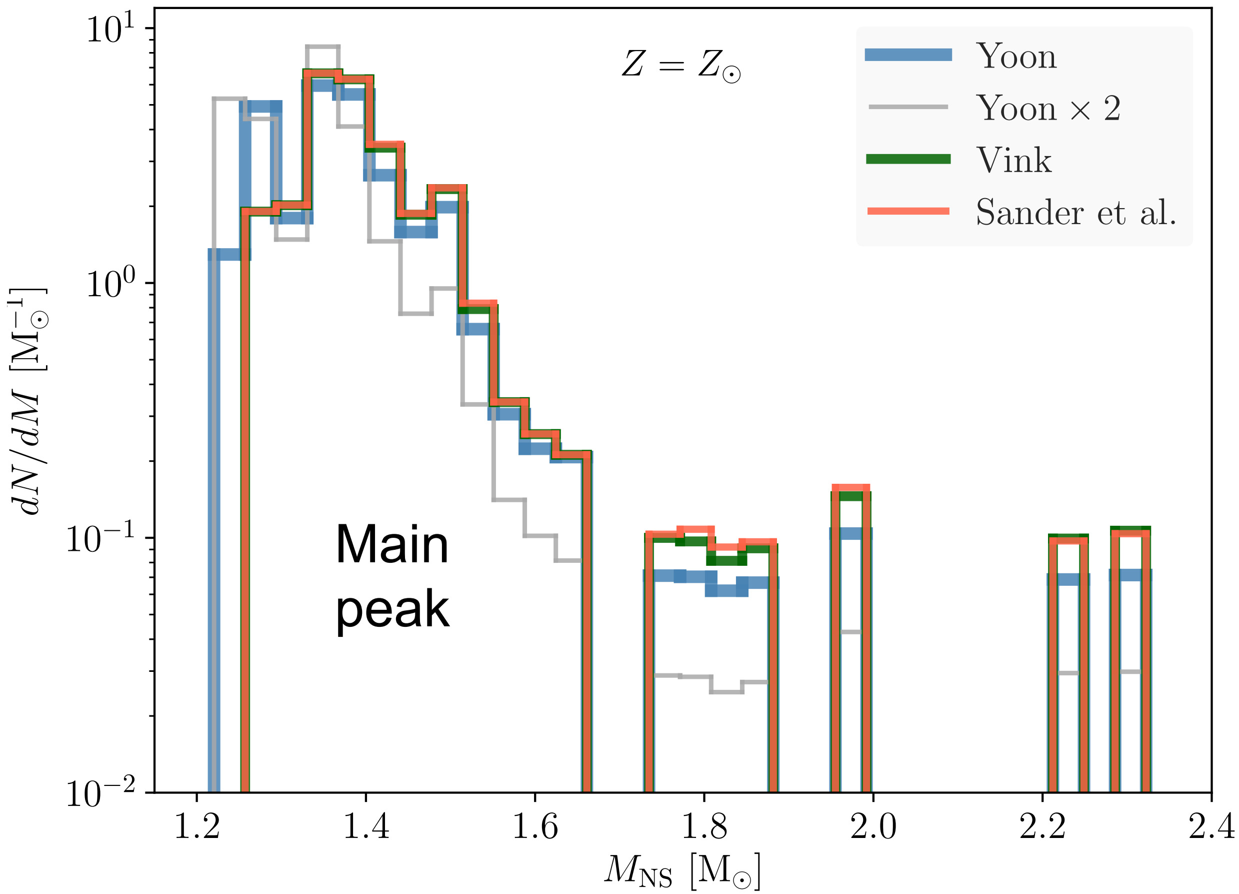
- We have underestimated $^{56}$Ni production in our models (unlikely based on physics arguments, neutron star masses, and the need to make most of iron in SN Ia not SN II or Ib)
- The observers have overestimated the bolometric luminosities of Type Ib and Ic supernovae, especially the brightest 1/3
- "Normal" Type Ib and Ic supernovae are not all powered by radioactive decay like the text books say. Magnetar? Relation to SN Ic BL, SLSN, GRB ?

To get the remnant mass distribution 4 choices of mass loss rate were explored and two metalliciies




Yoon = Yoon (2018)     Vink = Vink (2018)     Sander et al = Sander et al (2019)
2 x Yoon is regarded as “high” and Vink (2018) as “low” especially for large L.

## Neutron Star Initial Mass Function (in binaries)




Masses above 1.6 $M_O$ are produced by fall back. Note that their fraction is sensitive to mass loss

Table 3. Average Neutron Star Masses

| $\dot{M}$ | median [$M_\odot$] | mean [$M_\odot$] | $f_{NS}$ |
|---|---|---|---|
| Yoon | 1.348 | 1.382 | 0.776 |
| Yoon × 2 | 1.324 | 1.342 | 0.895 |
| Vink | 1.368 | 1.409 | 0.686 |
| Sander et al. | 1.368 | 1.410 | 0.685 |

Note. — All quantities are evaluated at solar metallicity with Salpeter $\alpha = 2.35$ across the entire helium star mass range. $f_{NS}$ is the fraction of supernova explosions.

The median is robustly between 1.32 and 1.37 $M_O$
This is consistent with observations
Very similar results for Z = 0.1 solar.
Lightest neutron star 1.24 $M_O$

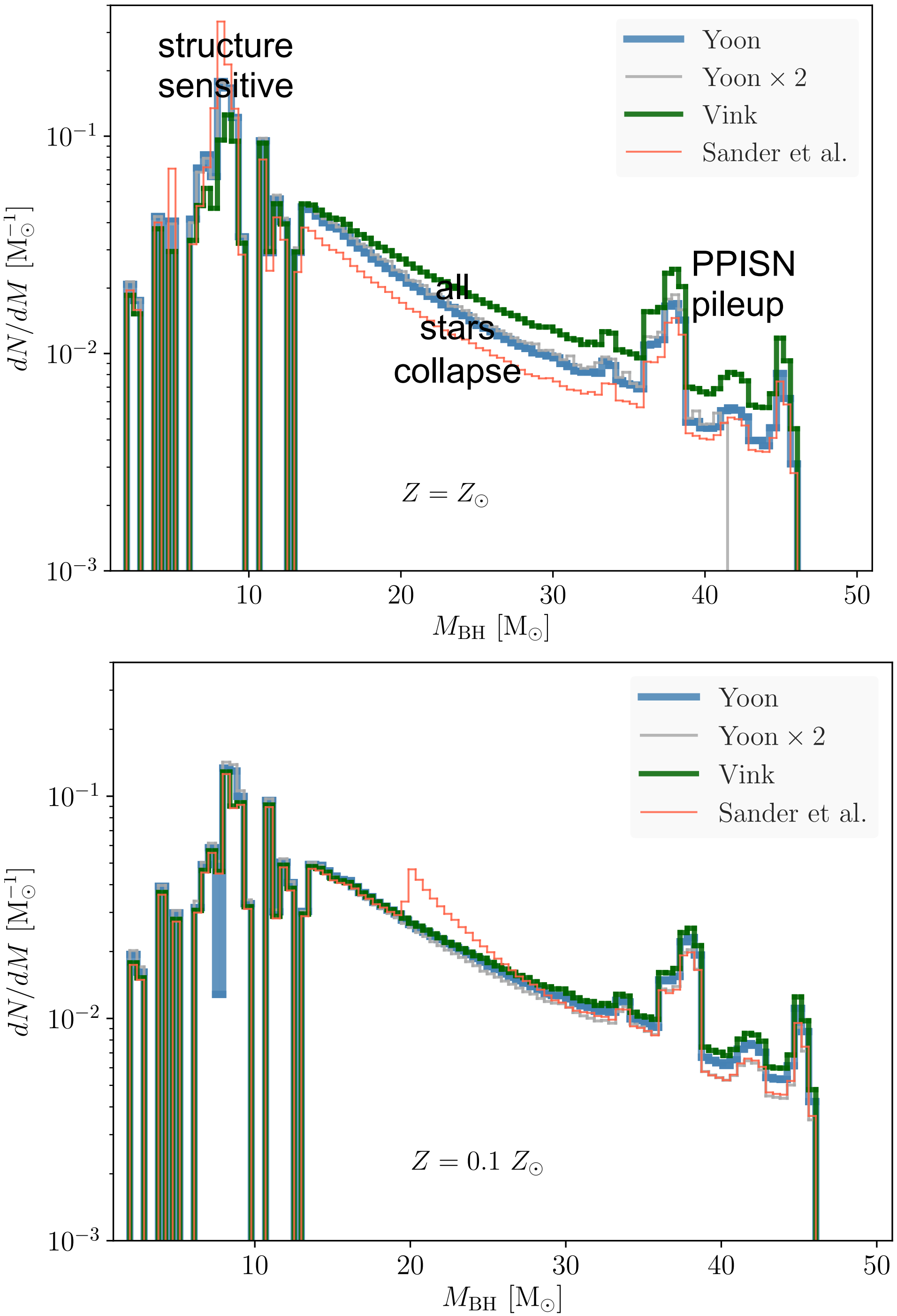



Table 4. Average Black Hole Masses

| $\dot{M}$ | median [$M_\odot$] | mean [$M_\odot$] | $f_{\rm BH}$ |
|---|---|---|---|
| $2.5 < M_{\rm He,i} < 40$ [$M_\odot$] | | | |
| | $Z = Z_\odot$ | $\alpha = 2.35$ | |
| Yoon | 8.9 | 10.3 | 0.16 |
| Yoon × 2 | 9.0 | 10.7 | 0.08 |
| Vink | 10.7 | 11.4 | 0.20 |
| Sander et al. | 8.3 | 9.9 | 0.24 |
| | $Z = 0.1\ Z_\odot$ | $\alpha = 2.35$ | |
| Yoon | 10.7 | 11.3 | 0.19 |
| Yoon × 2 | 10.5 | 11.1 | 0.19 |
| Vink | 10.8 | 11.4 | 0.20 |
| Sander et al. | 10.8 | 11.4 | 0.20 |
| $2.5 < M_{\rm He,i} < 150$ [$M_\odot$] | | | |
| | $Z = Z_\odot$ | $\alpha = 2.35$ | |
| Yoon | 12.3 | 15.9 | 0.22 |
| Yoon × 2 | 12.8 | 15.5 | 0.11 |
| Vink | 15.5 | 18.3 | 0.31 |
| Sander et al. | 9.0 | 14.4 | 0.32 |
| | $Z = 0.1\ Z_\odot$ | $\alpha = 2.35$ | |
| Yoon | 15.2 | 18.0 | 0.30 |
| Yoon × 2 | 14.4 | 17.2 | 0.28 |
| Vink | 15.7 | 18.5 | 0.32 |
| Sander et al. | 16.0 | 18.1 | 0.32 |

- No BH mass gap at 5 $M_O$ Can produce a continuous distribution from max neutron star mass on up. But there is a relative deficiency below 5 – 6 $M_O$

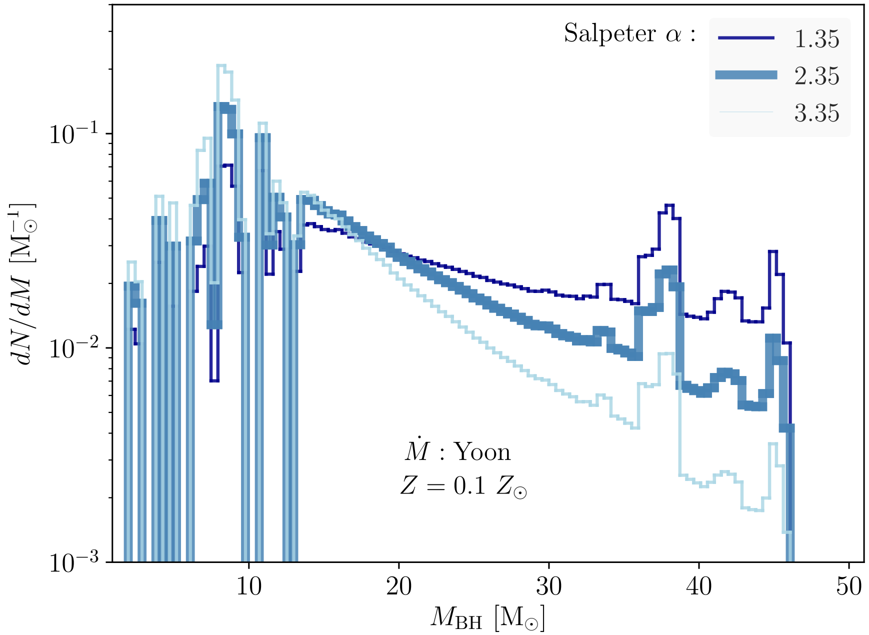
- BH mass gap at 46 to 133 (55 to 144) $M_O$ depending on $^{12}C(\alpha,\gamma)^{16}O$ in binaries. (PPISN). Smaller $^{12}C(\alpha,\gamma)^{16}O$ raises the gap and also weakens the PPI

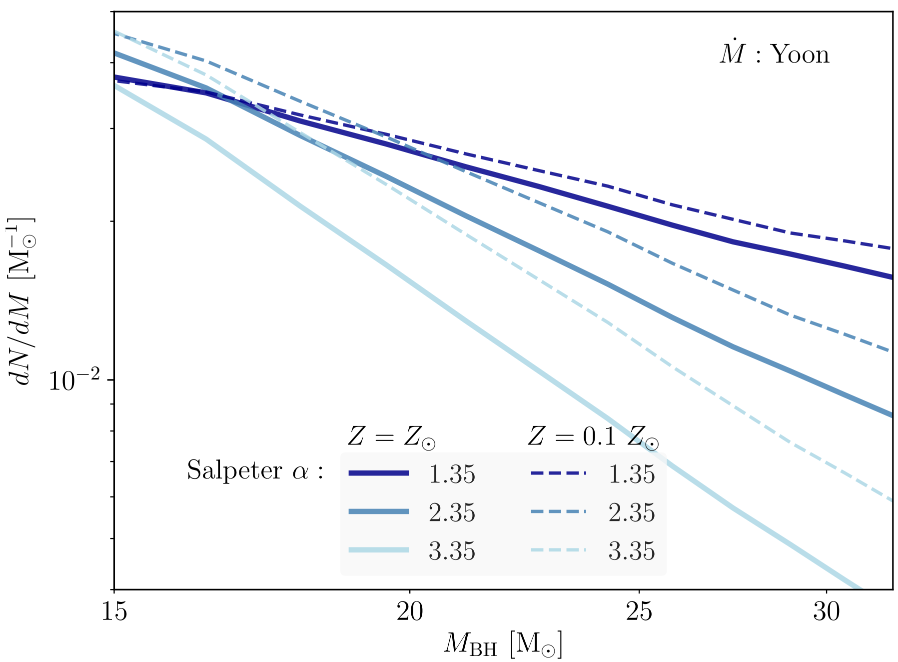
- Pile up around 38 - 40 $M_O$ (PPISN)

- BHs up to 70 $M_O$ can be made in single stars or detached binaries (H envelope implodes)

- Hint of a gap at 11 $M_{O,}$ sensitive to reaction rates and convection physics

- Remnant mass distribution is determined by preSN mass distribution for stripped stars (and helium core mass distribution in preSN for single stars)




- Assuming a Salpeter like (power law) distribution of initial stellar masses up to 130 $M_O$
- And a mass loss rate that is not very non-linear in the luminosity

Between 12 and 33 $M_O$ the distribution of black hole masses follows the IMF. This is because the preSN mass, all of which collapses is nearly a constant fraction of the initial star's mass

Measurements of the BH IMF in this mass range would constrain the stellar IMF for ZAMS stars in the range 50 to 130 $M_O$

# THE $\nu$-PROCESS[1]

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## ABSTRACT

As the core of a massive star collapses to form a neutron star, the flux of neutrinos in the overlying shells of heavy elements becomes so great that, despite the small cross section, substantial nuclear transmutation is induced. Neutrinos, especially the higher energy $\mu$- and $\tau$-neutrinos, excite heavy elements and even helium to particle unbound levels. The evaporation of a single neutron or proton, and the back reaction of these nucleons on other species present, significantly alters the outcome of traditional nucleosynthesis calculations leading to a new process: $\nu$-nucleosynthesis. Modifications to traditional hydrostatic and explosive varieties of helium, carbon, neon, oxygen, and silicon burning are considered. The results show that a large number of rare isotopes, including many of the odd-$Z$ nuclei from boron through copper, owe much of their present abundance in nature to this process. Specific nuclei due almost entirely to the $\nu$-process are $^{7}$Li, $^{11}$B, $^{19}$F, $^{138}$La, and $^{180}$Ta. Significant amounts of $^{10}$B, $^{15}$N, $^{22}$Na, $^{26}$Al, $^{31}$P, $^{35}$Cl, $^{39,40,41}$K, $^{45}$Sc, $^{47,49}$Ti, $^{50,51}$V, $^{55}$Mn, $^{59}$Co, and $^{63}$Cu are also produced, so much so that, within the uncertainties of the model, these nuclei also might owe their origin predominantly to the $\nu$-process. Neutrino-induced production of $^{11}$B argues against the existence of an unobserved low-energy component of cosmic rays, frequently invoked in spallation scenarios to account for the observed isotopic ratio of boron. Despite our success in producing many intermediate-mass isotopes, we find that the recently suggested neutrino-induced $r$-process in the helium shell is quite small in any of the realistic scenarios we explored.

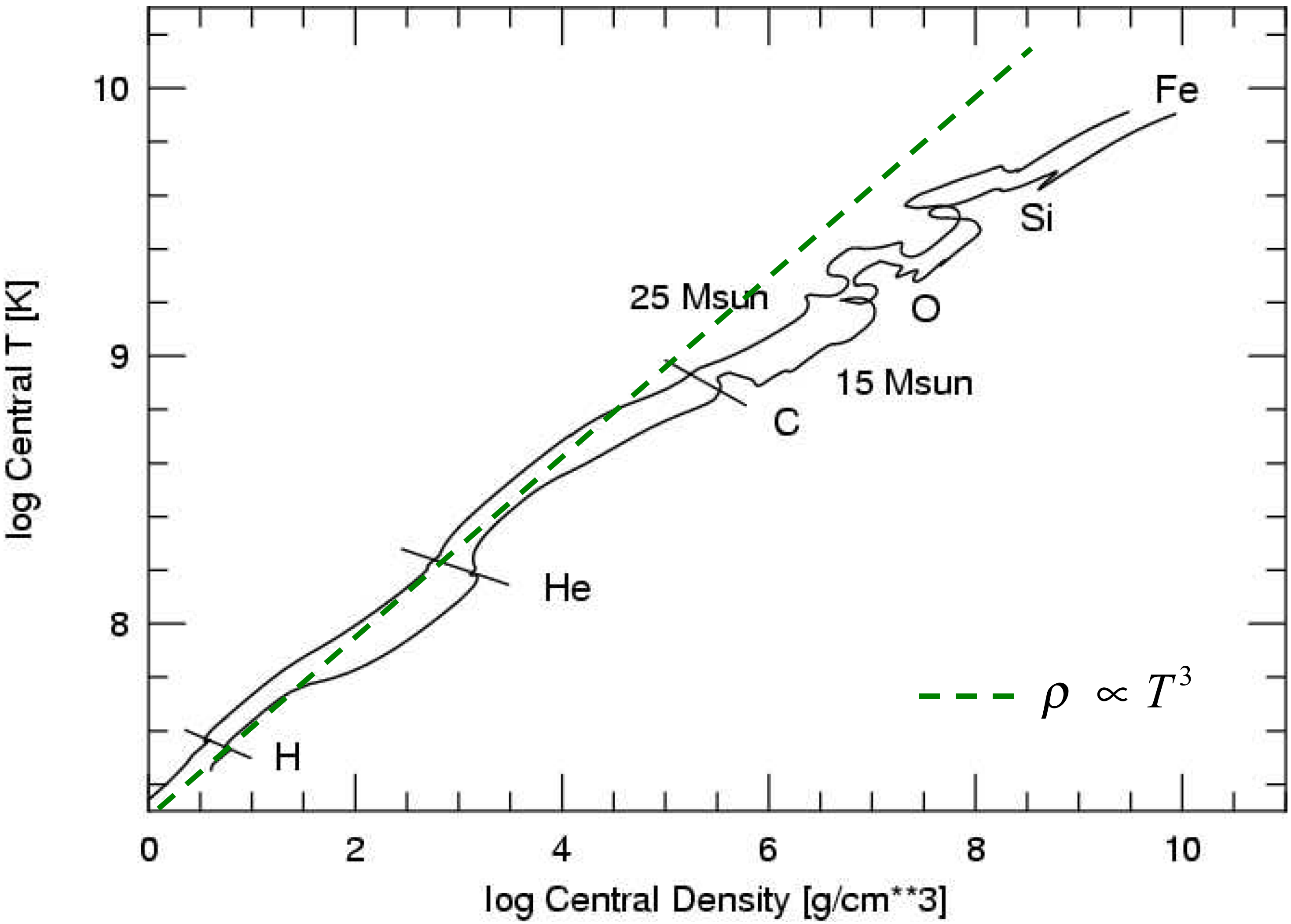
## Basics

If degeneracy is negligible and mass is constant, the Virial Theorem implies that the central temperature, central density and mass of a star follow a simple scaling. (This scaling is strictly true for any polytrope of single index n, uniform composition, and constant ratio of ideal gas pressure to total pressure, $\beta$, where degeneracy does not dominate)

$$\frac{T_c^3}{\rho_c} \propto M^2$$

More massive stars have higher entropy, less degeneracy, and burn their fuels at lower density

# Central Conditions

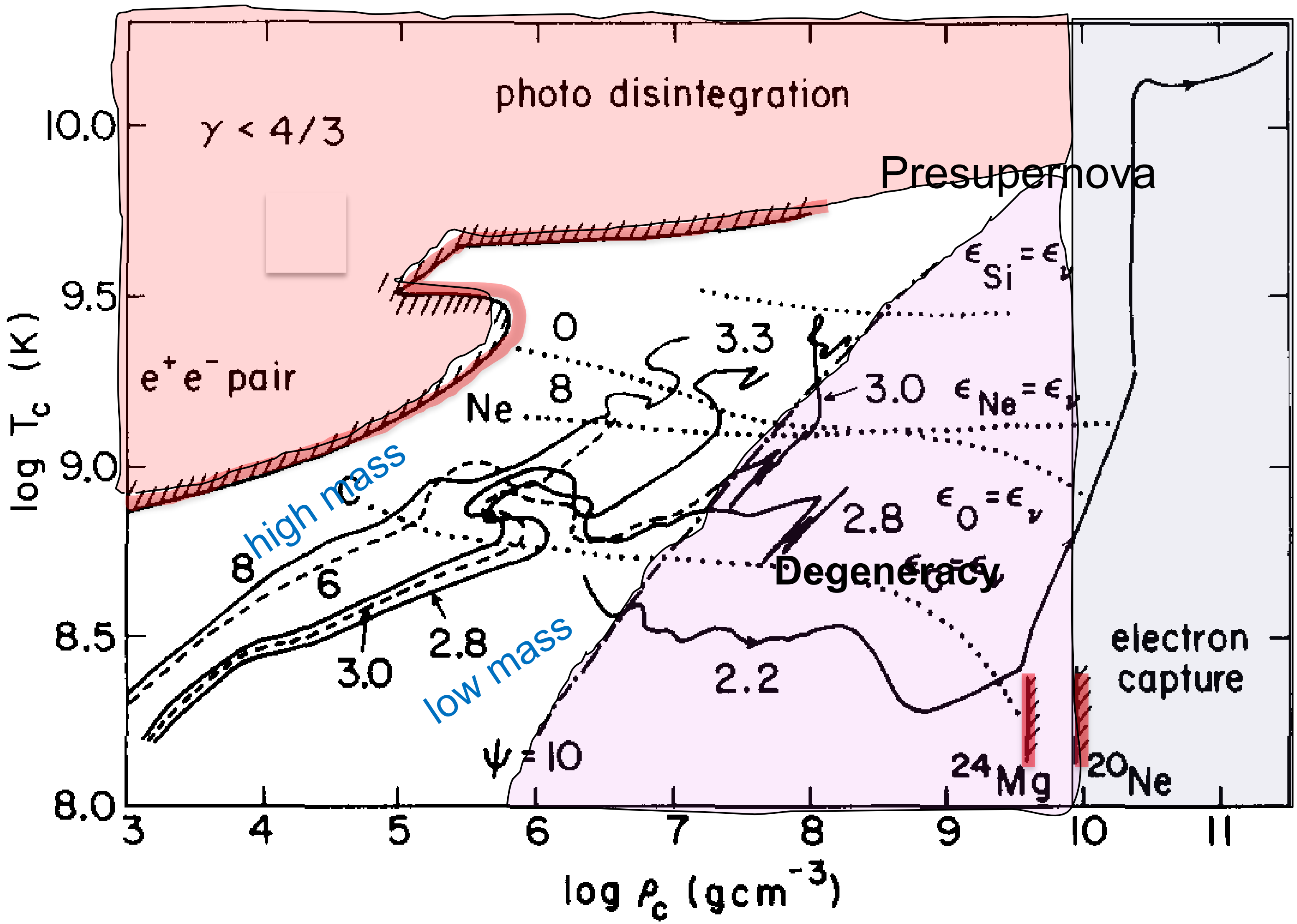



at death the iron cores of massive stars are somewhat degenerate

As a star of given mass evolves, its central temperature rises roughly as the cube root of its central density

More generally for helium cores of constant mass, 2.2, 2.8, 3.0, 3.3, 6 and 8 $M_O$ (Nomoto and Hashimoto 1988)

$M_{ZAMS} \approx 9 - 25\, M_\odot$




It turns out that $M_{He}$ =35 $M_O$ will just brush the e+e- pair instability

# Single Star Death Chart

| Mass (solar masses) | End point | Remnant |
|---|---|---|
| < ~8 | planetary nebula | CO white dwarf |
| ~8 to ~11 | degenerate core neutrino-powered low energy SN | Ne-O WD below 9? neutron star above 9 |
| ~11 - ~20 | neutrino-powered normal supernova; Islands of collapse at higher mass | neutron stars and black holes |
| 20 - 70 | without mass loss very few SN unless rotationally powered; SLSN?, GRB? | black hole<br><br>occasional neutron star |
| 70 – 150 | pulsational pair SN if low mass loss | black hole |
| 150 - 260 | pair instability SN if low mass loss | none |
| > 260 | pair induced collapse if low mass loss | black hole |

Degeneracy

Electron Capture

Photodisintegration

Electron Capture

Pair Instability

$\nu$-powered explosions?