THE DEATHS OF MASSIVE STARS AND THE BIRTH OF BLACK HOLES

Stan Woosley (UCSC)

with Tuguldur Sukhbold (Ohio)
Alex Heger (Monash)
Thomas Janka (MPI)
Thomas Ertl (MPI)
and Dan Kasen (UCB)

PREAMBLE

- **Humble Offer**: Our group now has thousands of presupernova models for Type II, Ib, Ic, and pair-instability supernovae of all masses. These are available to the consortium.

- **Conclusion:** Anyone getting a credible explosion in 3D using a standard progenitor for SN 1987A that gives 1.3 B of explosion energy in a non-rotating, neutrino-powered model can claim to have "solved the supernova problem"

  I don't know of anyone who has gotten over 0.9 B, but it is getting there …

Meanwhile …

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.

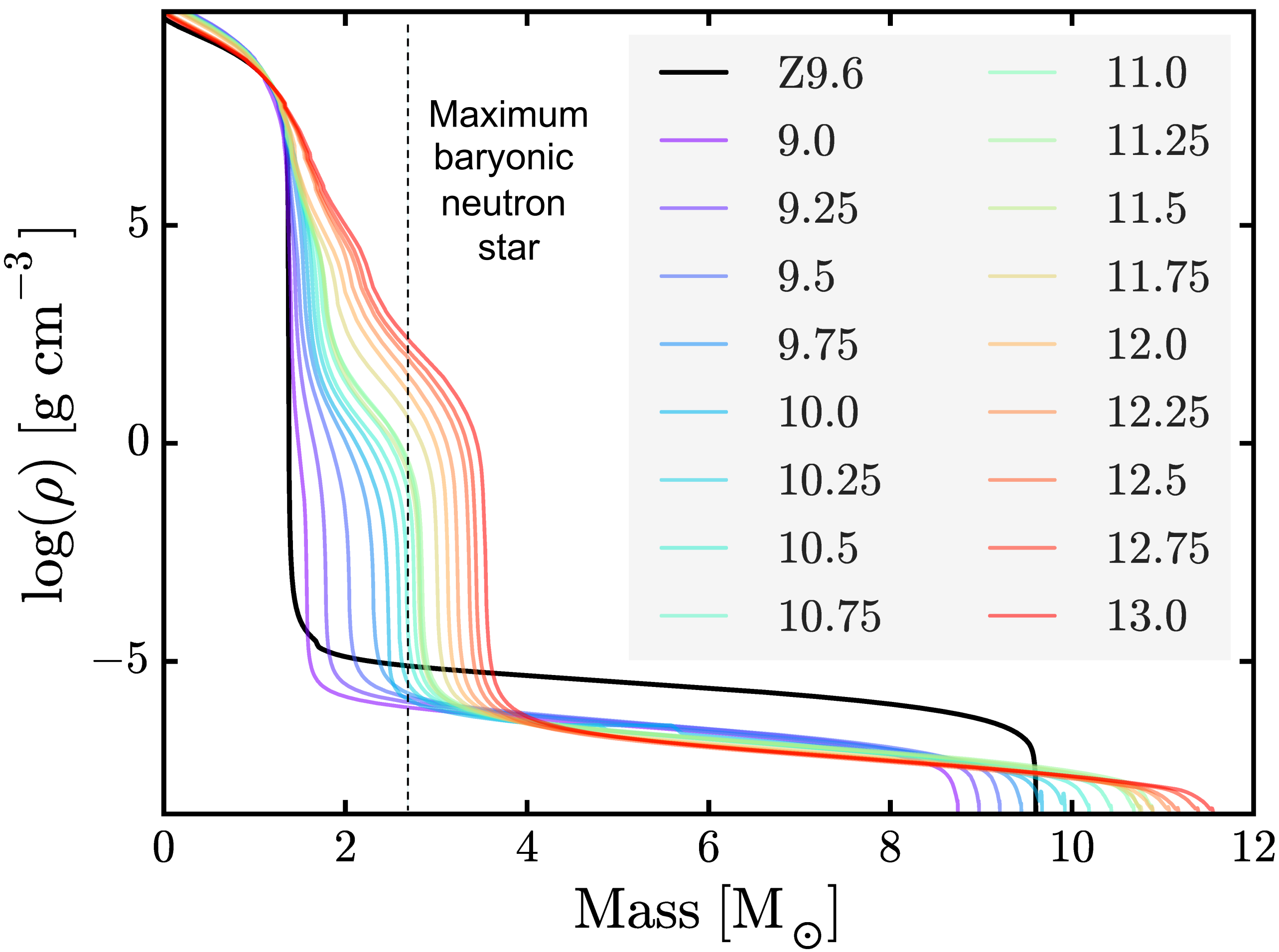
- Several groups now routinely get low energy explosions of low mass progenitors, roughly 8 to 12 solar masses. These may account for the Crab, in particular, and maybe half of all other supernovae. Heavier stars occasionally explode on the computer, but with low energy – few x 10^{50} erg

- Heavier stars are needed for nucleosynthesis, light curves, explosion energies above ~10^{51} erg, and remnant mass distributions, but it may be that most single stars over 20 solar masses usually fail to explode. This may barely be consistent with observations

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

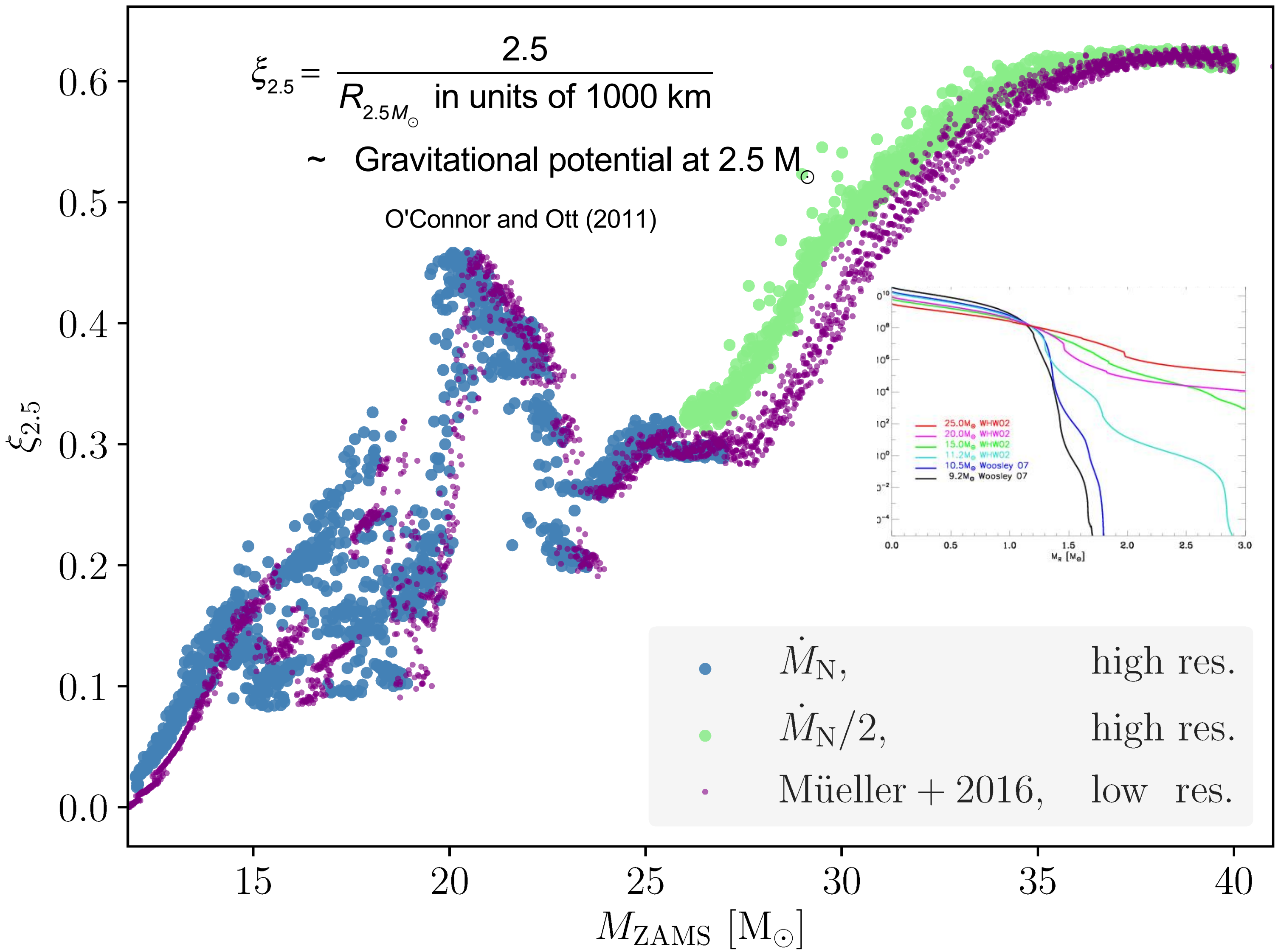
Now, as we all know …

The Outcome is Progenitor Dependent



Stars below 12 $M_{\odot}$ (He core 3.5 $M_{\odot}$) are comparatively easy to explode with neutrino transport and account for about half of observed supernovae. *They all make neutron stars.*

Above 12 M_O, the preSN models show some systematics that will certainly affect the outcome. We'd like to explore those systematics now, especially in an era of GW observations



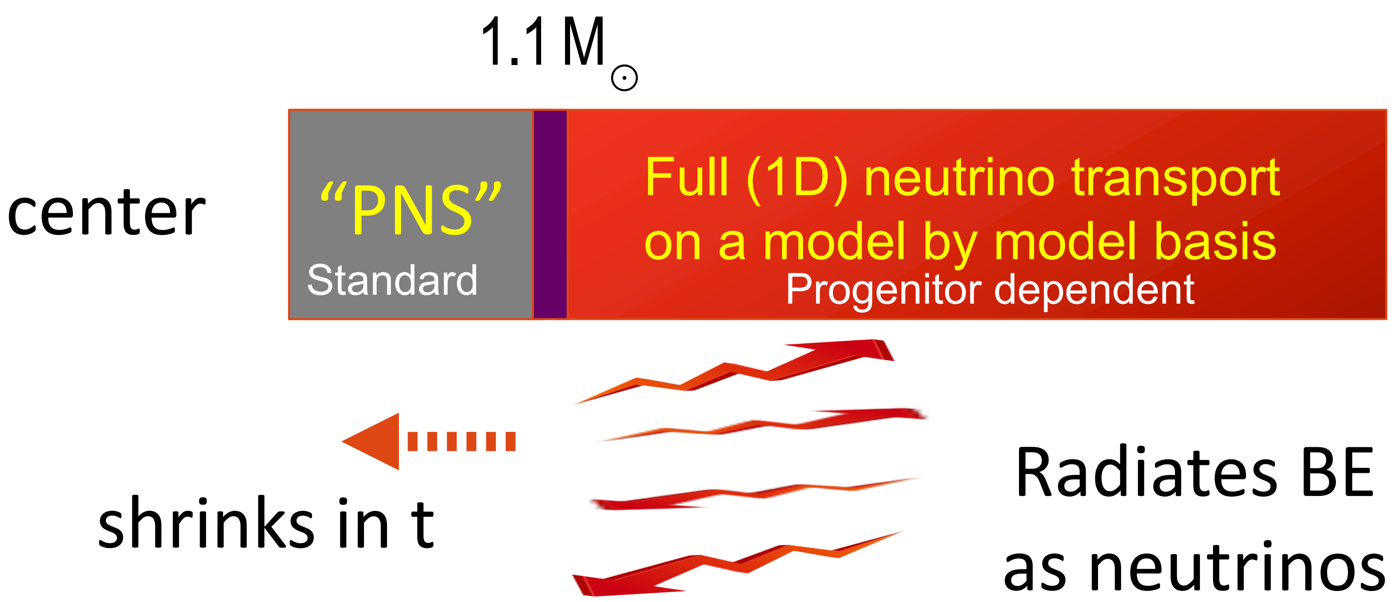
4000 models

Hard to Explode

Easy

Beyond Pistons

1D Neutrino-Transport Calculation with a standard central 1.1 M_O core



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

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

Ugliano et al (2012)

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

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

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

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

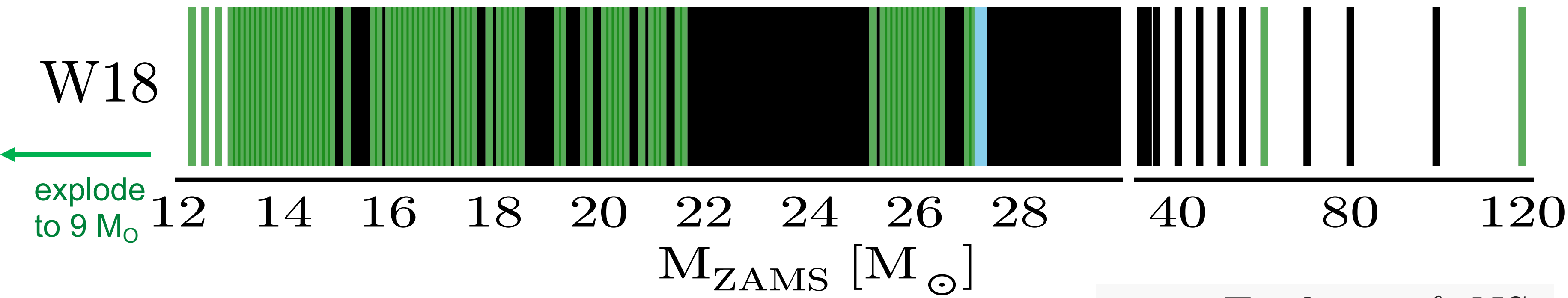
Neutrinos launched from edge of core with thermal distributions and the local temperature. 1D ν-transport after that.

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

	Model	$R_{c,f}$ [km]	Γ	ζ	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	87A
	W15	6.0	3.0	0.60	3.10	1.41	0.068	87A
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	87A
	N20	6.0	3.0	0.60	3.23	1.49	0.062	87A

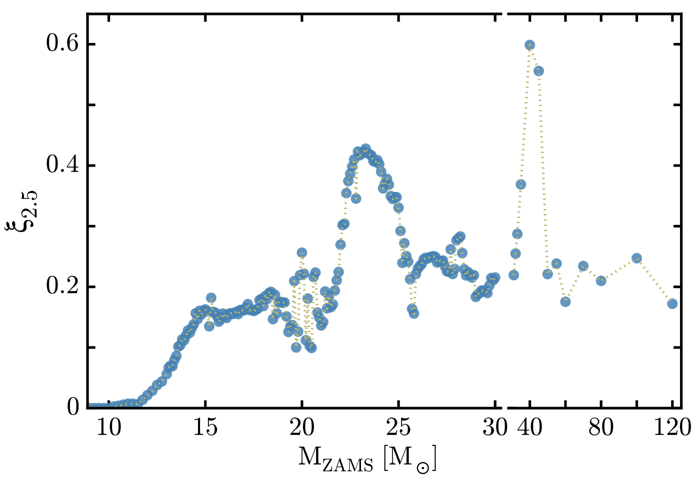
Central engine varied tuned to 5 models for 87A; 1 for the Crab
Required to give E_{51} and ^{56}Ni

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



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

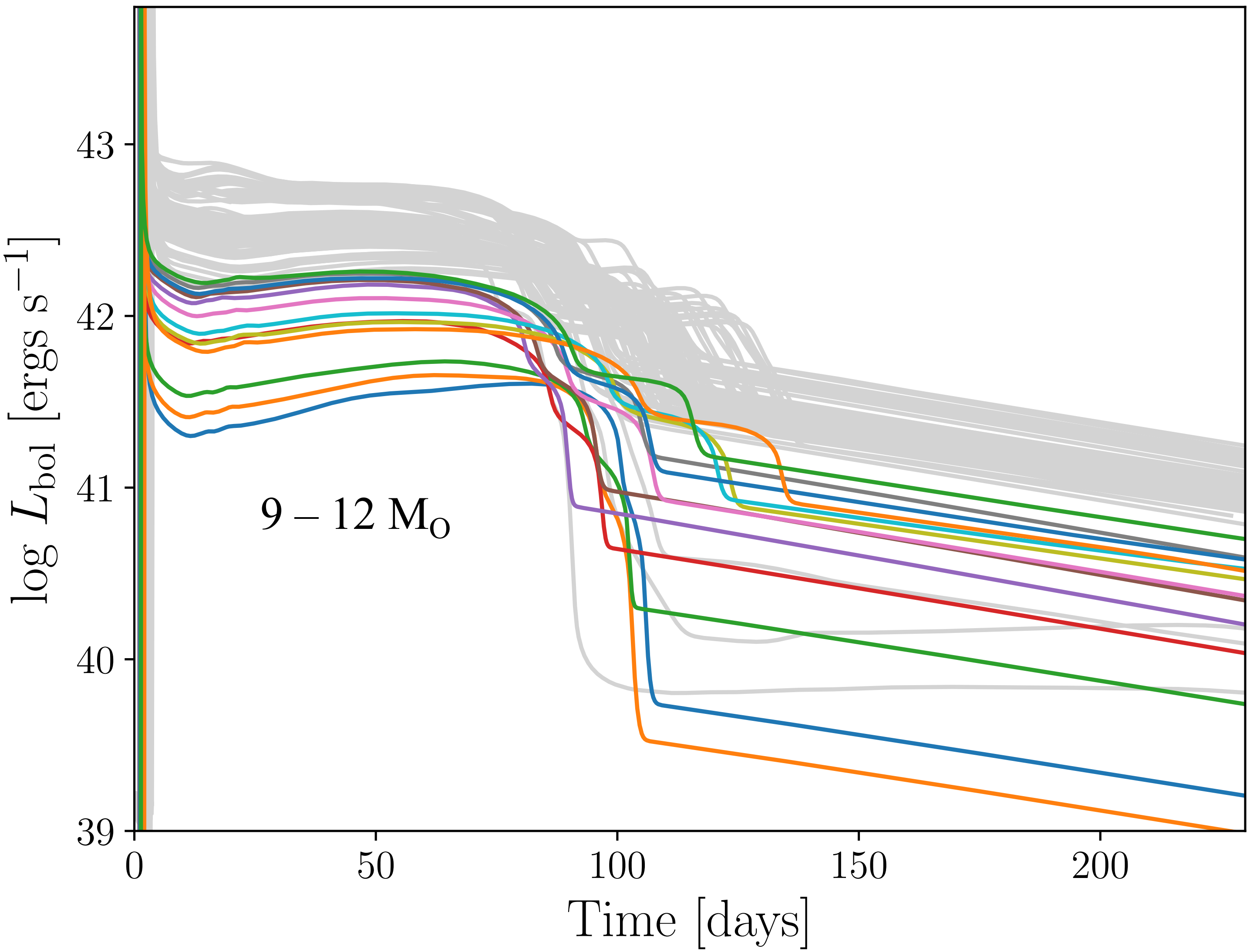
WR mass loss from Welstein and Langer (1999)
[large

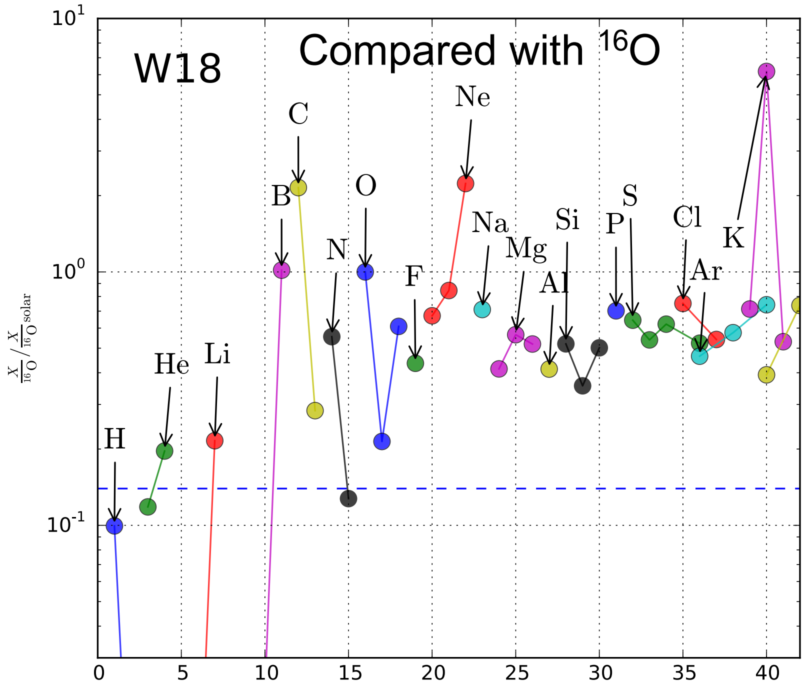


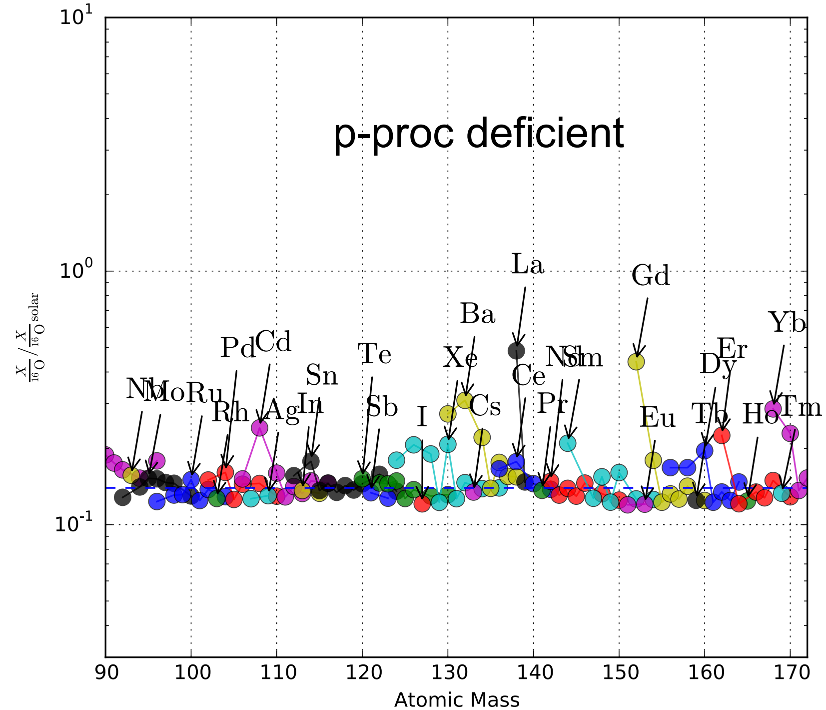
<u>Single stars</u>

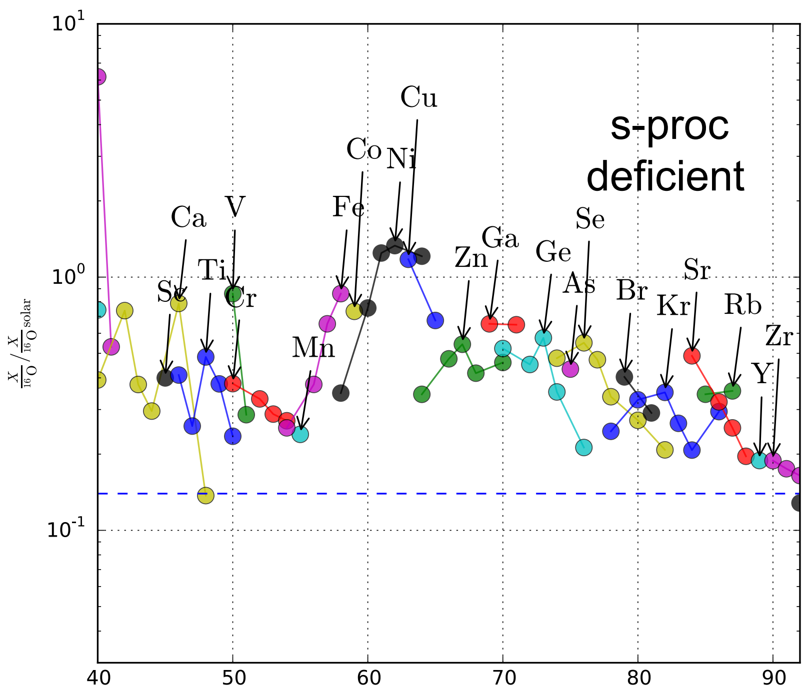
Average explosion energy	6 - 8 x 10^{50} erg
Average ^{56}Ni mass	0.04 – 0.06 $M_\odot$
Supernovae > 20 $M_\odot$	~10%
Fraction SN that make BH	~30%
Median neutron star mass	1.40
Median BH mass	9 (He core)
	14 (core plus env)

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









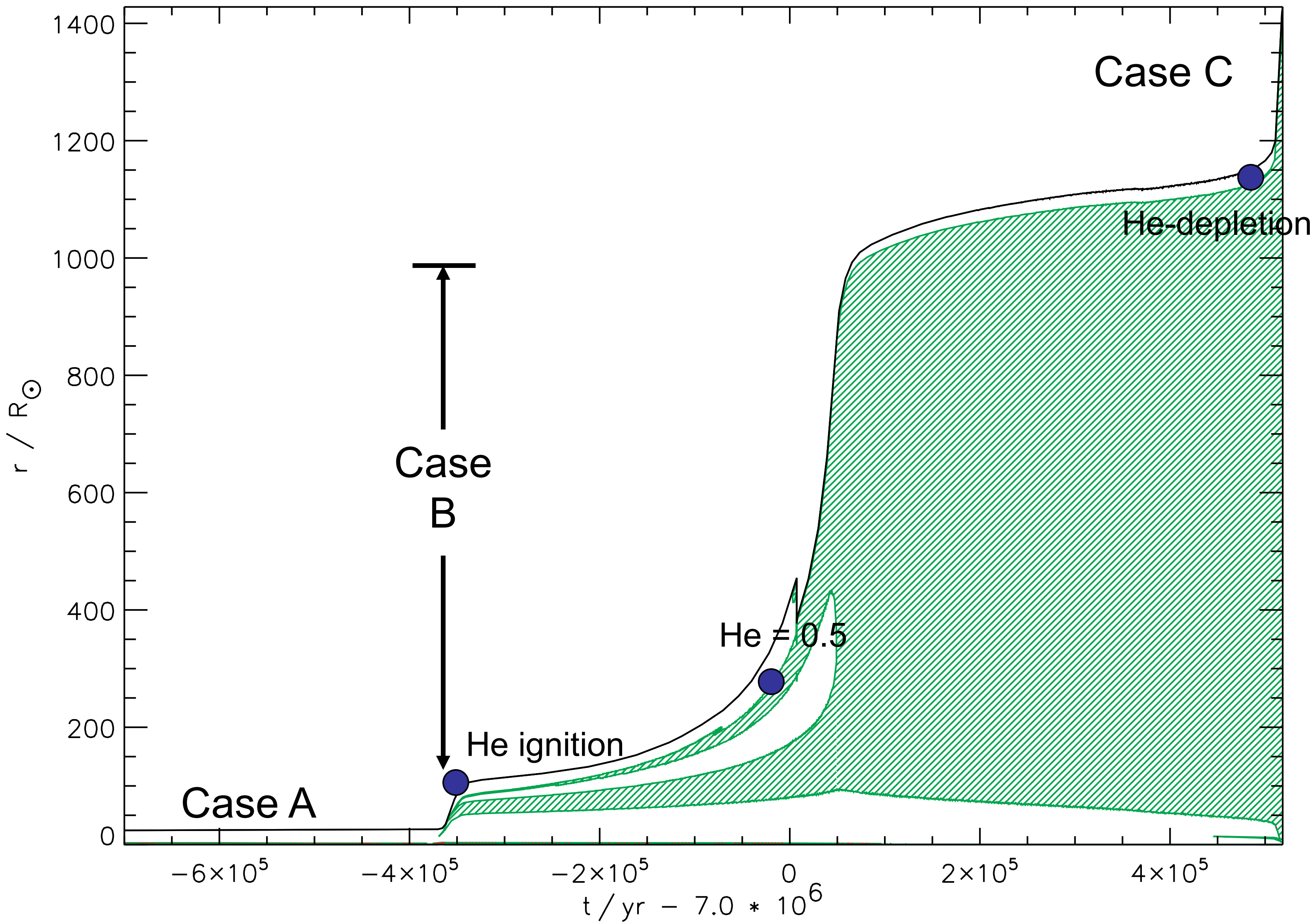
IMF averaged nucleosynthesis is reasonably good but a deficiency of s- and p-process. Need larger ^{22}Ne(α,n)^{25}Mg rate or more massive stars to explode.

Survey – Close Binaries
(Compact Remnant Masses
and Type Ibc Supernovae)

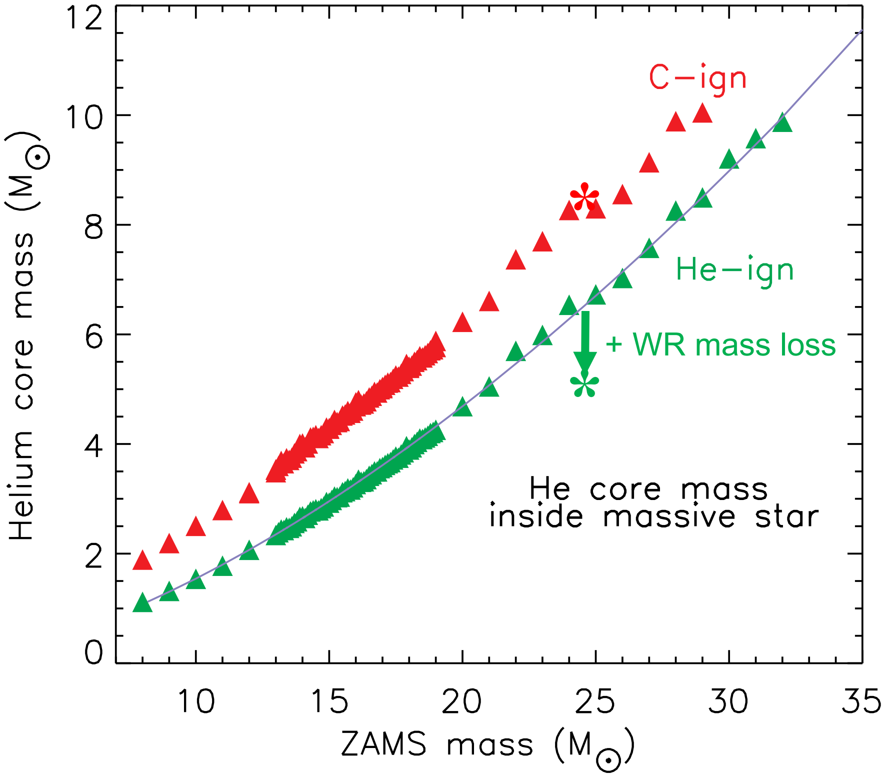
Woosley (2019, ApJ)
Ertl, Woosley, Sukhbold, Janka (2020)
Woosley, Sukhbold, Janka (2020)
Woosley, Sukhbold, Kasen (in prep)

- 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. It is assumed that for close binaries 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.

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 if 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 to the end, its mass would be the red points

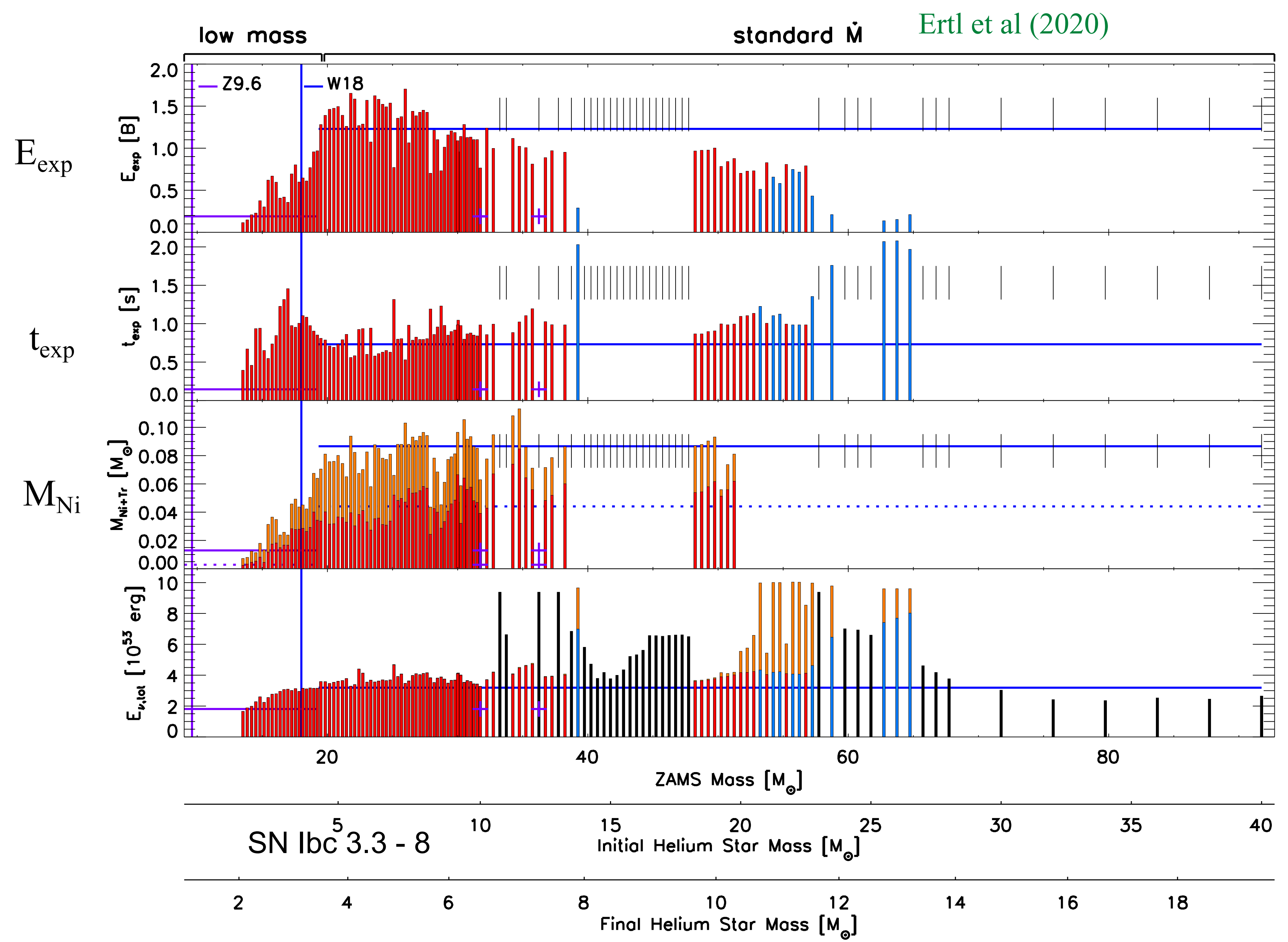
A 25 M_O star in a binary ends up as a 5 M_O SN progenitor instead of a RSG with an 8.4 M_O core.

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

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

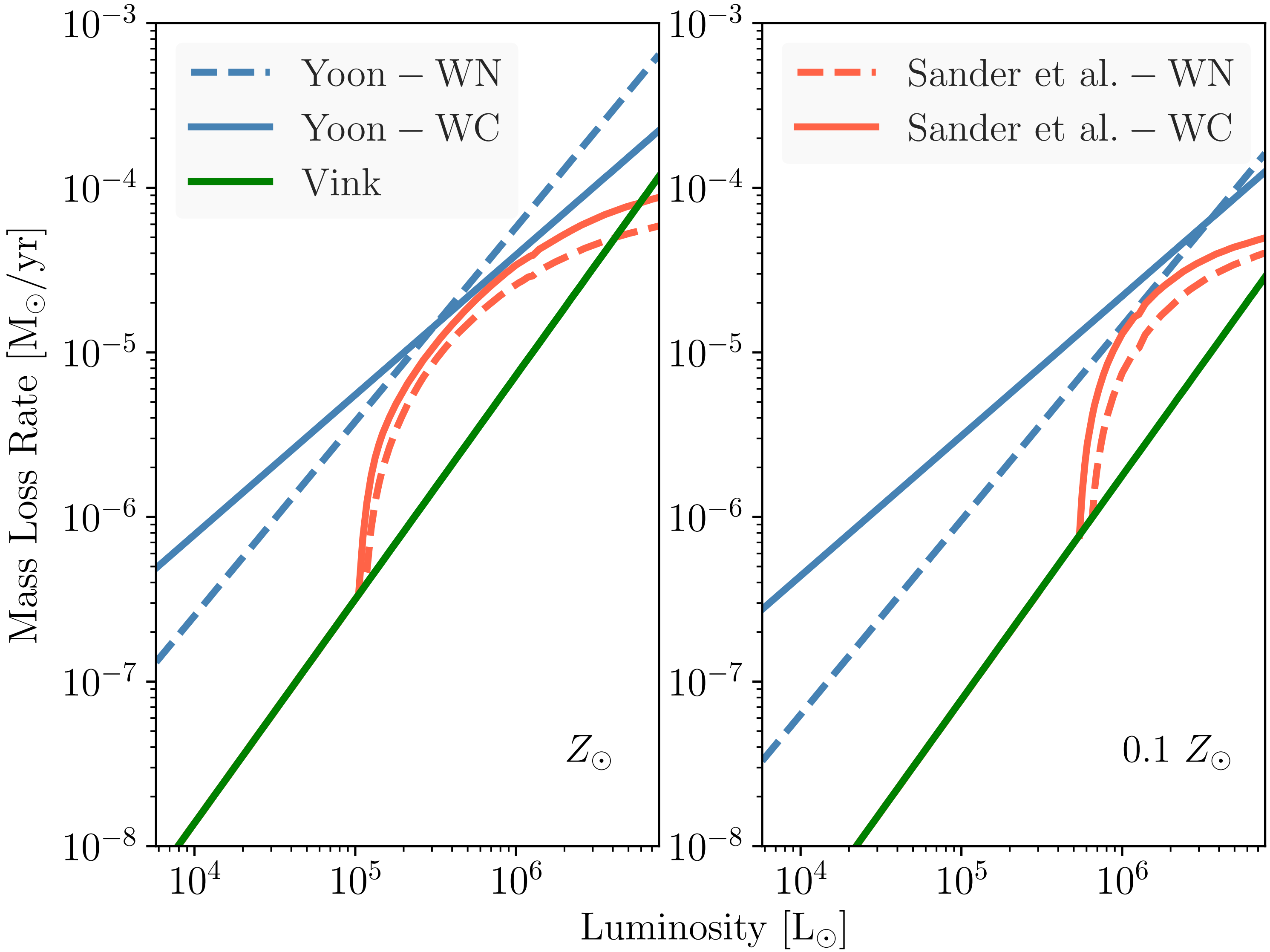
Yoon (2018)

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

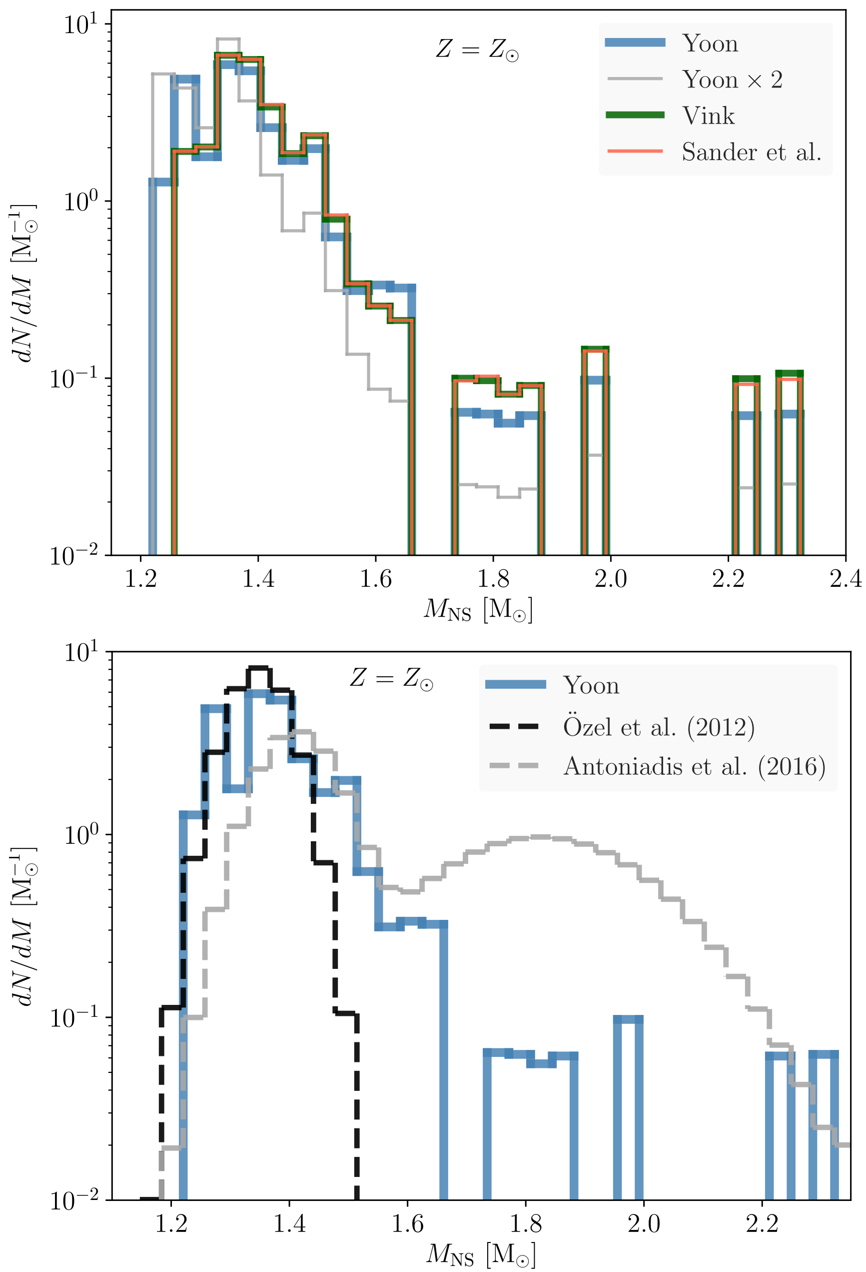


Ertl et al (2020)
low mass
standard Ṁ
E_exp
t_exp
M_Ni
Z9.6
W18
E_exp [B]
t_exp [s]
M_Ni+Tr [M_⊙]
E_ν,tot [10^53 erg]
ZAMS Mass [M_⊙]
SN Ibc 3.3 - 8
Initial Helium Star Mass [M_⊙]
Final Helium Star Mass [M_⊙]

To get the remnant mass distribution 4 choices of WR 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.



The Neutron Star Birth Function in Close Binaries

- Not particularly sensitive to metallicity or mass loss rate
- Main distribution from 1.2 to 1.7 solar masses made in successful explosions. Higher masses by fallback.
- Agrees well with observations of X-ray binaries (Ozel, Antoniadis) below 1.7 solar masses but not Antoniadis above. Those observations come from ms pulsars and accretion may have been involved.

Neutron Star Birth Masses

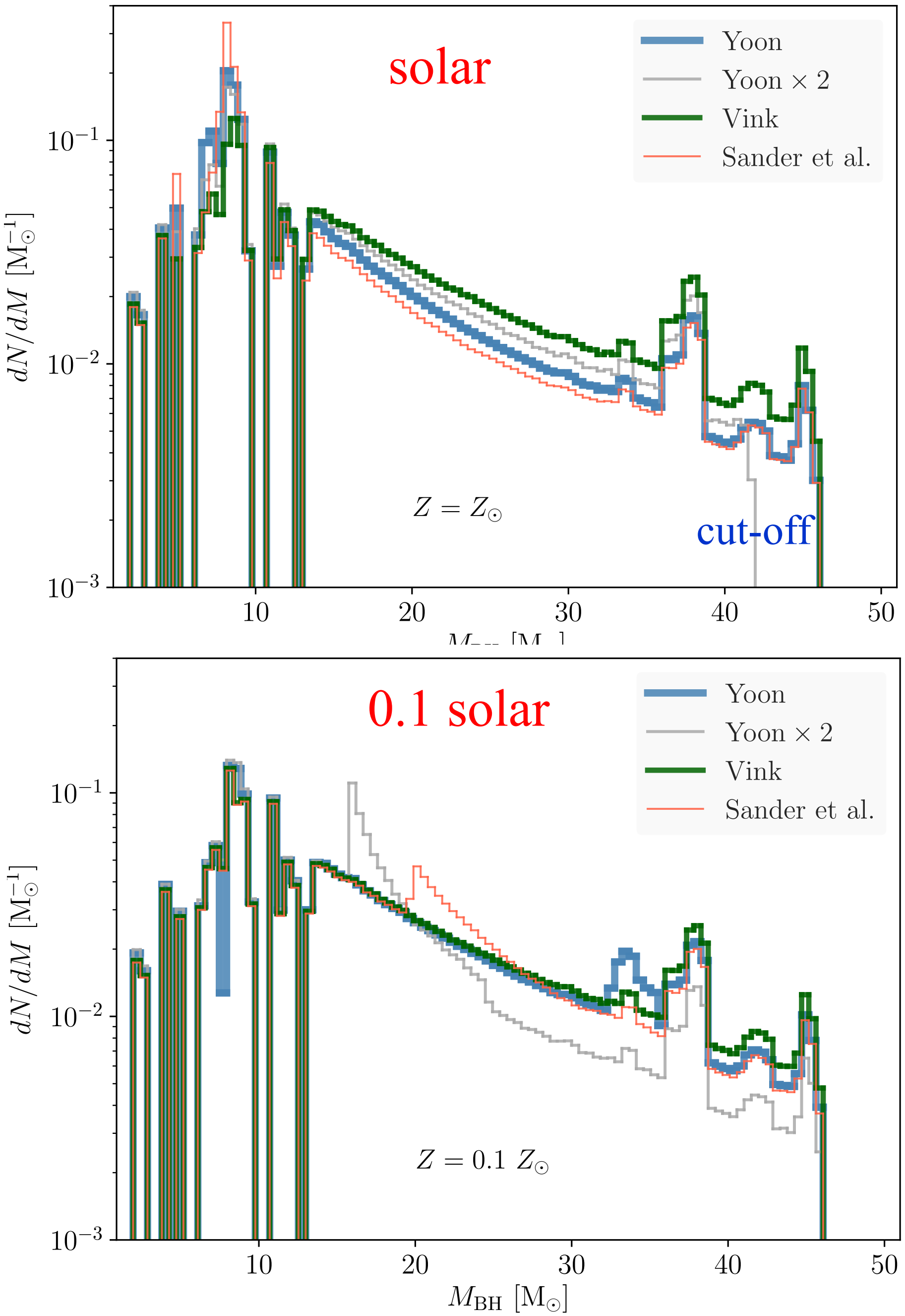
TABLE 3. AVERAGE NEUTRON STAR MASSES

$\dot{M}$	$M_{0.45}$ [$M_\odot$]	median [$M_\odot$]	$M_{0.55}$ [$M_\odot$]	f_{NS}
		$Z_{init} = Z_\odot$		
Yoon	1.341	1.349	1.359	0.784
Yoon × 2	1.314	1.320	1.326	0.907
Vink	1.360	1.368	1.376	0.686
Sander et al.	1.360	1.368	1.376	0.684
		$Z_{init} = 0.1\ Z_\odot$		
Yoon	1.355	1.364	1.372	0.700
Yoon × 2	1.349	1.357	1.366	0.715
Vink	1.361	1.369	1.378	0.683
Sander et al.	1.361	1.369	1.377	0.677

- Probably best mass loss rate is between Yoon and Yoon x 2 so the median neutron star gravitational mass should be 1.33 – 1.36 solar masses. (+0.02 if use Lattimer and Prakhash (2001))

- 70 – 90% of close binaries derived from these explosions contain a neutron star.

The Black Hole Birth Function in Close Binaries



- Not particularly sensitive to metallicity – though the number of black holes changes
- No “gap” below 5 solar masses. Fallback fills in the gap. Lightest prompt collapse 6.4 solar masses
- Mixed explosions and collapse below 12 solar masses. All preSN masses above 12 collapse promptly
- Truncated at 46 solar masses (45 – 55 depending on $^{12}C(\alpha,\gamma)^{16}O$) due to pulsational pair instability. Pile up below that.

Median Black Hole Mass

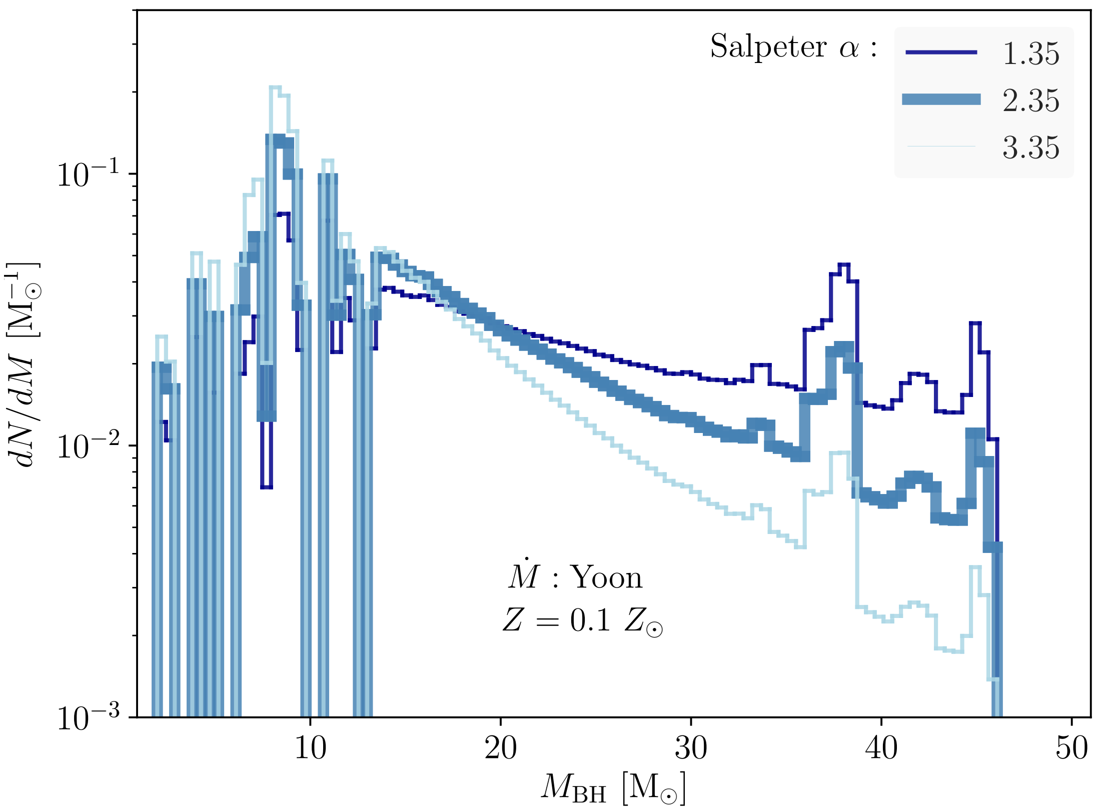
Table 4. Average Black Hole Masses

$\dot{M}$	$M_{0.45}$ [$M_\odot$]	median [$M_\odot$]	$M_{0.55}$ [$M_\odot$]	f_{BH}
$2.5 < M_{He,i} < 40$ [$M_\odot$]				
$Z_{init} = Z_\odot$ $\alpha = 2.35$				
Yoon	8.4	8.6	8.9	0.17
Yoon × 2	7.8	7.9	8.0	0.04
Vink	13.2	14.2	15.2	0.30
Sander et al.	8.4	8.6	8.9	0.29
$Z_{init} = 0.1\ Z_\odot$ $\alpha = 2.35$				
Yoon	12.1	13.7	14.6	0.27
Yoon × 2	10.9	11.8	13.3	0.24
Vink	13.6	14.5	15.6	0.30
Sander et al.	13.6	14.5	15.6	0.30
$2.5 < M_{He,i} < 150$ [$M_\odot$]				
$Z_{init} = Z_\odot$ $\alpha = 2.35$				
Yoon	9.5	11.3	13.1	0.22
Yoon × 2	11.5	13.2	14.3	0.09
Vink	14.3	15.5	16.8	0.31
Sander et al.	8.7	9.1	10.9	0.32
$Z_{init} = 0.1\ Z_\odot$ $\alpha = 2.35$				
Yoon	14.1	15.3	16.5	0.30
Yoon × 2	13.5	14.5	15.6	0.29
Vink	14.5	15.7	17.0	0.32
Sander et al.	14.7	16.0	17.3	0.32

Probably the preferred mass loss rate is between Yoon and Yoon x 2.

Assuming only main sequence stars with masses above 80 solar masses are sampled, the median BH mass is 8 – 12 solar masses depending on metallicity. This might be appropriate to X-ray binaries.

Between 4% and 27% of collapses make BHs. Sensitive to metalliciity. (for high mass loss rates there are no progenitors heavy enough to make BHs)



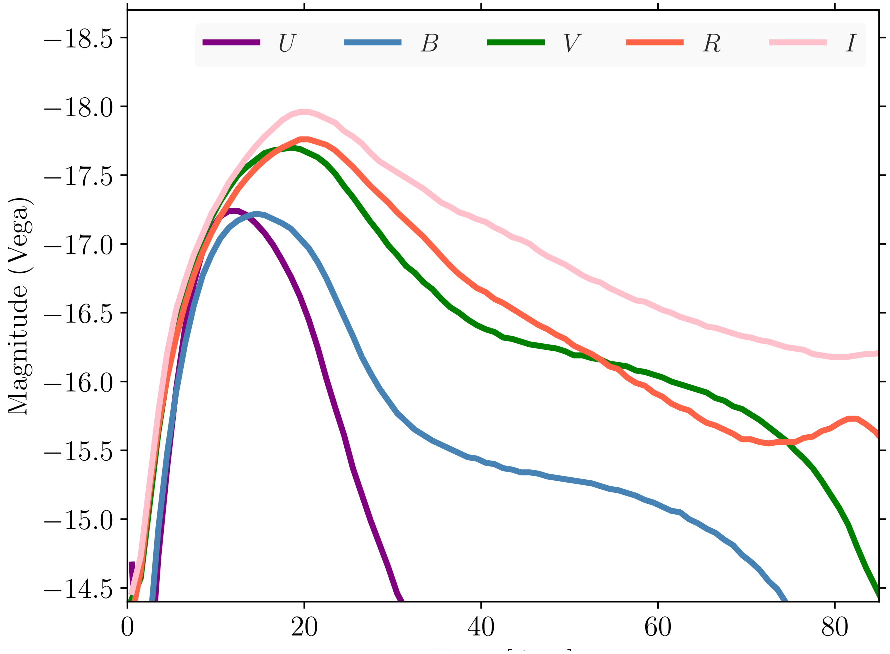
Between 12 and 33 M_O the distribution of black hole masses follows the IMF. This is because the preSN mass, all of which collapses is nearly a constant fraction of the initial star's mass

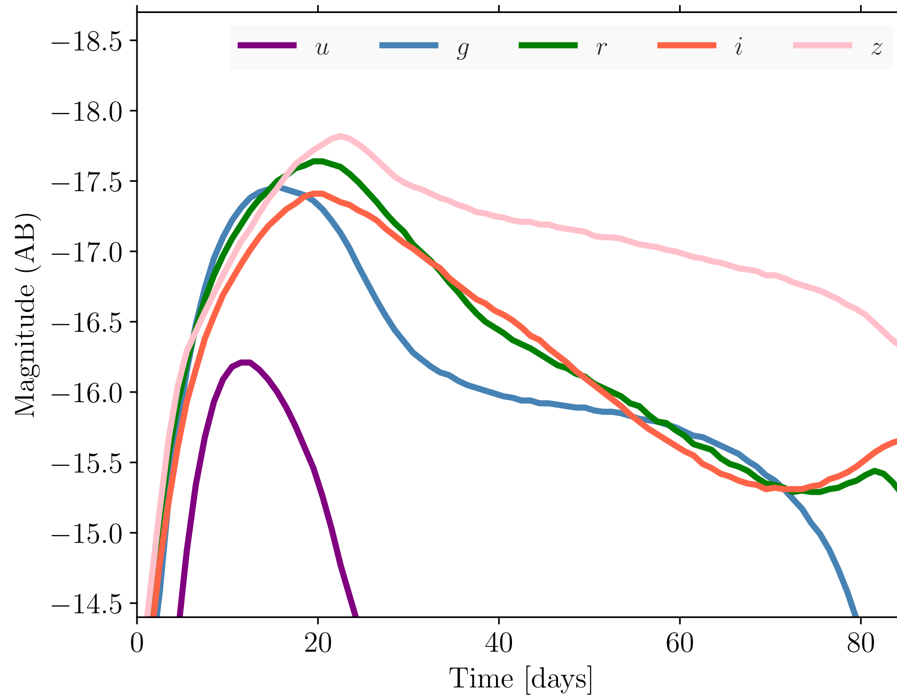
Measurements of the BH IMF in this mass range would constrain the stellar IMF for ZAMS stars in the range 50 to 130 M_O

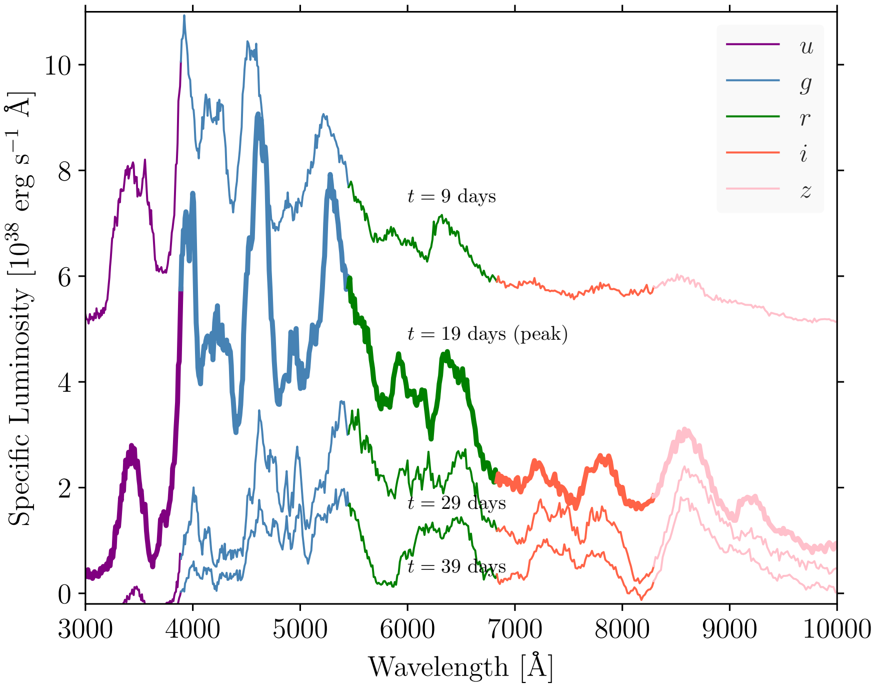
Type Ib and Ic Supernovae

Some General Constraints

- No model had kinetic energy greater than 2×10^{51} erg
- No model made more than 0.14 $M_{\odot}$ of ^{56}Ni
- No supernova was brighter than $10^{42.5}$ erg s^{-1} at peak
- It follows that any event not obeying these constraints is not a neutrino-powered, radioactivity illuminated supernova
- The models that looked like observed Type Ibc supernovae had presupernova masses 2.7 to 5.6 $M_{\odot}$ and were derived from helium stars 3.3 to 8.0 $M_{\odot}$ depending on mass loss rate and thus came from main sequence stars of 16 – 28 $M_{\odot}$



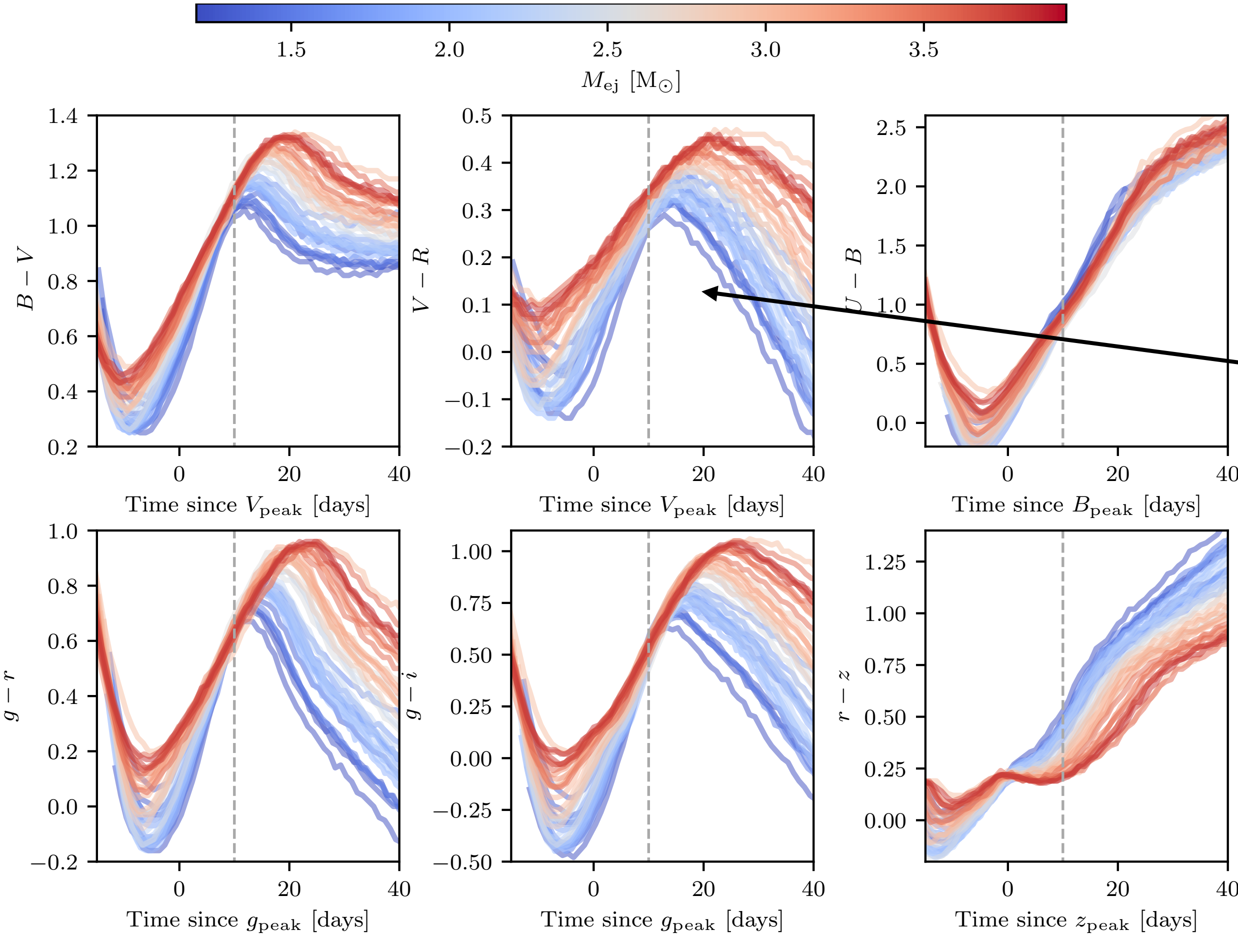


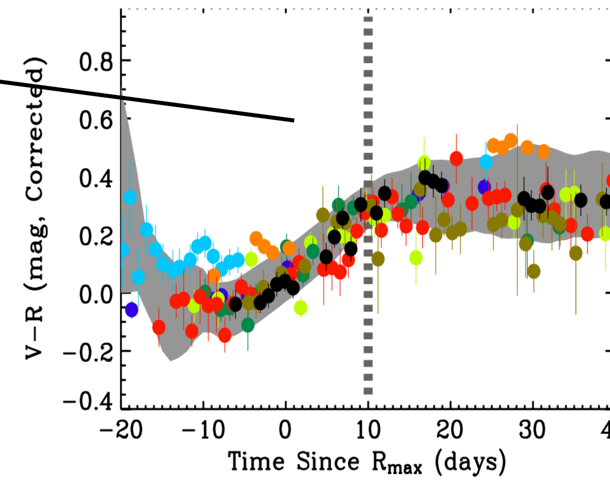


A typical case Model 4.5.
Initial helium star mass 4.5 M_{O},

MS mass	19.5 M_{O}
preSN mass	3.49 M_{O}.
Ejected mass	1.90 M_{O},
KE	1.28 x 10^{51}erg,
^{56}Ni	0.099 M_{O}

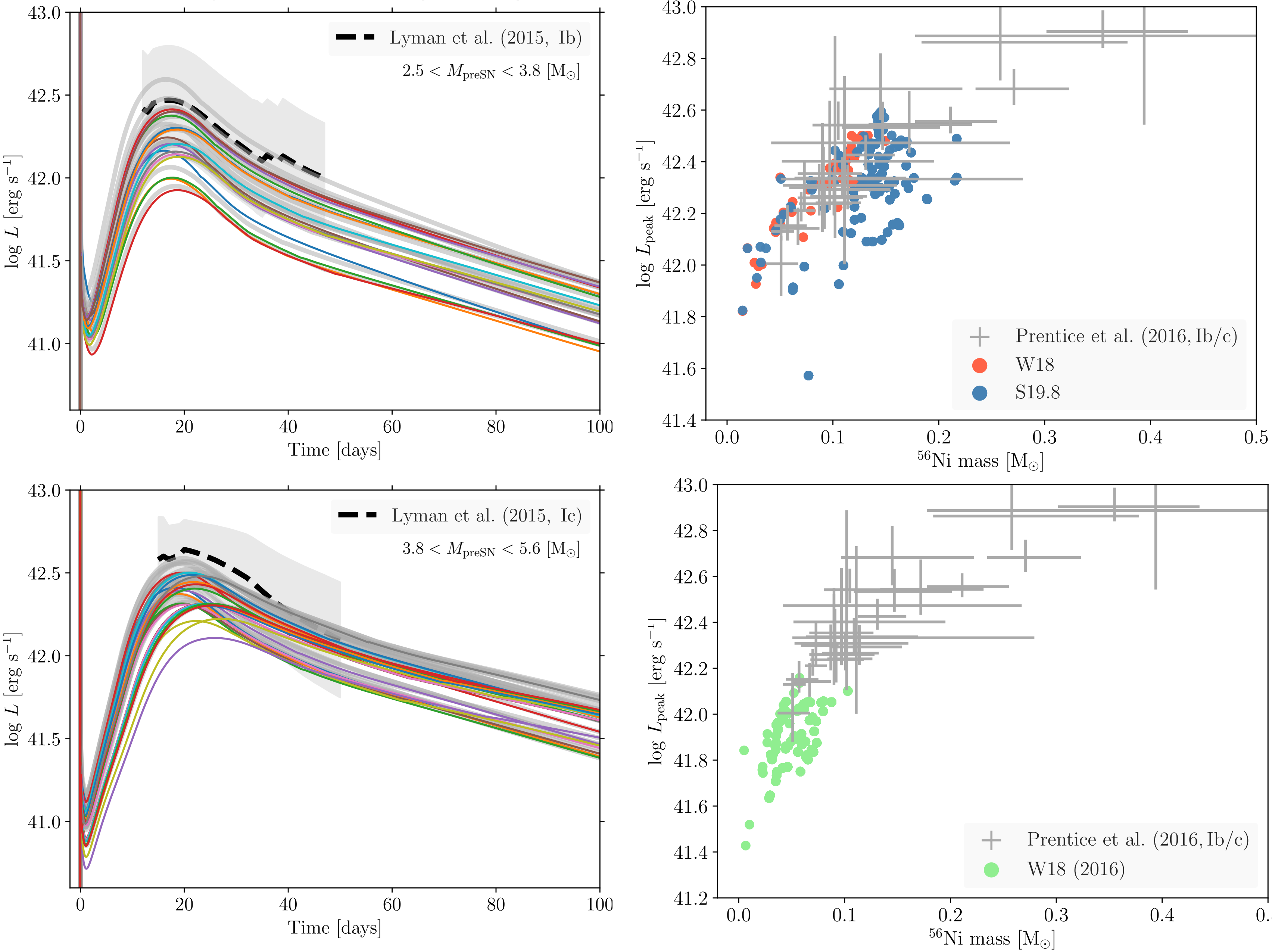
Similar to many observed events.

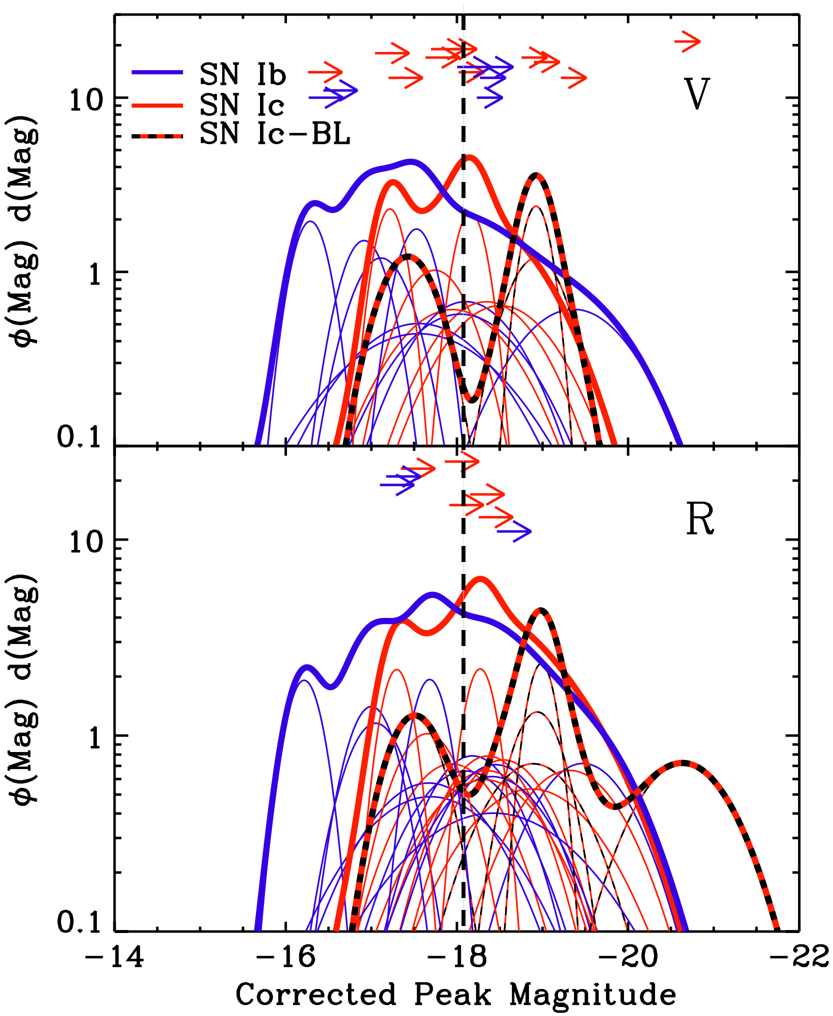




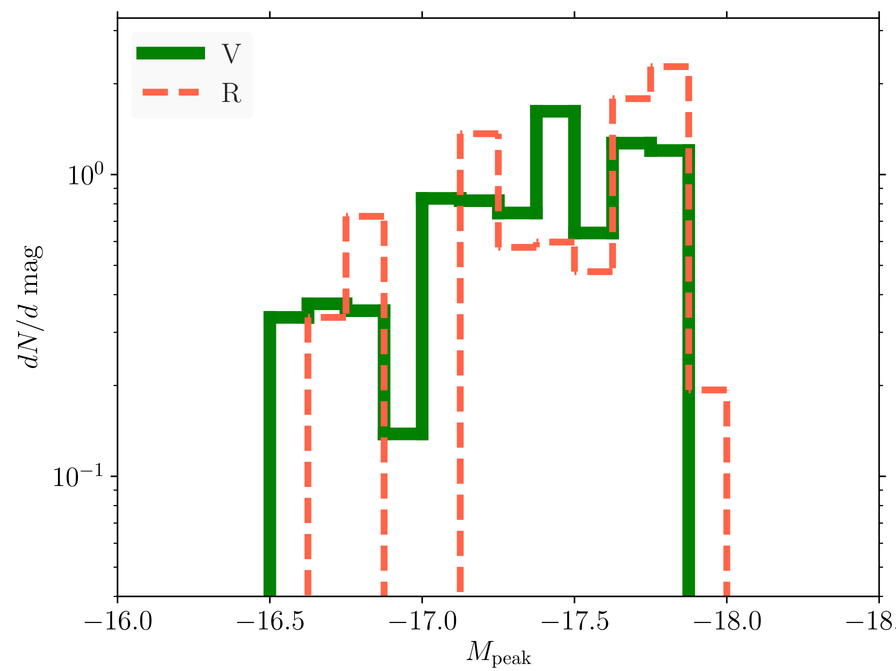
Drout et al (2011)
(V-R) SN Ibc

Bolometric curves below the median of Lyman et al l(2015) and Prentice et al (2016)



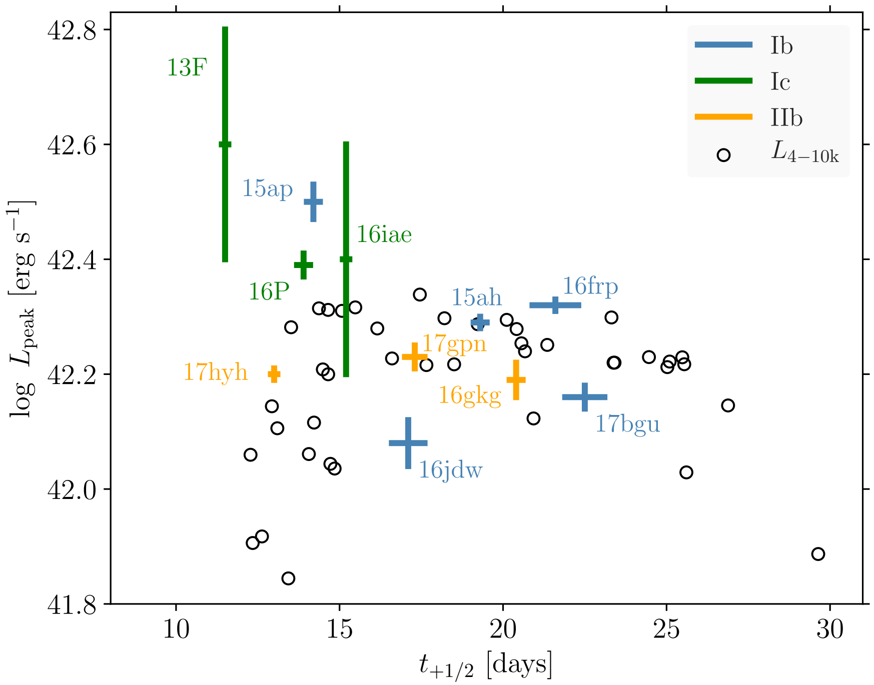


Drout et al
(2011)



Our distribution:

No absolute magnitude brighter than -18. Agrees with Drout's "uncorrected" set (not shown) with no host galaxy extinction but not with the "corrected" version on the upper left (ignore SN Ic-BL)



On the other hand, we agree pretty well with the recent tabulation of Prentice et al (2019) Our median peak luminosity [4000 – 10000 A] is $10^{42.20}$ erg s^{-1}

(13F was an unusual SN)

Table 4. $\log(L_{\rm p})$ statistics

Type	Median [erg s^{-1}]	Mean [erg s^{-1}]	N
IIb + IIb(I)	42.09±0.17	42.13±0.2	21
Ib + Ib(II)	$42.2\pm^{0.4}_{0.1}$	42.3±0.2	25
Ic-5/6/7	$42.3\pm^{0.3}_{0.2}$	42.3±0.3	19

Conclusions SN Ib and Ic

- Standard models based on neutrino-powered explosions and ^{56}Ni illumination agree pretty well with observations for half or more of the events. Median values are:

$M_{ej} = 2.0\ M_{\odot}$

$M(^{56}Ni) = 0.10\ M_{\odot}$

$t_{peak,bol} = 19$ days

$(B-V)_{V\text{-}peak} = 0.4 - 0.6$

$KE = 1.26 \times 10^{51}$ erg

$L_{peak,bol} = 10^{42.3}$ erg s^{-1}

$v \sim 8000$ km s^{-1}

- But - a lot of events categorized as normal Ib and Ic by the observers either have substantial observational error, e.g. in bolometric corrections or extinction, or these events require other energy sources (rotation) for explosion and/or illumination (magnetar).

  We know that broad lined SN Ic, XRF supernovae and GRB's are not neutrino powered.