Stellar Evolution and Nucleosynthesis

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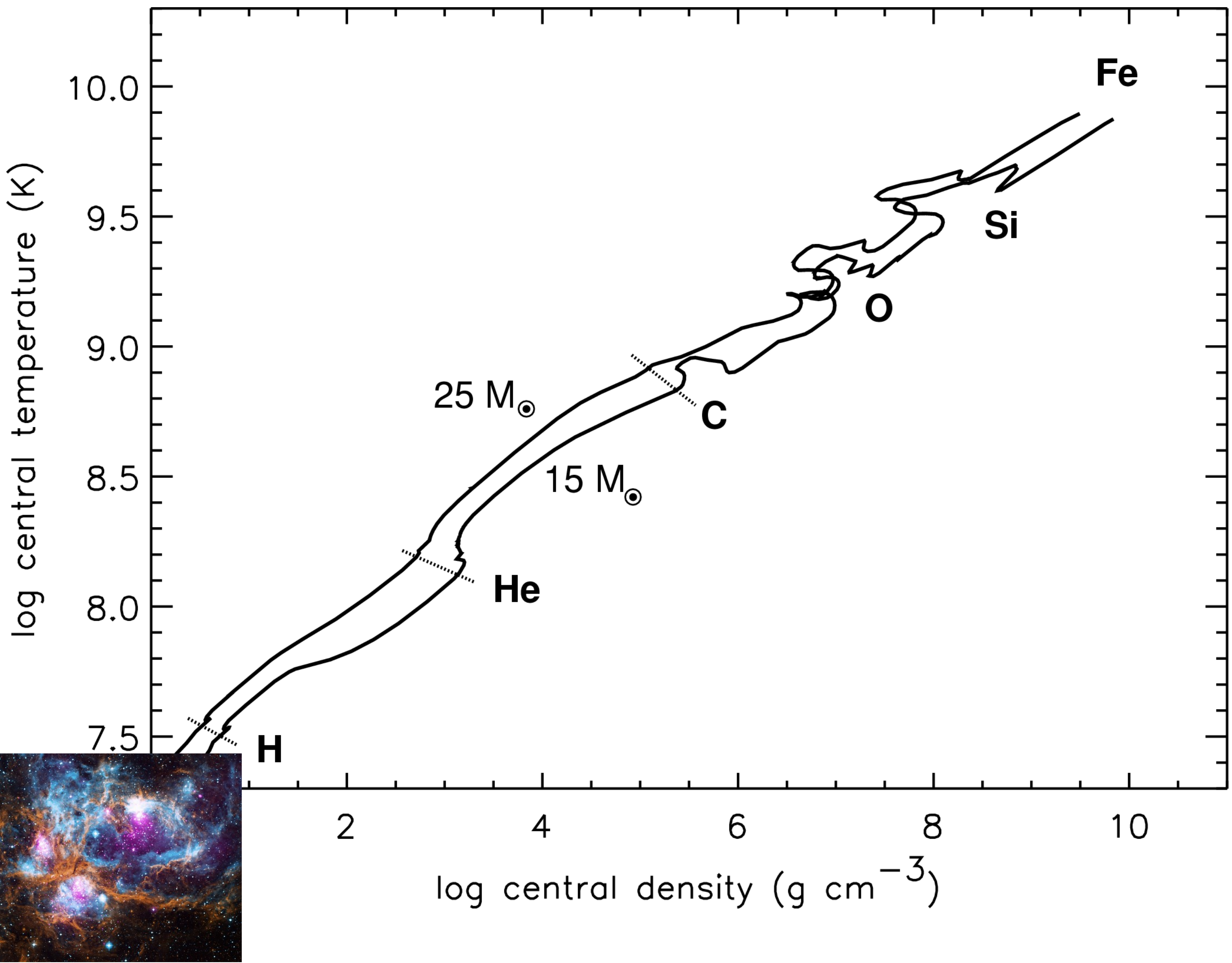
http://CosmicExplosions.org

Once formed, the evolution of a star is governed by gravity:

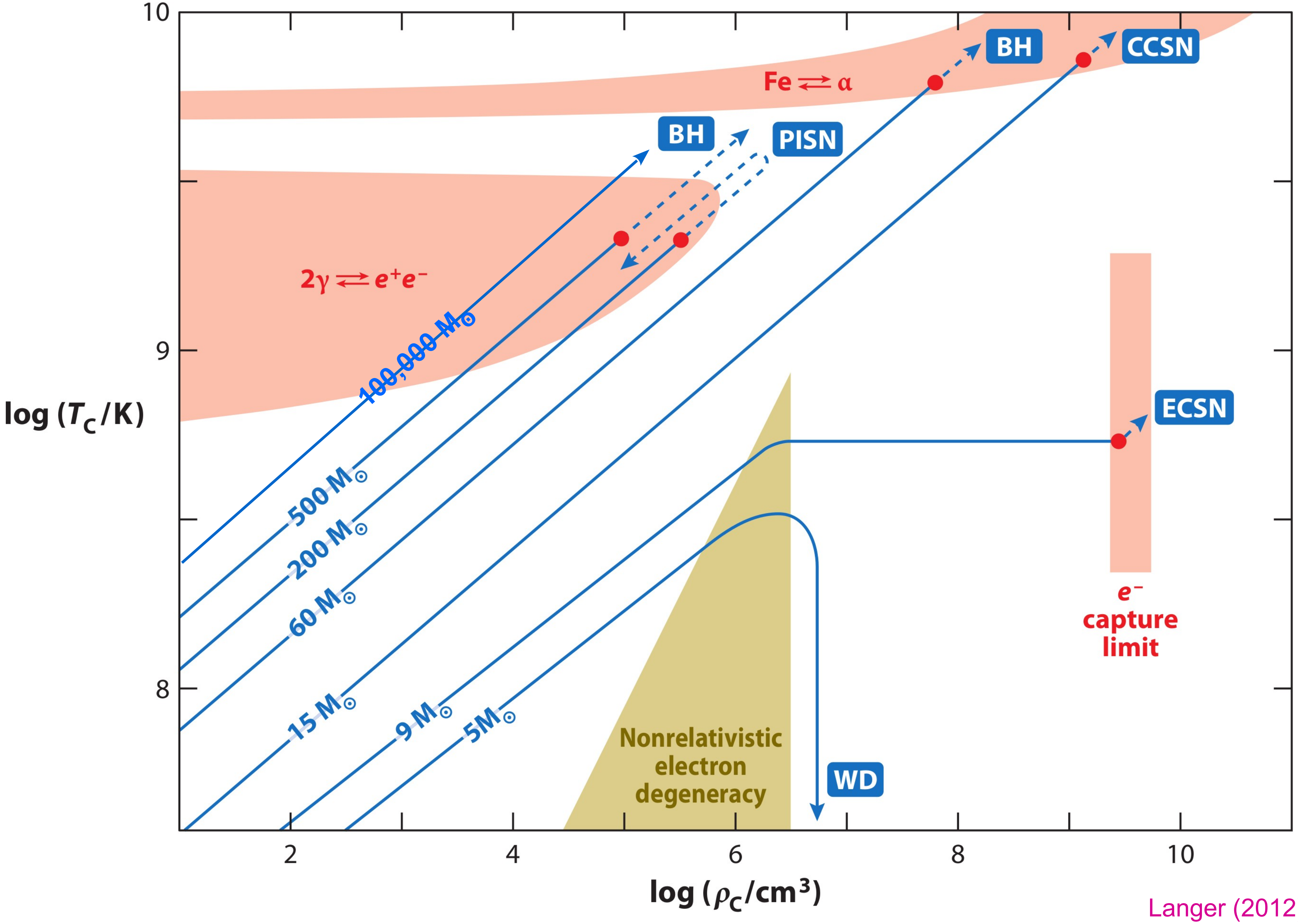
continuing contraction

to higher central densities and temperatures



Evolution of central density and temperature of 15 $M_\odot$ and 25 $M_\odot$ stars

Evolution of Center for Different Initial Masses

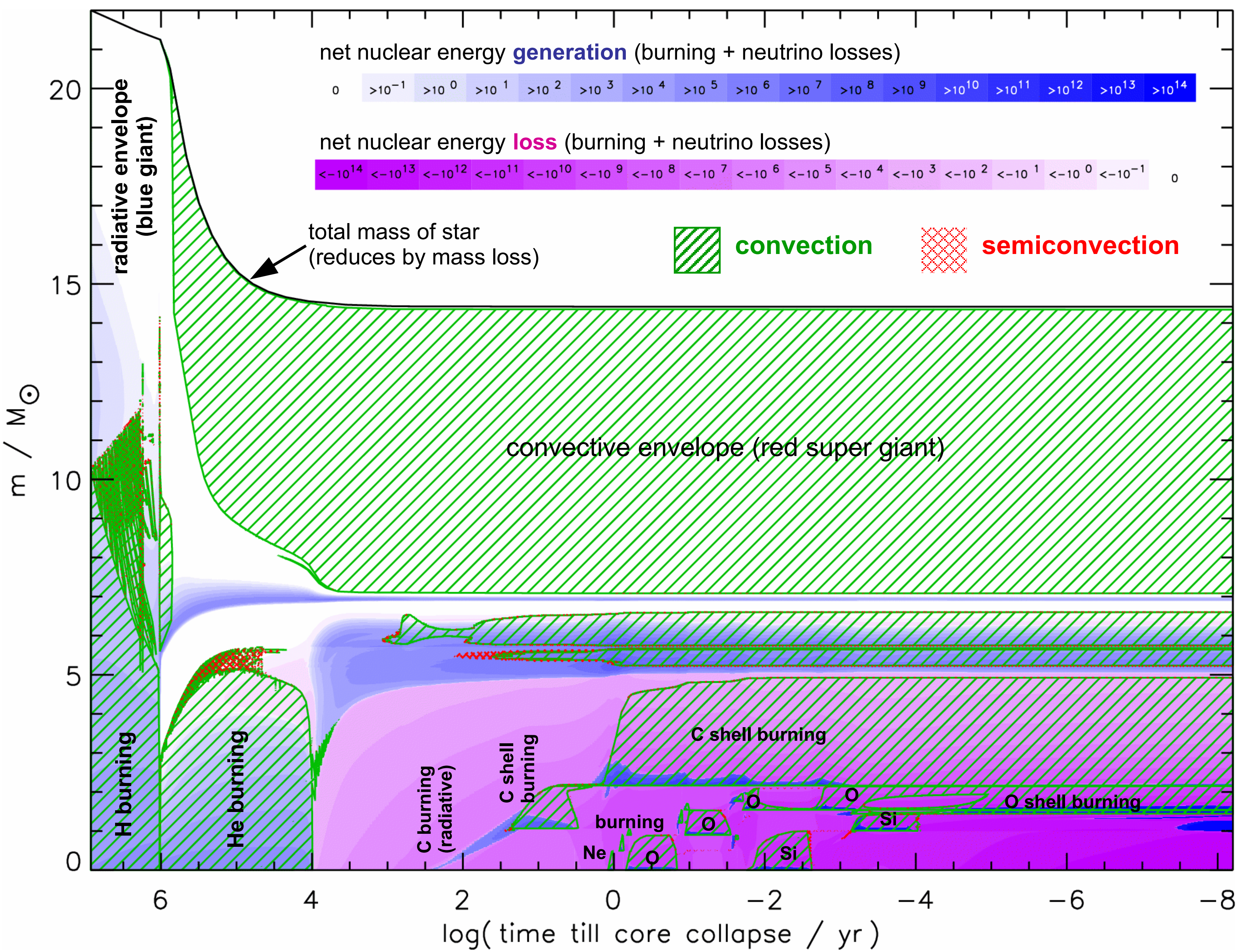


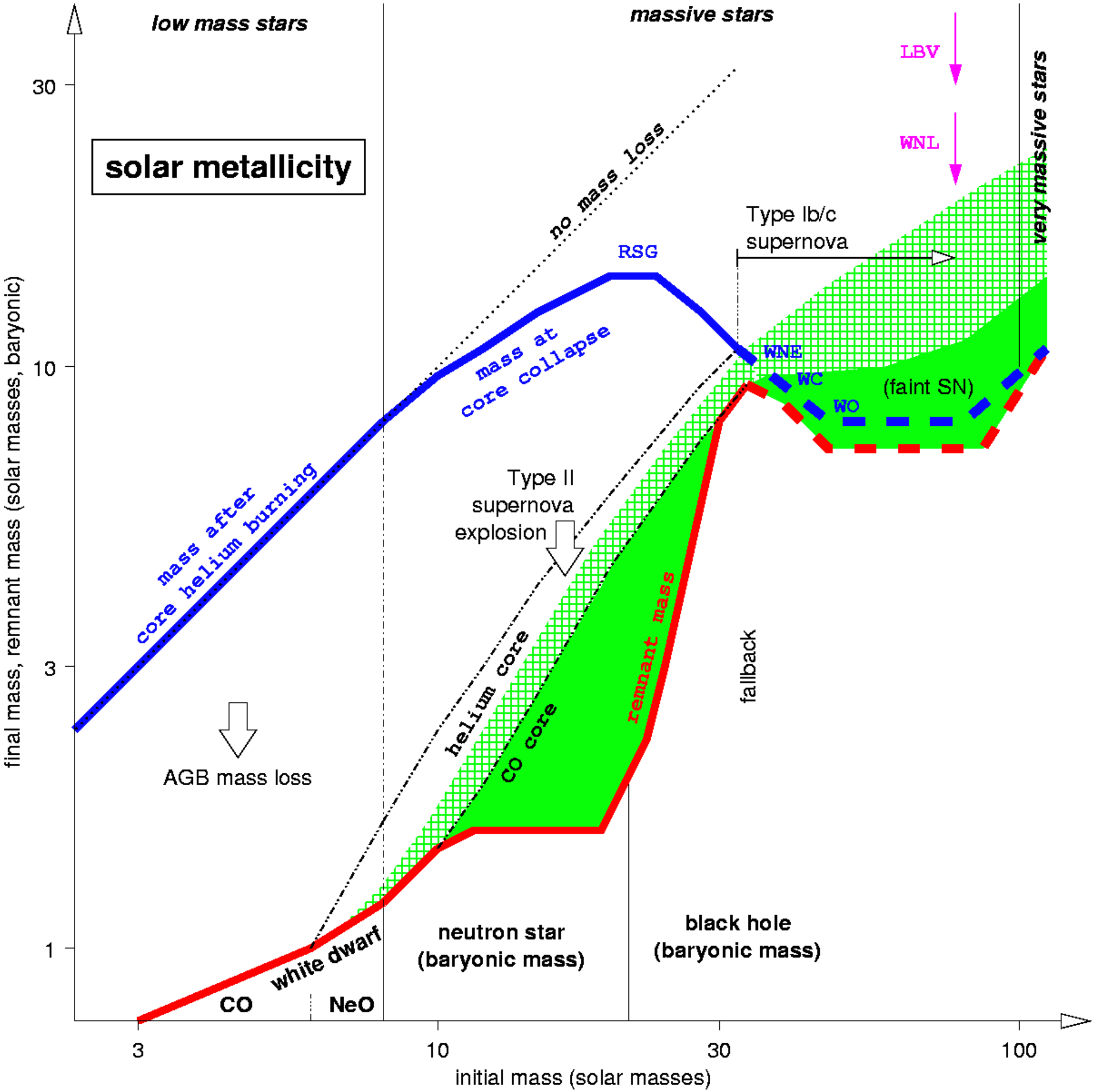
Langer (2012)

Nuclear burning stages

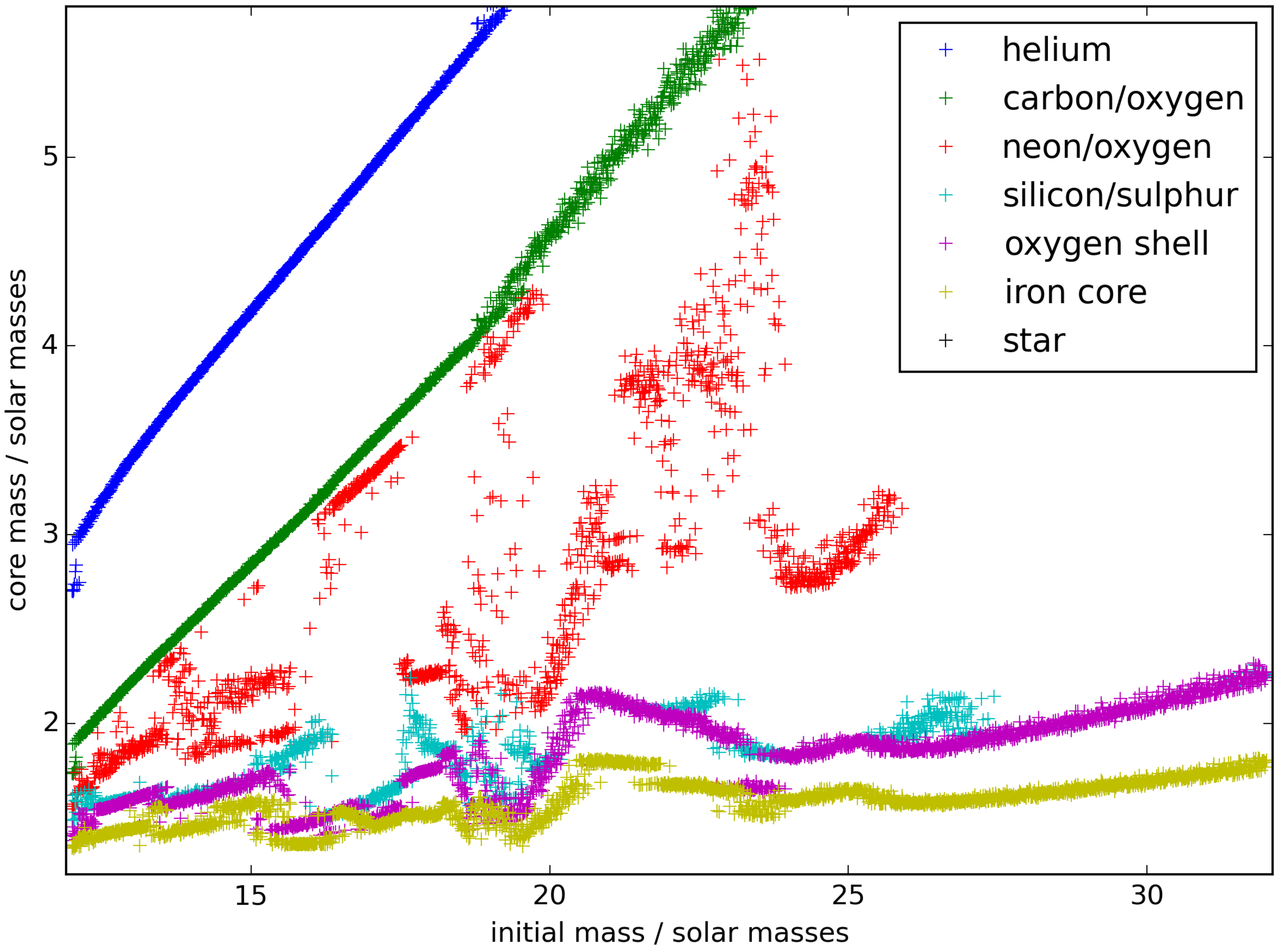
(20 $M_\odot$ stars)

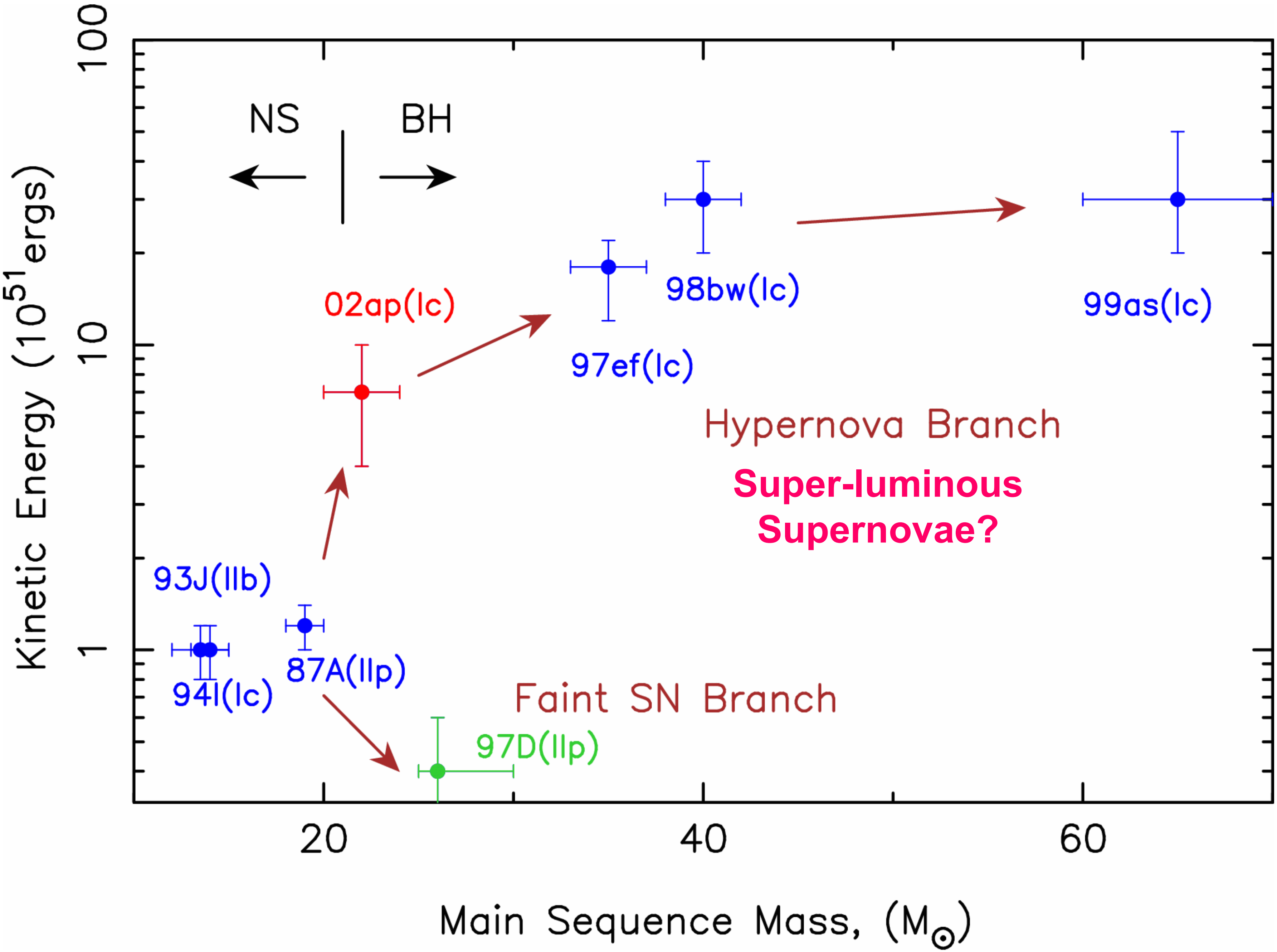
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\ H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\ {}^4He \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si,S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)\ldots$


net nuclear energy generation (burning + neutrino losses)
0
>10⁻¹ >10 0 >10 1 >10 2 >10 3 >10 4 >10 5 >10 6 >10 7 >10 8 >10 9 >10 10 >10 11 >10 12 >10 13 >10 14
net nuclear energy loss (burning + neutrino losses)
<-10 14 <-10 13 <-10 12 <-10 11 <-10 10 <-10 9 <-10 8 <-10 7 <-10 6 <-10 5 <-10 4 <-10 3 <-10 2 <-10 1 <-10 0 <-10 -1
0
convection
semiconvection
total mass of star
(reduces by mass loss)
radiative envelope
(blue giant)
convective envelope (red super giant)
H burning
He burning
C burning
(radiative)
C shell
burning
C shell burning
Ne
burning
O
O
O
O
O shell burning
Si
Si
m / M⊙
log(time till core collapse / yr)
20
15
10
5
0
6
4
2
0
−2
−4
−6
−8

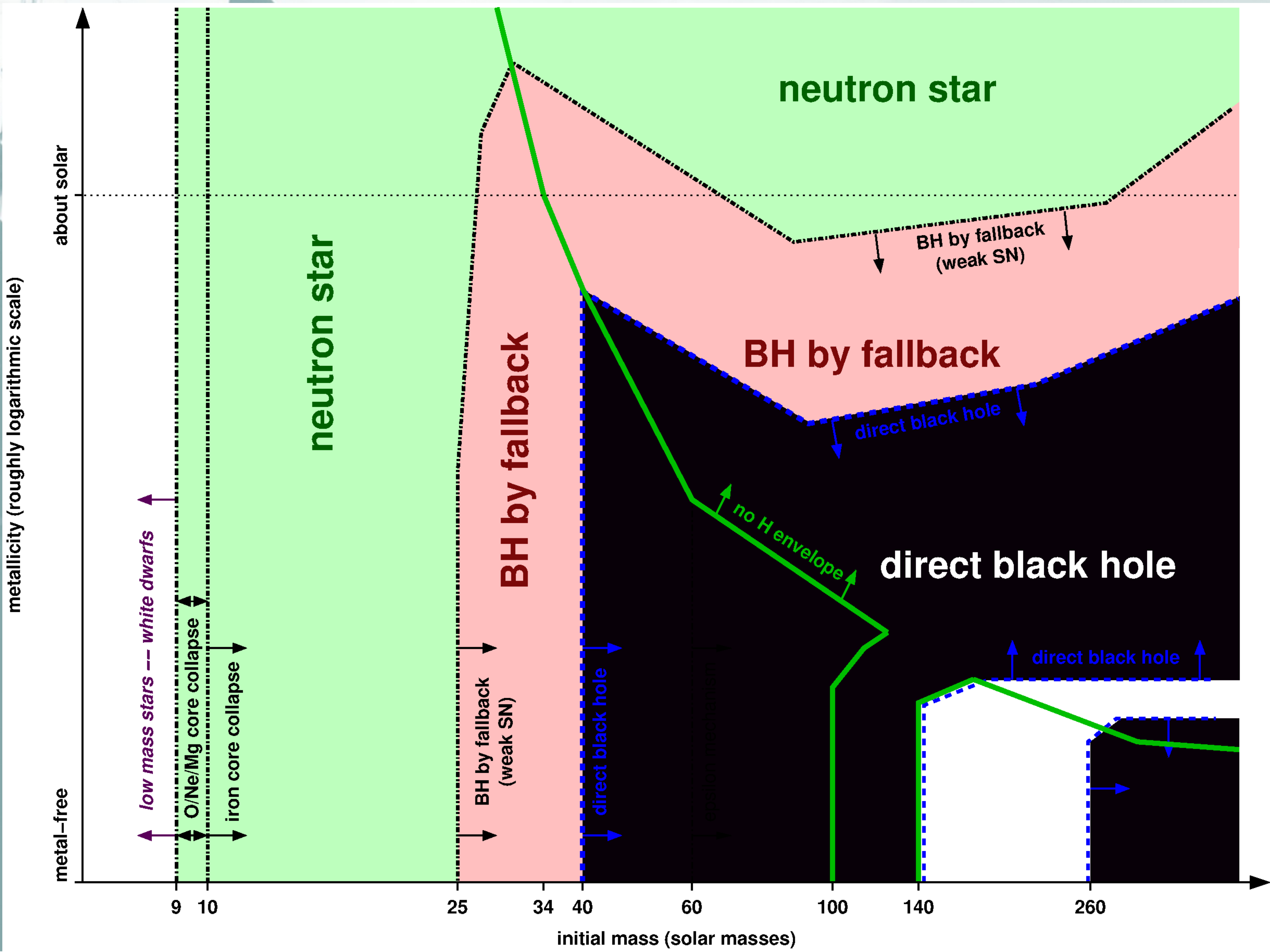


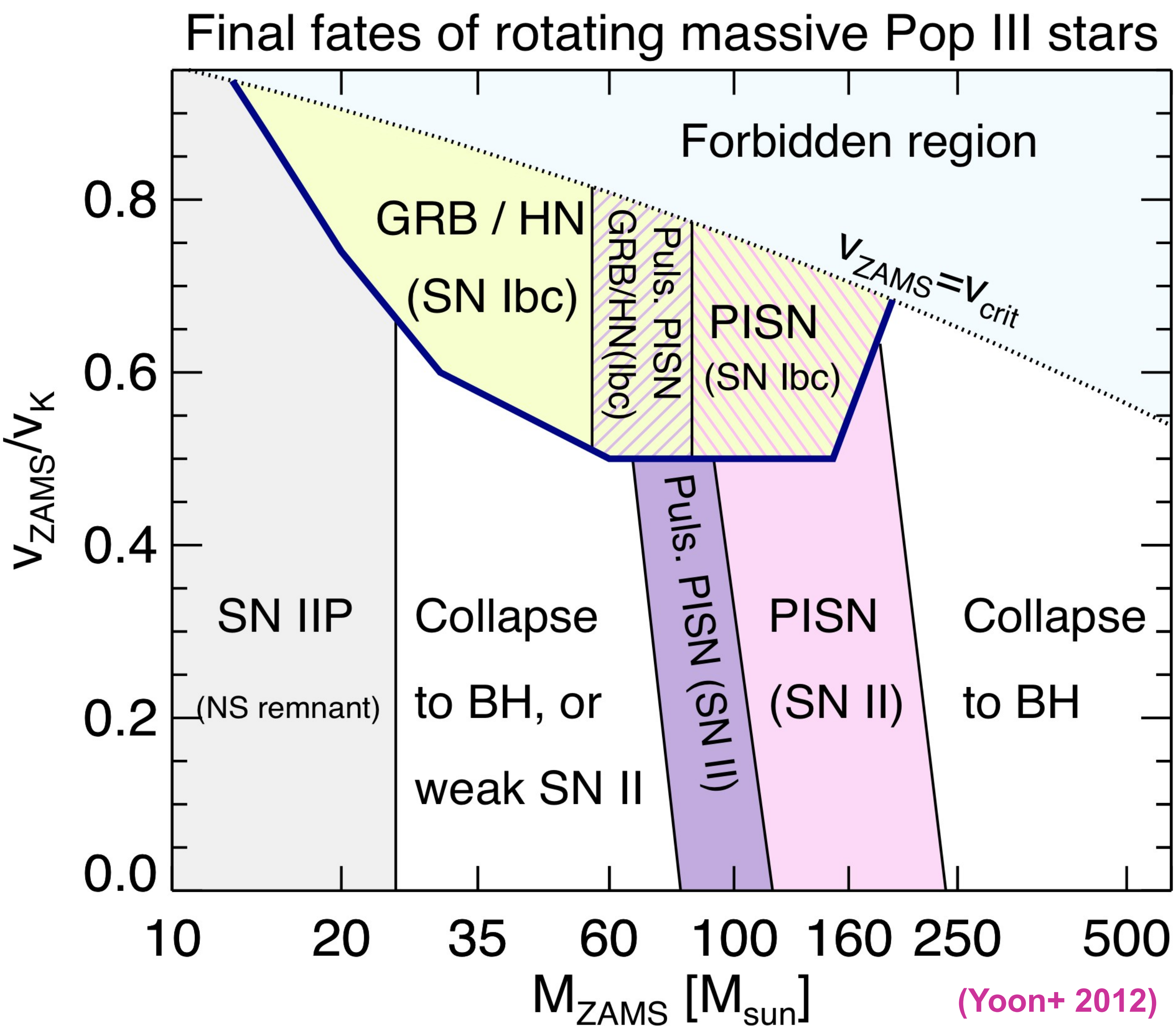
Ejected “metals”


helium
carbon/oxygen
neon/oxygen
silicon/sulphur
oxygen shell
iron core
star
core mass / solar masses
initial mass / solar masses
2
3
4
5
15
20
25
30



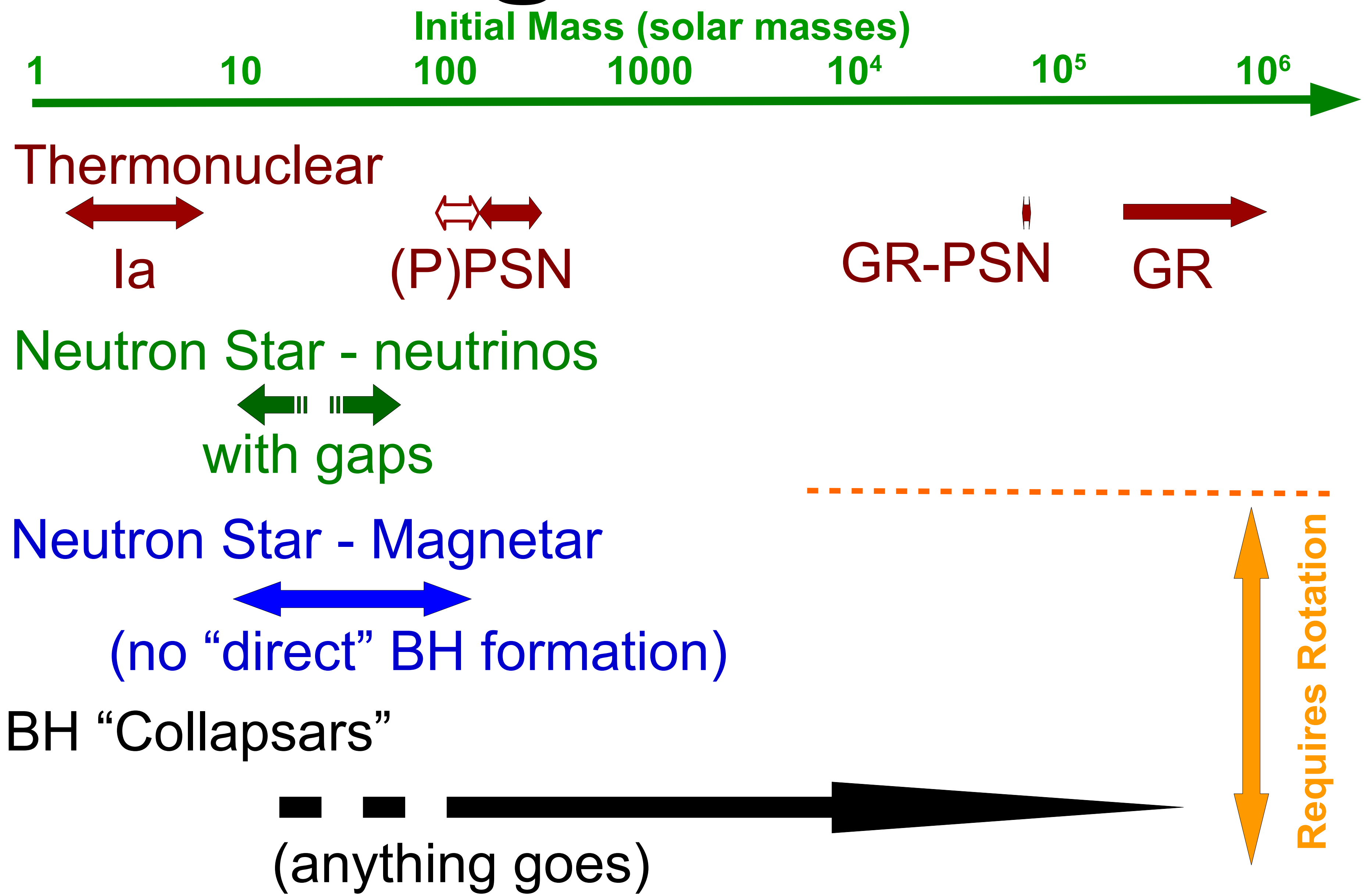
(Nomoto 2002, priv. com.)


neutron star
neutron star
BH by fallback
BH by fallback
BH by fallback
(weak SN)
BH by fallback
(weak SN)
direct black hole
direct black hole
direct black hole
direct black hole
no H envelope
low mass stars -- white dwarfs
O/Ne/Mg core collapse
iron core collapse
metallicity (roughly logarithmic scale)
about solar
metal-free
9
10
25
34
40
60
100
140
260
initial mass (solar masses)

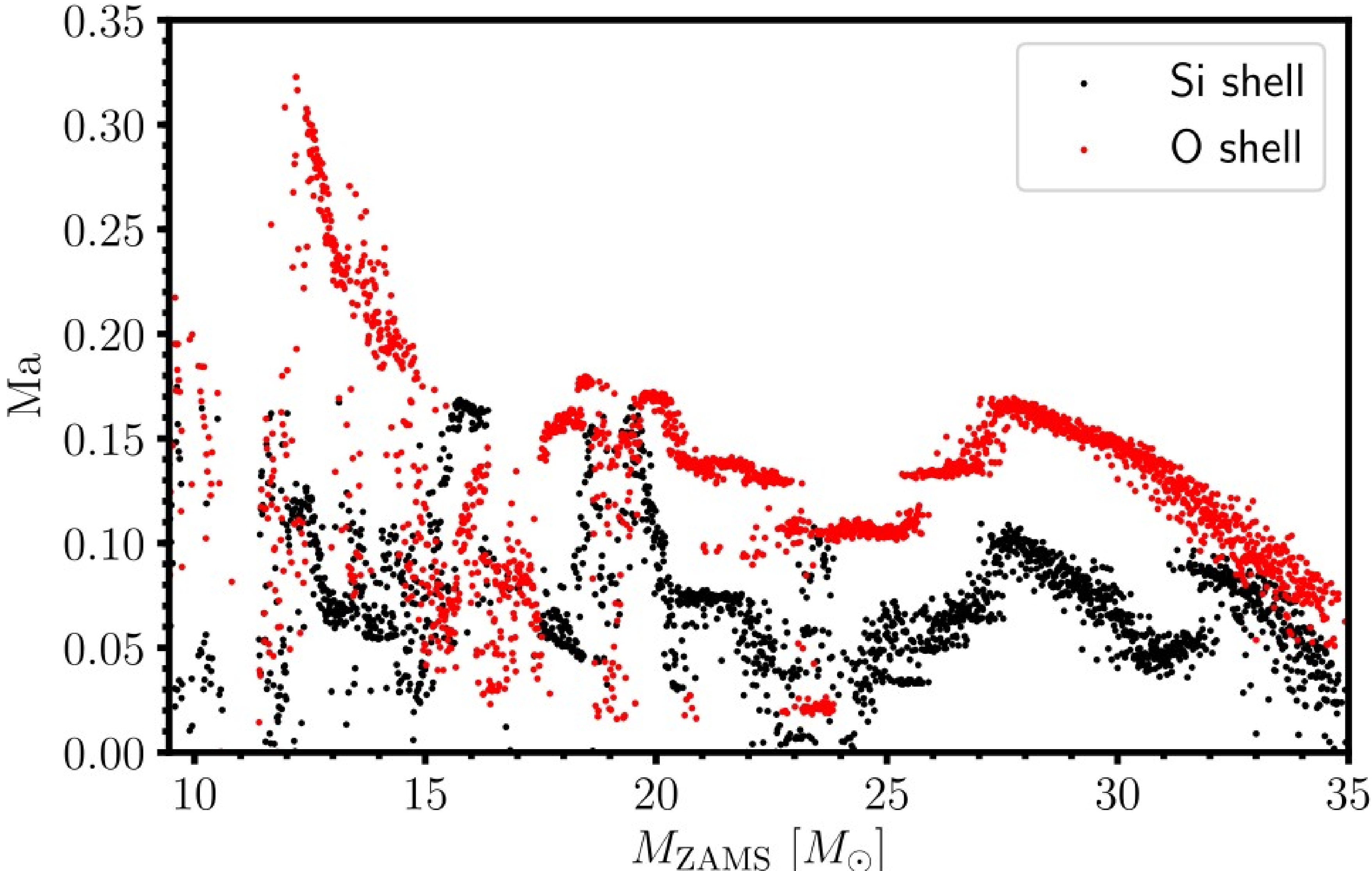


Final fates of rotating massive Pop III stars
Forbidden region
GRB / HN
(SN Ibc)
GRB/HN(Ibc)
Puls. PISN
PISN
(SN Ibc)
vZAMS=vcrit
SN IIP
(NS remnant)
Collapse
to BH, or
weak SN II
Puls. PISN (SN II)
PISN
(SN II)
Collapse
to BH
0.8
0.6
0.4
0.2
0.0
vZAMS/vK
10
20
35
60
100
160
250
500
MZAMS [Msun]
(Yoon+ 2012)

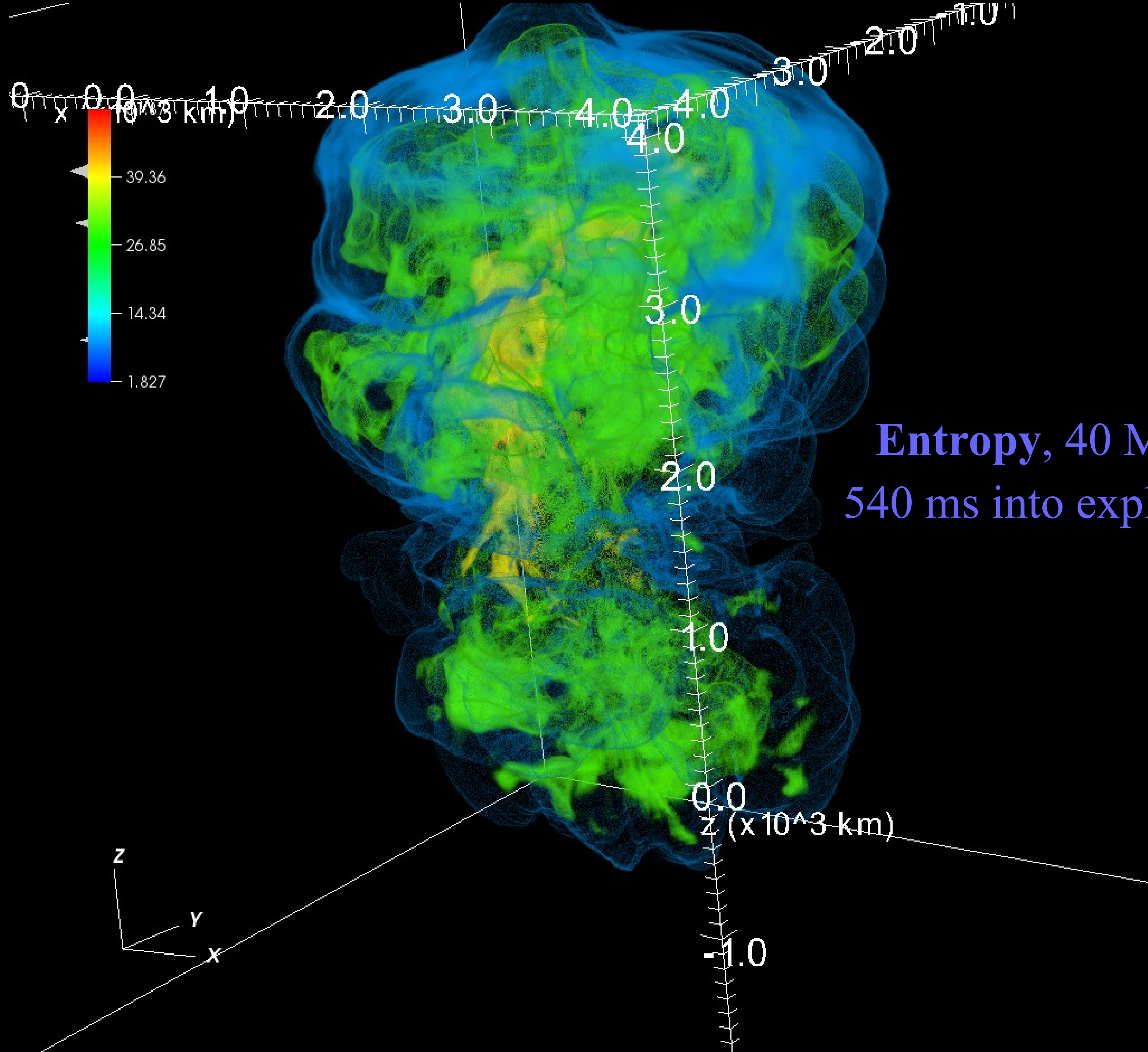
The Engines of SNe



Convective Mach Numbers at CC



(Collins+ 2018)

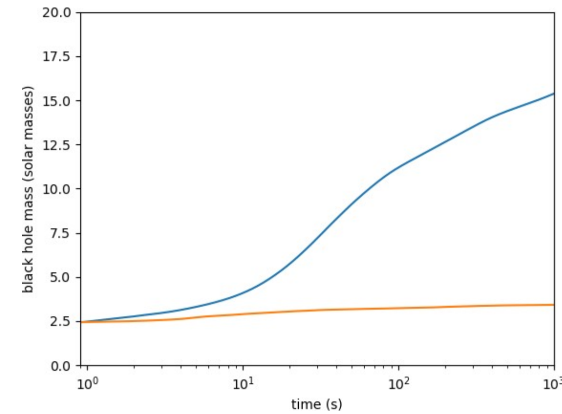


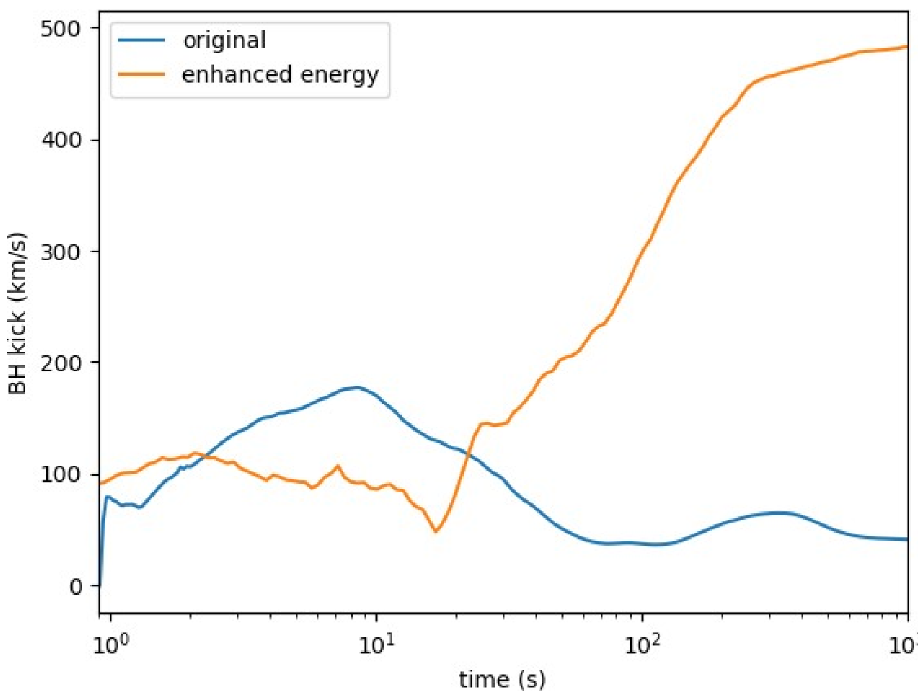
Entropy, 40 $M_{\odot}$ star
540 ms into explosion

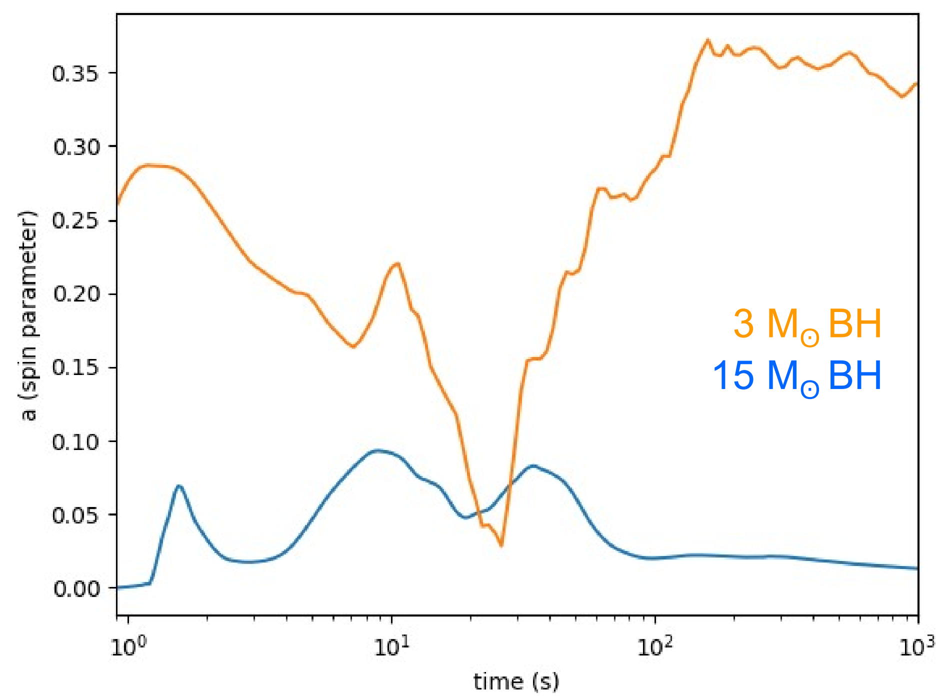
Mueller, Chan, Heger 2018

Spin and Kick in BH Formation

- Stars that make BH may have initial explosion
- Initial asymmetries may be swallowed by fallback, reducing kick and spin for large BHs
- For large explosion energies, spin and kick may persist, but making smaller BHs



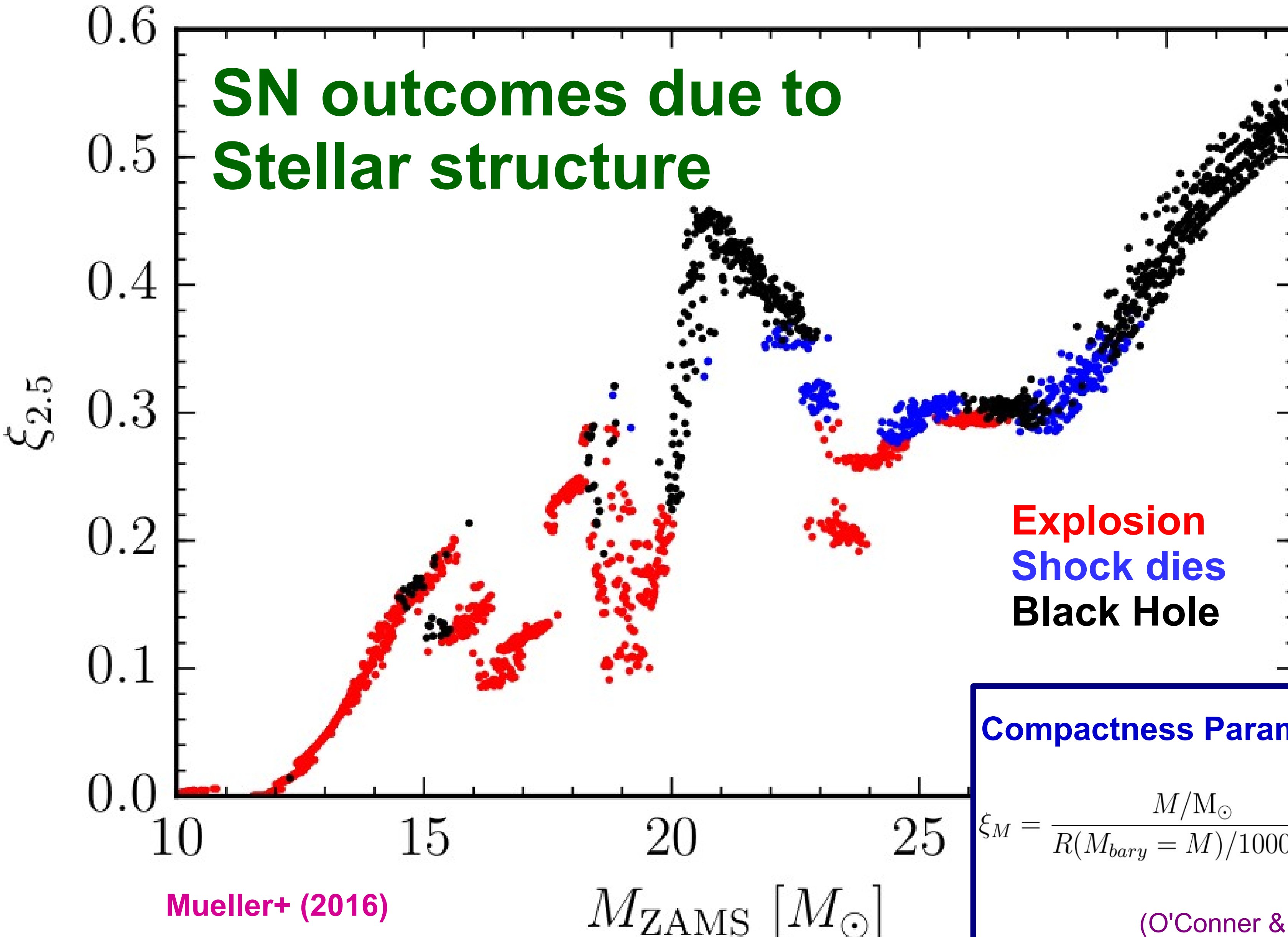




40 $M_\odot$ initial mass

(Chan+ 2018)

Signatures of Stellar Structure



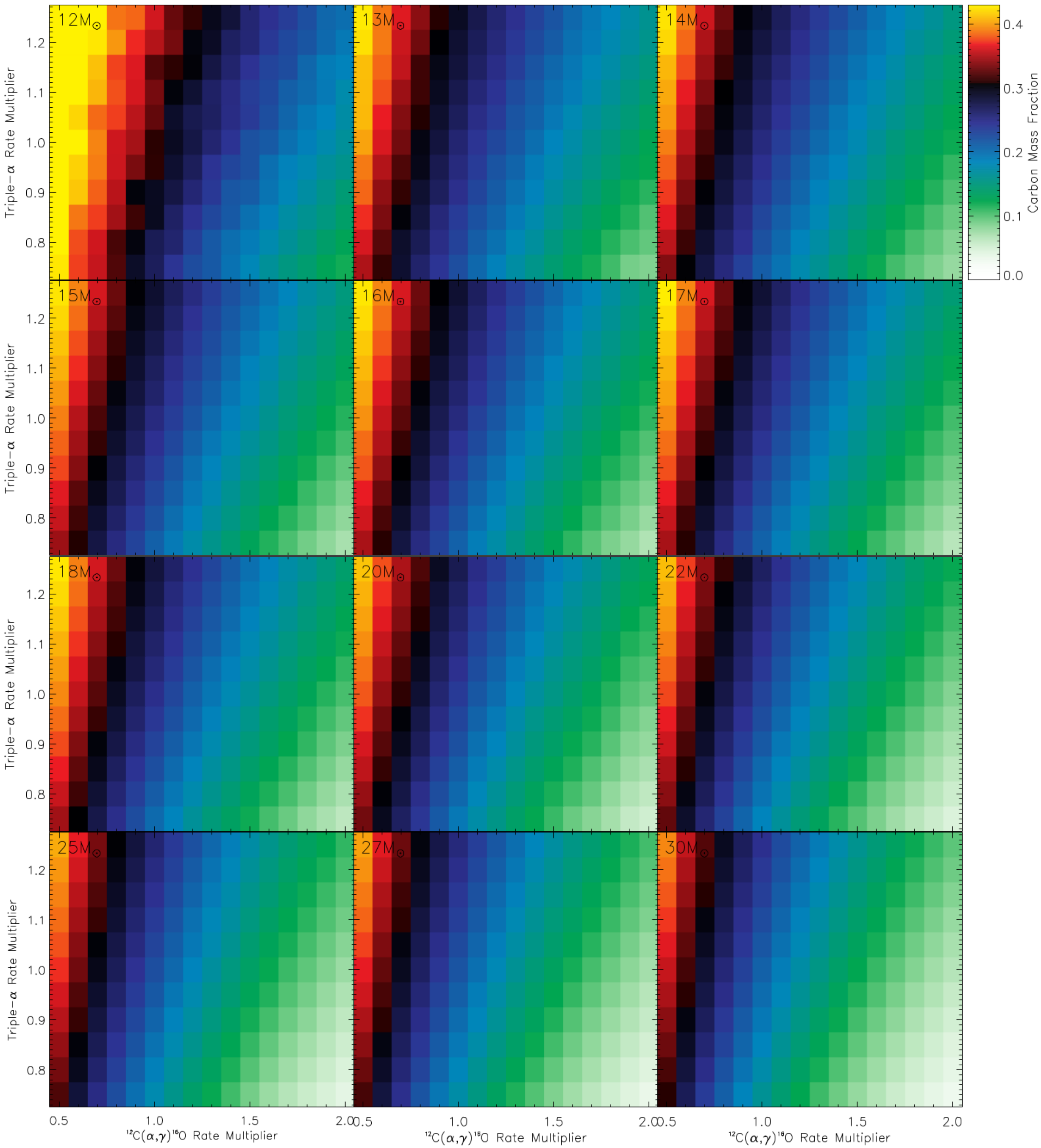
Mueller+ (2016)

Compactness Parameter

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

(O'Conner & Ott 2011)

^{12}C Production as a function of $^{12}C(\alpha,\gamma)$ and 3α reaction rates

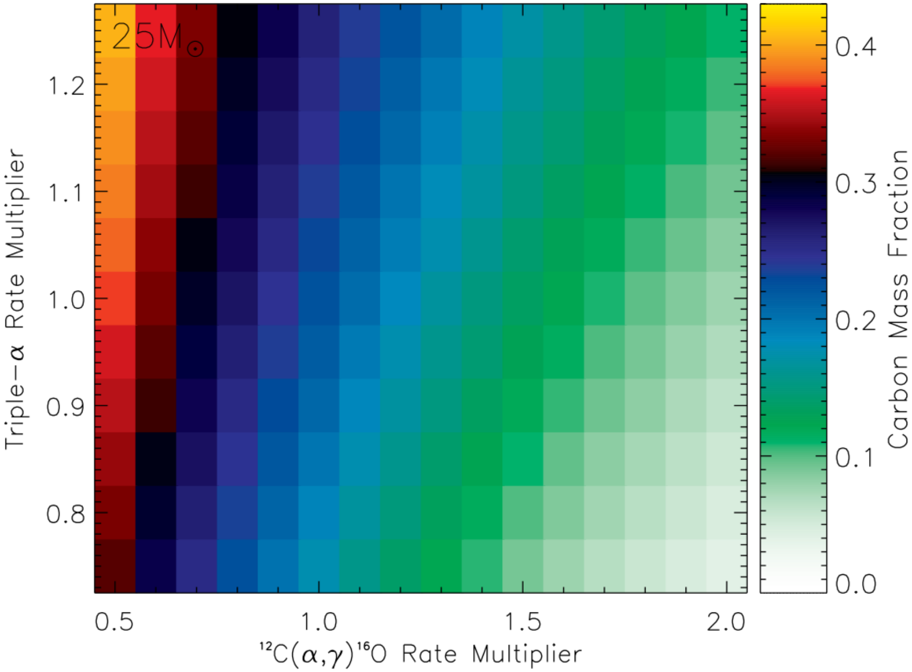


Carbon mass fraction at the end of helium burning depends the reaction rates and the mass of the star

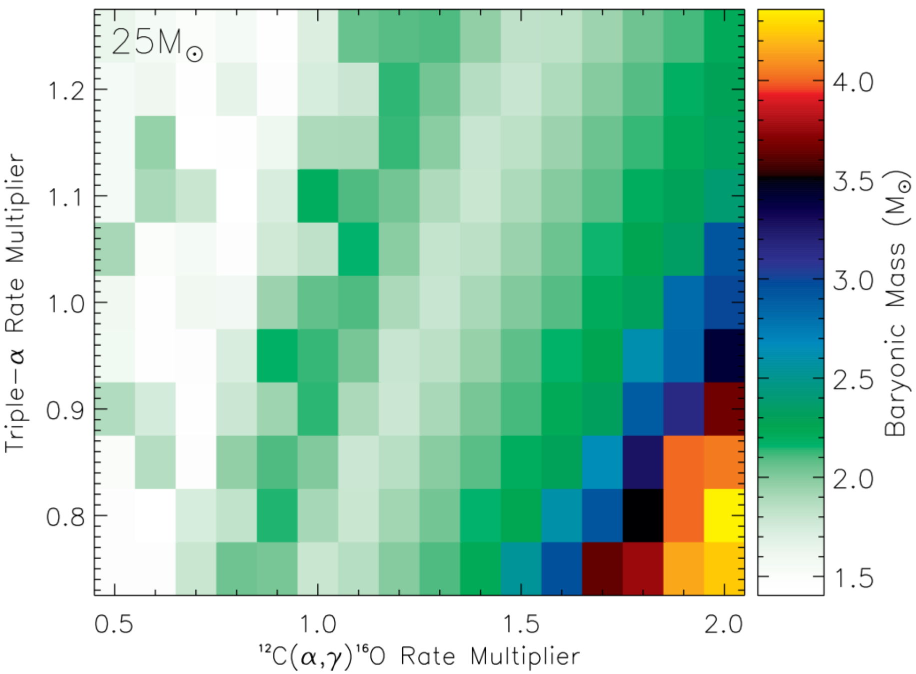
~2,000 stellar models

(West+ 2013)

Results



[Top]
Carbon mass fraction in the centre of a 25 $M_\odot$ star after core helium depletion

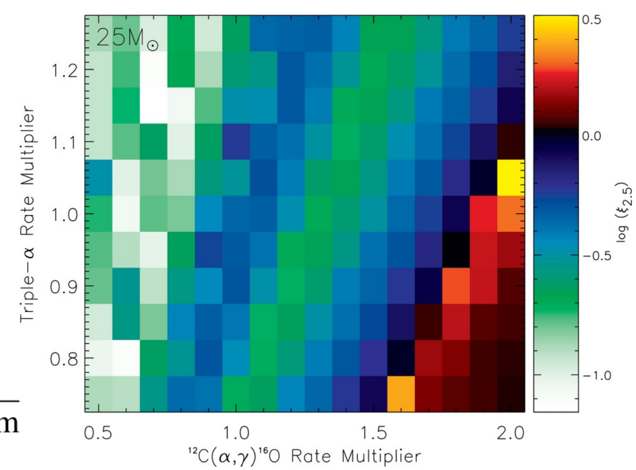


[Bottom Left]
Baryonic remnant mass after 1.2 B supernova explosion

West+ (2013)

Compactness

$$\xi_M = \frac{M/M_\odot}{R(M)/1000\,\mathrm{km}}$$

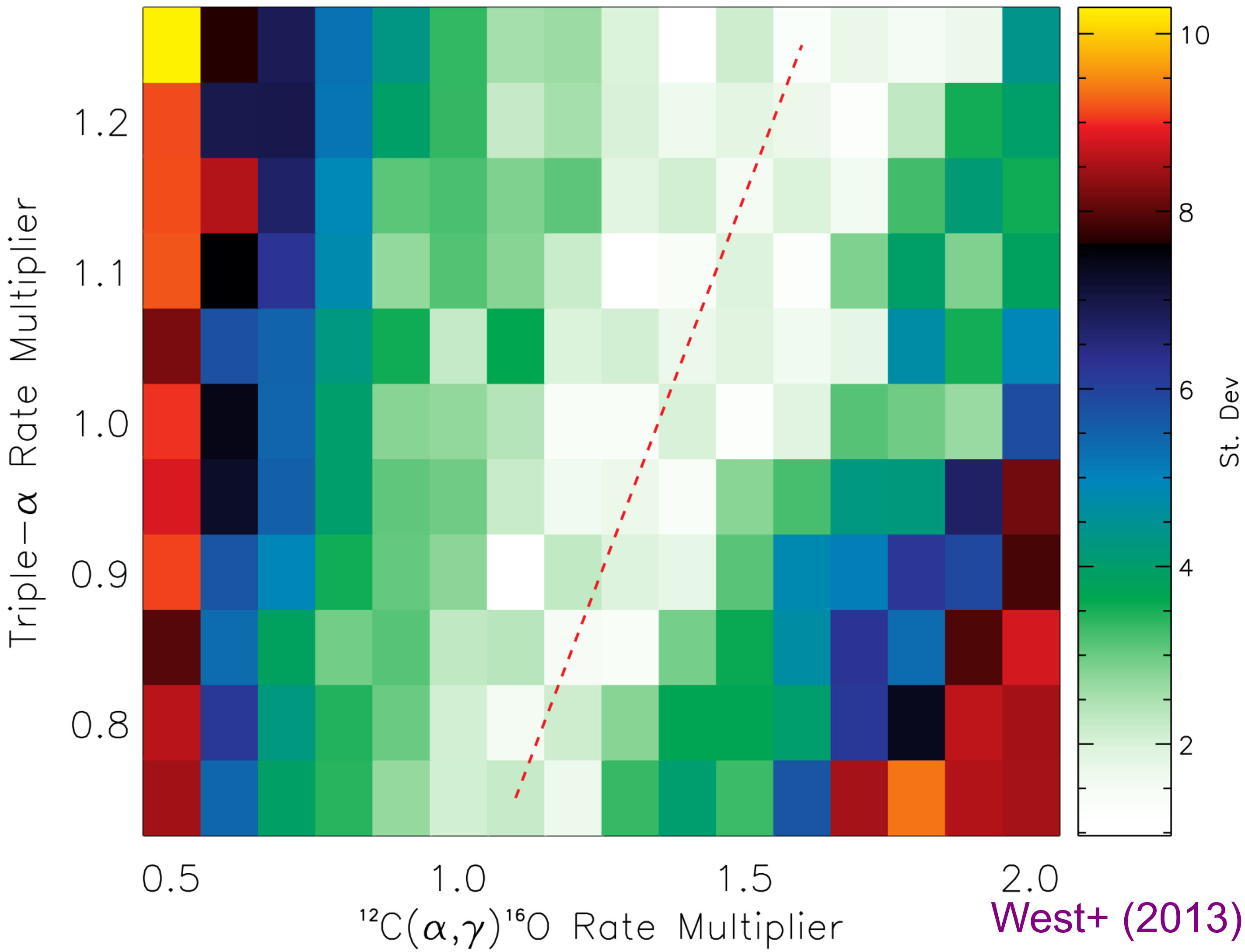


Result

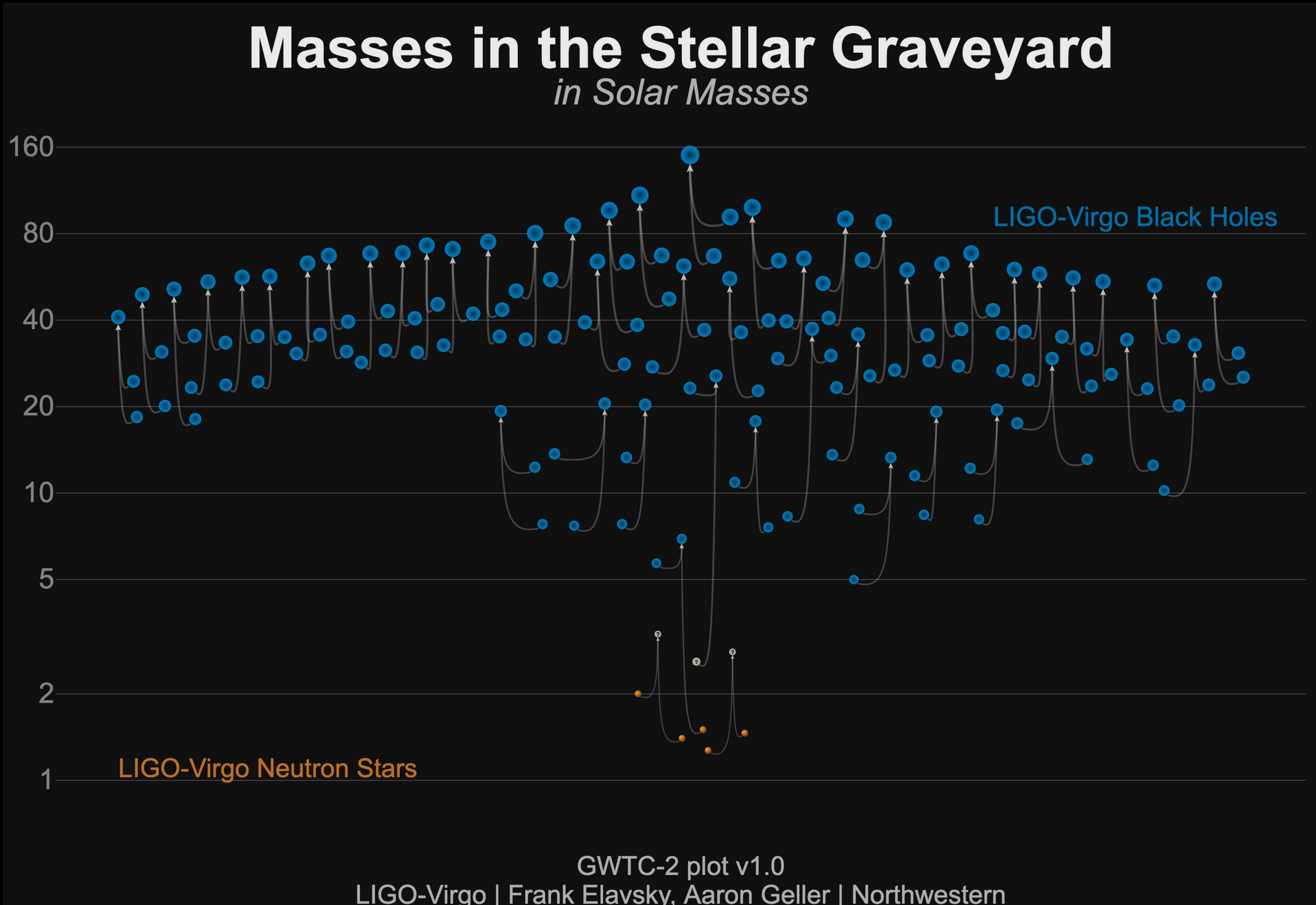
Region of best fit:

$R_{\alpha+C} = 1.0\ R_{3\alpha} + (0.35 \pm 0.2)$

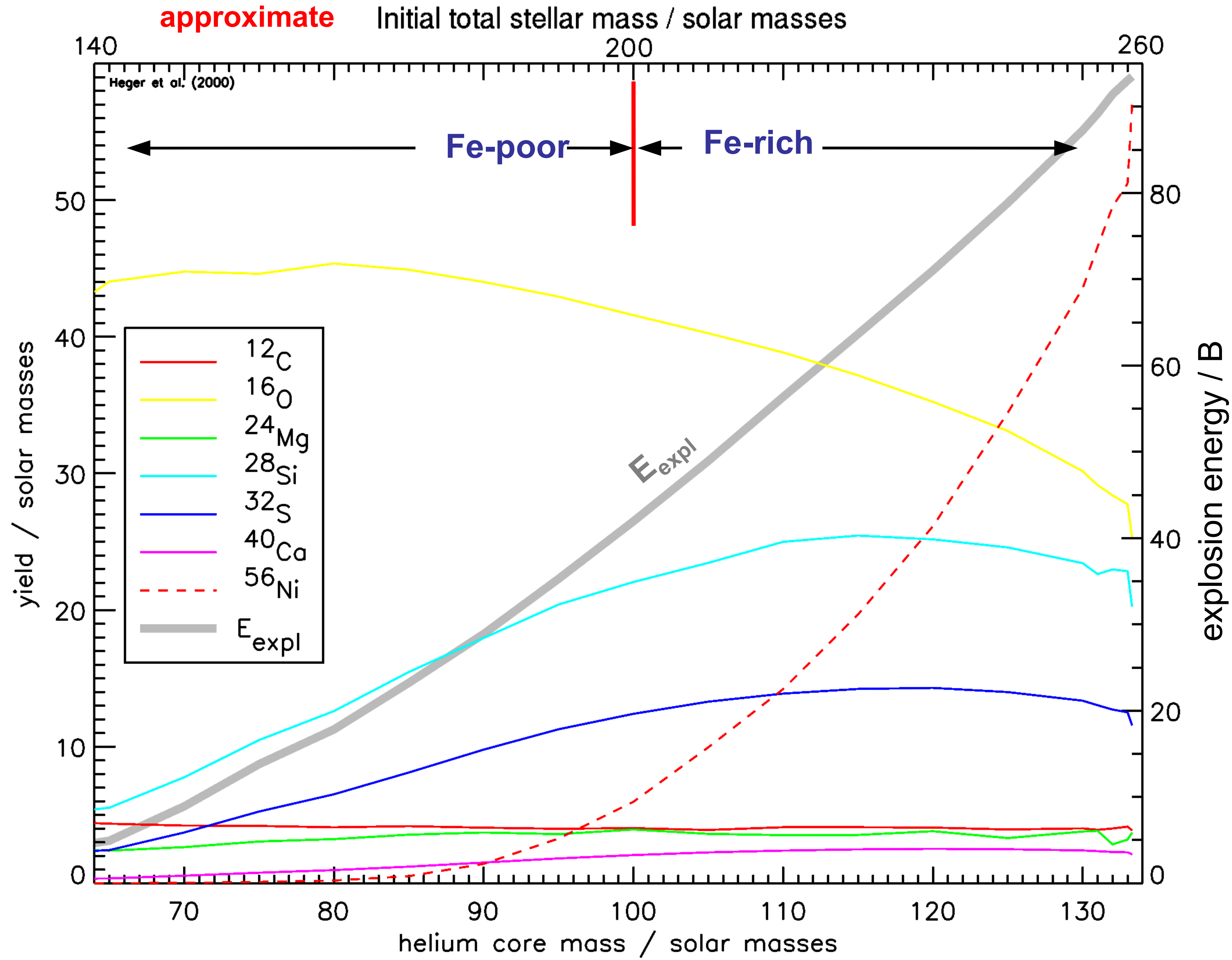
=> define effective Reaction Rate (ERR)



West+ (2013)

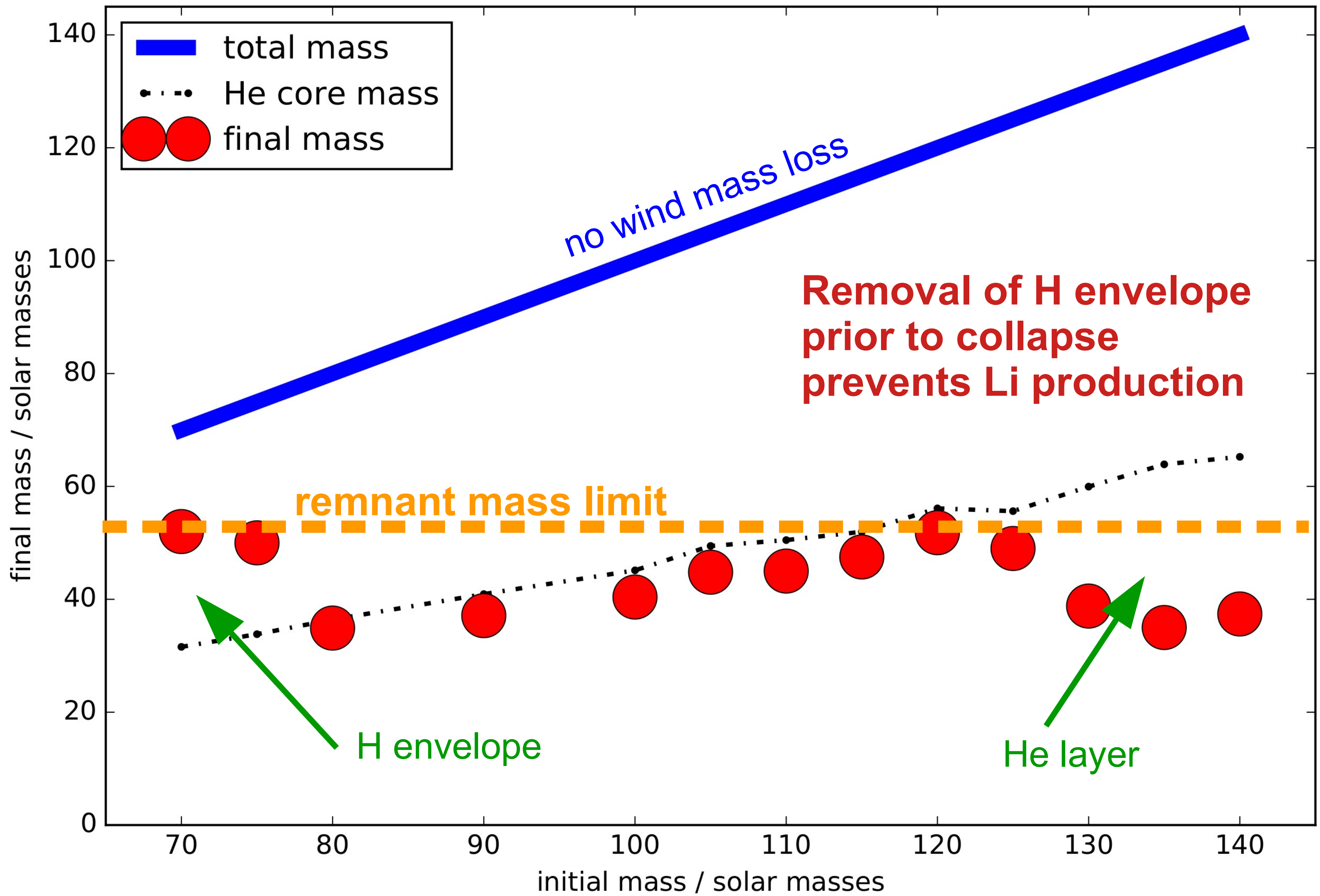


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern



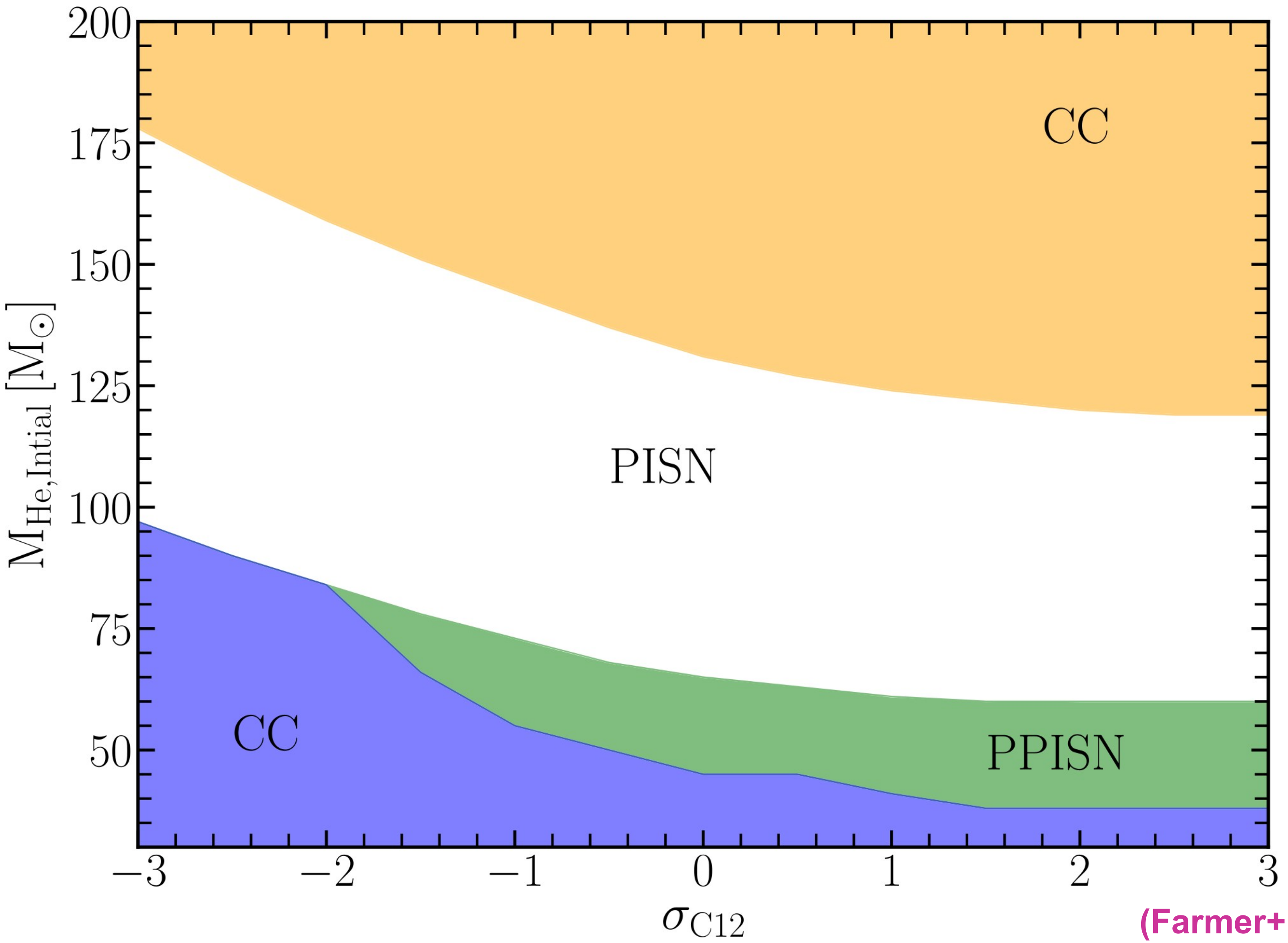
approximate
Initial total stellar mass / solar masses
140
200
260
Heger et al. (2000)
Fe-poor
Fe-rich
E_{expl}
^{12}C
^{16}O
^{24}Mg
^{28}Si
^{32}S
^{40}Ca
^{56}Ni
E_{expl}
yield / solar masses
0
10
20
30
40
50
explosion energy / B
0
20
40
60
80
70
80
90
100
110
120
130
helium core mass / solar masses

Pulsational Pair Instability Supernovae



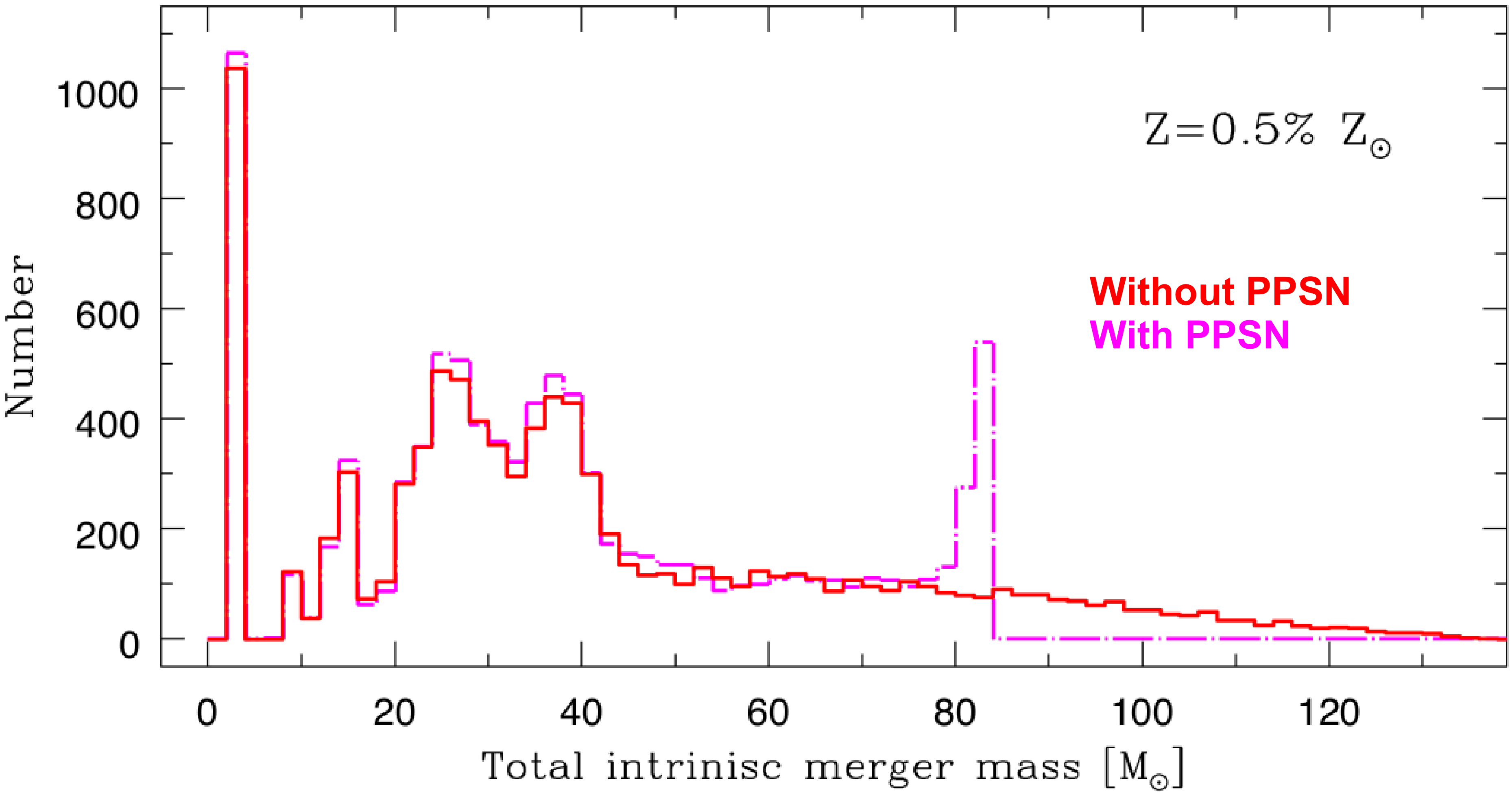
Plot after data from Woosley (2016)

PSN/PPSN as Function of Mass and $^{12}C(a,g)$ Rate



(Farmer+ 2020)

Impact of Pulsational Pair Instability SN On Binary Black Hole Merger Mass



(Belczynski+ 2016)

Conclusions

- Can do full-network 1D simulations, but still have many limitations from input physics, including rotation, magnetic fields, nuclear data, ...

- WANTED – nuclear data for reaction rates, masses and energy levels and the weak rates and nu loss rates to compute consistent models.

- Due to the multitude of effects, conversely, modeling can not be used easily to constrain nuclear data except for special cases.