Explosion and Nucleosynthesis of Massive and Very Massive Stars

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Science

http://CosmicExplosions.org

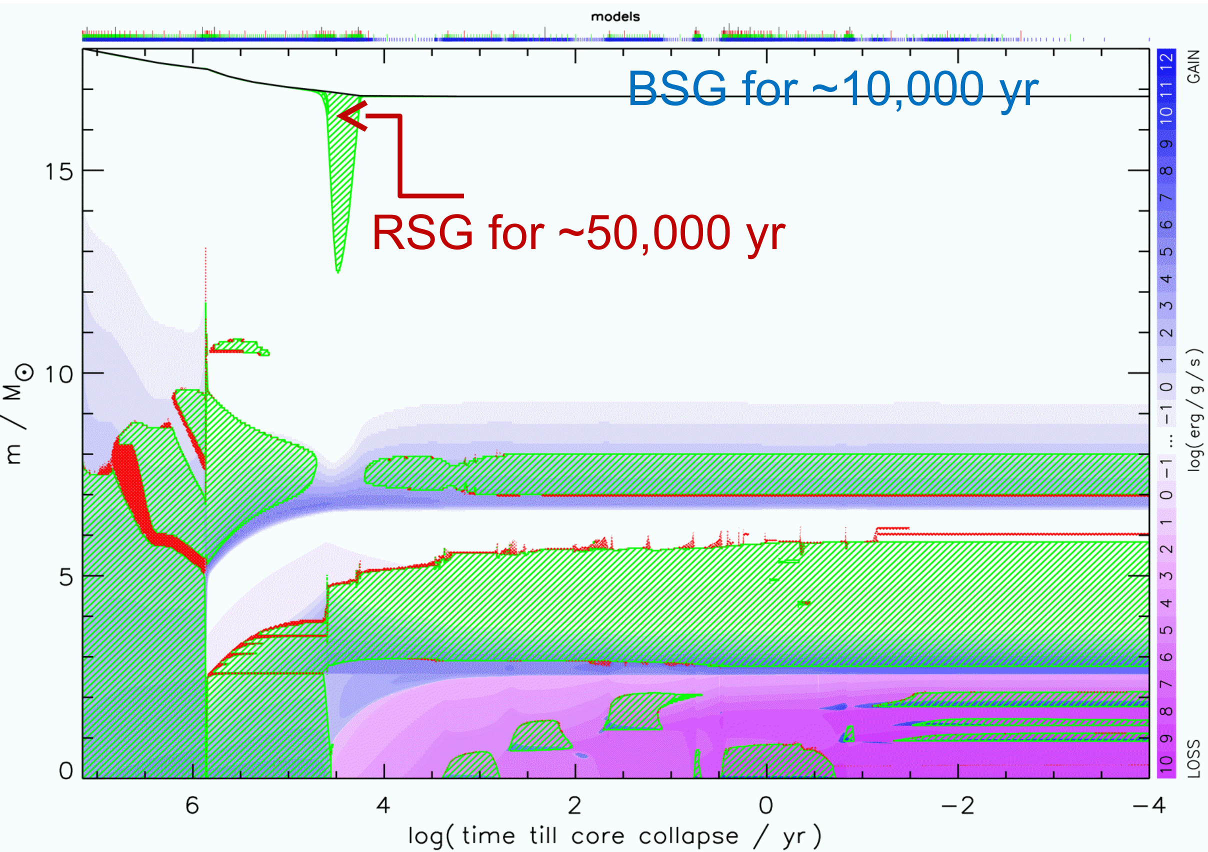
A Rotating Single Star Model for 87A

18 solar mass star

Initial rotation ~235 km/s

(Slide from 20 yr after meeting)

(Woosley *et al.* 2007)



Surface N/C enrichment

Ejected 0.1 - 0.2 solar at RSG-BSG transition

NS remnant with P ~13 ms

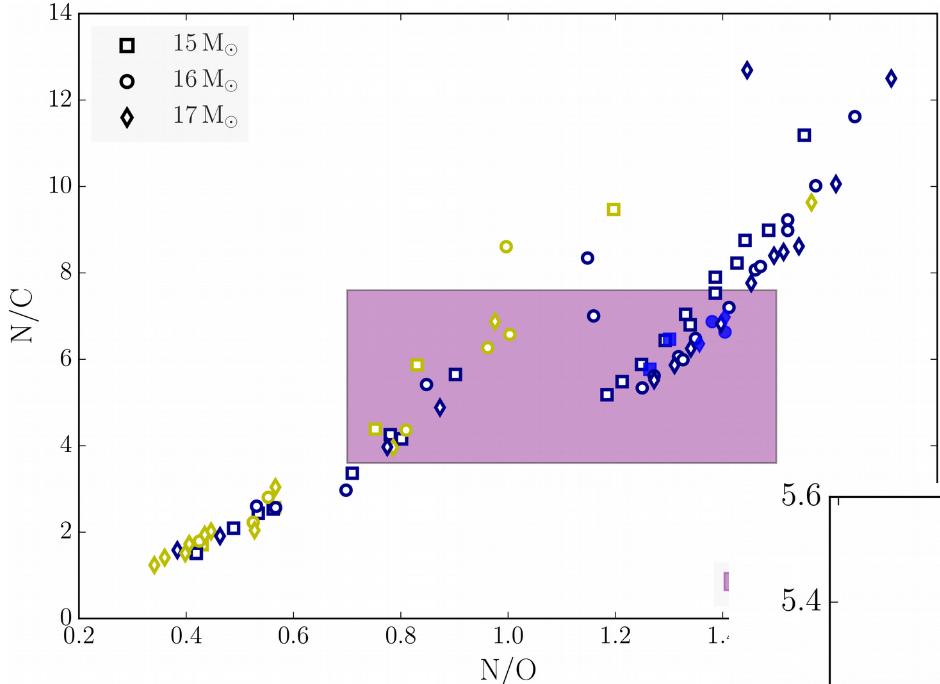
Fallback large because BSG

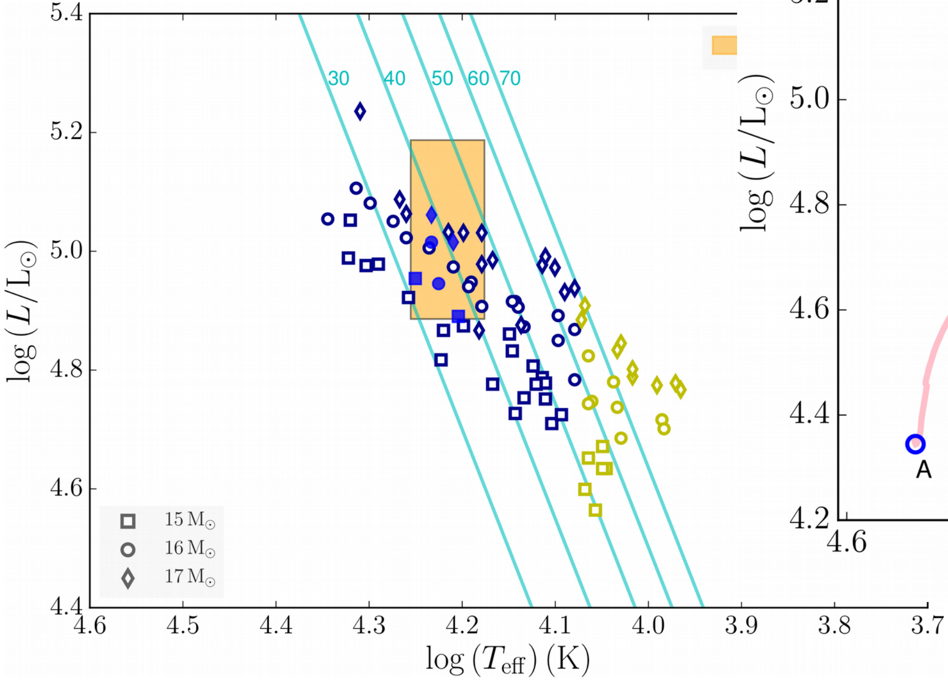
Accretion currently inhibited by the propeller mechanism?
(Eksi, Hernquist, Narayan 2005)

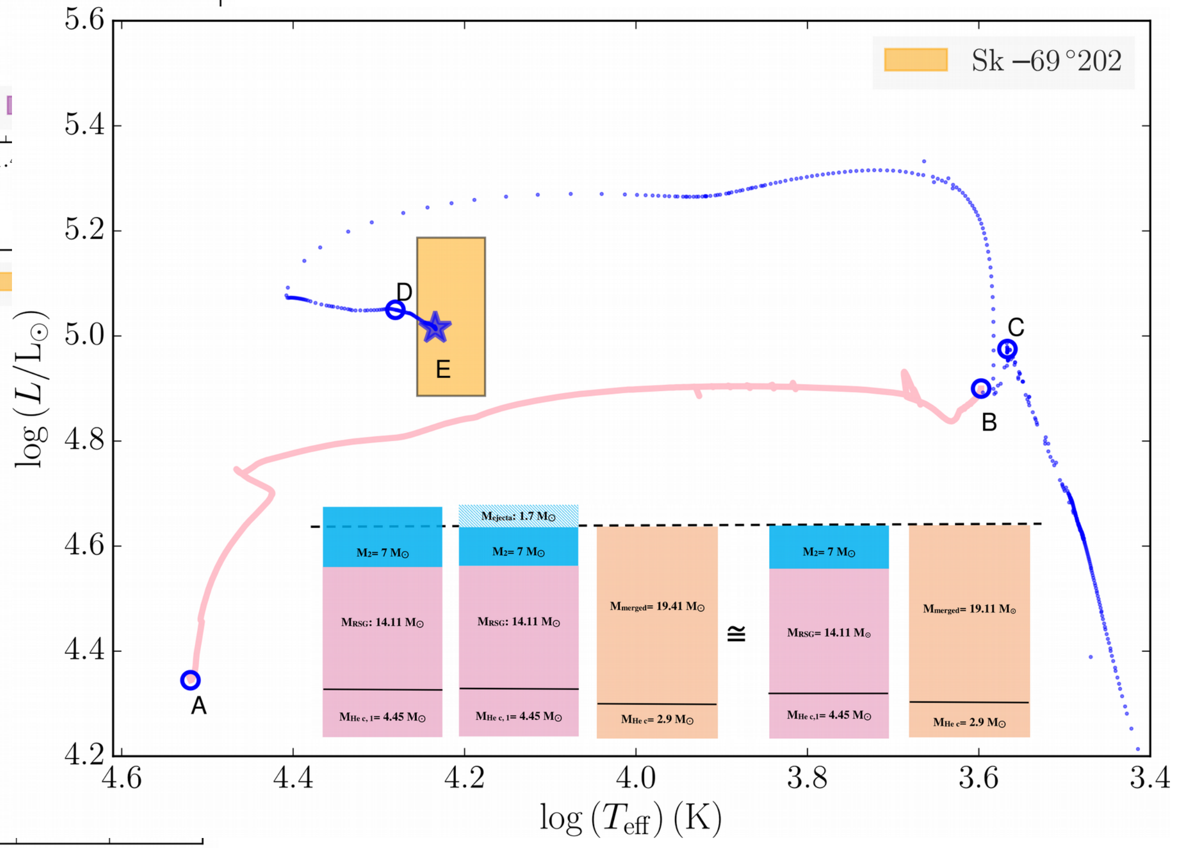
SN 1987A

Binary star models can reproduce HRD position and surface/nebula abundances **simultaneously**

(model inspired by Podsiadlowski et al.)





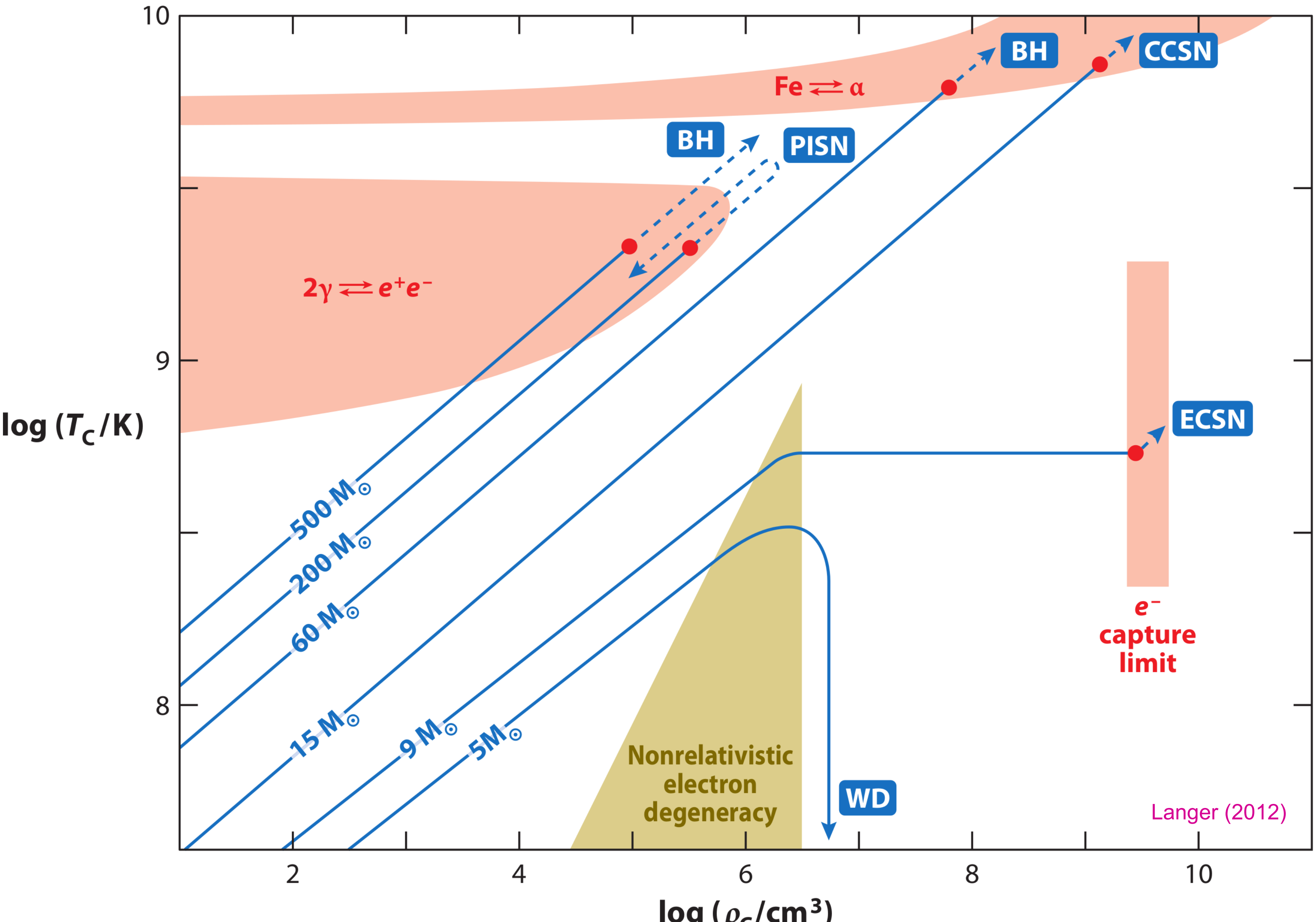


(Menon+ 2017)

Overview

- Massive stars
- Very massive stars
- Supernovae mechanisms
- Notes on Nucleosynthesis

Evolution of Center for Different Initial Masses

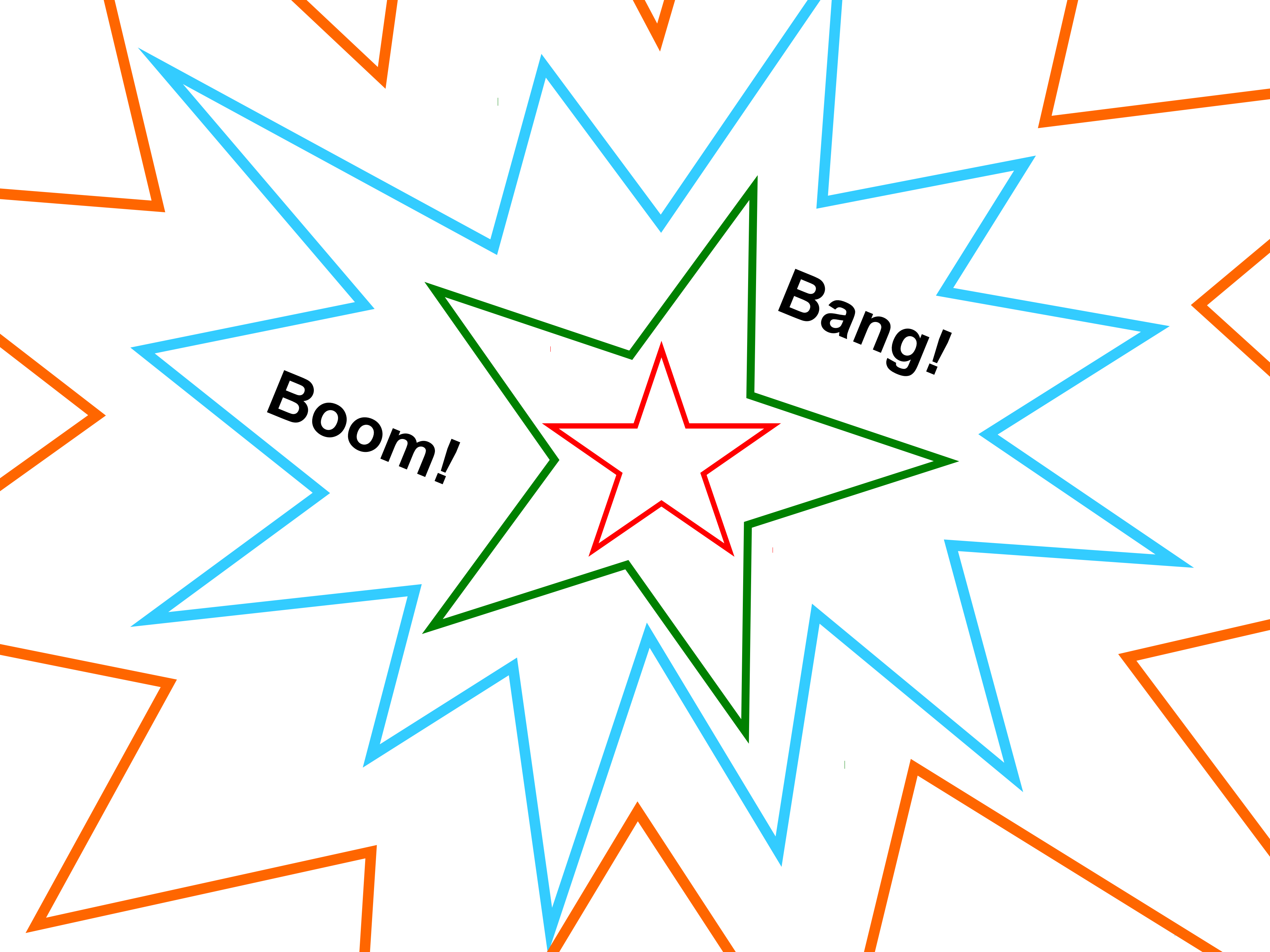


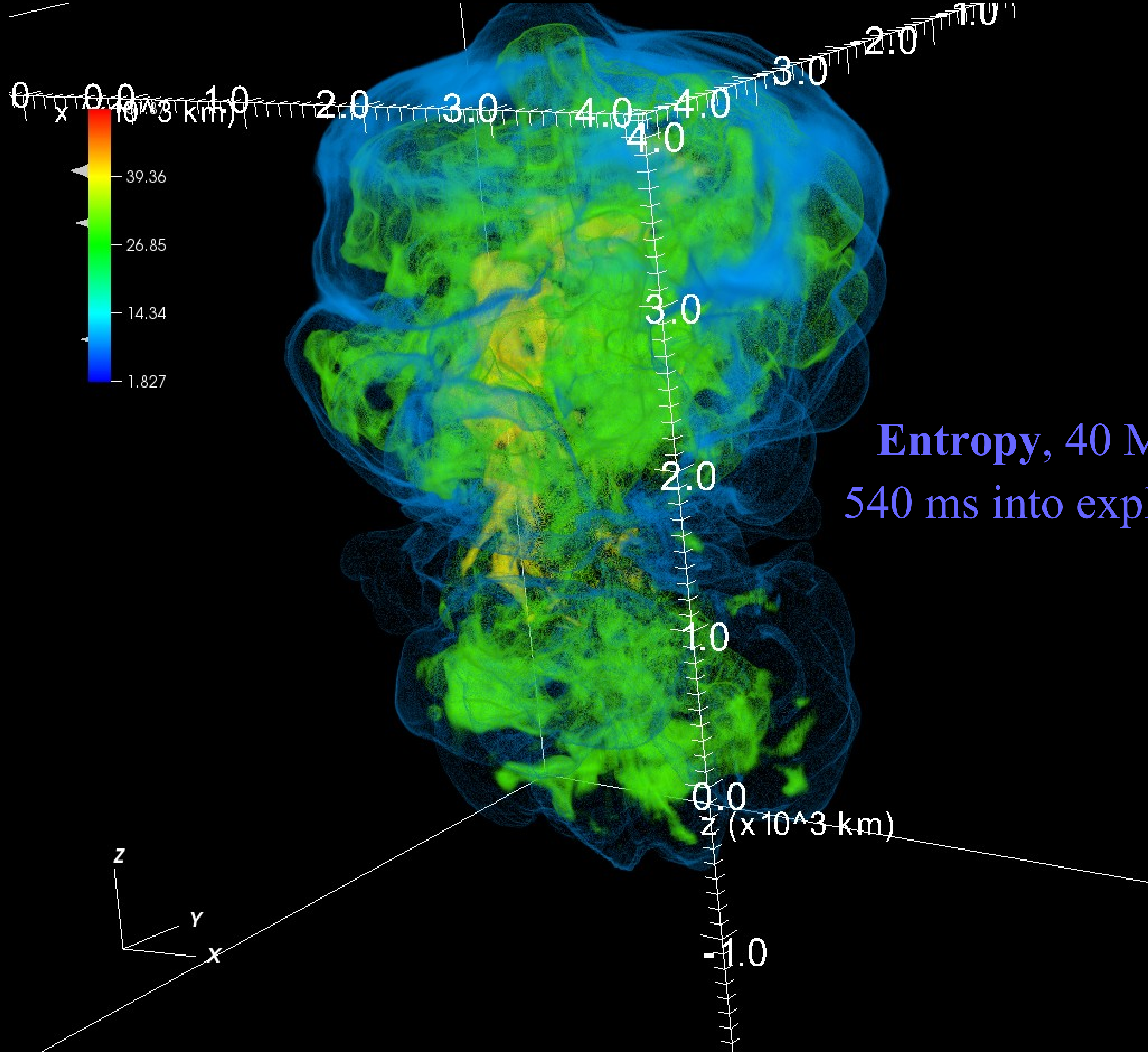
Nuclear burning stages

(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	$3\ He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
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	$^{28}Si(\gamma,\alpha)\ldots$

The Death of the Stars


Boom!
Bang!



Entropy, 40 M_o star
540 ms into explosion

Mueller, Chan, Heger 2017 in prep.

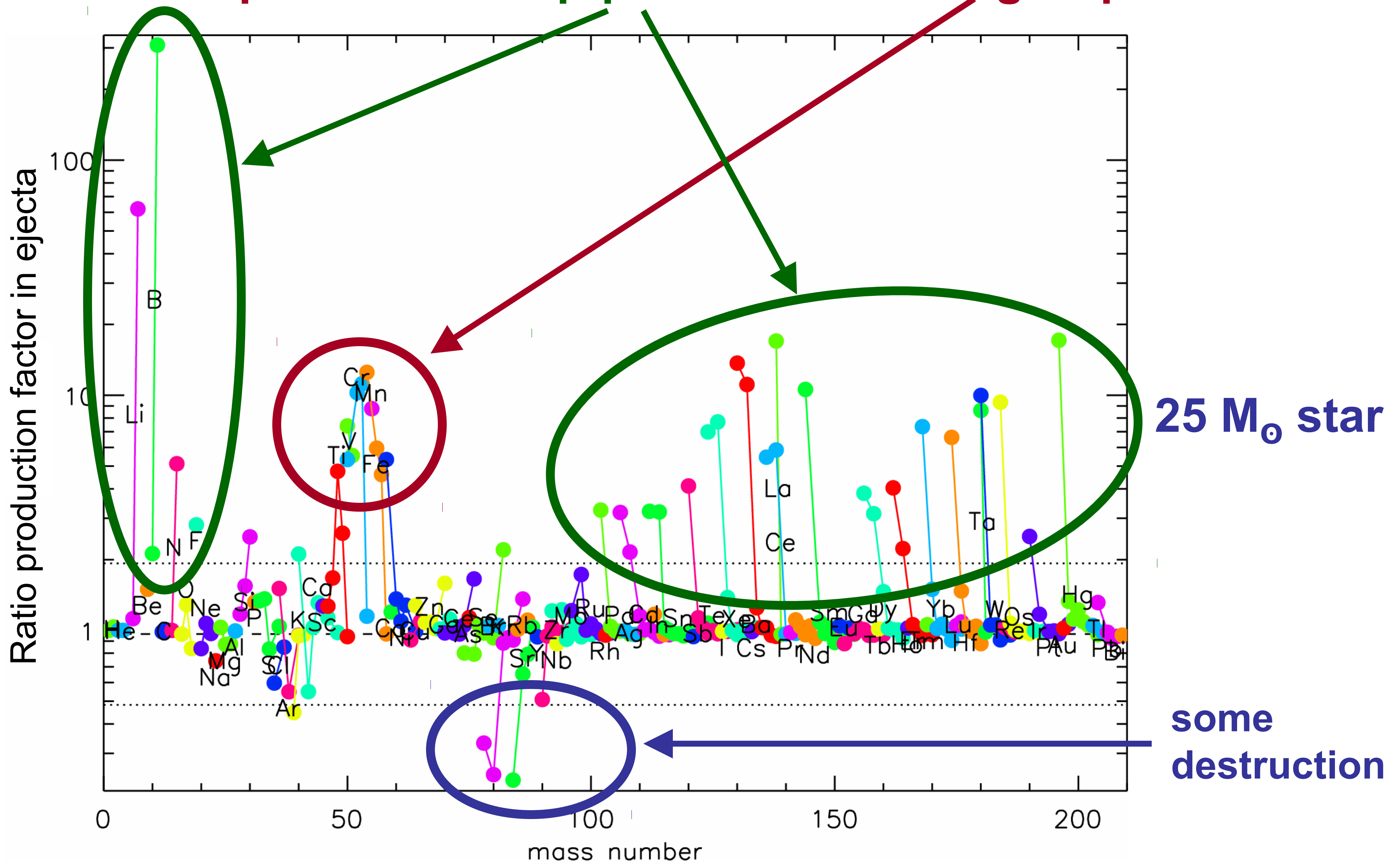
Explosive Nucleosynthesis

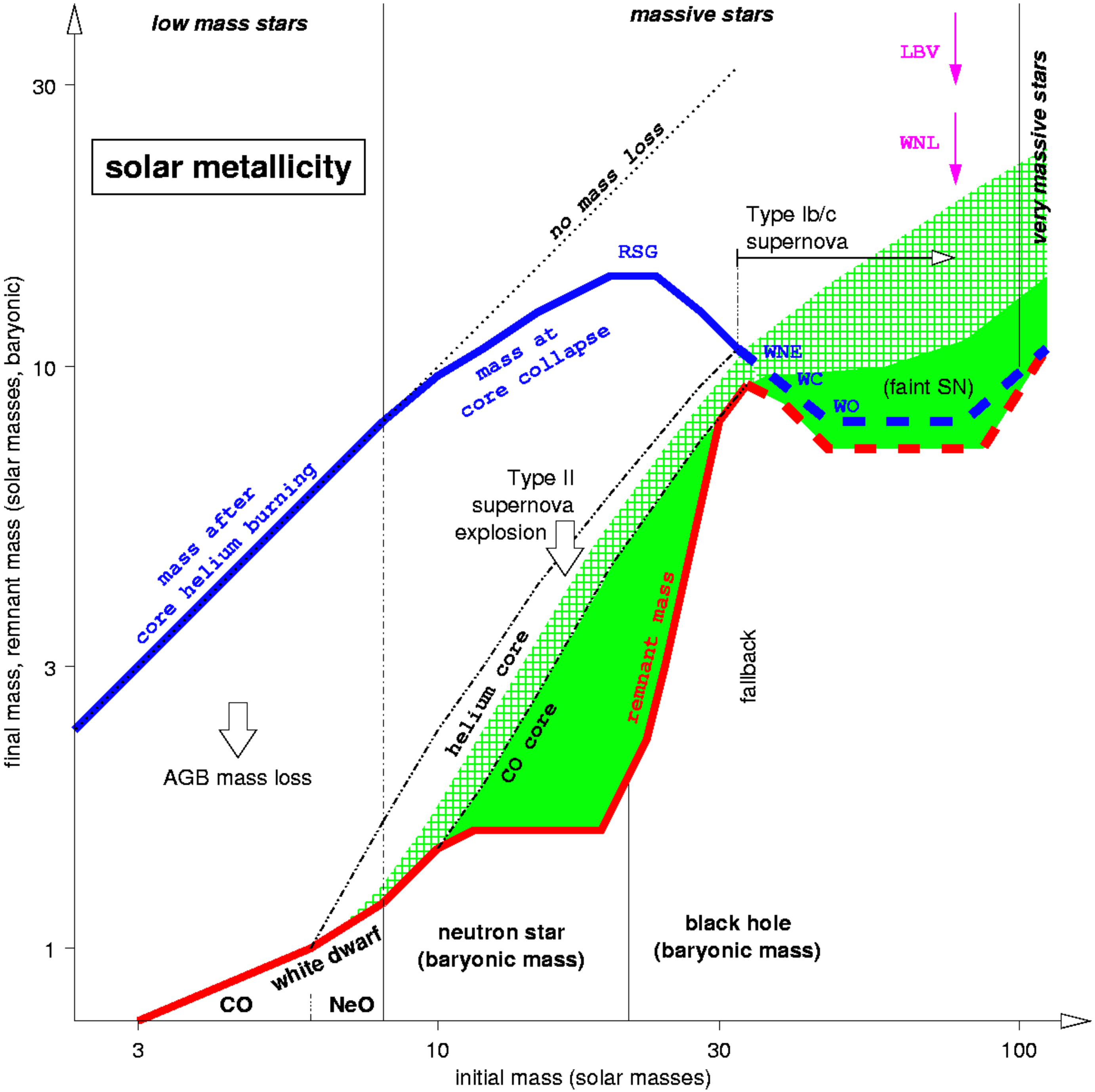
in supernovae from massive stars

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (s)	Main Reaction
Innermost ejecta	*r*-process? νp-process	-	>10?	1	(n,γ), β^-
Si, O	^{56}Ni	iron group	>4	0.1	(α,γ)
O	Si, S	Cl, Ar, K, Ca	3 - 4	1	$^{16}O + {}^{16}O$
O, Ne	O, Mg, Ne	Na, Al, P	2 - 3	5	(γ,α)
		p-process ^{11}B, ^{19}F, ^{138}La, ^{180}Ta	2 - 3	5	(γ,n)
		ν-process		5	(ν, ν'), (ν, e^-)

Explosive Nucleosynthesis contribution

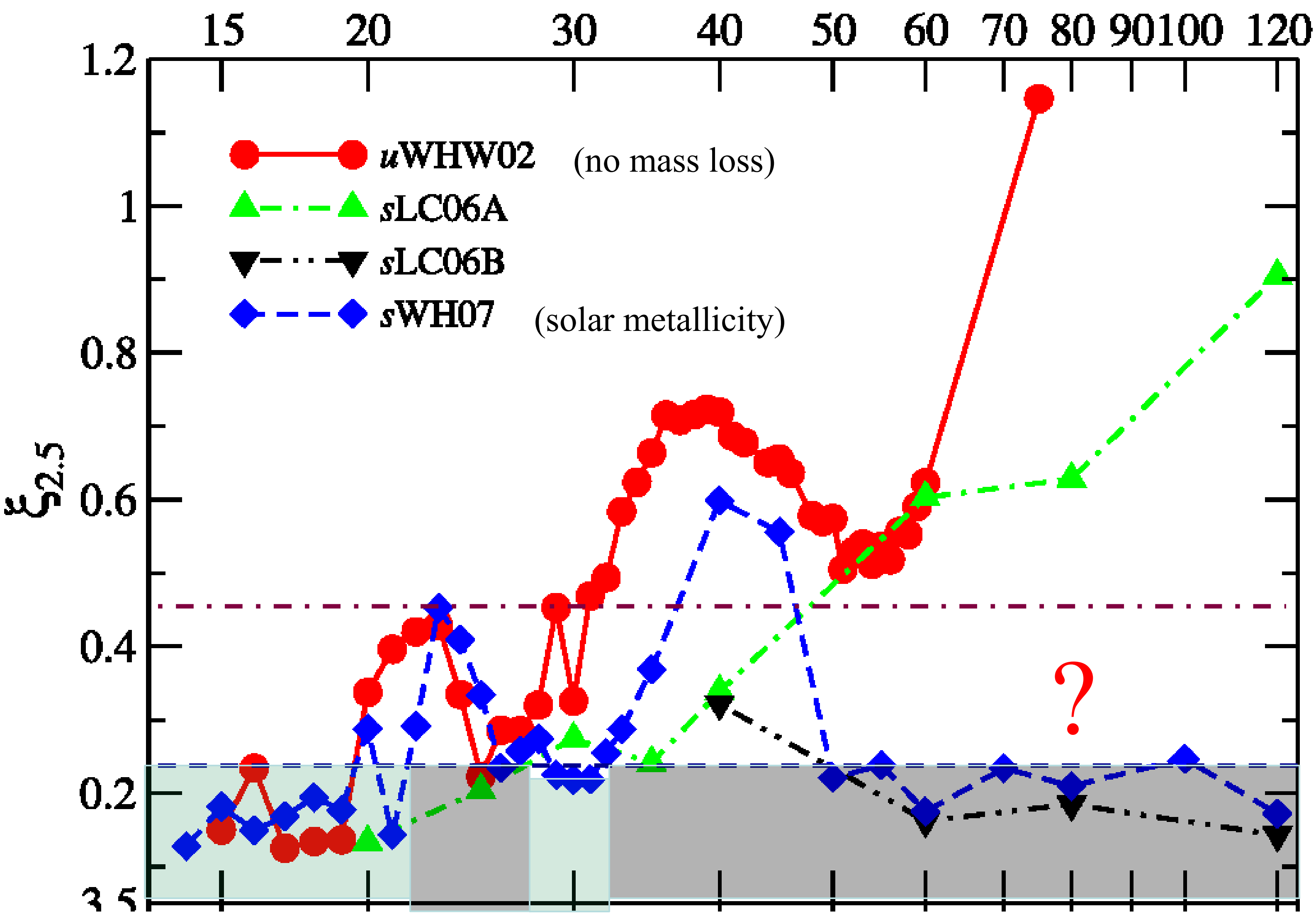
➔production of p-process and iron group





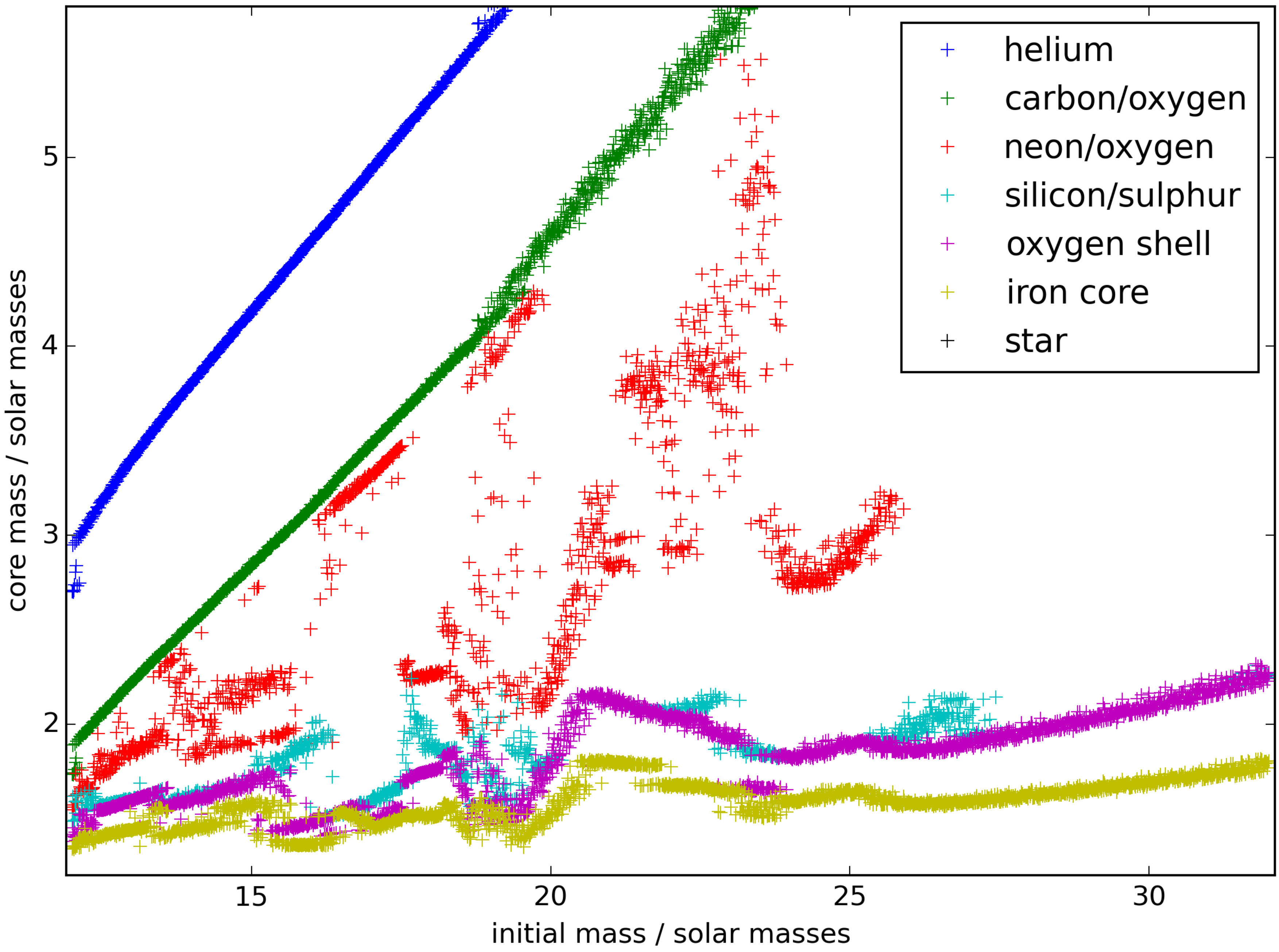
Ejected "metals"

Islands of SN and BH Production



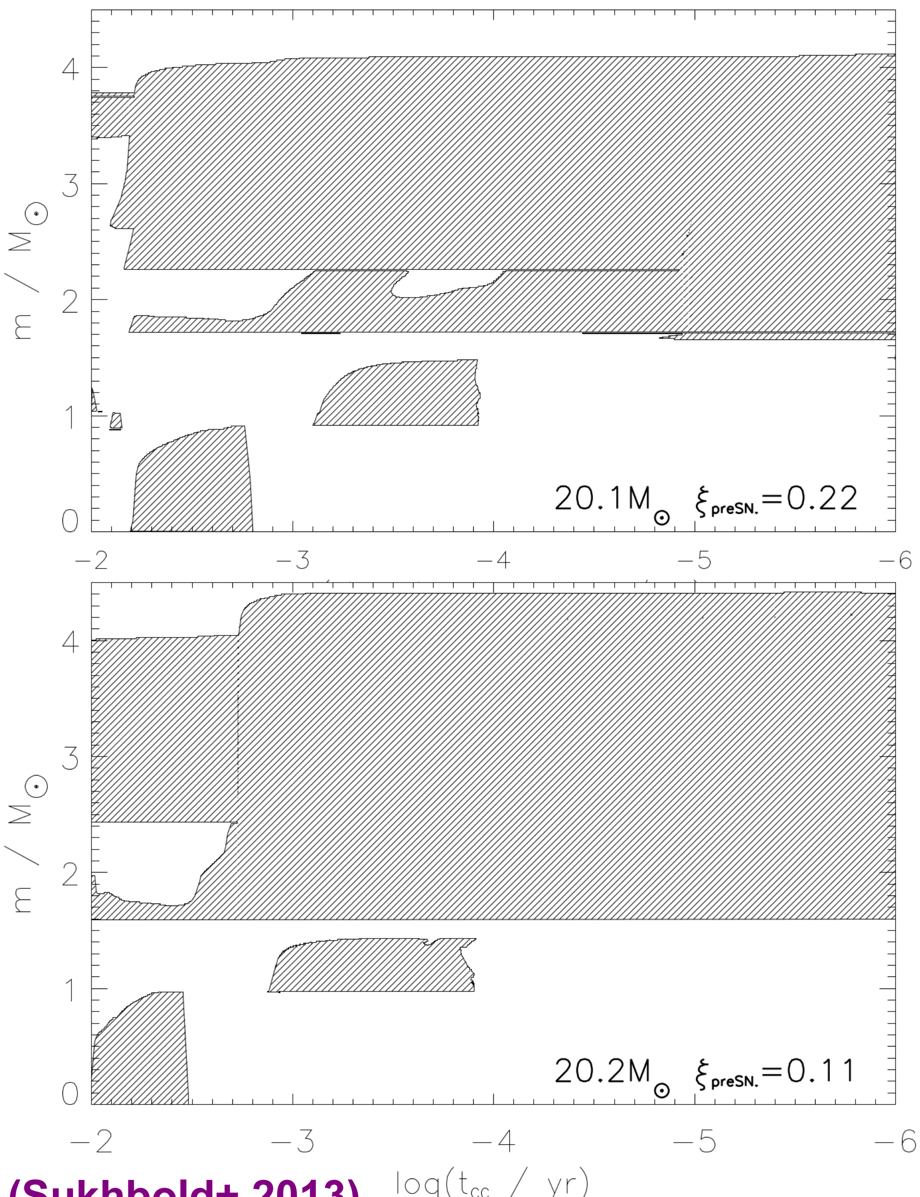
(Woosley 2012, priv. com.)

O'Connor and Ott (2011)



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

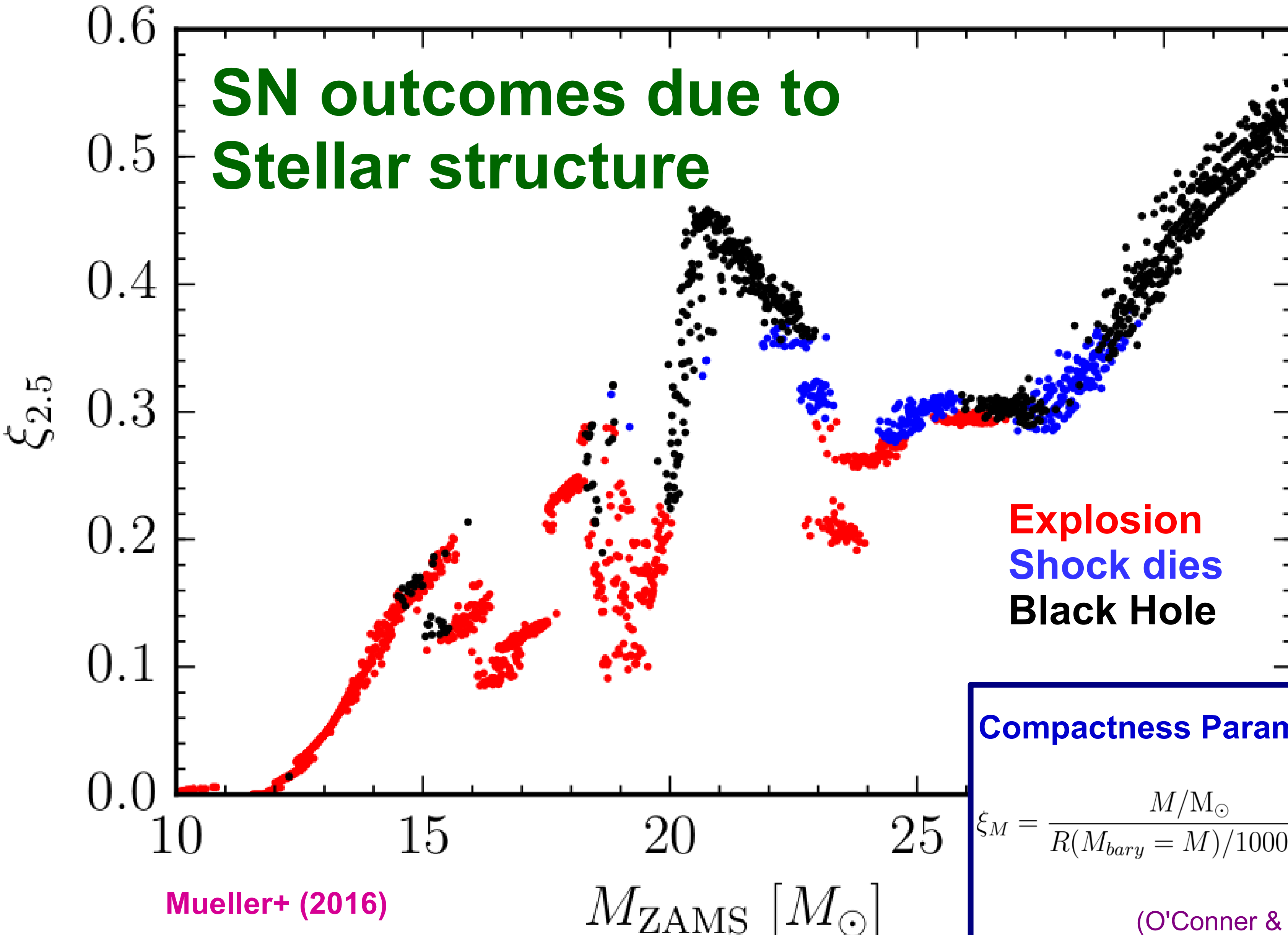
Sensitivity of Structure to Initial Mass



Small changes in initial mass can result in large changes in progenitor structure

(Sukhbold+ 2013)

Signatures of Stellar Structure?



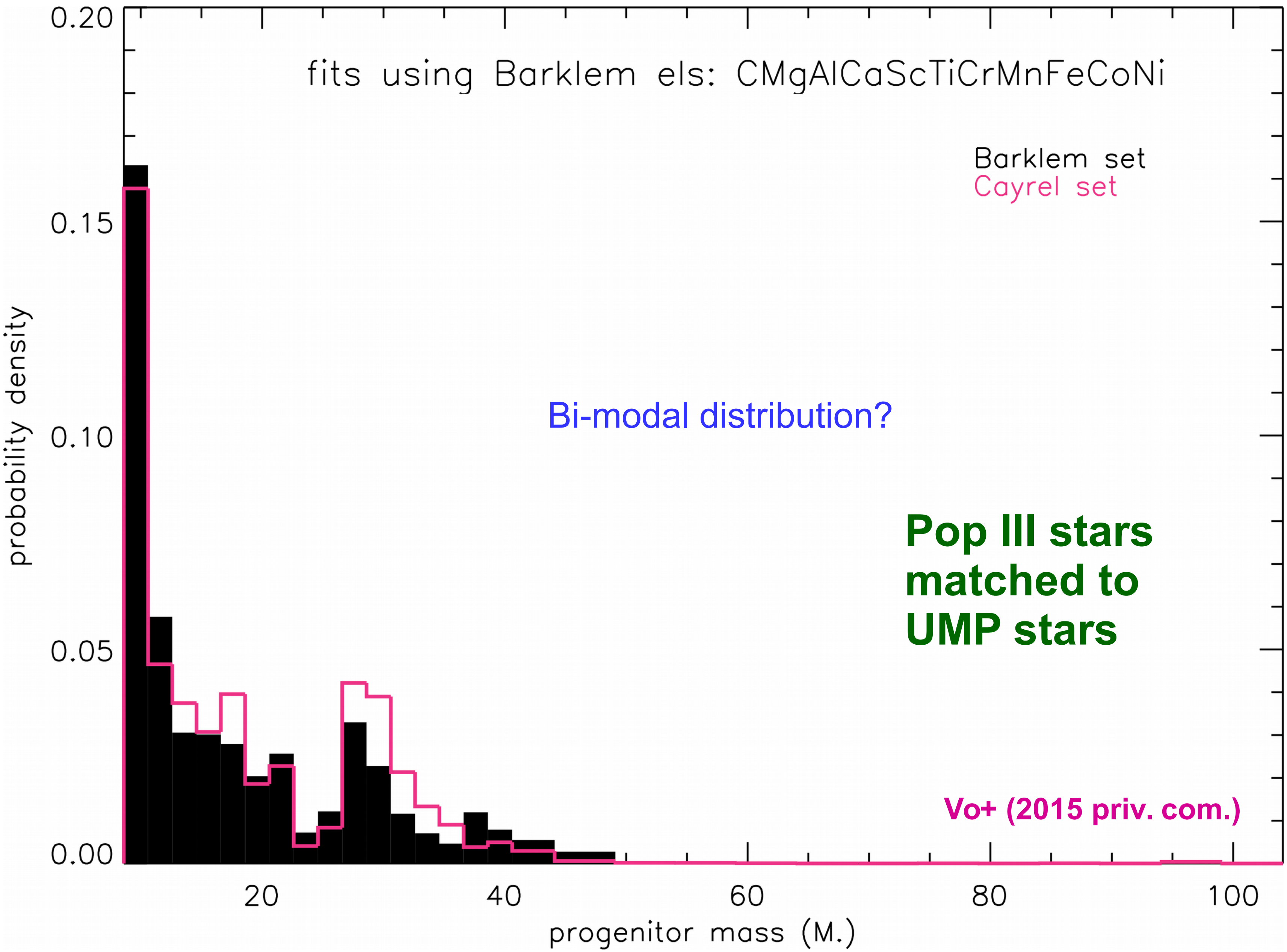
Mueller+ (2016)

Compactness Parameter

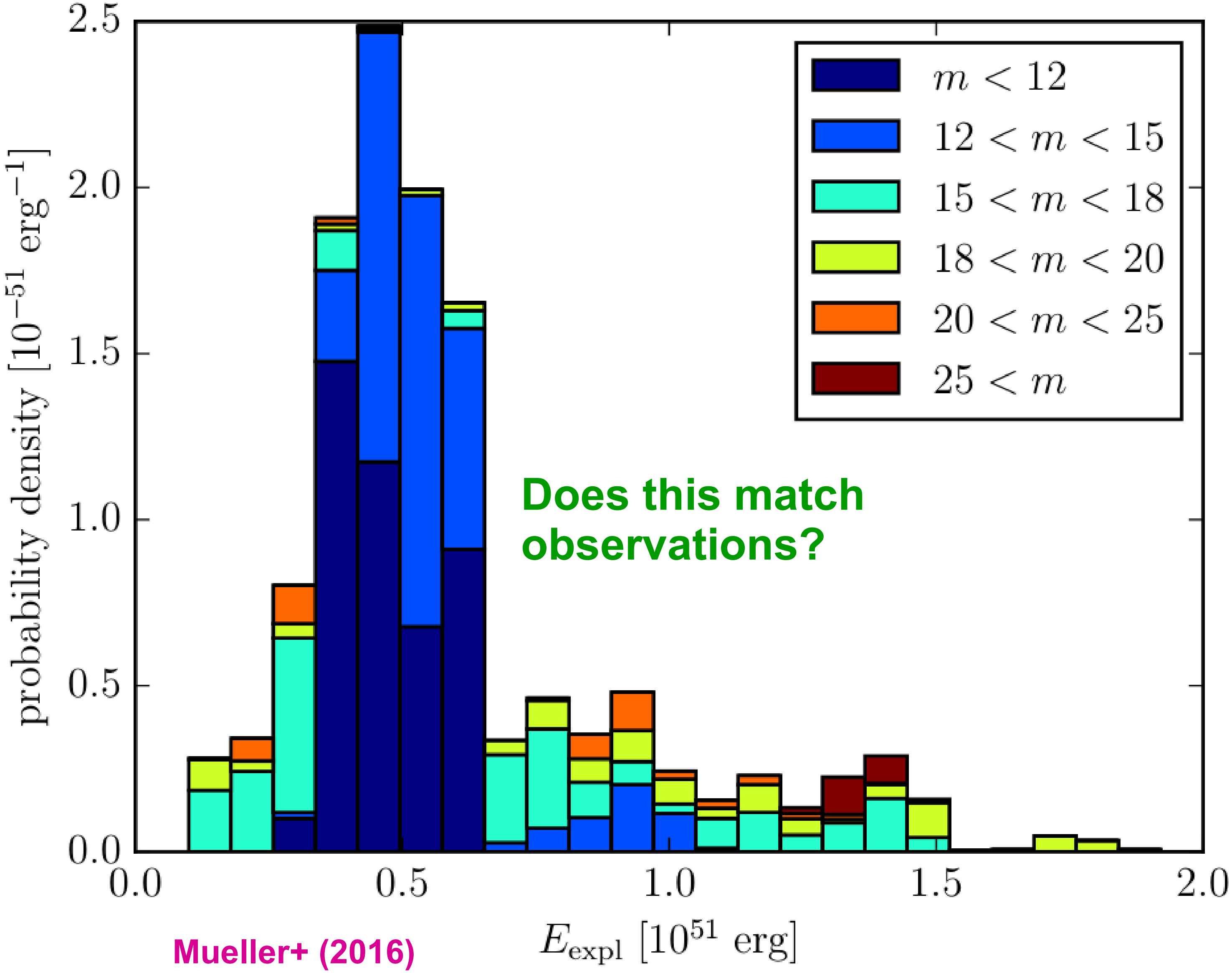
$$\xi_M = \frac{M/\mathrm{M}_\odot}{R(M_{bary} = M)/1000\,\mathrm{km}}\bigg|_{t_{bounce}},$$

(O'Conner & Ott 2011)

Reconstruction of the IMF



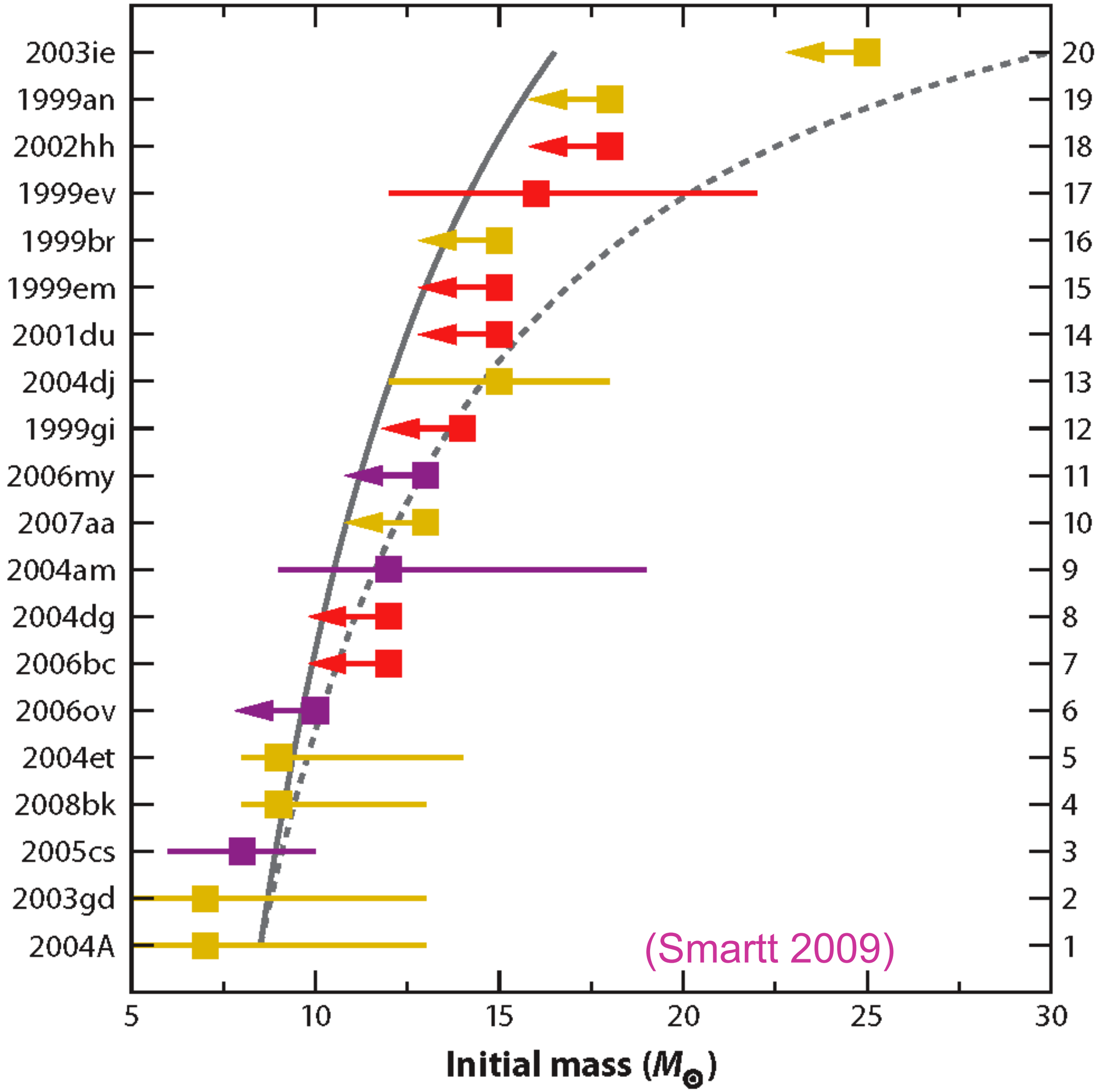
Signatures of Stellar Structure?



Mueller+ (2016)

Explosion energy is function of pre-SN structure as well

Supernova Progenitor Masses

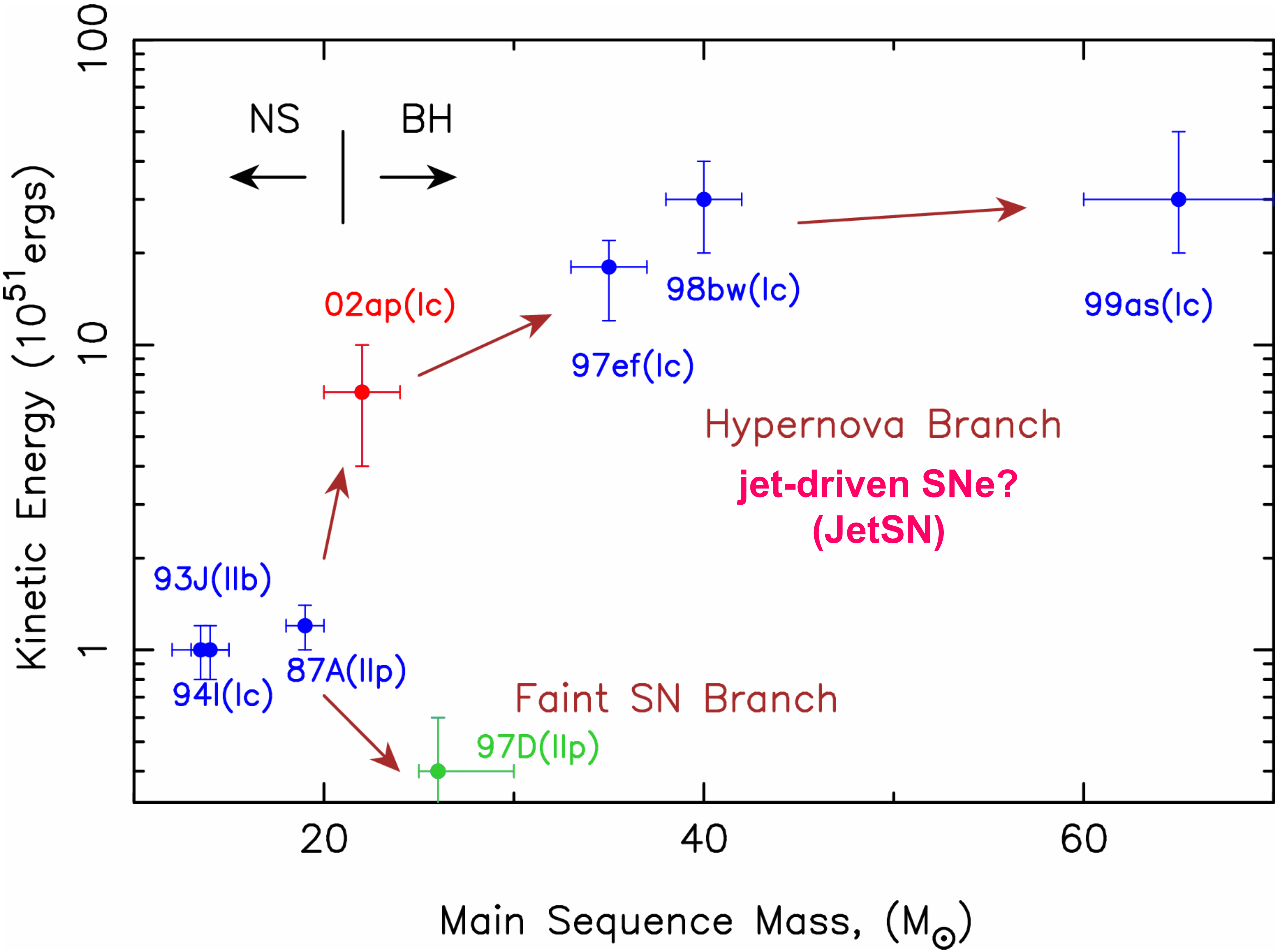


Presupernova stars for Type IIp and II-L

Solid Line:
Salpeter IMF with 16.5 $M_\odot$ cutoff

Dotted Line:
Salpeter IMF with 35 $M_\odot$ cutoff

► Exclude stars with $M_{initial}$ > 20 $M_\odot$ as Type IIP/IIL progenitors at 95% confidence level?



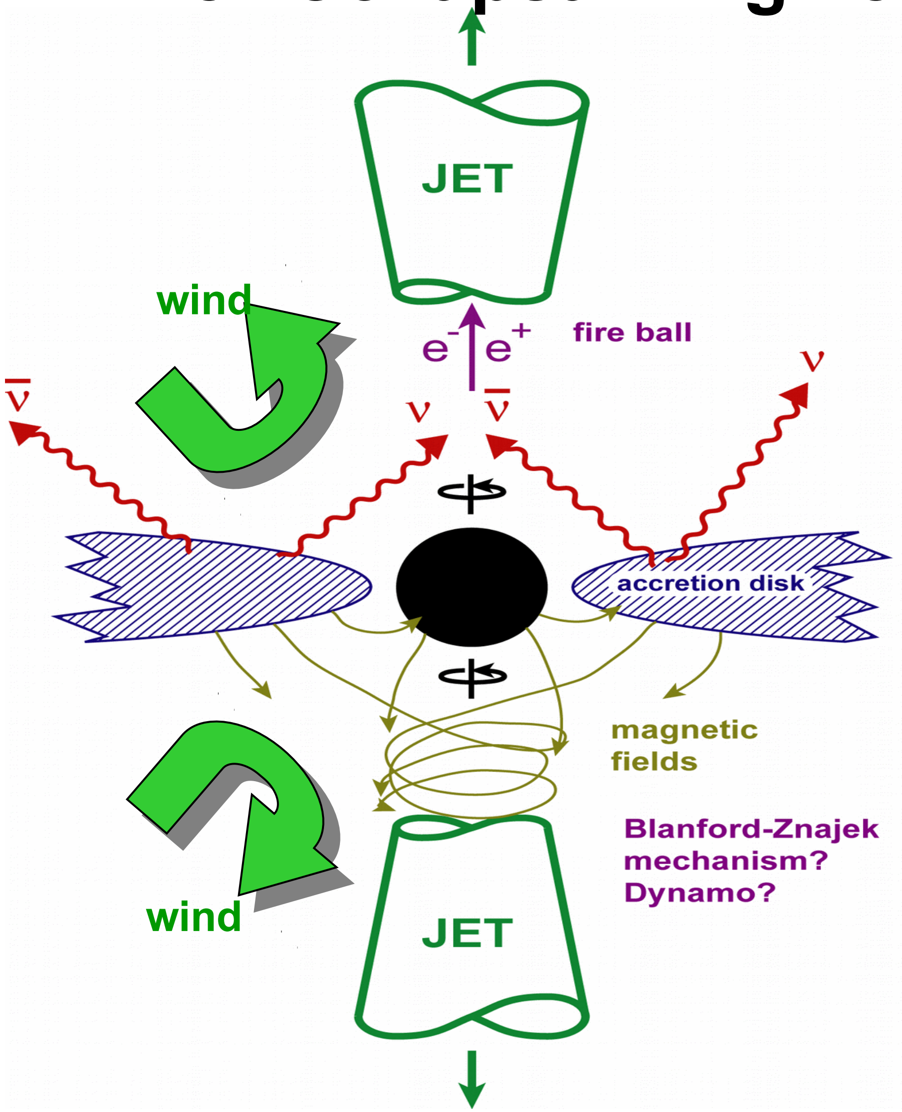
(Nomoto 2002, priv. com.)

How to Explode Big Stars Big

How else can massive stars explode?

$25M_\odot < M < 100M_\odot$, $M > 250M_\odot$

The "Collapsar Engine"



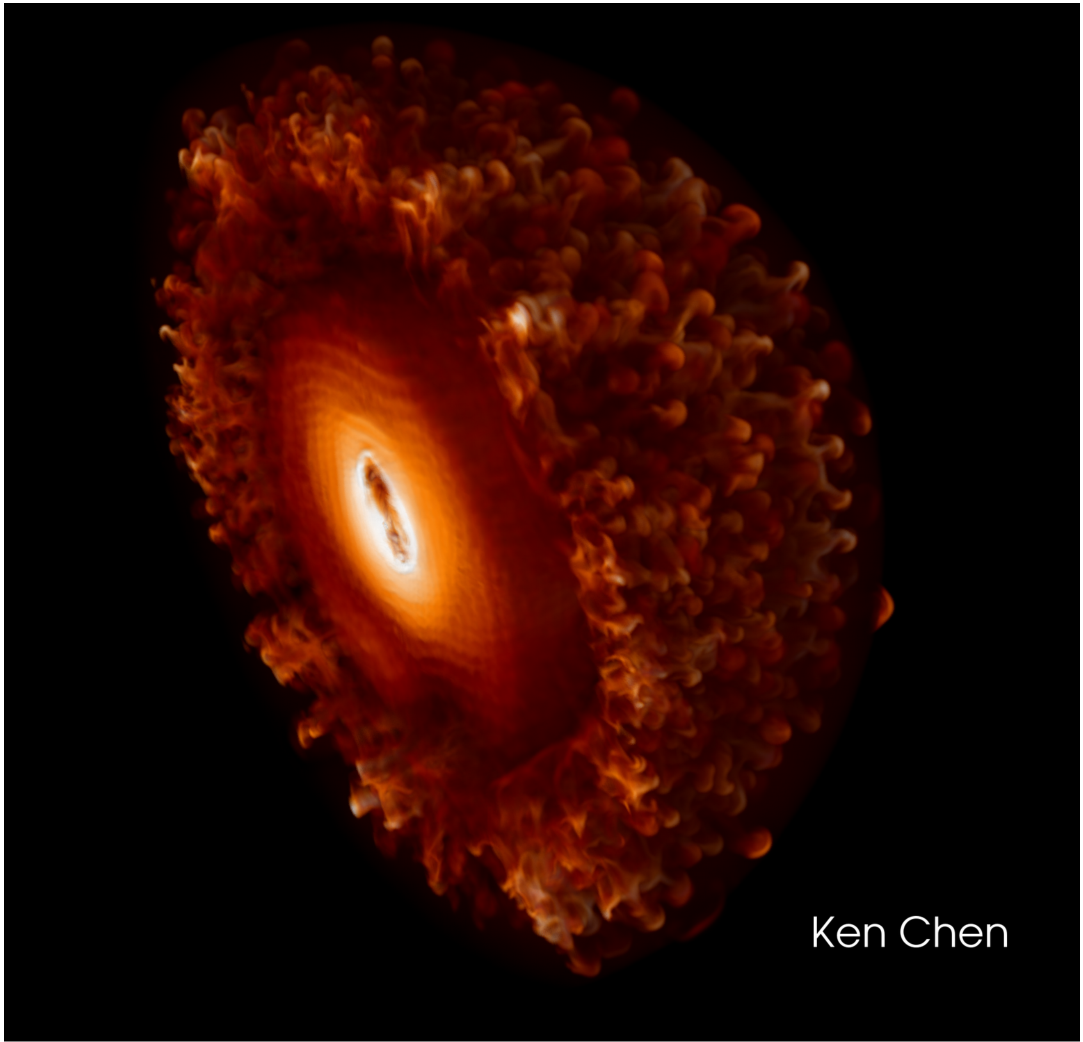
1. black hole forms inside the collapsing star
2. The infalling matter forms and accretion disk
3. The accretion disk releases gravitational energy (up to 42.3% of rest mass for Kerr BH)
4. Part of the released energy or winds off the hot disk explode the star

Magnetars

1. Rapidly rotating magnetized neutron star forms during core collapse
2. Magnetic fields efficiently convert rotational energy into explosion energy
3. Super-massive NS may collapse and make disk
4. Can this be the default case for SN?
5. Will jets be a common feature of this?

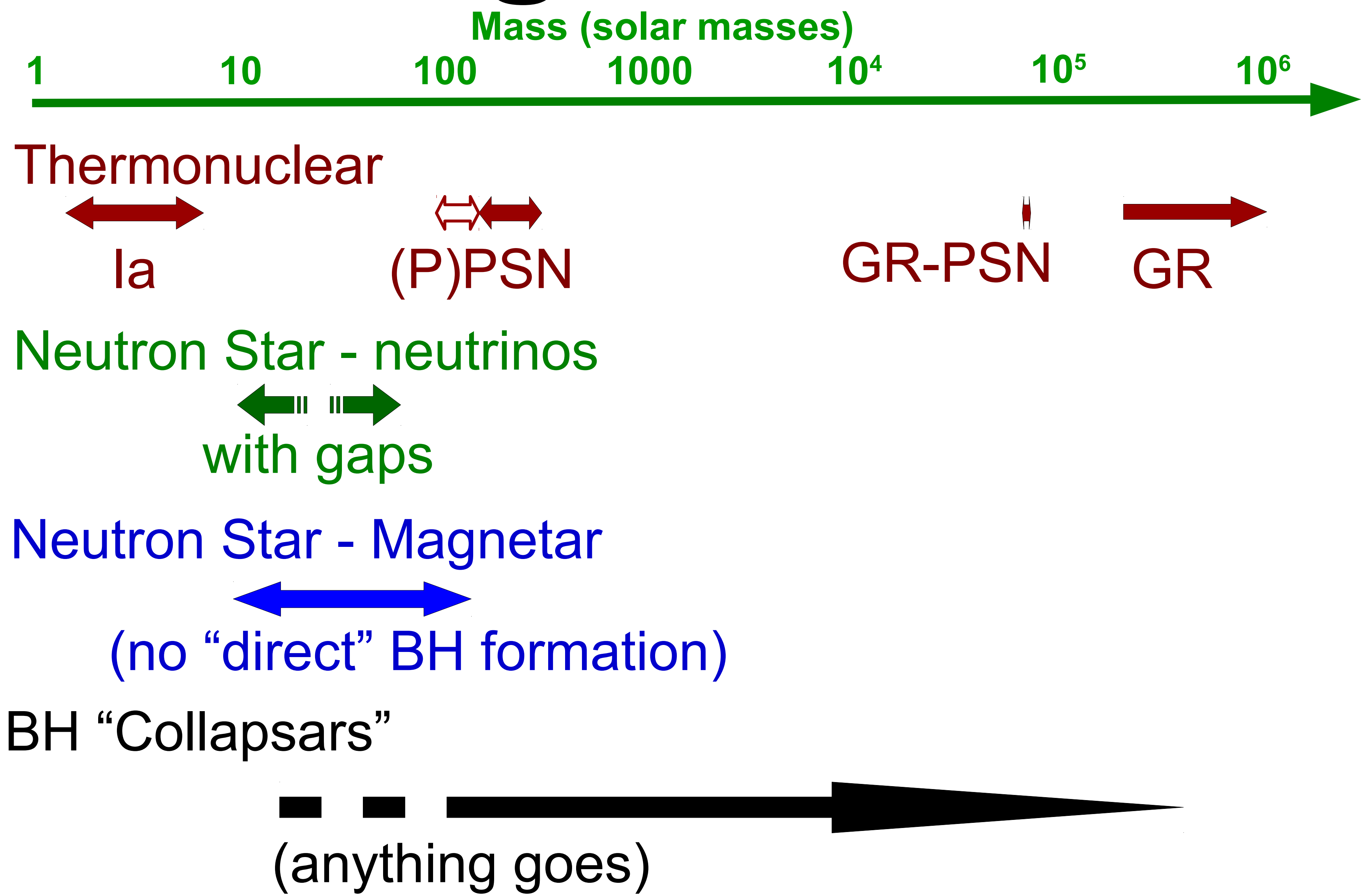
(Bildsten, Woosley, ...)

3D magnetar-powered supernova



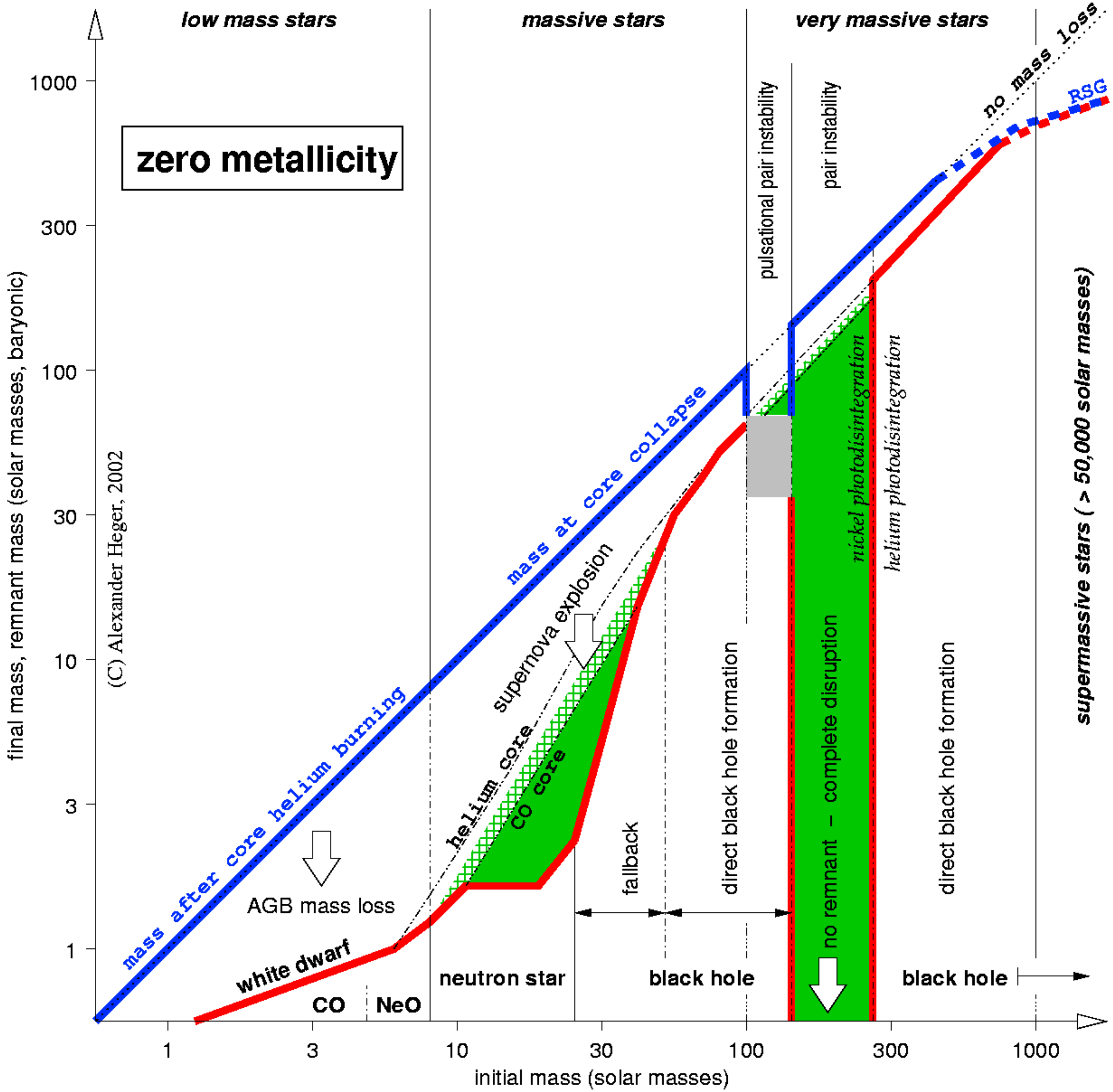
Fates...

The Engines of SNe

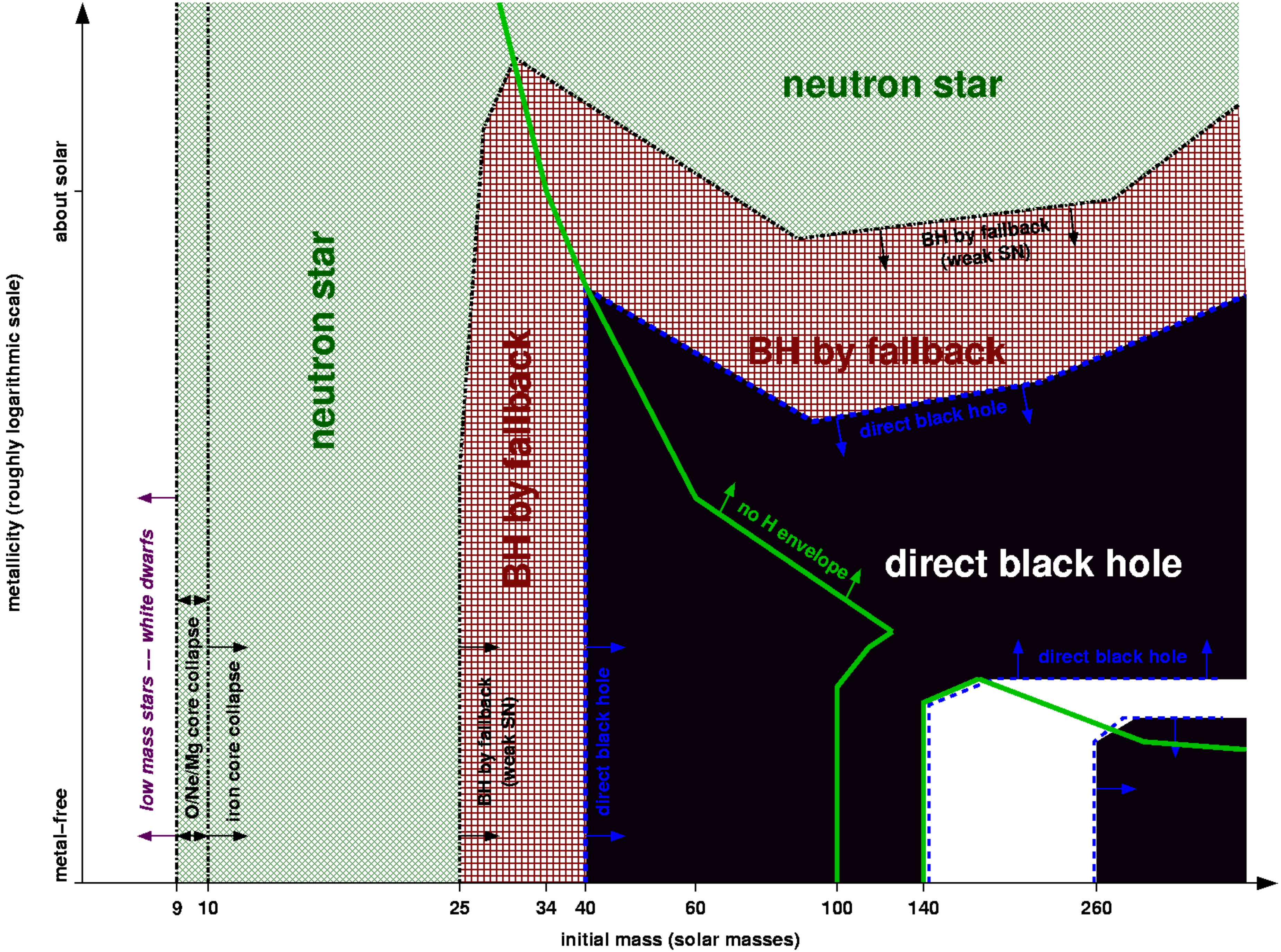


About
Pop III Stars

Ejected “metals”



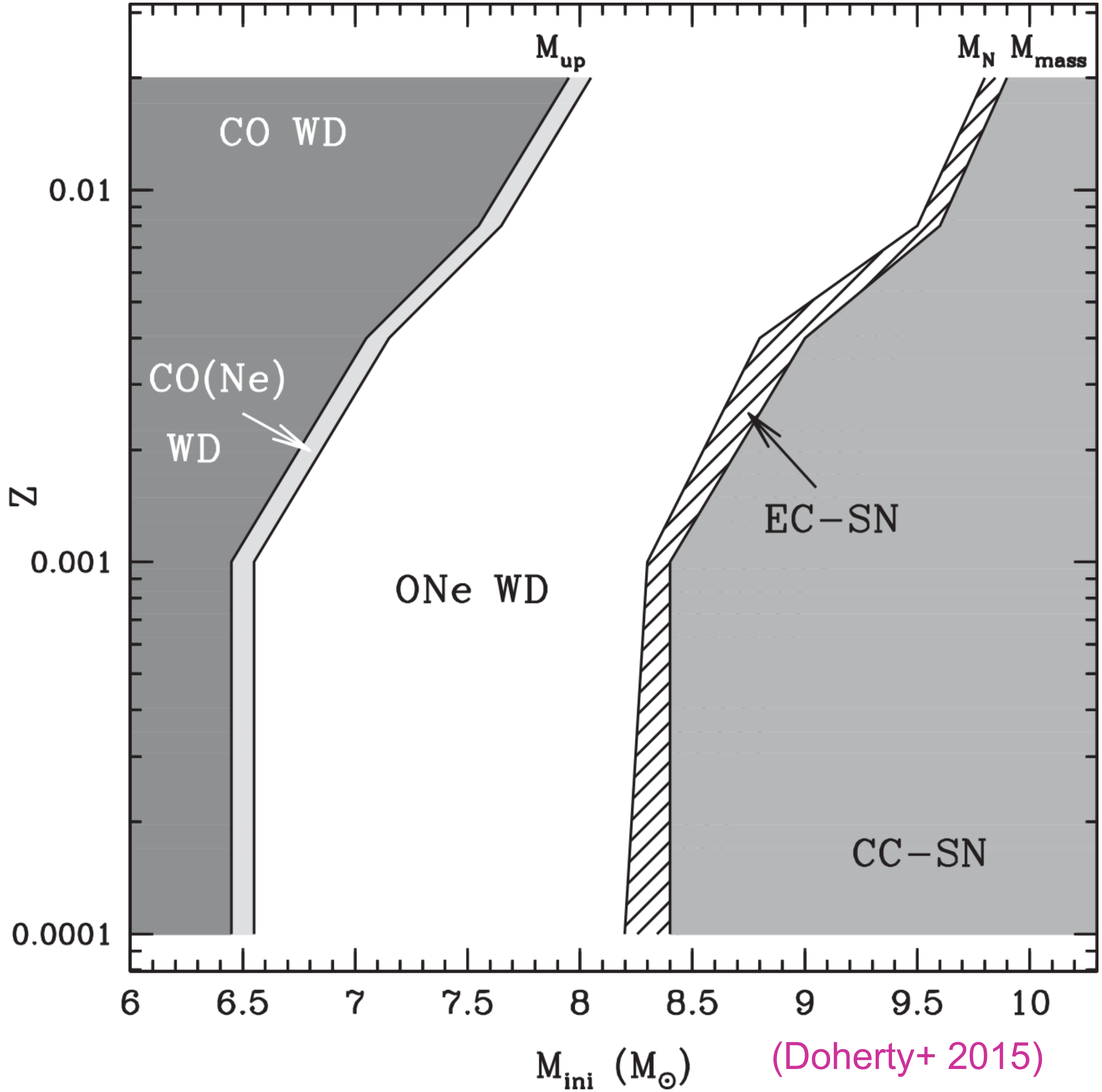
The Overall Picture



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
initial mass (solar masses)
9
10
25
34
40
60
100
140
260

Low-Mass Core Collapse Supernovae

The Lowest Mass Core Collapse SNe



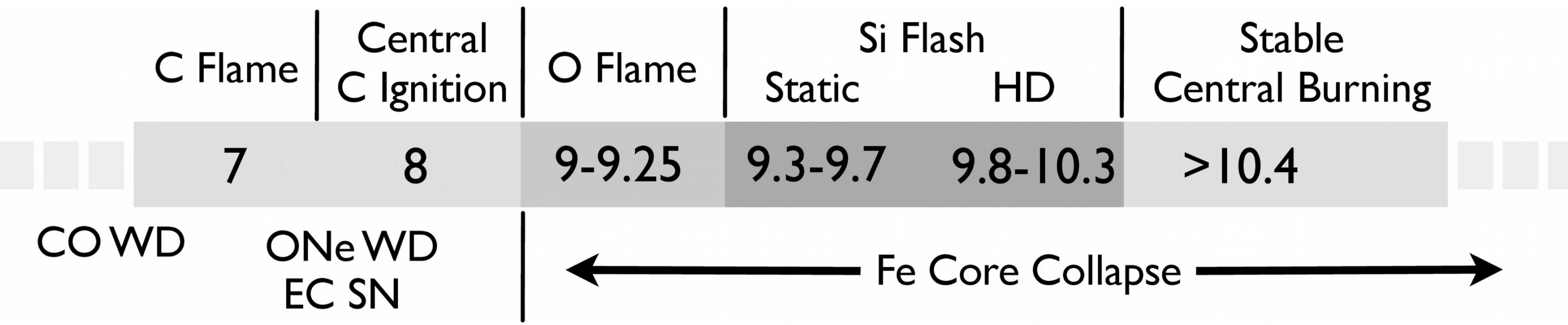
(Doherty+ 2015)

Detailed evolution models through end of evolution.

Similar results as Polearends+ (2007) but much reduced regime for ECSN and no SN Type 1.5 regime.

(Doherty+ also lays out a CO(Ne) transition regime for WDs, but this is not relevant to this talk)

Final Evolution and Outcomes



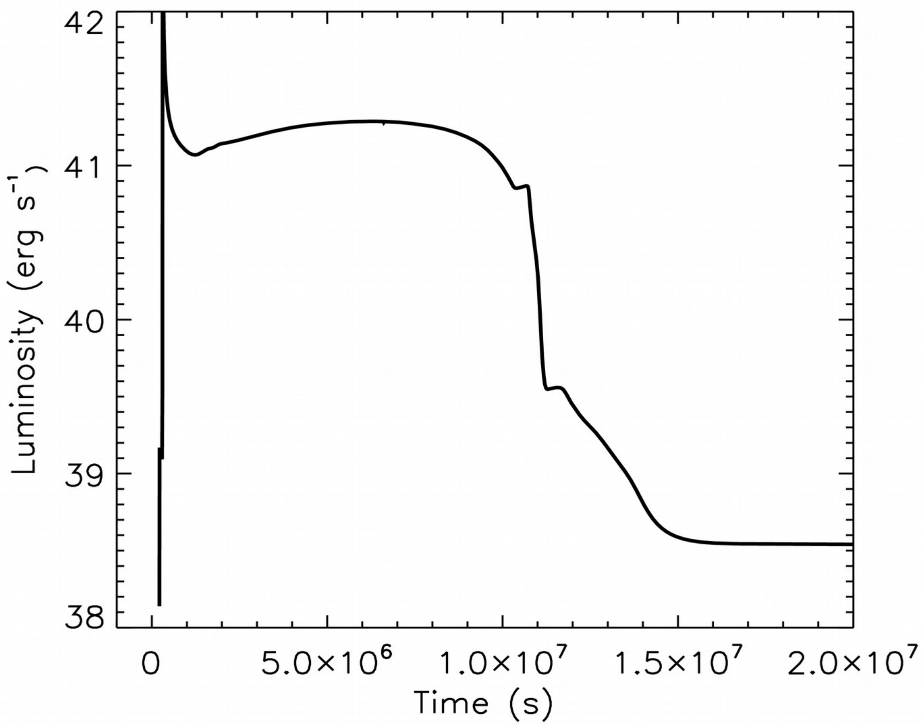
(Woosley & Heger 2015)

A variety of different of different outcomes due to sequence of degenerate central and shell nuclear burning phases.

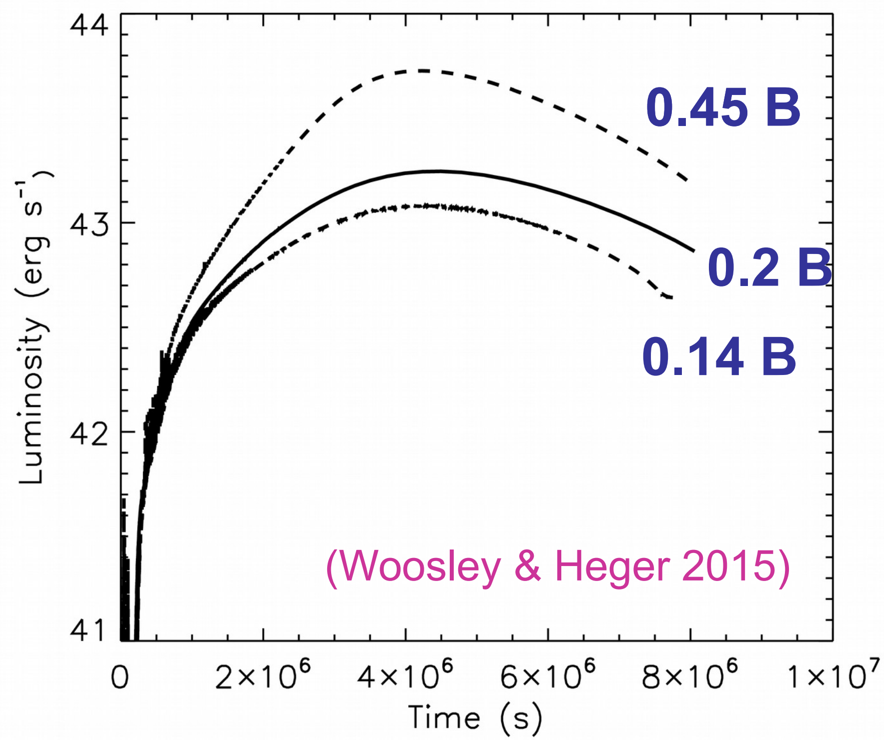
Off-centre ignition of shell burning can lead to a flame burning inward, e.g., NeO shell.

Silicon may ignite in a *flash* that can become hydrodynamic and eject the outer layers of the star

Supernovae from 10 $M_\odot$ Star

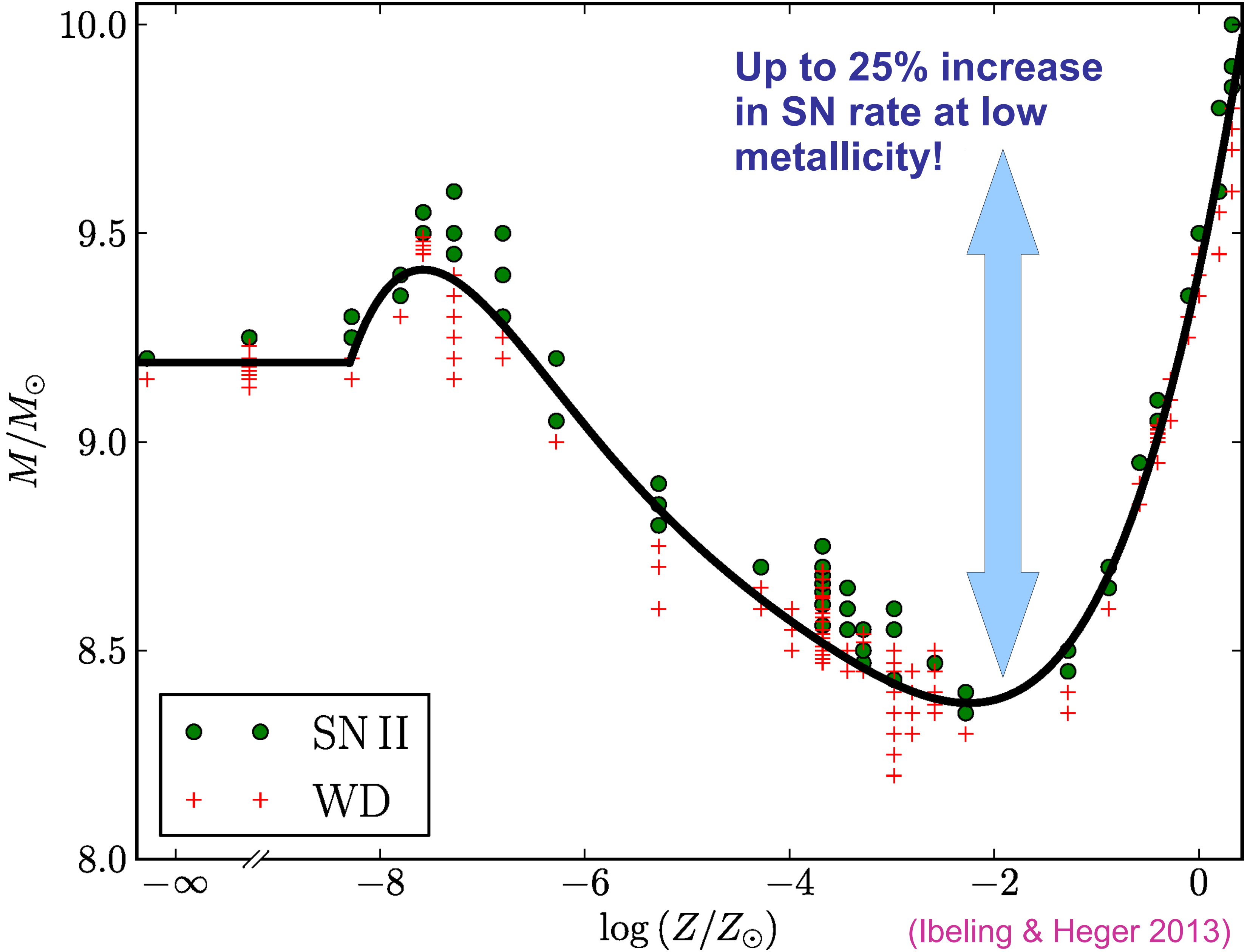


SN light curve from pre-SN silicon flash – faint Type IIp SN – about 400 days before final core collapse



SN light curve from final core-collapse – bright Type IIn supernova – due to pre-SN mass ejection

SN Mass Limit as Function of Metallicity



(Ibeling & Heger 2013)

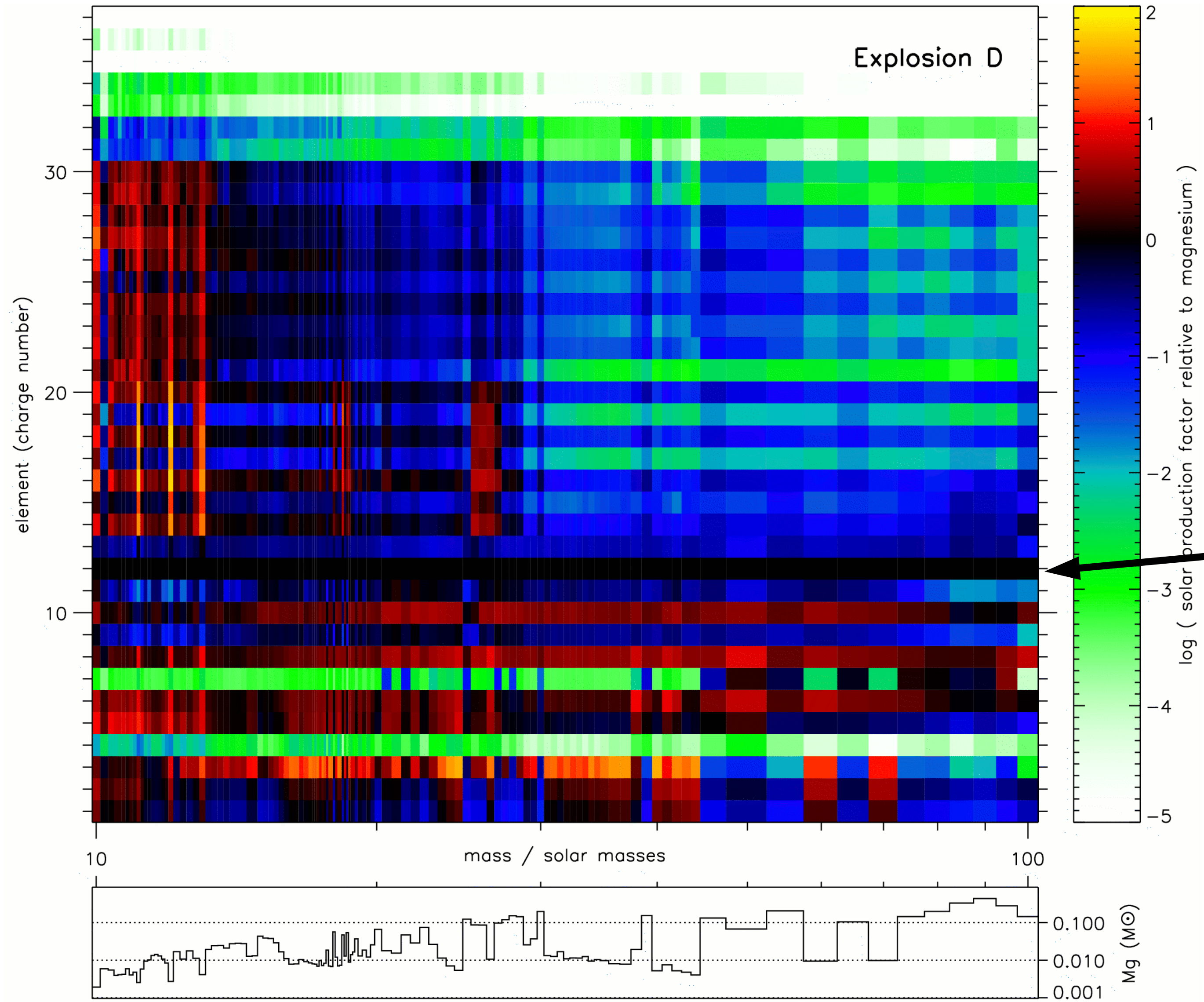
Nucleosynthesis in Massive Stars

Nucleosynthesis Yields

3 Key Ingredients:

- Hydrostatic and Explosive Nucleosynthesis
- Hydrodynamic Instabilities during SN (“Mixing”)
- What is eject, what goes into Remnant (“Fallback”)

Pop III Nucleosynthesis



Mg yield (ejecta mass fraction)

Elemental Yields as a function of initial mass

non-rotating stars

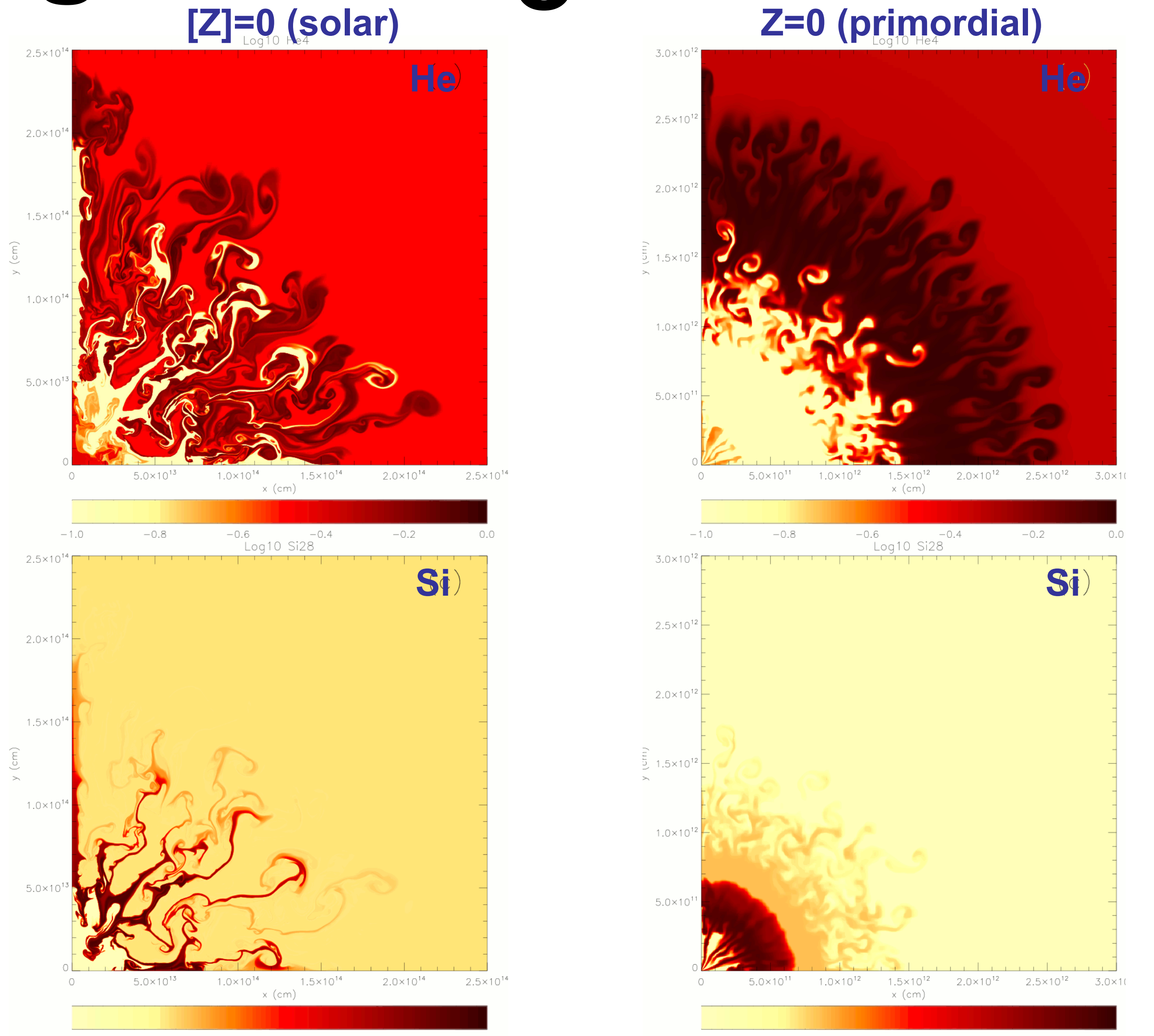
120 stellar masses

“complete” reaction network

Note: normalized to Mg

Heger & Woosley (2010)

Mixing in 25 $M_\odot$ Stars



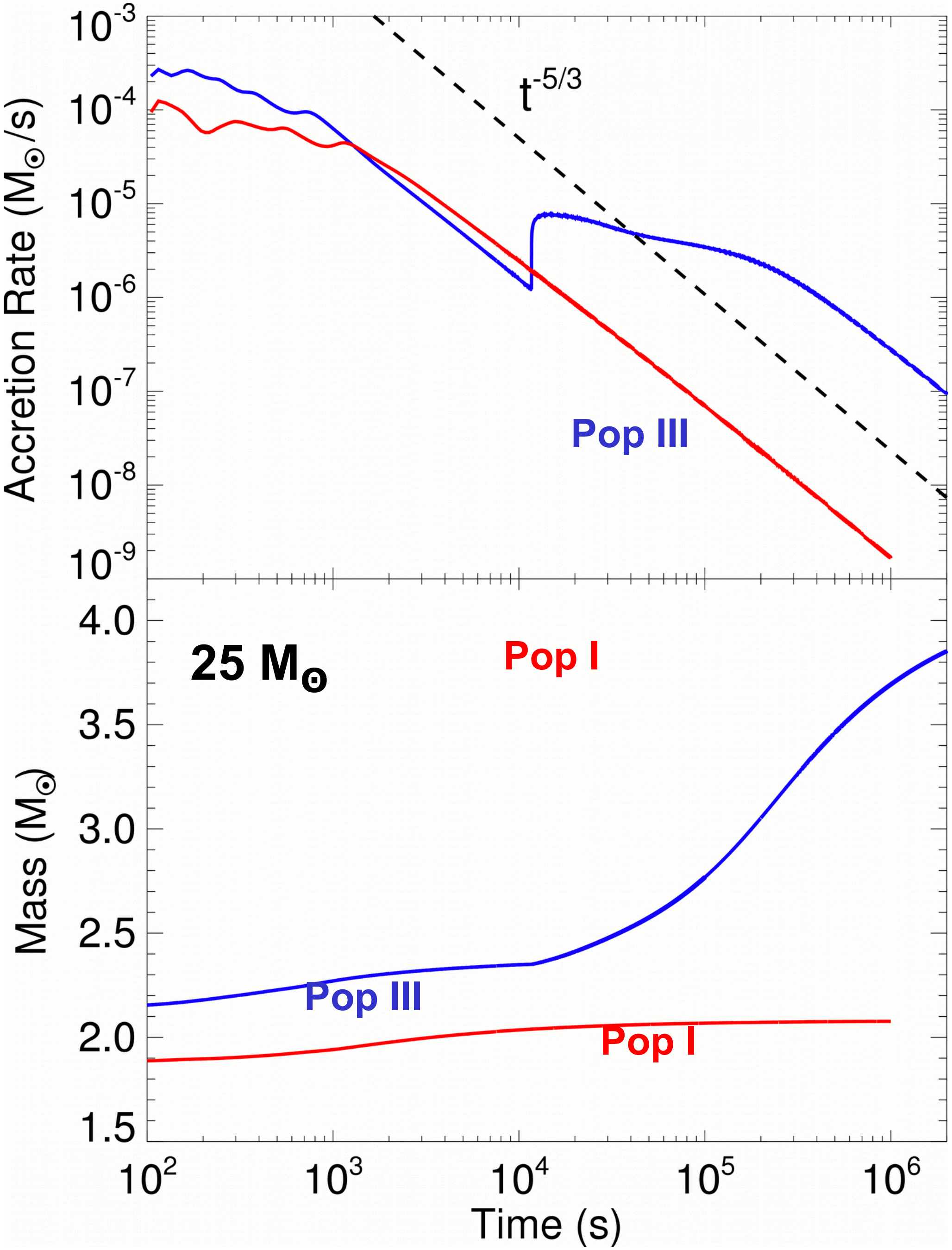
Growth of Rayleigh-Taylor instabilities

Interaction of instabilities (mixing) and fallback determines nucleosynthesis yields

➔ Pop III stars show much less mixing than modern Pop I stars due to their compact hydrogen envelope

Simulations: Candace Joggerst (UCSC/LANL T-2)

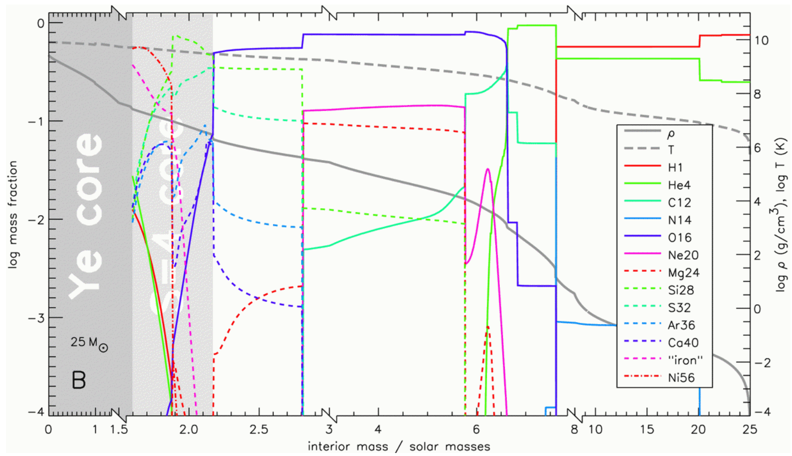
Fallback and Remnants



➔ **Pop III stars show much more fallback than modern Pop I stars due to their compact hydrogen envelope**

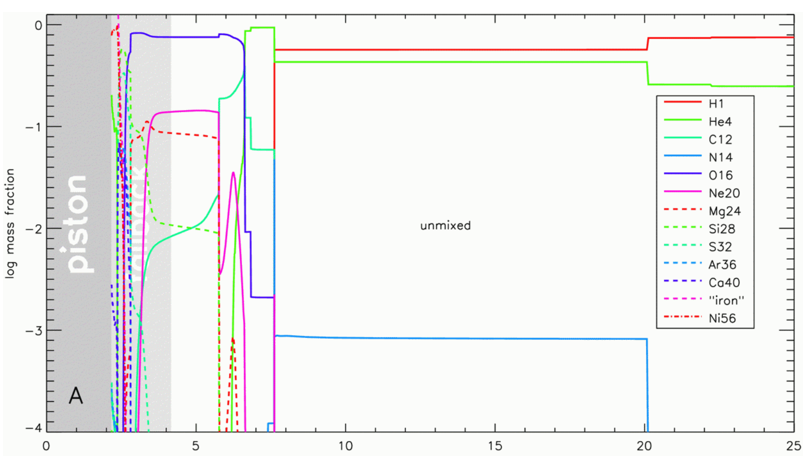
(Zhang, Woosley, Heger 2007)

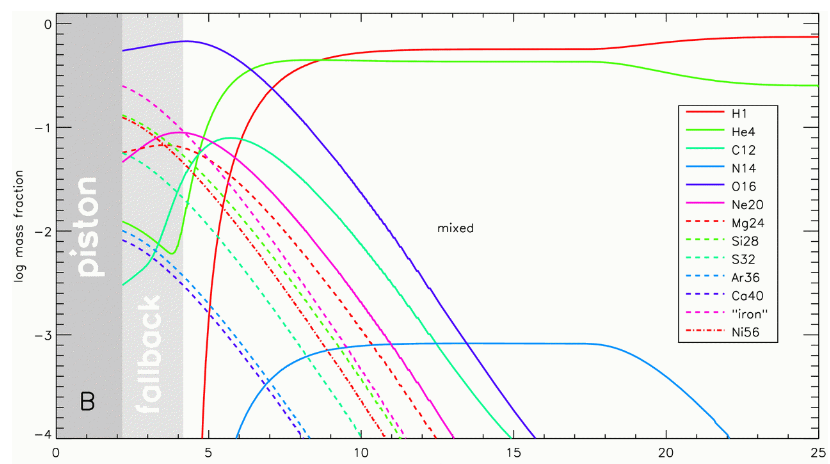
Supernovae, Nucleosynthesis, & Mixing



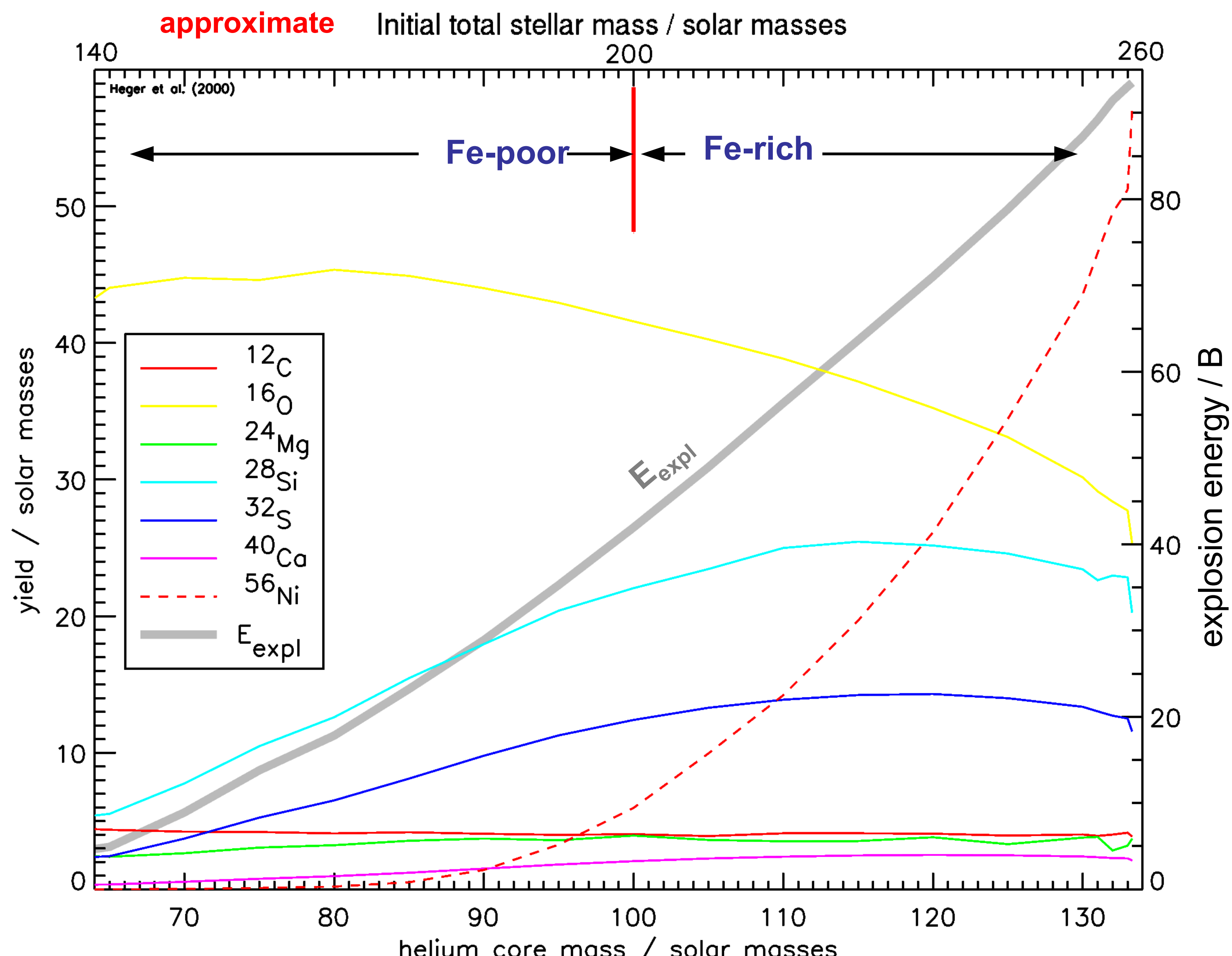
SN, no mixing

SN + mixing

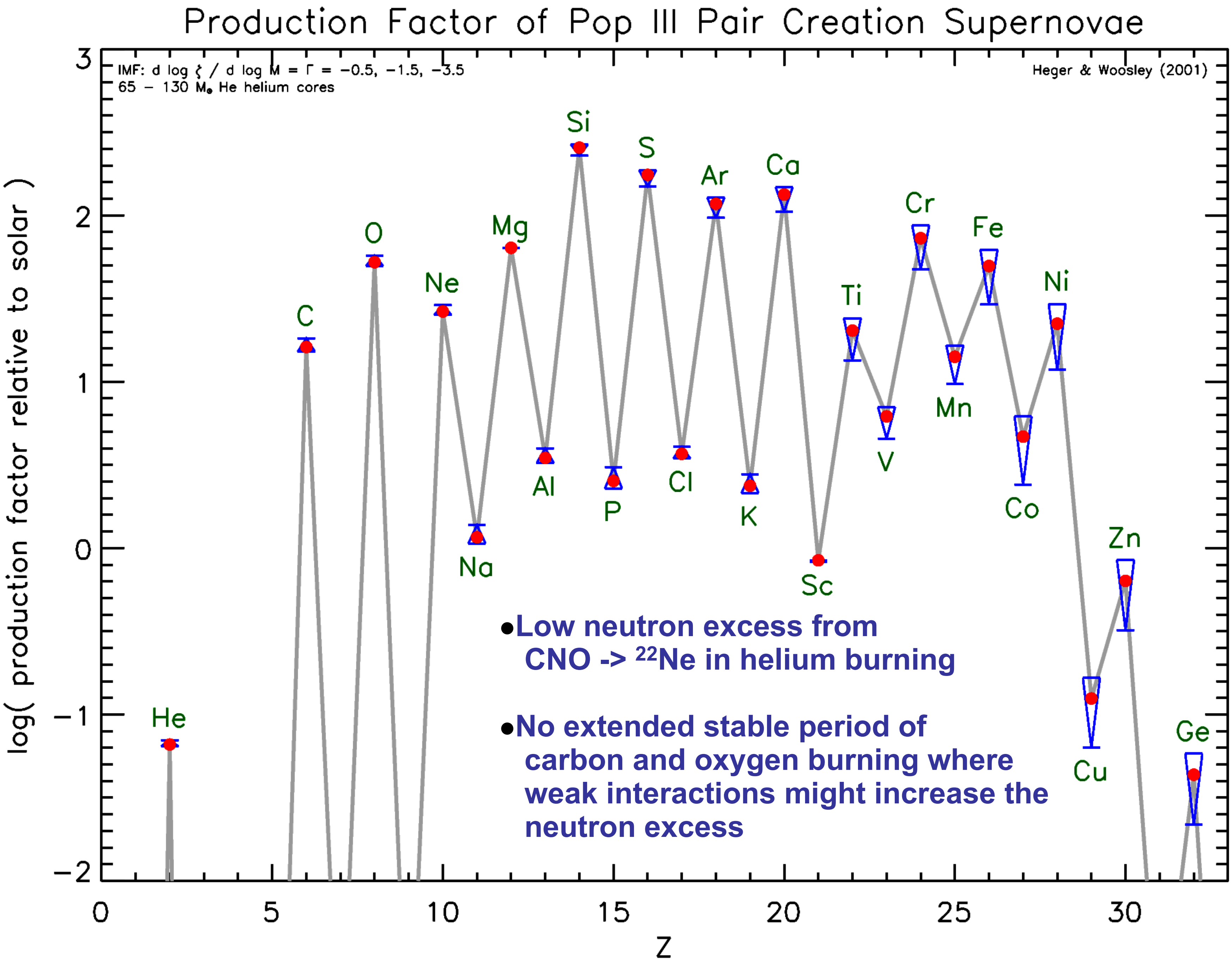




Nucleosynthesis in Pair-Instability Supernovae



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



- **Low neutron excess from CNO -> ^{22}Ne in helium burning**
- **No extended stable period of carbon and oxygen burning where weak interactions might increase the neutron excess**

➔Problem

Pair-Instability Supernovae do not reproduce the abundances as observed in very metal poor halo stars!

Conclusions

- A wide range of SN progenitor masses may explode, with varying explosion mechanism
- Supernova nucleosynthesis may be best constraint by abundance patterns from UMP stars
- Understanding “mixing” processes inside stars, remains a key priority, next to binary evolution, magnetic fields, and rotation
- Statistical comparisons of models to observations are necessary for quantitative constraints on pre-SN models