Nucleosynthesis in Massive Stars

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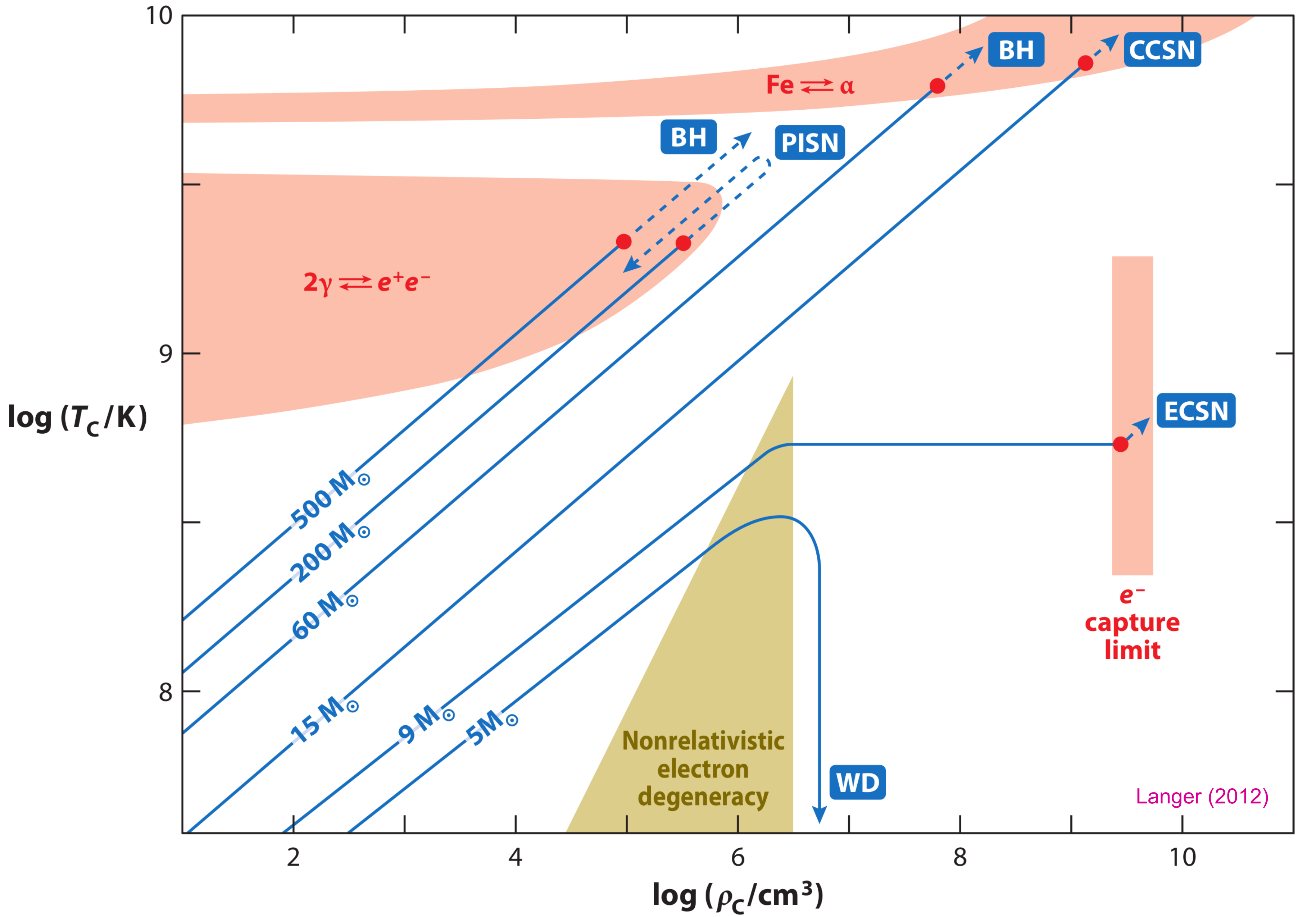
http://CosmicExplosions.org

Overview

- Massive stars
- Very massive stars
- Supernovae
- Nucleosynthesis

Evolution of Center for Different Initial Masses

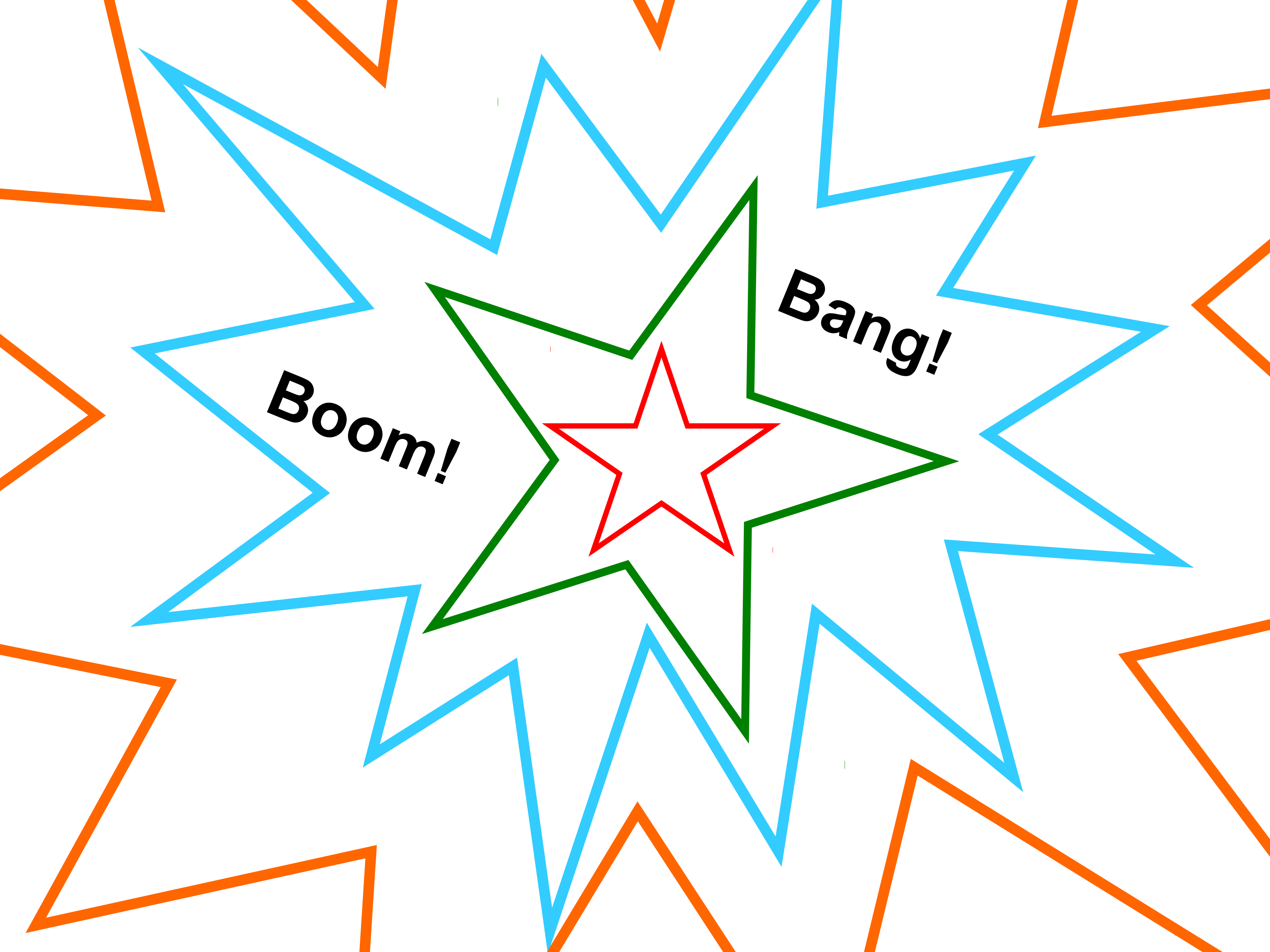


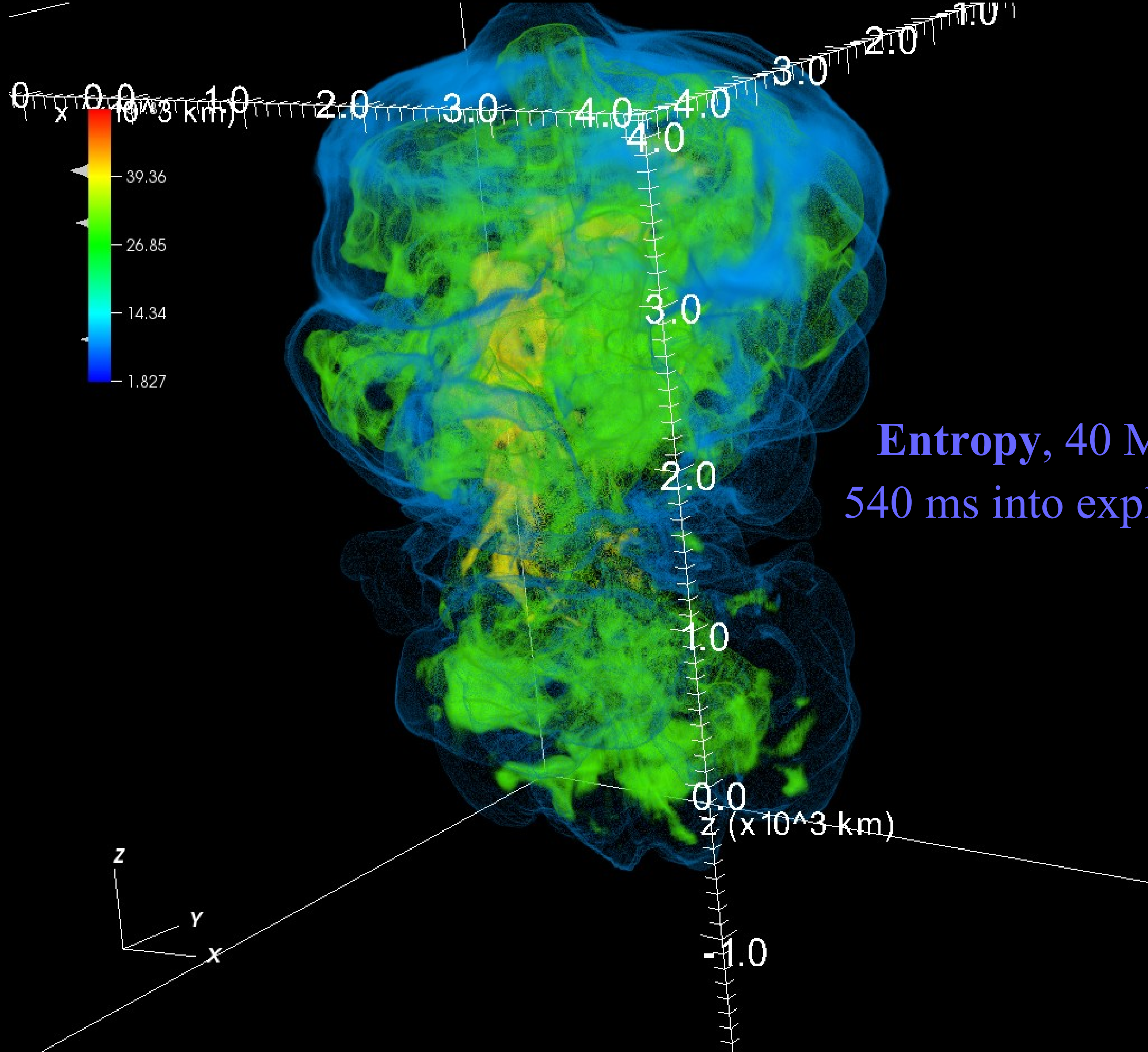
Nuclear burning stages

(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	$4\,H \xrightarrow{CNO} {}^{4}He$
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.

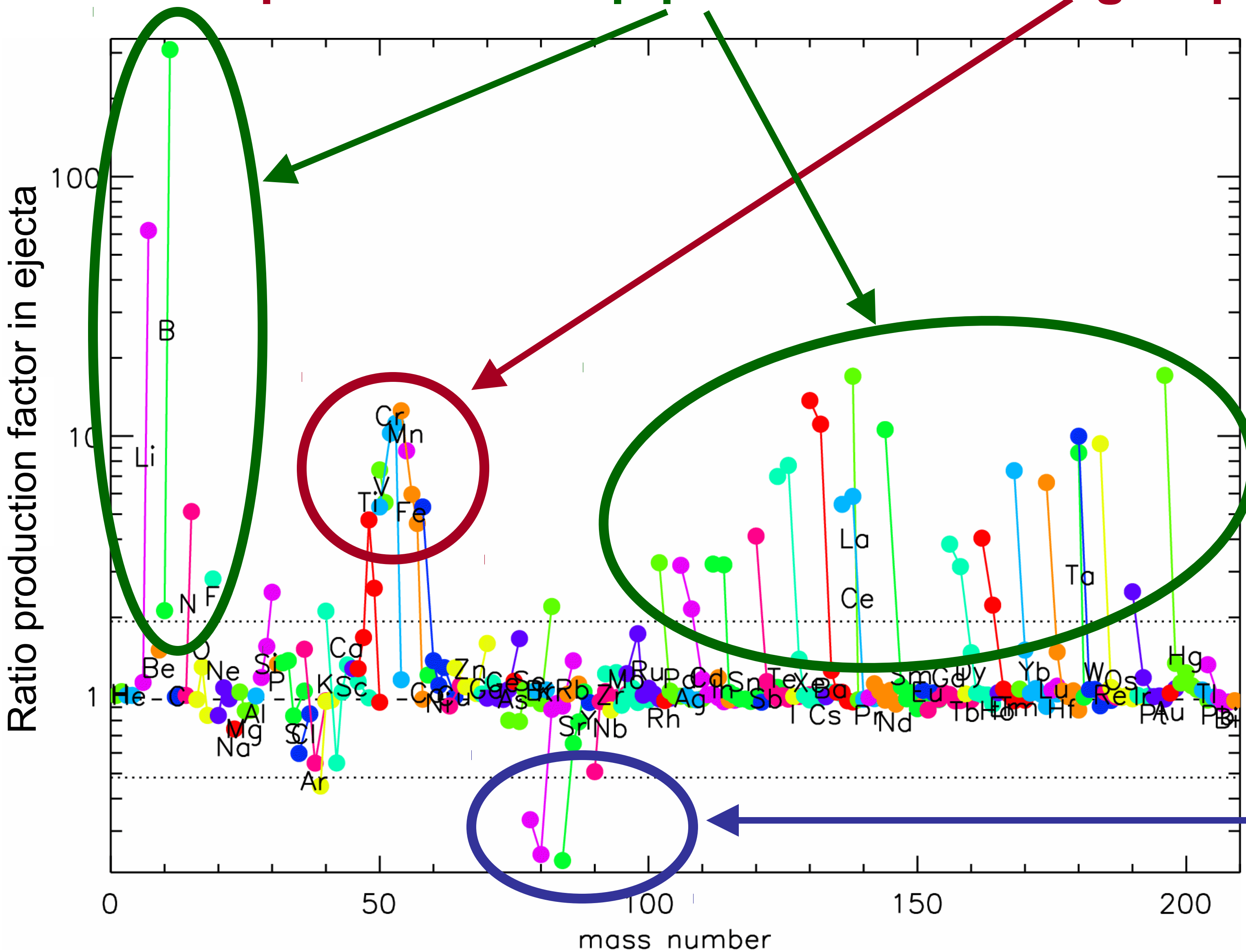
Explosive Nucleosynthesis

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

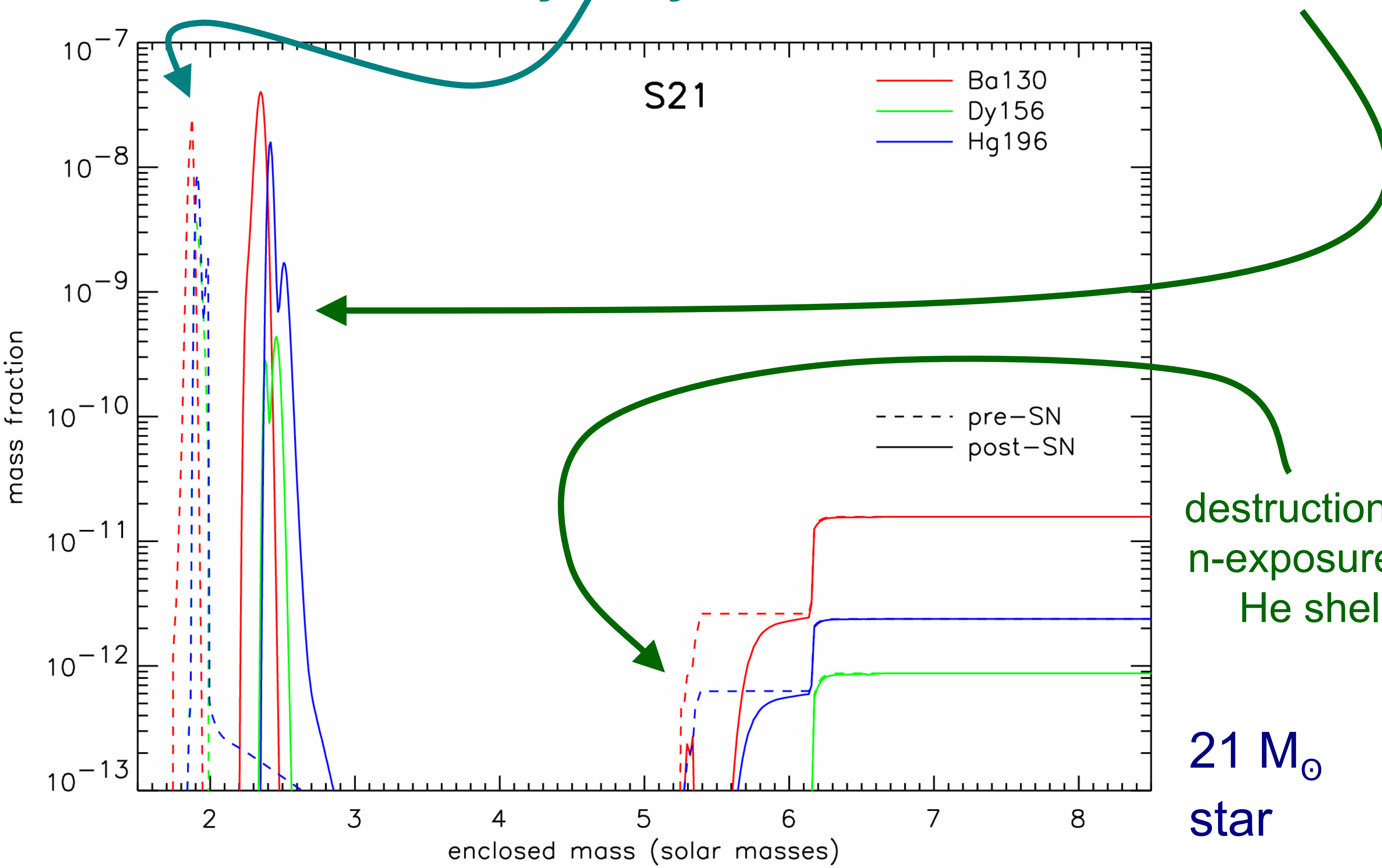


25 M_{o} star

some destruction

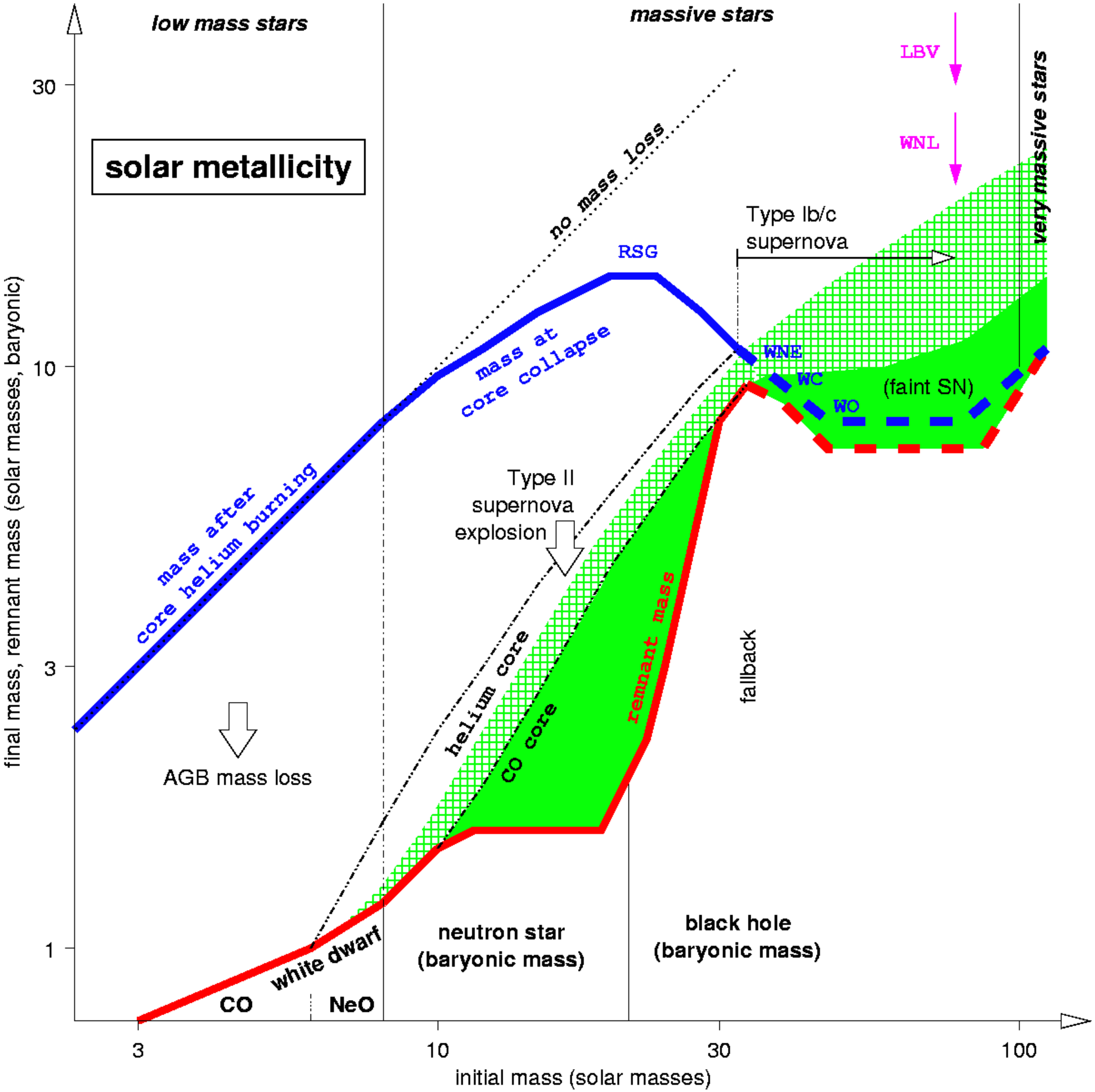
"Relocation" of the γ-process

γ-process can be made in implosive O shell burning, but peak abundance is **destroyed by SN** and **recreated further out**



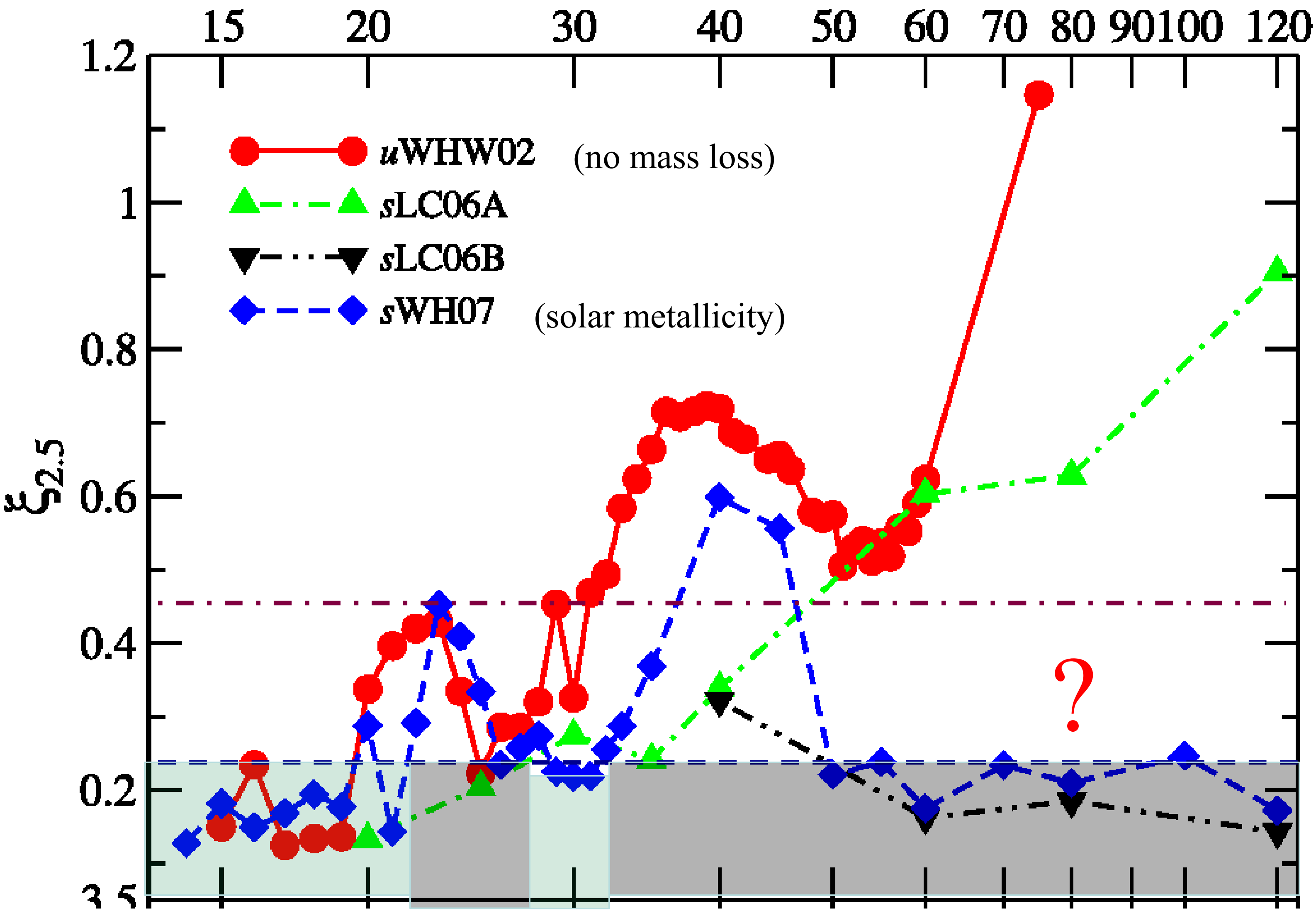
destruction by n-exposure in He shell

21 $M_\odot$ star



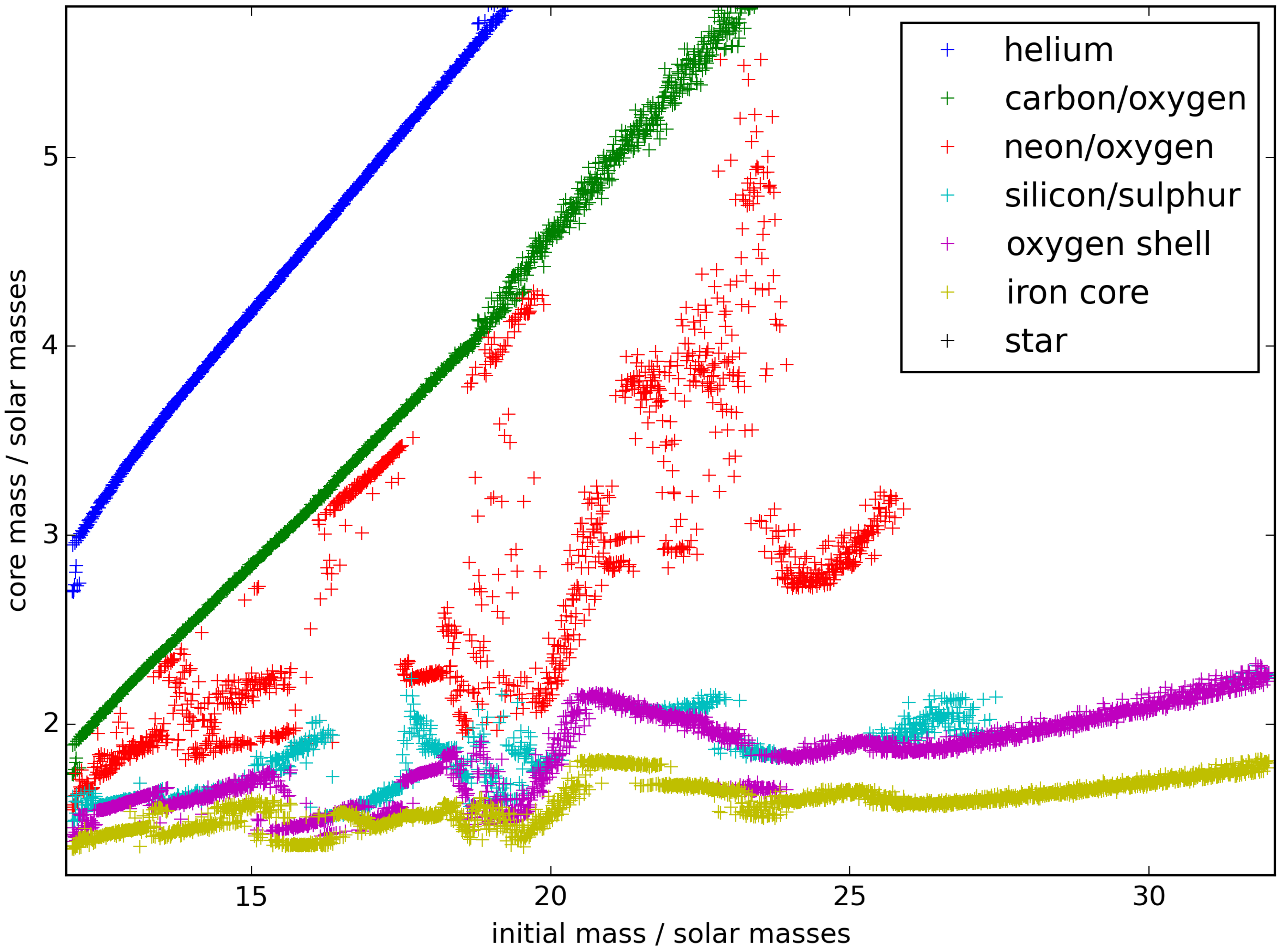
Ejected "metals"

Islands of SN and BH Production

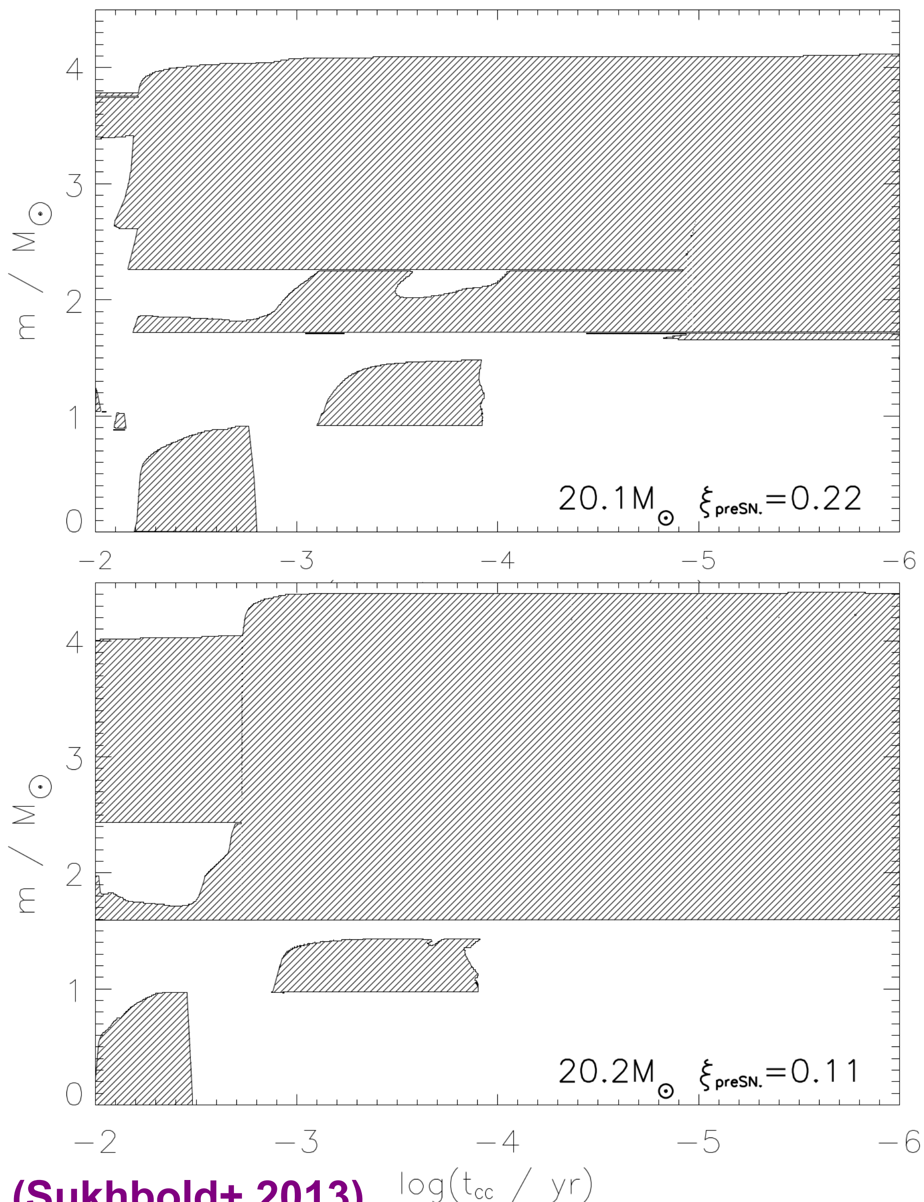


(Woosley 2012, priv. com.)

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

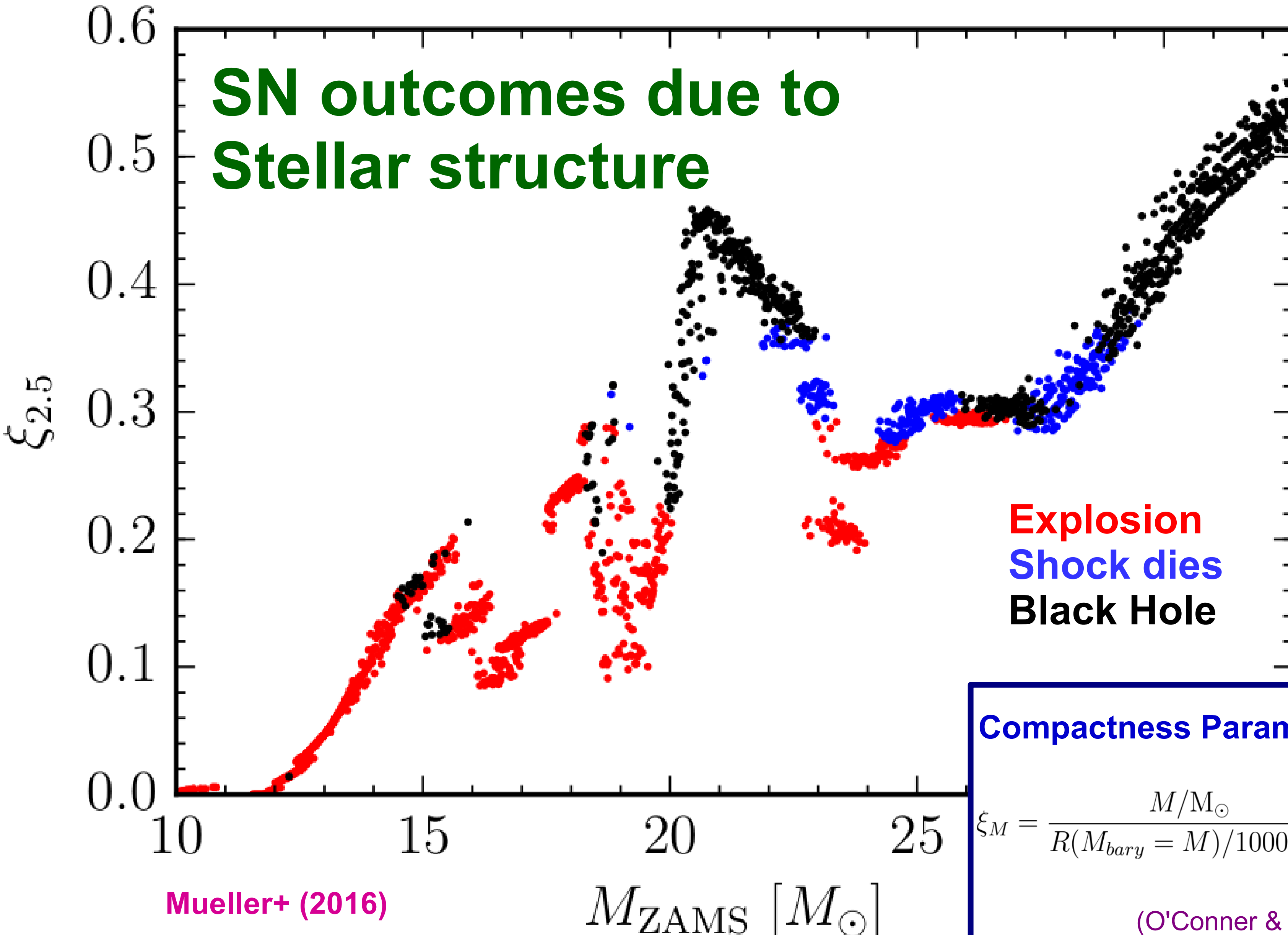
Sensitivity of Structure to Initial Mass



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

(Sukhbold+ 2013)

Signatures of Stellar Structure?



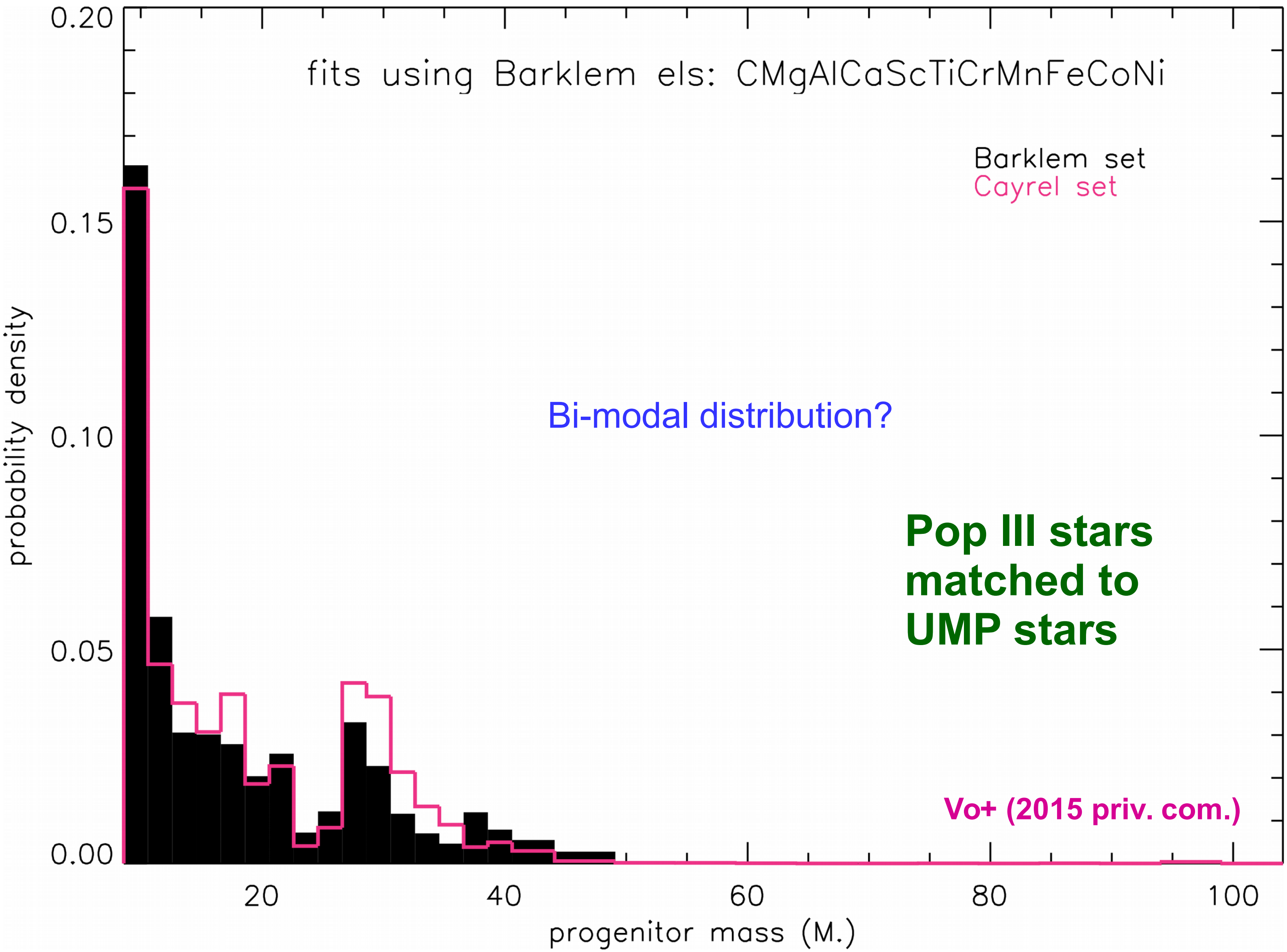
Mueller+ (2016)

Compactness Parameter

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

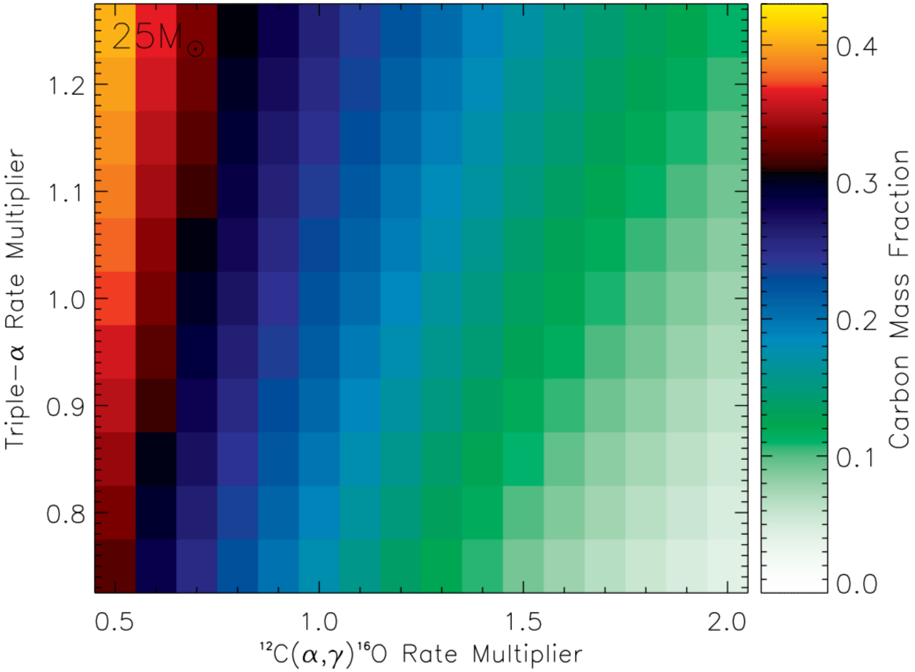
(O'Conner & Ott 2011)

Reconstruction of the IMF



The Impact of Nuclear Reaction Rates

Sensitivity to He burning rates

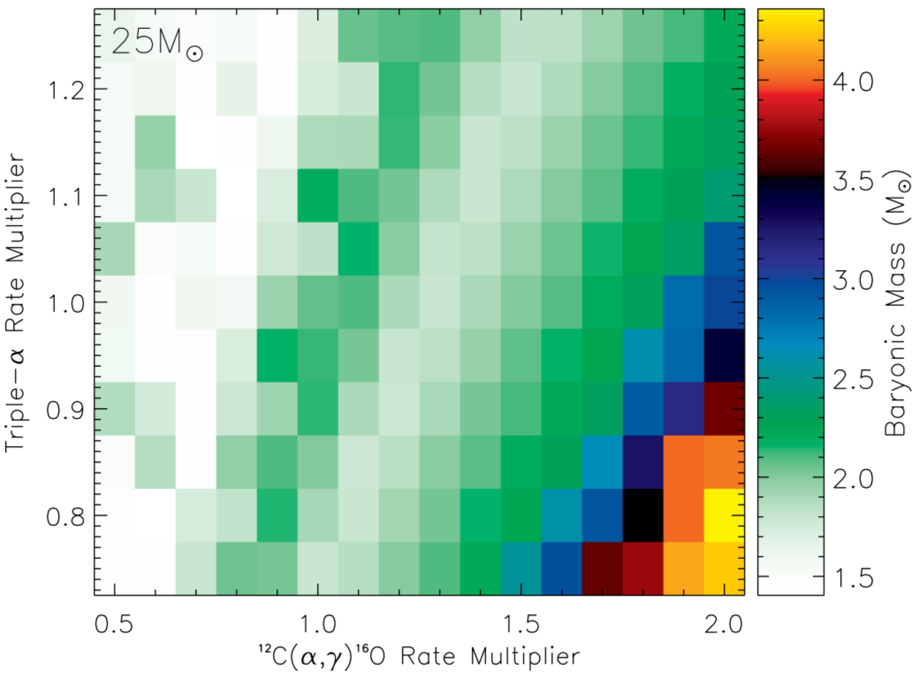


[Top]
Carbon mass fraction in the centre of a 25 $M_\odot$ star after core helium depletion

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

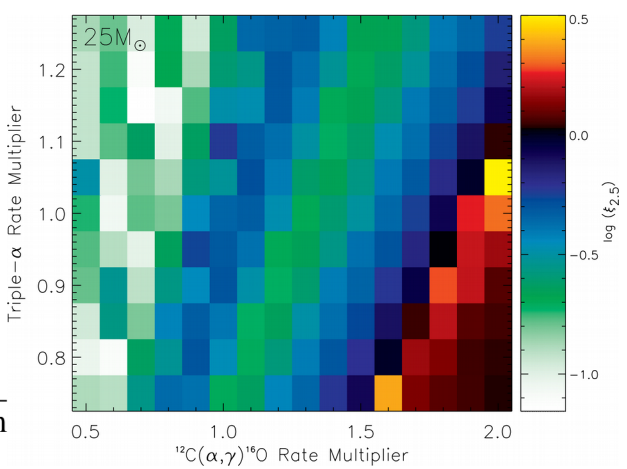
[Bottom Right]
Compactness Parameter

West+ (2013)



Compactness

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

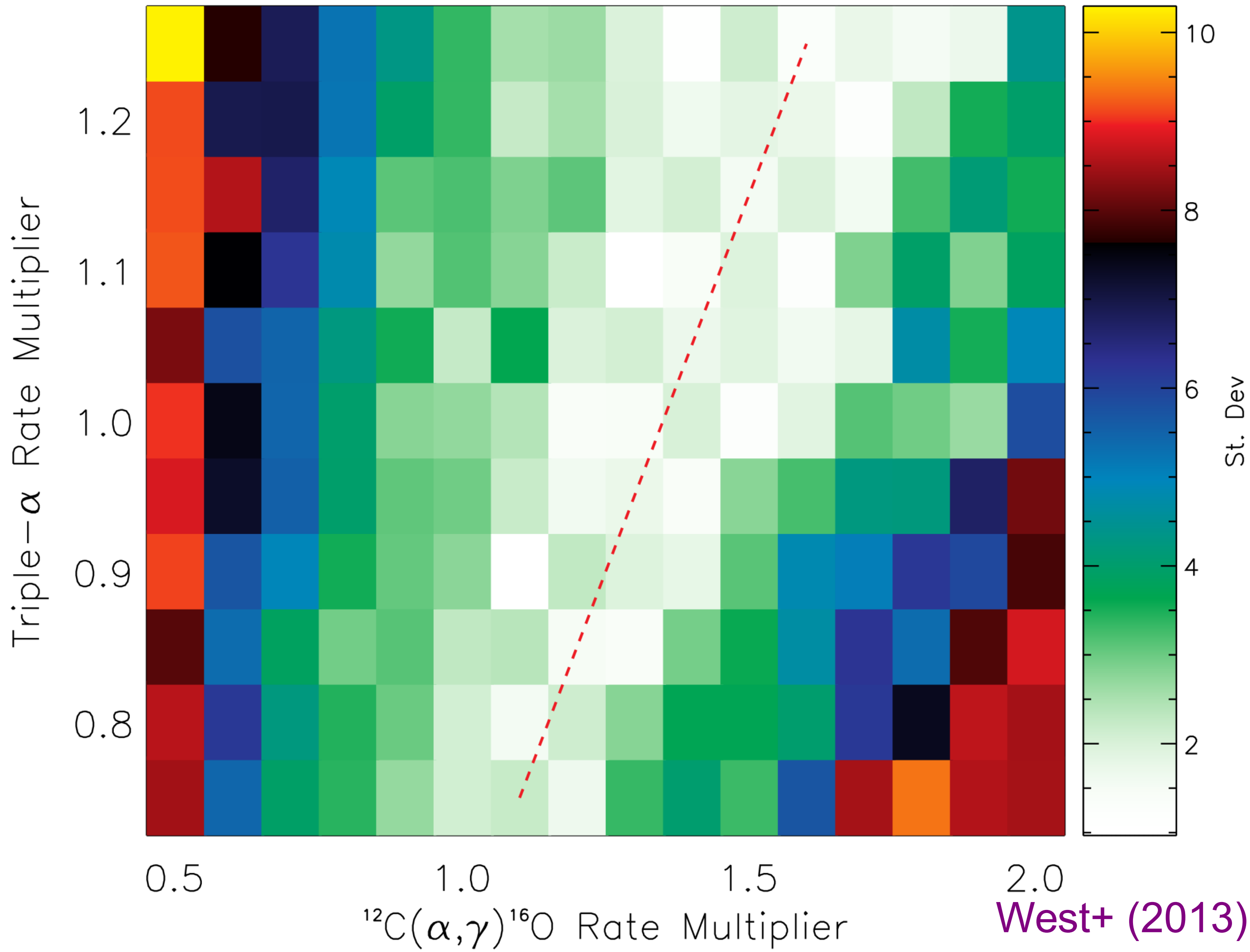


Result

Region of best fit:

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

=> define effective Reaction Rate (ERR)



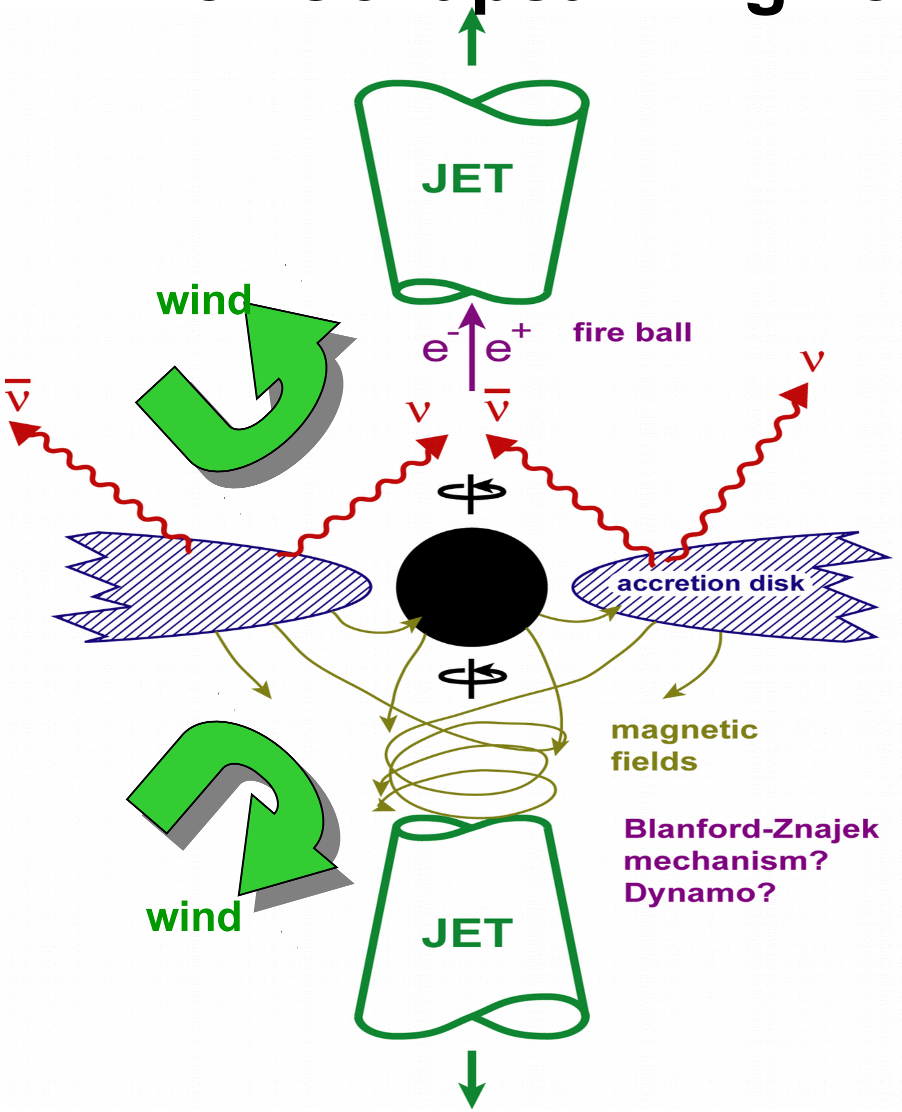
West+ (2013)

How to Explode
Big Stars
Big

How else can massive stars explode?

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

The "Collapsar Engine"



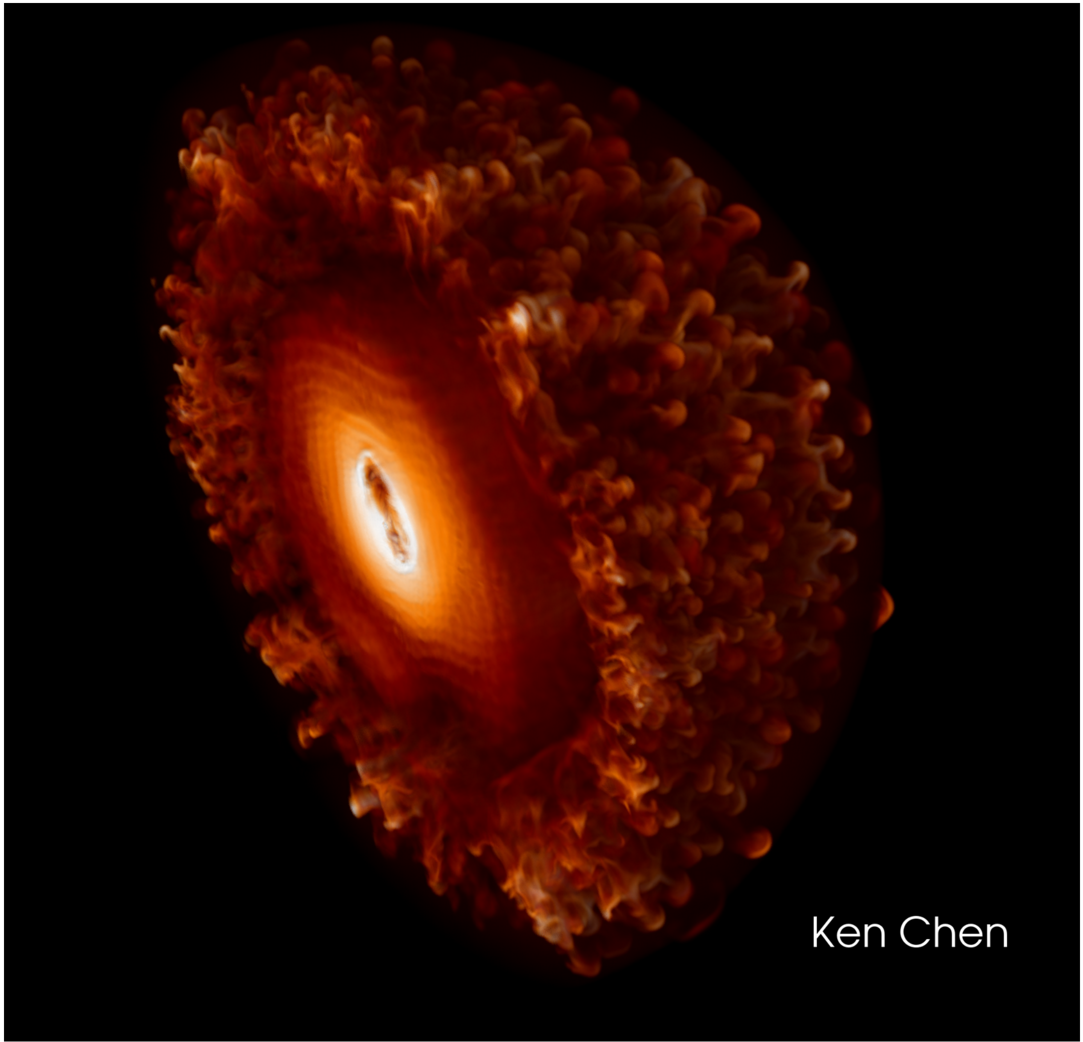
1. black hole forms inside the collapsing star
2. The infalling matter forms and accretion disk
3. The accretion disk releases gravitational energy (up to 42.3% of rest mass for Kerr BH)
4. Part of the released energy or winds off the hot disk explode the star

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?

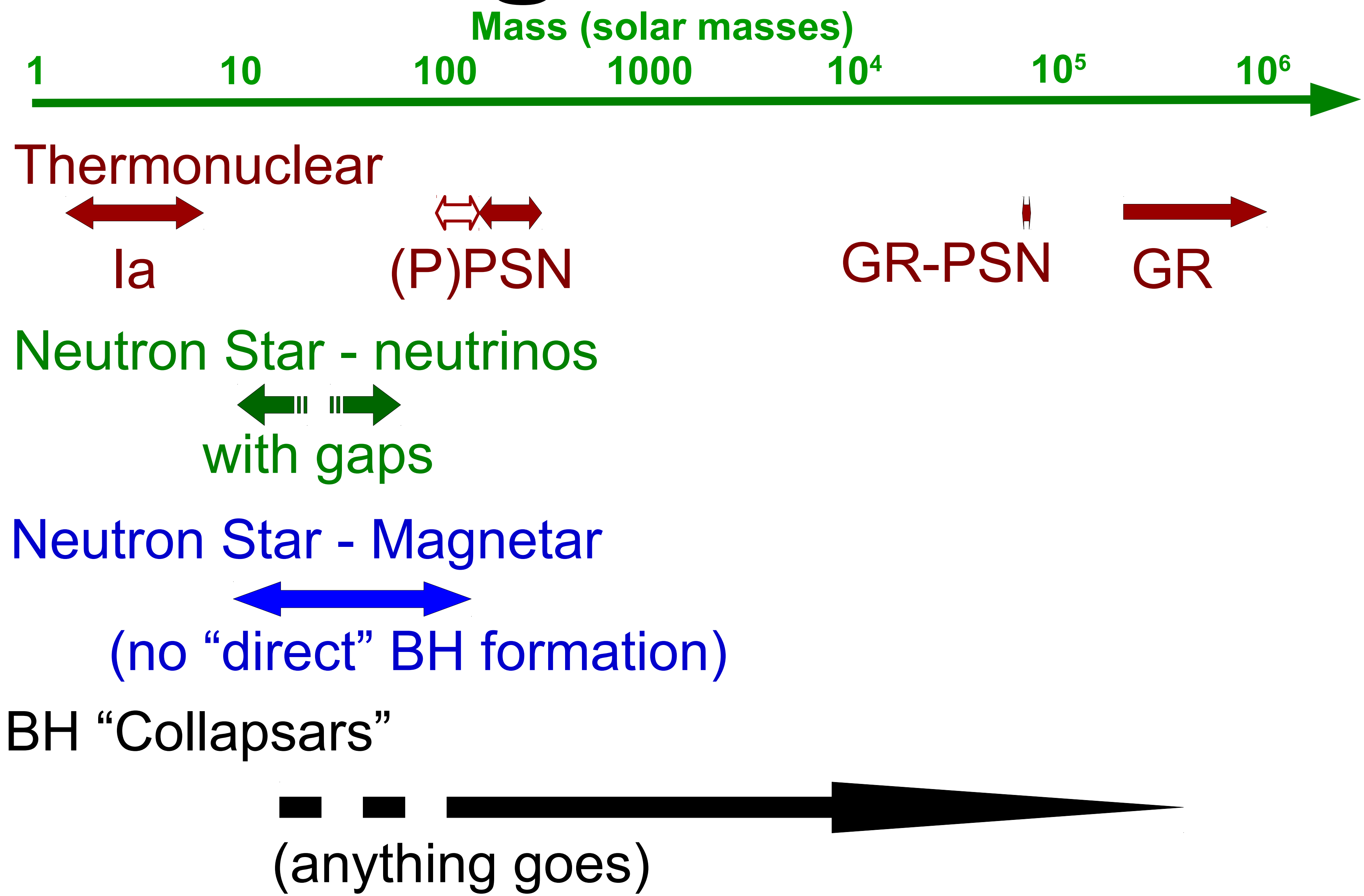
(Bildsten, Woosley, ...)

3D magnetar-powered supernova




Fates...

The Engines of SNe



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