Stellar Archaeology as a Time Machine to the First Stars
Kavli IPMU, The University of Tokyo, Tokyo, Japan, 4 December 2018

Nucleosynthesis in massive and very massive Pop III stars

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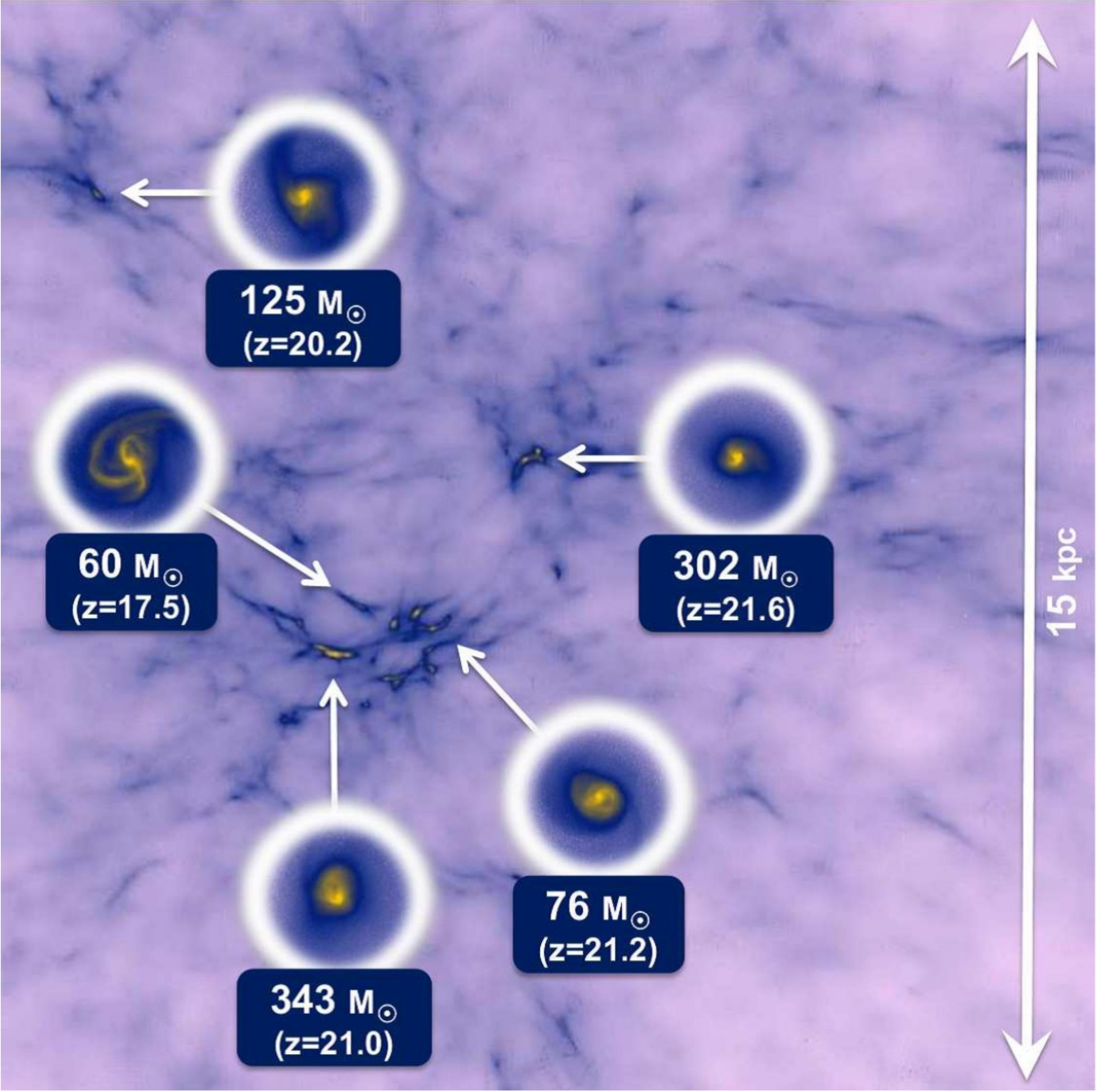
http://CosmicExplosions.org

Overview

- Introduction
- Massive Star Outcomes
- Hypernovae
- [Pulsational] Pair-Instability
- Massive CEMP stars
- Conclusions

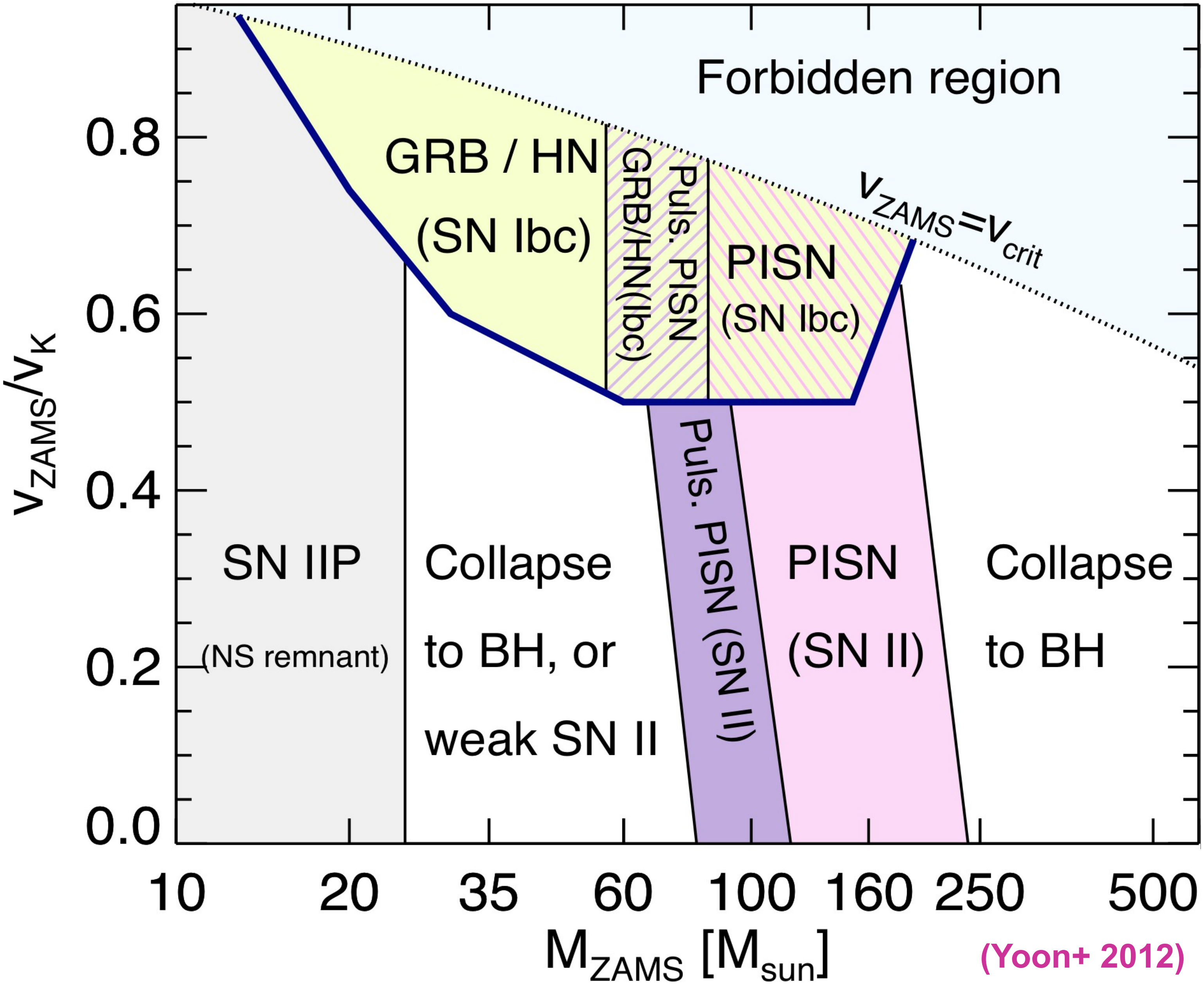
The Birth of Big Stars

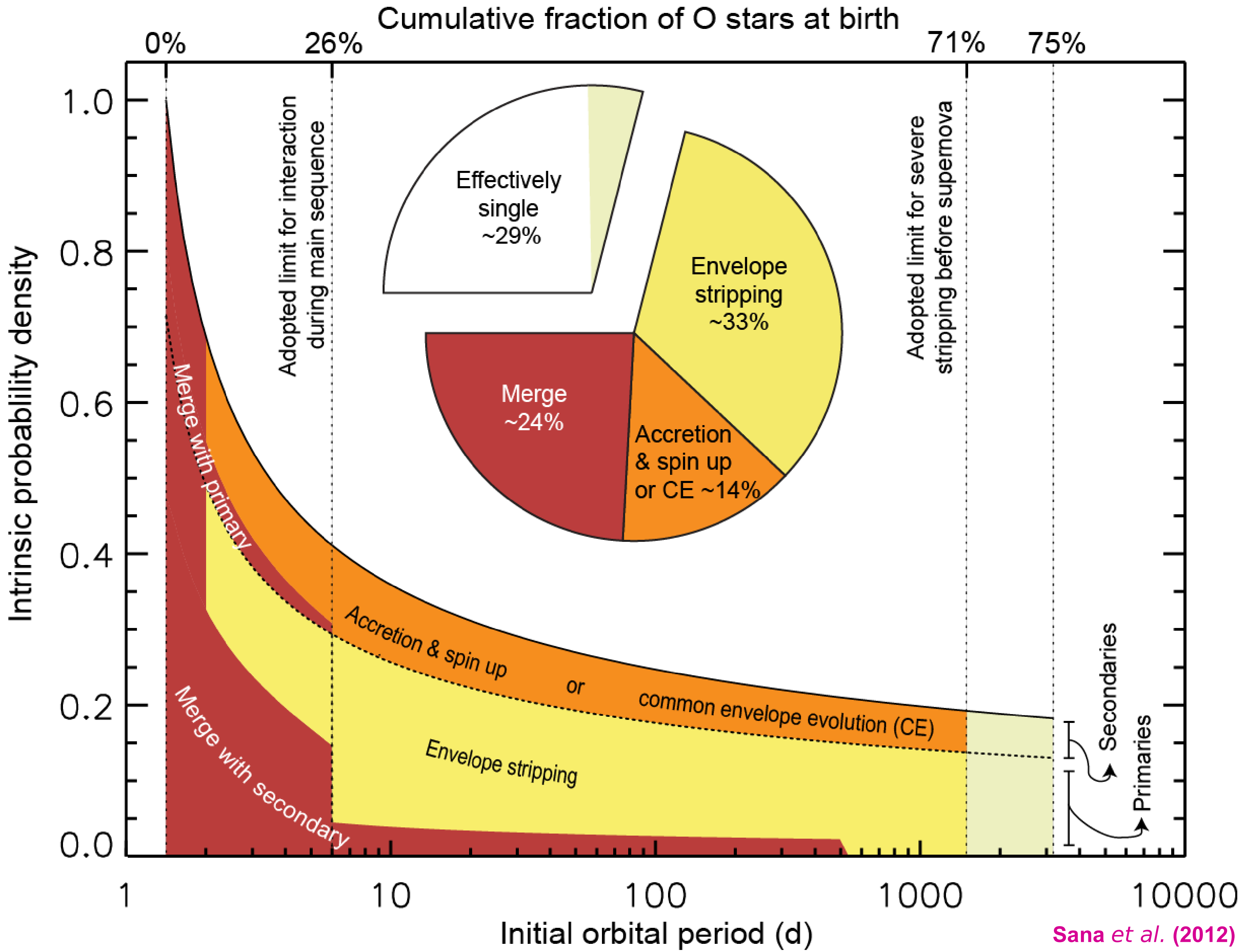
Formation Environment of the First Stars



(Hirano et al. 2013)

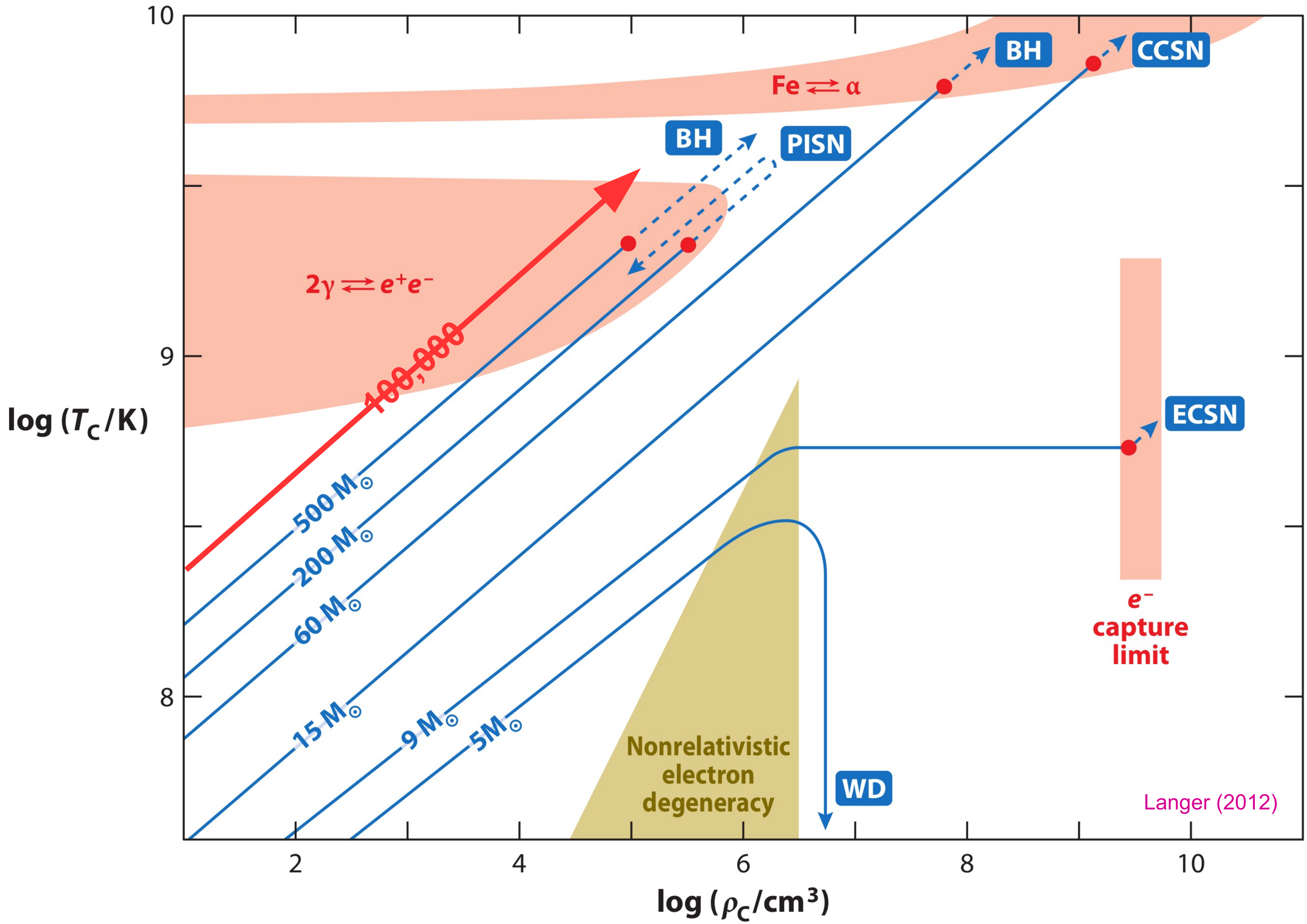
Final fates of rotating massive Pop III stars





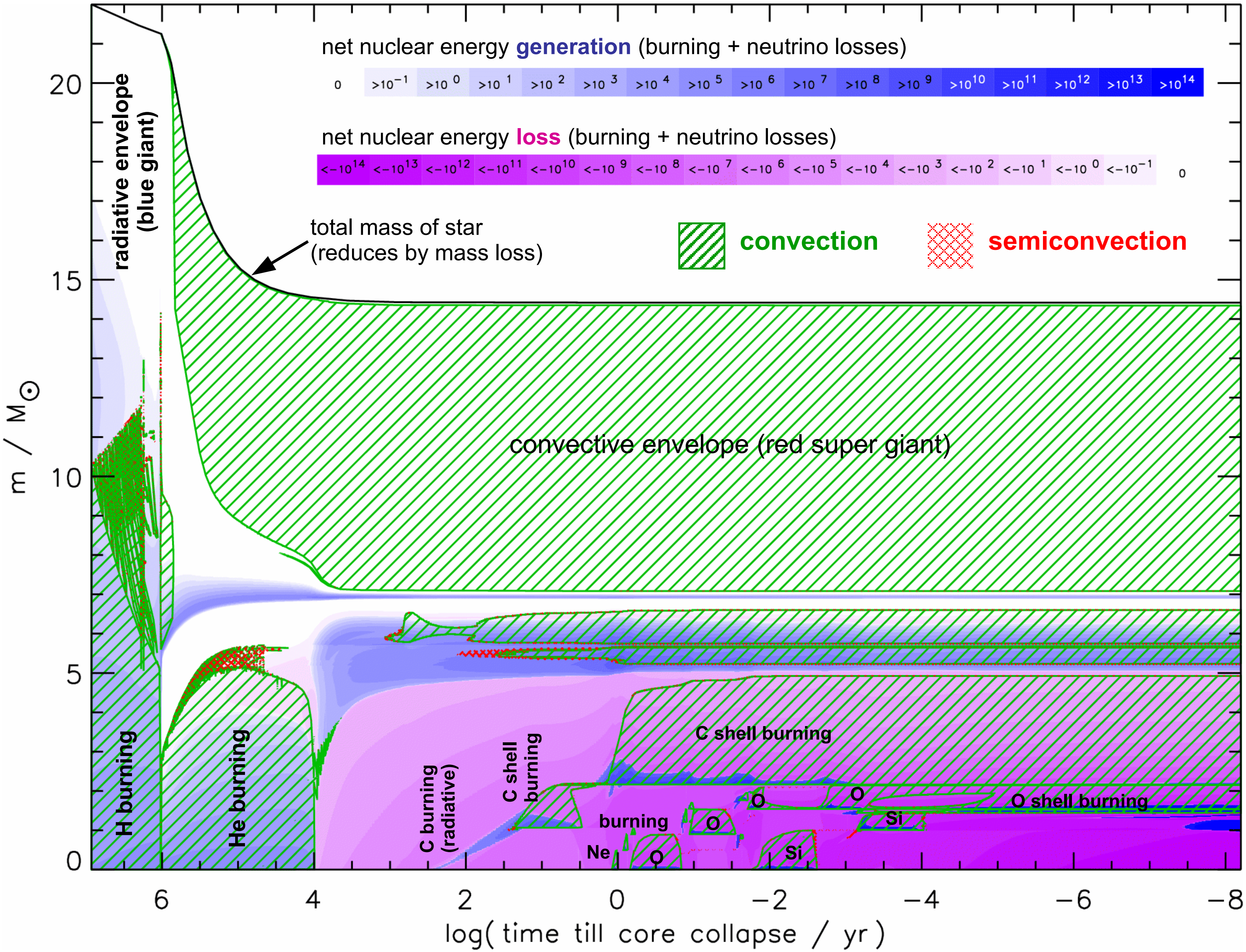
Sana *et al.* (2012)

Evolution of Center for Different Initial Masses

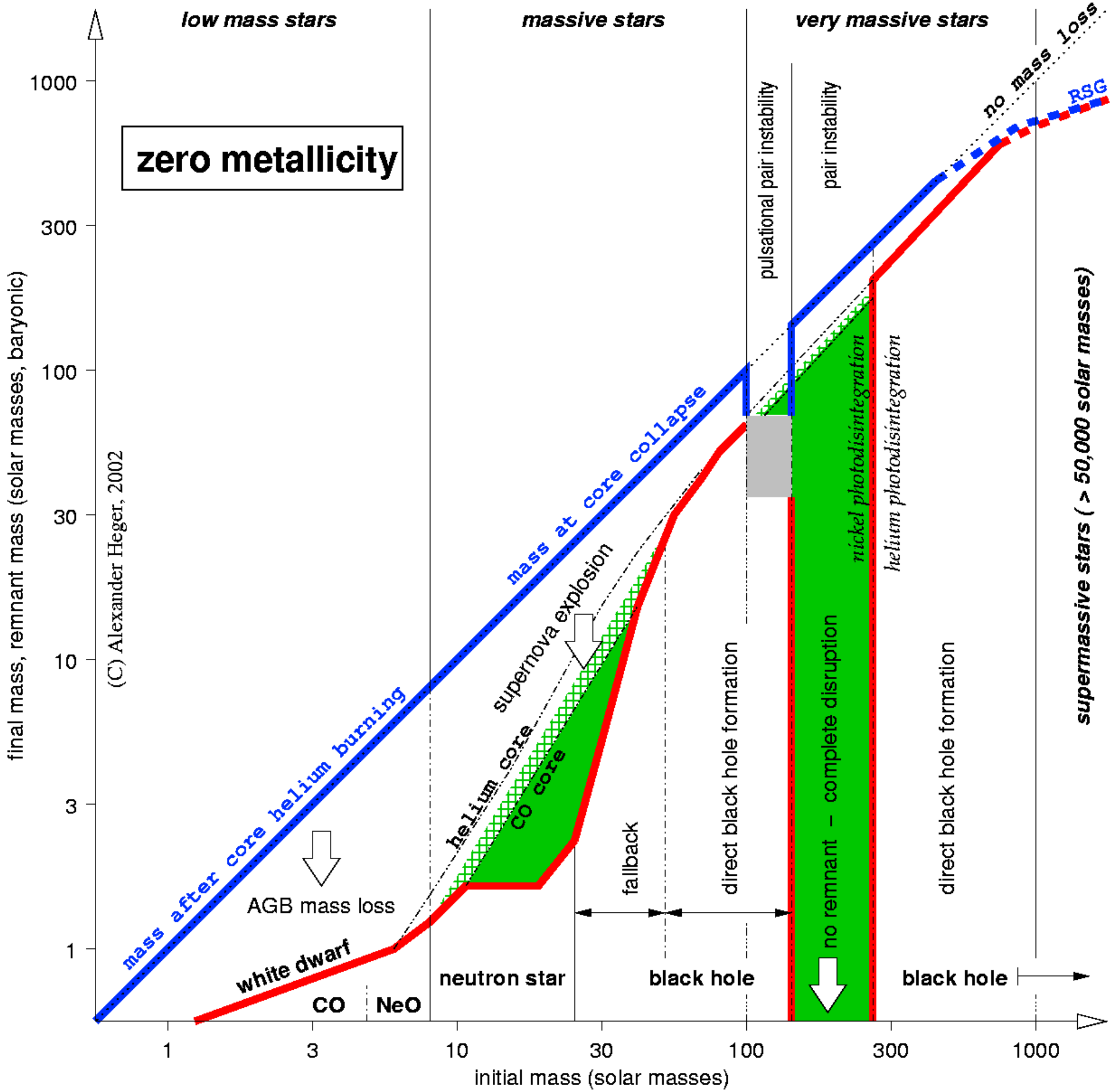


Nuclear Burning Stages

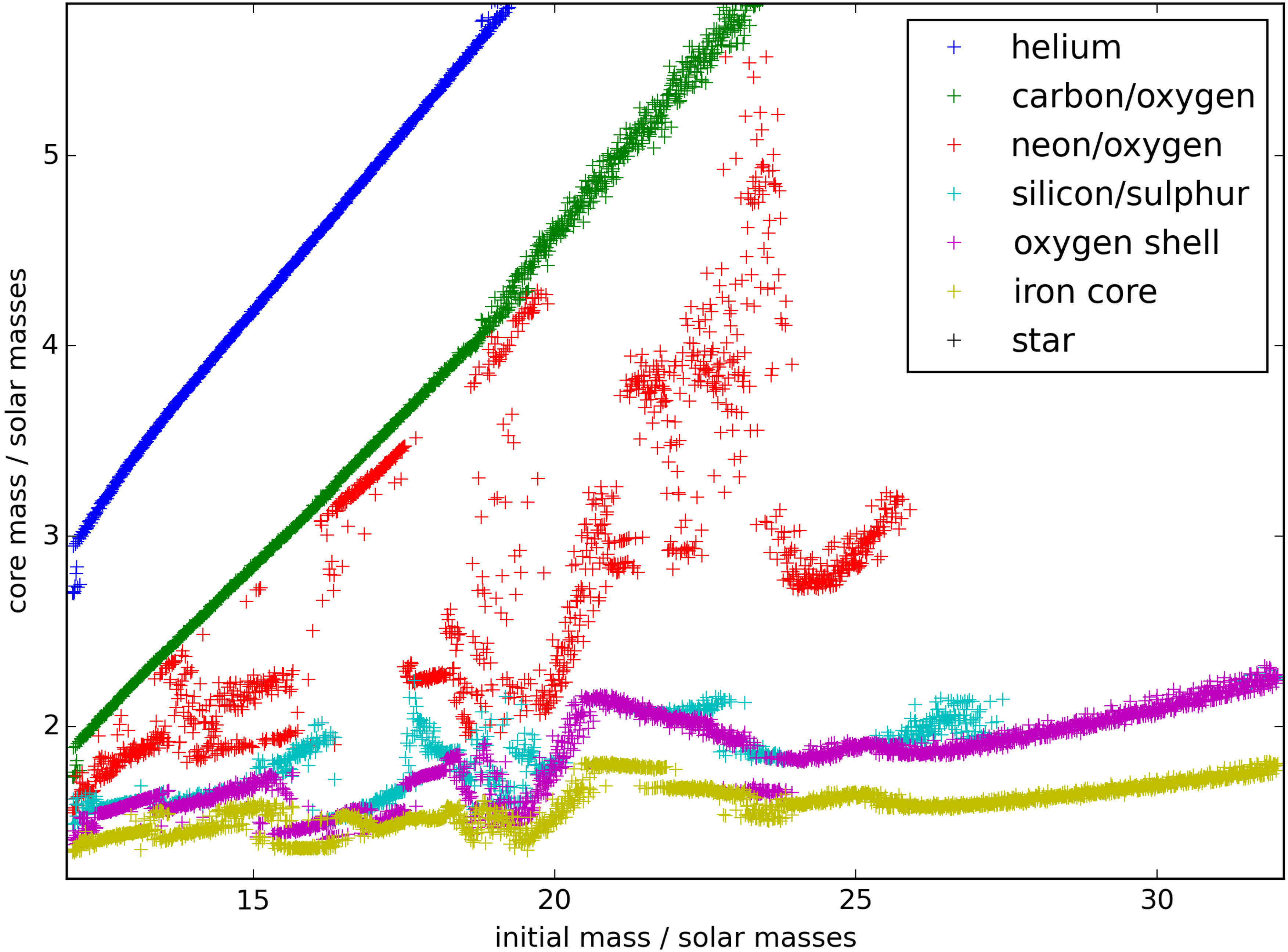
Burning stages		20 $M_\odot$ Star		200 $M_\odot$ Star	
Fuel	Main Product	T (10^9 K)	Time (yr)	T (10^9 K)	Time (yr)
H	He	0.02	10^7	0.1	2×10^6
He	O, C	0.2	10^6	0.3	2×10^5
C	Ne, Mg	0.8	10^3	1.2	10
Ne	O, Mg	1.5	3	2.5	3×10^{-6}
O	Si, S	2.0	0.8	3.0	2×10^{-6}
Si	Fe	3.5	0.02	4.5	3×10^{-7}



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
O shell burning
Ne
burning
O
O
O
O
Si
Si
m / M⊙
log(time till core collapse / yr)

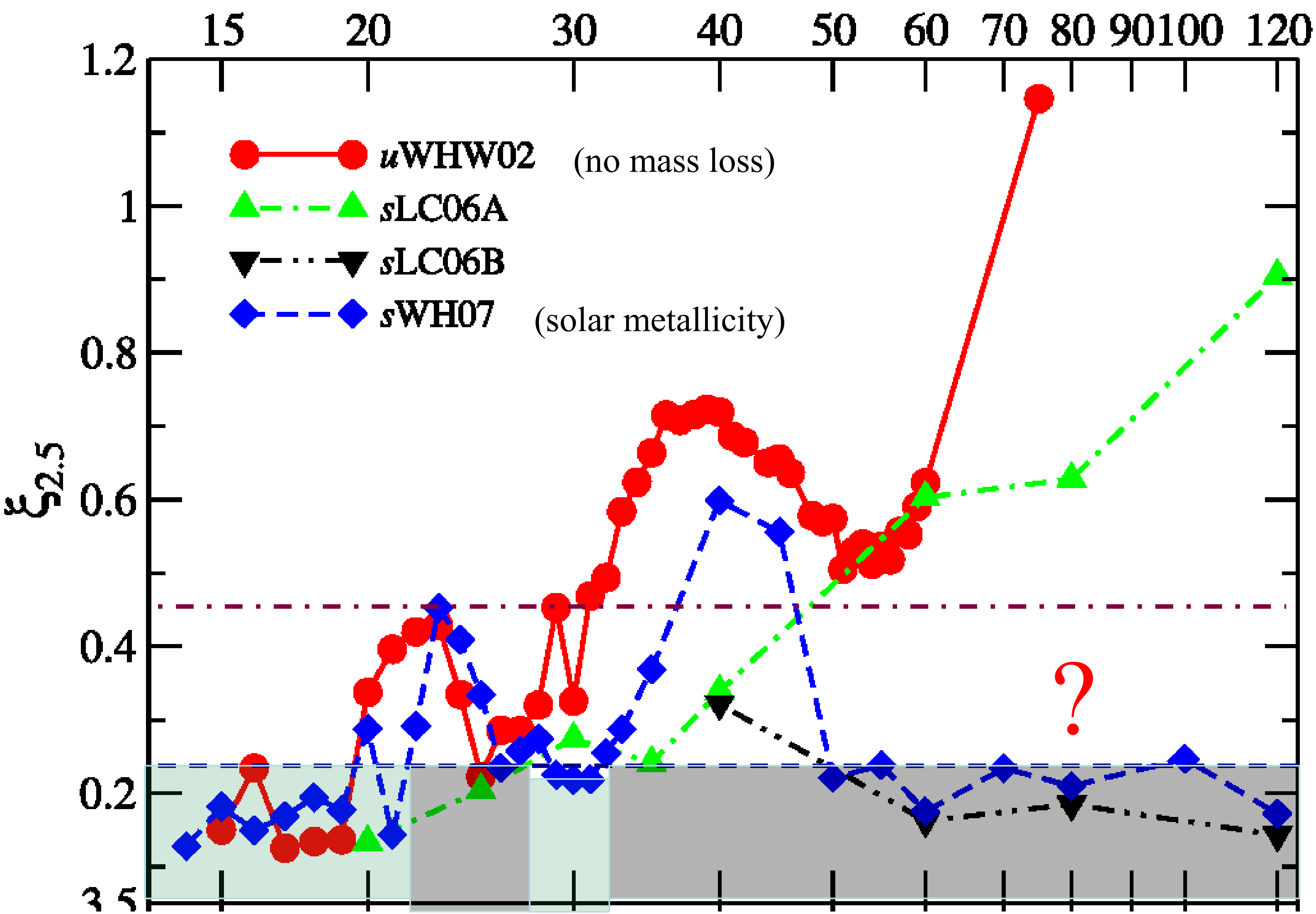


Ejected "metals"



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

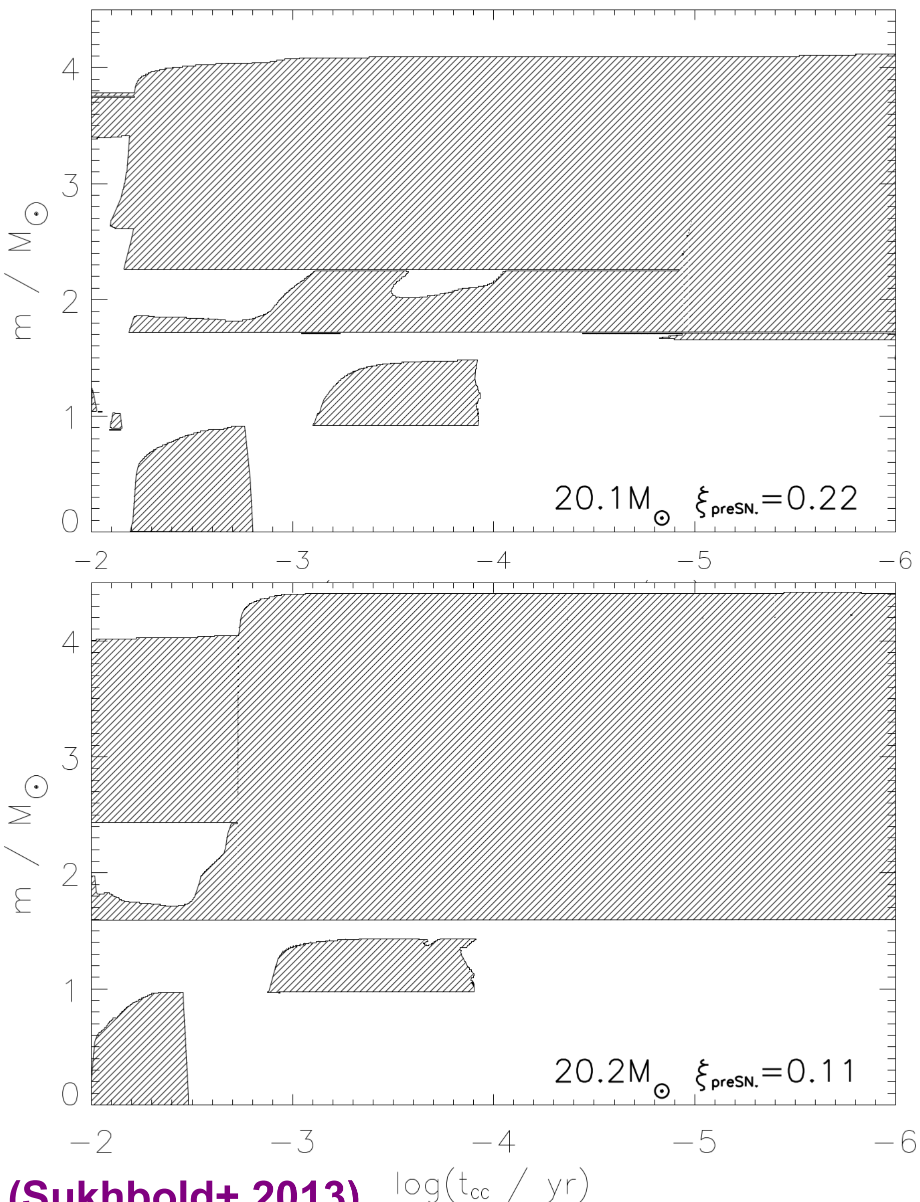
Islands of SN and BH Production



(Woosley 2012, priv. com.)

O'Connor and Ott (2011)

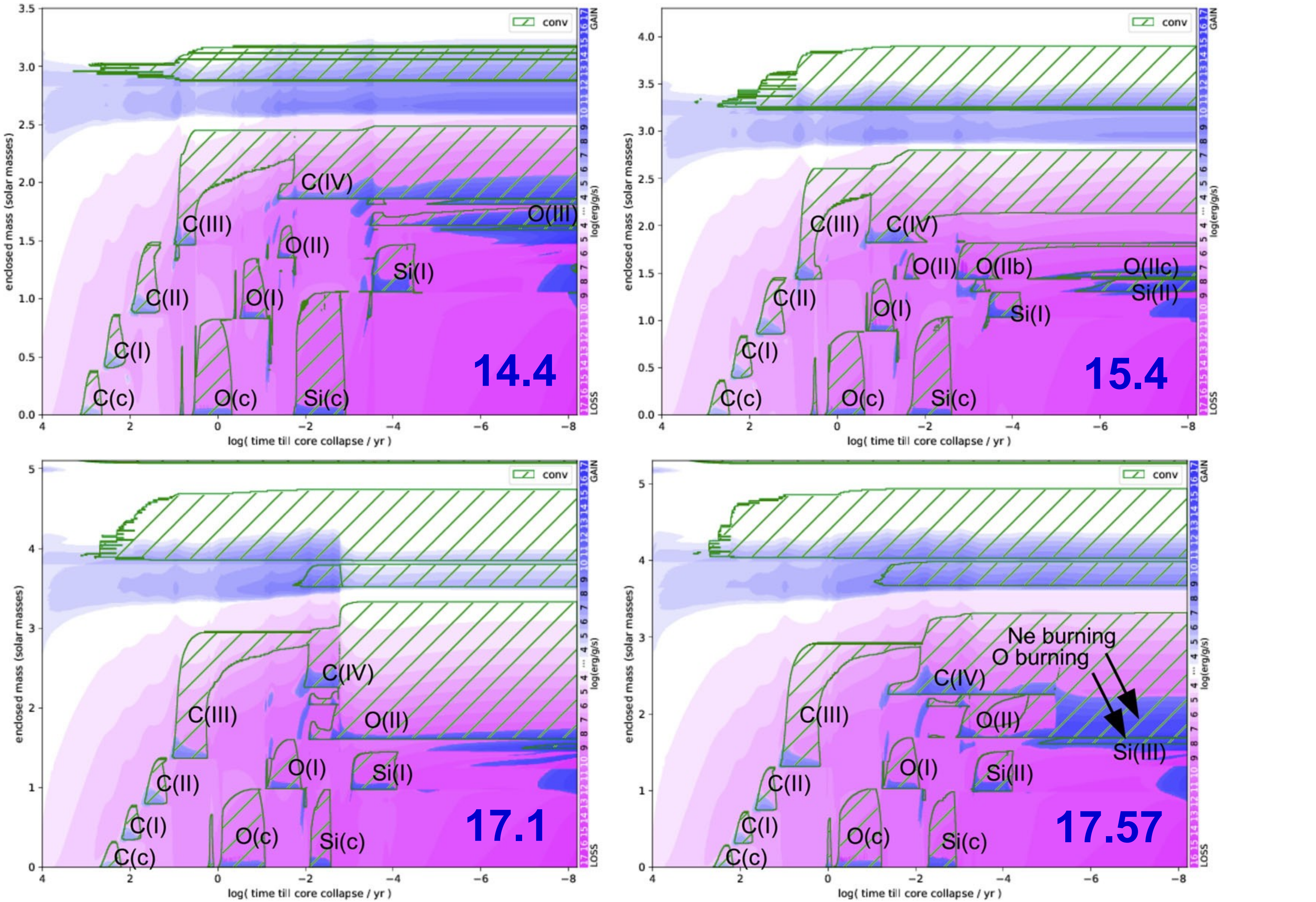
Sensitivity of Structure to Initial Mass



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

(Sukhbold+ 2013)

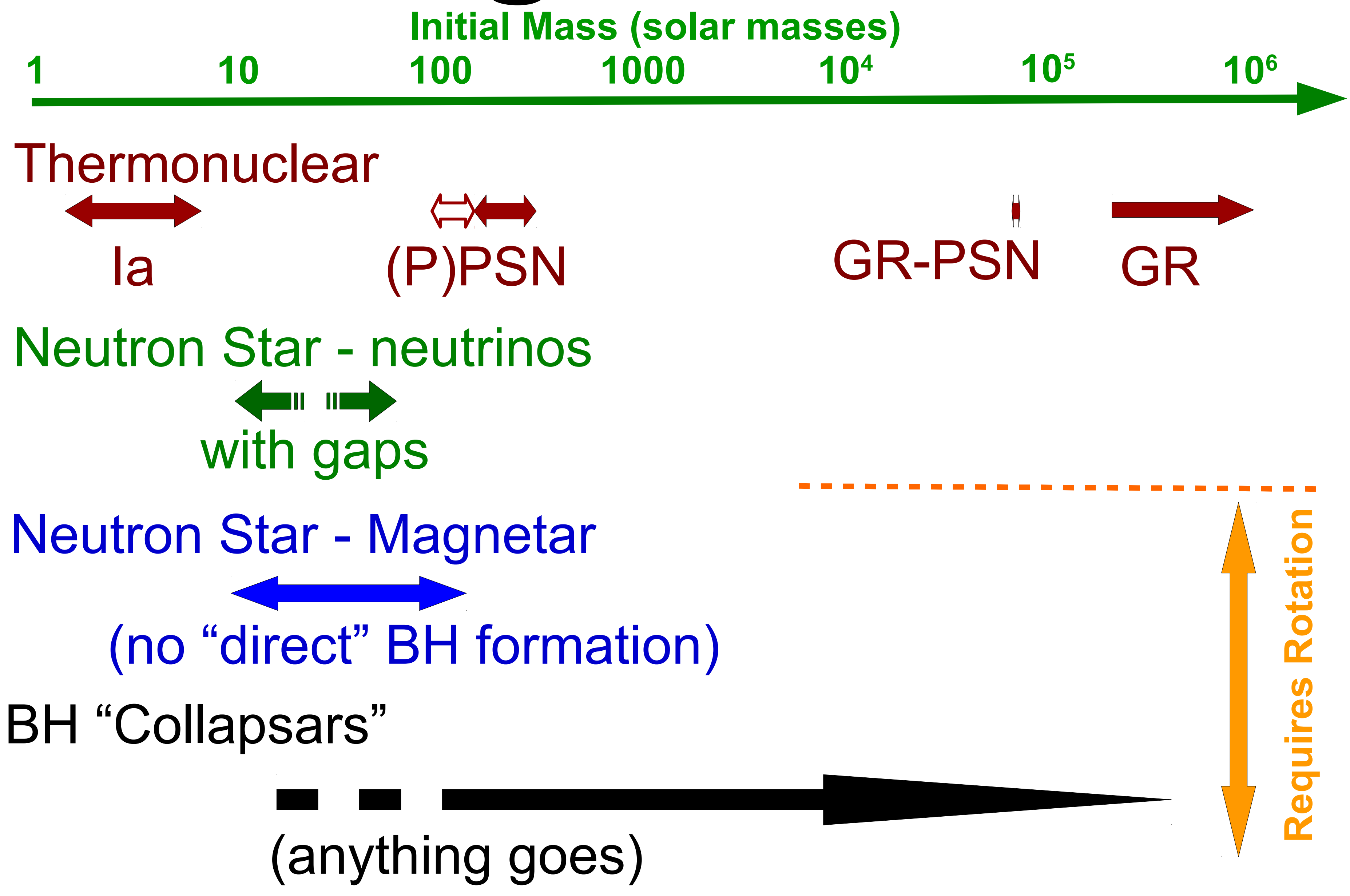
Outcomes for intermediate Massive Stars



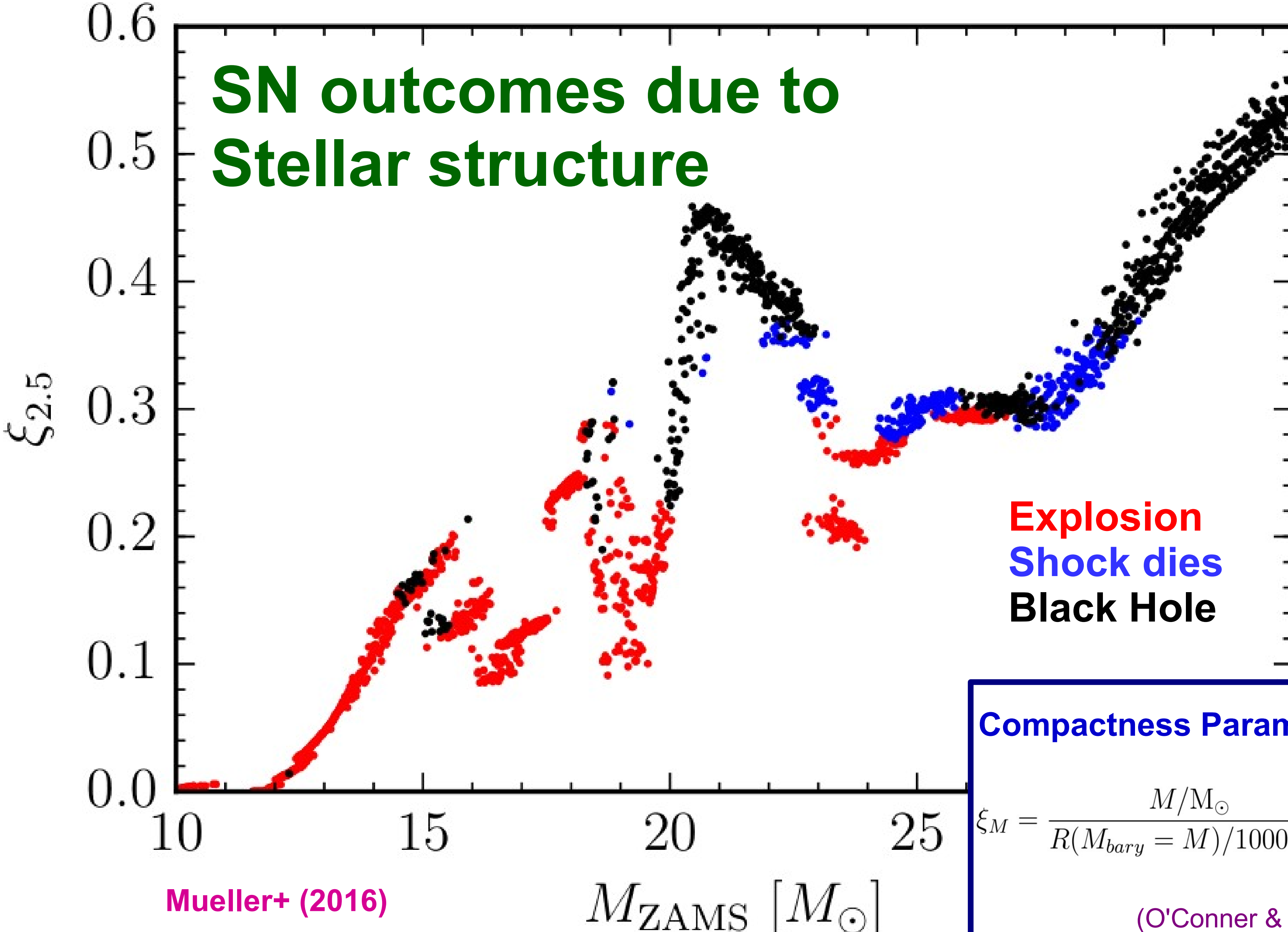
(Collins+ 2018)

The Death of the Stars

The Engines of SNe



Signatures of Stellar Structure



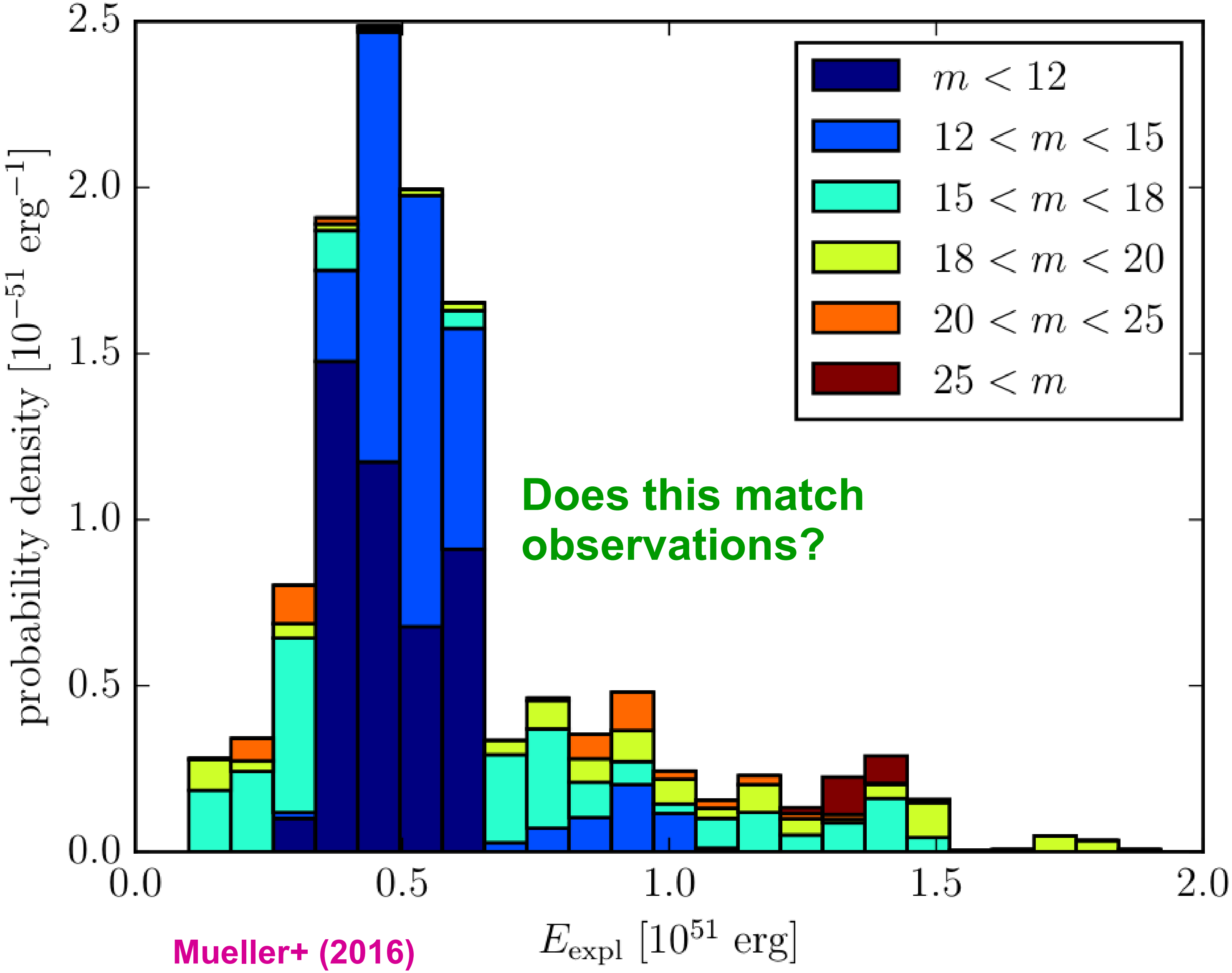
Mueller+ (2016)

Compactness Parameter

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

(O'Conner & Ott 2011)

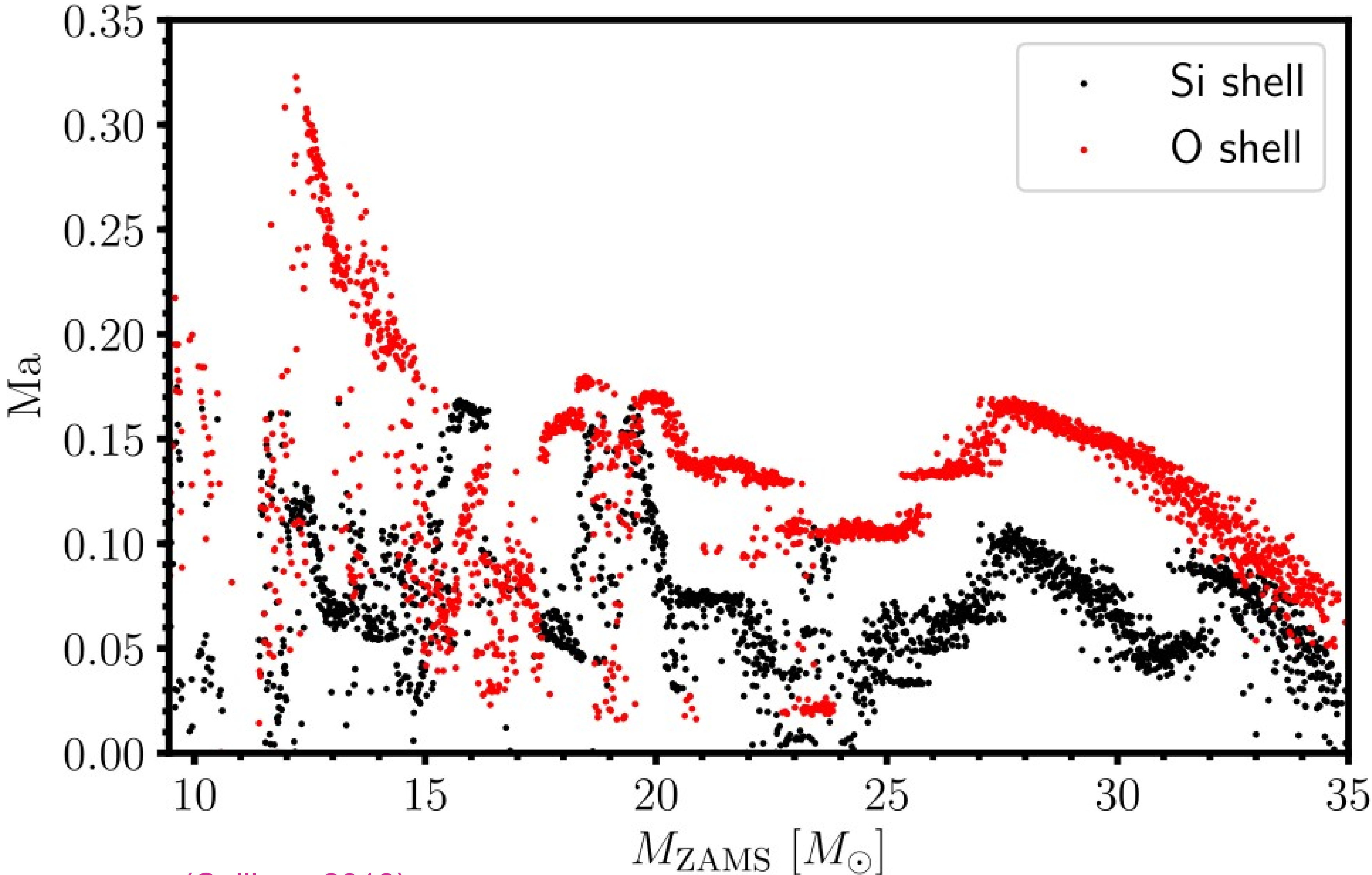
Signatures of Stellar Structure



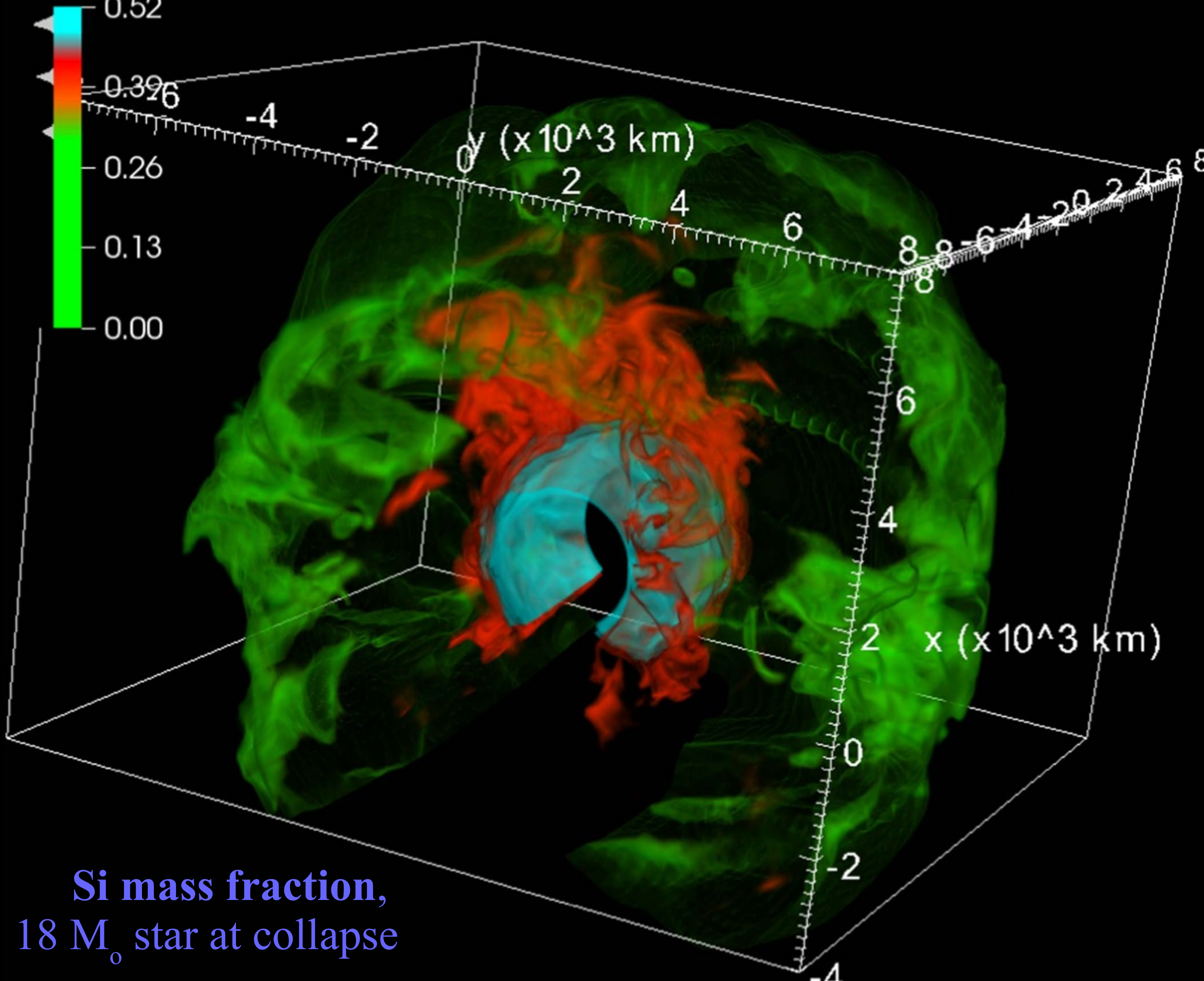
Mueller+ (2016)

Explosion energy can vary a lot with pre-SN structure

Convective Mach Numbers at CC

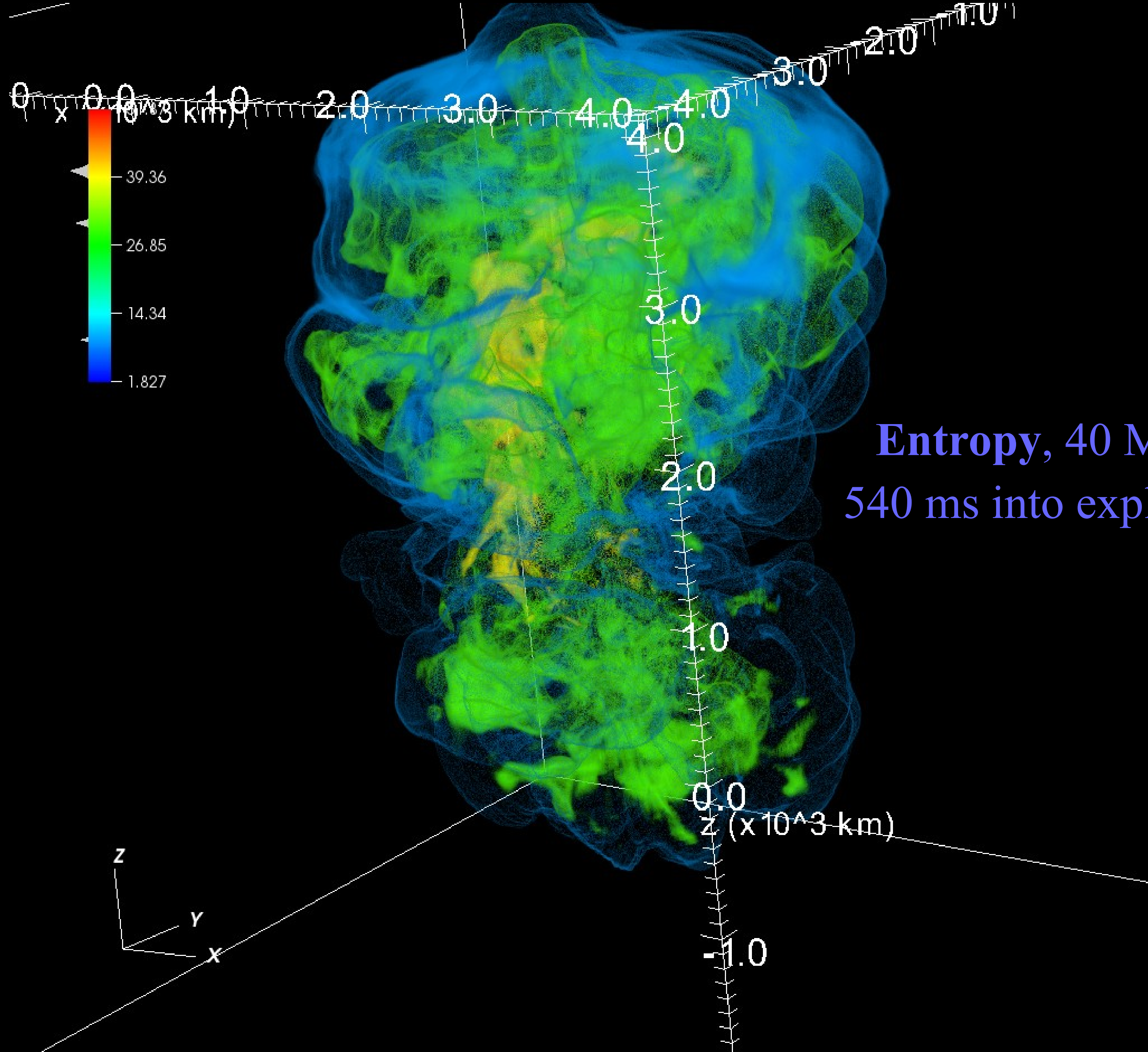


(Collins+ 2018)



Si mass fraction,
18 M_{o} star at collapse

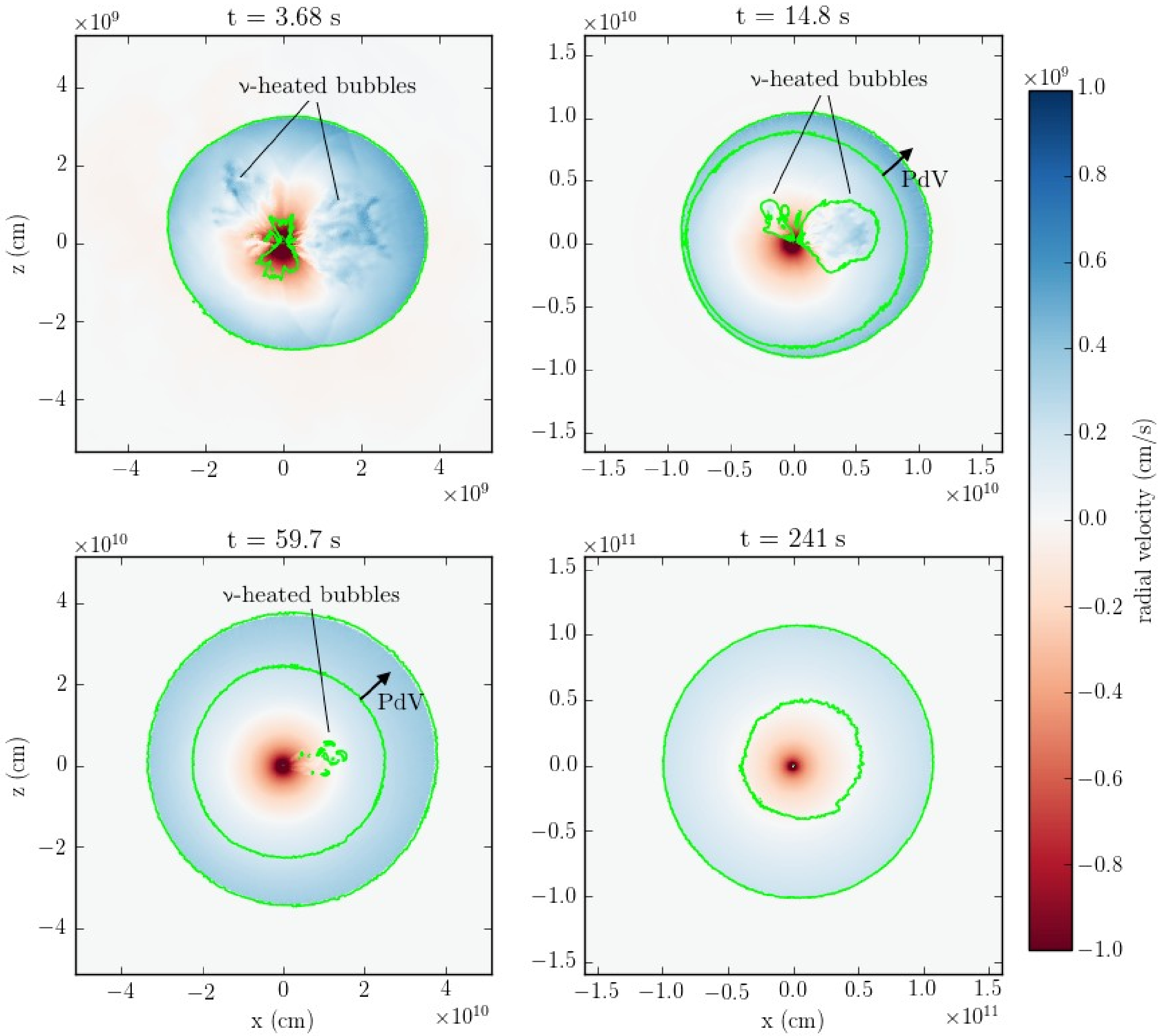
Mueller+ 2016



Entropy, 40 M$_o$ star
540 ms into explosion

Mueller, Chan, Heger 2018

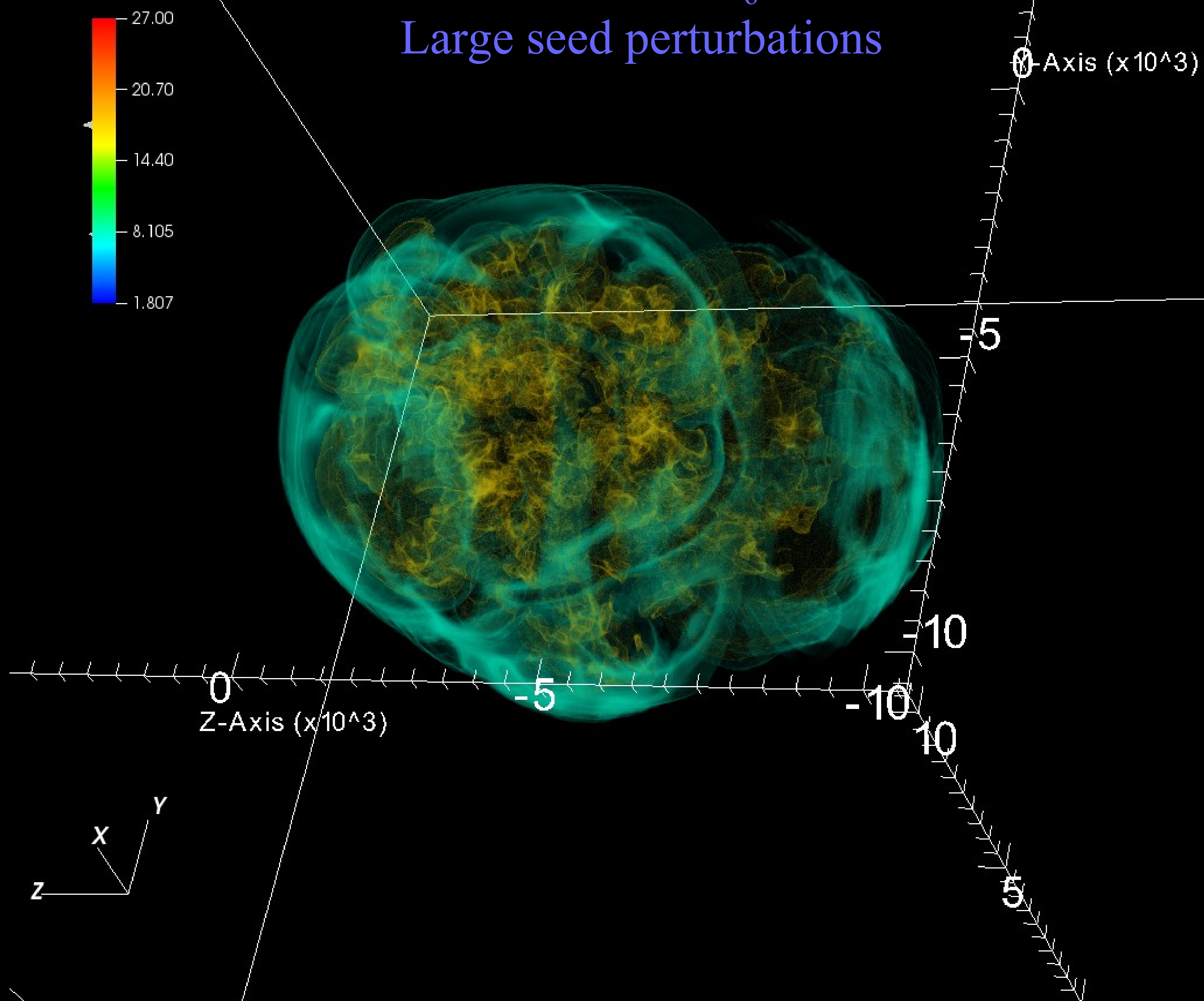
Fallback in a 40 $M_\odot$ Stars



(Chan+ 2018)

Entropy, 40 M_o star

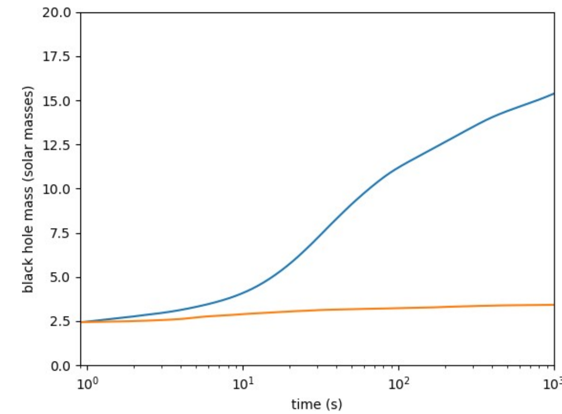
Large seed perturbations

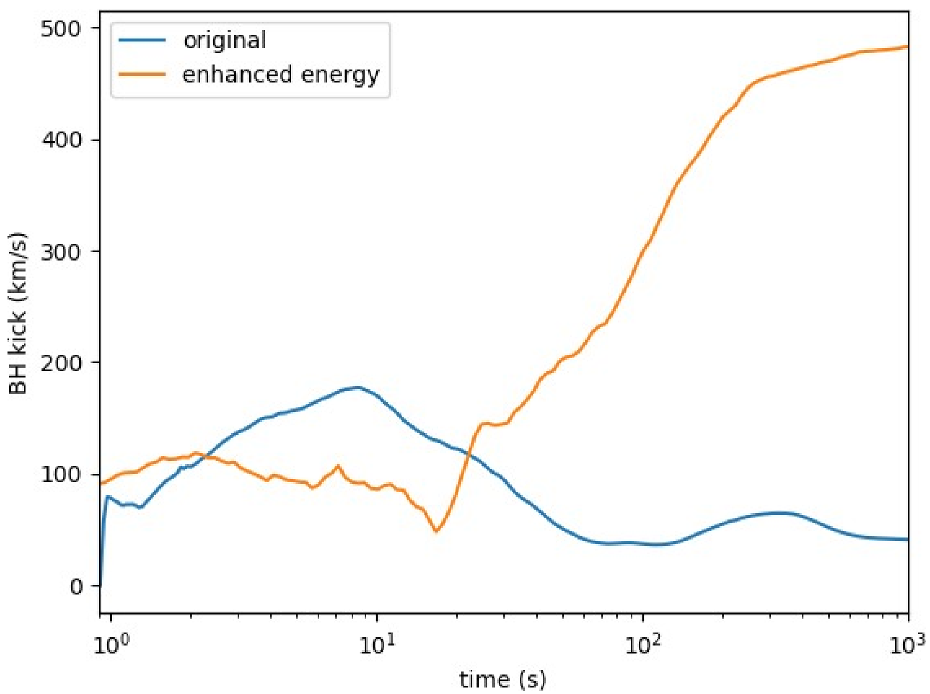


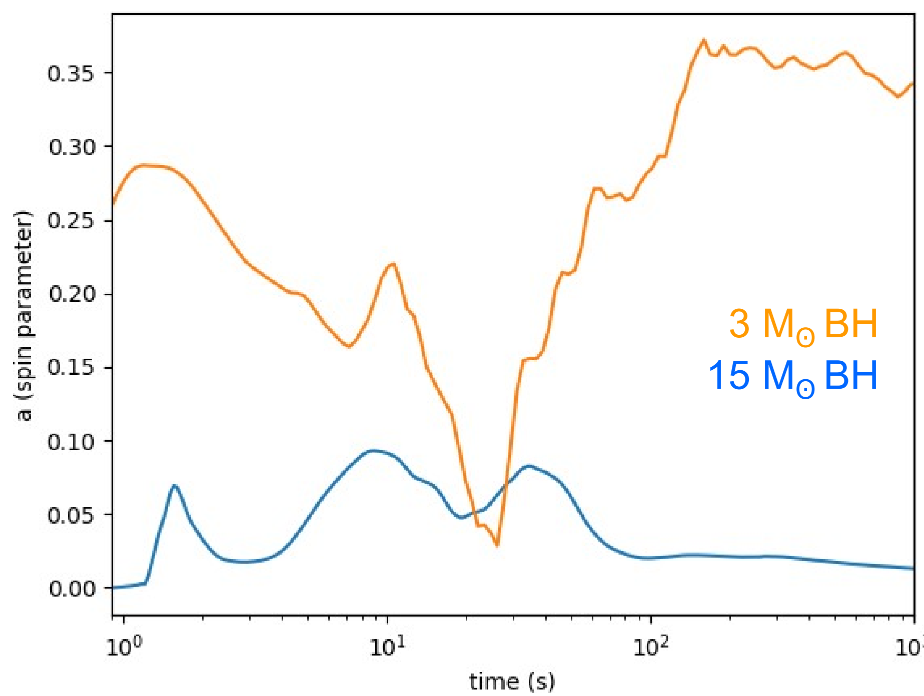
Chan, Mueller, Heger, in prep.

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



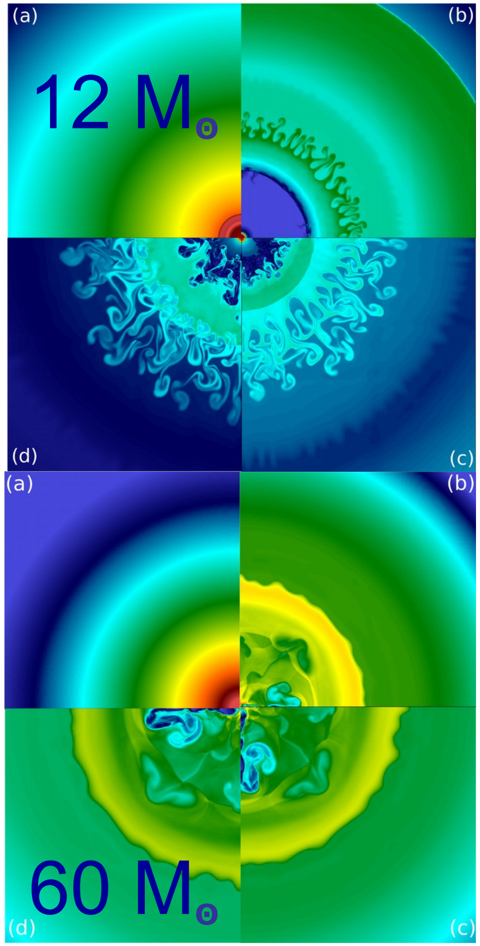




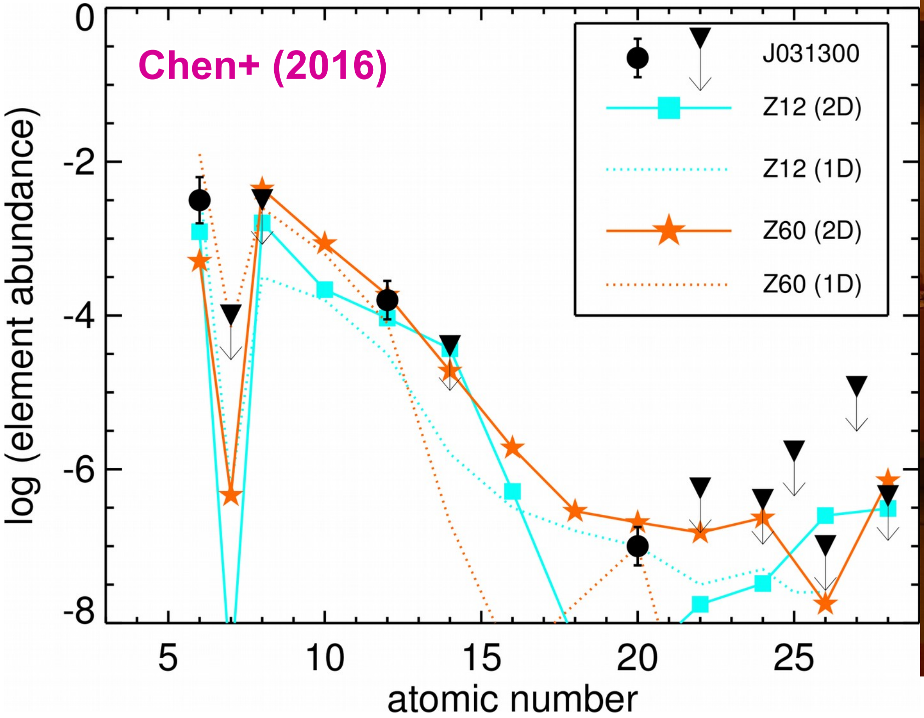
40 $M_\odot$ initial mass

(Chan+, in prep)

Multi-D SN Simulations
of SMSS J031300



Chen+ (2016)



→ for current multi-D mixing models match C, O, Mg, and Ca

Predictions for Fe group are different than hydrostatic model, e.g., Ca production!

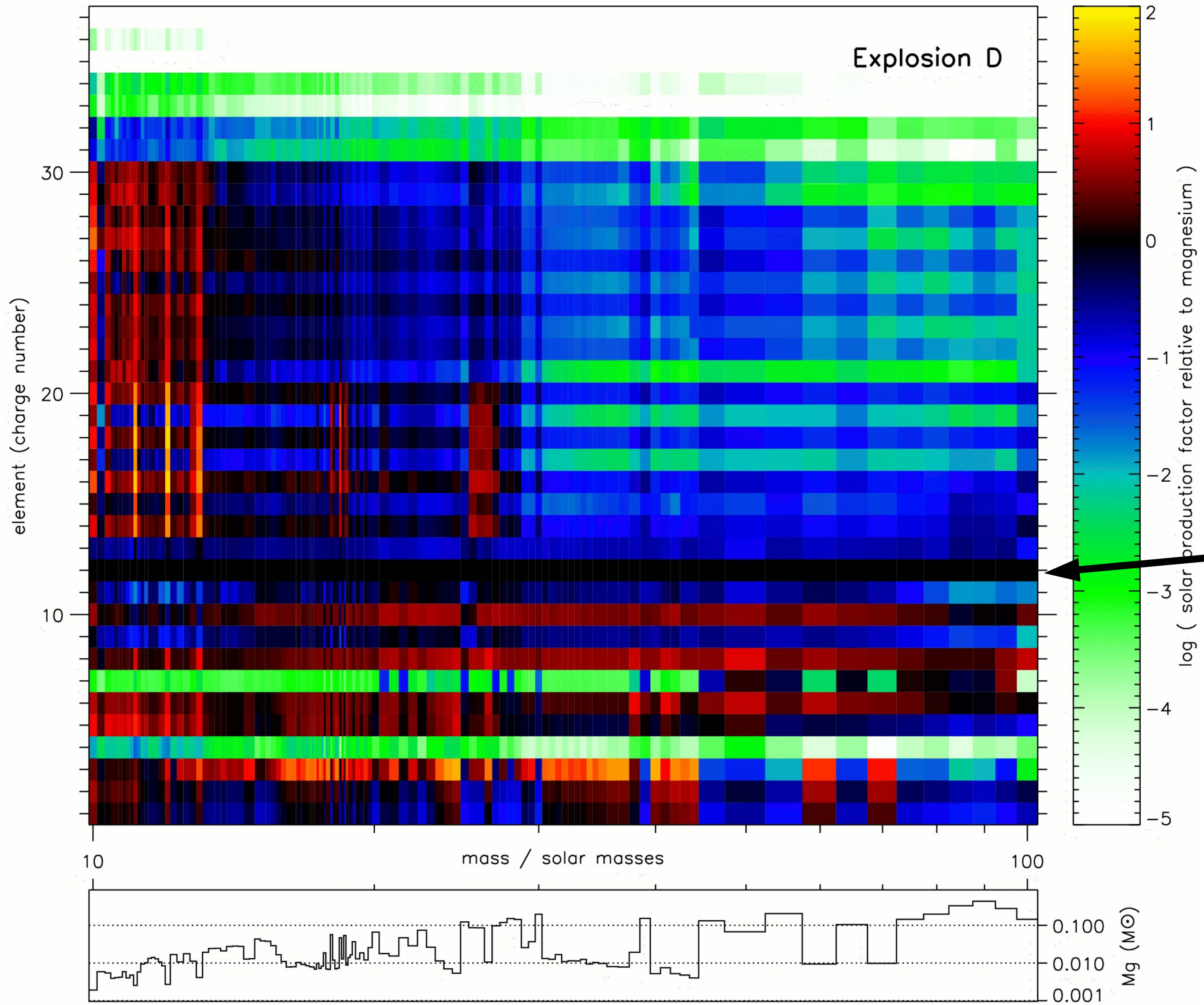
Nucleosynthesis for EMP Stars

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

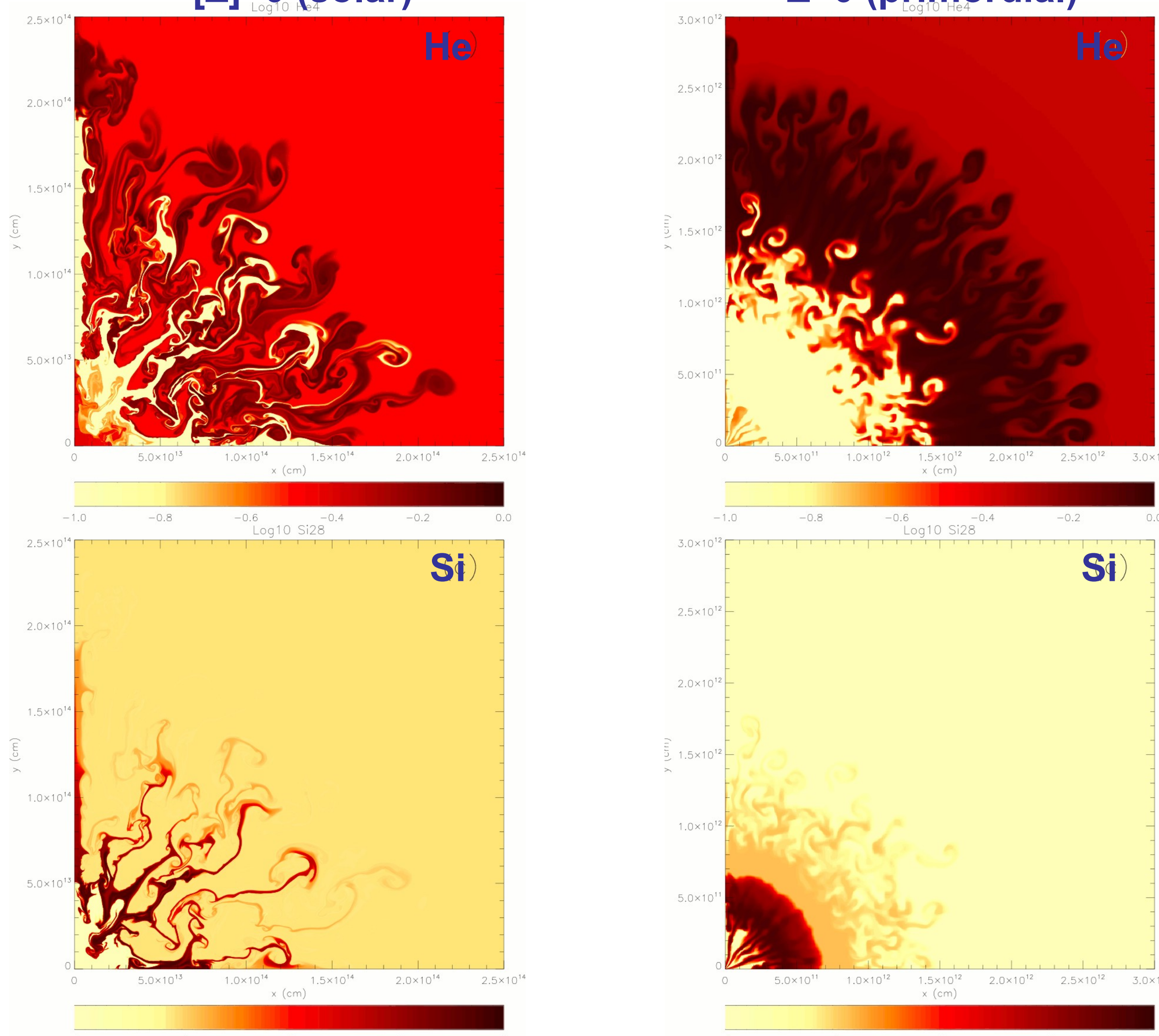
"complete" reaction network

Note: normalized to Mg

Heger & Woosley (2010)

Mixing in 25 $M_\odot$ Stars

[Z]=0 (solar) **Z=0 (primordial)**



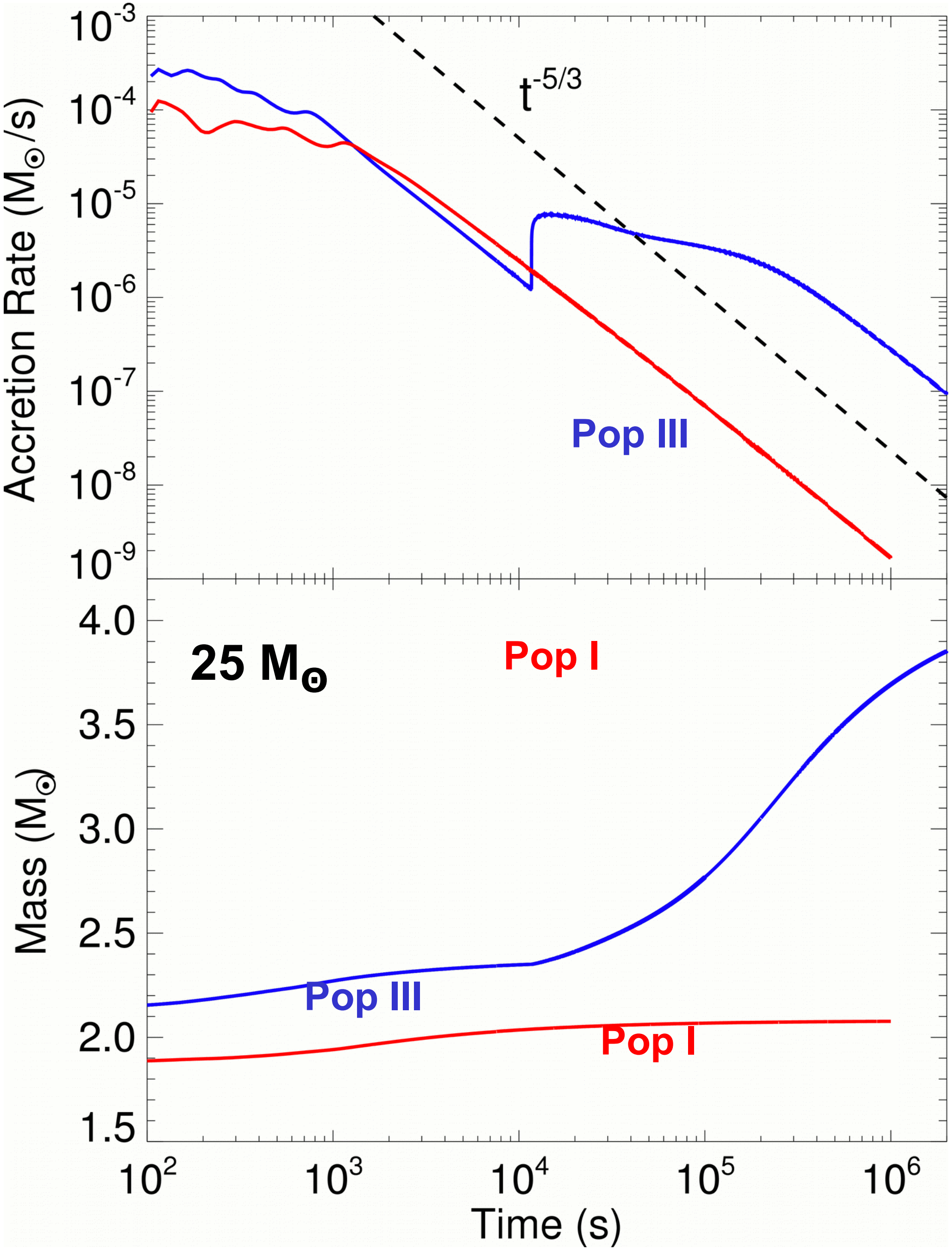
Growth of Rayleigh-Taylor instabilities

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

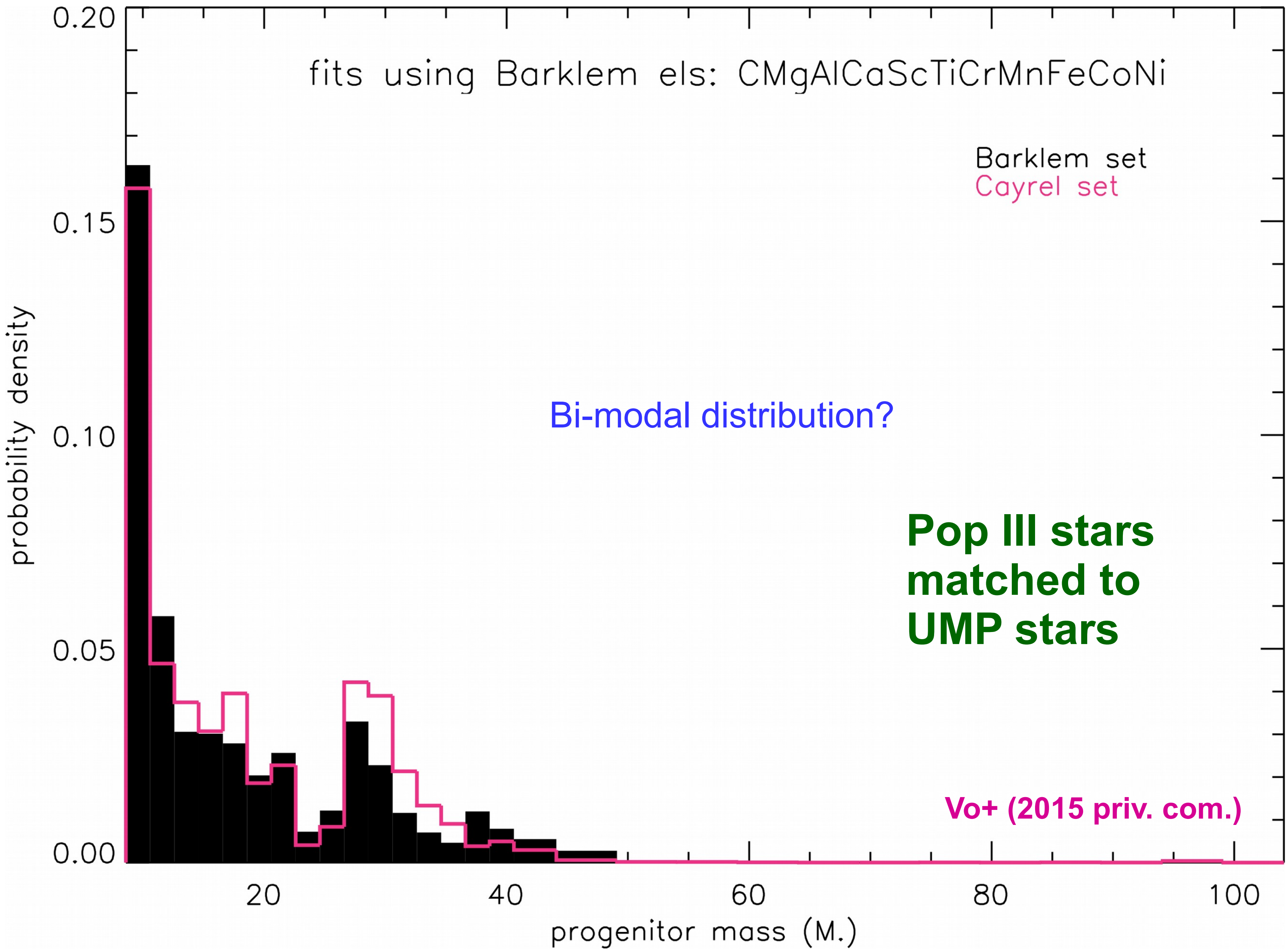


➔ **Pop III stars show much more fallback than modern Pop I stars due to their compact hydrogen envelope**

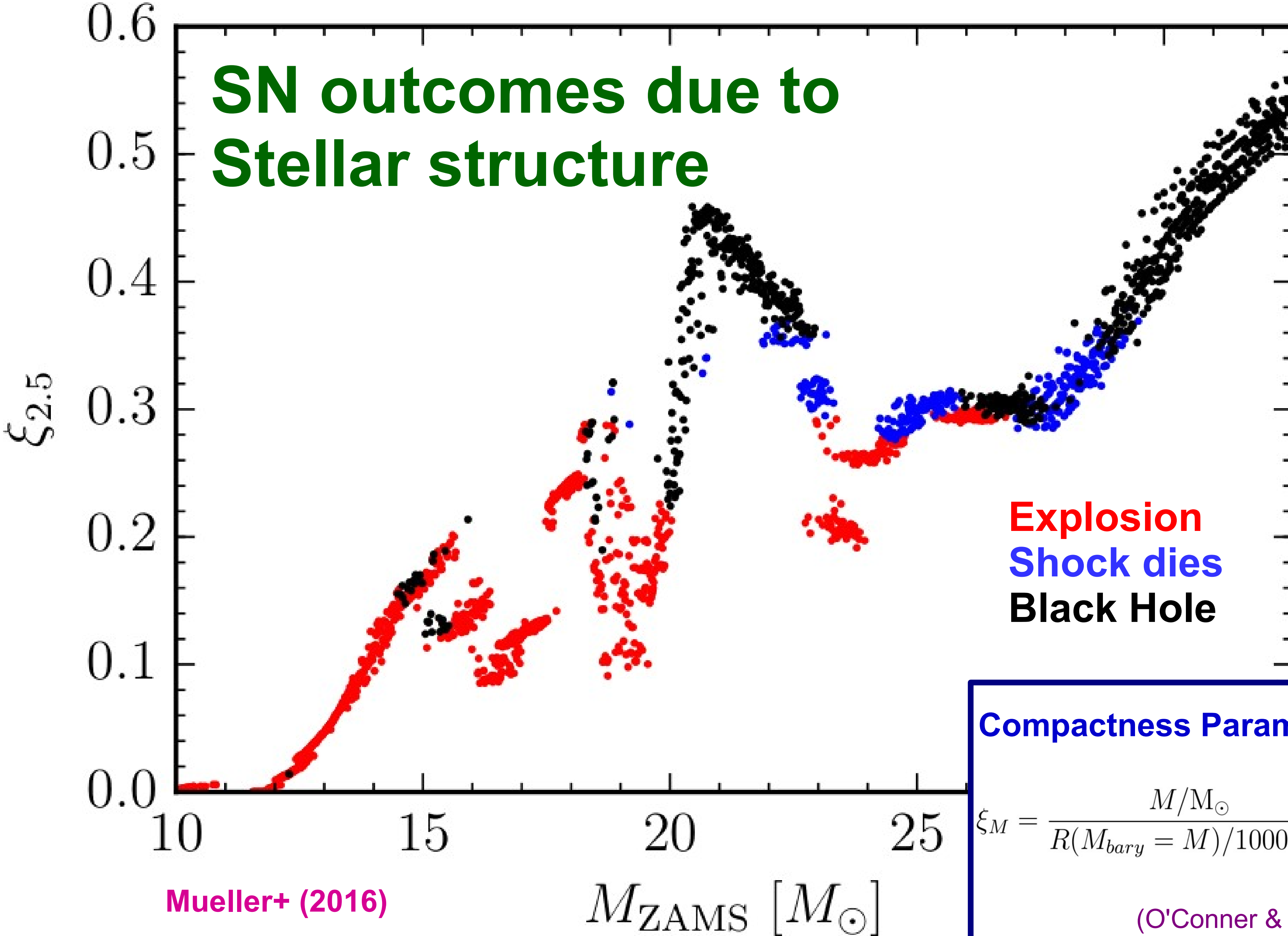
➔ **Explosion Fallback depend on stellar structure, e.g., as imposed by metallicity**

(Zhang, Woosley, Heger 2007)

Reconstruction of the IMF



Signatures of Stellar Structure?



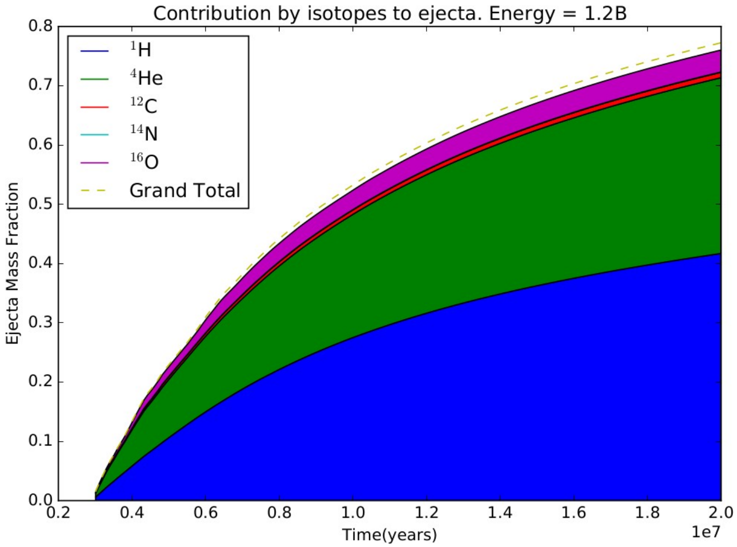
Mueller+ (2016)

Compactness Parameter

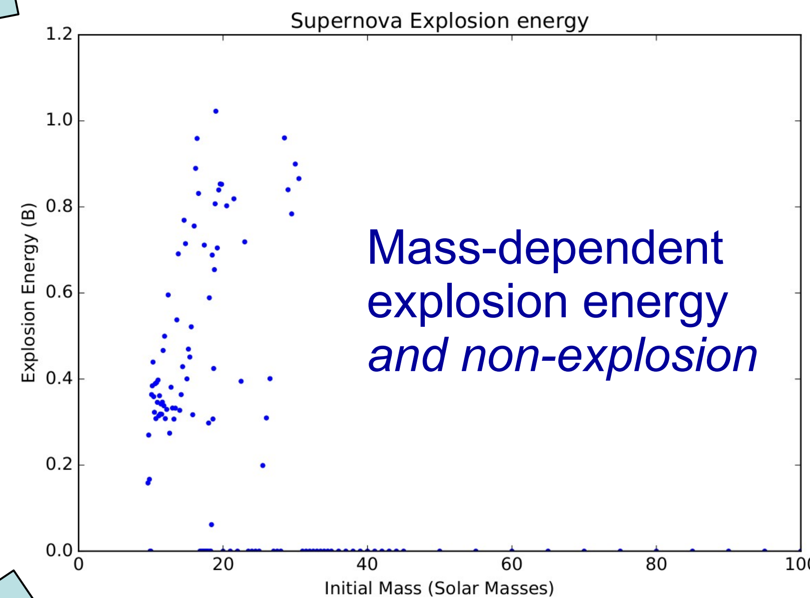
$$\xi_M = \frac{M/\mathrm{M}_\odot}{R(M_{bary} = M)/1000\,\mathrm{km}}\Big|_{t_{bounce}},$$

(O'Conner & Ott 2011)

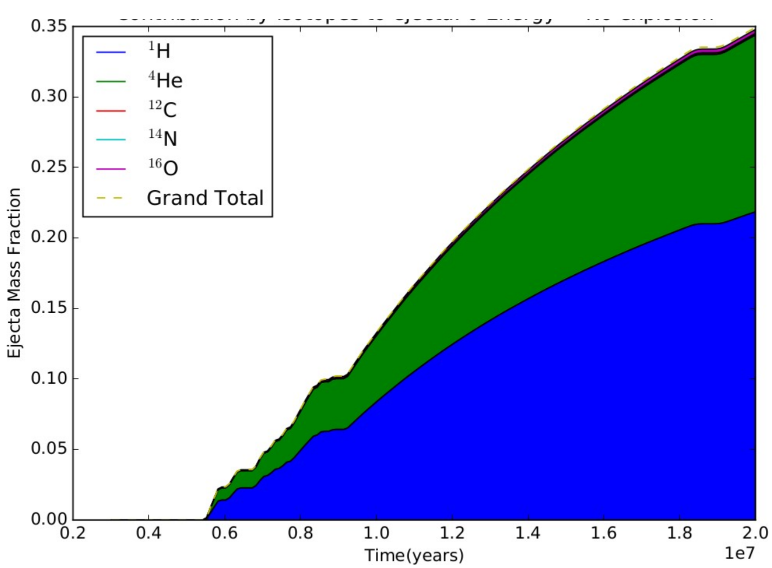
Time-Dependent Yields and SN Energies



all stars explode with 1.2 B



Mass-dependent explosion energy *and non-explosion*

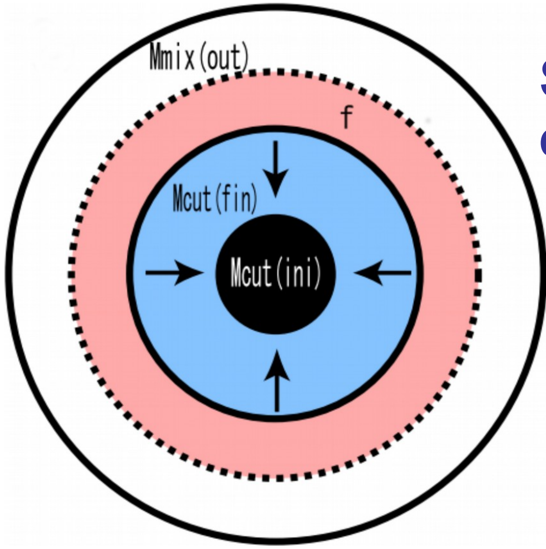


stars explode with proper explosion energy

(Duggan 2017)

Hypernove Jet-Explosions

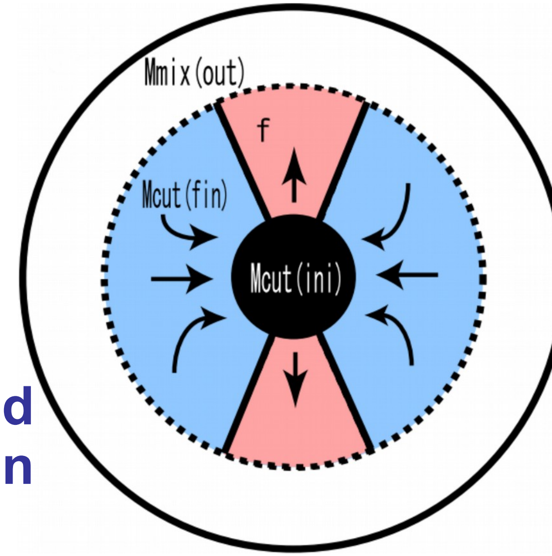
Hypernova Nucleosynthesis

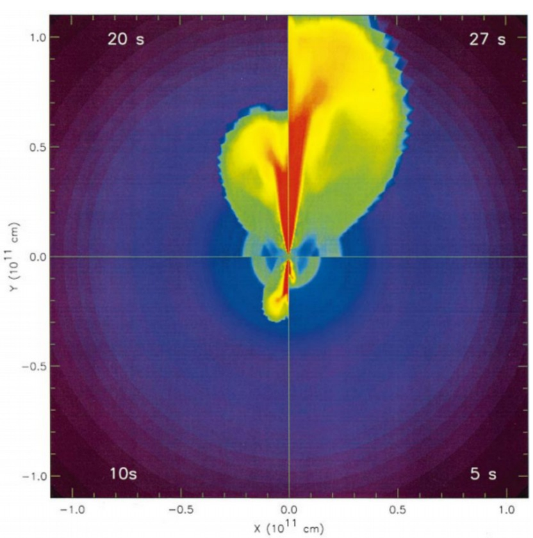


Spherical explosion

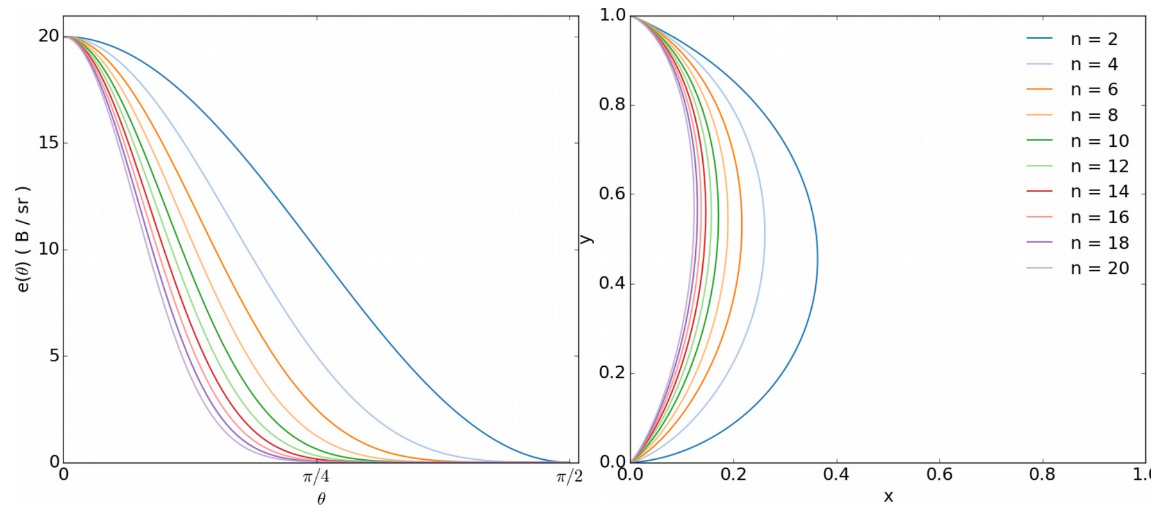
(Nomoto+ 2006)

Jetted explosion





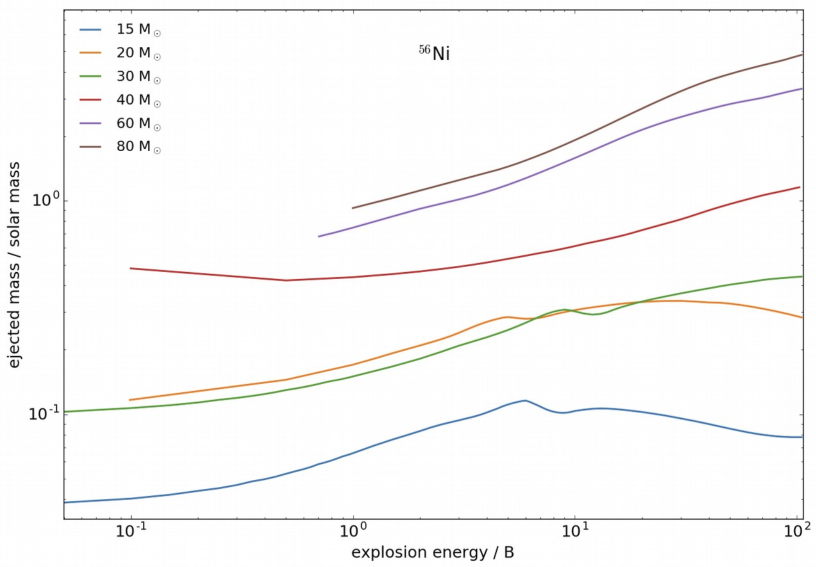
(MacFadyen+ 2001)



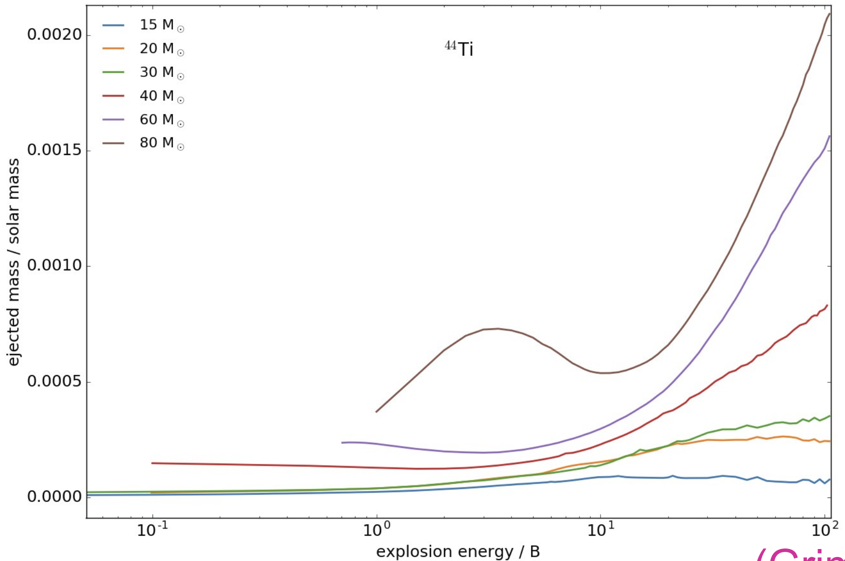
Simple Models

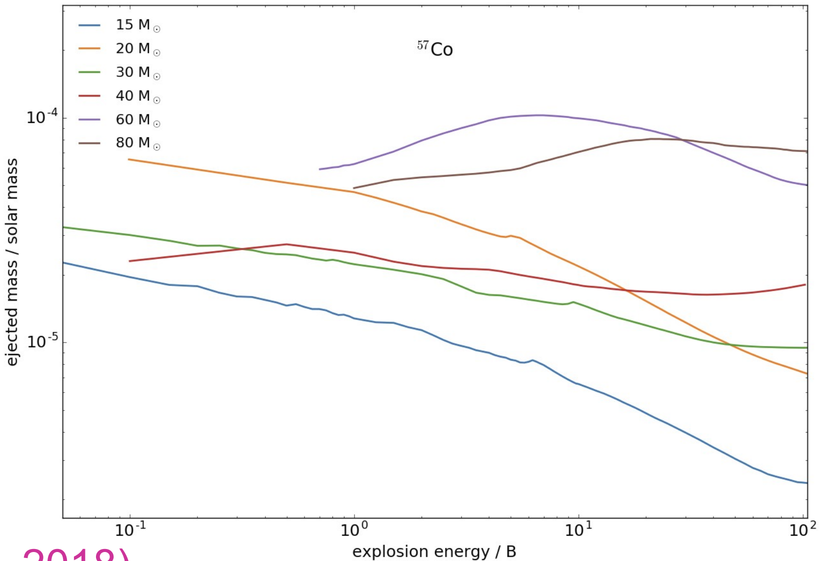
(Grimmett+ 2018)

Nucleosynthesis in Hypernovae



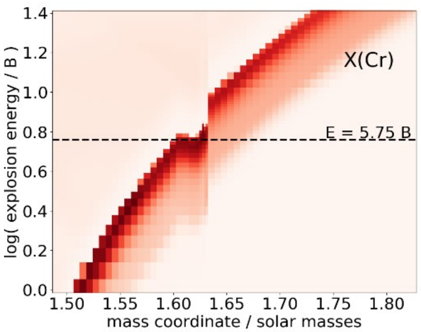
→ Can get wide variety of yields and ratios form jets and asymmetric explosions, in particular if not well-mixed when next generation of stars form!

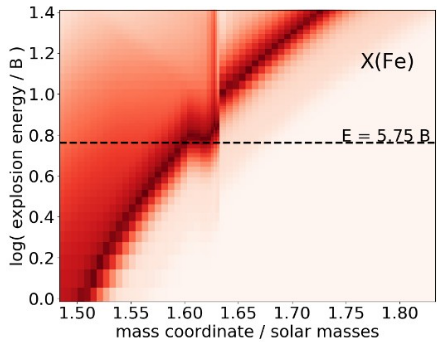


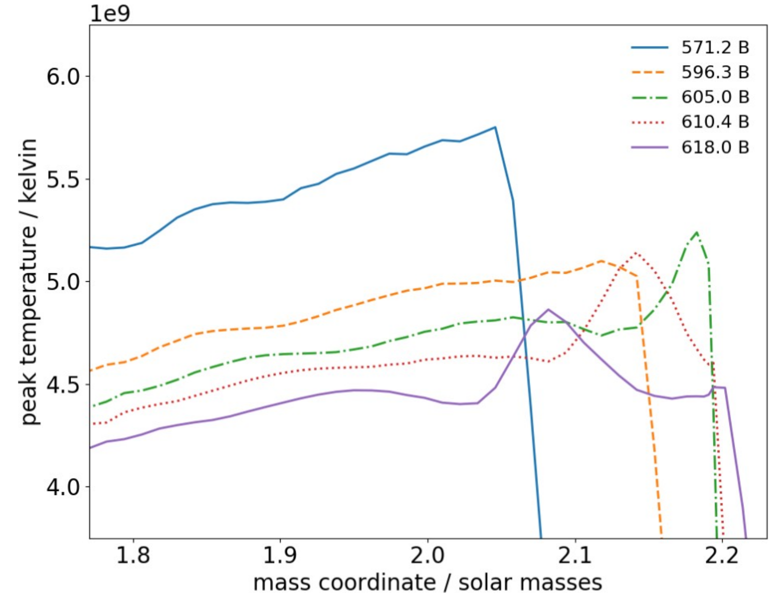


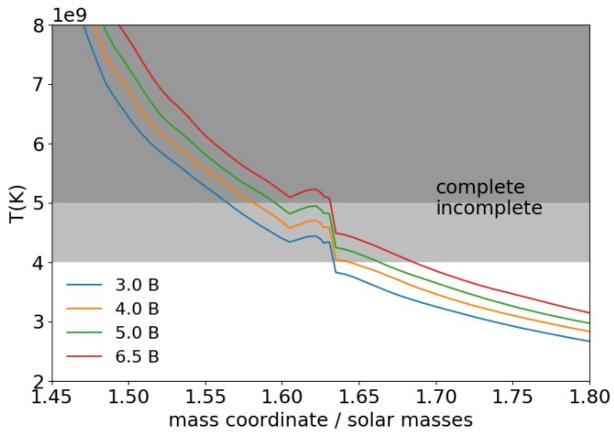
(Grimmett+ 2018)

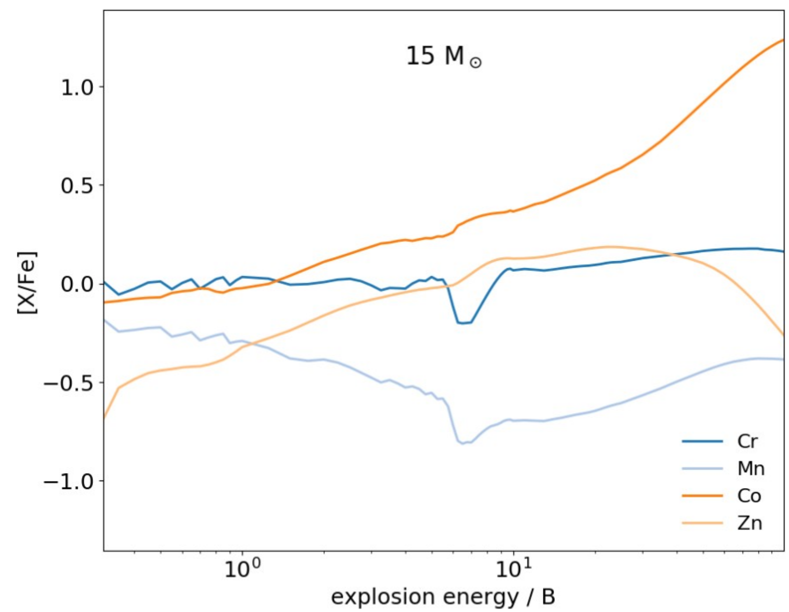
Nucleosynthesis in Hypernovae







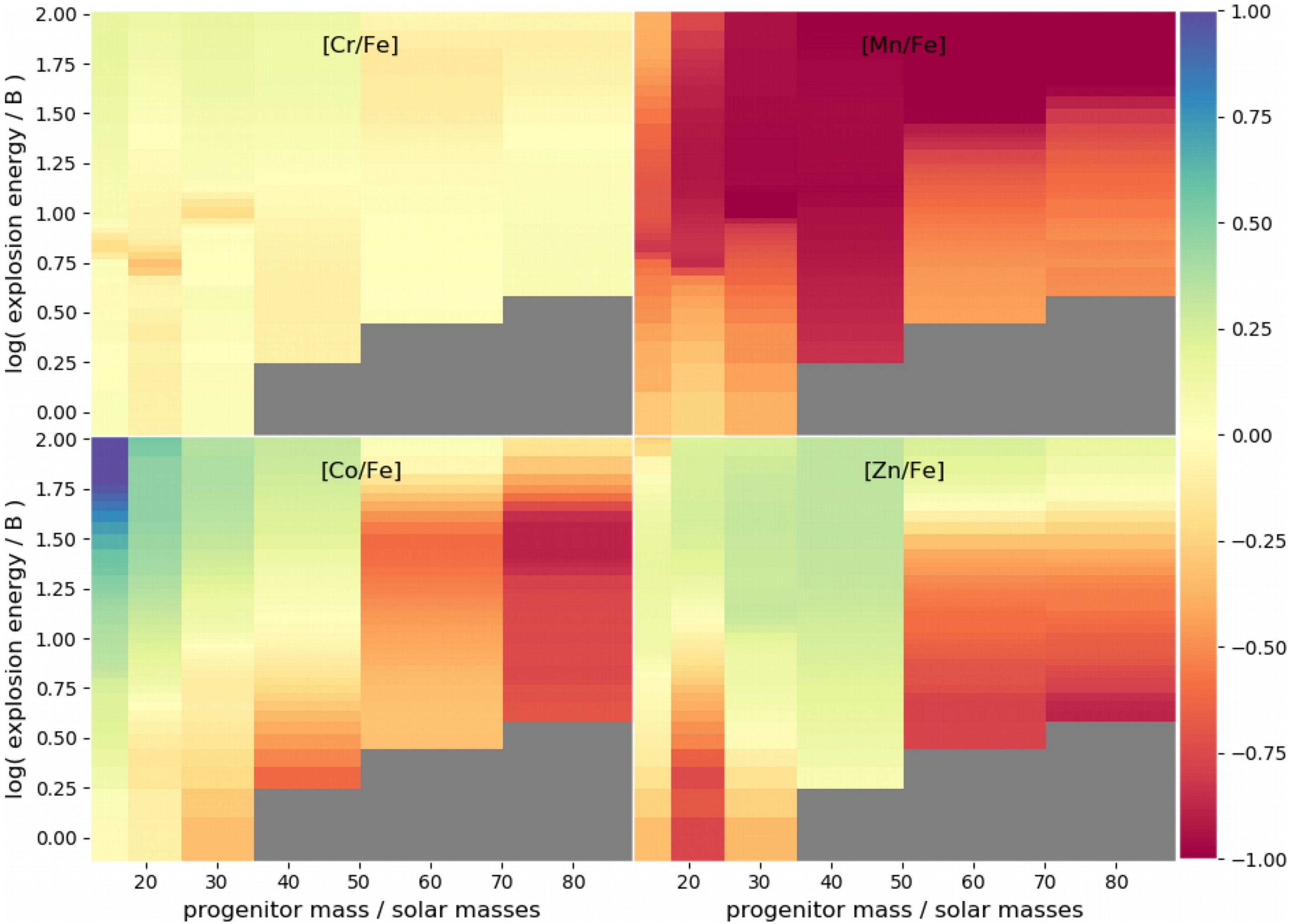




Reverse shock has significant impact on nucleosynthesis by changing freeze-out time scale

(Grimmett+ 2018)

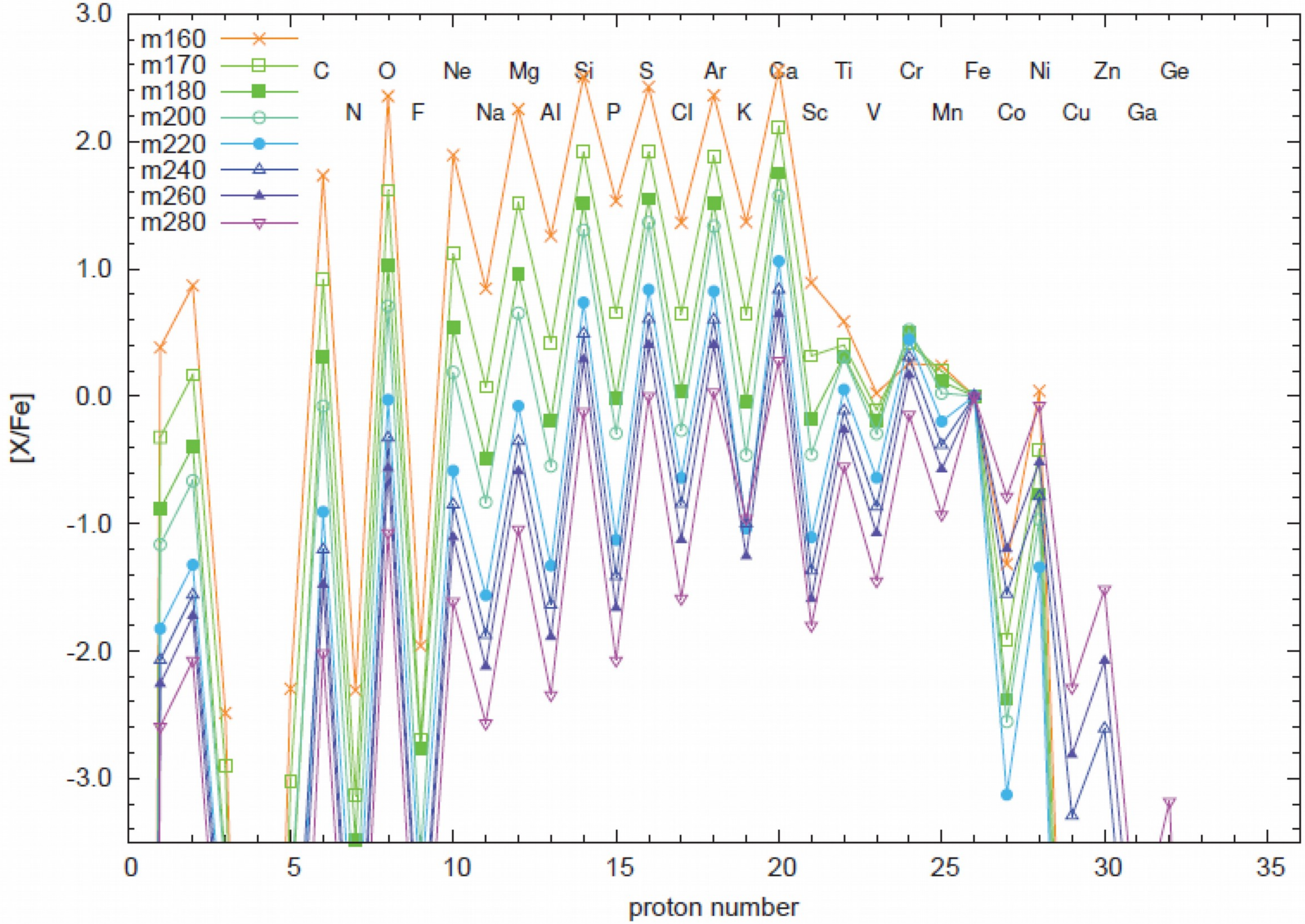
Nucleosynthesis in Hypernovae



(Grimmett+ 2018, 2019)

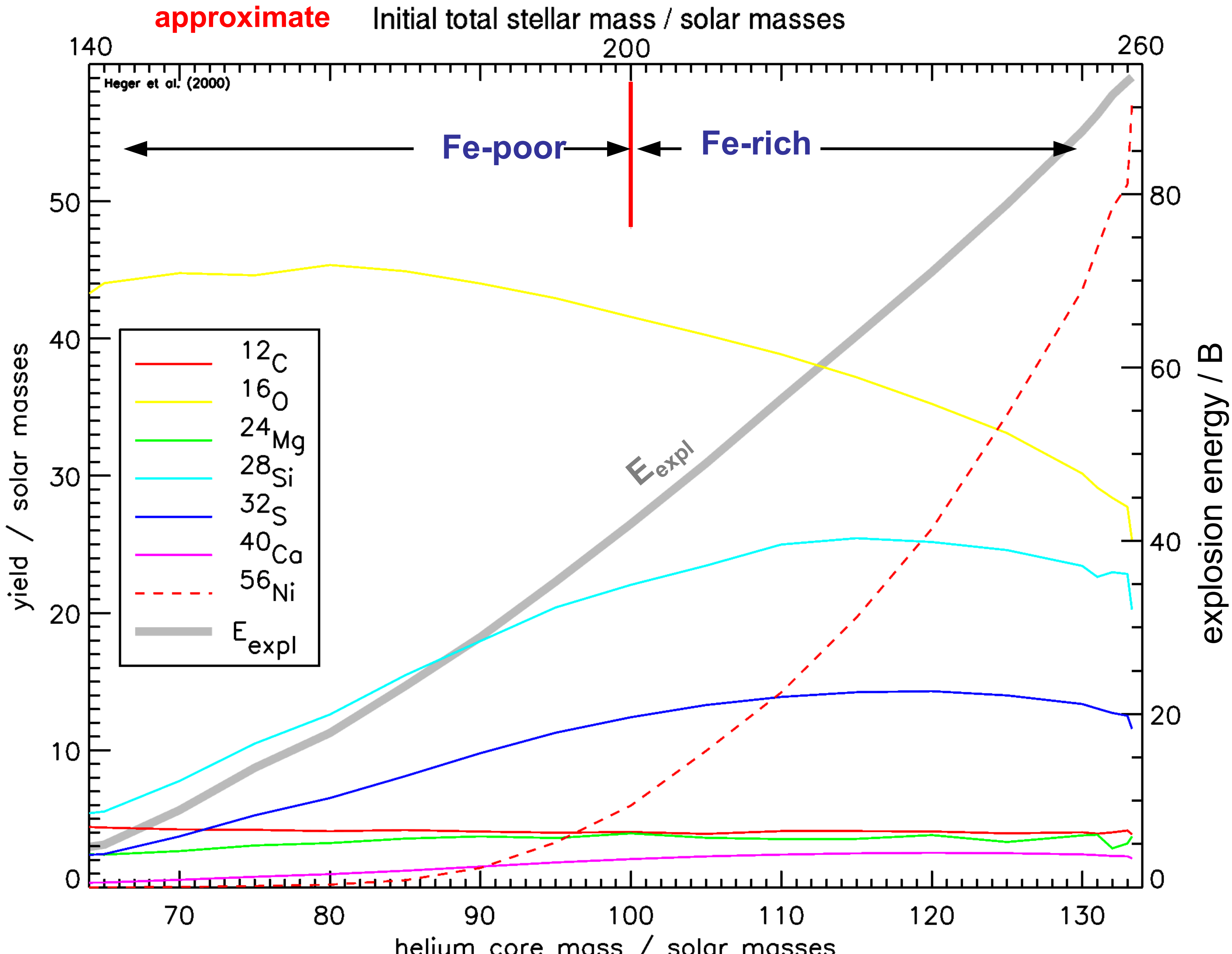
Pair-Instability Supernovae

Pair-Instability SN yields: large odd/even Z

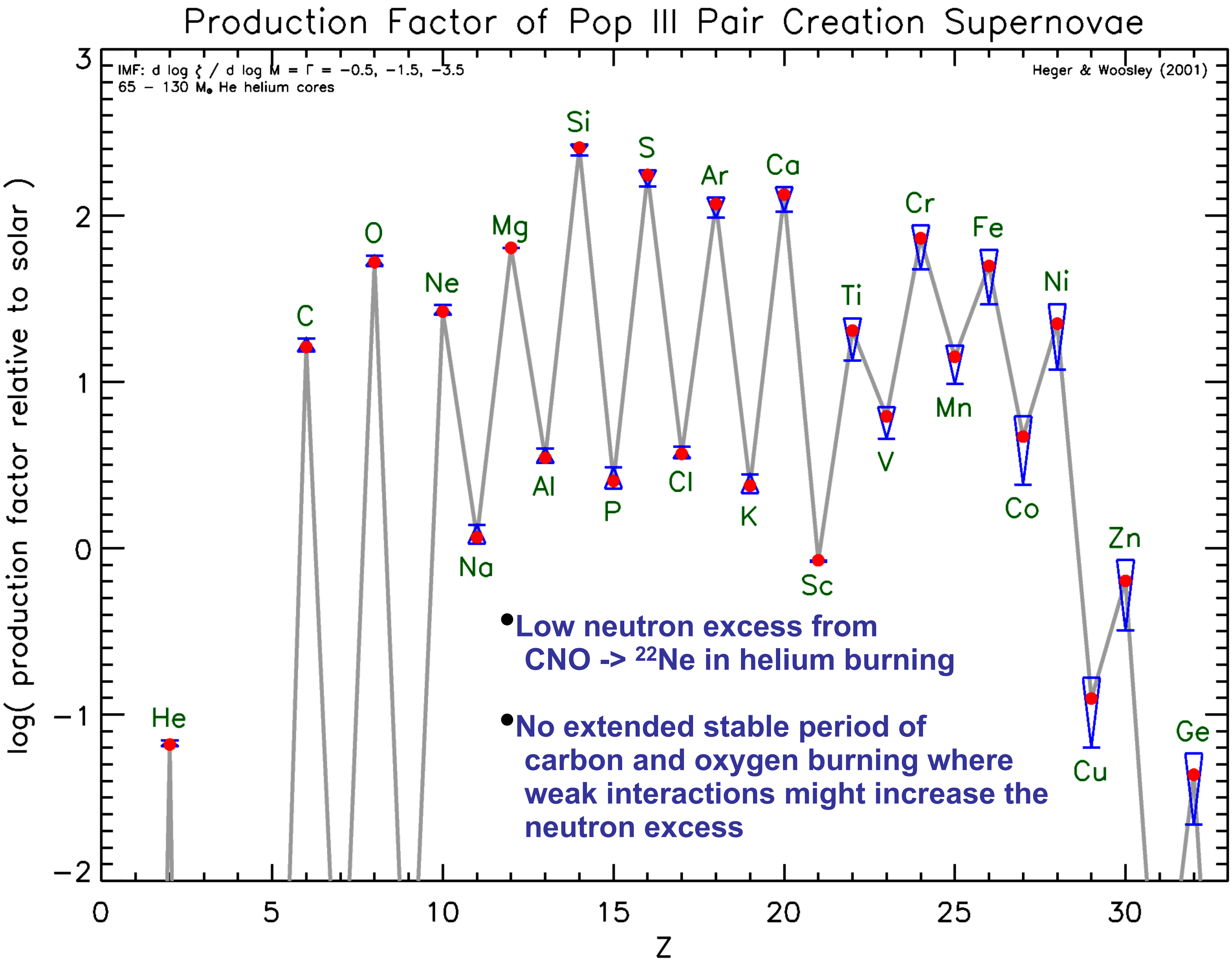


Takahashi+18

(from Ken Nomoto, Ringberg 2018)

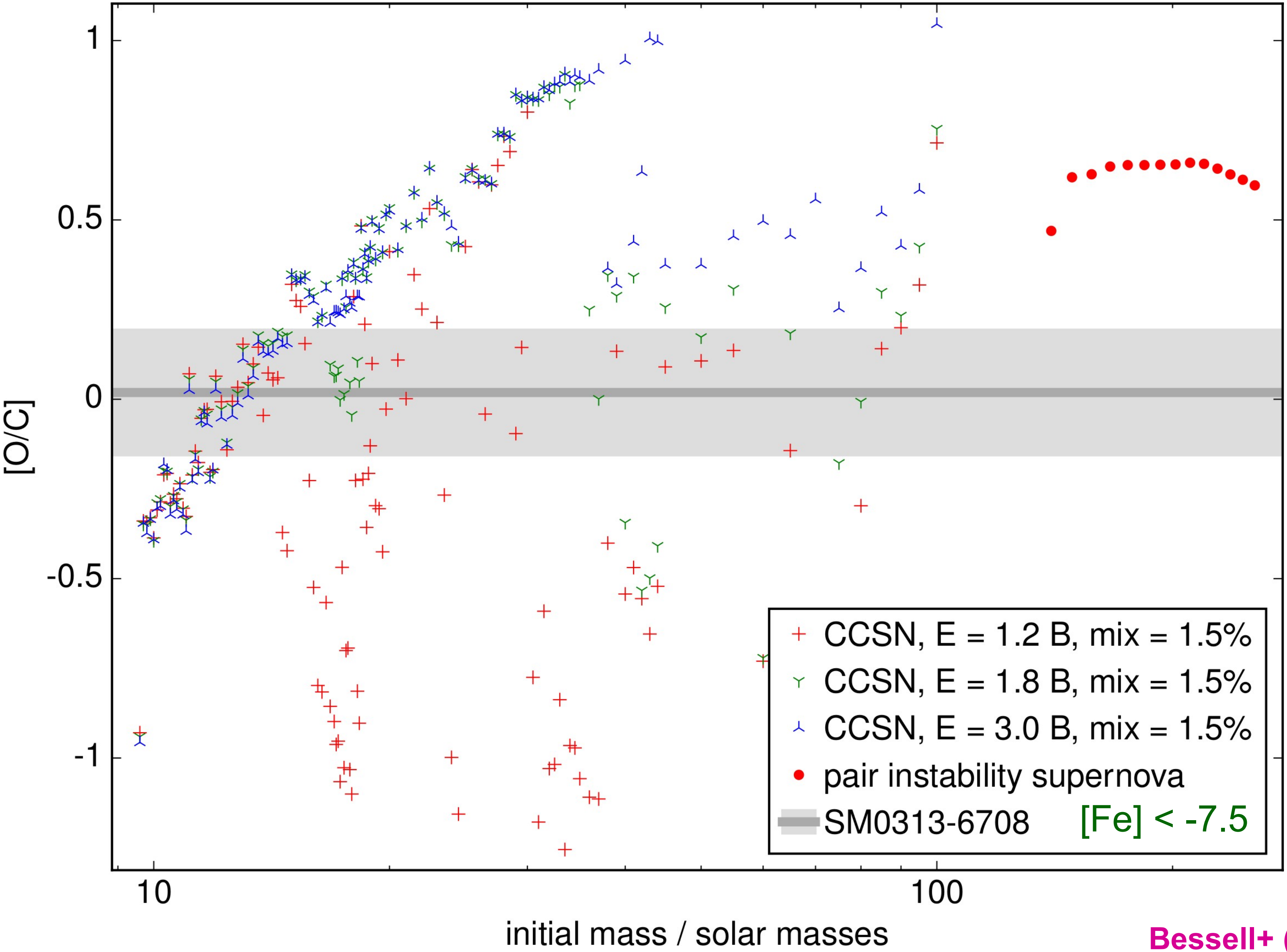


approximate
Initial total stellar mass / solar masses
140
200
260
Heger et al. (2000)
Fe-poor
Fe-rich
E_{expl}
^{12}C
^{16}O
^{24}Mg
^{28}Si
^{32}S
^{40}Ca
^{56}Ni
E_{expl}
yield / solar masses
0
10
20
30
40
50
explosion energy / B
0
20
40
60
80
70
80
90
100
110
120
130
helium core mass / solar masses

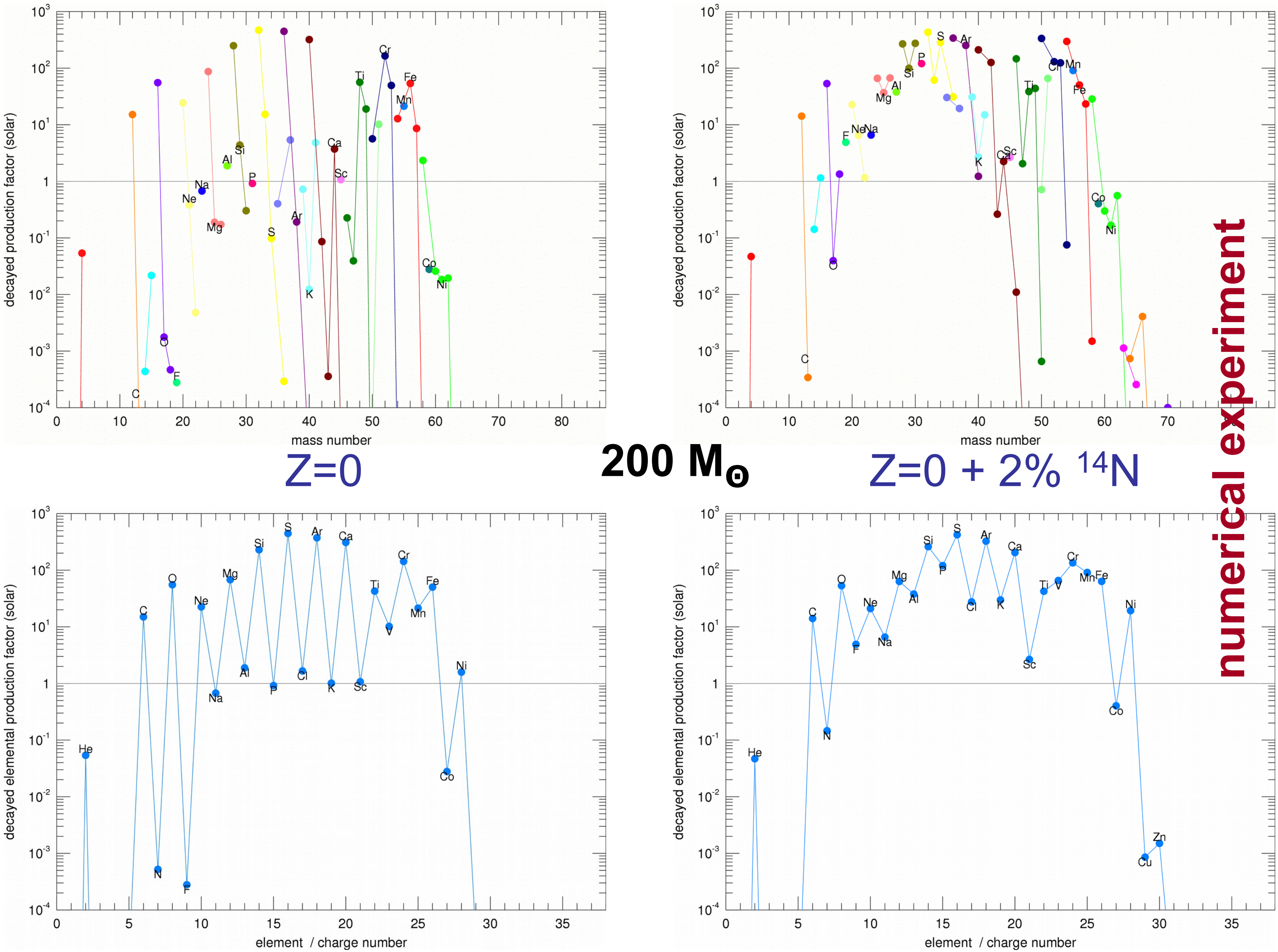


- **Low neutron excess from CNO -> ^{22}Ne in helium burning**
- **No extended stable period of carbon and oxygen burning where weak interactions might increase the neutron excess**

Constraints on SN and Progenitor from O/C

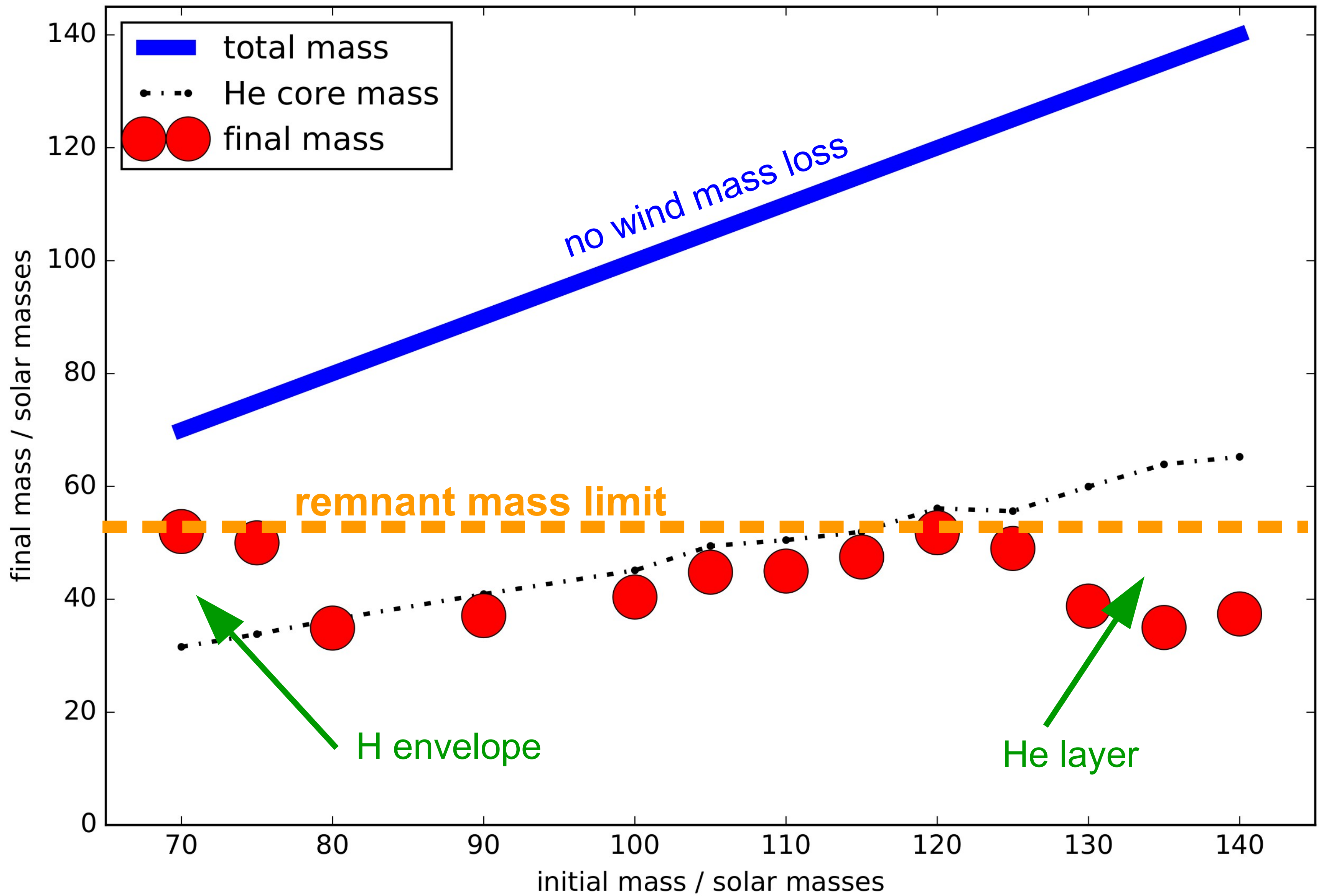


Bessell+ (2015)


200 M⊙
Z=0
Z=0 + 2% 14N
numerical experiment
decayed production factor (solar)
mass number
decayed elemental production factor (solar)
element / charge number
He C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn

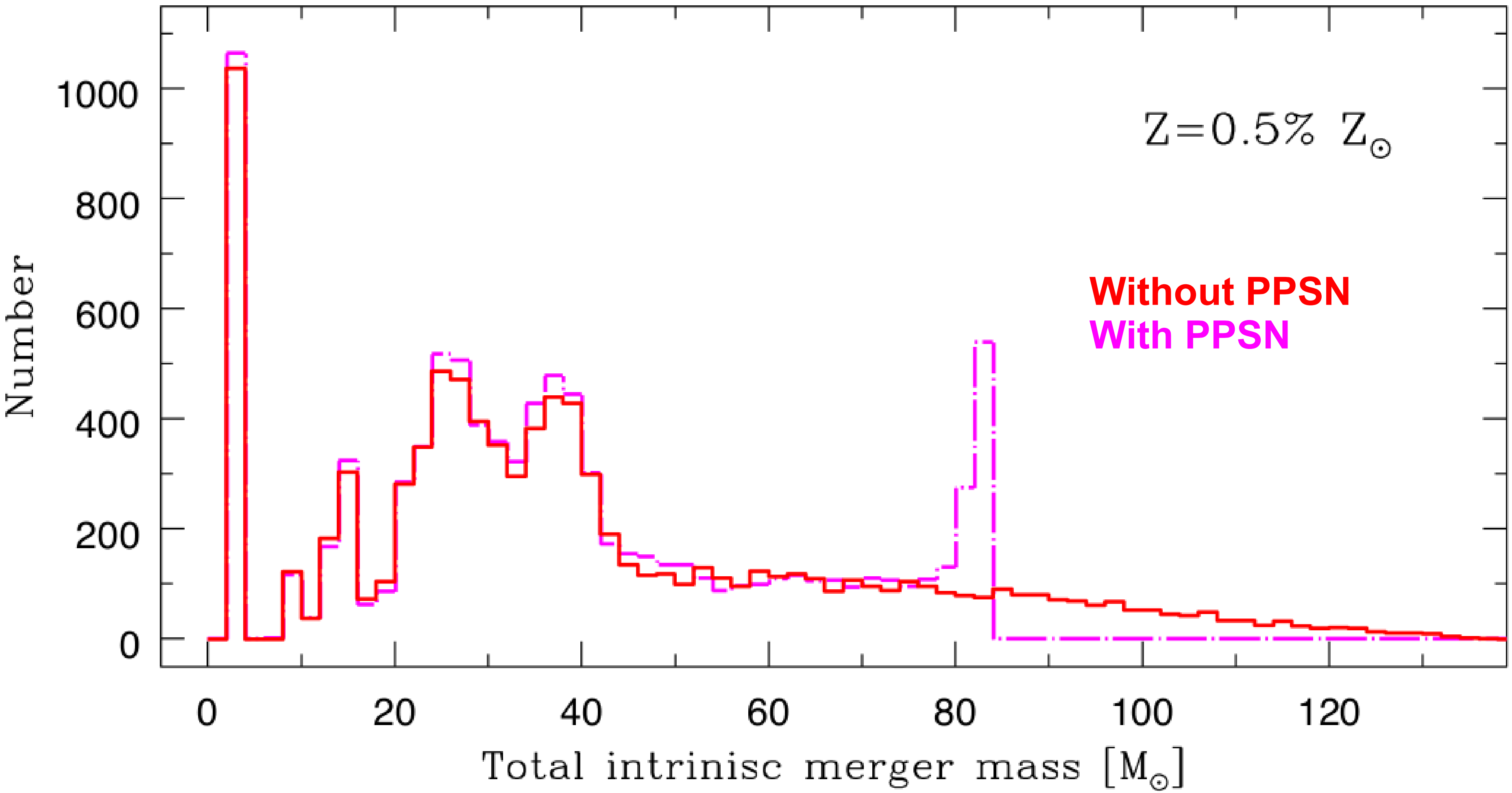
Pulsational Pair-Instability Supernovae

Pulsational Pair Instability Supernovae



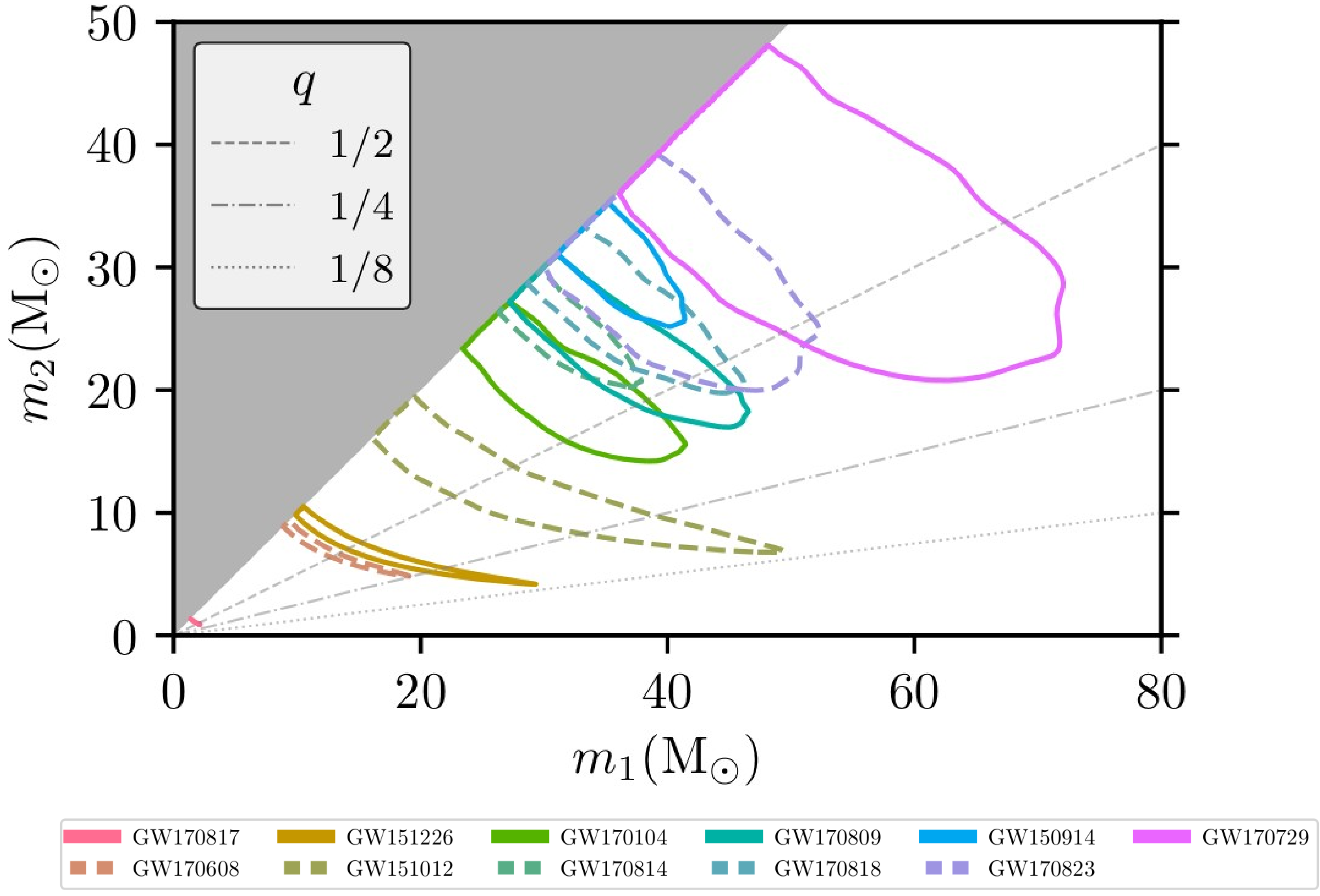
Plot after data from Woosley (2016)

Impact of Pulsational Pair Instability SN On Binary BH Merger Mass



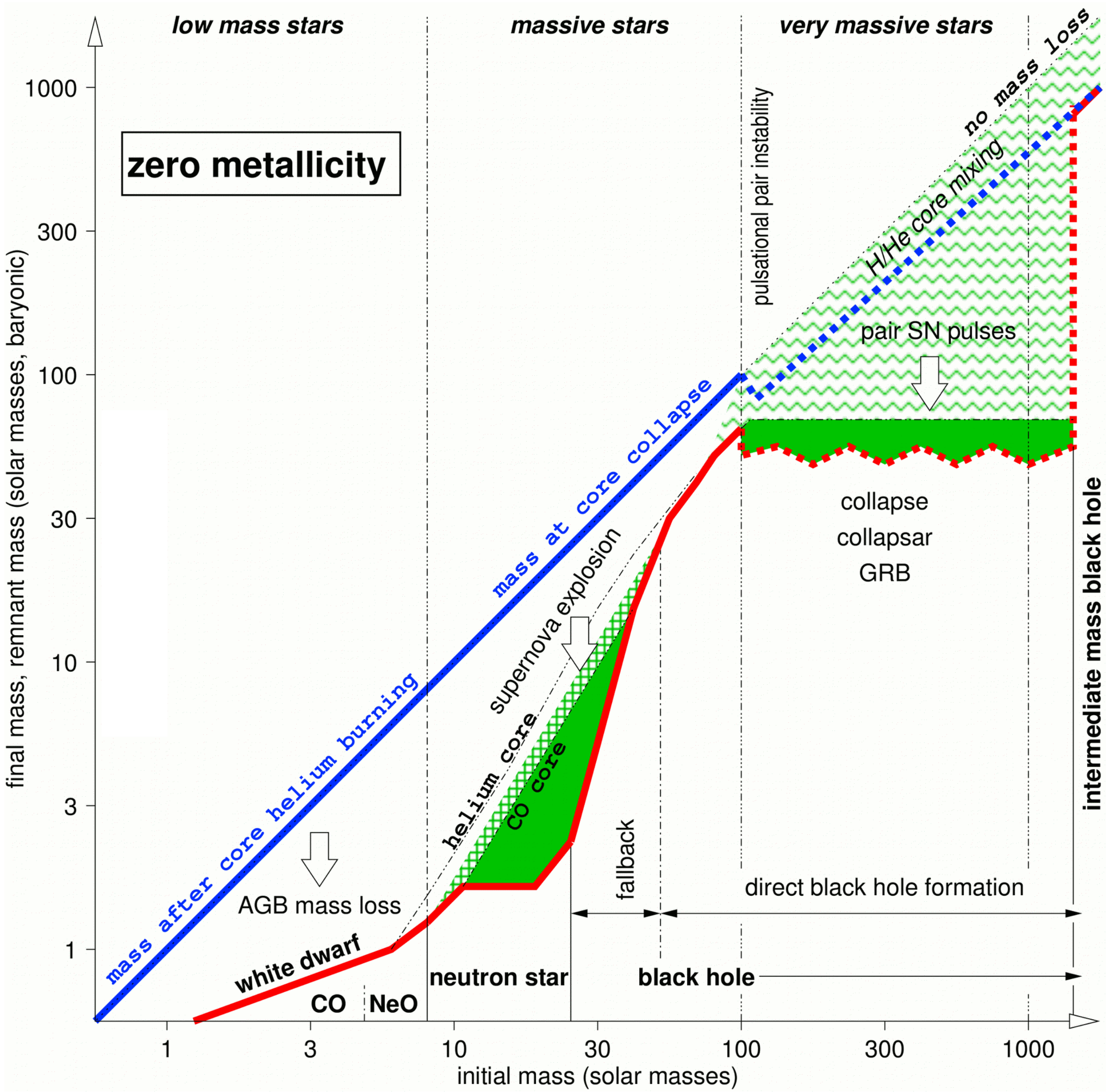
(Belczynski, Heger, Fryer, ... 2016)

Recent Results from LIGO



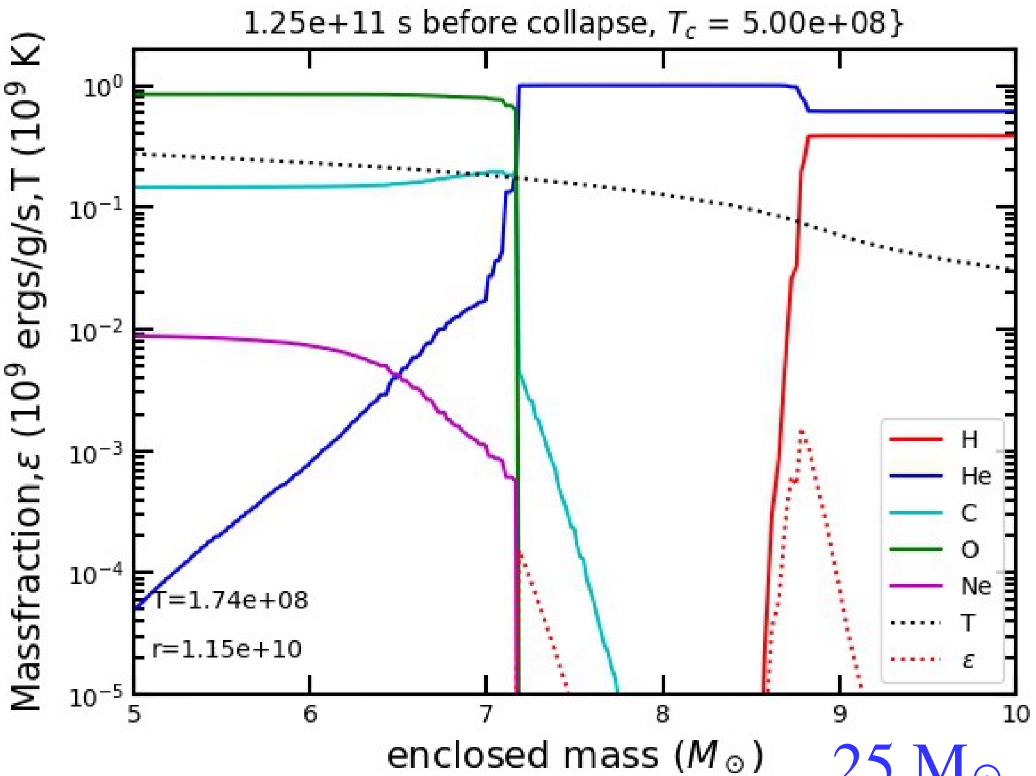
(LIGO Collaboration, arXiv:1811.12907)

[Pulsational] Pair Supernovae



Proton Ingestion

Proton Ingestion



(Bannerjee+ 2018)

25 $M_\odot$

Growth of convective He shell.

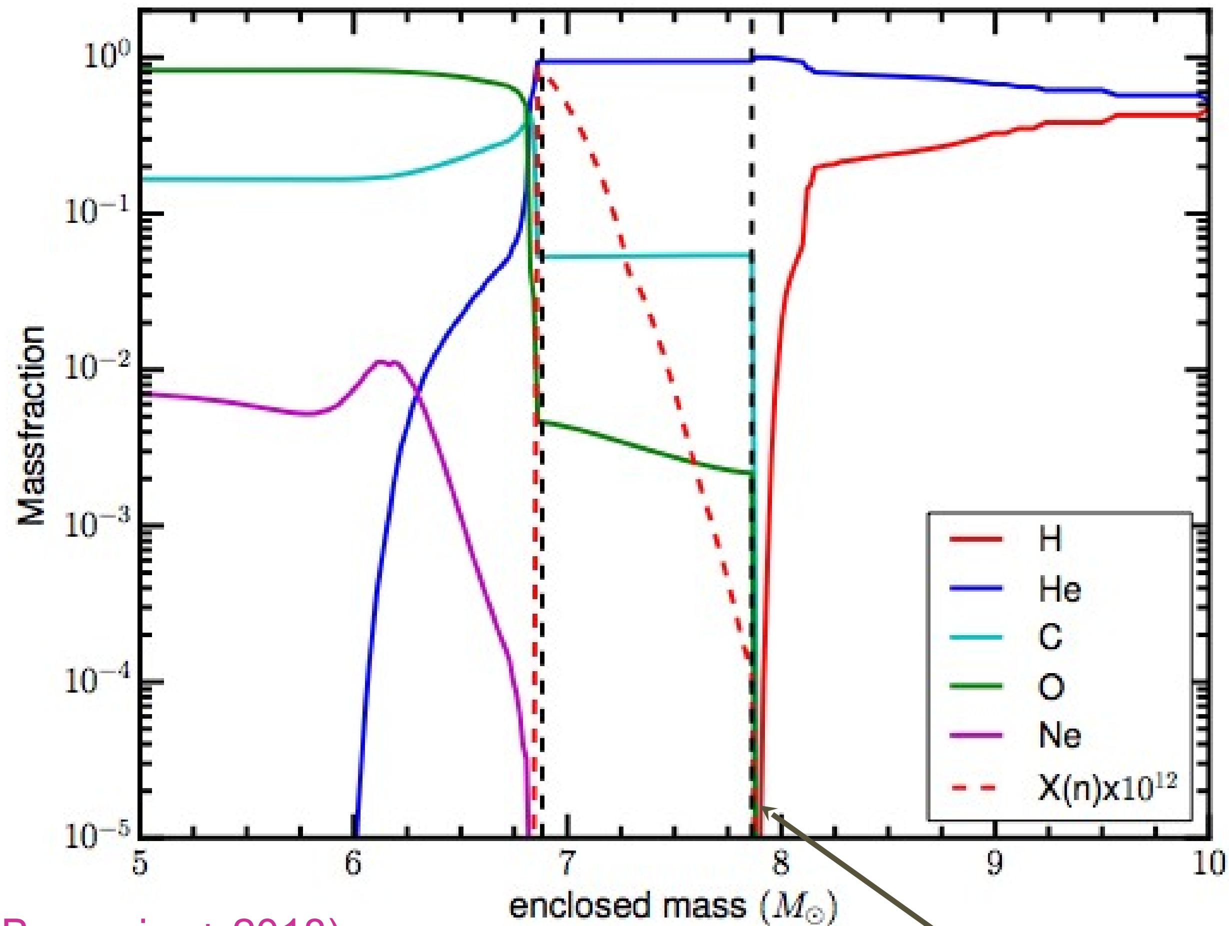
Mixing can occur at the convective boundary.

Including overshoot leads to 10^{-3}-10^{-5} $M_\odot$ of proton ingestion.

Occurs for 20 $M_\odot \lesssim M \lesssim 30\ M_\odot$.

Free Neutrons from Protons

10^5 s after p ingestion



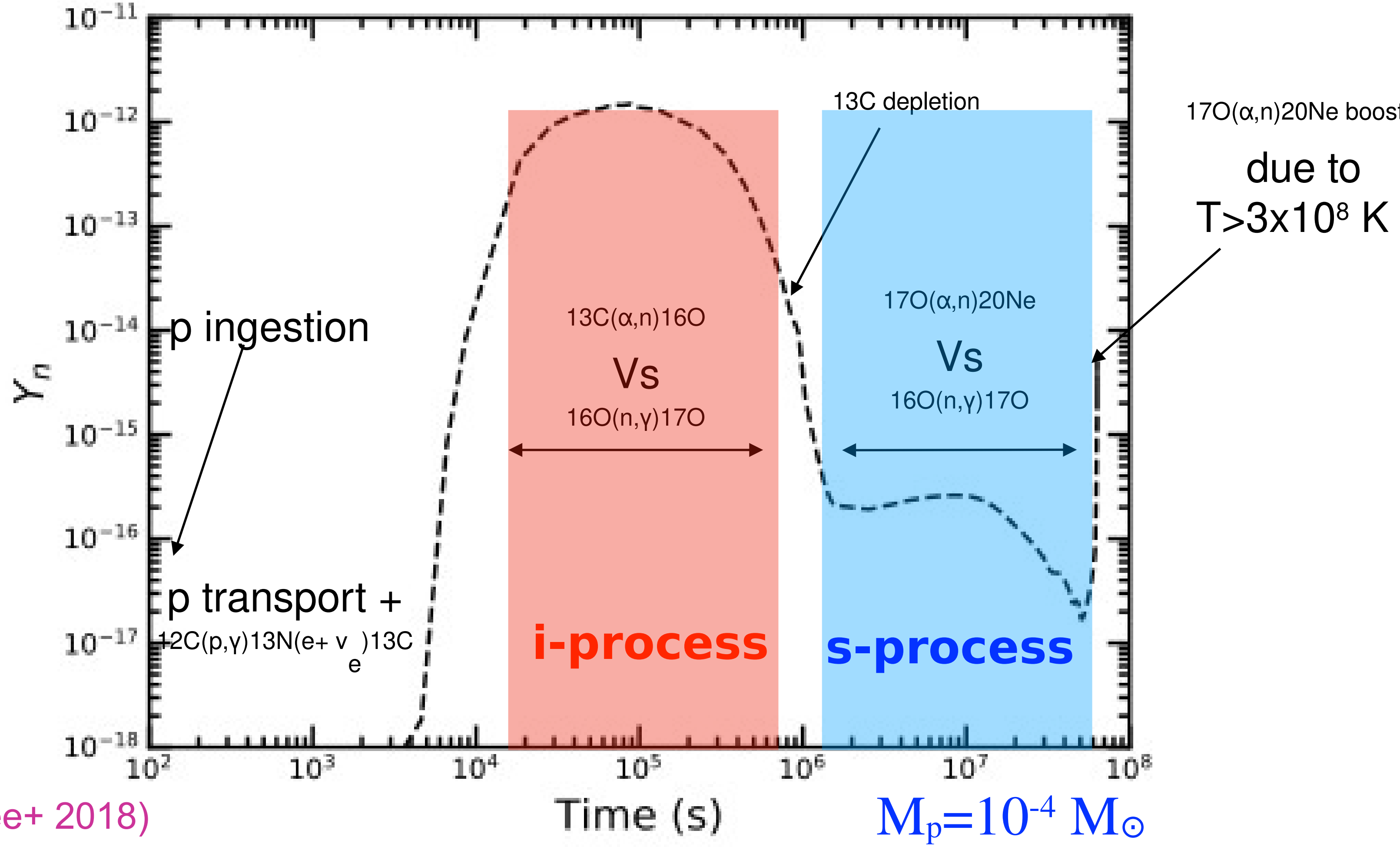
$M_p=10^{-4}\ M_\odot$

(Bannerjee+ 2018)

Single proton ingestion

Neutron production via $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(e^{+}\nu_e)^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$

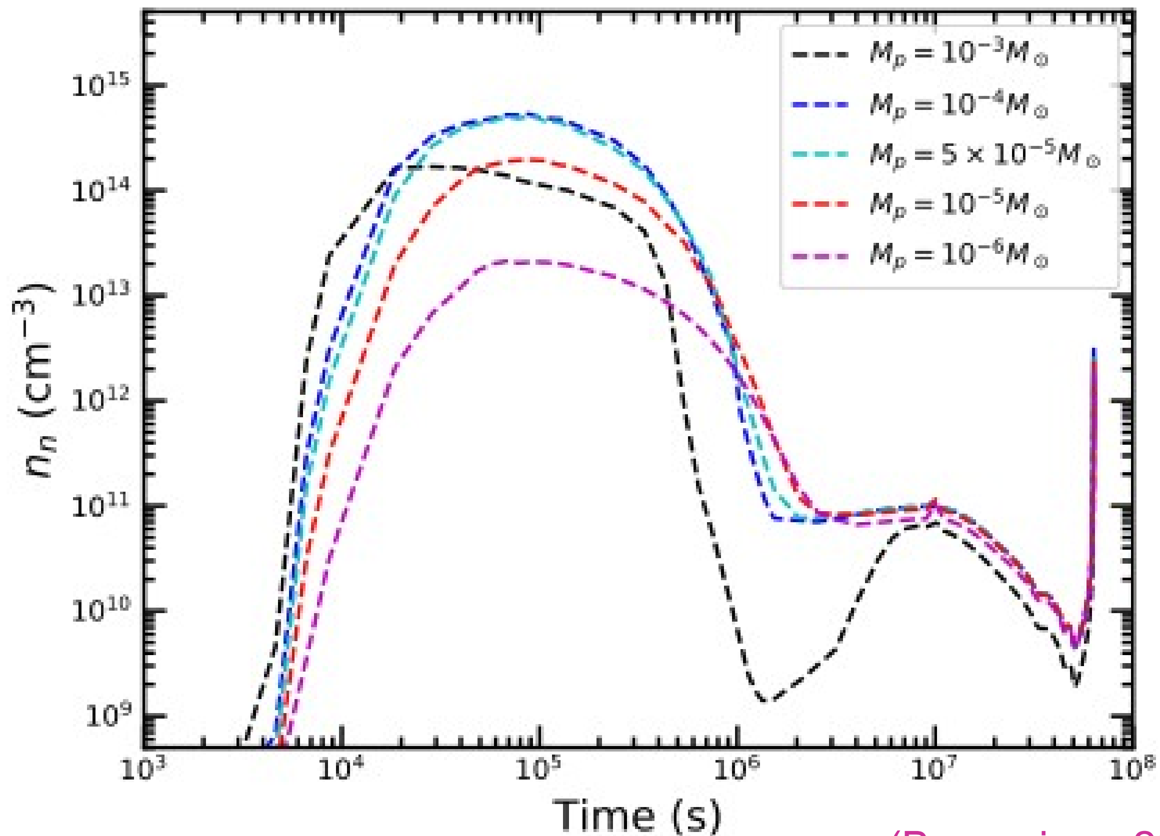
Free Neutrons from Protons



(Bannerjee+ 2018)

- **Mixing timescale ~5x10³ s.**
- Initially Y_n increases on a timescale of ~10⁴ s.
- Then Y_n decreases on a timescale of ~10⁵ s.
- Most of the neutrons captured by ^{16}O.
- **Primary neutron production**

Effect of Amount of Proton Ingestion

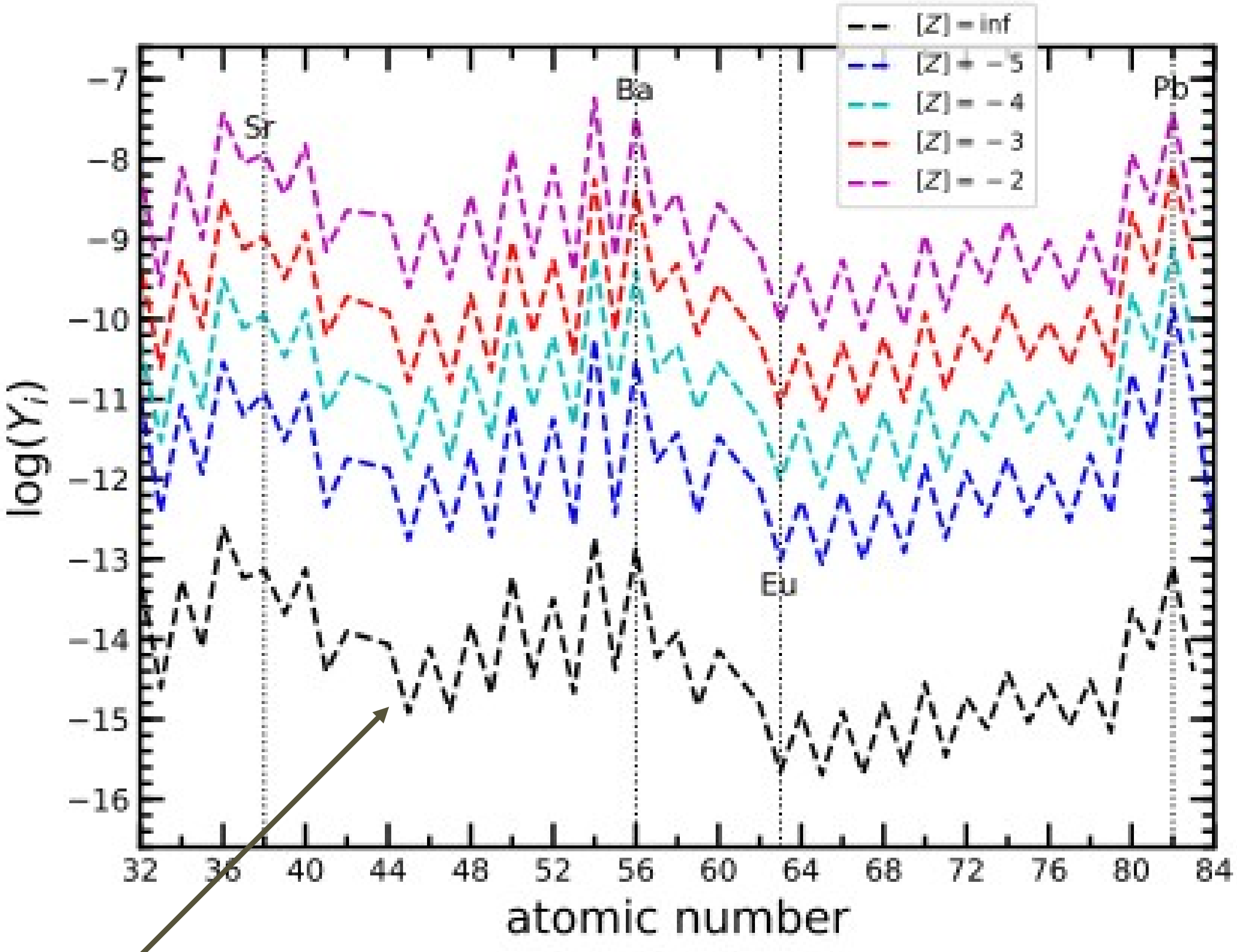


25 $M_\odot$

(Bannerjee+ 2018)

- **Neutron abundance depends on the amount of p ingestion**
- Peak $n_n > 10^{14}$ cm^{-3} density $10^{-3} \gtrsim M_p \gtrsim 10^{-5}$ $M_\odot$.
- Peak density decreases sharply for $M_p \lesssim 10^{-5}$ $M_\odot$.

Effect of Progenitor Metallicity



Z=0 yield similar to [Z] ∼ -7.5

$M_p = 10^{-4} M_{\odot}$

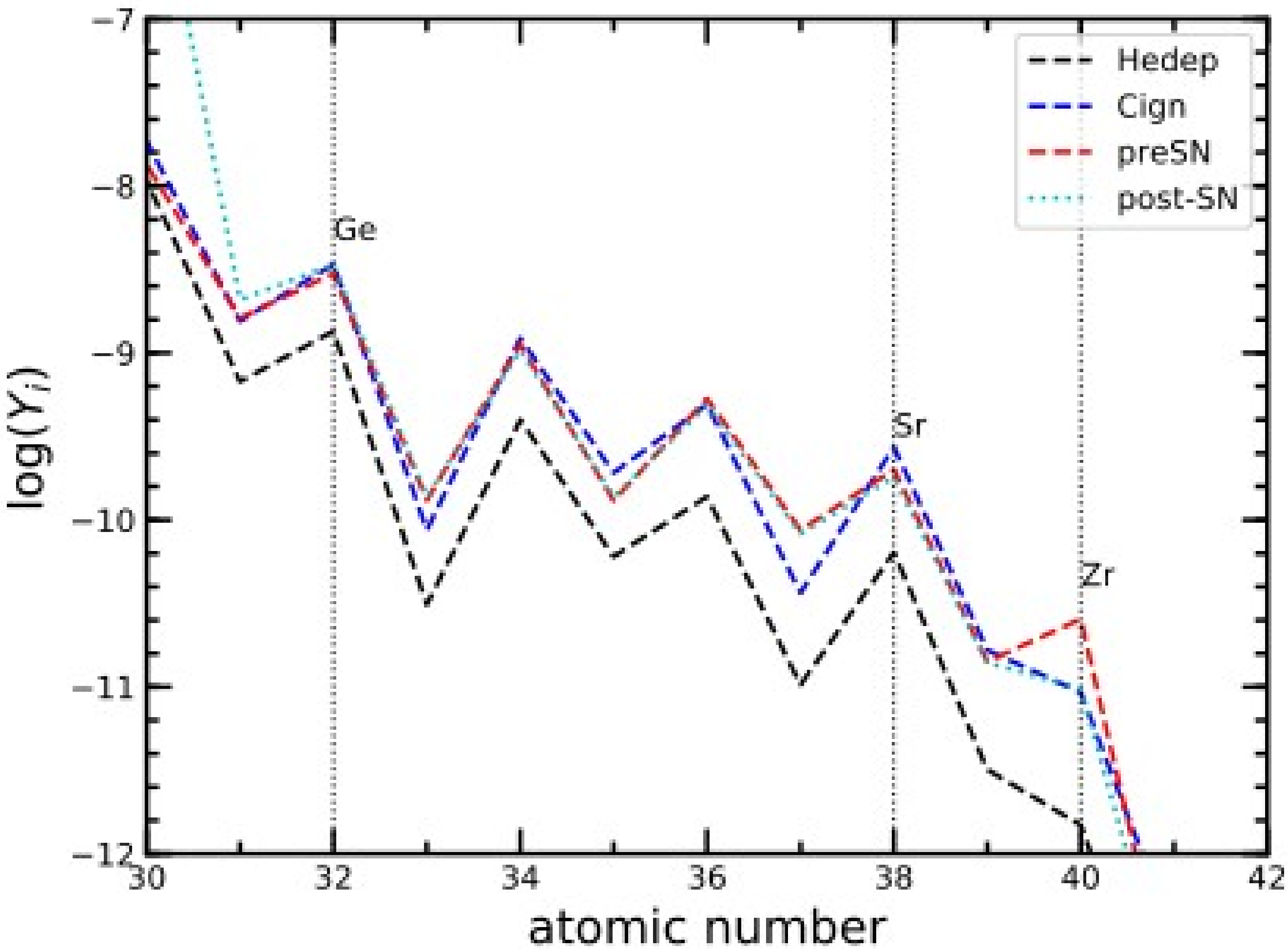
(Bannerjee+ 2018)

Massive CEMP Stars

Massive CEMP Stars

- Born with enhanced C (and N, O).
- Initial CNO converted to ^{14}N during H burning.
- ^{14}N is then converted in to ^{22}Ne during He burning.
- Neutrons from ^{22}Ne(α,n)^{25}Mg during late He burning.
- Low "metallicity" version of weak s-process.

Time Evolution

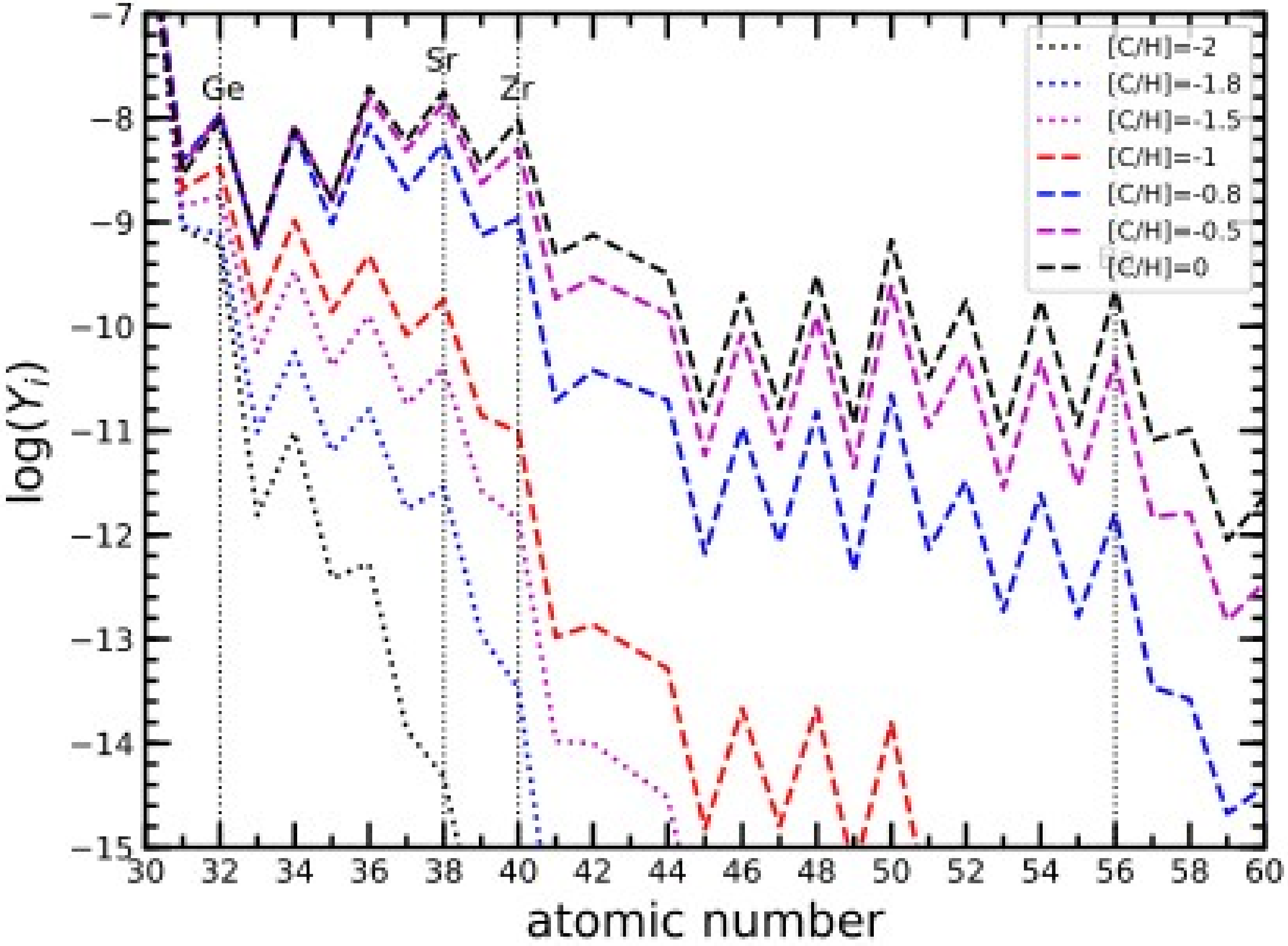


25 M☉, [Fe/H]=-3 [C/H]=-1

(Bannerjee+ 2018)

Most of the s-process occurs during the late stages of core He burning

[C/H] Dependence



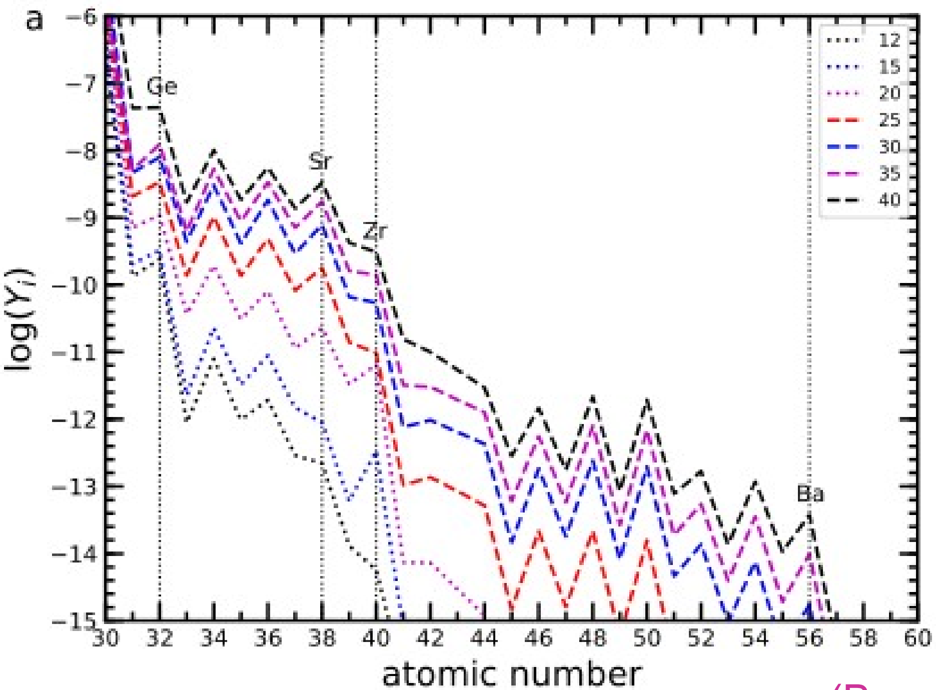
25 M⊙, [Fe/H]=-3

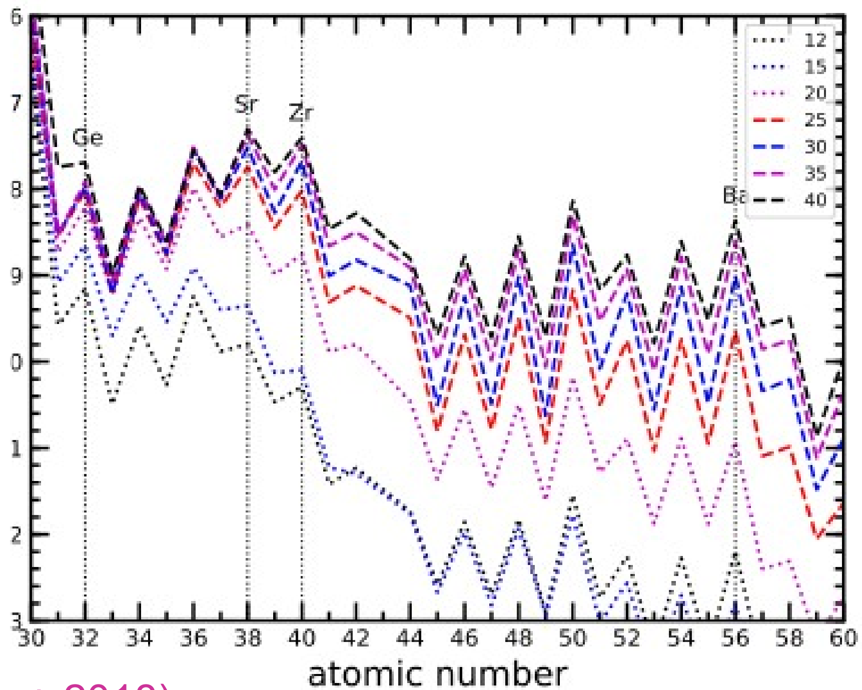
(Bannerjee+ 2018)

Primary ^{16}O major poison for [C/H]≲-1
Secondary $^{25,26}Mg$ major poisons for [C/H]≳-1
Secondary poisons scale mostly with [C/H] and not with [Fe/H].

Mass Dependence

[Fe/H]=-3





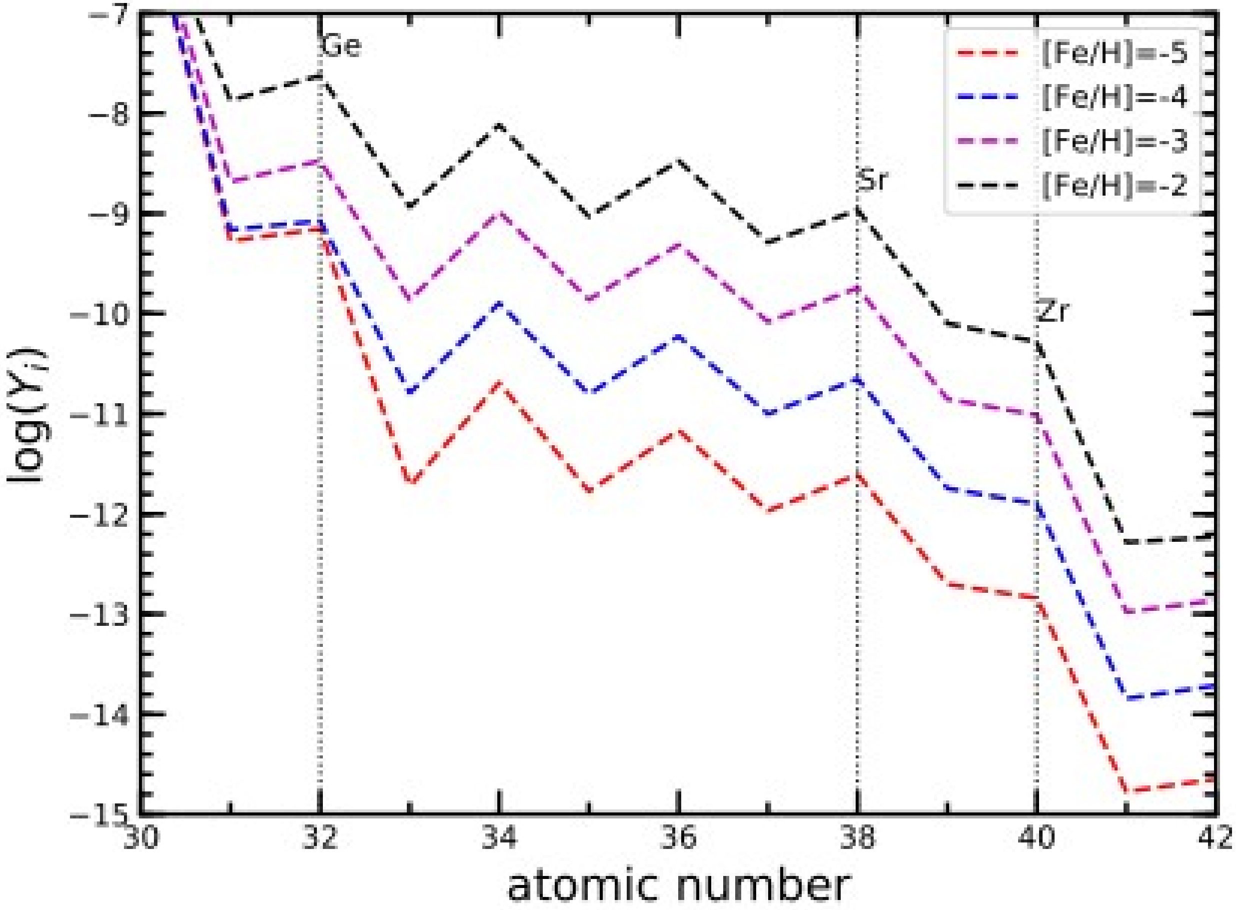
(Bannerjee+ 2018)

[C/H]=-1

[C/H]=0

More efficient for higher mass stars

[Fe/H] Dependence



25 $M_\odot$
[C/H]=-1

(Bannerjee+ 2018)

Scales almost linearly with [Fe/H]

Questions

- There is strong variations in massive star evolution and nucleosynthesis outcomes as a function of mass, and implicitly rotation, even “weather”.
- Nucleosynthesis contributions may not be present or unique for all masses, complicating *direct* IMF reconstruction
- Do Pair-Instability Supernovae exist?
  If so, is the odd-even effect washed out by mixing during He burning?
- Impact of mixing and ingestion? Contribution of massive CEMP stars to nucleosynthesis in UMP stars?
- We may learn about fates of the most massive stars from binary black hole populations, including BH IMF.