A Celebration of CEMP and a Gala of GALAH
Monash University, Australia, 14 November 2017

Nucleosynthesis in the First Stars

I have the the purest stars ...

MoCA
Monash Centre for Astrophysics

MONASH University

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Bernhard Müller (Monash)
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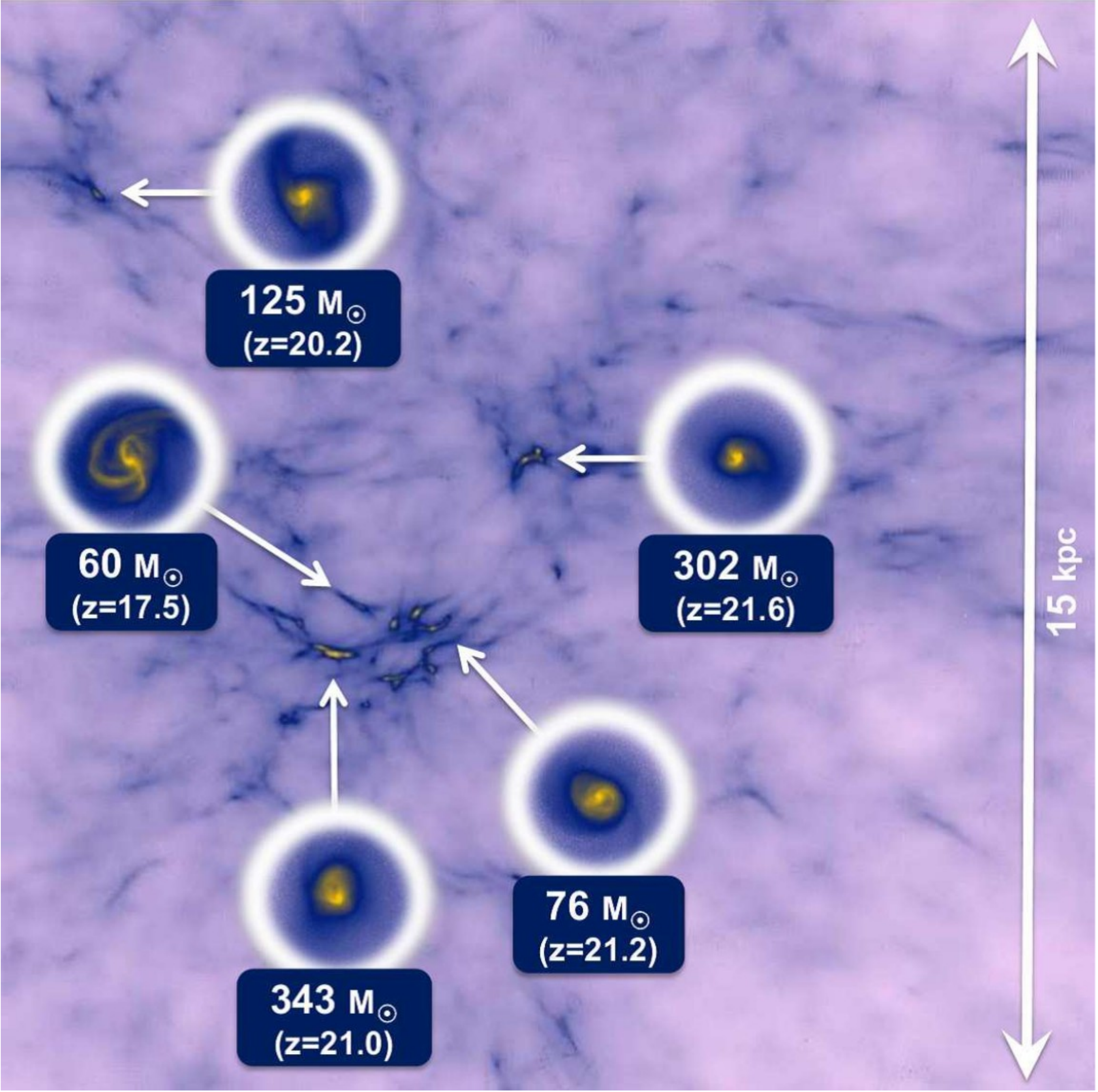
Ken Chen (AASIA)

http://CosmicExplosions.org

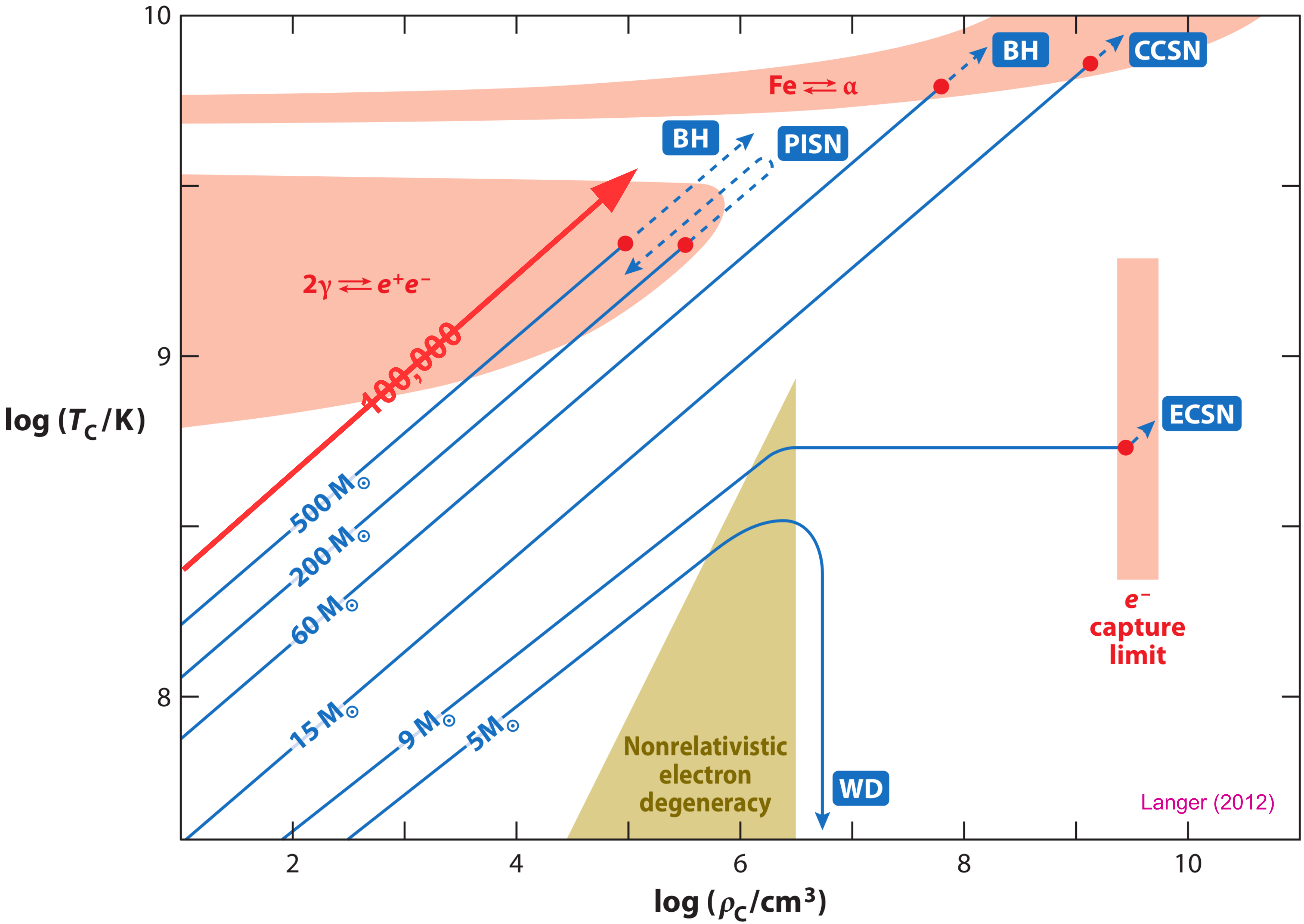
The Forge of Big Stars: Then and Now

Formation Environment of the First Stars



(Hirano et al. 2013)

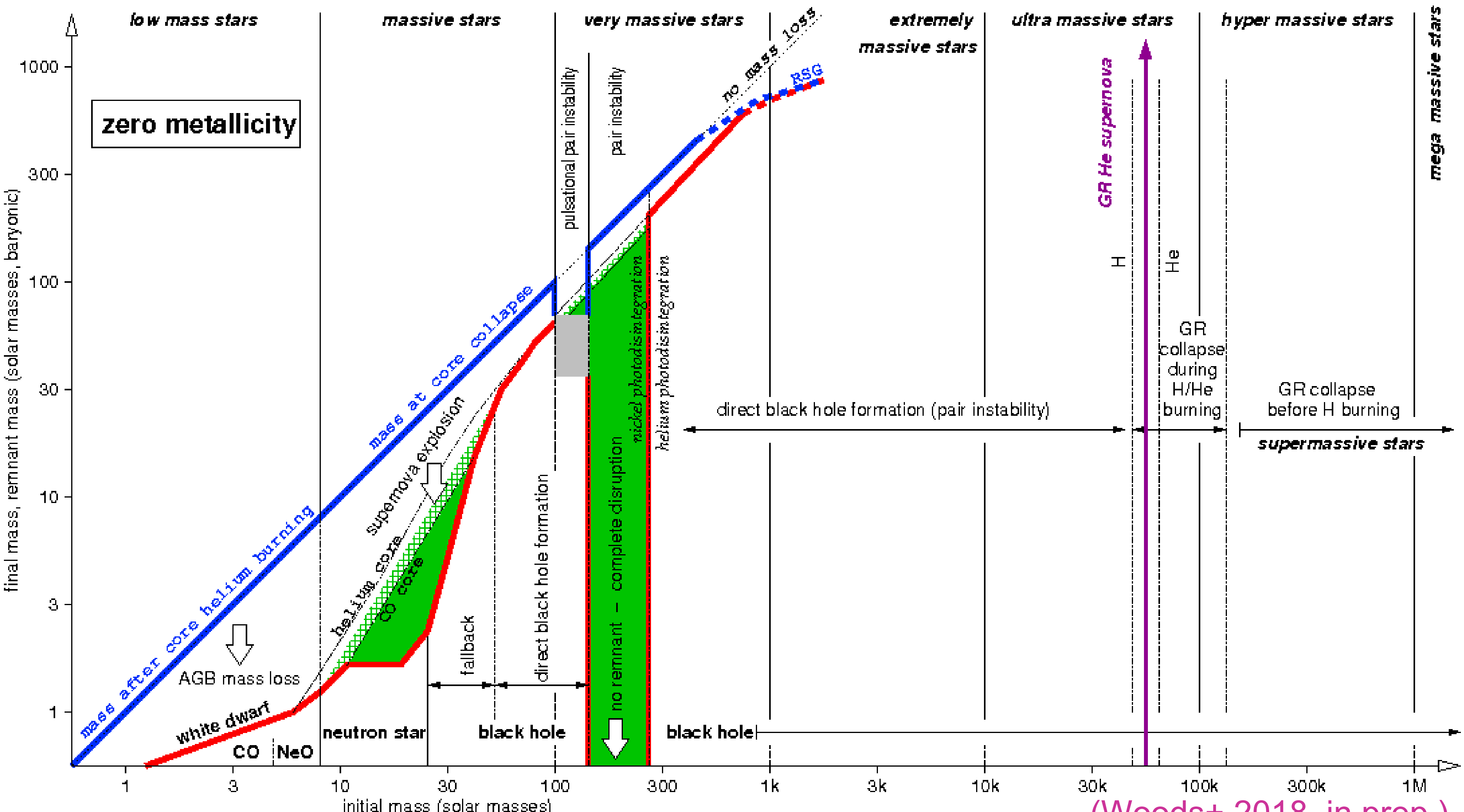
Evolution of Center for Different Initial Masses



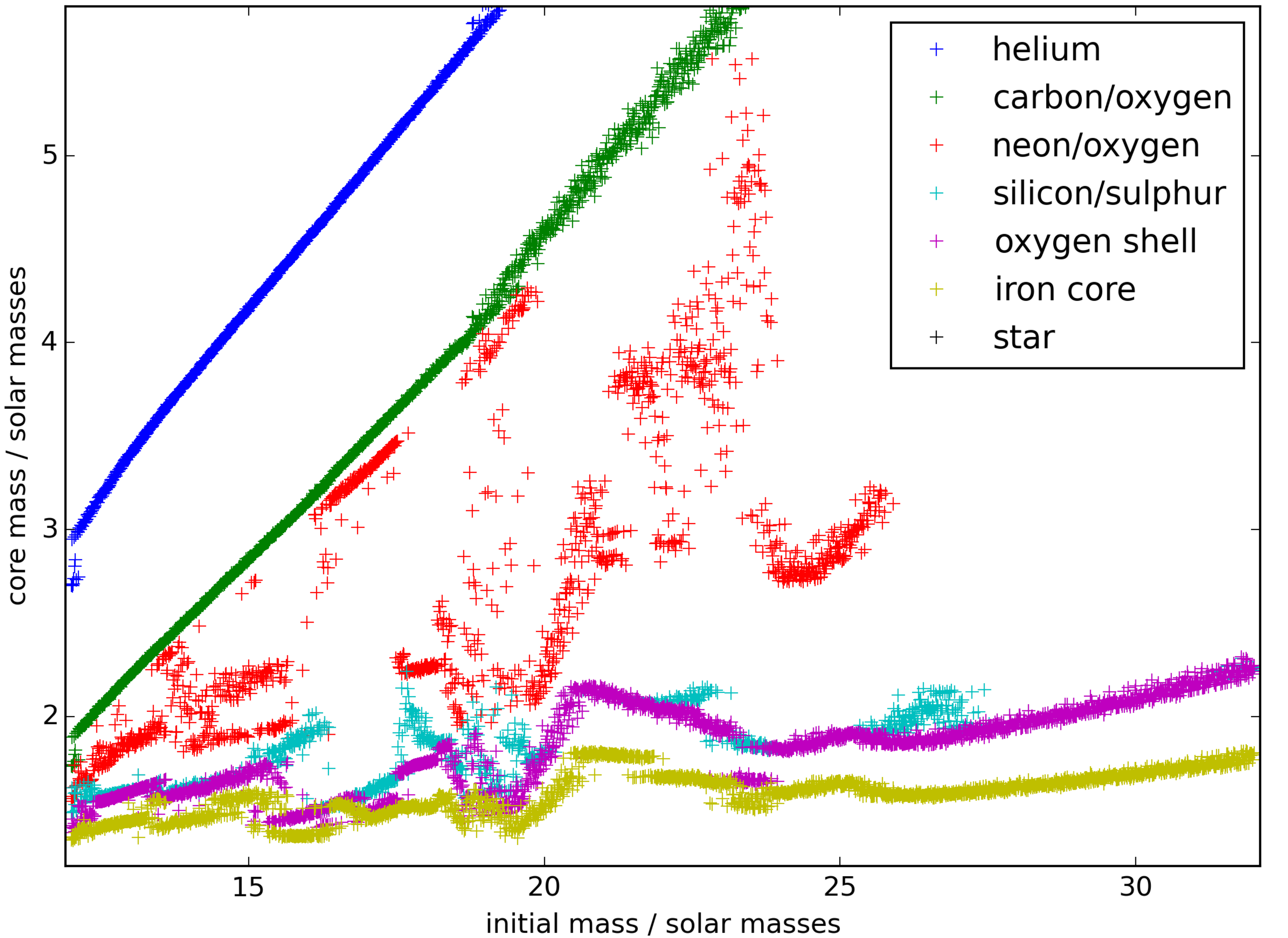
Nuclear Burning Stages

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}

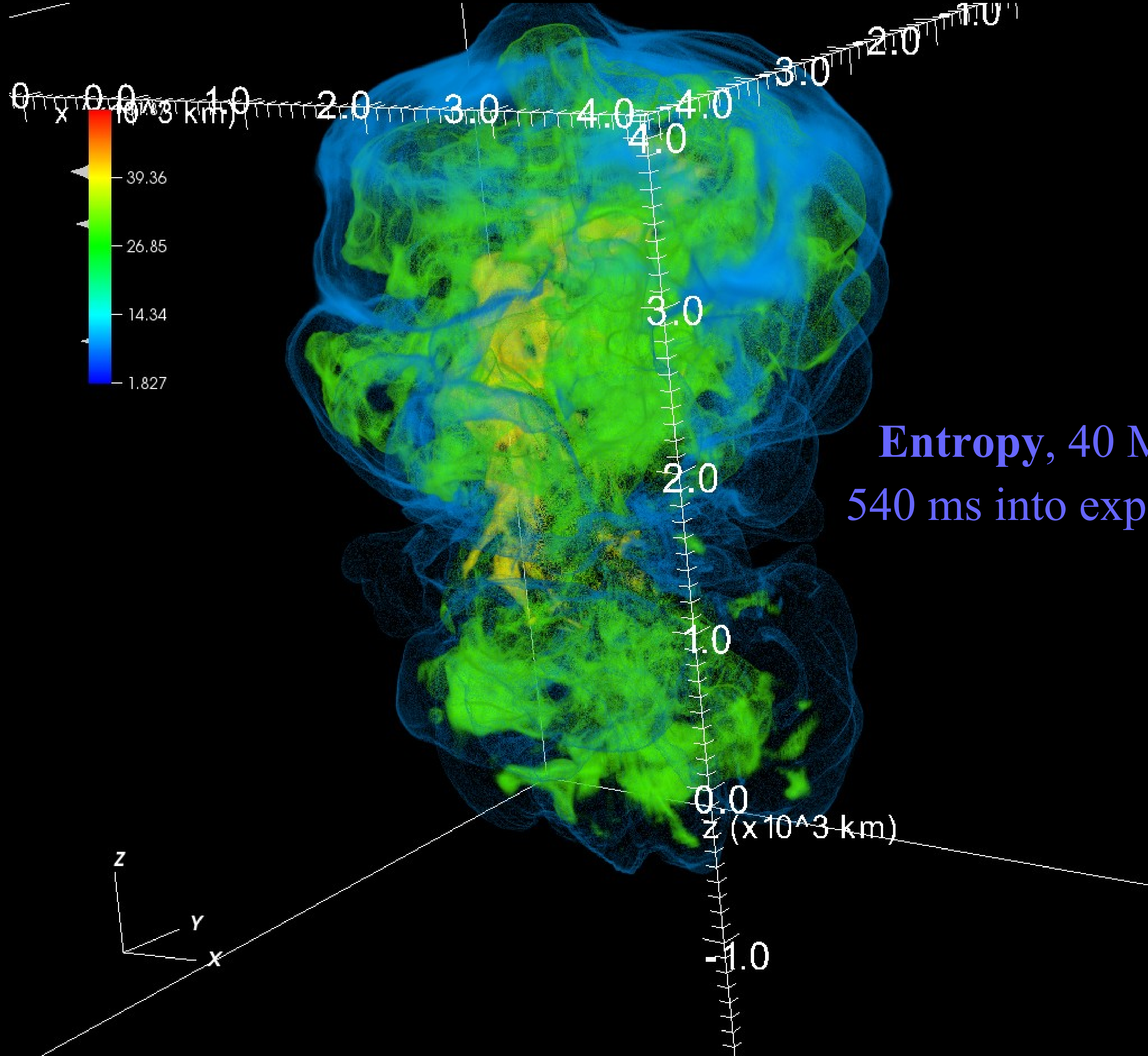
Supermassive Stars



(Woods+ 2018, in prep.)


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

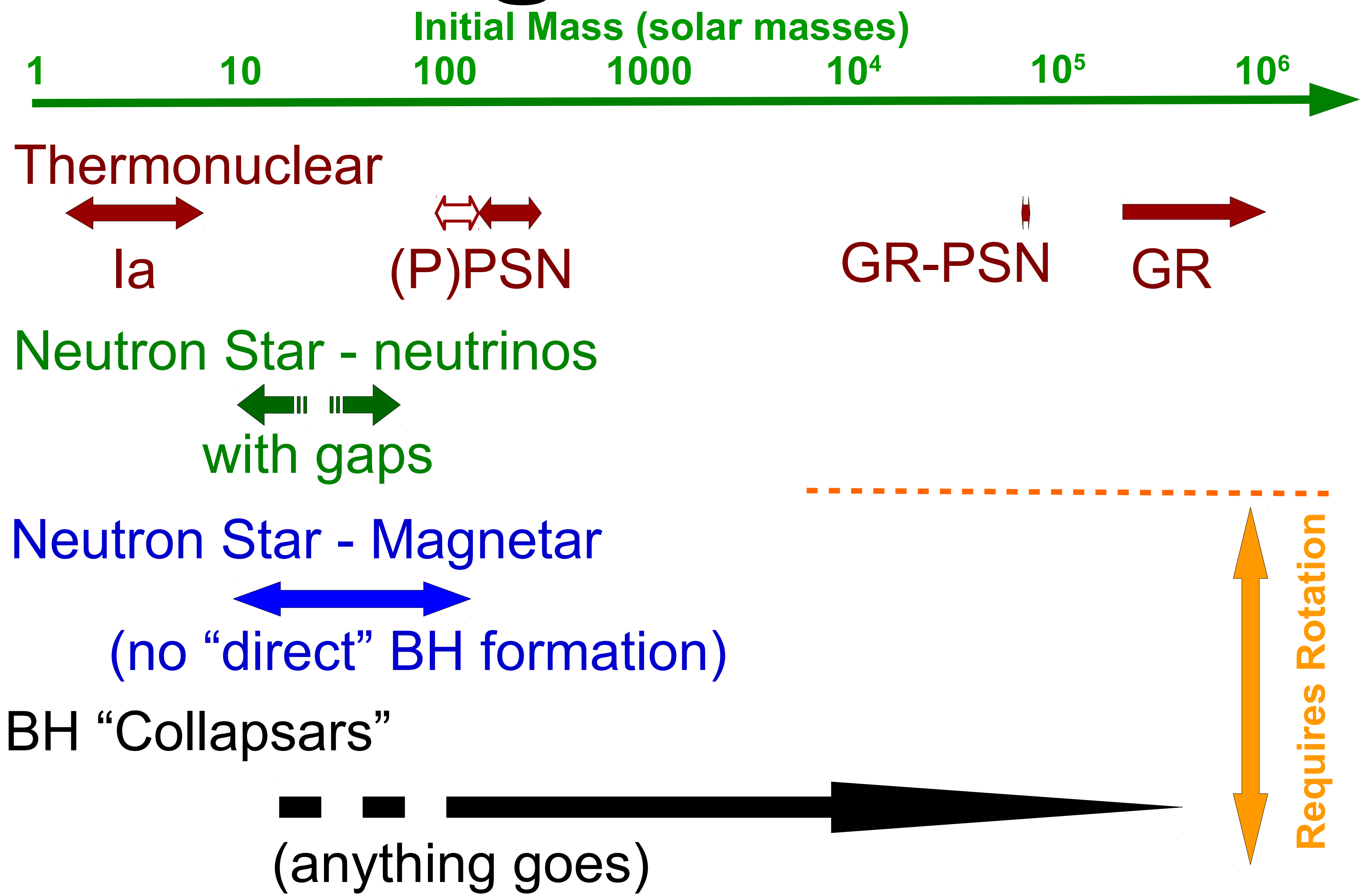

The
Death
of the
Stars



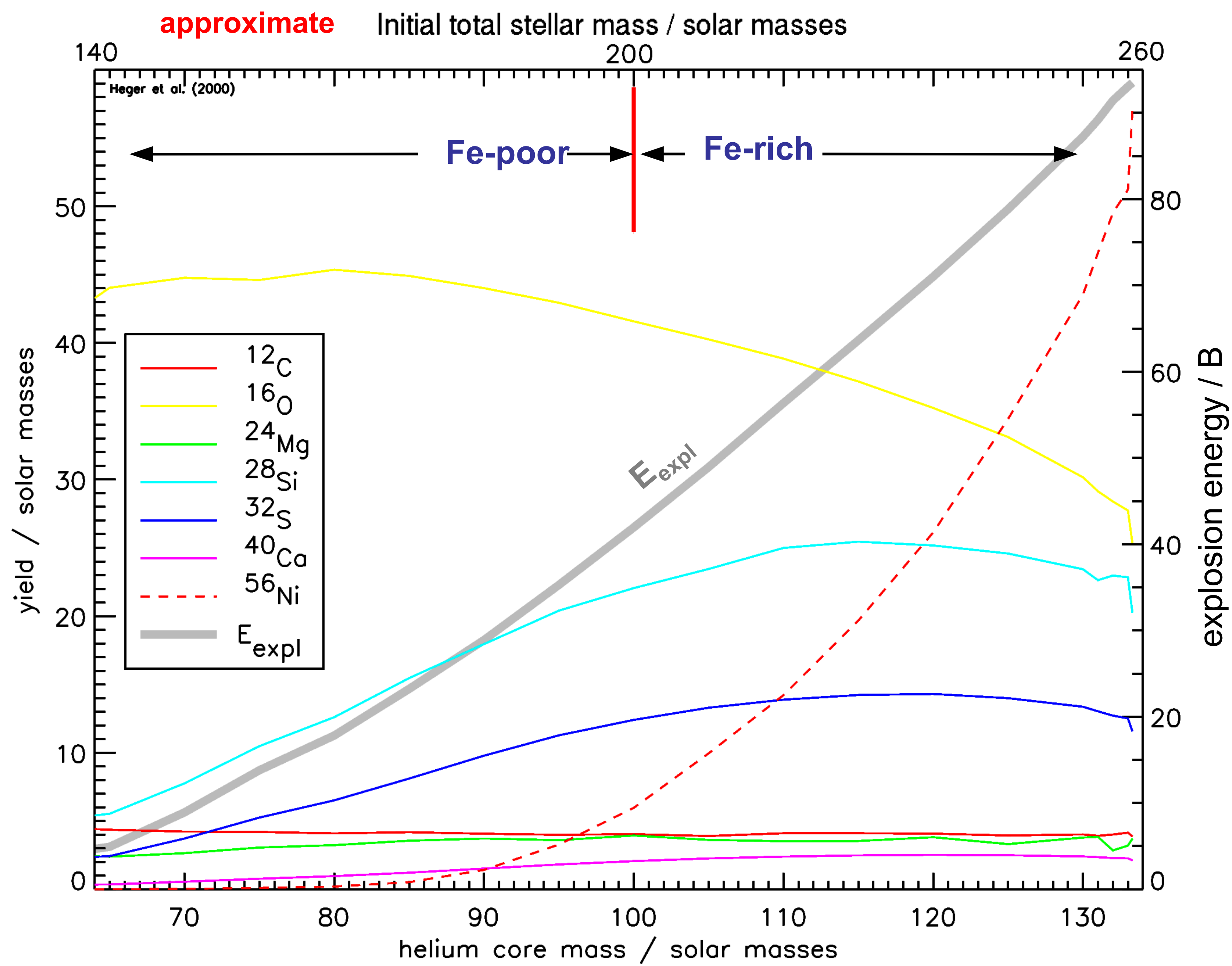
Entropy, 40 M_o star
540 ms into explosion

Mueller, Chan, Heger 2017 in prep.

The Engines of SNe

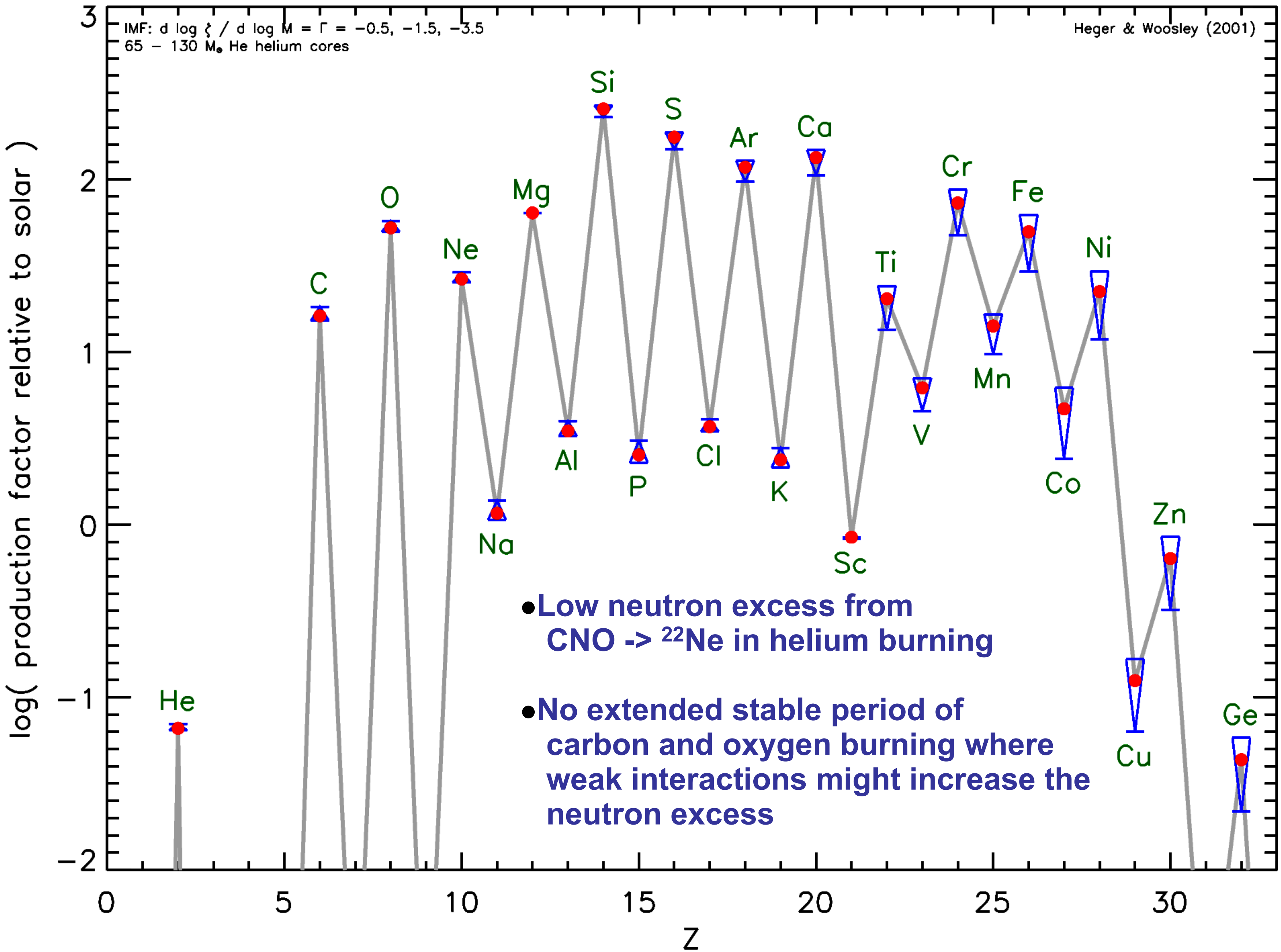


Pair-Instability Supernovae



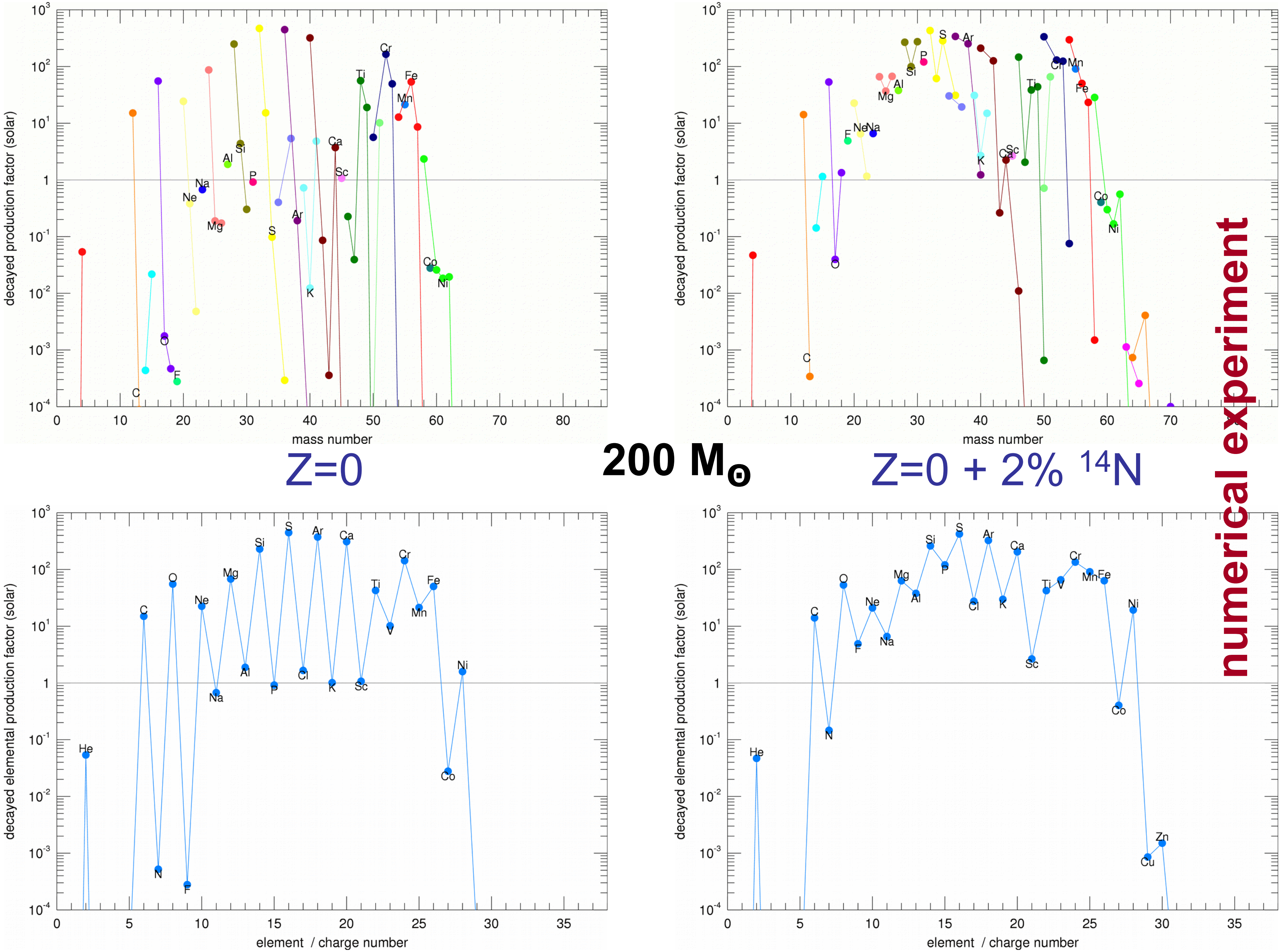
approximate
Initial total stellar mass / solar masses
140
200
260
Heger et al. (2000)
Fe-poor
Fe-rich
E_{expl}
^{12}C
^{16}O
^{24}Mg
^{28}Si
^{32}S
^{40}Ca
^{56}Ni
E_{expl}
yield / solar masses
explosion energy / B
0
10
20
30
40
50
0
20
40
60
80
70
80
90
100
110
120
130
helium core mass / solar masses

Production Factor of Pop III Pair Creation Supernovae



➔Problem

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


decayed production factor (solar)
mass number
decayed elemental production factor (solar)
element / charge number
Z=0
200 M$_\odot$
Z=0 + 2% ^{14}N
numerical experiment
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 **Nucleosynthesis**

Pulsational Pair Instability Supernovae

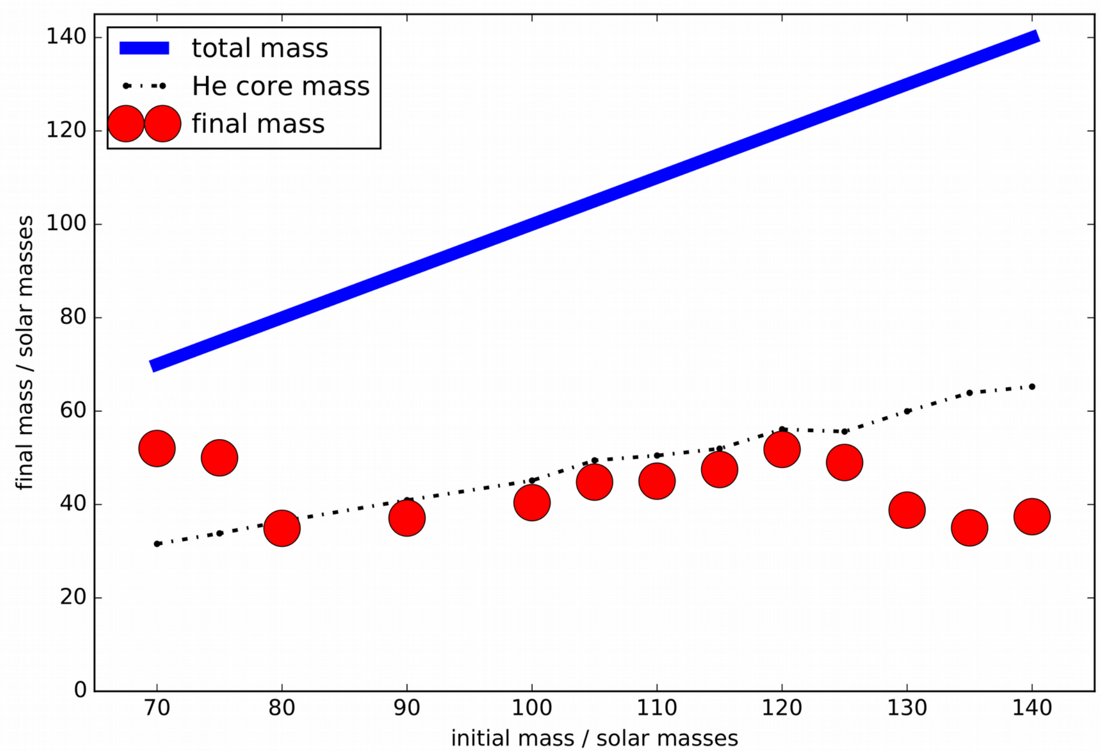
Only outer layers are ejected

→ no iron group elements synthesised are ejected

→ only up to intermediate-mass nuclei

→ abundance pattern could be consistent with Fe-free stars!

→ but exact abundance pattern may depend on uncertain pre-SN mixing physics.



Plot after data from Woosley (2016)

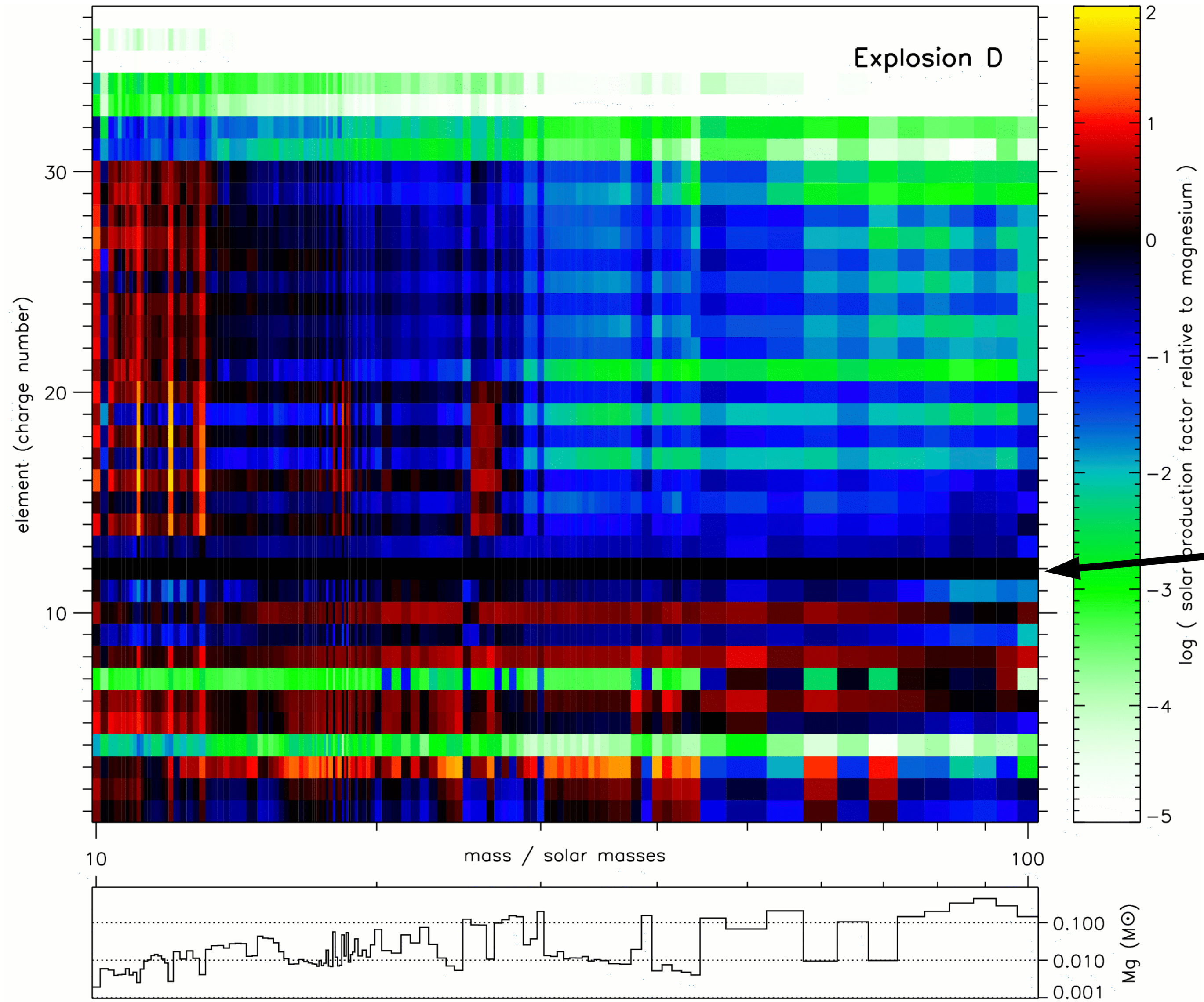
Nucleosynthesis for EMP Stars

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)

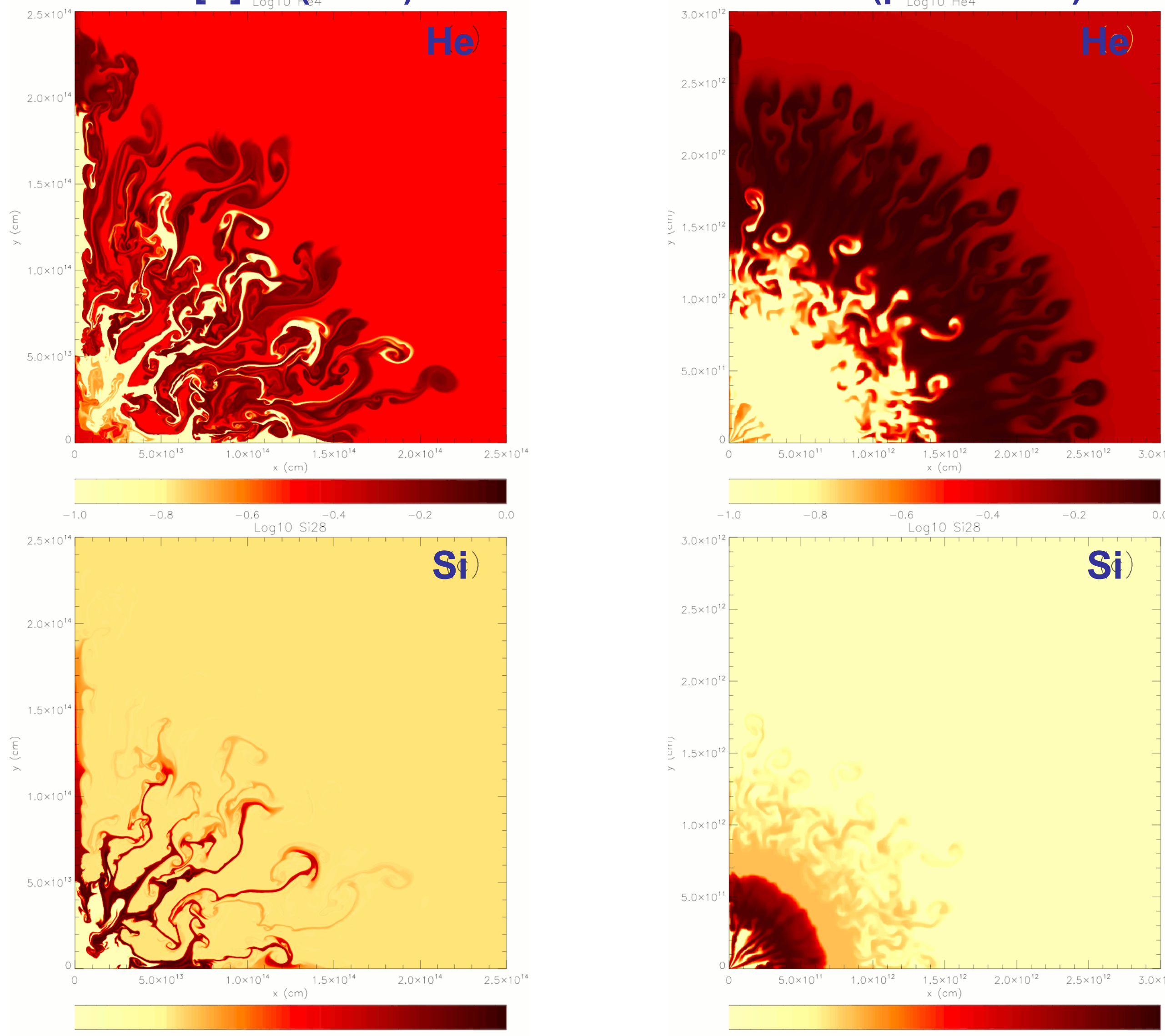
Mixing in 25 $M_\odot$ Stars

Growth of Rayleigh-Taylor instabilities

Interaction of instabilities (mixing) and fallback determines nucleosynthesis yields

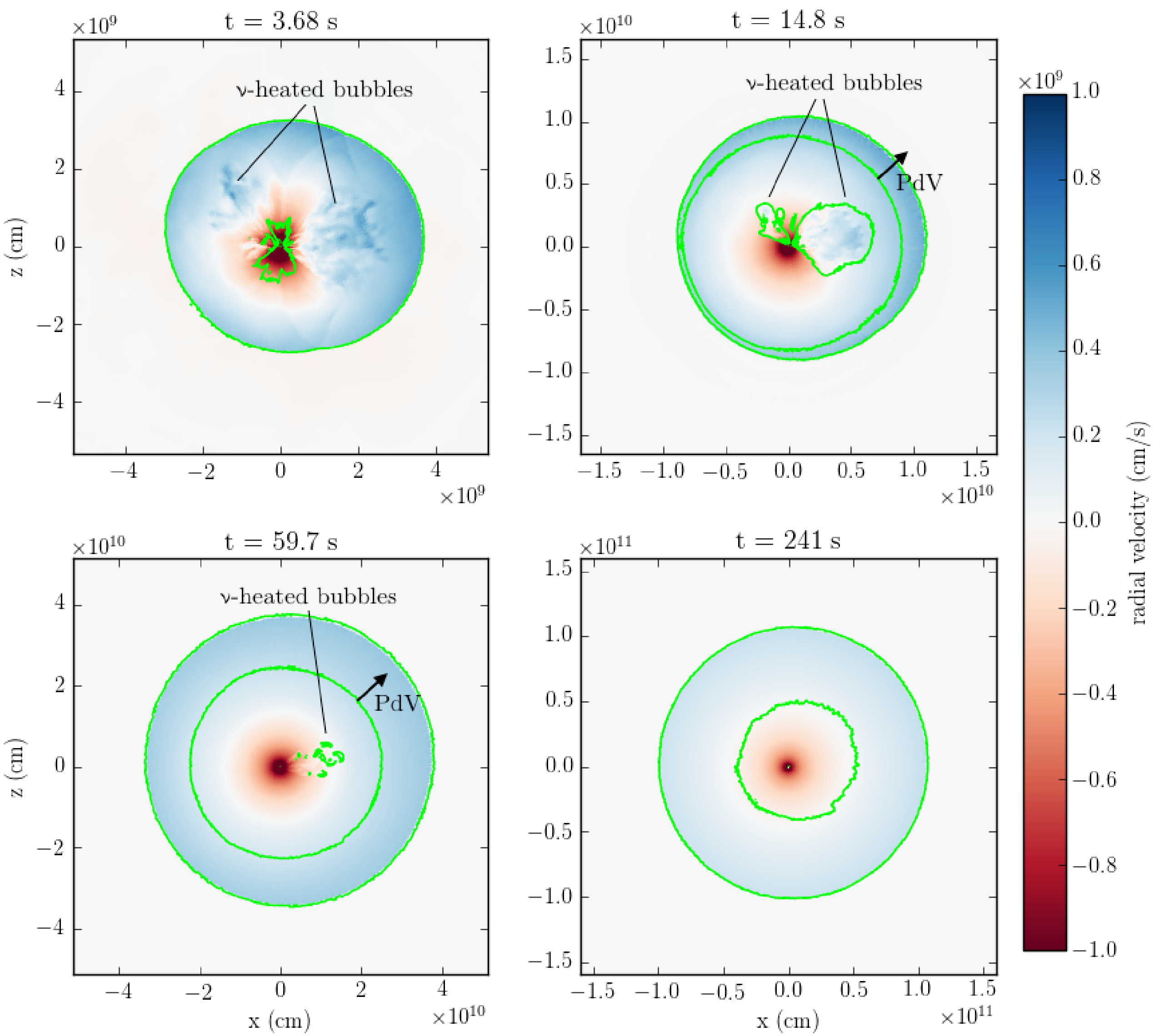
➔ Pop III stars show much less mixing than modern Pop I stars due to their compact hydrogen envelope

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



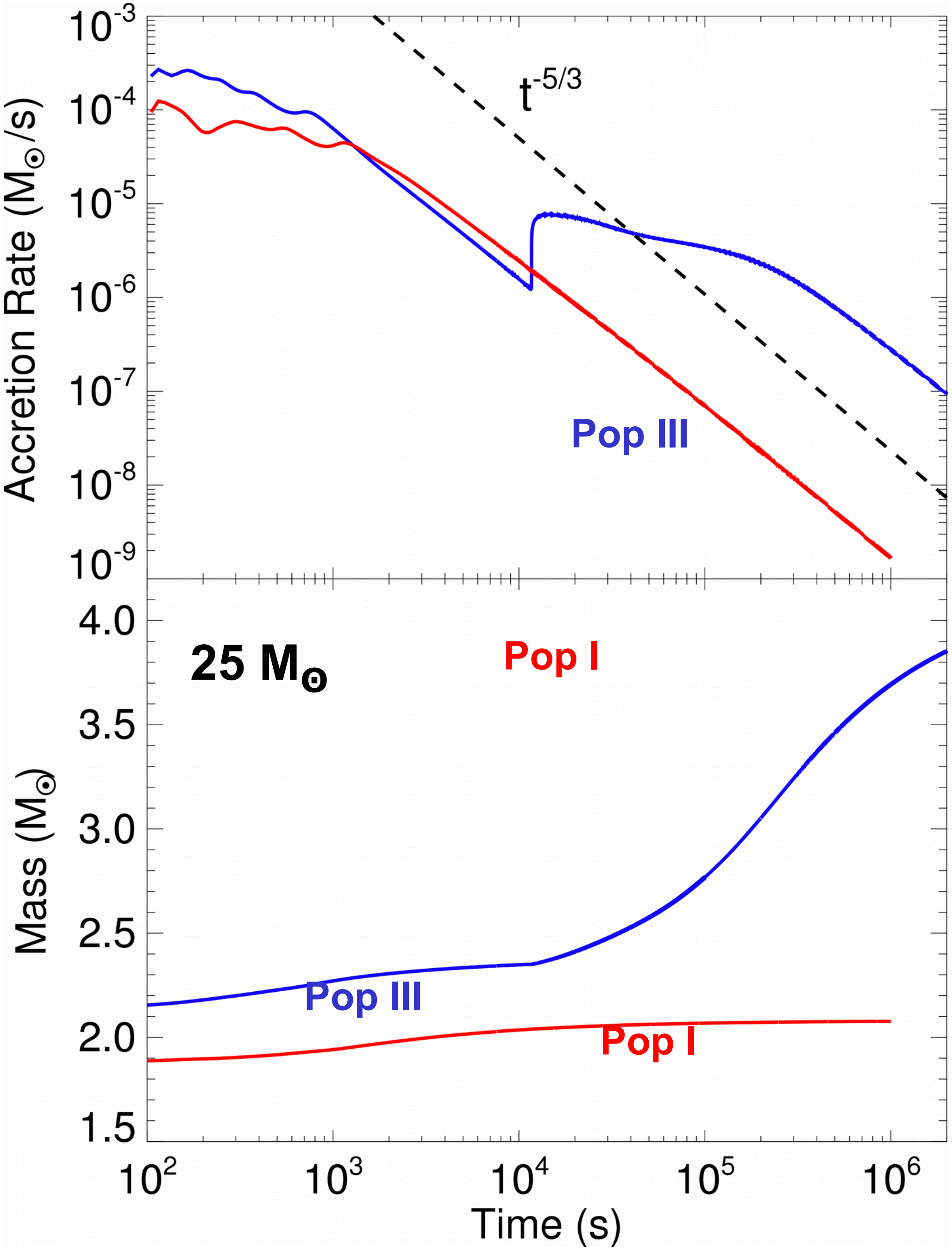
Simulations: Candace Joggerst (UCSC/LANL T-2)

Fallback in a 40 $M_\odot$ Stars



Chan+ (2017)

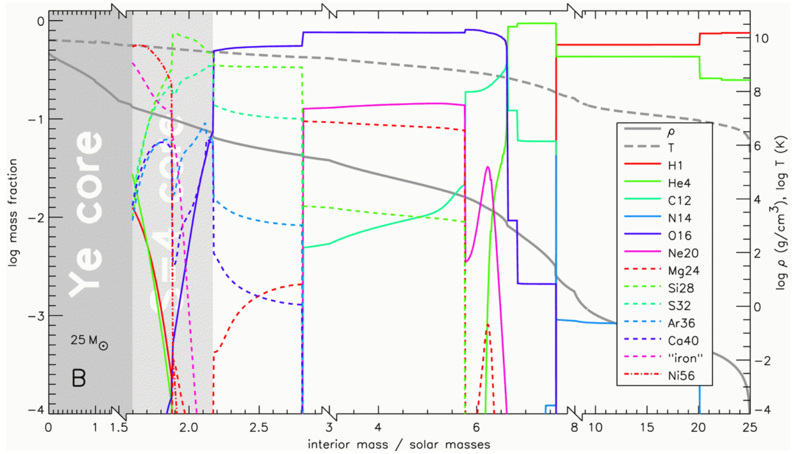
Fallback and Remnants



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

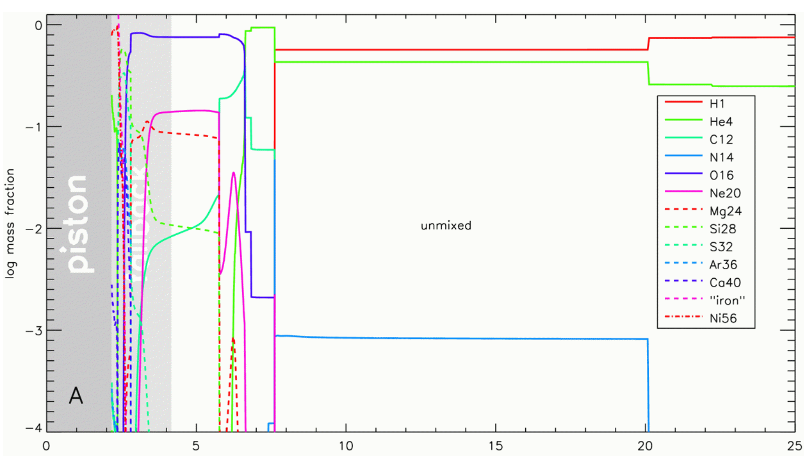
(Zhang, Woosley, Heger 2007)

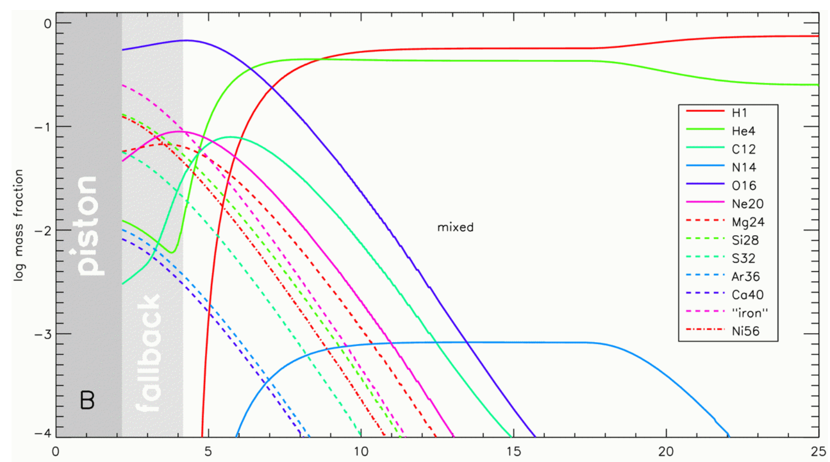
Supernovae, Nucleosynthesis, & Mixing



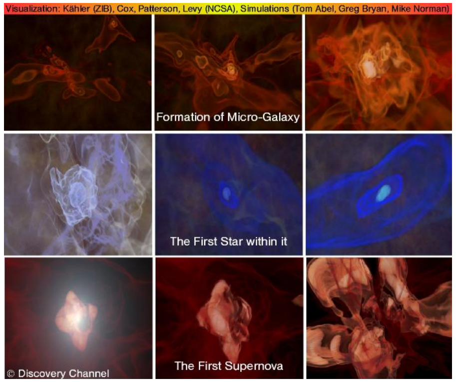
SN, no mixing

SN + mixing

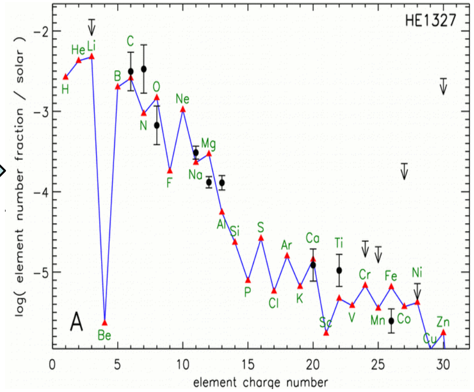




Reconstruction of the IMF



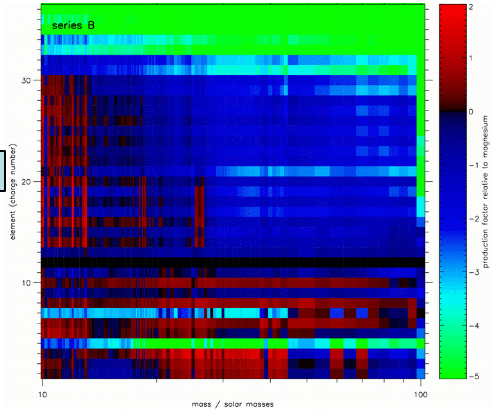
primordial stars form, nucleosynthesis ejected



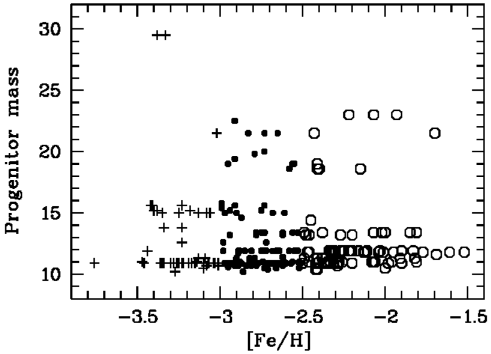
ejecta incorporated in low-Z halo stars

find low-Z halo stars (HERMES / SkyMapper / GALAH)

measure abundances (VLT, KECK, Gemini, …)



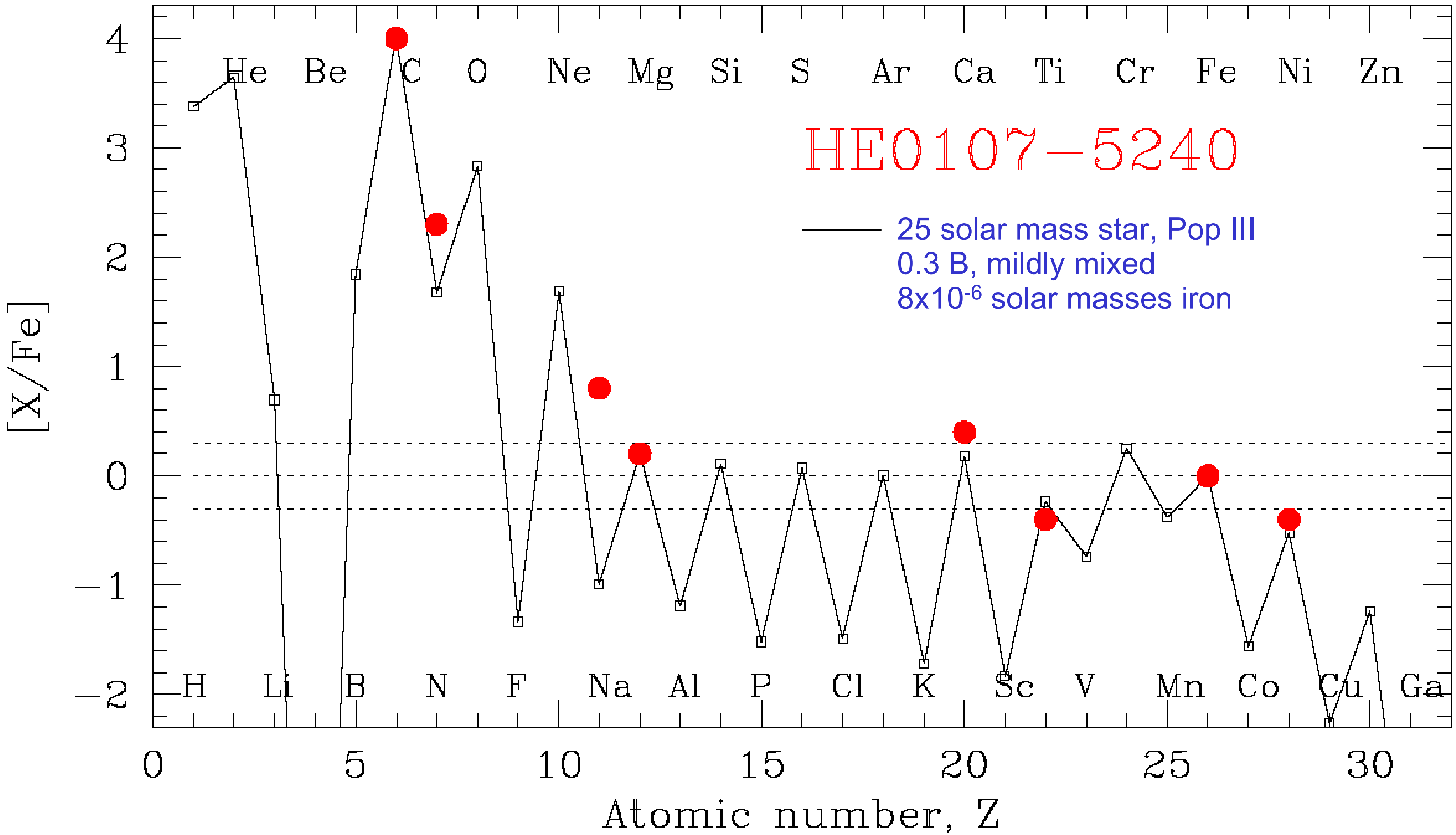
compare abundances to primordial star nucleosynthesis library



obtain IMF of population of progenitor stars

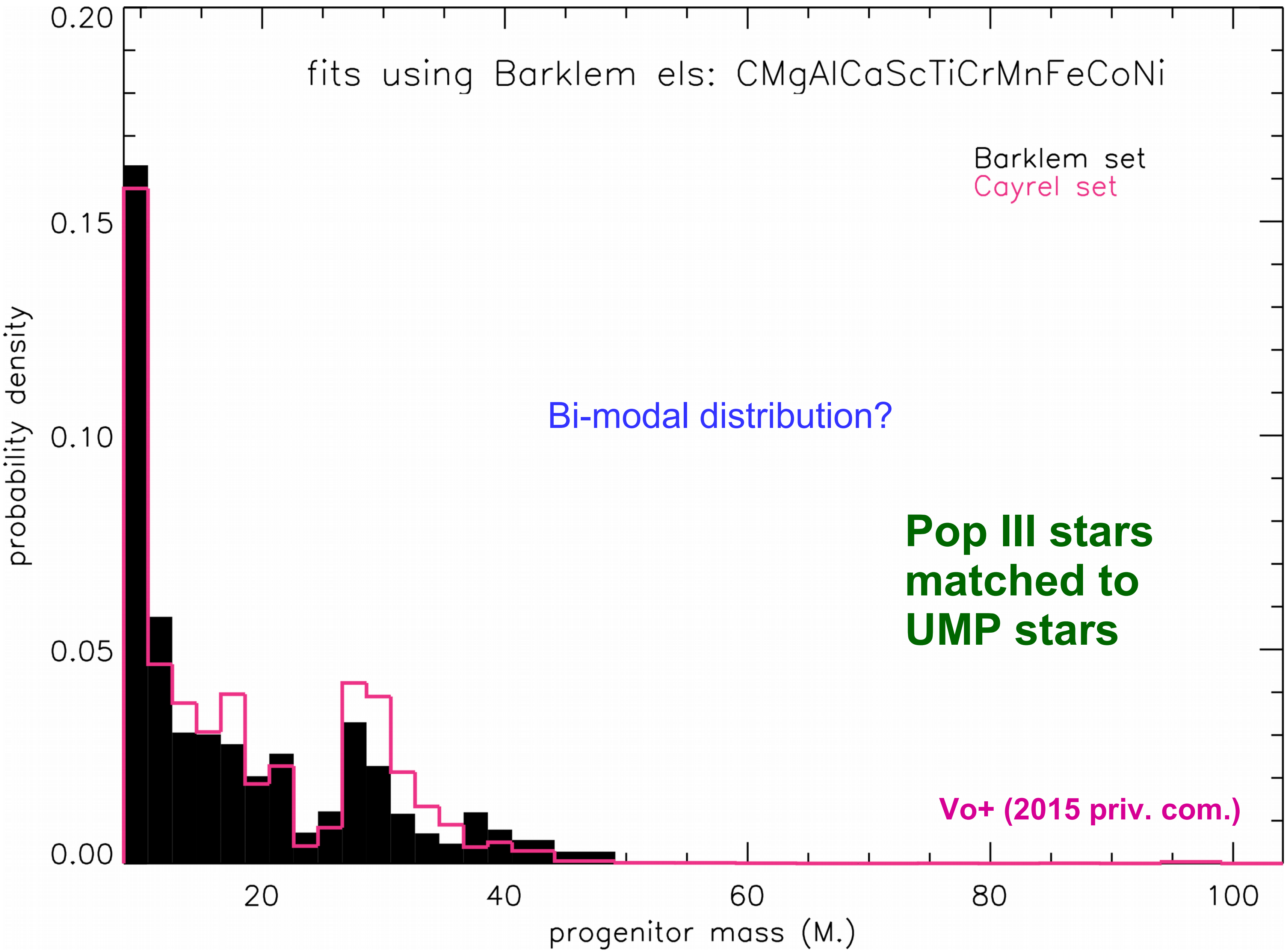
Frebel, priv. Com. (2007)
Vo+ (2015)

Fitting of Abundance Patterns to Stars

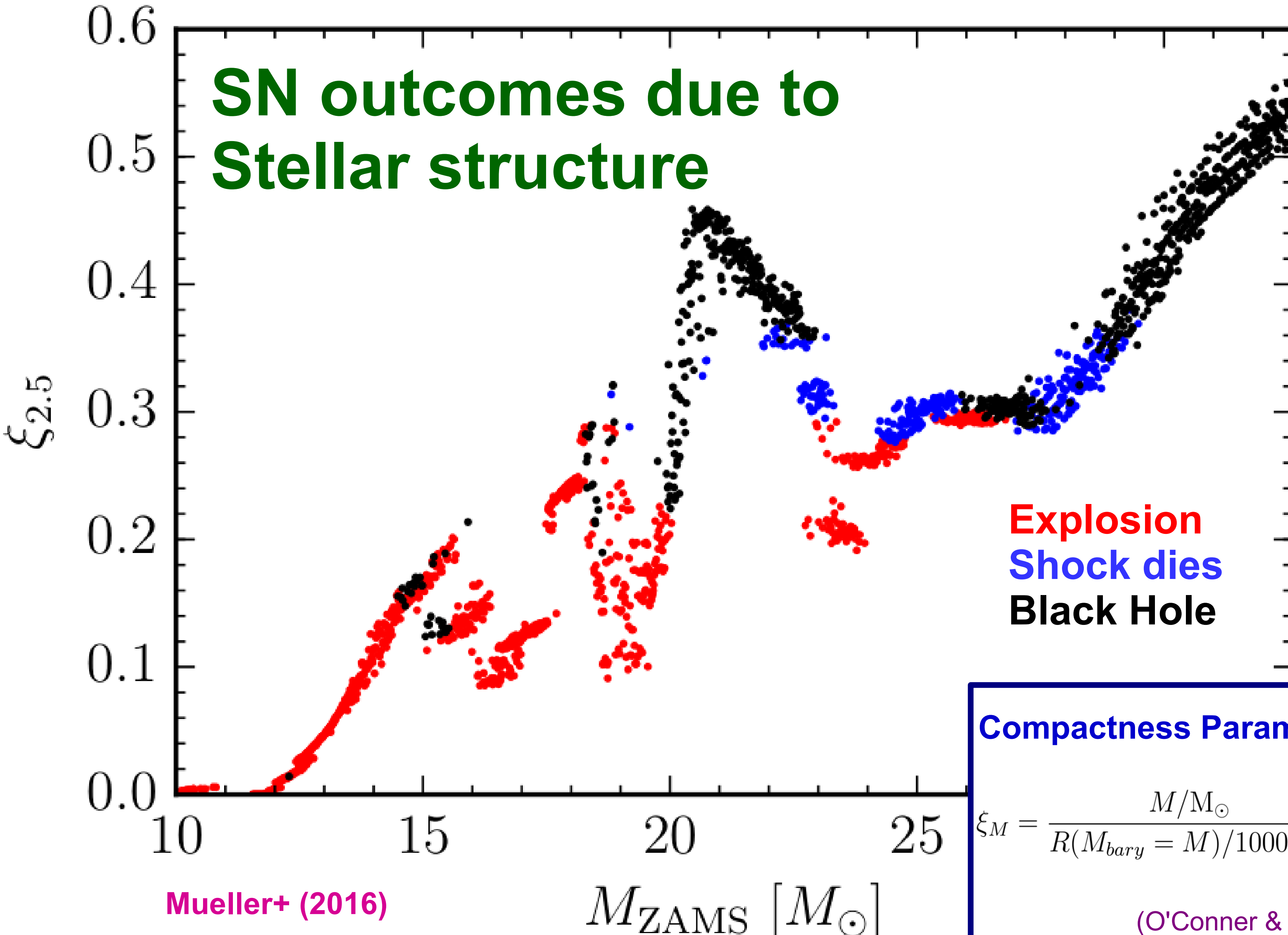


Umeda & Nomoto, Nature, 422, 871, (2003)

Reconstruction of the IMF



Signatures of Stellar Structure?



Mueller+ (2016)

Compactness Parameter

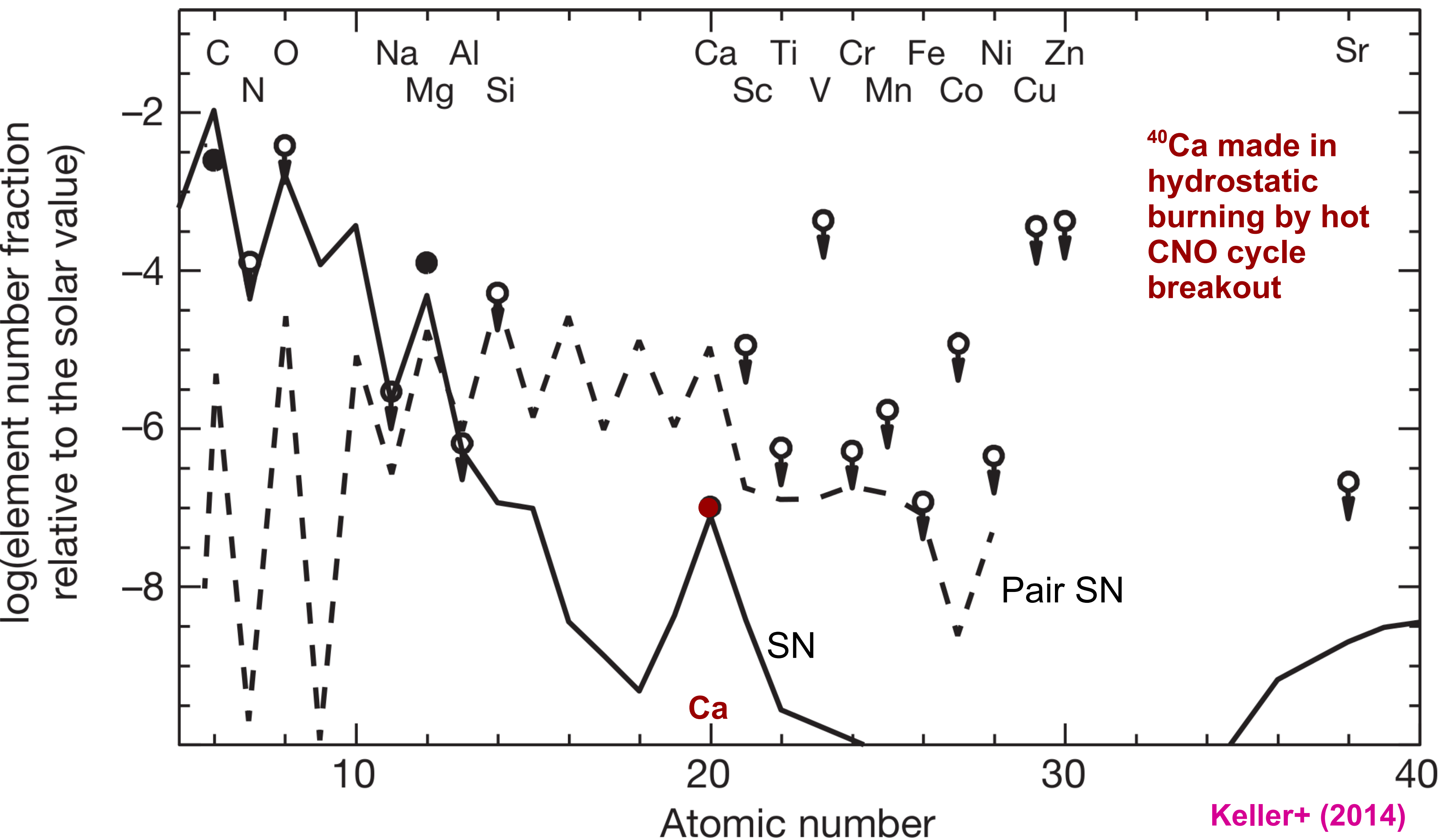
$$\xi_M = \frac{M/\mathrm{M}_\odot}{R(M_{bary} = M)/1000\,\mathrm{km}}\bigg|_{t_{bounce}},$$

(O'Conner & Ott 2011)

The Quest for CA

SMSS J031300.362670839.3

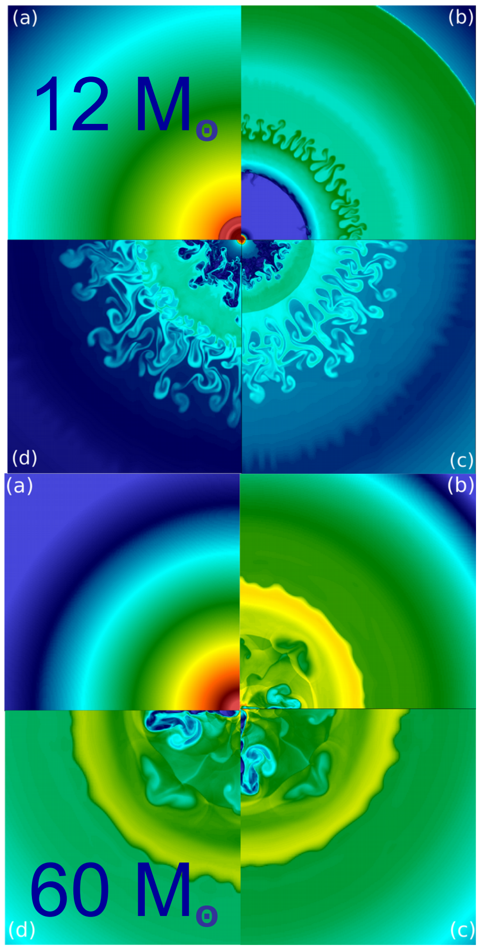
[Fe] < -7.1 (3σ)



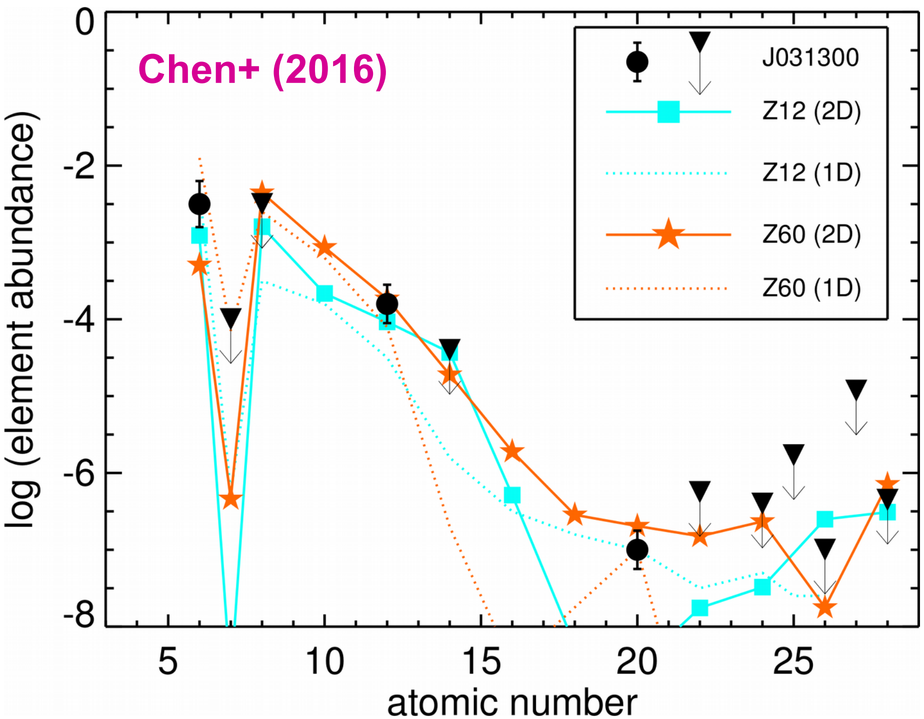
^{40}Ca made in hydrostatic burning by hot CNO cycle breakout

Keller+ (2014)

Multi-D SN Simulations
of SMSS J031300

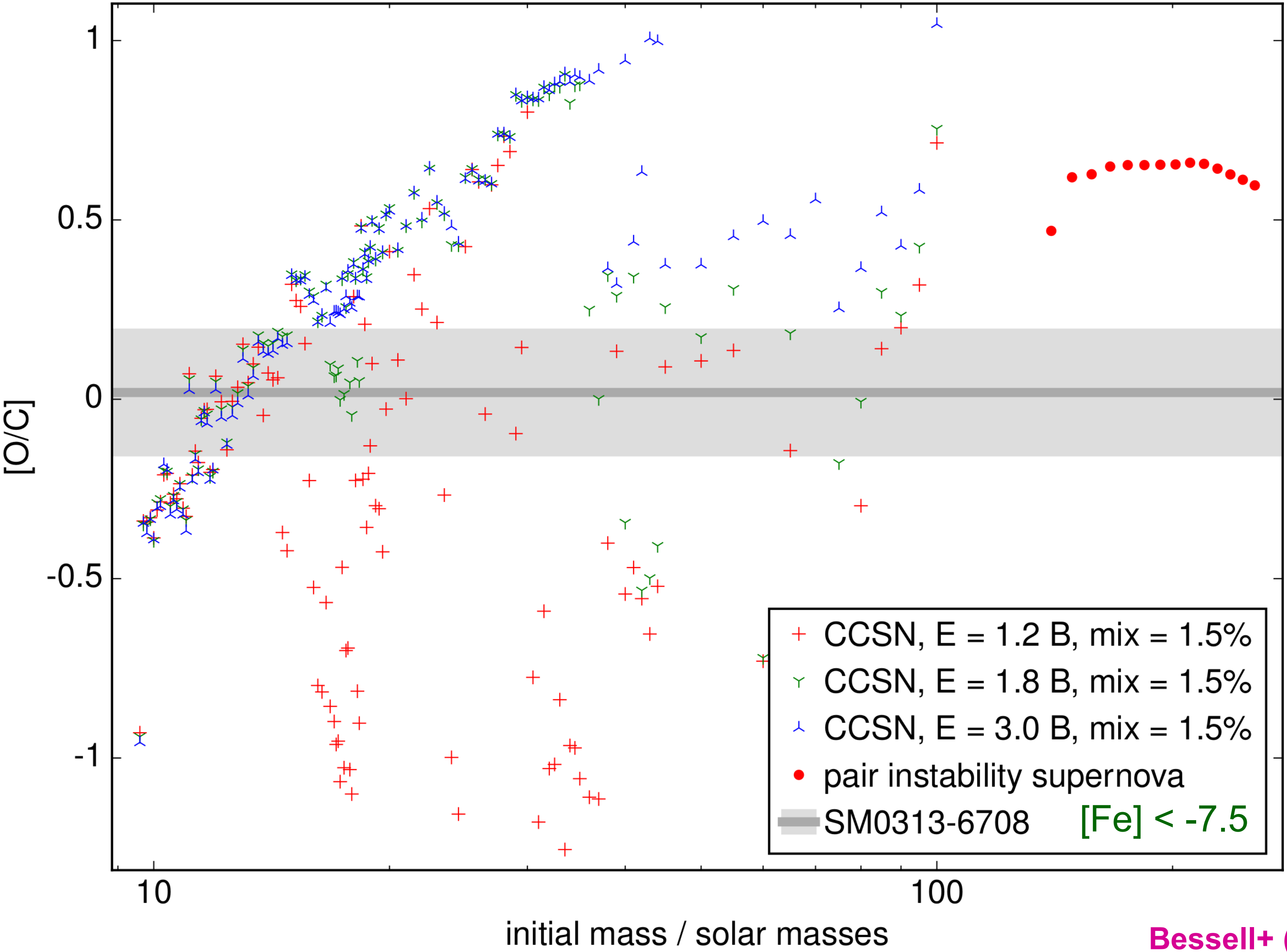


Chen+ (2016)



→ for multi-D current mixing models to match C, O, Mg, and Ca
Predictions for Fe group are different than hydrostatic model for Ca production!

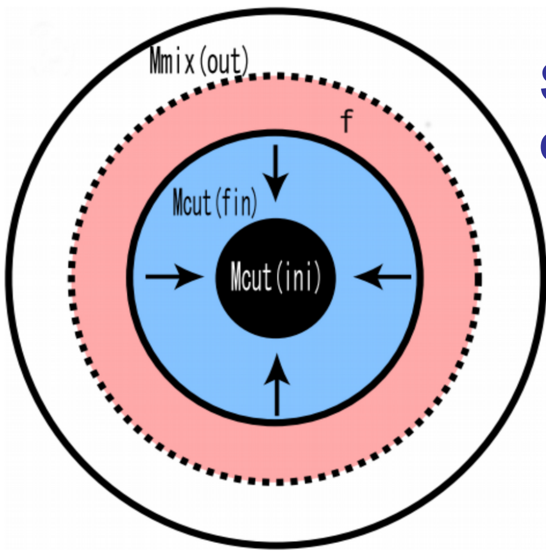
Constraints on SN and Progenitor from O/C



Bessell+ (2015)

Hypernove
Jet-Explosions

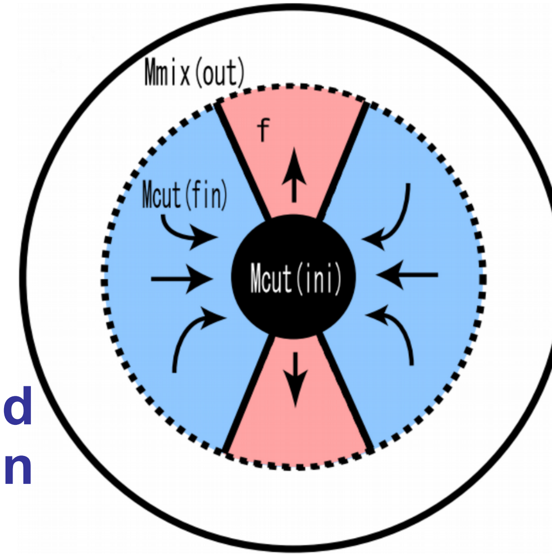
Hypernova Nucleosynthesis

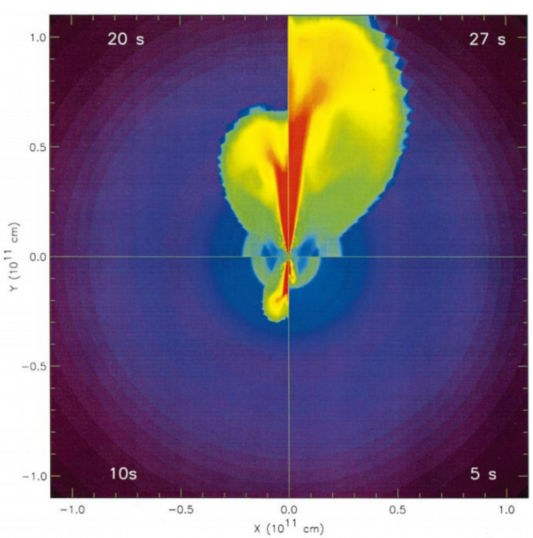


Spherical explosion

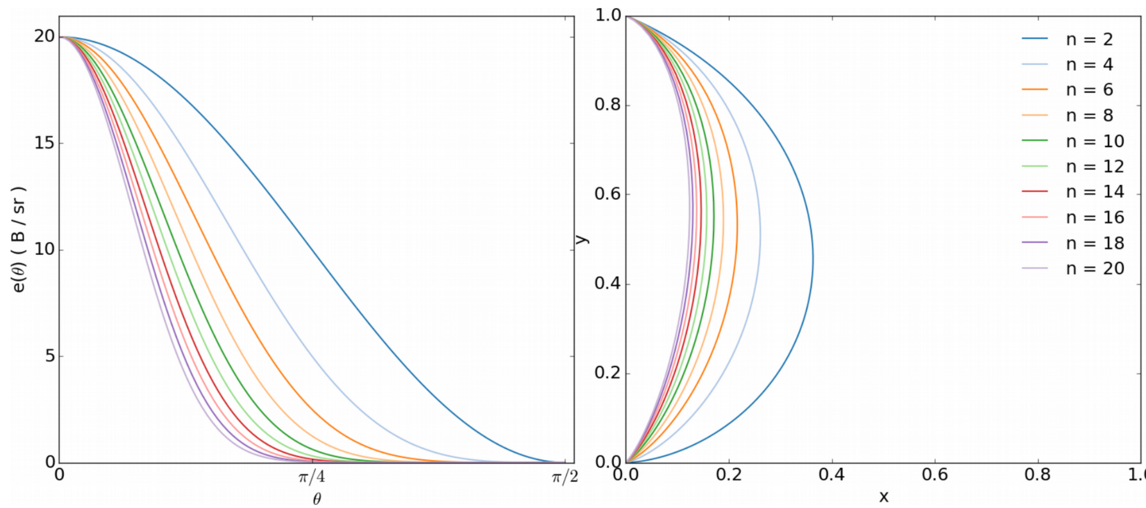
(Nomoto+ 2006)

Jetted explosion





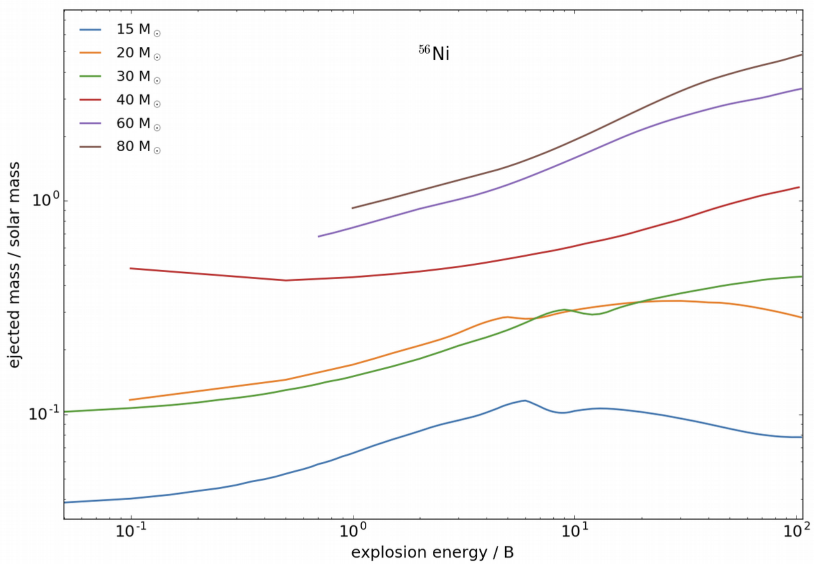
(MacFadyen+ 2001)



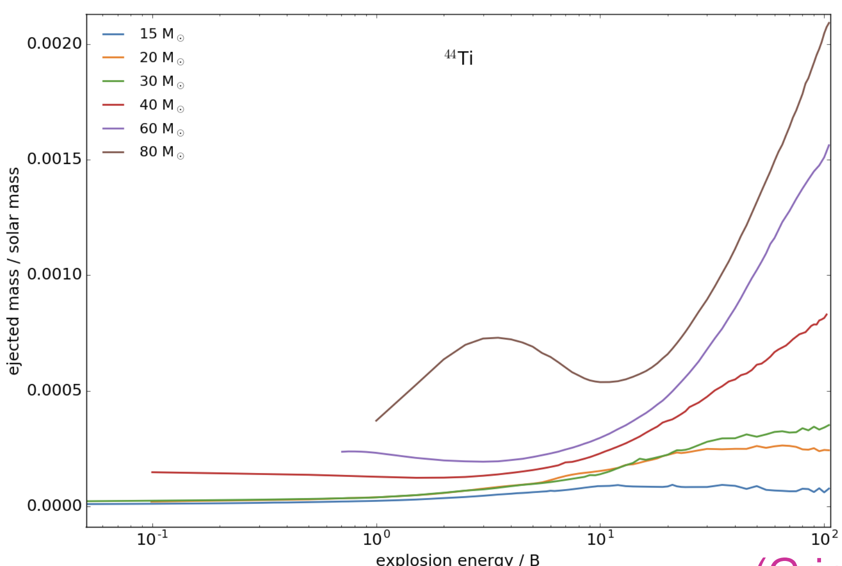
Simple Models

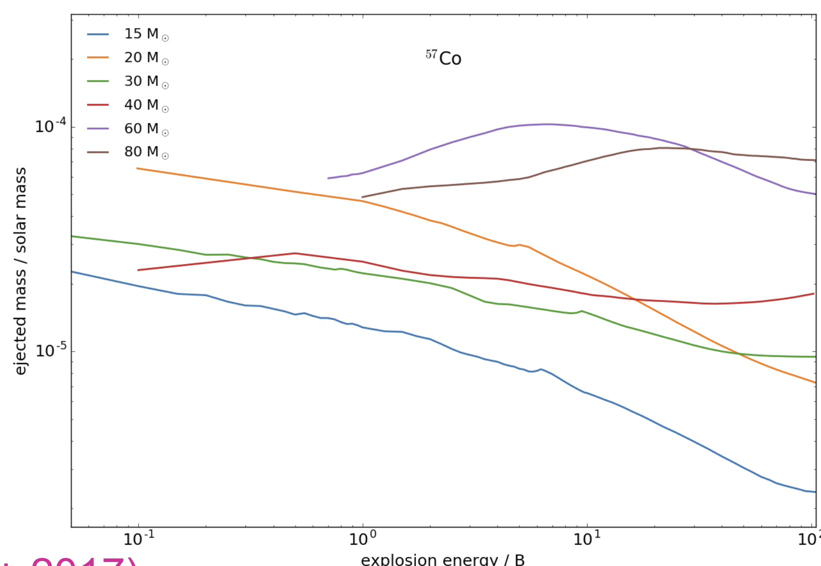
(Grimmett+ 2017)

Nucleosynthesis in Hypernovae



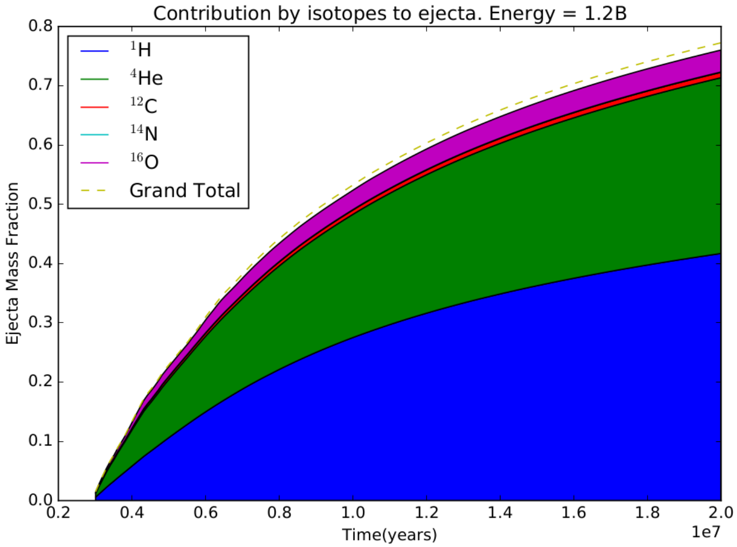
→ Can get wide variety of yields and ratios form jets and asymmetric explosions, in particular if not well-mixed when next generation of stars form!



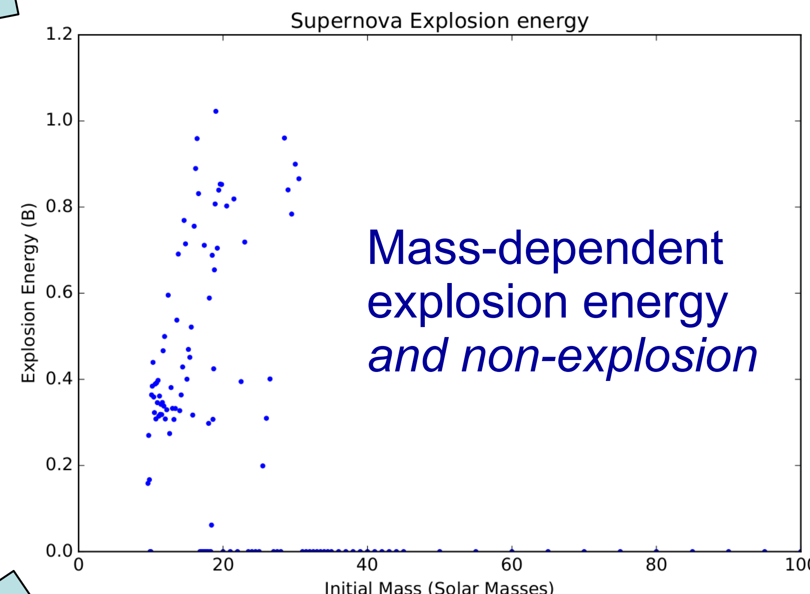


(Grimmett+ 2017)

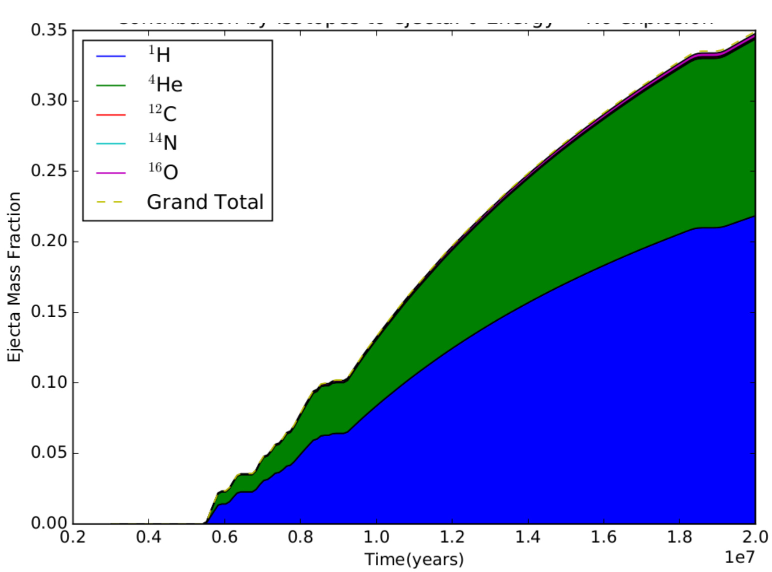
Time-Dependent Yields and SN Energies



all stars explode with 1.2 B



Mass-dependent explosion energy *and non-explosion*

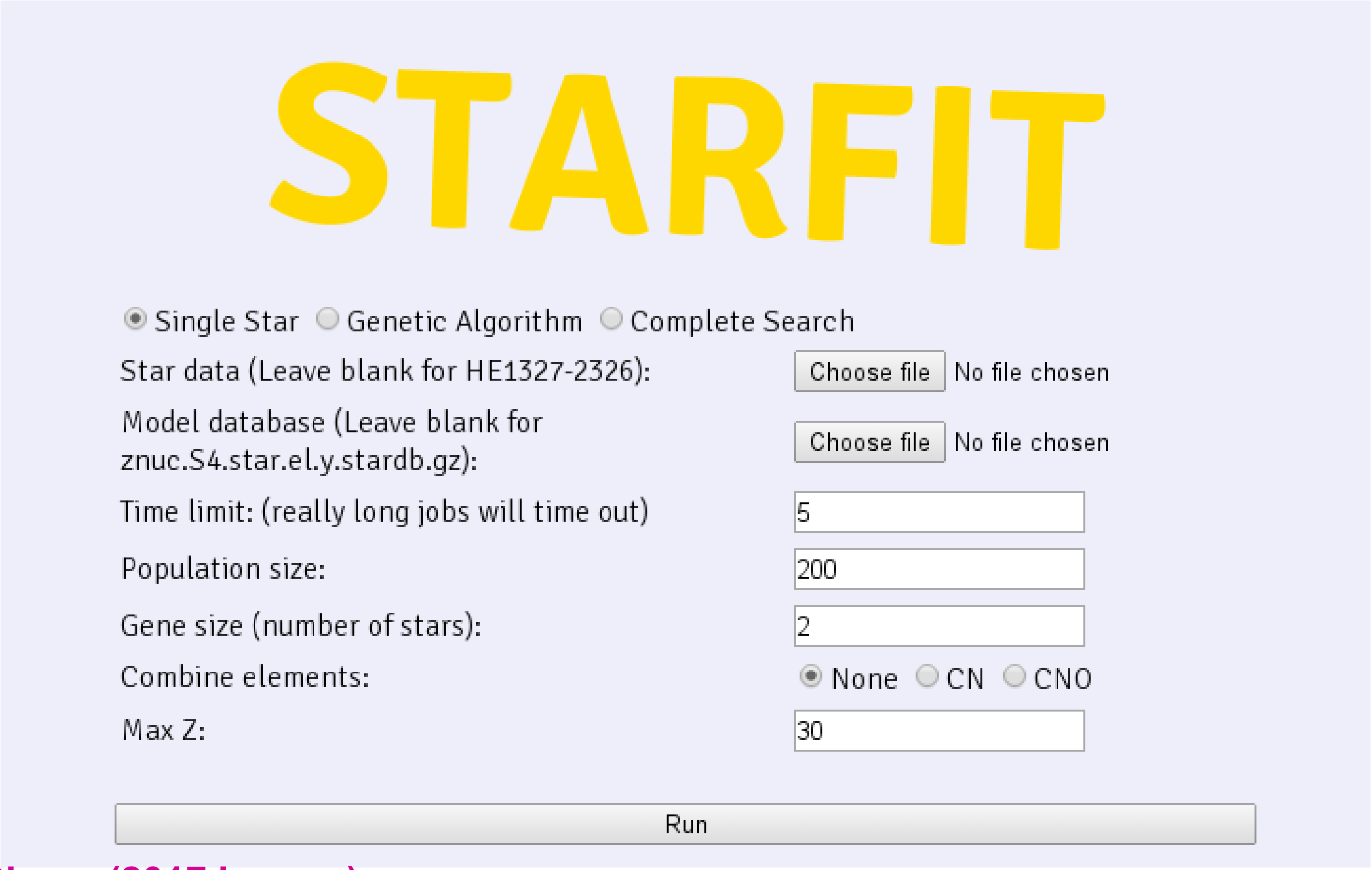


stars explode with proper explosion energy

(Duggan+ 2017)

Fit Your Own Star

http://starfit.org



Chan+ (2017 in prep)

Website under development by Conrad Chan

- **Use genetic algorithm or complete search**
- **Upload your own observational star data**
- **Upload your own data base**