AGB stars and the s-process

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The Helix Nebula — NGC 7293

Outline of Lectures

My two lectures cover the following topics:

1. The evolution and nucleosynthesis of AGB stars
2. The slow neutron capture process

INTRODUCTION

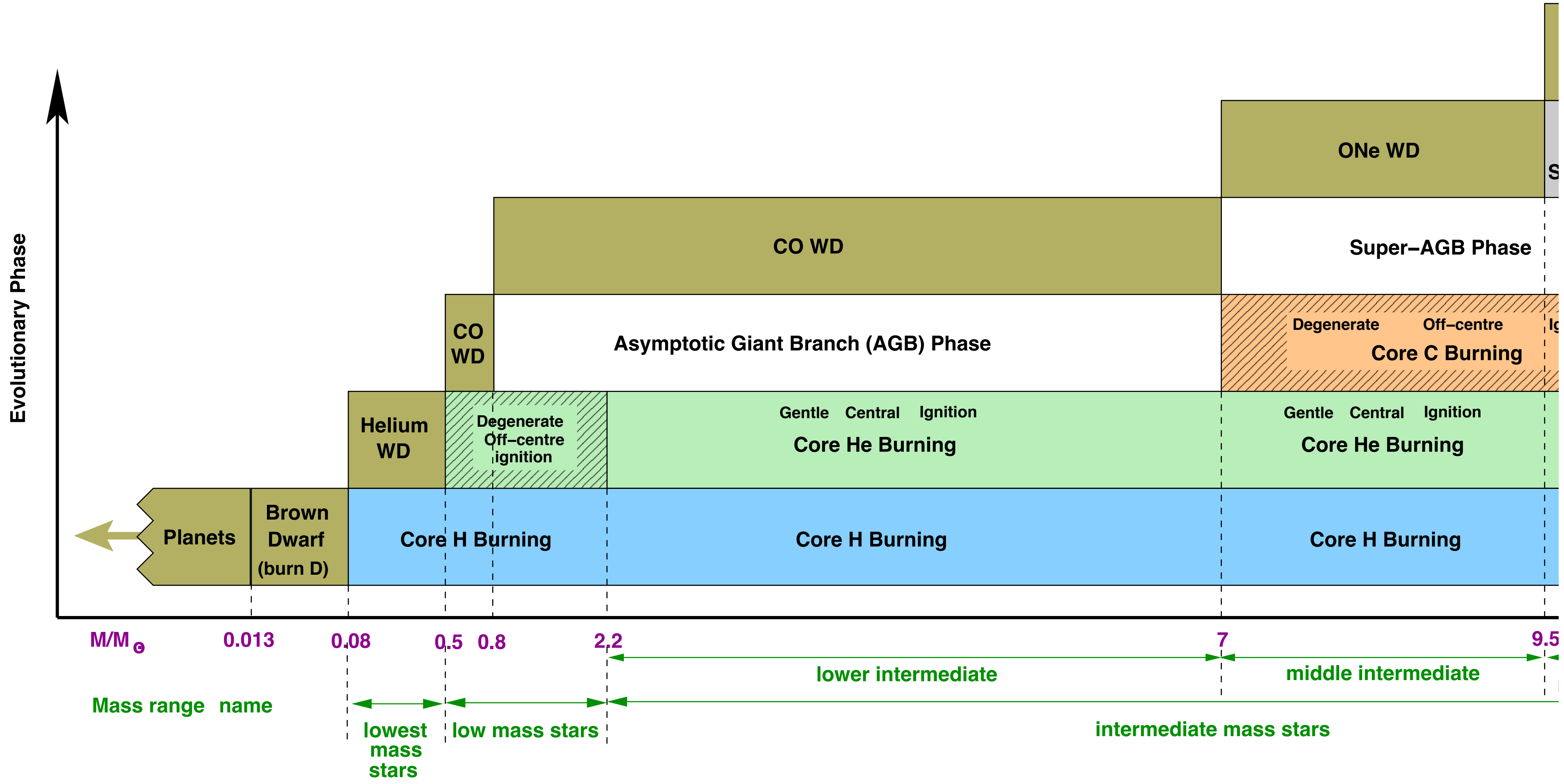
Introduction

- 13.7 billion years ago, the big bang made (mostly) hydrogen (~76%) and helium (24%)
- Everything else, including the material that makes up you and me, was cooked inside a giant stellar furnace
- What stars produce what elements?
- Our Sun is a star! How will it age? What elements will it make?

Credit: HST public archive

Low and intermediate-mass stars

Stars between about 0.8 to 8Msun, depending on metallicity



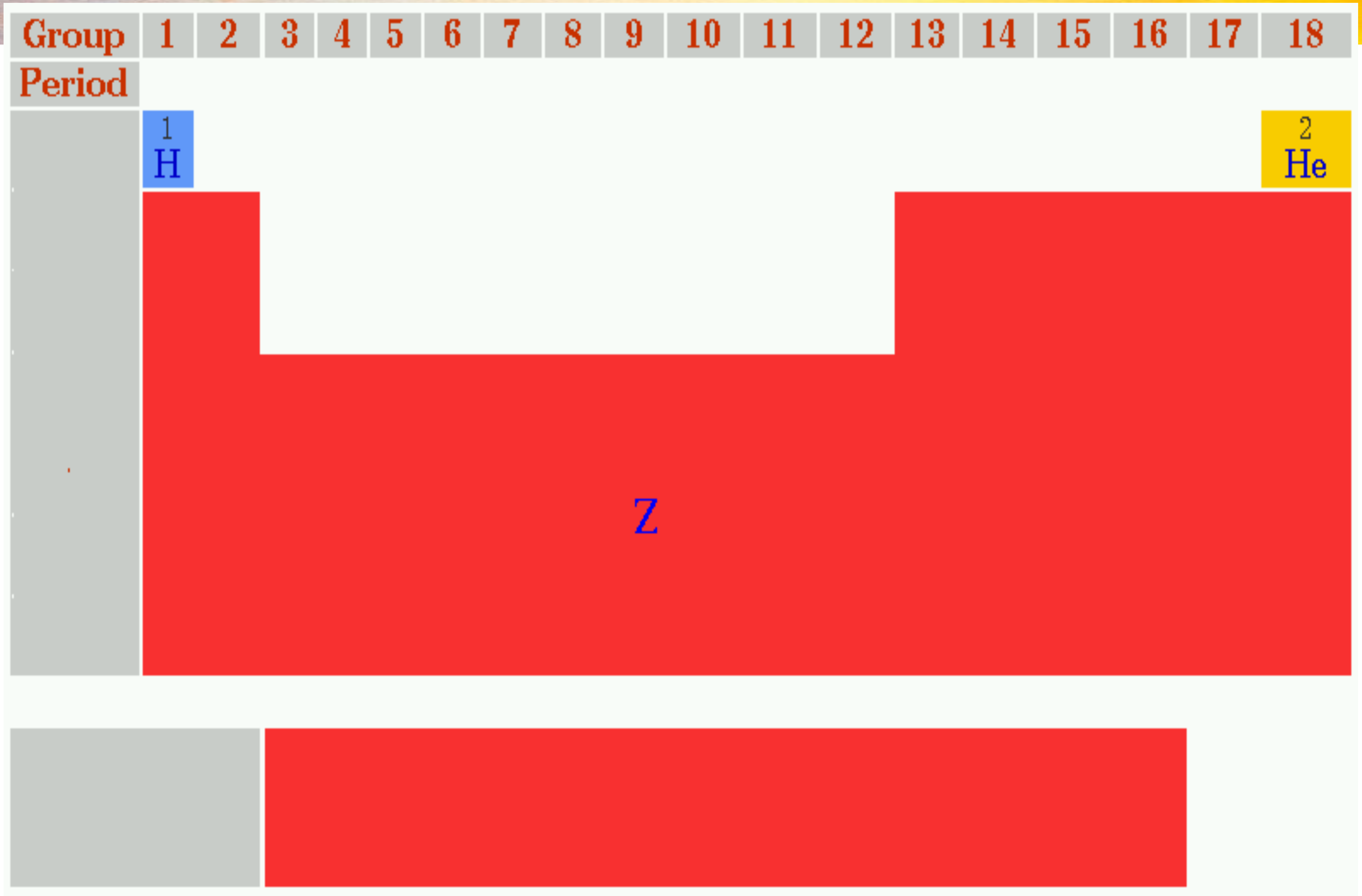
From Karakas & Lattanzio (2014)

Some definitions

- **Low-mass stars**:
  – Initial masses from 0.8 to 2.2 solar masses (maximum mass for core He-flash)
- **Intermediate-mass stars**:
  – Initial masses from 2.2 to 7 Msun (maximum mass for making a CO white dwarf)
- **Super-AGB** and electron-capture supernovae:
  – Initial masses between 8-12Msun
- **Massive stars**:
  – Initial masses: $\gtrsim 12$ Msun

These definitions are for a solar composition, Z = 0.014 (solar)

Periodic Table



Periodic Table

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period																		
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
*Lanthanoids			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
**Actinoids			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

The stars that make elements

Very low mass stars (≤ 0.8Msun, depending on Z) are still on the main sequence fusing hydrogen in their cores

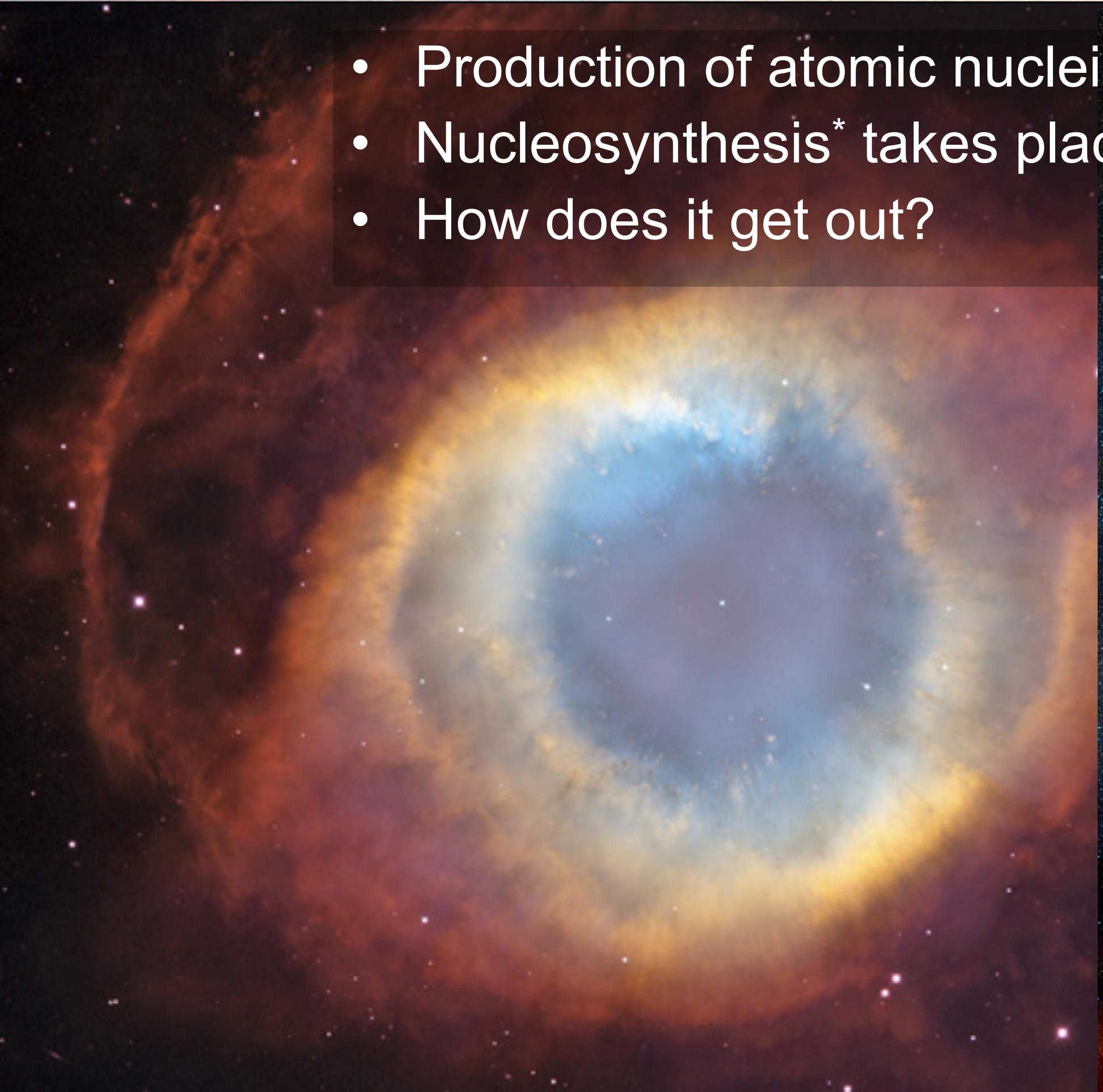
→ These stars have not contributed to the chemical evolution of our Galaxy

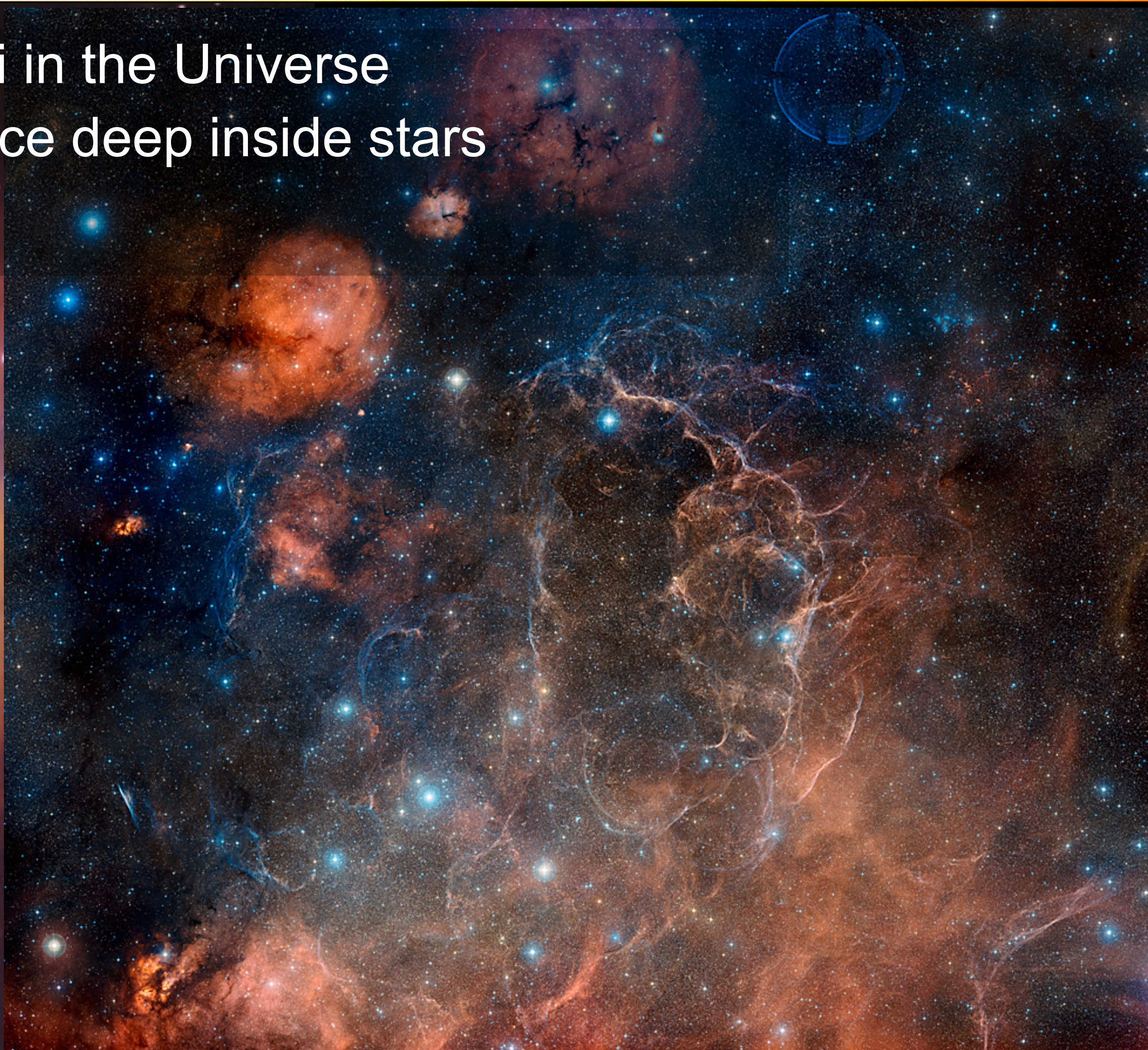
The most important are:

1. Massive stars that explode as Type II (core collapse) supernova ($\gtrsim$ 10 solar masses);
2. Stars that evolve through the first and asymptotic giant branches ($\lesssim$ 8 solar masses)
3. Explosive events involving binary evolution also important (e.g., Type Ia, merging neutron stars, novae).

Nucleosynthesis

- Production of atomic nuclei in the Universe
- Nucleosynthesis* takes place deep inside stars
- How does it get out?





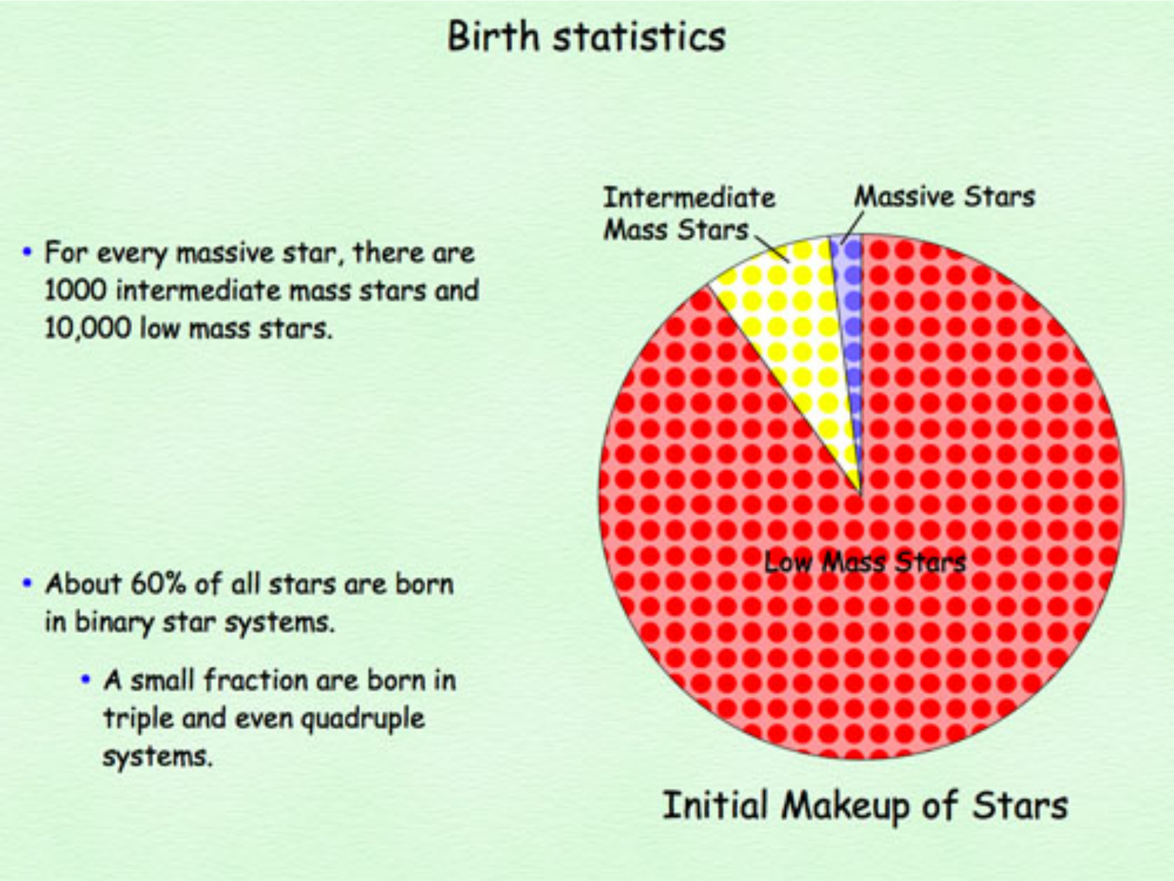
Into the interstellar medium

We need a way of moving the material from the stellar core, where thermonuclear reactions take place, to the surface.

From there, we then need a way of moving the processed material into the ISM:

1. Low and intermediate-mass stars: no explosion! Mixing + mass loss returns the material.
2. Single massive stars: mass loss + core-collapse supernova explosions.
3. Explosive binary phenomena: including merging neutron stars, Type Ia supernovae, novae.

Star birth masses



From Frank Timmes website

How long do stars live?

Age of the galaxy ≈ 12 x 10^9 years; Universe ≈ 13.7 x 10^9 years

Initial mass (M_{sun})	Main sequence lifetime	Total stellar lifetime
25	6.7 Myr	7.5 Myr
15	11Myr	13 Myr
5	80 Myr	100 Myr
2	900 Myr	1.2 Gyr
1	10 Gyr	12 Gyr
0.8	20 Gyr	> 32 Gyr

1 Myr = 1,000,00 years; 1 Gyr = 1000 Myr

Ages from Karakas & Lattanzio (2007); Woolsley et al. (2002)

A note on abundances

- Theoretically, we use the concept of mass fraction:

Sum of mass of H + He + ‘metals’ = 1

- Where you have seen **X = hydrogen**, **Y = helium** and **Z** = are the metals, or everything else, the **global metallicity**.

Example:

- In the Sun: X = 0.7154, Y = 0.2703, Z = 0.0142 (Asplund et al. 2009)
- Most of Z is in the form of CNO nuclei, that is $Z_{CNO} \approx 0.65\,Z$, where 42% of Z is in the form of oxygen.

Example, the primordial ^{4}He abundance is around Y ≈ 0.245 by mass.

- The abundance by number is 0.245/4.0 = 0.061.

A note on abundances

- Observed stellar abundances are commonly presented in the following:

$$A(x) = \log_{10}\frac{N(x)}{N(H)} + 12$$

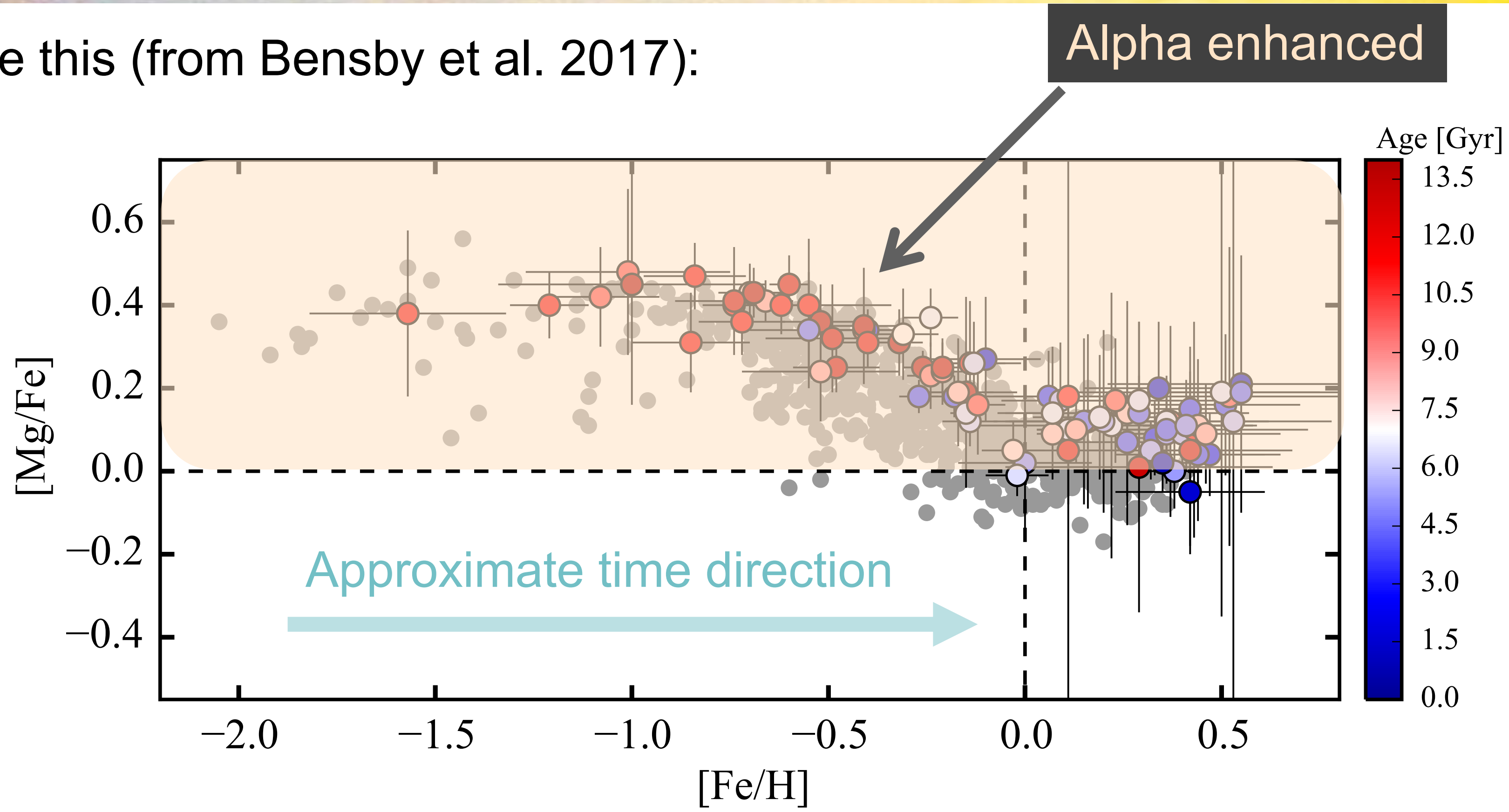
- This is common spectroscopic notation. The definition of

$$[x/y] = \log_{10}\left(N(x)/N(y)\right)_{star} - \log_{10}\left(N(x)/N(y)\right)_{sun}$$

- Where N(x) = abundance (by number) of species “x” and N(y) is the abundance of species “y”, e.g., [Fe/H] which is the main proxy for Z.
- Converting between abundances and models is important.
- Roughly, [Fe/H] $\sim \log\left(\frac{Z_{star}}{Z_{sun}}\right)$

Stellar abundances

Often looks like this (from Bensby et al. 2017):



- The gray points are solar neighbourhood dwarf stars and the coloured are microlensed dwarf stars in the Milky Way bulge.
- Stars with [Fe/H] < 0 are metal-poor; e.g., [Fe/H] = -1 have $Z \sim 10^{-1} Z_{\odot}$.
- Stars with [Mg/Fe] > 0 are considered alpha-enhanced.

Textbooks on nucleosynthesis

There are a number of good textbooks on the subject including

1. Clayton, D. D., “Principles of stellar evolution and nucleosynthesis”, 1984
2. Arnett, D., “Supernovae and Nucleosynthesis”, 1996
3. Iliadis, C., “Nuclear Physics of Stars”, 2015 (2^{nd} Ed)
4. Pagel, B., “Nucleosynthesis and Chemical Evolution of Galaxies”, 2009
5. Ryan, S. & Norton, A. J., “Stellar Evolution and Nucleosynthesis”, 2010 – good undergrad textbook

BASIC STELLAR EVOLUTION

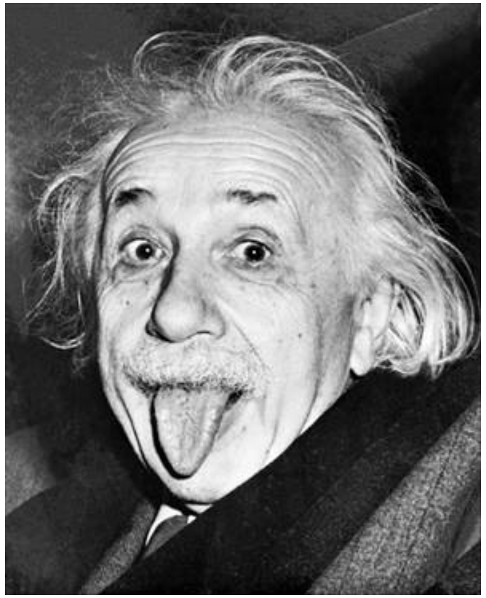
Reference

To put together these lectures, I used a lot of material published in my review paper:

- Karakas, A. & Lattanzio, J. C., "*Nucleosynthesis and stellar yields of low and intermediate-mass stars*", 2014, Publications of the Astronomical Society of Australia (PASA), 30, e30 and the *many* references therein

How do stars produce energy?

- Once the temperature of a proto-star reaches about 10 million degrees Kelvin, nuclear fusion begins!
- Hydrogen fusion *or burning* (i.e., similar to a H-bomb)
- 4 protons → ^{4}He + 2 e^+ + 2 neutrinos + energy
- Where does the energy come from?
- From $E = mc^2$: the mass of 4 protons > 1 ^{4}He nuclei



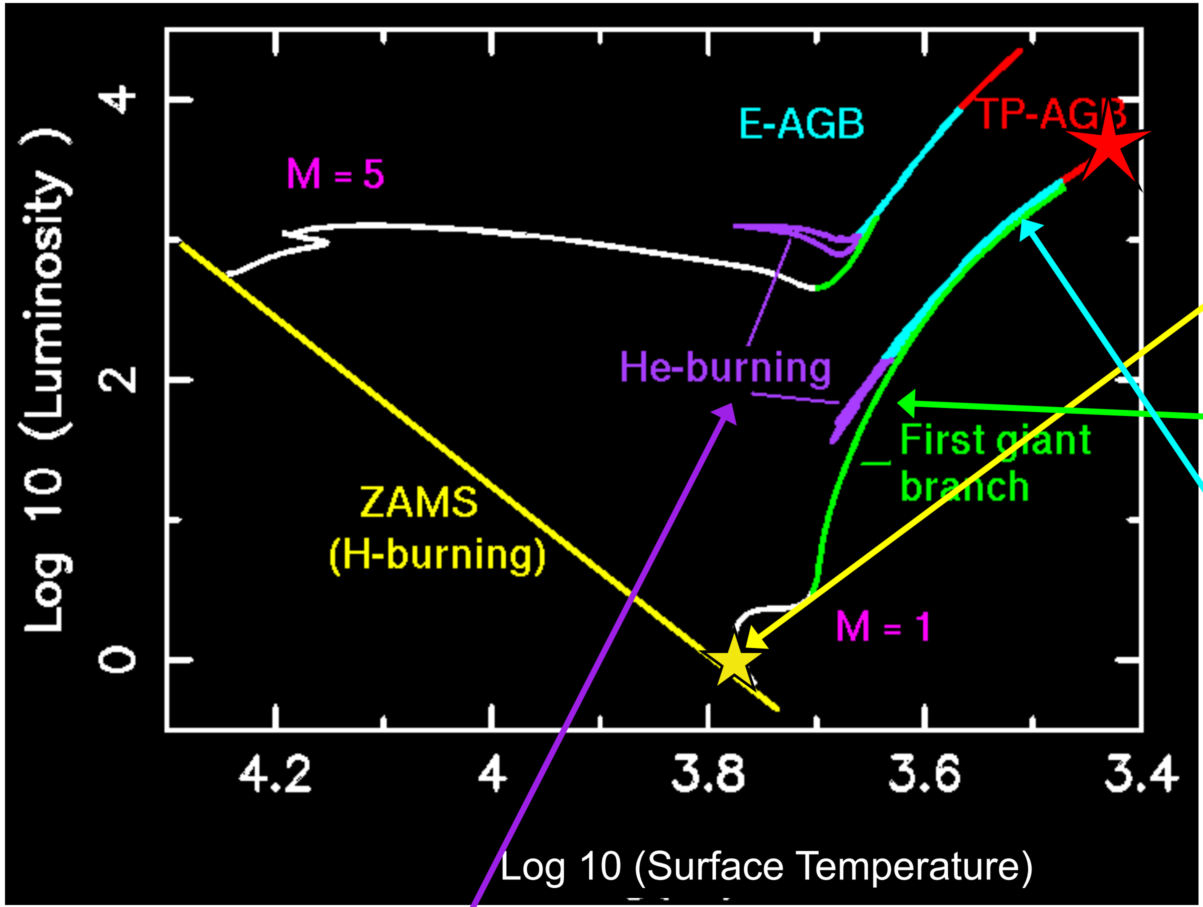
- How much energy?
- Energy released = 26 MeV

  = 4×10^{-12} Joules

But the Sun does this 10^{38} times a second!

An overview of stellar evolution

The x-axis: logarithm of the surface temperature of the star (in Kelvin)
The y-axis: logarithm of the brightness (amount of energy a star radiates per unit time)



Mira-type variables

Main sequence:
where our Sun is now
- 1Msun: t ~ 10 Gyr
- 5Msun: t ~ 100 Myr

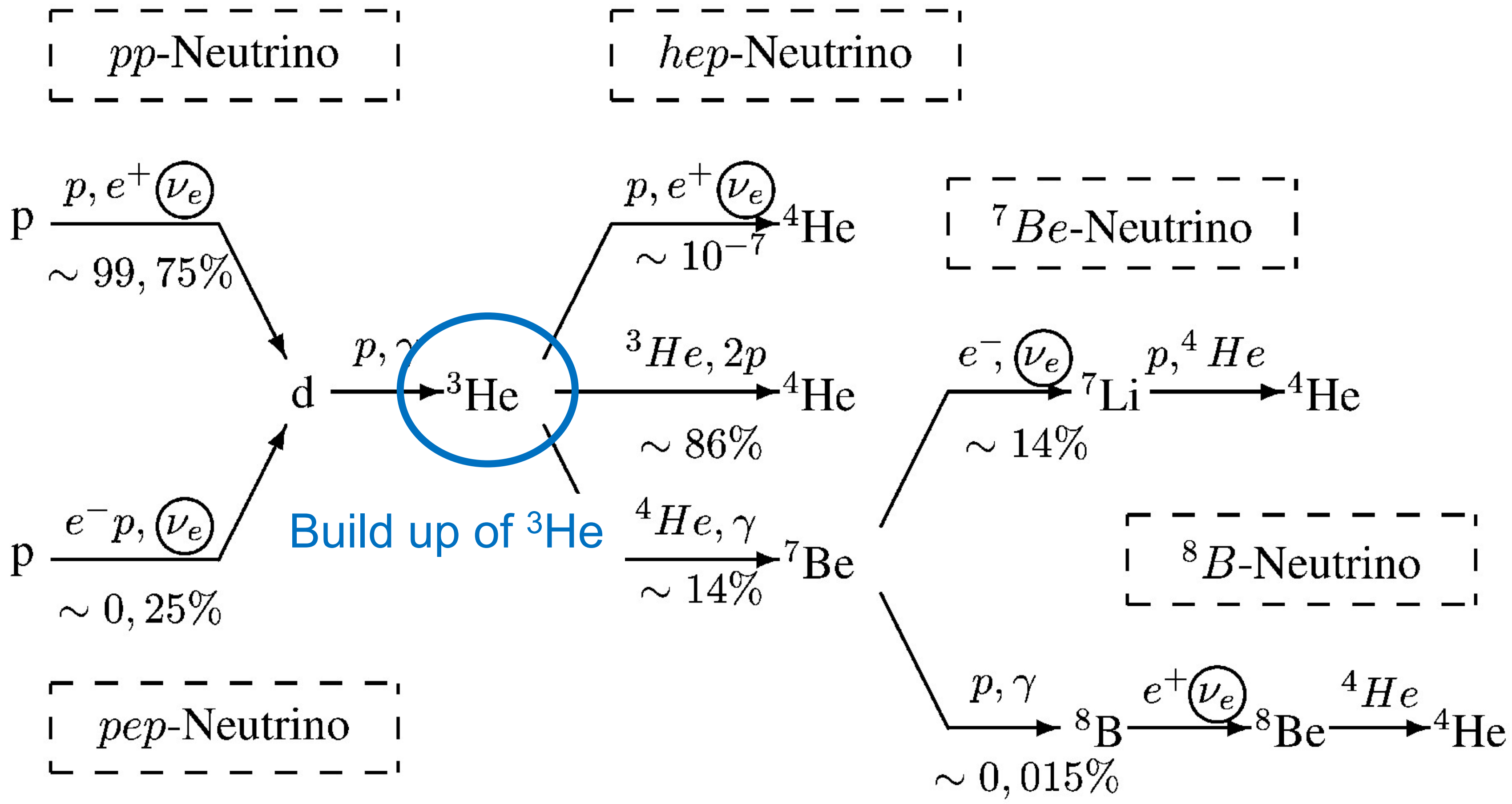
Red Giant Branch:
core contracts
outer layers expand

Second-giant phase:
after core He-burning
star becomes a red giant
for the second time
→ *Asymptotic giant branch (AGB)*

Core He burning

H-burning: Proton proton chains

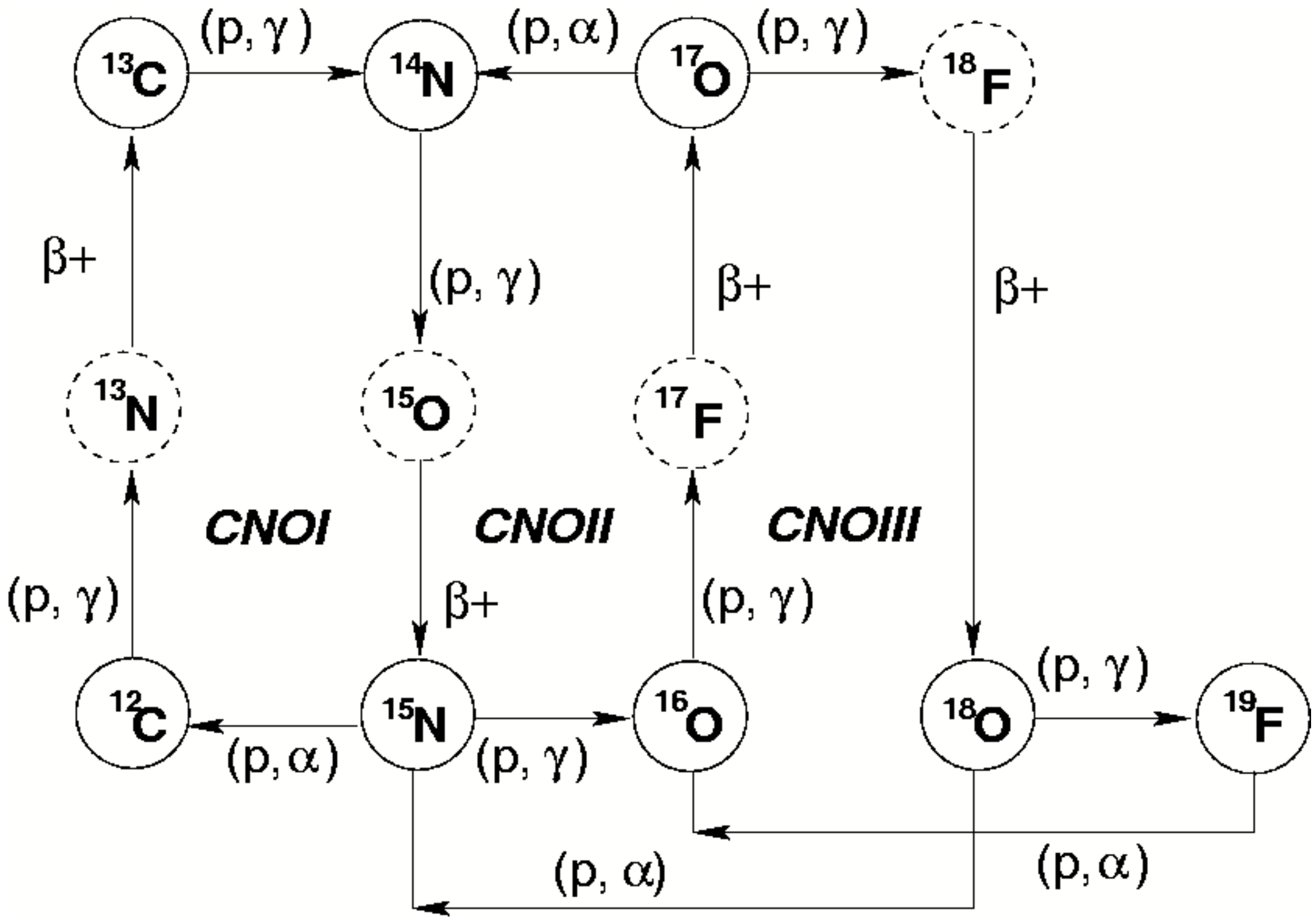
Main result: 4 p → ^4He + energy + stuff

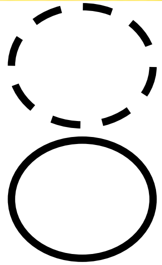


From MPA, Neutrino Astrophysics Group

H burning: CNO cycles

The full CNO cycles:





13N half life = 9.965 min
15O half life = 122.24 s
17F half life = 64.49 s
18F Half life = 109.77min

C+N+O remains constant

Re-arranges C, N, O nuclei into ^{14}N

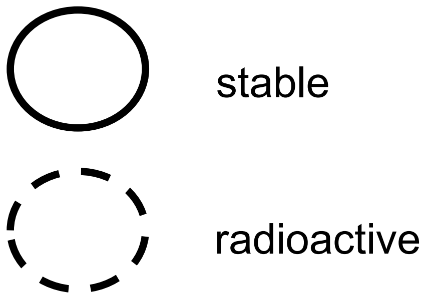
H-burning: CNO equilibrium ratios

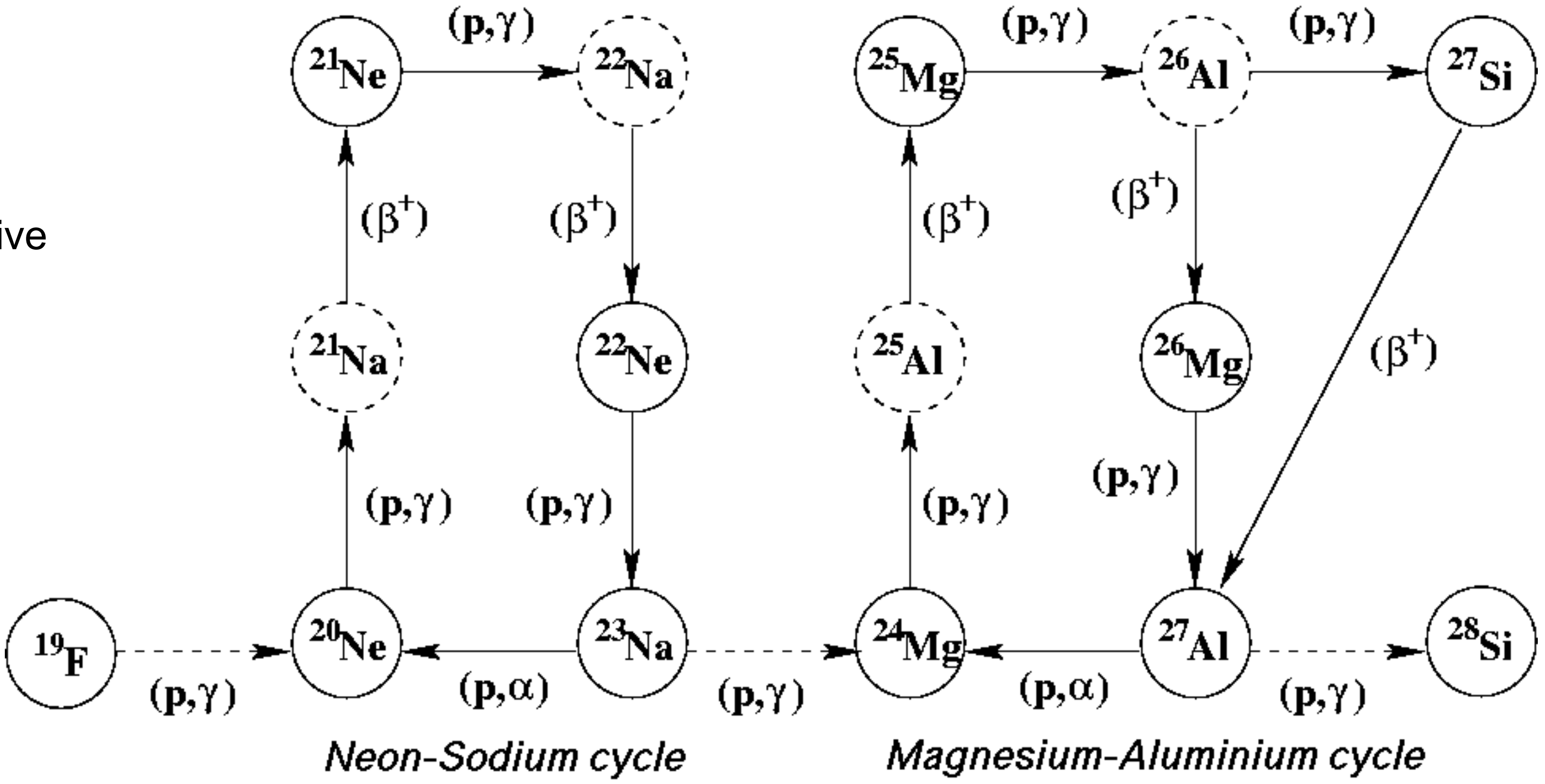
Ratios	Surface of Sun	CNO equilibrium
$^{12}C:^{14}N:^{16}O$	3:1:9	1:120:10
$^{12}C/^{13}C$	90	~3

- The CNO ratios at stellar surface and from the CNO cycle equilibriums are very different.
- ^{13}C and ^{14}N increase, while ^{16}O barely changes.
- Low $^{12}C/^{13}C$ ratios (< 30) at the surface of a star an indication that material was exposed to CN cycling.

Advanced H-burning cycles

The reactions of the Ne-Ne chain (left) and Mg-Al chain (right):



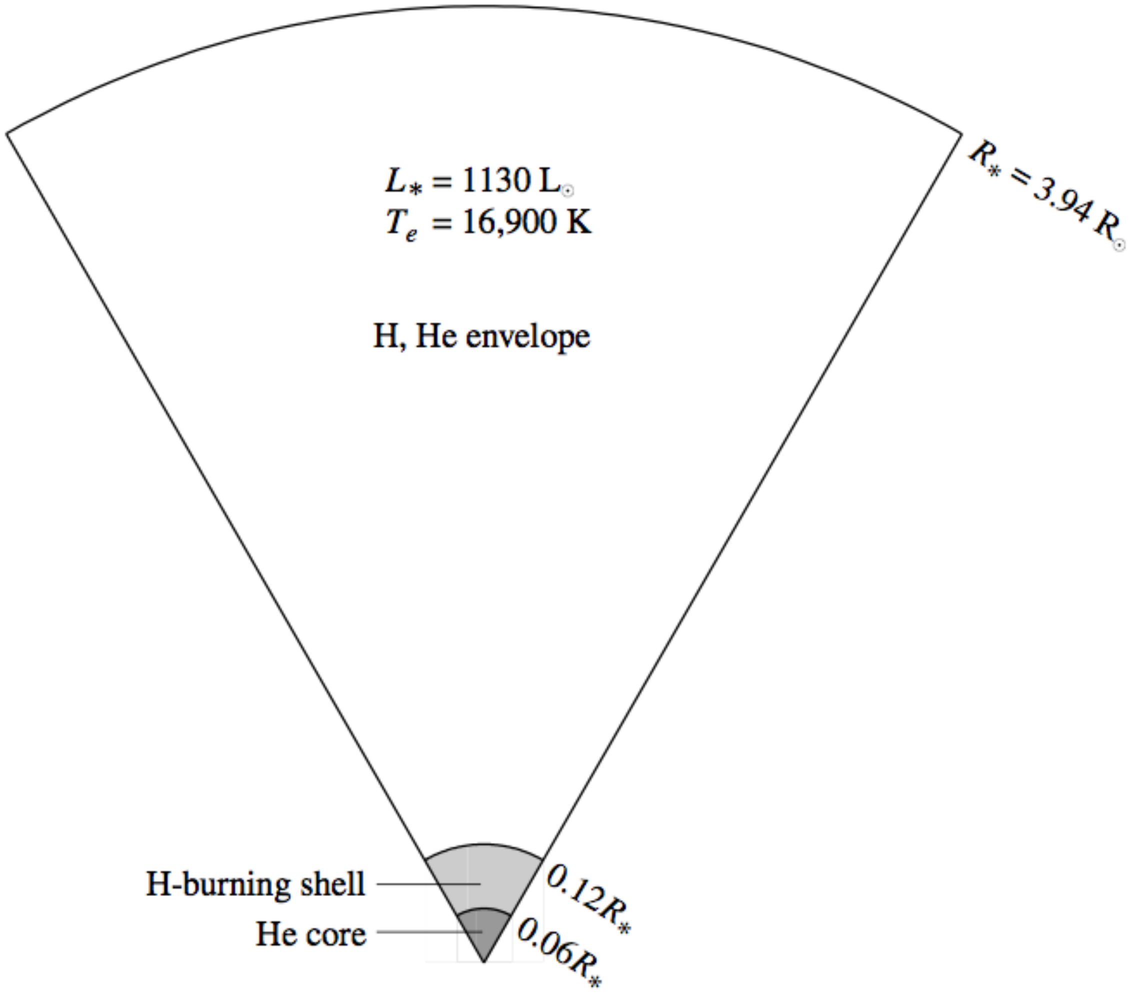


Requires hotter temperatures, $T \gtrsim 30 \times 10^6$ K (Arnould et al. 1999)

Post-main sequence structure

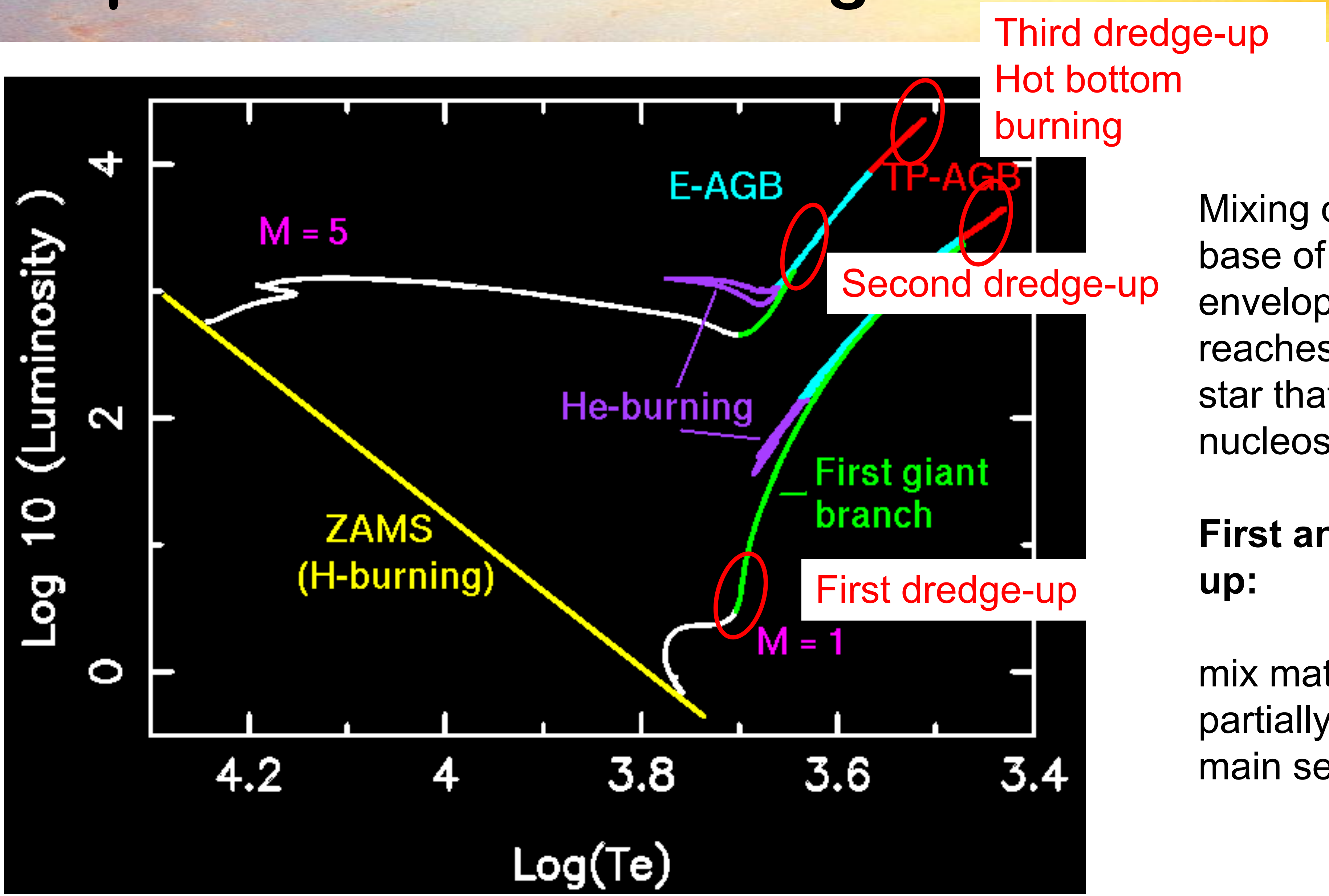
At the end of the H-burning phase:

- Inert He core, that is contracting and heating
- Shell of H-burning around the core.
- An envelope that is *expanding*.



- Figure from Carroll & Ostlie

Expansion causes mixing



Mixing occurs when the base of the convective envelope deepens, and reaches inner regions of the star that have experienced nucleosynthesis.

First and second dredge up:

mix material that was partially processed on the main sequence: H-burning.

First dredge-up

- As the star becomes a giant the outer layers expand and cool.
- At the surface the material is less ionised and there are more ways for photons to interact with matter → opacity increases.
- Convection grows deeper into the star.
- This has the effect of the convective envelope *moving deeper* inwards (in mass!).
- The convective envelope may reach a part of the star that experienced partial or complete H-burning during the previous main sequence.
- Mixes burned material to the surface → dredge-up!

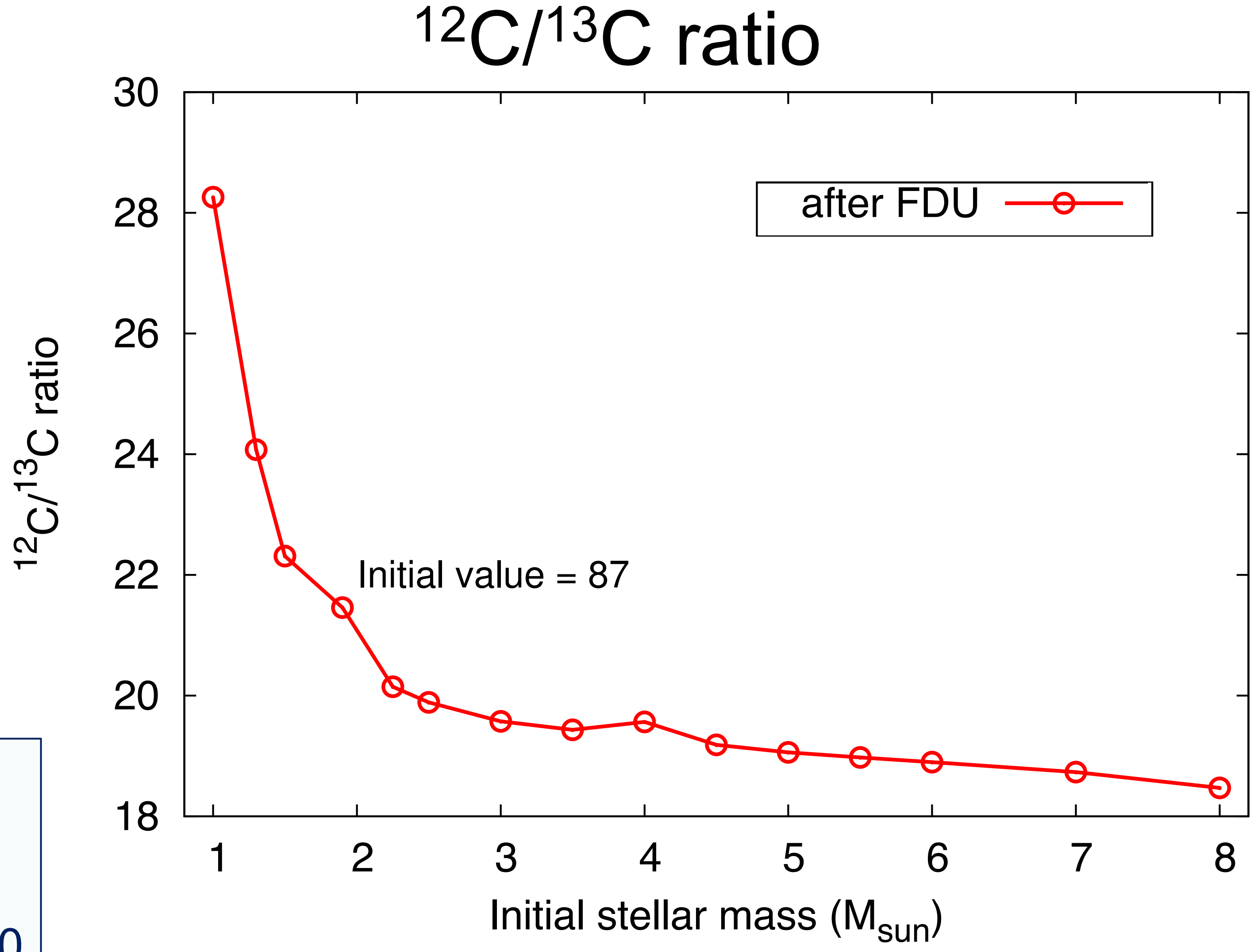
First dredge-up: what we see

- Isotopic ratios in stellar physics are usually by number unless otherwise stated.
- To convert from mass fraction, divide by atomic mass:

$$Y_k = \frac{X_k}{A_k}$$

- Here X_k = mass fraction of species *k* and A_k = atomic mass of species *k*

Example: Convert to mass fraction:
[12 x Y(^{12}C)] /[13 x Y(^{13}C)] = X(^{12}C)/X(^{13}C)
E.g., for the initial ratio = 87 x (12/13) = 80

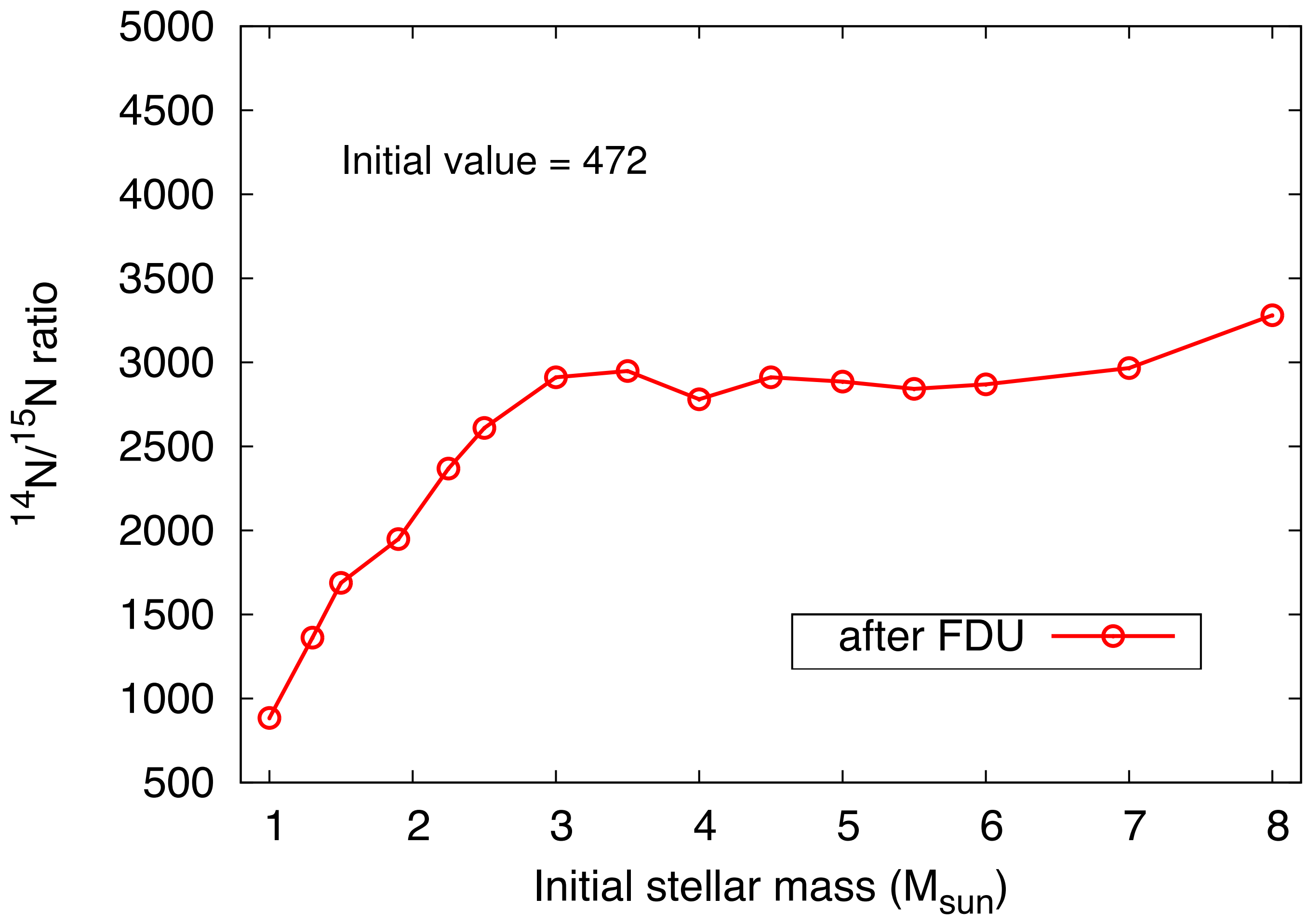


From Karakas & Lattanzio (2014)

What do we see at the surface?

$^{14}N/^{15}N$ can increase by a factor of 6!

$^{14}N/^{15}N$ ratio

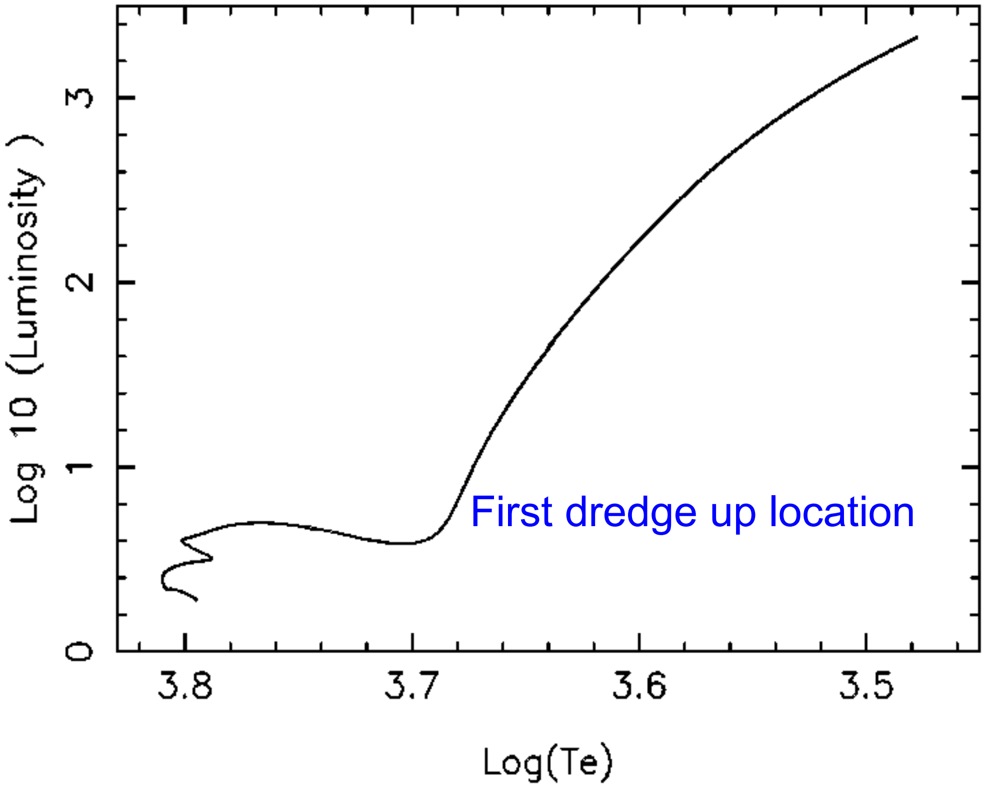


From Karakas & Lattanzio (2014)

Summary: First dredge up

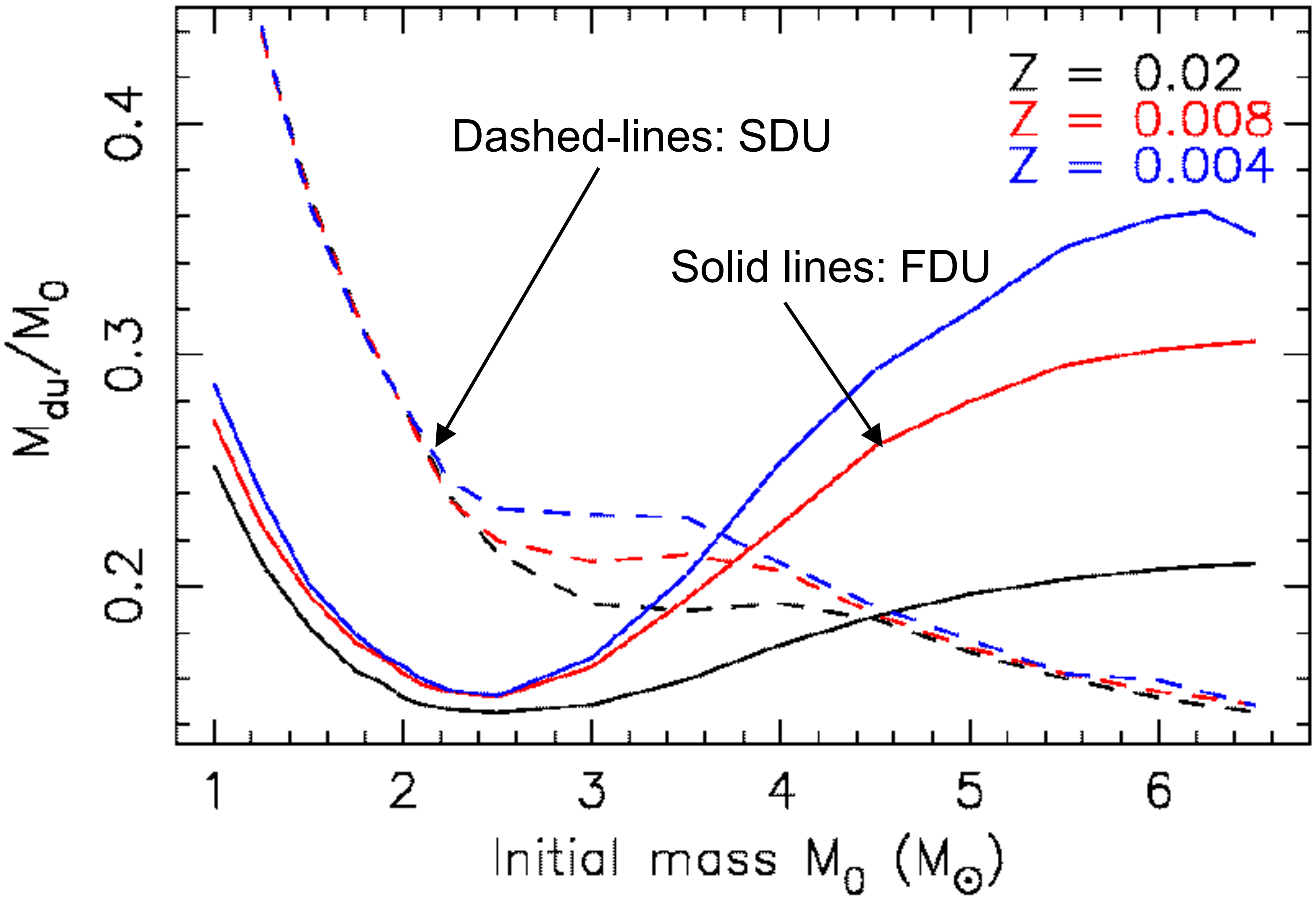
- Mixes material to the surface that was partially processed by H-burning during the previous main sequence.
- Main changes at the surface:
  - Reduction in Li, $^{12}C/^{13}C$ ratio
  - Increases in ^{3}He, N
  - Little change to ^{16}O but ^{17}O increases while ^{18}O decreases
  - Hence, $^{16}O/^{17}O$ decreases while $^{16}O/^{18}O$ increases

Example: 1.25Msun, Z = 0.02 model



We are seeing the results of the pp chains and CNO cycle mixed to the stellar surface!

Depth of first and second dredge-up



From my thesis but also see Boothroyd & Sackmann (1999); Karakas & Lattanzio (2014)

Frist dredge-up and stellar yields

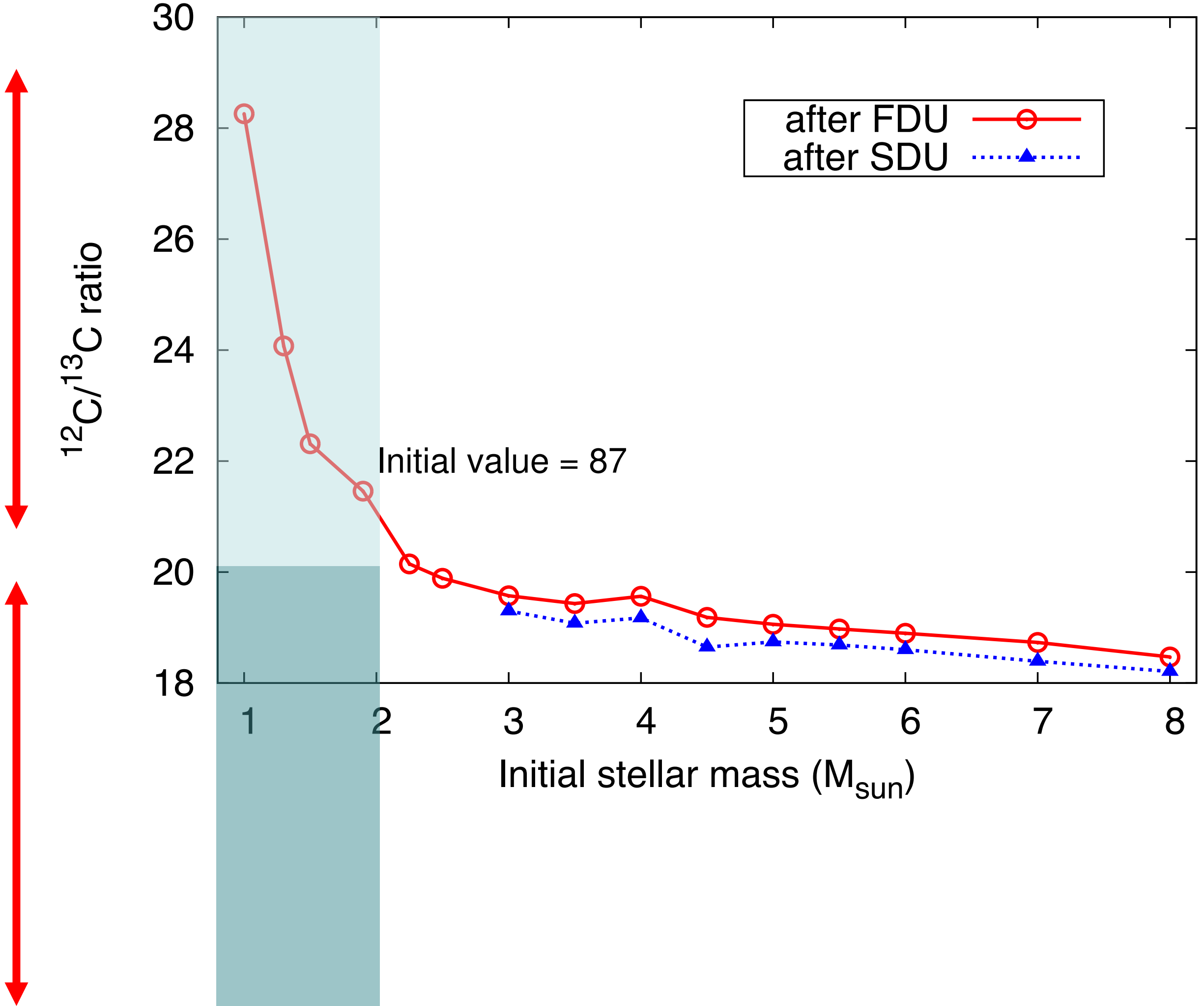
- The first dredge-up changes the surface composition but the effect on the stellar yields of most masses is small compared to the AGB phase
- By stellar yield: mass lost through stellar winds, integrated over the whole stellar lifetime
- The yield will include mass lost during the RGB and the AGB (and all phases inbetween)
- This is because the AGB phase results is strong changes to the surface composition
- Except stars that do not experience mixing on the AGB, usually M $\lesssim$ 1.2 Msun, depending on Z.

Comparison to observations

Observations of low-mass giants in the field or in clusters show that the $^{12}C/^{13}C$ ratio is less than 20 (e.g., Gilroy 1989)

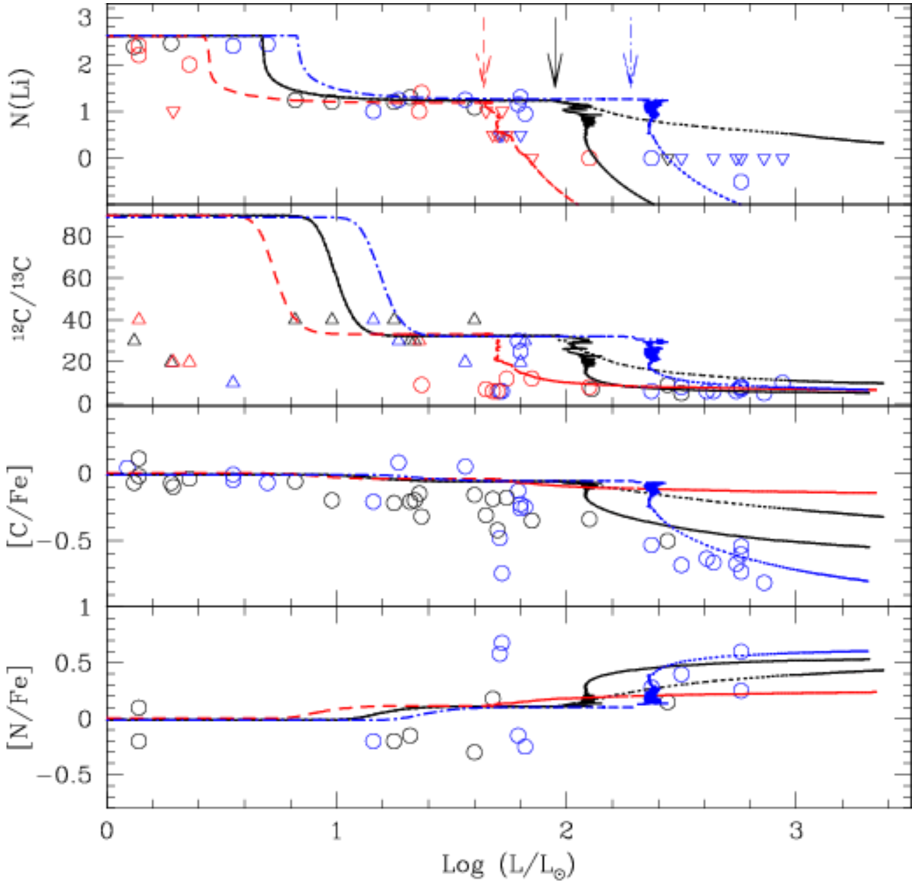
Predicted range

Observational range



Extra mixing in low-mass giant stars

- M < 2Msun
- The result is to mix products of the CN cycle to the surface.
- This results in further reductions in $^{12}C/^{13}C$ and C/N.
- Lithium also be destroyed (maybe).
- The mechanism?
- We still don’t know.
- Rotation? Unlikely to be main driver (Palacios et al. 2006)
- Thermohaline mixing favoured in recent years.



From Charbonnel & Zahn (2007)

References: Smith & Tout (1992), Boothroyd & Sackmann (1999), Nollett et al. (2003), Stancliffe et al. (2009), Angelou et al. (2012), Lattanzio et al. (2015), Henkel et al. (2017)

Effect on the overall stellar yields

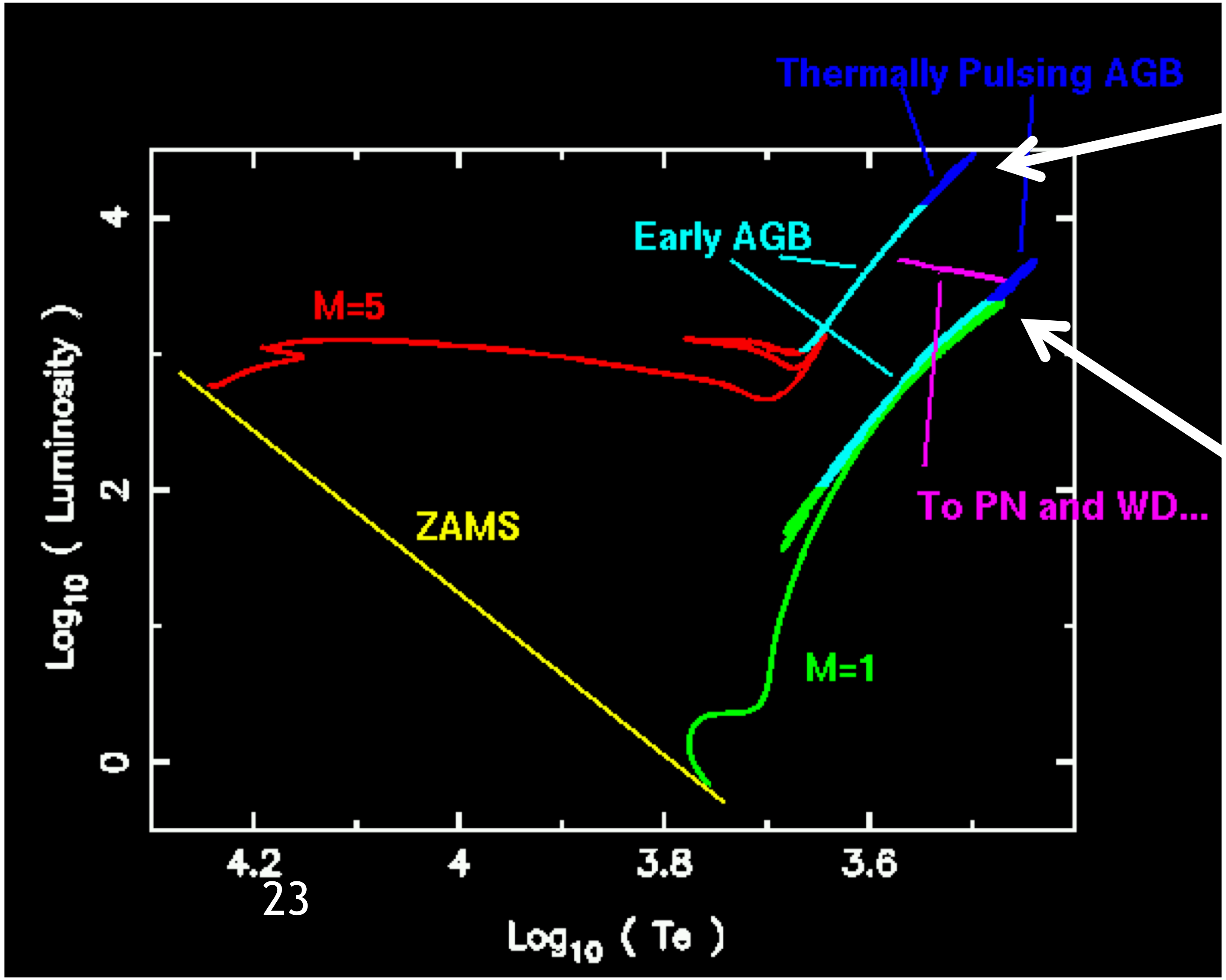
Extra mixing only affects a few isotopes:

1. ^{3}He – big reduction in the yield
2. ^{7}Li – reduction or production? Not clear
3. ^{12}C, ^{13}C (C elemental abundance) – C abundance down, ^{13}C isotopic abundance up
4. ^{14}N, ^{15}N (N elemental abundance) – N abundance up, in particular ^{14}N but ^{15}N down
5. Oxygen isotopes? Not clear extra mixing is important.

References: Discuss both thermohaline mixing and rotation Charbonnel & Lagarde (2010), Lagarde et al. (2011, 2012a,b – note that rotation can change the internal structure and the surface changes after FDU for a few elements e.g., N)

Helium Ignition

Requires T = 100 million K



For stars of mass > 2 $M_\odot$ He ignition in the core happens smoothly

For stars of mass < 2 $M_\odot$ He ignition happens suddenly (***flash***) because the core is degenerate

Core He Burning

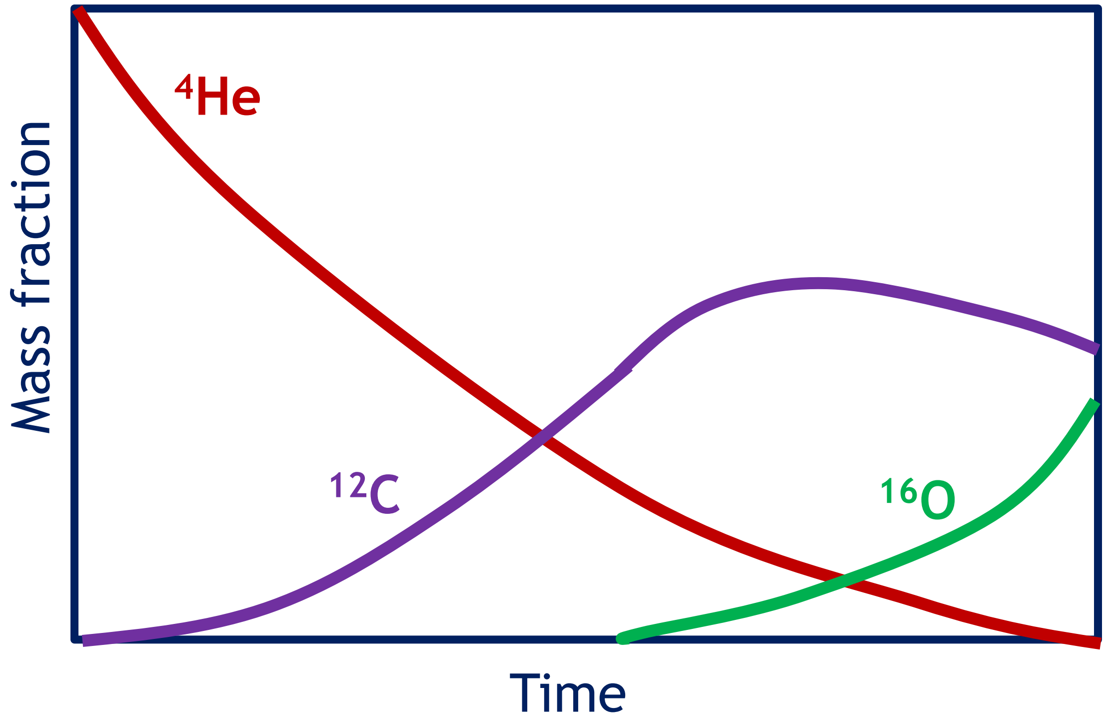
- Helium burns into ^{12}C via triple alpha:

$$3\,^{4}He \rightarrow {}^{12}C + \gamma$$

- But ^{4}He can also fuse with ^{12}C:

$$^{12}C + {}^{4}He \rightarrow {}^{16}O + \gamma$$

- So **He decreases** and **C increases**..
- ..until **C decreases and O increases**…
- Final C/O depends on the rate of the $^{12}C + \alpha$ reaction.



Helium burning

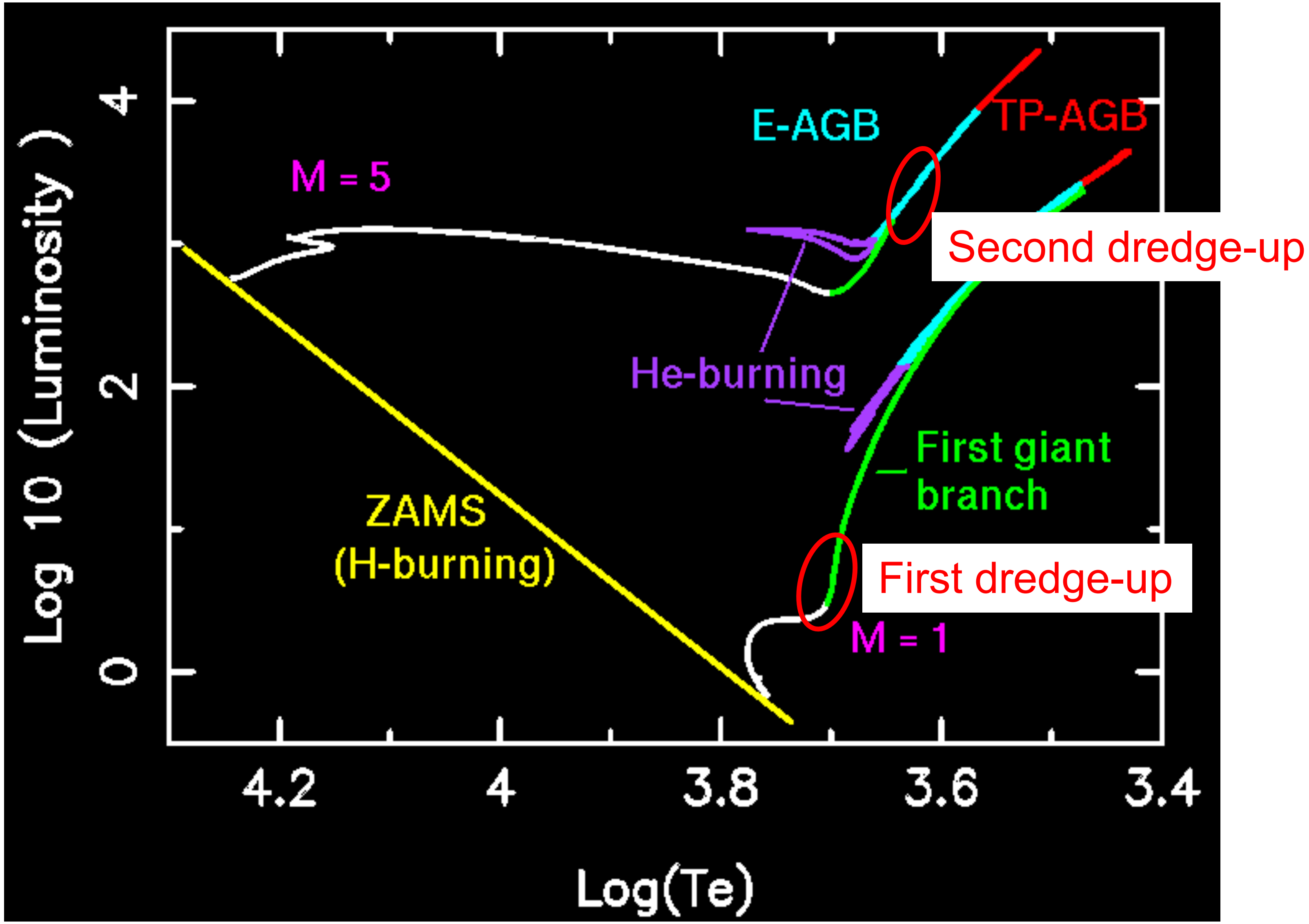
- At slightly higher T and density the $^{12}C(\alpha, \gamma)^{16}O$ reaction occurs once a supply of ^{12}C is available
- The $^{12}C(\alpha, \gamma)^{16}O$ reaction also supplies energy
- At the end of core He-burning, the composition of the core is roughly 50% ^{12}C and 50% ^{16}O
- Although the final C/O greatly depending on the rates and can be as extreme as C:O = 0.10:0.90.
- Temperature dependence for the triple-α rate turns out to be roughly $\varepsilon \propto T^{40}$!
- This means that helium burning leads to a very steep temperature gradient → convection

EVOLUTION AND NUCLEOSYNTHESIS OF AGB STARS

The early asymptotic giant branch

- Following core He-exhaustion, the star evolves up the second giant branch, or AGB.
- A helium burning shell is established around the contracting C-O core, which narrows as the star evolves.
- Eventually the shell becomes thin and partially degenerate.
- Helium burning is unstable under such conditions → leads to thermal pulses or He-shell instabilities.
- However, the early part of the AGB is the longest in time and is where the second mixing event occurs.

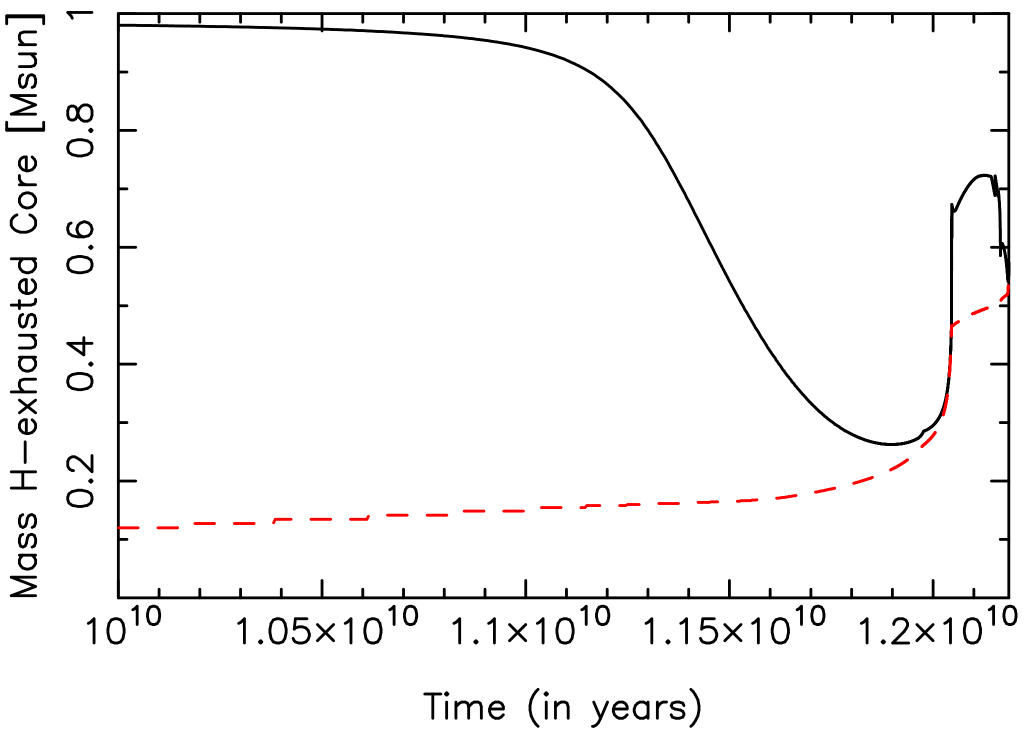
Where mixing takes place



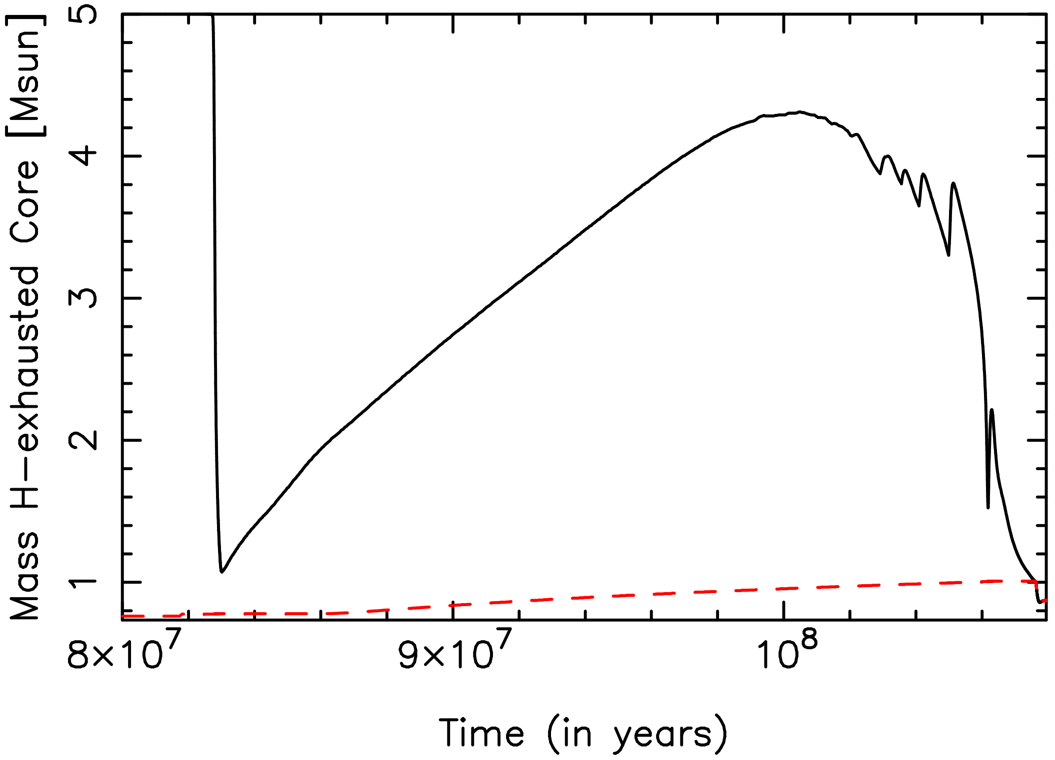
Second dredge up

- Convection reaches deeper during the ascent of the AGB compared to the RGB for intermediate-mass stars over ~4.5 Msun (for solar metallicity)

1Msun, Z = 0.014

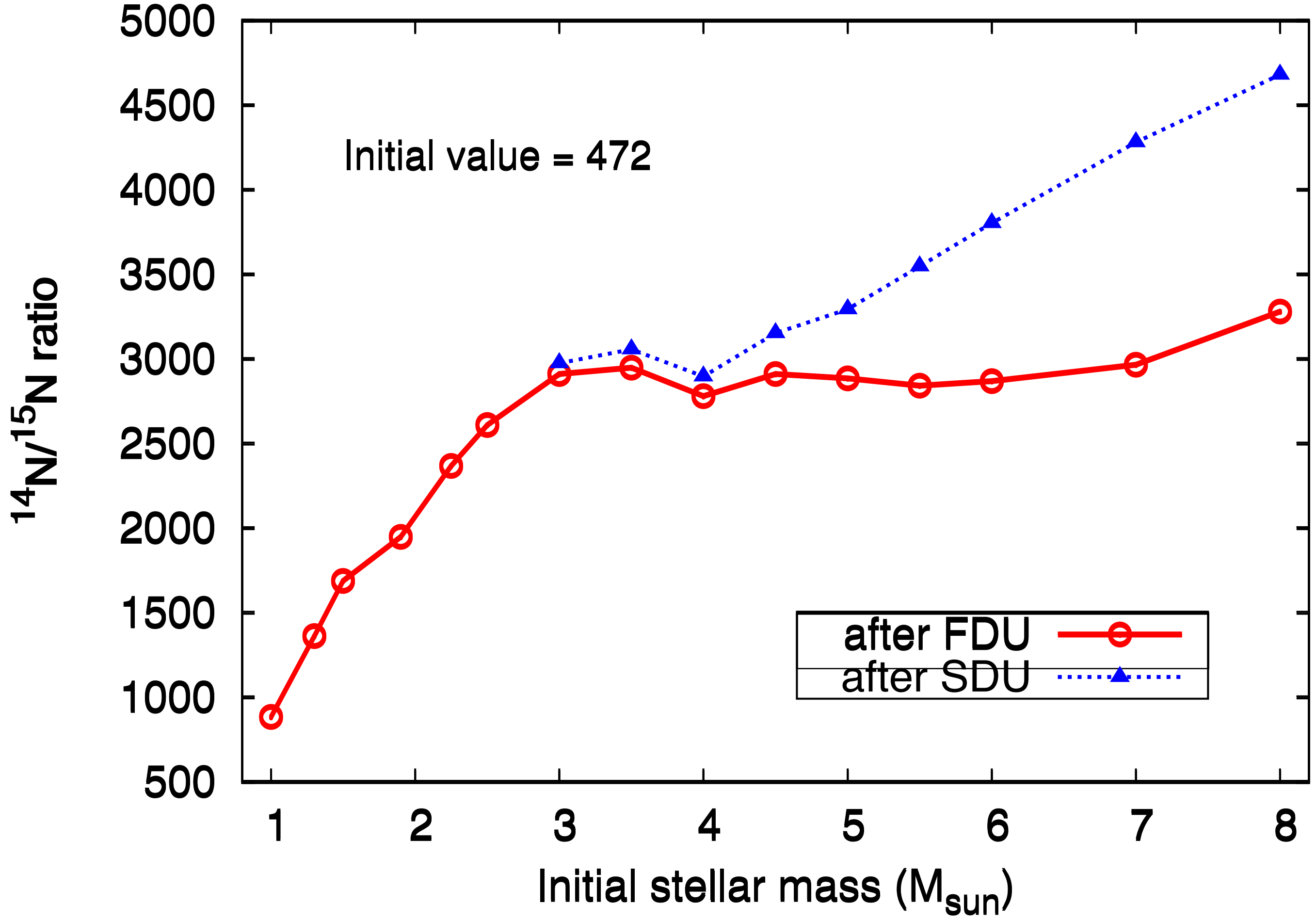


5Msun, Z = 0.014



Adding in second dredge-up

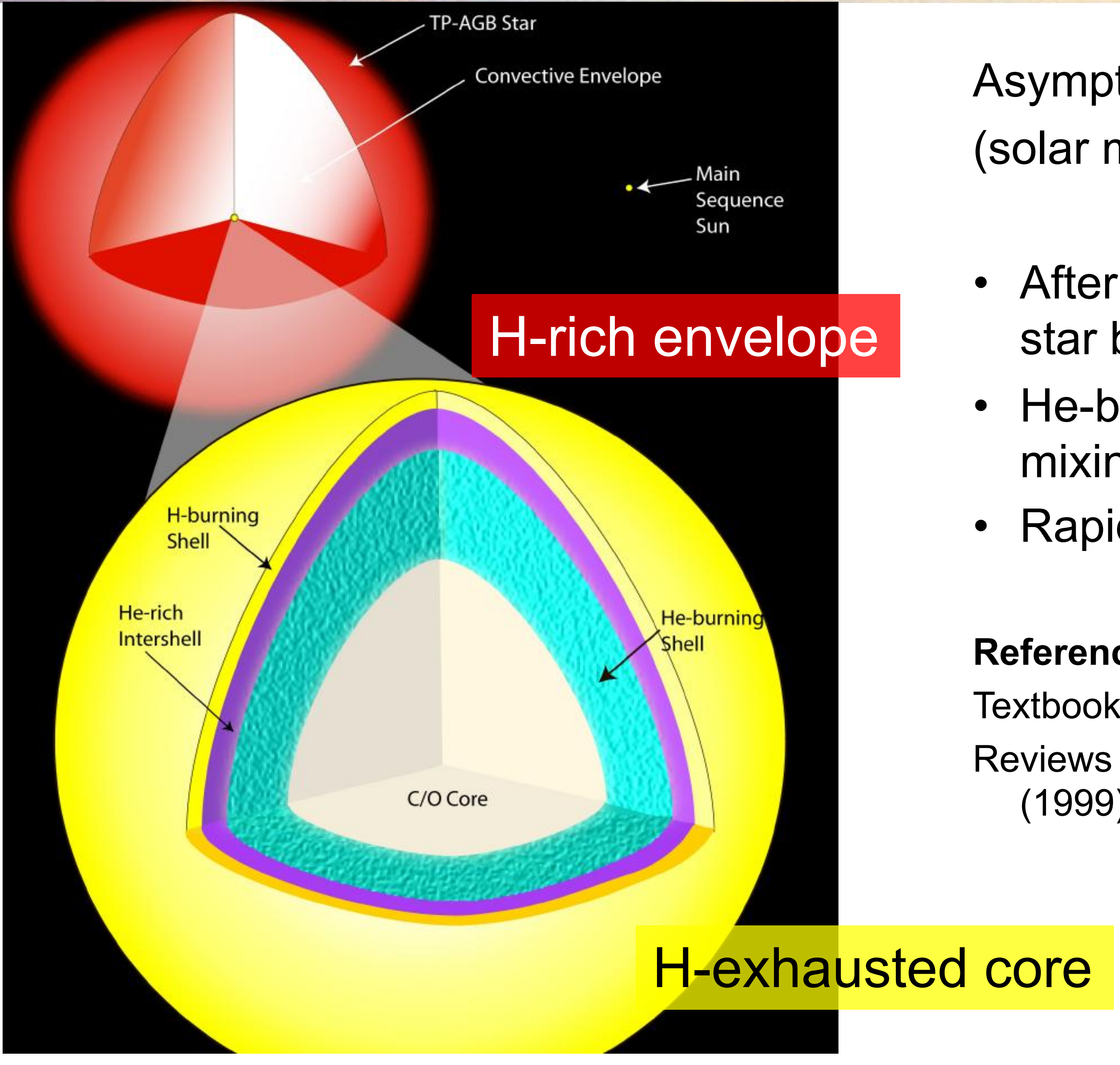
$^{14}N/^{15}N$ is mostly affected by SDU, along with helium, which can increase by up to $\Delta Y \sim 0.1$



$^{14}N/^{15}N$ ratio

From Karakas & Lattanzio (2014)

Asymptotic Giant Branch stars



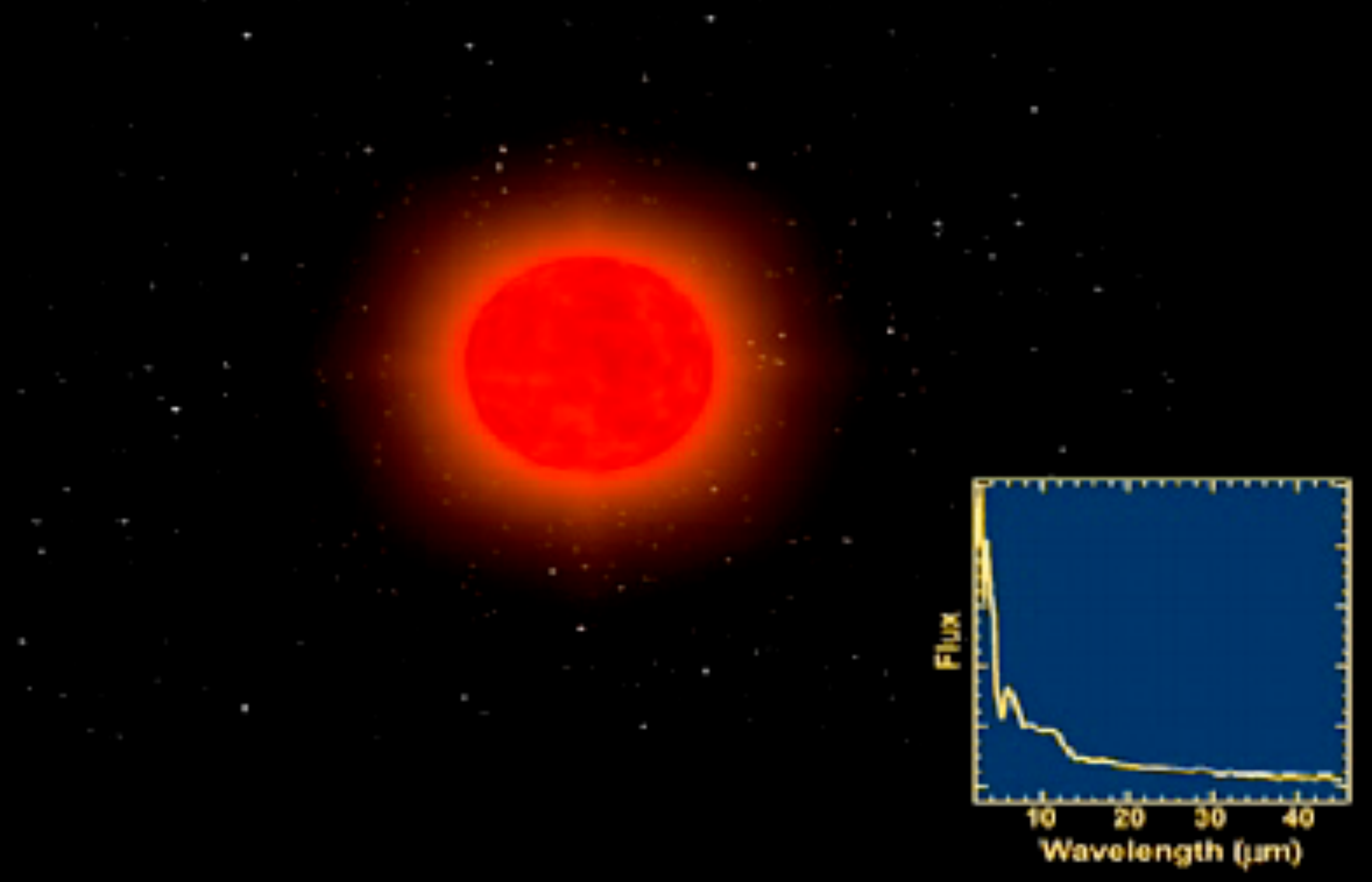
Asymptotic Giant Branch stars:
(solar metallicity upper limit: $8M_{sun}$)

- After core He-burning, the C-O core contracts and the star becomes a giant again.
- He-burning shell is thermally unstable → causes mixing.
- Rapid, episodic mass loss erodes the envelope.

References:

Textbook by Habing & Olofsson (2003)

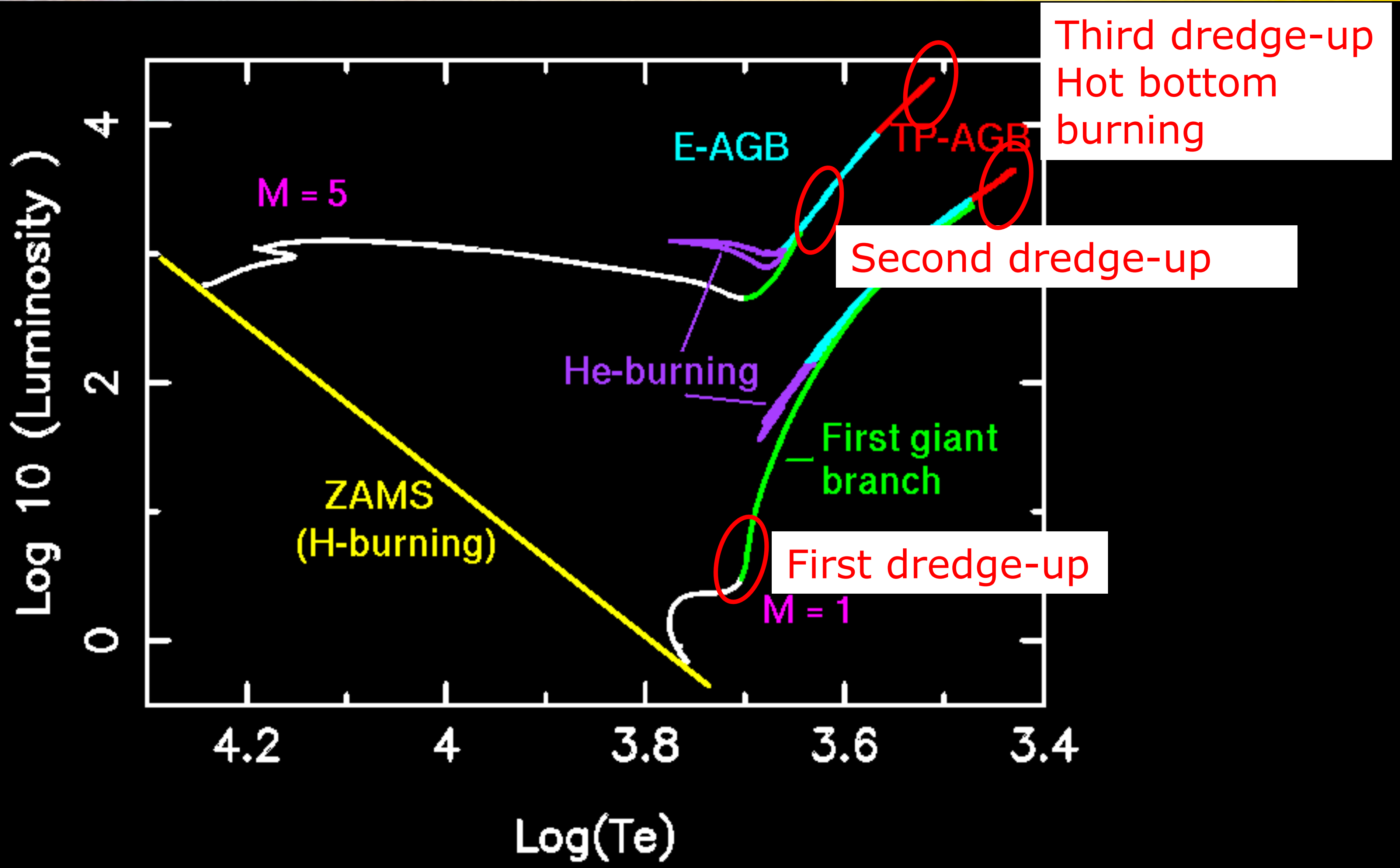
Reviews by Karakas & Lattanzio (2014), Herwig (2005), Busso et al. (1999), Iben (1991) etc.



Artist impression.

Courtesy of Pedro Garcia-Lario, ESA and Anibal García-Hernandez, IAC

Where mixing takes place



Products of nucleosynthesis

Low and intermediate-mass stars go through central hydrogen and helium burning

During the AGB, they have shells burning H and He

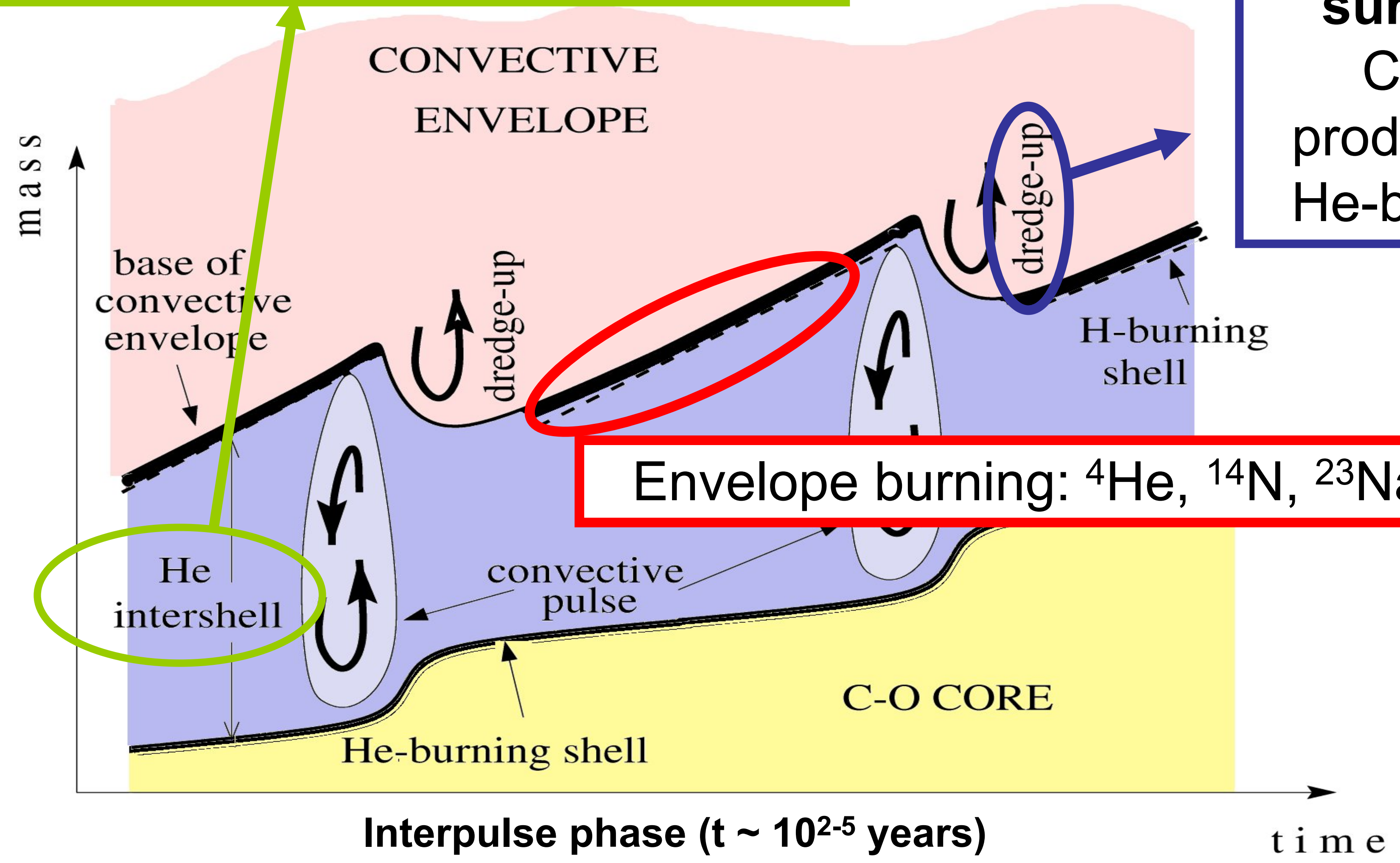
1. First dredge-up: Products of (partial) H burning
2. Second dredge-up: Products of H burning
3. Third dredge-up: Products of H, He-burning and neutron-capture nucleosynthesis
4. Hot bottom burning: Products of H-burning
5. Extra mixing processes: Products of H-burning

→ We we will now discuss the AGB phase of evolution

AGB nucleosynthesis

^{4}He, ^{12}C, ^{19}F, *s*-process elements: Zr, Ba, ...

At the stellar surface: C>O, products of He-burning



Envelope burning: ^{4}He, ^{14}N, ^{23}Na

Interpulse phase (t ~ 10^{2-5} years)

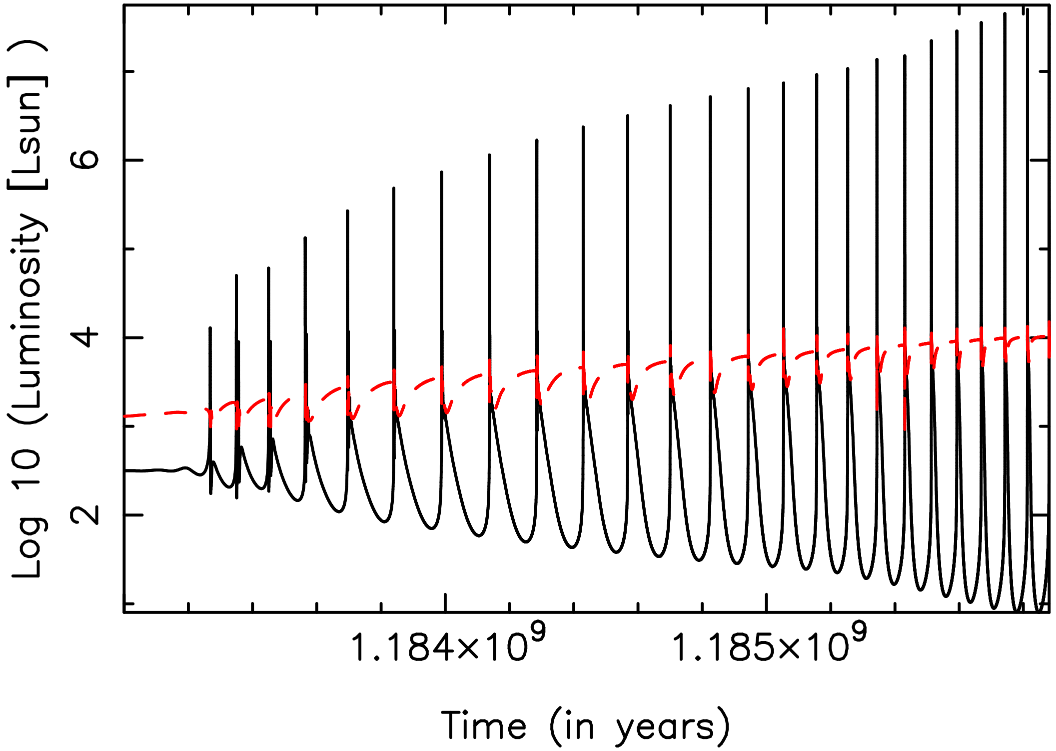
He-shell instabilities

- The He-shell thins as the star ascends the AGB and becomes thermally unstable.
- He-burning in a thin shell leads to a thermal runaway, similar to the core He-flash. Why?
- Not caused by electron degeneracy, although the shell is partially degenerate.
- Caused by the shell being thin.
- Contracting shell $\rightarrow$ hotter $\rightarrow$ $\varepsilon \propto T^{40}$ $\rightarrow$ but shell can't expand enough to cool $\rightarrow$ thermal runaway.
- Luminosities can reach > 10^8 solar luminosities.

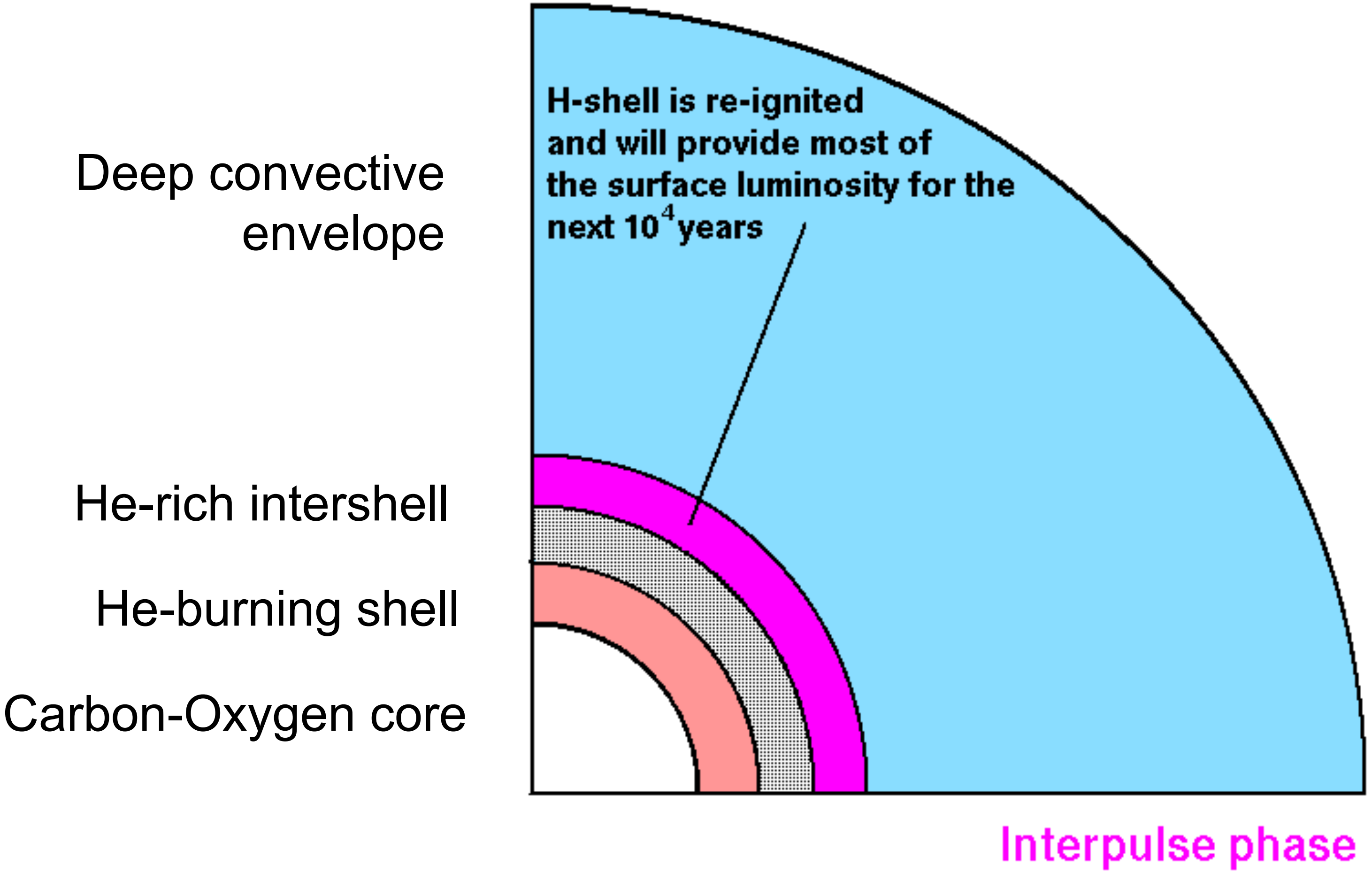
He-shell burning in AGB stars

- Up to ~10^8 Lsun can be generated by a thermal pulse
- Energy goes into expanding the star
- He-shell becomes unstable to convection → mixes products of He-burning throughout shell

2Msun, Z = 0.014 model star:



The thermal pulse cycle



The AGB Evolution Cycle

1. On phase: He-shell burns brightly, producing up to 10^8 L_{sun}, drives a convection zone in the He-rich intershell and lasts for ~ 100 years
2. Power-down: He-shell dies down, energy released by flash drives expansion which extinguishes the H-shell
3. Third dredge-up: convective envelope moves inward into regions mixed by flash-driven convection. Mixes partially He-burnt material to surface.
4. Interpulse: star contracts and H-shell is re-ignited, provides most of the surface luminosity for the next ~10^5 years

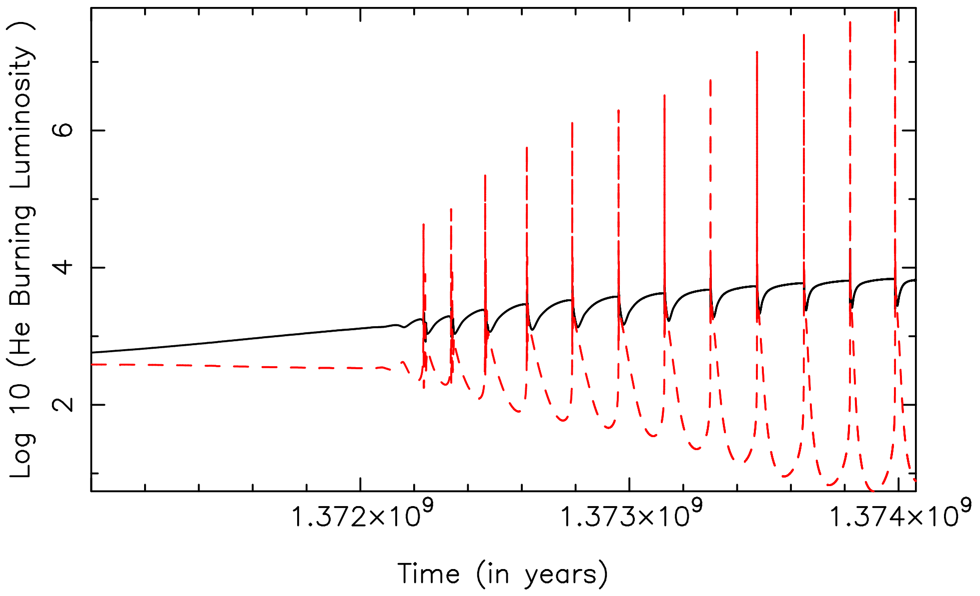
Pulse (He-burning) → TDU (mixing) → Interpulse

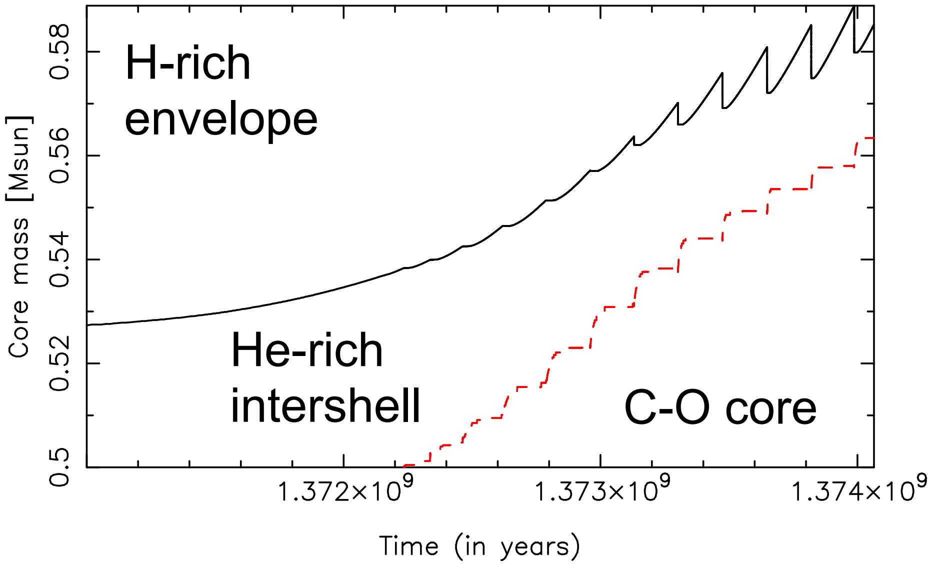
Few ~10^2 yrs → ~10^2 years → ~10^5 yrs

Third dredge-up

- Badly named, can re-occur after each thermal pulse
- Inward movement of convective envelope, reaches into the He-shell
- Right-hand panel shows the evolution of the core in a low-mass AGB model
- Six (third)-dredge-up events are visible. Each one will mix He-shell material to the surface

Typical Galactic C-rich AGB star: 1.8Msun, Z = 0.01





Non-energetic reactions

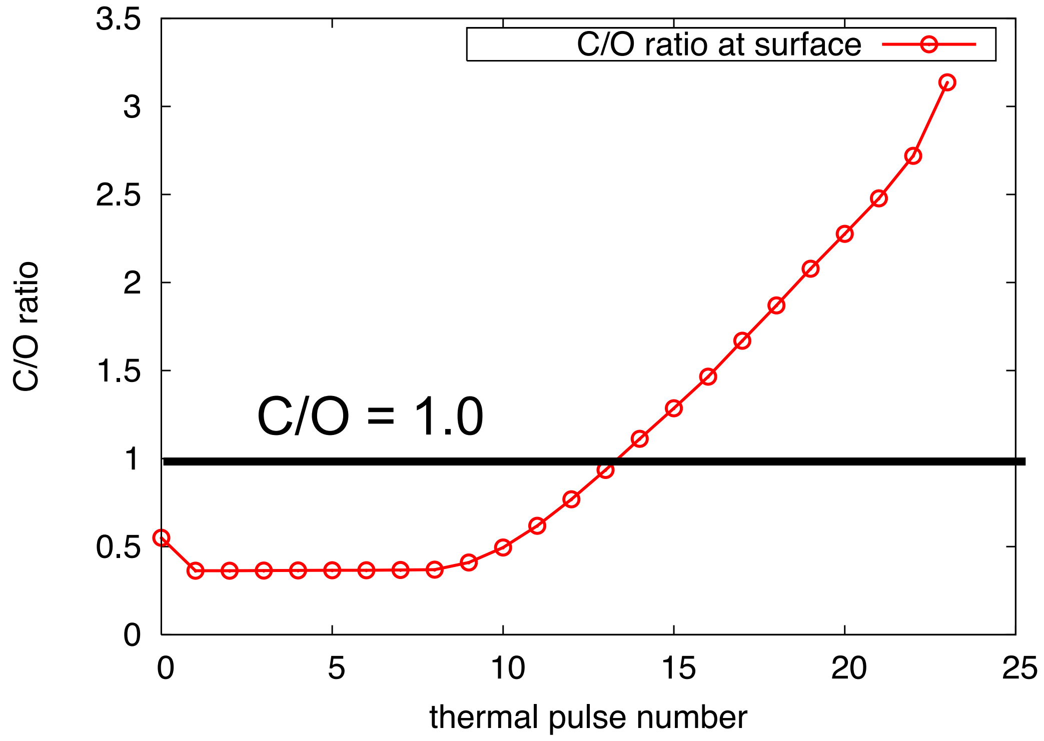
- He-burning occurs in the *ashes* of H-burning
- The composition is typically 98% ^{4}He, ~2% ^{14}N
- Remember that the CNO cycle produces mostly ^{14}N, which can capture alpha particles to produce secondary nuclei, depending on T:
  - $^{14}N(\alpha, \gamma)^{18}F(\beta^+\nu)^{18}O(\alpha, \gamma)\mathbf{^{22}Ne}$
  - $\mathbf{^{22}Ne} + \alpha \rightarrow \mathbf{^{25,26}Mg}$ (+n or γ) when T > 300 million K
- These reactions produce little energy but are important for nucleosynthesis
- Example, the $^{22}Ne(\alpha,n)^{25}Mg$ (Q = -0.478MeV) reaction releases *free* neutrons that can be used to produce heavy elements i.e., $^{56}Fe(n,\gamma)^{57}Fe(n,\gamma)$…

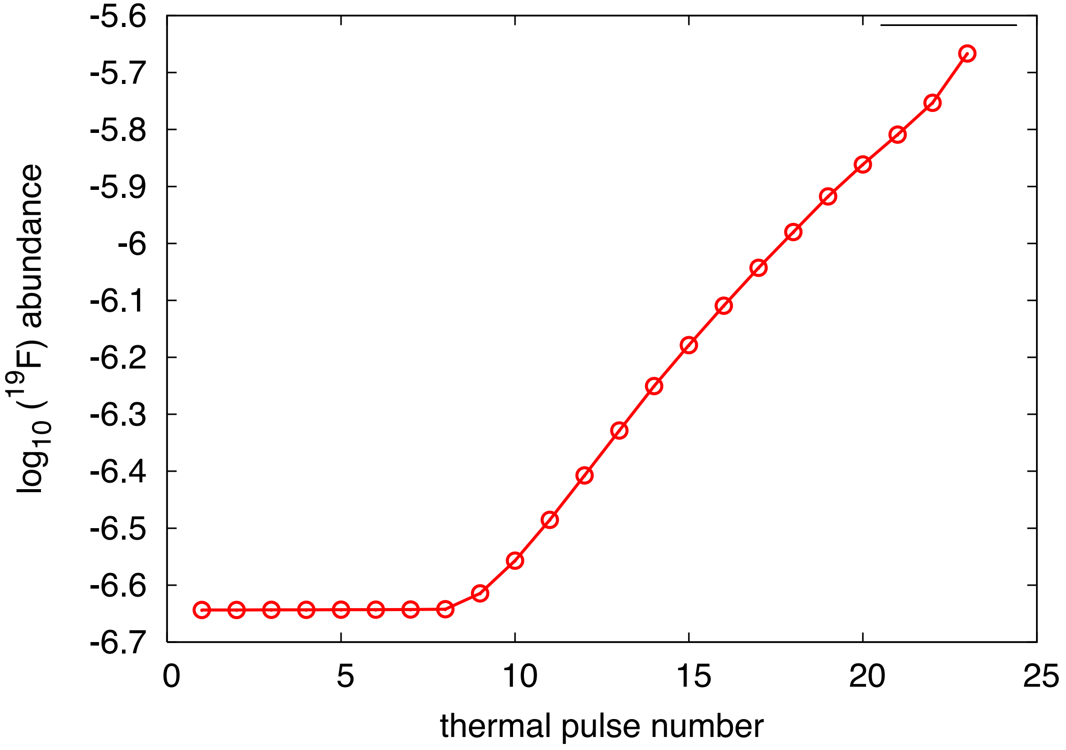
Products of He-shell nucleosynthesis

3Msun, Z = 0.014:

Surface abundance of carbon (left) and fluorine (right) during the AGB

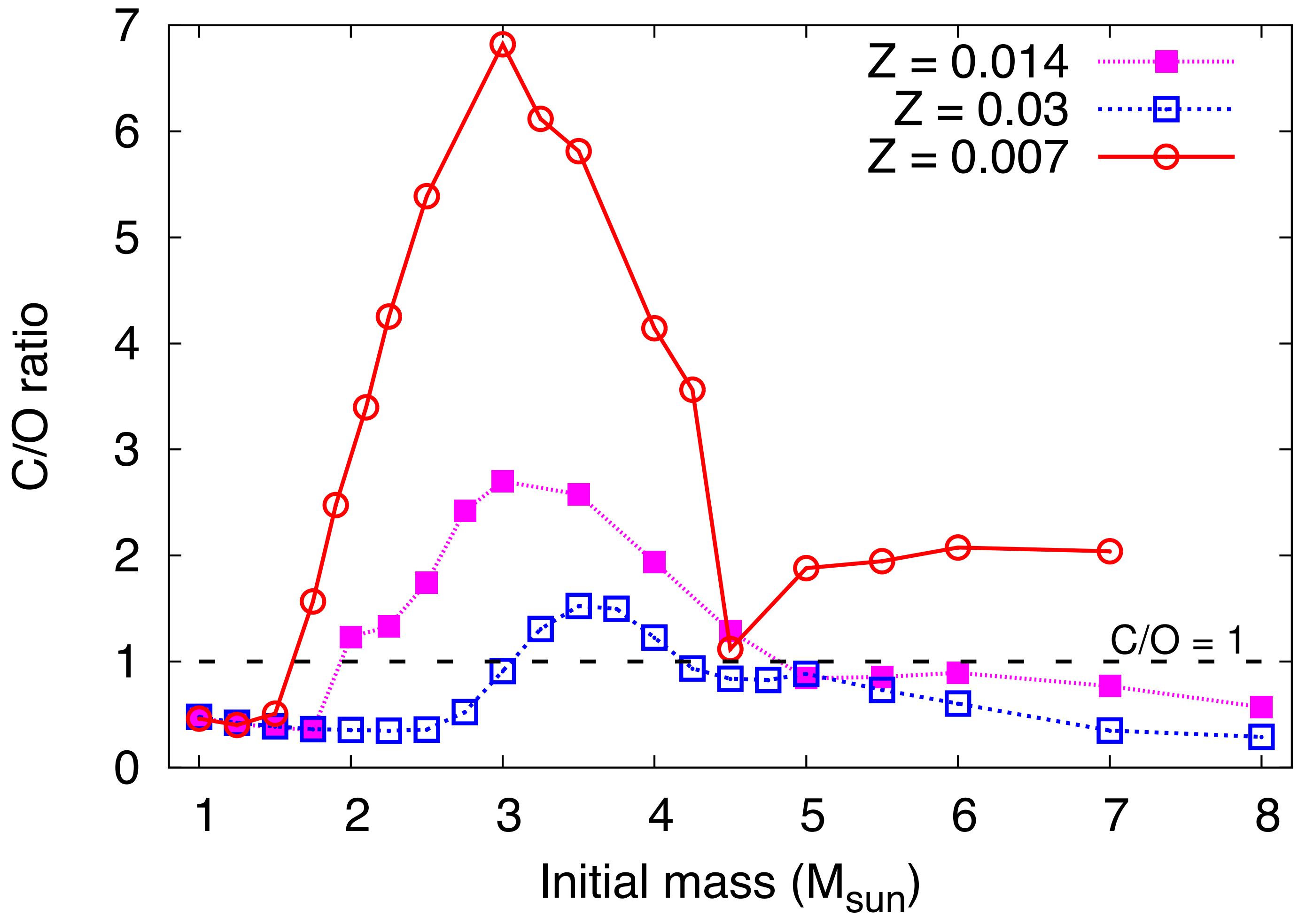
→ We can make a carbon-rich star, which has C/O > 1





AGB stars can become carbon rich

From Karakas (2014) for [Fe/H] = -0.3, 0.0, +0.3



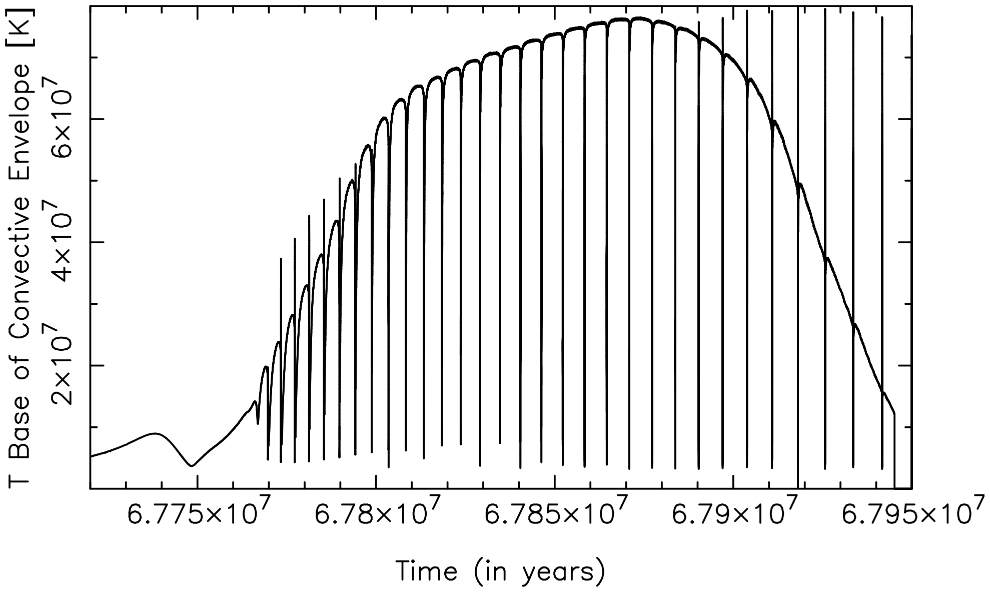
Hot bottom burning

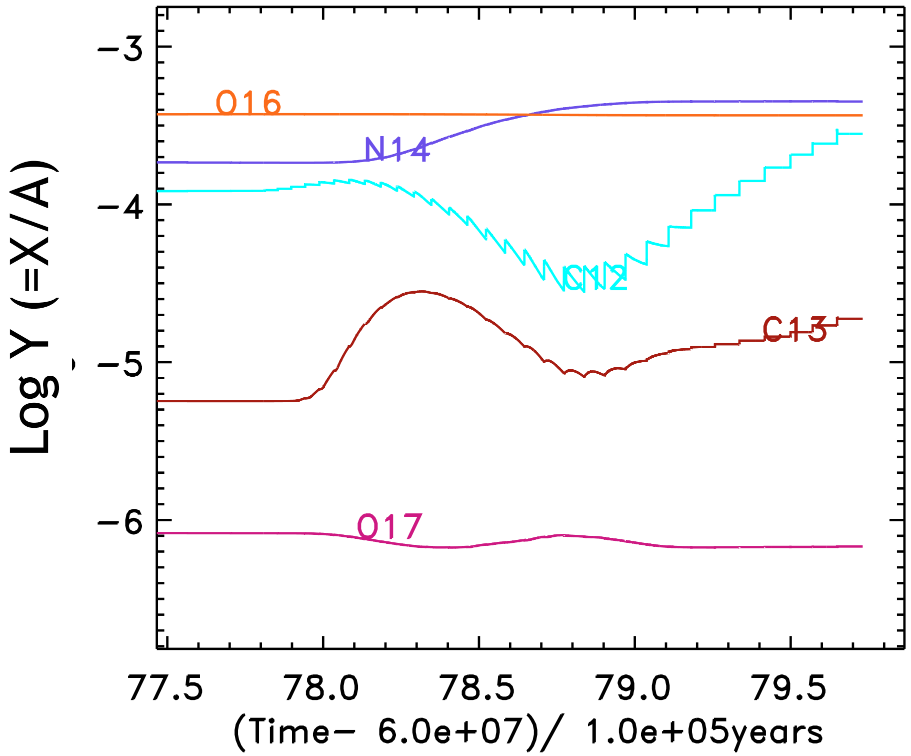
Occurs in stars over about 4.5Msun for Z = 0.014

Along with thermal pulses and the third dredge-up, these stars also have:

- Second dredge-up: Biggest ΔY (up to 0.1)
- Hot bottom burning: Proton-capture nucleosynthesis at base of envelope (products: N, Na, Al)

Example: 6Msun, Z = 0.02



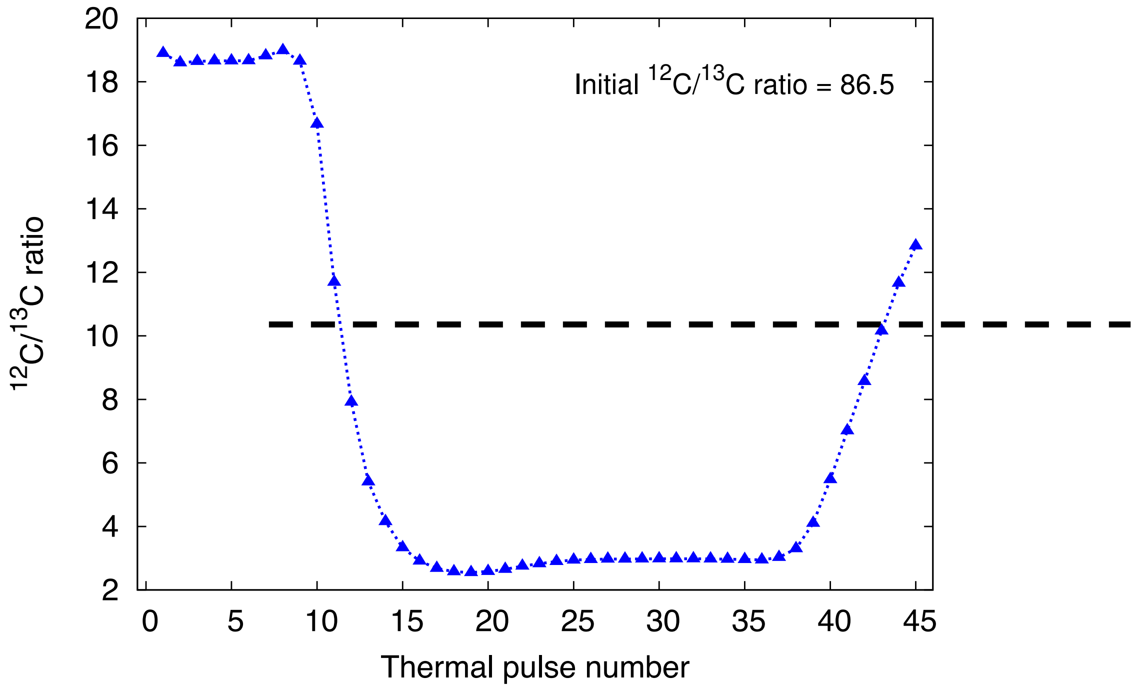


Hot bottom burning and third dredge up

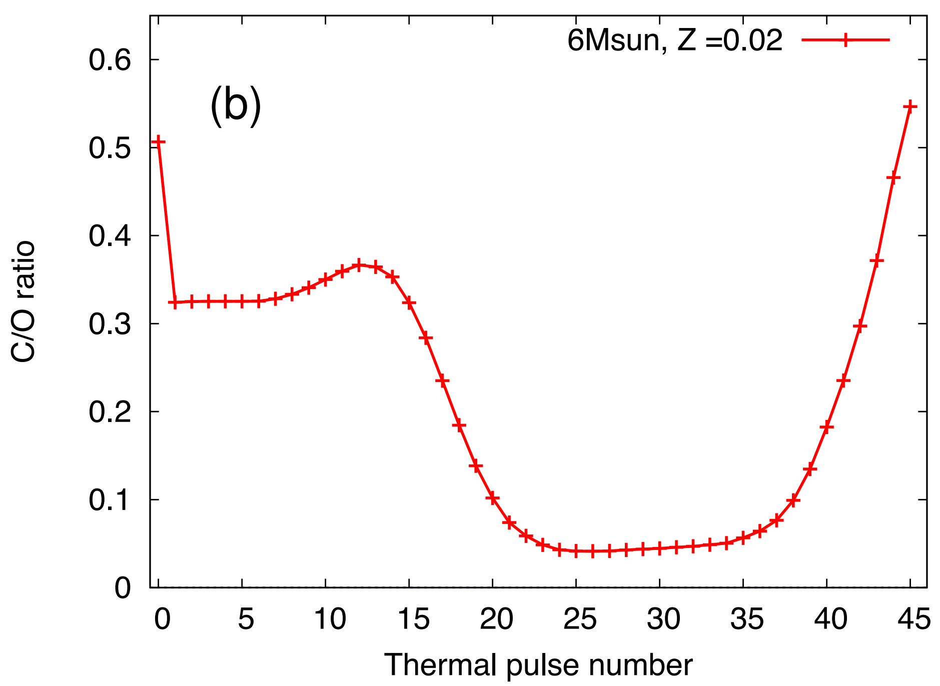
Example: 6Msun, Z = 0.02

Third dredge-up (TDU) and HBB act together

CN cycle is acting close to equilibrium for ~20 thermal pulses



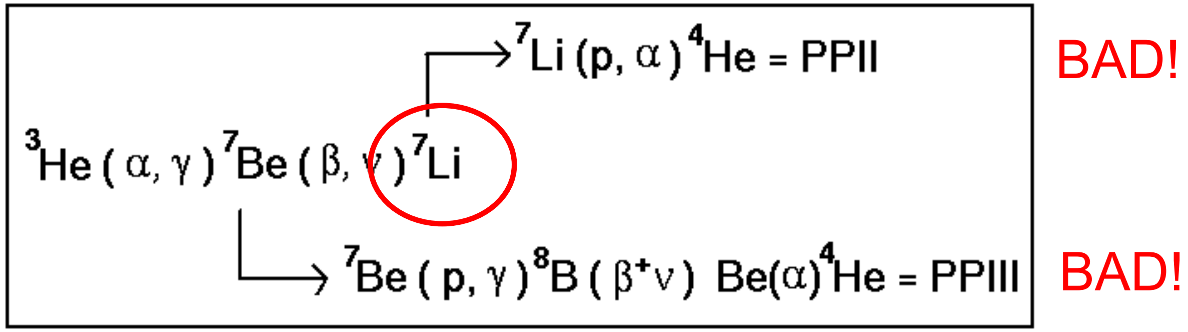
$^{12}C/^{13}C$ ~ 3 is the equilibrium ratio



The C/O ratio never exceeds 1

Lithium production

- The first thing to happen is that ^{7}Li is produced via the Cameron-Fowler Beryllium Transport Mechanism
- This is basically pp chains plus convection!
- The idea is that lithium is made by $^{3}He(\alpha, \gamma)^{7}Be$
- and then to use convection to move the ^{7}Be away from the hot region before it can complete the ppII or ppIII chains:

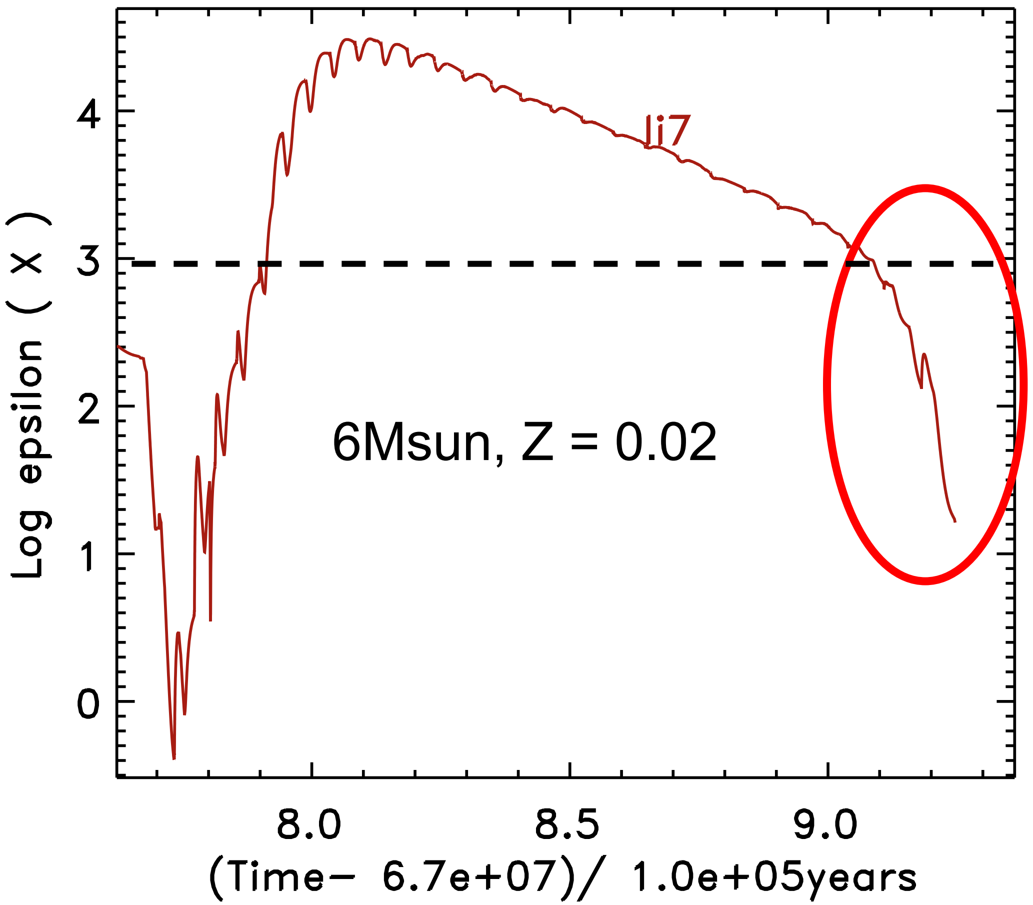


Cameron-Fowler mechanism

Lithium production

Lithium is produced by the Cameron-Fowler mechanism: ^7Be is transported by convection, where it captures an electron to produce ^7Li

$\log \varepsilon(Li)_{max} = \log_{10}(Li/H)+12 = 4.5$

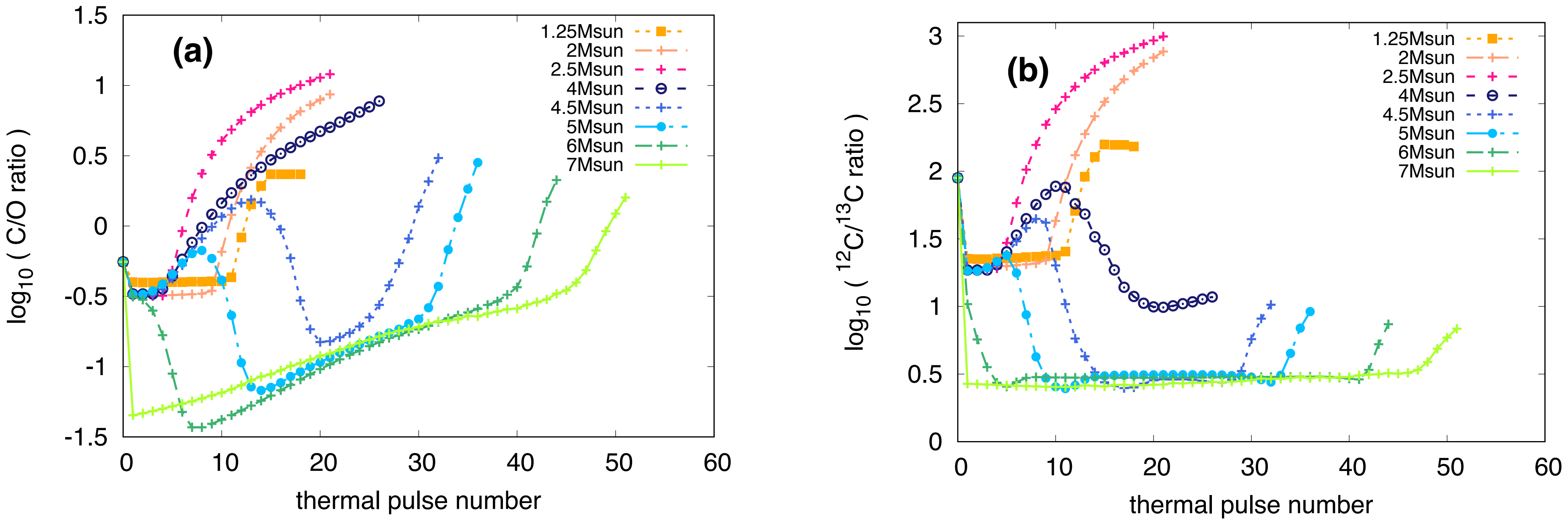


- Most mass is lost here
- Overall no net production of Li

Summary: Composition of AGB stars

- **C/O > 1:** 1.5 to 4.5M_{sun} for [Fe/H] ~ 0 → C stars, Ba, CH
  - Third dredge-up: He-shell burning (e.g., ^{12}C, F, ^{22}Ne etc)
- **C/O < 1:** M < 1.5Msun and M > 4.5M_{sun} for [Fe/H] ~ 0
  - M > 4.5Msun: H-burning in convective envelope (e.g., Li, ^{13}C, ^{14}N, Na, ^{26}Al)
  - M < 1.5Msun: First dredge-up ONLY

Models of [Fe/H] = -0.7 from Karakas et al. (2018)

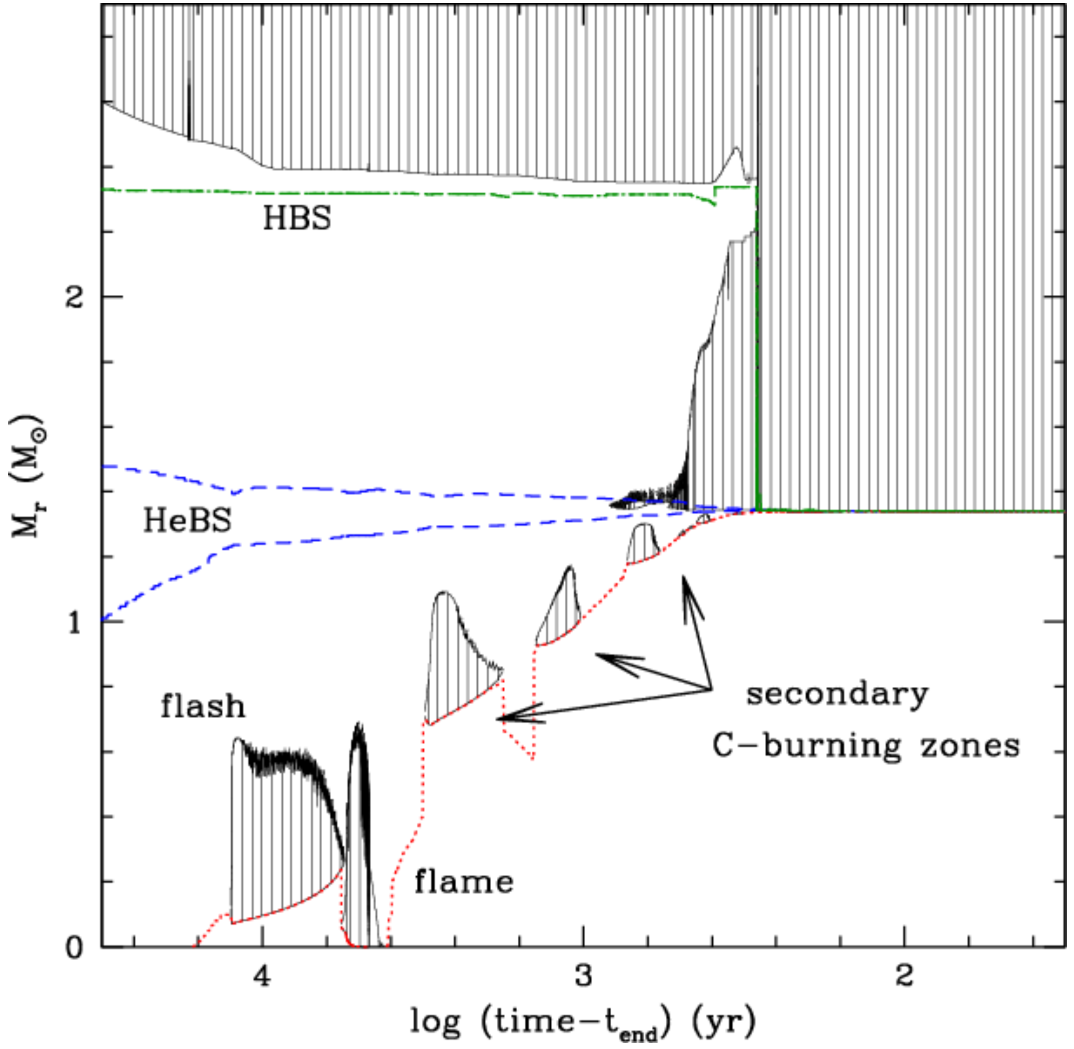


Super-AGB stars: 8-10 Msun stars

- The first models of stars in the range 8 to 10Msun were by Nomoto (1984), Garcia-Berro & Iben (1994), Ritossa et al. (1996), and Gutierrez et al. (1996).
- The paper by Garcia-Berro & Iben (1994) gave the name “super-AGB” for stars that ignite carbon and then experience thermal pulses.
- These calculations are difficult, and no one really worked on them for a long time after, until Gil-Pons et al. (2001, 2002) and then Siess (2006)
- Now, many studies of theses difficult objects!

Off-centre carbon ignition

- Stars between ~8 to 10Msun go through degenerate carbon ignition
- Before ascending the thermally-pulsing AGB with O-Ne cores
- Q: What fraction explode as supernovae or leave massive white dwarfs?
- E.g., Poelarends et al. (2008), Gil-Pons et al. (2013), Jones et al. (2014)
- The brightest AGB stars in young populations, with Mbol ~ −7.6, brighter than the traditional AGB limit (Mbol ~ −7.1)



7.5Msun, Z= 10^{-4} model by Siess (2007)

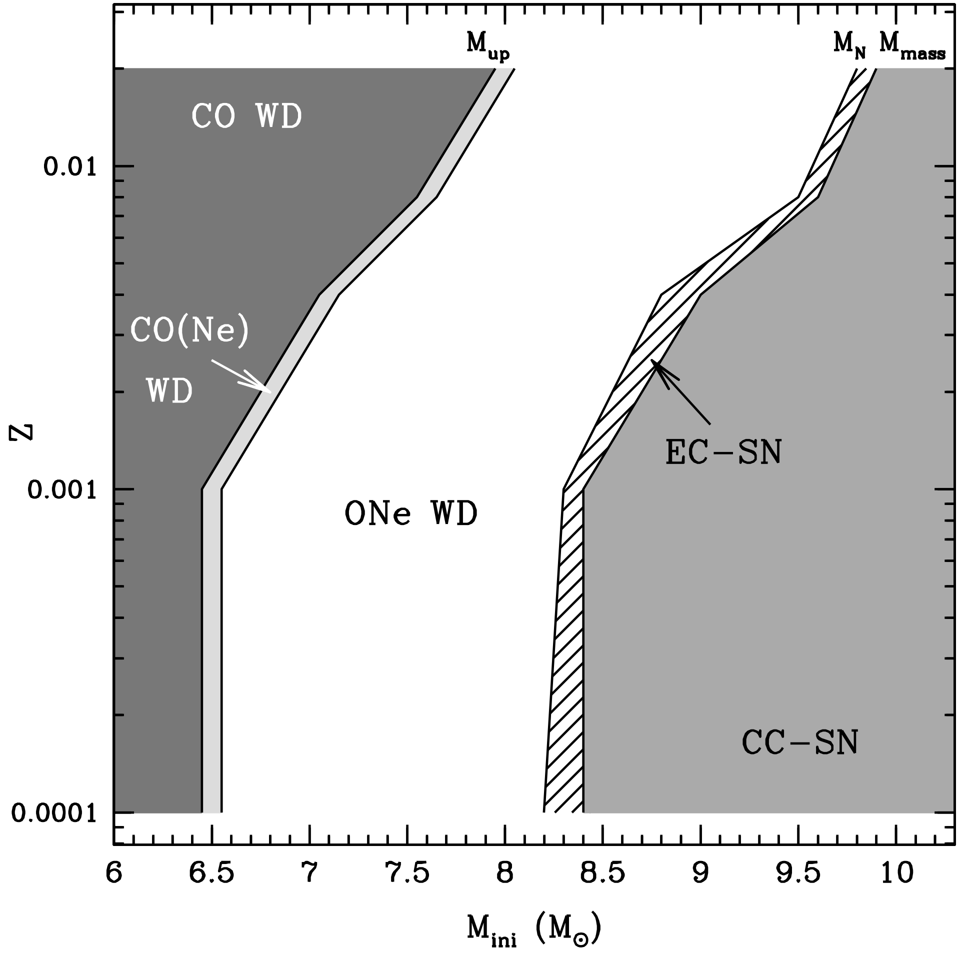
Final fate of Super-AGB stars?

The final fate of super-AGB stars is uncertain

- Will they mostly produce massive ONe white dwarfs
- What fraction will explode as electron capture supernova?
- What are their nucleosynthesis products? H burning? He-shell burning? The rapid neutron capture process?
- What happens when they are in a binary system? Will more explode?
- How do they affect the enrichment of the galaxy?

Lots of questions! Very exciting stuff

See Doherty et al. (2017) for a review!



From Doherty et al. (2015)

AGB stars and the s-process

A/Prof Amanda Karakas

School of Physics & Astronomy, Monash University, Australia

ARC Centre of Excellence for All Sky Astrophysics in 3D

The Helix Nebula — NGC 7293

MONASH University

ASTRO 3D

THE S-PROCESS

Outline of Lecture 2

We will look at:

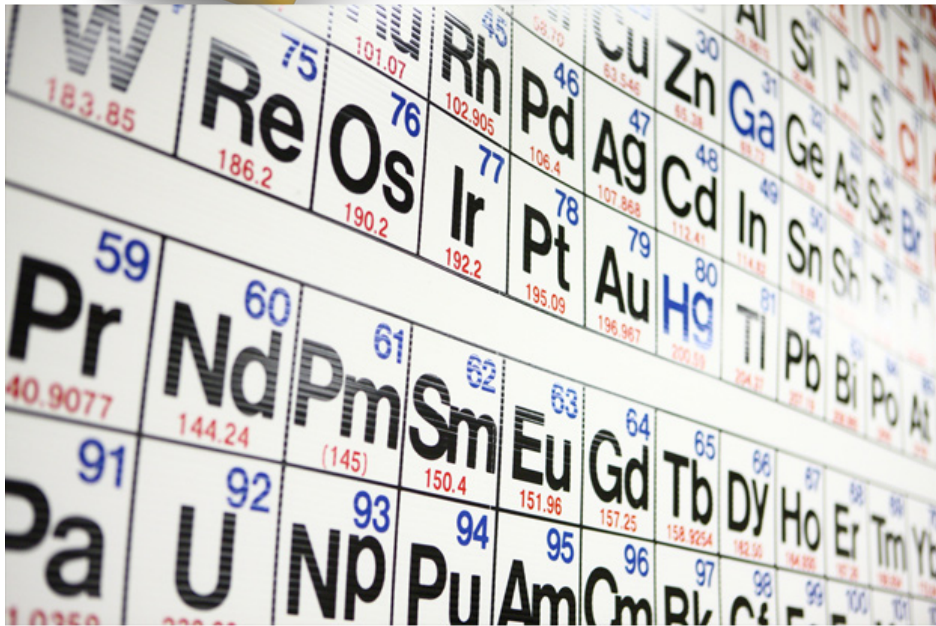
1. Introduction to the s-process
2. Sites of s-process production
3. Puzzles and the i-process
4. Chemical evolution of heavy elements

Production of heavy elements

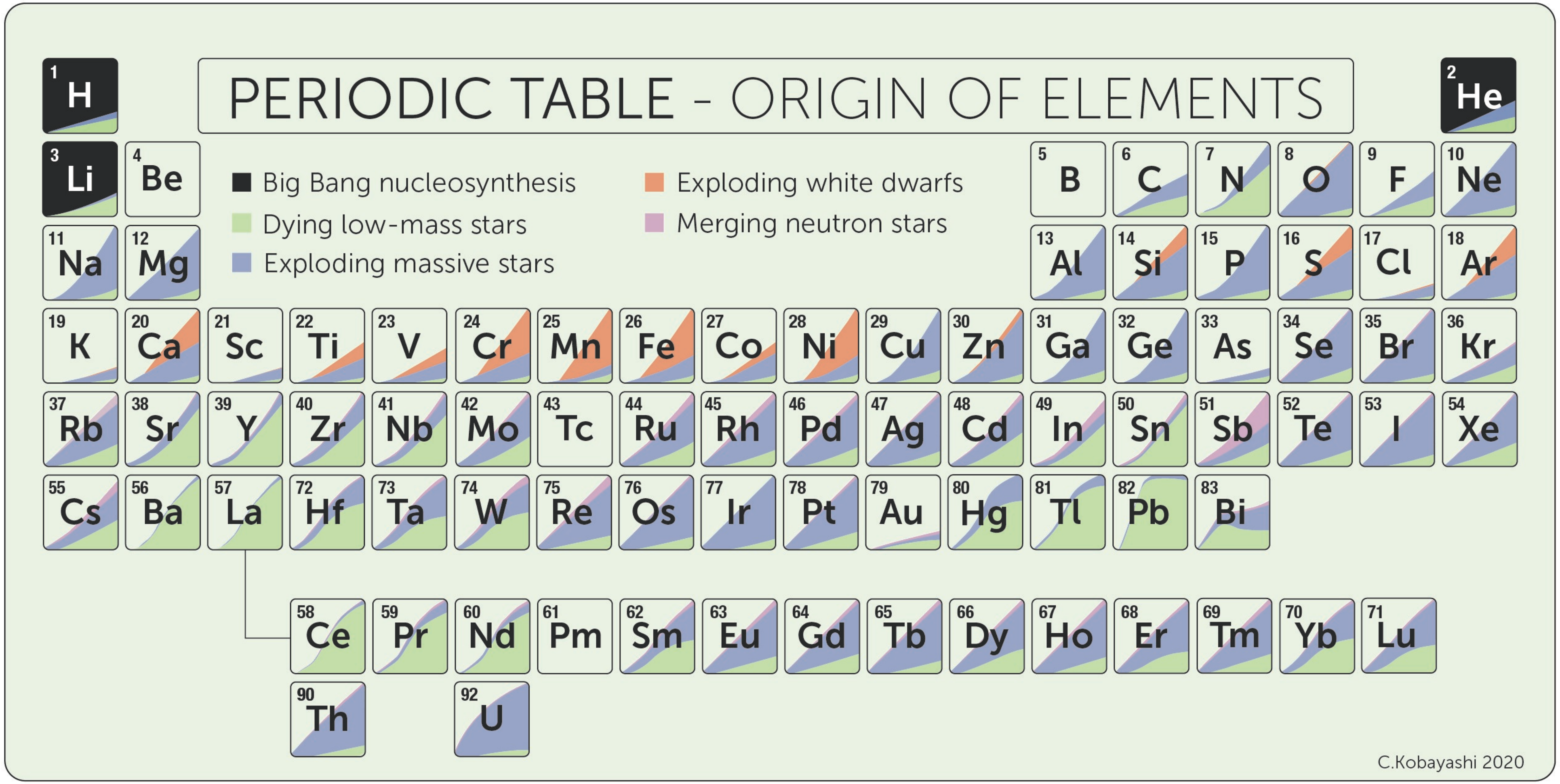
- By heavy elements we mean heavier than iron (Fe)
- Z is large → the electrostatic repulsion inhibits fusion reactions
- Most heavy nuclei are formed by neutron addition onto Fe-peak elements
- Two processes:
  - *r-process* (rapid neutron capture)
  - *s-process* (slow neutron capture)

References:

Lattimer & Schramm (1974), Meyer (1994), Sneden, Cowan & Gallino (2008), Käppeler et al. (2011)



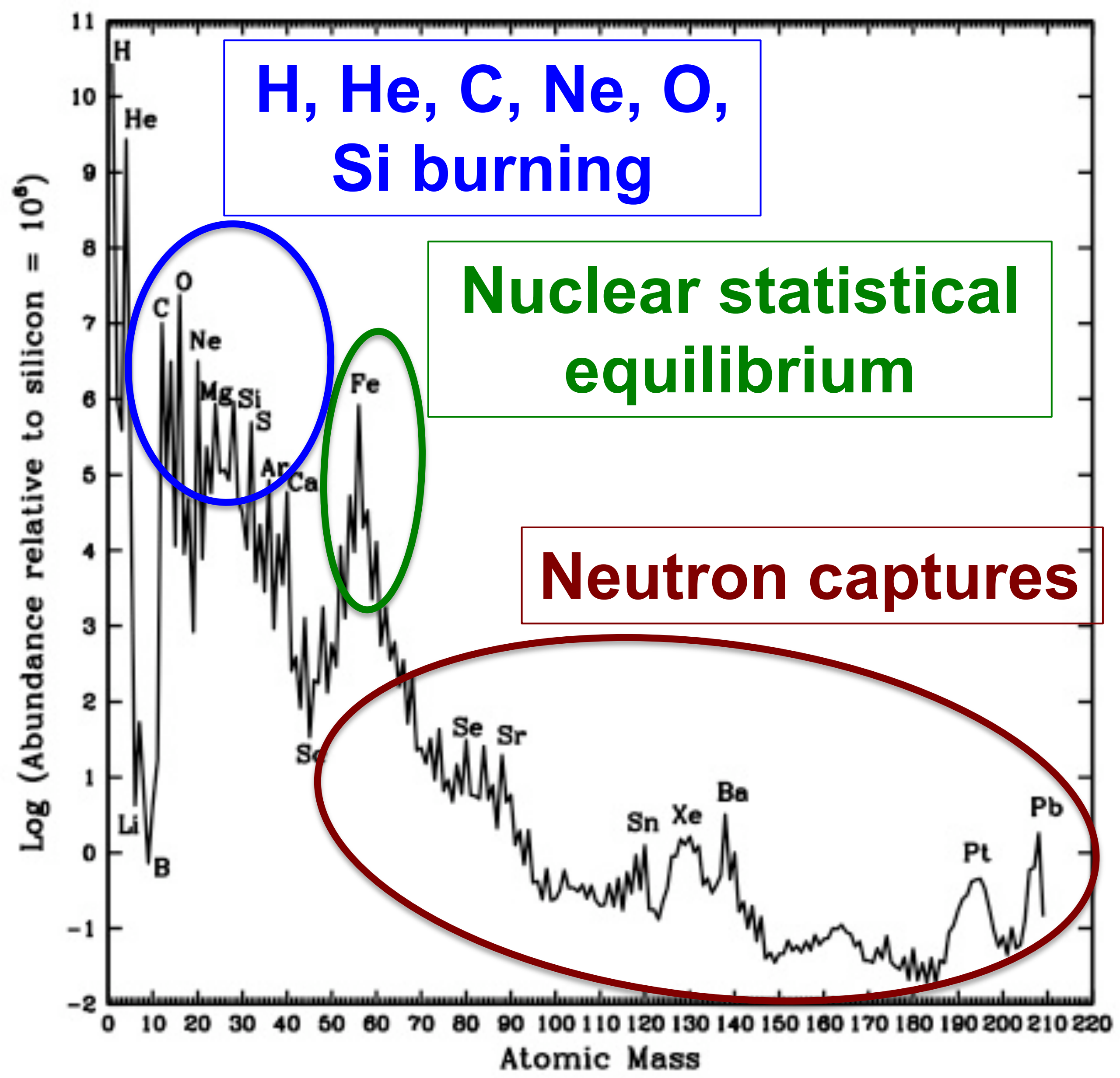
The origin of the elements



From Kobayashi, Karakas & Lugaro (2020)

Credit: Chiaki Kobayashi/Sahm Keily

Solar System abundances: *nucleosynthesis*



Example of neutron capture

- Neutron captures start with Fe:

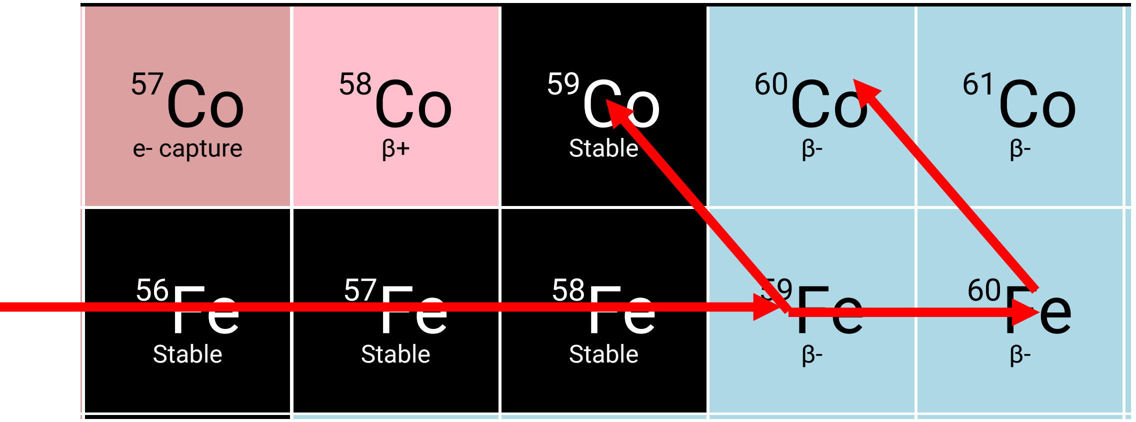
$$^{56}Fe + n \rightarrow {}^{57}Fe + n \rightarrow {}^{58}Fe + n \rightarrow \mathbf{{}^{59}Fe}$$

- What happens next? ^{59}Fe is unstable. It can do one of two things:

$^{56}Fe + n \rightarrow {}^{57}Fe + n \rightarrow {}^{58}Fe + n \rightarrow \mathbf{{}^{59}Fe} \longrightarrow \mathbf{+\ n} \rightarrow {}^{60}Fe$

$\searrow$ ^{59}Co

?



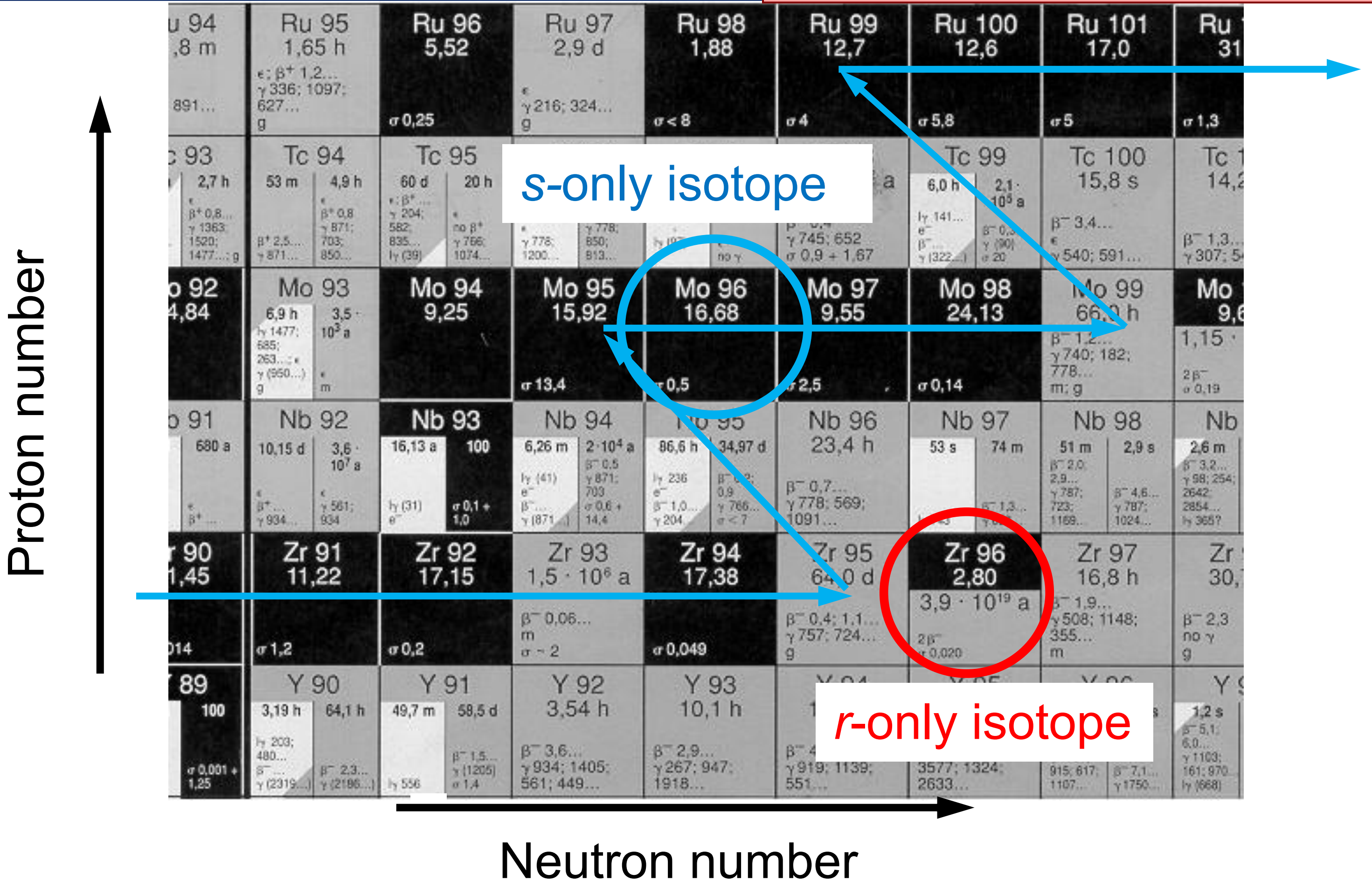
?

Details depend on the neutron density

The slow and rapid processes

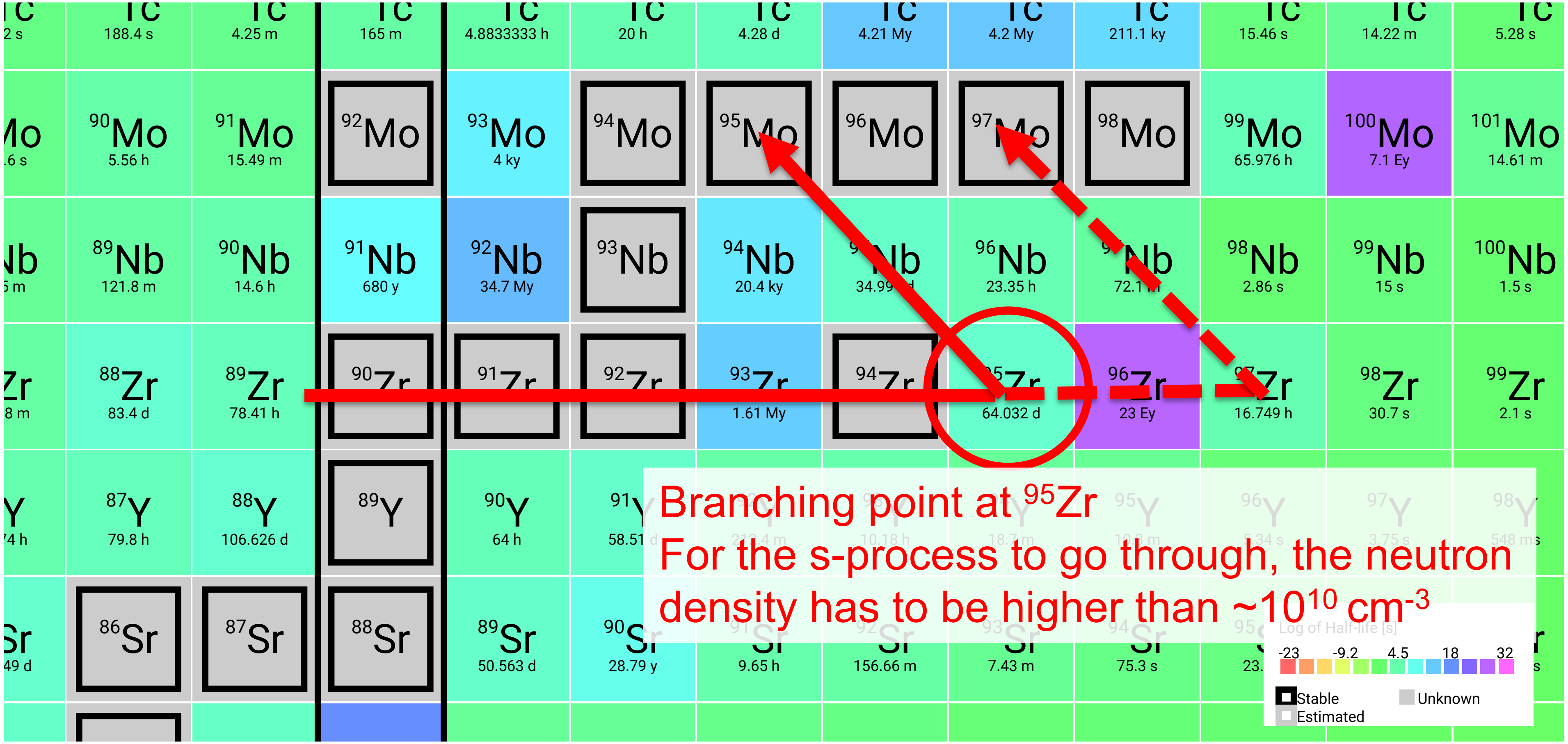
During the *s* process:
Time scale (n,γ) >> time scale β decay
$N_n \sim 10^8$ n/cm^3

During the *r* process:
Time scale (n,γ) << time scale β decay
$N_n > 10^{20}$ n/cm^3



Branching points

https://people.physics.anu.edu.au/~ecs103/chart/



^{93}Zr is marked as stable It is not. It does have a long half-life (1.6 million years) so is stable for the purposes of the s-process.

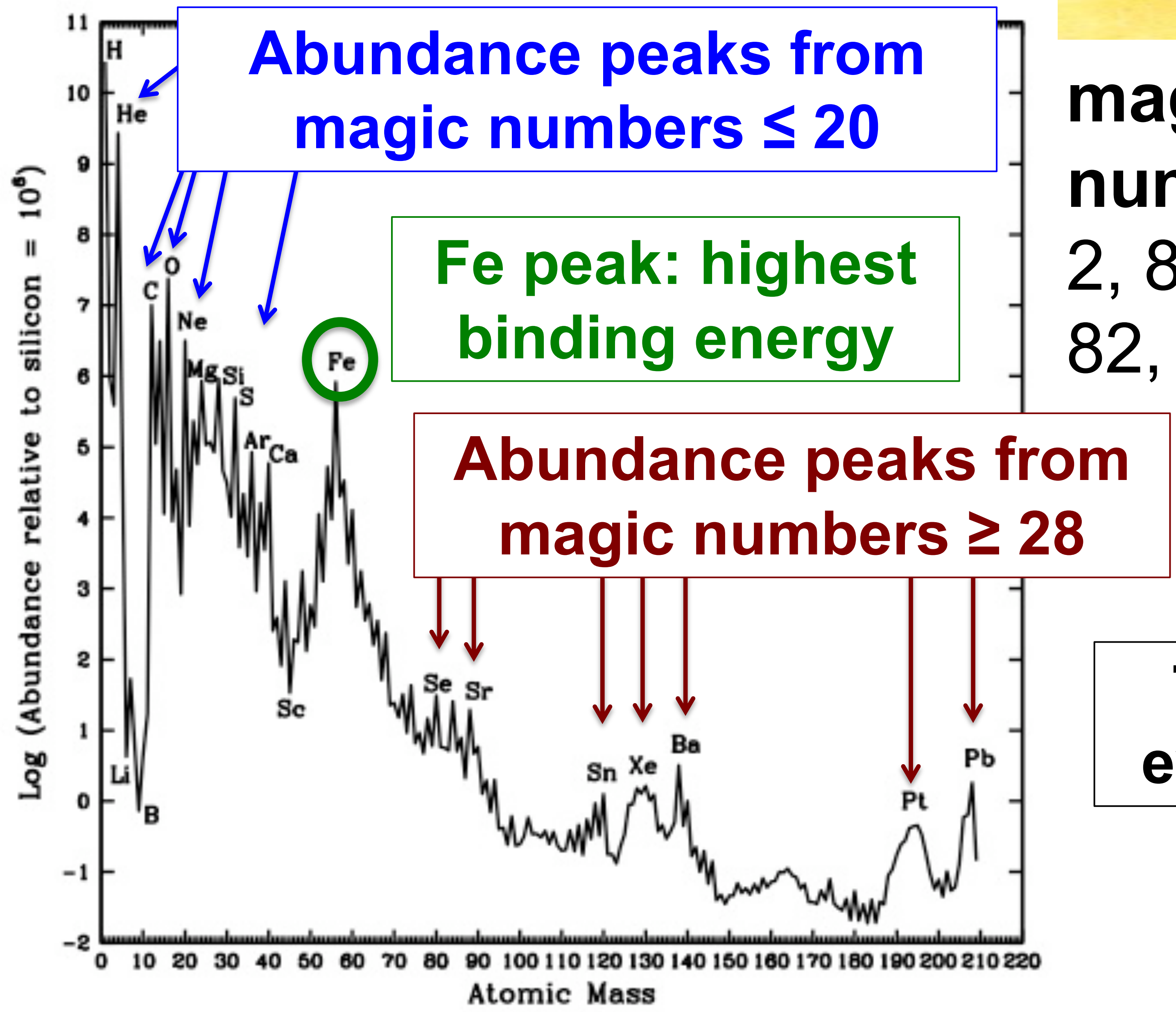
Magic Numbers

- Quantum mechanics teaches us about the stability of closed electron shells.
- Similar things happen in the *nucleus.*
- When a complete energy level is filled it is particularly stable:

it has a low σ for reactions!

- This happens at 2, 8, 20, 28, 50, 82 and 126.
- These Magic Numbers apply to n or p.
- If it applies to n and p the nucleus is said to be “doubly magic”.
- Examples: ${}^{16}_{8}O$, ${}^{56}_{28}Ni$, ${}^{208}_{82}Pb$ are all doubly magic nuclei.

The *nuclear physics* of the Solar System abundances



magic numbers: 2, 8, 20, 28, 50, 82, and 126.

The odd-even effect

Neutron-capture cross sections

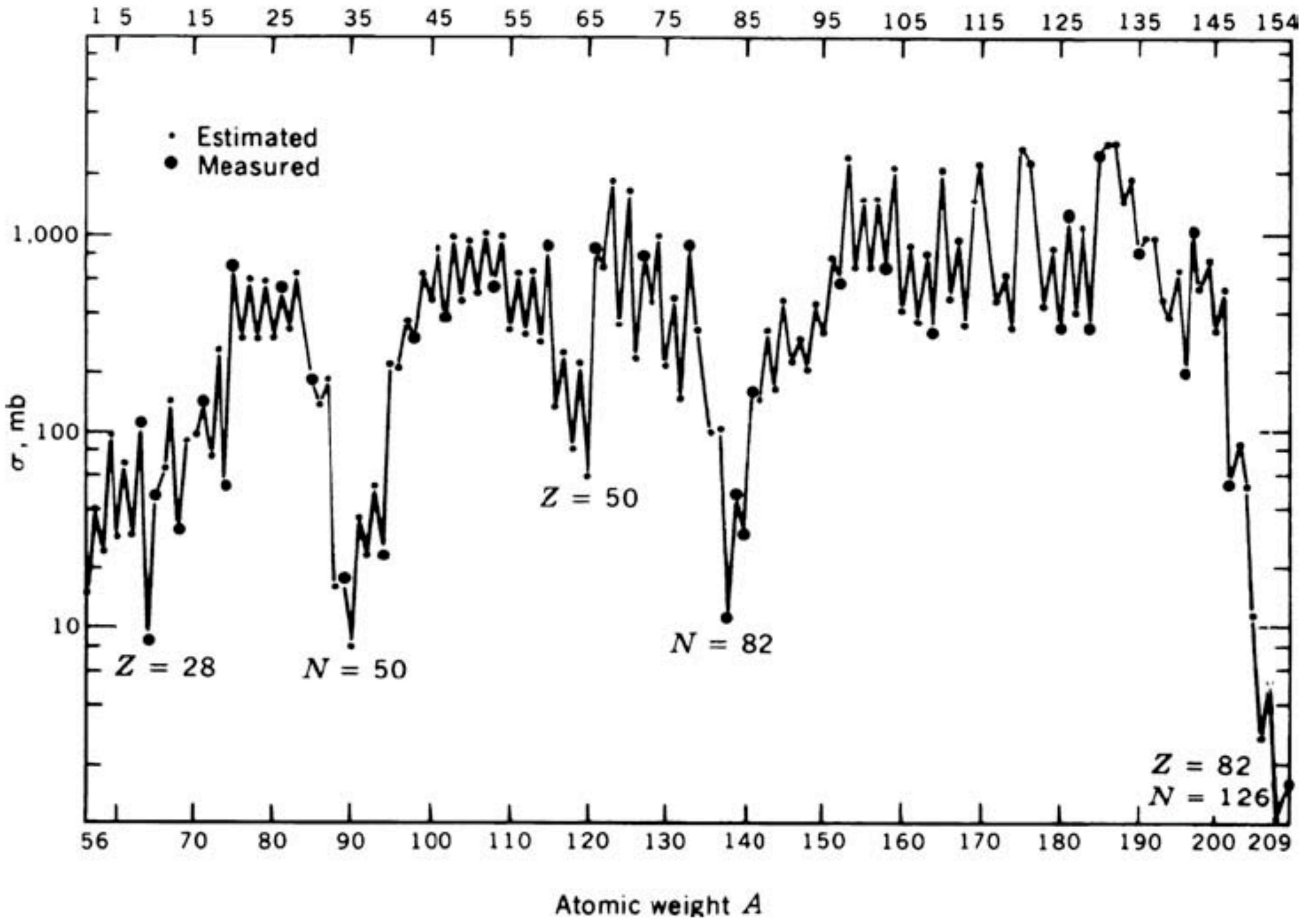


Fig. 6.2. Neutron-capture cross-sections at energies near 25 keV. Very large dips occur at the magic numbers. After Clayton (1984). Copyright by the University of Chicago. Courtesy Don Clayton.

- Here $\sigma =$ cross section
- Probability of capturing a neutron
- Measured in milli-barn (mb), here the barn = 10^{-28} m^2.
- Typical neutron-capture cross sections are measured in millibarn (mb) but may be ~1000 mb (1 b).

Neutron-capture cross sections

Name	Z, Proton number	A, atomic mass	σ (mb)	Solar System fraction of isotope
^{16}O	8	16	0.038 ± 0.004	99.757 %
^{56}Fe	26	56	11.7 ± 0.5	91.754 %
^{135}Ba	56	135	455 ± 15	6.592 %
^{138}Ba	56	138	4.0 ± 0.2	71.698 %
^{138}Ce	58	138	179 ± 5	0.250 %
^{140}Ce	58	140	11 ± 0.4	88.450 %
^{208}Pb	82	208	0.36 ± 0.03	52.4 %

- Cross sections are Maxwellian averaged cross sections at 30 keV (~350 million K)
- From Kadonis Database: http://exp-astro.physik.uni-frankfurt.de/kadonis/index.php
- Percentages from: https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

Note: T (kelvin) ~ 1.16 x 10^7 T (keV)

Neutron-capture cross sections

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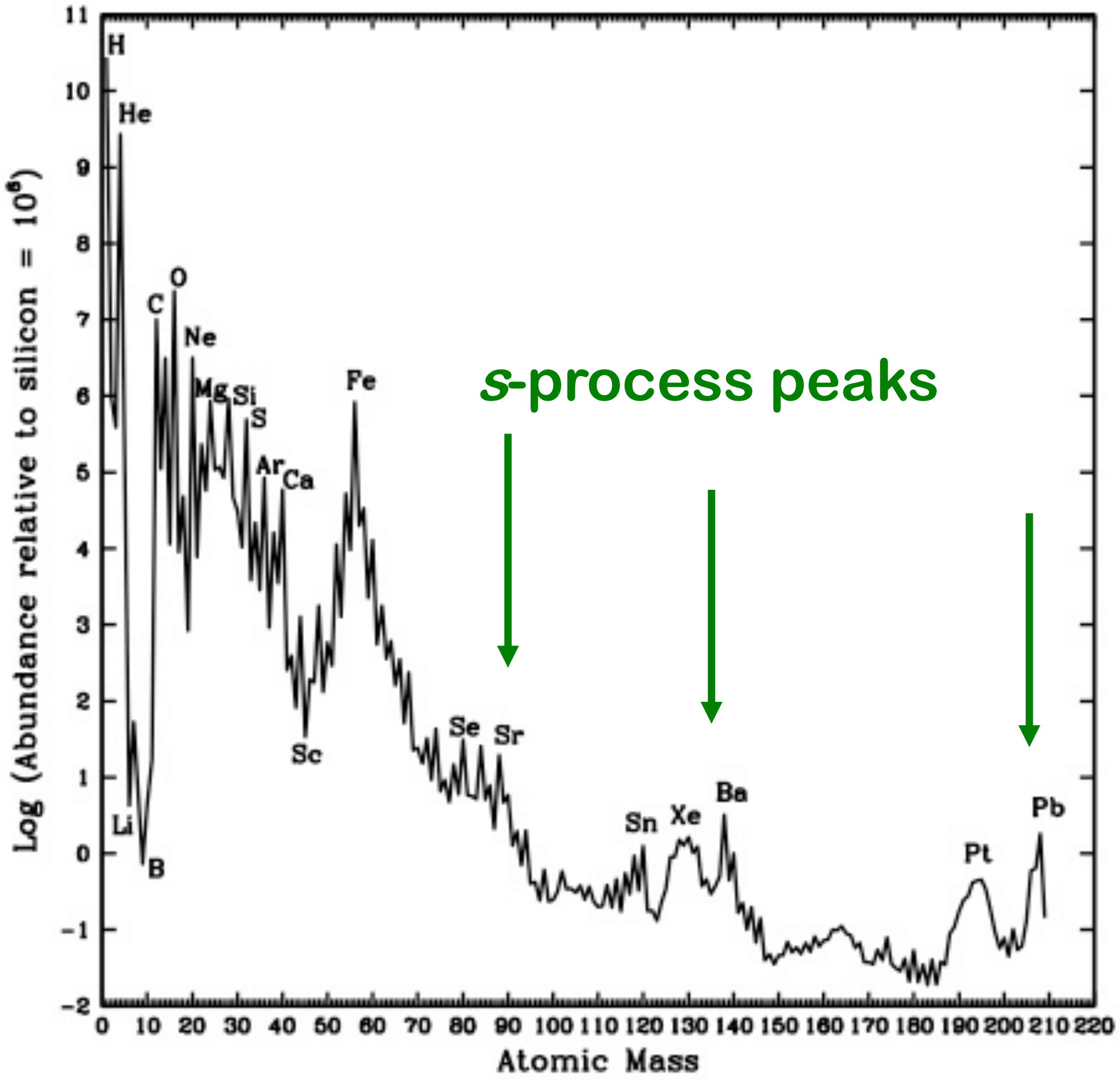
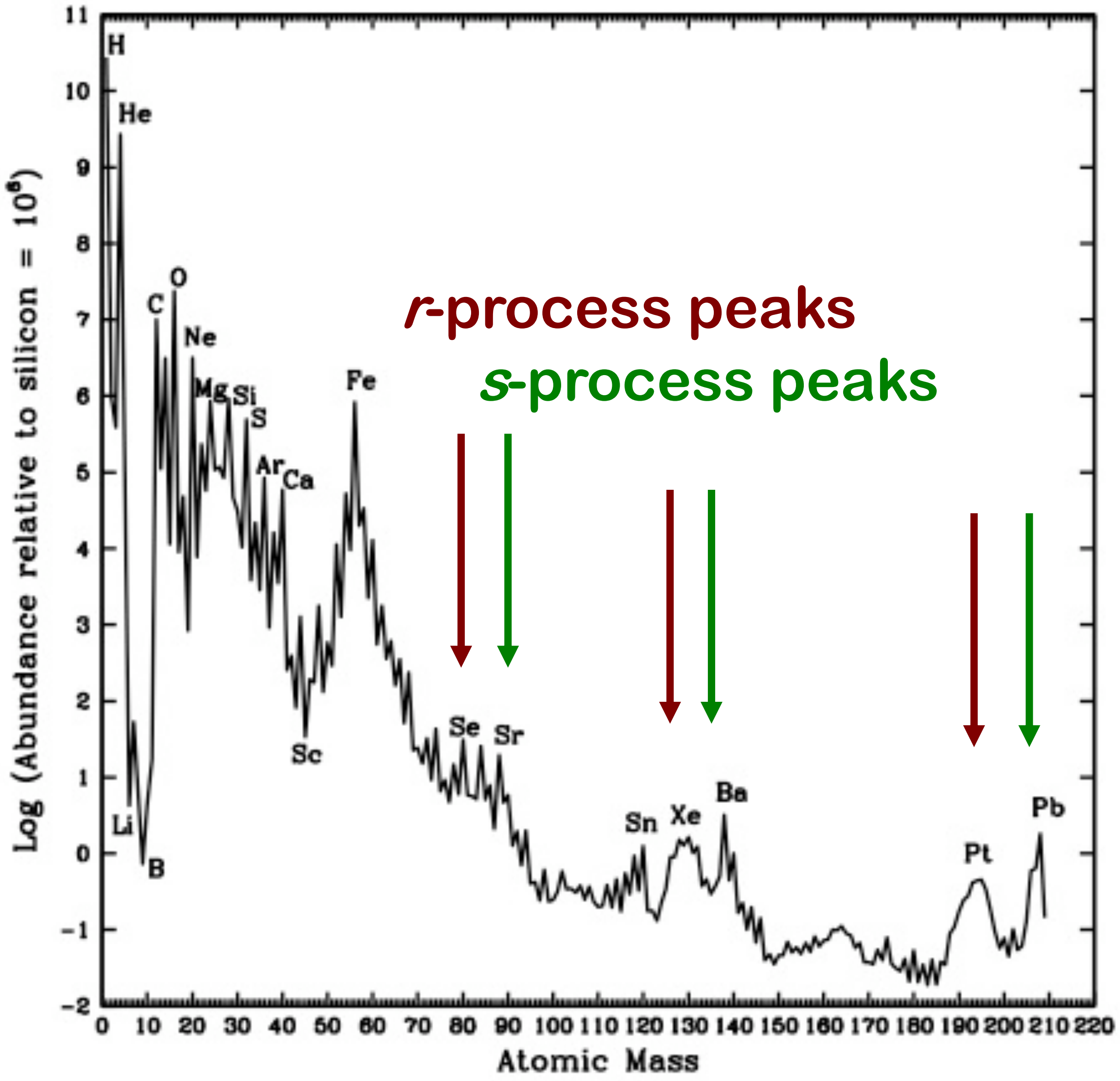
The Solar System abundances



The *s*-process peaks correspond to **stable nuclei** with neutron magic numbers $N = 50, 82, 126$ because the neutron capture path goes rights through them.

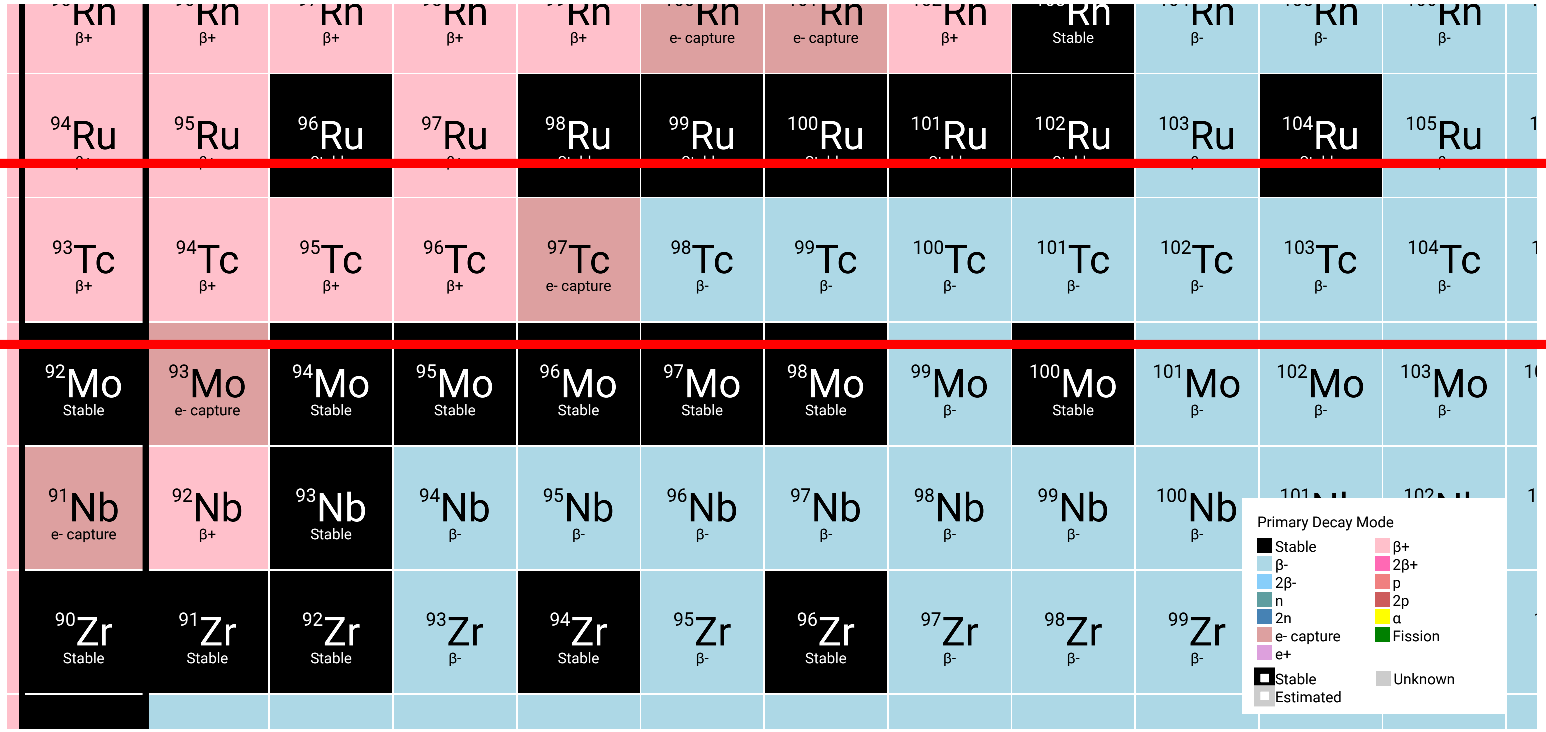
The Solar System abundances



The *s*-process peaks correspond to **stable nuclei** with neutron magic numbers $N = 50, 82, 126$ because the neutron capture path goes rights through them.

The *r*-process peaks correspond to **unstable nuclei** with neutron magic numbers

Anything strange here?



Technetium, Tc, has no stable isotope.
Longest lived are ^{97}Tc and ^{98}Tc with
$t_{1/2}$ = 4.2 million years

But Tc is observed in some stars!

- Which stars?
- AGB stars….
- That is a hint…!

Which isotope is made by the s-process?

Observing Tc in stars proves that nucleosynthesis happened in the star recently(ish)… Why?

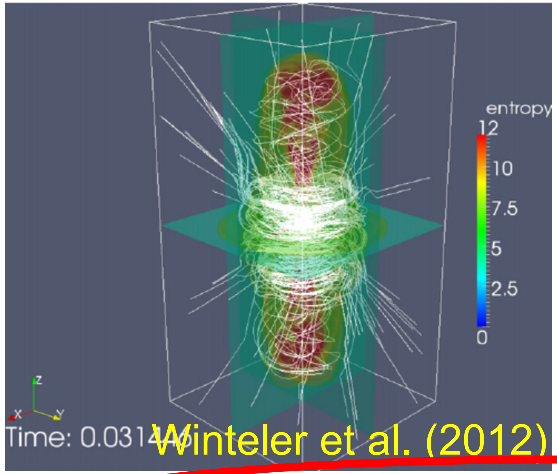
Because ^{99}Tc has $t_{1/2}$ ~ 200,000 years

SITE(S) OF THE S-PROCESS

Sites of heavy element nucleosynthesis

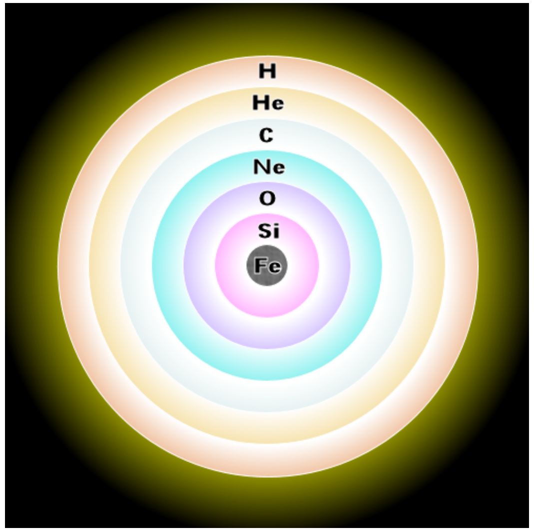
Neutron star mergers

Magneto-hydrodynamically driven supernovae → unusual supernovae

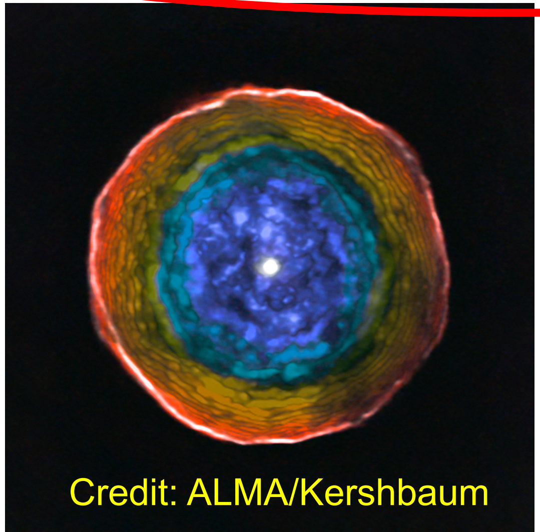


The r-process ~50%

Massive stars, m > 12 Msun



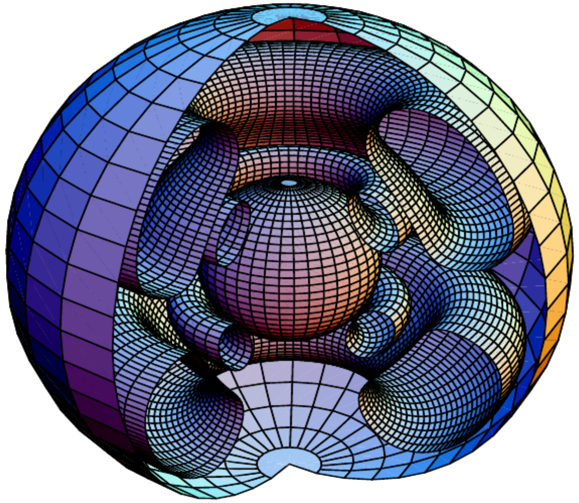
Asymptotic giant branch stars, m < 8 Msun



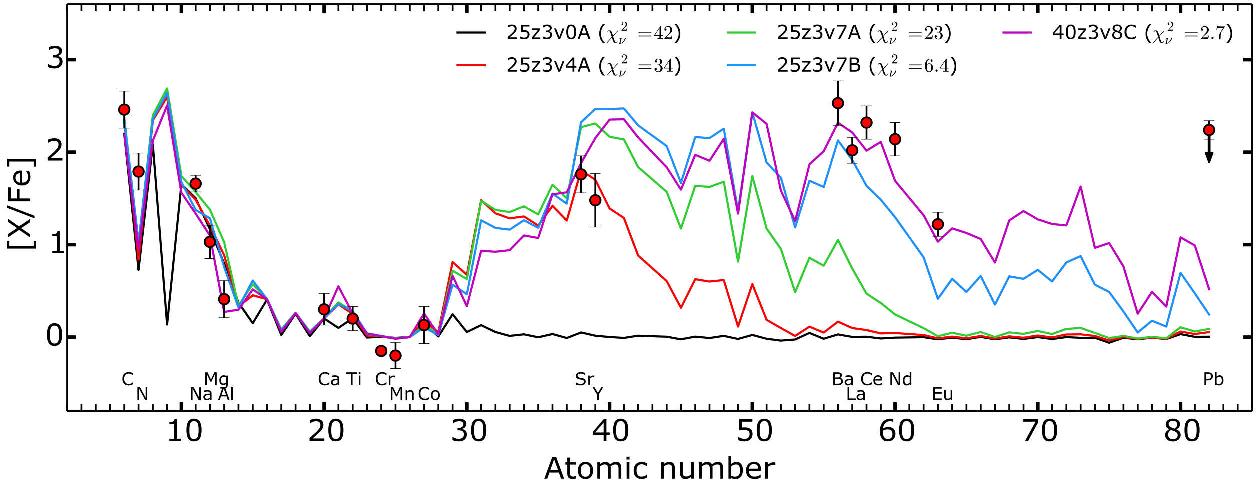
The s-process ~50%

The s-process in massive stars

- Produce heavy elements in their He- and C-burning shells.
- Mainly the *weak* s-process, from Cu to the Sr peak
- Main neutron source is: ^{22}Ne$(\alpha,n)^{25}$Mg
- The ^{22}Ne abundance scales with Z
- Except, when there is rapid rotation!



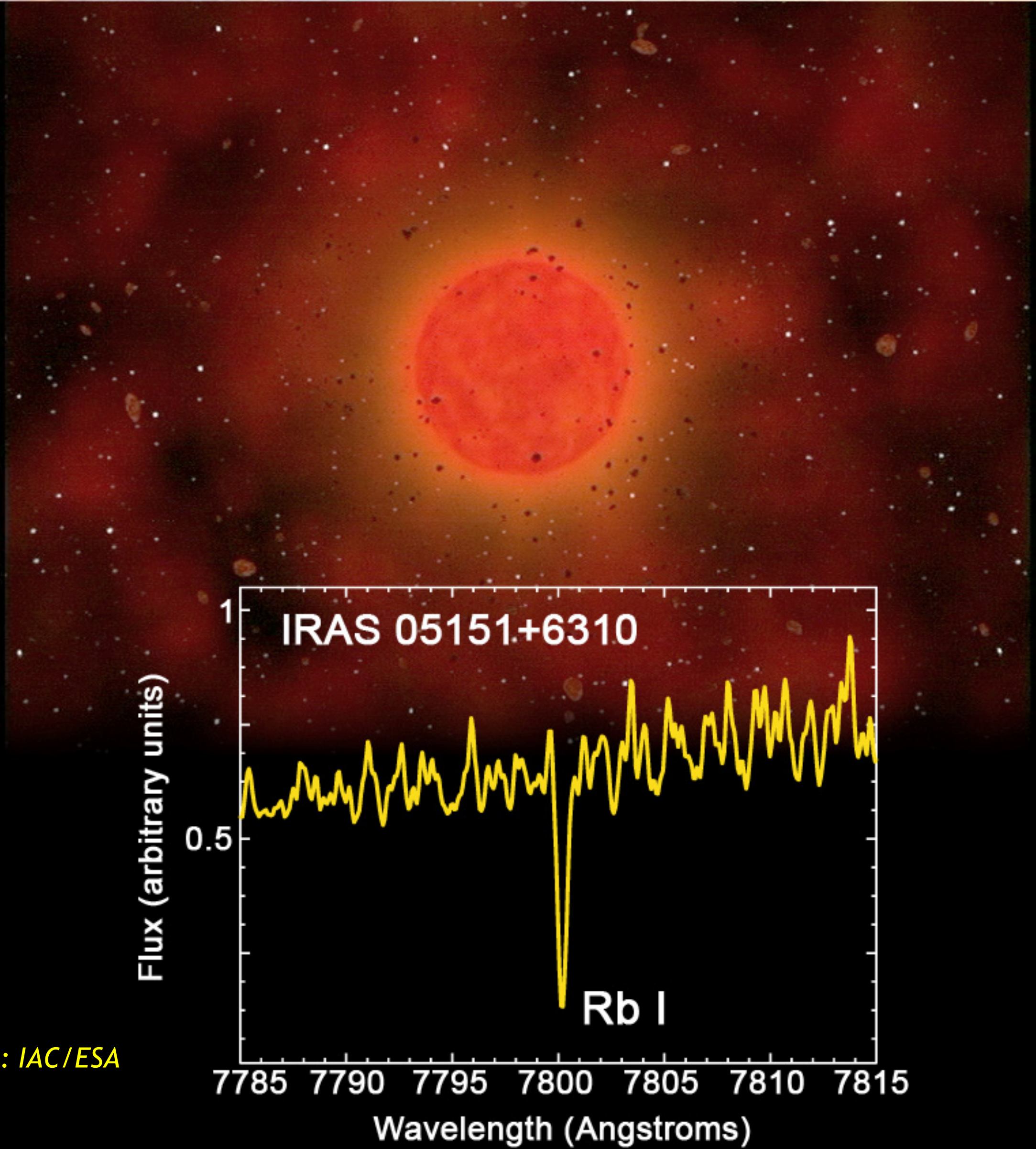
From Choplin & Hirschi (2020)



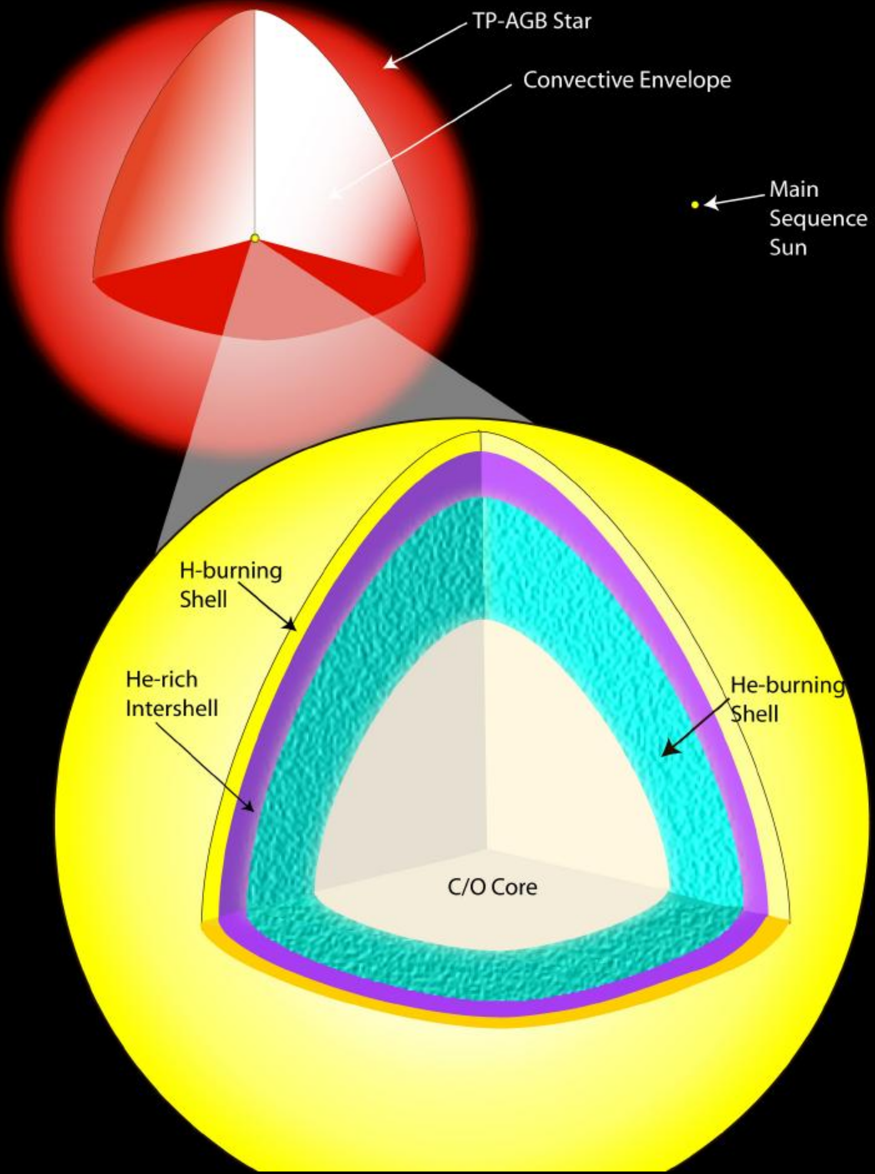
Best fit 40Msun model, with rapid rotation, compared to HE0336+0113

Also Limongi & Chieff (2018), Frischknecht et al. (2016), Pignatari et al. (2010) etc.

AGB stars as element factories

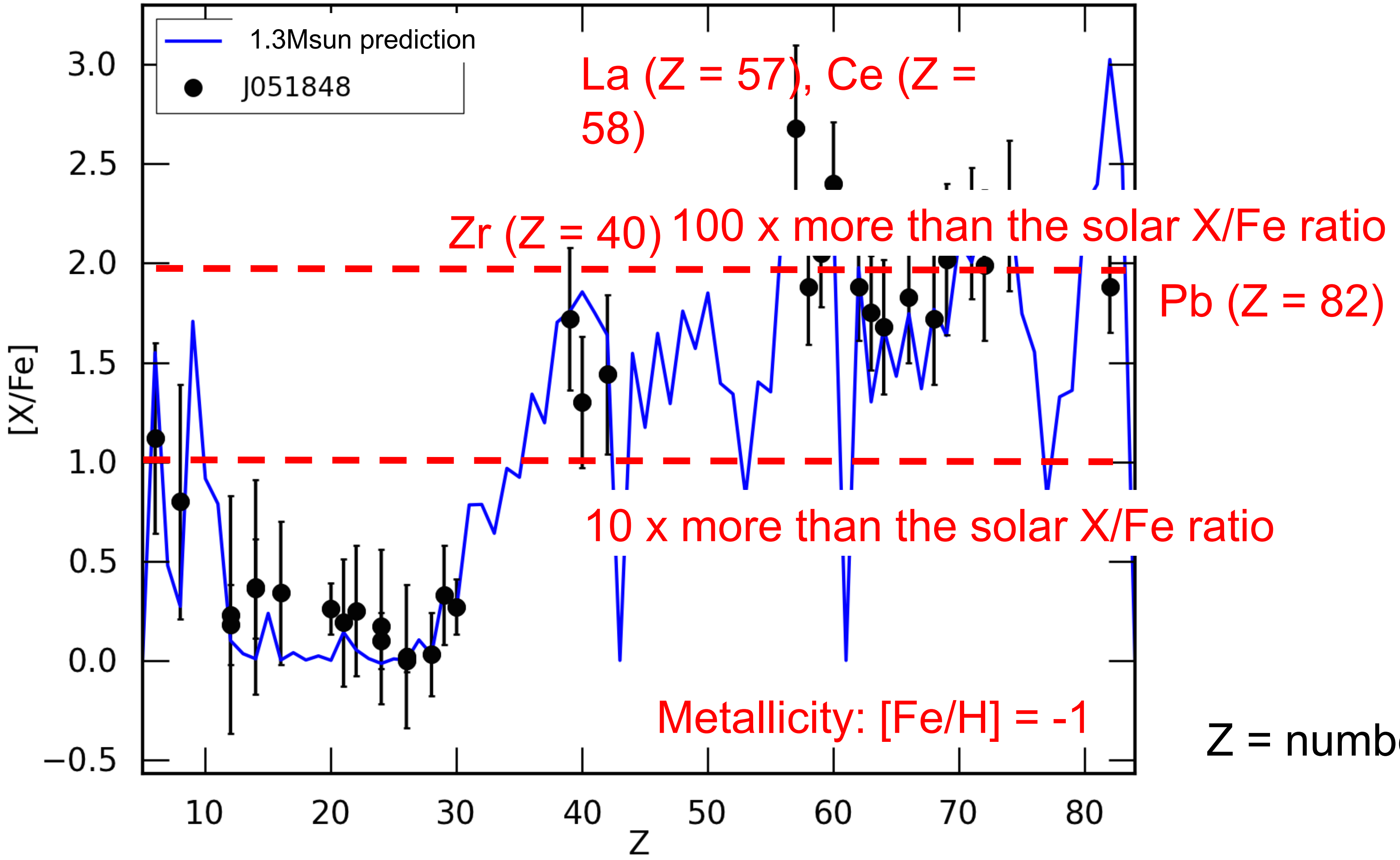


Credit: IAC/ESA



Evidence of heavy-element production

- Y-axis is abundance ratio of X/Fe, relative to the Sun, in log units
- Post-AGB star located in the Large Magellanic Cloud



Z = number of protons

Credit: Kenneth De Smedt (KU Leuven)

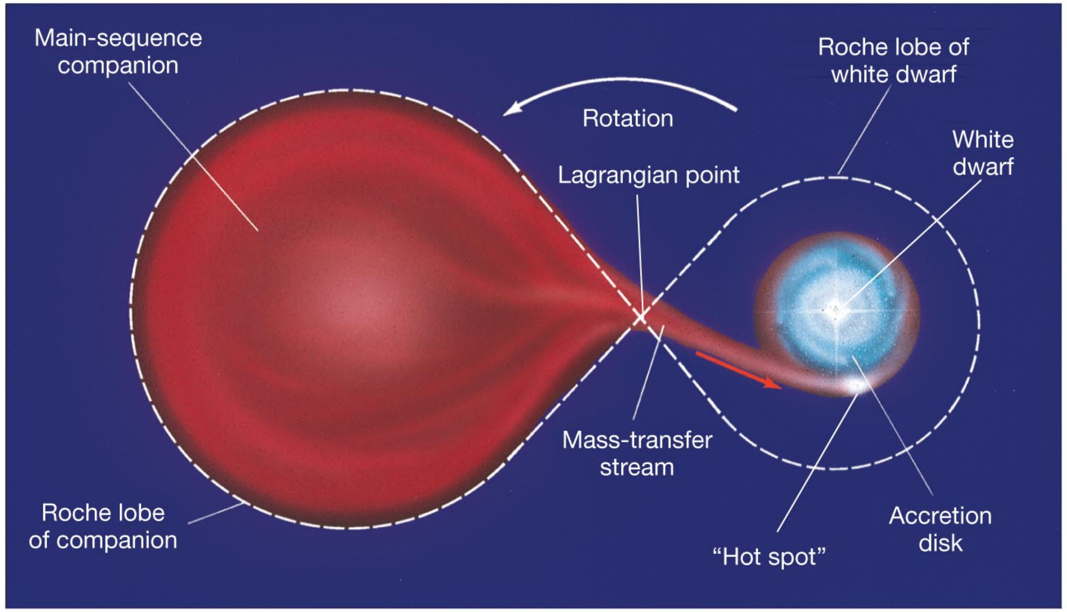
Intrinsic and extrinsic AGB stars

- In order to discuss this question we need to make a few new definitions related to s-process enrichments:
  - **Intrinsic** = star that is self-enriched in s-process elements; is currently on the AGB experiencing thermal pulses and third dredge-up (N, SC, S, C-type AGB star).
  - **Extrinsic** = a star that obtained its s-process elements from another star, perhaps as a result of binary mass transfer (e.g., barium stars, CH stars, CEMP stars etc).

- How do we know a star is an "intrinsic" AGB star or extrinsic?
- Remember radioactive Tc?
- If a giant star is enriched in carbon, s-elements and Tc it must be "intrinsic" and recently made its own heavy elements.

Extrinsic s-process rich stars

- What if we find a star enriched in s-process elements (and maybe carbon) and there is no Tc present in the atmosphere?
- The star we observe is not an AGB star experiencing thermal pulses, and obtained its enrichment elsewhere.
- The next question: Is the star we see a binary?
- If yes, then the star obtained its heavy elements from binary mass transfer.



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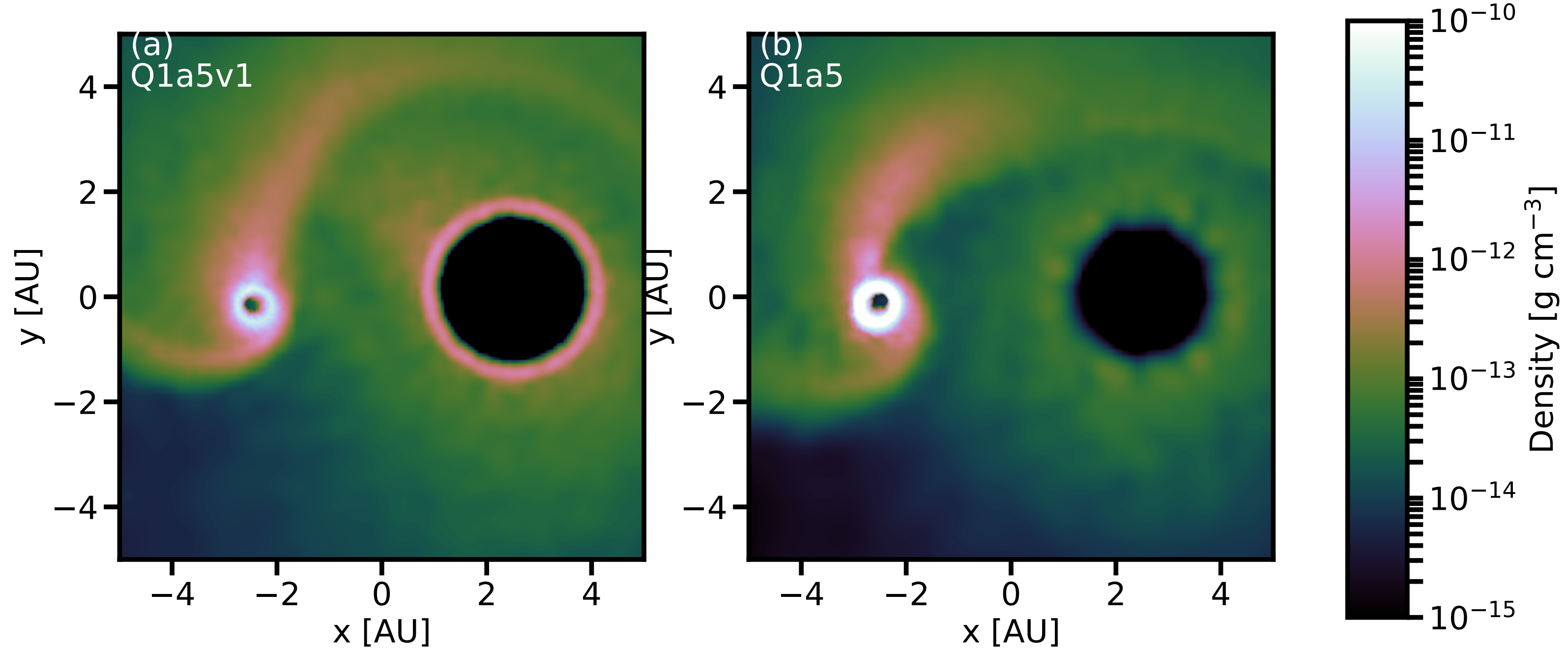
Roche Lobe Overflow
(Credit: Pearson Education)

Barium, CH-, CEMP stars

- Long-period binaries where the originally more massive companion is now a white dwarf.
- We see evidence of nuclear processed material (e.g., C, Ba) on the surface of the present-day giant star.
- Evidence for mass transfer by stellar wind accretion.

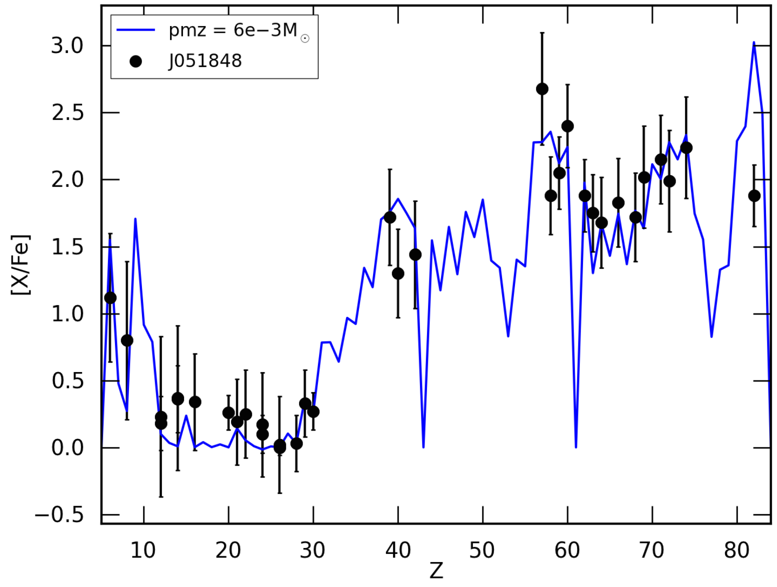
3D hydro simulations from Saladino et al. (2019):



What AGB mass range make s-process elements?

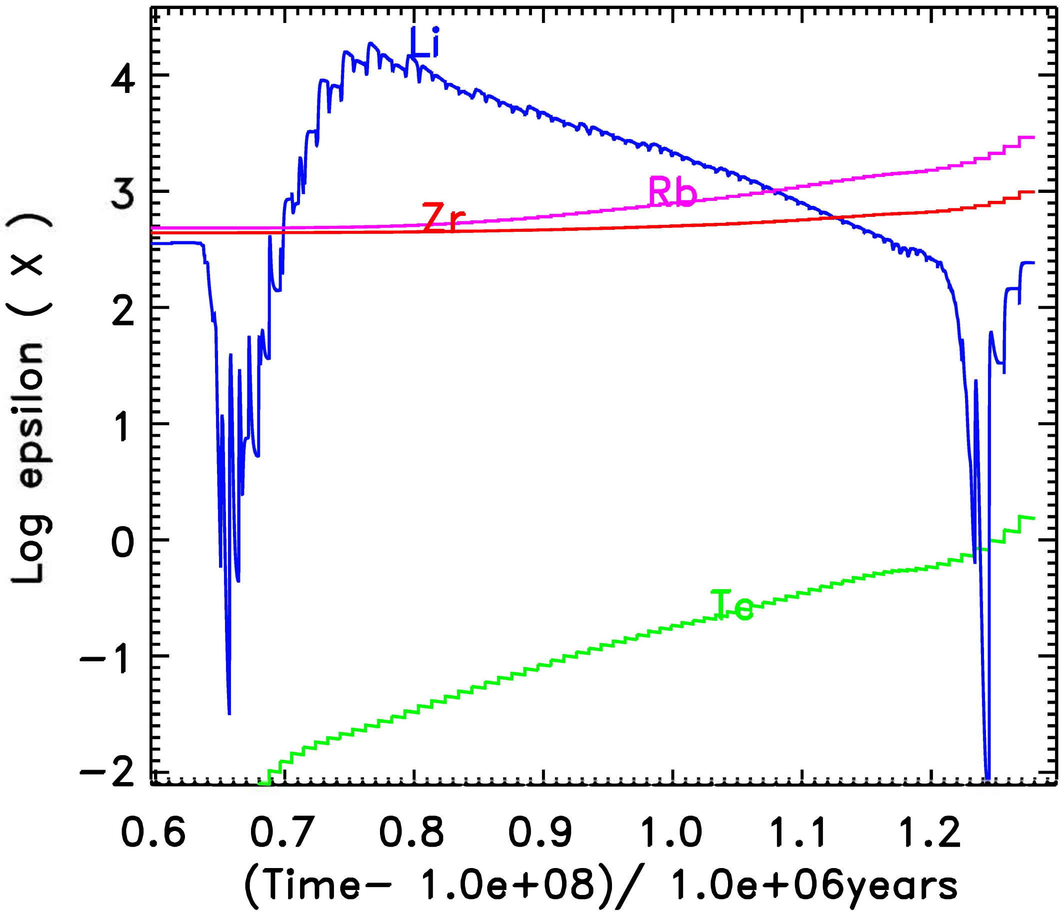
- Observationally, the intrinsic AGB stars are mostly carbon-rich low-mass stars with initial masses $\lesssim 3$ Msun
  - (e.g., Wallerstein & Knapp 1998, Gallino et al. 1998, Busso et al. 1999).
- Determining mass is difficult! (pre-GAIA… see Shetye et al. 2019, 2021)
- How are we sure??
- Post-AGB stars in the Magellanic Clouds have well determined masses. These originated from initial masses of 1-2Msun.

From before, showing strong s-process enrichment in a LMC post-AGB star.
The well known distance means we can estimate the luminosity → estimate core mass → initial mass.



What AGB mass range make s-process elements?

- What about intermediate-mass stars?
- There is evidence that intermediate-mass AGB stars make s-process elements including Zr and Rb
  - (Smith & Lambert 1990, Wood et al. 1983, Garcia-Hernandez et al. 2006, 2009).
- We have observations of Rb-rich AGB stars in the Milky Way Galaxy.
- These are also oxygen rich, which is evidence of hot bottom burning.
- There are also very bright O-rich, Zr rich stars in the Magellanic Clouds.

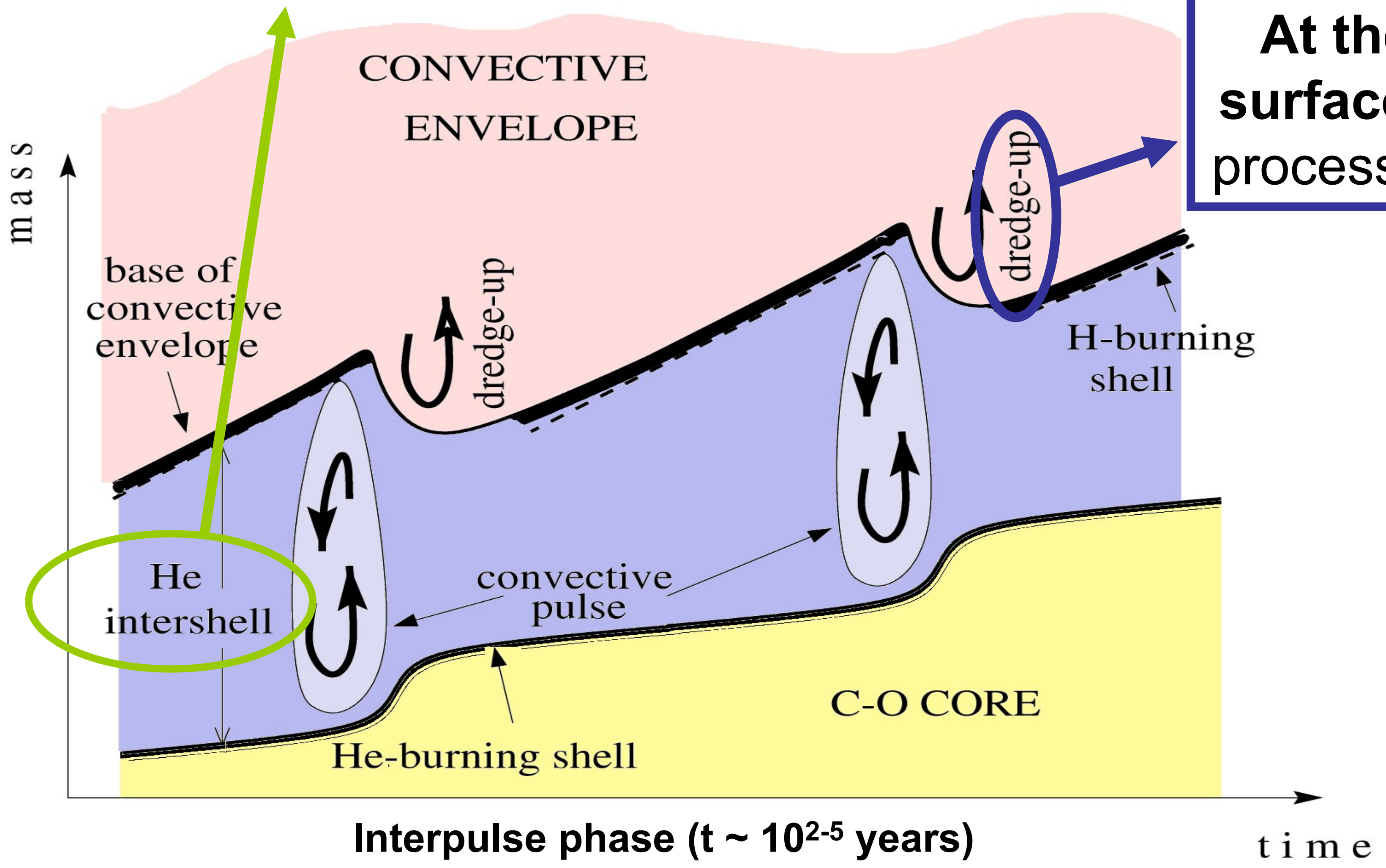


5Msun, Z = 0.02 model from Garcia-Hernandez et al. (2013)

The s-process in AGB stars

^{4}He, ^{12}C, ^{19}F, *s*-process elements: Zr, Ba, ...

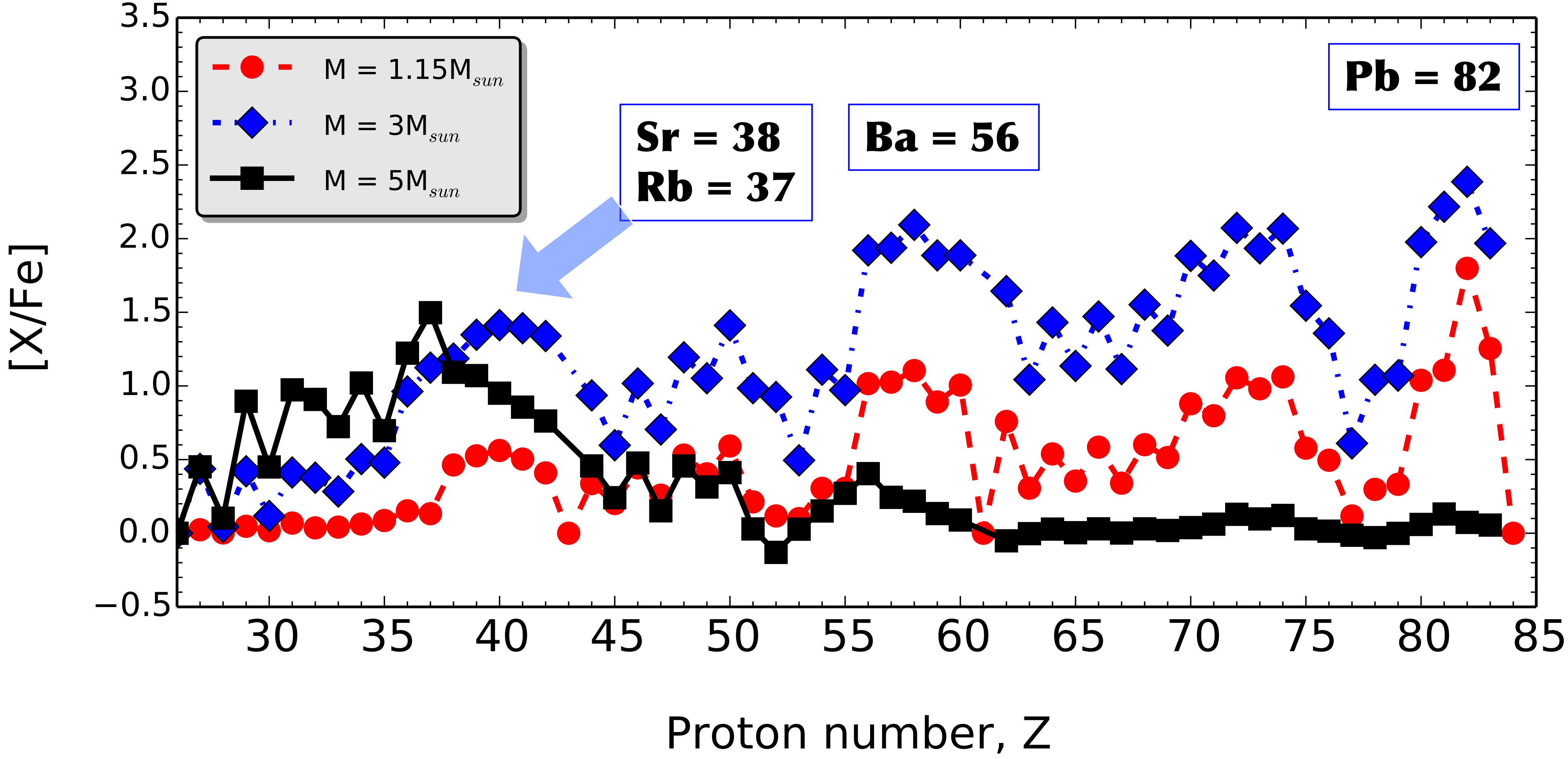
At the stellar surface: C>O, s-process elements



Interpulse phase (t ~ 10^{2-5} years)

The s-process: The effect of mass

Variation of stellar mass from low-metallicity models of [Fe/H] = −0.7 from Karakas et al. (2018):



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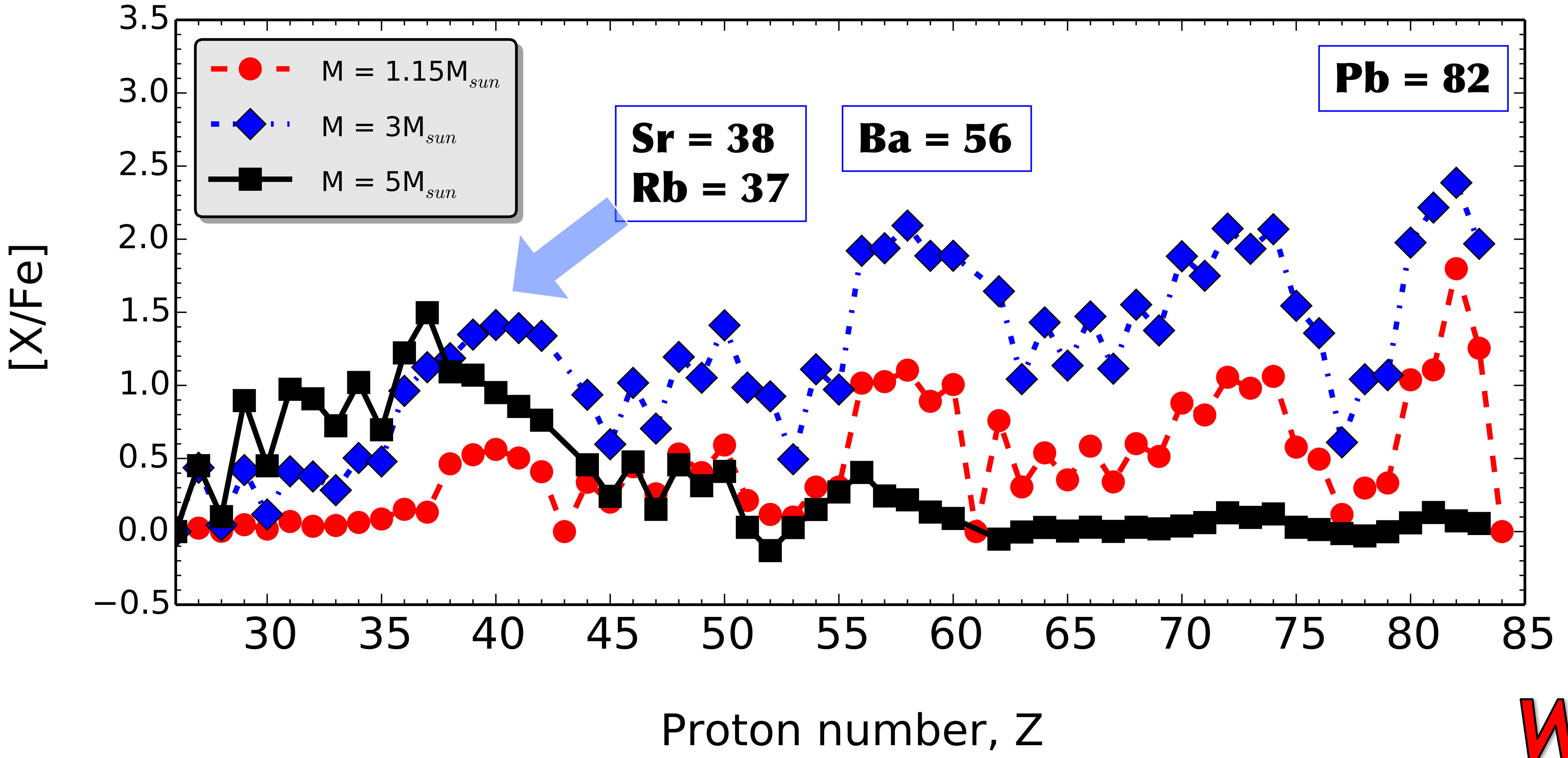
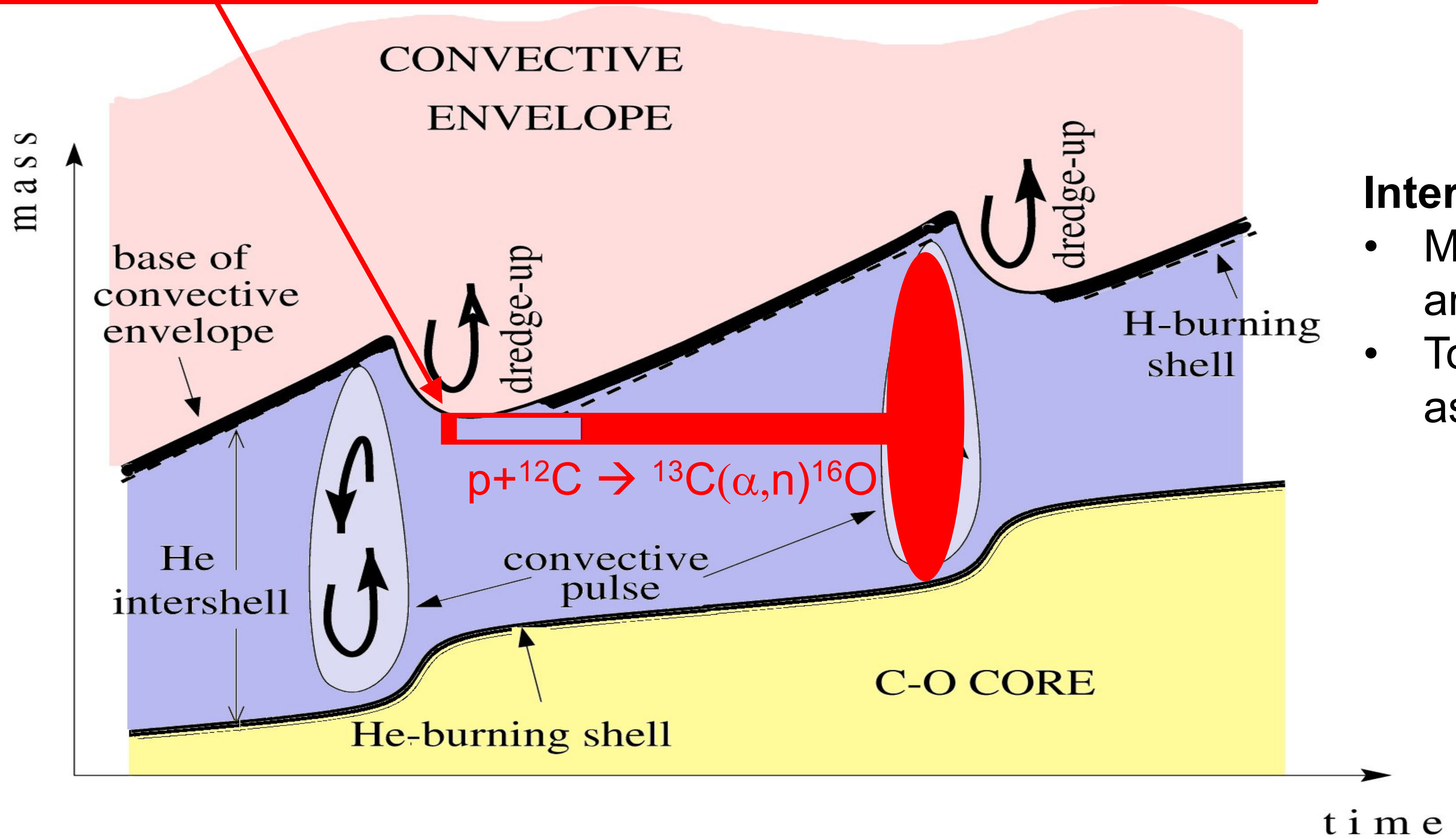


Why?

Producing neutrons in the He-shell

Neutrons are released in ^{13}C pockets – these form by mixing *a bit* of hydrogen into the intershell

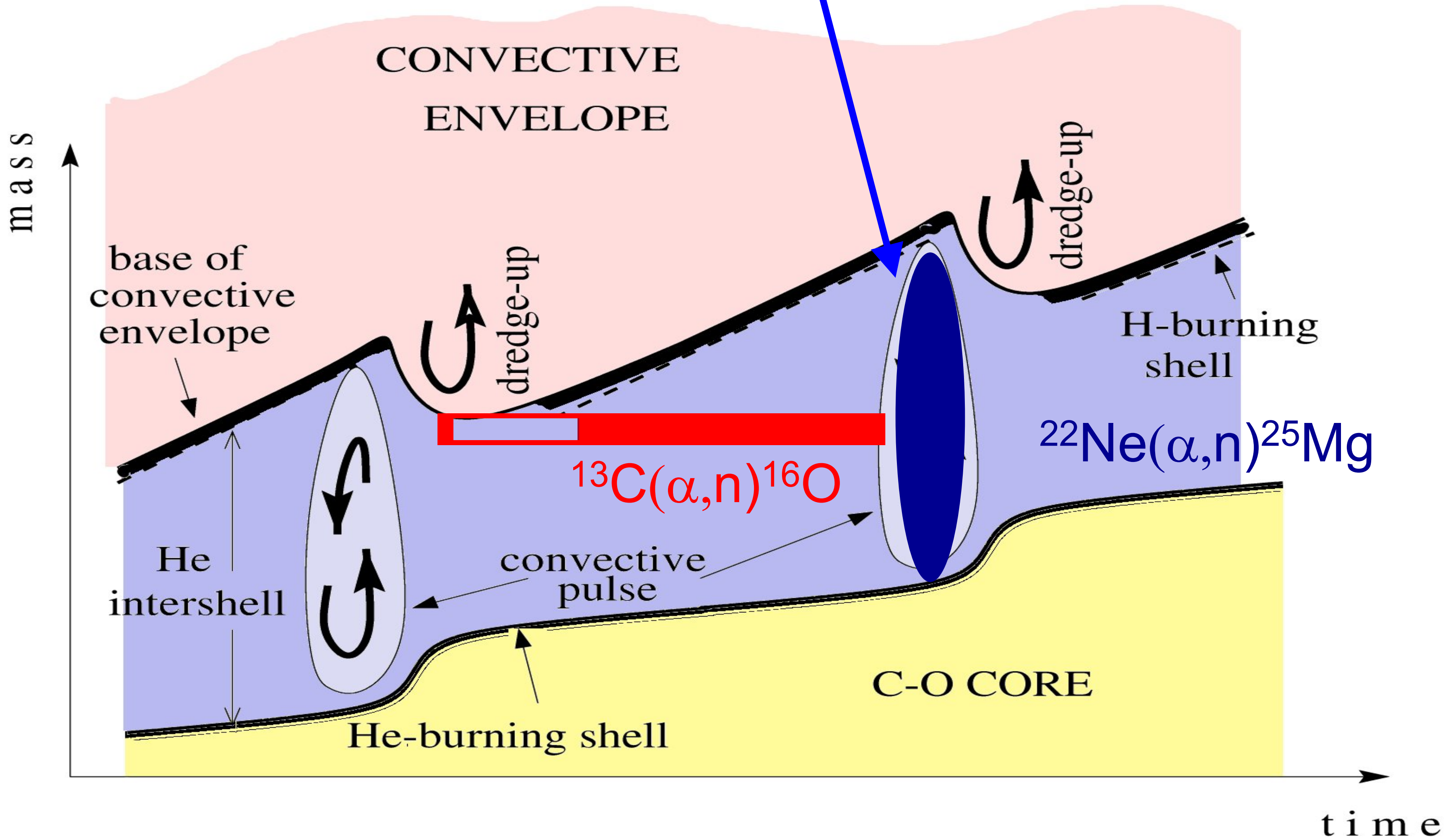


Intershell:

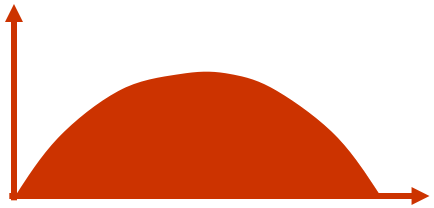
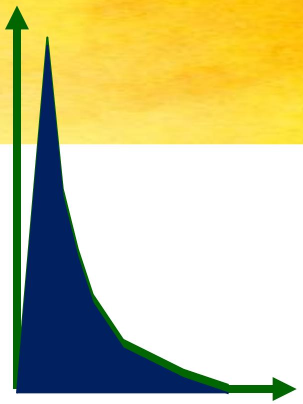
- Mostly ^{4}He (~75%) and ^{12}C (~25%)
- Top layers are ashes of H-burning

Neutron production in the He-shell

Extra burst of neutrons from the $^{22}Ne(\alpha,n)^{25}Mg$ reaction, which takes place during thermal pulses



Theoretical models

Typical neutron density profile in time:	 Low mass	 Intermediate mass
Neutron source	$^{13}C(a,n)^{16}O$	$^{22}Ne(a,n)^{25}Mg$
Maximum neutron density	10^{8} n/cm^{3}	10^{13} n/cm^{3} ?
Timescale	10,000 yr	10 yr
Neutron exposure	0.3 mbarn^{-1}	0.02 mbarn^{-1}

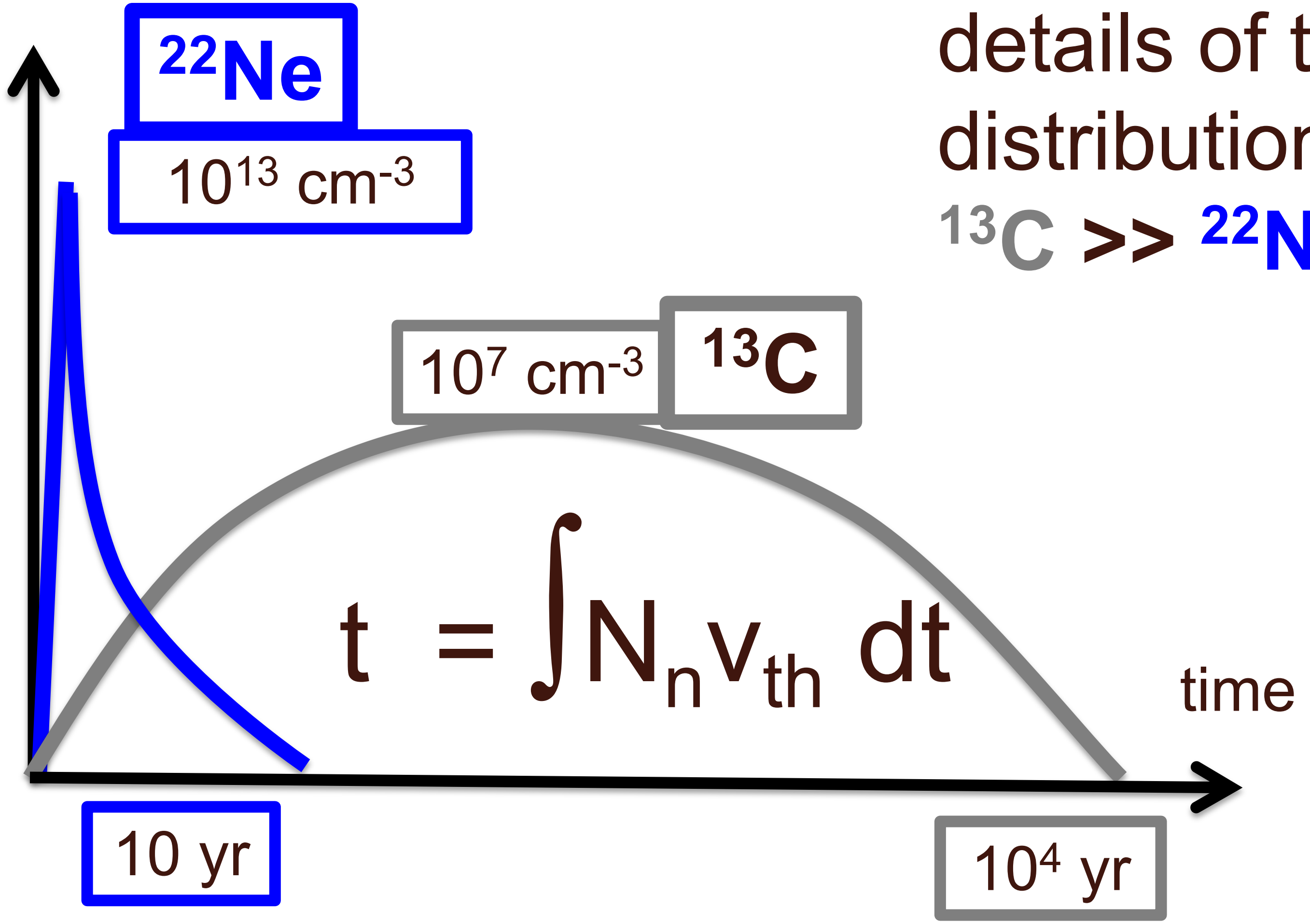
(at solar metallicity)

Neutron density (cm^{-3}): defines the details of the s-process path

^{22}**Ne** **>>** ^{13}C

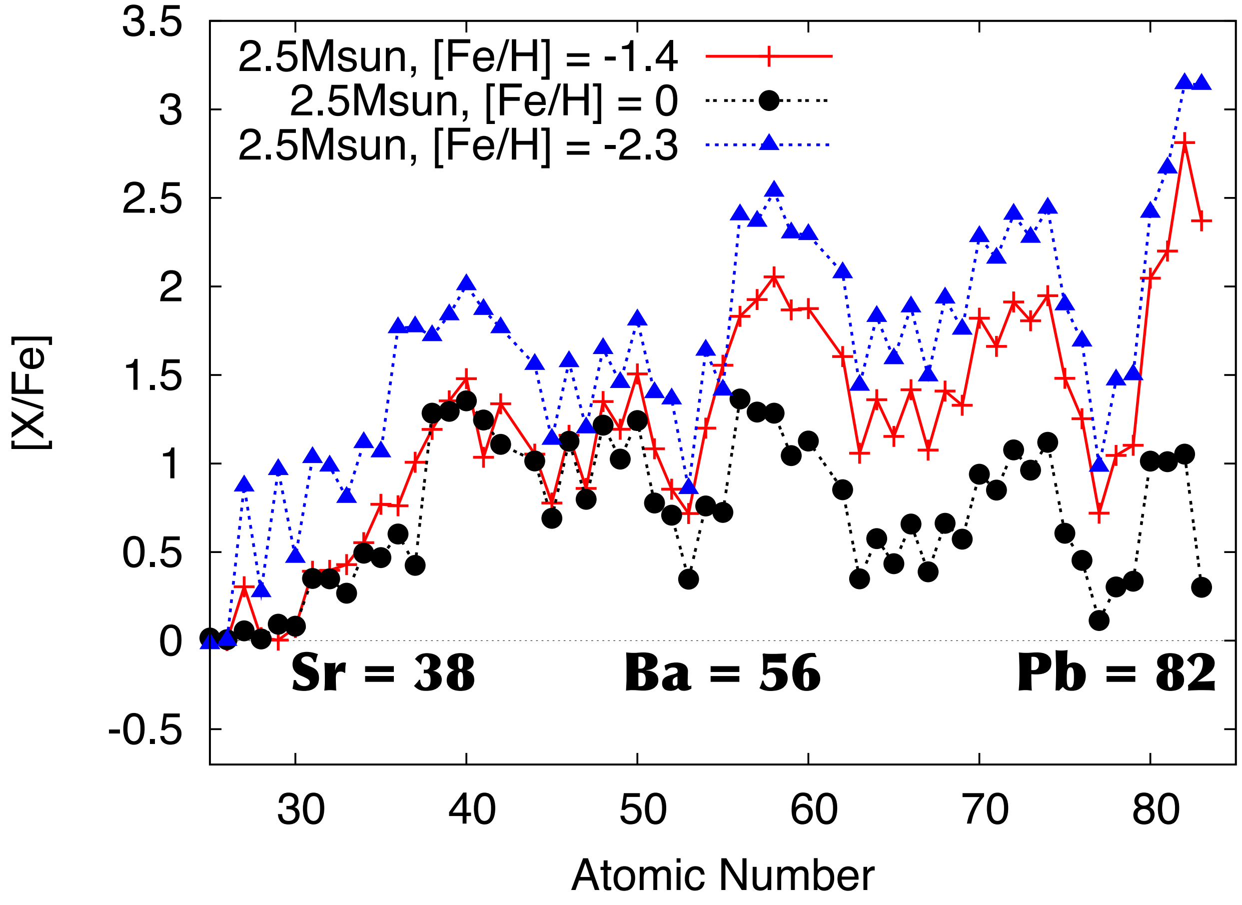
Neutron exposure t ($mbarn^{-1}$): defines the details of the overall distribution

^{13}C **>>** ^{22}**Ne**



The s-process: The effect of metallicity

Decrease in metallicity results in more s-process elements at the 2nd peak (Ba, La), then at the 3rd (Pb)



e.g., see also Gallino et al. (1998), Busso et al. (2001)

Why does metallicity do this?

1. ^{13}C nuclei result in neutrons via $^{13}C(\alpha,n)^{16}O$ and the main neutron absorber is ^{56}Fe:

Neutron density ≈ ^{13}C / ^{56}Fe

2. ^{13}C in the pocket is produced by proton captures on primary ^{12}C, from triple-alpha in the He shell:

^{13}C is a primary neutron source!

Clayton (1988)

What are the implications?

3. The neutron density scales with the inverse of ^{56}Fe, i.e., with the metallicity.

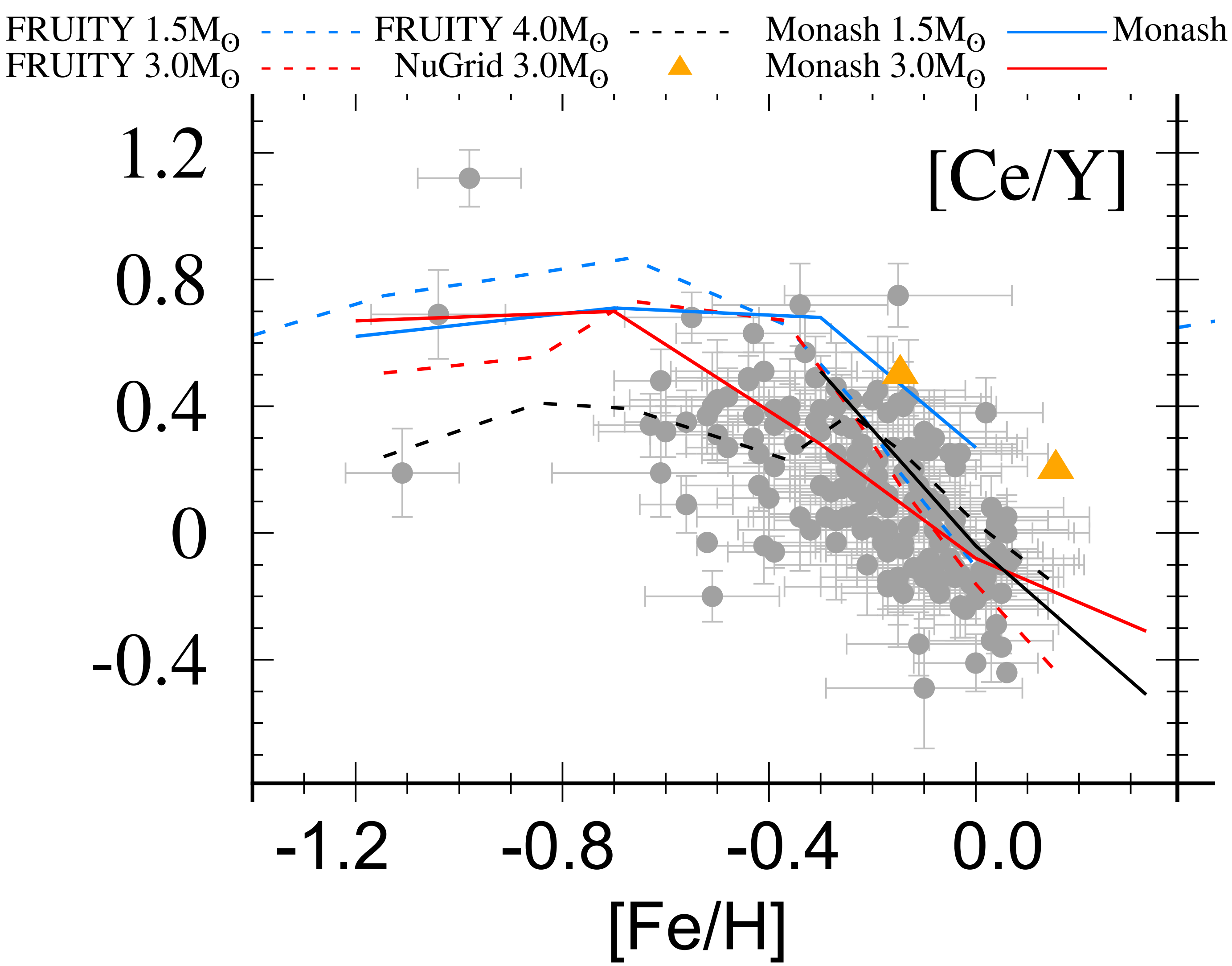
This means that lower metallicity stars produce more neutrons and more heavier elements.

[Ba/Sr] (or [Ce/Y]) should increase with decreasing metallicity

Is this true?

From observations of Barium stars

Cseh et al. (2018) compared the data with model predictions:

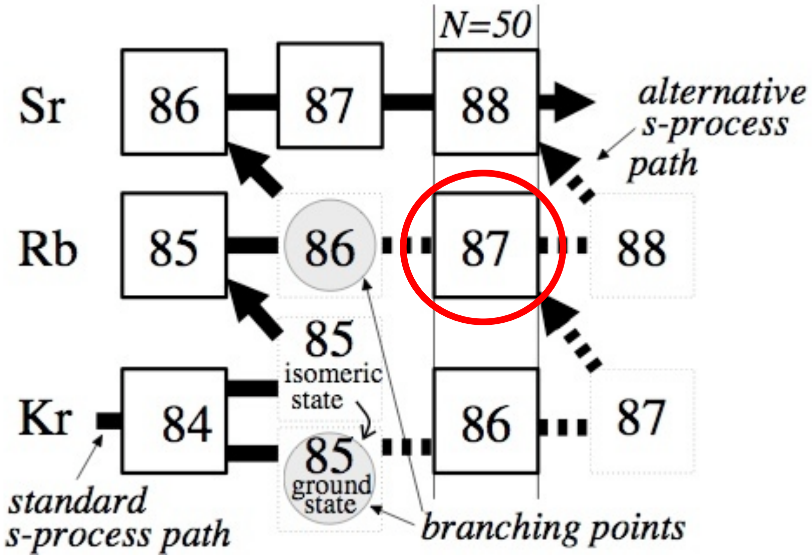


Neutron density indicators

At high neutron densities, two branching points open that allow rubidium to be produced. At N_n=5 x 10^8 n/cm^3 ~80% of the flux goes through ^{85}Kr, and the branching at ^{86}Rb opens to make ^{87}Rb

1. ^{85}Rb has a high σ = 240 mb (30 keV)
2. ^{87}Rb is magic, has a low σ = 15 mb (30 keV)

→ Rb in AGB stars in an indicator of the neutron density!



^{86}Kr, ^{87}Rb, and ^{88}Sr are all magic, with low neutron capture cross sections
In low-mass stars: ^{88}Sr produced
In massive AGB: ^{87}Rb

Zr,Sr/Rb > 1 → low-mass AGB
Zr,Sr/Rb < 1 → > 4Msun AGB

Intrinsic s-process indicators

- [ls/Fe] = light s-process elements (e.g., Y, Sr, Zr) where
  [ls/Fe] = ([Y/Fe] + [Sr/Fe] + [Zr/Fe]) / 3
- [hs/Fe] = heavy s-process elements, typically choose 2-4 elements (e.g., Ba, La, Ce)
- Example for 3Msun models of different metallicity:

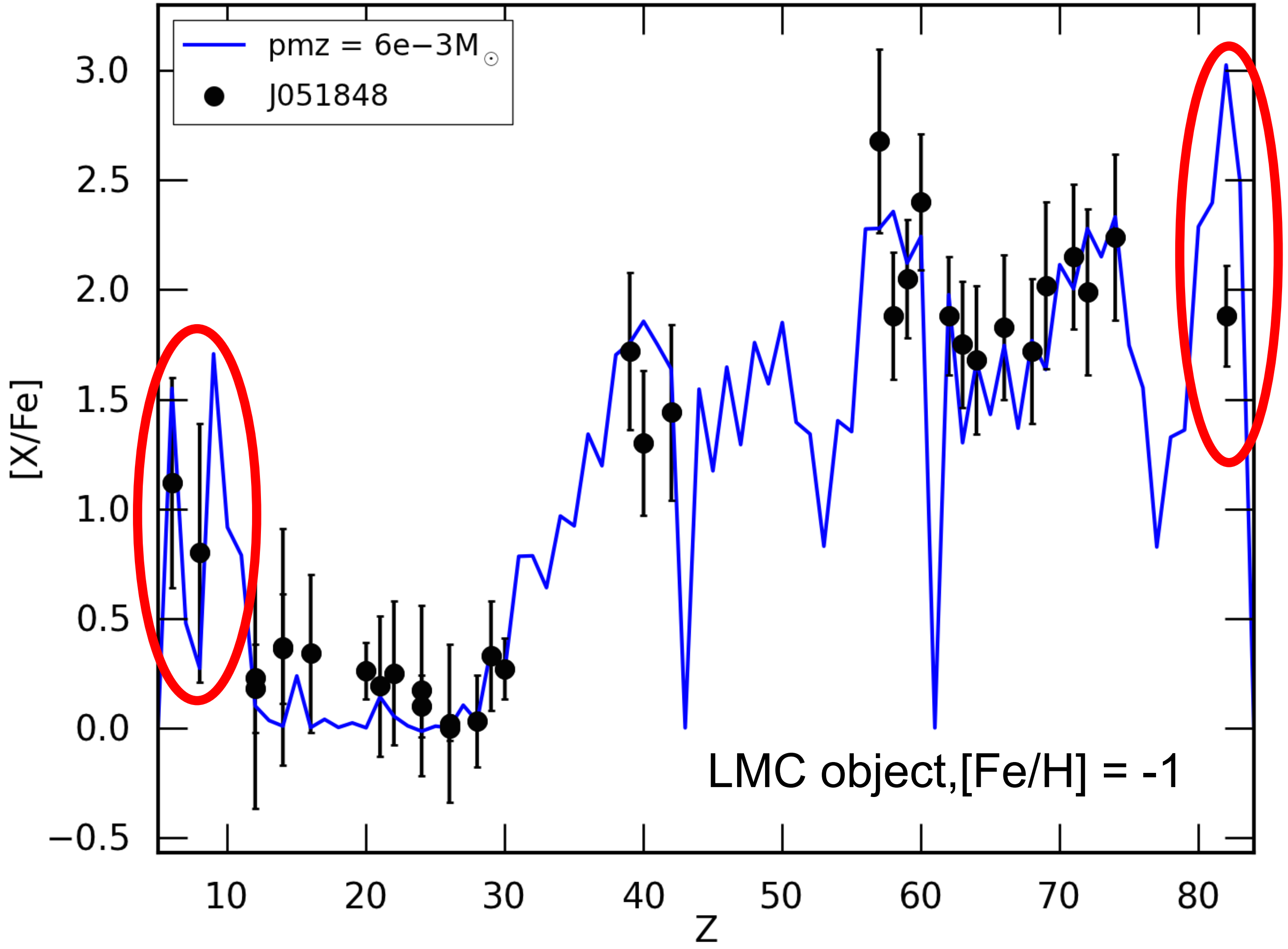
[Fe/H]	[Rb/Zr]	[ls/Fe]	[hs/Fe]	[hs/ls]	[Pb/hs]
+0.3	-0.57	1.16	0.92	-0.24	-0.39
0.0	-0.73	1.47	1.44	-0.03	-0.28
-0.3	-0.70	1.64	1.96	0.32	-0.20
-0.7	-0.30	1.32	1.98	0.67	+0.40
-1.8	+0.12	1.30	1.66	0.36	+1.03

PUZZLES AND THE I-PROCESS

Problems with theoretical picture

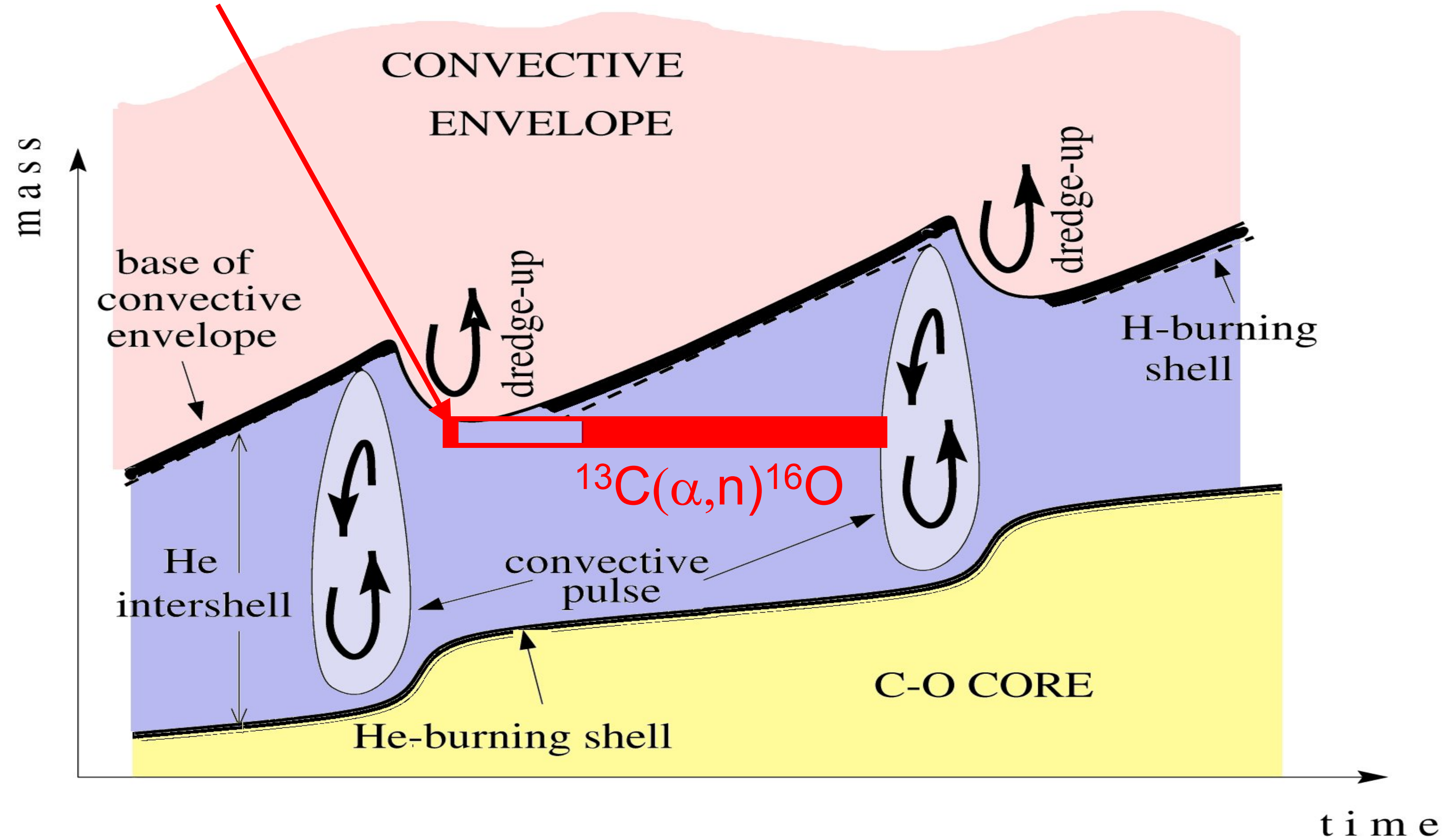
Post-AGB stars: Evolved from stars of low-mass, 1-1.5Msun at relatively low metallicity, [Fe/H] ~ -1 (e.g., De Smedt et al. 2014; van Aarle et al. 2013)

Figure from Kenneth De Smedt



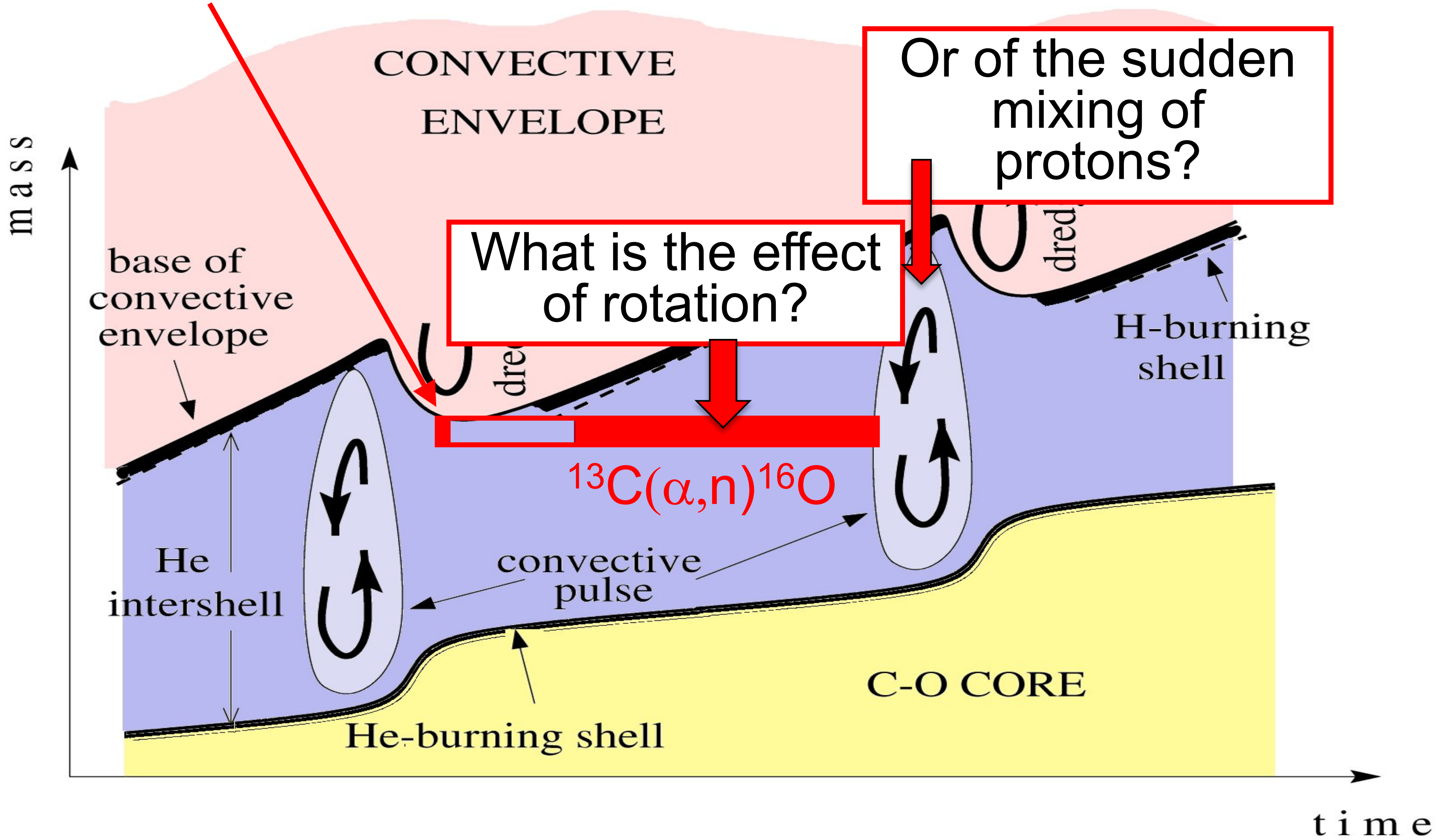
Neutron production is still poorly understood

Neutrons form in ^{13}C pockets – we don't know how these form!



Neutron production is still poorly understood

How much hydrogen is need to make a ^{13}C pocket? We don't really know. This is a big uncertainty in models of the s-process



The intermediate neutron-capture process

Neutron flux determines whether we have an s or r-process:

- r-process: $N_n > 10^{20}$ n/cm^3
- s-process: $N_n < 10^{13}$ n/cm^3

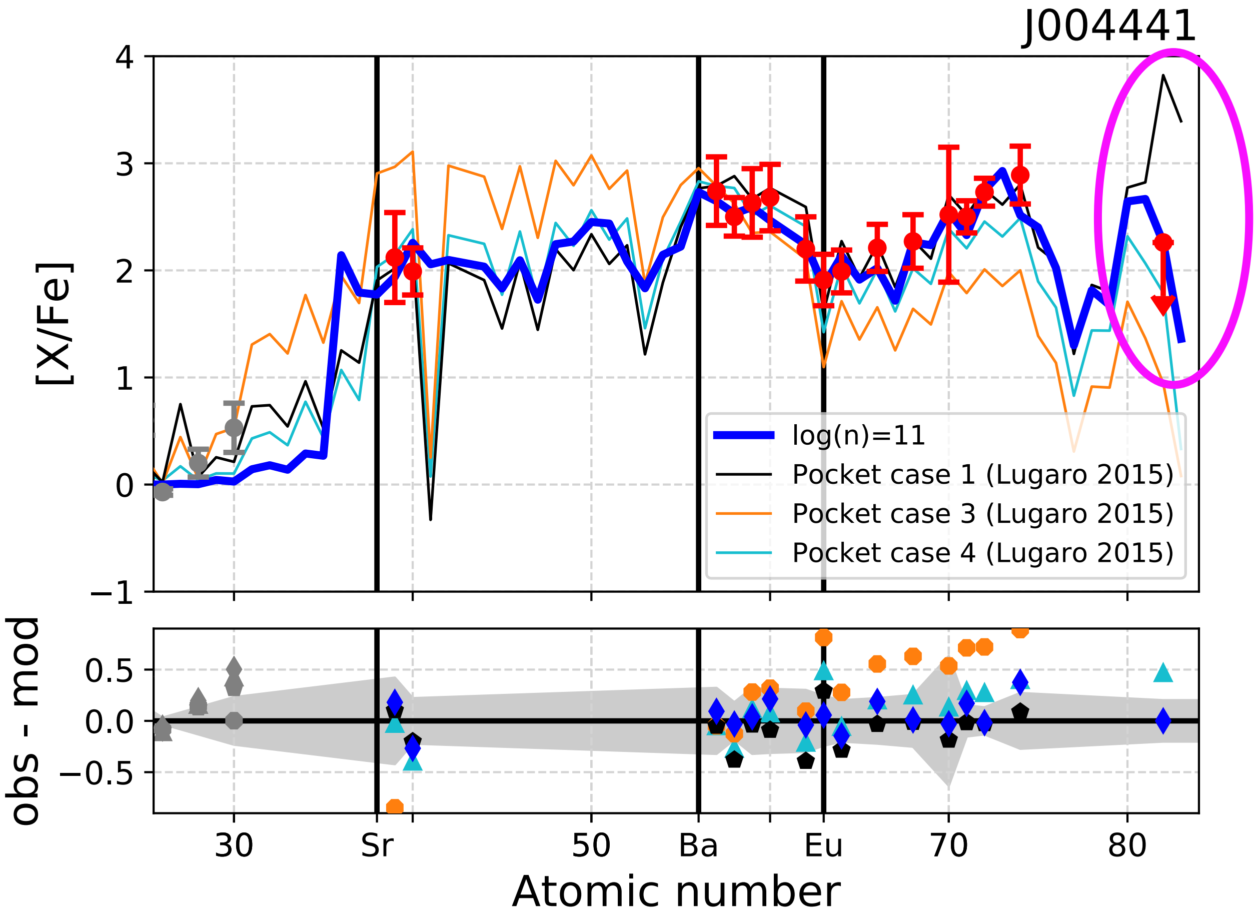
During the *r* process:
Time scale (n,g) << τ_β

During the *s* process:
Time scale (n,g) >> τ_β

- Intermediate-neutron capture process (Cowan & Rose 1977)
- Proton ingestion into a He-burning region will produce neutron densities of ~10^{15} n/cm^3 (Campbell et al. 2010, Herwig et al. 2011)
- Are the Pb abundances in post-AGB stars evidence of this?
- What about the carbon-enhanced metal-poor stars, which show enrichments in both s and r-process elements? (Lugaro et al. 2012)

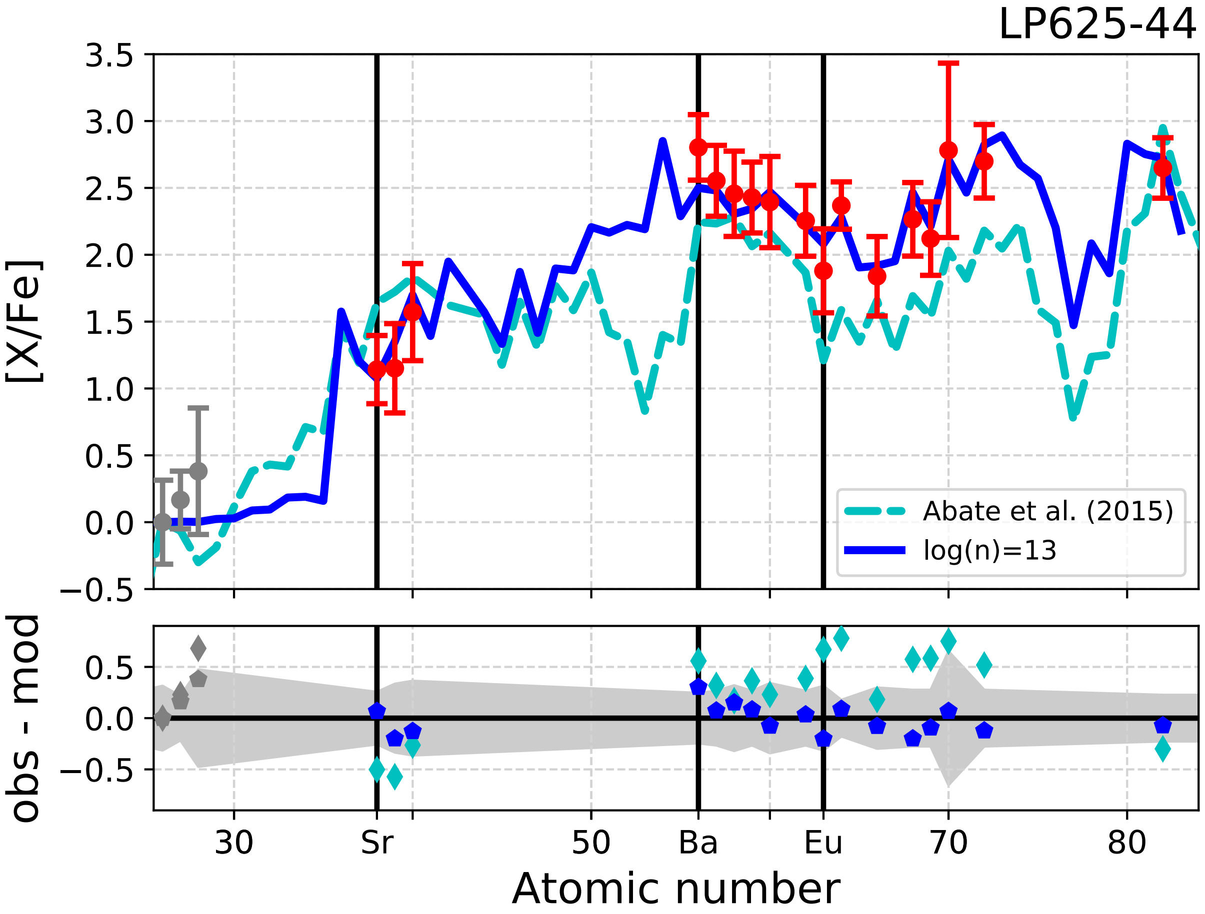
The i-process in post-AGB stars

- Neutron density of ~10^{11} n/cm^3 can produce a pattern that matches (solid blue line). From Hampel et al. (2019):



CEMP-*r/s* stars: what was the progenitor?

- Best-fitting model for CEMP-*s*/*r* star LP625-44 (solid blue) compared to an s-process with an r-process foundation,
- From Hampel et al. (2019):



Where does the *i*-process occur in nature?

- Low and intermediate-mass stars of low-metallicity? (Lugaro et al. 2015, Jones et al. 2016)
- Metal-free massive stars? (Banerjee et al. 2018, Clarkson et al. 2018)
- Accreting white dwarfs? (e.g., Hillebrandt et al. 1986, Côté et al. 2018, Denissenkov et al. 2017, 2019)

How will the i-process affect the (early) chemical evolution of the Galaxy?

Côté et al. 2018 suggests important for the first s-process peak (Sr, Y, Zr).
Anything else?

CHEMICAL EVOLUTION OF HEAVY ELEMENTS

Chemical evolution of heavy elements

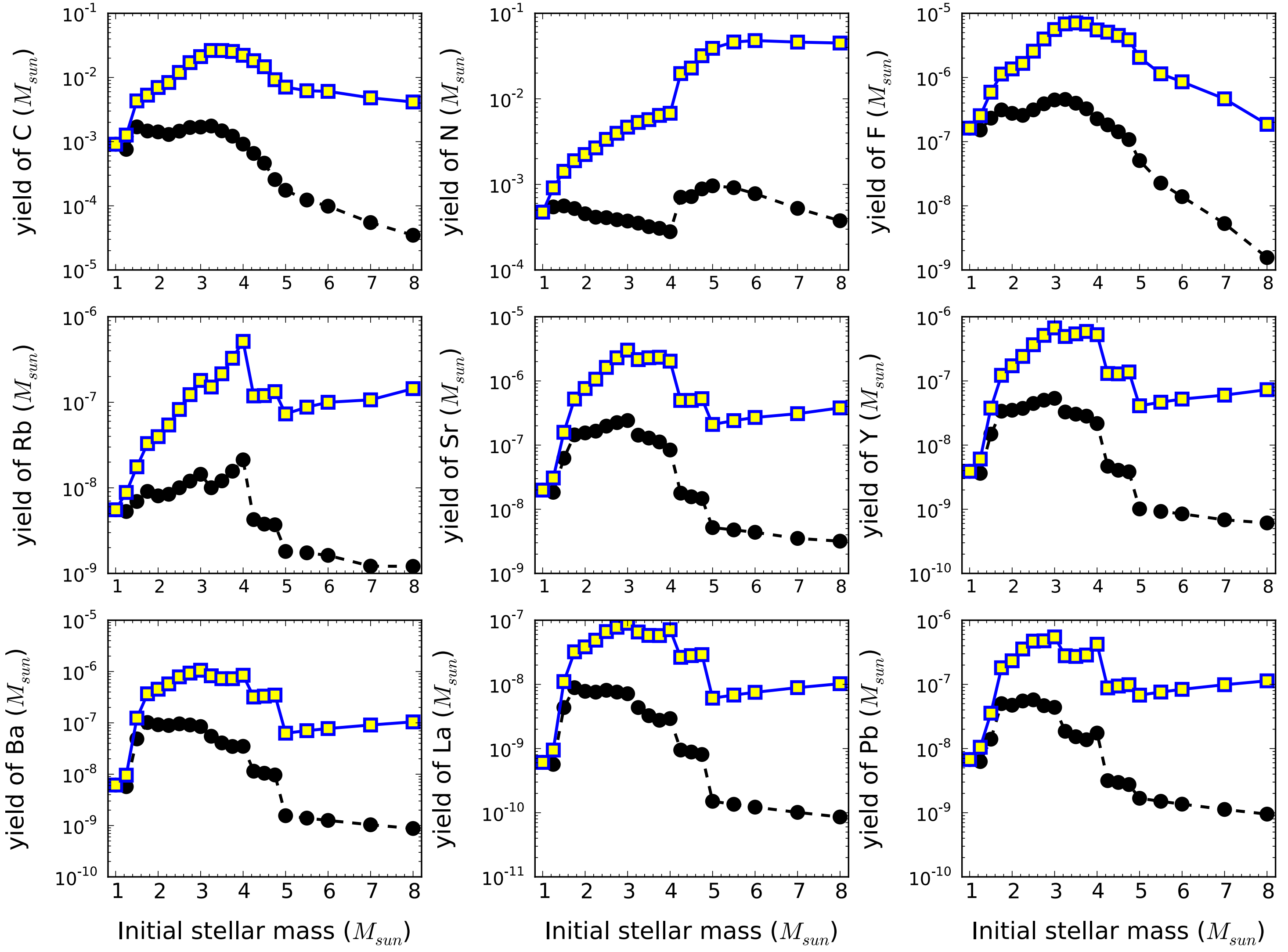
- First, make a chemical evolution model that matches broad observational features of the Galaxy (e.g., metallicity distribution function)
- **References**: Pagel (textbook), Tinsley (1980), Kobayashi et al. (2011, 2020)
- Add yields of heavy elements:
  1. AGB yields including s-process elements.
  2. Massive star yields including s-process.
  3. r-process yields from merging neutron stars.
  4. Magneto-rotational SN yields for the r-process.

Caveats can include:

- The delay-time distribution of neutron star mergers is highly uncertain.
- Massive star yields significantly depend on the details of rotation.
- AGB yields depend on the treatment of the ^{13}C pocket and mass-loss.

AGB chemical yields

Example: [Fe/H] = 0 (solar) from Karakas & Lugaro (2016)



Yield = amount of an isotope ejected into the ISM over the star's lifetime

Yield definition:

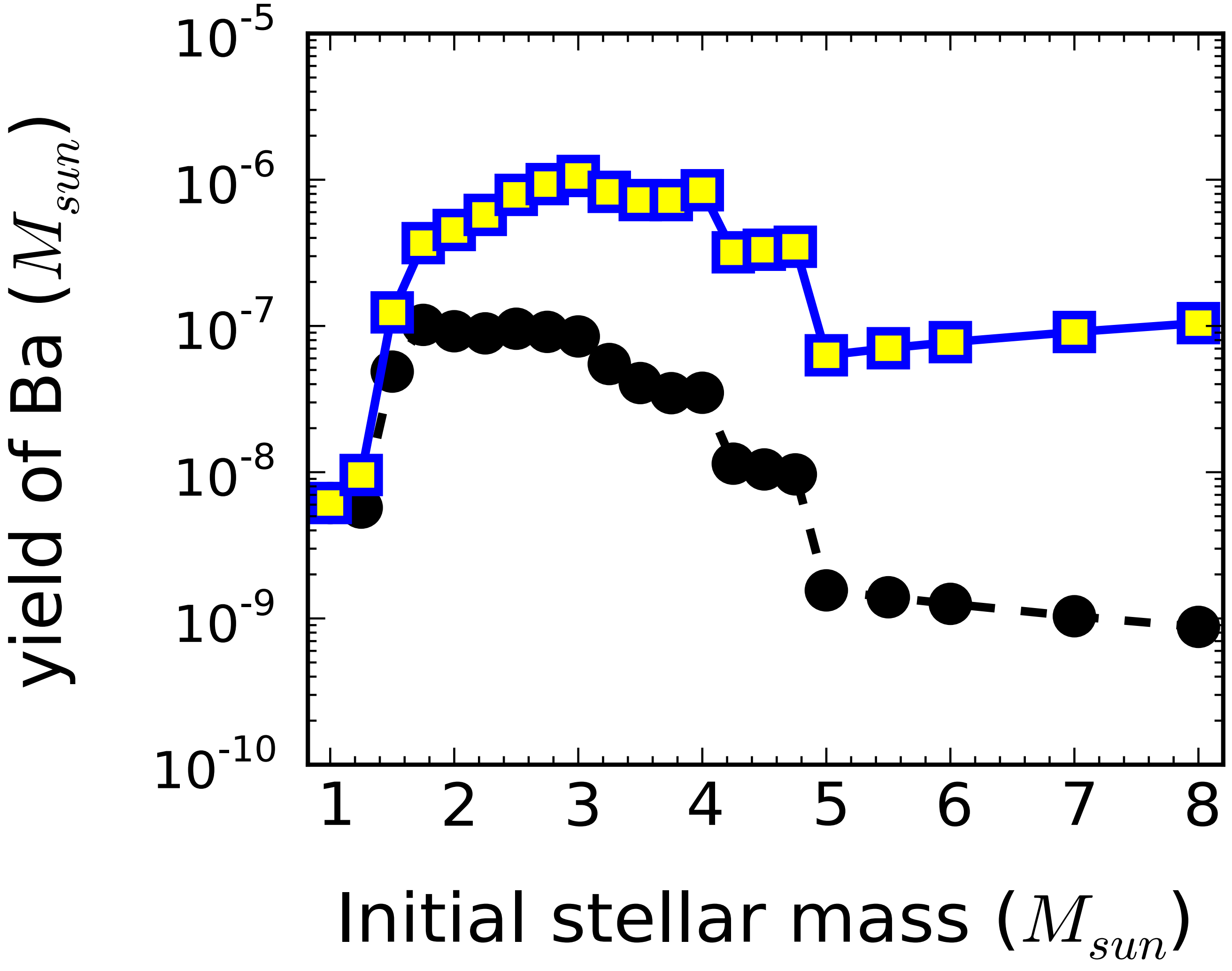
$$y_k = \int_0^{\tau} [X_k(t) - X_k(0)] \frac{dM}{dt} dt$$

Black dots = weighted by the Salpeter initial mass function, i.e.,

$$\frac{dN}{dM} \propto M^{-2.3}$$

AGB chemical yields

Example: Ba from models of [Fe/H] = 0 (solar) from Karakas & Lugaro (2016)



Yield = amount of an isotope ejected into the ISM over the star's lifetime

Black dots = weighted by an IMF

- Here we see that the intermediate-mass range are *weighted out* by the IMF.
- That is, their contribution is less important because there are so few of them.

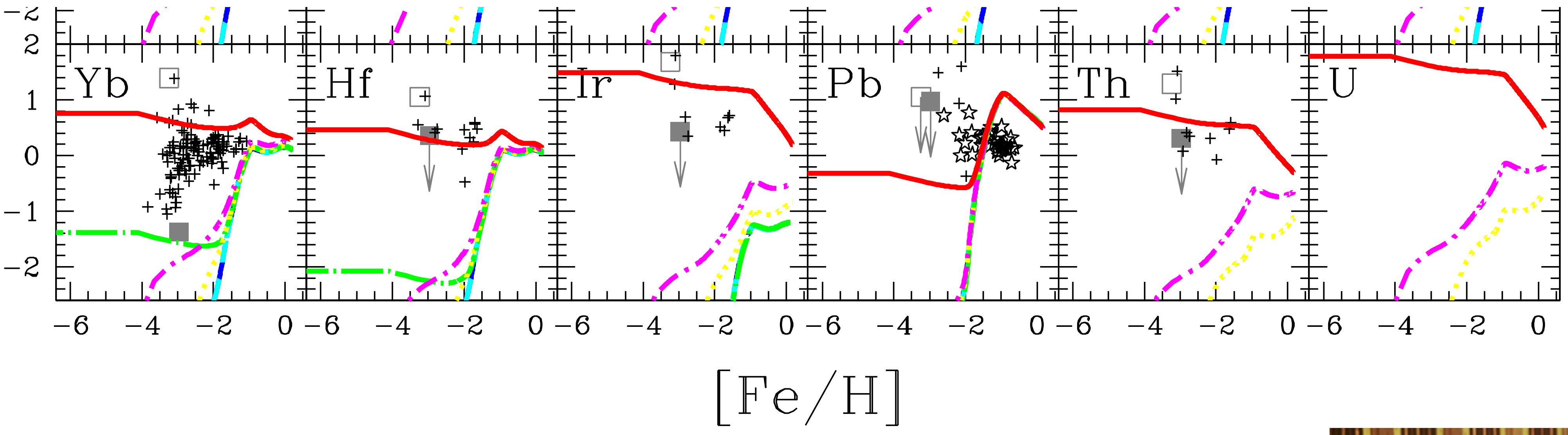
AGB yields with s-process elements

- **Monash group:** Lugaro et al. (2012), Fishlock et al. (2014), Karakas & Lugaro (2016), Karakas et al. (2018); yields of 1 to ~8Msun ($-2.3 \leq$ [Fe/H] $\leq +0.3$)
- **FRUITY database:** Cristallo et al. (2015); includes a few models with rotation ($-2.15 \leq$ [Fe/H] $\leq +0.15$)
- **NuGrid/MESA:** Pignatari et al. (2016), Ritter et al. (2018), Battino et al. (2019); for Z = 0.001, 0.006, 0.01 and 0.02, 0.03
- **At very low metallicities:** Goriely & Siess (2001), Campbell et al. (2010), Bisterzo et al. (2010), and Cruz et al. (2013) but no tabulated yields

What is lacking? Yields for low metallicity for all masses. Super-AGB yields.

Galactic chemical evolution models

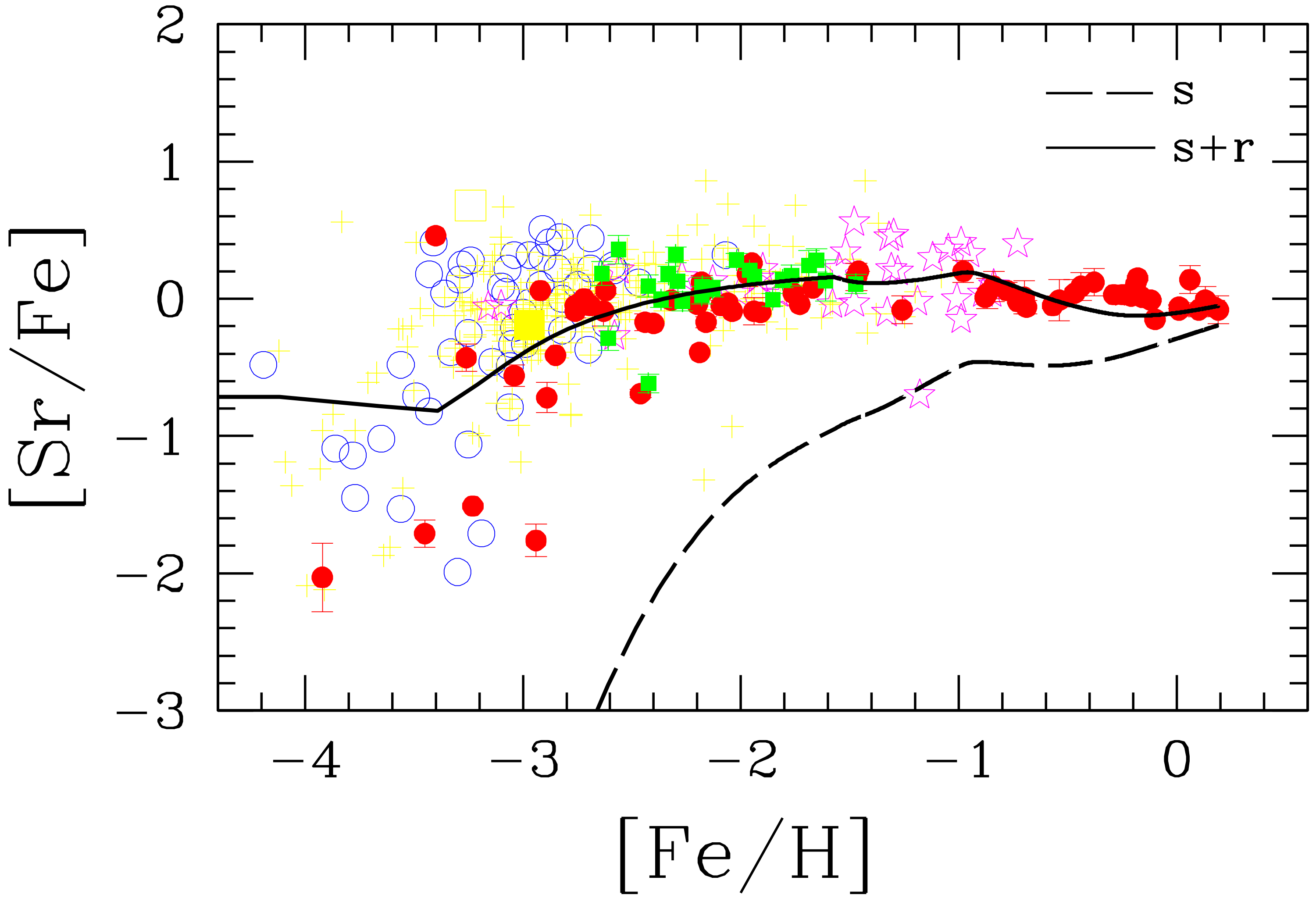
From Kobayashi, Karakas & Lugaro (2020)



- Yb = Ytterbium, Hf = Halfnium, Ir = Iridium, Pb = Lead,
- Th = Thorium, U = Uranium.

See also Côté et al. (2018); Prantzos et al. (2020)

History of Strontium in the Galaxy



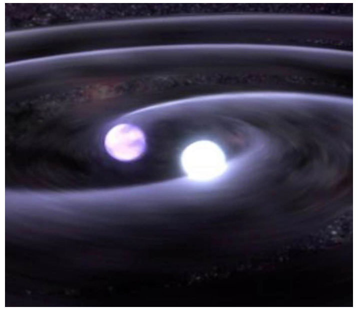
This model matches the solar composition of Sr with yields from s- and r-processes alone.

Do we even need an i-process? Maybe, at low metallicities?

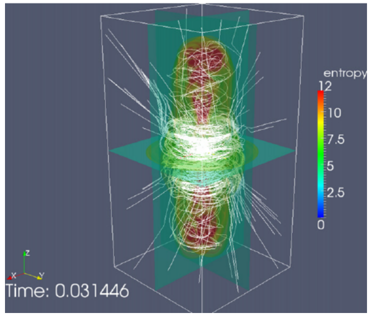
From Kobayashi, Karakas & Lugaro (2020)

Summary: Origin of heavy elements

Neutron star mergers

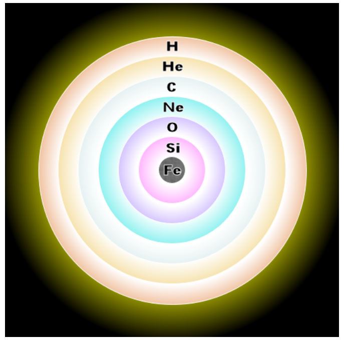


Unusual supernovae?

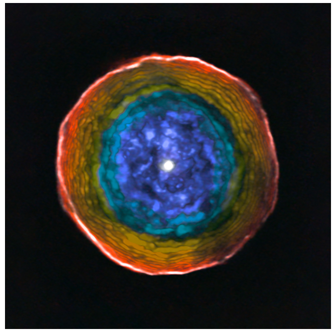


The r-process
~50%?

Massive stars

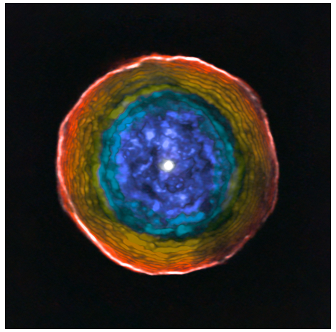


Asymptotic giant branch stars

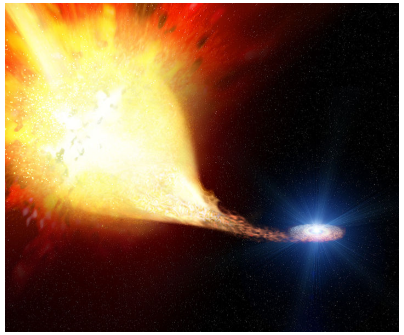


The s-process
~50%

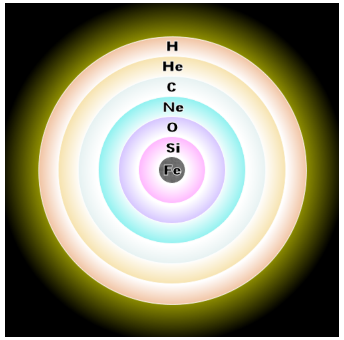
AGB stars?



Accreting white dwarfs?



Massive stars?



The i-process
??

Summary

- AGB stars are the last complex phase of evolution of low and intermediate-mass stars.
- Brief phase leads to complex nucleosynthesis which depends on mass and metallicity.
- Main result: AGB stars make carbon, nitrogen, fluorine etc.
- The s-process is one pathway involving neutron captures to make roughly half of all elements heavier than iron.
- Main site of the s-process is AGB stars, where details depend on neutron production and ultimately, density.
- There is observational evidence for an intermediate-neutron capture process in nature. Site is AGB stars? Accreting white dwarfs? Metal-poor massive stars?
- Still many open questions!