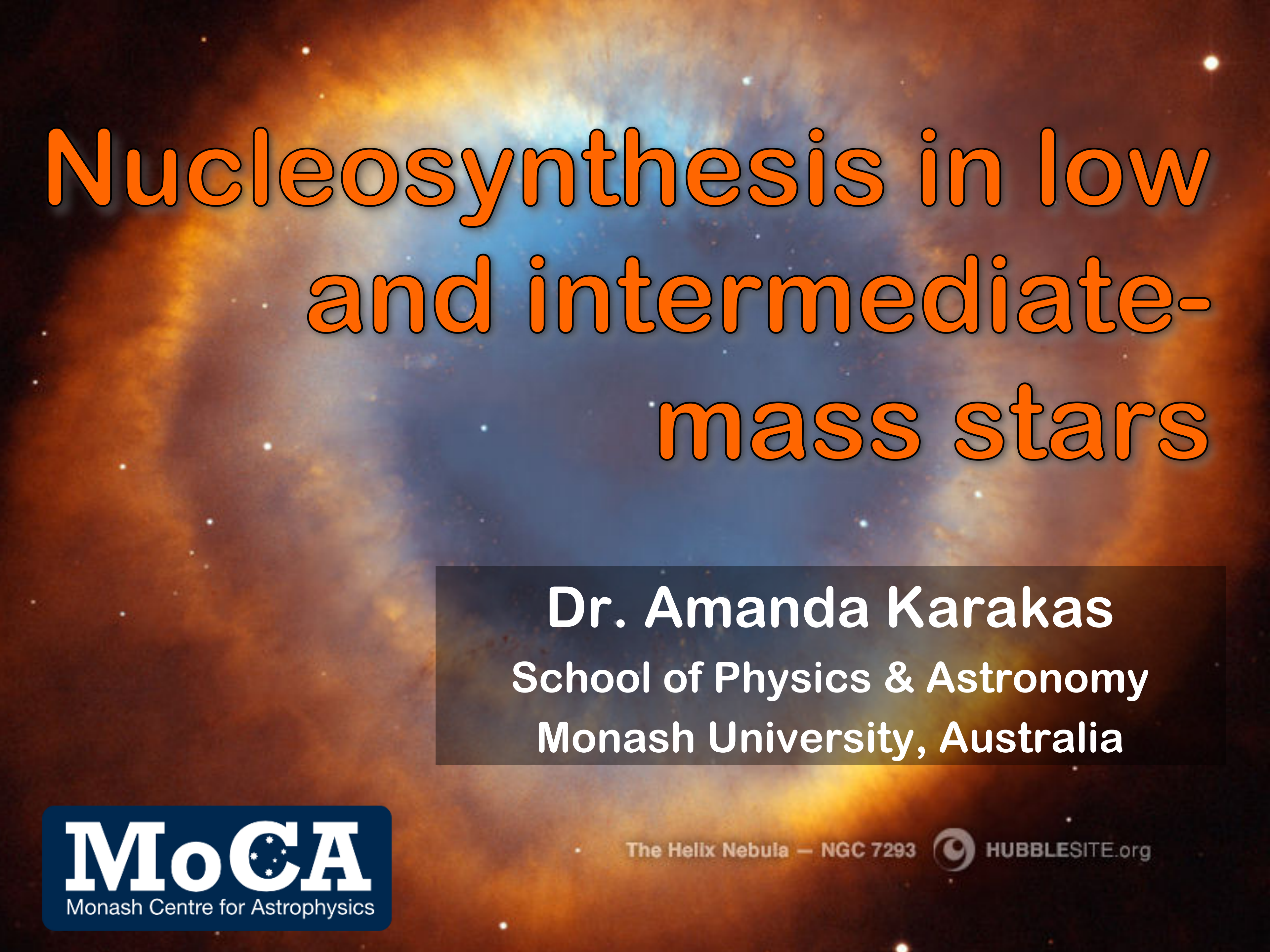

Nucleosynthesis in low and intermediate-mass stars

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MoCA
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Outline of Lectures

I’m giving three lectures, which will be broken down into the following components:

1. Introduction – some basics
2. Nucleosynthesis prior to the asymptotic giant branch (AGB) phase
3. The evolution and nucleosynthesis of AGB stars
4. The slow neutron capture process

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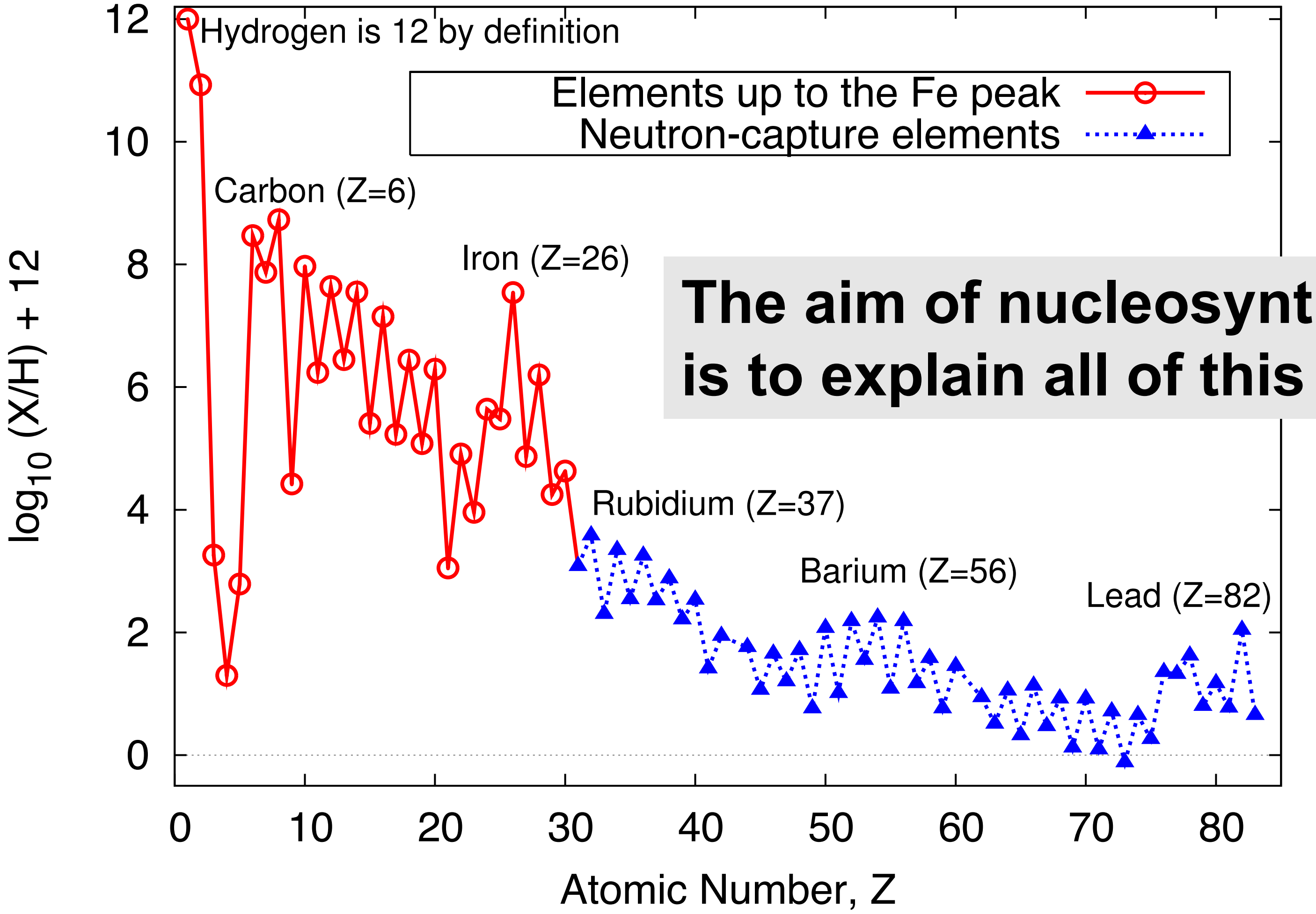
Introduction

- We are all made of star stuff!
- 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

The Origin of the Elements

Abundance distribution in our solar system



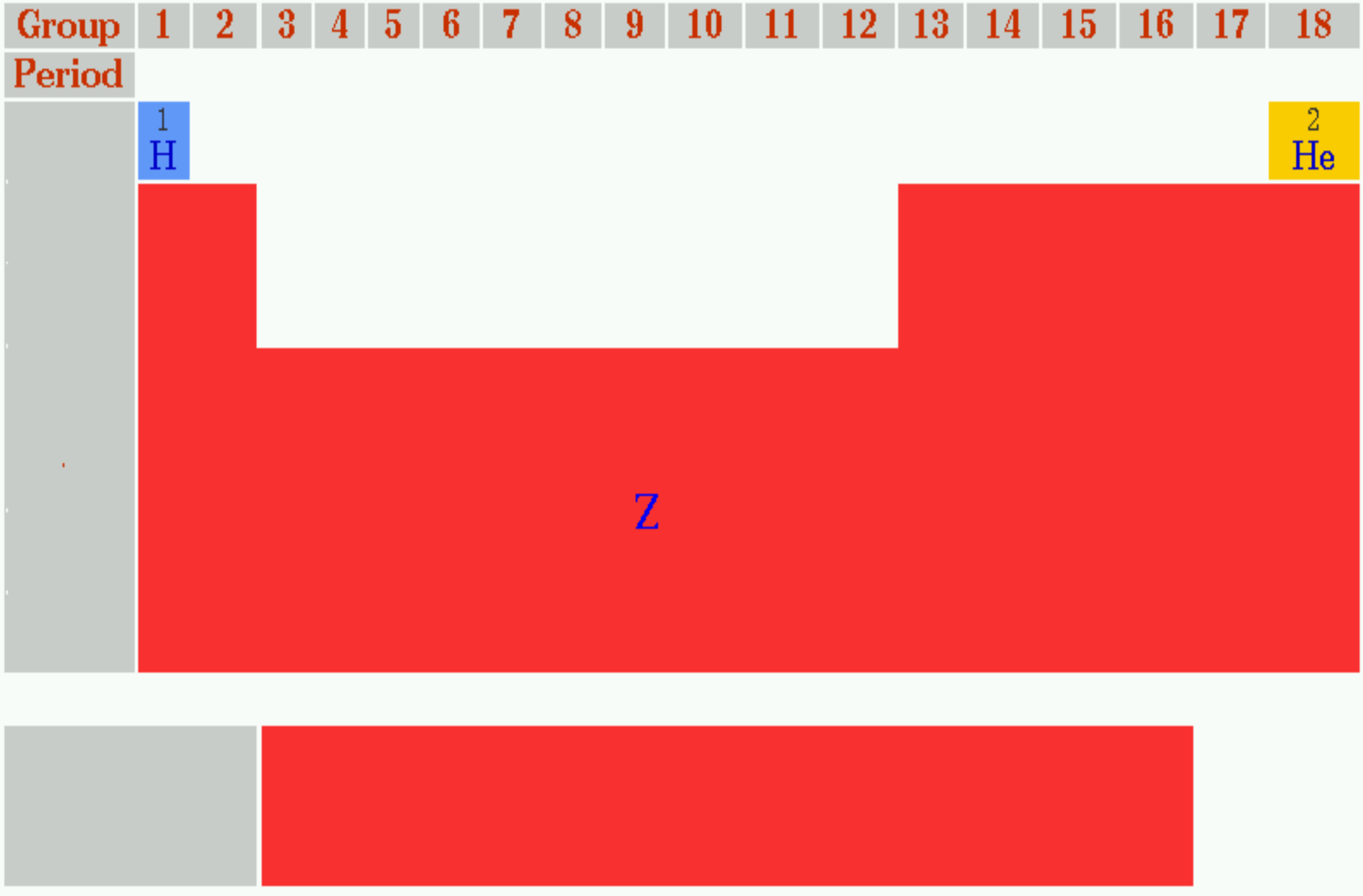
The aim of nucleosynthesis is to explain all of this graph!

Using solar abundances from Asplund et al. (2009)

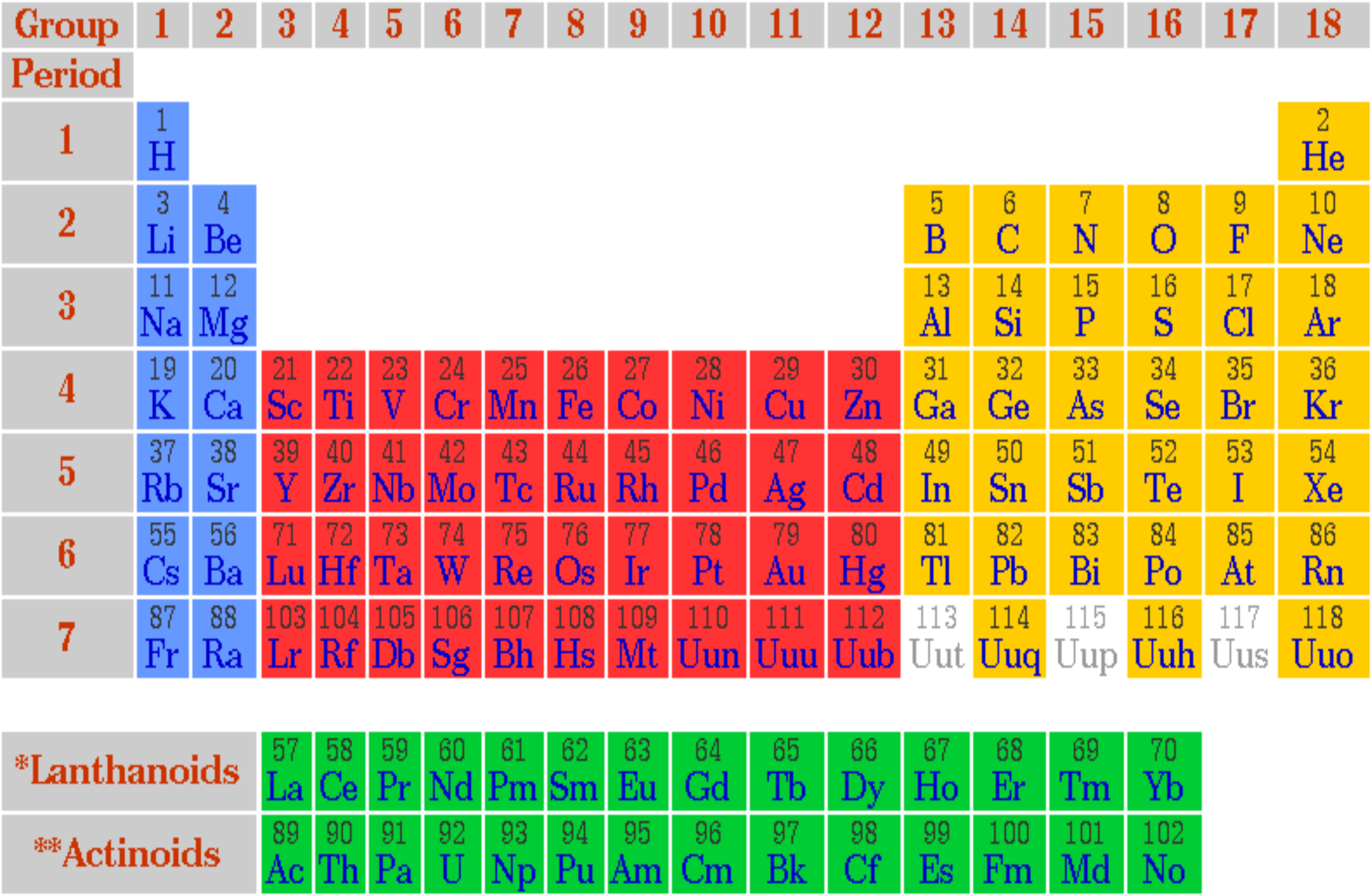
Some basics

- Low-mass stars:
  - Initial masses from 0.8 to ~2.0 solar masses (maximum mass for core He-flash)
- Intermediate-mass stars:
  - Initial masses from 2.0 to 8 Msun (minimum mass for carbon ignition)
- Super-AGB and electron-capture supernovae:
  - Initial masses between 8-10Msun
- Massive stars:
  - Initial masses: $\gtrsim 10$ Msun
- These definitions are for Z = 0.014 (solar)
- X = hydrogen mass fraction, Y = helium mass fraction, Z = 1 - X - Y = “metals”
- In the Sun: X = 0.7154, Y = 0.2703, Z = 0.0142 (Asplund et al. 2009)

Periodic Table



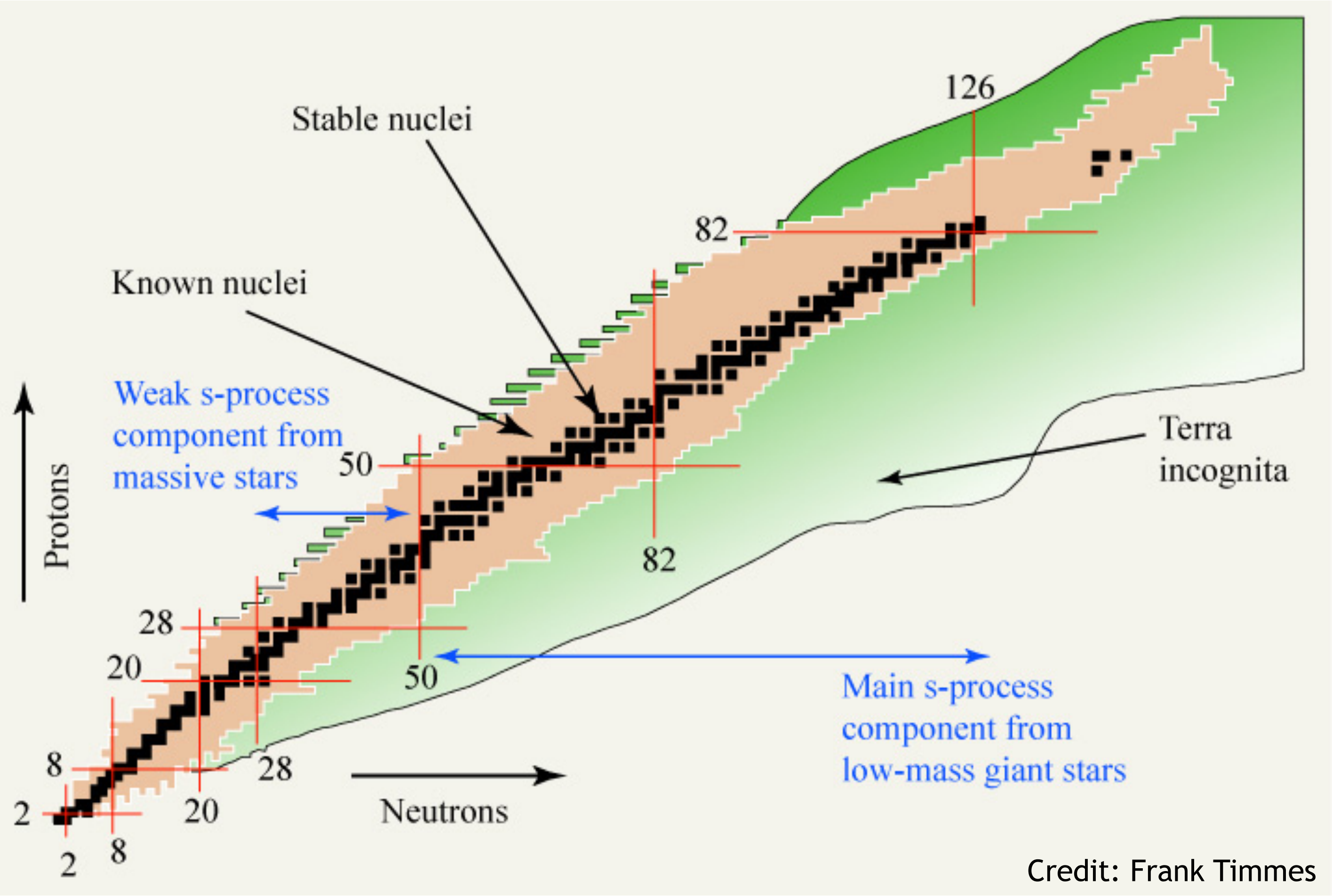
Periodic Table



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		

Chart of the Nuclides

The further a nucleus is from the valley of nuclear stability, the more unstable it is to β± decay i.e. the shorter is its half-life



Credit: Frank Timmes

Nucleosynthesis

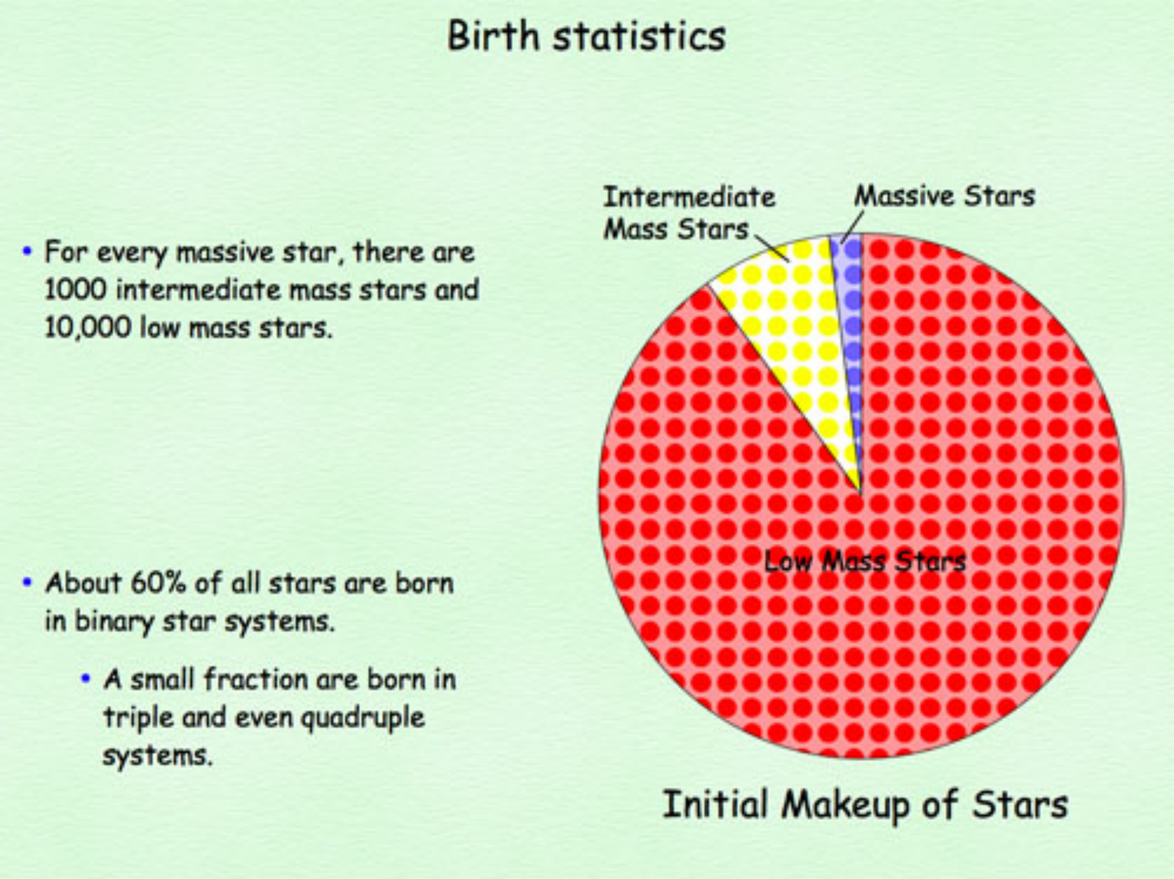
- Production of atomic nuclei in the Universe
- Nucleosynthesis* takes place deep inside stars
- How does it get out?

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 (Romero, Karakas) → no explosion! Mixing + mass loss returns the material
2. Massive stars and core collapse supernova explosions (Kobayashi)
3. Chemical enrichment and Galactic archaeology (Melendez, Alves Brito, Kobayashi)

Star birth masses



Birth statistics

- For every massive star, there are 1000 intermediate mass stars and 10,000 low mass stars.

- About 60% of all stars are born in binary star systems.
  - A small fraction are born in triple and even quadruple systems.

Initial Makeup of Stars

From Frank Timmes website

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

In terms of single stars, 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)

How long do stars live?

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

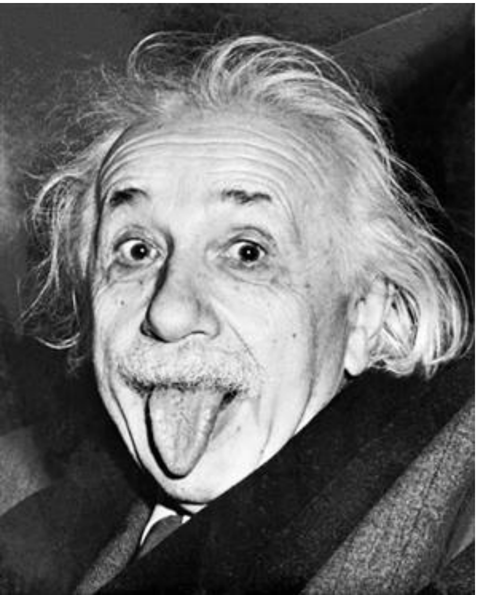
Initial mass (M_{sun})	**Main sequence lifetime**	**Total stellar lifetime**
25	6.7 Myr	7.5 Myr
15	11Myr	13 Myr
5	80 Myr	100 Myr
2	900 Myr	1.2 Gyr
1	10 Gyr	12 Gyr
0.8	20 Gyr	> 32 Gyr

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

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

How do stars work?

- 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

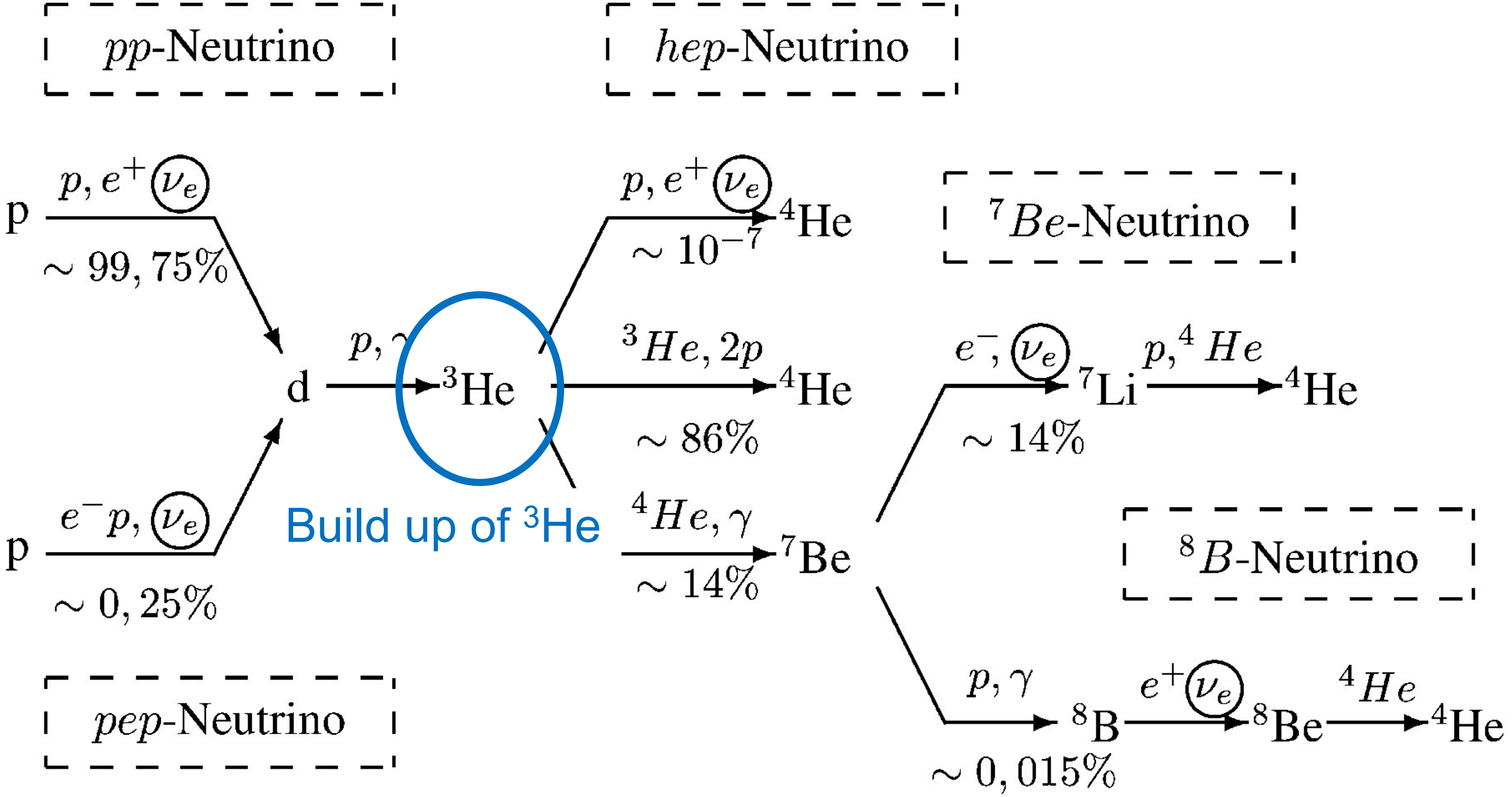


- How much energy?
- Energy released = 26 MeV = 4×10^{-12} Joules

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

H-burning: Proton proton chains

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



Build up of ^{3}He

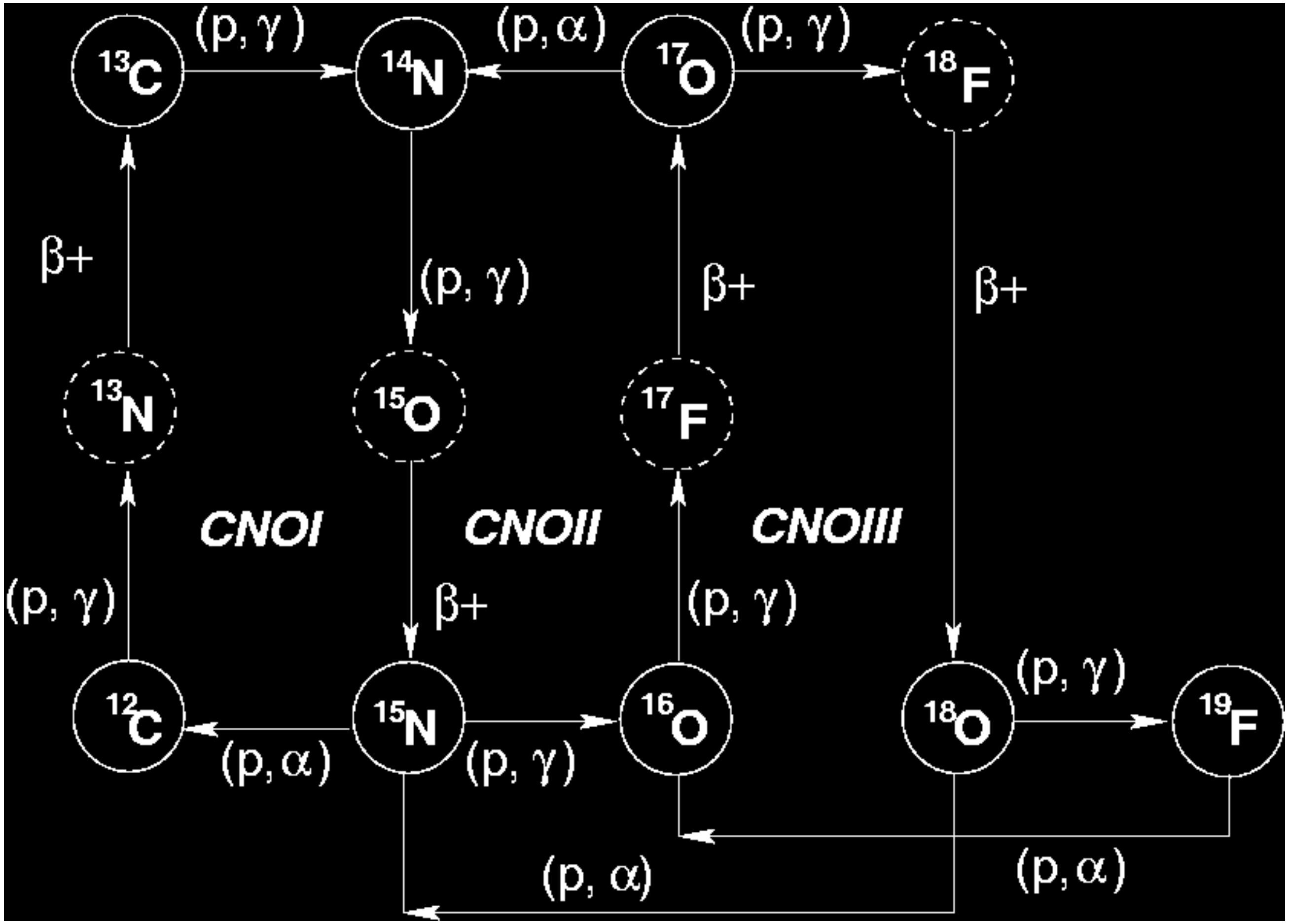
From MPA, Neutrino Astrophysics Group

H-burning: CNO cycles

Main result: 4 p → ^{4}He + energy + stuff
The total number of C+N+O nuclei is conserved

While total number conserved we find:

- C+N+O nuclei are converted into ^{14}N
- First C, N nuclei are involved
- Then O isotopes at hotter temperatures

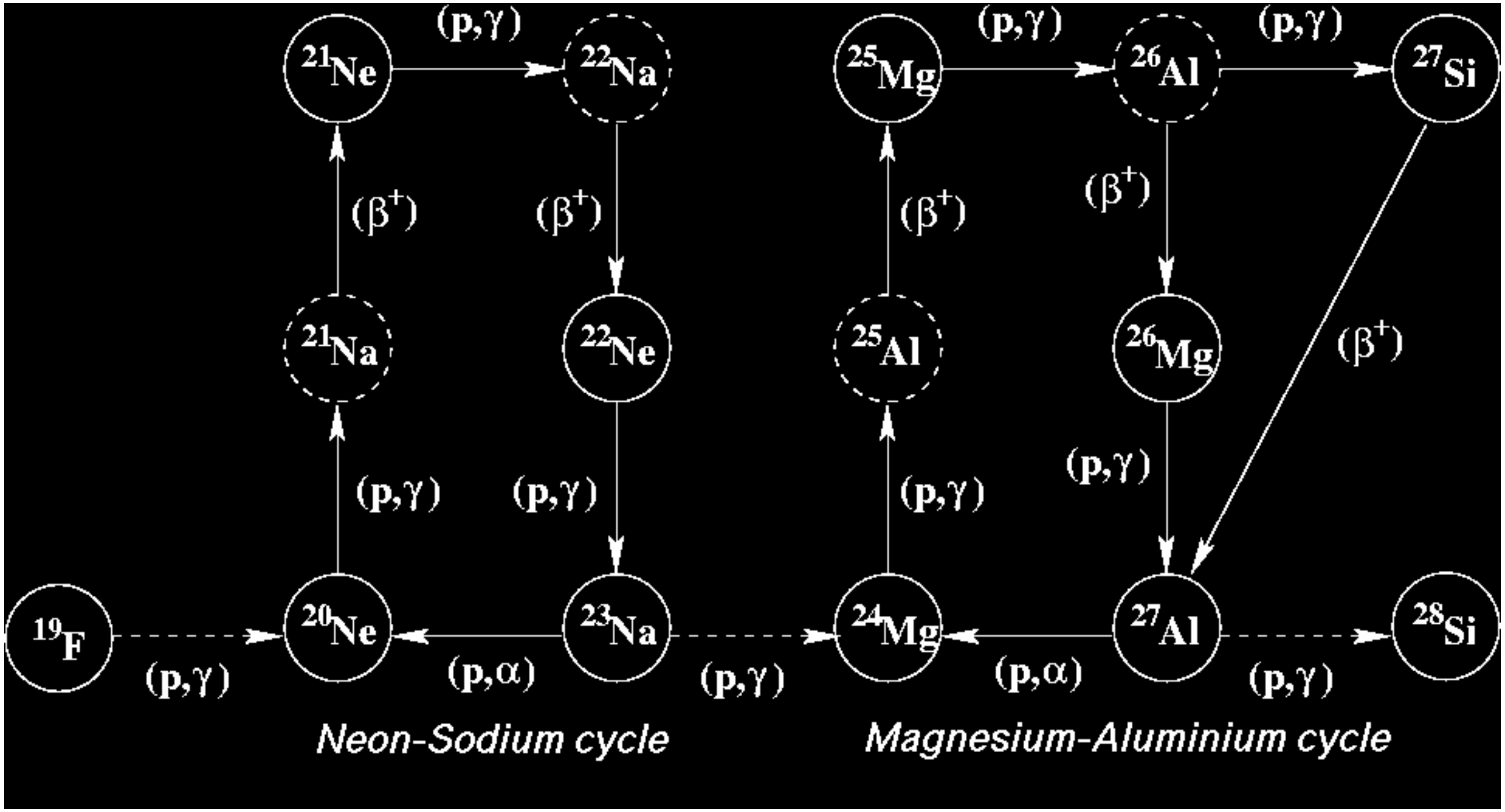


H-burning: CNO equilibrium ratios

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
- ^{16}O abundance 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



- Requires hotter temperatures, $T \gtrsim 30 \times 10^6$ K
- Increase in the abundance of ^{23}Na at the expense of ^{22}Ne
- Produces radioactive ^{26}Al and re-arranges the heavy Mg isotopes

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 (2nd 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

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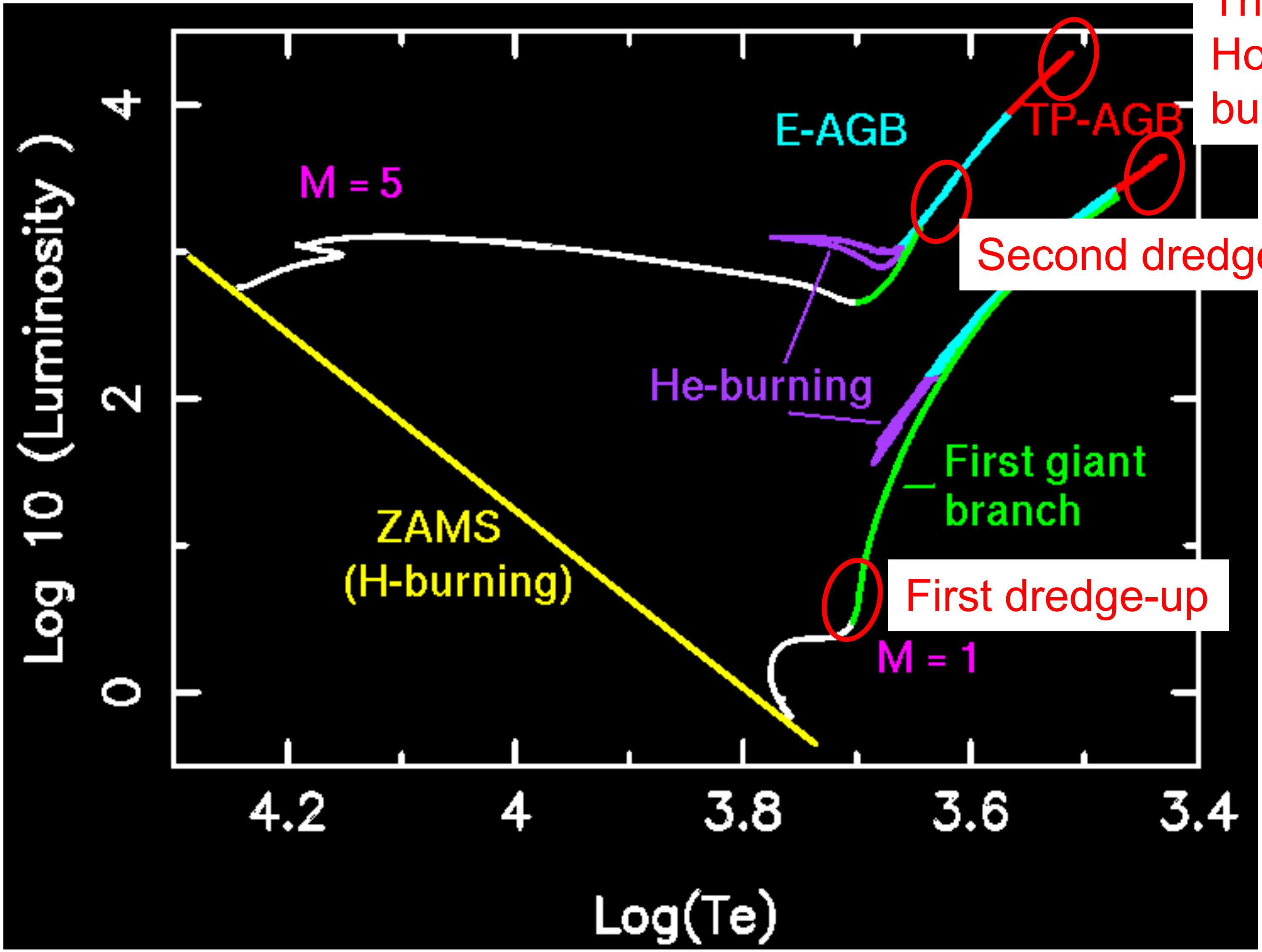
Reference

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

Where mixing takes place



Third dredge-up
Hot bottom burning

Second dredge-up

First dredge-up

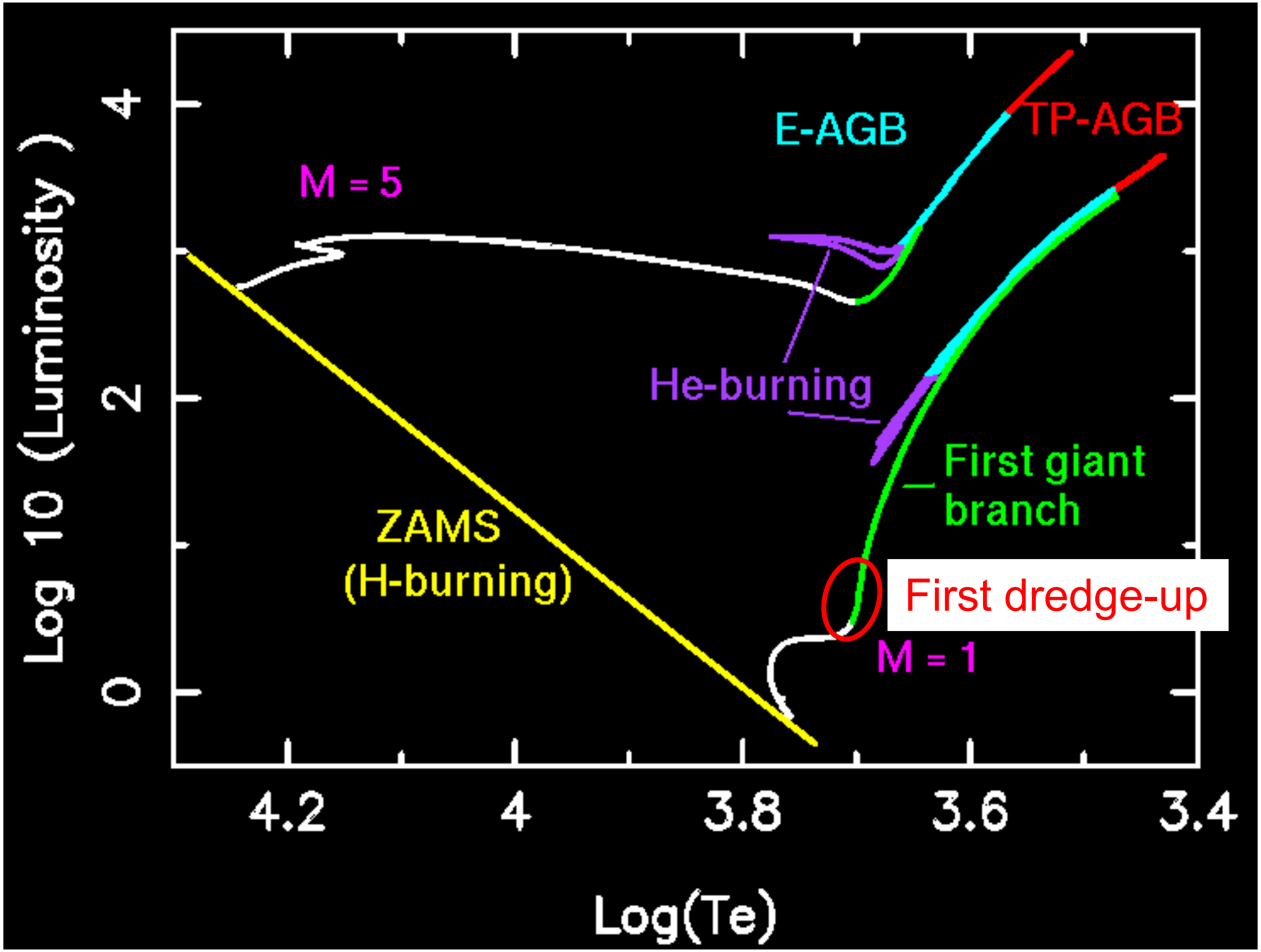
What I’m not talking about

- Surface composition can change by other, non-standard or classical mixing mechanisms:

1. Diffusion/gravitational settling
2. Rotation – but I’ll mention it in the context of RGB and AGB surface abundance changes
3. Binary evolution – Chiaki will mention in context of Type Ia supernova

Do these affect the yields and Galactic chemical evolution?

Where mixing takes place



First dredge-up

Evolution after core H-burning

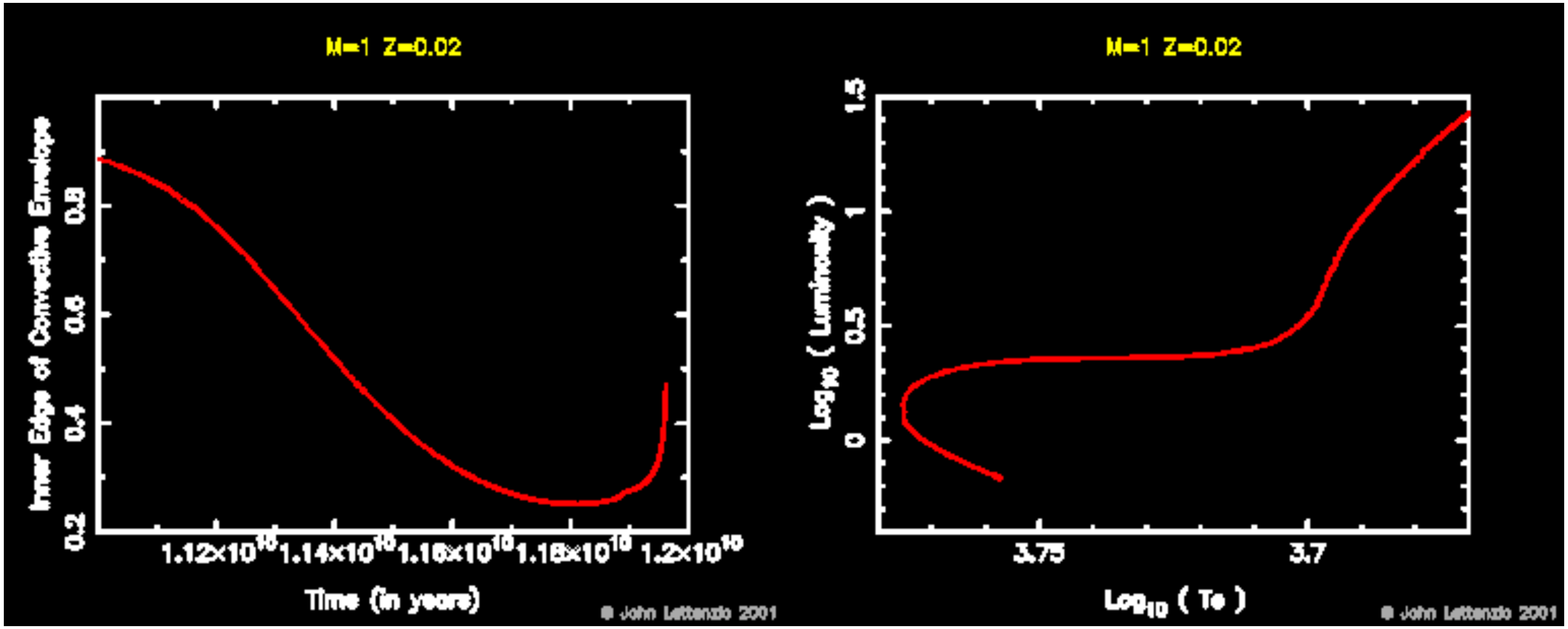
- After core H-burning has ceased, the core begins to contract
- Hydrogen burning is established in a shell around the contracting, inert He-core
- The envelope becomes convective, and moves inward into regions partially processed by previous H-burning on the main sequence

→ This is the first important mixing event

→ Known as the “first dredge-up”

The first dredge-up: 1Msun

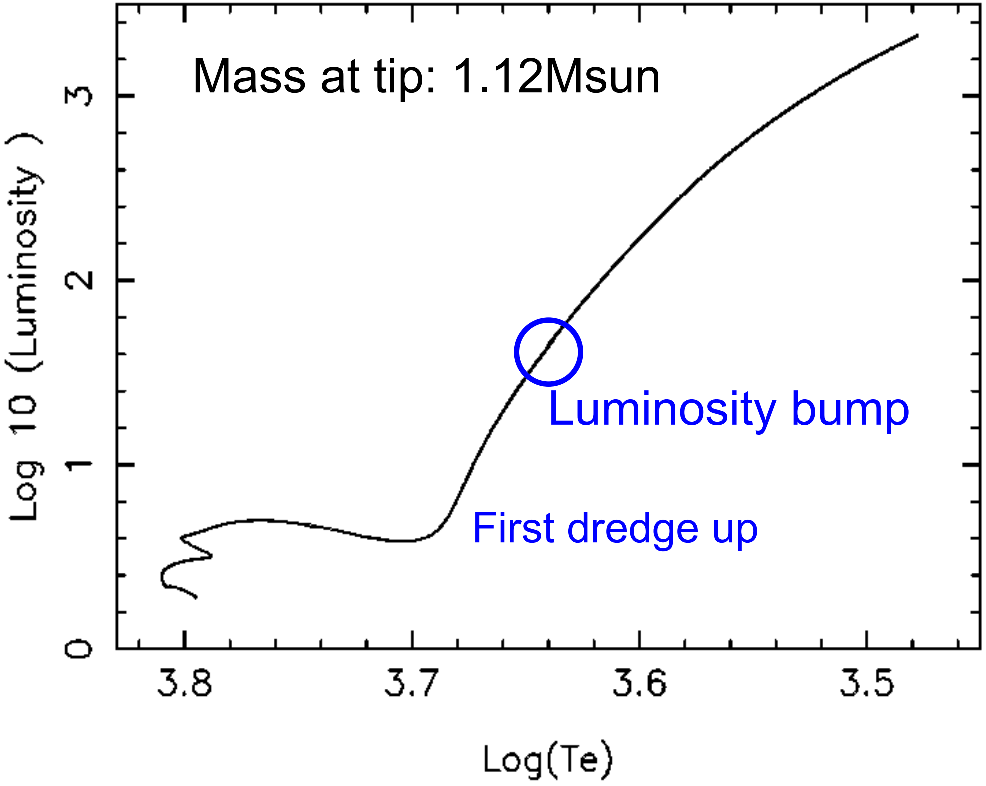
Movies from Prof. John Lattanzio’s website:
http://www.maths.monash.edu.au/~johnl/StellarEvolnV1/



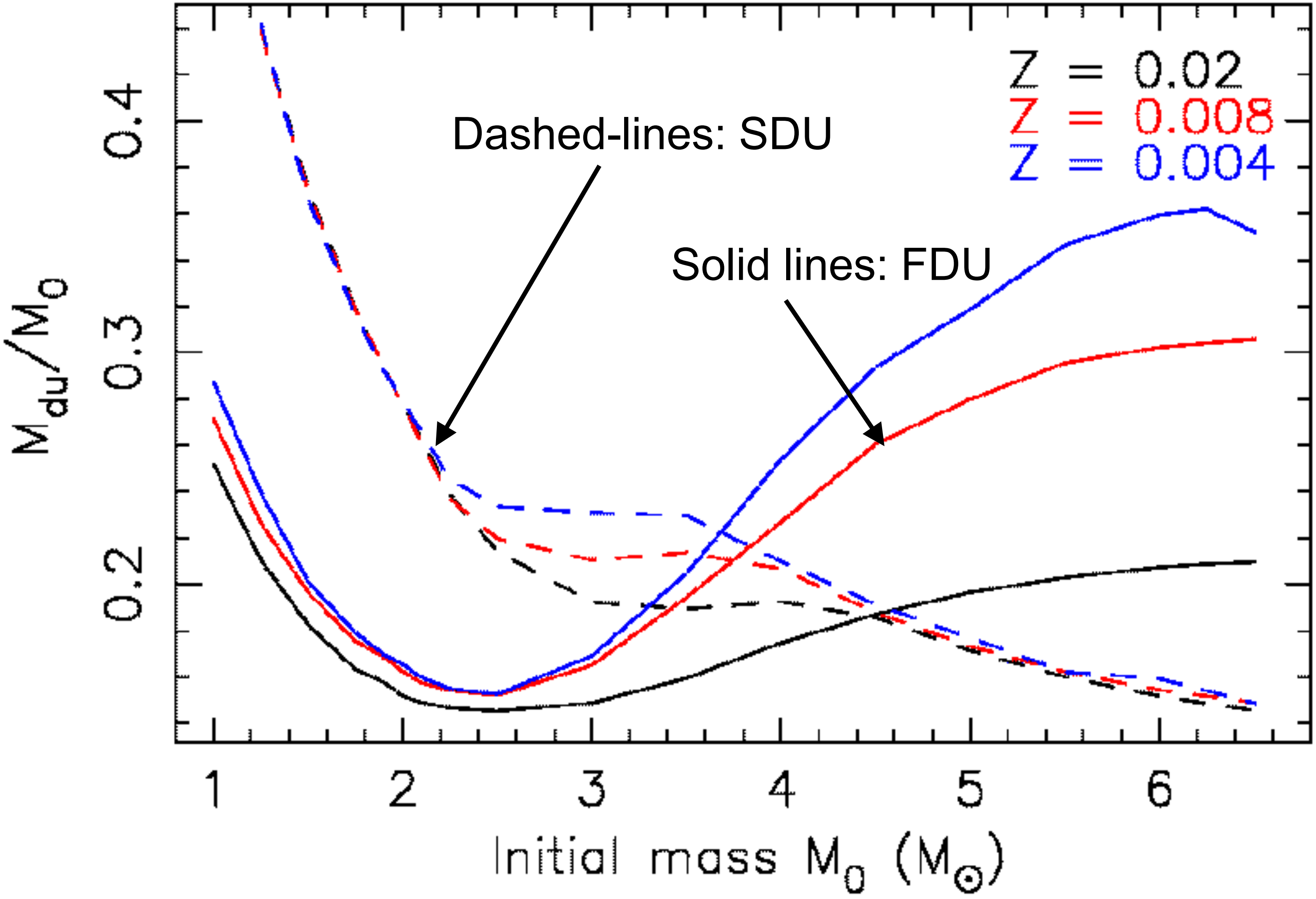
First dredge up

- Mixes up material partially processed during the previous main sequence
- This is the first dredge-up (FDU)
- Main changes:
  - 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
  - Small changes predicted for heavier elements (e.g, F, Na)

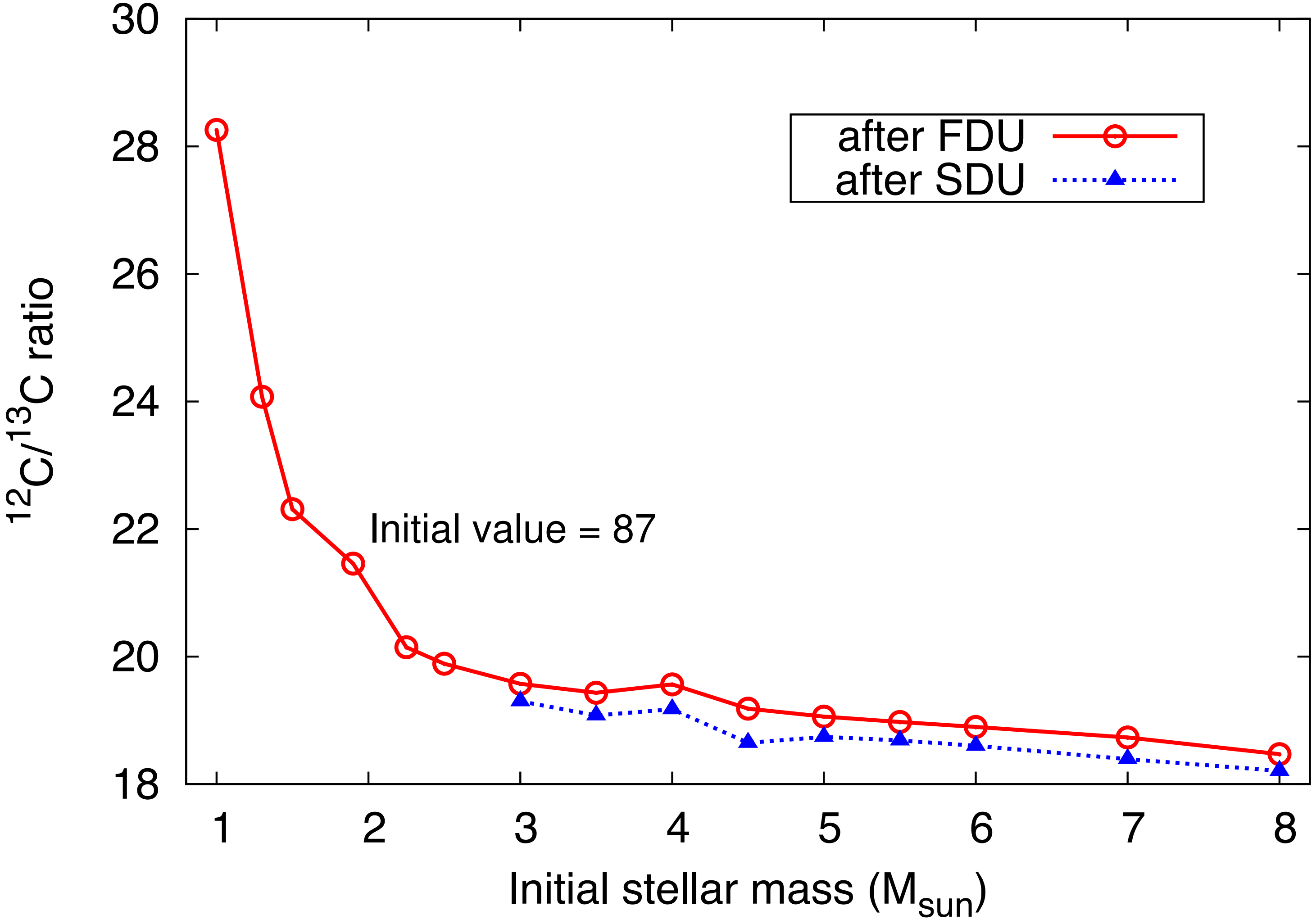
Example: 1.25Msun, Z = 0.02 model



First and second dredge-up

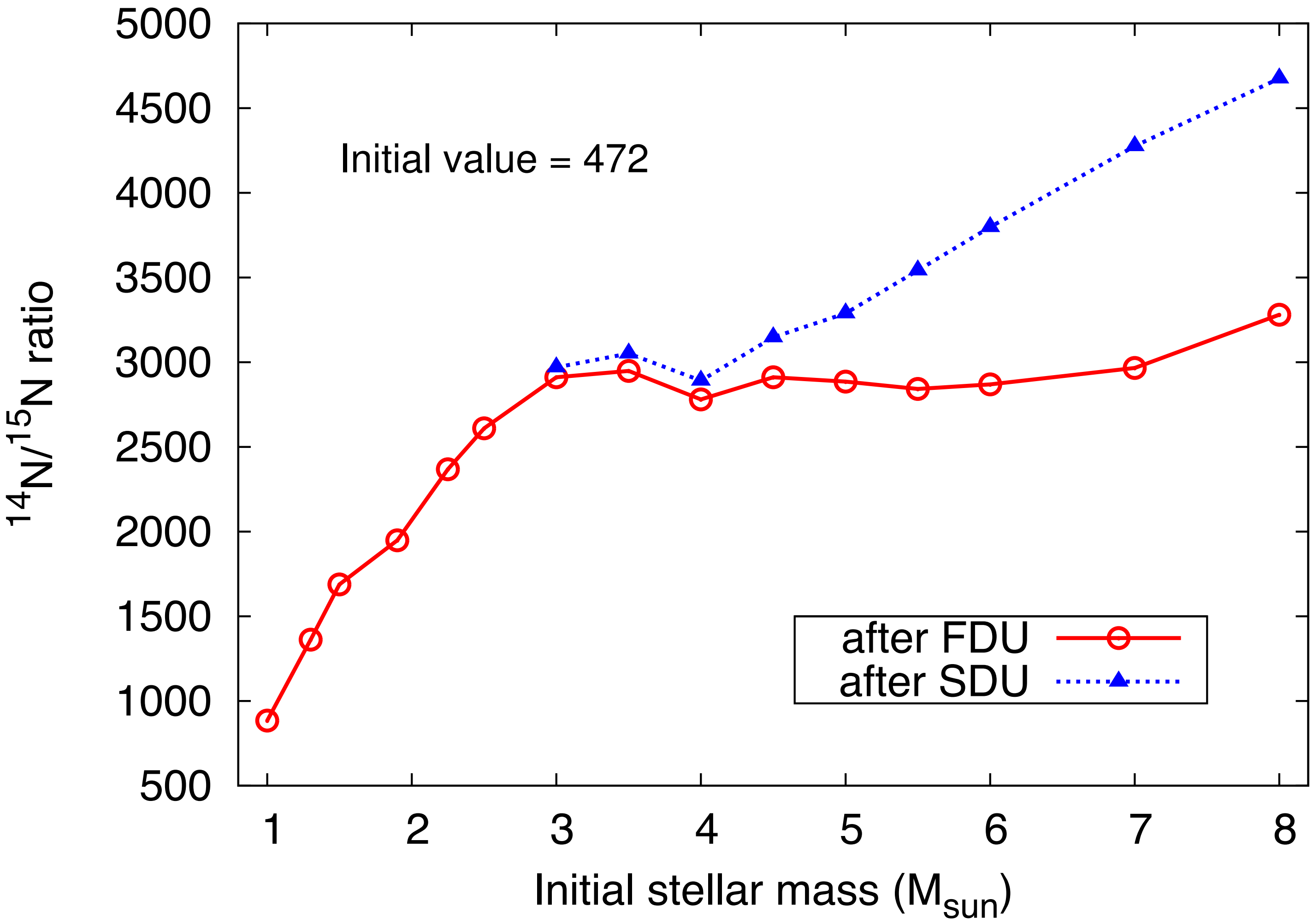


What do we see at the surface?



From Karakas & Lattanzio (2014)

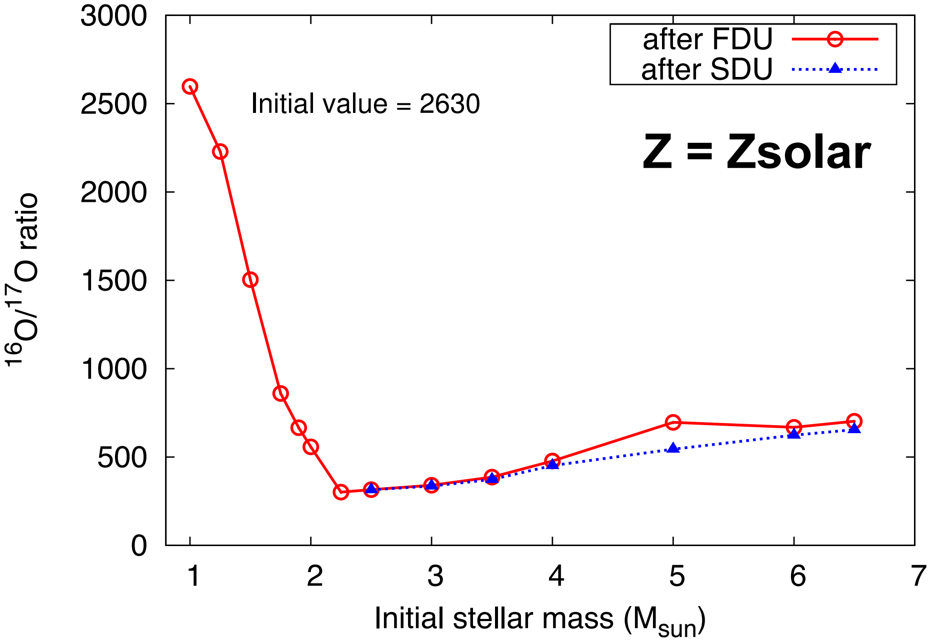
What do we see at the surface?



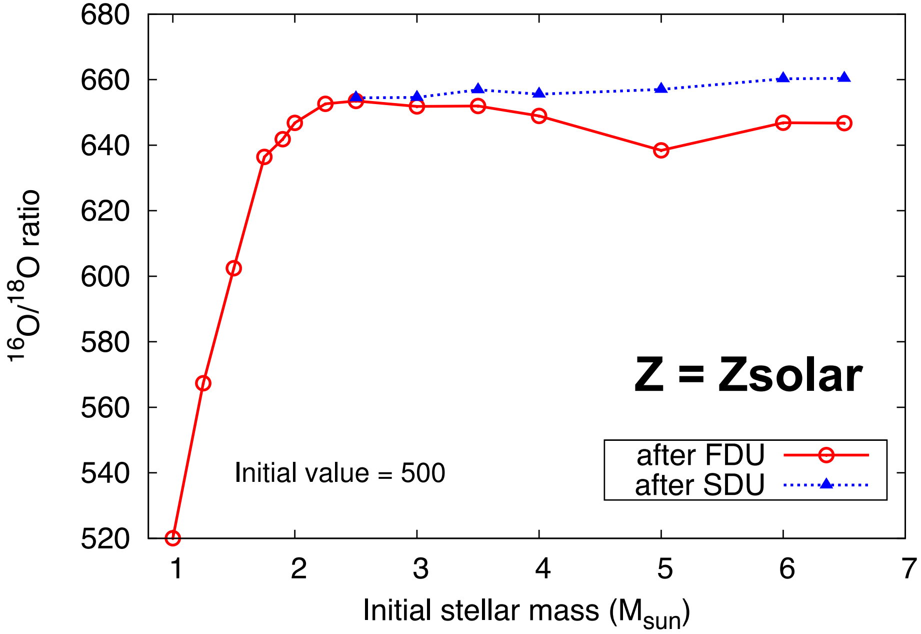
From Karakas & Lattanzio (2014)

Oxygen isotope ratios after FDU

- Mixes up material partially processed during the previous main sequence
- Oxygen isotope ratios: $^{16}O/^{17}O$ can decrease by up to 80% whereas $^{16}O/^{18}O$ increases by ~30% (e.g., Boothroyd & Sackmann 1999)



$^{16}O/^{17}O$ ratio at surface after FDU (red) and SDU (blue)



$^{16}O/^{18}O$ ratio at surface after FDU (red) and SDU (blue)

From Karakas & Lattanzio (2014)

Frist dredge-up and stellar yields

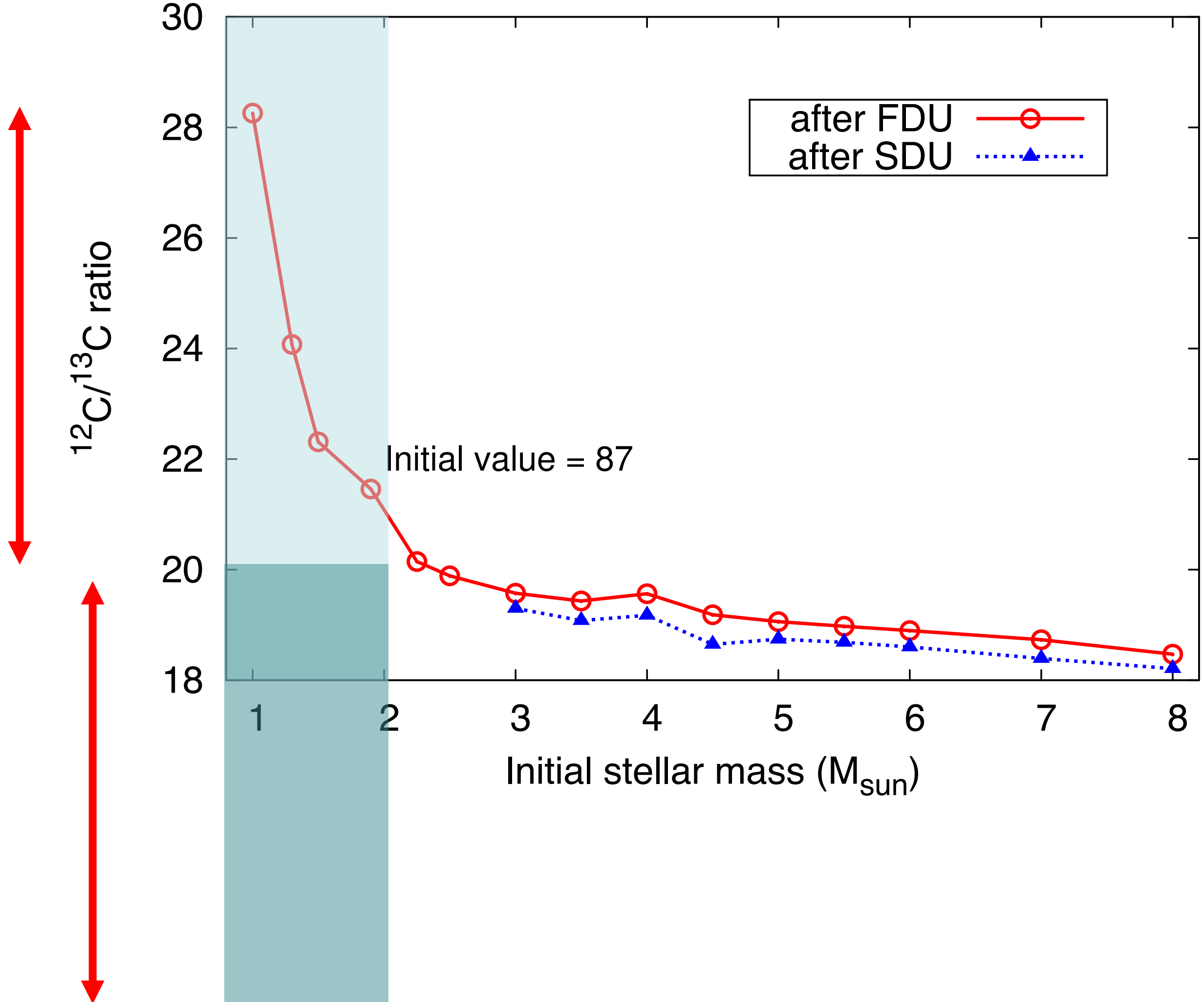
- The first dredge-up changes the surface composition but the effect on the stellar yields of most masses is small compared to the AGB phase
- By stellar yield: mass lost through stellar winds, integrated over the whole stellar lifetime
- So it includes mass lost during the RGB and the AGB (and all phases 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 – 1.5 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

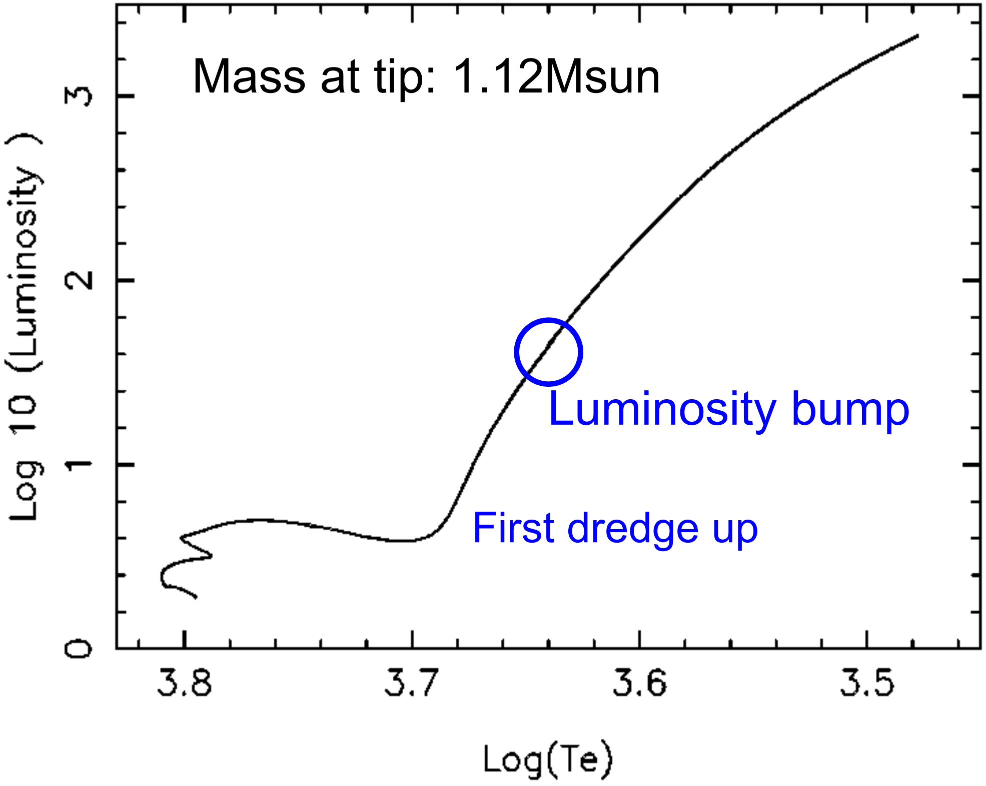
Observational range



Extra mixing in low-mass red giants

- M < 2Msun
- Standard stellar models:
- Only *one* mixing event between the main sequence and tip of the first giant branch
- The first dredge-up:
- ^{12}C/^{13}C ~ 20, C/N ~ 1.5
- Disk FGB stars (e.g., Gilroy 1989 1991) have ^{12}C/^{13}C ~ 10, and C/N ~ 1.0
- Evidence that some form of chemical transport is acting in low-mass giant envelopes
- When?

Example: 1.25Msun, Z = 0.02 model



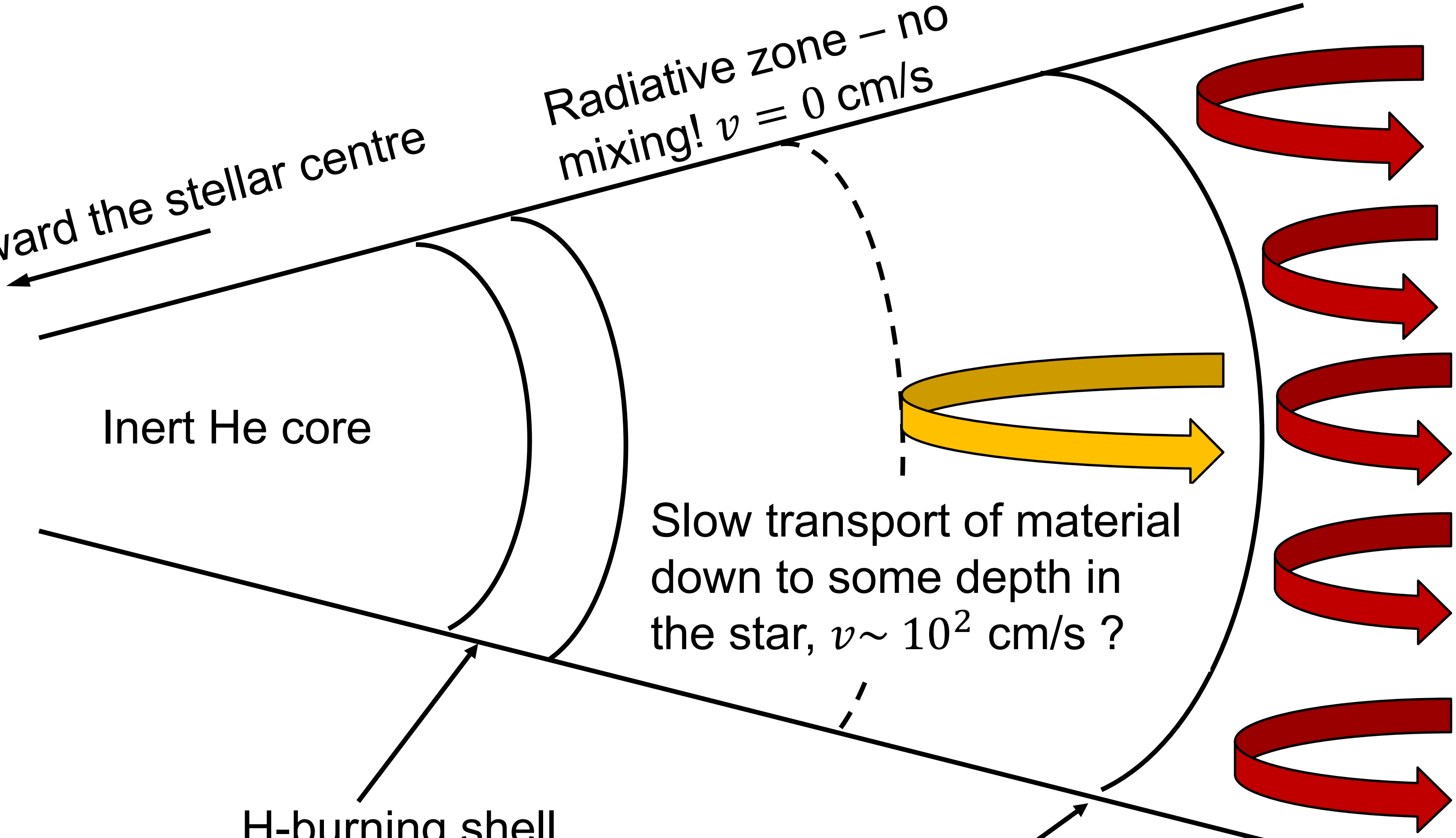
Mass at tip: 1.12Msun

Luminosity bump

First dredge up

How does the extra mixing work?

The RGB stellar structure looks like this:



Convection:
$v = 10^5$cm/s

Toward the stellar centre

Radiative zone – no mixing! $v = 0$ cm/s

Inert He core

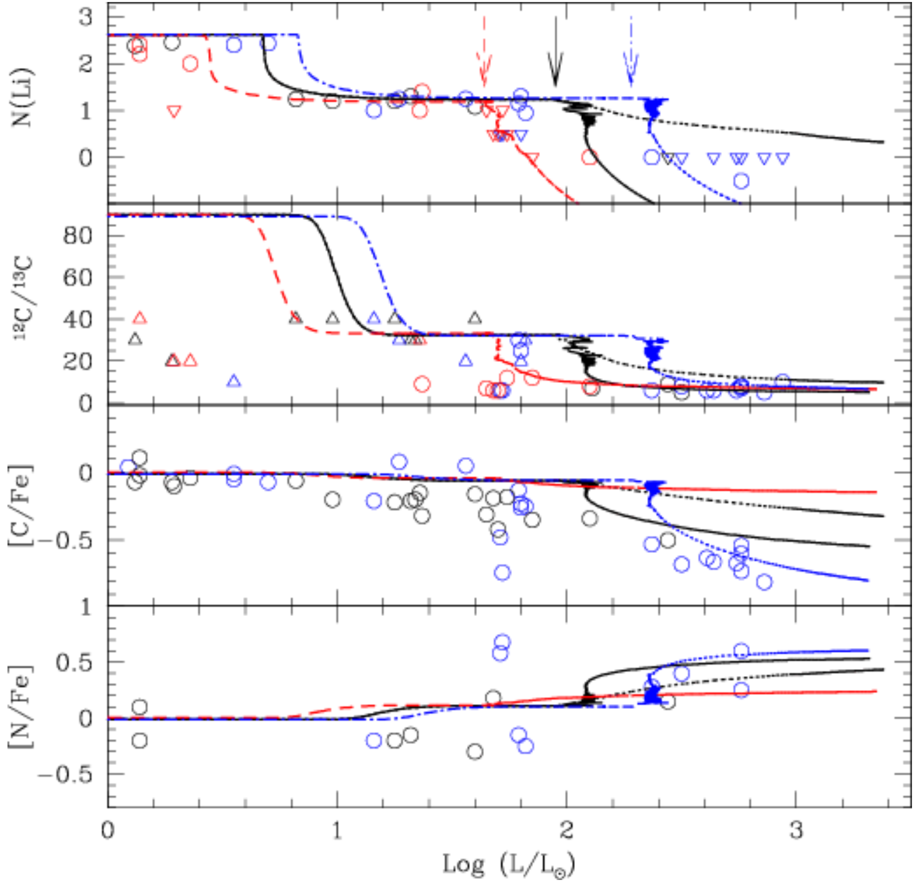
Slow transport of material down to some depth in the star, $v \sim 10^2$ cm/s ?

H-burning shell

Base of convective envelope

Extra mixing in low-mass giant stars

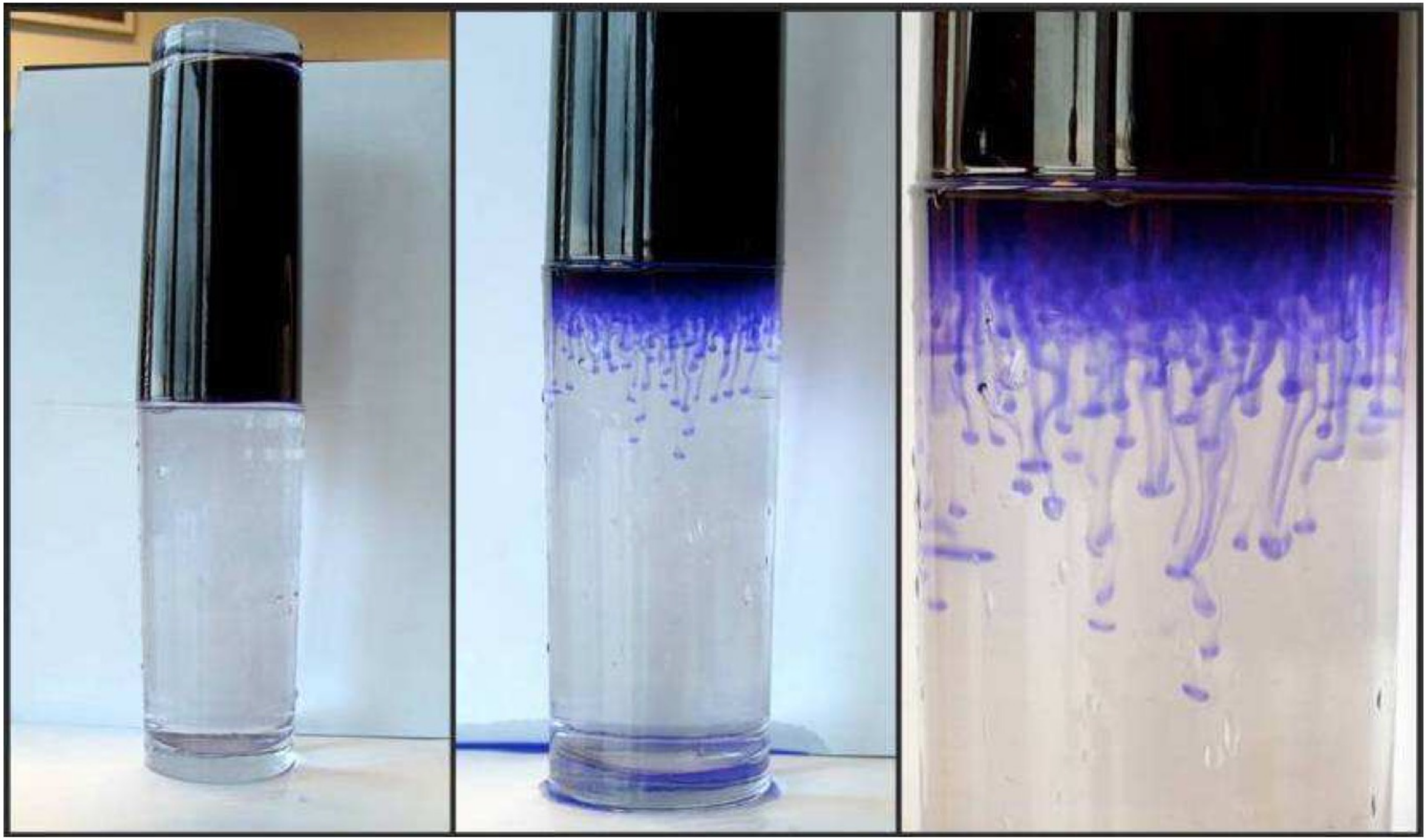
- M < 2Msun
- The result of extra mixing is to mix products of CN cycle to the surface
- This results in a reduction in $^{12}C/^{13}C$ and C/N
- Lithium may also be destroyed
- The mechanism?
- We still don't know
- Rotation? Unlikely to be main driver (Palacios et al. 2006)
- Thermohaline mixing favoured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



From Charbonnel & Zahn (2007)

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

Thermohaline mixing



See Karakas & Lattanzio (2014)

Experiment by R. Izzard and E. Glebbeck

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? No evidence deep 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)

Core helium burning

- Following core He-ignition, there is a stable period of core helium fusion
- The coulomb repulsion is larger for He than for H
- More energy is required for fusion to occur
- This means higher burning temperatures → shorter lifetimes!
- Typical He-burning lifetimes are ~100 million years for low-mass stars (~1Msun), compared to 10^{10} years for H-burning
- Core He-burning lasts about 20 million years for the 5Msun, compared to 80 million years for H-burning

Helium burning

- Simultaneous collision of 3 ^{4}He nuclei too rare to provide the burning rate required
- Fred Hoyle (1954) predicted a resonance in ^{12}C to speed up the collision
- Hoyle's state was experimentally measured shortly after his prediction
- Typical T ~ 1-2 x 10^8 K, density ~ $10^{3\text{-}4}$ g cm^{-3}
- The main reaction takes place in three steps:

$$Step\,1: \quad {}^4He + {}^4He \leftrightarrow {}^8Be$$

$$Step\,2: \quad {}^4He + {}^8Be \leftrightarrow {}^{12}C^*$$

$$Step\,3: \quad {}^{12}C^* \rightarrow {}^{12}C + 2\gamma$$

- The ^{12}C* indicates that the nucleus is in an excited state

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

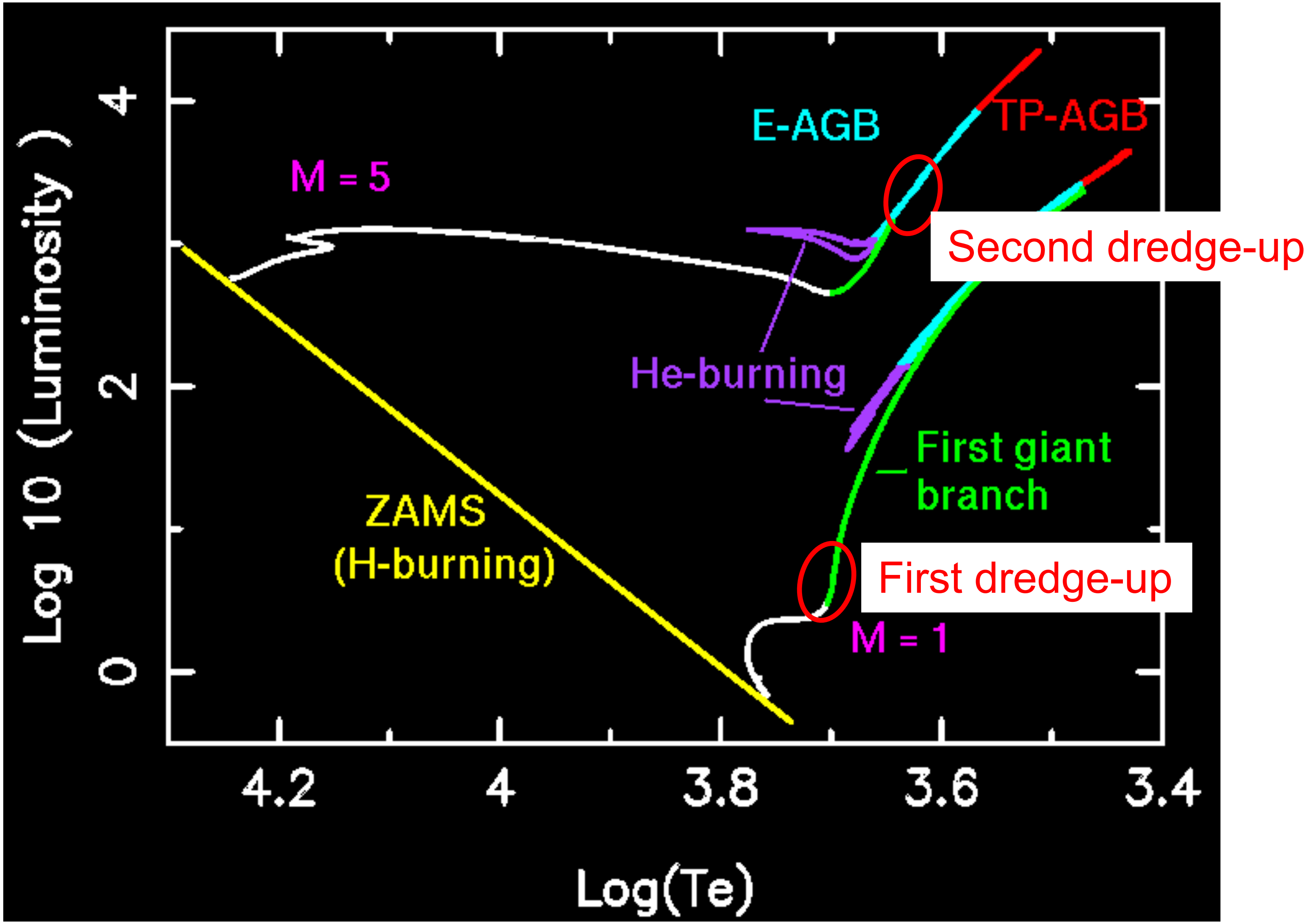
After core helium burning

- Following the exhaustion of helium, the core contracts and heats
- The composition is roughly 50% carbon and 50% oxygen,
- The core composition depends on the rates of the triple-alpha ($3\alpha \rightarrow {}^{12}C$) and ${}^{12}C(\alpha,\gamma){}^{16}O$ reactions
- These reactions are difficult to determine in a laboratory
- The final mass of the C-O core depends on the details of convection, which is a big uncertainty in stellar evolution models

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



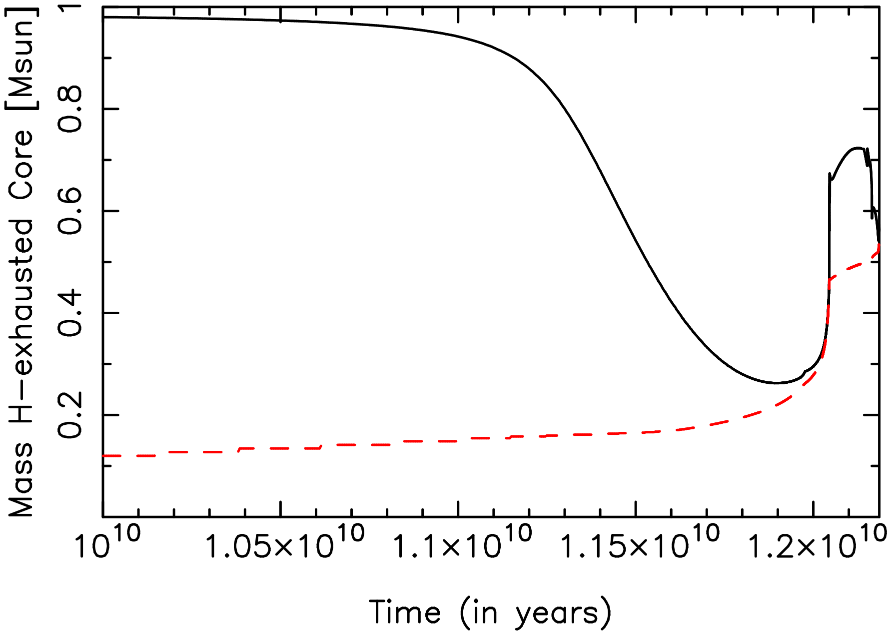
Second dredge-up

First dredge-up

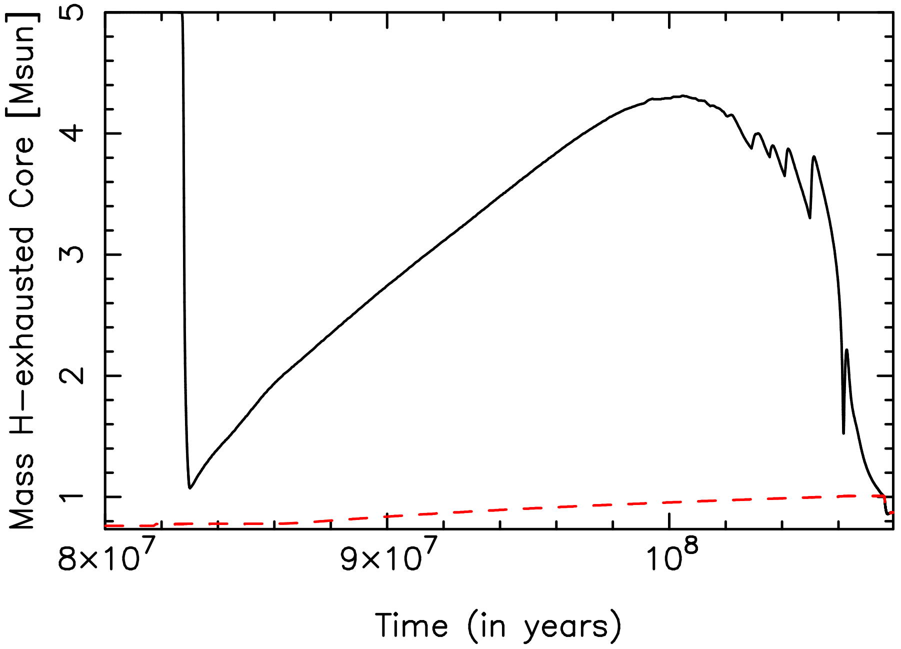
Second dredge up

- 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



Structure during second dredge-up

Results for a 5 Msun, Z = 0.02 model: