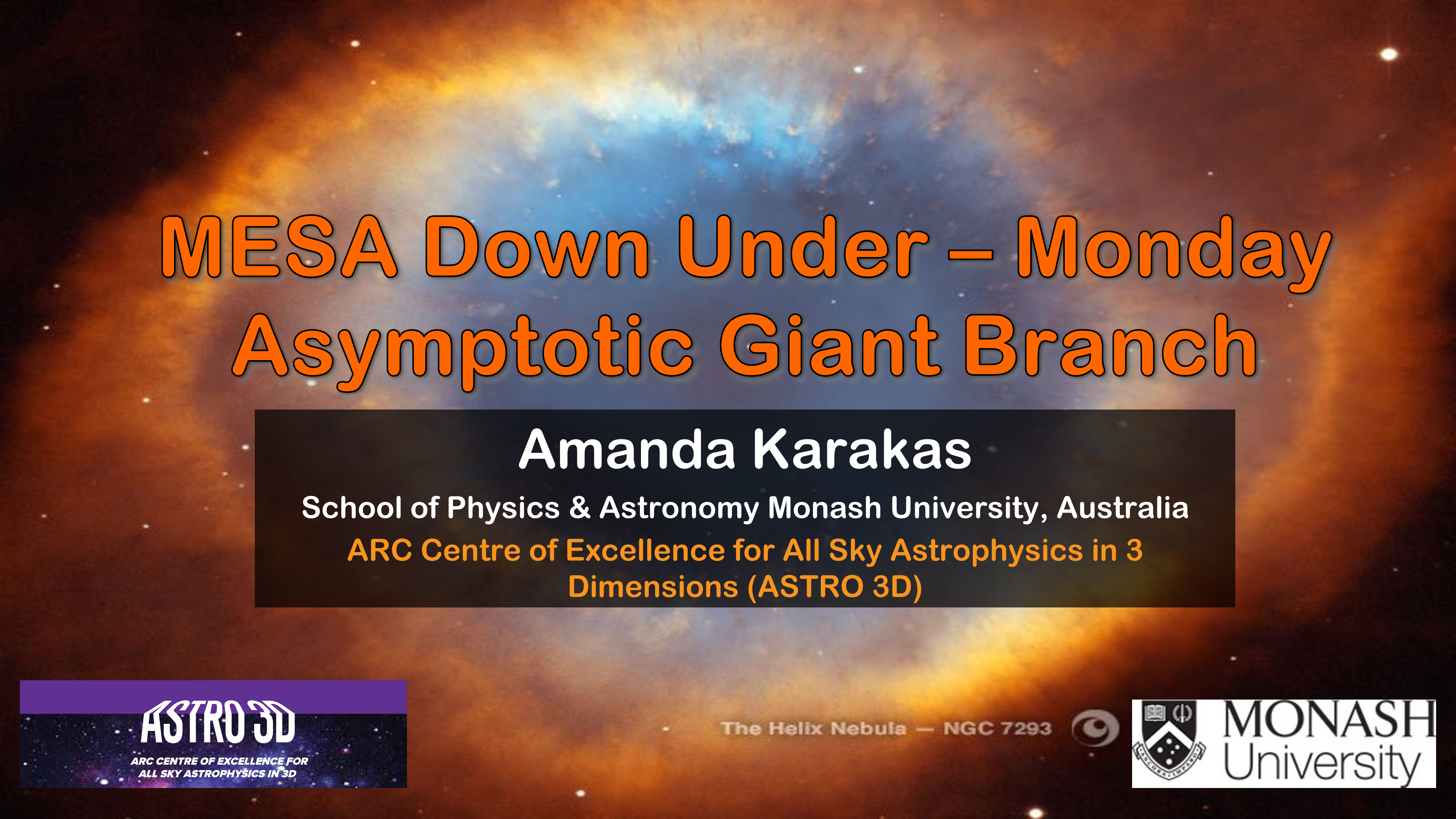

MESA Down Under – Monday Asymptotic Giant Branch

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ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D)

The Helix Nebula — NGC 7293

Outline

We will start with a brief introduction before learning about:

1. Lecture 1 – the pre-asymptotic giant branch phase
2. Lecture 2 – the early AGB phase, second dredge-up and carbon ignition
3. Lecture 3 – the thermally-pulsing AGB phase.

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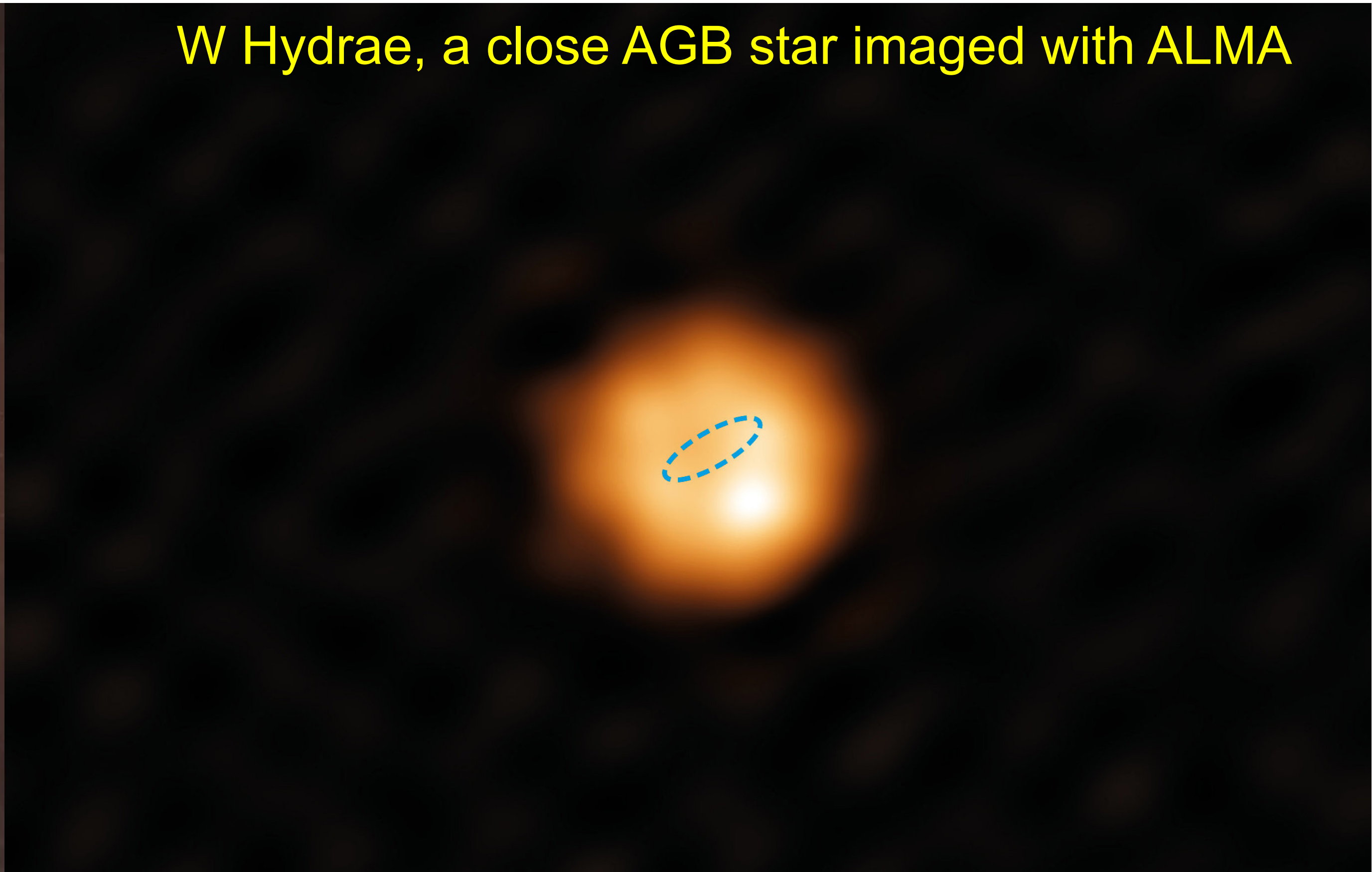
Introduction

- Stars comprise most of the visible universe.
- They produced the chemical elements in the periodic table, much of the dust in galaxies, and the energy from their explosions move the gas around.
- We still mostly use 1D stellar evolution models to predict their behaviour.

Stars are mostly spherical

- This is especially the case for young, unevolved stars such as those on the main sequence (e.g., the Sun), and stars on the sub-giant, and red giant branch.
- This assumption is not so good for for ageing red giants (i.e., AGB stars!

Composite image of the Sun



W Hydrae, a close AGB star imaged with ALMA

Stars made most of the chemical elements?

- The best nuclear furnaces are stars, but which ones?

Stellar sites of element production:

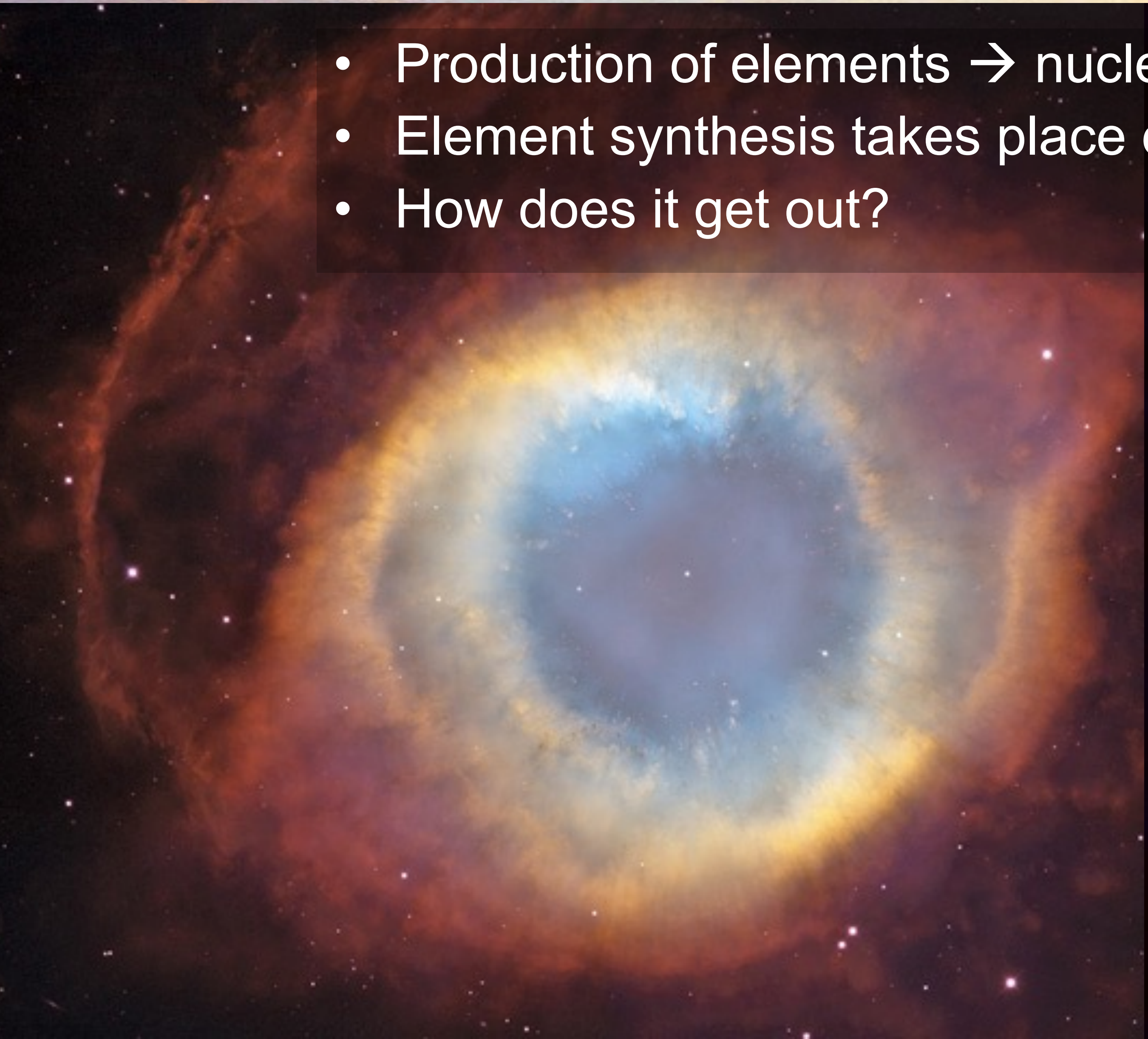
1. Low and intermediate-mass stars ($m \lesssim 8\, M_{\odot}$), because there are many of them, especially at the lower mass end due to the initial mass function.
2. Massive stars ($m \gtrsim 12\, M_{\odot}$) that explode as core-collapse supernovae, because they expel a large amount of mass per explosion.
3. Binary explosions (Type Ia, novae, neutron star mergers).

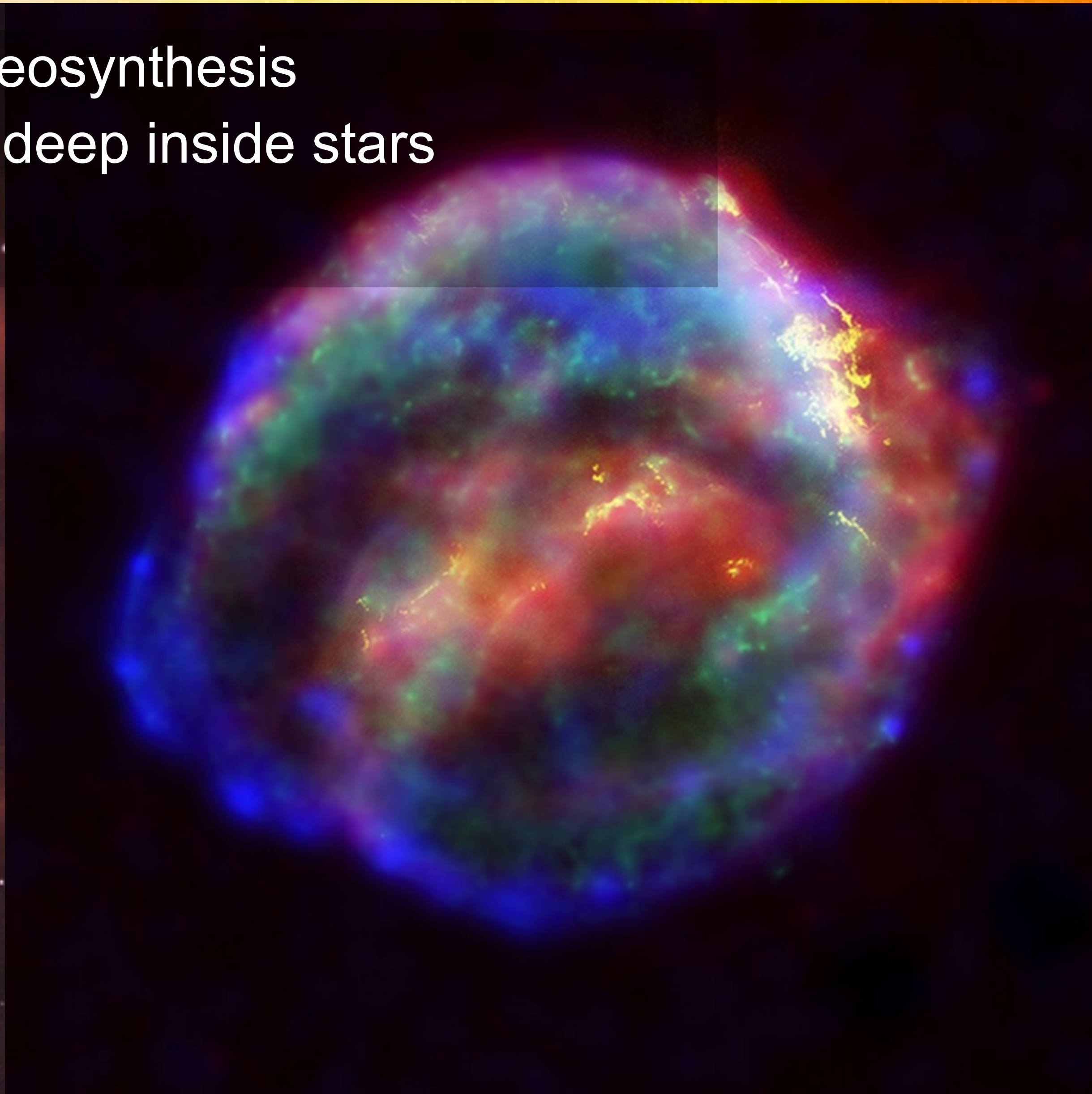
Not all elements were synthesized inside stars:

***Question**: Can you name these elements and the processes that made them?*

The origin of the elements

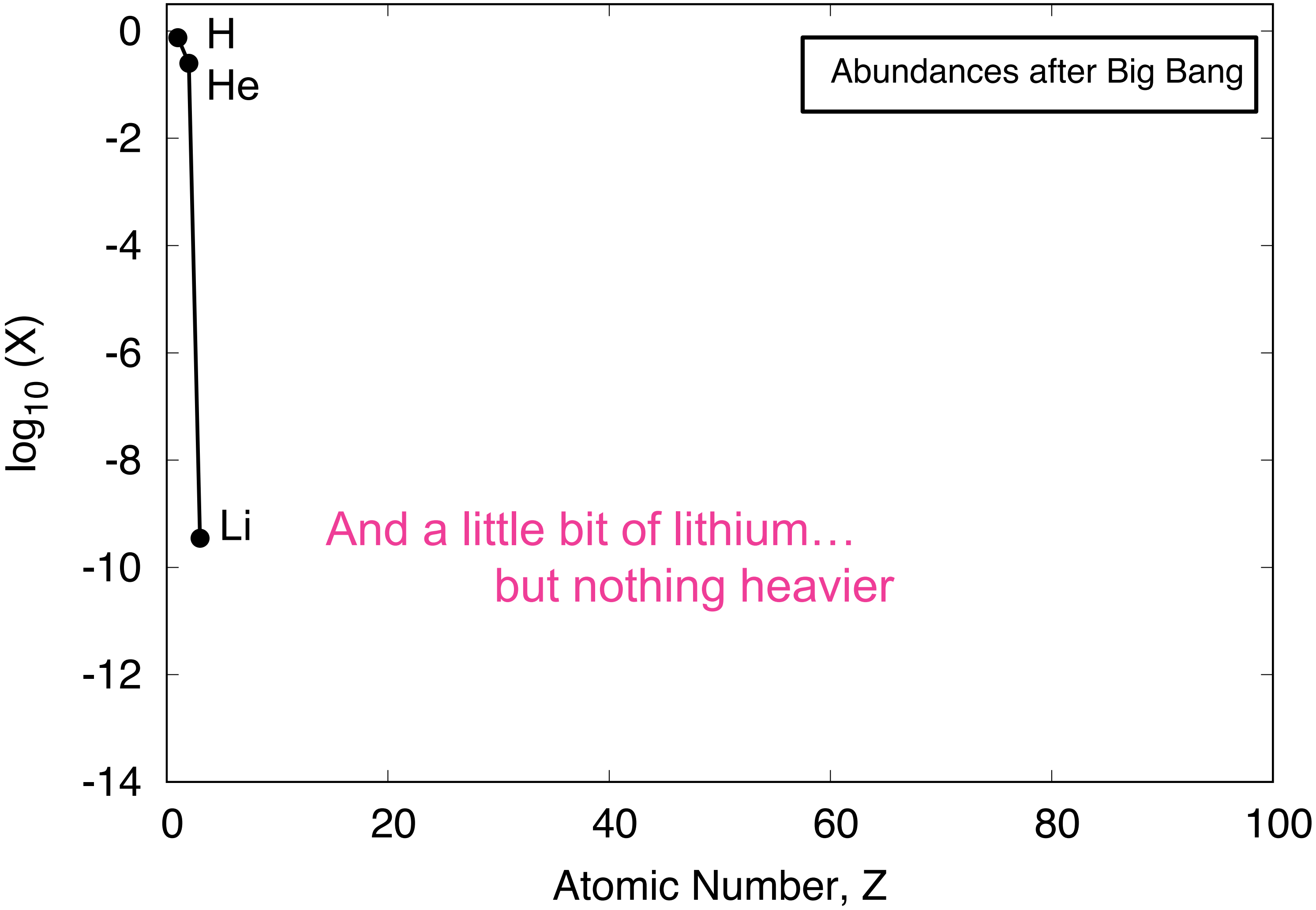
- Production of elements → nucleosynthesis
- Element synthesis takes place deep inside stars
- How does it get out?





The big bang created hydrogen, helium

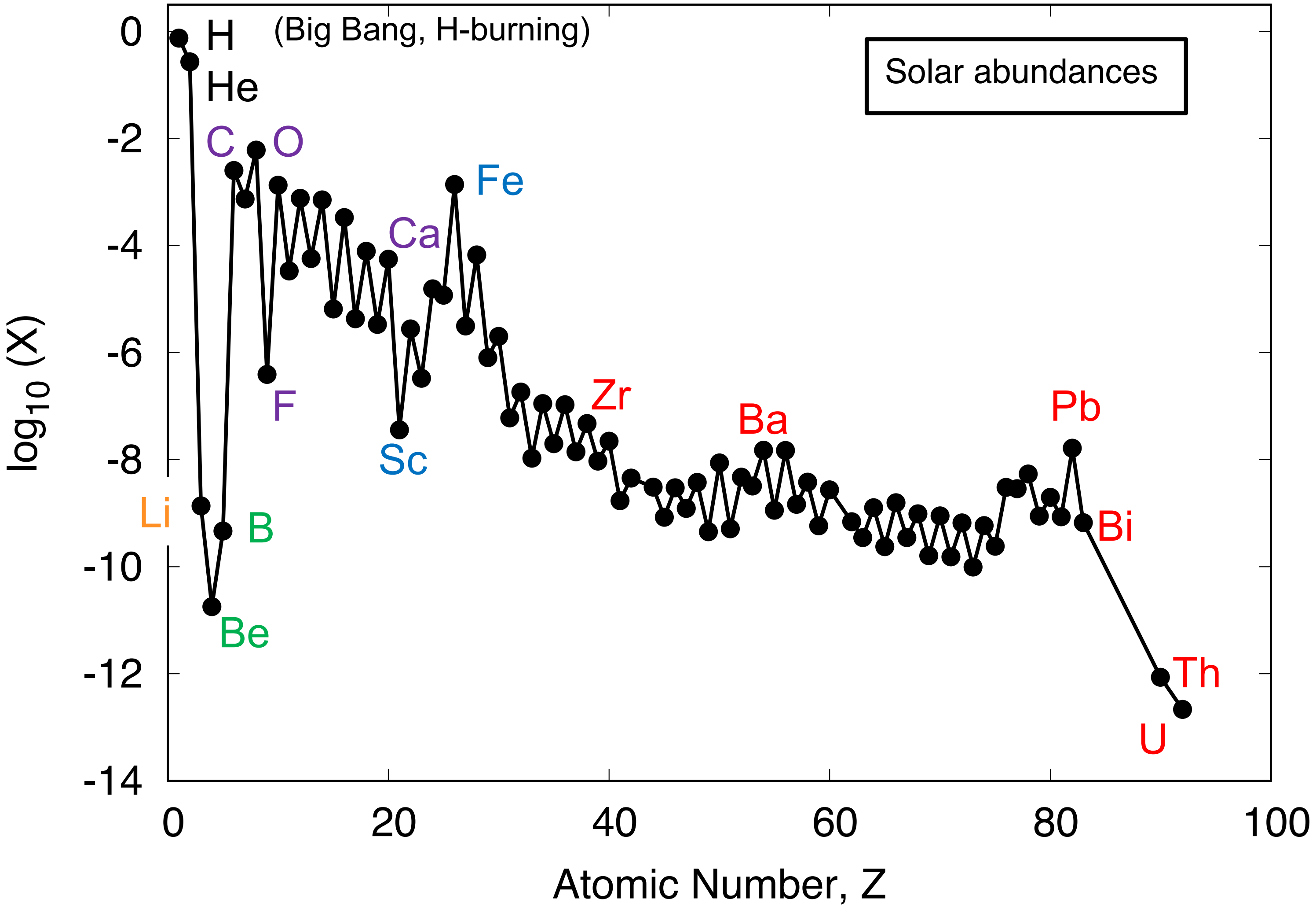
These are abundances just after the big bang.



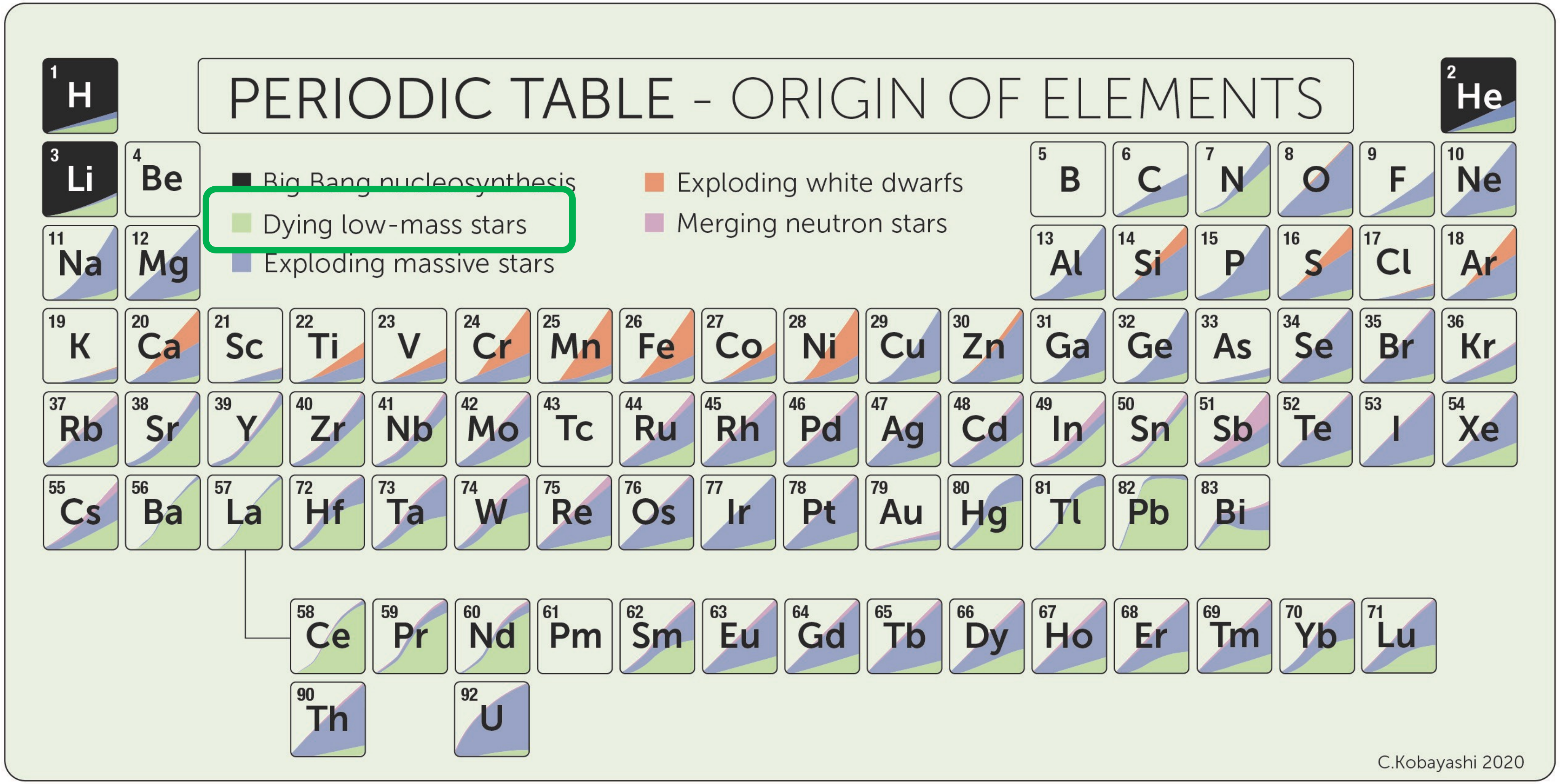
And a little bit of lithium…
but nothing heavier

At the time of the Sun’s birth

The composition of the Sun’s gas cloud, ~9Gyr after big bang.



Origin of the elements



PERIODIC TABLE - ORIGIN OF ELEMENTS

■ Big Bang nucleosynthesis
■ Dying low-mass stars
■ Exploding massive stars
■ Exploding white dwarfs
■ Merging neutron stars

C.Kobayashi 2020

Using data from Kobayashi, Karakas & Lugaro (2020) *Credit: Chiaki Kobayashi/Sahm Keily*

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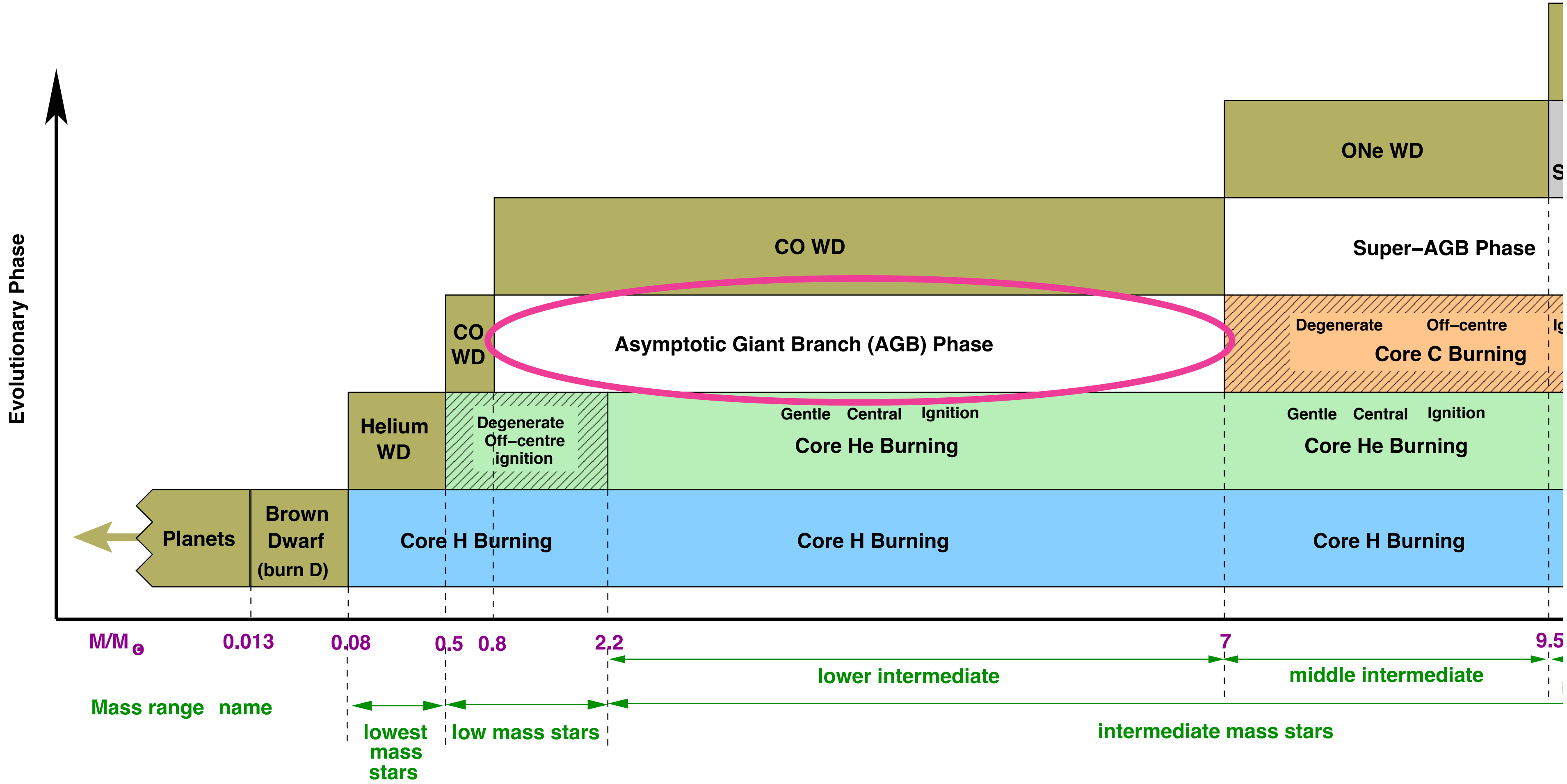
Low and intermediate-mass stars

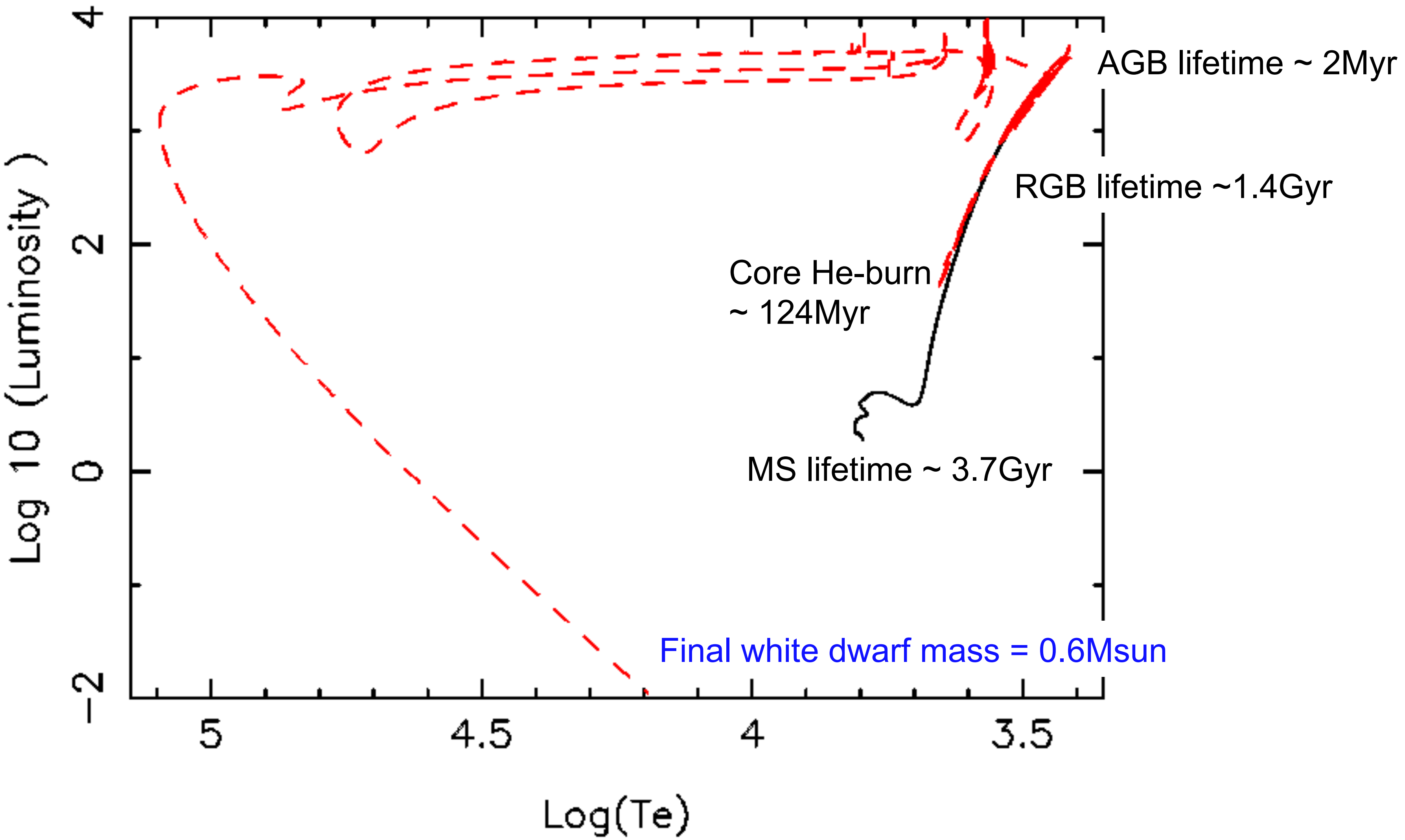
Stars between about 0.8 to 8Msun, depending on metallicity



From review paper by Karakas & Lattanzio (2014)

Evolution on the Hertzsprung-Russell diagram

Evolutionary track for a 1.25Msun, Z = Z_{solar} model



AGB lifetime ~ 2Myr

RGB lifetime ~1.4Gyr

Core He-burn
~ 124Myr

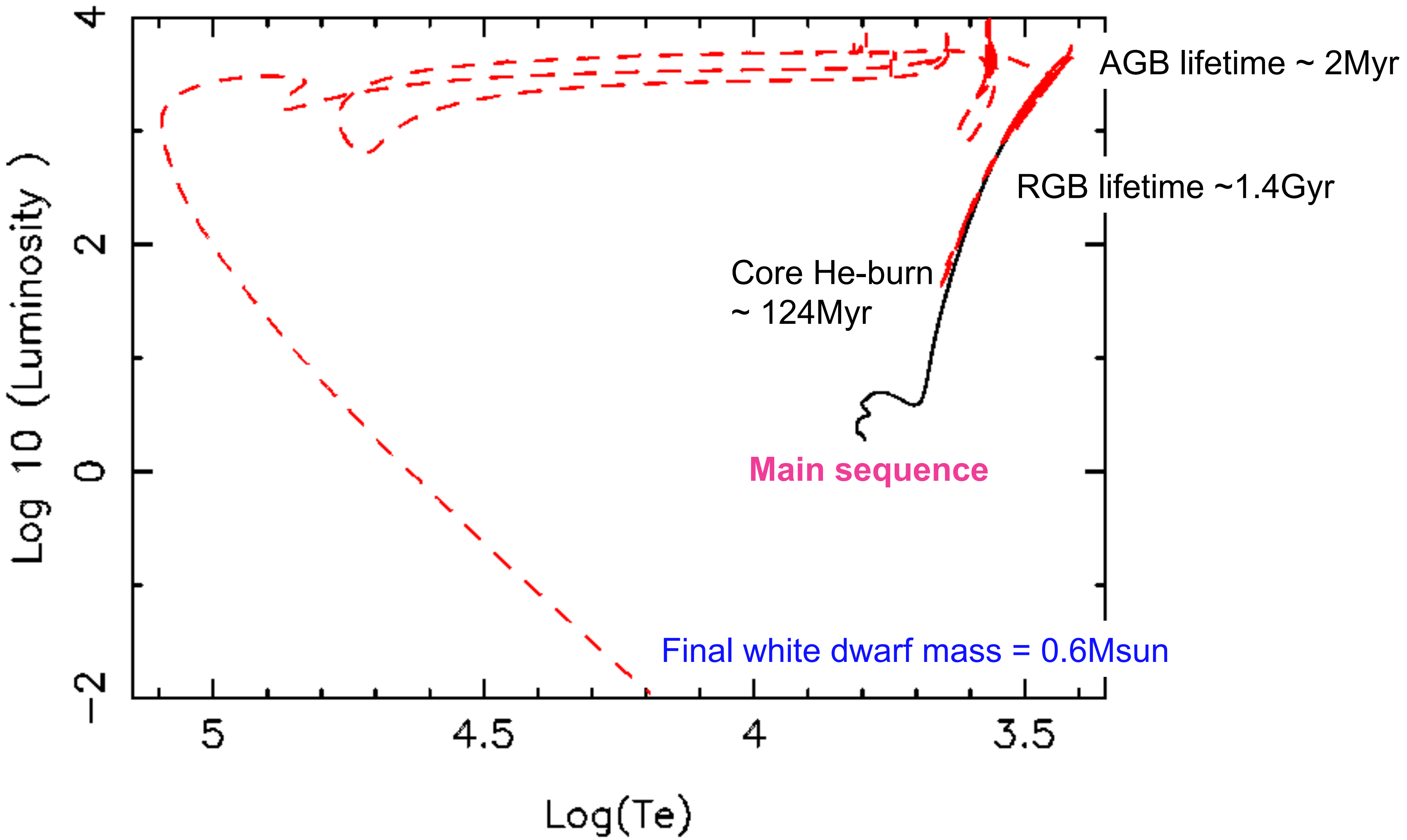
MS lifetime ~ 3.7Gyr

Final white dwarf mass = 0.6Msun

Pre-AGB evolution

- Why are we spending a whole lab worrying about what happens to stars before they even get to the AGB?
- Because the evolution of low- and intermediate-mass stars post-main sequence is determined by the mass of the H-exhausted core.
- That means that the luminosity of an AGB star is not dependent on the initial mass but on its current core mass.
- Similarly, whether a star experiences the core He-flash, or second dredge-up is also determined by the mass of the core.
- So, we need to spend a bit of time thinking about what determines the size of a star’s H-exhausted core.
- And obviously, that is going to be the main sequence.
- And if a star has a convective core or not.

Let's start with the main sequence



AGB lifetime ~ 2Myr

RGB lifetime ~1.4Gyr

Core He-burn
~ 124Myr

Main sequence

Final white dwarf mass = 0.6Msun

The structure of main sequence stars

From Onno Pols lecture notes

For solar metallicity

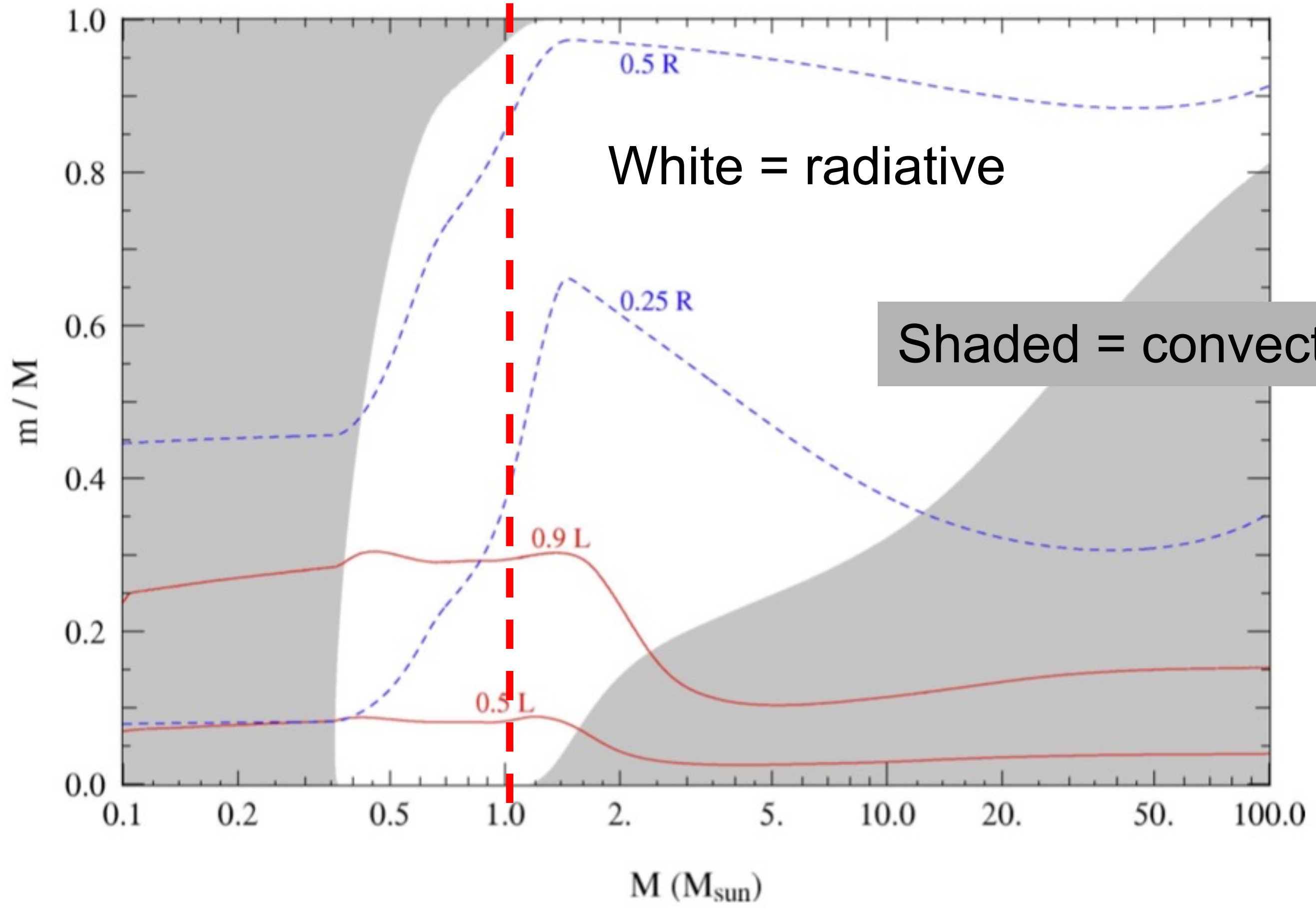
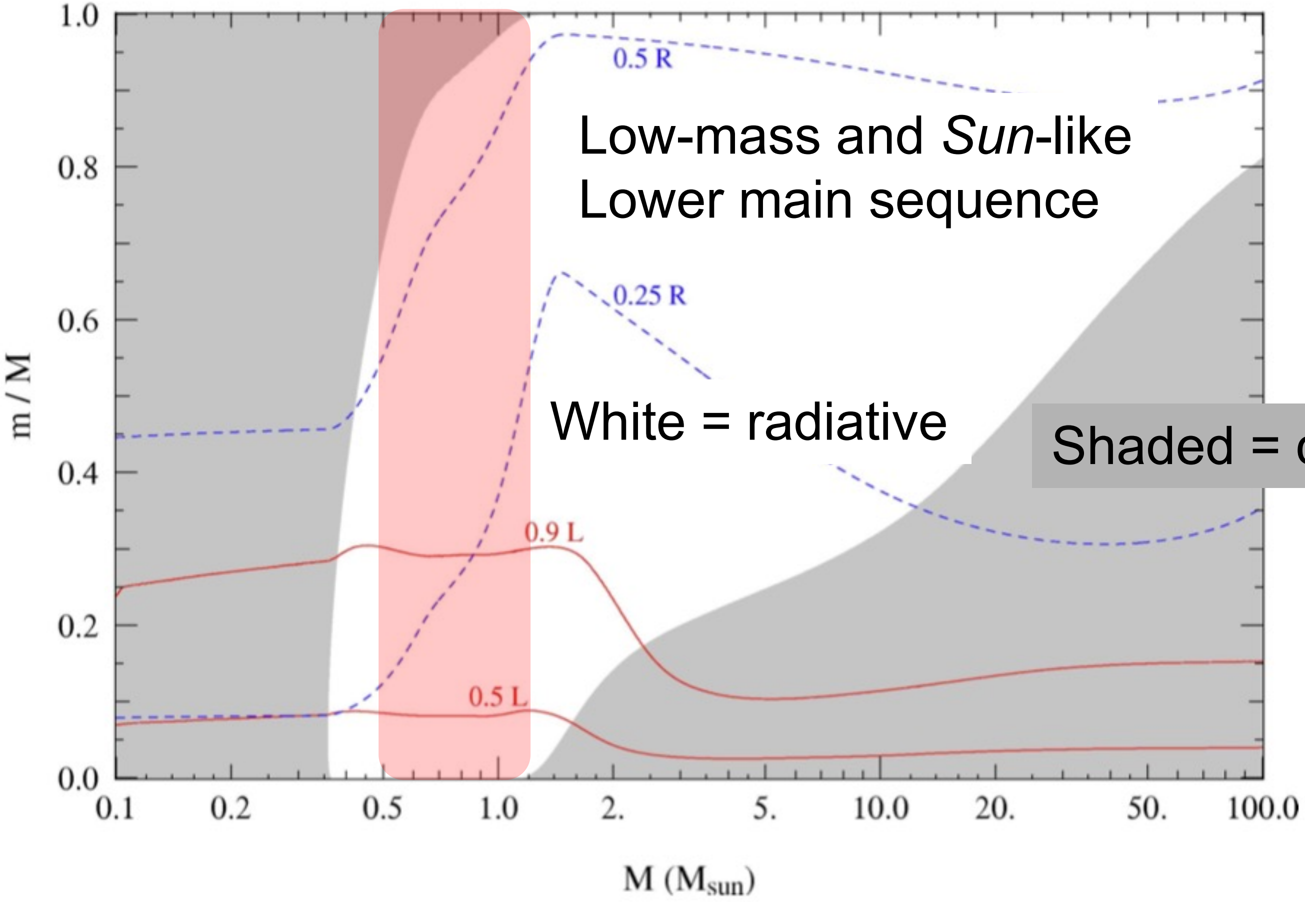


Figure 9.8. Occurrence of convective regions (gray shading) on the ZAMS in terms of fractional mass coordinate m/M as a function of stellar mass, for detailed stellar models with a composition $X = 0.70$, $Z = 0.02$. The solid (red) lines show the mass shells inside which 50% and 90% of the total luminosity are produced. The dashed (blue) lines show the mass coordinate where the radius r is 25% and 50% of the stellar radius R. (After KIPPENHAHN & WEIGERT.)

Stars with radiative cores

Stars with masses between ~0.6 to 1.2Msun :

- Observed as G, K dwarfs
- They have long-lifetimes, where the upper mass limit has a MS lifetime of ~4 Gyr
- These stars have thin (in mass) convective outer layers.
- Convective boundary mixing issues don’t play a strong role in the structural evolution on the main sequence, or beyond.



Low-mass and *Sun*-like
Lower main sequence

White = radiative

Shaded = convective

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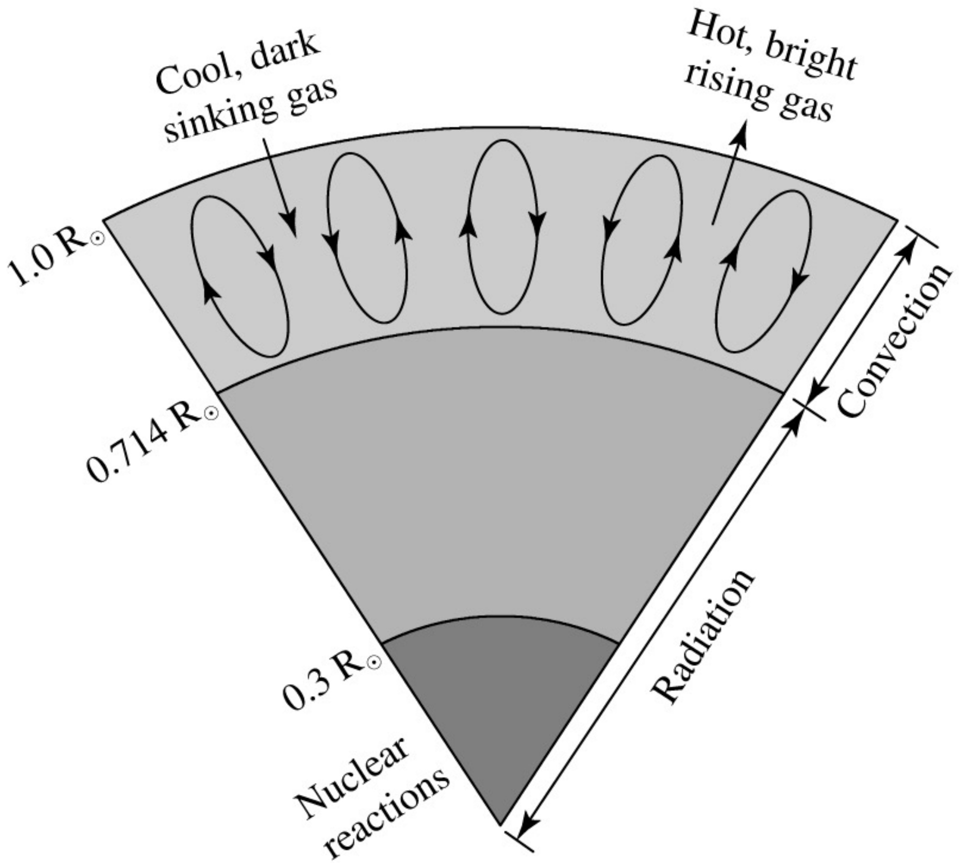
What causes the change in structure at around 1Msun?

- Stars more massive than ~1Msun develop a convective *core.*
- Higher central T leads to hydrogen burning via CNO cycles, not pp-chains.
- Energy dependence $\propto T^{20}$ for CNO compared to $\propto T^4$ for pp-chains.

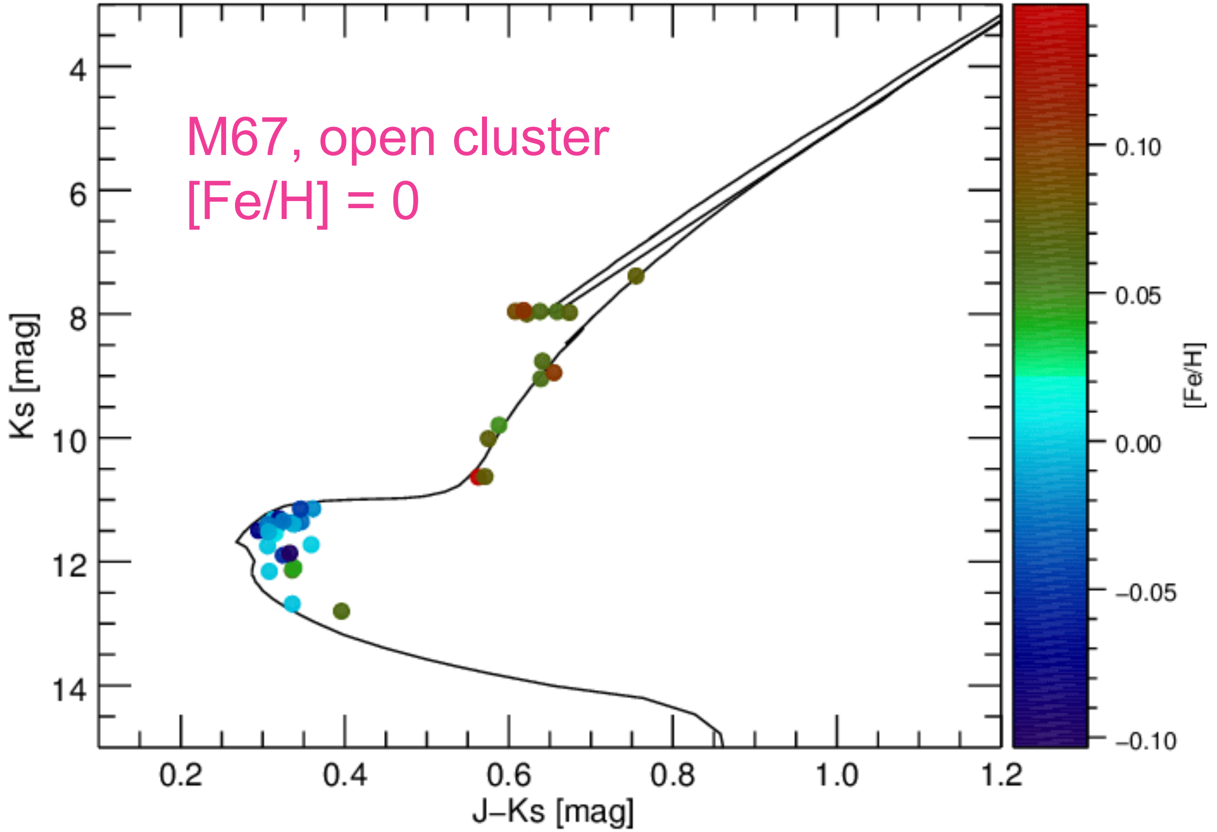


The higher energy dependence of the CNO cycles leads to a higher dT/dr → convection.

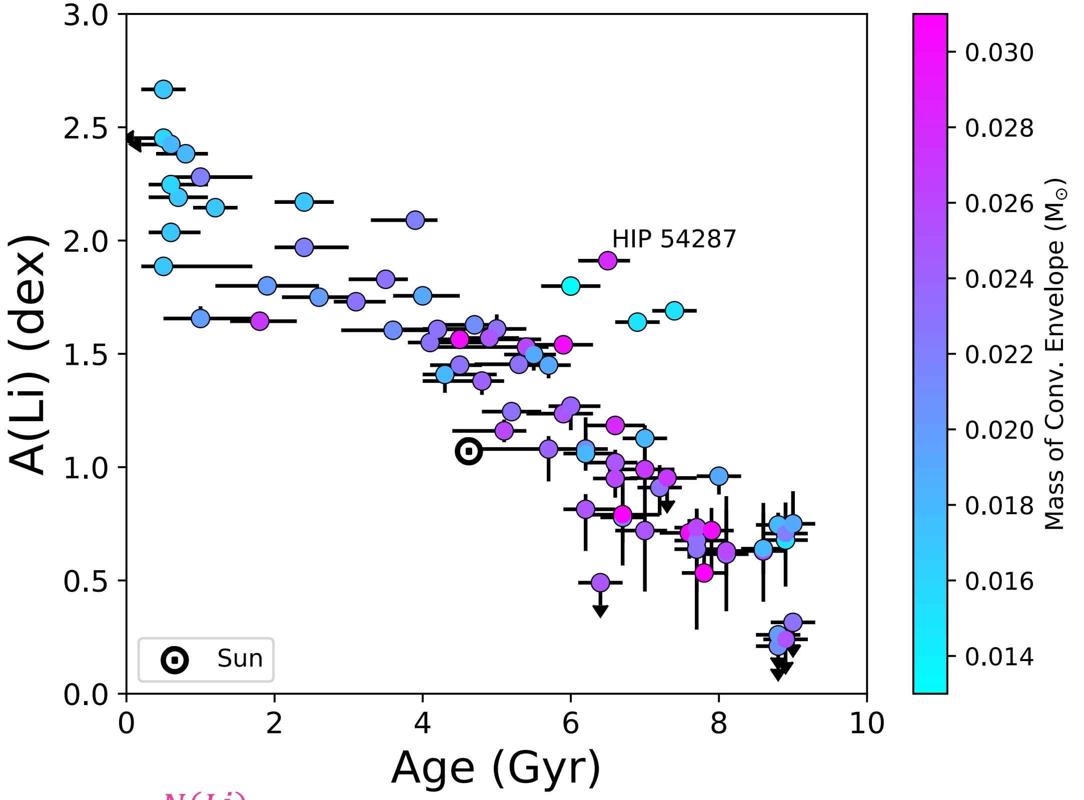
Abundances of Sun-like stars with convective envelopes

Evidence for slow non-canonical mixing processes: Atomic diffusion…

Motta et al. (2018), showing CMD of M67 using Apogee DR14 data:



Carlos et al. (2018) showing Li abundances for 77 solar twins



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

Note on convective boundaries

- In 1D stellar evolution codes, we define the border between the radiative and convective zone based on the ratio of the radiative to adiabatic gradients.
- We can obtain an expression for the radiative gradient, ∇_{rad}, by using the temperature gradient from the diffusion approximation

$$\frac{dT}{dr} = -\frac{3}{16\pi ac}\frac{\kappa}{r^2}\frac{\rho L}{T^3}$$

- Multiply by dr/dP - the equation for hydrostatic equilibrium - to get dT/dP

$$\frac{dP}{dr} = \rho\frac{GM}{r^2}$$

$$\frac{dT}{dP} = \frac{dT}{dr}\frac{dr}{dP} = \frac{3}{16\pi ac}\frac{\kappa L}{GmT^3}$$

$$\nabla_{\text{rad}} = \left(\frac{\text{dln}T}{\text{dln}P}\right)_s = \frac{P}{T}\frac{dT}{dP} = \frac{3}{16\pi ac}\frac{\kappa LP}{GmT^4}$$

Here $d\ln P$ is taken as a measure of depth in the star

What about the adiabatic gradient?

This is $\nabla_{\mathrm{ad}} = \frac{d\ln T}{d\ln P}$

It comes from relationships for adiabatic change for a perfect gas:

$$\frac{dP}{P} - \frac{\gamma}{\gamma - 1}\frac{\mathrm{d}T}{T} = 0$$

…and…

$$\boxed{PT^{(\gamma-1)/\gamma} = K_2}$$

$$d\ln P + \frac{\gamma}{1-\gamma} d\ln T = 0$$

$$1 + \frac{\gamma}{1-\gamma}\frac{d\ln T}{d\ln P} = 0$$

$$\nabla_{\mathrm{ad}} = \frac{d\ln T}{d\ln P} = \frac{\gamma - 1}{\gamma}$$

$$= \frac{5/3 - 1}{5/3} = \bigcirc\!\!\!\!\!\!\!\; 2/5$$

for perfect gas

Schwarzschild Criterion

$$\boxed{\nabla_{rad} > \nabla_{ad}}$$

- If $\nabla_{rad} > \nabla_{ad}$ then convection carries energy.
- If $\nabla_{rad} < \nabla_{ad}$ then radiation carries energy.

What happens where $\nabla_{rad} = \nabla_{ad}$?

The acceleration of a blob of gas is zero (gradients are equal) but that doesn’t mean that the blob has zero velocity.

Ledoux Criterion

We can also define a composition gradient defined on changes made to the mean molecular weight, μ. We can define

$$\nabla_\mu = \left(\frac{d\ln\mu}{d\ln P}\right)_s$$

The radiative layer is stable,

$$\boxed{\nabla_{rad} < \nabla_{ad} + \frac{\varphi}{\delta}\nabla_\mu}$$

If there are no composition gradients, then $\nabla_{rad} < \nabla_{ad}$

Where φ and δ come from writing the equation of state in differential form, i.e.,

$$\frac{d\rho}{\rho} = \alpha\frac{dP}{P} - \delta\frac{dT}{T} + \varphi\frac{d\mu}{\mu}$$

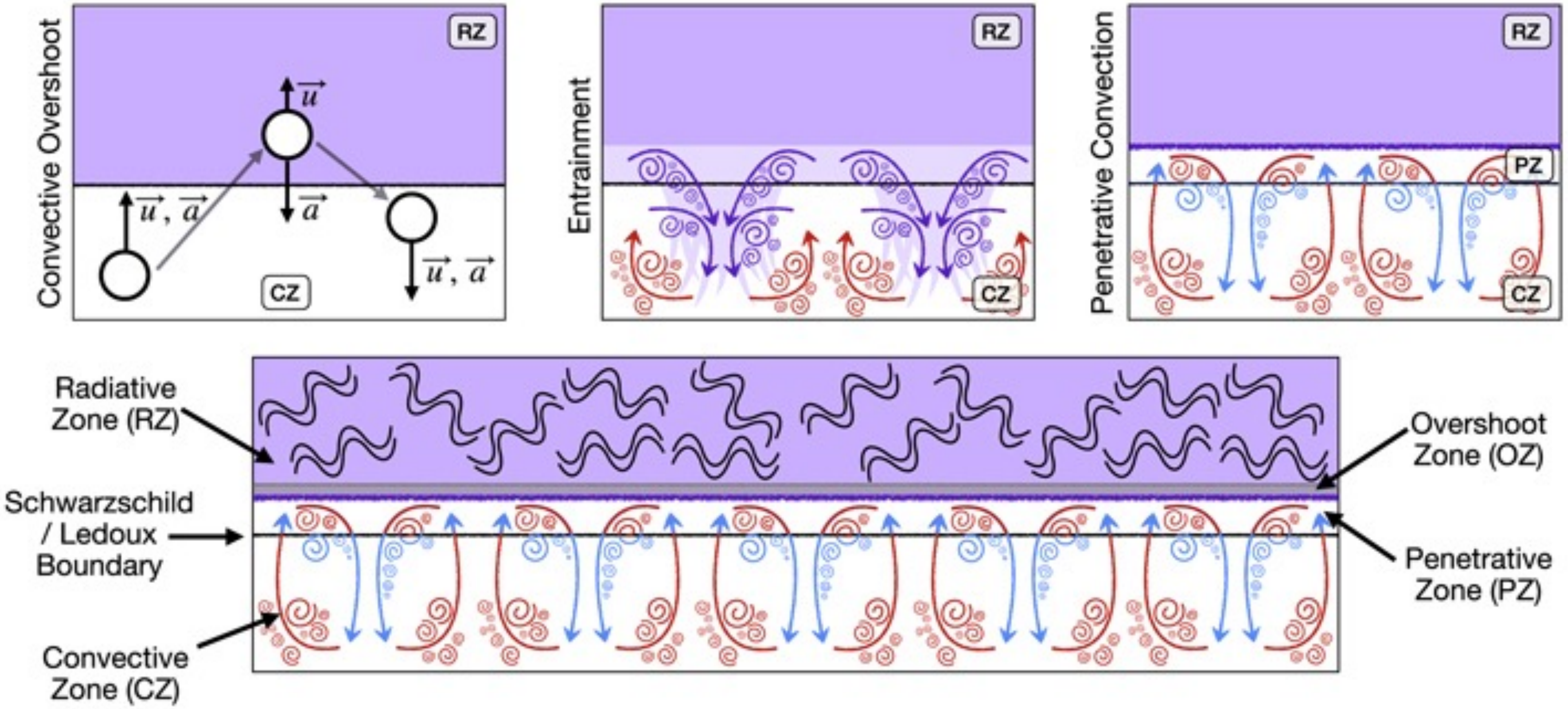
Convective overshoot

- Because blobs of gas may have non-zero velocity where the gradients are equal, there may be some mixing beyond the formal border.
- This is convective overshoot.
- Convective core overshooting refers to an extension of the stellar core beyond the boundaries defined by the classical Schwarzschild criterion.
- It is common to characterize the distance, d_{ov}, to which convective elements penetrate beyond the classical Schwarzschild core by defining an overshooting parameter $\alpha_{\rm ov}$ such that $d_{\rm ov} = \alpha_{\rm ov} H_{\rm p}$, in which $H_{\rm p}$ is the pressure scale height (e.g., Claret & Torres 2016)

Convective boundary mixing

Convective boundary mixing refers to mixing of fluid beyond the formal boundary by 3 different mechanisms:

1. Core overshooting.
2. Entrainment;
3. Penetrative convection

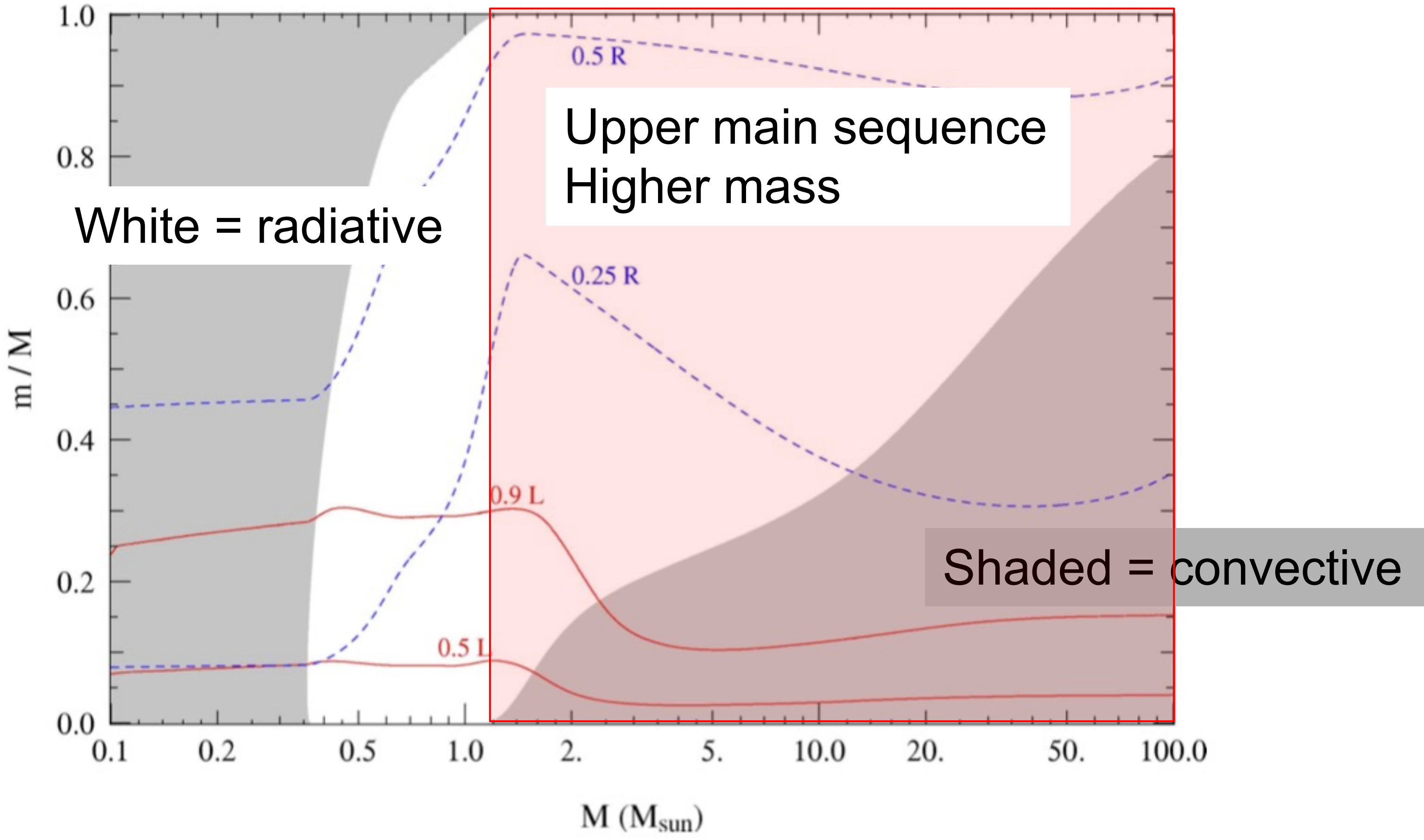


From E. Anders et al. (2022) – *“Convective boundary mixing processes”*

Stars with convective cores

Stars with masses $\gtrsim 1.2M_{\odot}$

- Observed as F, A, B type main sequence stars.
- These stars have a range of MS lifetimes, from a few Gyr to as short as ~30 Myr for 8Msun.
- Here the structure of the convective core determines their post-main sequence evolution.



White = radiative

Upper main sequence
Higher mass

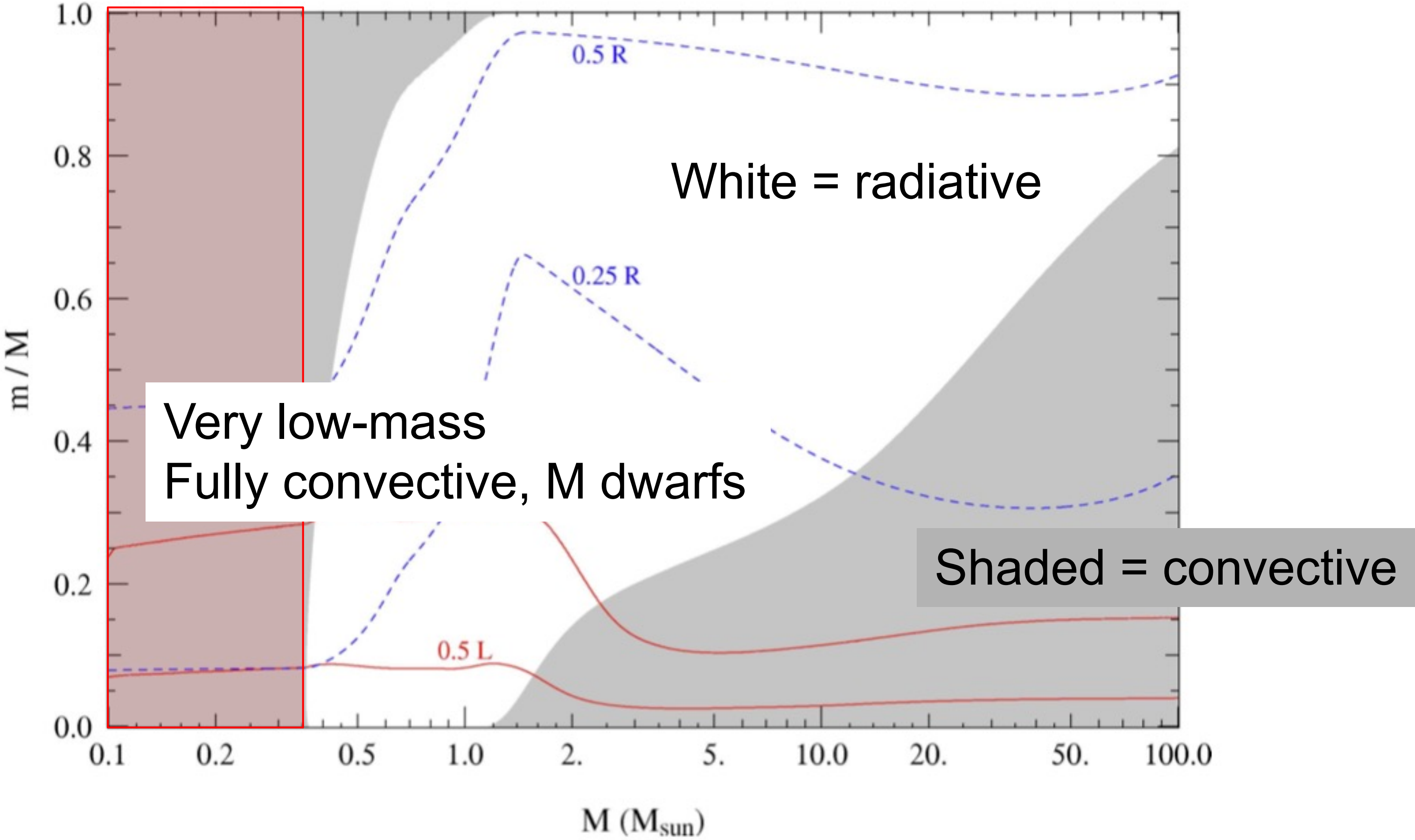
Shaded = convective

Figure 9.8. Occurrence of convective regions (gray shading) on the ZAMS in terms of fractional mass coordinate m/M as a function of stellar mass, for detailed stellar models with a composition $X = 0.70$, $Z = 0.02$. The solid (red) lines show the mass shells inside which 50% and 90% of the total luminosity are produced. The dashed (blue) lines show the mass coordinate where the radius r is 25% and 50% of the stellar radius R. (After Kippenhahn & Weigert.)

Fully convective stars

Stars with M $\lesssim 0.5\ M_\odot$:

- Very long lifetimes (M dwarfs)
- Low luminosities, so dim and mostly visible in the IR.
- Fully convective, with molecular bands dominating the spectra.
- Active atmospheres.
- Common planet hosts?



White = radiative

Very low-mass
Fully convective, M dwarfs

Shaded = convective

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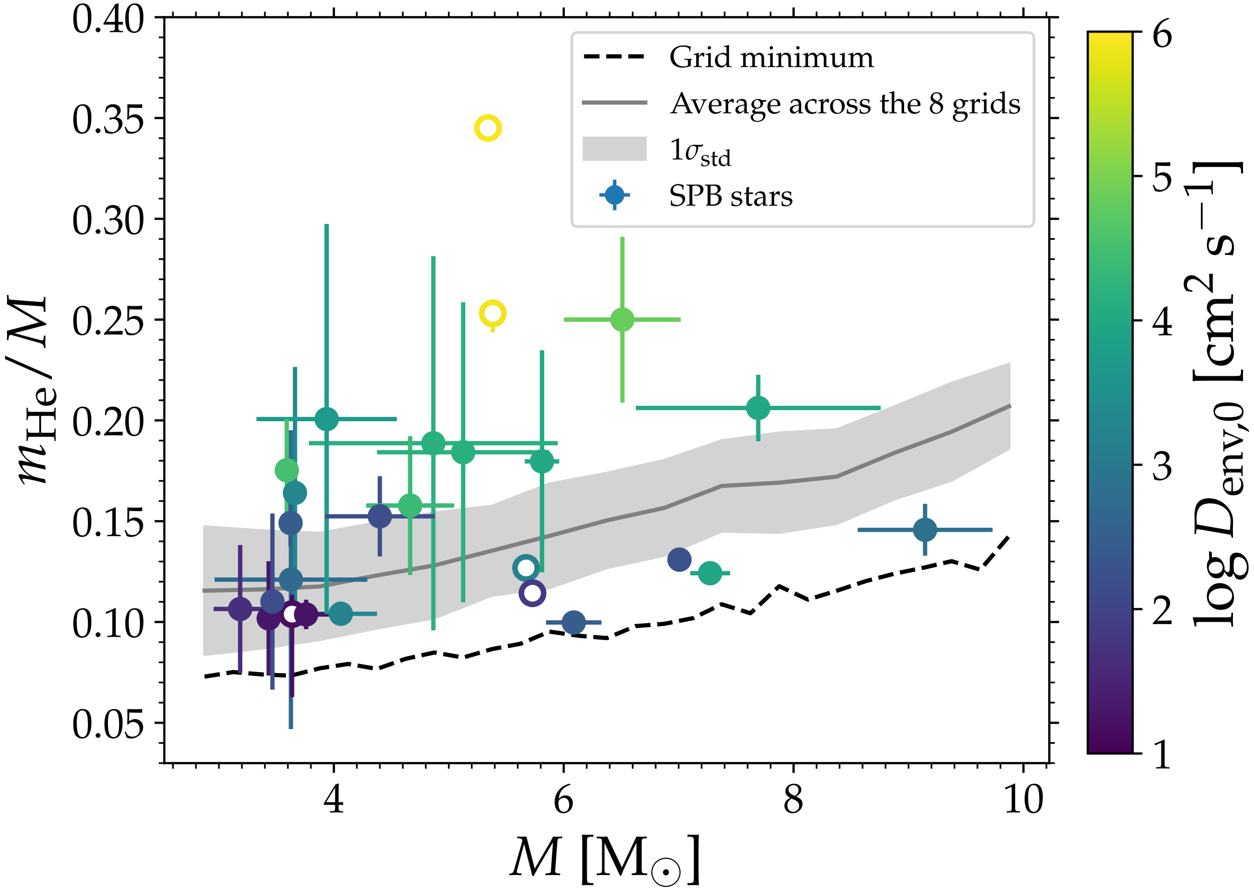
Consequence of convective boundary mixing

- If we can mix fresh hydrogen into the convective core, the main-sequence lifetime will be extended.
- Second, the mass of the H-exhausted core will be larger, post main sequence.
- Clearly, how large the core will grow, and also the extended duration of the main sequence, will depend on how the mixing is implemented numerically.
- Larger amounts of mixing will result in larger cores and longer lifetimes.

How much mixing is needed?

- Can use gravity modes to probe the structure of intermediate-mass stars with convective cores (Pedersen et al. 2021, Nature Astronomy). This is difficult work owing to rotation coupling with pulsations.
- From Pedersen(2022):



See also

Shroeder, Pols & Eggleton (1997),

Claret & Torres (2018) etc.

Mini-lab 1 wrap up

- You saw that the amount of convective boundary mixing on the main sequence can have a dramatic effect on the mass of the H-exhausted core at the end of the main sequence.
- The amount of mixing also effects the observable properties, as you saw by plotting the HR diagram.
- Questions to consider:
  - What is a reasonable amount of convective boundary mixing? Clearly one case you explored was unphysical. What about the others?
  - What are the other consequences of mixing? Extended main-sequence lifetimes, increased turn-off luminosities.
  - What about consequences beyond the main-sequence? We explore this in mini-lab 2.

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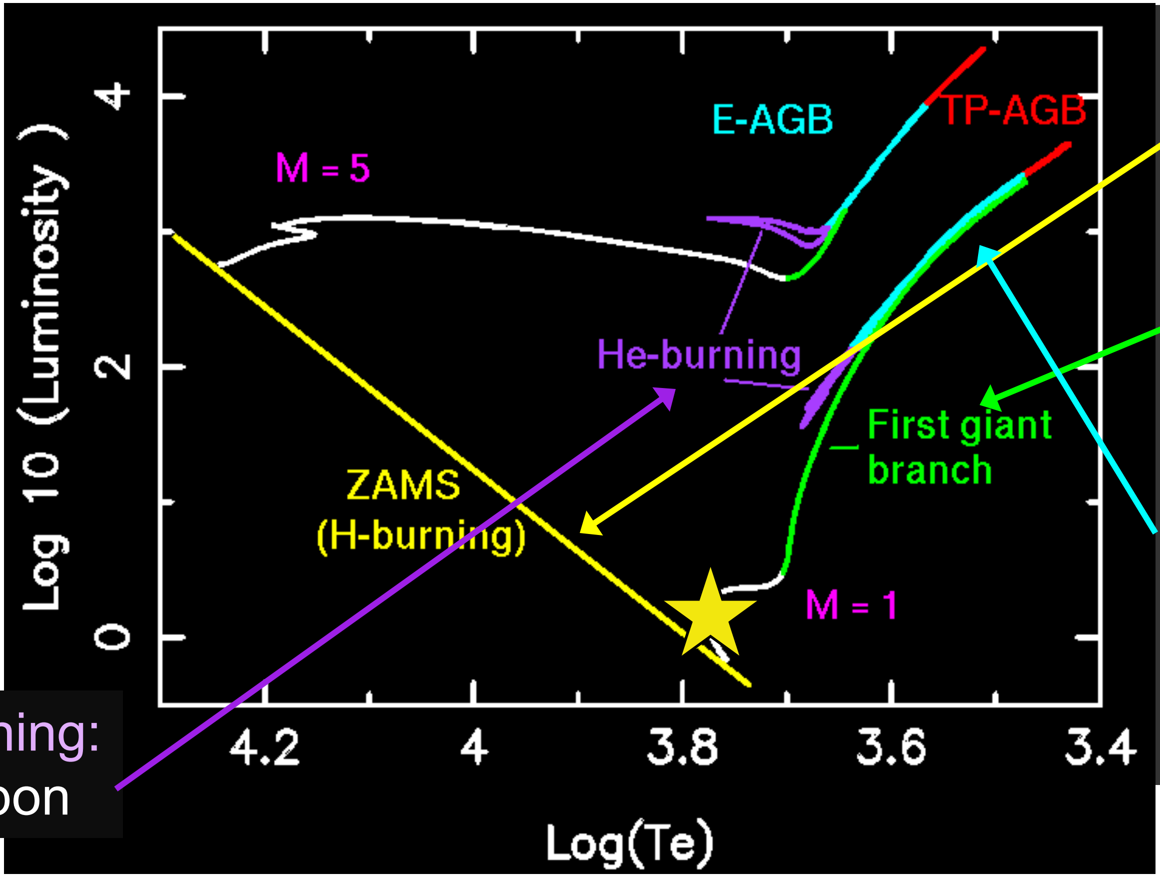
Basic Stellar Evolution

The x-axis: logarithm of the surface temperature of the star
The y-axis: logarithm of the luminosity or amount of energy a star radiates per unit time.



Main sequence:
H to Helium
$\tau \sim 10^{10}$ yrs for 1
$\sim 10^{8}$ yrs for 5

Red Giant Branch:: core contracts outer layers expand

Second-giant phase:
after core He-burning
star becomes a red giant for the second time

Core He burning:
He to Carbon

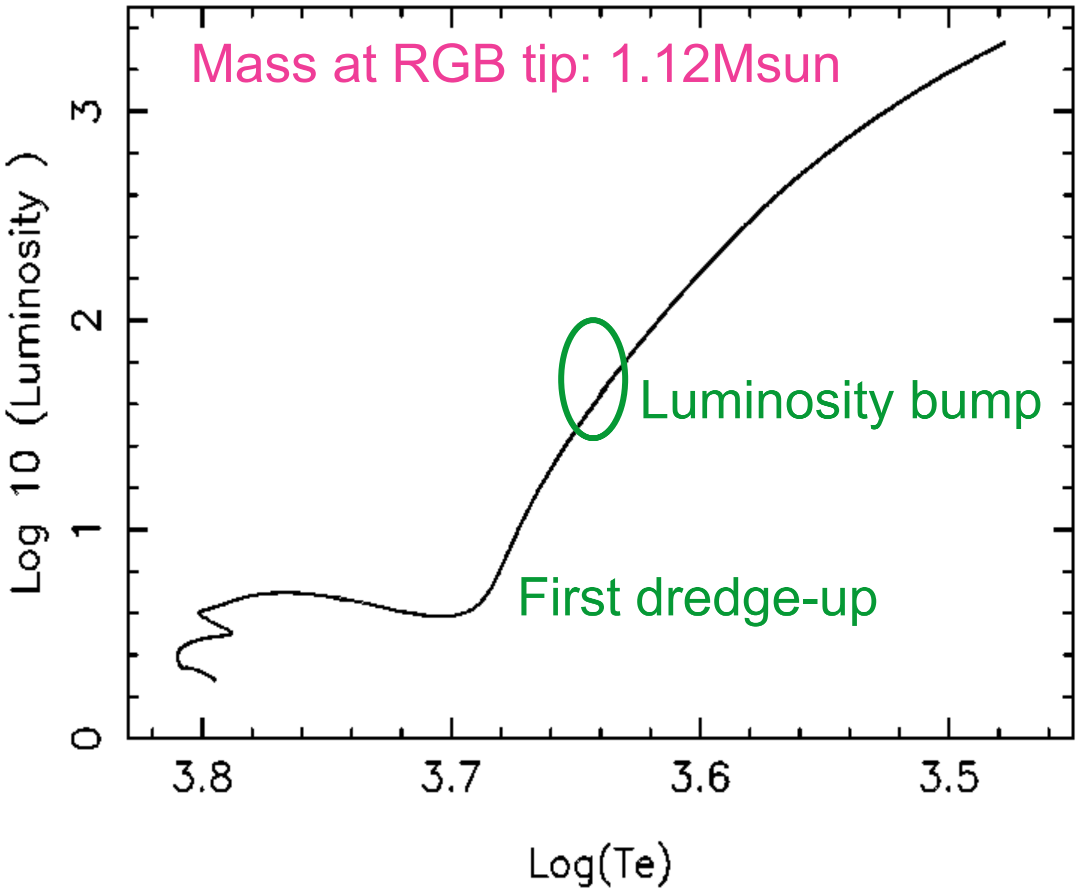
Up to the tip of the first giant branch

- After the end of core H-burning, the star moves right on the HR diagram, at constant luminosity during the establishment of a H-burning shell.
- The inner He-core is contracts, and the outer layers expand.
- Once the star reaches the base of the first giant branch (or red giant branch) we see the first surface abundance changes.

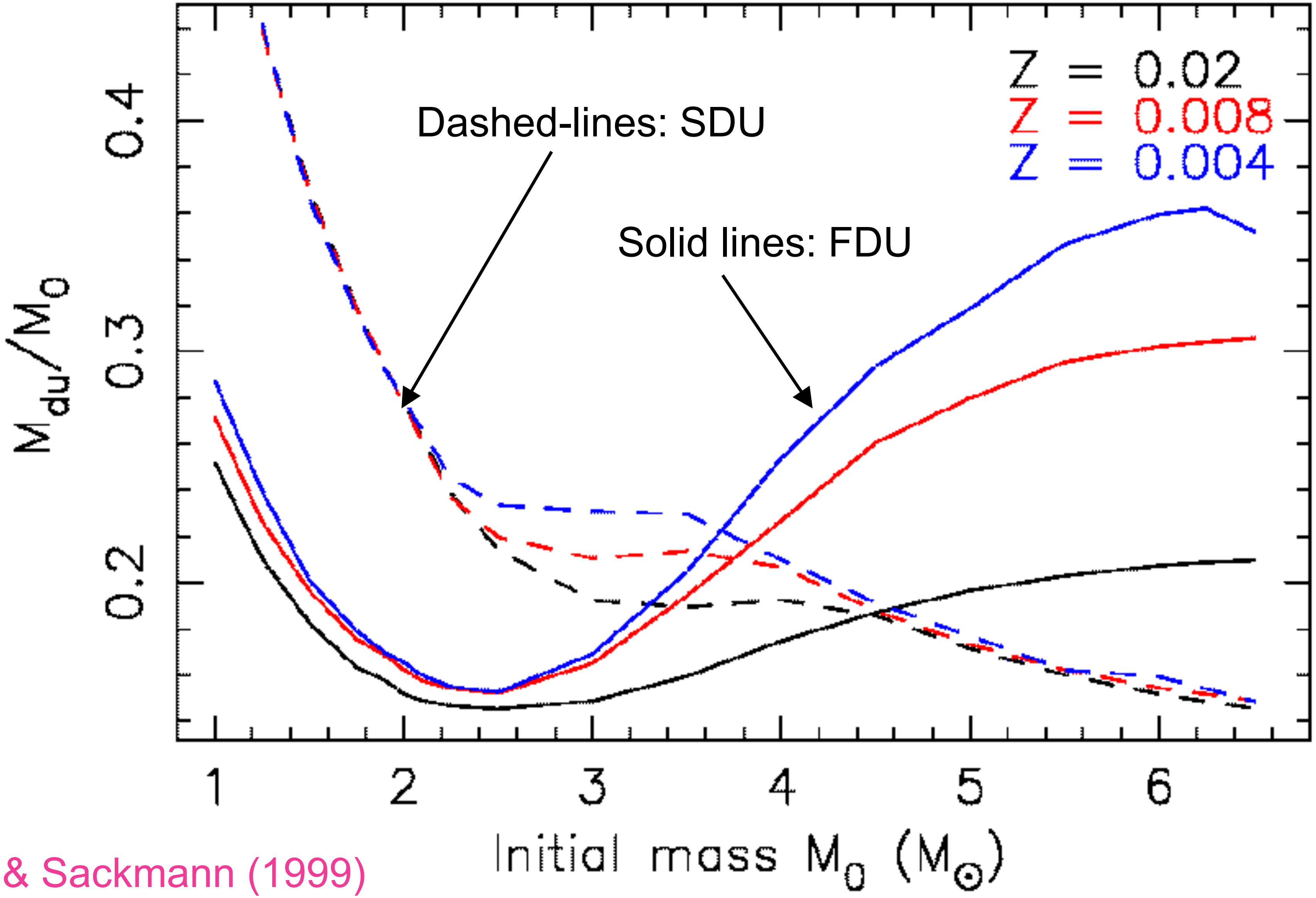
Surface abundance changes:

- This is the first dredge-up:
  - Reduction in Li, $^{12}C/^{13}C$ ratio, C/N ratio
  - Increases in ^{3}He, N

Example: 1.25Msun, Z = Z_{solar} model



First and second dredge-up



Dashed-lines: SDU

Solid lines: FDU

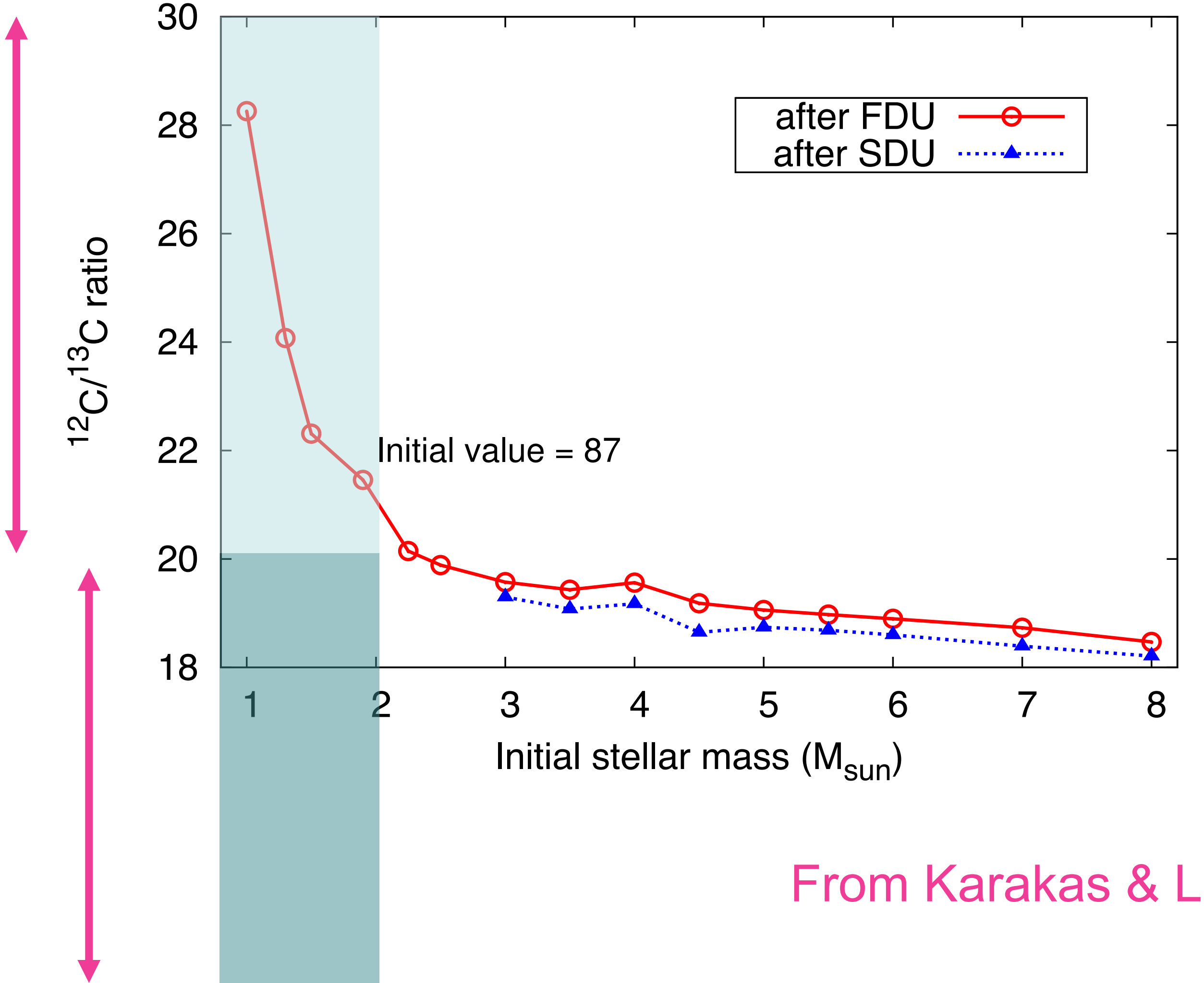
See Boothroyd & Sackmann (1999)

Chemical composition of red giant branch stars

Observations of low-mass field or cluster giants show that the $^{12}C/^{13}C$ ratio is less than 20 (e.g., Gilroy 1989, McCormick et al. 2023)

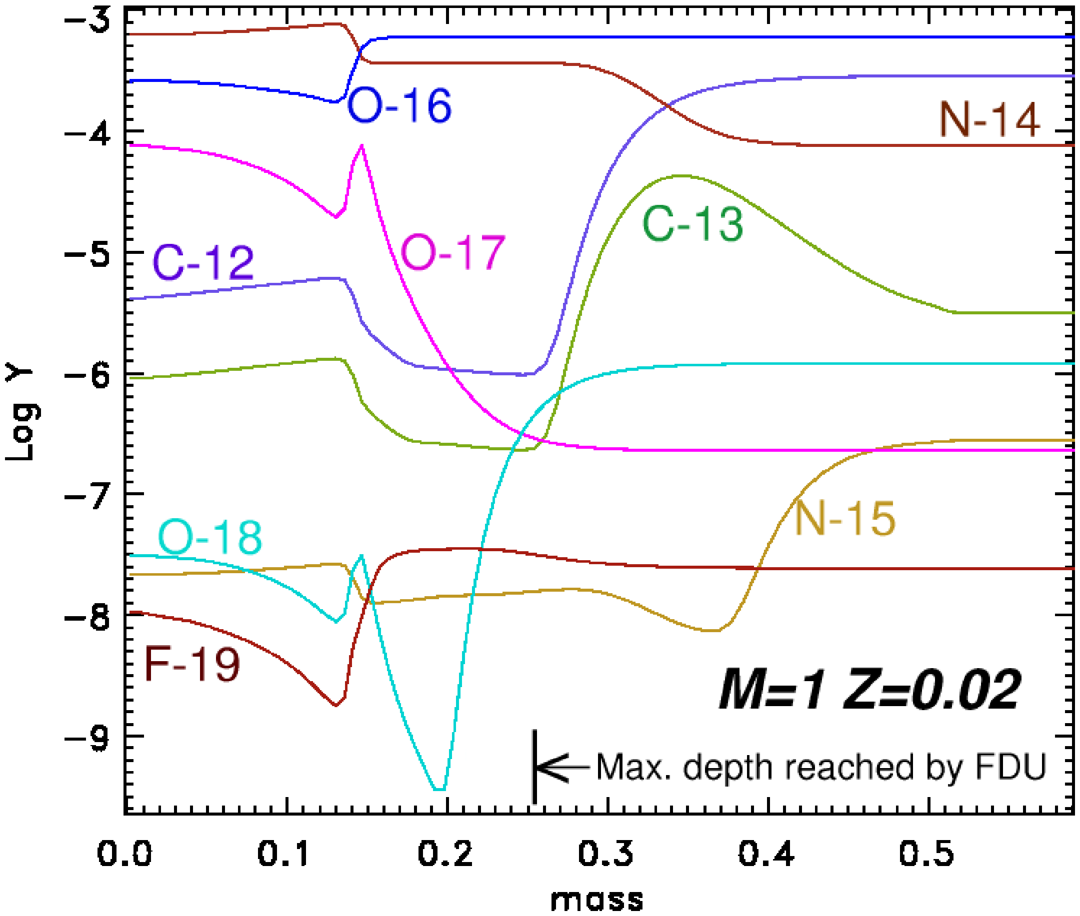
Predicted range

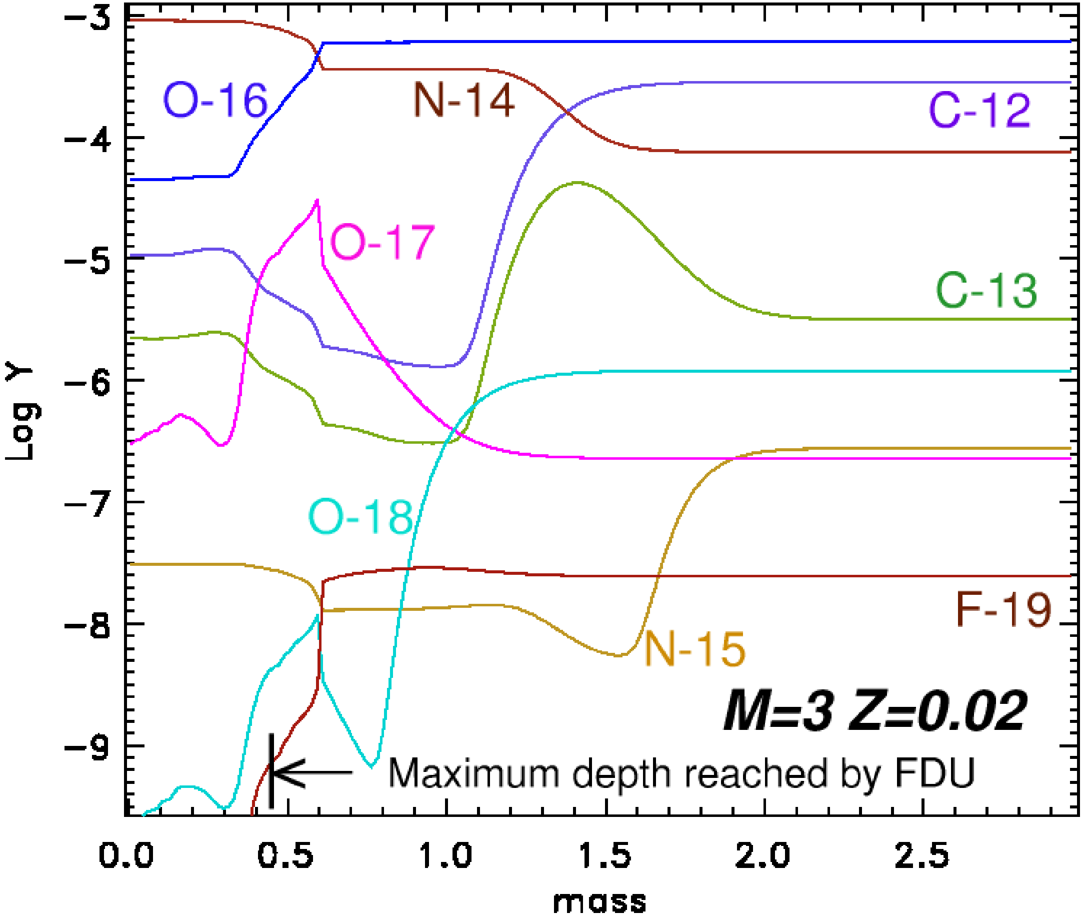
Observational range



From Karakas & Lattanzio (2014)

Pre-FDU profiles as a function of mass



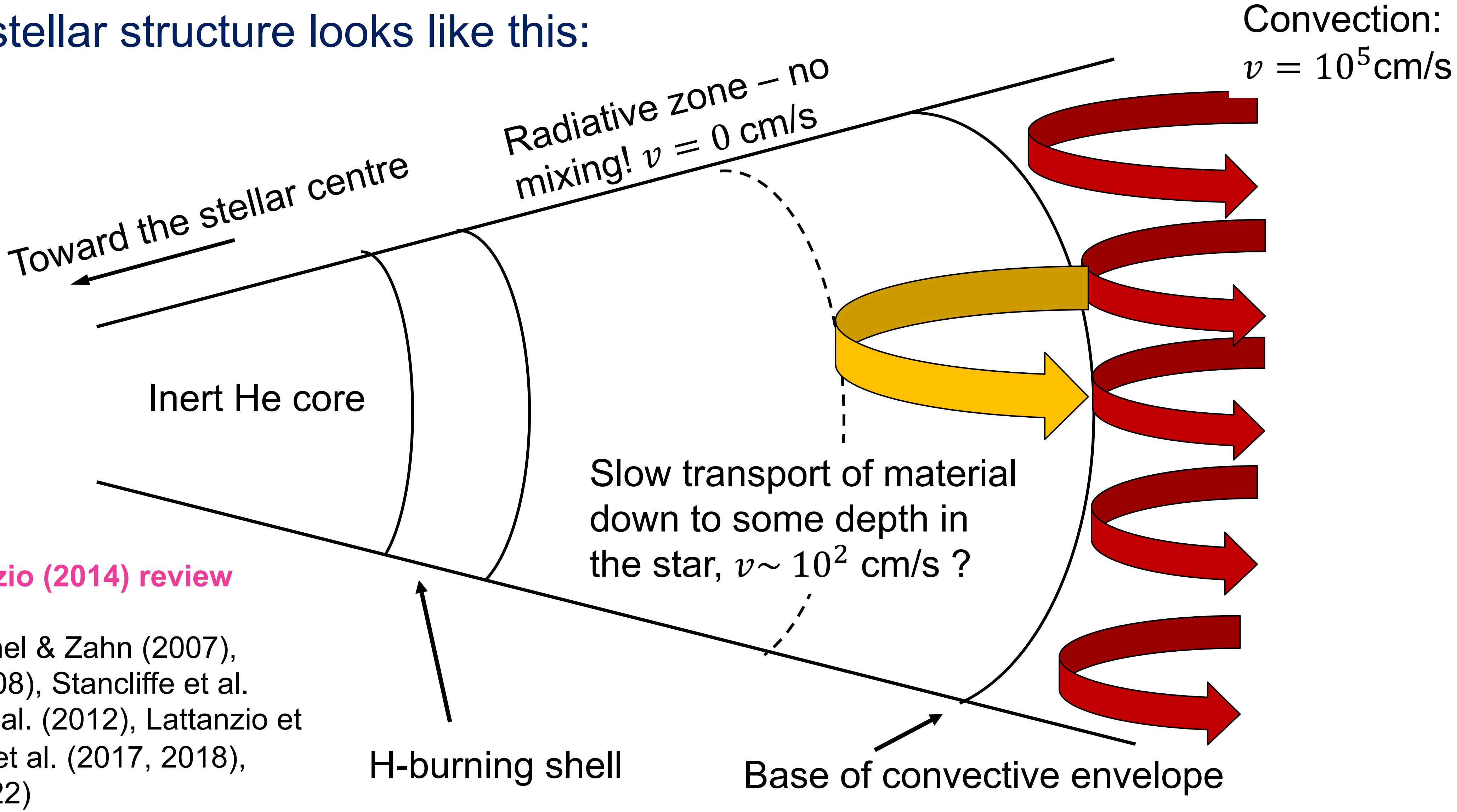


In the 1Msun, about 75% of the star is mixed by FDU

In the 3Msun, about 85% of the star is mixed by FDU

Extra mixing on the RGB?

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

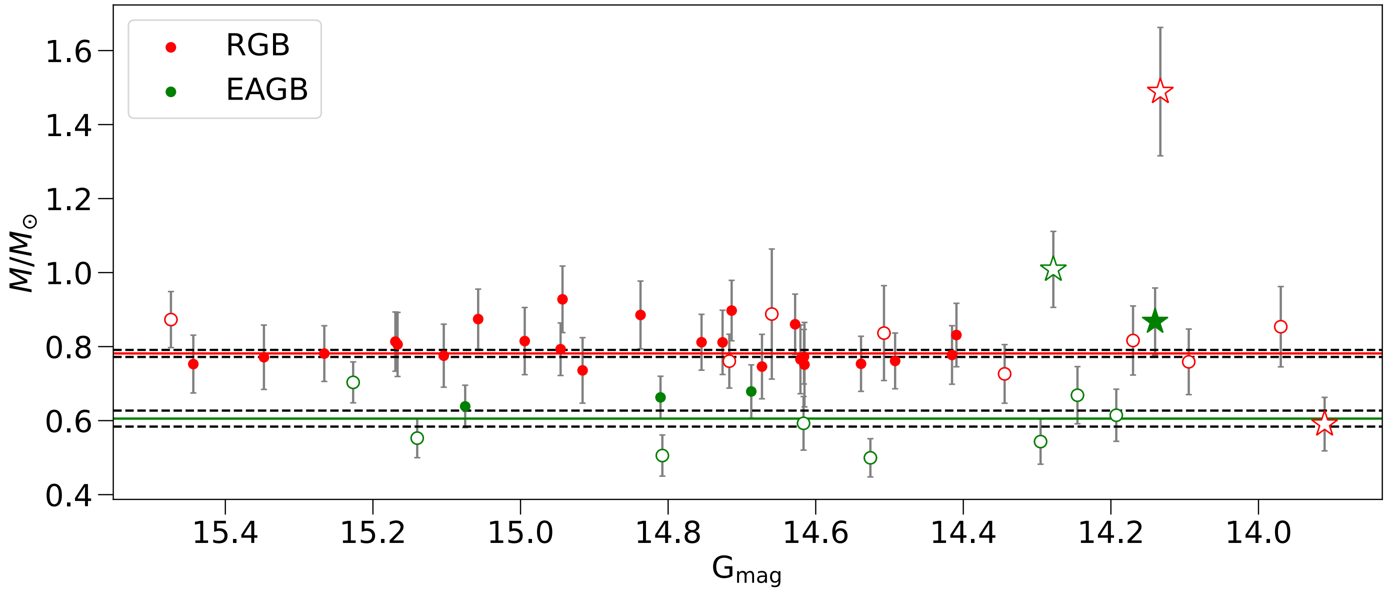
Base of convective envelope

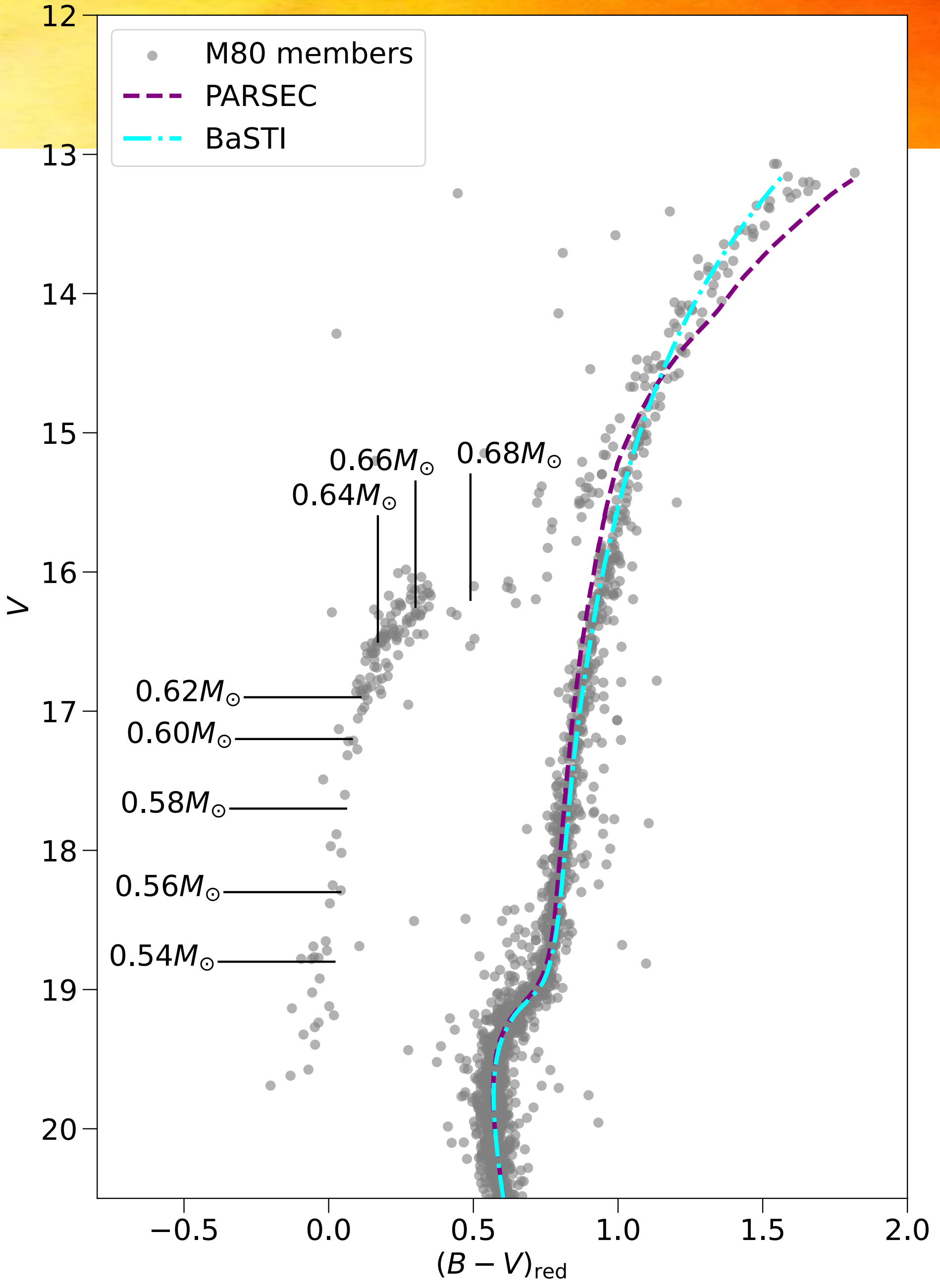
Karakas & Lattanzio (2014) review

See also Charbonnel & Zahn (2007), Eggleton et al. (2008), Stancliffe et al. (2009), Angelou et al. (2012), Lattanzio et al. (2015), Henkel et al. (2017, 2018), Tayar & Joyce (2022)

RGB mass-loss

- We are still unsure how much mass stars lose on the RGB.
- Asteroseismology can be used to study this. The results suggest little to no mass-loss in metal-rich open clusters, where MSTO masses ~1.6Msun (Handberg et al. 2017)
- GCs show between 0.1 to ~0.25Msun (Howell et al. 2024).





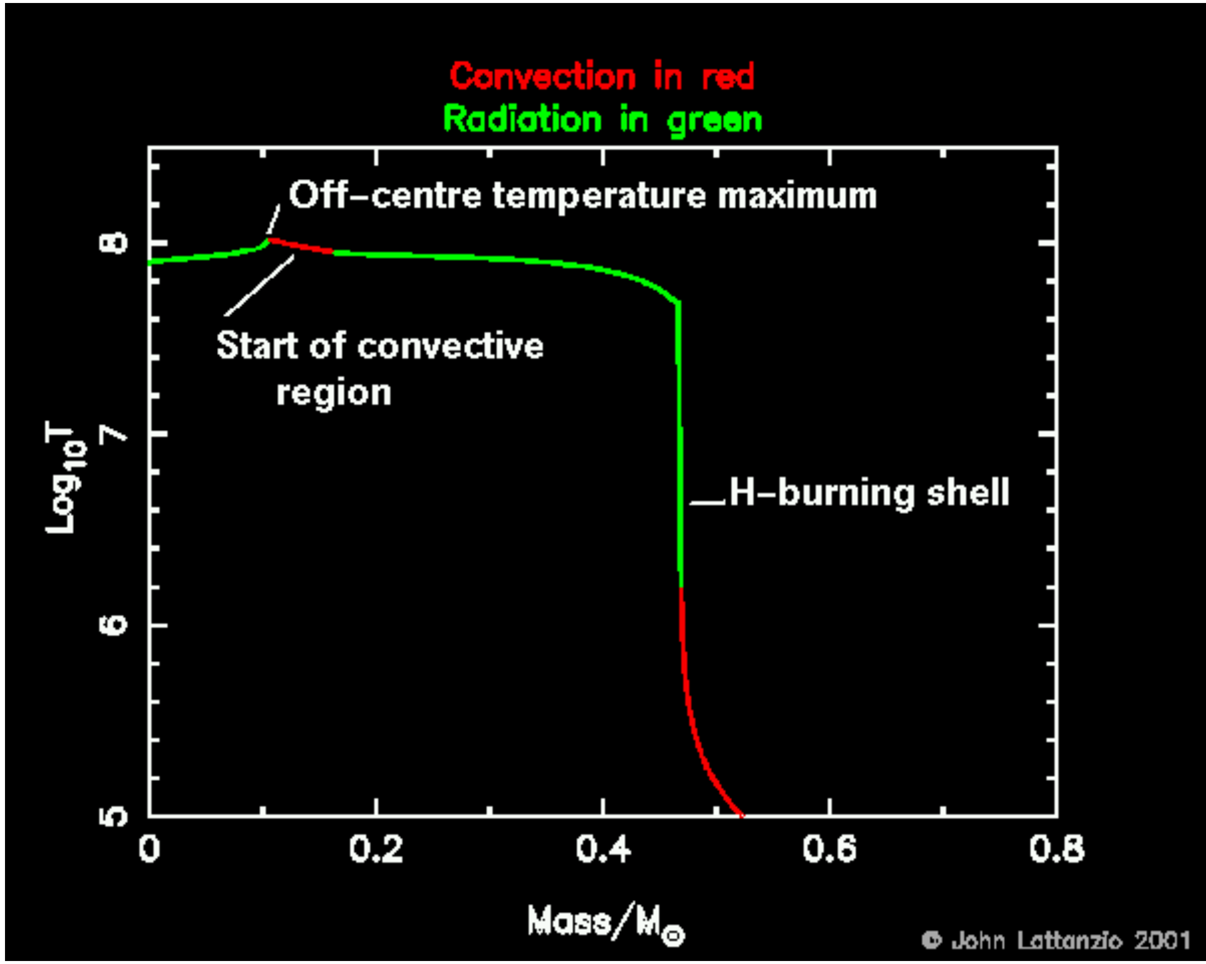
Core helium ignition

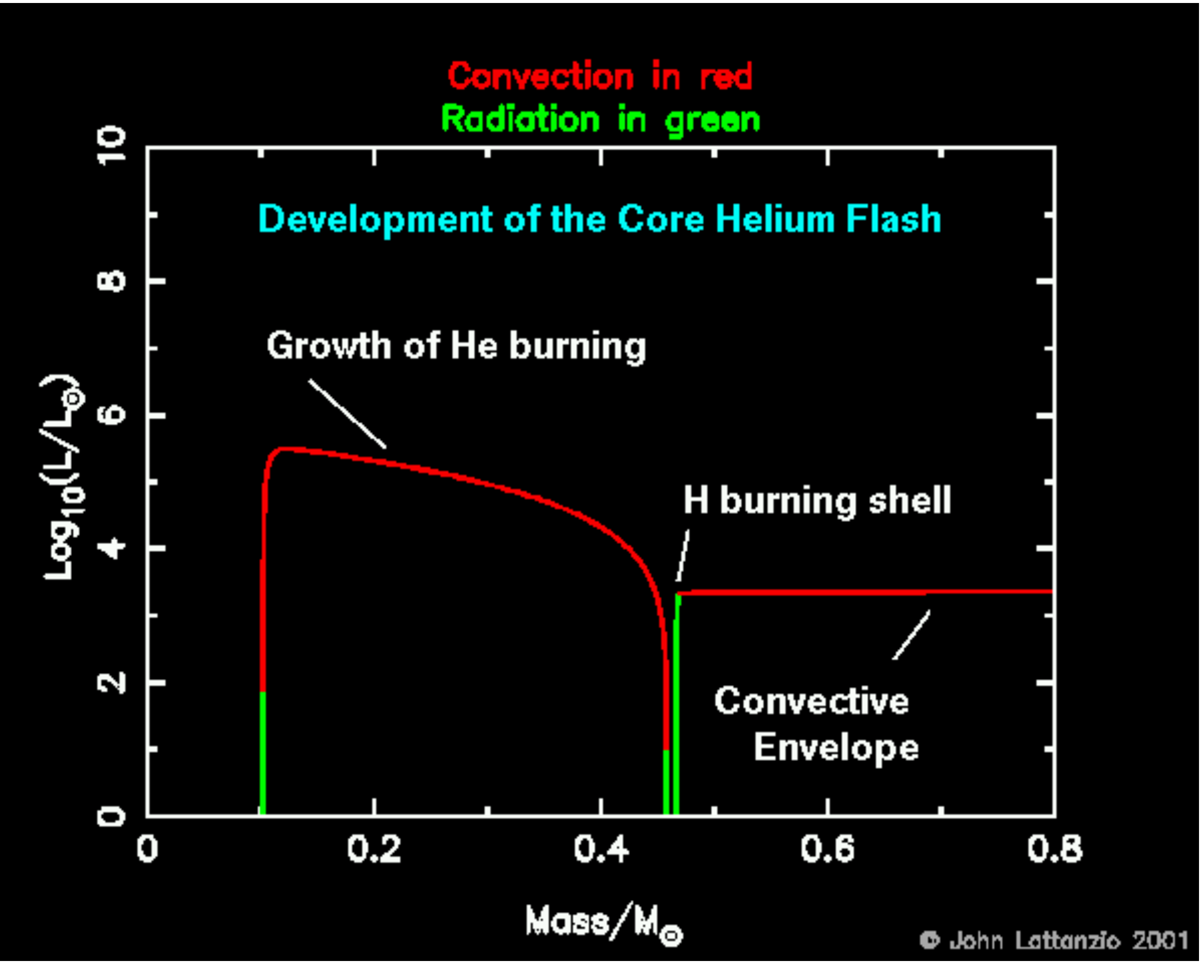
- The helium core continues to contract and heat.
- Once the temperature inside the core reaches about 10^8 K, core He ignition takes place.
- Low-mass stars need to contract substantially before reaching this temperature

  → *the central regions to become electron-degenerate*
- Neutrino energy losses from the core cause the temperature maximum to move outward.
- Eventually, the triple alpha reactions are ignited at the point of maximum temperature.
- Equation of state is only slightly dependent on T, leading to a thermonuclear runaway: The core He flash

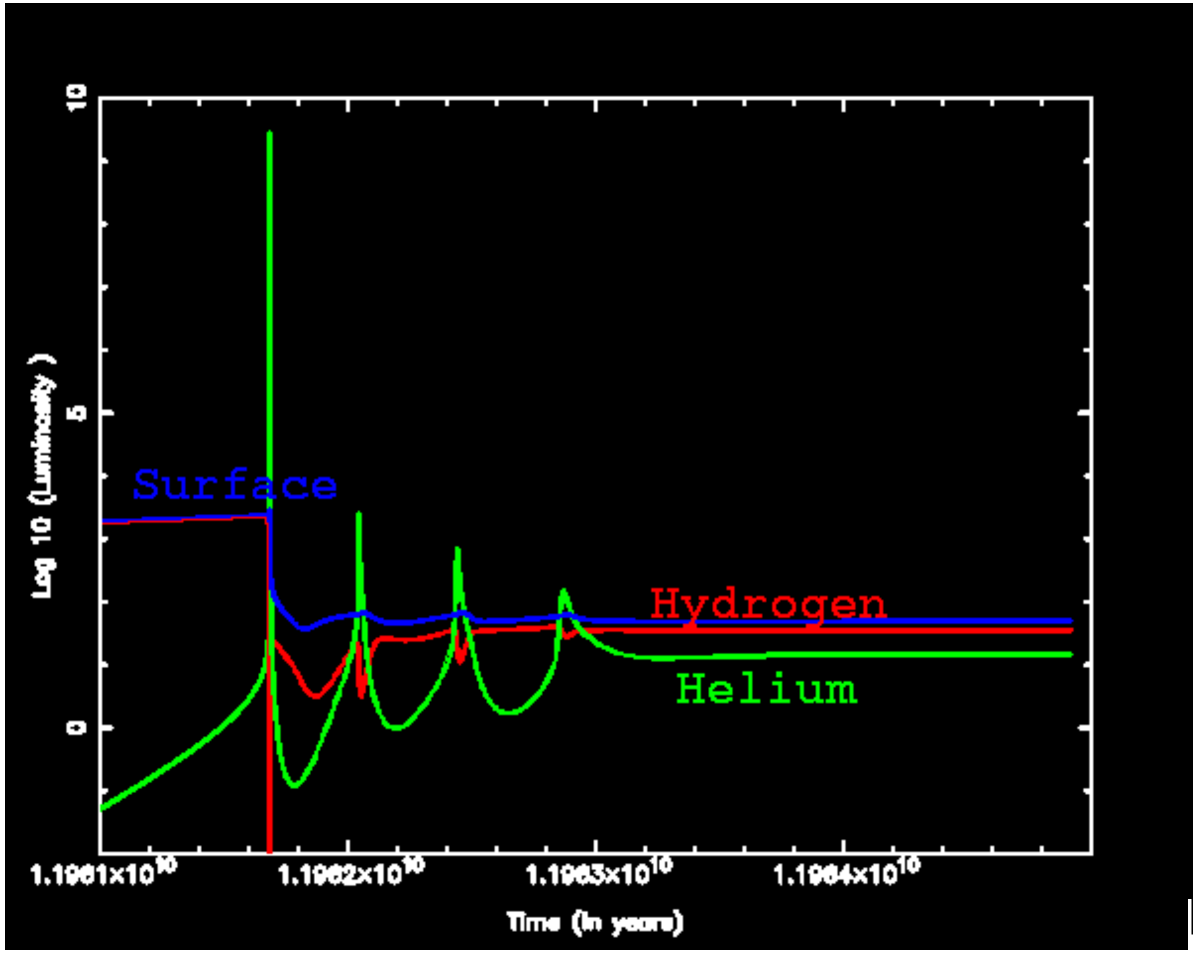
The core helium-flash

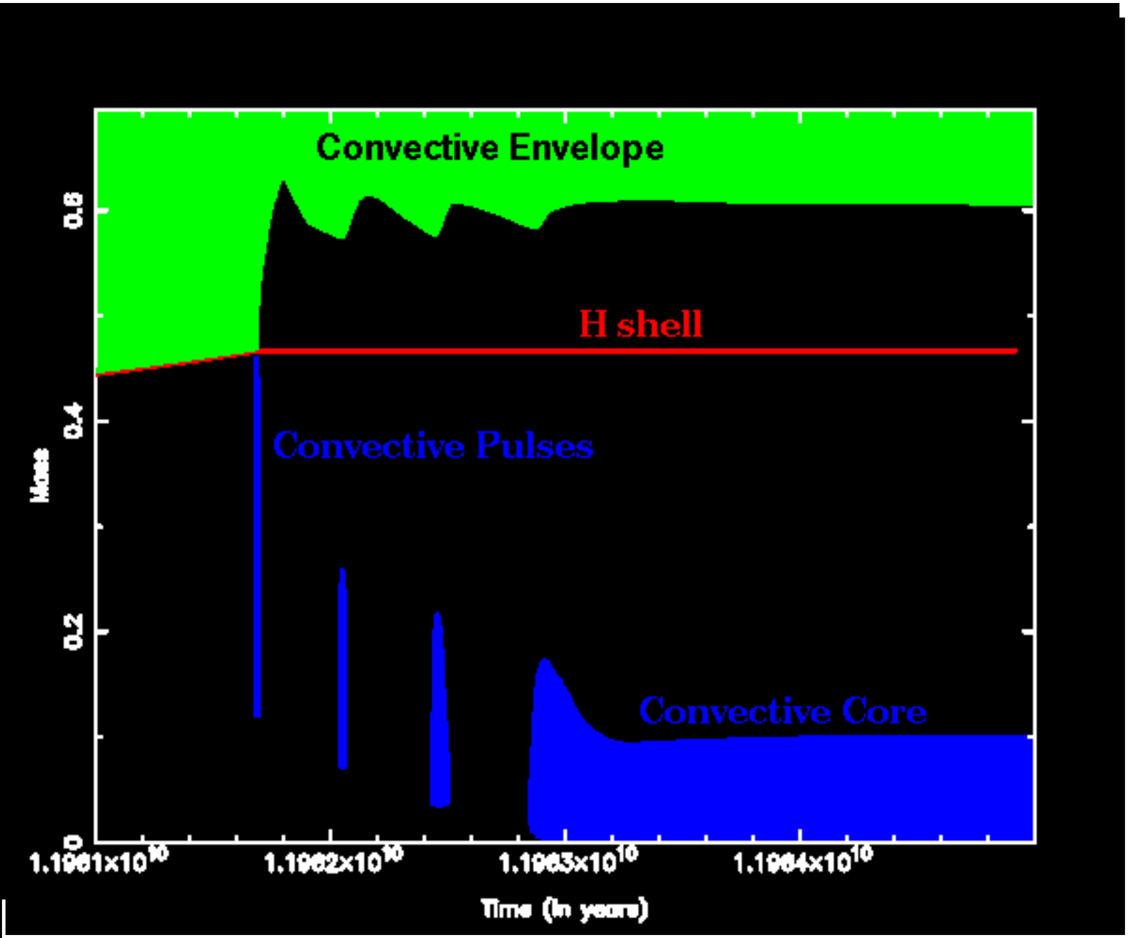
The maximum initial mass is around 2Msun but is determined by the mass of the H-exhausted core. Core overshoot on the main sequence will lower this mass to ~1.7Msun.





The core helium-flash





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, hence more energy is required to fusion to occur.
- This means higher burning temperatures and because energy generation $\propto T^{40}$, shorter lifetimes!
- Typical He-burning lifetimes are ~100 million years for low-mass stars (~1Msun), compared to ~10^{10} for H-burning.
- Whereas core He-burning lasts about 20 million years for the 5Msun, compared to 80 million years for H-burning.

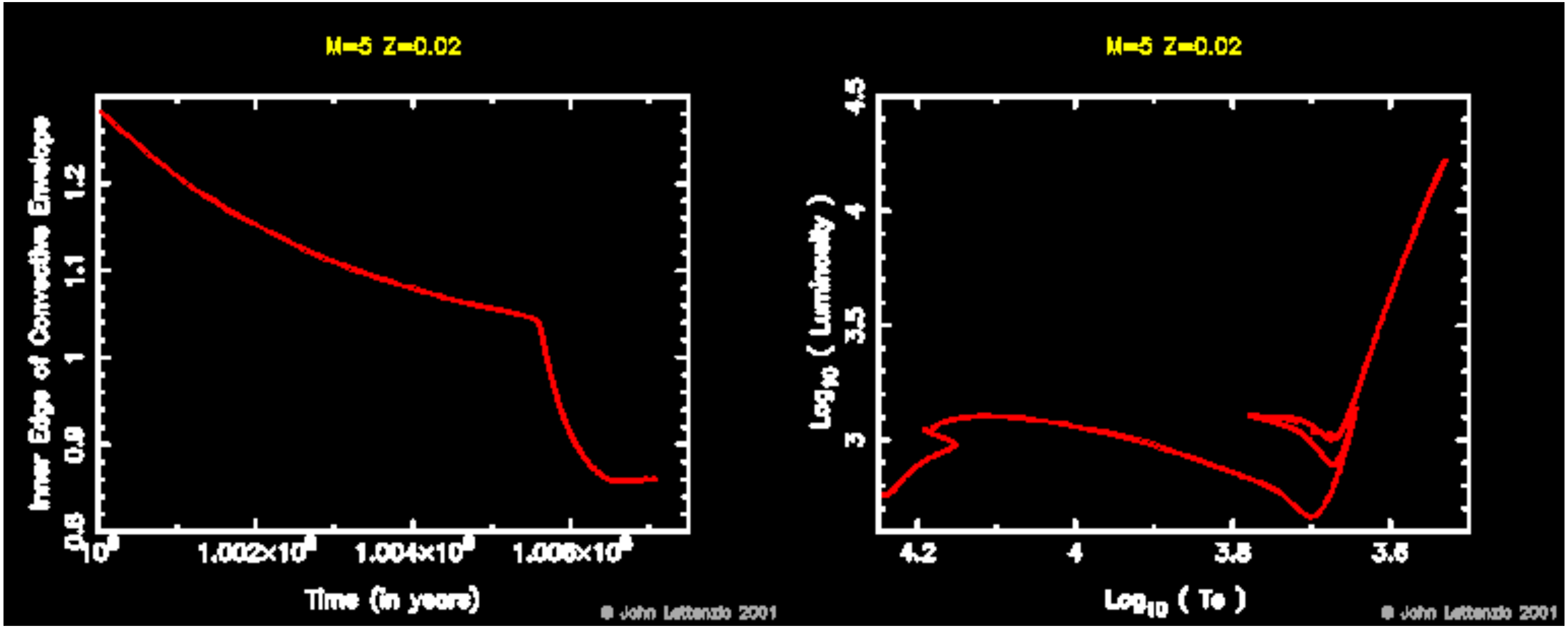
The early asymptotic giant branch

- Following core He-exhaustion, the star evolves up the second giant branch, or asymptotic giant branch (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

→ This is the second dredge-up

Structure during second dredge-up

Results for a 5 Msun, $Z = Z_{solar}$ model:

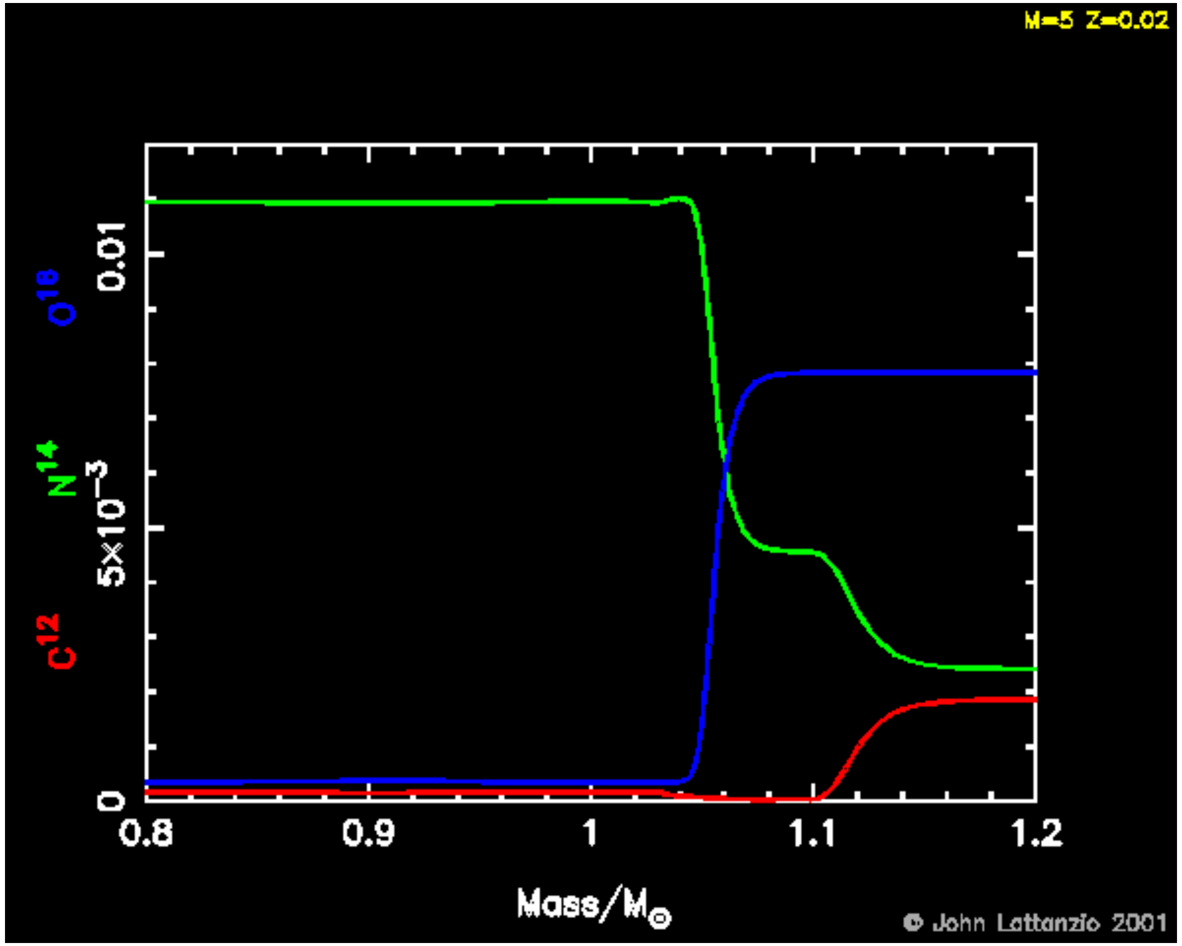


The second dredge-up: 5Msun

- We only predict surface abundance changes in stellar models above about 4Msun, for solar Z.

- The minimum stellar mass for second dredge-up is determined by the H-exhausted core mass, not the initial mass, and it is $M_H \geq 0.8M_{\odot}$.

- Core overshooting on the main sequence increases the mass of the core. Hence, the minimum mass for SDU shifts to lower initial stellar masses.



© John Lattanzio 2001

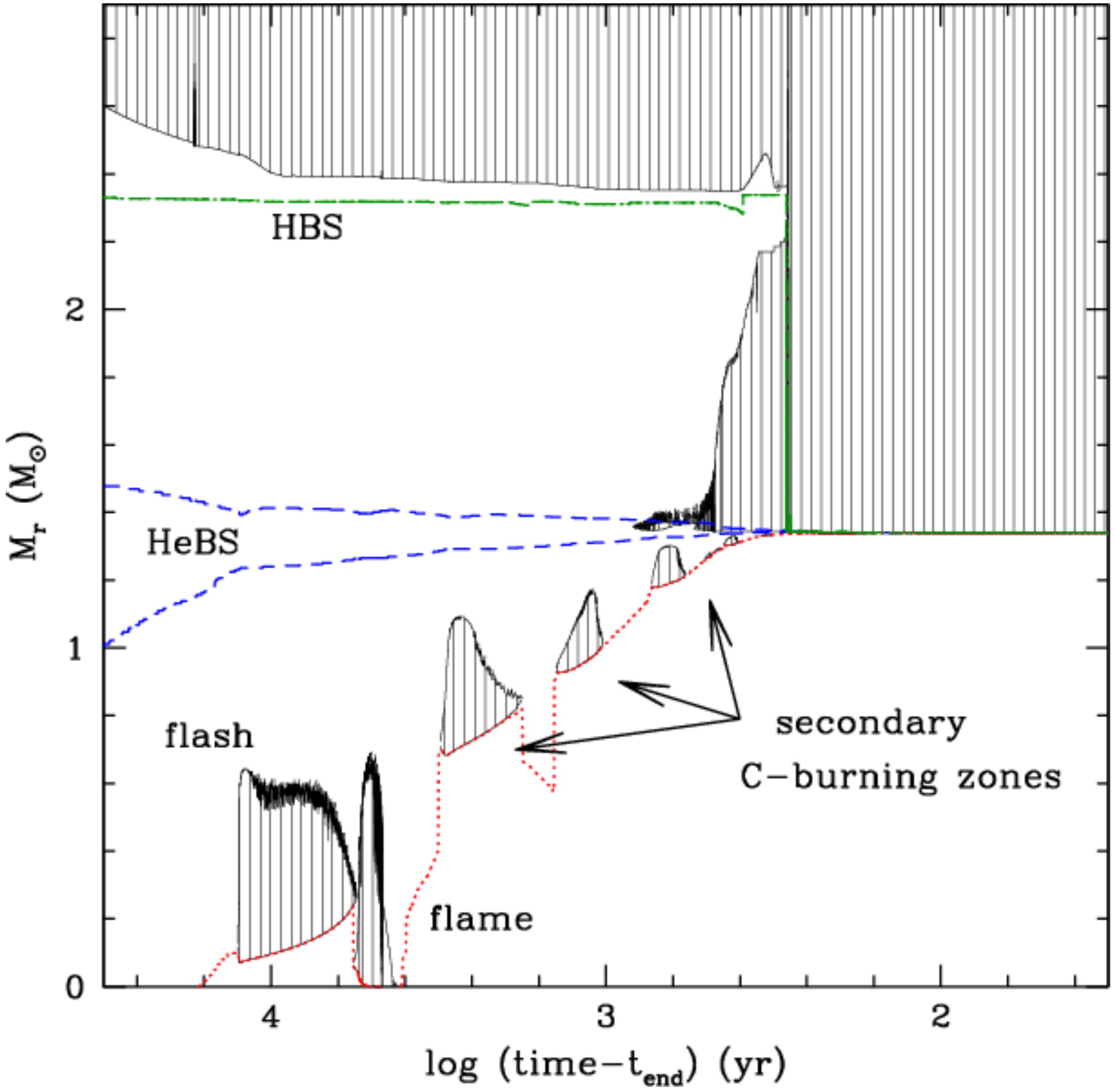
Off-centre carbon ignition

- Stars with $m \gtrsim$ 8Msun ignite carbon off centre, under electron degenerate conditions.
- The ignition occurs during second dredge-up, while the star is ascending the early-AGB.
- Carbon is ignited if the temperature in the core exceeds $\approx$ 0.5 GK. The maximum temperature in the core is determined by the H-exhausted core mass.
- Stars within 8-10 Msun will develop an O-Ne core following C burning, but won't ignite anything heavier.
- These stars will experience thermal pulses, and evolve much like their lower mass counterparts

→ *super-AGB stars (review by Doherty et al. 2017).*

Super-AGB stars and their fate

- The H-exhausted core mass at the end of core He-burning determines:
  - 1) second dredge-up, and
  - 2) whether the core gets hot enough for carbon ignition.
- Motivation to understand mixing on the main sequence (and core He-burning phase).



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

Mini-lab 2 wrap up

- In the lab you examined the evolution of intermediate-mass stars through the early-AGB phase.
- You examined the effect of convective boundary mixing on the first and second dredge-ups. What did you find?
- Why would the ^{12}C/^{13}C ratio be invariant to the amount of mixing? And why is this ratio not affected by SDU?
- But this is not the case for ^{14}N/^{15}N. Think about the CNO cycles – we start with the CN cycle, converting ^{12,13}C to ^{14}N. Then at higher temperatures (which means deeper) the ON cycles convert O isotopes to ^{14}N.
- We find that the structure and surface composition of model stars at the start of the AGB depends on the amount of convective boundary mixing.

Outline

We will start with a brief introduction before learning about:

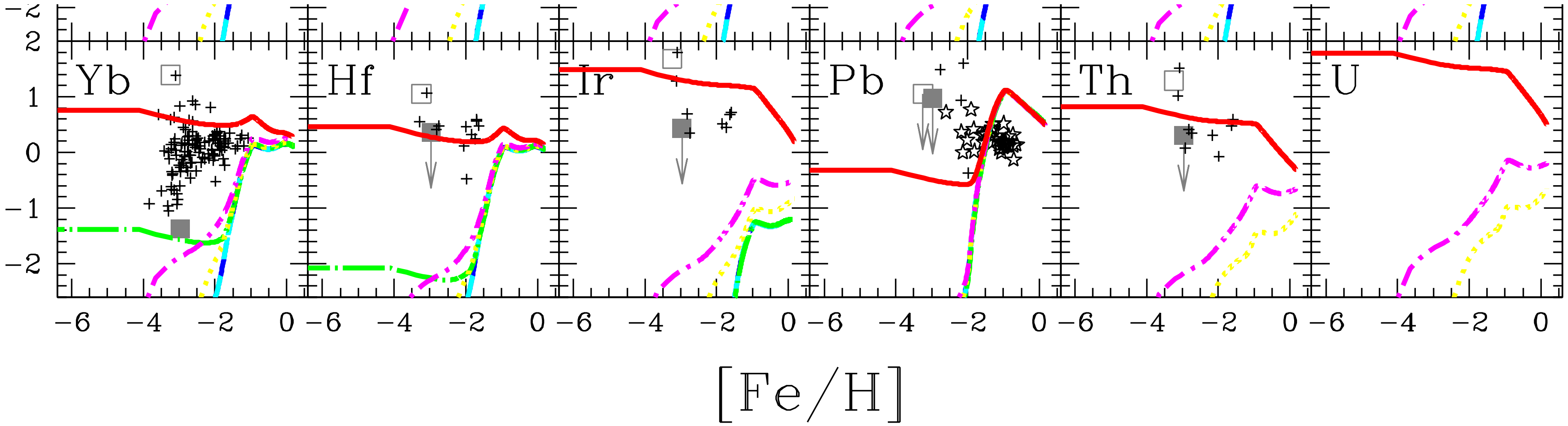
1. Lecture 1 – the pre-asymptotic giant branch phase
2. Lecture 2 – the early AGB phase, second dredge-up and carbon ignition
3. Lecture 3 – the thermally-pulsing AGB phase.

Before we get started…

- You will spend the next 15 minutes getting your mini-lab 3 runs set up.
- While your model is running, please read through Section 3.
- If you are still struggling to get the model running in 5 minutes, please let the TA on your table know!

Chemical Elements Trivia

Kobayashi, Karakas & Lugaro (2020)



If you have read everything and have a bit of time then:

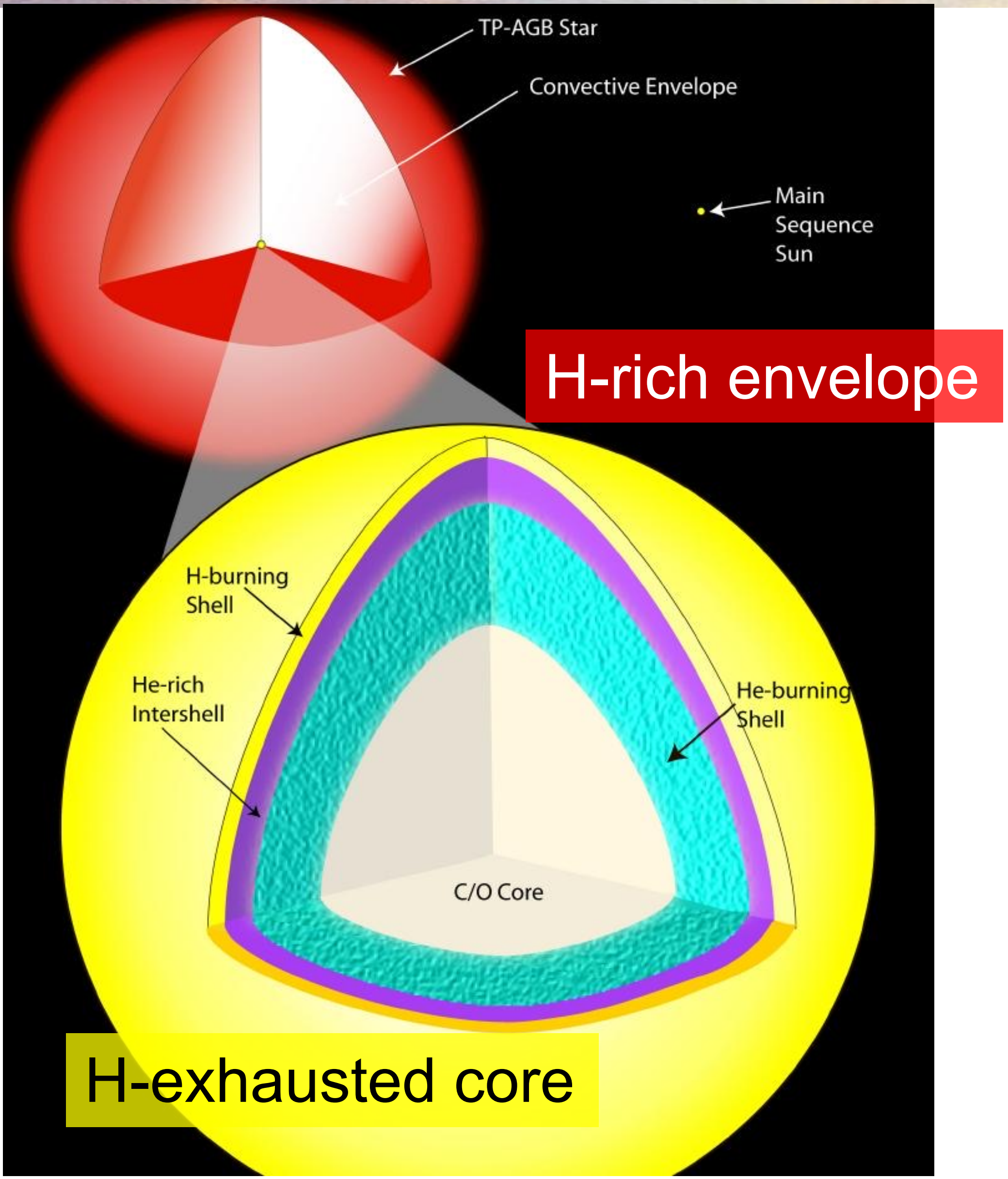
***Question 1**: Name the only elements ending in "d"?*

***Question 2**: Name the only three elements ending in "um" as opposed to "ium"?*

***Question 3:** Name the elements named after solar system objects?*

(no cheating with Google!)

Thermally-pulsing Asymptotic giant branch



Thermally-pulsing AGB (TP-AGB) stars:

- Less common in surveys because AGB lifetime is short but they are bright; only red supergiants are brighter
- Evolved stars with a CO core, shells burning helium and hydrogen.
- He-burning shell is thermally unstable → causes mixing.
- Rapid, episodic mass loss erodes the envelope.

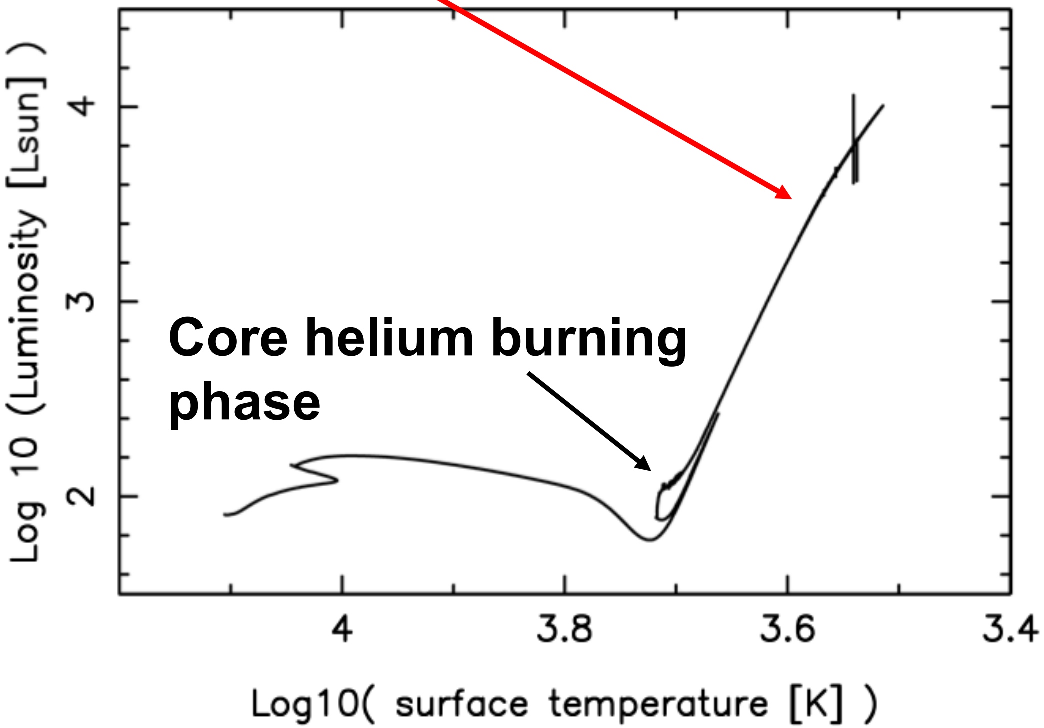
Review: Karakas & Lattanzio (2014)

Key points:

- **Range of lifetimes: 30 Myr to ~10 billion years**
- **Winds releases elements into galaxy**
- **Contribute C, N, F and the s-process in galaxies**

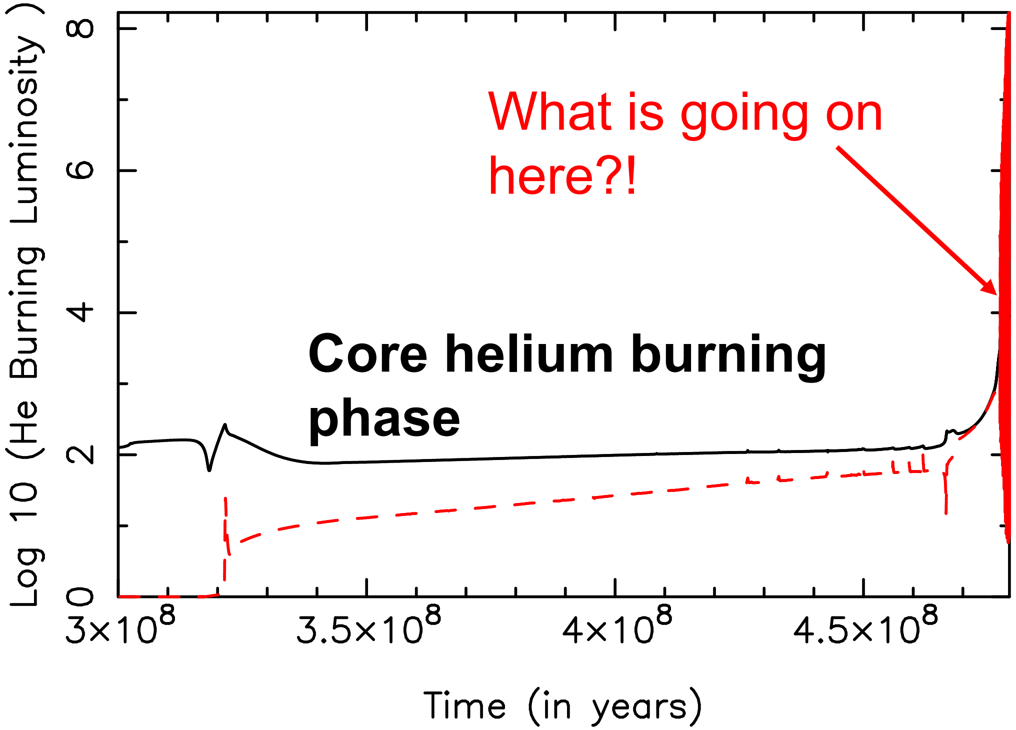
A case study: 3Msun, Z= Zsolar

Evolutionary track from main sequence to *asymptotic giant branch*



Core helium burning phase

Radiated luminosity (black, solid line) and from helium-burning reactions (red, dashed)



What is going on here?!

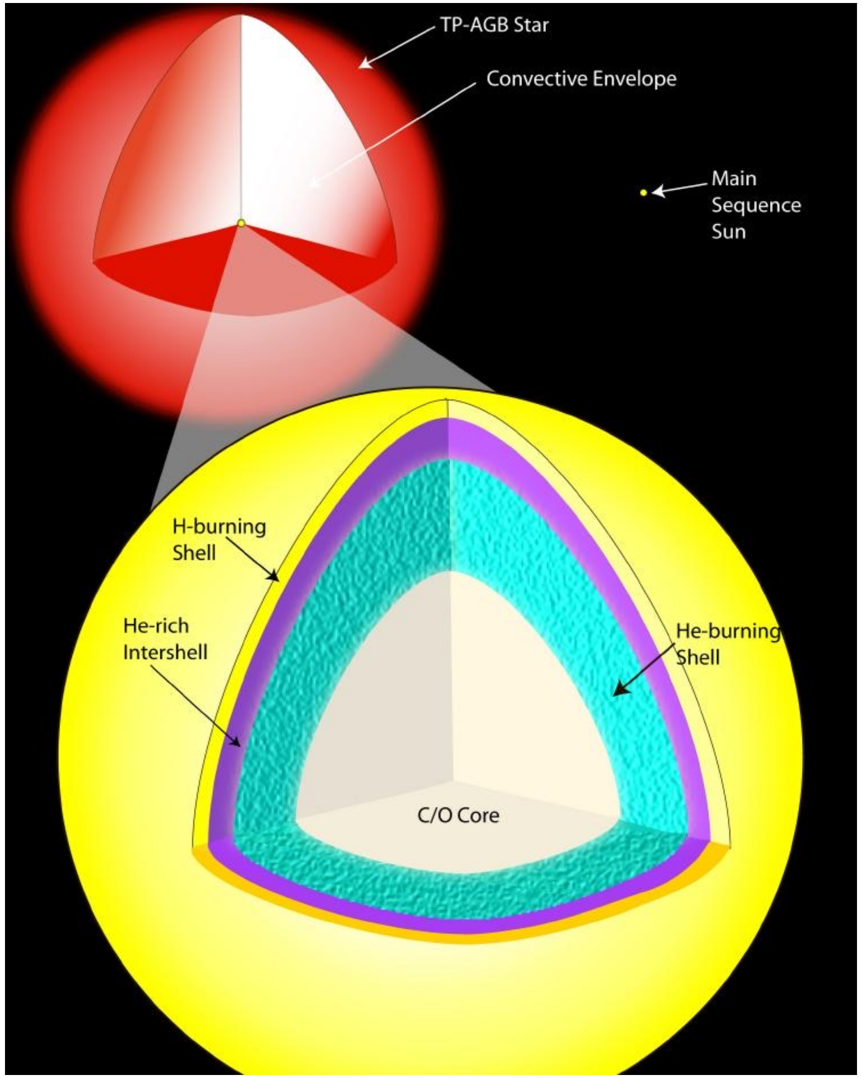
Core helium burning phase

Let's examine the relative sizes

Let's say we have a 3Msun star, near the beginning of the thermally pulsing AGB phase:

Relative size (by mass)
- Total mass 3Msun
- Core mass ≈ 0.6Msun
- Envelope mass ≈ 2.4 Msun

Relative size (by radius)
- Total radius: ~200 Rsun
- Radius of H-exhausted core: ~0.05 Rsun (4000x less!)



Grapefruit, r ~ 5cm (0.05m)

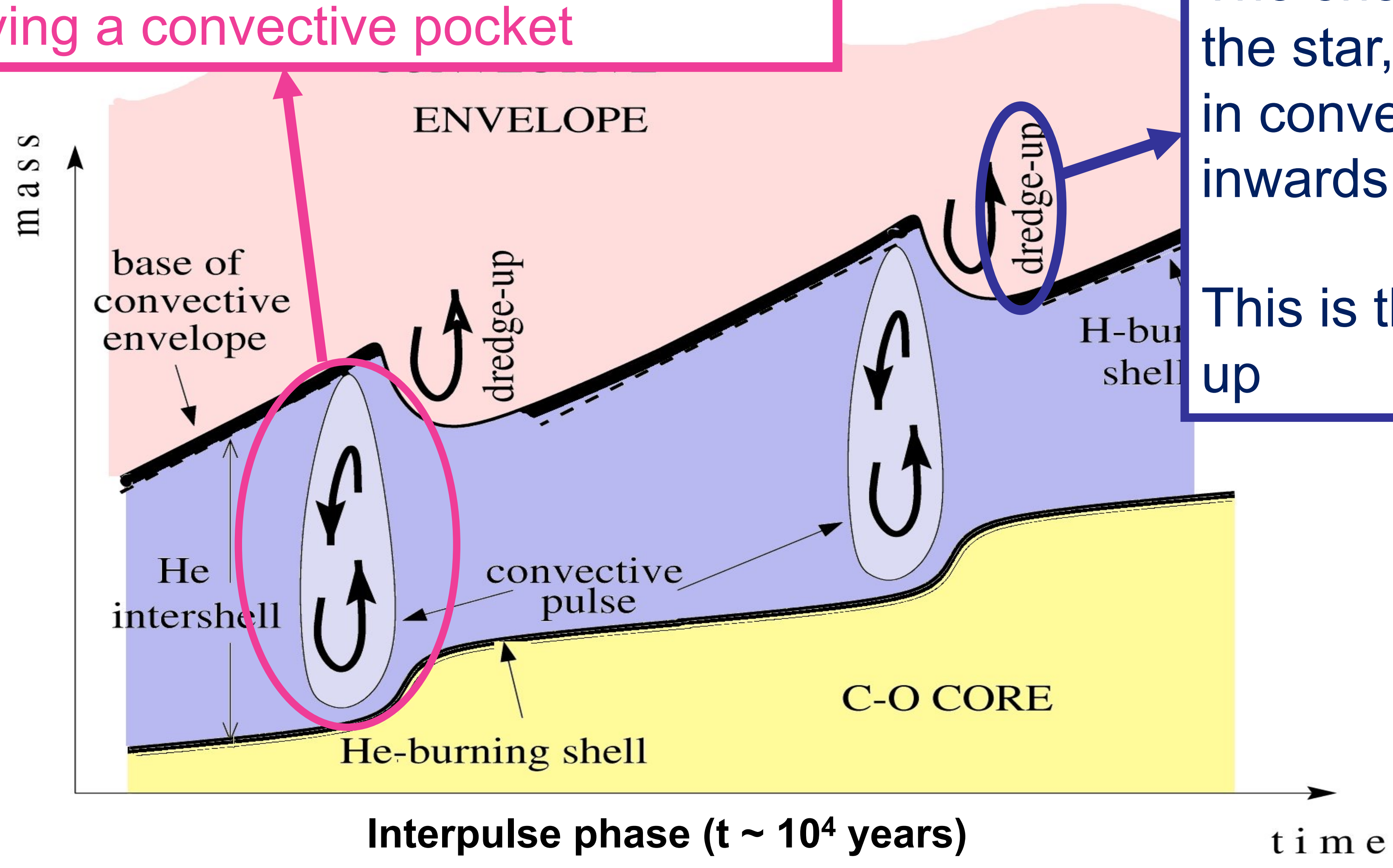
Shipping container, $l \sim 200\ m$

Schematic AGB evolution

He-shell burning begins at the base of the shell, driving a convective pocket

The energy expands the star, which results in convection moving inwards, in mass

This is third-dredge-up



Interpulse phase (t ~ 10^4 years)

He-shell instabilities

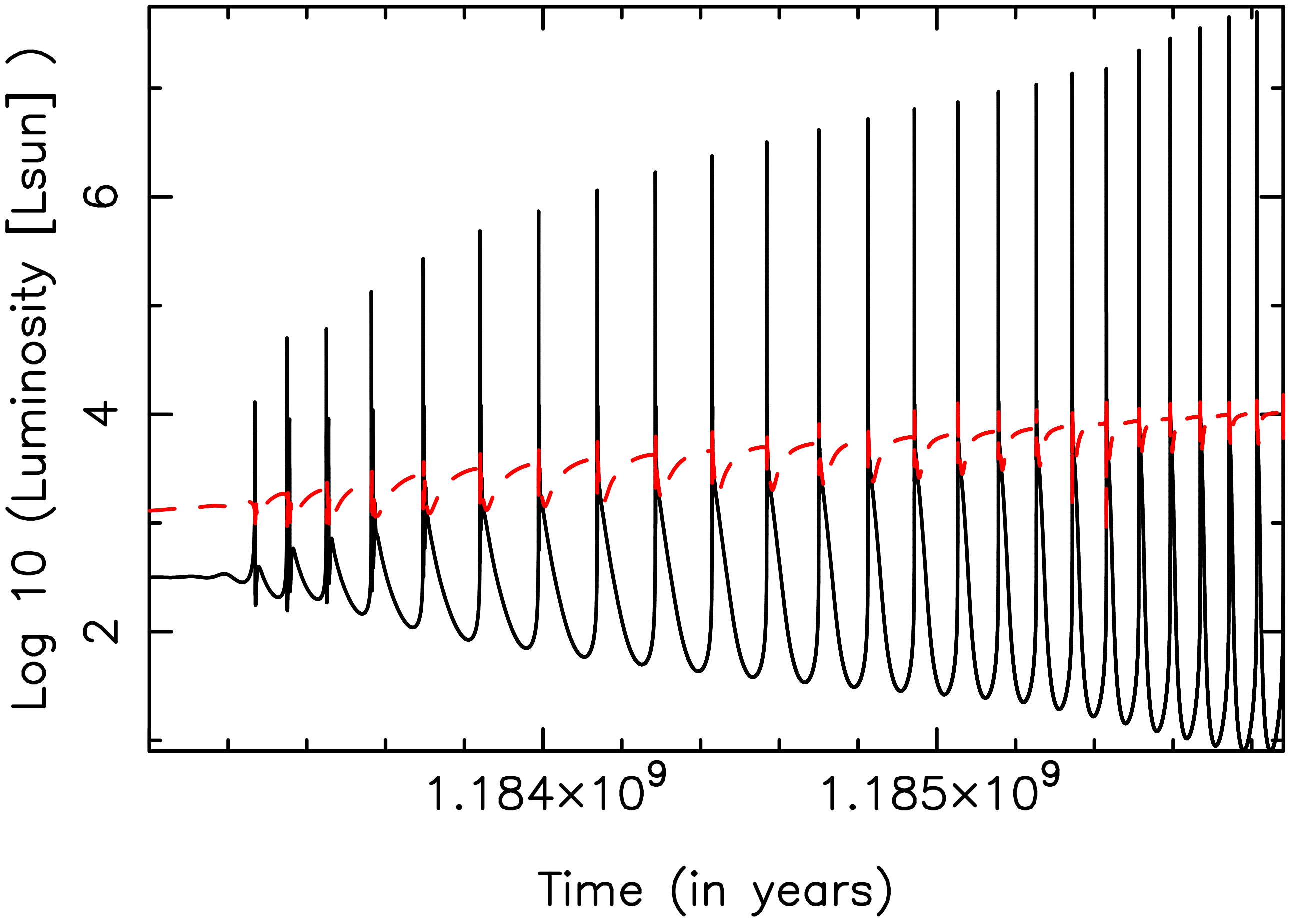
- The He-shell thins as the star ascends the AGB and becomes thermally unstable.
- He-burning in a thin shell leads to a thermal runaway, similar to the core He-flash. Why?
- Not caused by electron degeneracy, although the shell is partially degenerate
- Caused by the shell being thin!
- Contracting shell → hotter → $\varepsilon \propto T^{40}$ → but shell can’t expand enough to cool → thermal runaway.
- Luminosities can reach > 10^8 solar luminosities (that is, $few \times 10^{41}$ erg/s).

He-shell burning in AGB stars

- Energy goes into expanding the star; radiated luminosity only changes by a small amount (red line).
- He-shell luminosities approach 10^8 Lsun by the end of the TP-AGB phase.

Example: 2Msun, Z = 0.014

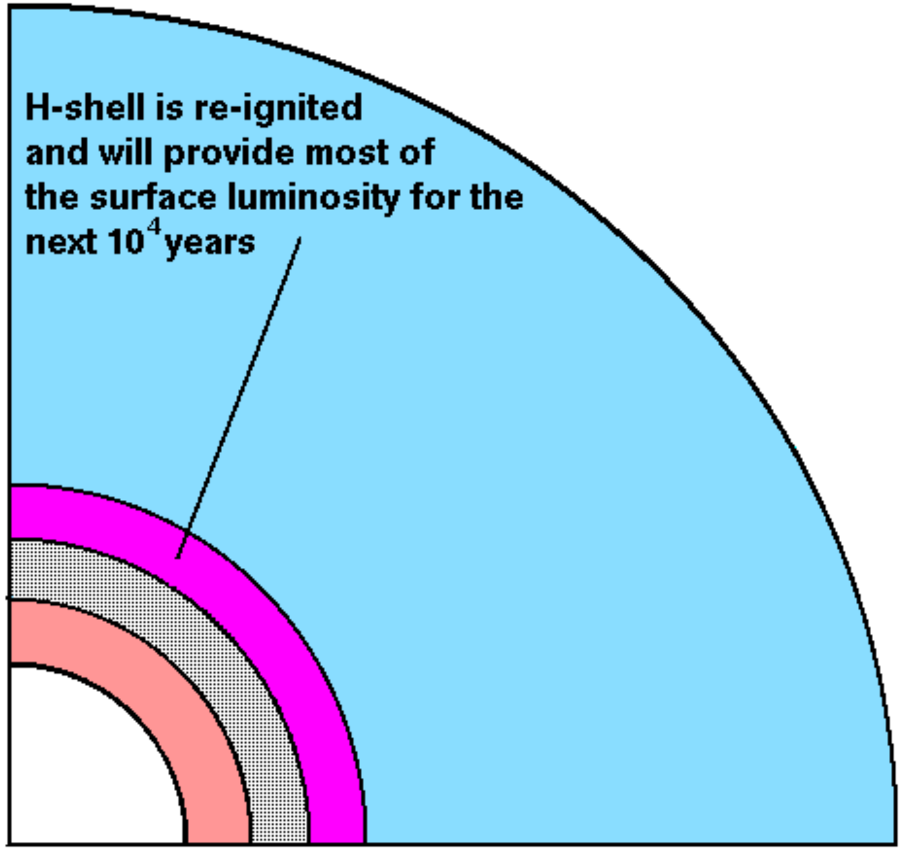
Typical mass of an AGB star in our Galaxy



The thermal pulse cycle

Thermal pulse (He-burning) → TDU (mixing) → Interpulse (H-burning)

Few x 10^2 yrs → 10^2 years → few x 10^{4-5} yrs



Deep convective envelope

He-rich intershell

He-burning shell

Carbon-Oxygen core

H-shell is re-ignited and will provide most of the surface luminosity for the next 10^4 years

Interpulse phase

Anatomy of a thermal pulse

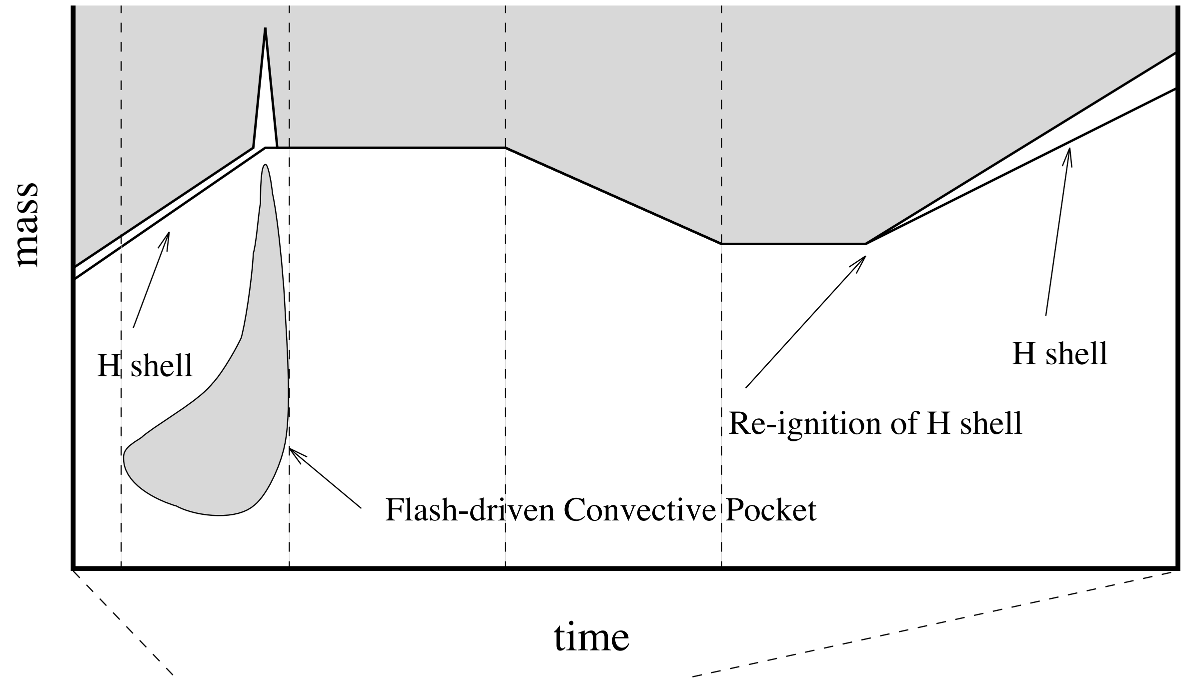


Figure 3 (a). One thermal pulse.

Mixing zones

Shell movement

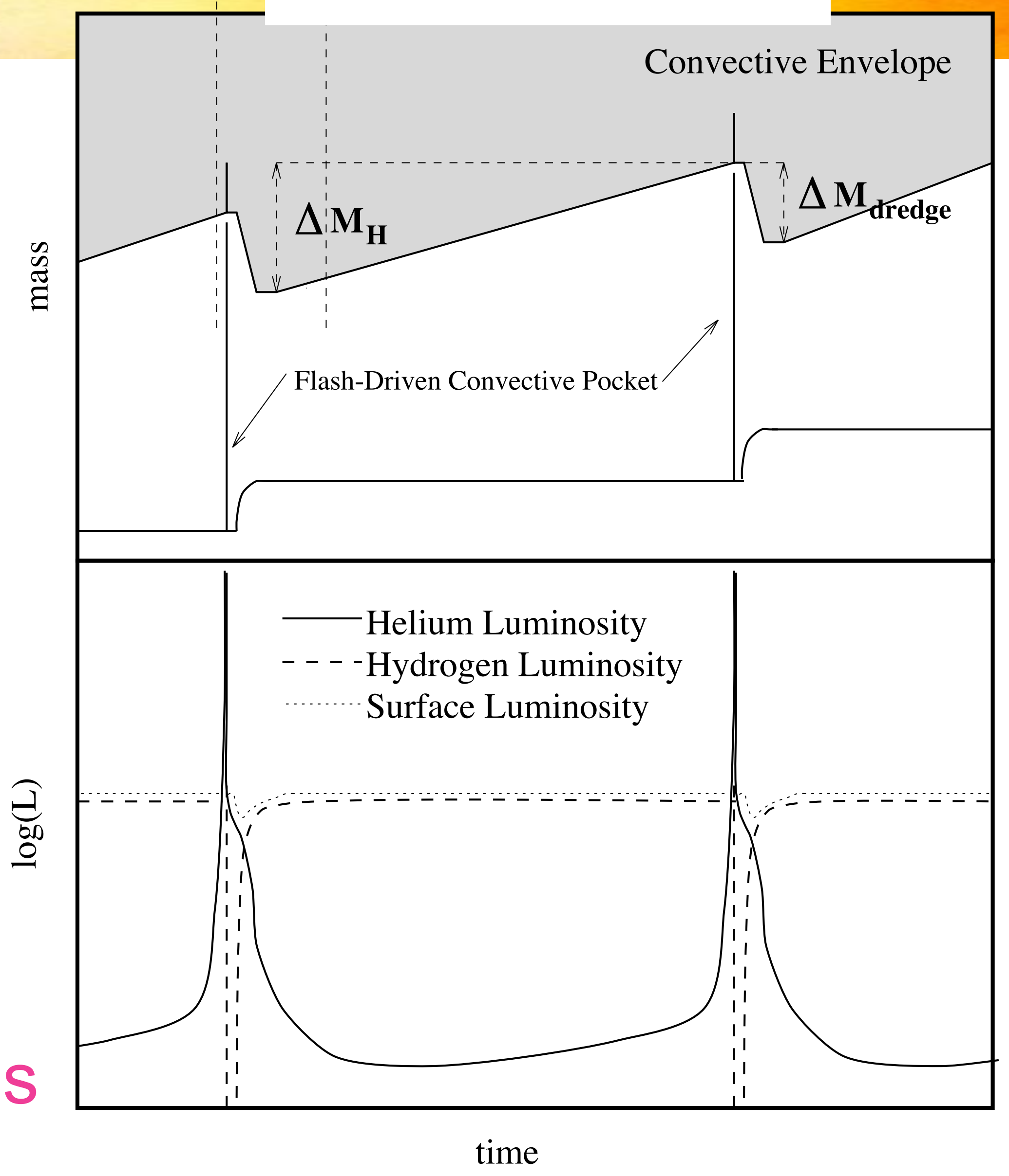


Figure 3 (b). Two consecutive thermal pulses

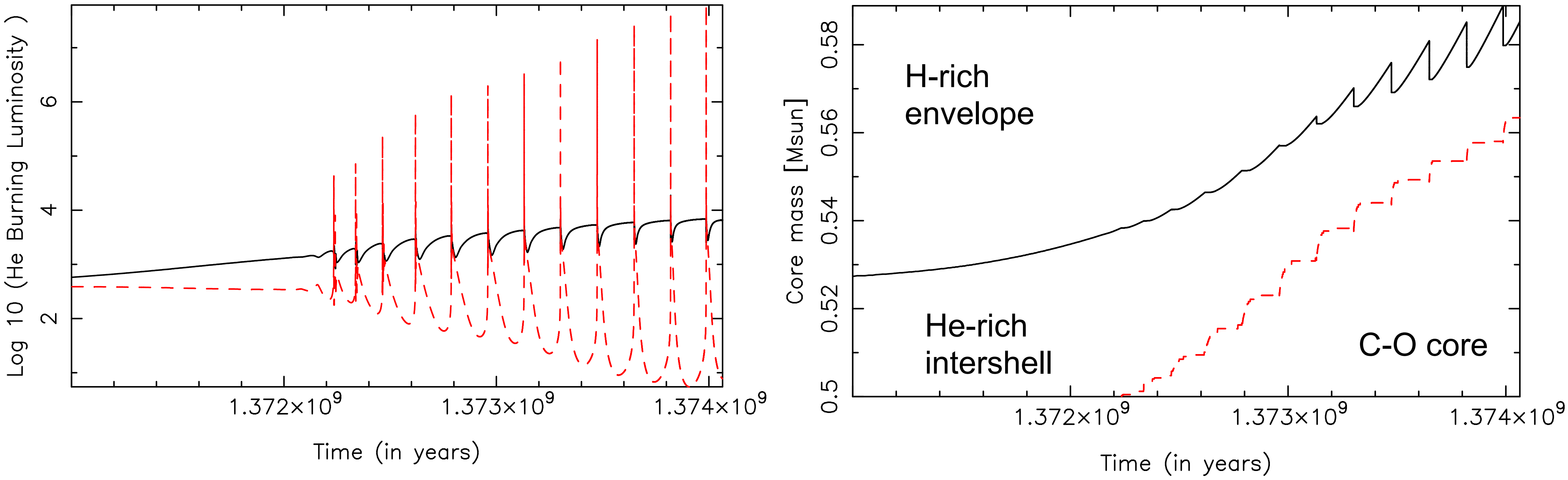
Energy sources

From Frost & Lattanzio (1996)

Third dredge-up

- Inward movement of convective envelope, reaches into the He-shell.
- Right-hand panel shows the evolution of the H-exhausted core (black line).
- Six (third)-dredge-up events are visible. Each one will mix He-shell nucleosynthesis to the surface:

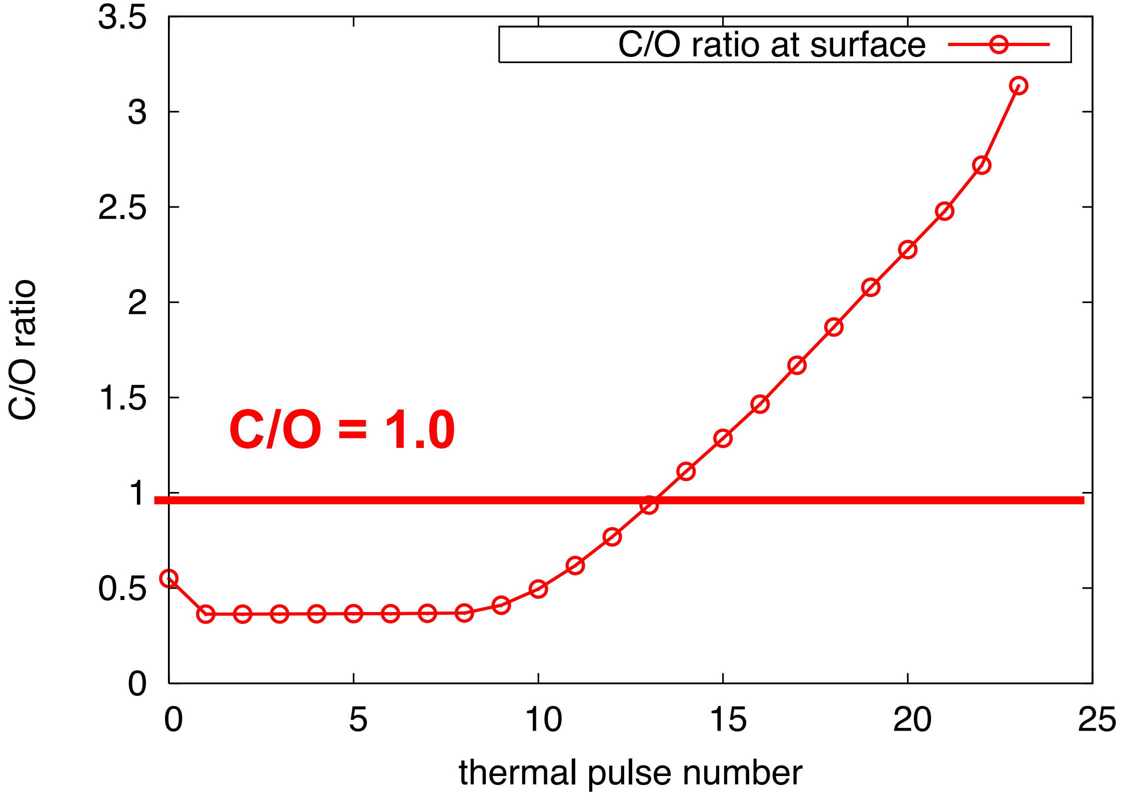
Typical Galactic C-rich AGB star: 1.8Msun, Z = 0.01

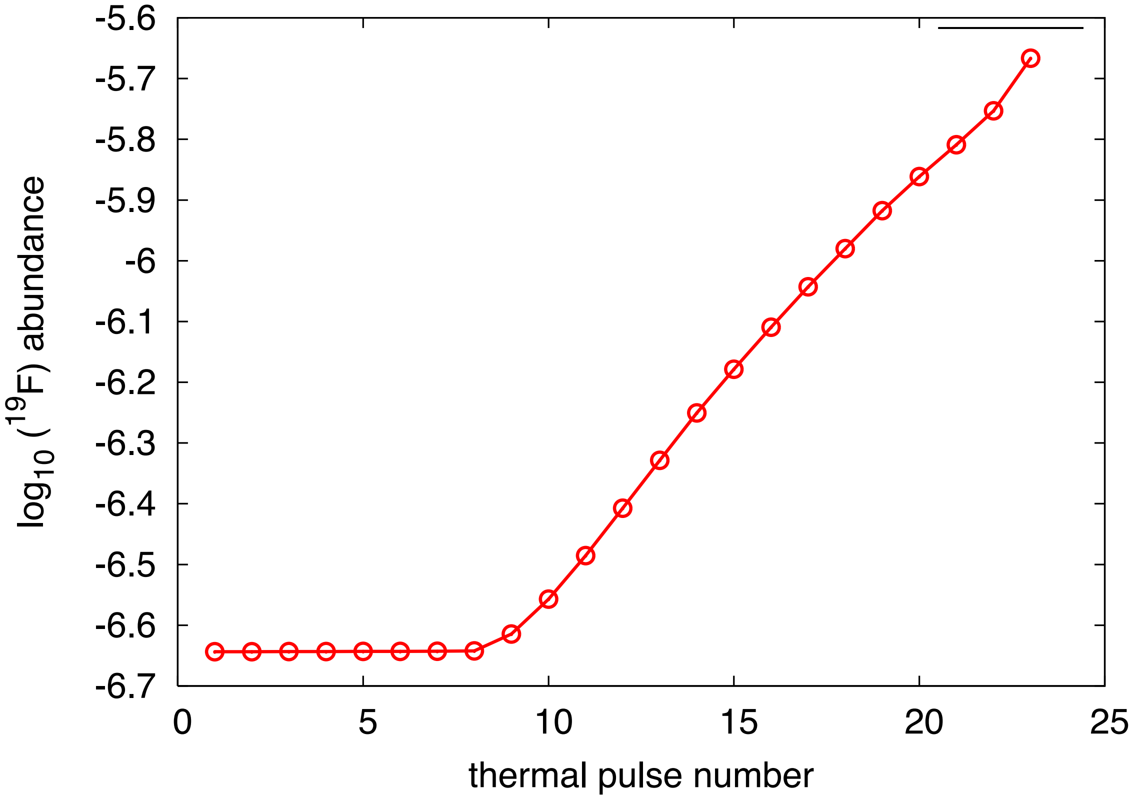


Evolution of abundances at the surface

Example: 3Msun, Z = 0.014

Surface abundance of the C/O ratio (left) and fluorine (right) during the AGB





When C/O > 1, the surface of the star is “C rich”

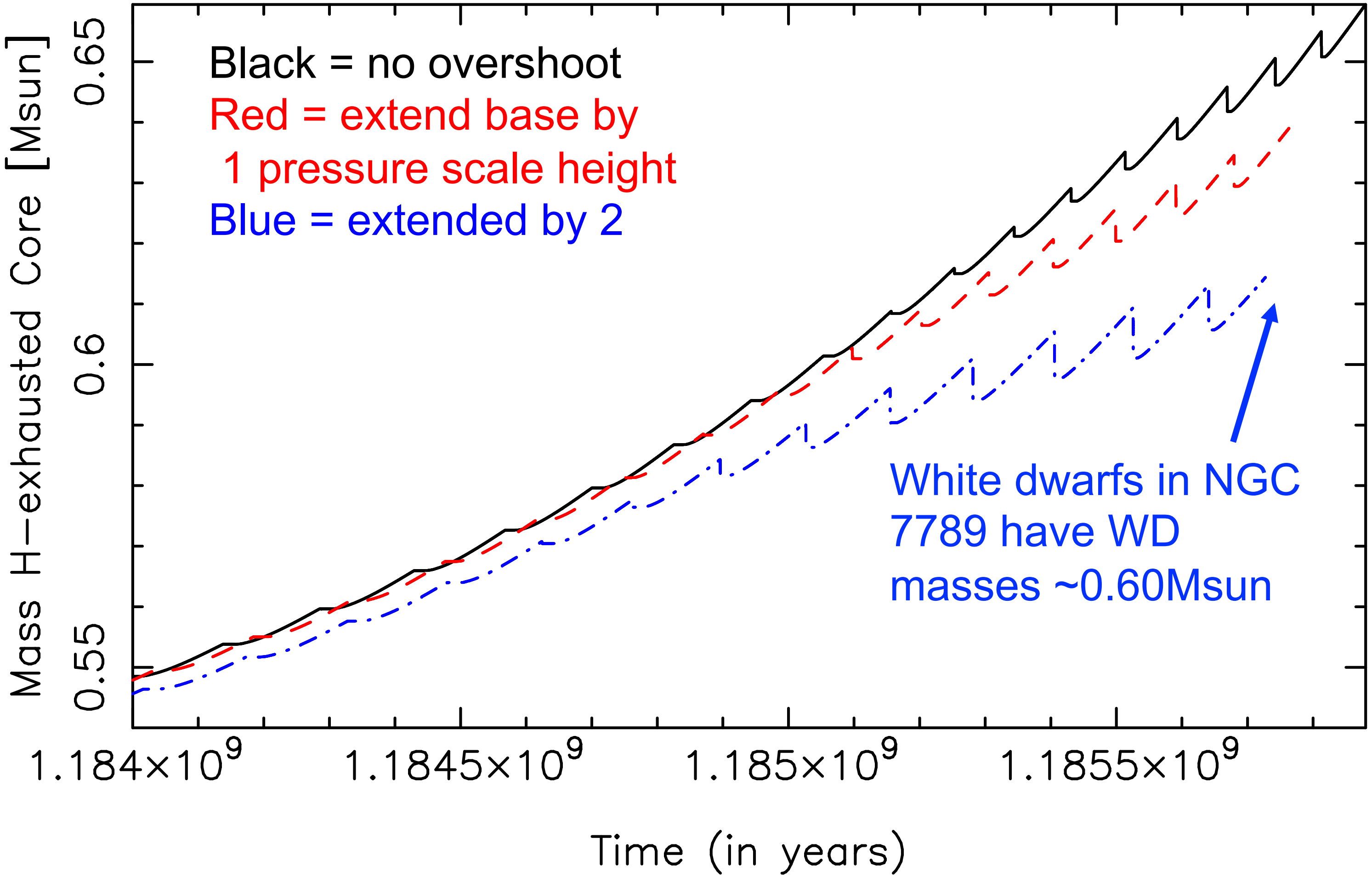
Third dredge-up uncertainties

- It is important to know if the models are providing an accurate description of mixing in real AGB stars
- Because the third dredge-up determines how much He-shell material is mixed from the core to envelope
- Do current models predict enough third dredge-up?
- Or too much?
- And how does mixing vary as a function of mass, metallicity, etc.?

→ *Do the model predict the right mass and luminosity ranges for carbon stars?*

Constraining the amount of mixing

Use the 2Msun, Z = 0.014 model as a test case

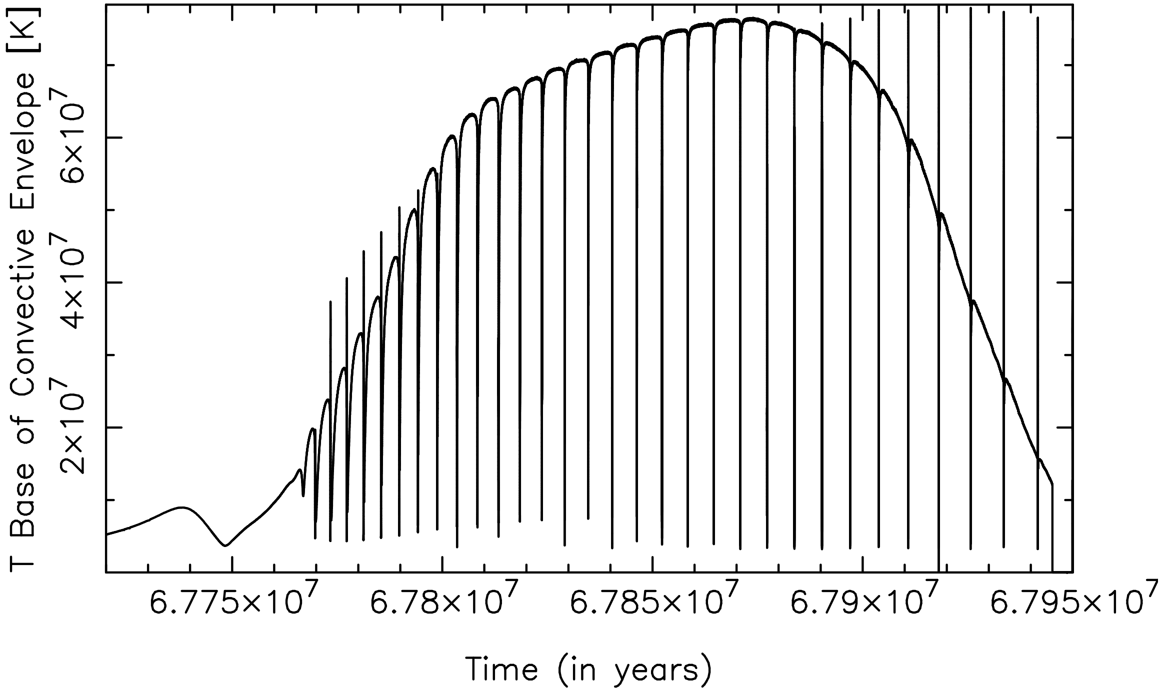


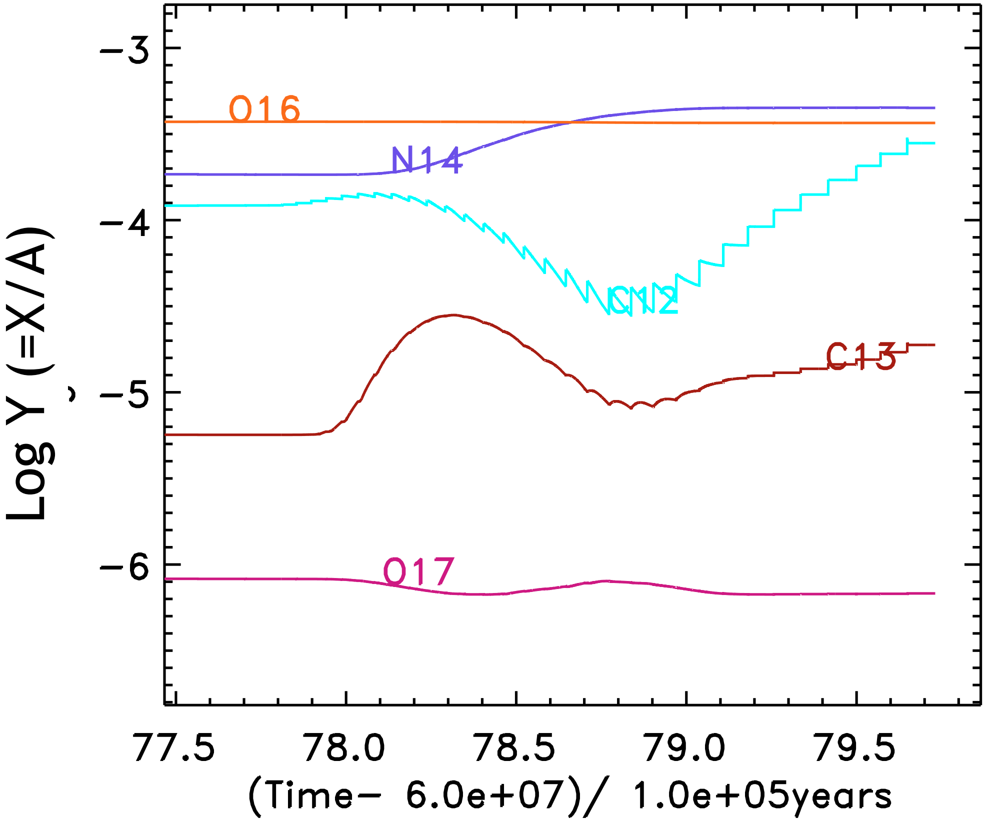
Intermediate-mass AGB stars

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



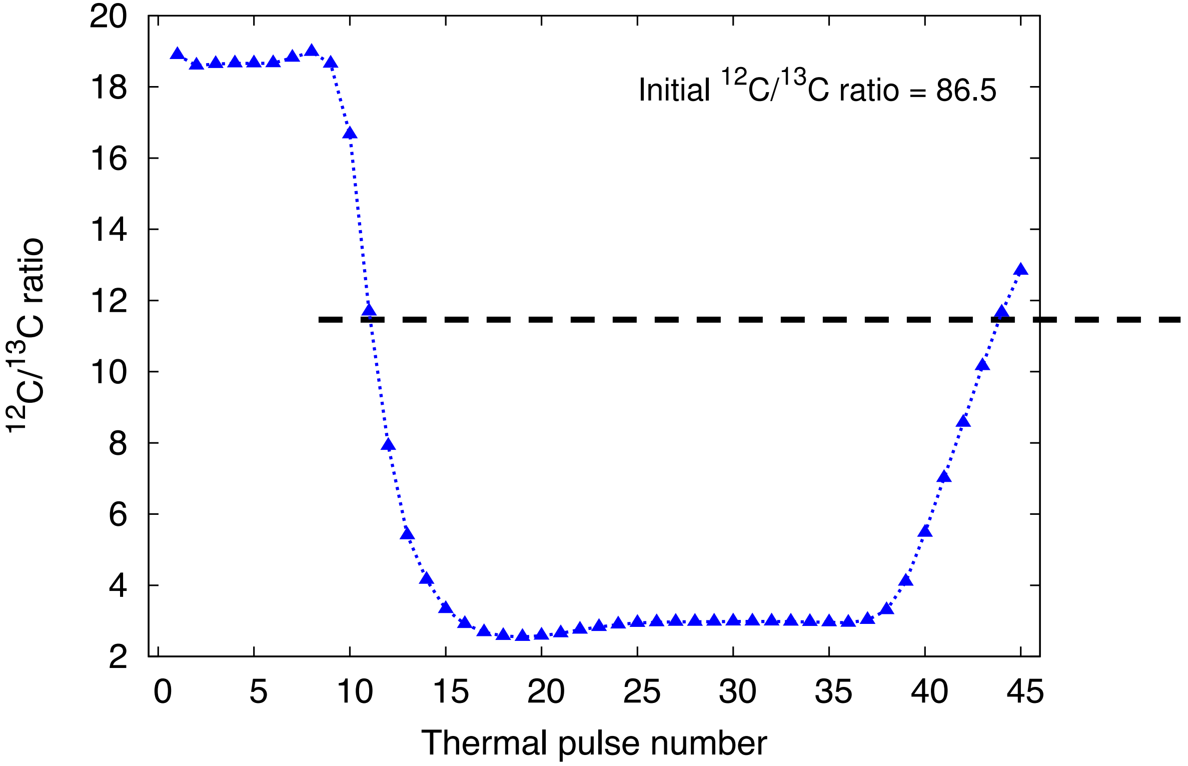


Hot bottom burning & TDU

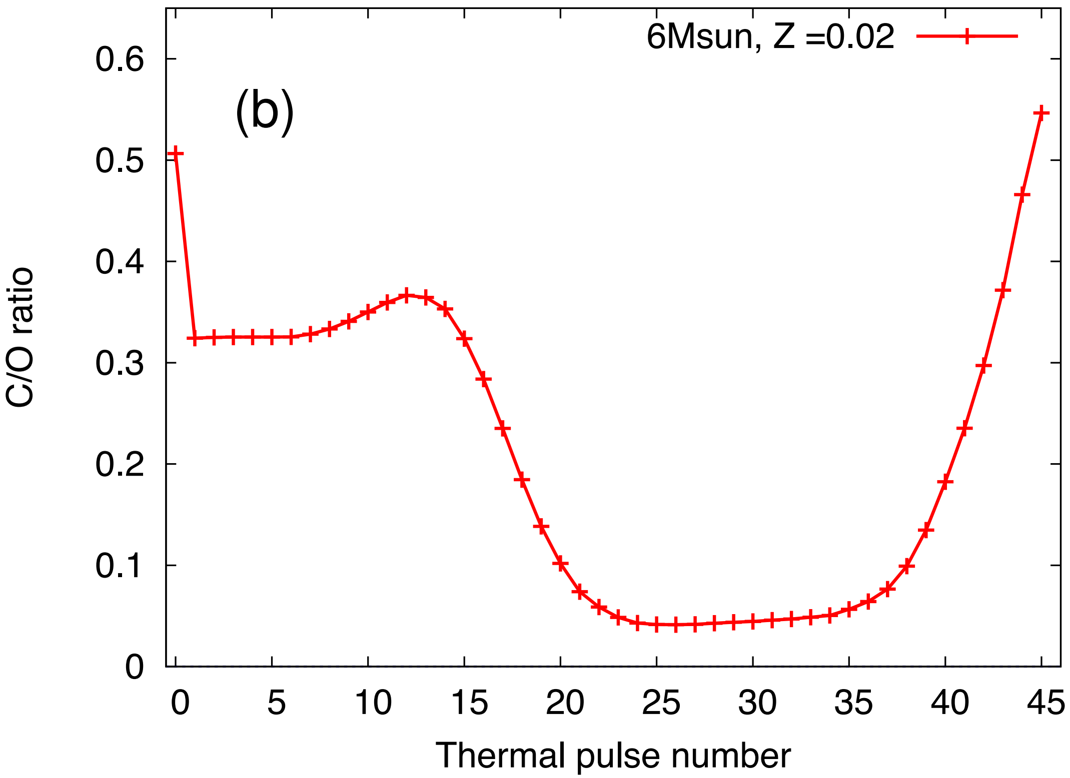
Example: 6Msun, Z = 0.02

Third dredge-up (TDU) and HBB can act together

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



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

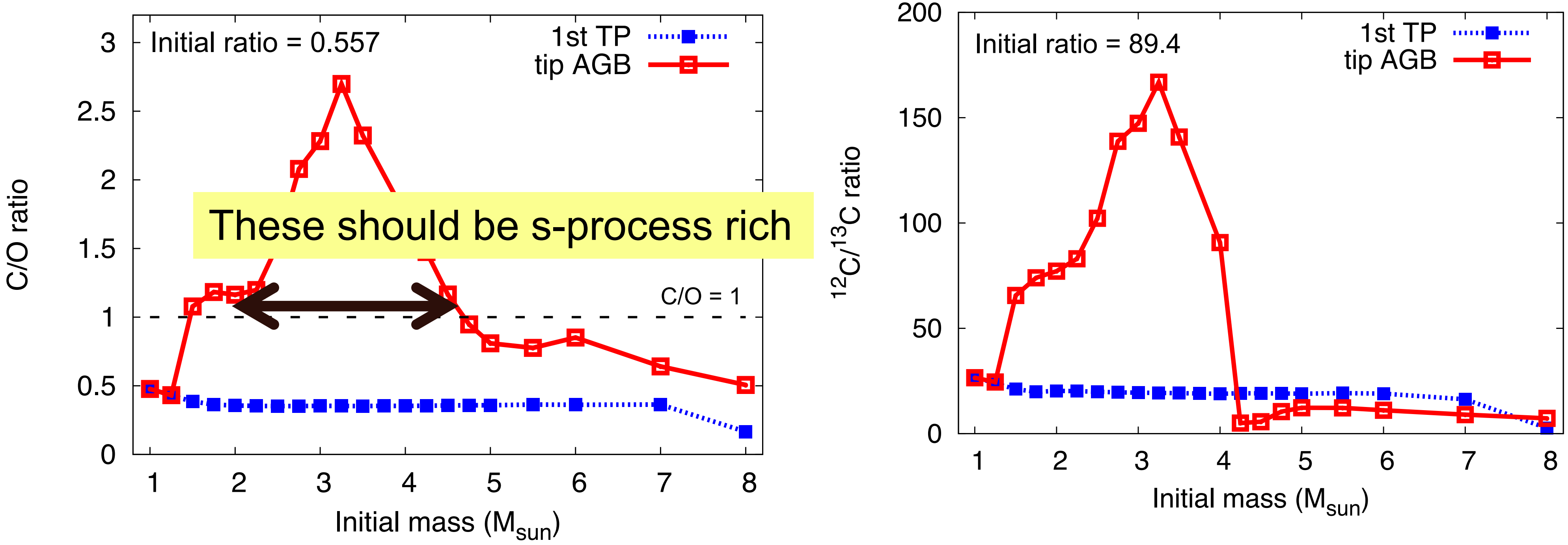


The C/O ratio never exceeds 1

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), **s-process rich**
- **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), s-process rich?
  - M < 1.5Msun: First dredge-up and extra-mixing on RGB

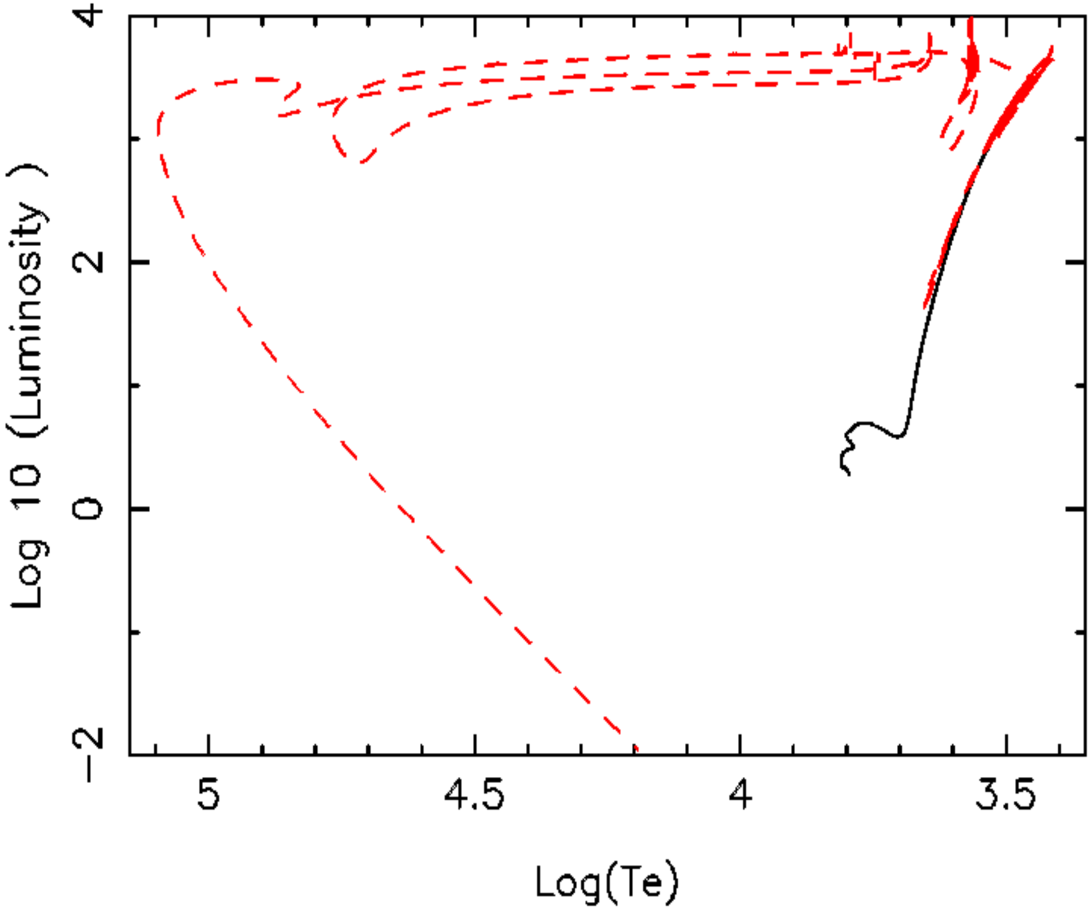
Models of [Fe/H] = 0.0 from Karakas & Lugaro (2016)



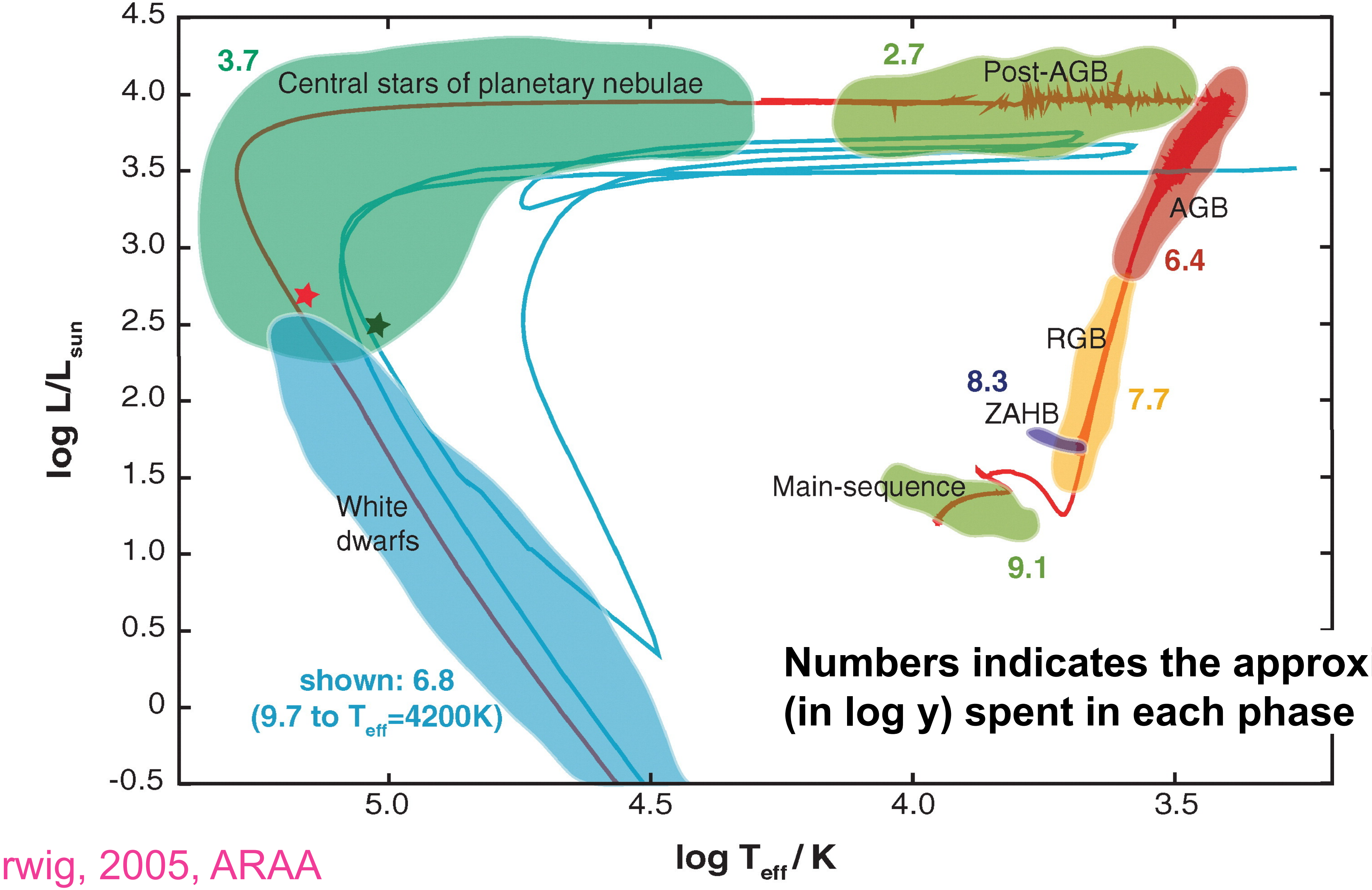
These should be s-process rich

What ends the AGB phase?

- The envelope is being eroded by mass loss from the outside.
- And on the inside the H-shell is moving outward into the envelope.
- Something has to give!
- The largest effect is the mass-loss.
- But eventually the H-shell approaches
  the surface…
- The surface gets hotter
- The star leaves the giant branch…



HR diagram for M=2$M_\odot$ model



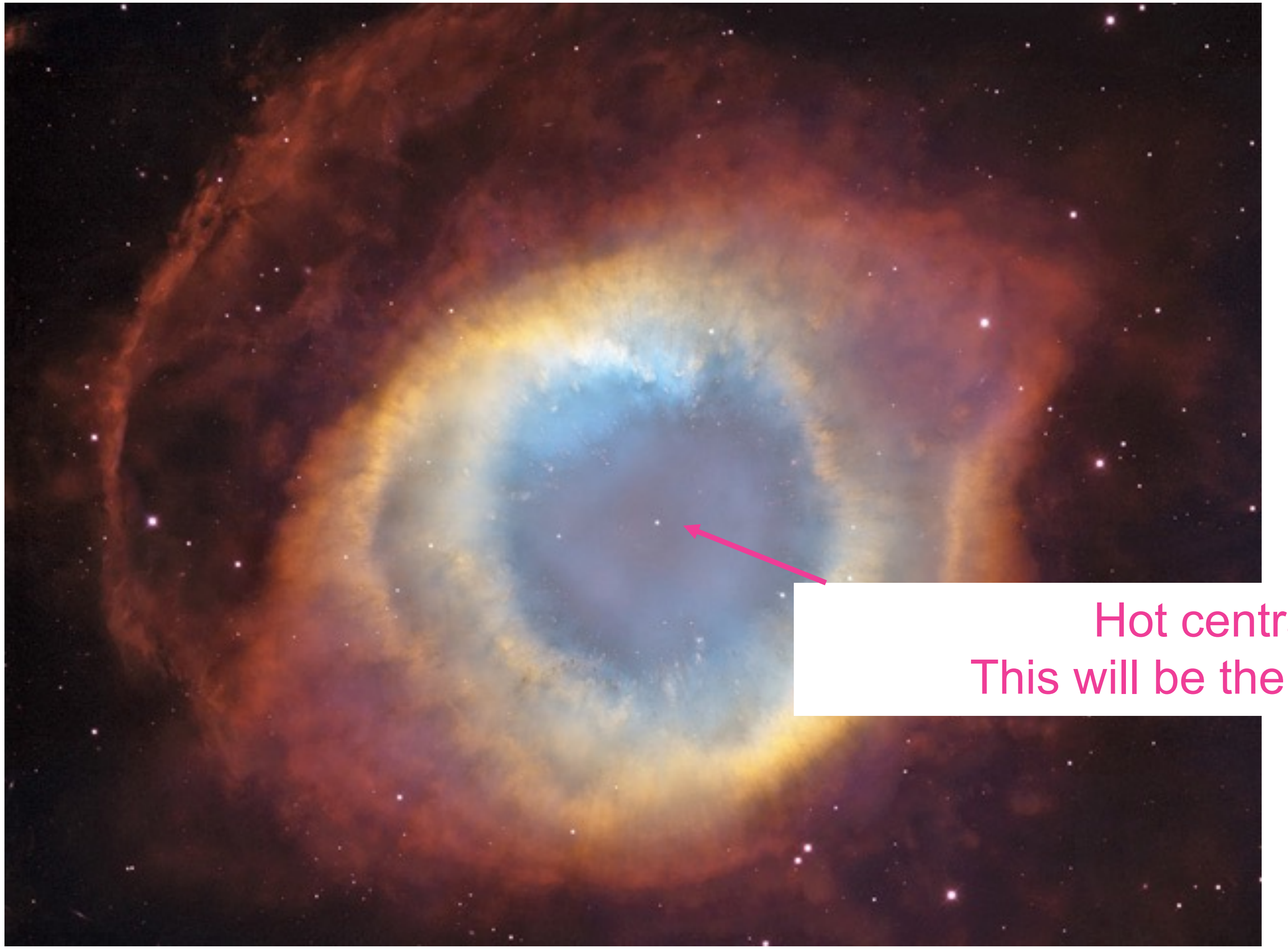
Numbers indicates the approximate time (in log y) spent in each phase

Herwig, 2005, ARAA

Post-AGB stars and Planetary Nebulae

- After leaving the AGB the stars evolve quickly to higher surface temperature, at almost constant luminosity.
- The higher temperatures ionize the circumstellar material.
- They become spectacular planetary nebulae (PN).
- The gaseous PN is the remnant of the envelope that once surrounded the core.
- The glowing nebula is lit by the UV radiation coming from the hot central star.
- Planetary nebulae and their central stars reveal much information about the evolution that took place during the AGB.

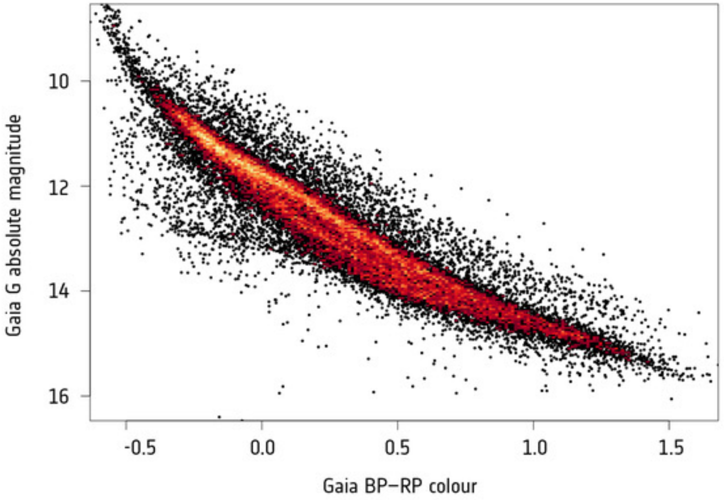
Planetary nebula



Hot central star
This will be the white dwarf

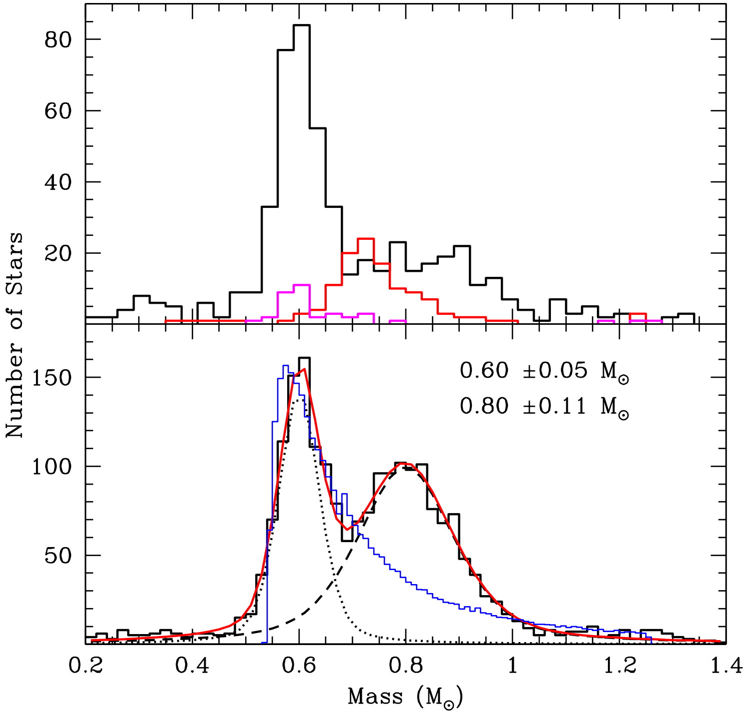
Mass distribution of white dwarfs

We used to have about 250 white dwarfs to play with

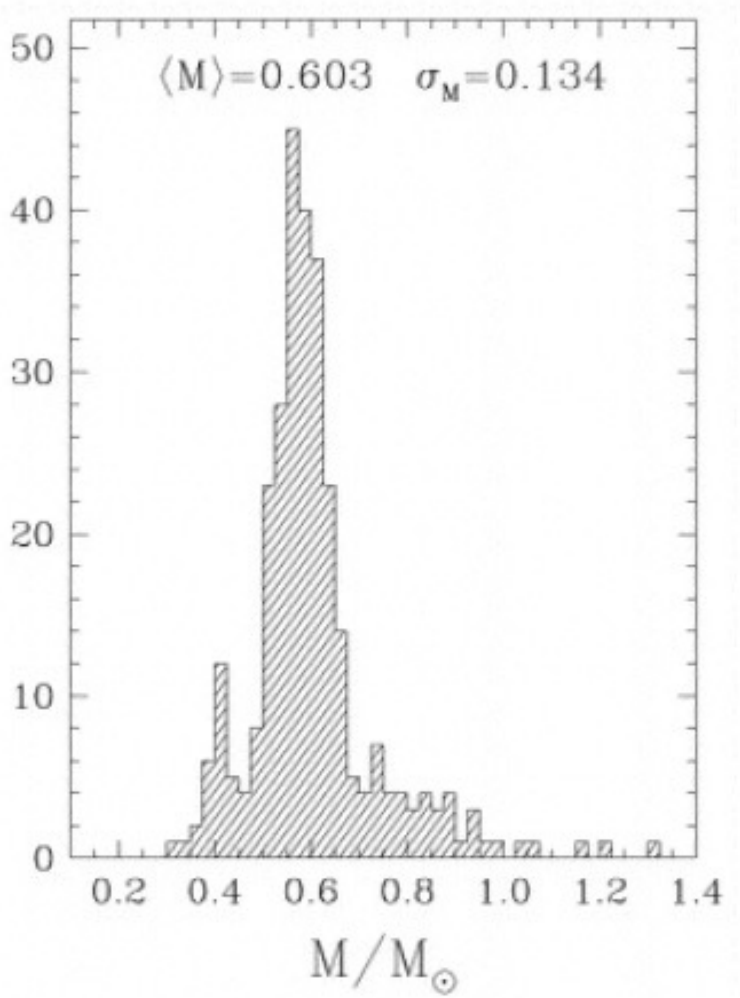


This is a HRD of white dwarfs from Gaia space satellite
Credit: ESA/Gaia

We now have ~14,000 of them!
What can we learn?



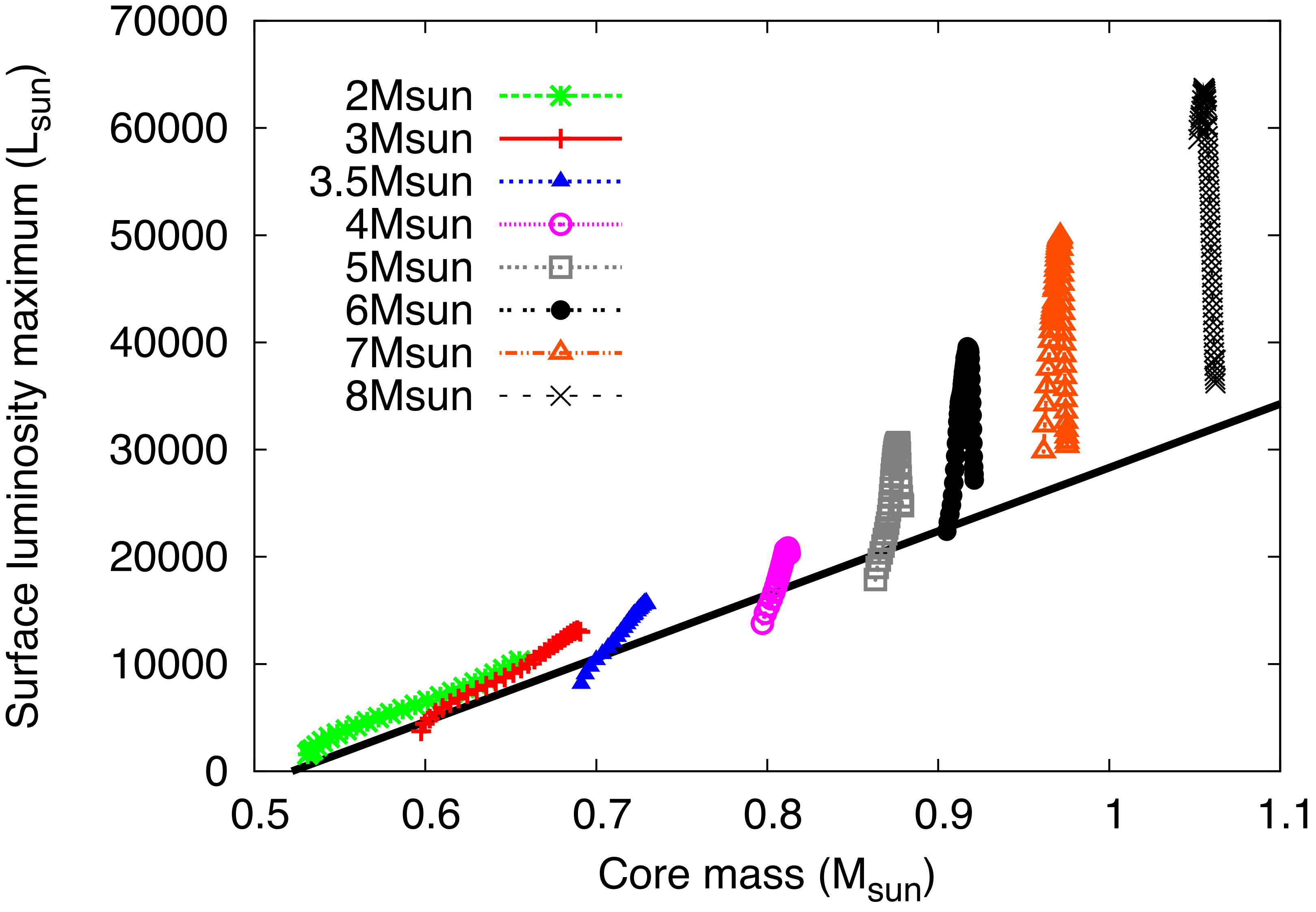
From Kilic et al. (2018)
Evidence of a merged population?



Mini-lab 3 wrap up

- In this lab we examined the structure and evolution of a 3Msun star during the thermally-pulsing AGB phase.
- We examined the thermal pulse cycle in some detail.
- And the effect of convective boundary mixing on the thermal pulse cycle.
- What did you find?
- The behaviour of the no mix and mix cases were qualitatively the same – they should be!
- But the mix case was brighter and larger (and hence, cooler).
- Why do we observe these differences? Let’s examine the core-mass luminosity relationship…

Core-mass luminosity relationship

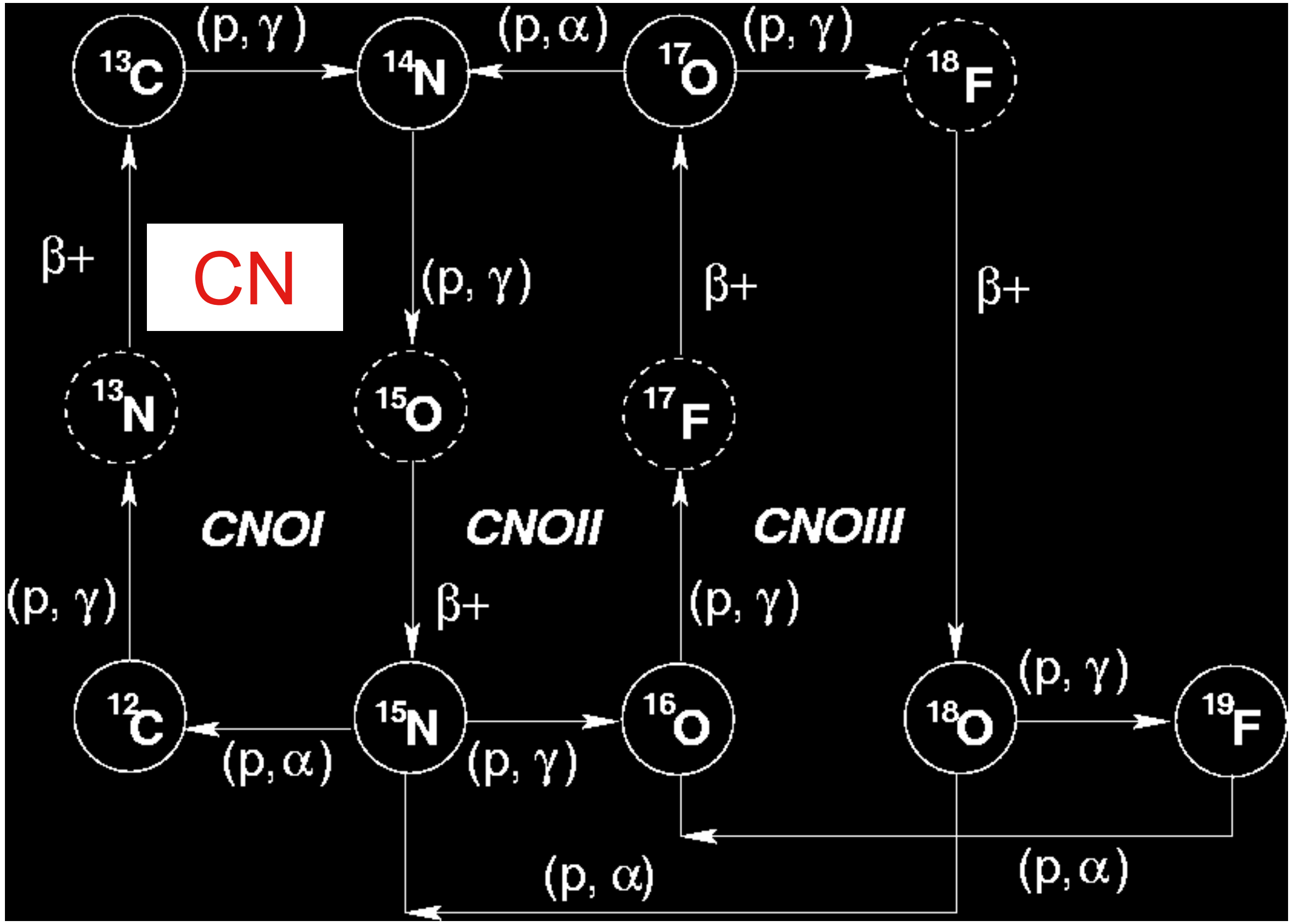


Thanks for listening!

Usually a wider binary

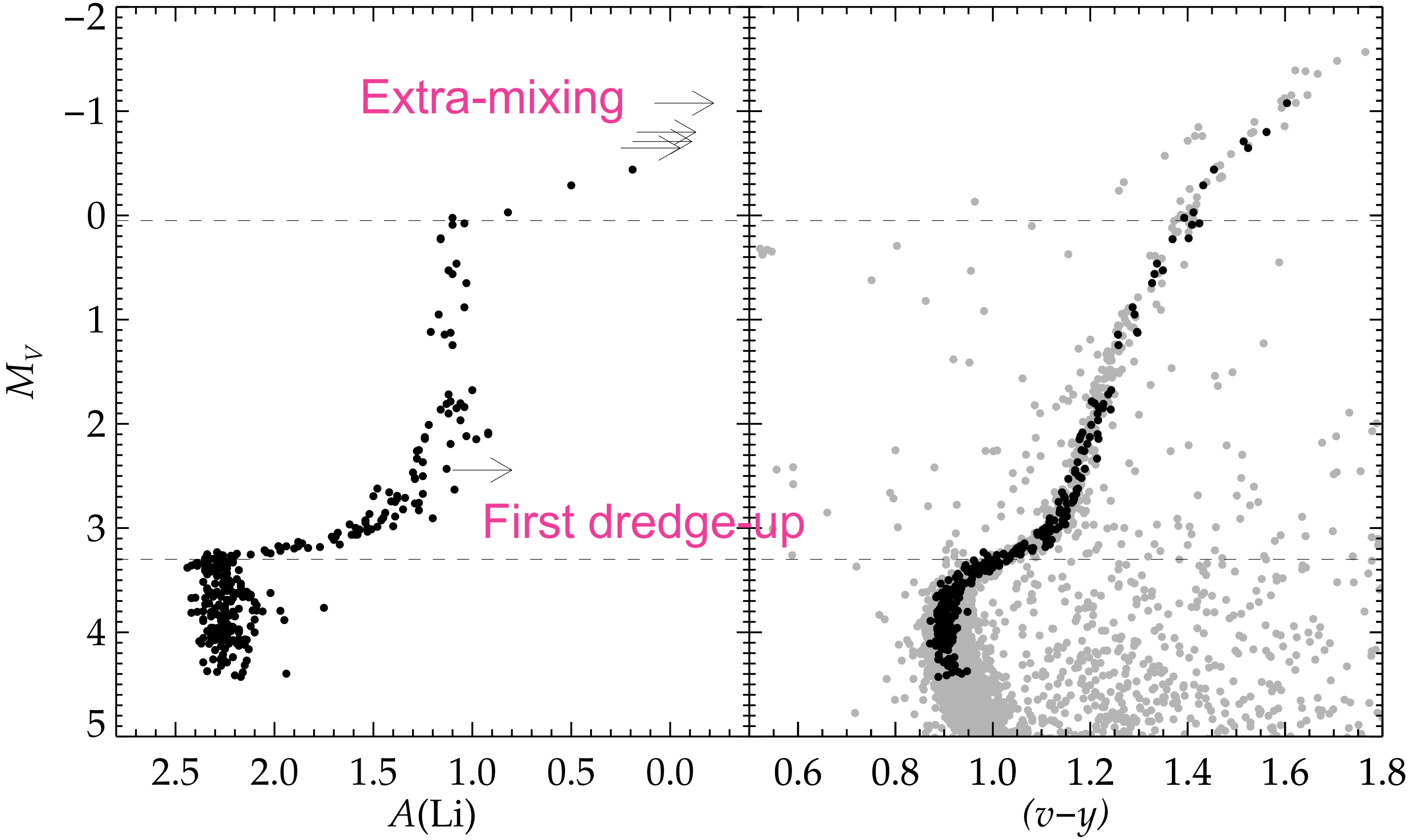
EXTRA SLIDES

CNO cycles


^{13}C
(p, γ)
^{14}N
(p, α)
^{17}O
(p, γ)
^{18}F
β+
CN
(p, γ)
β+
β+
^{13}N
^{15}O
^{17}F
CNOI
CNOII
CNOIII
(p, γ)
β+
(p, γ)
^{12}C
^{15}N
^{16}O
^{18}O
(p, γ)
^{19}F
(p, α)
(p, γ)
(p, α)
(p, α)

Demonstration of mixing on the RGB

Lind et al. (2009) examined the Li abundance in an old metal-poor cluster, NGC 6397 along the RGB:



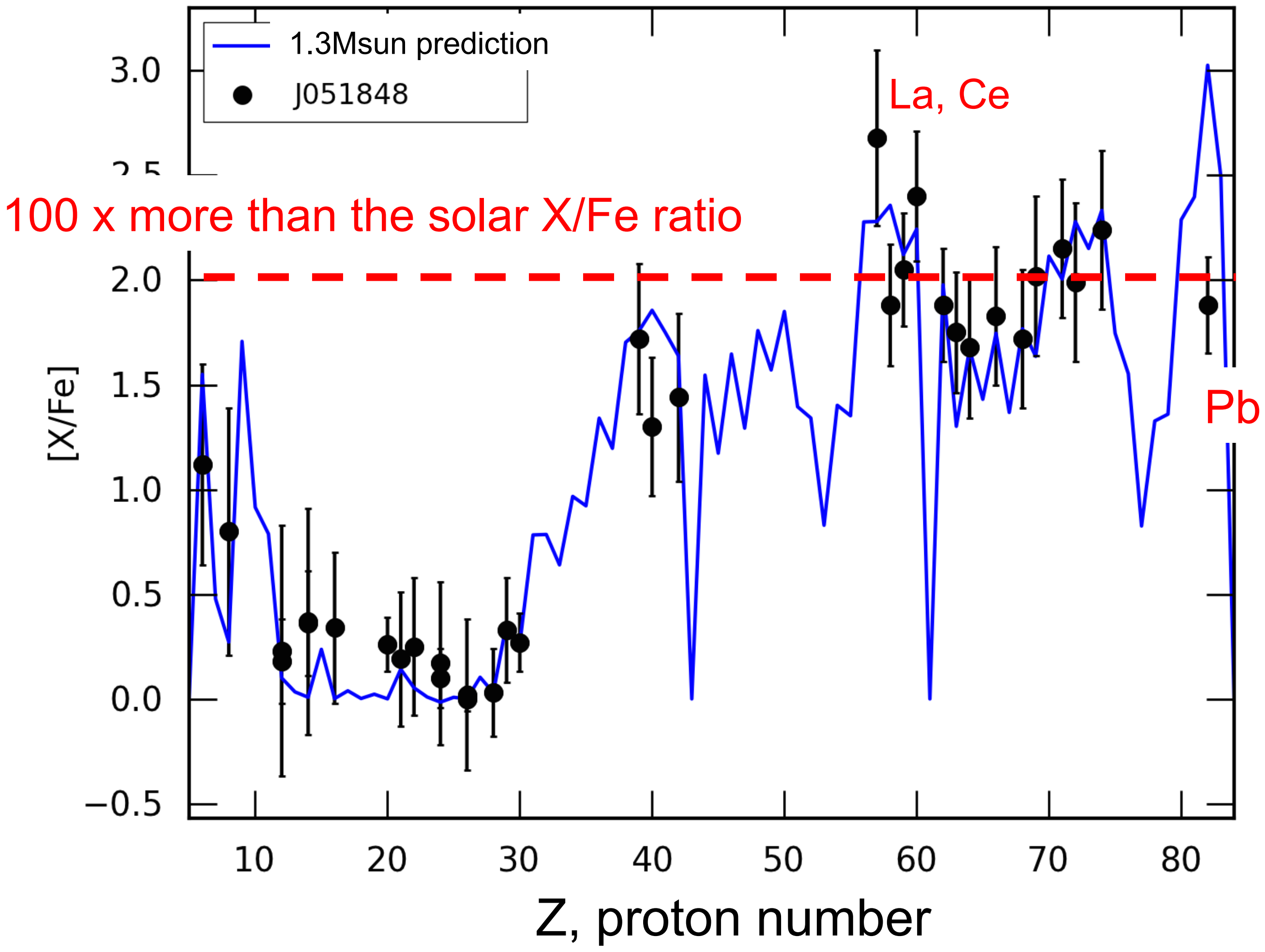
How are we sure AGB stars make s-process elements?

- Observations show that low-mass AGB stars are the *main* site of the s-process in nature.
- Typically [*s*/Fe] ≥ +1.0, that is, an order of magnitude increase of heavy elements over Fe, relative to the Sun.
- Stardust SiC grains from low-mass C-rich AGB stars show strong s-process signatures.
- Massive stars also make s-process elements, especially the first peak up to Sr

Reference

- Textbook chapter by Lugaro, Karakas & Dell'Agli in Sachiko Amari's textbook on stardust grains.

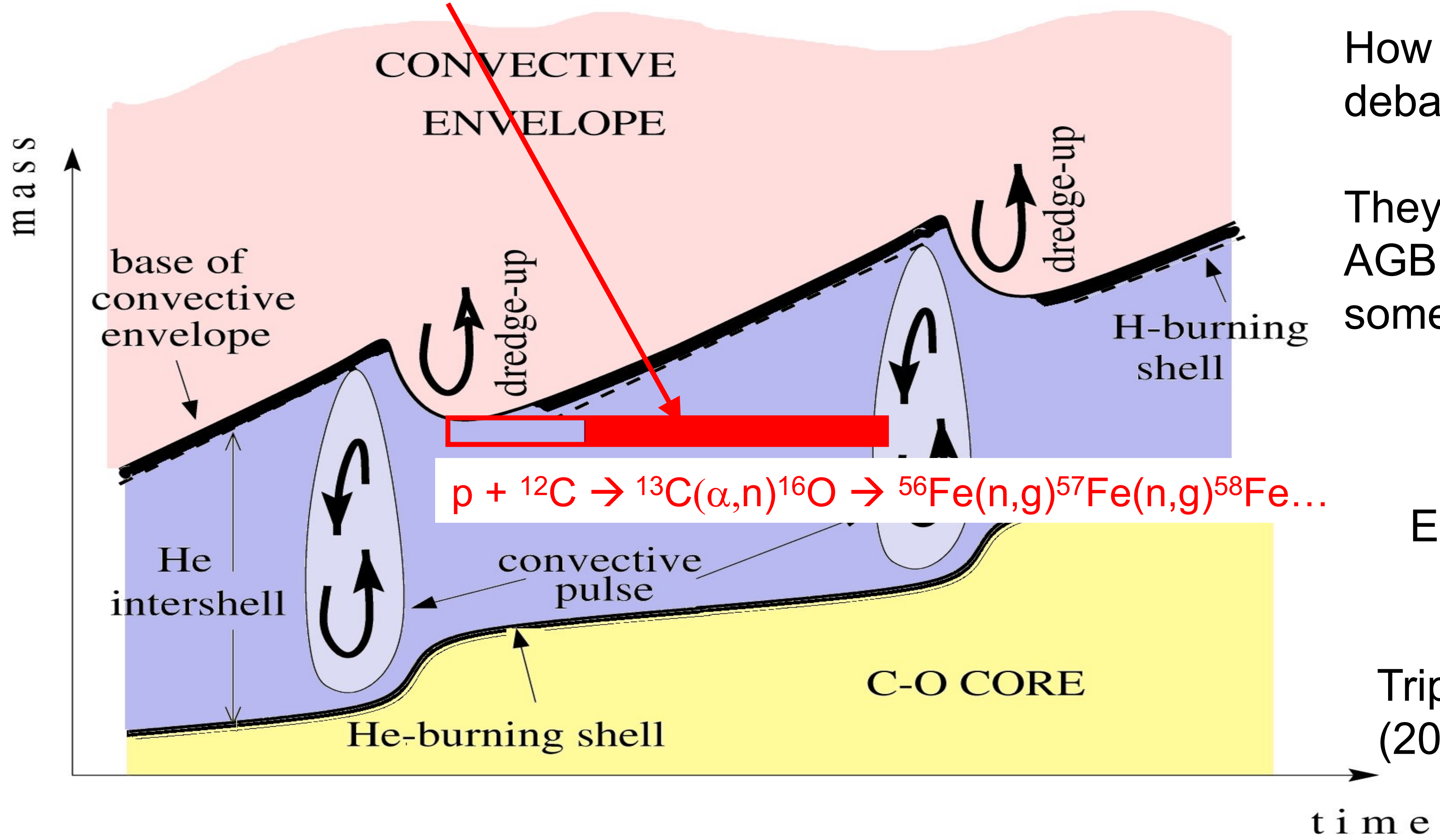
Post-AGB star in the Large Magellanic Clouds



Credit: Kenneth De Smedt (KU Leuven)

The s-process in low-mass AGB stars

Neutrons are released in ${}^{13}C$ pockets – these form by mixing hydrogen into the radiative He-shell (Straniero et al. 1997)



$p + {}^{12}C \rightarrow {}^{13}C(\alpha,n){}^{16}O \rightarrow {}^{56}Fe(n,g){}^{57}Fe(n,g){}^{58}Fe$…

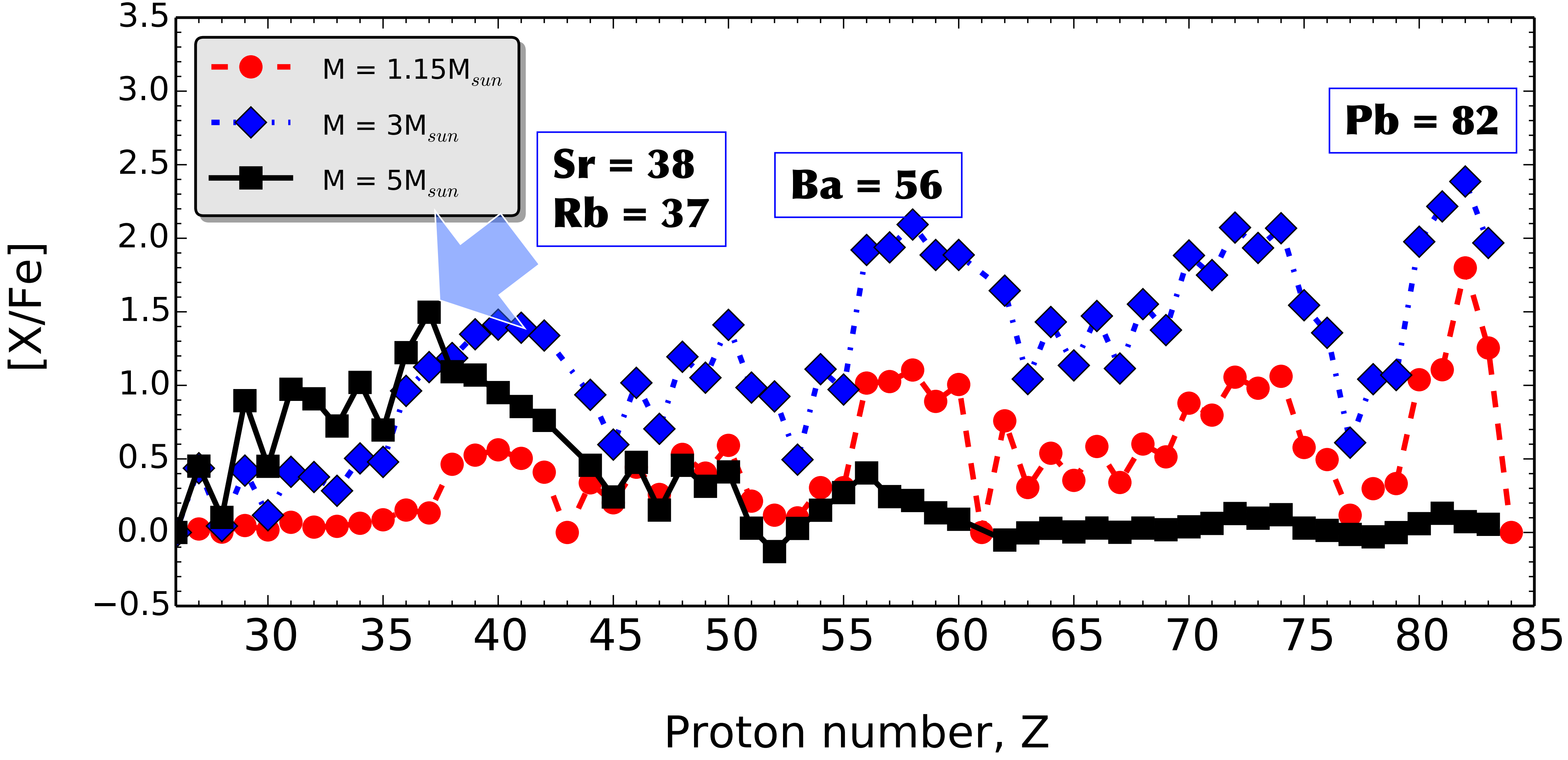
How ${}^{13}C$ pockets form is still debated.

They do not form self consistently in AGB model calculations and require some mixing of protons, somehow.

E.g., Gallino et al. (1998), Goriely (2000), Lugaro et al. (2012), Cristallo et al. (2009, 2015), Trippella et al. (2016), Battino et al. (2016, 2019), Buntain et al. (2017), Busso et al. (2021)

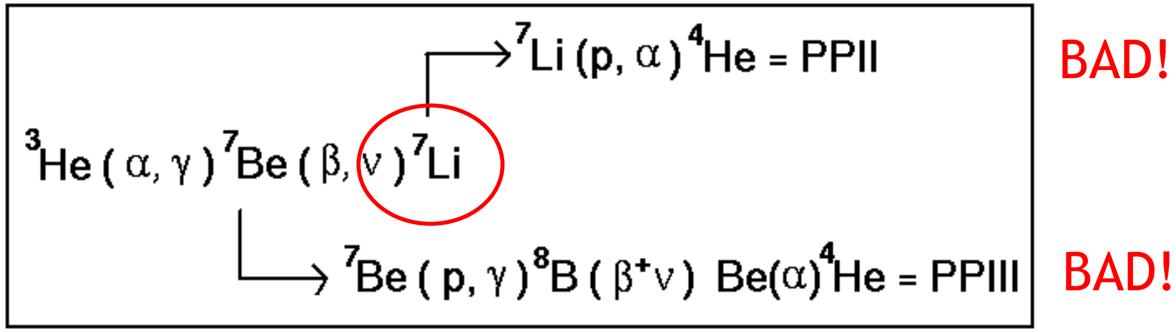
The s-process in AGB models

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



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 $^{3}\mathrm{He}(\alpha, \gamma)^{7}\mathrm{Be}$
- and then to use convection to move the ^{7}Be away from the hot region before it can complete the PPII or PPIII chains:



$^{7}\mathrm{Li}\,(p, \alpha)\,^{4}\mathrm{He}$ = PPII

BAD!

$^{3}\mathrm{He}\,(\alpha, \gamma)\,^{7}\mathrm{Be}\,(\beta, \nu)\,^{7}\mathrm{Li}$

$^{7}\mathrm{Be}\,(p, \gamma)\,^{8}\mathrm{B}\,(\beta^{+}\nu)\ \mathrm{Be}(\alpha)\,^{4}\mathrm{He}$ = PPIII

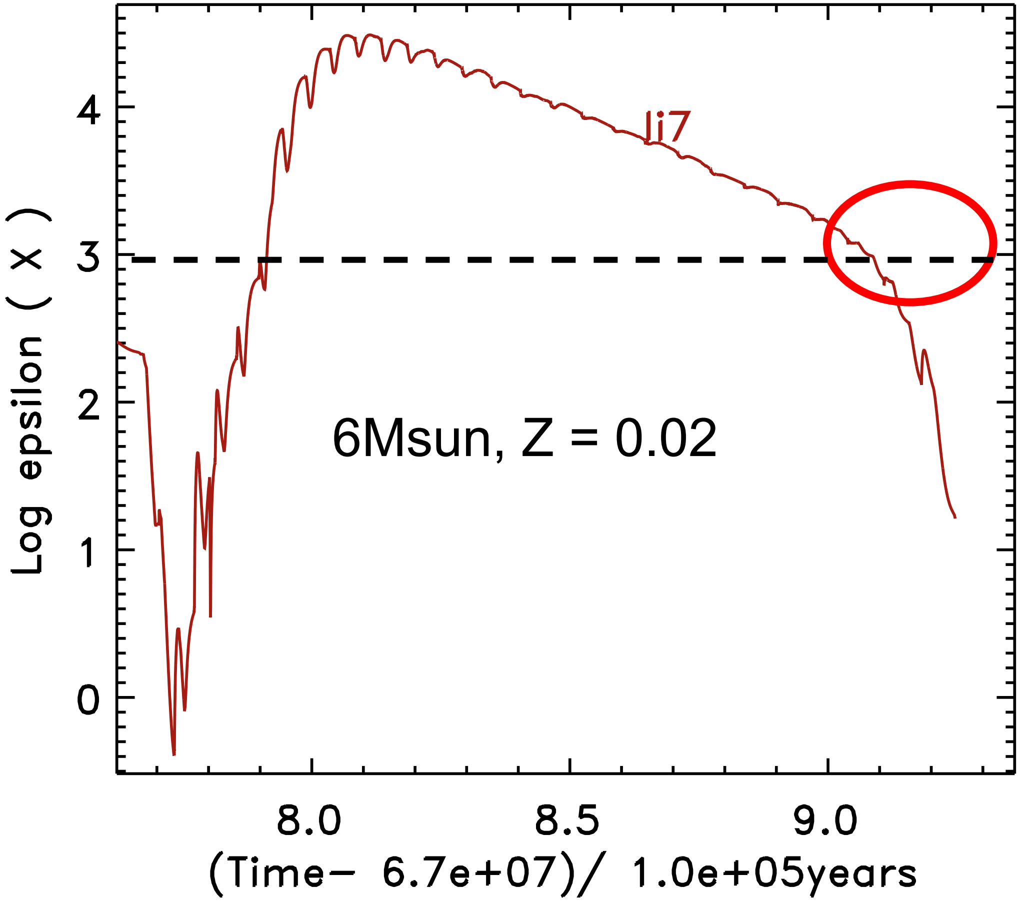
BAD!

Cameron-Fowler mechanism

Lithium production

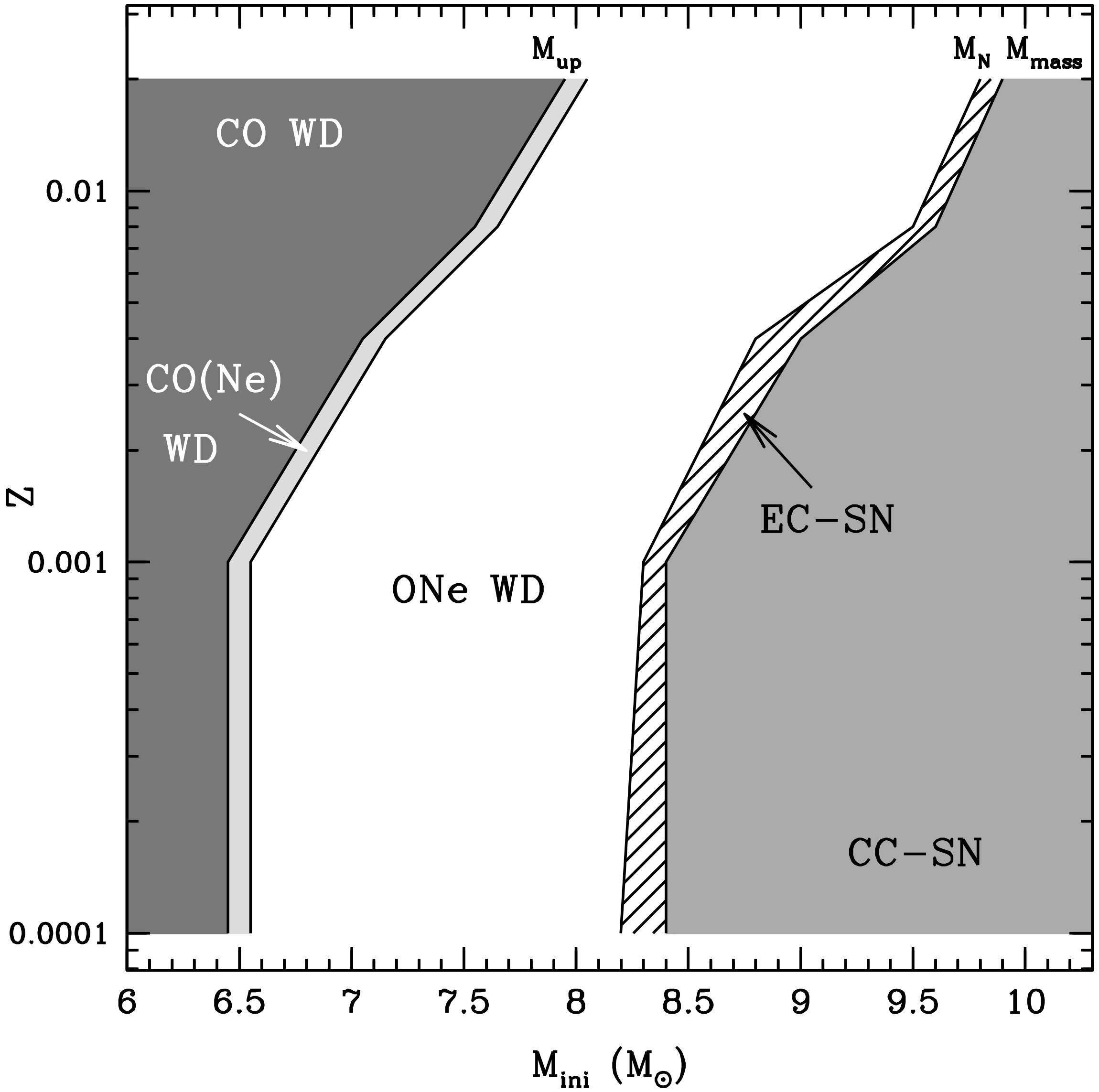
Lithium is produced by the Cameron-Fowler mechanism: ^{7}Be is transported by convection, where it captures an electron to produce ^{7}Li

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



Super-AGB stars as a function of metallicity

- The fate of super-AGB stars is unknown.
- If the core mass grows to ~1.37Msun then the star may explode as an electron-capture supernovae (Nomoto 1984).
- If mass-loss erodes the envelope before this happens, the star ends its life as a massive, O-Ne white dwarf (e.g., Poelarends et al. 2008).
- We haven't found super-AGB stars… but we predict that they should be the brightest AGB stars in young stellar populations, with Mbol ~ −7.6, brighter than the traditional AGB limit (Mbol ~ −7.1)



From Doherty et al. (2015)

Products of nucleosynthesis

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

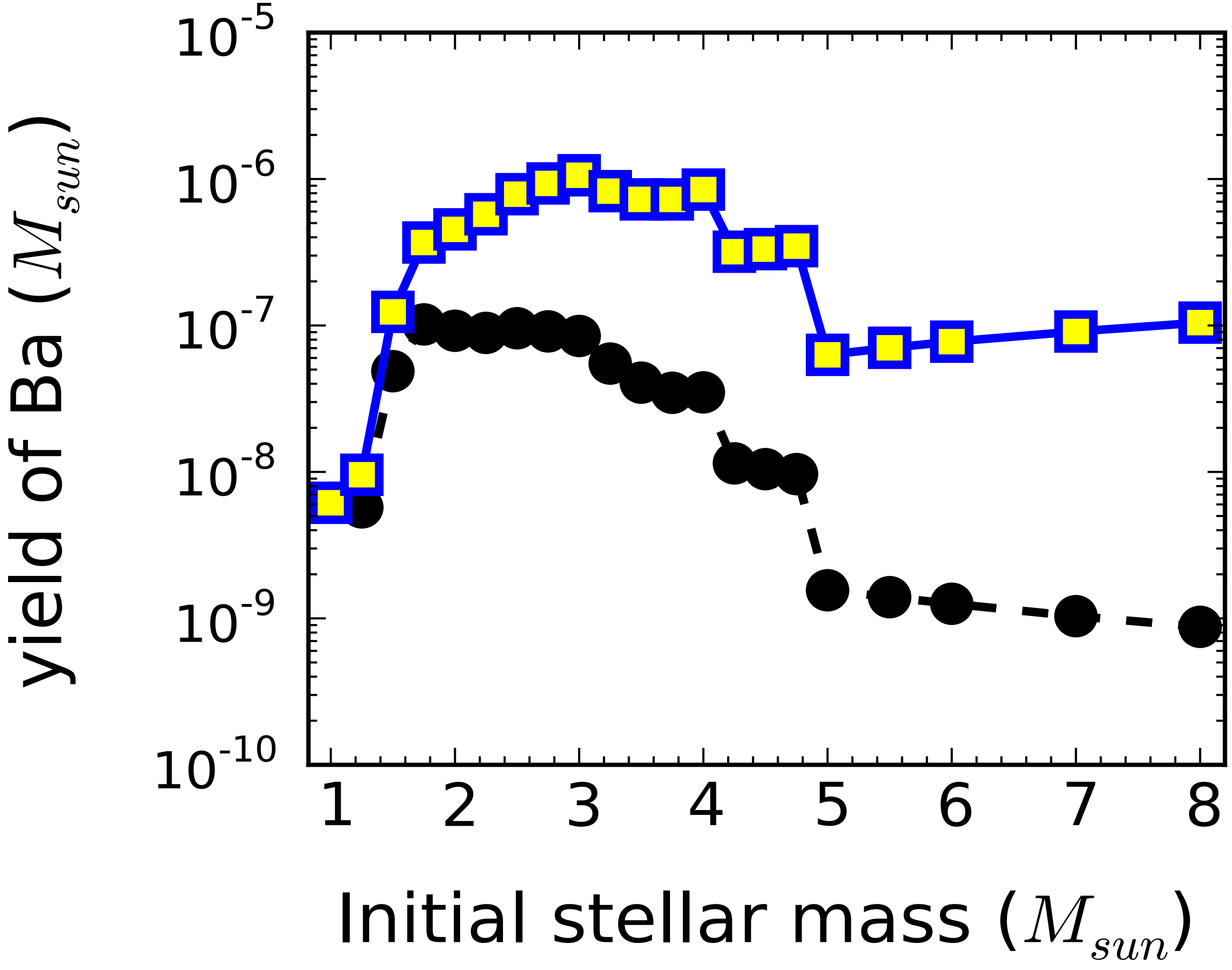
During the AGB, they have shells burning H and He:

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 TP-AGB phase of evolution

Theoretical yields for whole stellar populations

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



Yield = amount of an element ejected over the star’s lifetime

Black dots = weighted by an initial mass function

What is missing?

- Extended nuclear networks to include i-process.
- Stellar yield sets of very metal-poor AGB stars
- Metal-rich? See Giulia Cinquegrana’s talk