Heaven's Kitchens

Origins of the Chemical Elements

David L. Lambert
The W.J. McDonald Observatory

How I became interested in astronomical gastronomy!

WITHOUT FAME

THE ROMANCE OF A PROFESSION

by

OTTO EISENSCHIML

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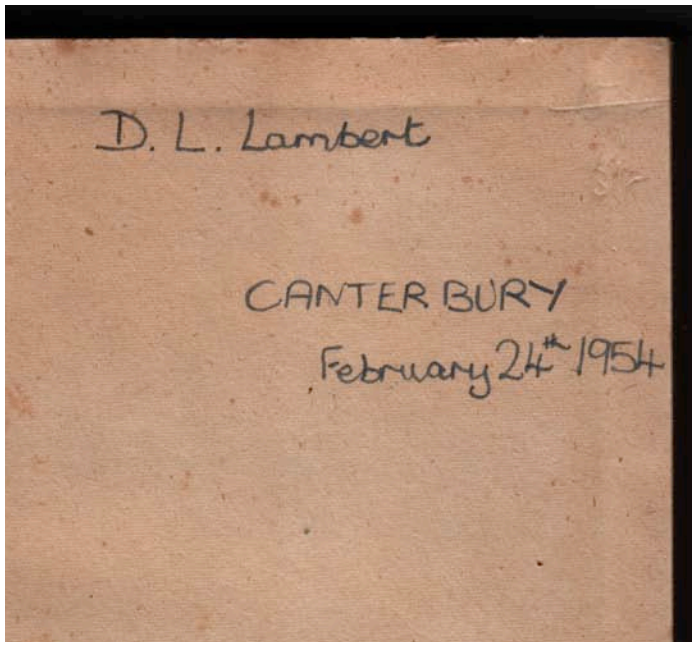
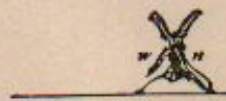


FRONTIERS OF ASTRONOMY

by

FRED HOYLE



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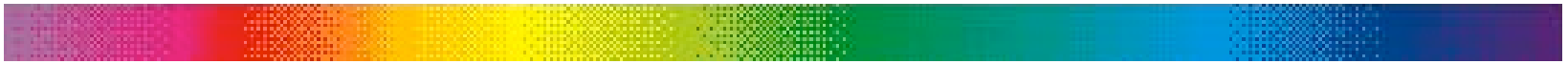
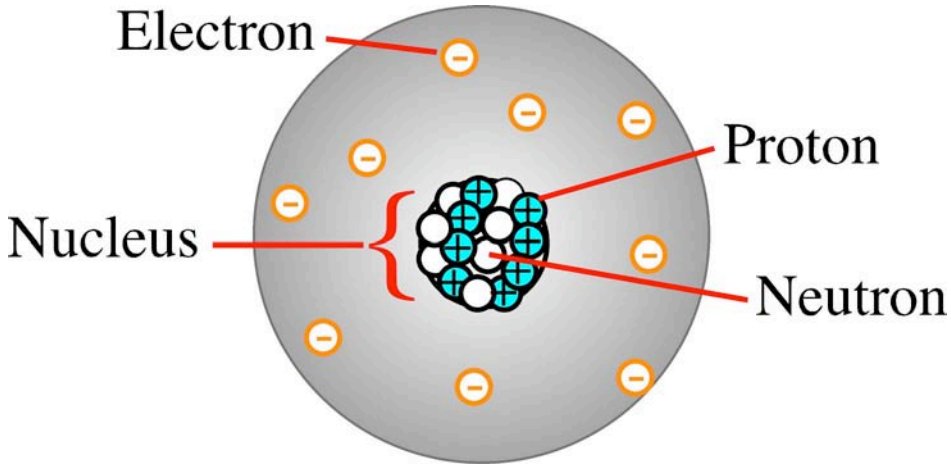


I mean by elements, as those chemists that speak plainest do by their Principles, certain primitive and simple, or perfectly unmingled bodies, which not being made of any other bodies, or of one another, are the ingredients of which all perfectly mixt bodies are immediately compounded.

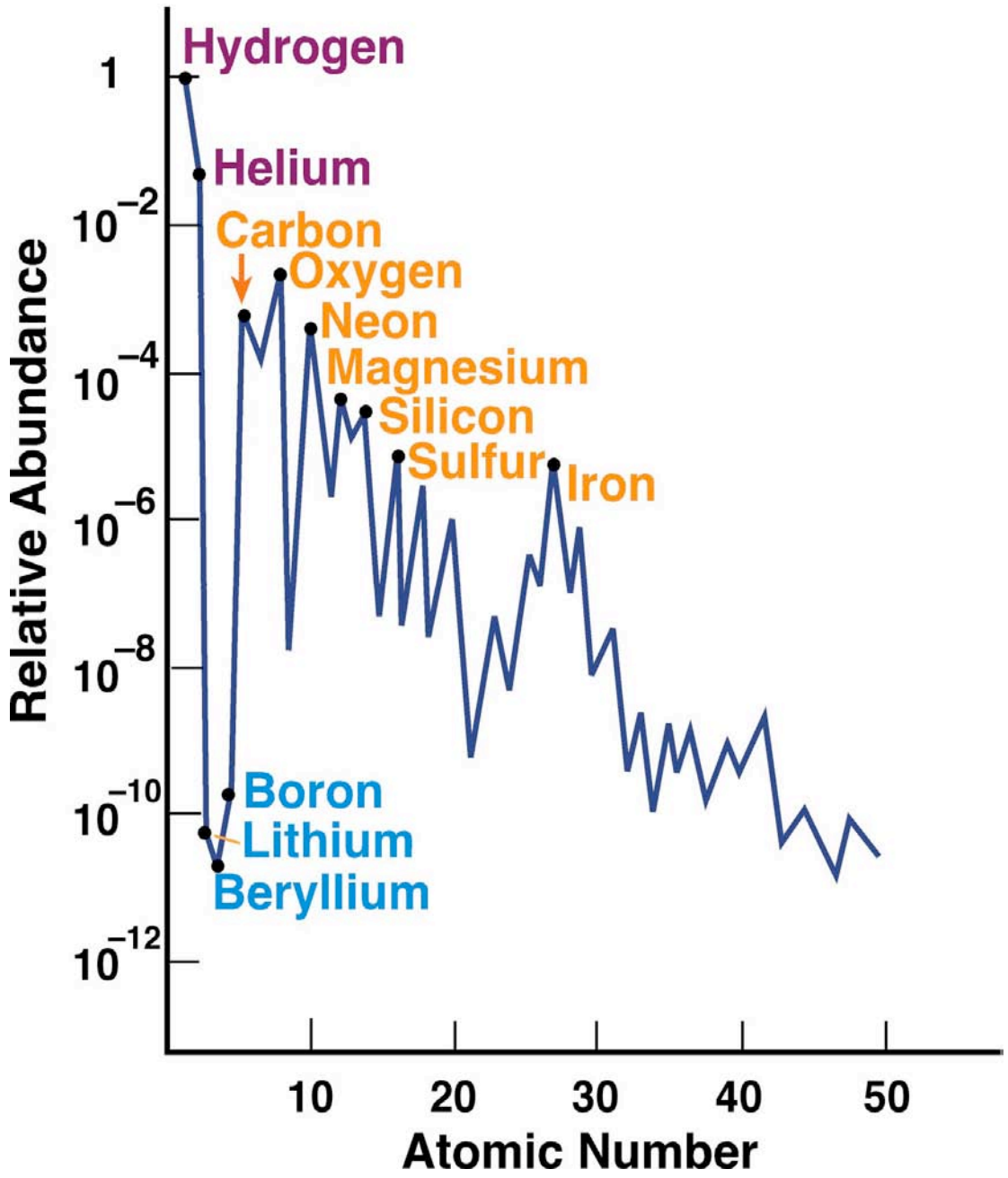
Robert Boyle

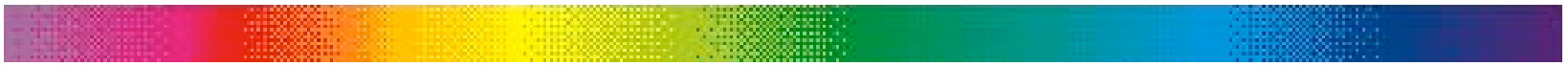
The Sceptical Chemist, 1661

- An atom consists of a ‘large’ electron cloud around a ‘tiny’ nucleus
- Electrons have negative charge
- Nucleus has
  - protons of positive charge
  - neutrons of no charge.



- Elements are distinguished by Atomic Number, Z = number of protons in the nucleus
- Eighty-one natural elements run from Hydrogen (Z=1) to Bismuth (Z = 83).
- Technetium (Z = 43) and Promethium (Z = 61) are radioactive and have decayed.
- There are a few naturally occurring radioactive active elements: Uranium (Z = 92) and Thorium (Z = 90) and their decay products.


Hydrogen
Helium
Carbon
Oxygen
Neon
Magnesium
Silicon
Sulfur
Iron
Boron
Lithium
Beryllium
Relative Abundance
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10
20
30
40
50
Atomic Number



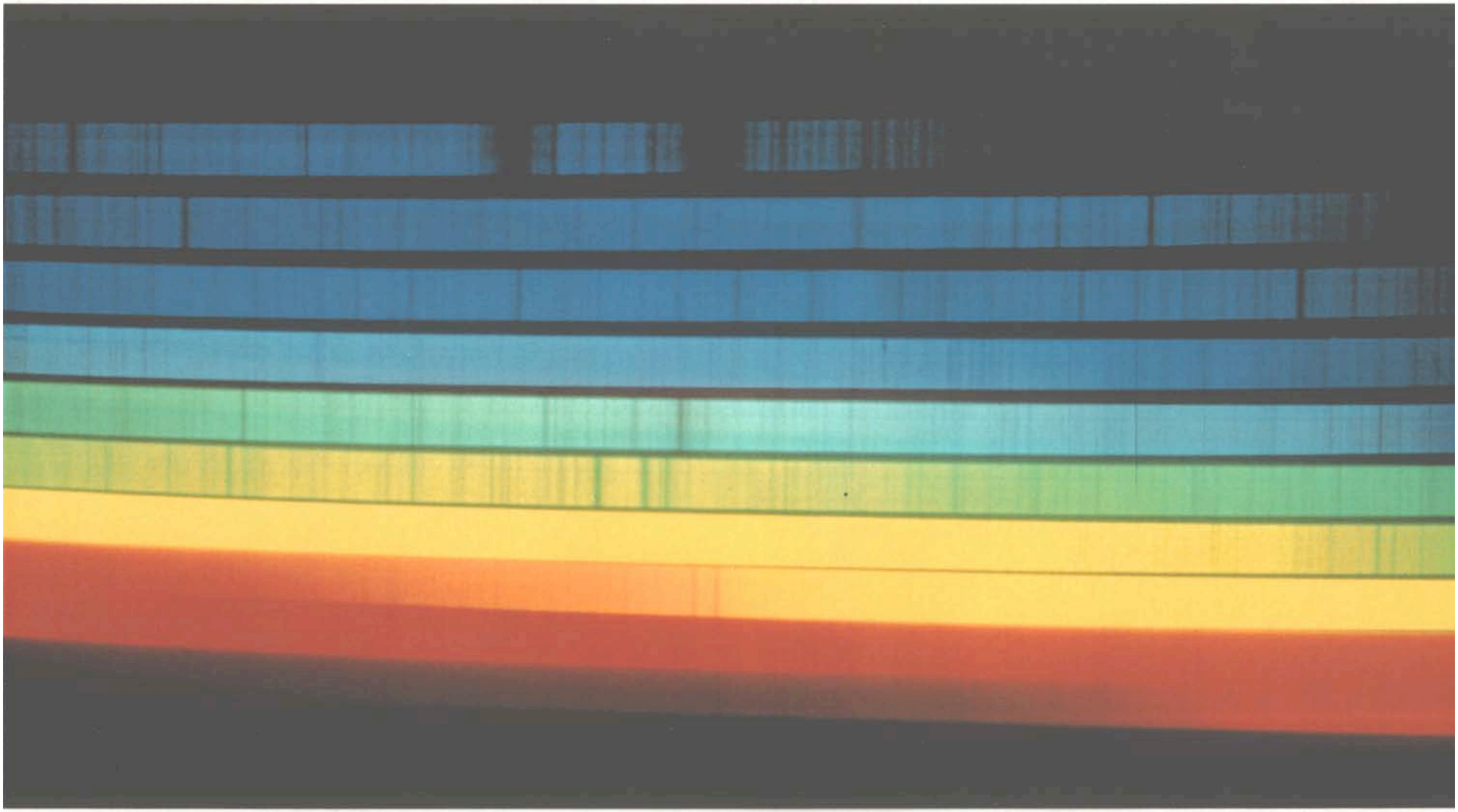
How, when, and where were the chemical elements synthesized?

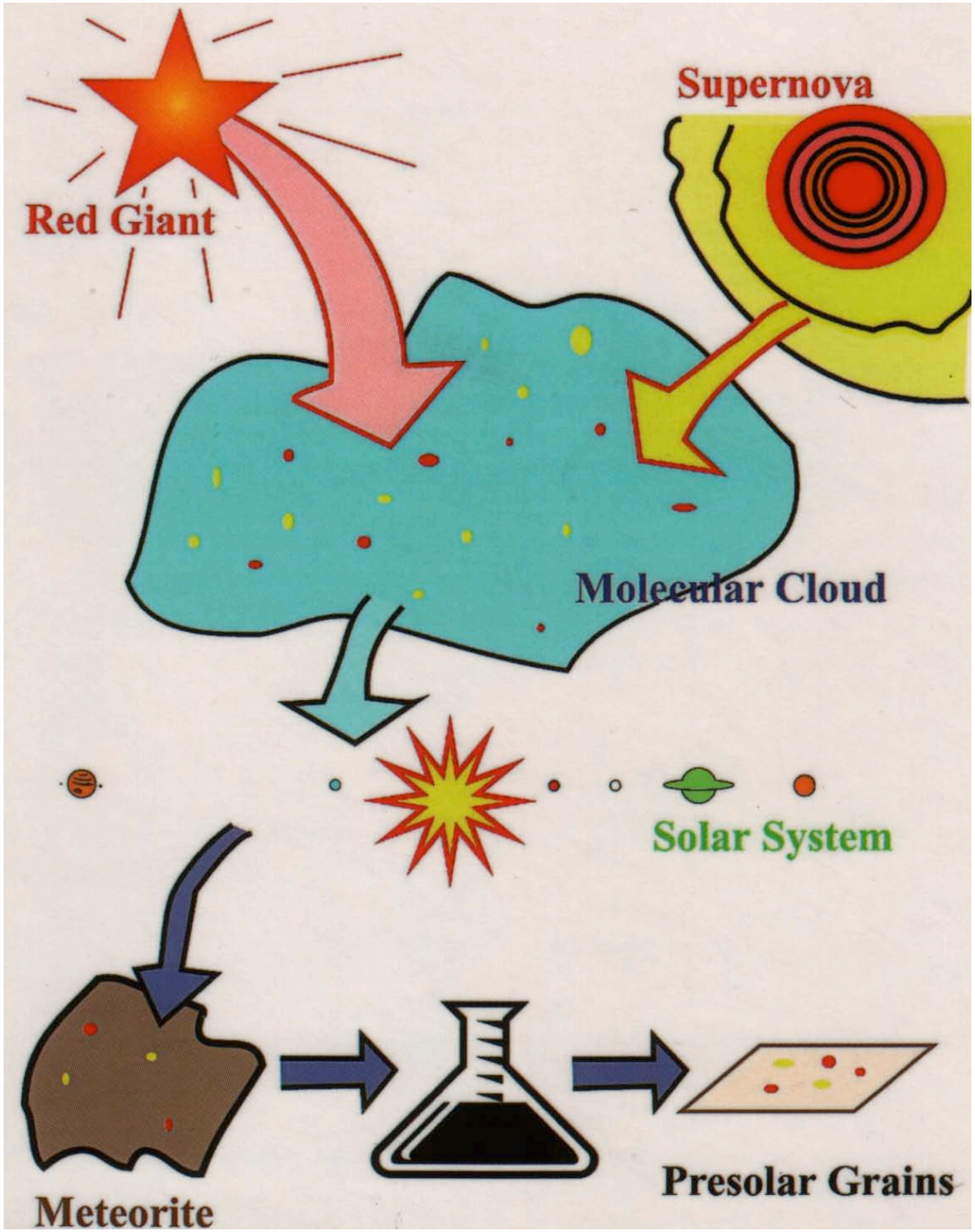
Evidence provided by

- Spectroscopy of stars, …
- Cosmic rays
- Stardust in meteorites

Nous concevons la possibilité de déterminer leurs formes, leurs distances, leurs grandeurs et leurs mouvements; tandis que nous ne saurions jamais étudier par aucun moyen leur composition chimique, ou leur structure minéralogique, et, à plus forte raison, la nature des corps organisés qui vivent à leur surface, etc.

Auguste Comte
(1798 – 1857)



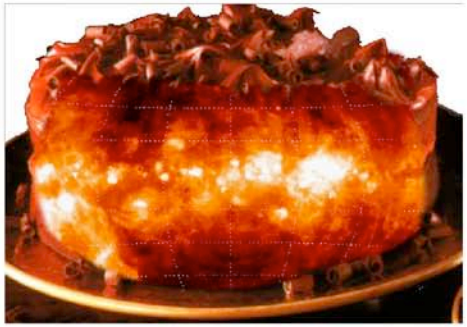

Supernova
Red Giant
Molecular Cloud
Solar System
Meteorite
Presolar Grains

Menu

Primordial Soup

Stellar Entrées

Interstellar Desserts



Primordial Soup

- Primordial soup from the Big Bang via the 3-minute recipe
  - Thermonuclear fusion in rapidly cooling expanding mixture of protons and neutrons
  - Main constituents of the soup are

    ^{1}H and ^{4}He with $^{4}He/^{1}H \approx 10\%$
  - Minor constituents are ^{2}H, ^{3}He, and ^{7}Li
  - Synthesis limited by rapid expansion and lack of stable A = 5 and 8 nuclei

Stellar Entrées

Braised Betelgeuse

Fresh Technetium

Chandra Burgers

Stellar Entrées

I think that the suspicion has been generally entertained that the stars are the crucibles in which the lighter atoms which abound in the nebulae are compounded into more complex elements.

A.S. Eddington

Stellar Entrées

We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him to go and find
A HOTTER PLACE.

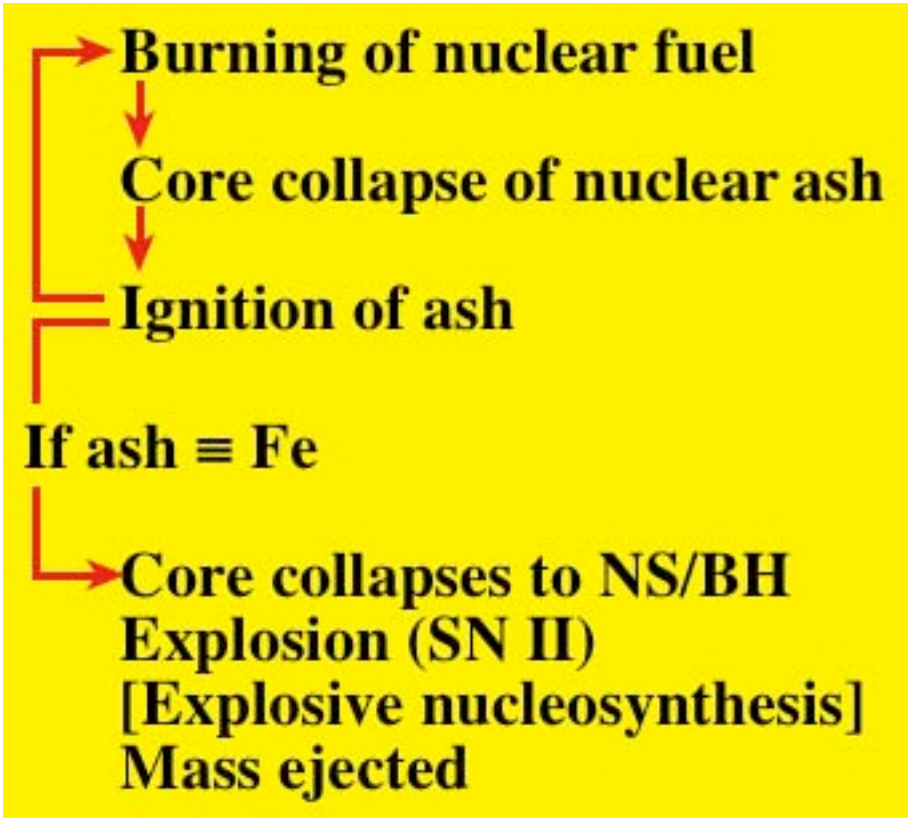
A.S. Eddington

Introduction to Stellar Structure

- Gravity balanced by pressure (gas, radiation, degenerate electron) gradient
- Temperature gradient → Luminosity
- Energy flow out by radiation and convection
- Energy replaced by nuclear energy and/or gravitational collapse

Braised Betelgeuse

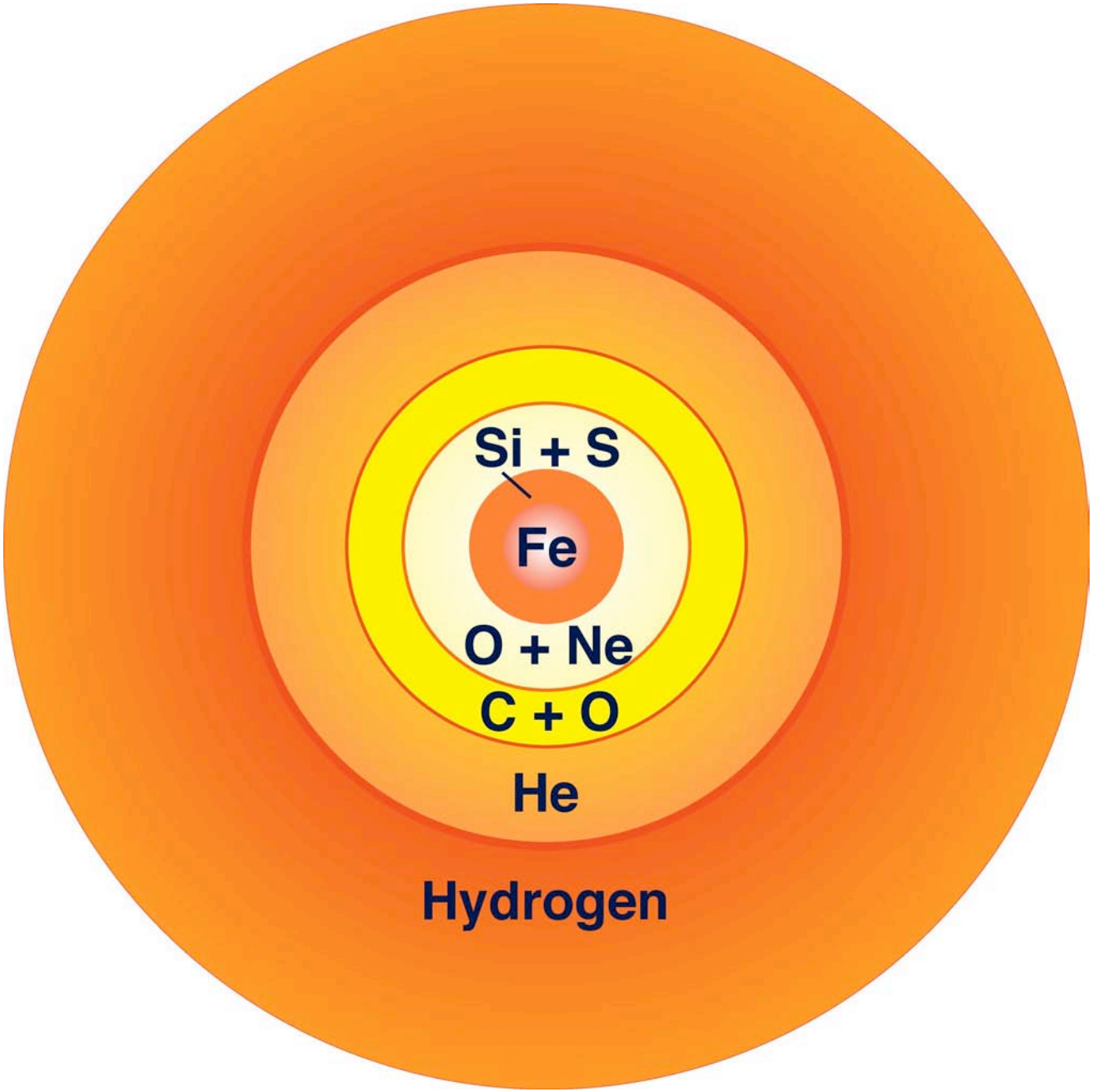
Evolution of High Mass Stars



Hydrogen Burning

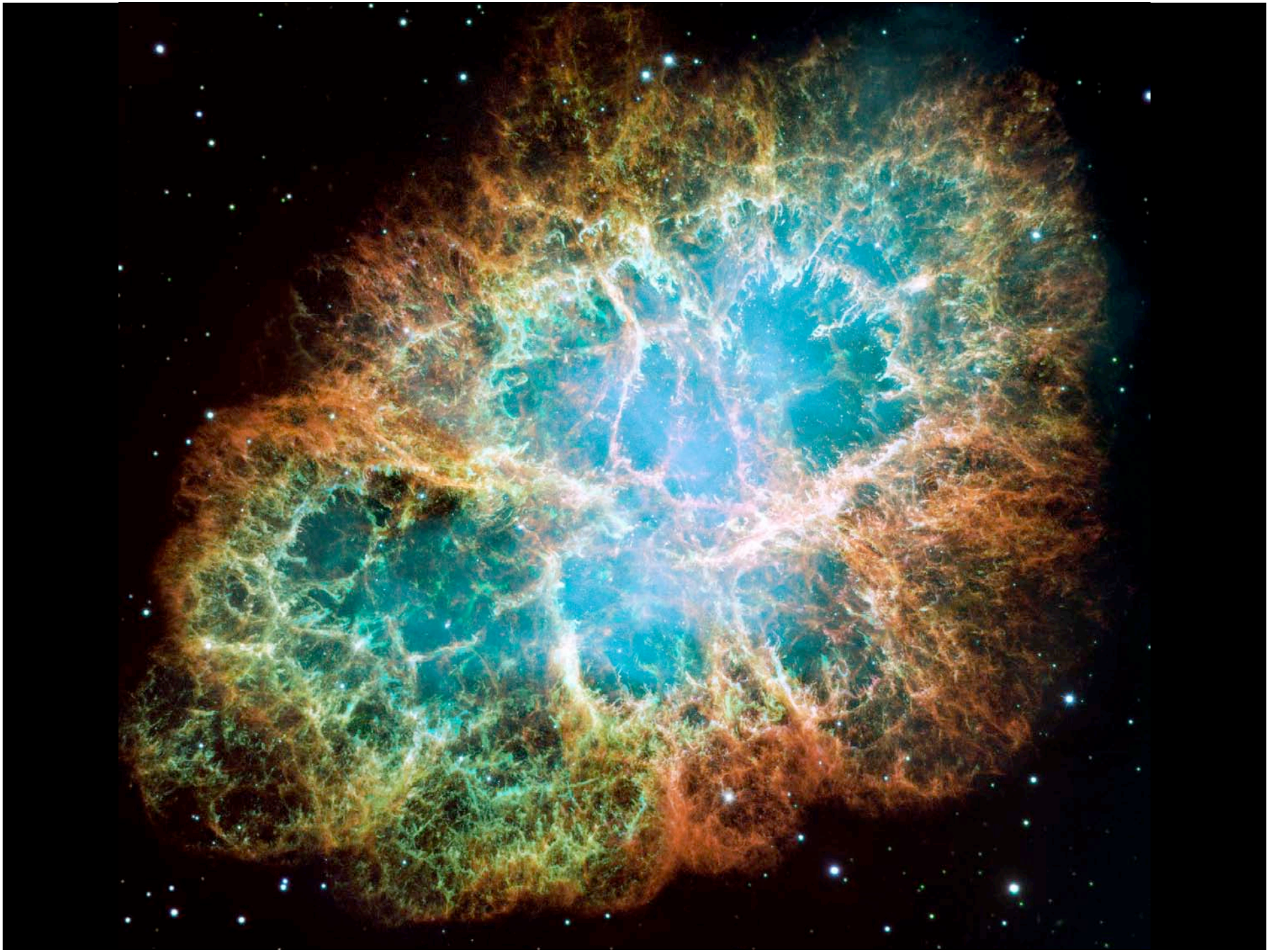
- $^{4}H \rightarrow He + Energy$
- $E = mc^2$
- 0.7% of H to Energy
- Sunlight from H-burning

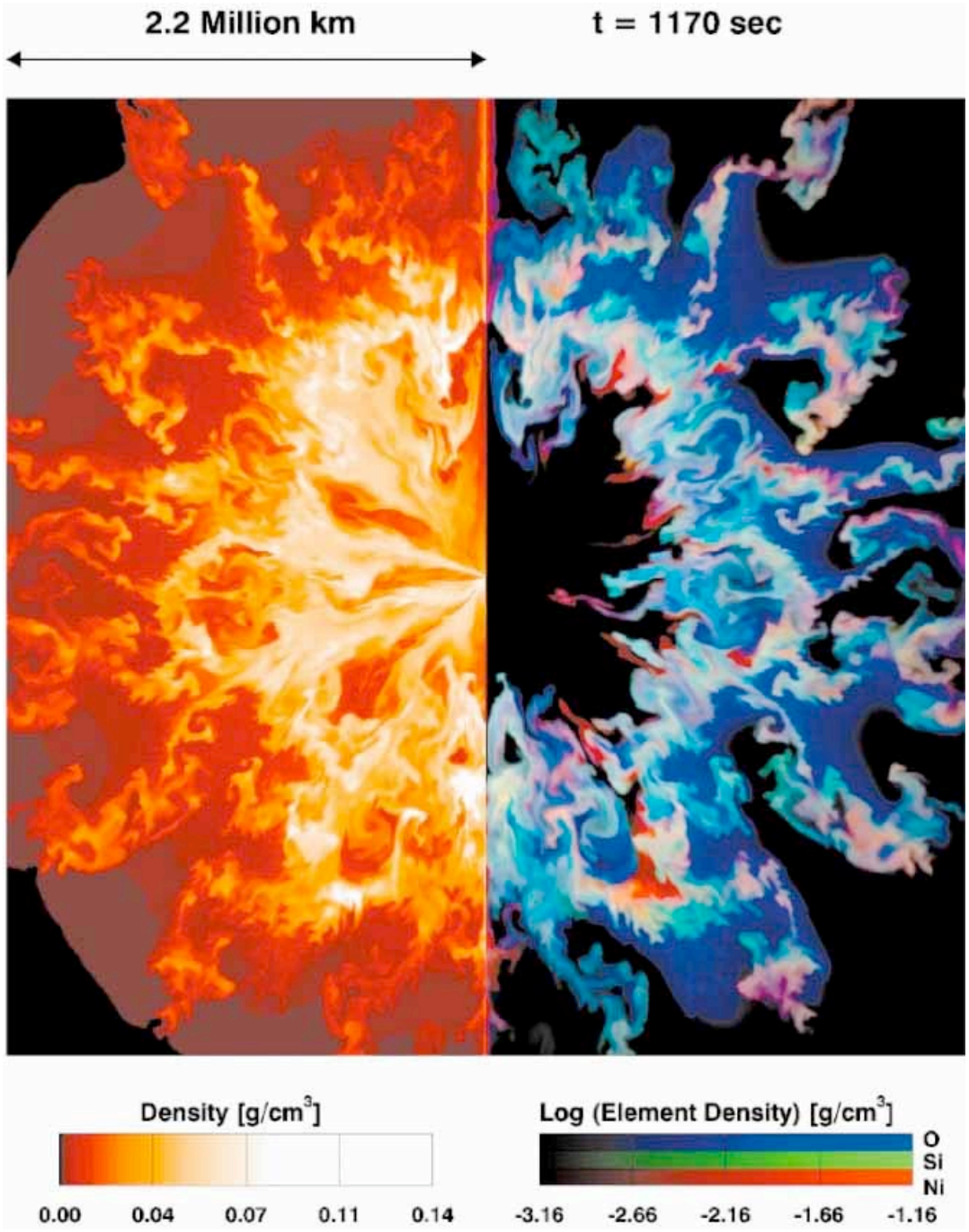
Fuel	Products	Minimum Ignition Temperature	Duration
H	**He**	**4×10^6 K**	**7 million yrs**
He	**C,O**	**120×10^6 K**	**500,000 yrs**
C	**Ne, Na, Mg, O**	**600×10^6 K**	**600 yrs**
Ne	**O, Mg**	**1.2×10^9 K**	**1 year**
O	**Si, S, P**	**1.5×10^9 K**	**6 months**
Si	**Ni to Fe**	**2.7×10^9 K**	**1 day**


Si + S
Fe
O + Ne
C + O
He
Hydrogen

Supernova Explosion!

- Inner layers of ‘onion’ reprocessed
- Neutron flood makes heavier elements
- Products ejected into the Galaxy

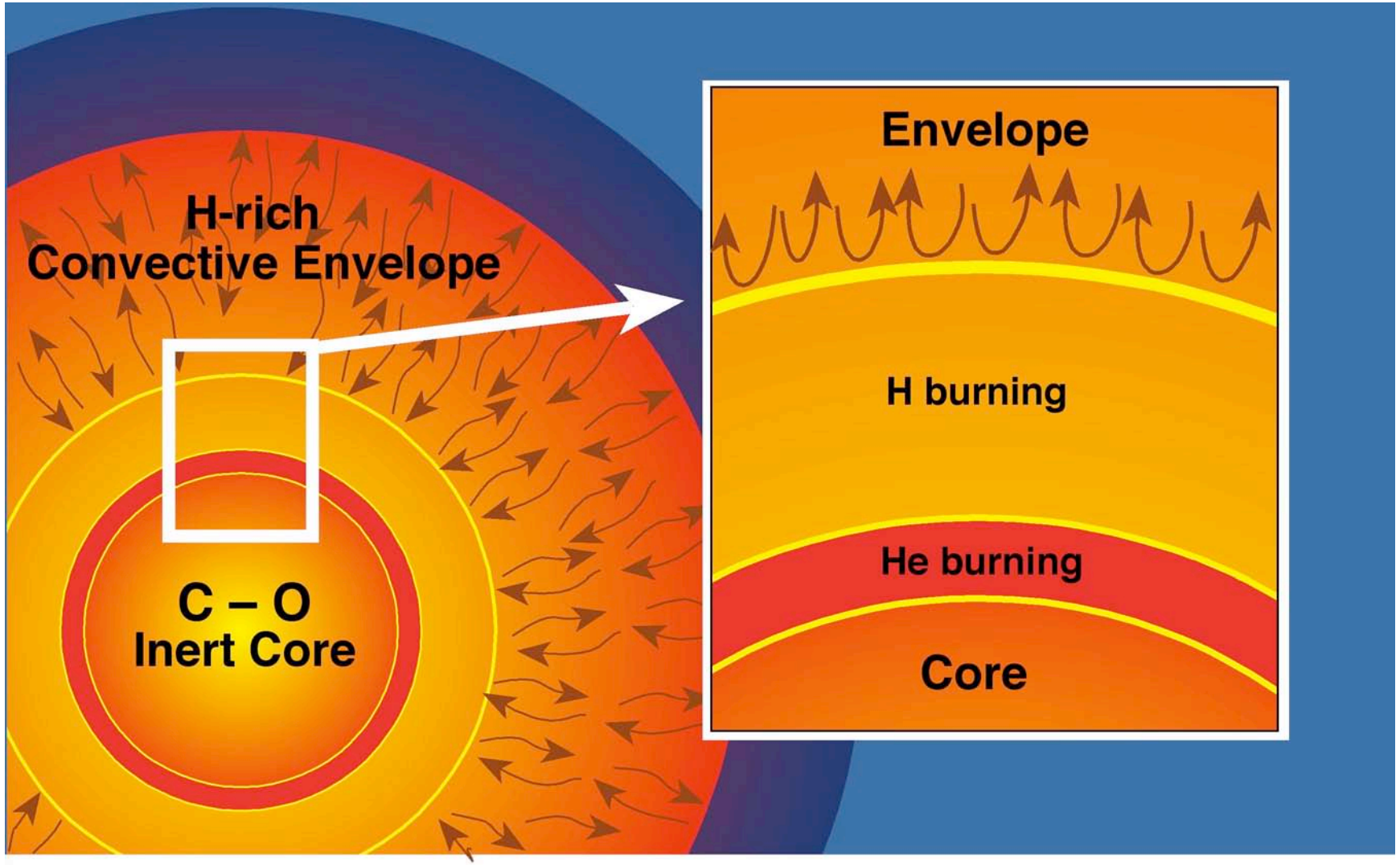



2.2 Million km
t = 1170 sec
Density [g/cm3]
0.00
0.04
0.07
0.11
0.14
Log (Element Density) [g/cm3]
O
Si
Ni
-3.16
-2.66
-2.16
-1.66
-1.16

Fresh Technetium

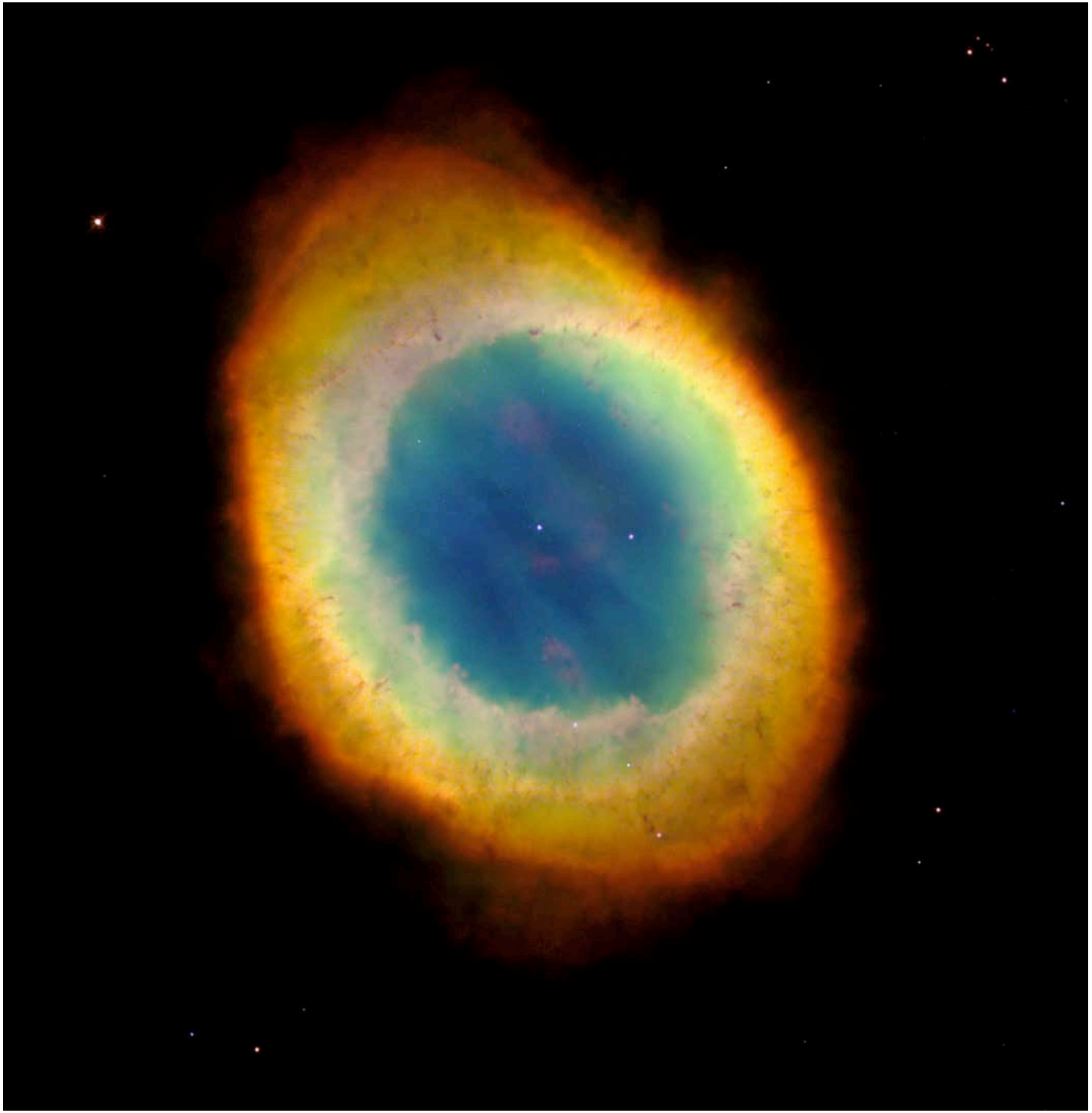
Evolution of Low Mass Stars

- Experience H and then He-burning
- $\Rightarrow$ core of C and O
- Core supported by degenerate electrons: pressure $\sim T$ independent
- Mass shed by red giant leaves C-O core as white dwarf with $M_{WD} \leq 1.4\ M_{\odot}$
- White dwarf cools and fades

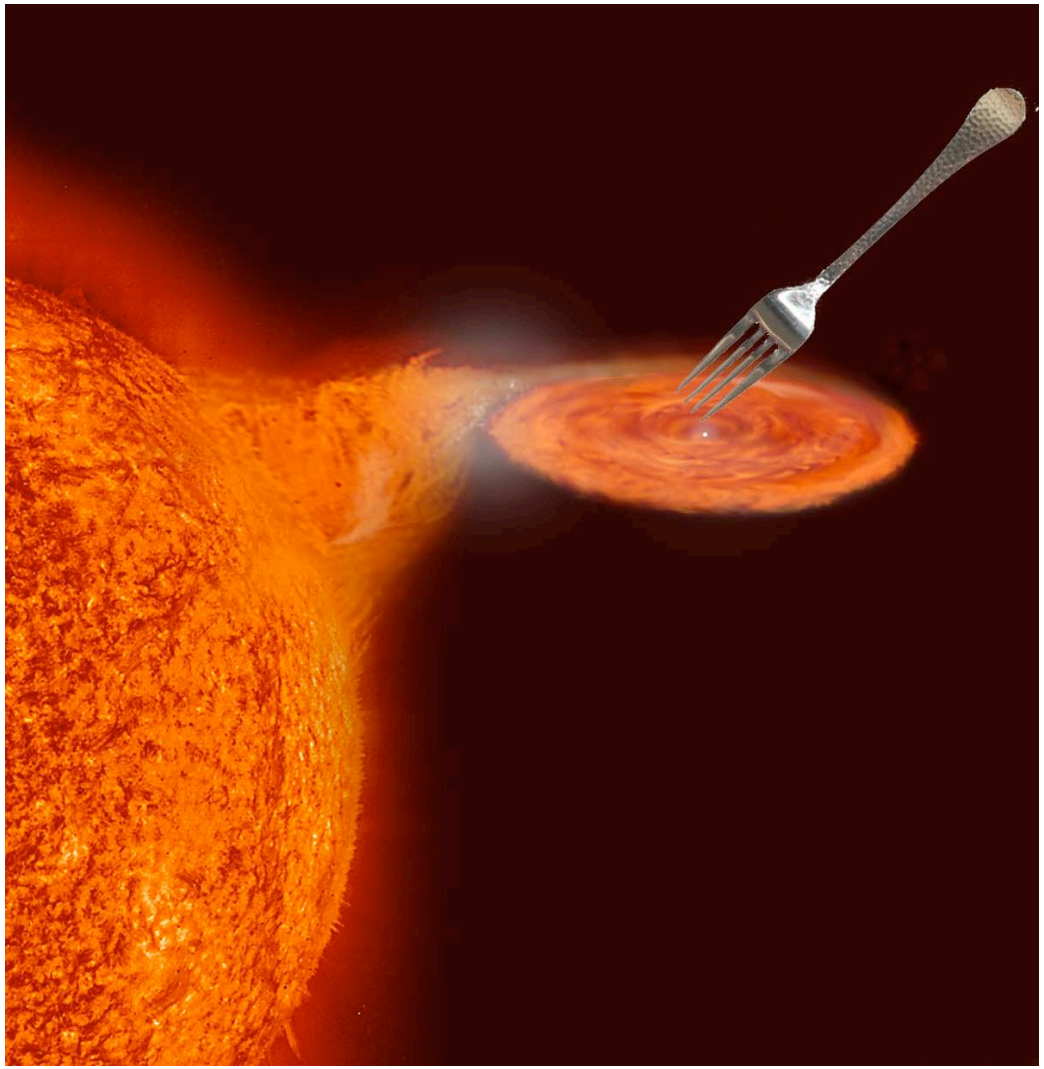

H-rich
Convective Envelope
C – O
Inert Core
Envelope
H burning
He burning
Core

Red Giants

- Outer layers ejected at low velocity
- Key contributions to
  - carbon
  - heavy elements (technetium) by neutron capture

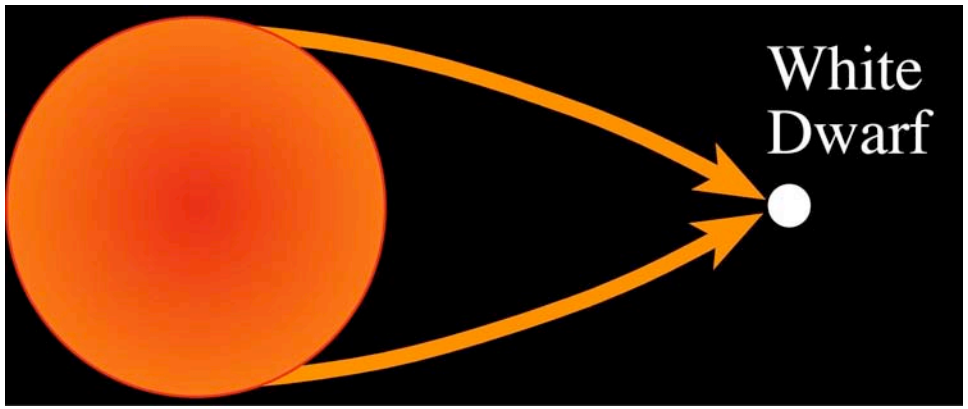


Chandra Burgers

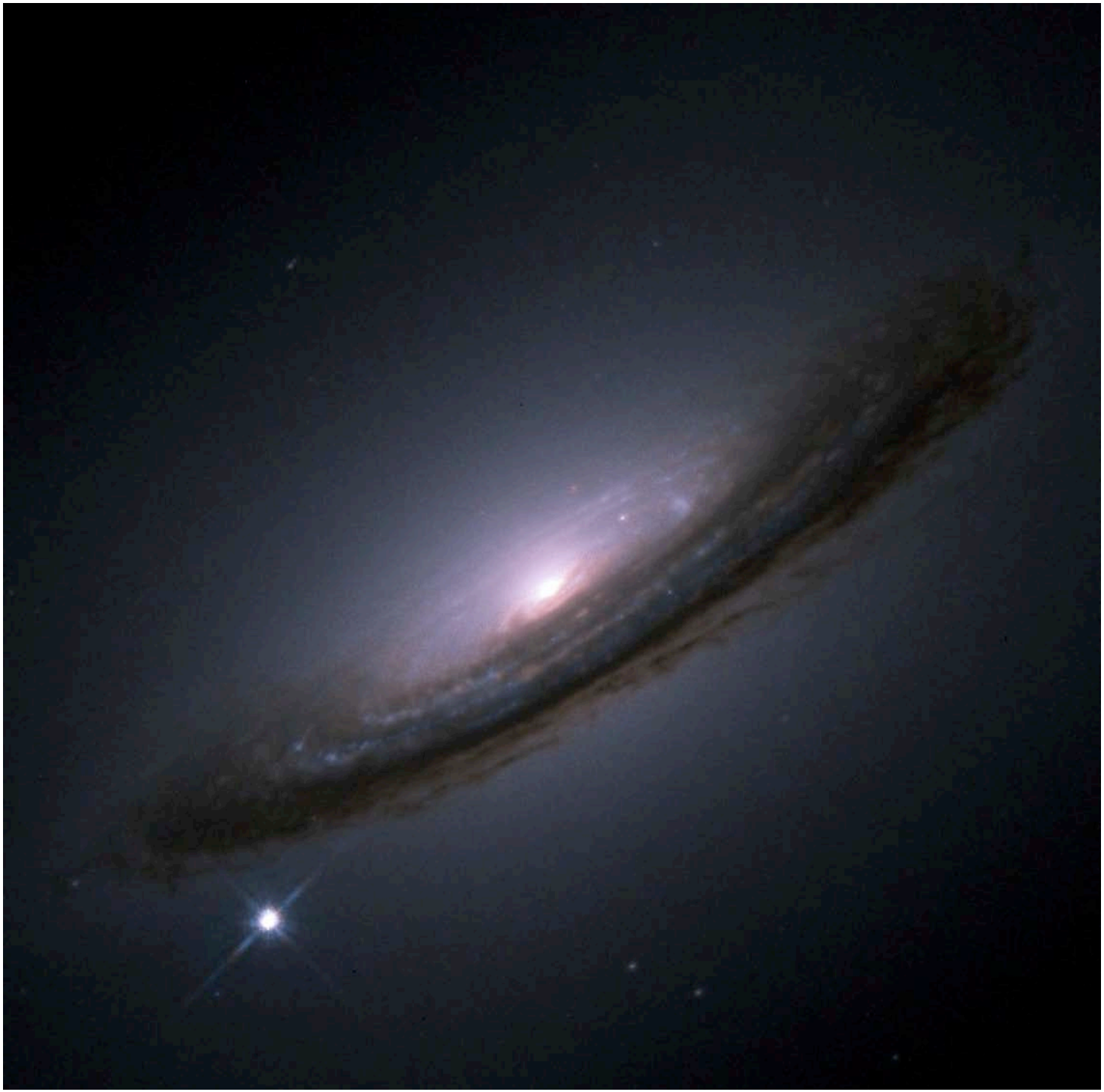


Supernovae Type Ia

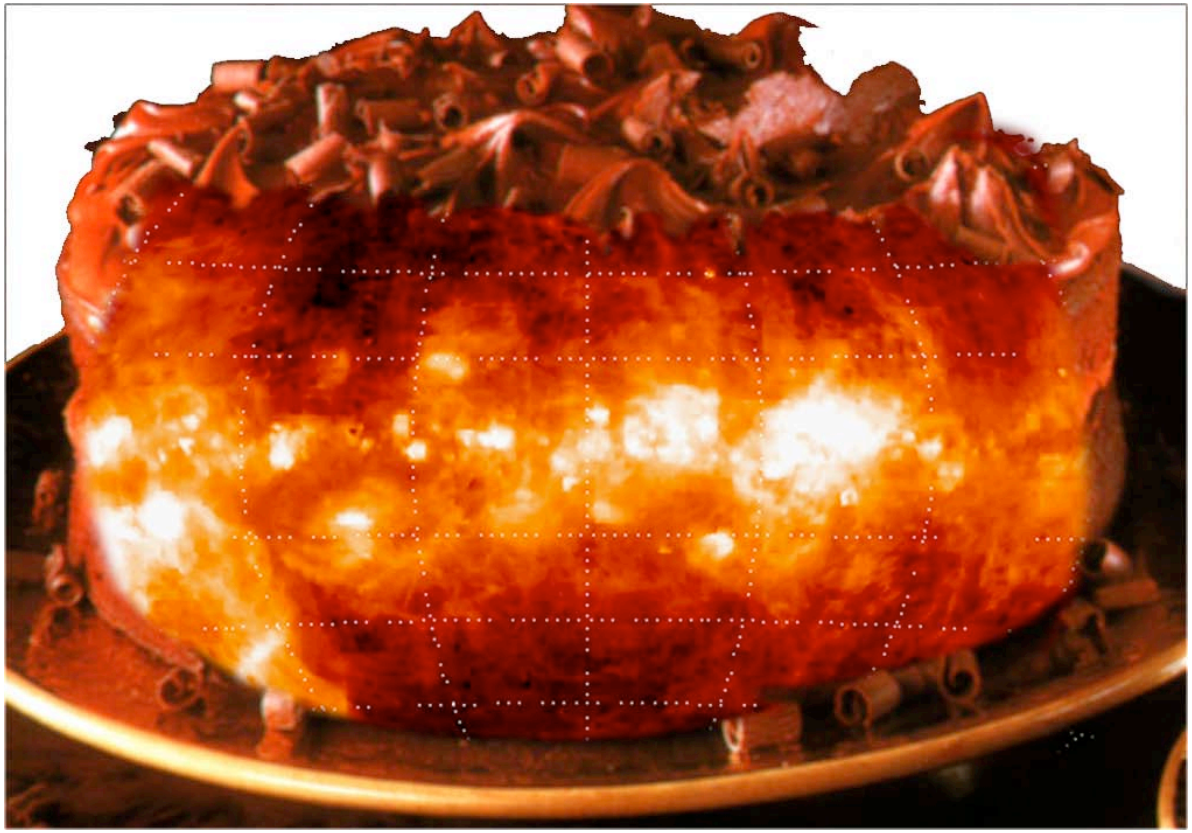
Thermonuclear explosion of white dwarf
drives to exceed Chandrasekhar mass



Explosive nucleosynthesis
→ “Fe”



Interstellar Desserts



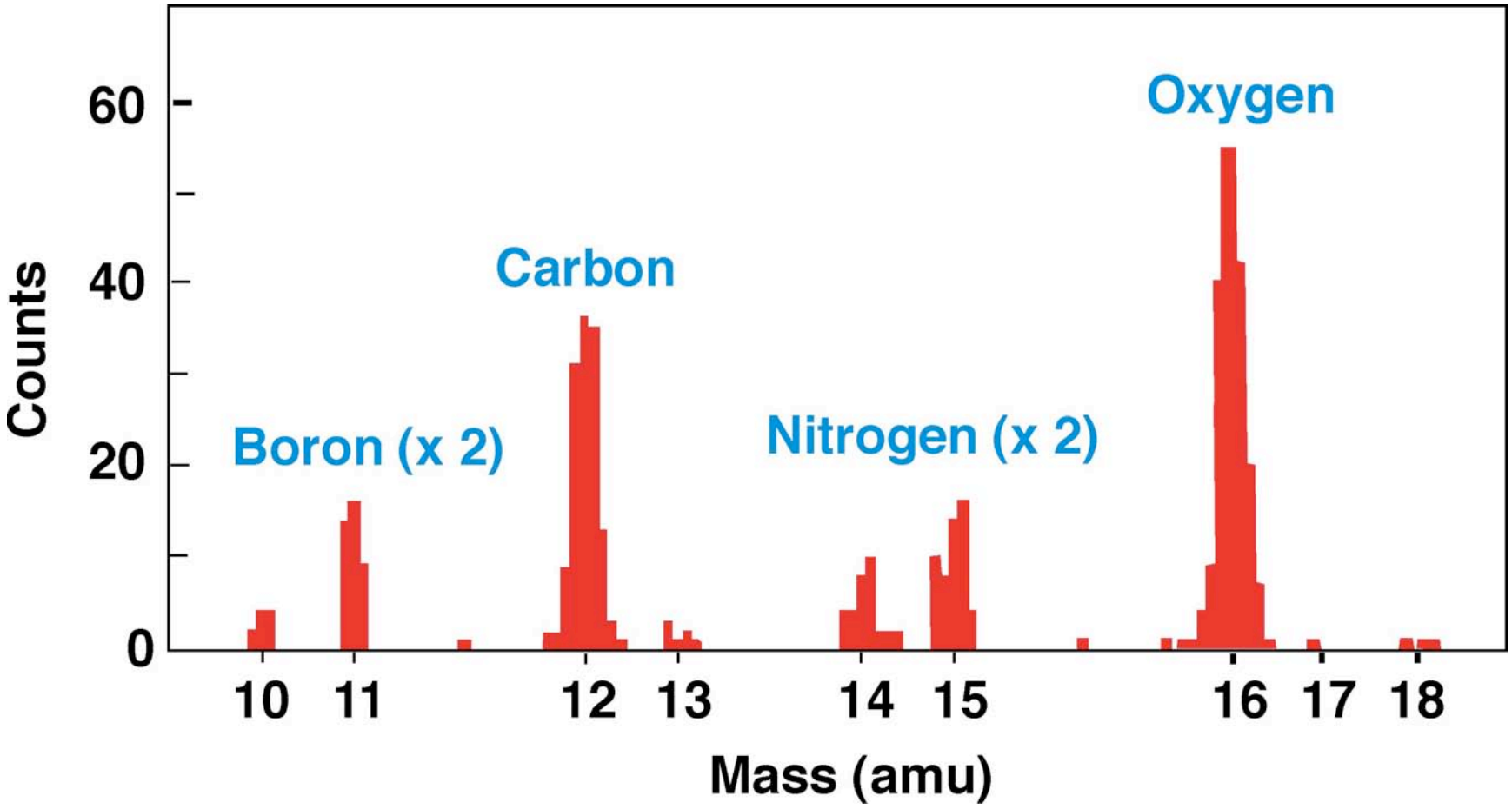
Interstellar Desserts

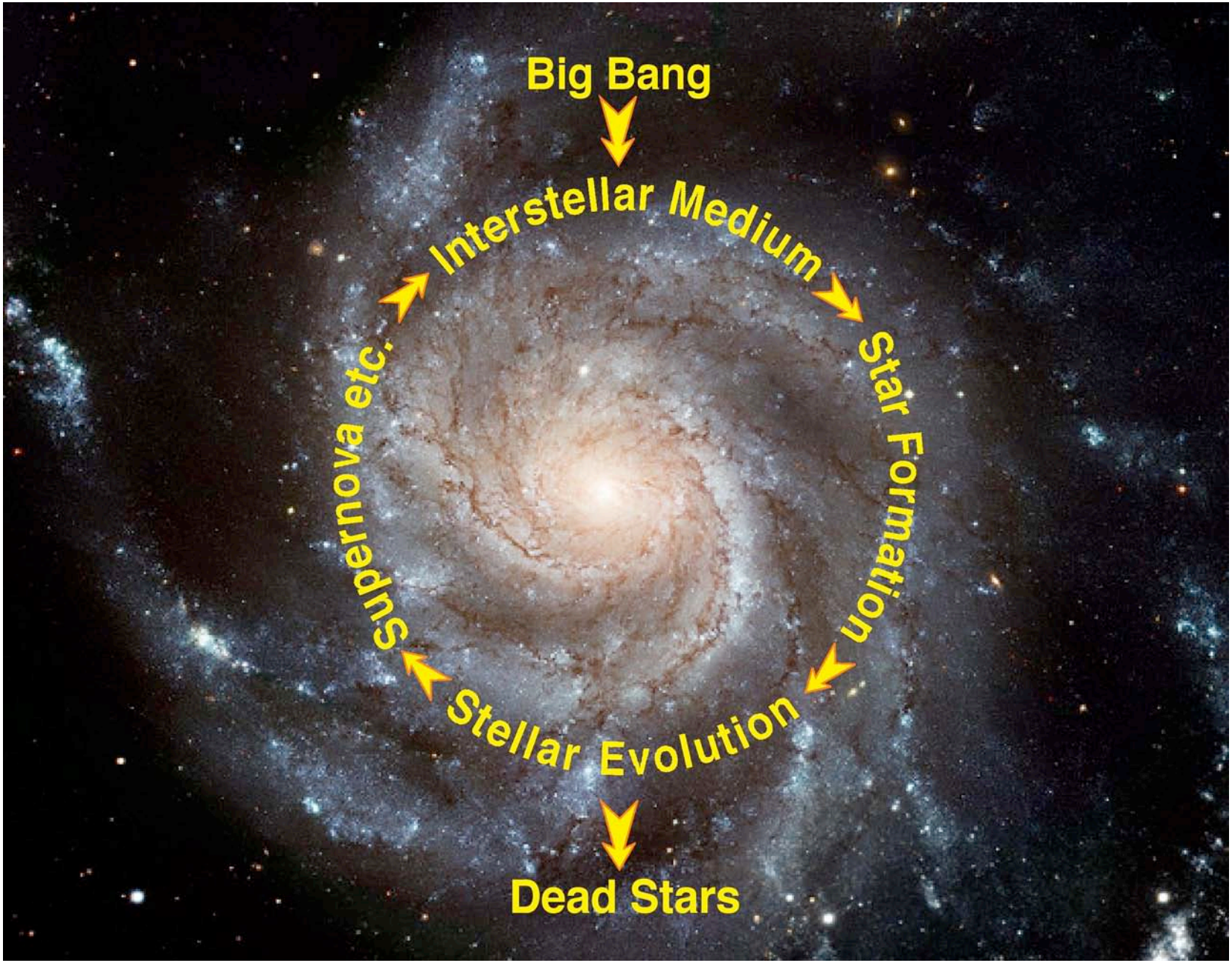
- Spallation and fusion reactions between cosmic rays and ambient nuclei e.g.,

  $p + O \rightarrow Li, Be, B$

  $\alpha + \alpha \rightarrow {}^{6}Li, {}^{7}Li$

Li, Be, B

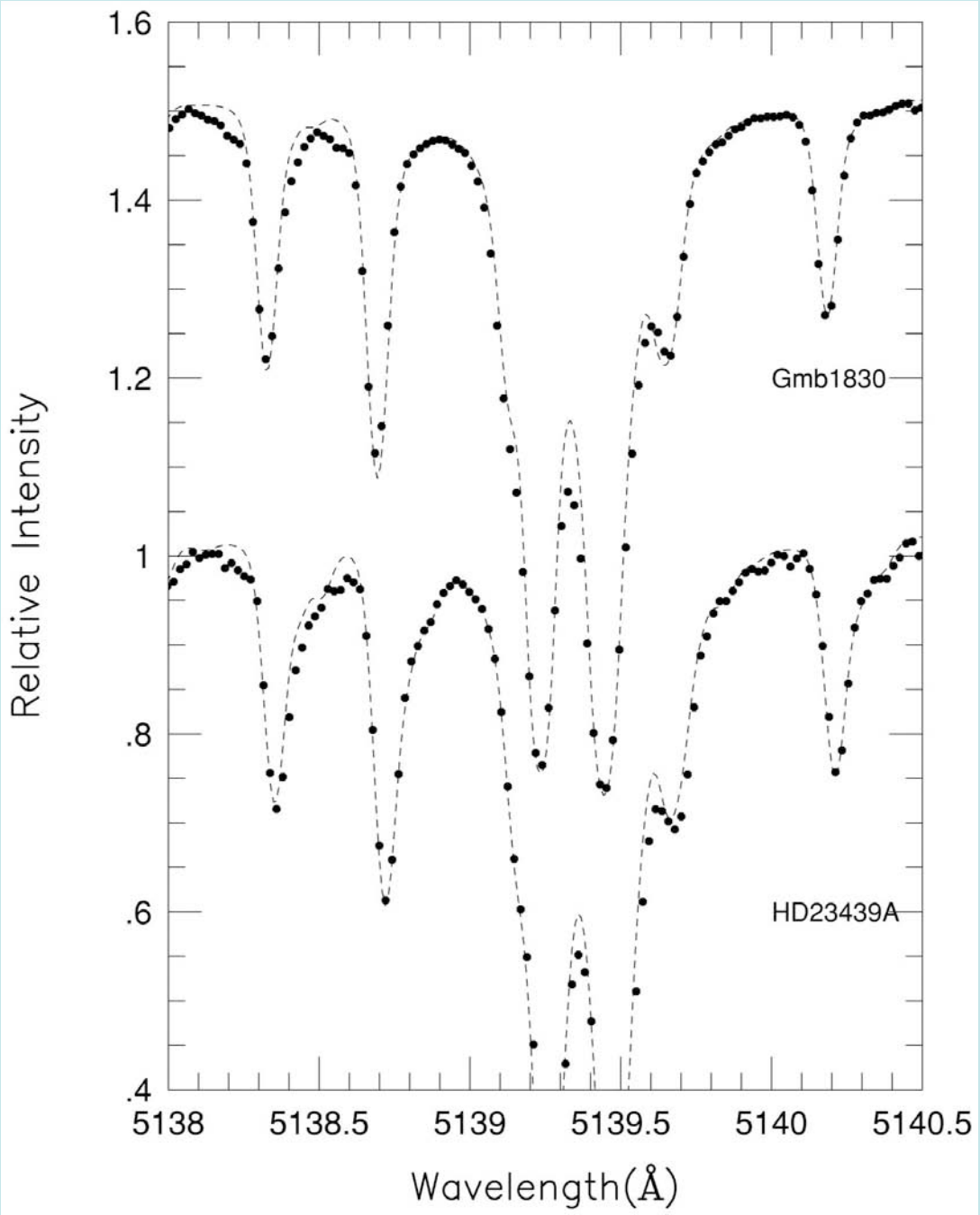

Counts
60
40
20
0
Boron (x 2)
Carbon
Nitrogen (x 2)
Oxygen
10
11
12
13
14
15
16
17
18
Mass (amu)


Big Bang
Interstellar Medium
Star Formation
Stellar Evolution
Supernova etc.
Dead Stars

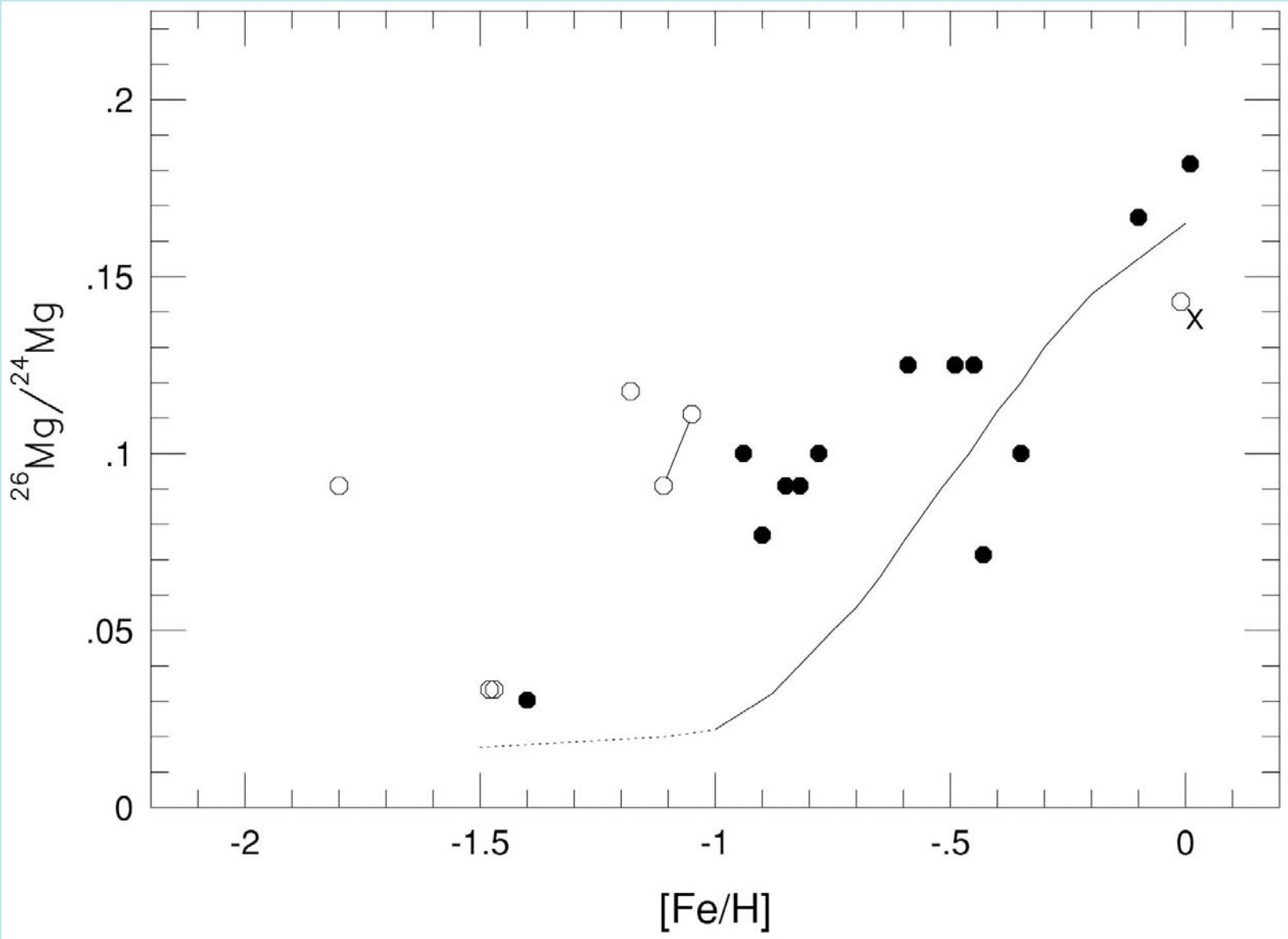
Fun at the telescope

- The magnesium isotopes: ^{24}Mg, ^{25}Mg, ^{26}Mg
  - Models of supernovae predict yield of ^{25}Mg and ^{26}Mg to decline as the initial composition of the star tends to pure H and He

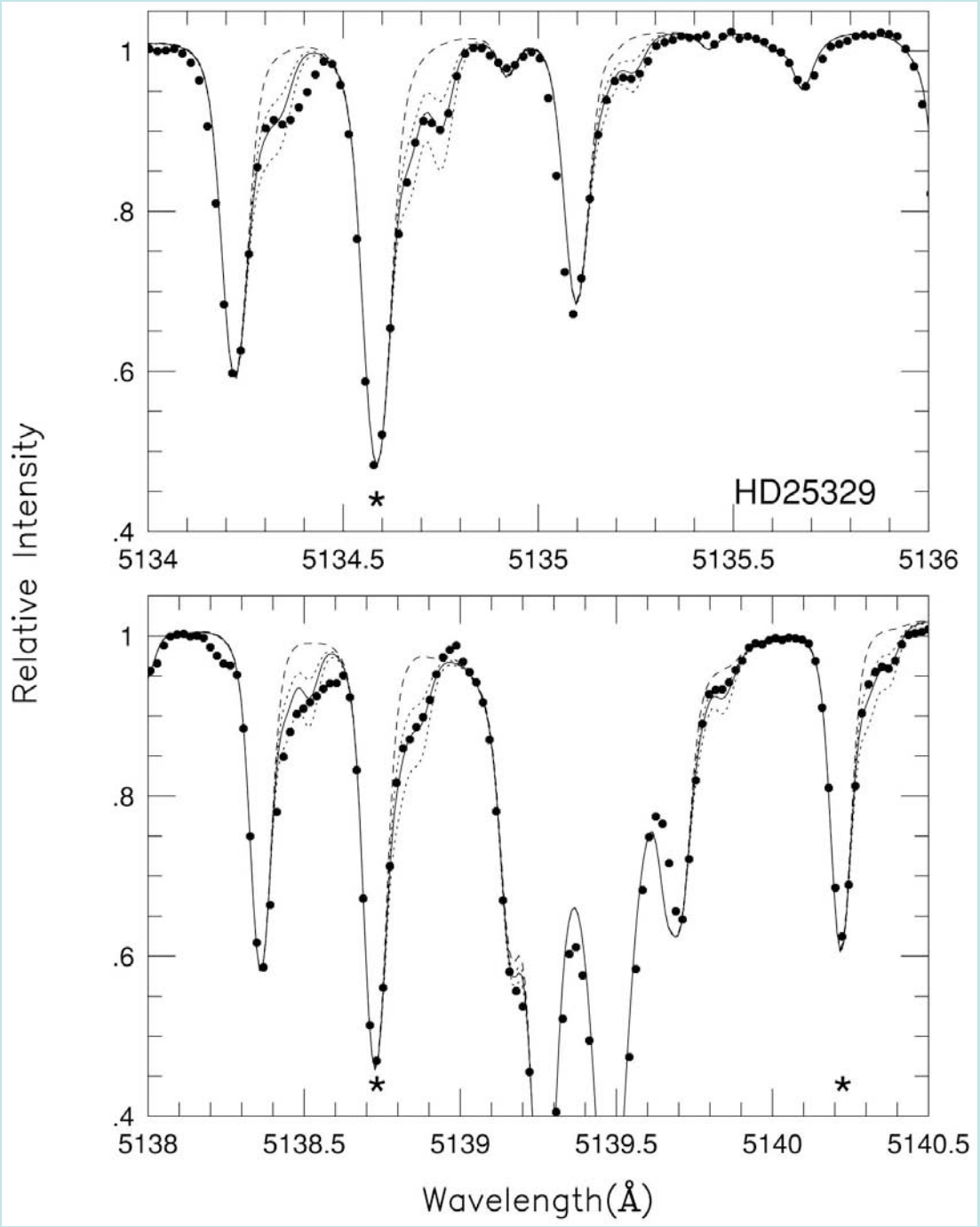
Evolution of the Magnesium Isotopes

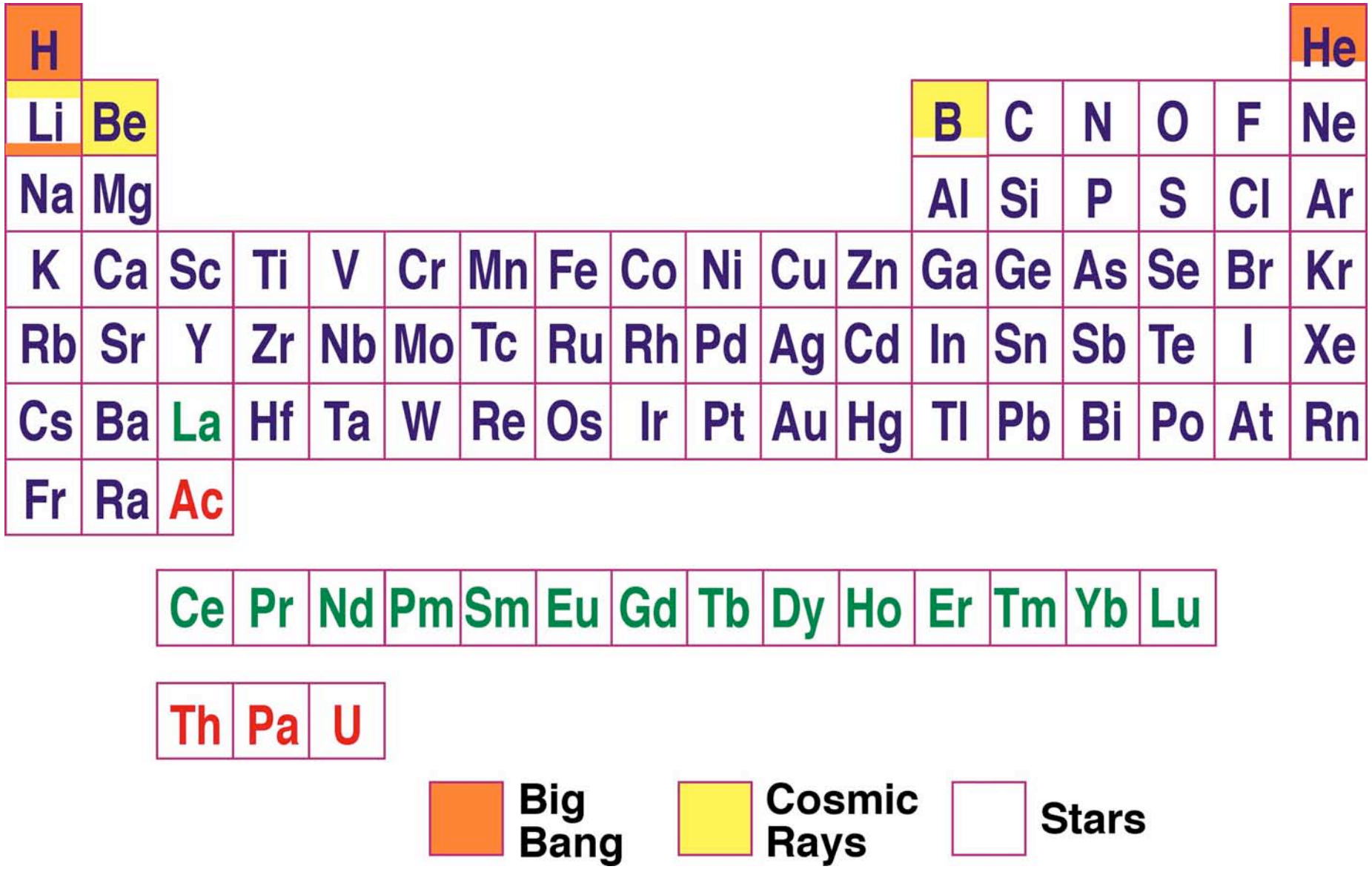


Evolution of the Magnesium Isotopes



Evolution of the Magnesium Isotopes




H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Tc
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Po
At
Rn
Fr
Ra
Ac
Ce
Pr
Nd
Pm
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Th
Pa
U
Big Bang
Cosmic Rays
Stars

Where do common elements come from?

- Hydrogen, Z = 1
  - Water, H_2O
  - Big Bang survivor
- Helium, Z = 2
  - Airships, coolant
  - Earth: Product of U and Th decay
  - Stars: 90% Big Bang, 10% Stars

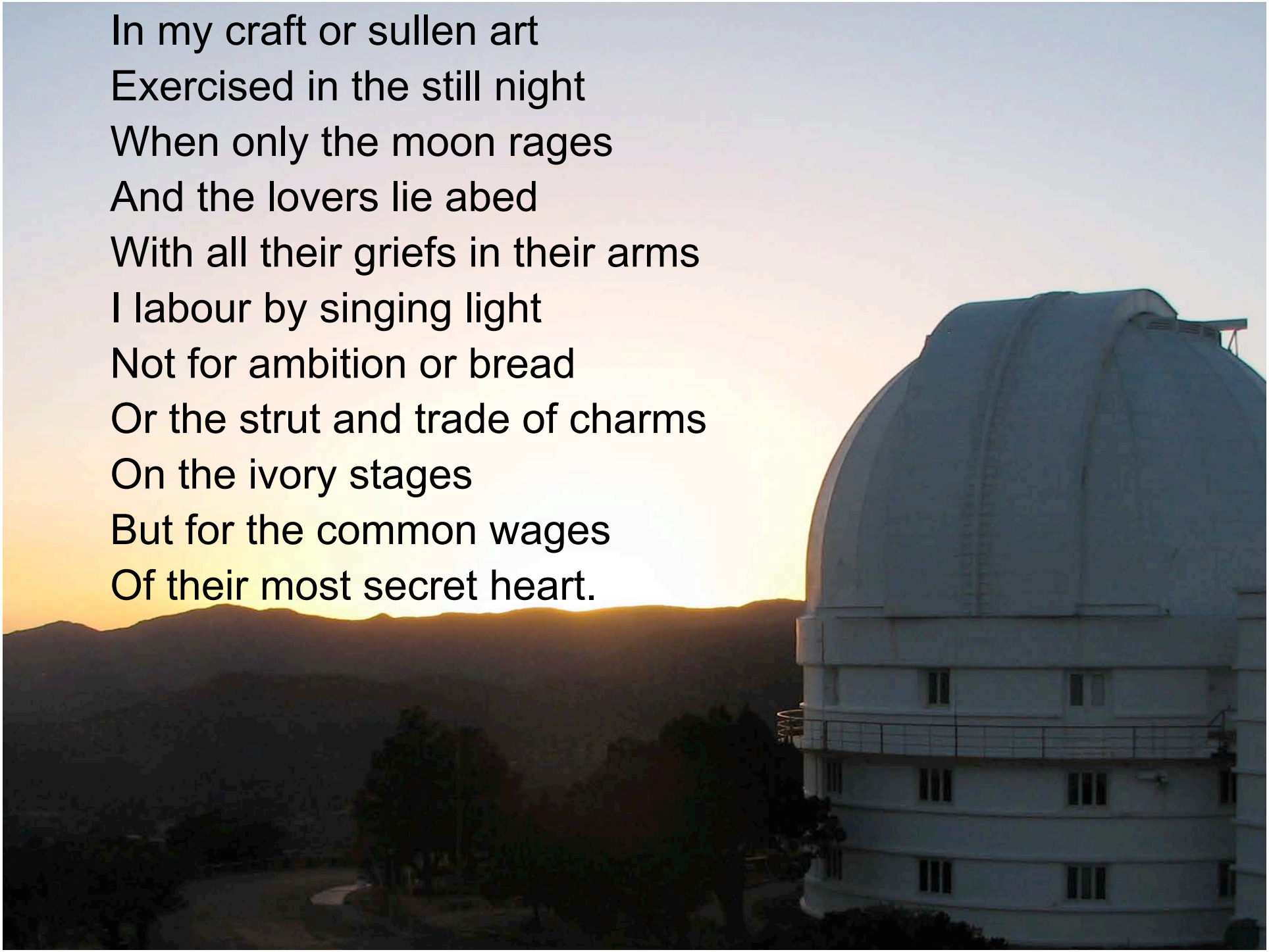
- Lithium, Z = 3
  - Greases, medicine, nuclear bombs
  - 10% Big Bang, 10% Spallation, 80% Red giants, Supernovae II
- Beryllium, Z = 4
  - Alloys, beryl (emeralds)
  - 100% Spallation
- Boron, Z = 5
  - Pyrex, bleaches, fireproofing
  - 30% Spallation, 70% Supernovae II (?)

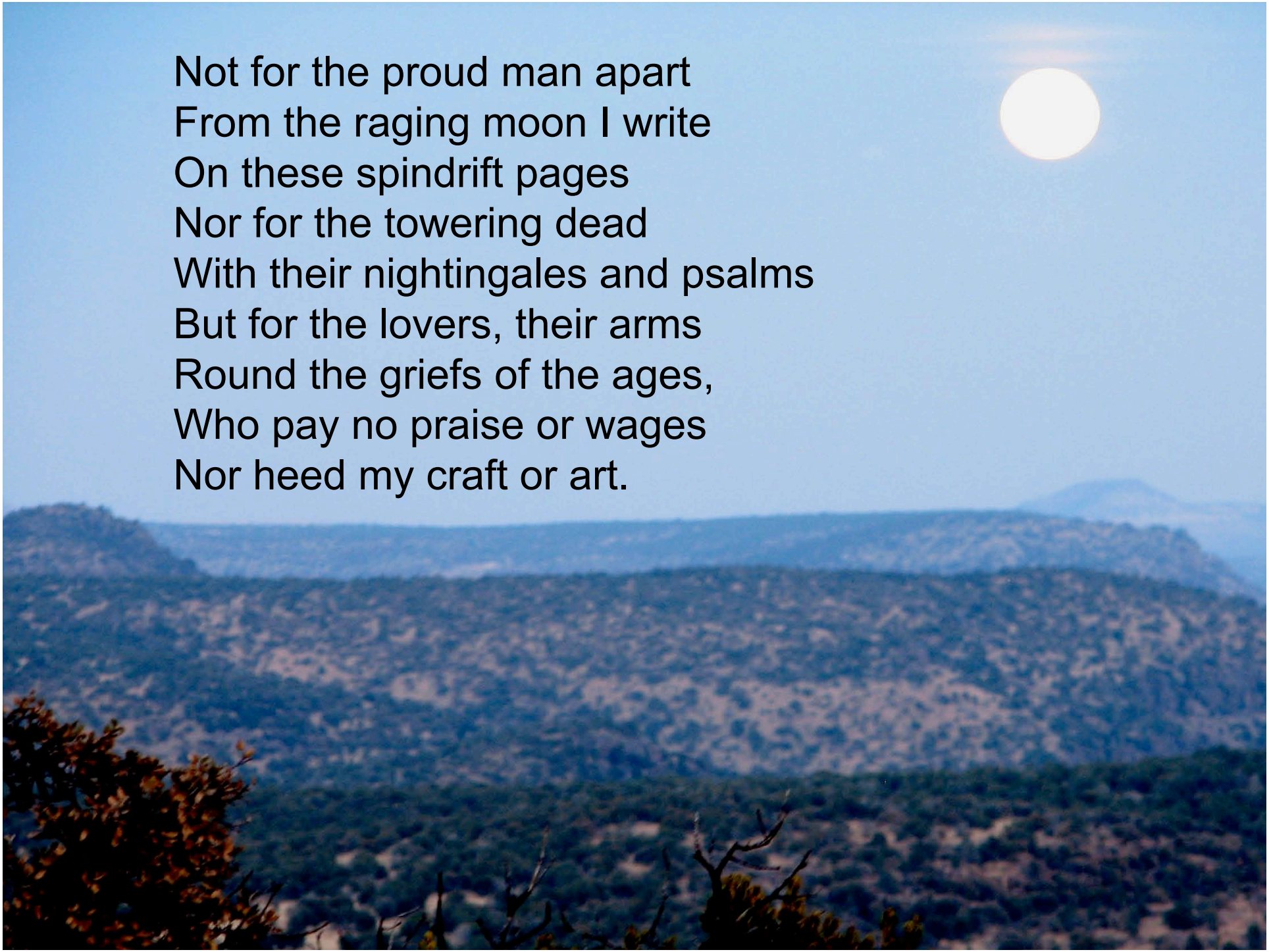
- Carbon, Z = 6 to Nickel, Z = 28
  - Lighter elements – Carbon to Silicon – primarily from massive stars and their supernovae (Type II)
  - Heavier elements – Silicon to Nickel – primarily from exploding white dwarfs (Supernovae of Type Ia)

Beyond nickel, elements are made by neutron captures on iron

- Barium, Z = 56
  - X-ray medicine, spark plugs
  - Red Giants
- Europium, Z = 63
  - Red phosphor in TVs
  - Supernovae Type II
- Gold, Z = 79
  - Precious metal
  - Red giants and Supernovae Type II


In My Craft Or
Sullen Art
By Dylan Thomas


In my craft or sullen art
Exercised in the still night
When only the moon rages
And the lovers lie abed
With all their griefs in their arms
I labour by singing light
Not for ambition or bread
Or the strut and trade of charms
On the ivory stages
But for the common wages
Of their most secret heart.


Not for the proud man apart
From the raging moon I write
On these spindrift pages
Nor for the towering dead
With their nightingales and psalms
But for the lovers, their arms
Round the griefs of the ages,
Who pay no praise or wages
Nor heed my craft or art.