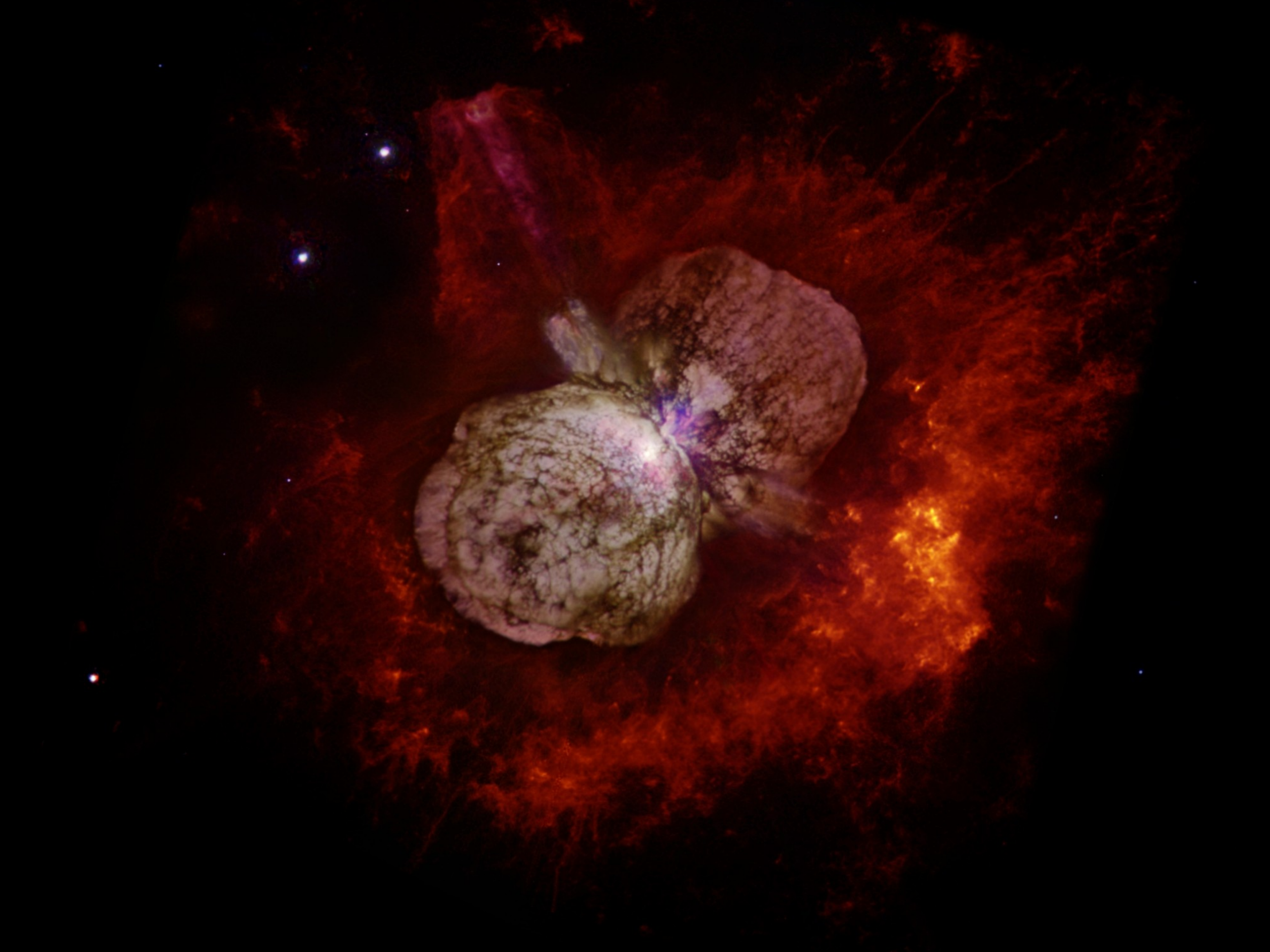


Origin of the Elements:

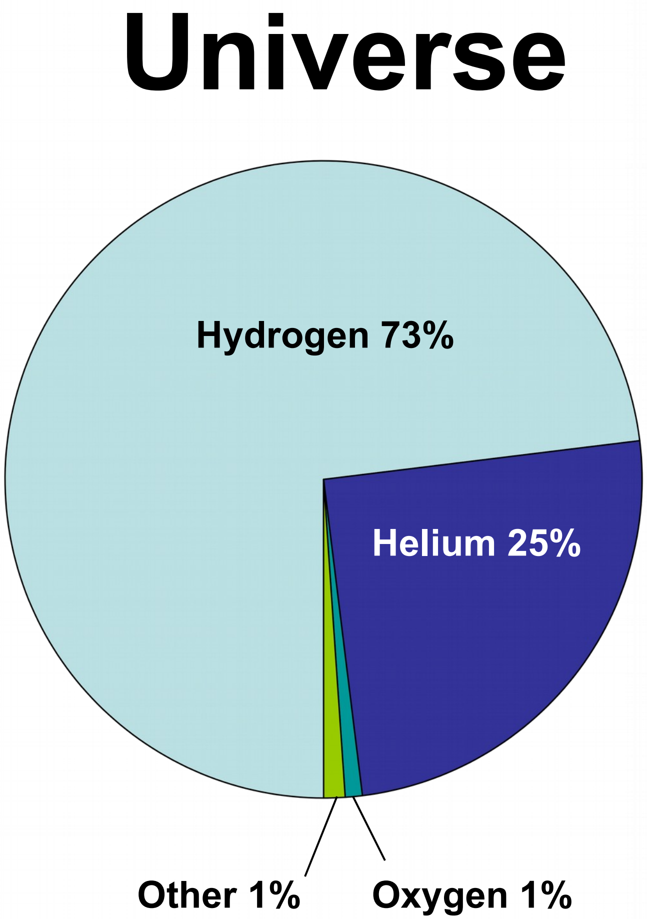
Evolution and Nucleosynthesis in Massive Stars

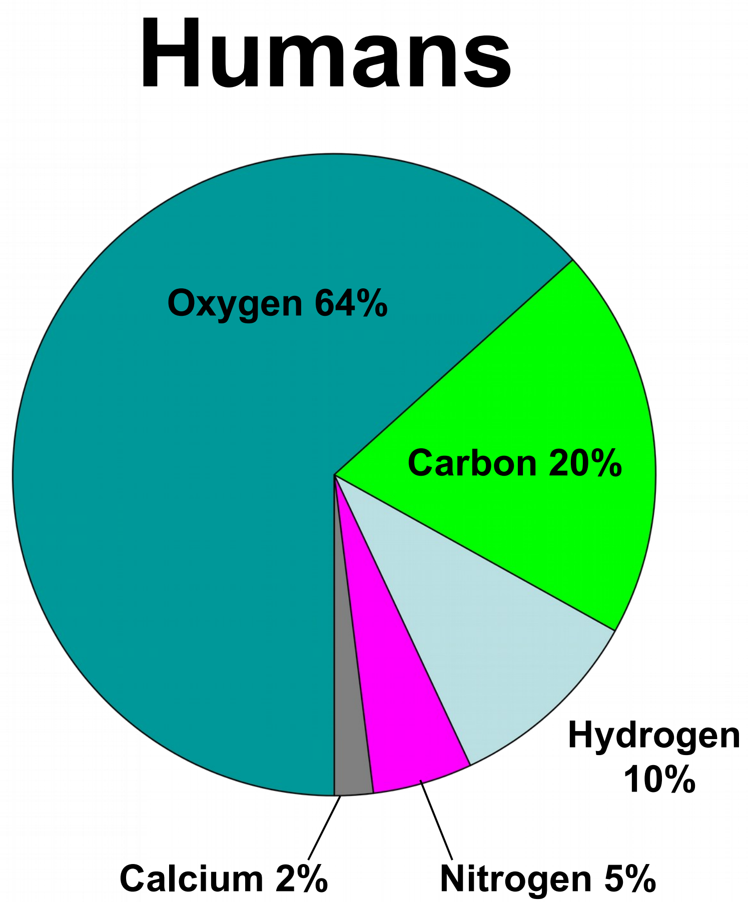
Alexander Heger

Overview

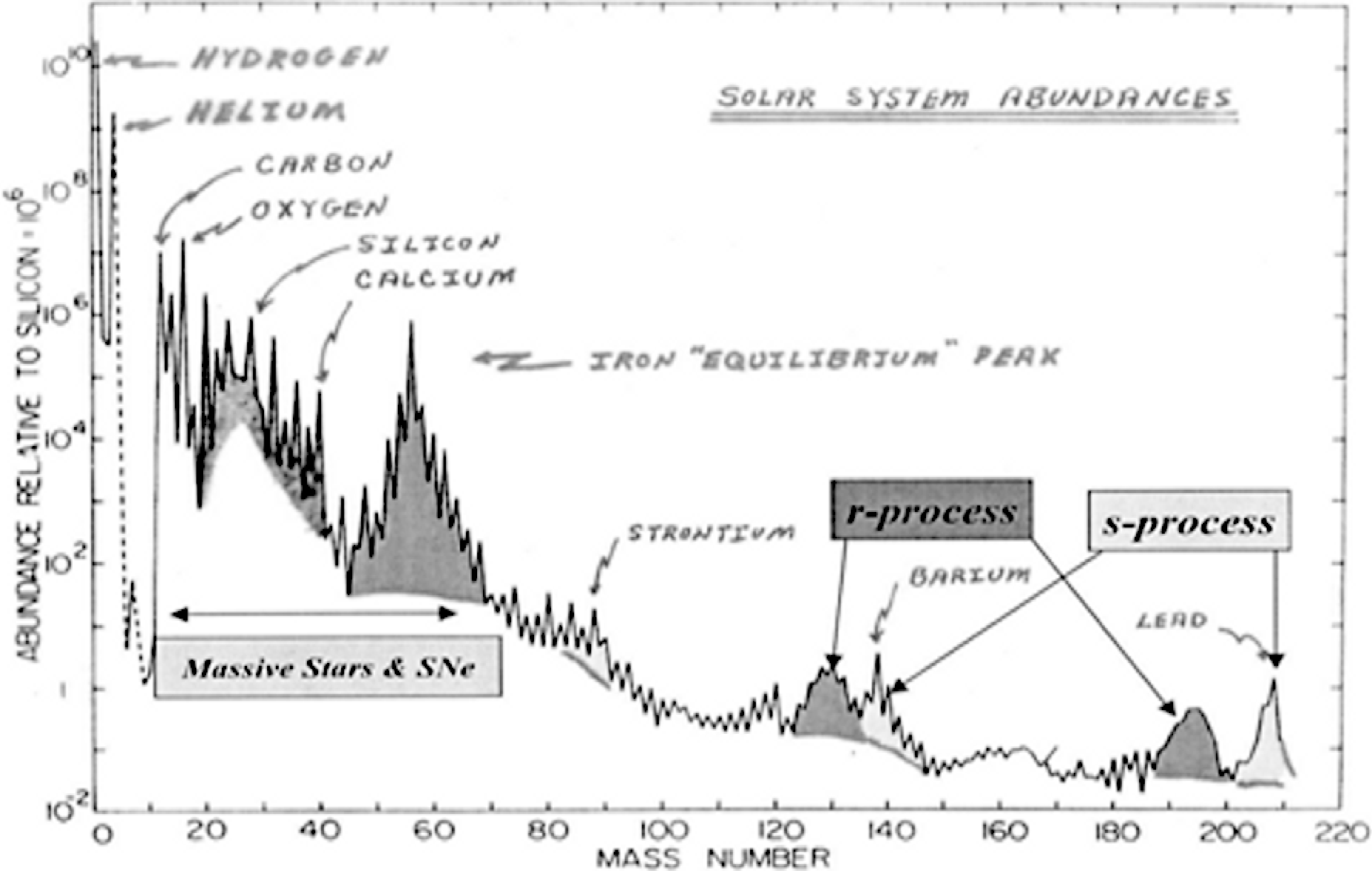
- Presupernova Evolution
- Nucleosynthesis
- Varieties of Stellar Deaths

Abundance by Weight



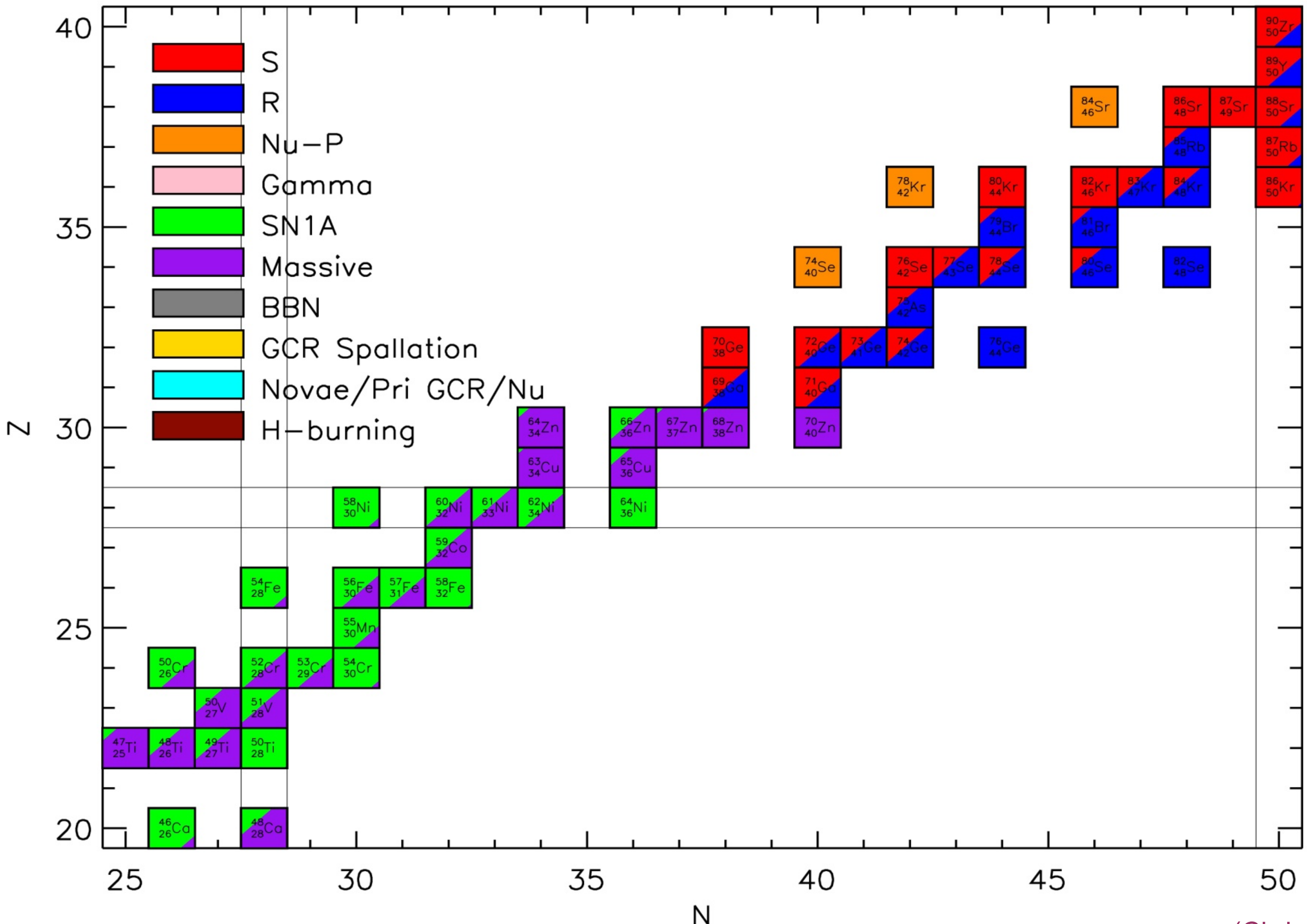


"Cosmic" Abundances of the ~~Elements~~ Isobars

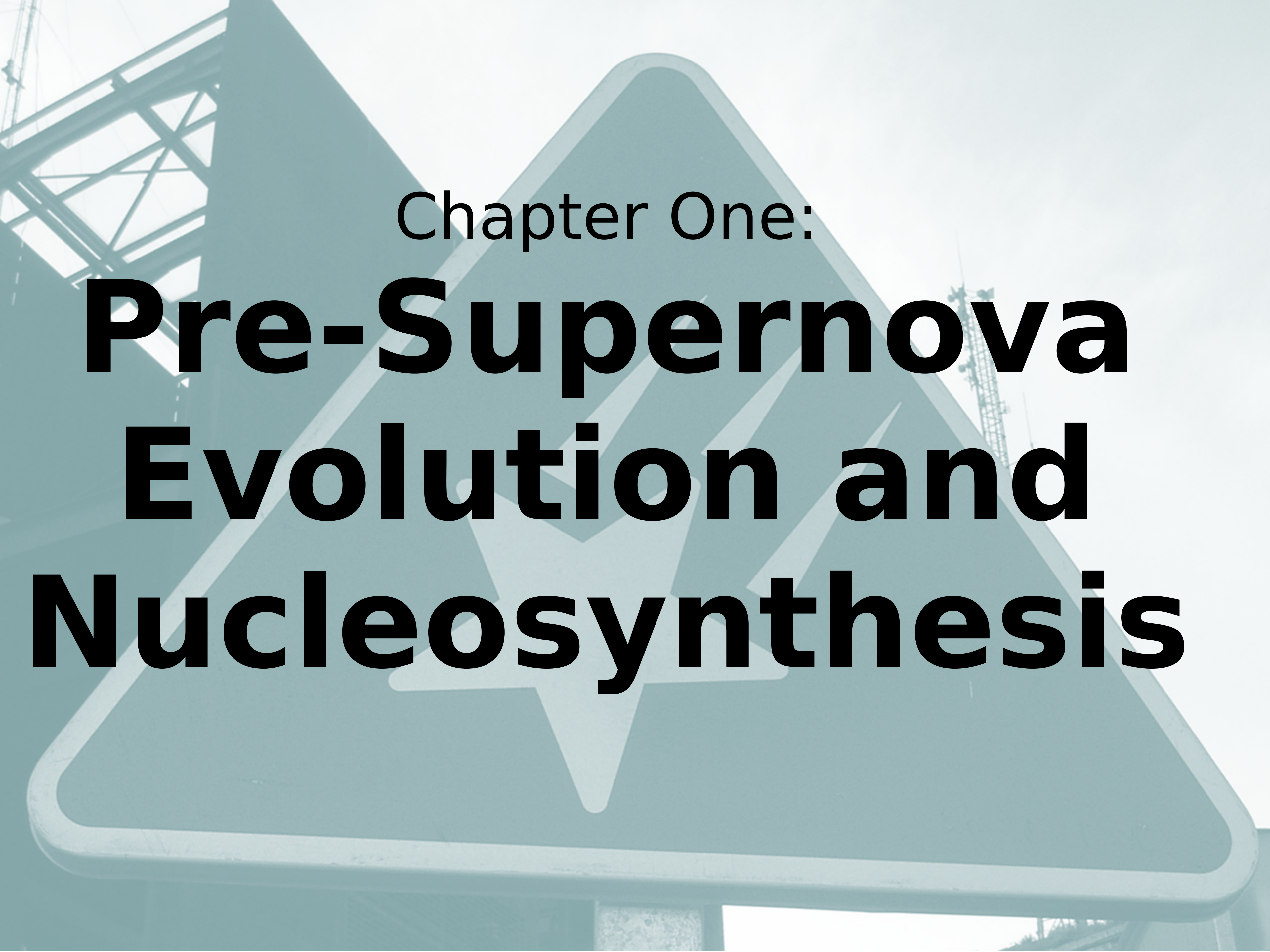


Isotope Decomposition by Process

(for illustrative purposes only)

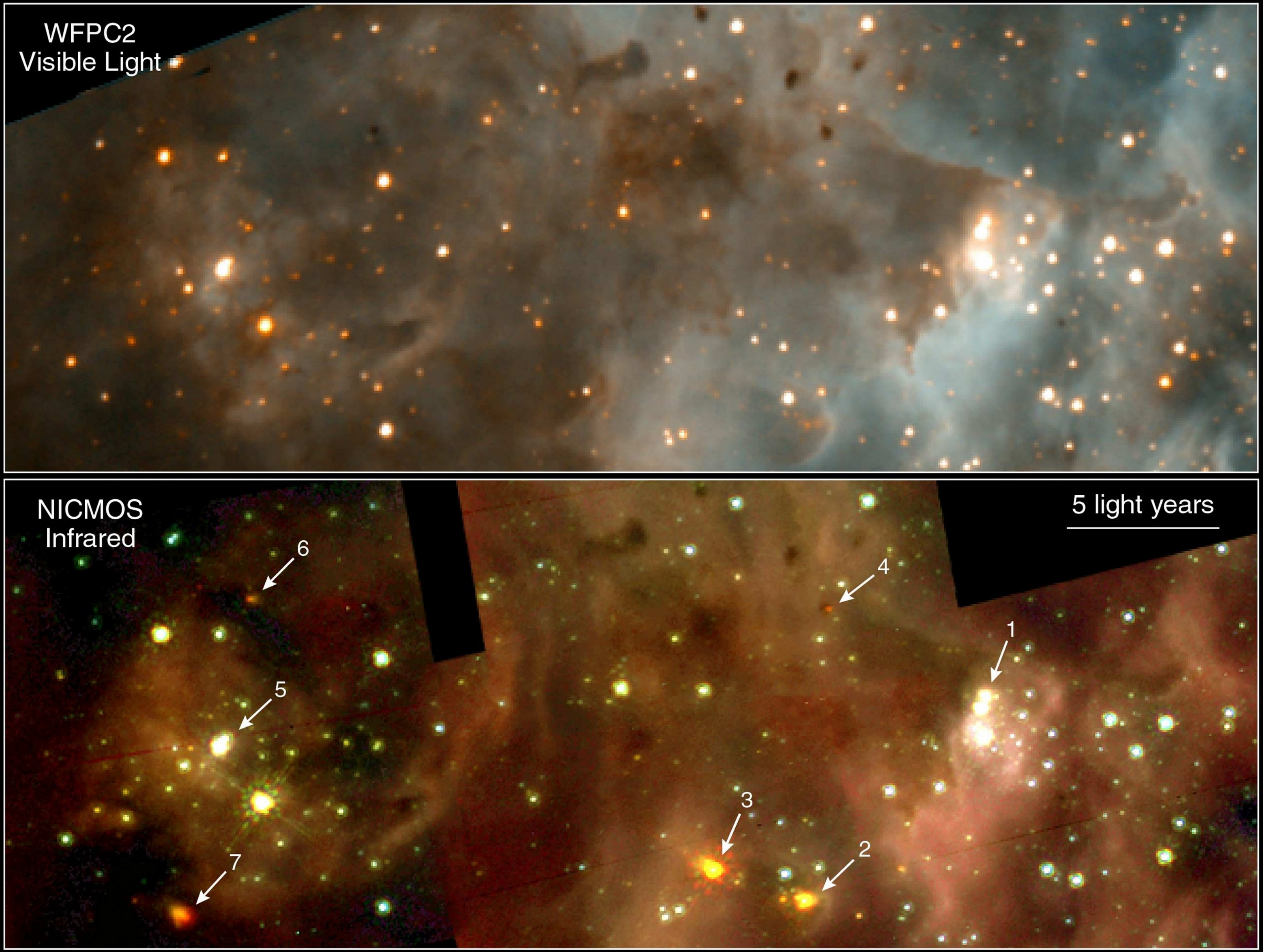


(Chris West 2010)



Chapter One:

Pre-Supernova Evolution and Nucleosynthesis

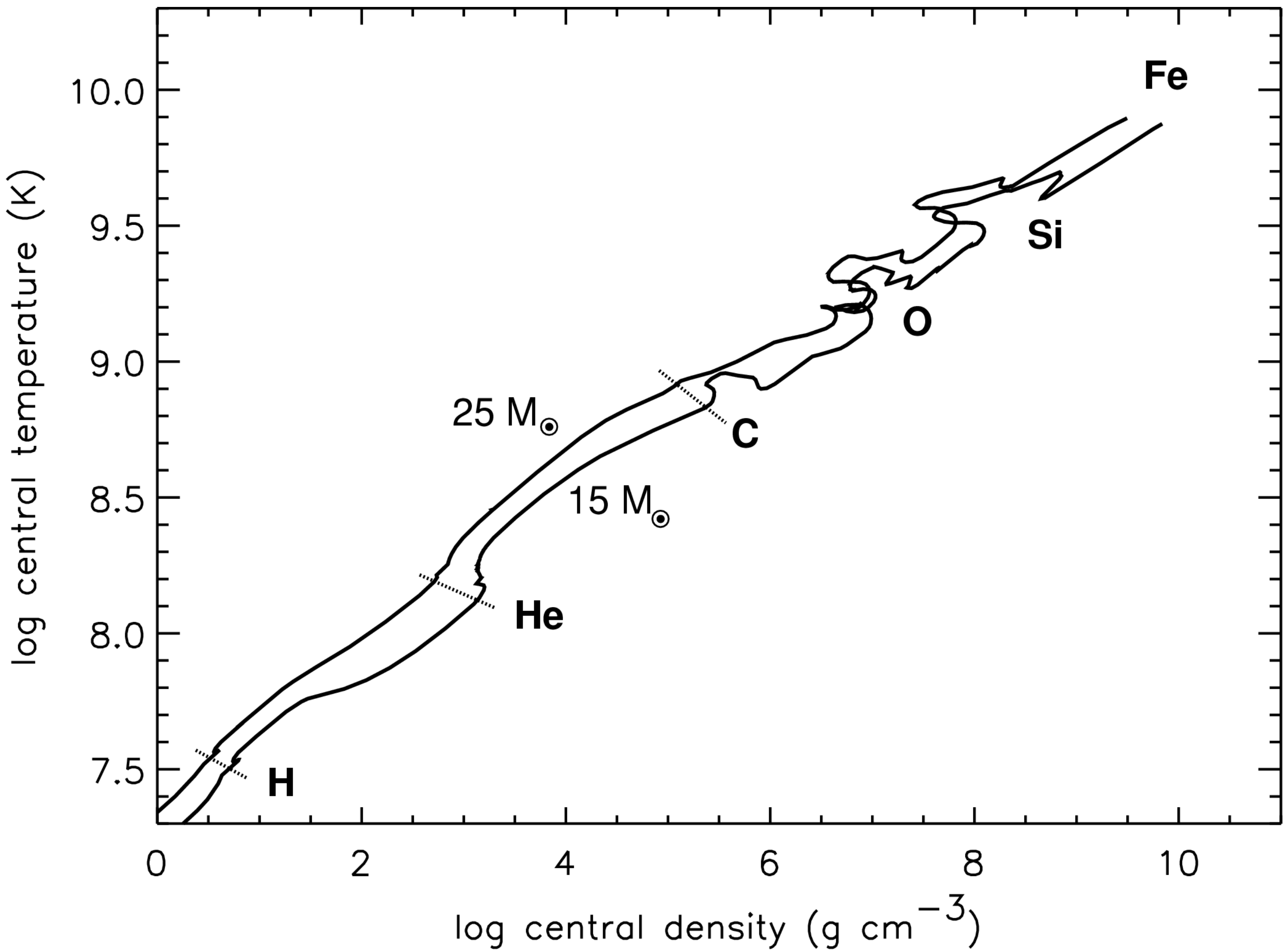


30 Doradus Details

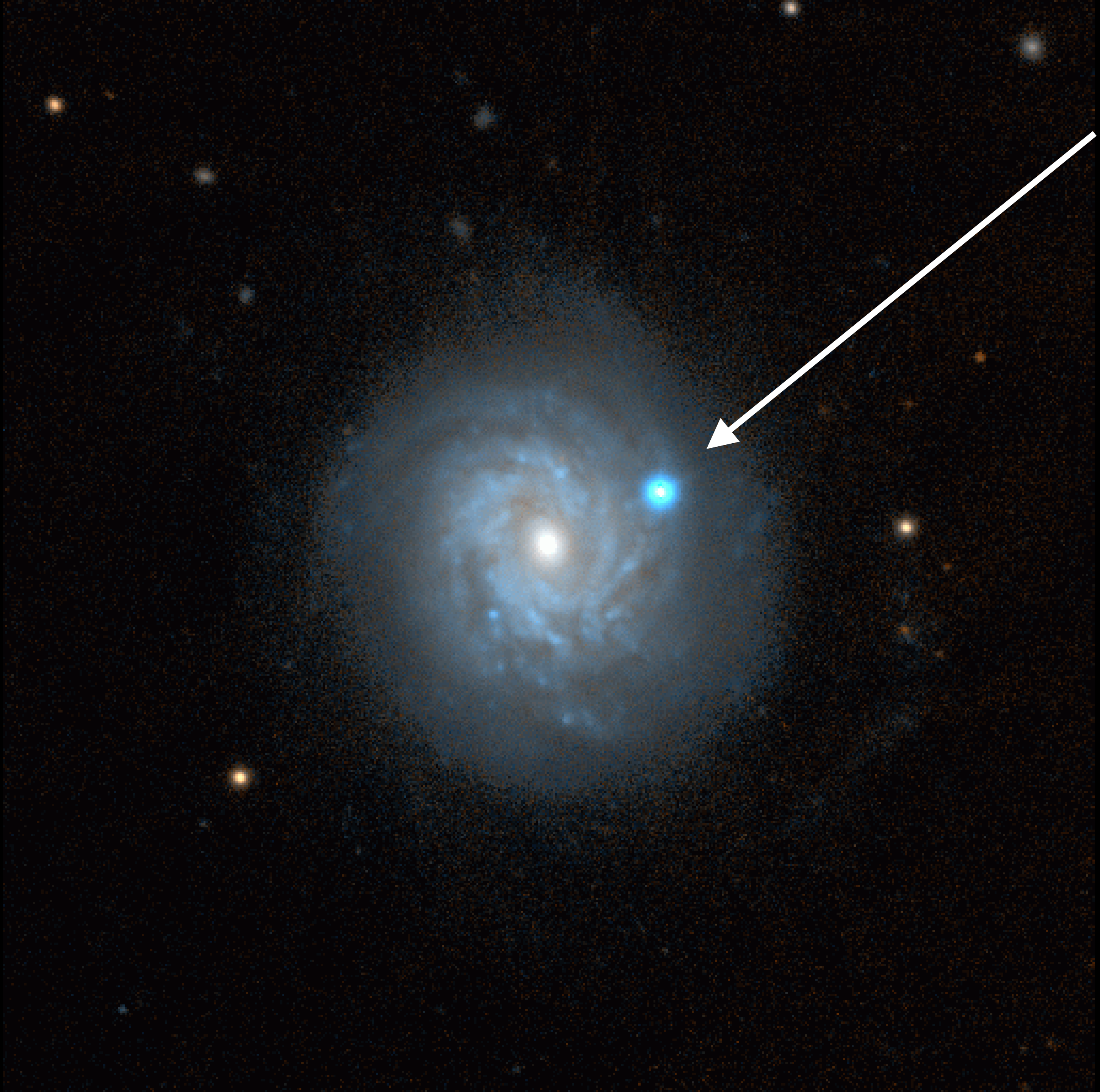
Hubble Space Telescope • WFPC2 • NICMOS

PRC99-33b • STScI OPO • N. Walborn (STScI), R. Barbá (La Plata Observatory) and NASA

Once formed, the evolution of a star is governed by gravity:
continuing contraction
to higher central densities and temperatures



Evolution of central density and temperature of 15 $M_\odot$ and 25 $M_\odot$ stars

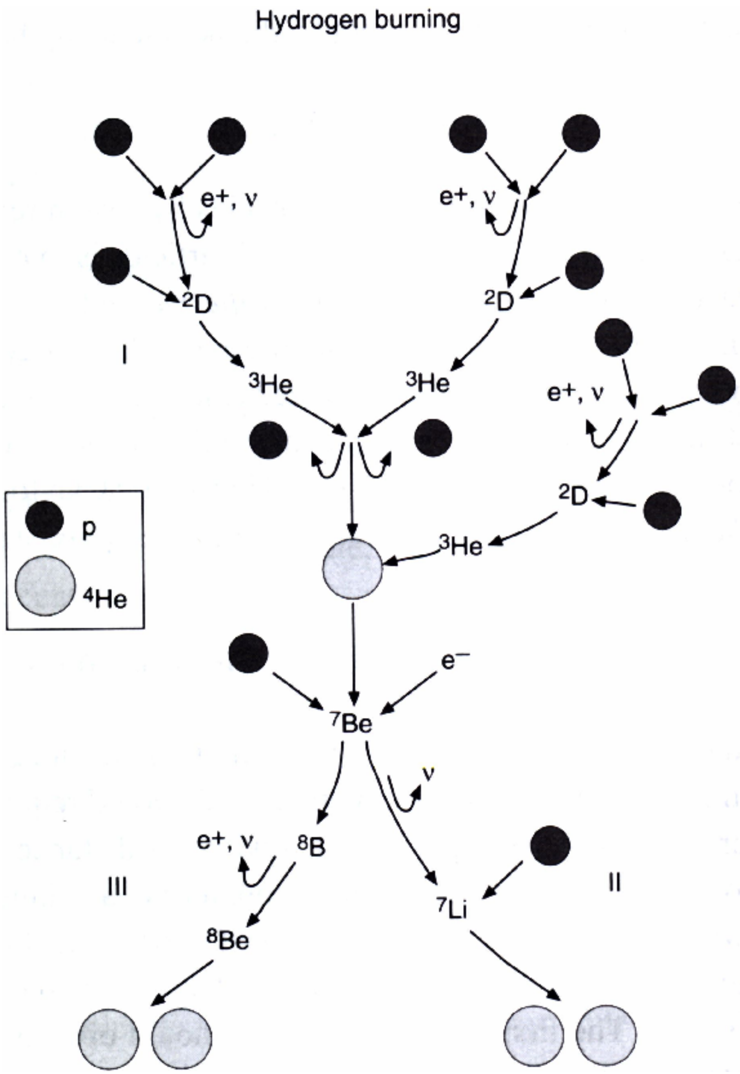


NGC3982

Part One:

Nuclear Burning Stages

Hydrogen-Burning: pp Chains



$$^1H + {}^1H \rightarrow {}^2H + e^+ + \nu$$
$$^2H + {}^1H \rightarrow {}^3He + \gamma$$

$$^3He + {}^3He \rightarrow {}^4He + 2\,{}^1H \quad (pp1)$$

$$^3He + {}^4He \rightarrow {}^7Be + \gamma \qquad (18.62)$$

$$^7Be + e^- \rightarrow {}^7Li + \nu$$
$$^7Li + {}^1H \rightarrow {}^4He + {}^4He \quad (pp2)$$

$$^7Be + {}^1H \rightarrow {}^8B + \gamma$$
$$^8B \rightarrow {}^8Be + e^+ + \nu$$
$$^8Be \rightarrow {}^4He + {}^4He \quad (pp3)$$

Energy release:

$Q(pp1) = 26.20 MeV$

$Q(pp2) = 25.67 MeV$

$Q(pp3) = 19.20 MeV$

Reaction rate: $\langle \sigma v \rangle \propto T^4$

Hydrogen Burning: CNO Bi-Cycle

$$^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma$$

$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu$$

$$^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma$$

$$^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma$$

$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu$$

$$^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He$$

$$\rightarrow {}^{16}O + \gamma$$

$$^{16}O + {}^{1}H \rightarrow {}^{17}F + \gamma$$

$$^{17}F \rightarrow {}^{17}O + e^{+} + \nu$$

$$^{17}O + {}^{1}H \rightarrow {}^{14}N + {}^{4}He$$

Energy release:
$Q(CNO) = 24.97 MeV$

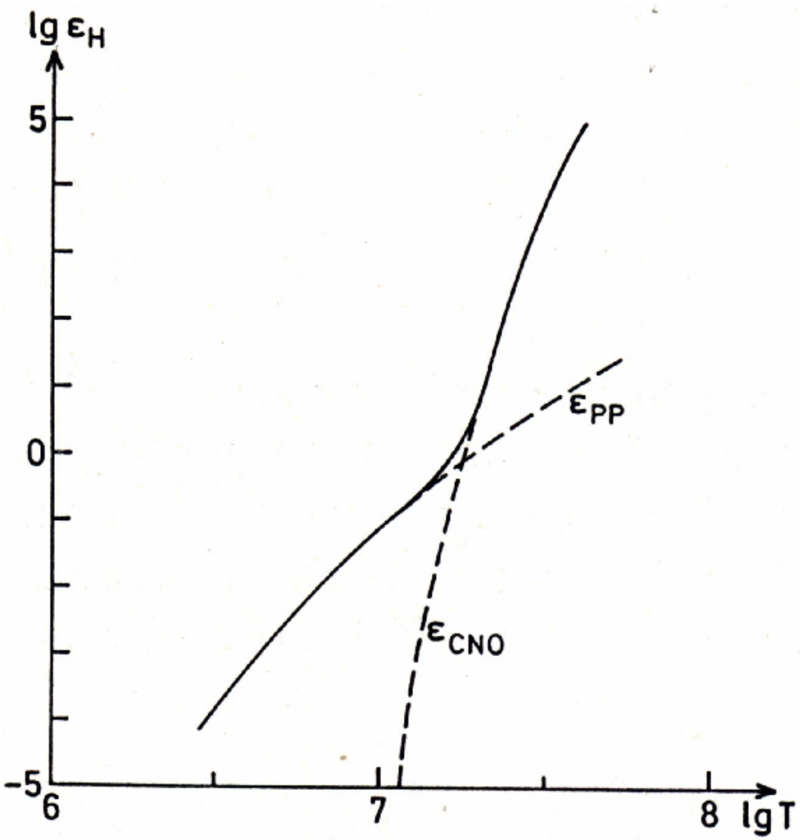
Reaction rate: $\langle \sigma v \rangle \propto T^{16}$

Branching:
CNO-1 : CNO-2 $\sim$ 10,000 : 1

Hydrogen Burning: CNO Bi-Cycle

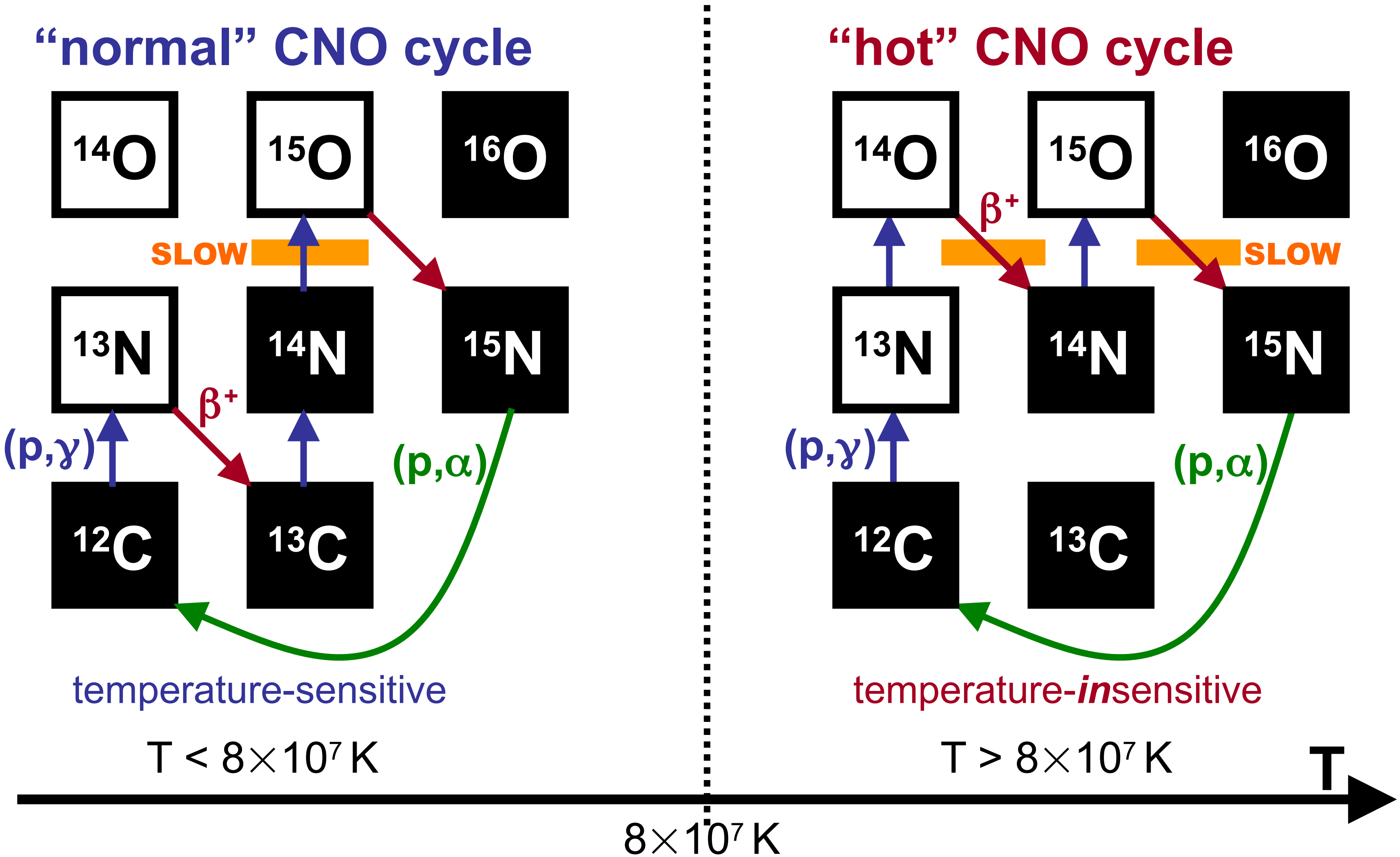
- Usually the beta-decays are fast compared to the capture reactions, (p,γ).
- ^{14}O: $\tau_{1/2} = 70$ sec
  ^{15}O: $\tau_{1/2} = 122$ sec
  ^{13}N: $\tau_{1/2} = 10\,\text{min}$
  ^{17}F: $\tau_{1/2} = 64$ sec
  ^{18}O: $\tau_{1/2} = 110\,\text{min}$
- ^{14}N(p,γ)^{15}O usually is the slowest “bottleneck” reaction.
- CNO cycle burning converts most CNO isotopes into ^{14}N.

Competition of Hydrogen-Burning Modes



Transition from pp-chains
in low-mass stars (low T)
to CNO chains
in high-mass stars (high T)

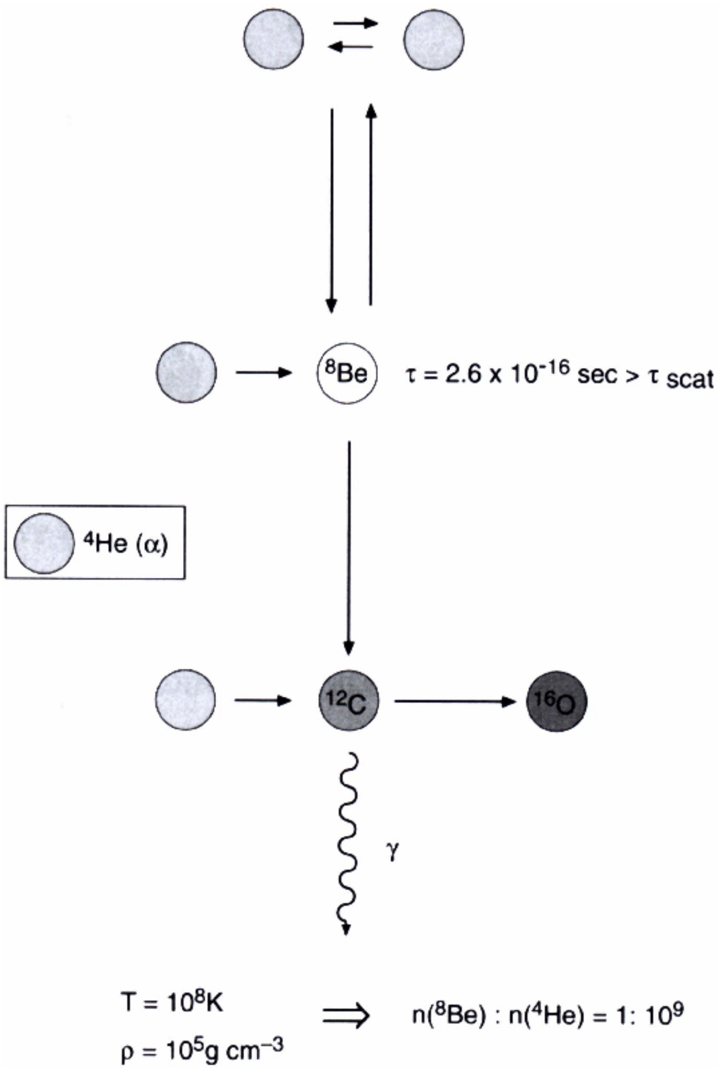
Hydrogen Burning by CNO Cycle



time for an eddy to burn its hydrogen content by **hot** CNO cycle

$$\tau_H = 11\ \mathrm{h} \left(\frac{0.02}{Z}\right)\left(\frac{X_0}{0.7}\right)$$

Helium Burning



Step 1:

$^4\mathrm{He} + {}^4\mathrm{He} \rightleftharpoons {}^8\mathrm{Be}$

Built up equilibrium abundance of ^{8}Be

Lifetime of ^{8}Be is only 2.6×10^{-16} s!

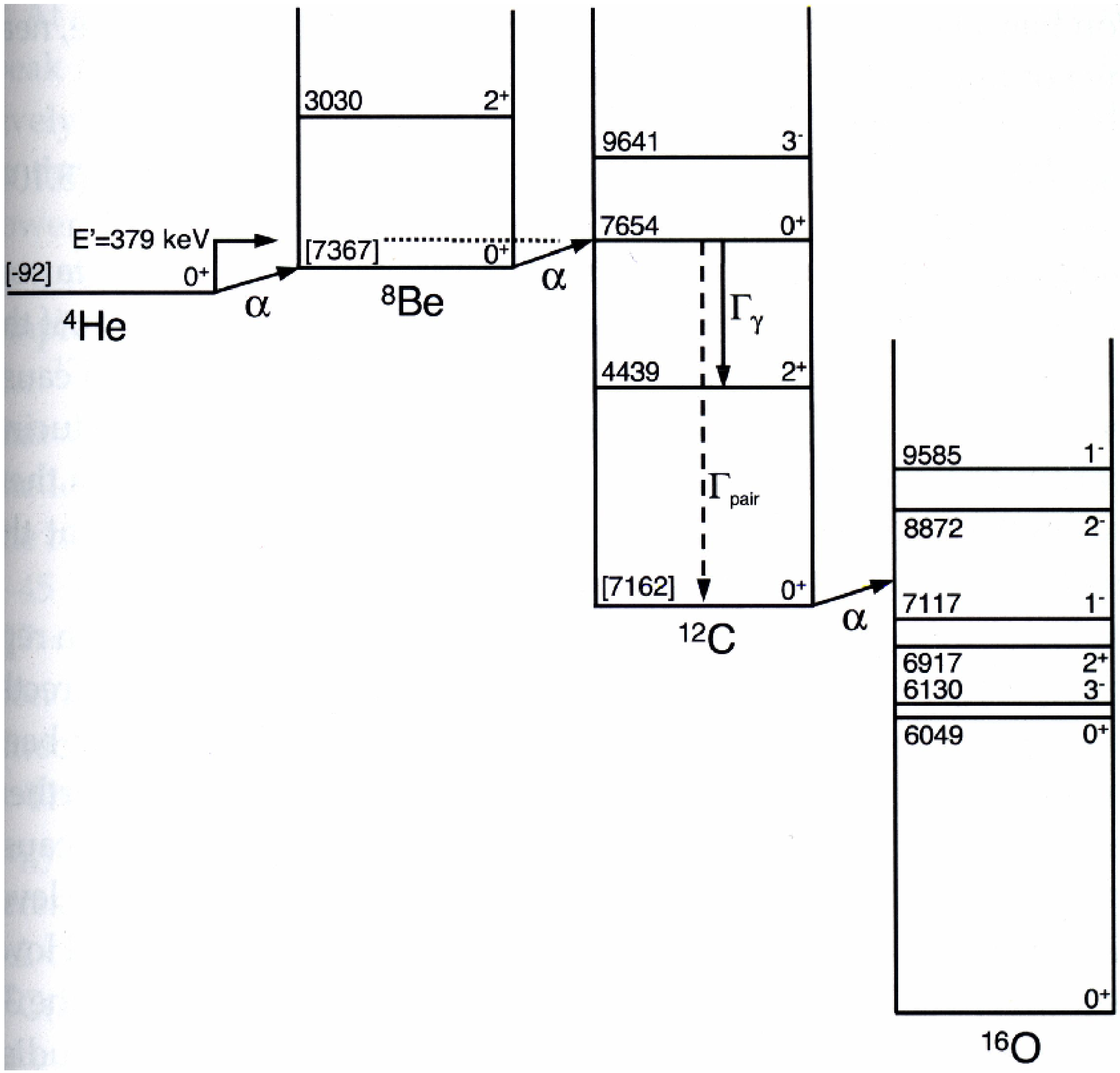
Step 2:

$^8\mathrm{Be} + {}^4\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma$

$Q_{3\alpha} = 7.275\,\mathrm{MeV}$

$< \sigma v > \propto \rho^2 T^{40}$

Helium Burning Level Scheme



Additional Helium Burning Reactions

Oxygen Production

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

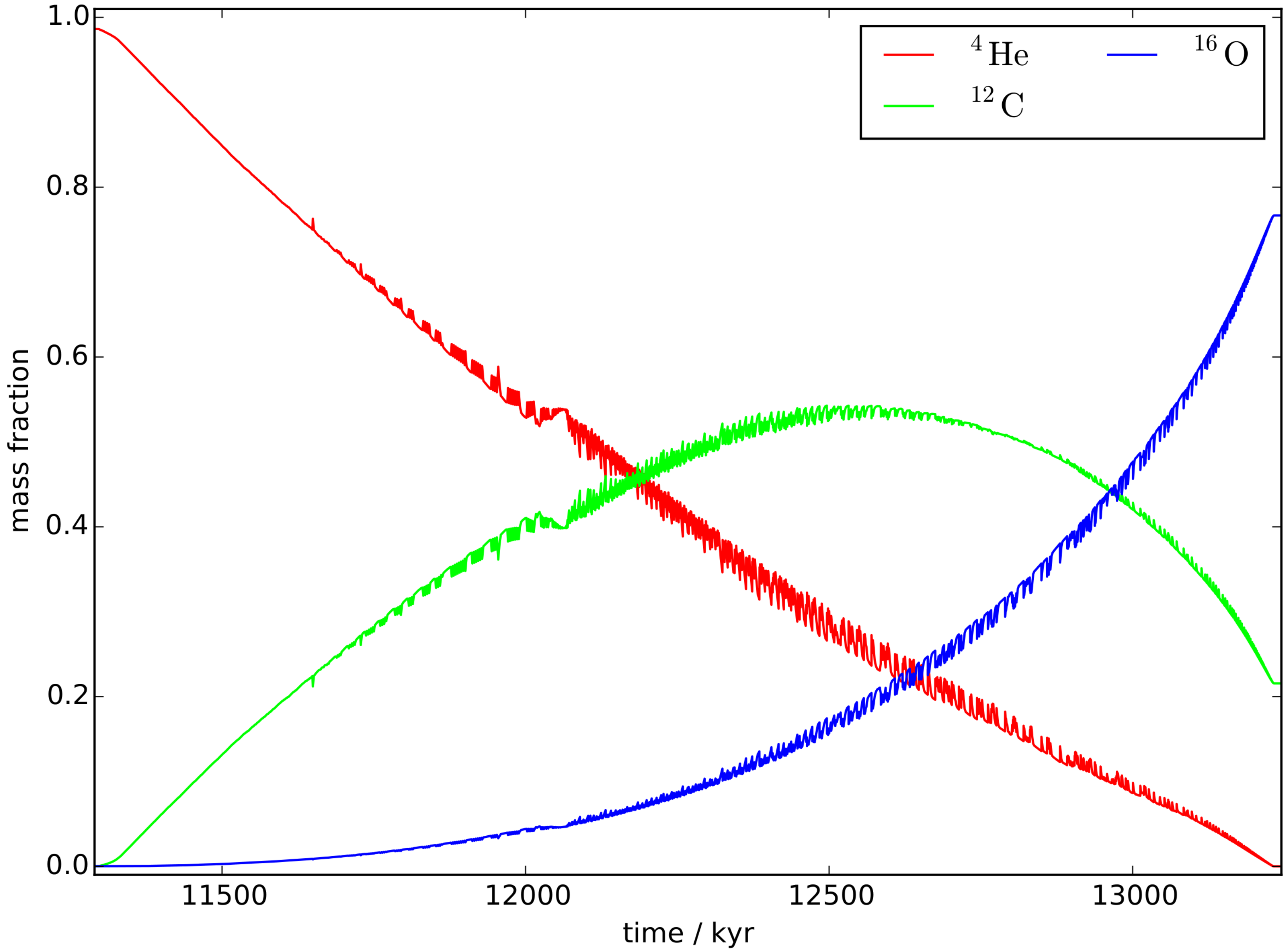
$Q = 7.162\,\mathrm{MeV}$

$\langle \sigma v \rangle \ \propto \rho T^{40}$

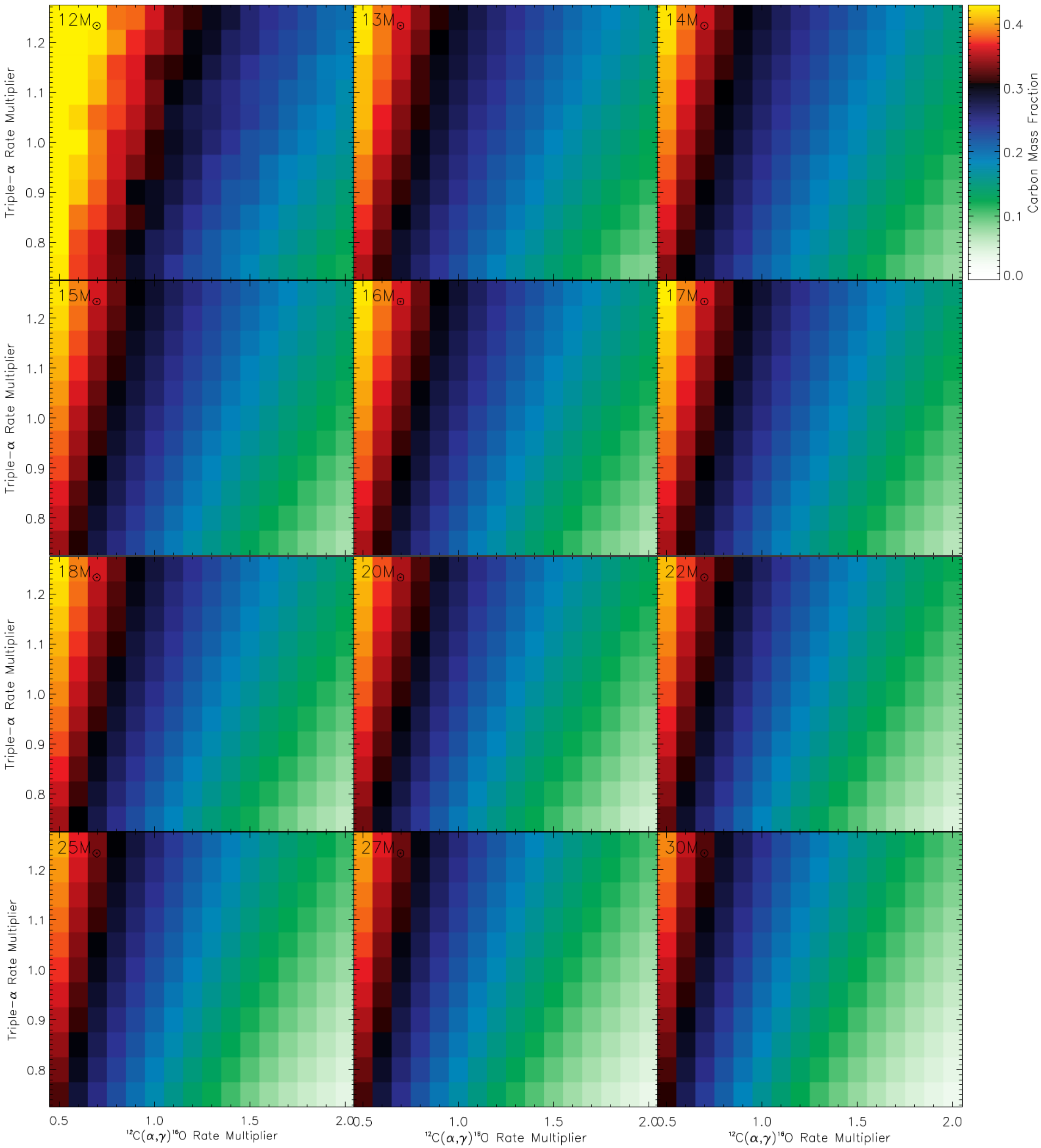
The final abundance of carbon is set by the competition of 3α and $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reactions;

The production of $^{16}\mathrm{O}$ can only start when a sufficient amount of $^{12}\mathrm{C}$ has been made.

Competition of Helium Burning Reactions



^{12}C Production as a function of $^{12}C(\alpha,\gamma)$ and 3α reaction rates

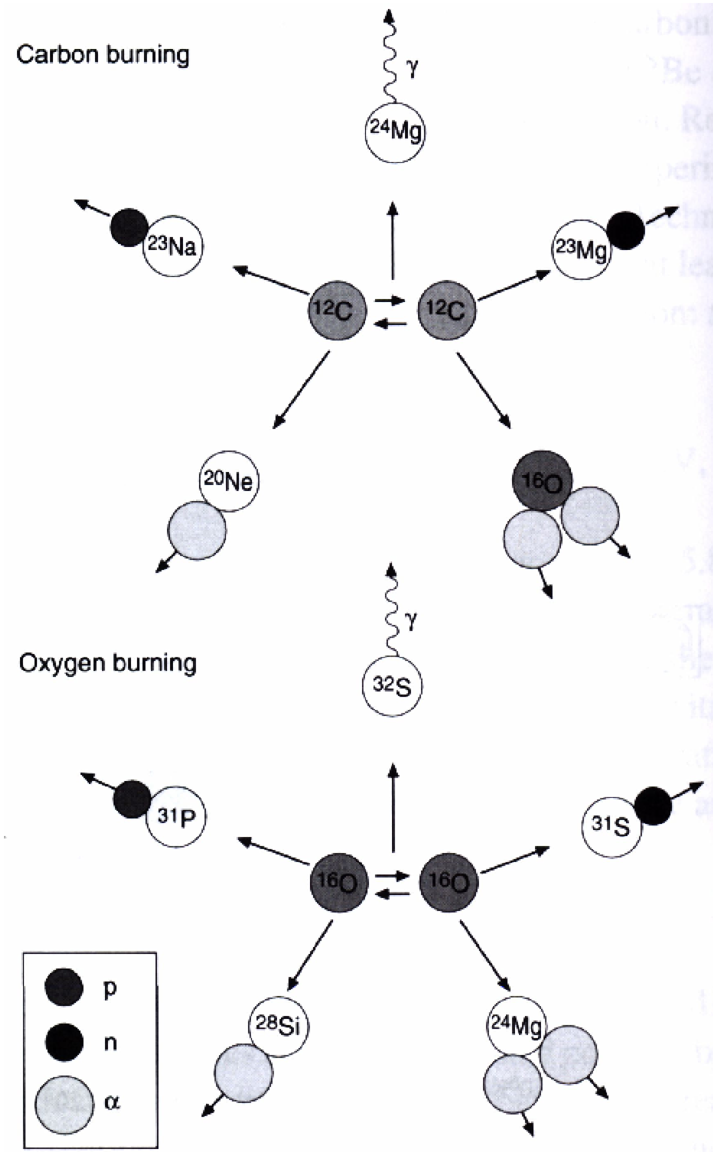


Carbon mass fraction at the end of helium burning depends the reaction rates and the mass of the star

~2000 stellar models

(West+ 2013)

Carbon and Oxygen Burning



Carbon Burning

$$
\begin{aligned}
{}^{12}\mathrm{C} + {}^{12}\mathrm{C} &\rightarrow {}^{24}\mathrm{Mg} + \gamma \quad , \quad 13.931 \\
&\rightarrow {}^{23}\mathrm{Mg} + n \quad , \quad -2.605 \\
&\rightarrow {}^{23}\mathrm{Na} + p \quad , \quad 2.238 \\
&\rightarrow {}^{20}\mathrm{Ne} + \alpha \quad , \quad 4.616 \\
&\rightarrow {}^{16}\mathrm{O} + 2\alpha \quad , \quad -0.114
\end{aligned}
$$

Average $Q = 13\,\mathrm{MeV}$

Oxygen Burning

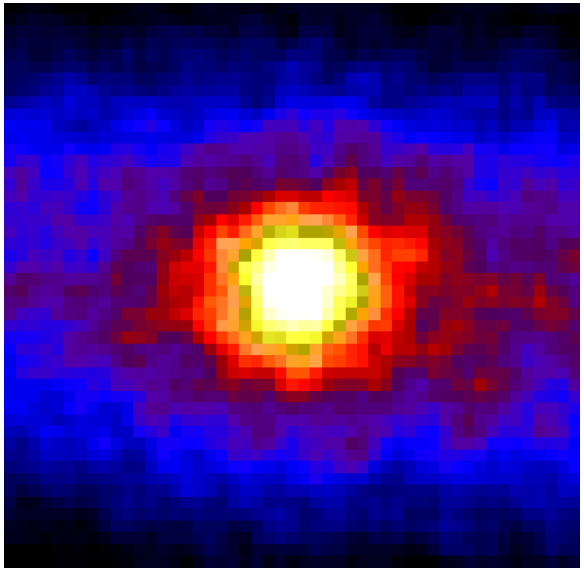
$$
\begin{aligned}
{}^{16}\mathrm{O} + {}^{16}\mathrm{O} &\rightarrow {}^{32}\mathrm{S} + \gamma \quad , \quad 16.541 \\
&\rightarrow {}^{31}\mathrm{P} + p \quad , \quad 7.677 \\
&\rightarrow {}^{31}\mathrm{S} + n \quad , \quad 1.453 \\
&\rightarrow {}^{28}\mathrm{Si} + \alpha \quad , \quad 9.593 \\
&\rightarrow {}^{24}\mathrm{Mg} + 2\alpha \quad , \quad -0.393
\end{aligned}
$$

Average $Q = 16\,\mathrm{MeV}$

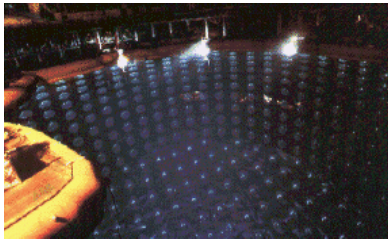
Neutrino losses from electron/positron pair annihilation

- Important for carbon burning and beyond
- For $T>10^9$ K (about 100 keV), occasionally:
  $$\gamma \rightarrow e^+ + e^-$$
  and usually
  $$e^+ + e^- \rightarrow 2\gamma$$
  but sometimes
  $$e^+ + e^- \rightarrow \overline{\nu}_e + \nu_e$$
-
- The neutrinos exit the stars at the speed of light while the e^+, e^-, and the γ's all stay trapped.

- This is an important energy loss with
  $$\varepsilon_\nu \approx -10^{15}\,(T/10^9\,\mathrm{K})^9 \text{ erg g}^{-1}\text{ s}^{-1}$$
- For carbon burning and beyond, each burning stage gives about the same energy per nucleon, thus the lifetime goes down as T^{-9}



The sun as seen by Kamiokande



Neon Burning

Neon burning proceeds by a combination of photo-disintegrations and α captures:

$$^{20}\text{Ne} + \gamma \rightarrow {}^{16}\text{O} + {}^{4}\text{He} , \quad Q = -4.73\,\text{MeV}$$

This reaction dominates over the inverse reaction known from helium burning for $T > 1.5 \times 10^9\,\text{K}$.

Subsequently, the ^{4}He is captured on another ^{20}Ne nucleus:

$$^{20}\text{Ne} + {}^{4}\text{He} \rightarrow {}^{24}\text{Mg} + \gamma .$$

The net result is

$$2\,{}^{20}\text{Ne} + \gamma \rightarrow {}^{16}\text{O} + {}^{24}\text{Mg} + \gamma , \quad Q = +4.583\,\text{MeV}$$

Nuclear burning stages

(20 $M_{\odot}$ stars)

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\ H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\ He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si,S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)\ldots$

Silicon/Sulfur Burning

Actually, often we have more sulfur in the star than there is silicon, but it is custom to call this phase "silicon burning".

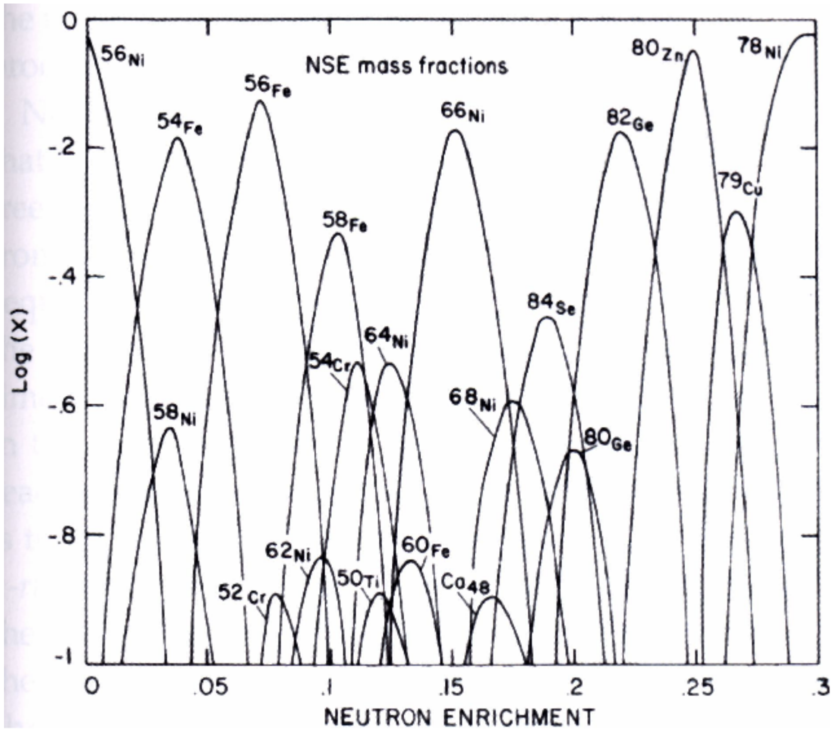
Typical burning temperature is $3 \ldots 3.5 \times 10^9$ K.

Similar to neon burning, silicon burning proceeds as a series of photo-disintegration reactions, mostly, (γ, α), and helium capture reactions, (α, γ) to build up iron group elements.

$(\gamma, \alpha) \rightleftharpoons (\alpha, \gamma)$

At the high T and ρ of these conditions, also *weak reactions* occur, converting protons into neutrons and leading to a *neutron excess*. This allows to actually make stable iron isotopes.

Beyond Silicon Burning



NSE distribution for
$T = 3.5 \times 10^9$ K,
$\rho = 10^7$ g/cm^3

After silicon burning T and ρ is so high that the nuclei are in **nuclear statistical equilibrium**, i.e., the reactions are fast compared to the evolution time-scale of the star, and the abundance distribution of the nuclei is given by a *Saha equation*.

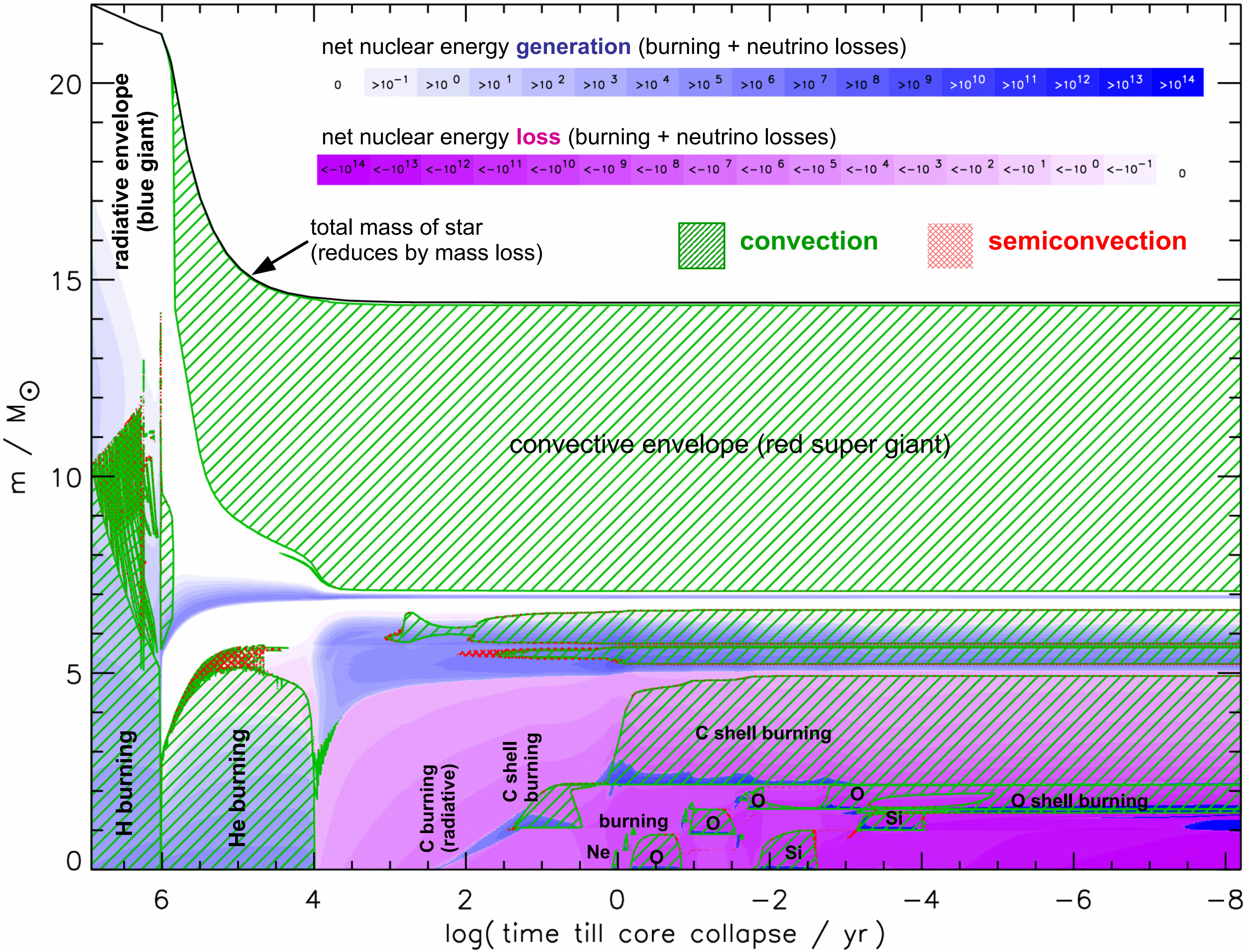
Summary of Energies

Nuclear Fuel	*Process*	$T_{threshold}$ 10^6 K	*Products*	*Energy per Nucleon (MeV)*
H	p–p	~4	He	6.55
H	CNO	15	He	6.25
He	3α	100	C, O	0.61
C	C + C	600	O, Ne, Na, Mg	0.54
O	O + O	1000	Mg, S, P, Si	~0.3
Si	Nuc. eq.	3000	Co, Fe, Ni	<0.18

Nitrogen Burning

$^{14}N(\alpha,\gamma)^{18}F(\beta^{+}\nu_{e})^{18}O(\alpha,\gamma)^{22}Ne$

- **^{14}N is made as slowest reactant in CNO cycle**
- **It is made from initial metals, not as a primary product**
- **Depending on metallicity, the abundance can be come significant; it will be more important for more metal-rich stars.**
- **^{14}N burning occurs at the onset – before – central helium burning and can have its own convective burning phase, take a few % of helium burning time.**


net nuclear energy generation (burning + neutrino losses)
net nuclear energy loss (burning + neutrino losses)
total mass of star
(reduces by mass loss)
convection
semiconvection
radiative envelope
(blue giant)
convective envelope (red super giant)
H burning
He burning
C burning
(radiative)
C shell
burning
C shell burning
Ne
burning
O
Si
O shell burning
m / M☉
log(time till core collapse / yr)