GALACTIC CHEMICAL EVOLUTION

A. Introduction to nucleosynthesis

B. GCE: formalism and ingredients

C: The solar neighborhood and the evolution
of intermediate elements (C-Fe)

D: Heavy (>Fe) and light (LiBeB) elements;
the Bulge; satellite galaxies and Halo formation

E: The Disk and the Extragalactic Universe

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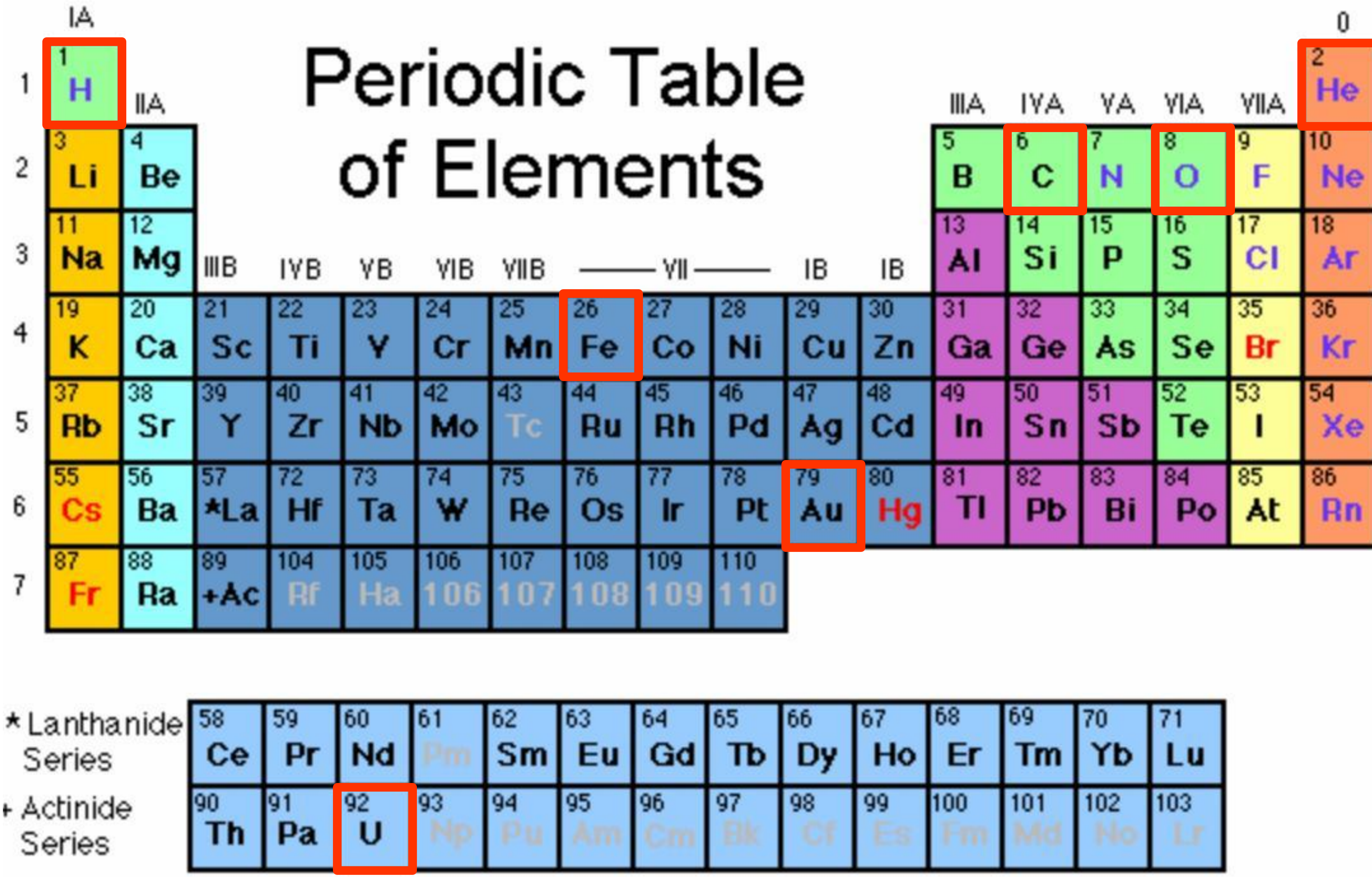
GALACTIC CHEMICAL EVOLUTION

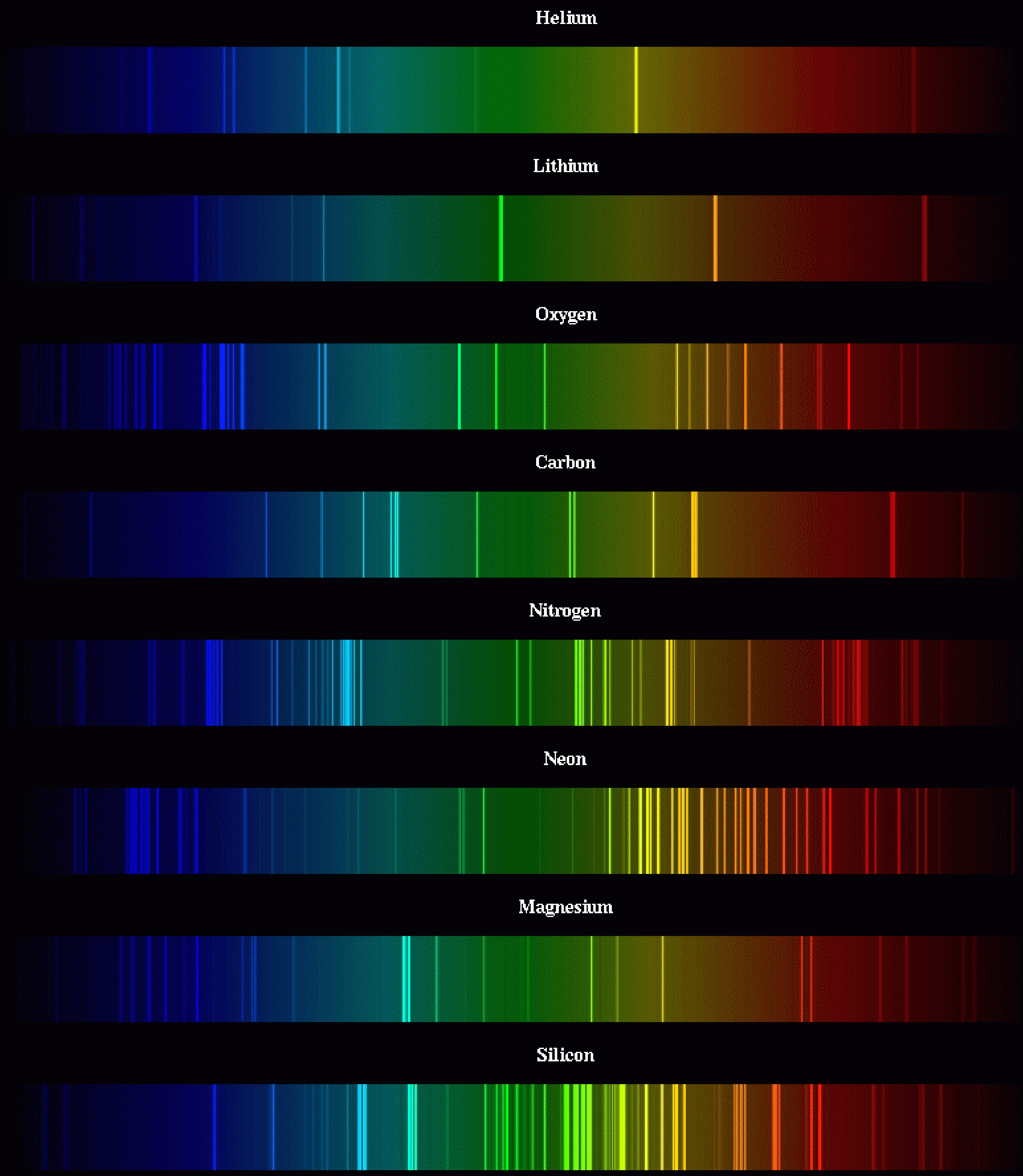
Part I : Introduction to Nucleosynthesis



Periodic Table of Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IB	IIIA	IVA	VA	VIA	VIIA	0
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	57 *La	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	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110								

* Lanthanide Series	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	71 Lu
+ Actinide Series	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	103 Lr



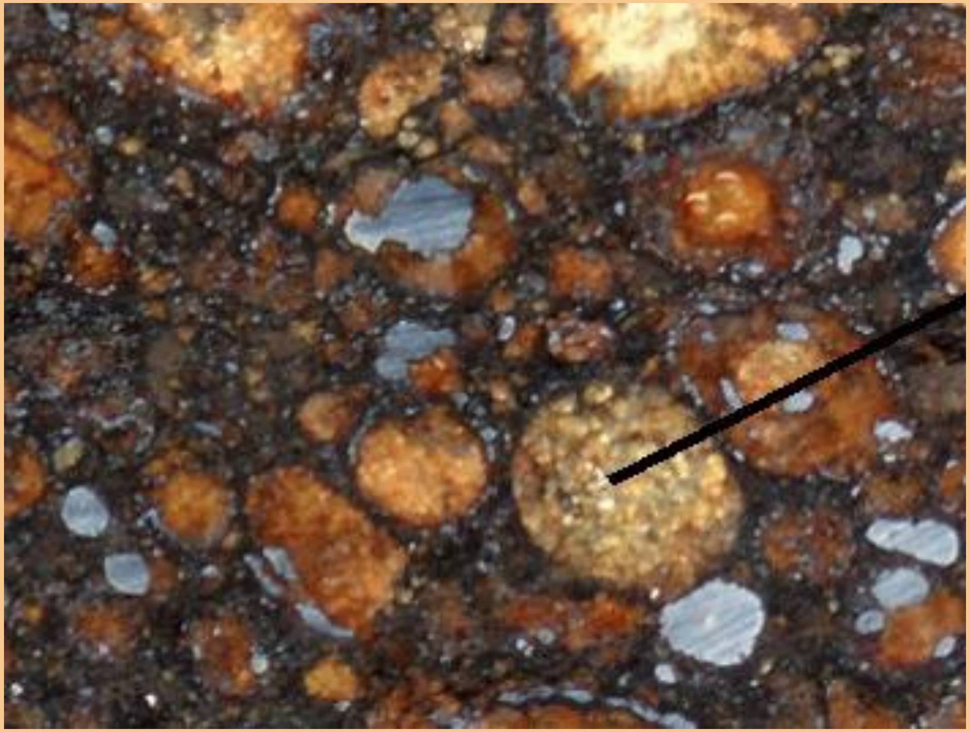
Solar Photosphere, (absorption line spectrum)

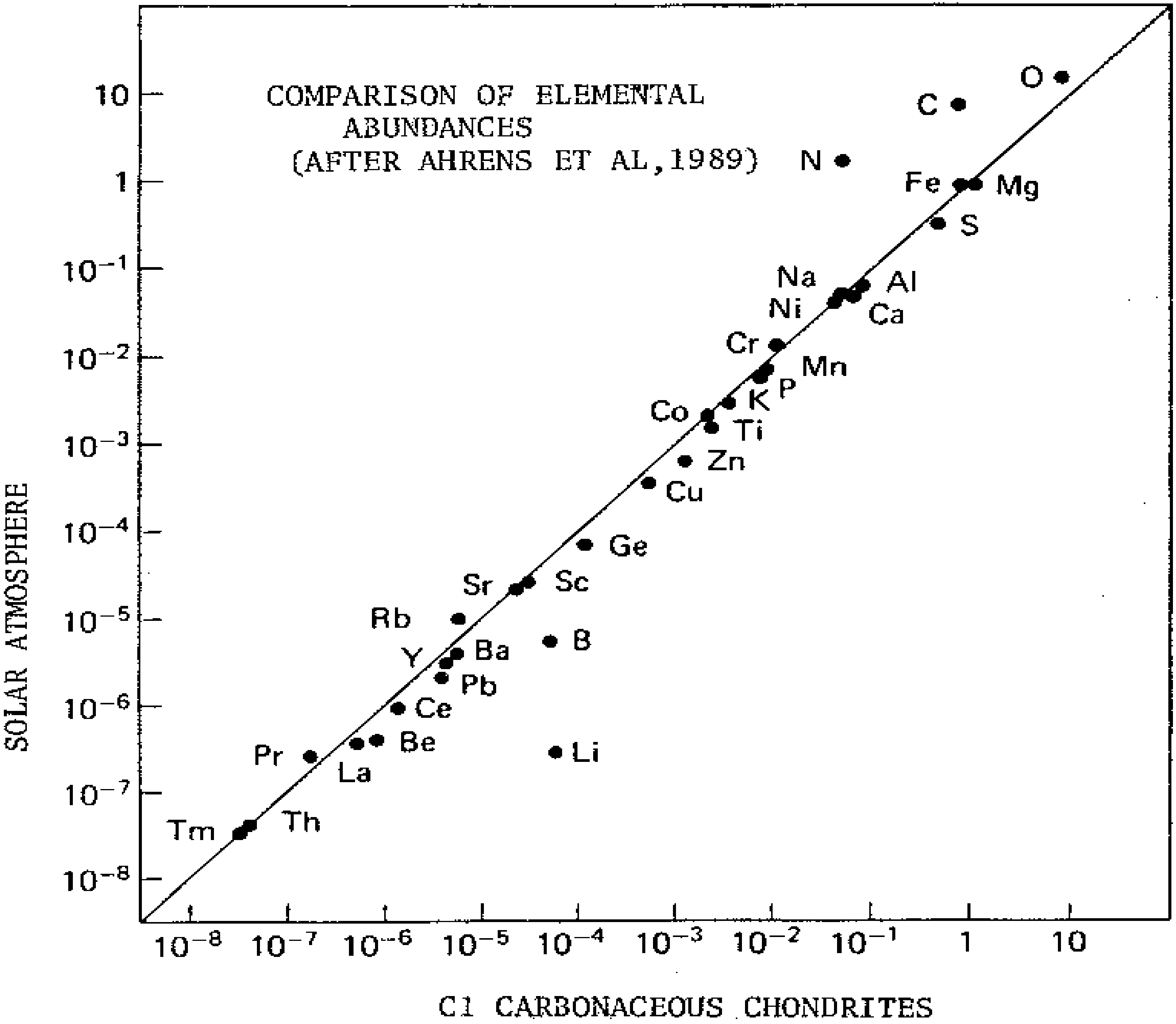
unmodified by nucleosynthesis in Sun’s core, it reflects the composition of the gas from which the Sun formed 4.5 Gyr ago

Elemental composition determined

C1 Carbonaceous chondrites
formed in early Solar system
and unaffected by fractionation

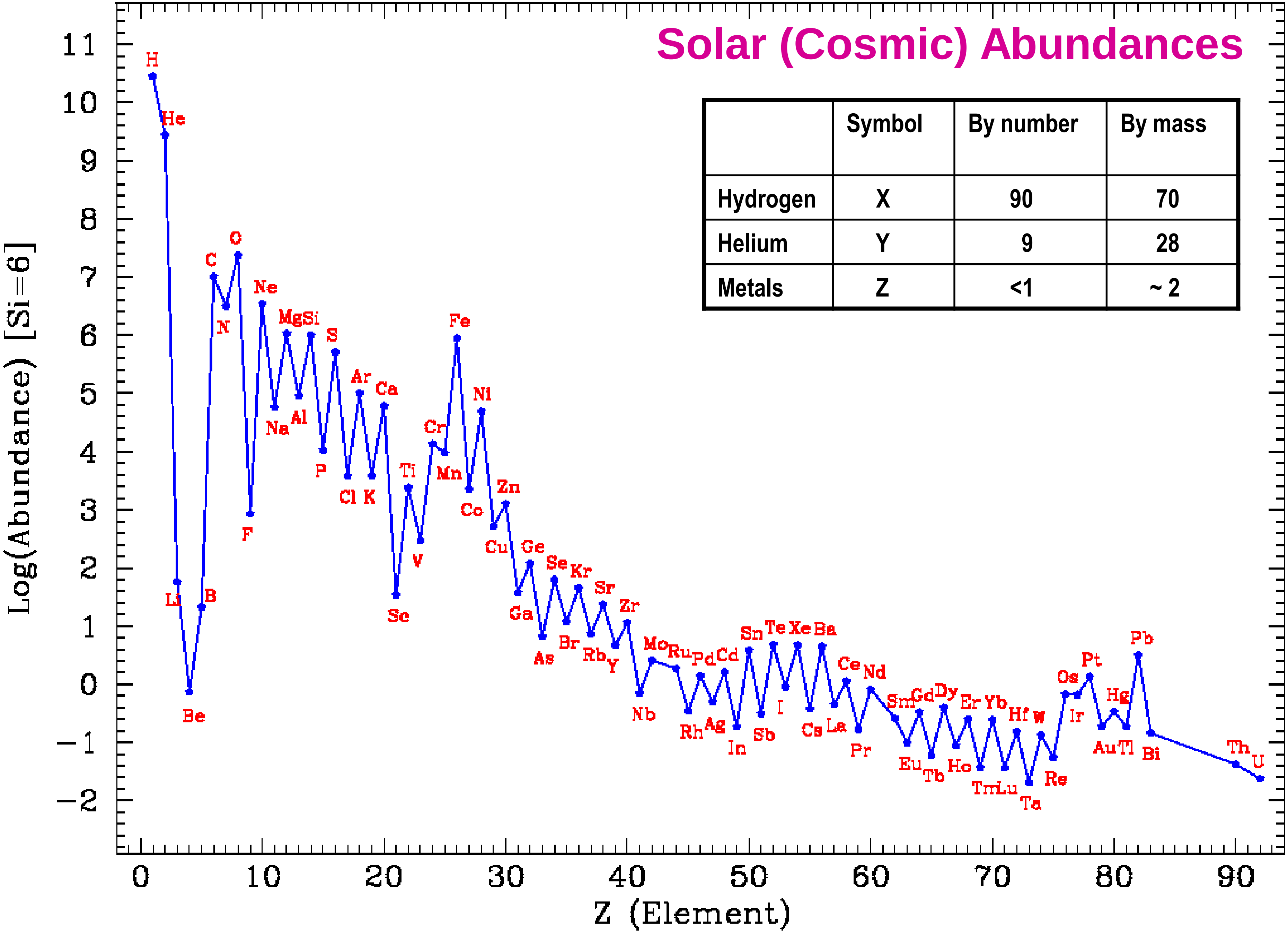
Isotopic composition determined




COMPARISON OF ELEMENTAL ABUNDANCES (AFTER AHRENS ET AL,1989)
SOLAR ATMOSPHERE
C1 CARBONACEOUS CHONDRITES
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
O
C
N
Fe
Mg
S
Na
Al
Ni
Ca
Cr
Mn
P
K
Co
Ti
Zn
Cu
Ge
Sr
Sc
Rb
B
Y
Ba
Pb
Ce
Be
Pr
Li
La
Tm
Th

Solar (Cosmic) Abundances

	Symbol	By number	By mass
Hydrogen	X	90	70
Helium	Y	9	28
Metals	Z	<1	~ 2



Abundance scales

1) By mass (Mass fraction): X_i $\Sigma X_i = 1$

X: H Y: He Z: Metals (A>4) $X+Y+Z=1$

Sun: $X_\odot=0.71$ $Y_\odot=0.275$ $Z_\odot=0.015$

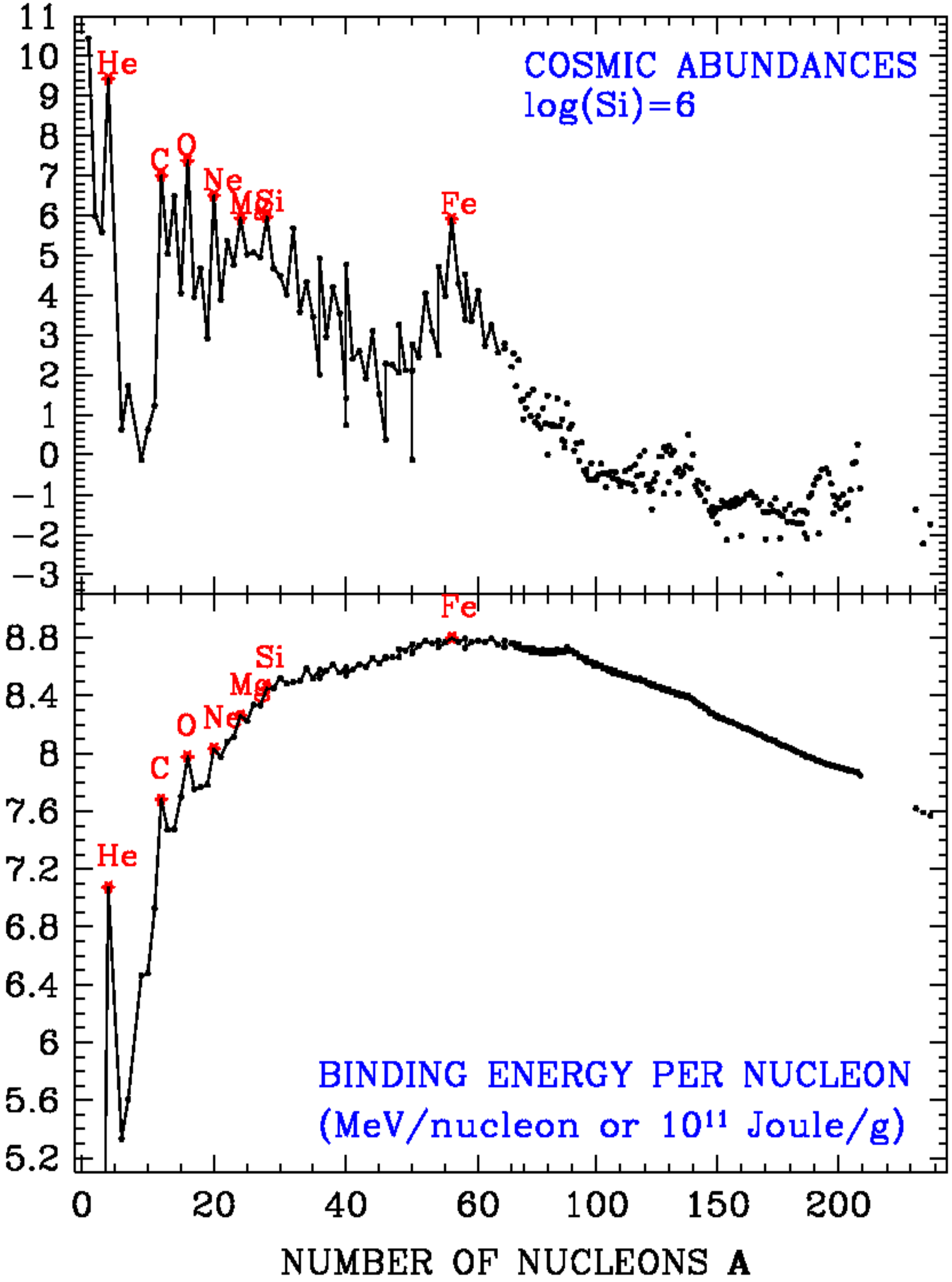
2) By number : $N_i = X_i / A_i$

Observers : $N_H = 10^{12}$ $A_H = \log(N_H) = 12$

$$\varepsilon_X = A_X - A_H$$

3) Relative to solar ratio $(X_i / X_j)_\odot$.

$[X_i/X_j] = \log(X_i/X_j) - \log(X_i/X_j)_\odot$ $[X_i/X_j]_\odot = 0$



Cosmic abundances of nuclides are roughly correlated with

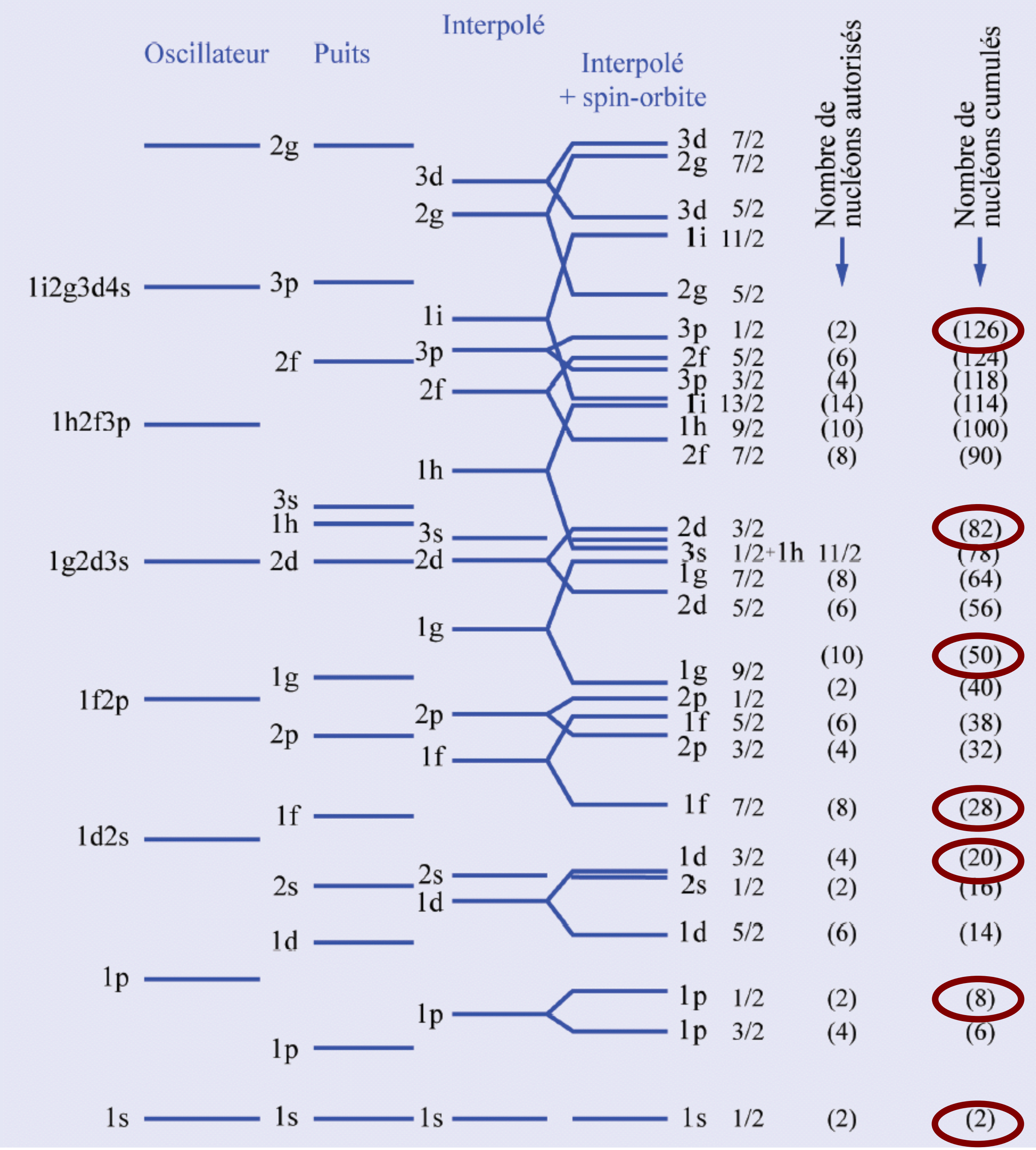
nuclear stability

(alpha-nuclei, Fe peak nuclei or nuclei with even nucleon number are more abundant than their neighbors)

Nuclear processes have shaped the **cosmic abundances** of the chemical elements

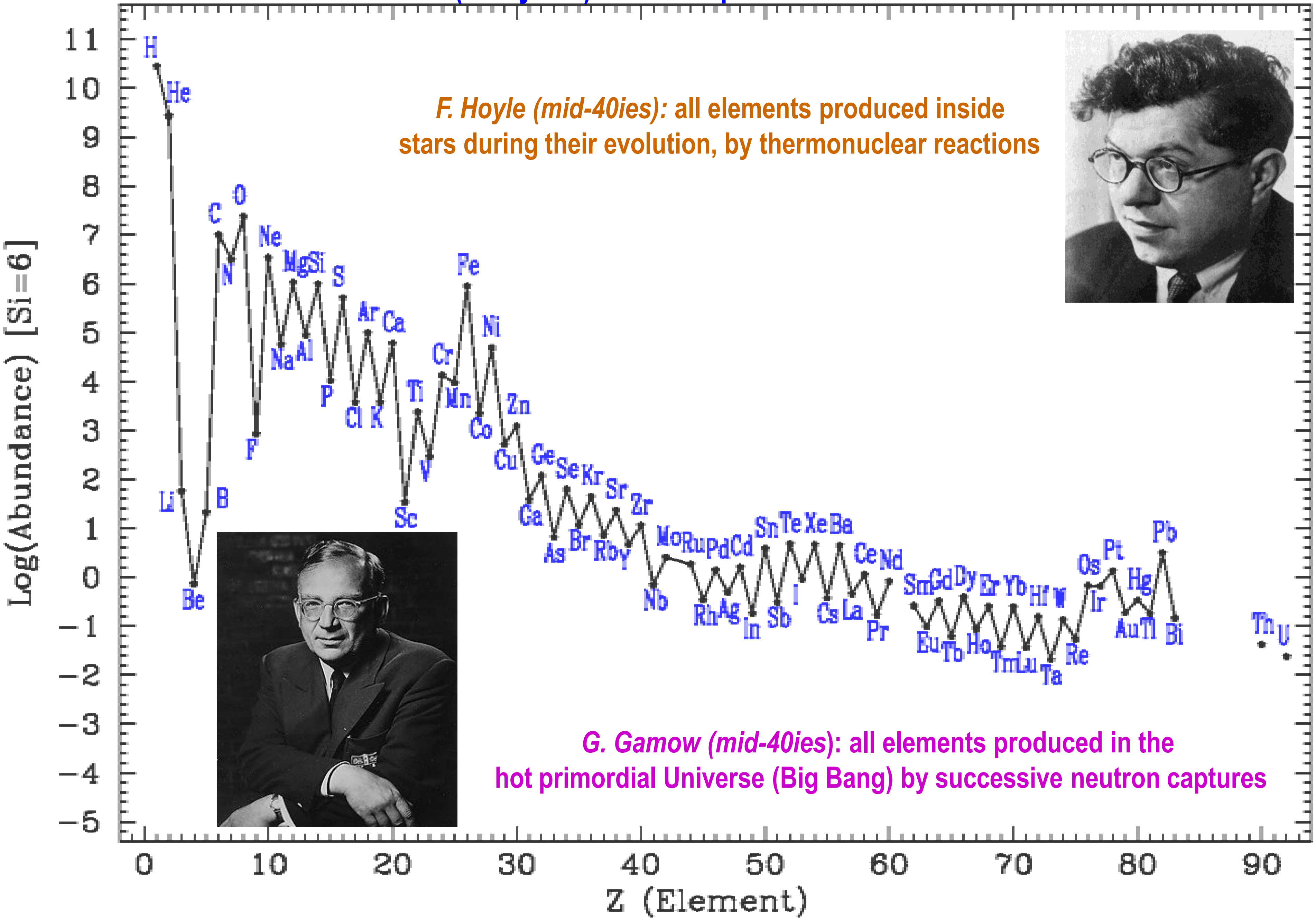
Nuclear shell model suggests that nuclei with **“magic”** nucleon numbers (2, 8, 20, 28, 50, 82,…) are more strongly bound than their neighbors

They are also found to be more abundant in the Universe



Solar (= Cosmic) abundances : related to nuclear properties (nuclear binding energies)

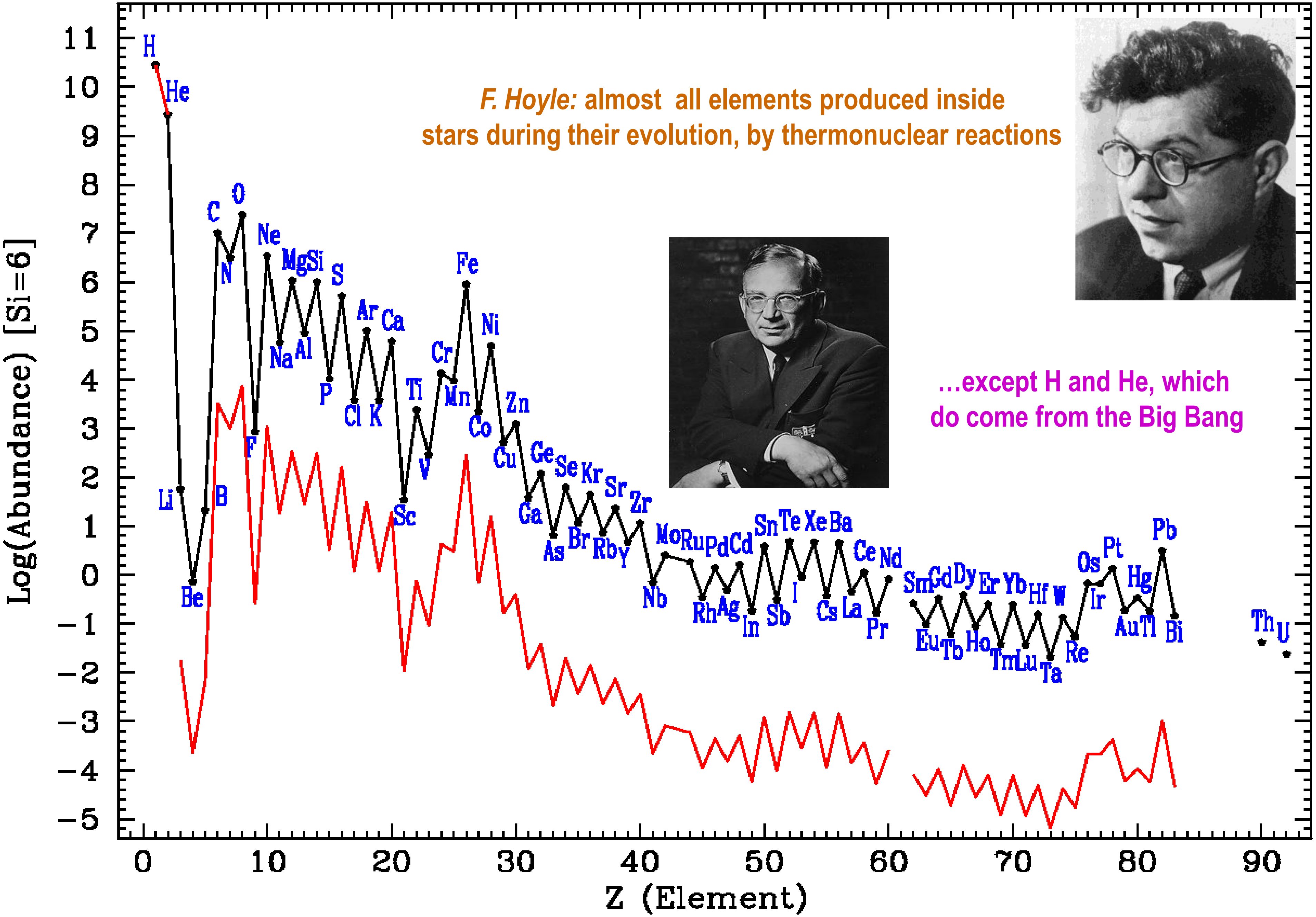
➔ a hot (many MK) site is required : which one ?



F. Hoyle (mid-40ies): all elements produced inside stars during their evolution, by thermonuclear reactions

G. Gamow (mid-40ies): all elements produced in the hot primordial Universe (Big Bang) by successive neutron captures

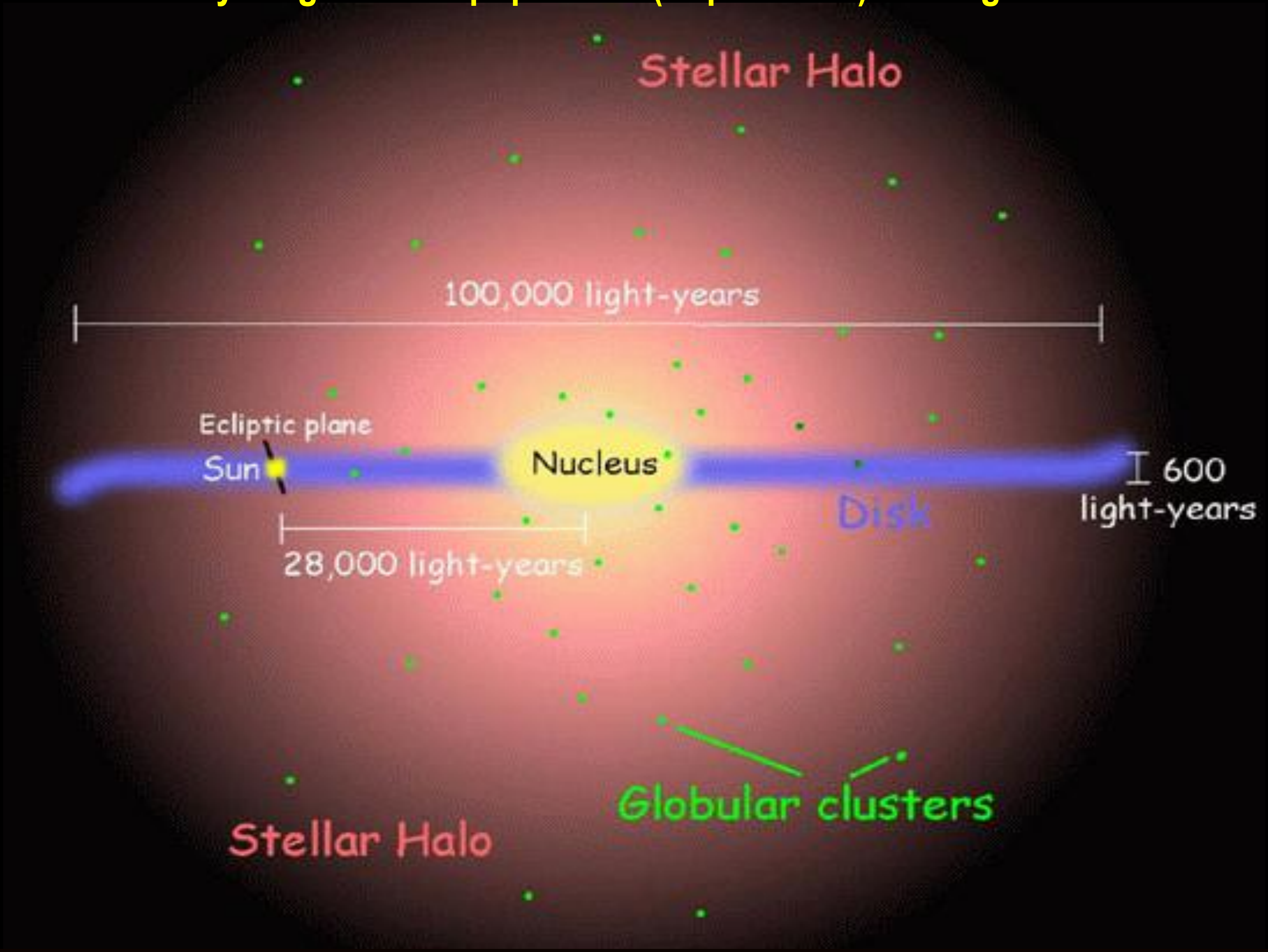
Early 50ies: **metal (heavier than He) abundances are not always the same ;**
Galactic halo stars have low metallicities



***F. Hoyle:* almost all elements produced inside stars during their evolution, by thermonuclear reactions**

…except H and He, which do come from the Big Bang

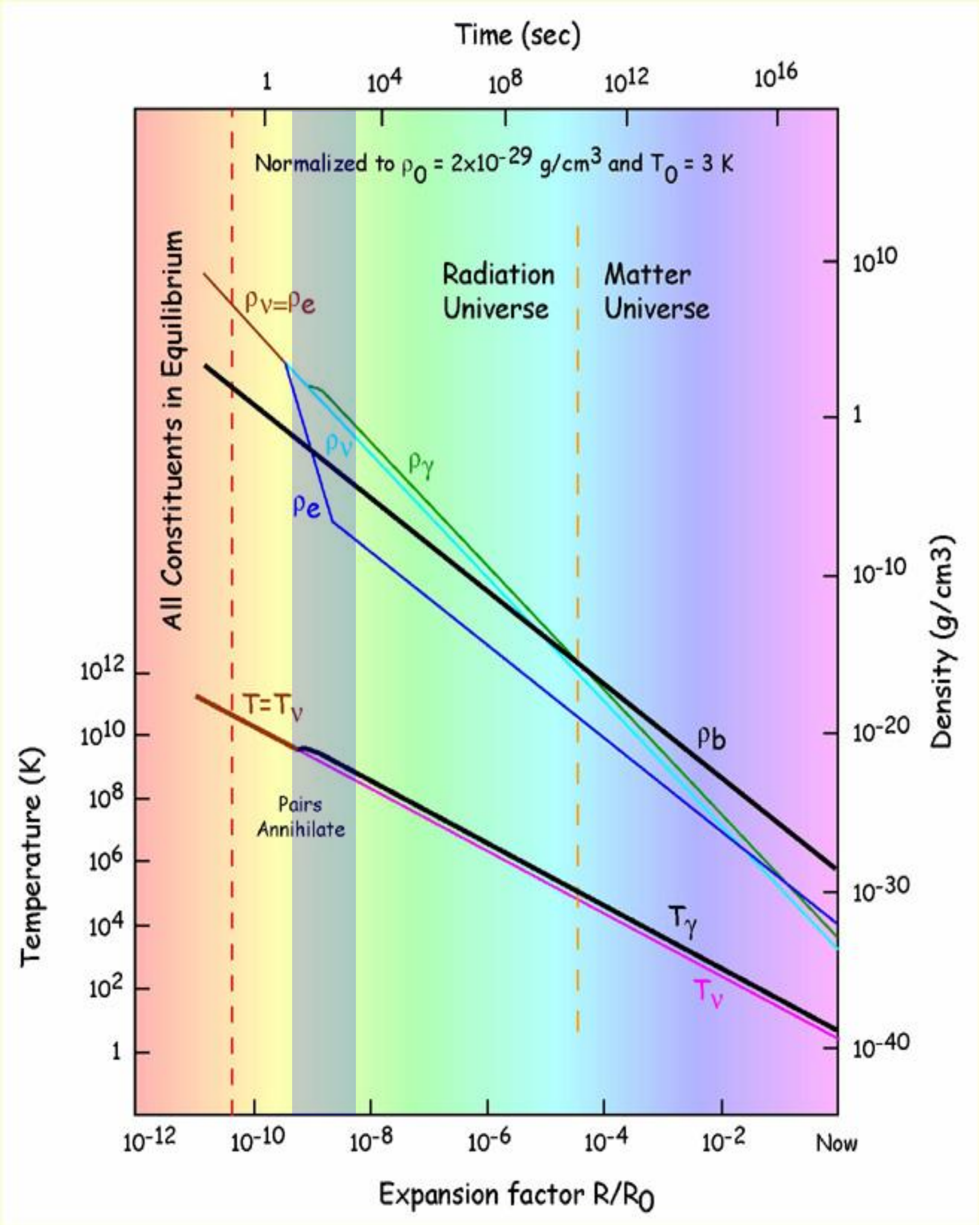
Old stars of galactic halo (Population II) contain less heavy elements (metals) than the younger stellar population (Population I) of the galactic disk

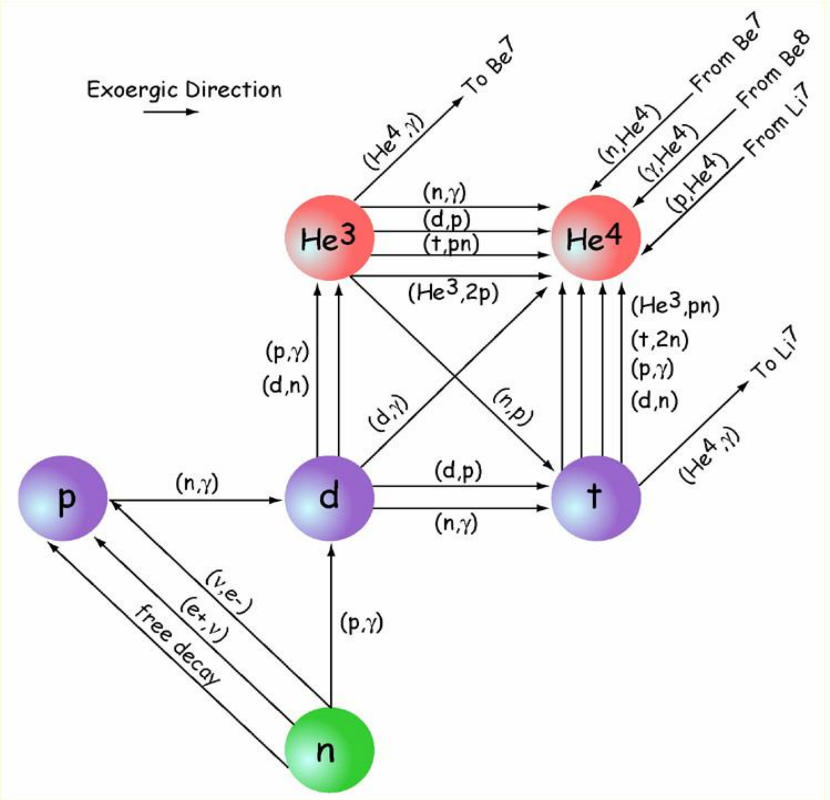


The chemical composition of the Milky Way was substantially different in the past

1957: *Origin of the elements in stars*

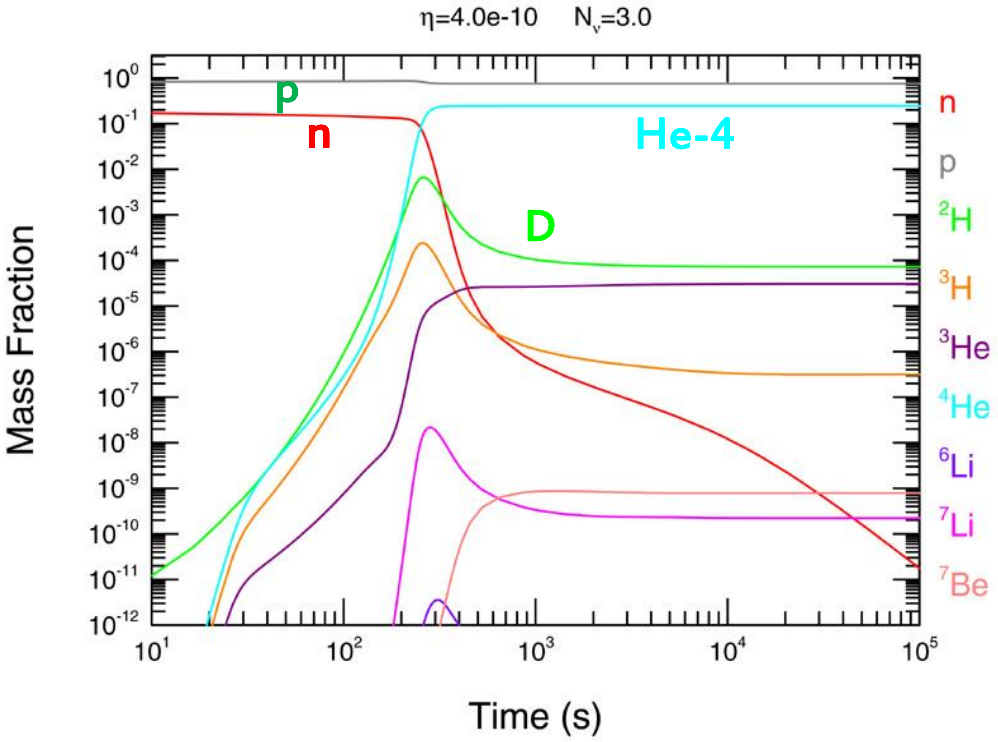
Primordial Nucleosynthesis





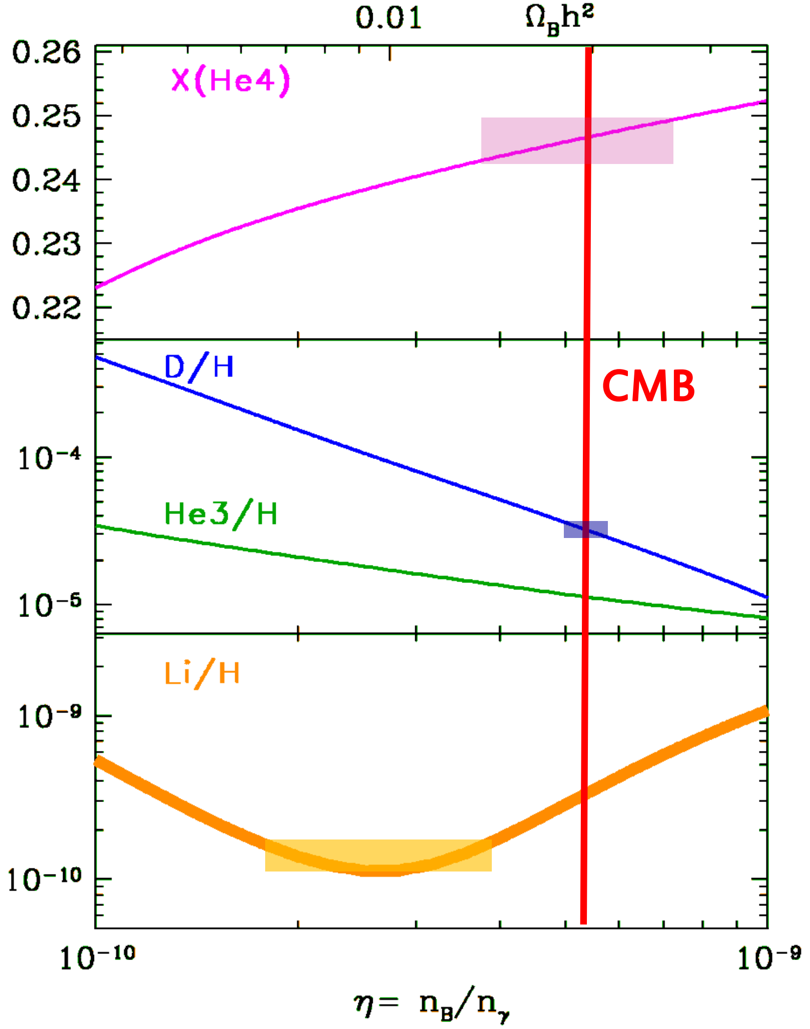
H and He isotopes are produced
from **p** and **n**
in the early hot Universe
at 1 GK ≥ T ≥ 100 MK
(“first” 3 minutes)

Primordial Nucleosynthesis



-Only way to produce so much He4 (~25 % by mass)

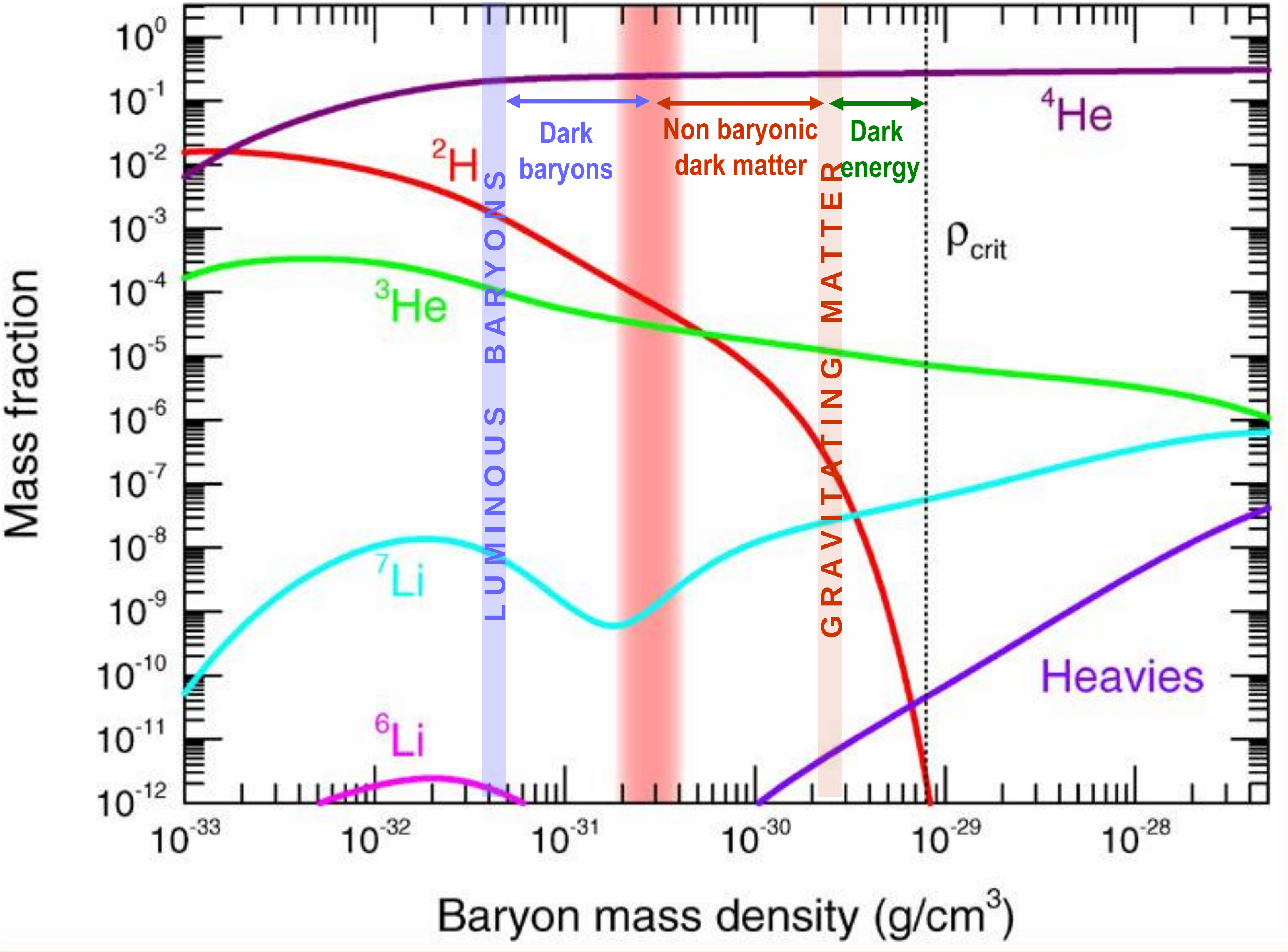
-Only way to produce Deuterium
(destroyed in stellar interiors)



Abundances predicted by theory agree well with those observed in old
- or little evolved - objects (old stars, small nearby galaxies, remote gas clouds):
perfectly for D, **satisfactorily for He-4**, **poorly for Li-7**

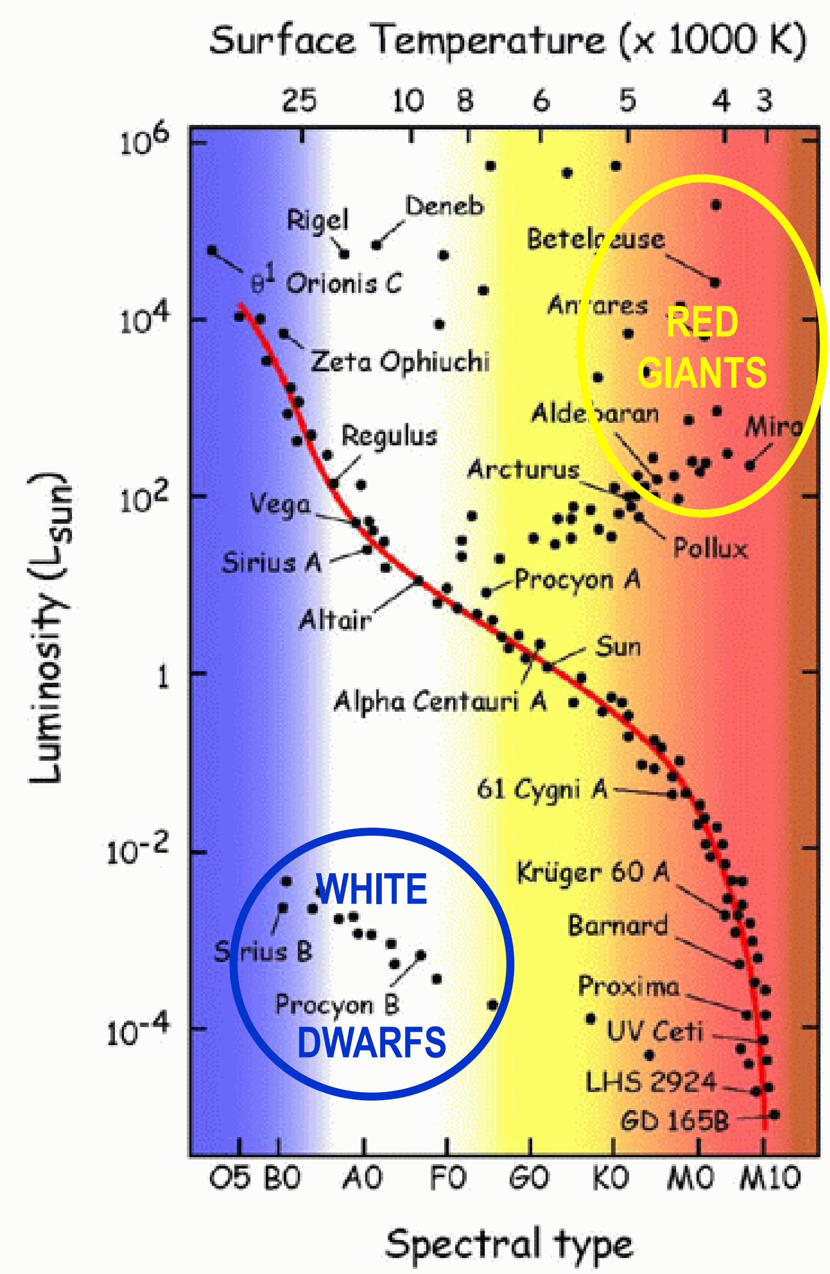
Nuclear reaction rates, and resulting abundances, depend on **baryon density**

The cosmic baryonic density is much less than critical (~ 4%) BUT



STARS: Luminosity vs Effective Temperature (Magnitude vs Colour)

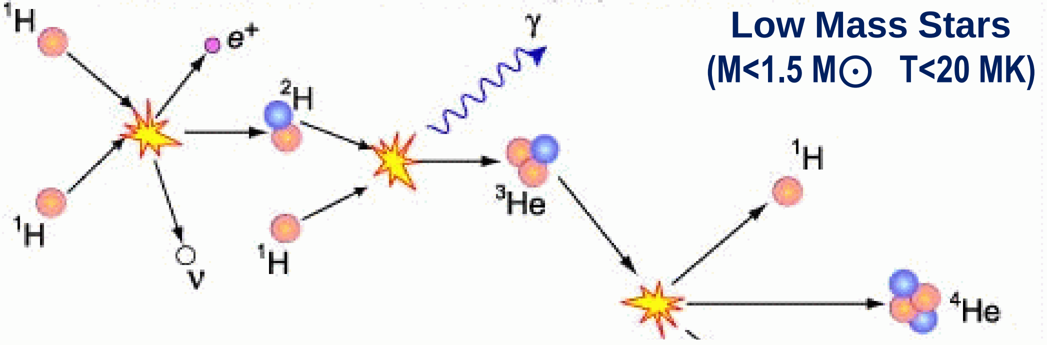
Hertzsprung – Russel Diagram (HRD)



Main Sequence: Hydrogen burning

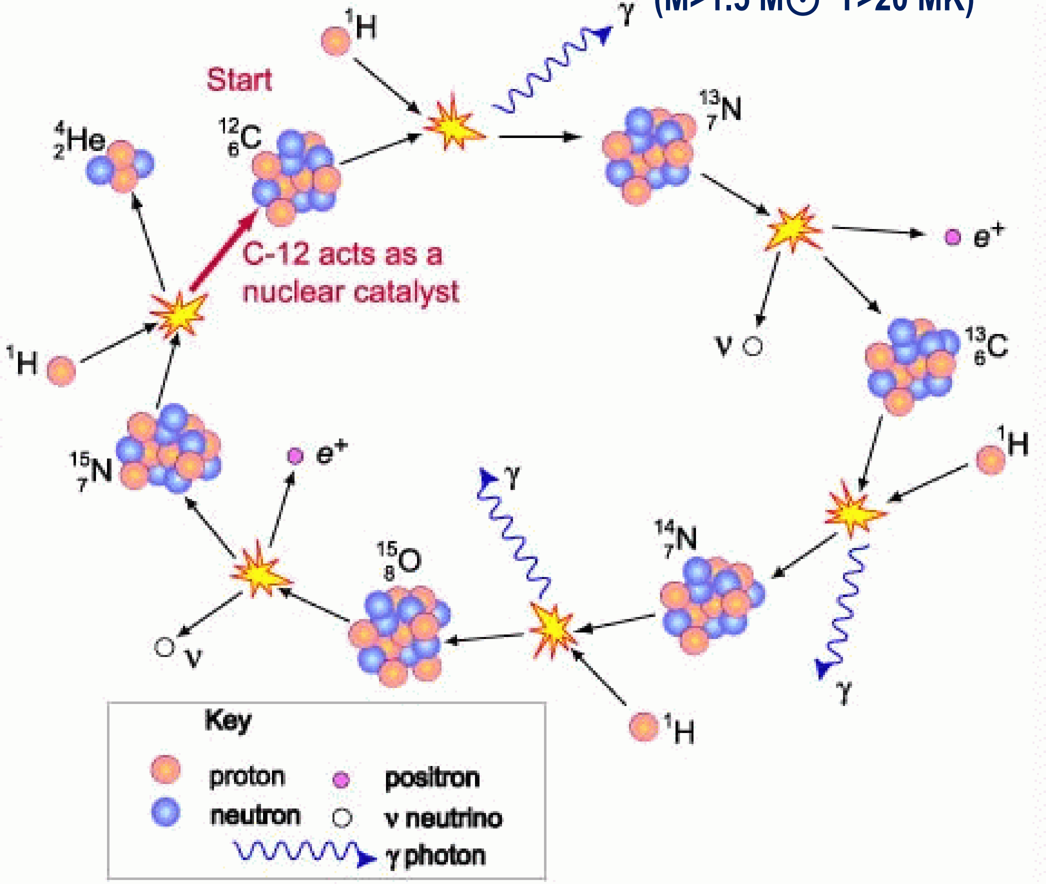
Main Form of Proton-Proton (pp) Chain in Sun and Low Mass Stars

(M<1.5 M⊙ T<20 MK)

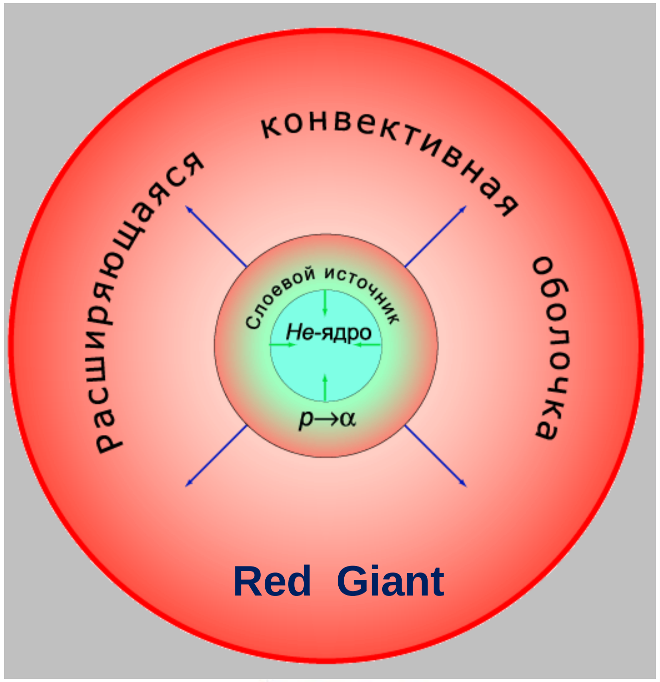


The CNO Cycle in Massive Stars

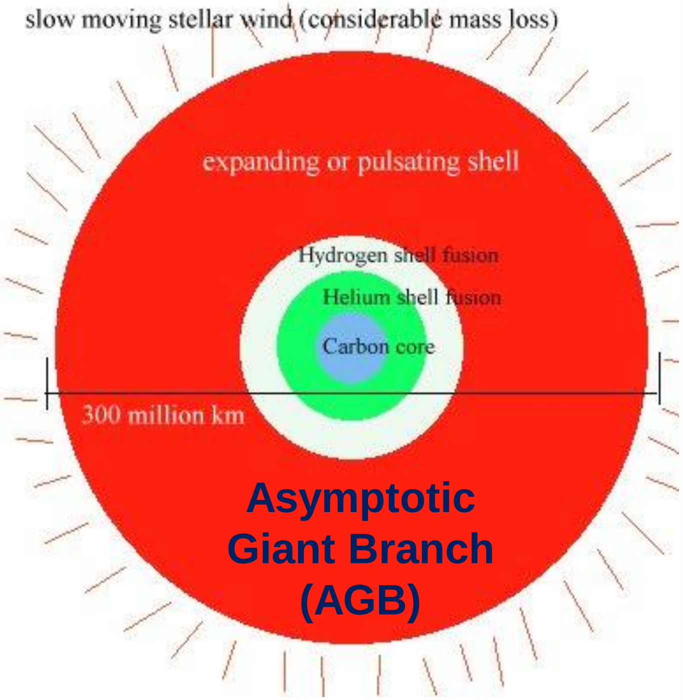
(M>1.5 M⊙ T>20 MK)



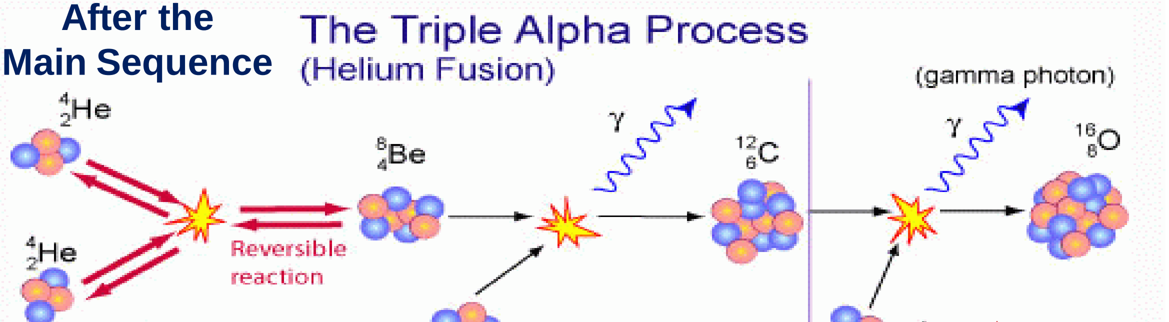
After the Main Sequence

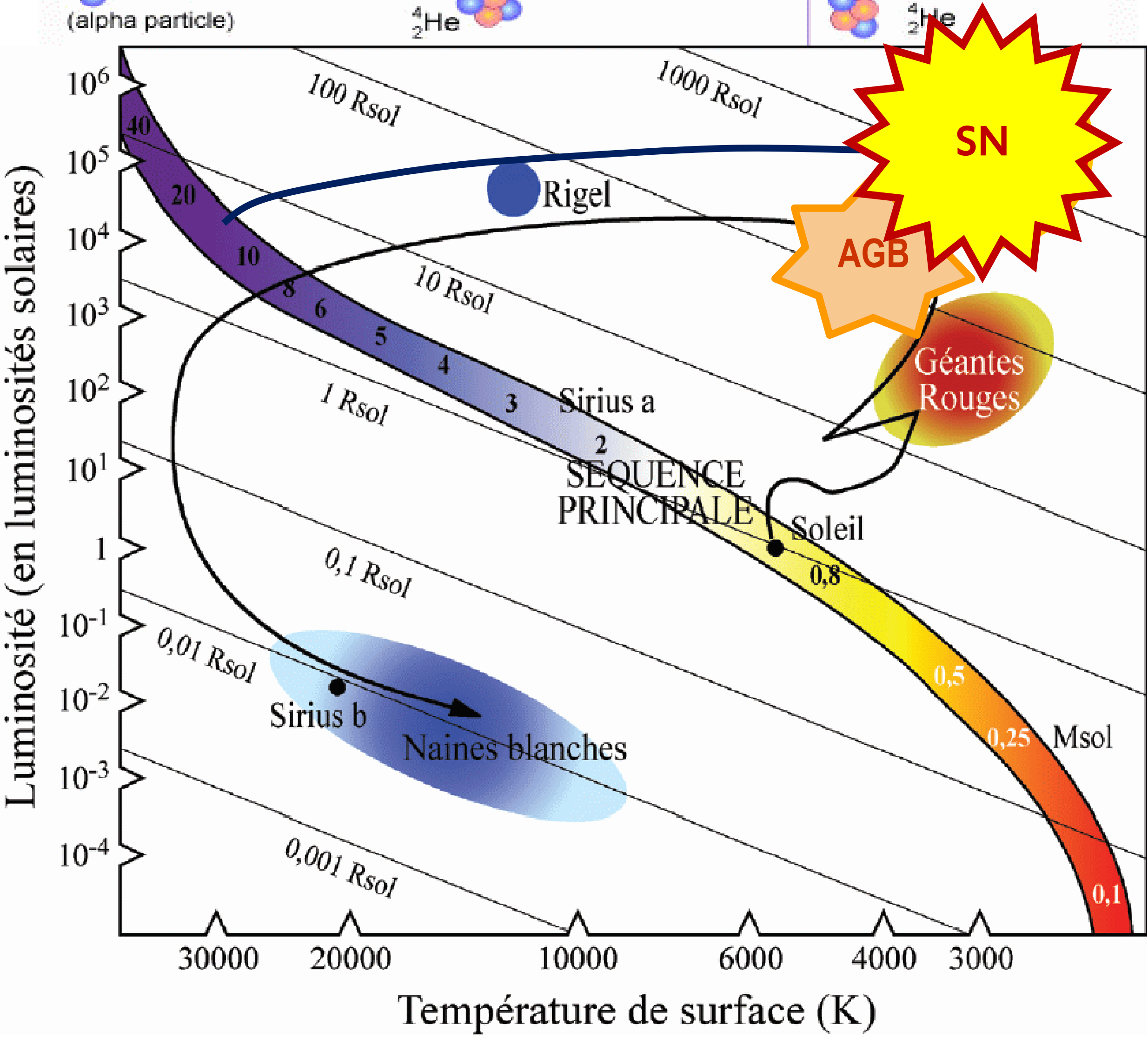


Red Giant



Asymptotic Giant Branch (AGB)





Advanced burning stages in massive stars

T ~ 200 million K

Important Reactions in Helium Burning

Energy generation:

$^{4}\mathrm{He}(2\alpha,\gamma)^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$

Neutron source:

$$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+})^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}\begin{matrix}(\alpha,\gamma)^{26}\mathrm{Mg}\\(\alpha,n)^{25}\mathrm{Mg}\end{matrix}$$

T ~ 900 million K

Important Reactions in Carbon Burning

Basic:

$$^{12}\mathrm{C}\left(^{12}\mathrm{C},\begin{matrix}\alpha\\p\end{matrix}\right)\begin{matrix}^{20}\mathrm{Ne}\\^{23}\mathrm{Na}\end{matrix}$$

$^{23}\mathrm{Na}(p,\alpha)^{20}\mathrm{Ne}$

$^{23}\mathrm{Na}(p,\gamma)^{24}\mathrm{Mg}$

T ~ 1500 million K

Neon Burning

Basic reactions:

$^{20}\mathrm{Ne}(\gamma,\alpha)^{16}\mathrm{O}$

$^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}(\alpha,\gamma)^{28}\mathrm{Si}$

T ~ 2000 million K

Oxygen Burning

Basic reactions:

$$^{16}\mathrm{O}\left\{\begin{matrix}(^{16}\mathrm{O},p)^{31}\mathrm{P}\\(^{16}\mathrm{O},\alpha)^{28}\mathrm{Si}\\(^{16}\mathrm{O},n)^{31}\mathrm{S}(\beta^{+})^{31}\mathrm{P}\end{matrix}\right.$$

$^{31}\mathrm{P}(p,\alpha)^{28}\mathrm{Si}(\alpha,\gamma)^{32}\mathrm{S}$

$^{28}\mathrm{Si}(\gamma,\alpha)^{24}\mathrm{Mg}(\alpha,p)^{27}\mathrm{Al}(\alpha,p)^{30}\mathrm{Si}$

$^{32}\mathrm{S}(n,\gamma)^{33}\mathrm{S}(n,\alpha)^{30}\mathrm{Si}(\alpha,\gamma)^{34}\mathrm{S}$

Si – “Melting” ($T \geq 3.\ 10^9$ K)

At high temperatures **photodesintegrations [(γ,α) (γ,p)(γ,n)]** become very rapid

Ejected particles (**n,p,α**) are captured by nuclei to form nuclei with larger binding energies

Si28 + γ ⇔ Mg24 + α   Si28 + α ⇔ S32+ γ   S32 + α ⇔ Ar36+ γ   Ar36 + α ⇔ Ca40+ γ…

$$\text{Reaction: } 1 + 2 \longrightarrow 3 + 4 \ (+ \mathrm{S}\ )$$

$$\begin{aligned}\text{Reaction energy: } \mathrm{S} &= (\mathrm{m}_1 + \mathrm{m}_2 - \mathrm{m}_3 - \mathrm{m}_4)\ \mathrm{c}^2 \\ &= \mathrm{Q}_3 + \mathrm{Q}_4 - \mathrm{Q}_1 - \mathrm{Q}_2\end{aligned}$$

$$[\ \text{Nucleus Binding Energy:}$$

$$\mathrm{Q} = (\mathrm{Z}\ \mathrm{m}_P - \mathrm{N}\ \mathrm{m}_N - \mathrm{m})\ \mathrm{c}^2\ ]$$

$$\text{Cross section: } < \sigma v >_{34} \propto < \sigma v >_{12}\ \mathrm{e}^{-S/kT}$$

$$\text{High T} \longrightarrow \textbf{Equilibrium: } \mathrm{Rate}_{12} = \mathrm{Rate}_{34}$$

$$\mathrm{N}_1\ \mathrm{N}_2 < \sigma v >_{12} = \mathrm{N}_3\ \mathrm{N}_4 < \sigma v >_{34}$$

$$\frac{\mathrm{N}_3\ \mathrm{N}_4}{\mathrm{N}_1\ \mathrm{N}_2} \propto \mathrm{e}^{\mathrm{S}/\mathrm{kT}}$$

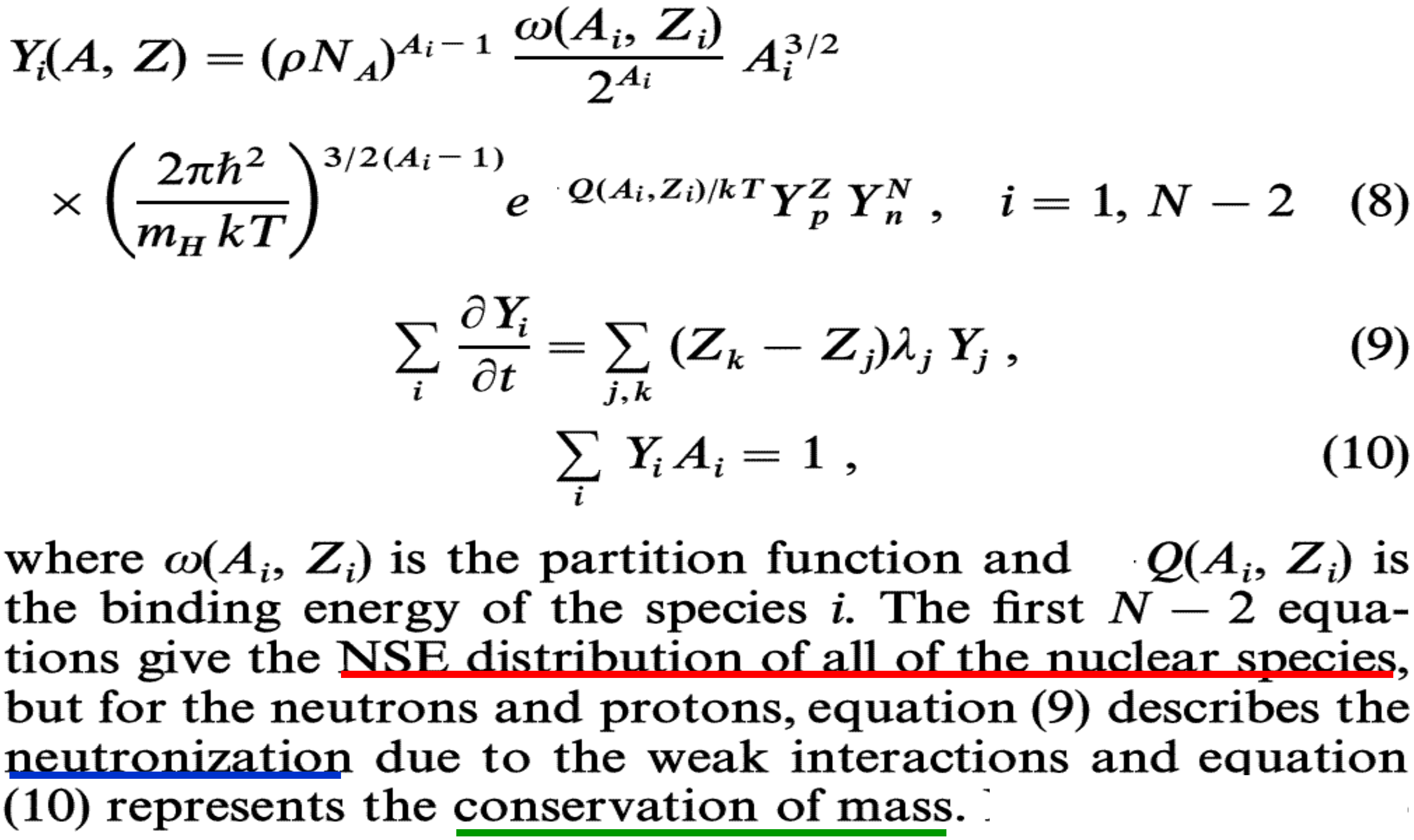
Matter composition shifts to Fe-peak nuclei (largest binding energies)

Energy produced: $E/m \sim 1.9\ 10^{17}$ erg/gr~ 0.2 MeV/nucleon

NUCLEAR STATISTICAL EQUILIBRIUM (NSE)

When all **strong nuclear reactions** are equilibrated, the **abundance** of a nucleus depends on its **binding energy**, the ambient **temperature** and **density** and the **neutron excess** **η=(N-Z)/(N+Z)**

Weak interactions (mostly electron captures)
never reach equilibrium (because neutrinos escape),
and slowly increase η **(neutronisation)**

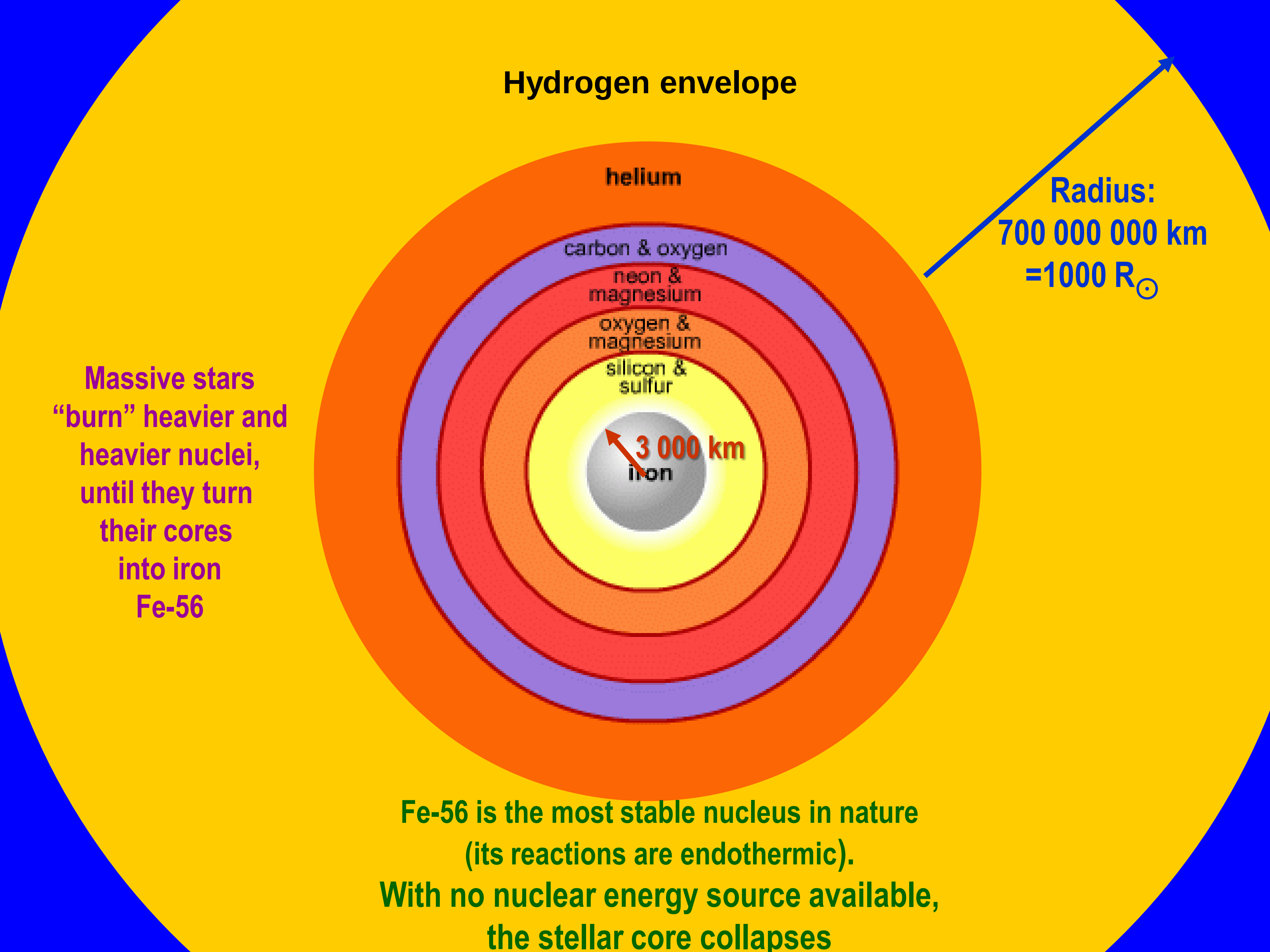


$$Y_i(A, Z) = (\rho N_A)^{A_i - 1} \frac{\omega(A_i, Z_i)}{2^{A_i}} A_i^{3/2} \times \left(\frac{2\pi\hbar^2}{m_H kT}\right)^{3/2(A_i - 1)} e^{Q(A_i, Z_i)/kT} Y_p^Z Y_n^N , \quad i = 1, N - 2 \qquad (8)$$

$$\sum_i \frac{\partial Y_i}{\partial t} = \sum_{j,k} (Z_k - Z_j)\lambda_j Y_j , \qquad (9)$$

$$\sum_i Y_i A_i = 1 , \qquad (10)$$

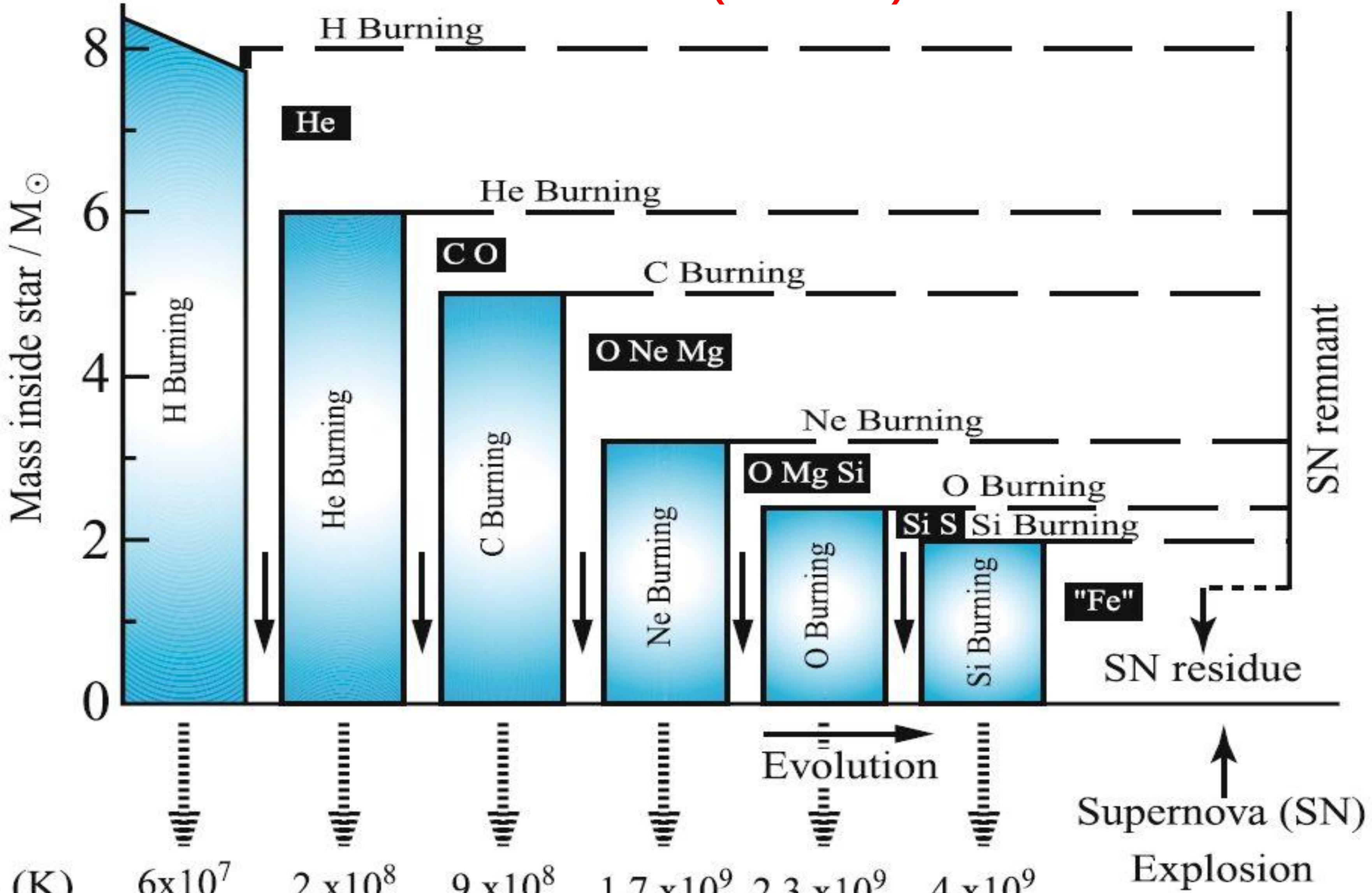
where $\omega(A_i, Z_i)$ is the partition function and $Q(A_i, Z_i)$ is the binding energy of the species i. The first $N - 2$ equations give the NSE distribution of all of the nuclear species, but for the neutrons and protons, equation (9) describes the neutronization due to the weak interactions and equation (10) represents the conservation of mass.



Massive stars
“burn” heavier and
heavier nuclei,
until they turn
their cores
into iron
Fe-56

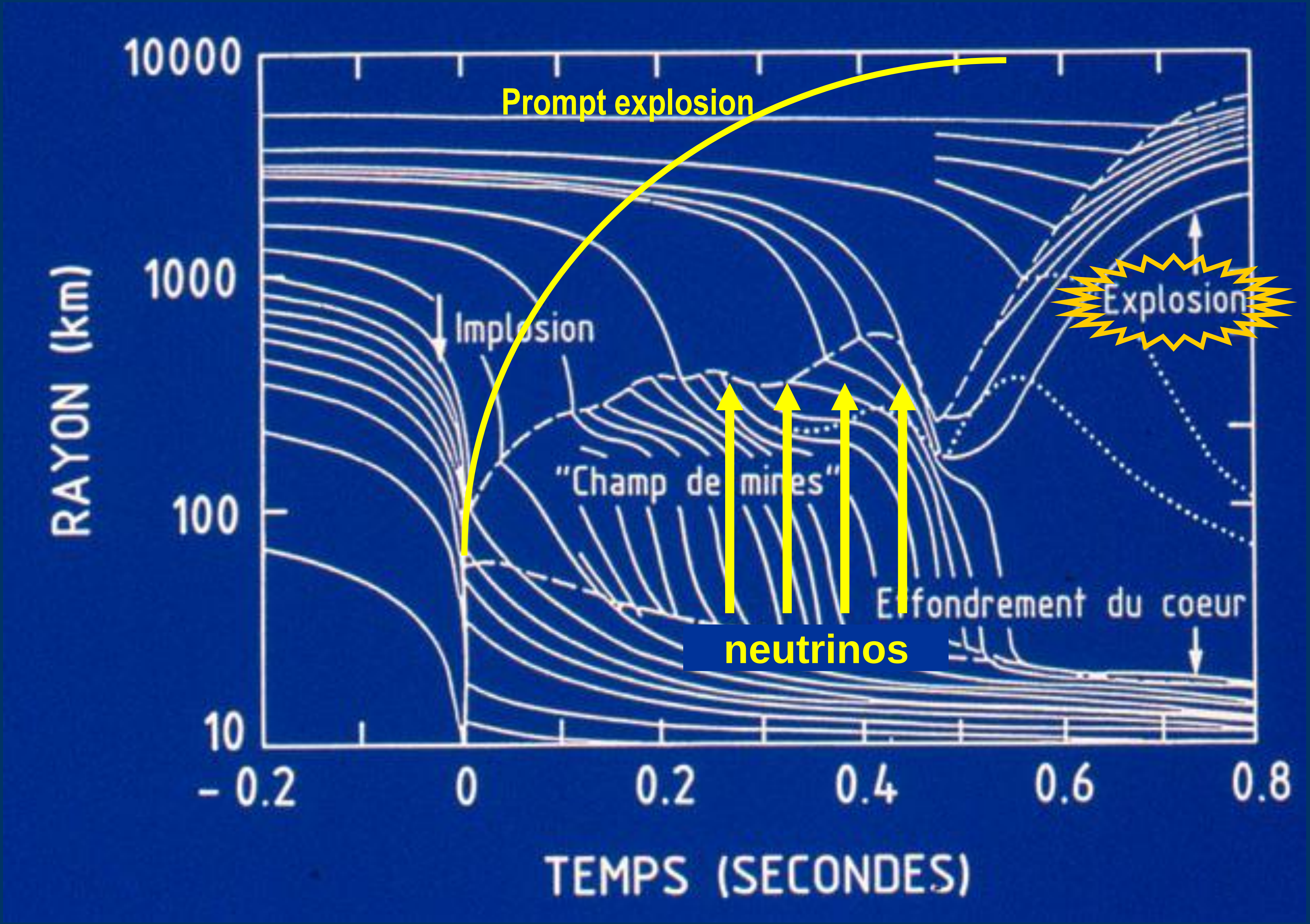
Fe-56 is the most stable nucleus in nature
(its reactions are endothermic).
With no nuclear energy source available,
the stellar core collapses

Massive star evolution (schematic)

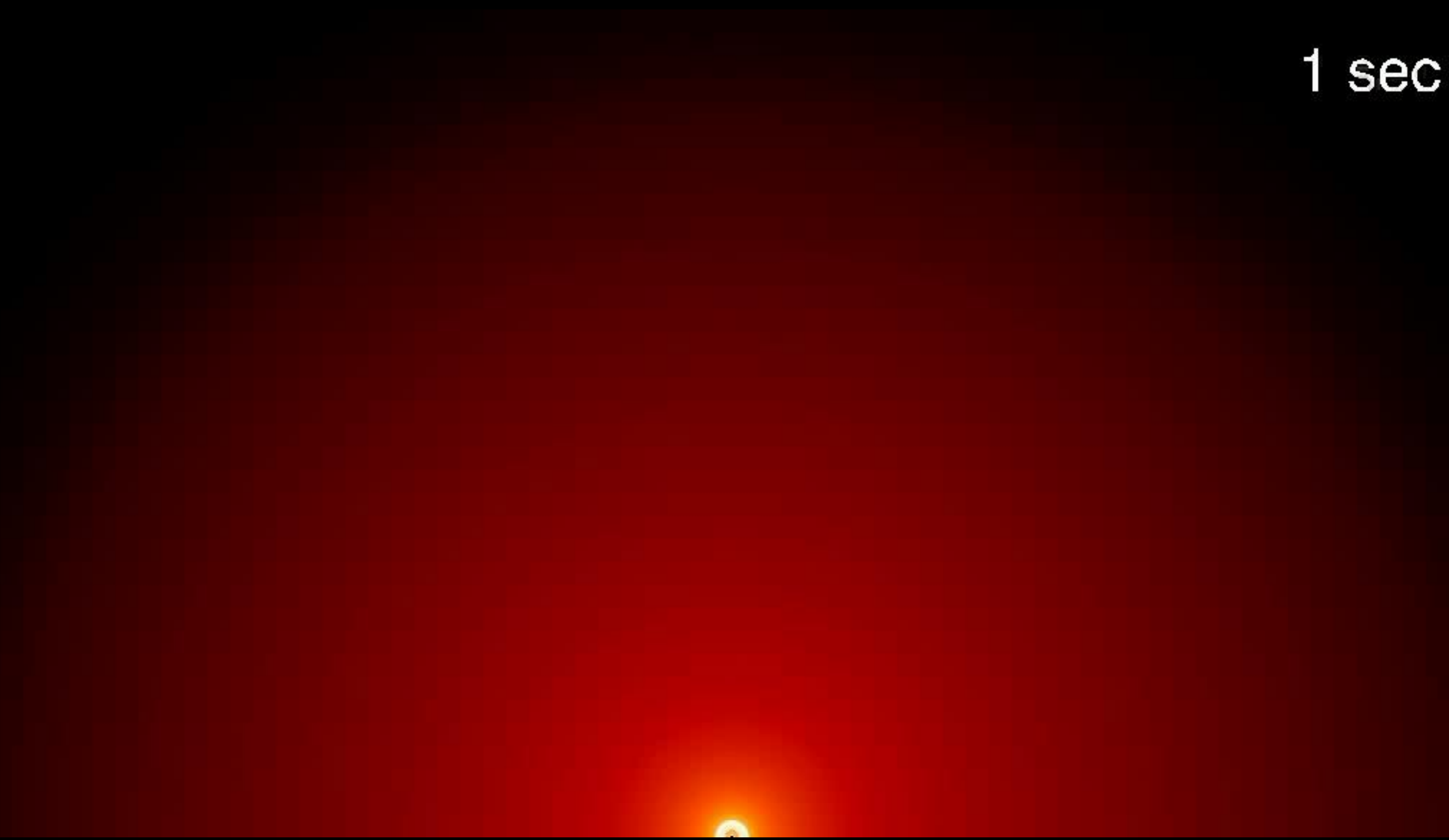


T_C (K)	$6x10^7$	$2\ x10^8$	$9\ x10^8$	$1.7\ x10^9$	$2.3\ x10^9$	$4\ x10^9$
ρ_C ($g.cm^{-3}$)	5	700	$2\ x10^5$	$4\ x10^6$	10^7	$3\ x10^7$
Time scale	$7\ 10^6$ years	$5\ x10^5$ years	600 years	0.5 years	6 days	1 day

Delayed explosion of supernovae



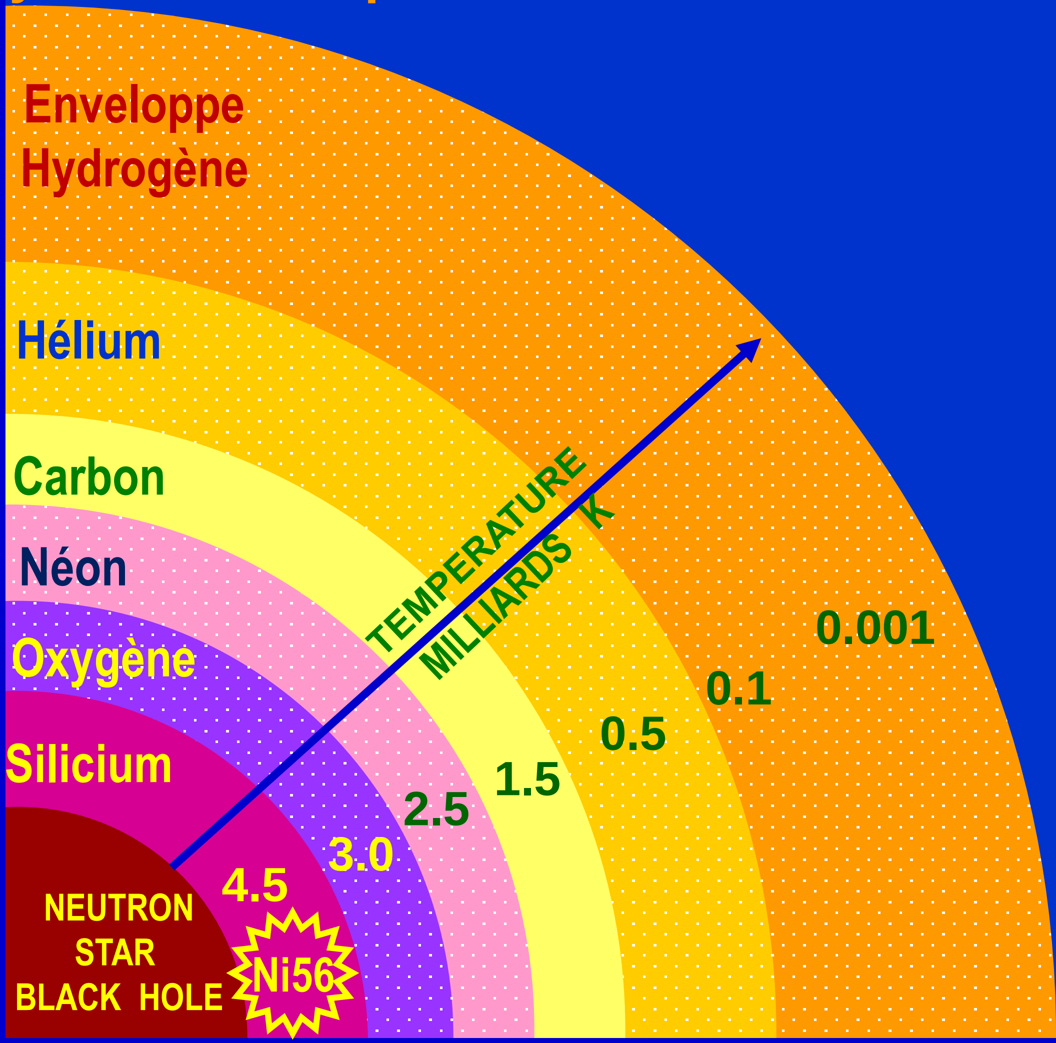
Does not seem to work either, but only for the smallest stars…


1 sec

Explosive nucleosynthesis in supernovae

In case of successful explosion
the shock wave propagates in the
envelope and heats the stellar layers
to high temperatures, inducing
explosive nucleosynthesis

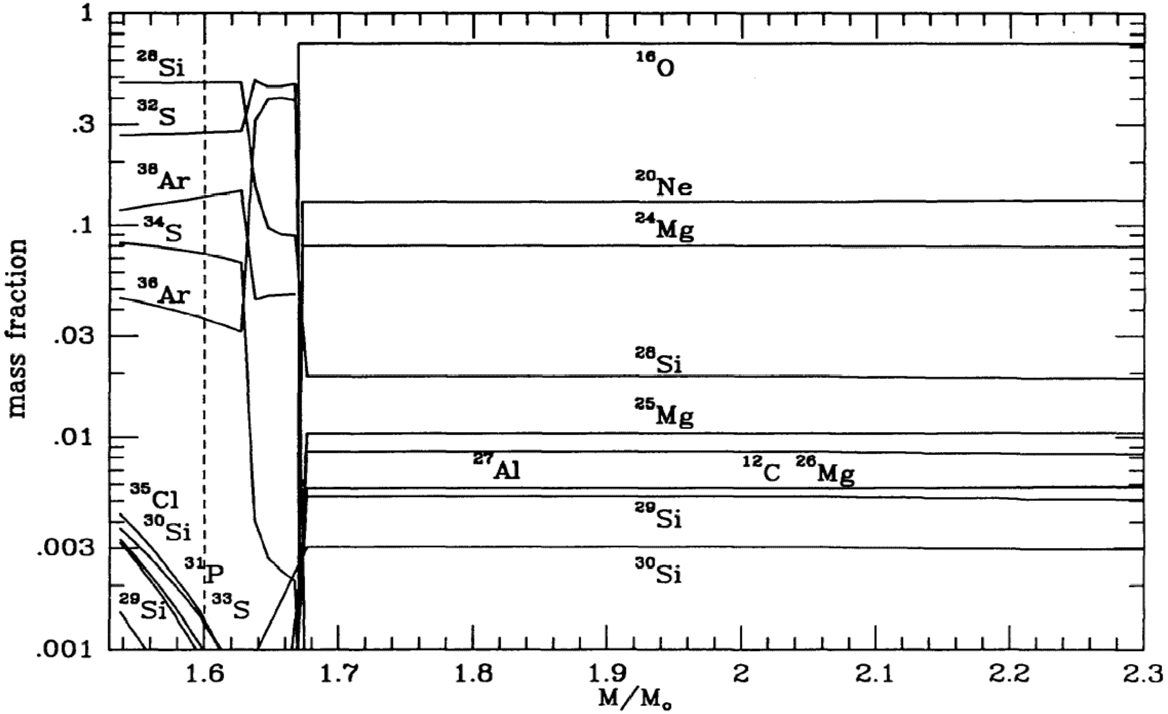
Products of hydrostatic and
explosive nucleosynthesis
are ejected
in the interstellar medium



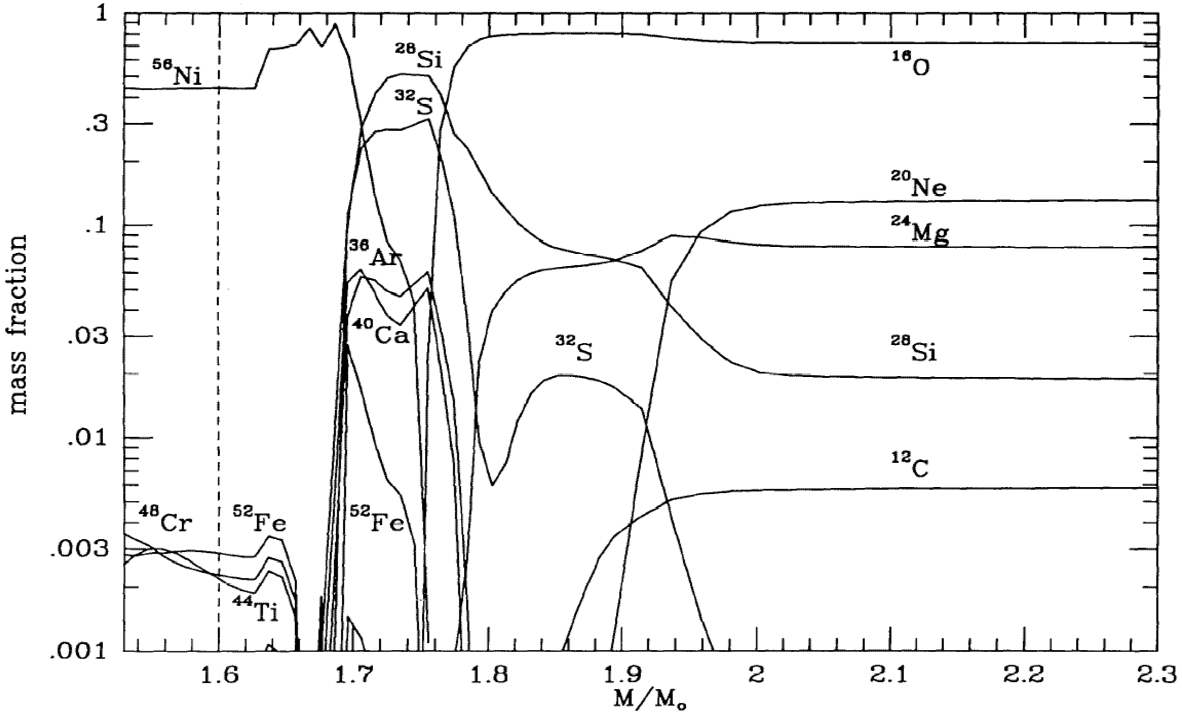
Supernovae are
the chief-alchemists
of the Universe

Stable Fe-56 is made in the
unstable (radioactive) form of Ni-56 :
Ni-56 ➔ Co-56 ➔ Fe-56

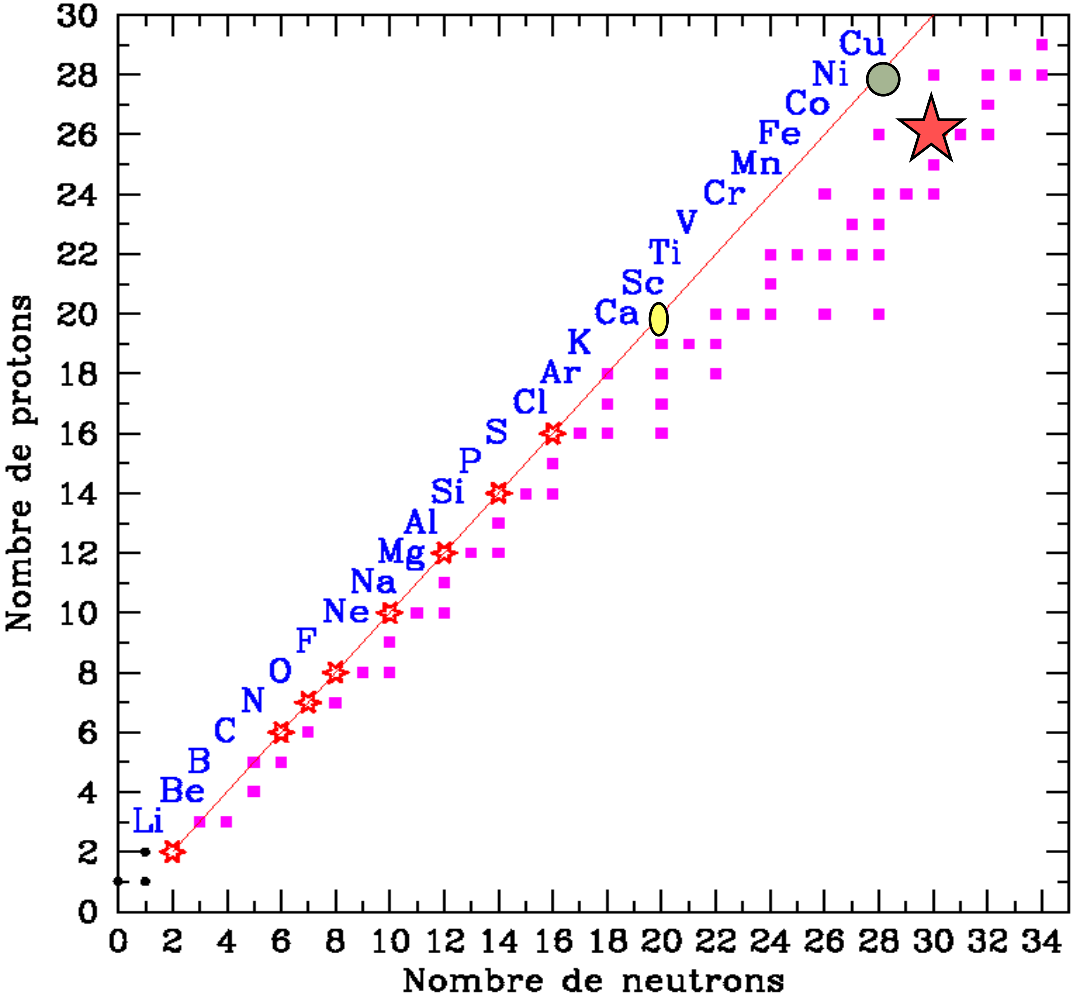
20 $M_\odot$ star:
Pre-explosive composition
of inner layers



20 $M_\odot$ star:
Post-explosive composition
of inner layers



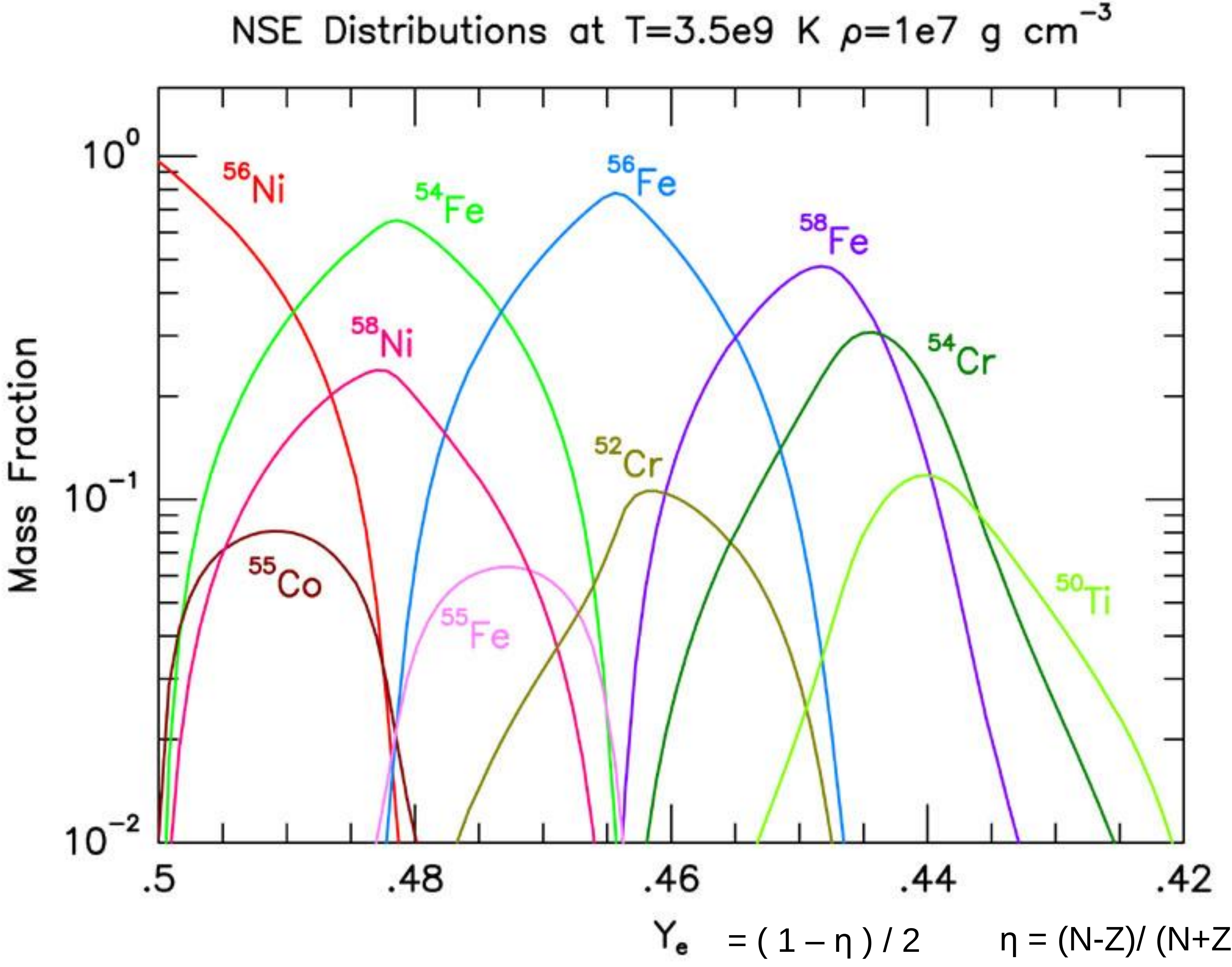
THE WAY TOWARDS **NSE** (Nuclear Statistical Equilibrium)



Ca40 is the last stable nucleus with N=Z on the way of Si-melting towards NSE

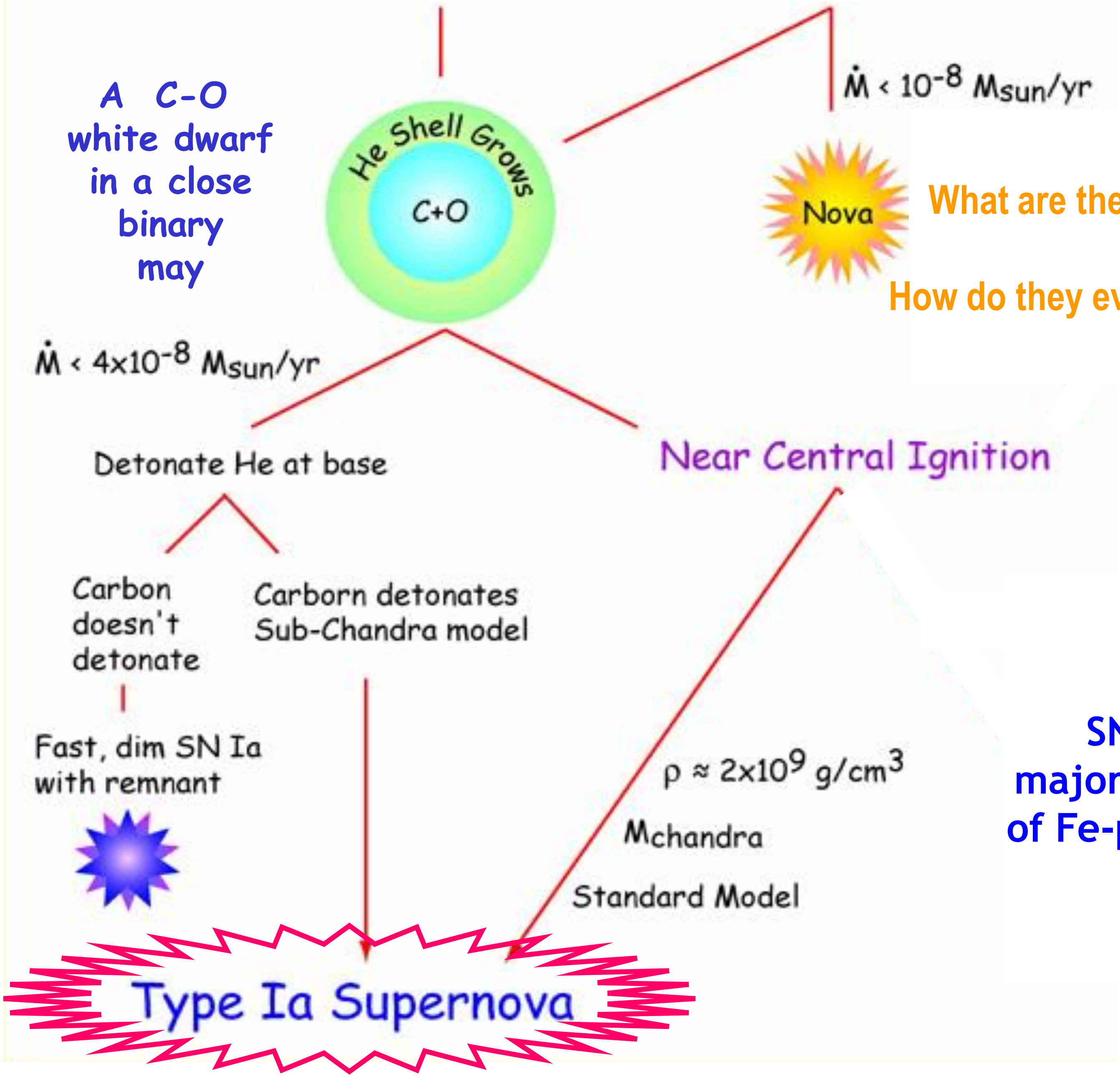
In the stellar core weak interactions shift the neutron excess towards **η~0.05 – 0.10** and **Fe56 dominates the NSE composition**

Note : in explosive nucleosynthesis, weak interactions have no time to operate and η remains close to 0. **Ni56 dominates the NSE composition**



$= (1 - \eta) / 2$ $\eta = (N-Z)/ (N+Z)$

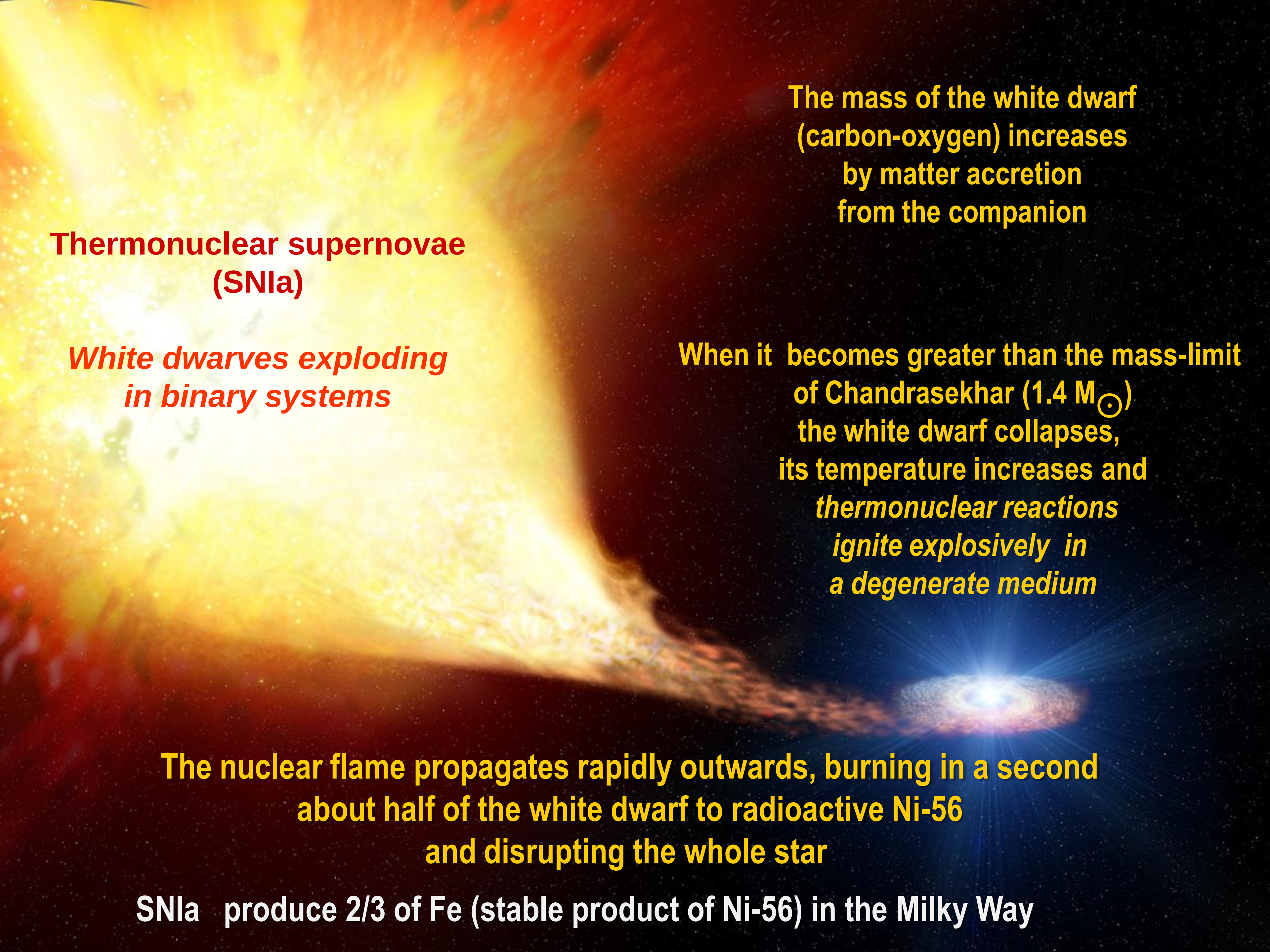
Stellar explosions in binary systems



What are the progenitors ?

How do they evolve up to SNIa?

SNIa are
major producers
of Fe-peak nuclei



Thermonuclear supernovae (SNIa)

White dwarves exploding in binary systems

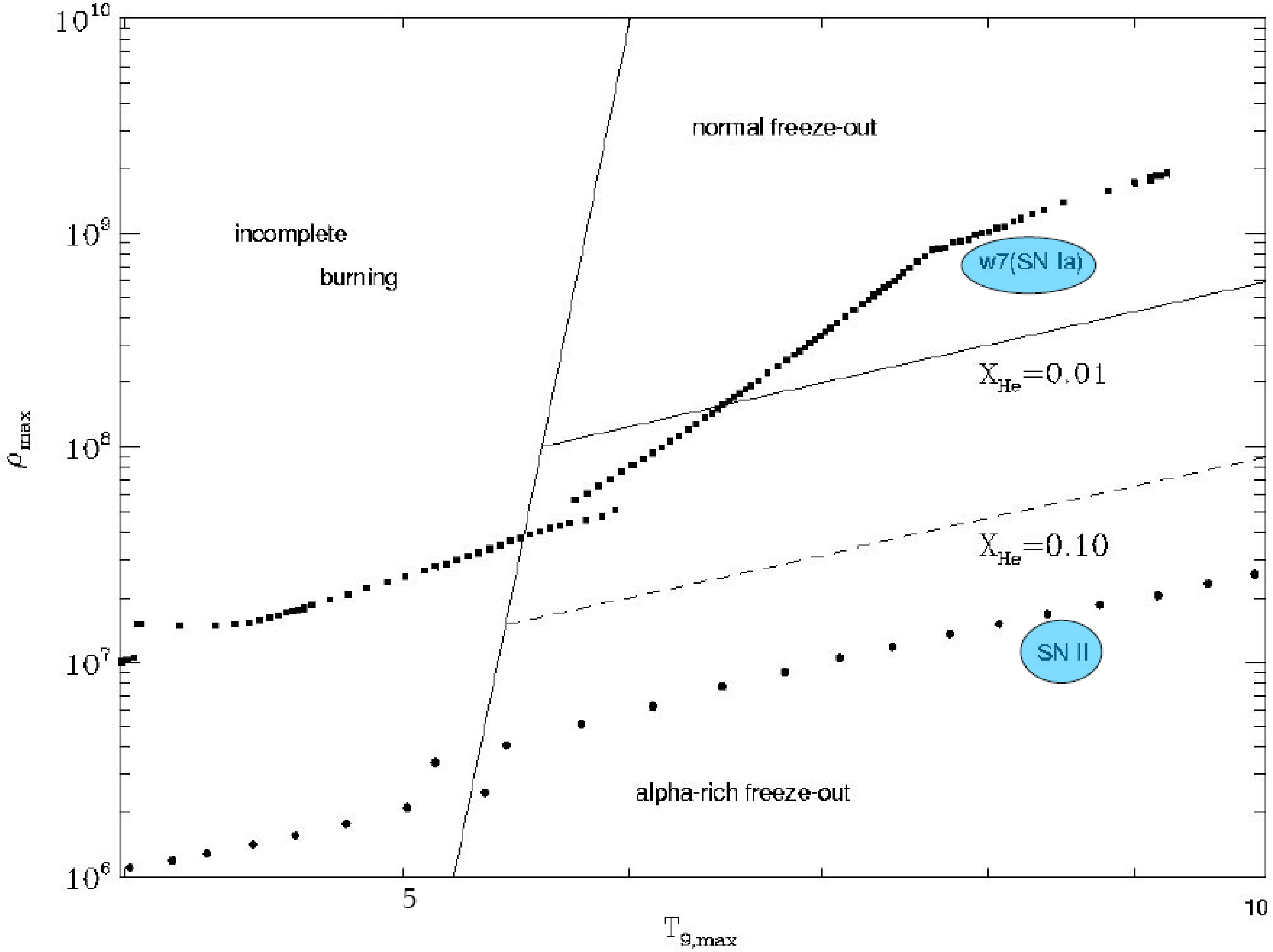
The mass of the white dwarf
(carbon-oxygen) increases
by matter accretion
from the companion

When it becomes greater than the mass-limit
of Chandrasekhar (1.4 $M_\odot$)
the white dwarf collapses,
its temperature increases and
thermonuclear reactions
ignite explosively in
a degenerate medium

The nuclear flame propagates rapidly outwards, burning in a second
about half of the white dwarf to radioactive Ni-56
and disrupting the whole star

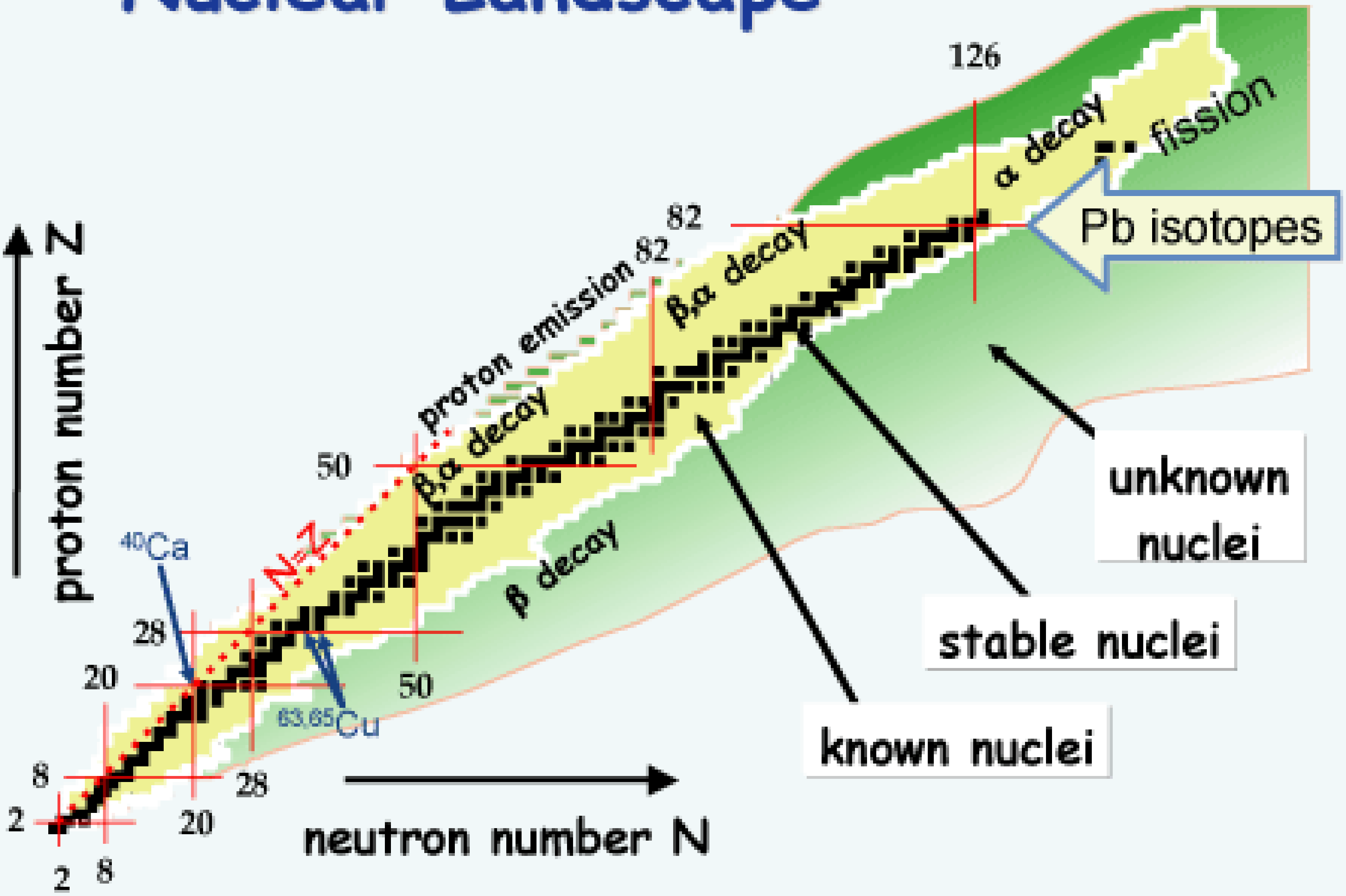
SNIa produce 2/3 of Fe (stable product of Ni-56) in the Milky Way

Explosive Si-Burning



Explosive Burning above a critical temperature destroys (photodisintegrates) all nuclei and (re-)builds them up during the expansion. Dependent on density, the full NSE is maintained and leads to only Fe-group nuclei (normal freeze-out) or the reactions linking ^{4}He to C and beyond freeze out earlier (alpha-rich freeze-out).

Nuclear Landscape



Pb isotopes

unknown nuclei

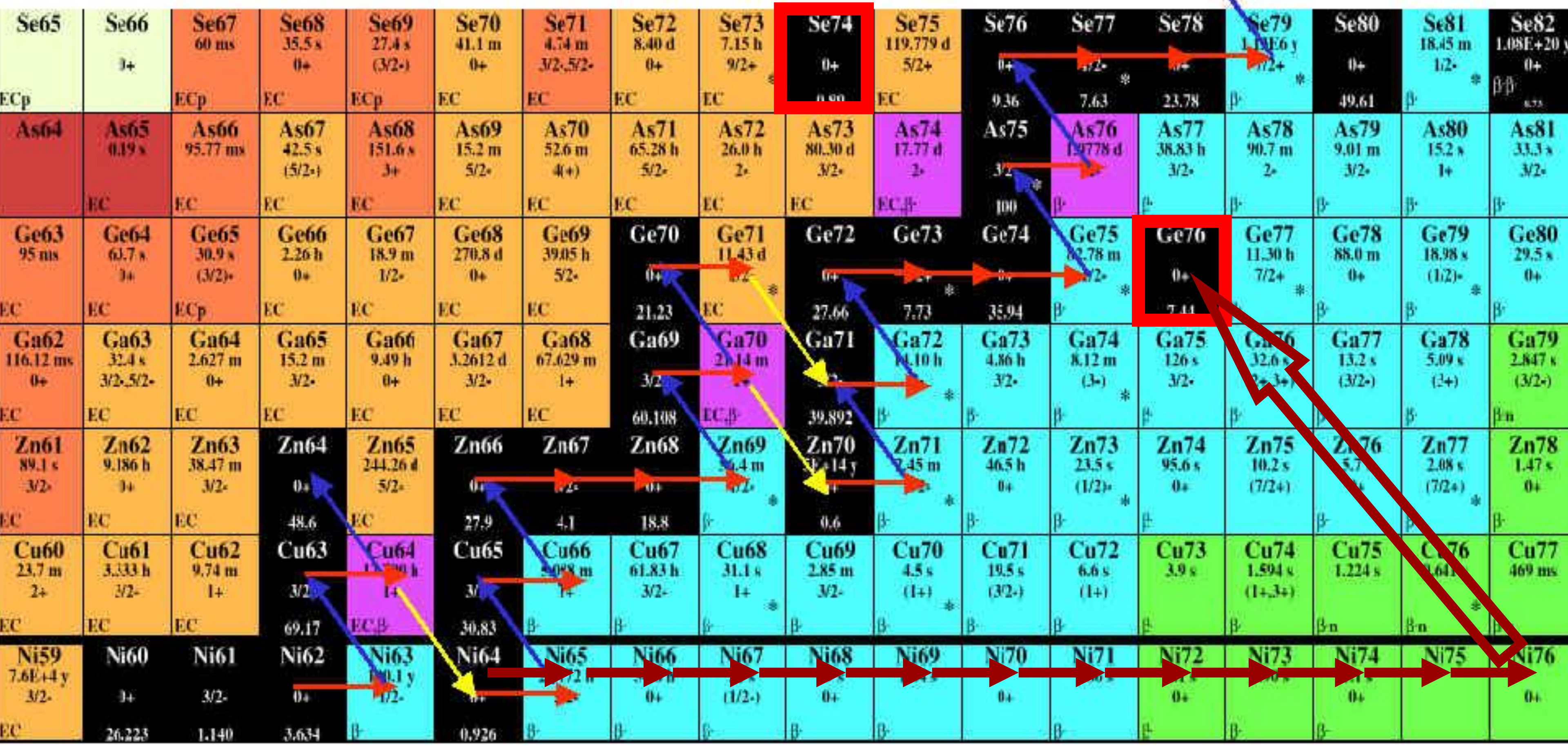
stable nuclei

known nuclei

THE PRODUCTION OF HEAVIER THAN Fe NUCLEI

Neutron captures, on timescales:

long w.r.t. the β-decay lifetimes (few neutrons available): **S-process**
short w.r.t. the β-decay lifetimes (many neutrons available): **R-process**



Se65 ECp	Se66 3+	Se67 60 ms ECp	Se68 35.5 s 0+ EC	Se69 27.4 s (3/2-) ECp	Se70 41.1 m 0+ EC	Se71 4.74 m 3/2-,5/2- EC	Se72 8.40 d 0+ EC	Se73 7.15 h 9/2+ EC	Se74 0+ 0.89	Se75 119.779 d 5/2+ EC	Se76 0+ 9.36	Se77 [illegible] 7.63	Se78 [illegible] 23.78	Se79 1.[illegible]E6 y 7/2+ β-	Se80 0+ 49.61	Se81 18.45 m 1/2- β-	Se82 1.08E+20 y 0+ β-β- 8.73
As64	As65 0.19 s EC	As66 95.77 ms EC	As67 42.5 s (5/2-) EC	As68 151.6 s 3+ EC	As69 15.2 m 5/2- EC	As70 52.6 m 4(+) EC	As71 65.28 h 5/2- EC	As72 26.0 h 2- EC	As73 80.30 d 3/2- EC	As74 17.77 d 2- EC,β+	As75 3/2- 100	As76 1.[illegible]778 d [illegible] β-	As77 38.83 h 3/2- β-	As78 90.7 m 2- β-	As79 9.01 m 3/2- β-	As80 15.2 s 1+ β-	As81 33.3 s 3/2- β-
Ge63 95 ms EC	Ge64 63.7 s 3+ EC	Ge65 30.9 s (3/2)- ECp	Ge66 2.26 h 0+ EC	Ge67 18.9 m 1/2- EC	Ge68 270.8 d 0+ EC	Ge69 39.05 h 5/2- EC	Ge70 0+ 21.23	Ge71 11.43 d 1/2- EC	Ge72 0+ 27.66	Ge73 [illegible] 7.73	Ge74 [illegible] 35.94	Ge75 [illegible]2.78 m [illegible]/2- β-	Ge76 0+ 7.44	Ge77 11.30 h 7/2+ β-	Ge78 88.0 m 0+ β-	Ge79 18.98 s (1/2)- β-	Ge80 29.5 s 0+ β-
Ga62 116.12 ms 0+ EC	Ga63 32.4 s 3/2-,5/2- EC	Ga64 2.627 m 0+ EC	Ga65 15.2 m 3/2- EC	Ga66 9.49 h 0+ EC	Ga67 3.2612 d 3/2- EC	Ga68 67.629 m 1+ EC	Ga69 3/2- 60.108	Ga70 2[illegible].14 m [illegible] EC,β-	Ga71 [illegible] 39.892	Ga72 [illegible].10 h [illegible] β-	Ga73 4.86 h 3/2- β-	Ga74 8.12 m (3-) β-	Ga75 126 s 3/2- β-	Ga76 32.6 s (2+,3+) β-	Ga77 13.2 s (3/2-) β-	Ga78 5.09 s (2+) β-	Ga79 2.847 s (3/2-) β-n
Zn61 89.1 s 3/2- EC	Zn62 9.186 h 0+ EC	Zn63 38.47 m 3/2- EC	Zn64 0+ 48.6	Zn65 244.26 d 5/2- EC	Zn66 0+ 27.9	Zn67 [illegible]/2- 4.1	Zn68 0+ 18.8	Zn69 [illegible].4 m [illegible]/2- β-	Zn70 [illegible]E+14 y [illegible] 0.6	Zn71 2.45 m [illegible] β-	Zn72 46.5 h 0+ β-	Zn73 23.5 s (1/2)- β-	Zn74 95.6 s 0+ β-	Zn75 10.2 s (7/2+) β-	Zn76 5.7[illegible] [illegible] β-	Zn77 2.08 s (7/2+) β-	Zn78 1.47 s 0+ β-
Cu60 23.7 m 2+ EC	Cu61 3.333 h 3/2- EC	Cu62 9.74 m 1+ EC	Cu63 3/2- 69.17	Cu64 [illegible] h 1+ EC,β-	Cu65 3/[illegible] 30.83	Cu66 [illegible] m 1+ β-	Cu67 61.83 h 3/2- β-	Cu68 31.1 s 1+ β-	Cu69 2.85 m 3/2- β-	Cu70 4.5 s (1+) β-	Cu71 19.5 s (3/2-) β-	Cu72 6.6 s (1+) β-	Cu73 3.9 s β-	Cu74 1.594 s (1+,3+) β-	Cu75 1.224 s β-n	Cu76 [illegible].641 s β-n	Cu77 469 ms β-
Ni59 7.6E+4 y 3/2- EC	Ni60 3+ 26.223	Ni61 3/2- 1.140	Ni62 0+ 3.634	Ni63 [illegible]0.1 y 1/2- β-	Ni64 [illegible] 0.926	Ni65 [illegible]2 h [illegible] β-	Ni66 [illegible] 0+ β-	Ni67 [illegible] (1/2-) β-	Ni68 [illegible] 0+ β-	Ni69 [illegible] β-	Ni70 [illegible] 0+	Ni71 [illegible] β-	Ni72 [illegible] 0+ β-	Ni73 [illegible] β-	Ni74 [illegible] 0+ β-	Ni75	Ni76 0+

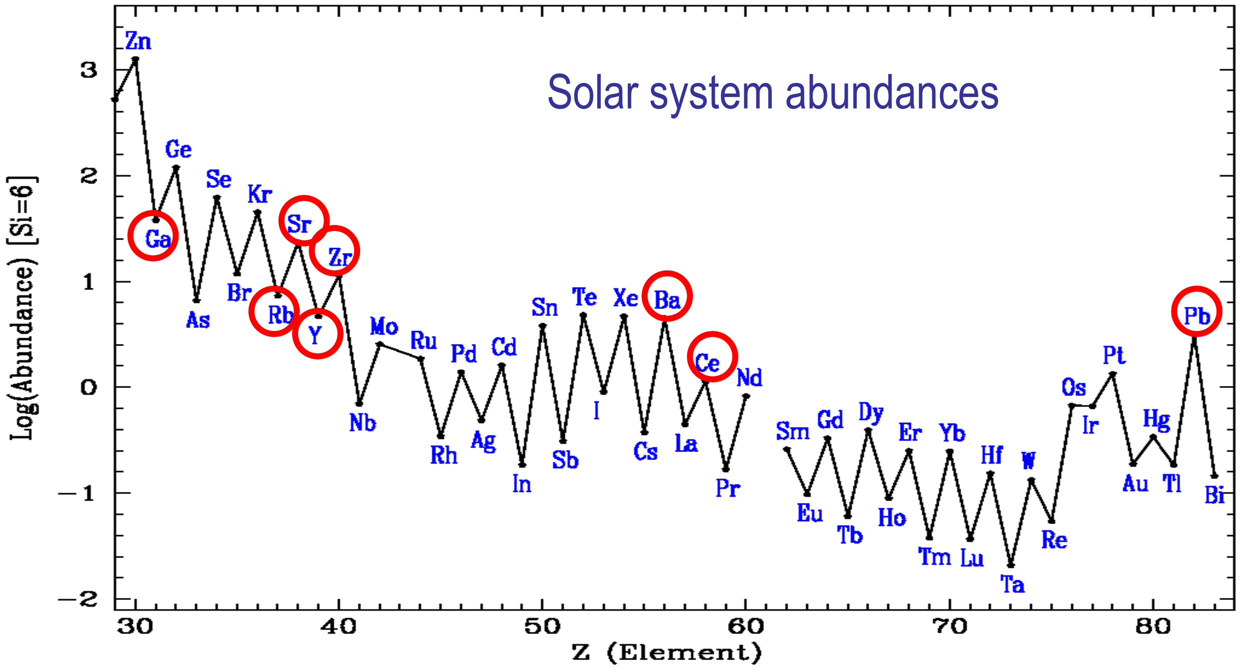
S-nuclei: in the valley of nuclear stability

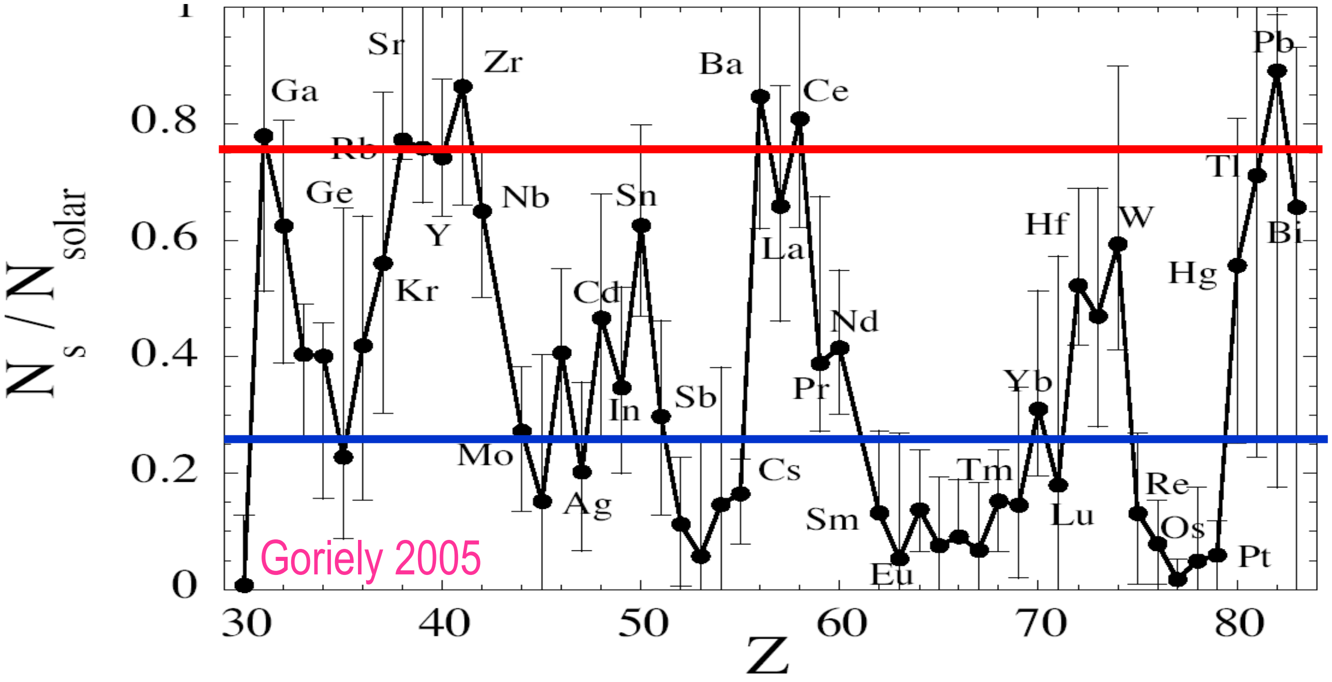
R-nuclei: neutron rich

Most nuclei have mixed (S- and R-) origin, but there exist pure S- or R- nuclei

Nuclei unreachable by n-captures: P-nuclei

The heavier than Fe-peak nuclei





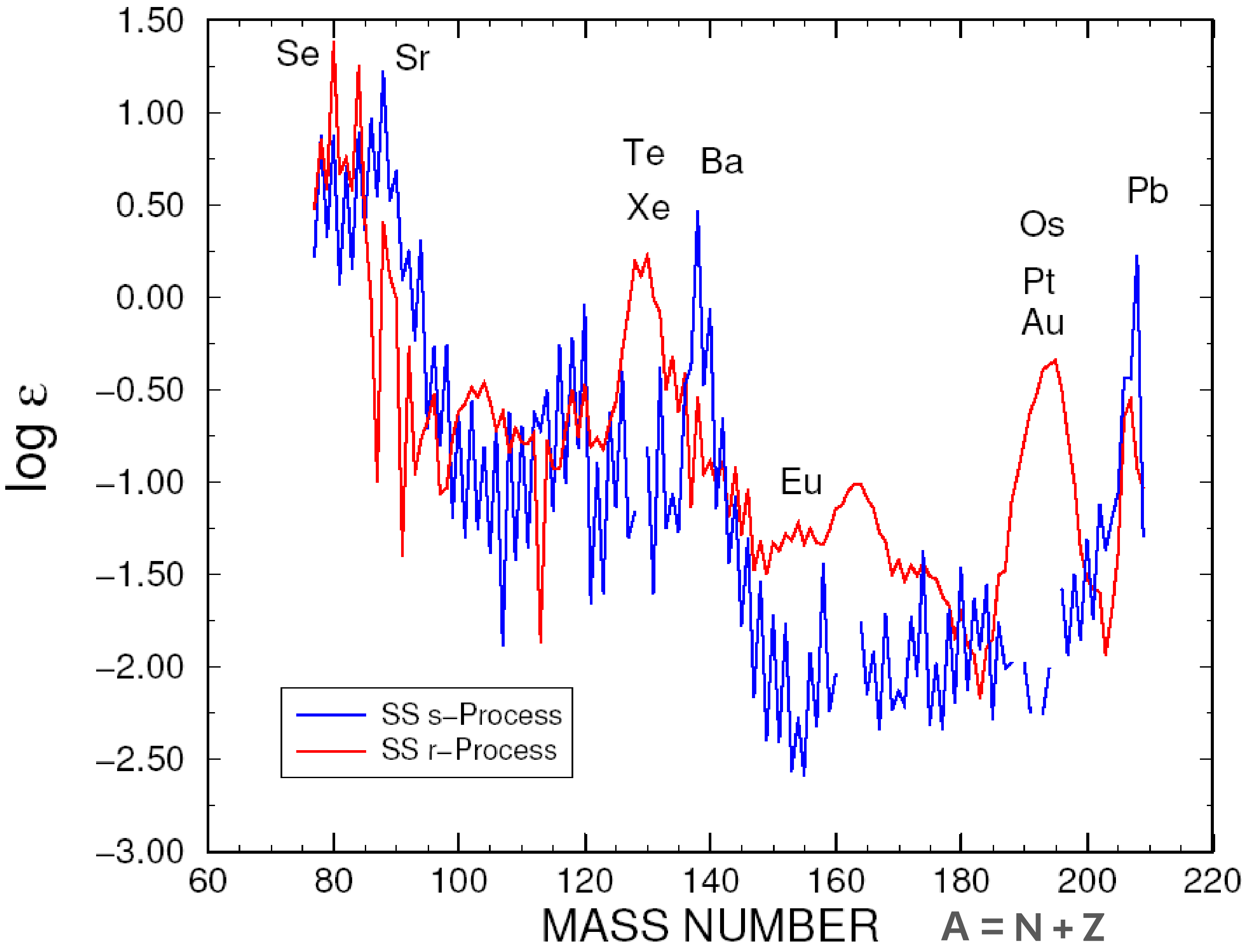
They are produced by neutron captures, on long or short timescales (s- and r- process)

Most heavy elements have a mixed origin (s- and r- process)

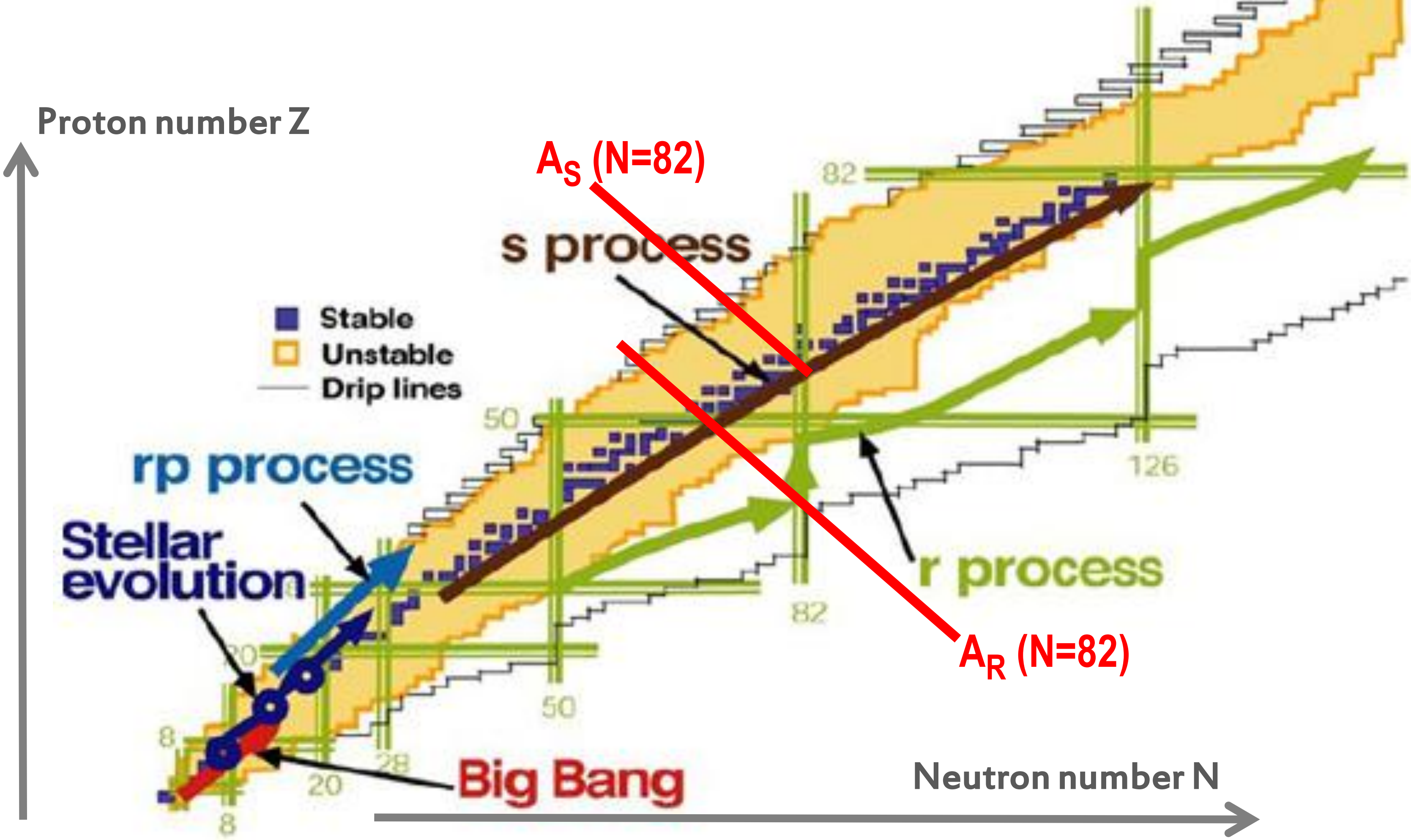
The solar abundances of a handful of elements are dominated by the s-process (Sr, Y, Zr, Ba, La,Ce, Pb)

While others are dominated by the r-process (Ag, Te,I, Xe, Cs, S, Eu, Gd, Tb, Dy, Ho, Er, Tm, Lu, Re, Os, Ir, Pt, Au, U, Th)

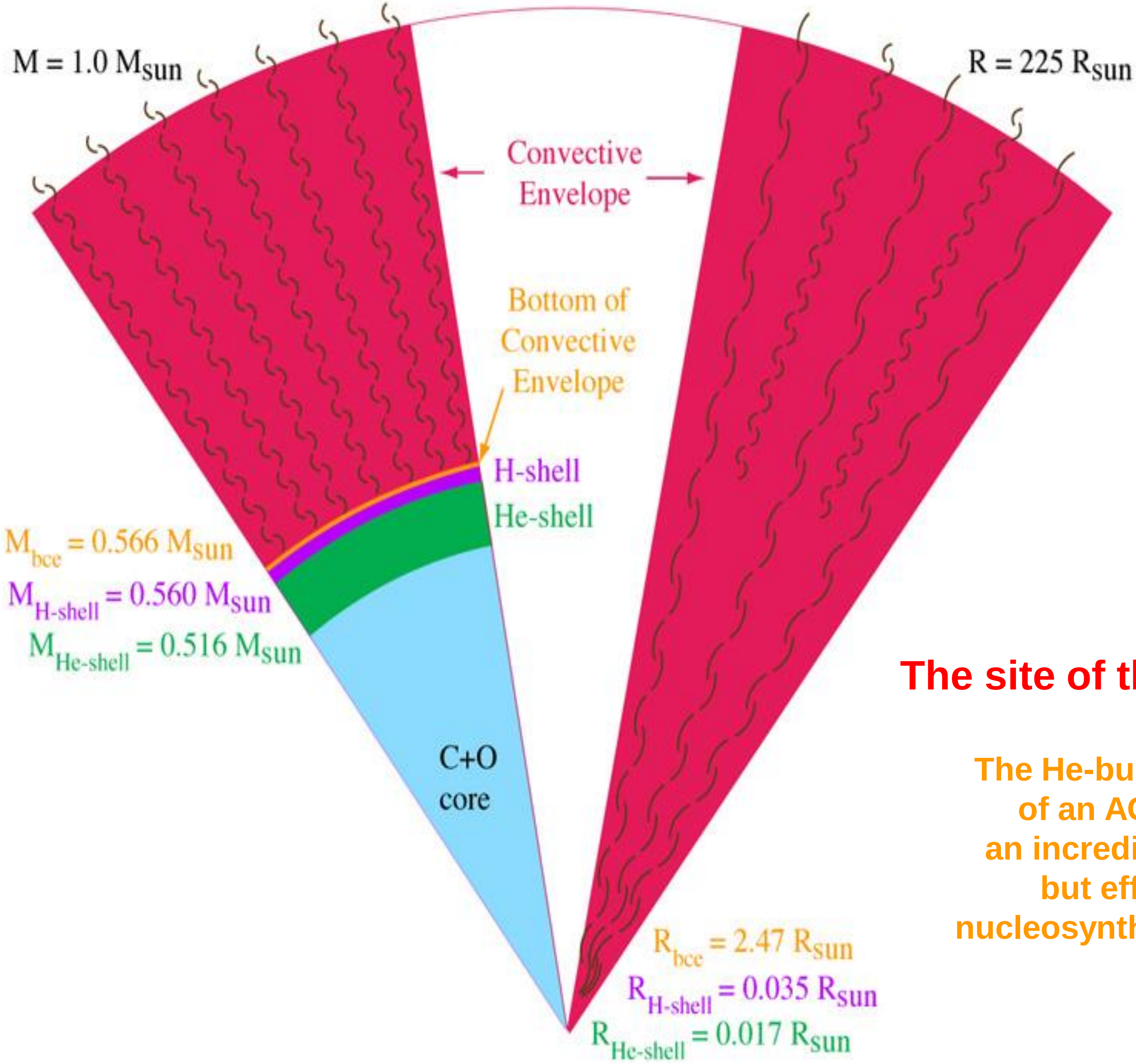
Abundances of heavier than Fe nuclei



The abundance peaks are associated to nuclei with "magic" nucleon numbers (N=50, 82, 126) of enhanced stability



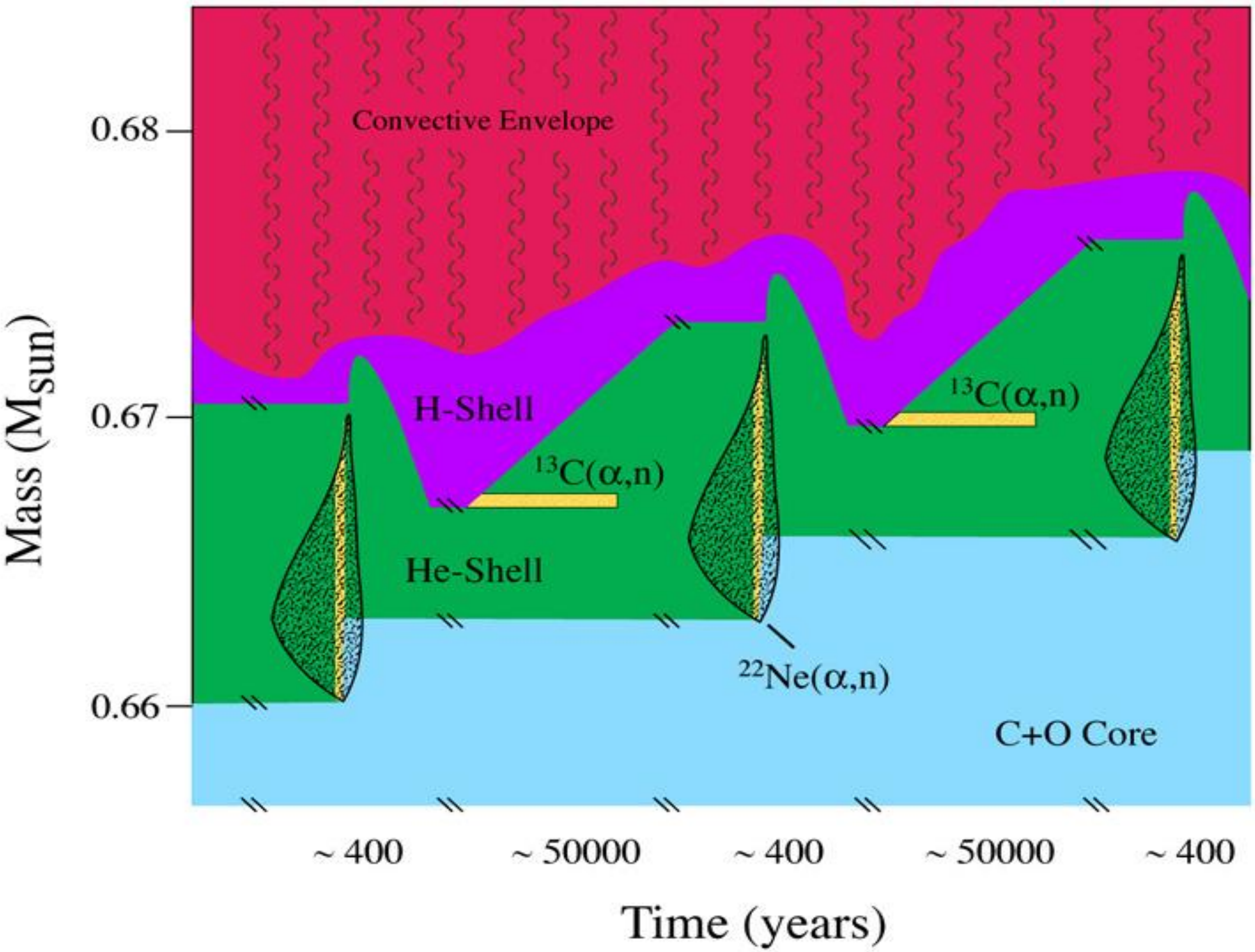
process	conditions	timescale	site
s-process (n-capture, …)	T~ 0.1 GK τ_n~ 1-1000 yr, n_n~10^{7-8}/cm^3	10^2 yr and 10^{5-6} yrs	Massive stars (weak) Low mass AGB stars (main)
r-process (n-capture, …)	T~1-2 GK τ_n ~ μs, n_n~10^{24} /cm^3	< 1s	Type II Supernovae ? Neutron Star Mergers ?
p-process ((γ,n), …)	T~2-3 GK	~1s	Type II Supernovae



The site of the s-process

The He-burning shell of an AGB star: an incredibly small, but efficient, nucleosynthesis factory

Neutrons are released through C13(α,**n**)O16 or Ne22(α,**n**)Mg25

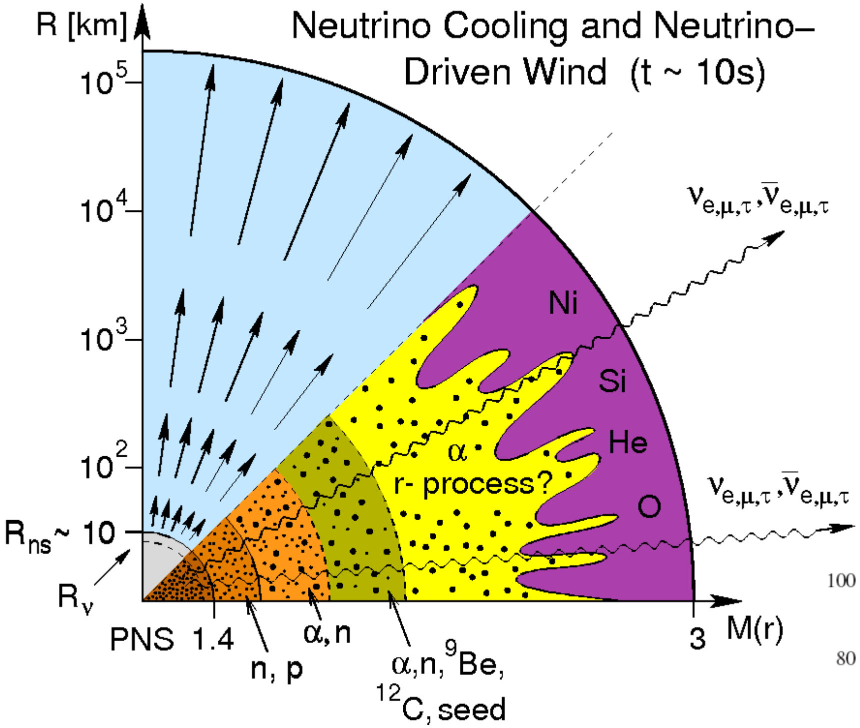


During **thermal pulses**, S-nuclei are convected to upper regions, then to the stellar envelope and then to the surface, from where **stellar wind** expells them to the **interstellar medium**

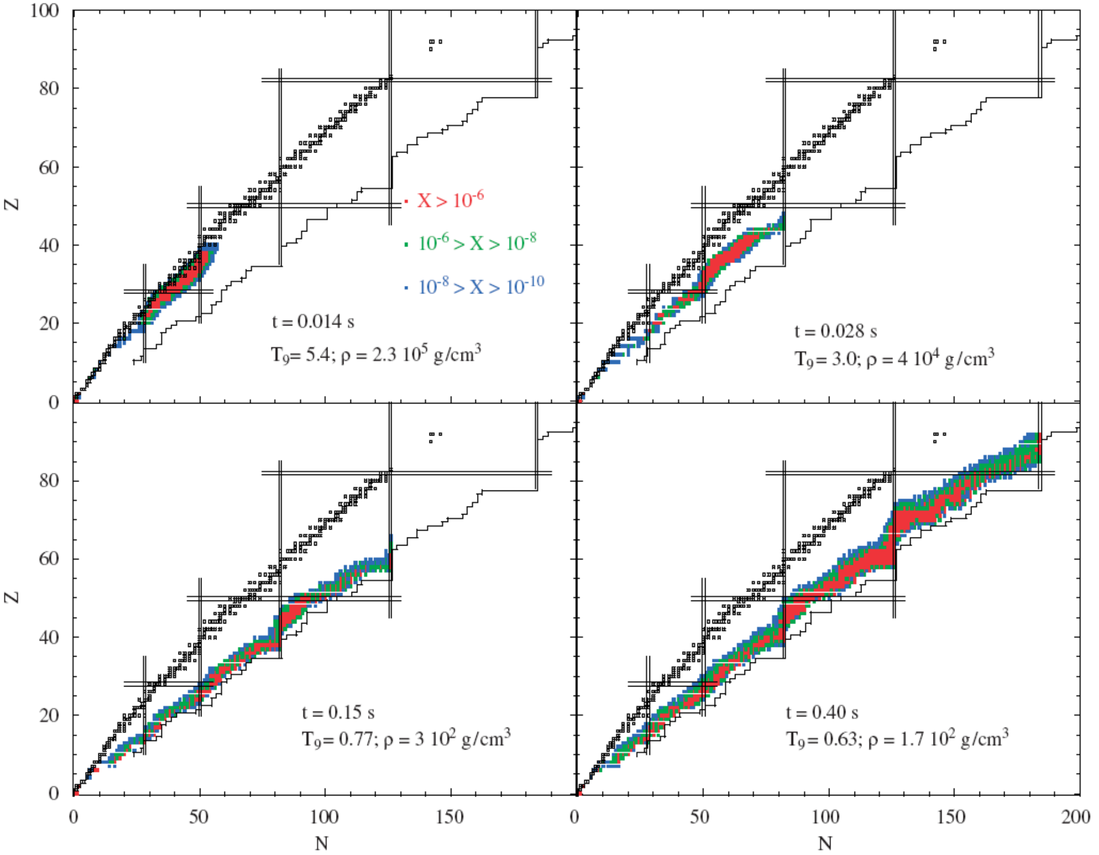
The site of the r-process

The innermost layers of
core collapse supernovae (?)

or, neutron star mergers ?

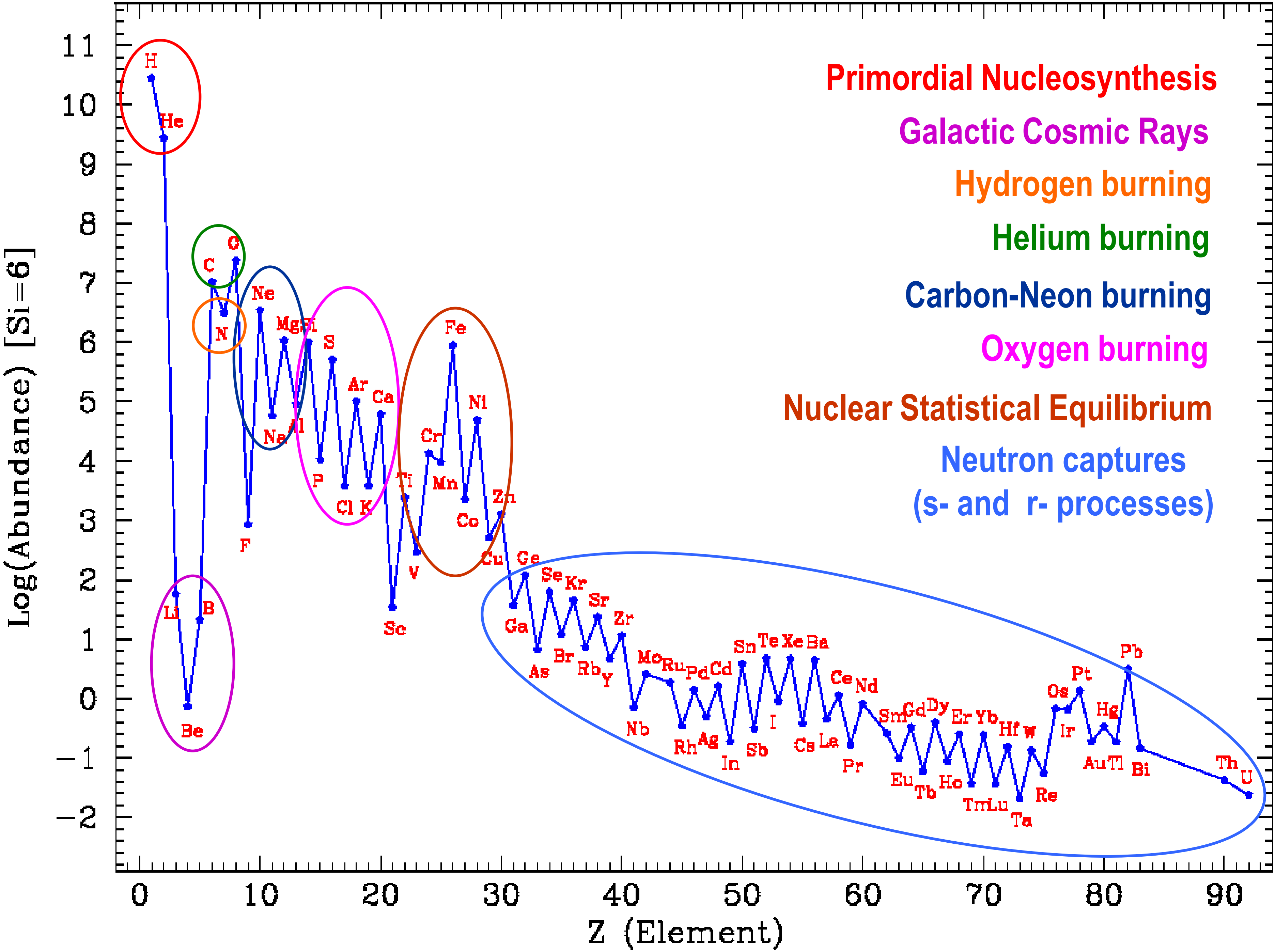


R-process path



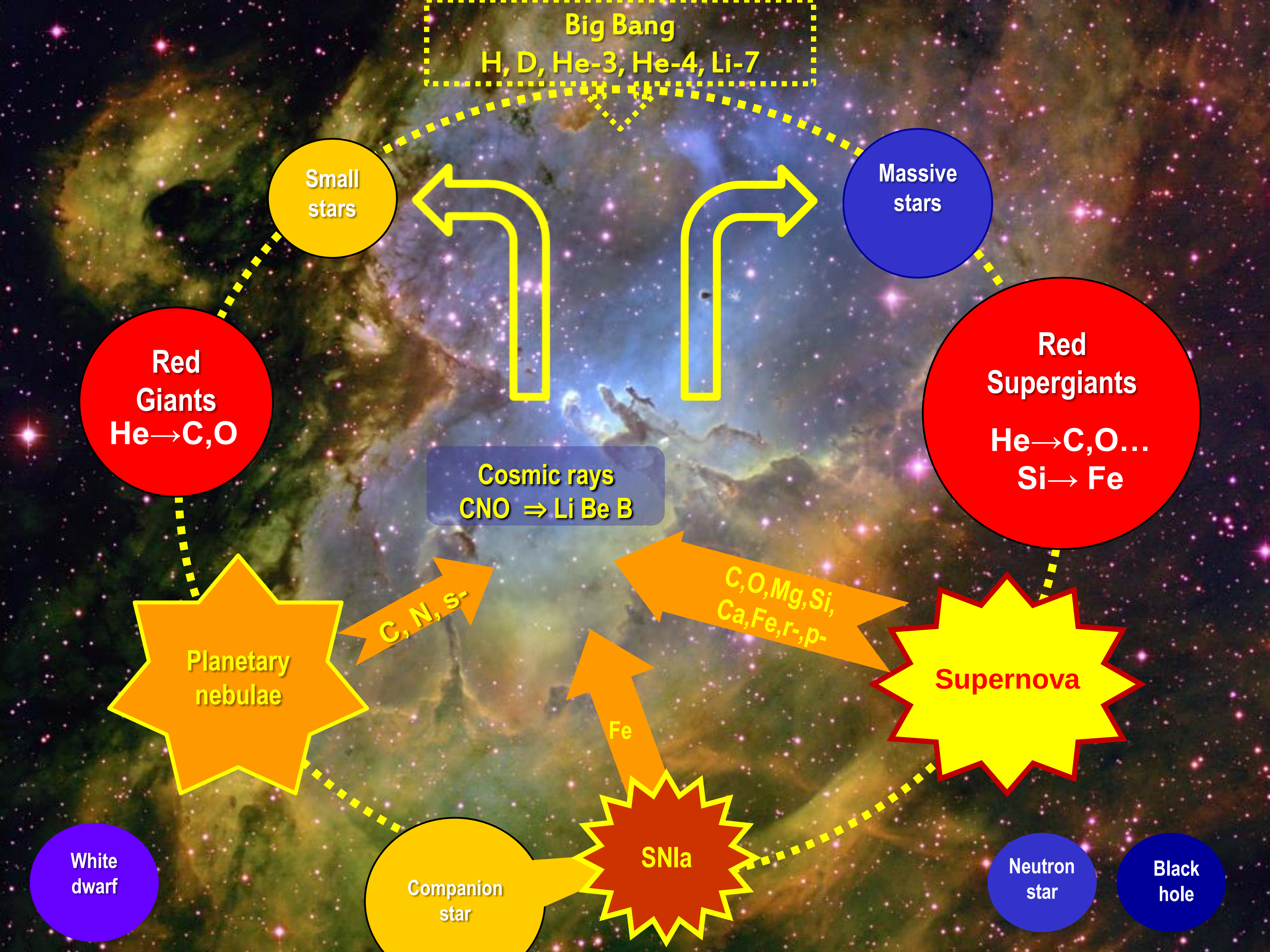
R-process studies are much more demanding in nuclear physics than those of any other nucleosynthetic process because they involve *nuclei far from the stability valley*

Quantity		Effect
S_n	neutron separation energy	path
$T_{1/2}$	β-decay half-lives	• abundance pattern • timescale
P_n	β-delayed n-emission branchings	final abundance pattern
fission (branchings and products)		• endpoint • abundance pattern? • degree of fission cycling
G	partition functions	• path (very weakly)
$N_A\langle\sigma v\rangle$	neutron capture rates	• final abundance pattern during freezeout ? • conditions for waiting point approximation


Primordial Nucleosynthesis
Galactic Cosmic Rays
Hydrogen burning
Helium burning
Carbon-Neon burning
Oxygen burning
Nuclear Statistical Equilibrium
Neutron captures
(s- and r- processes)
Log(Abundance) [Si=6]
Z (Element)
11
10
9
8
7
6
5
4
3
2
1
0
−1
−2
0
10
20
30
40
50
60
70
80
90
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
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U

Summary of Origins

Species	Site	Species	Site
H	Big Bang	Ar	Oxygen burning
He	Big Bang + stars	K	Oxygen burning + s-process
Li	Big Bang, L* + nu process	Ca	Oxygen burning
Be	Cosmic rays	Sc	s-process
B	Nu-process	Ti	Expl Si burning
C	Helium burning, L*+M*	V	Expl Si burning
N	CNO cycle, L*+ VMS	Cr	Expl Si burning
O	Helium burning	Mn	Expl Si burning, Ia
F	Nu-process	Fe	Expl Si burning, Ia
Ne	Carbon burning	Co	alpha-rich freeze out
Na	Carbon burning	Ni	alpha-rich freeze out
Mg	Carbon burning	Cu	alpha-rich freeze out + s-process
Al	Neon burning	Zn	Nu-powered wind
Si	Oxygen burning	p-proc	Explosive neon burning, O-burning
P	Neon Burning	s-proc	Helium burning, L* and M*
S	Oxygen burning	r-proc	Nu wind, jets?
Cl	Oxygen burning + s-proc		



Big Bang
H, D, He-3, He-4, Li-7

Small stars

Massive stars

Red Giants
He→C,O

Red Supergiants
He→C,O…
Si→ Fe

Cosmic rays
CNO ⇒ Li Be B

Planetary nebulae

C, N, s-

C,O,Mg,Si,
Ca,Fe,r-,p-

Supernova

Fe

SNIa

Companion star

White dwarf

Neutron star

Black hole