Massive stars

School on “The synthesis of the elements”

Granada (12-16 April 2010)

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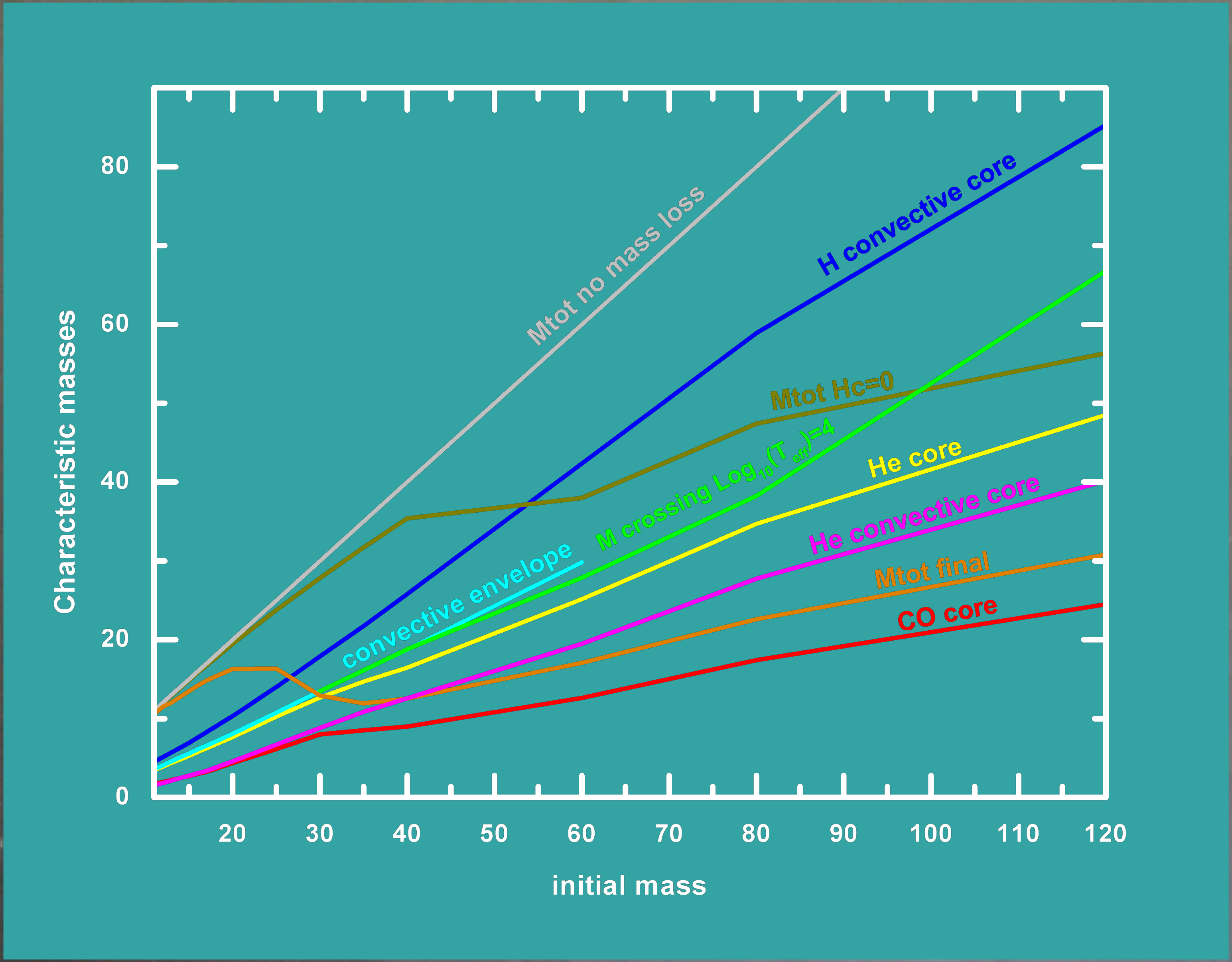
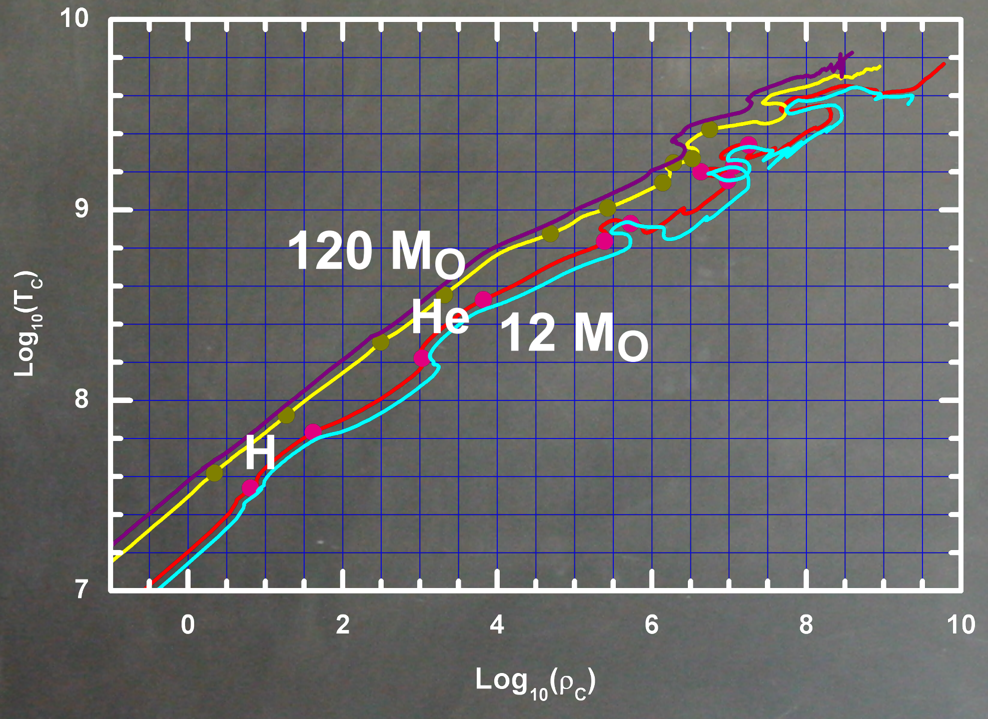
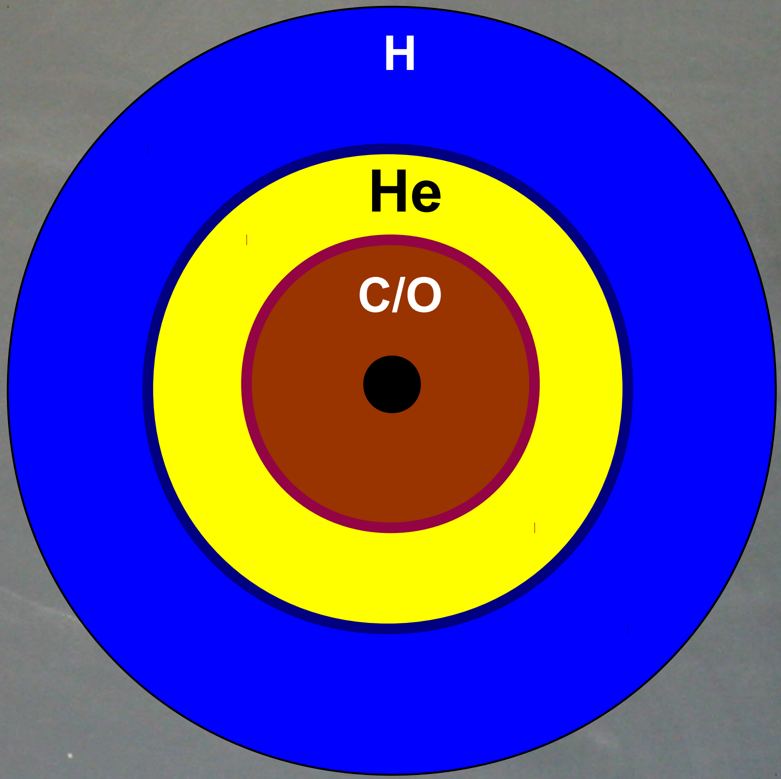
Part 3


Mtot no mass loss
H convective core
Mtot Hc=0
M crossing Log10(Teff)=4
He core
He convective core
convective envelope
Mtot final
CO core
Characteristic masses
initial mass
0
20
40
60
80
20
30
40
50
60
70
80
90
100
110
120



10
9
8
7
0
2
4
6
8
10
$Log_{10}(T_C)$
$Log_{10}(\rho_C)$
120 M_O
12 M_O
H
He



H
He
C/O

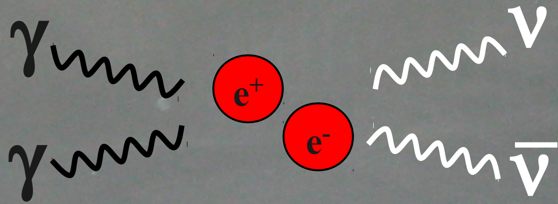
Let's enter the advanced burnings...

The central temperature at the central He exhaustion is of the order of $4\ 10^{8}$ K and at roughly $8\ 10^{8}$ K the next fuel, carbon, starts burning.

But in the mean time....

...as the temperature increases, the peak of the Planck distribution moves towards higher energies and the number of photons having energy equal to 0.511 MeV (i.e. the mass of the electrons) increases dangereously.

When this happens, $\gamma+\gamma$ begin to efficiently produce electrons-positron pairs.



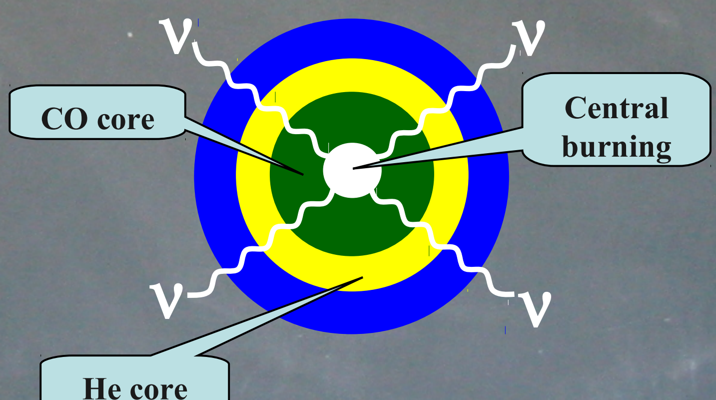
A blackbody radiation has its maxmum wavelenght at : λ_{MAX} $=2.898\ 10^{-3}\ T^{-1}$ [m / K]

BUT:

$$E = h\nu = hc/\lambda = hcT/(2.898\ 10^{-3}) = 4.3\ 10^{-10}\ T\ [MeV]$$

HENCE:

$$T = E/\ 4.3\ 10^{-10} = 0.5\ /\ 4.3\ 10^{-10} \Rightarrow 1.15\ 10^{9}\ K$$



Energy budget

$$t = E / L$$

H=>He	$6.44\ 10^{18}$ erg gr^{-1}	$t = 1.06\ 10^{11}\ (L/L_0)^{-1}$ [yr / M_O]
He=>C	$5.84\ 10^{17}$ erg gr^{-1}	$t = 9.64\ 10^{9}\ (L/L_0)^{-1}$ [yr / M_O]
C=>Ne	$1.85\ 10^{17}$ erg gr^{-1}	$t = 3.05\ 10^{9}\ (L/L_0)^{-1}$ [yr / M_O]
O=>Si	$2.89\ 10^{17}$ erg gr^{-1}	$t = 4.77\ 10^{9}\ (L/L_0)^{-1}$ [yr / M_O]
Si=>Ni	$1.88\ 10^{17}$ erg gr^{-1}	$t = 3.10\ 10^{9}\ (L/L_0)^{-1}$ [yr / M_O]

L => total luminosity: L_γ

$M = 80\ M_O$ $t = E / 10^6$

H=>He	$6.44\ 10^{18}$ erg gr^{-1}
He=>C	$5.84\ 10^{17}$ erg gr^{-1}
C=>Ne	$1.85\ 10^{17}$ erg gr^{-1}
O=>Si	$2.89\ 10^{17}$ erg gr^{-1}
Si=>Ni	$1.88\ 10^{17}$ erg gr^{-1}

Mcc	Estimated lifetime	Real lifetime	Revised lifetime	L_{TOT}
60	$6\ 10^6$	$3.2\ 10^6$		10^6
20	$2\ 10^5$	$3.3\ 10^5$		10^6
1.5	$4.5\ 10^3$	$4.7\ 10^2$		10^6
1	$4.8\ 10^3$	$4.6\ 10^{-2}$		10^6
1	$3.1\ 10^3$	$4.3\ 10^{-3}$		10^6

L => total luminosity: $L_\gamma + L_\nu$

$M=80\ M_O$ $t = E / 10^6$

- H=>He $6.44\ 10^{18}$ erg gr^{-1}
- He=>C $5.84\ 10^{17}$ erg gr^{-1}
- C=>Ne $1.85\ 10^{17}$ erg gr^{-1}
- O=>Si $2.89\ 10^{17}$ erg gr^{-1}
- Si=>Ni $1.88\ 10^{17}$ erg gr^{-1}

Mcc	Estimated lifetime	Real lifetime	Revised lifetime	L_{TOT}
60	$6\ 10^6$	$3.2\ 10^6$		10^6
20	$2\ 10^5$	$3.3\ 10^5$		10^6
1.5	$4.5\ 10^3$	$4.7\ 10^2$	$4.5\ 10^2$	10^7
1	$4.8\ 10^3$	$4.6\ 10^{-2}$	$4.8\ 10^{-2}$	10^{11}
1	$3.1\ 10^3$	$4.3\ 10^{-3}$	$3.1\ 10^{-3}$	10^{12}

All the advanced phases are really neutrino dominated...

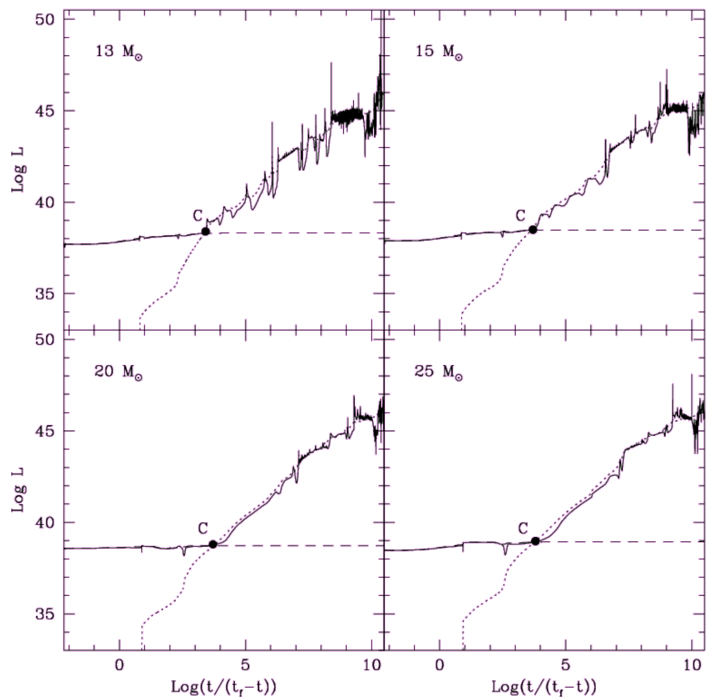
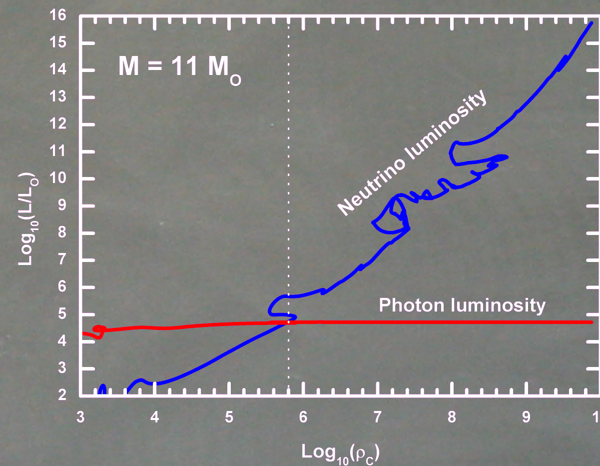
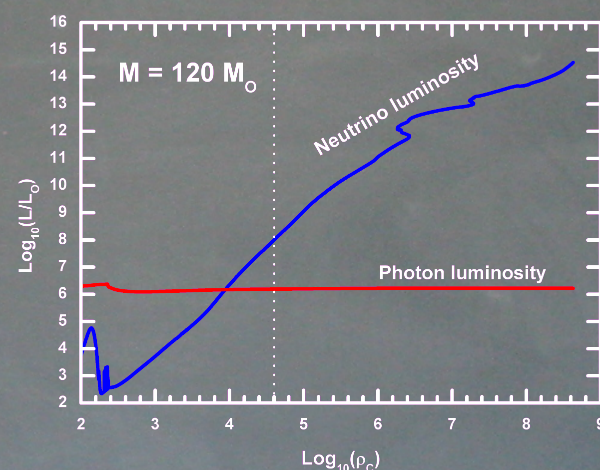


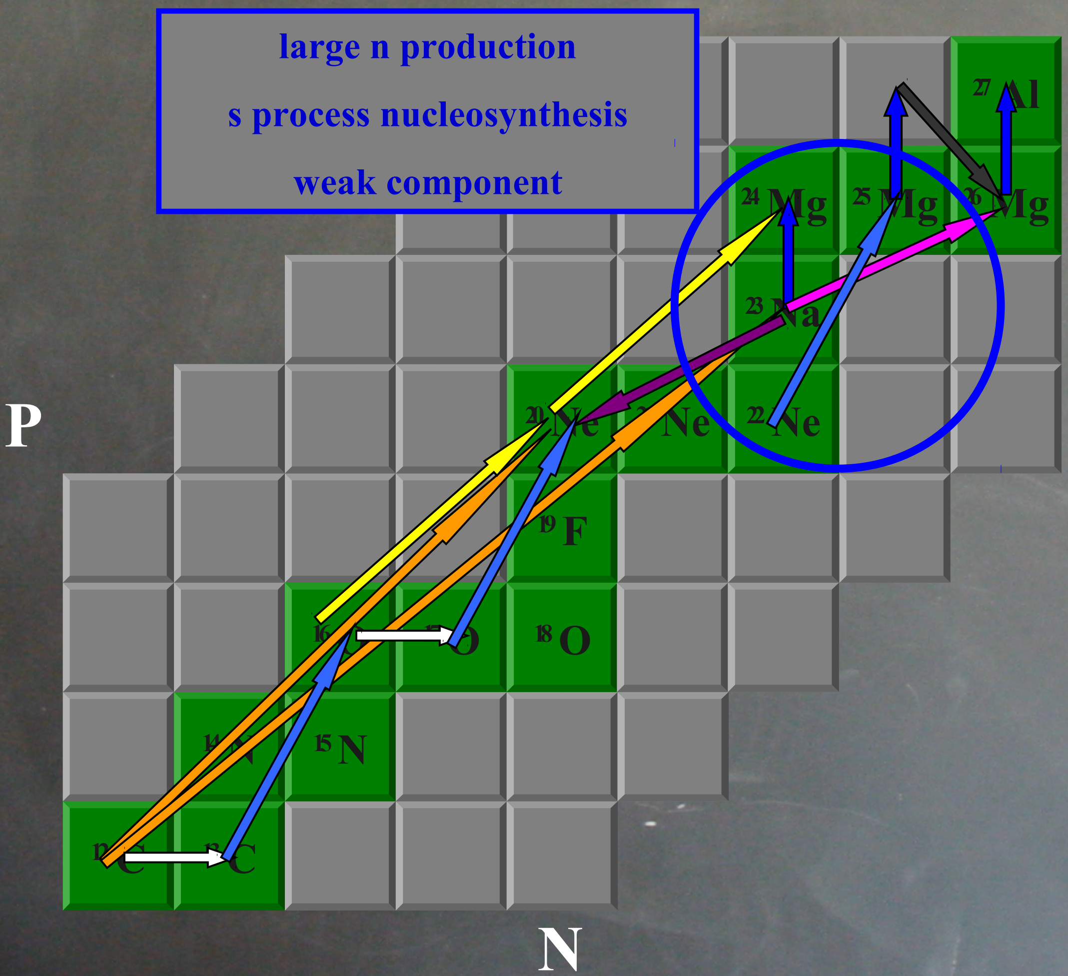
FIG. 7.—Temporal behavior of the various luminosities: photons (*dashed lines*), neutrinos (*dotted lines*), and nuclear (*solid lines*). The carbon-burning ignition is indicated in each panel by the big filled dot labeled "C."

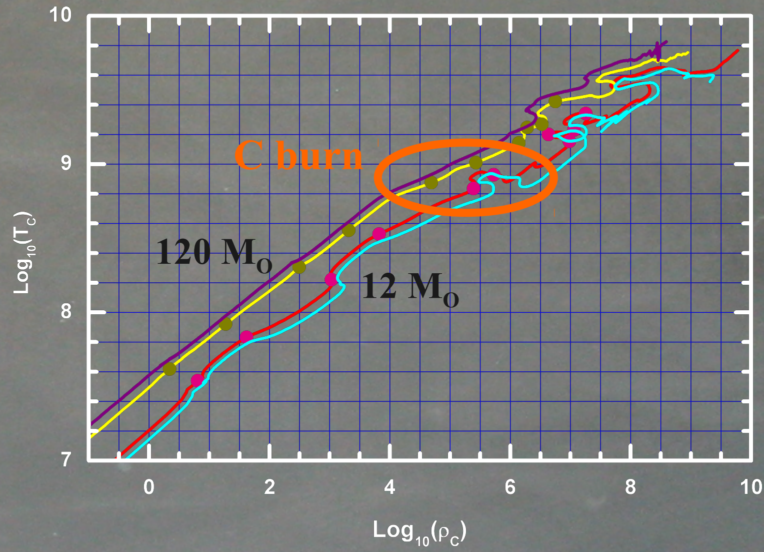


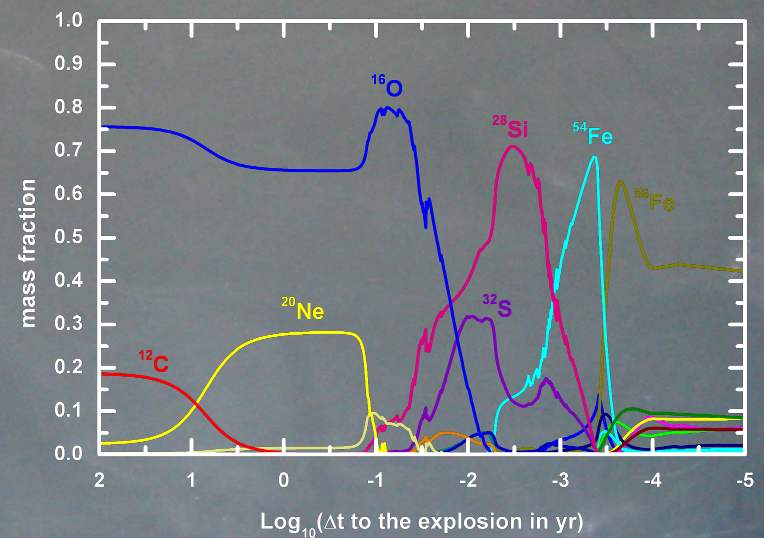


C burning

Typical temperature: 0.8-1.0 BK







Just the main processes in ...

C burning

Panel a)

$^{12}C(^{12}C,\alpha)^{20}Ne$

$^{12}C(^{12}C,p)^{23}Ne$

$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(\alpha,n)^{16}O$ $\quad$ $^{12}C(n,\gamma)^{13}C(\alpha,n)^{16}O$

$^{25}Mg(n,\gamma)^{26}Mg(p,\gamma)^{27}Al$

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

$^{20}Ne(n,\gamma)^{21}Ne$

Panel b)

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

$^{12}C(^{12}C,\alpha)^{20}Ne$

$$^{12}C(^{12}C,p)^{23}Na \begin{cases} (p,\alpha)^{20}Ne \\ (p,\gamma)^{24}Mg \\ (\alpha,p)^{26}Mg \end{cases}$$

$^{22}Ne(\alpha,n)^{25}Mg(p,\gamma)^{26}Al(\beta^+)^{26}Mg(p,\gamma)^{27}Al$

$^{22}Ne(p,\gamma)^{23}Na$

$^{20}Ne(n,\gamma)^{21}Ne(\alpha,n)^{24}Mg$

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

$^{12}C(n,\gamma)^{13}C(\alpha,n)^{16}O$

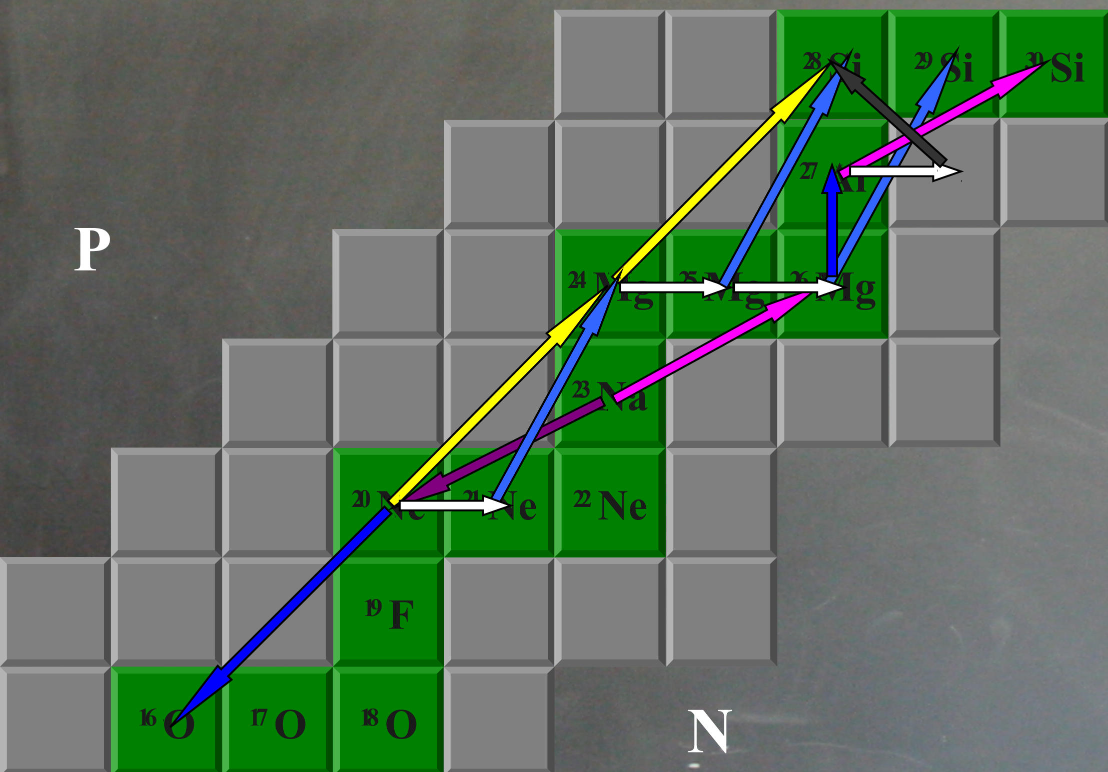
FIG. 6.—Most efficient nuclear processes during the central carbon burning. (*a*) The first part of the carbon burning; (*b*) the second part of carbon burning.

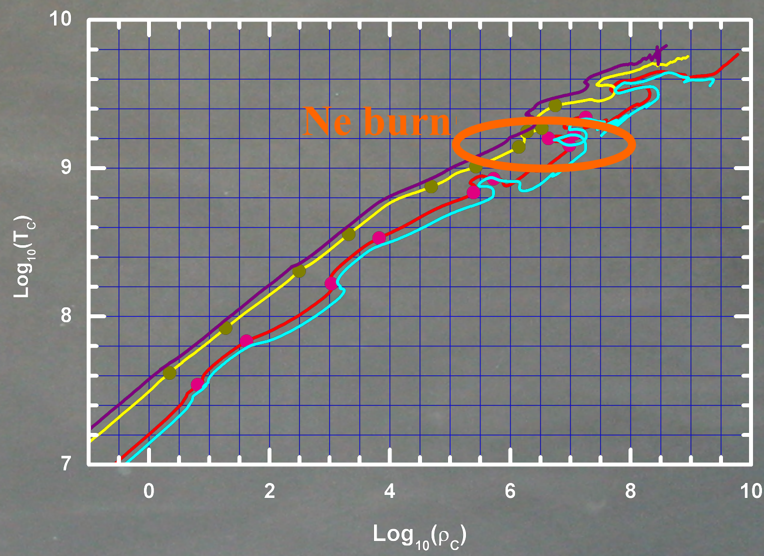
Trailer time!

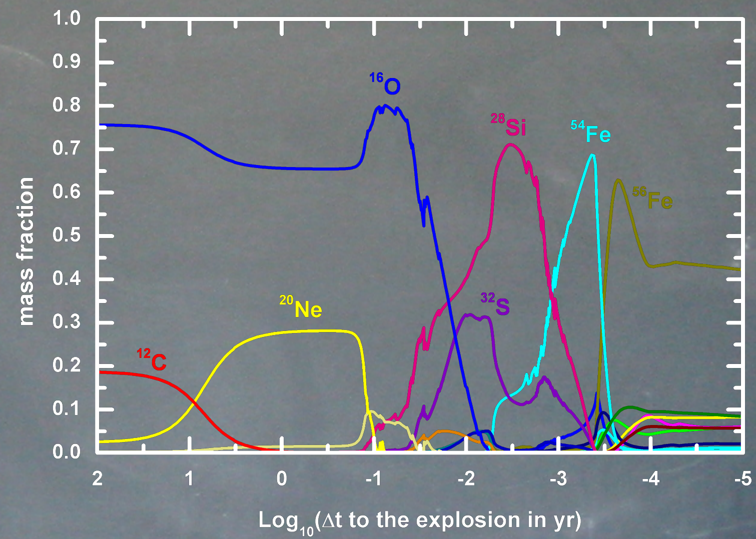
C burning movie

Ne burning

Typical temperature: 1.3-1.6 BK







Just the main processes in ...

Ne burning

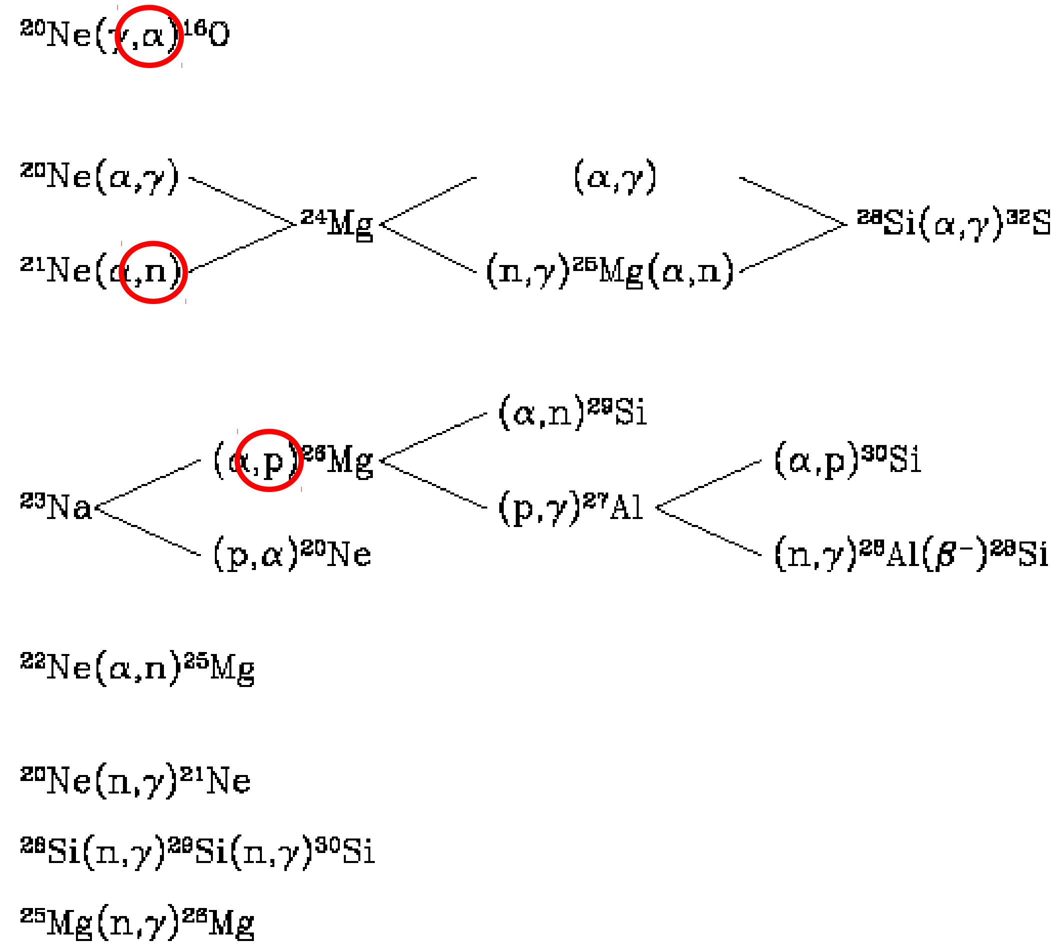


FIG. 8.—Most efficient nuclear processes during the central neon burning

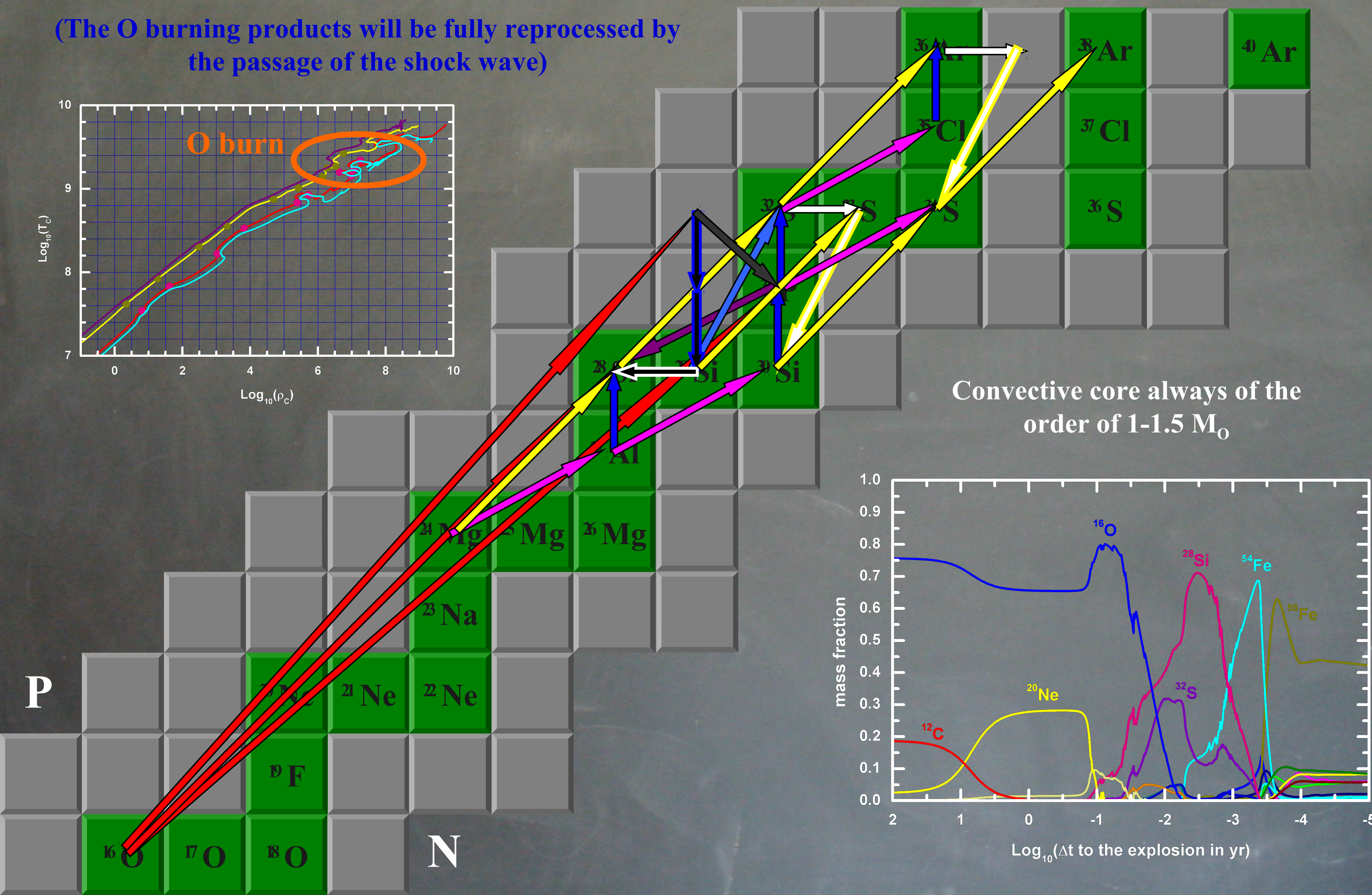
Trailer time!

Ne burning movie

O burning

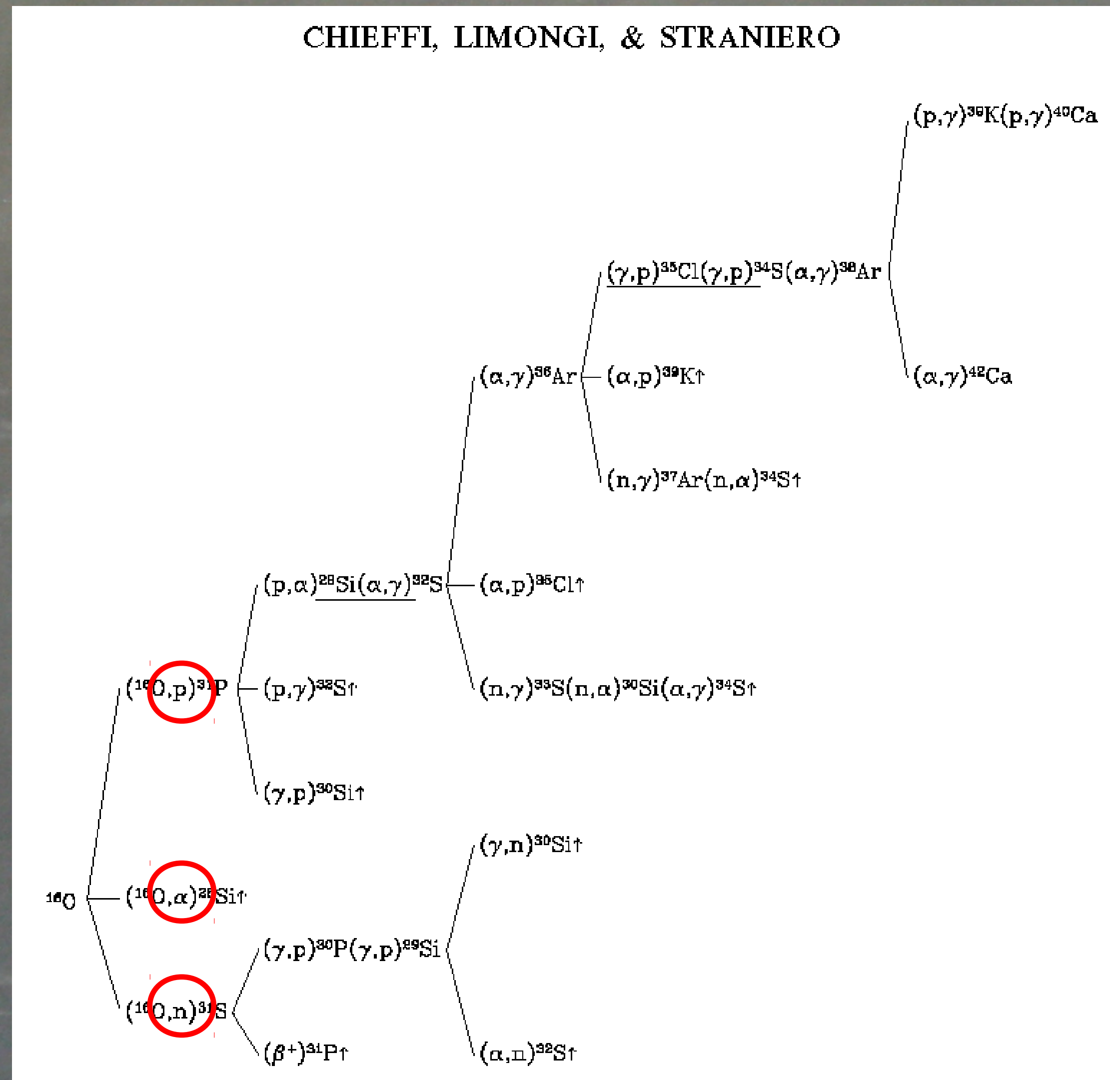
Typical temperature: 2.-2.5 BK

(The O burning products will be fully reprocessed by the passage of the shock wave)



Just the main processes in ...

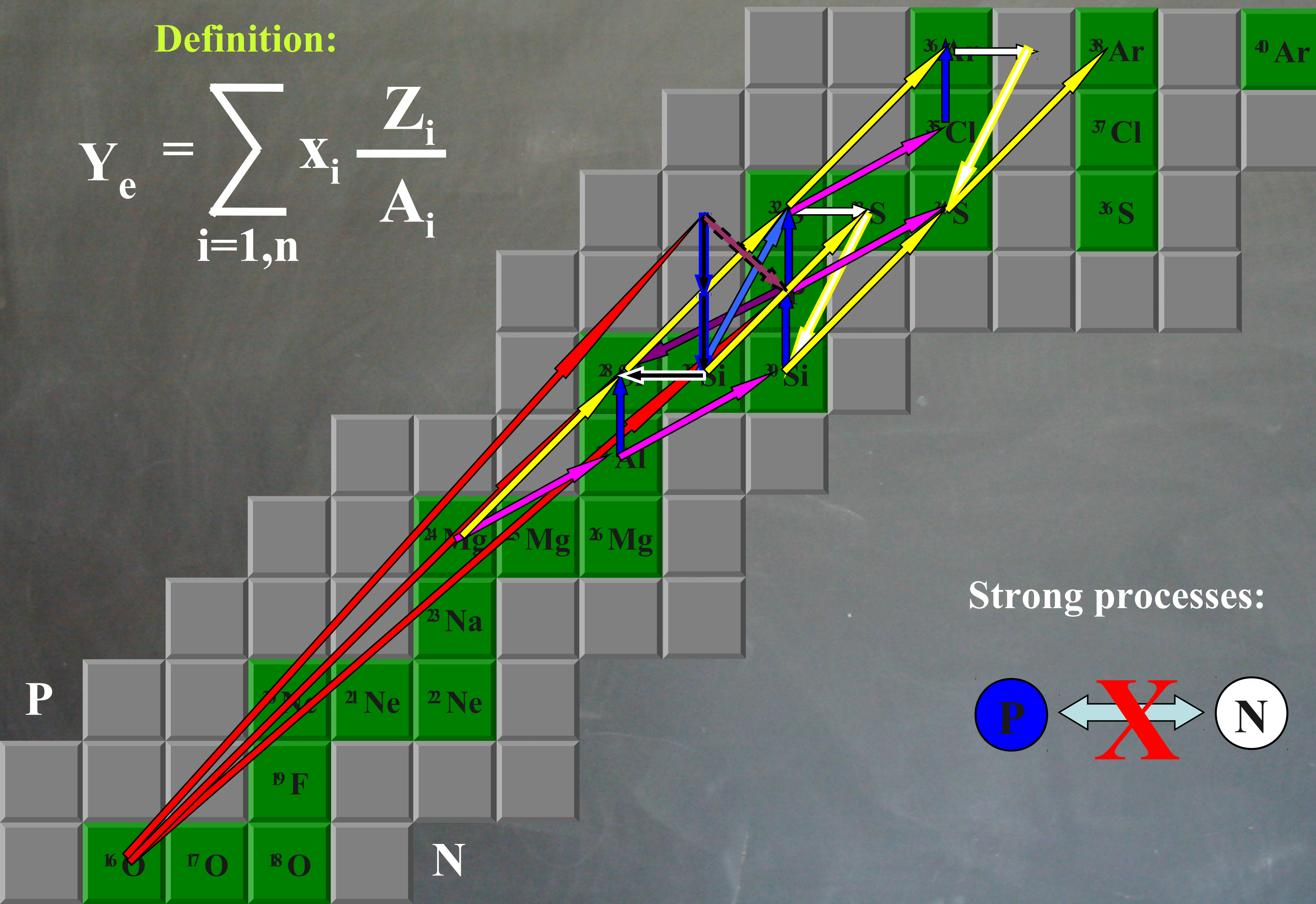
O burning



neutronization

Definition:

$$Y_e = \sum_{i=1,n} x_i \frac{Z_i}{A_i}$$

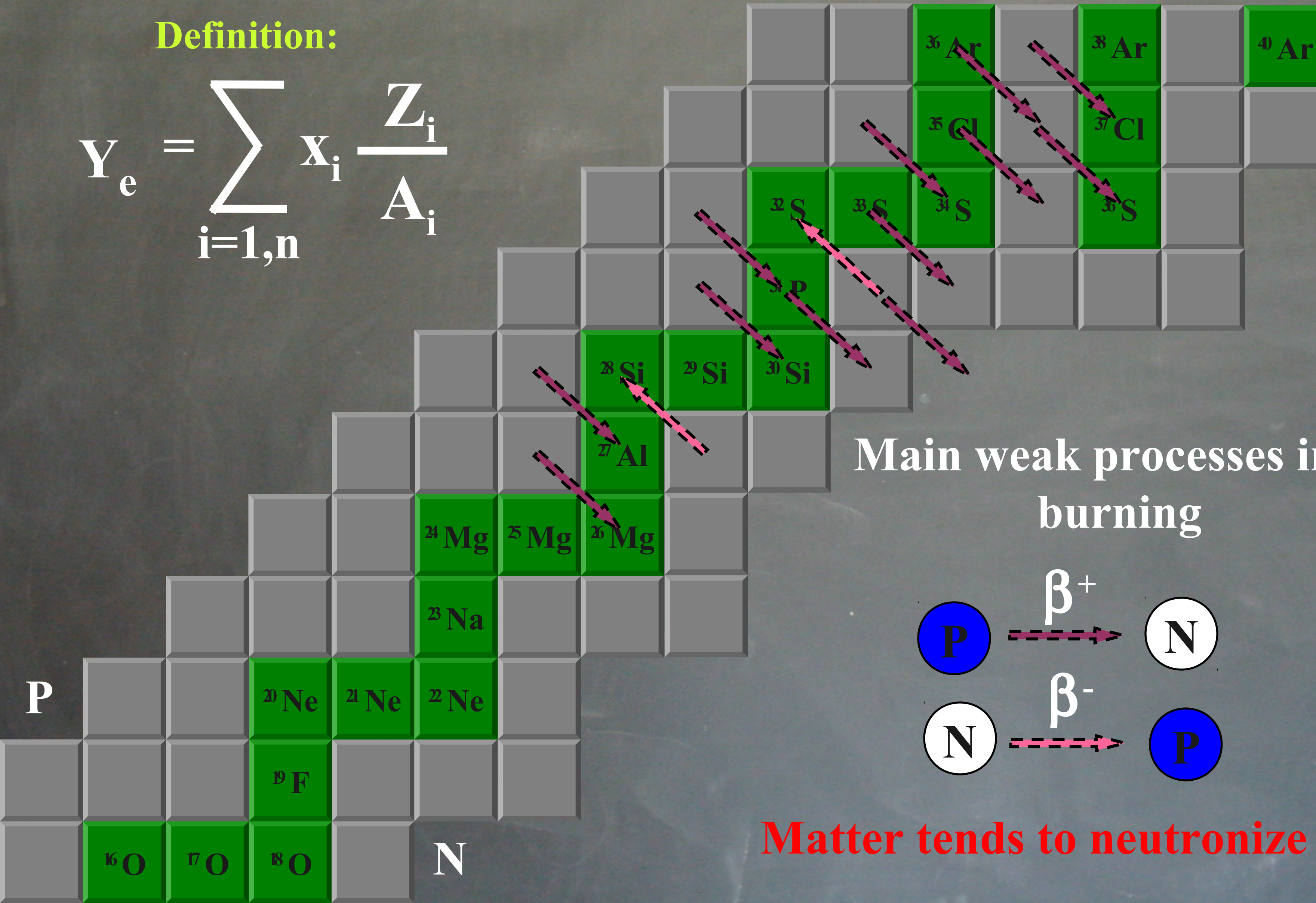


Strong processes:

neutronization

Definition:

$$Y_e = \sum_{i=1,n} x_i \frac{Z_i}{A_i}$$



Main weak processes in O burning

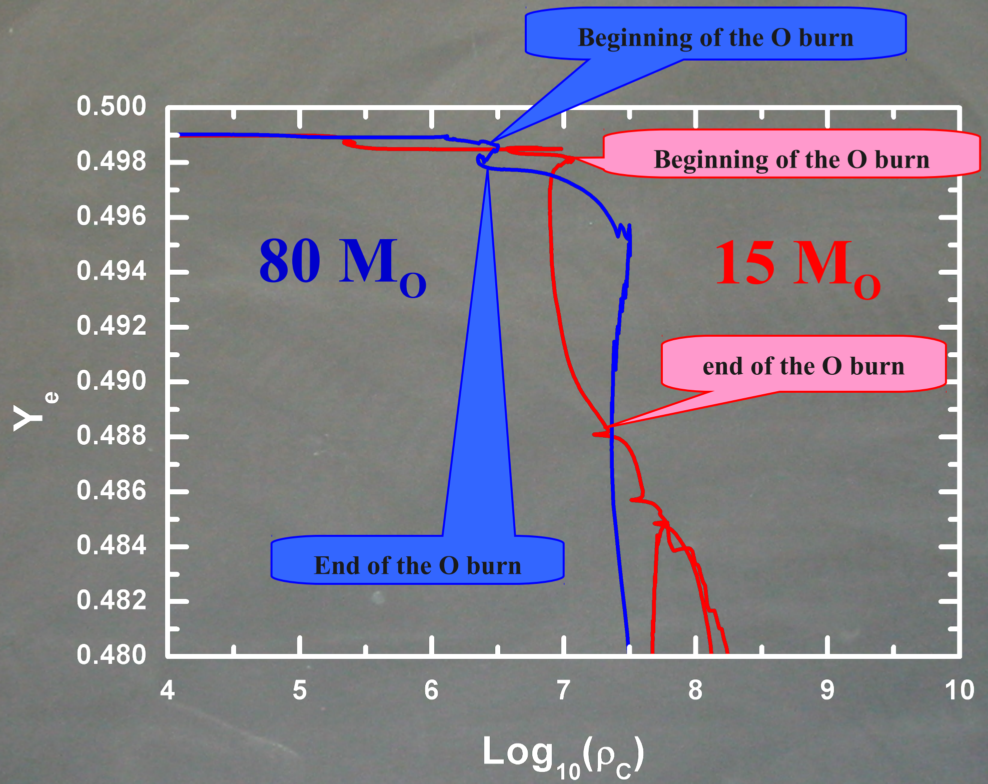
Matter tends to neutronize !

neutronization

Definition:

$$Y_e = \sum_{i=1,n} x_i \frac{Z_i}{A_i}$$

Degree of neutronization depends on the initial mass (actually on CO core mass)



RULE: The smaller the M_{CO} the higher the degree of neutronization at the end of the central O burning.

Beyond the O burning

$$i\,(j,k)\,m \rightleftarrows m\,(k,j)\,i$$

Reverse process

R_{ij} → Rate of the i(j,k)m process

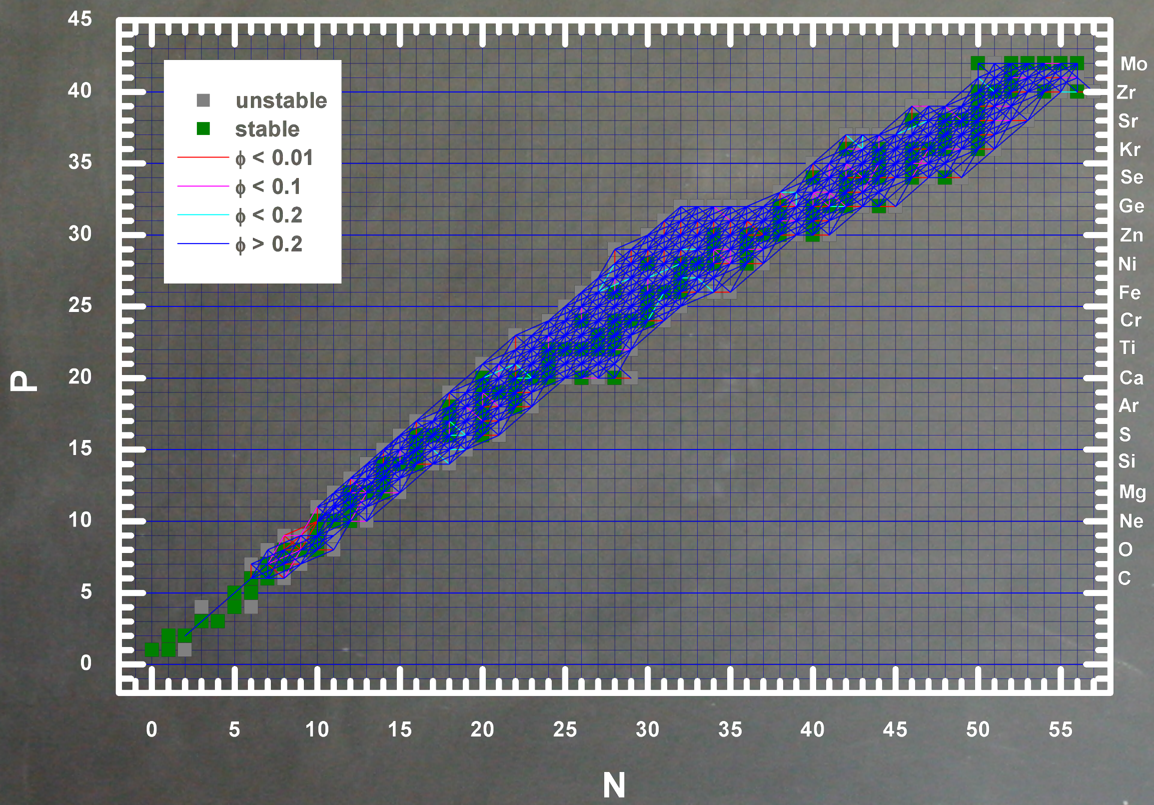
R_{km} → Rate of the i(j,k)m process

$$\Phi_{ij} = \frac{|R_{ij} - R_{km}|}{Max(r_{ij}, r_{km})}$$

Φ= 0 means perfect equilibrium

Φ =1 means one process dominates over the other

The approach to the Nuclear Statistical Equilibrium



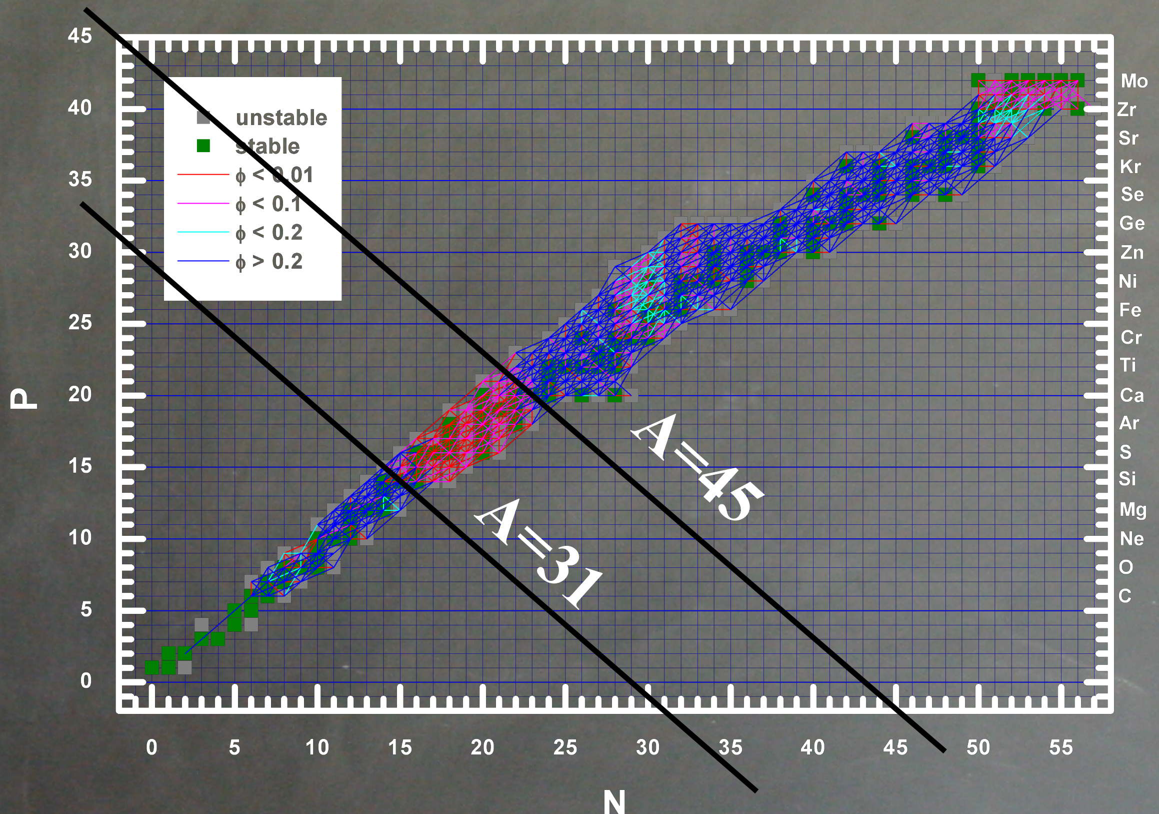
T=1.9 BK

Beginning of the O burning

Y_e=0.4987

Almost all the processes are far from the equilibrium with their reverse

The approach to the Nuclear Statistical Equilibrium



T=2.7 BK

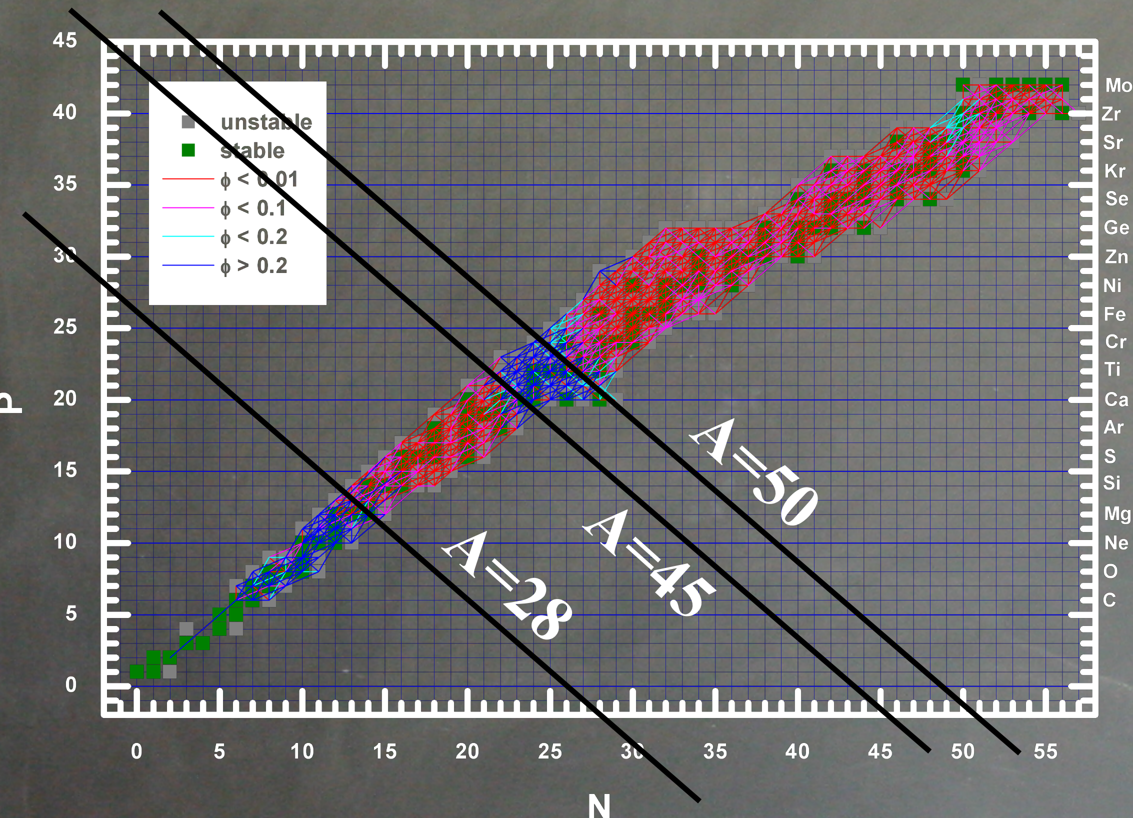
End of the O burning

Y_e=0.4978

A first cluster forms between A=31 and and A=45

Definition: a CLUSTER is a group of nuclei connected by processes that are at the equilibrium with their reverse.

The approach to the Nuclear Statistical Equilibrium



T=2.9 BK

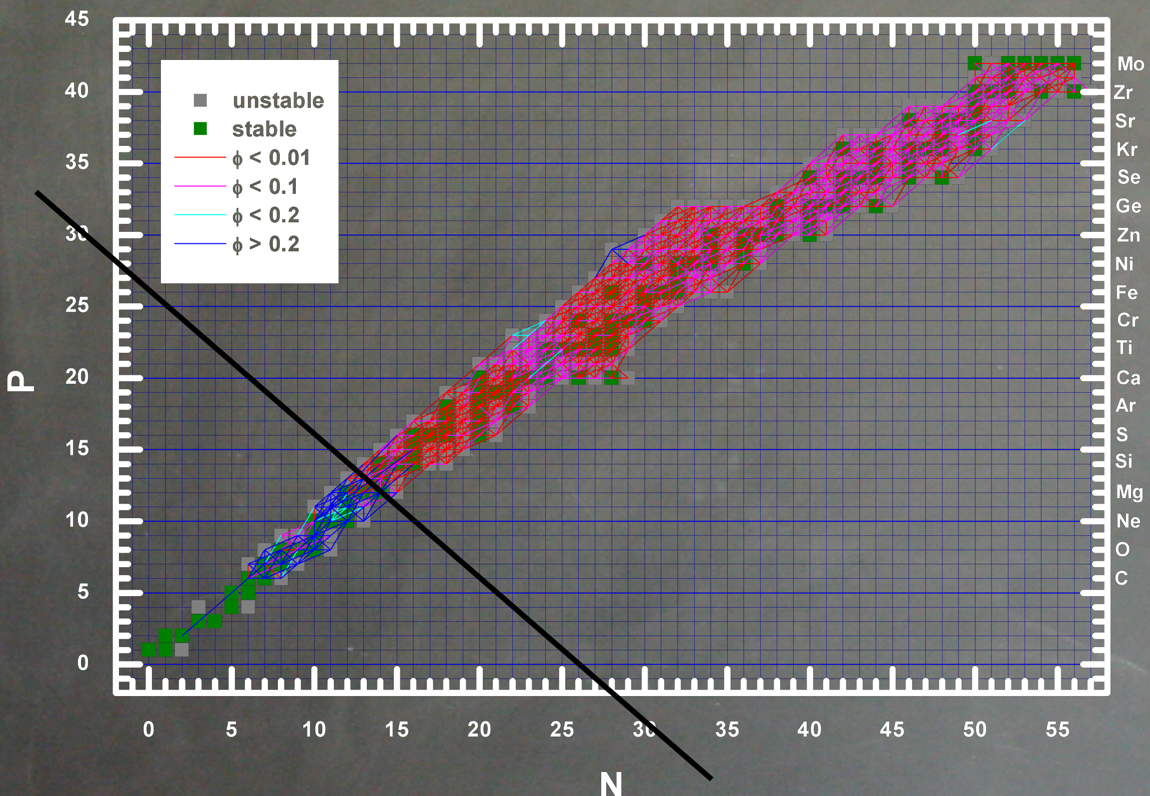
A little bit before the Si burning
Y_e=0.4976

The first cluster extends now between A=28 and A=45
but
a second one forms at A>50

Within each cluster the abundances of the various nuclei depend on their equilibrium with respect to the sea of α and p. Such an equilbrium abundance is determined by an equation that looks like a Saha equation:

$$Y(n,z)=f\,(\rho, T, \text{a nucleus not in equilibrium})$$

The approach to the Nuclear Statistical Equilibrium



T=3.4 BK

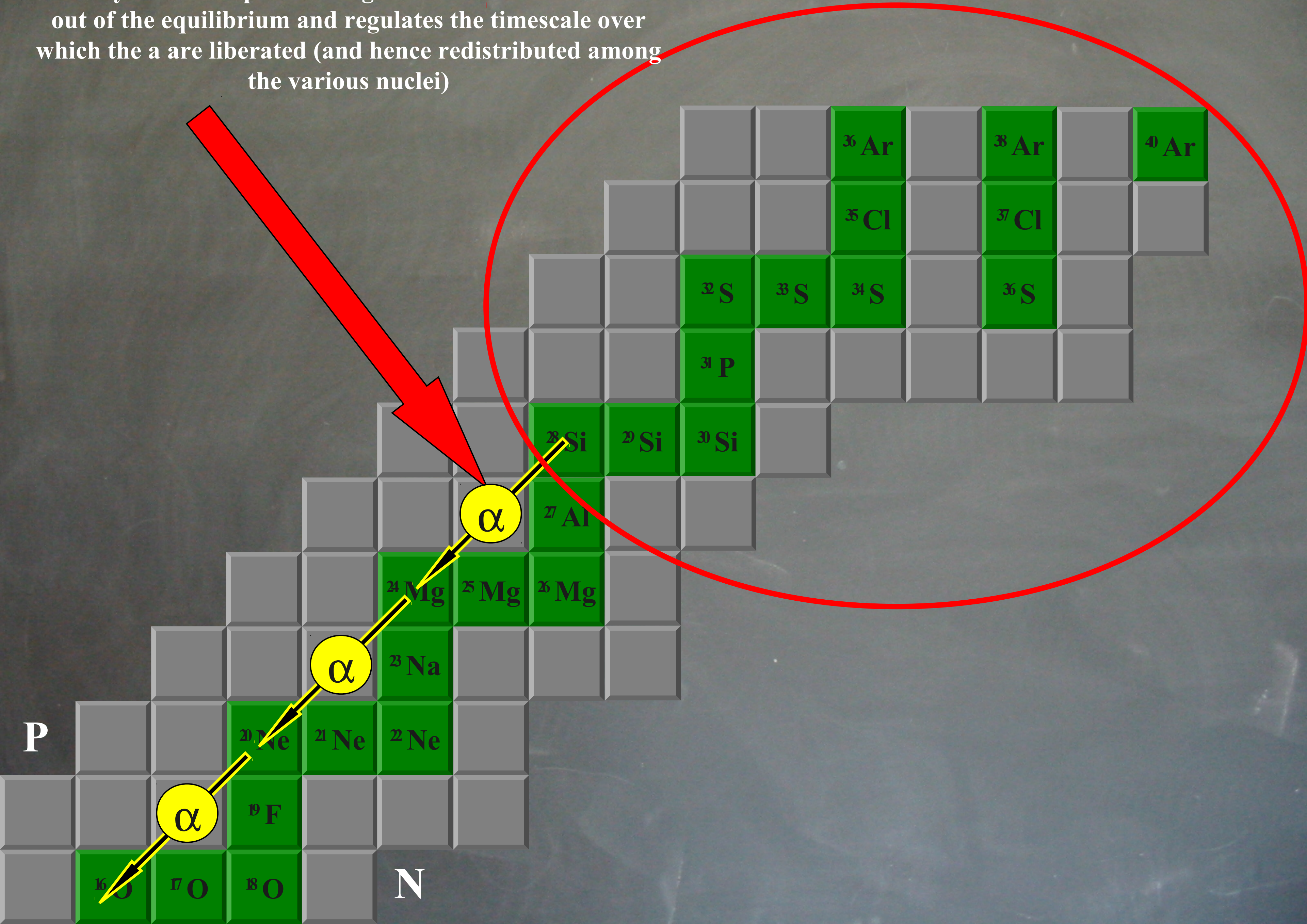
Beginning of the Si burning

Y_e=0.4955

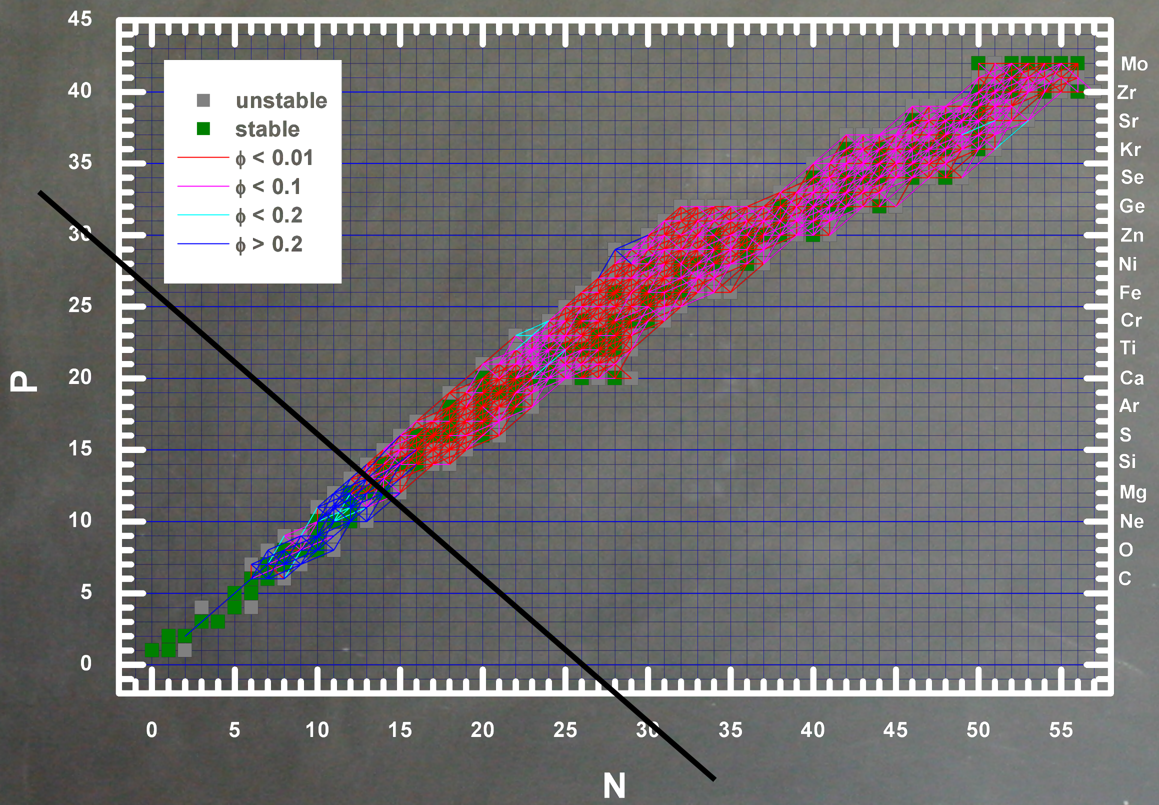
The two clusters begin to merge and form an unique cluster that starts at A=28

^{28}Si is not at the equilibrium. It is destroyed by the γ,α photodisintegration

Actually the whole photodintegration from ^{28}Si to the α is out of the equilibrium and regulates the timescale over which the a are liberated (and hence redistributed among the various nuclei)



The approach to the Nuclear Statistical Equilibrium



T=3.4 BK

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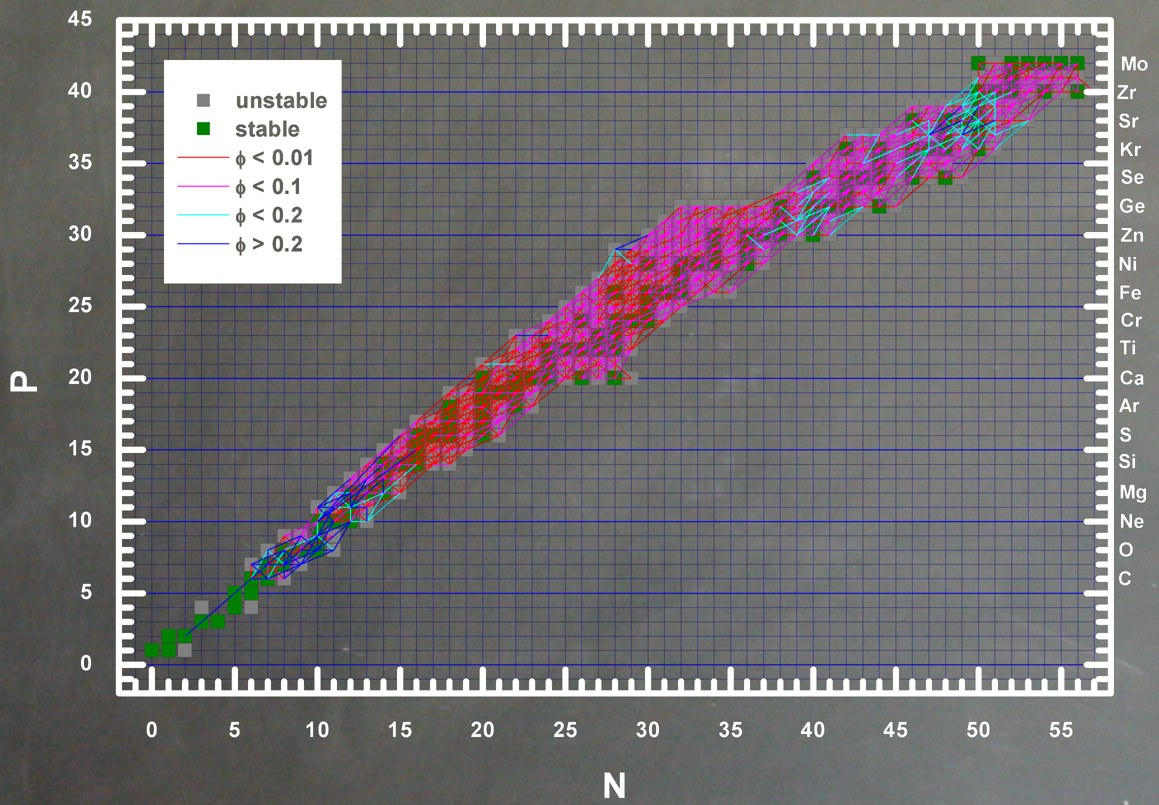
The approach to the Nuclear Statistical Equilibrium



T=4.1 BK

End of the Si burning

Y_e=0.4780

Nuclei with A<28 do not reach the equilibrium

Most of the matter located in the nucleus(i) that has(ve) the highest binding energy for the Ye present at the moment. Remember that the weak processes are not at the equilibrium and must be taken into account explicitly!

At 5 BK full Nuclear Statistical equilibrium is attained

The abundances of the various nuclei are governed by a set of equations of this kind:

$$Y(n,z) = f(\rho,T) \cdot e^{\frac{-Q(n,z)}{KT}} \cdot Y_p^{z} \cdot Y_n^{n}$$

The system is closed by the conditions:

Mass conservation

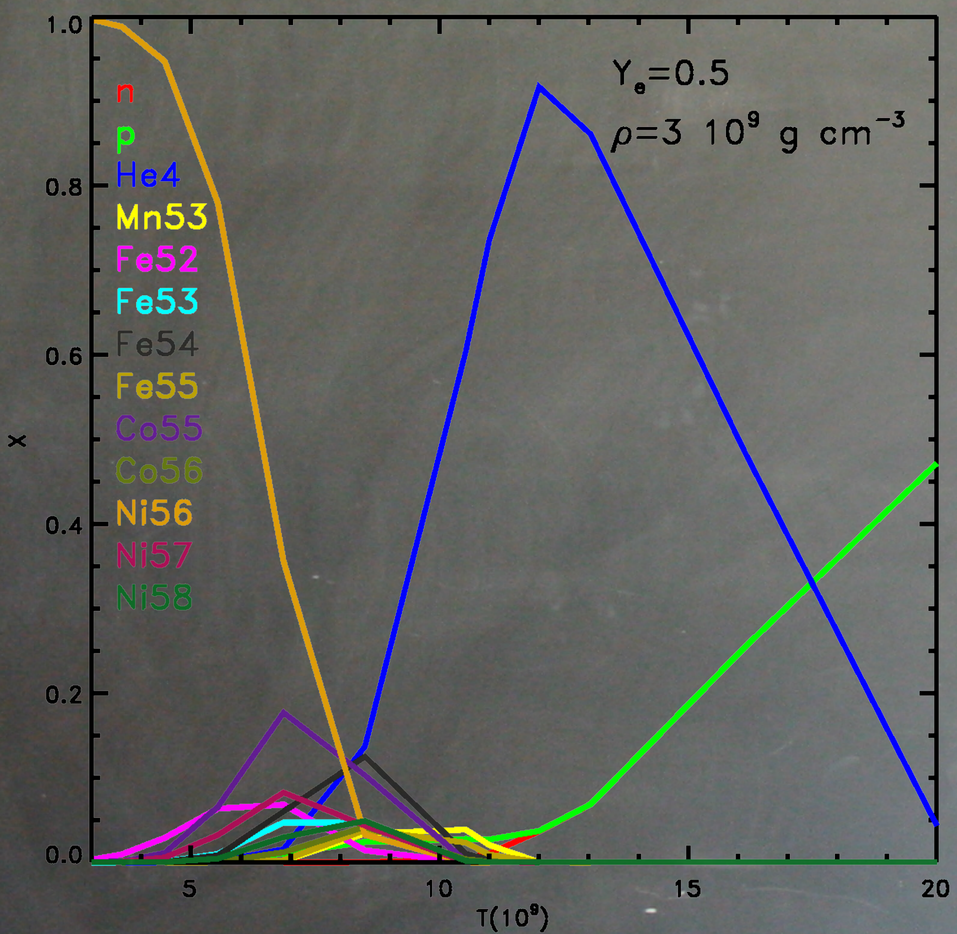
$$\frac{\sum Y_i \cdot A_i}{\sum Y_i} =$$

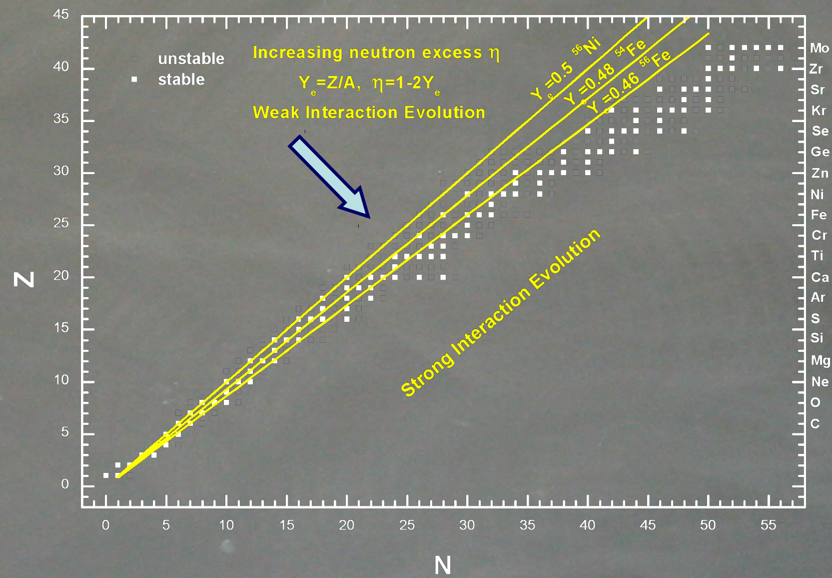
Electron mole number conservation

Ye = constant (at each time)

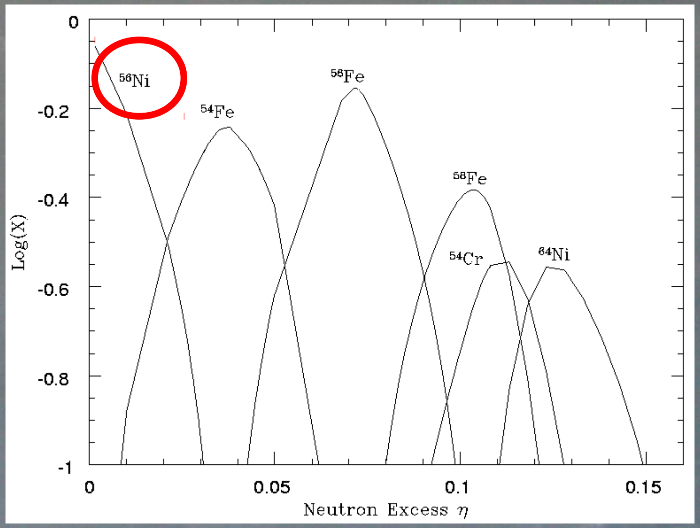
The abundances of all the nuclei depend only on ρ , T and Y_e

Most abundant elements in NSE conditions as a function of the temperature



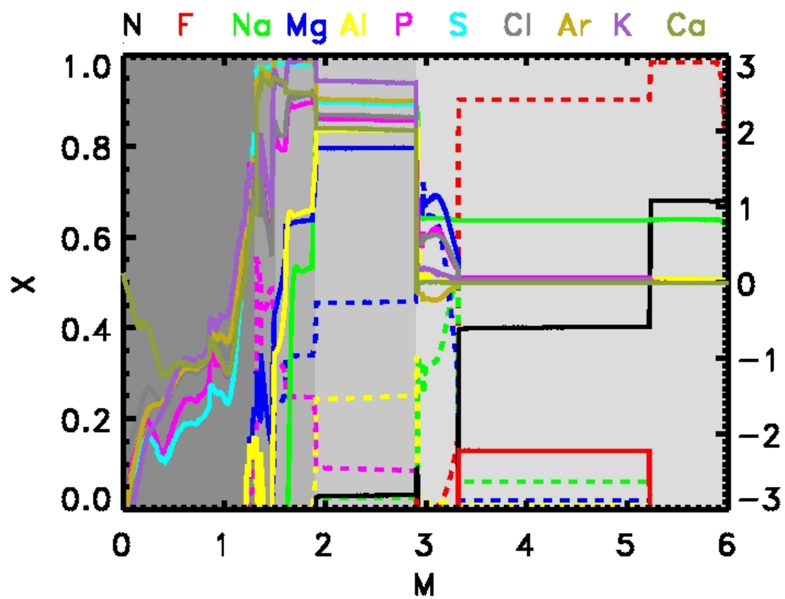


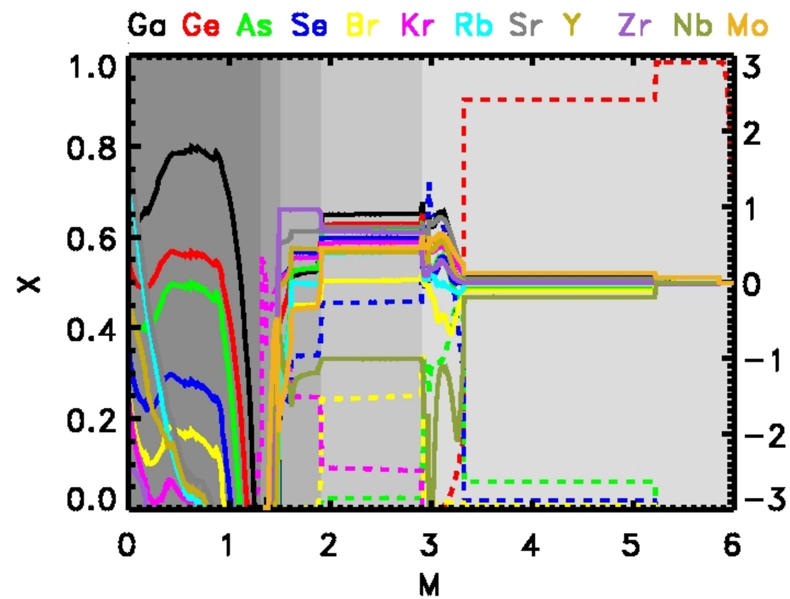
$T = 5\cdot10^9$ K $\rho = 10^8$ g/cm^3

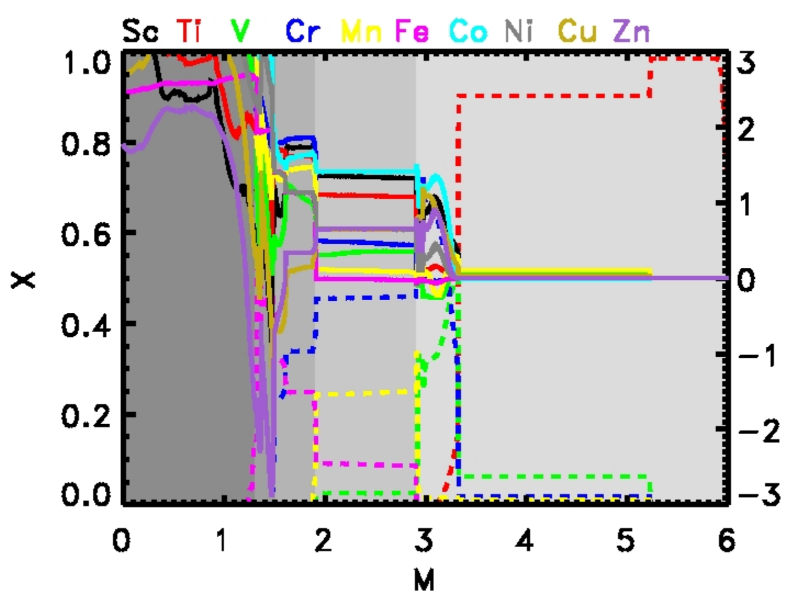


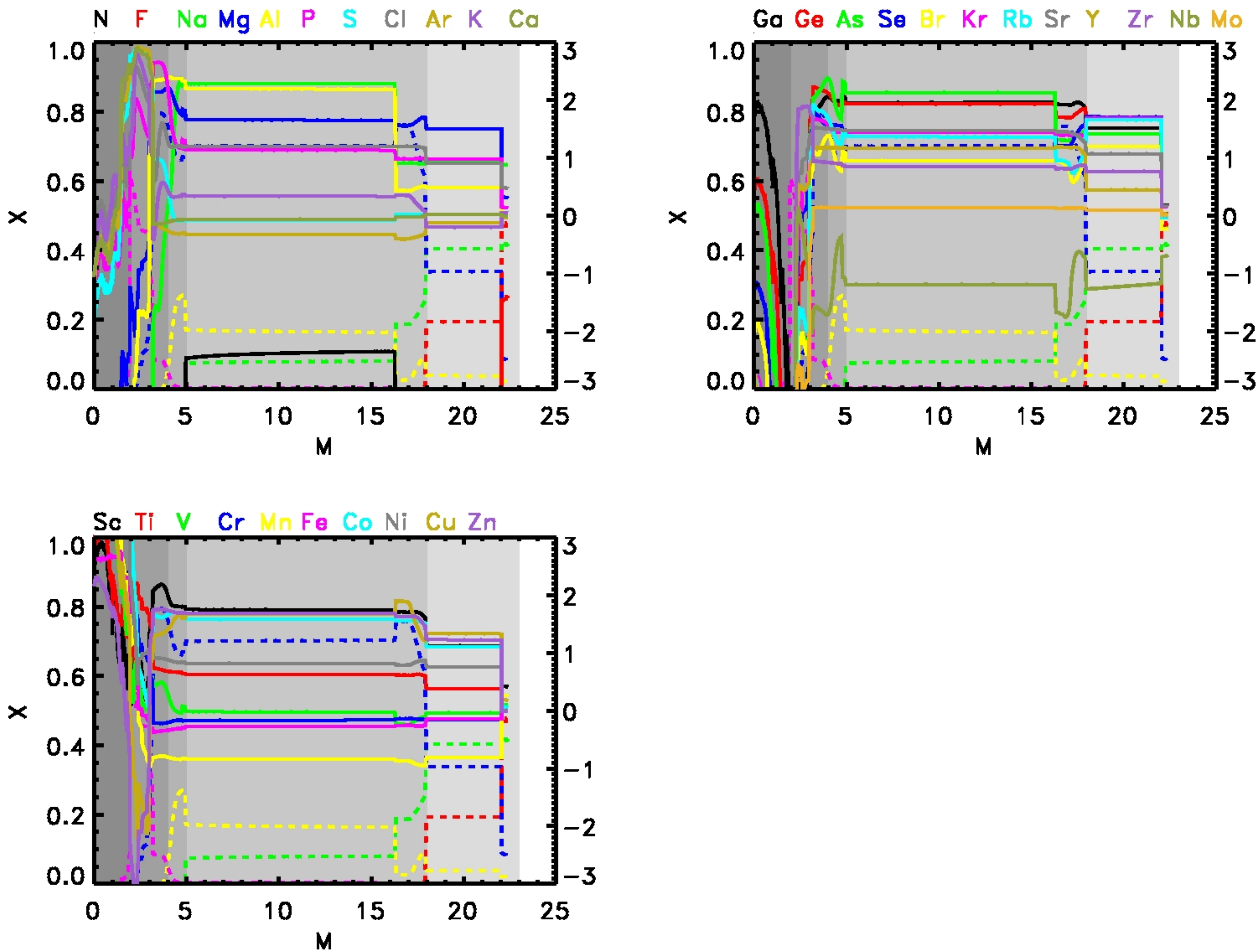
Trailer time!

O & Si burnings movie

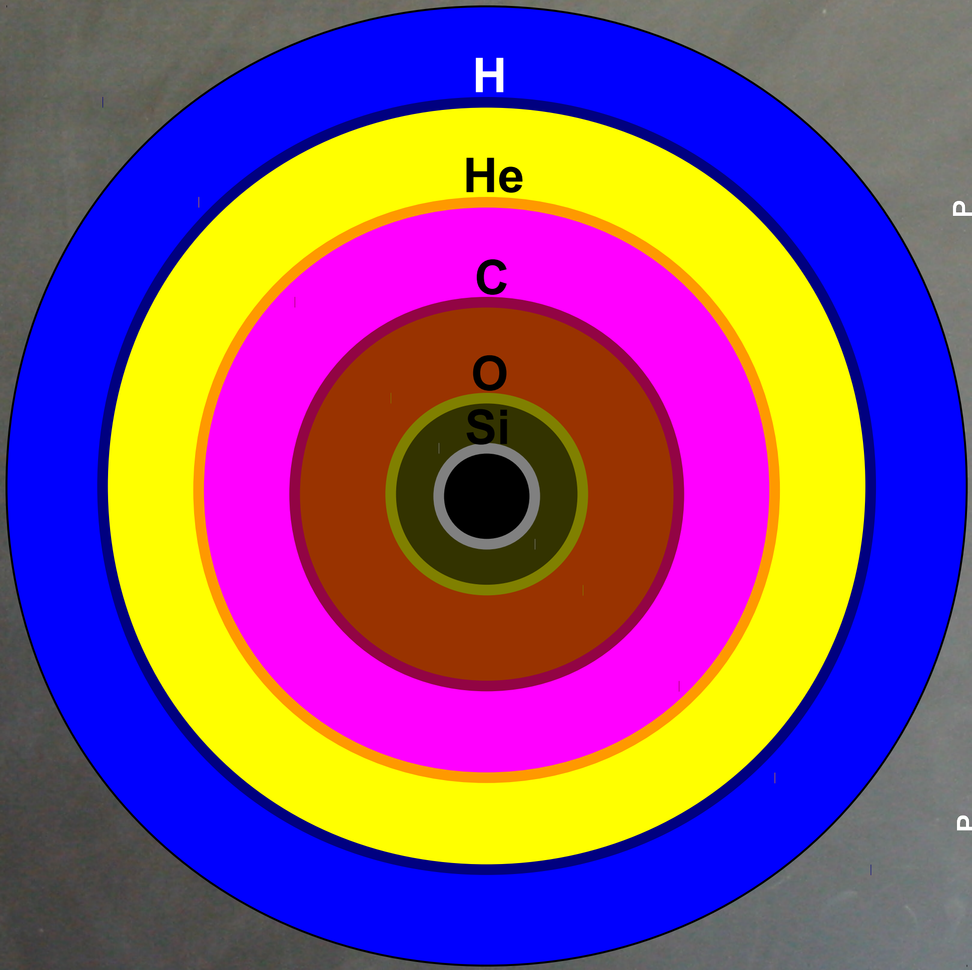

N F Na Mg Al P S Cl Ar K Ca
X
M
0 1 2 3 4 5 6
0.0 0.2 0.4 0.6 0.8 1.0
−3 −2 −1 0 1 2 3

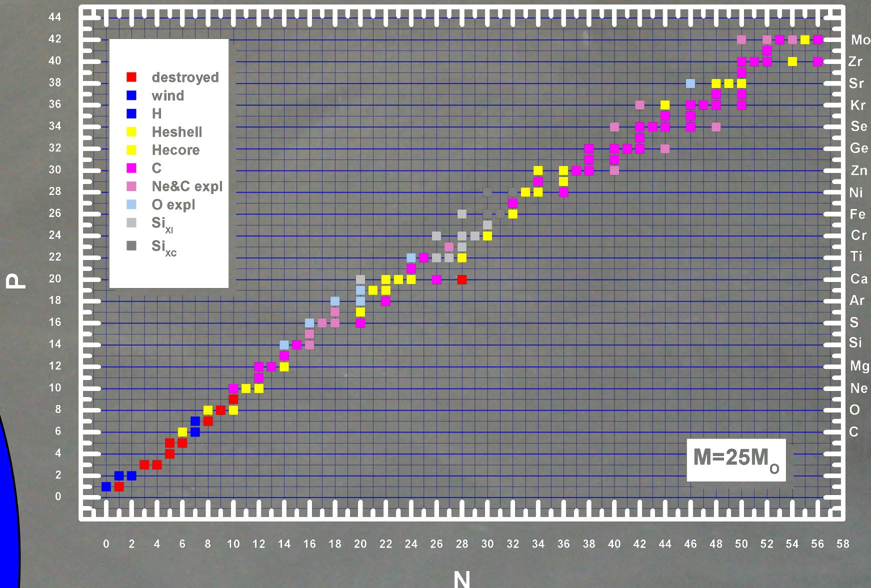

Ga Ge As Se Br Kr Rb Sr Y Zr Nb Mo
X
M
0 1 2 3 4 5 6
0.0 0.2 0.4 0.6 0.8 1.0
−3 −2 −1 0 1 2 3

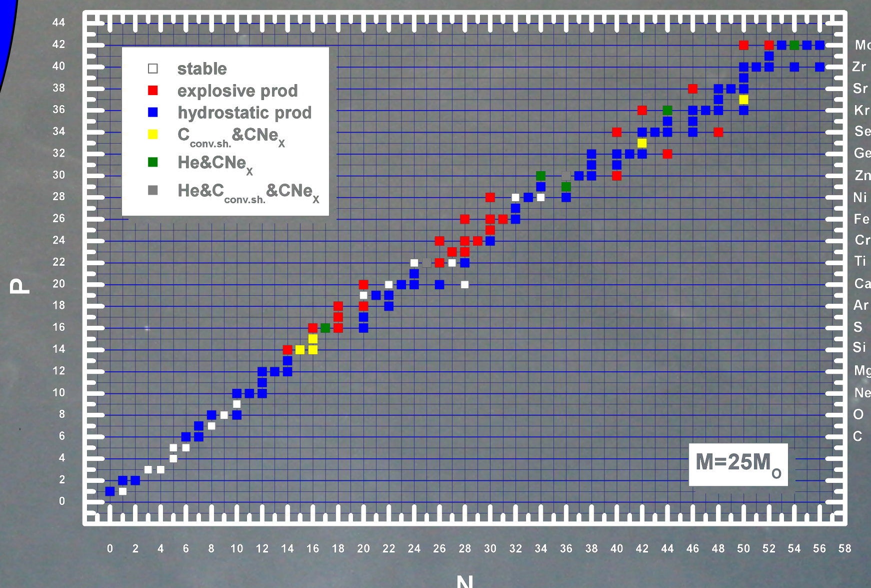

Sc Ti V Cr Mn Fe Co Ni Cu Zn
X
M
0 1 2 3 4 5 6
0.0 0.2 0.4 0.6 0.8 1.0
−3 −2 −1 0 1 2 3



N F Na Mg Al P S Cl Ar K Ca
Ga Ge As Se Br Kr Rb Sr Y Zr Nb Mo
Sc Ti V Cr Mn Fe Co Ni Cu Zn
X
M


H
He
C
O
Si


destroyed
wind
H
Heshell
Hecore
C
Ne&C expl
O expl
Si$_{xi}$
Si$_{xc}$
M=25M$_O$
P
N
Mo
Zr
Sr
Kr
Se
Ge
Zn
Ni
Fe
Cr
Ti
Ca
Ar
S
Si
Mg
Ne
O
C


stable
explosive prod
hydrostatic prod
C$_{conv.sh.}$&CNe$_x$
He&CNe$_x$
He&C$_{conv.sh.}$&CNe$_x$
M=25M$_O$
P
N
Mo
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Sr
Kr
Se
Ge
Zn
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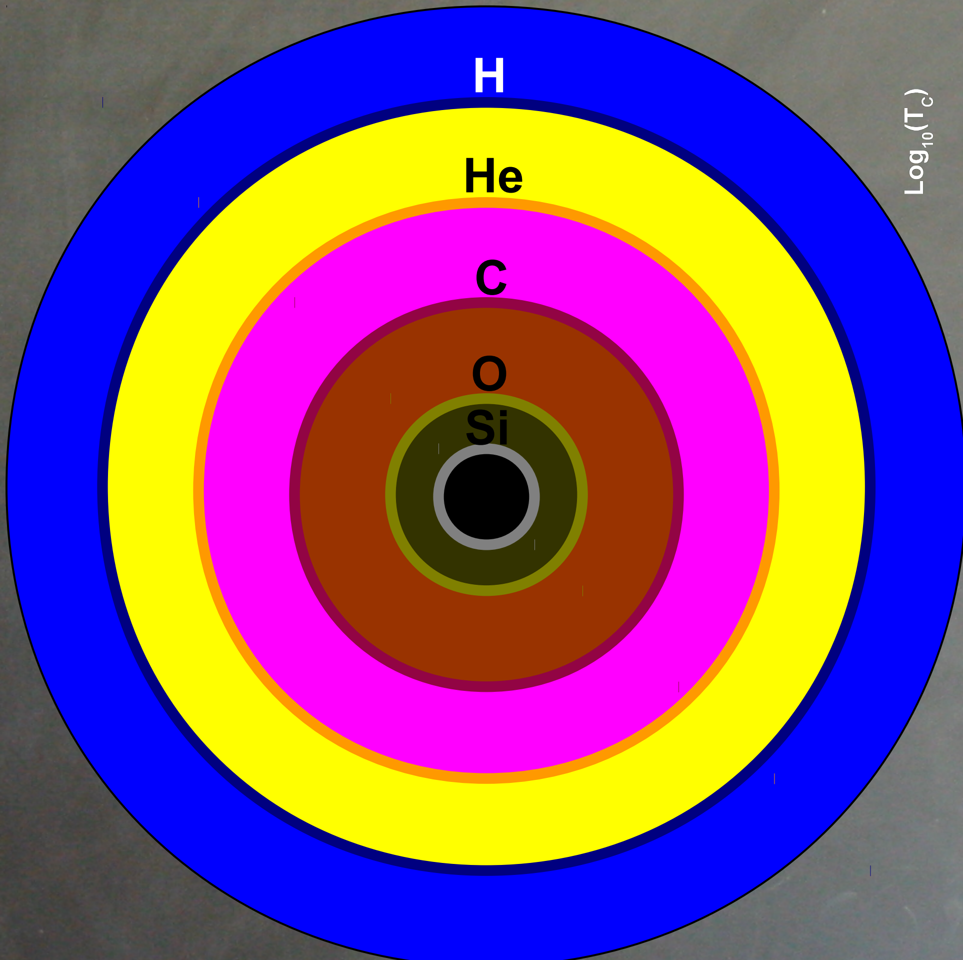
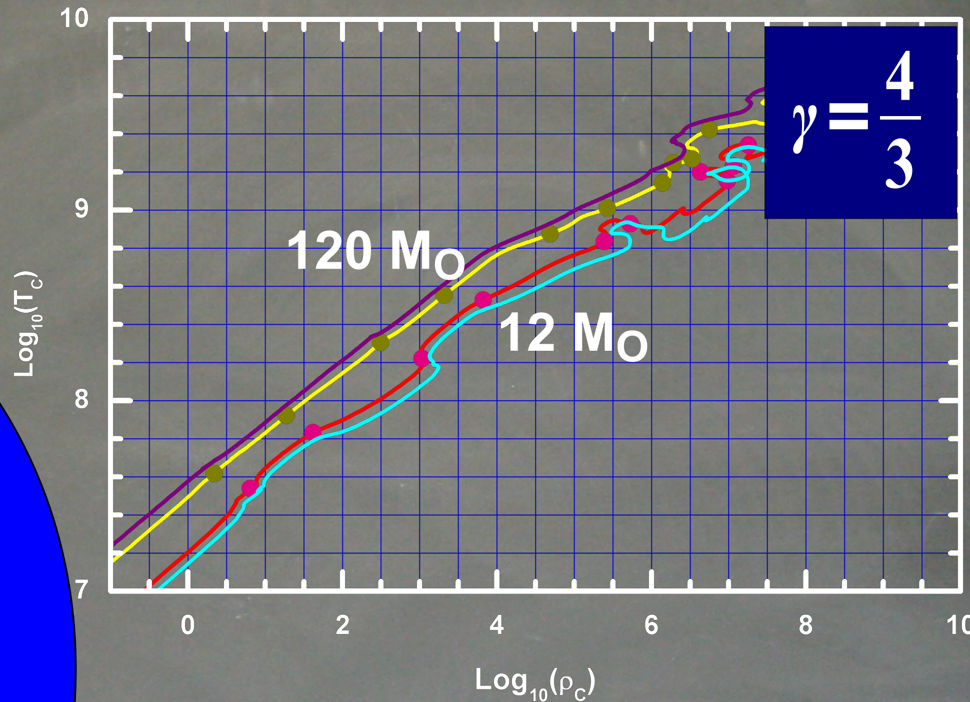
Fe
Cr
Ti
Ca
Ar
S
Si
Mg
Ne
O
C





$$\gamma = \frac{4}{3}$$

Virial theorem

$$3(\gamma-1)U+\Omega=0$$

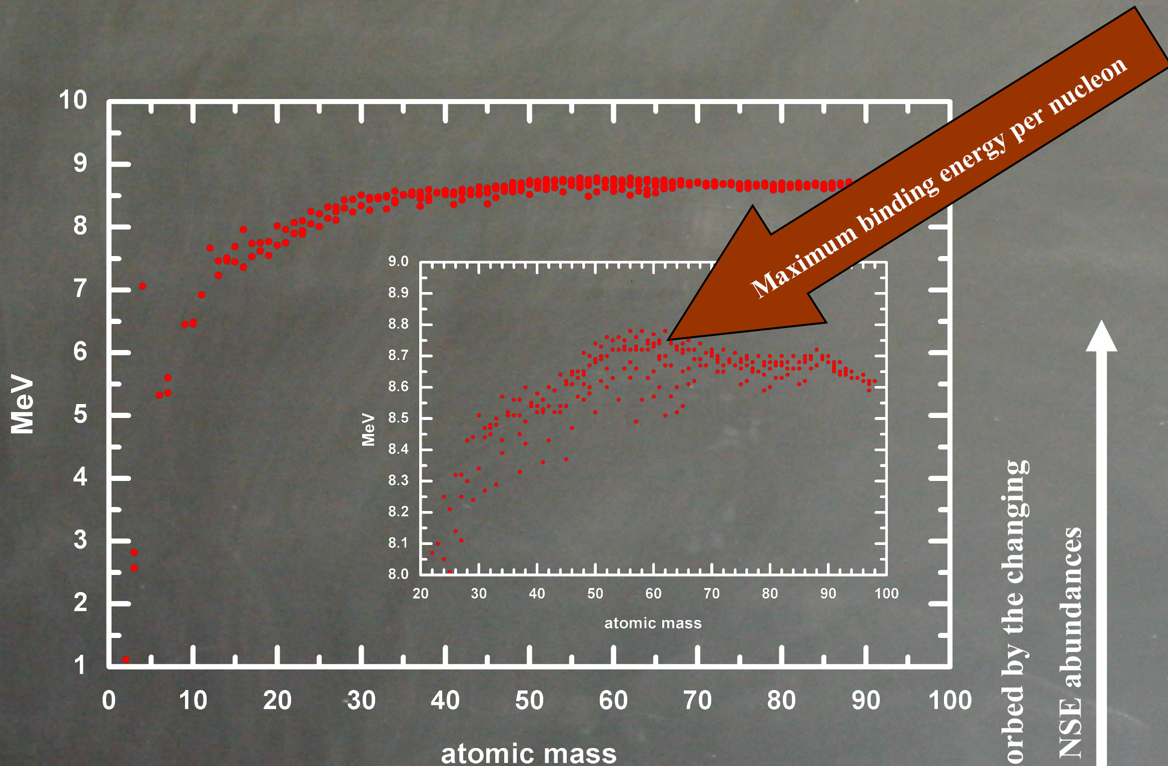
$$U+\Omega\equiv E_{TOT}=0$$

$$\Delta E_{TOT}\equiv$$

NO delay is required for a contraction,

the structure is only marginally stable

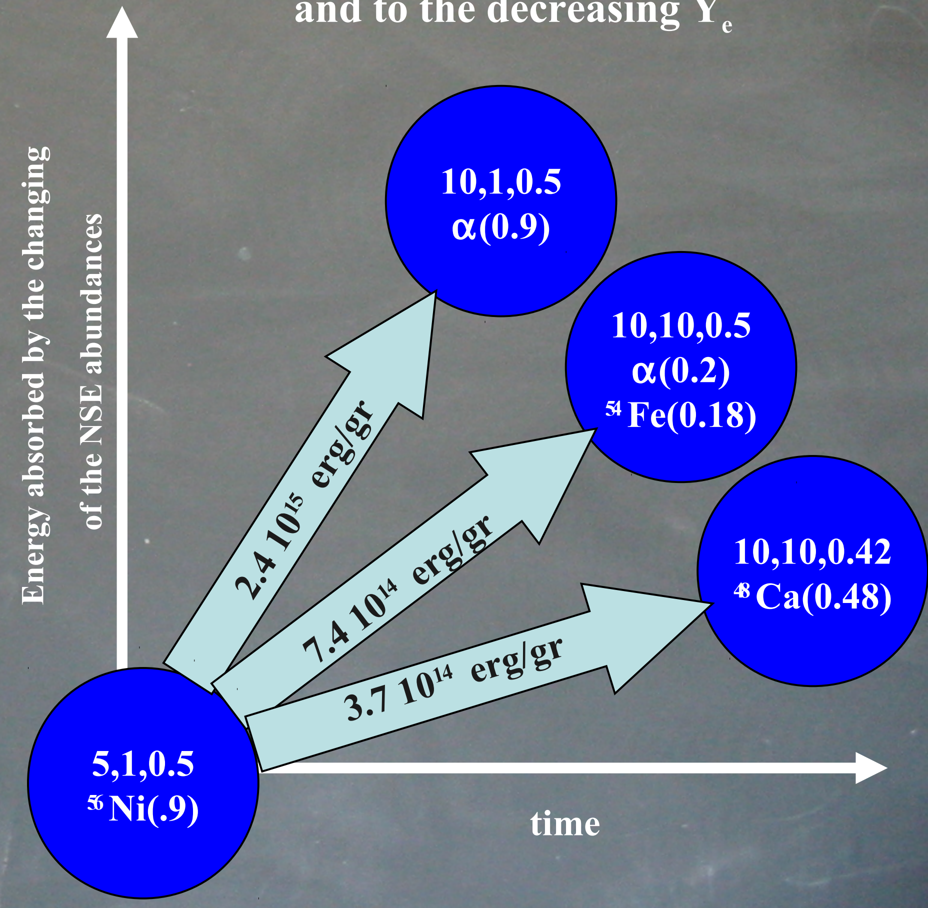
What happens to the inner core after the central Si burning?

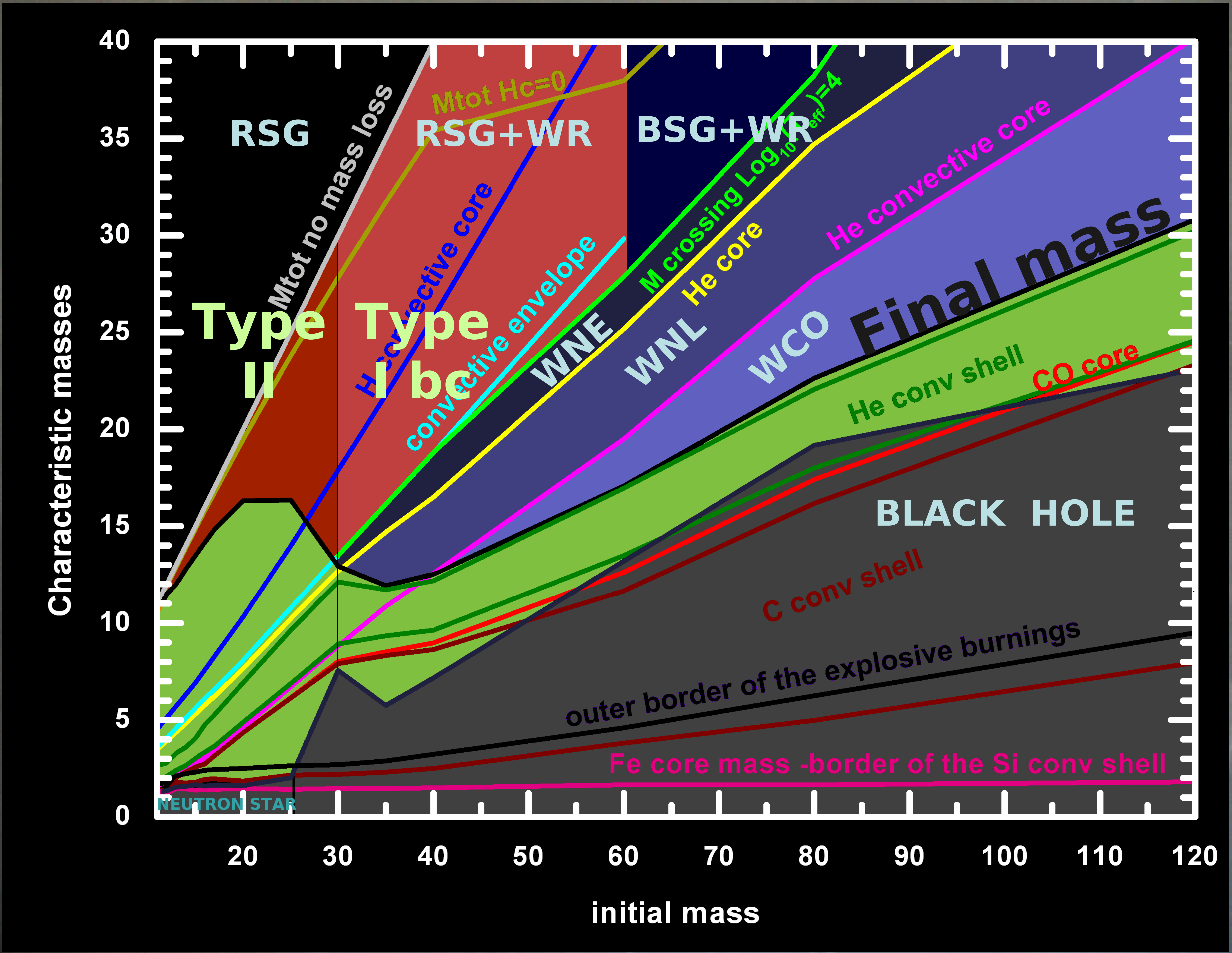


NSE abundances

readjust to the increasing T and ρ

and to the decreasing Y_e





Characteristic masses
initial mass
0
5
10
15
20
25
30
35
40
20
30
40
50
60
70
80
90
100
110
120
RSG
RSG+WR
BSG+WR
Mtot no mass loss
Mtot Hc=0
H convective core
convective envelope
M crossing Log10(Teff)=4
He core
He convective core
Type II
Type I bc
WNE
WNL
WCO
Final mass
He conv shell
CO core
C conv shell
outer border of the explosive burnings
Fe core mass -border of the Si conv shell
BLACK HOLE
NEUTRON STAR