WE-Heraeus Summer School
on Nuclear Astrophysics in the Cosmos

12-17 July 2010

Element production
stellar evolution
explosive nucleosynthesis

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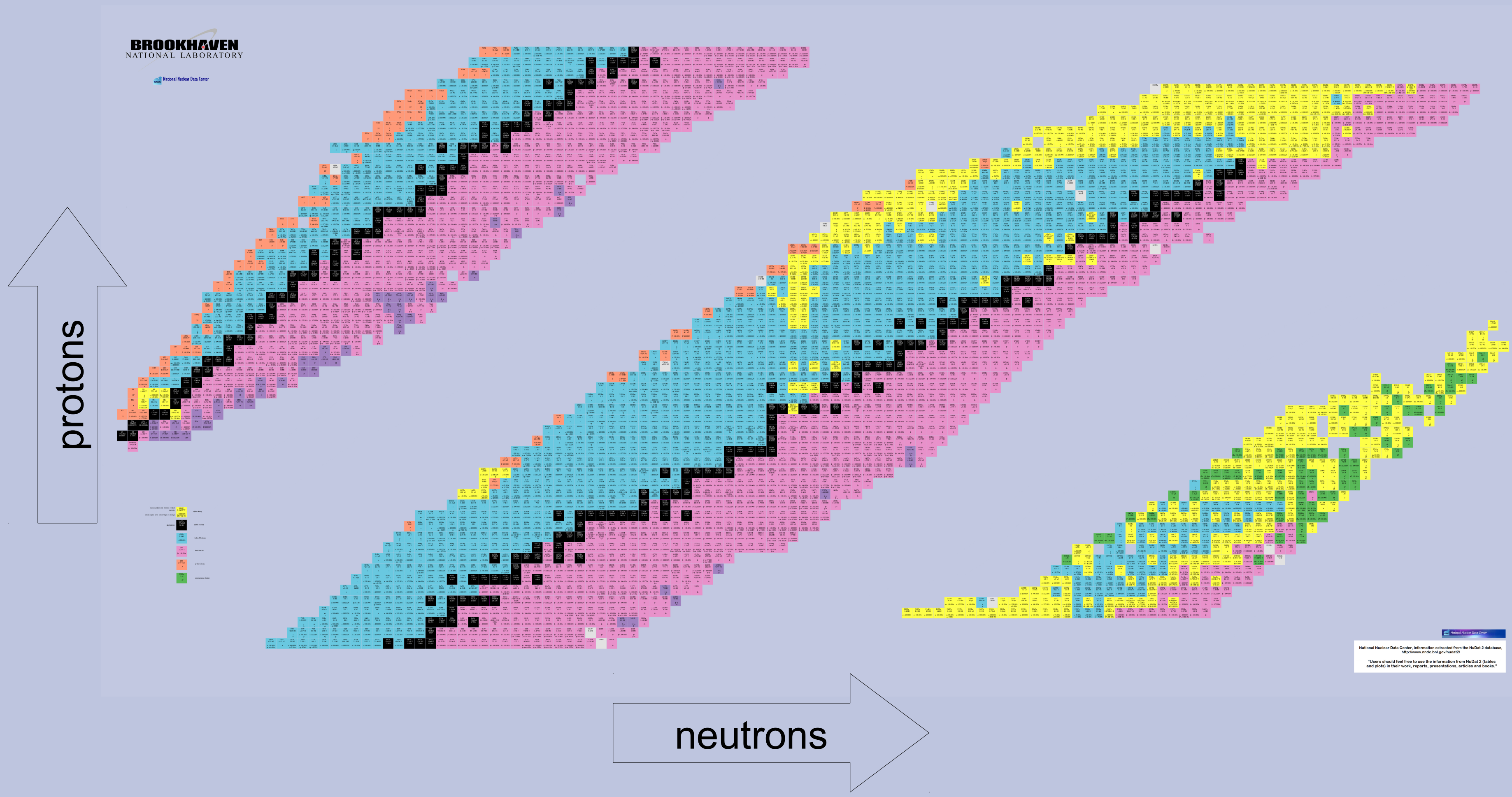
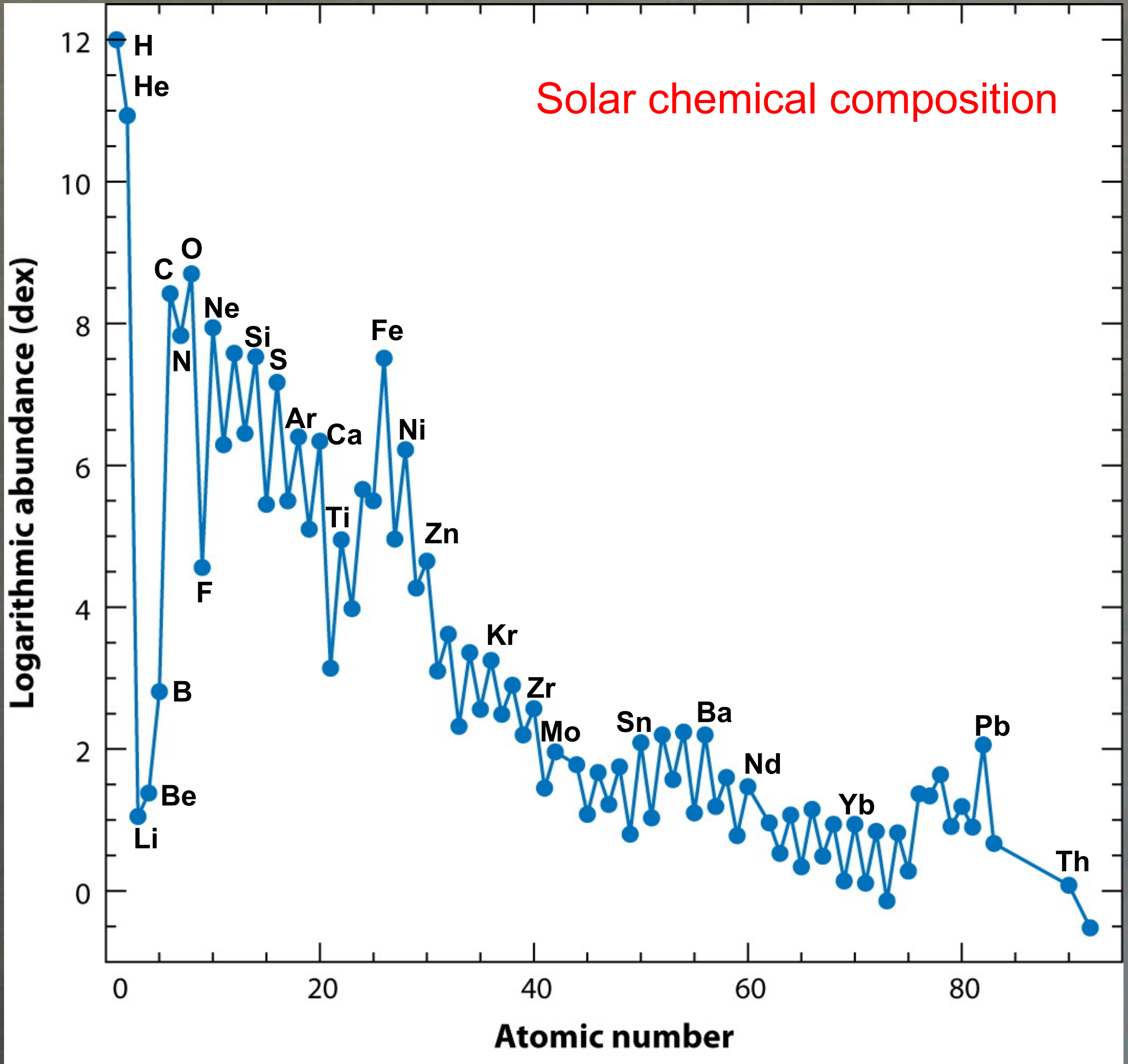
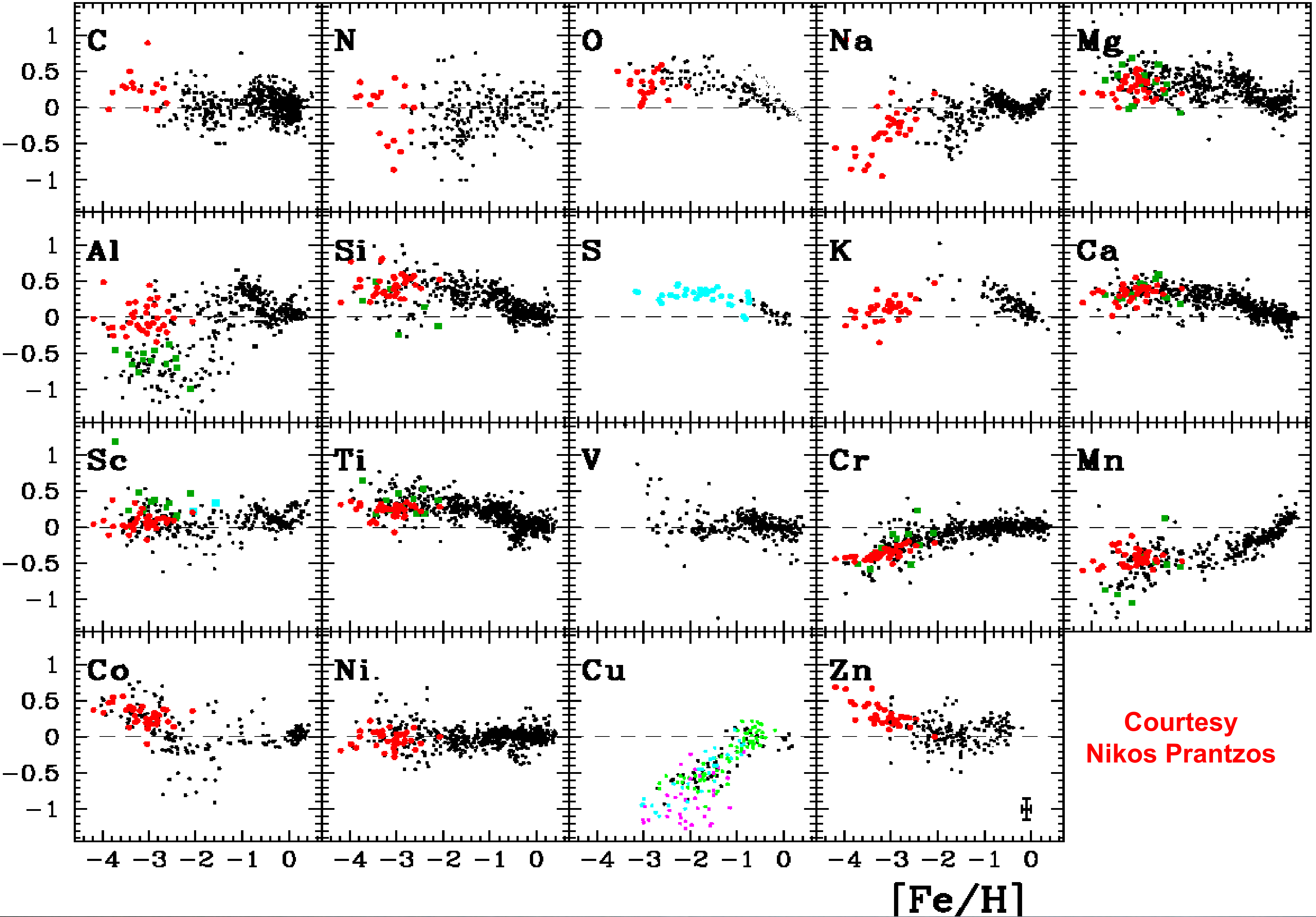




Asplund M, et al. 2009.

Annu. Rev. Astron. Astrophys. 47:481–522



Courtesy
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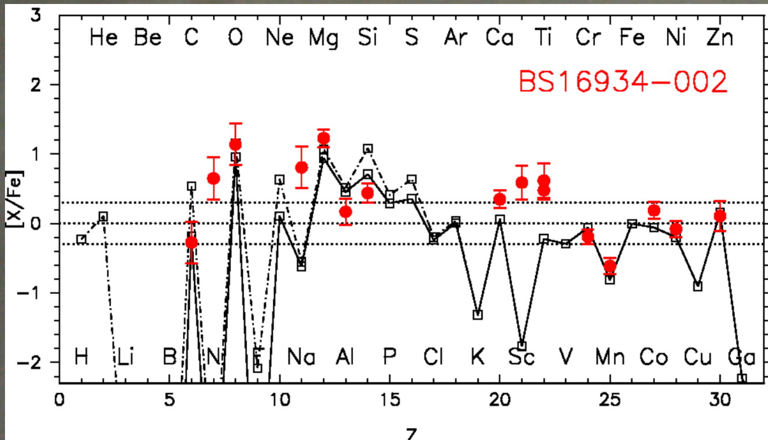
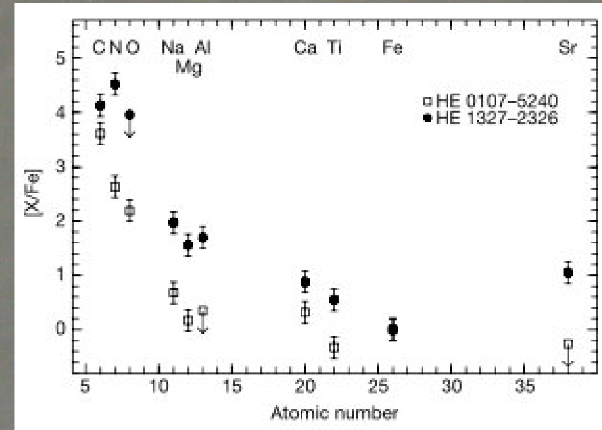
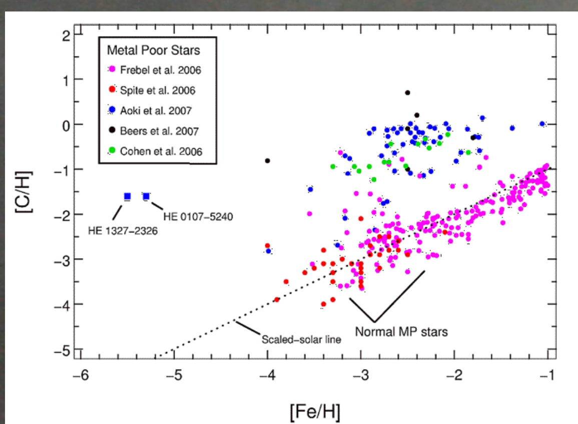
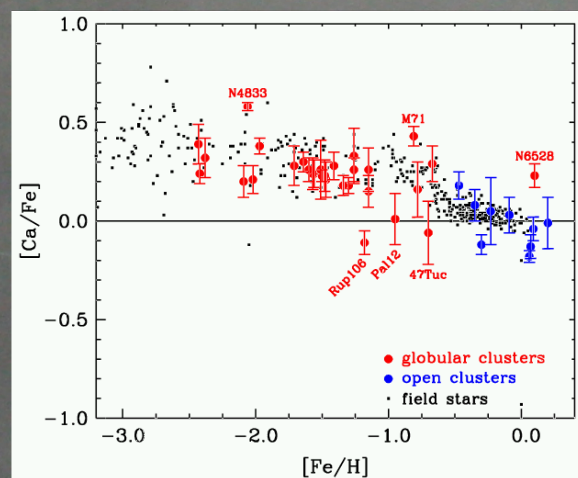


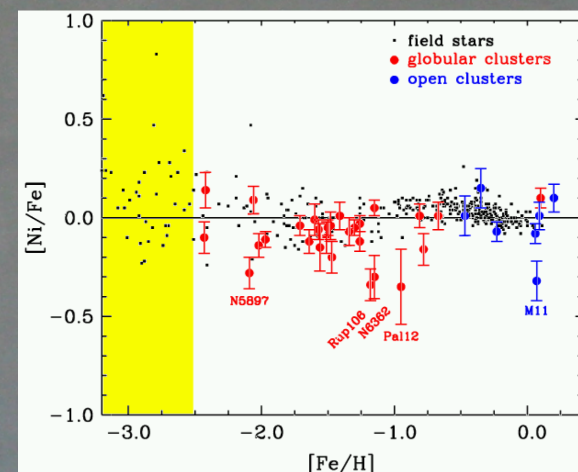
Aoki et al. 2007 ApJ 660,747



Frebel et al. 2005 Nature 434,871







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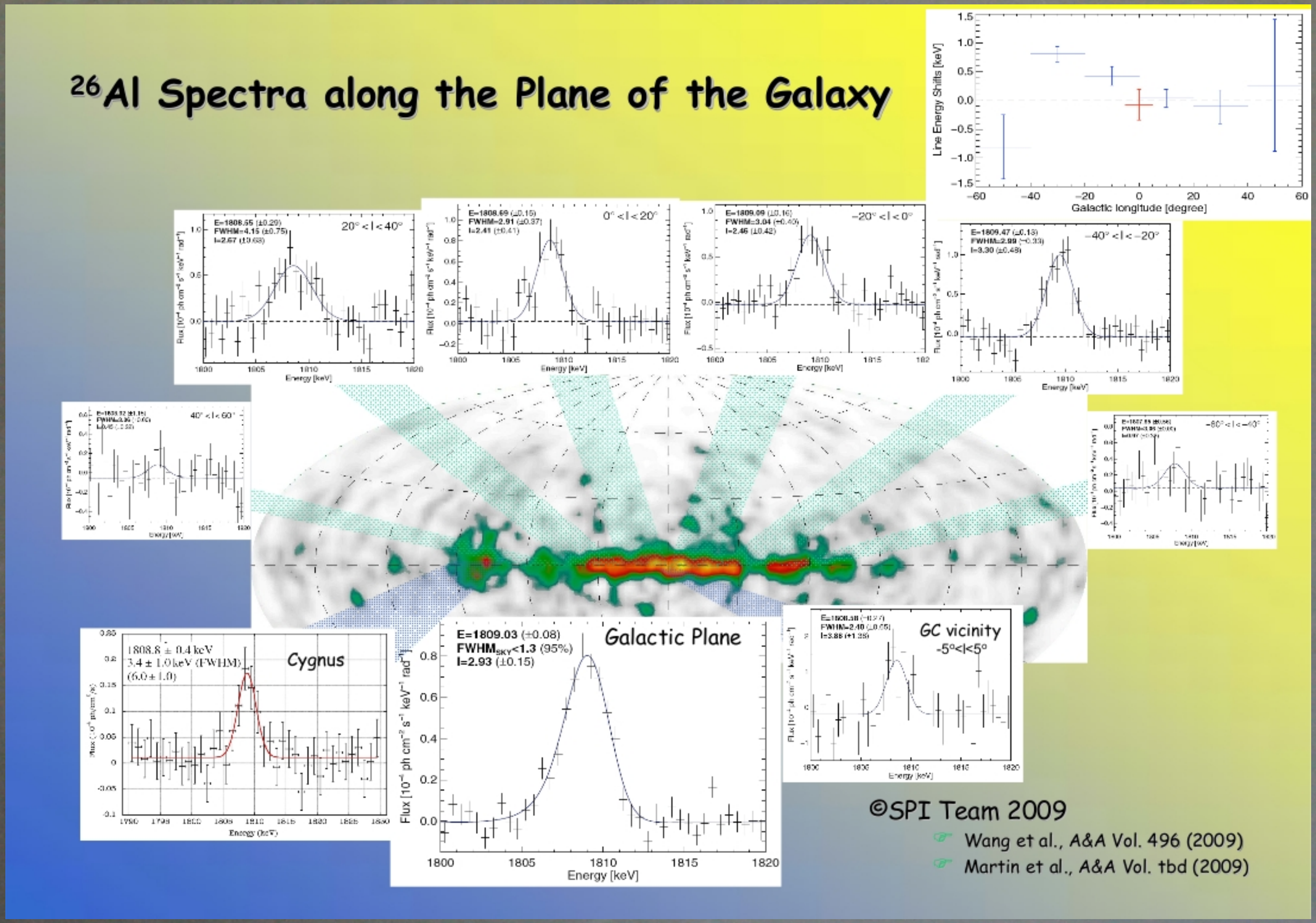
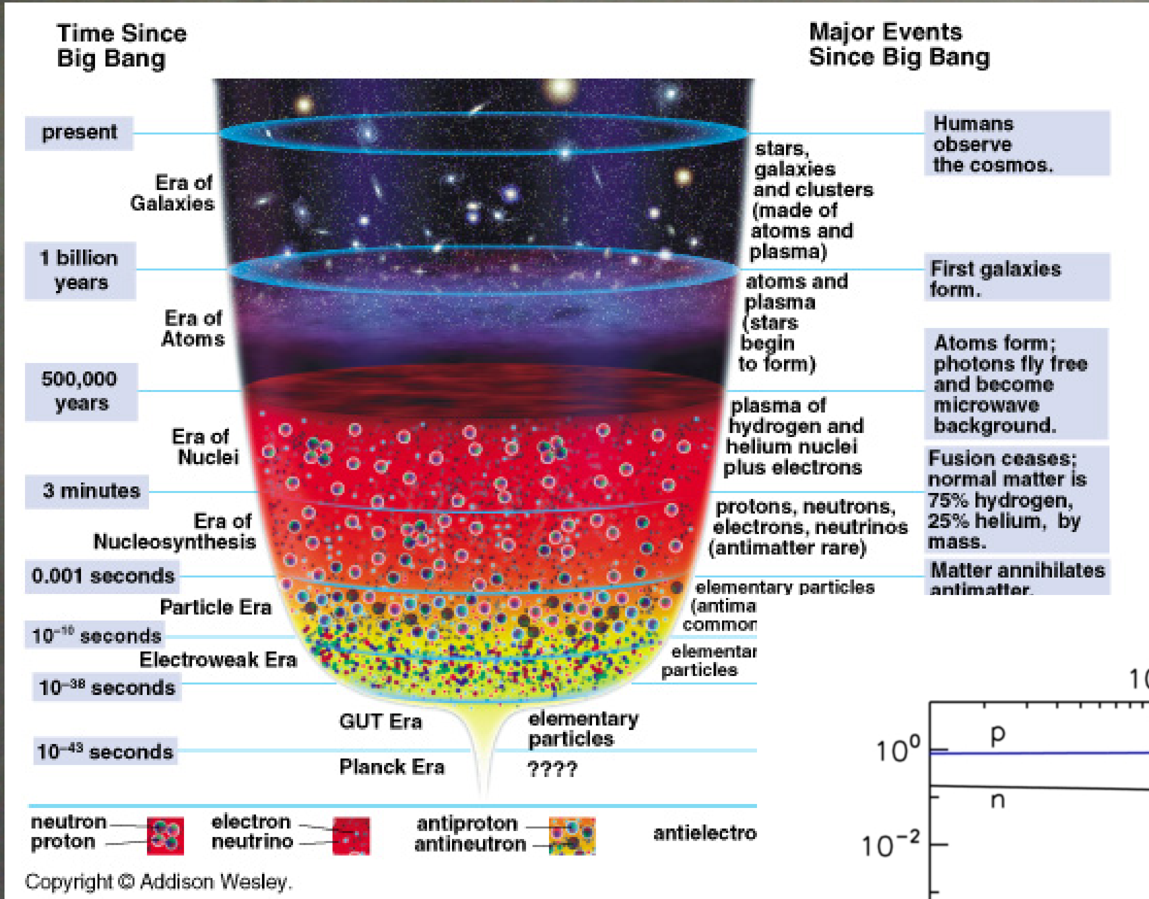


+

^{60}Fe ^{44}Ti ^{56}Ni


Time Since Big Bang
Major Events Since Big Bang
present
Era of Galaxies
1 billion years
Era of Atoms
500,000 years
Era of Nuclei
3 minutes
Era of Nucleosynthesis
0.001 seconds
Particle Era
10^-10 seconds
Electroweak Era
10^-38 seconds
GUT Era
10^-43 seconds
Planck Era
stars, galaxies and clusters (made of atoms and plasma)
atoms and plasma (stars begin to form)
plasma of hydrogen and helium nuclei plus electrons
protons, neutrons, electrons, neutrinos (antimatter rare)
elementary particles
elementary particles
????
Humans observe the cosmos.
First galaxies form.
Atoms form; photons fly free and become microwave background.
Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
neutron
proton
electron
neutrino
antiproton
antineutron
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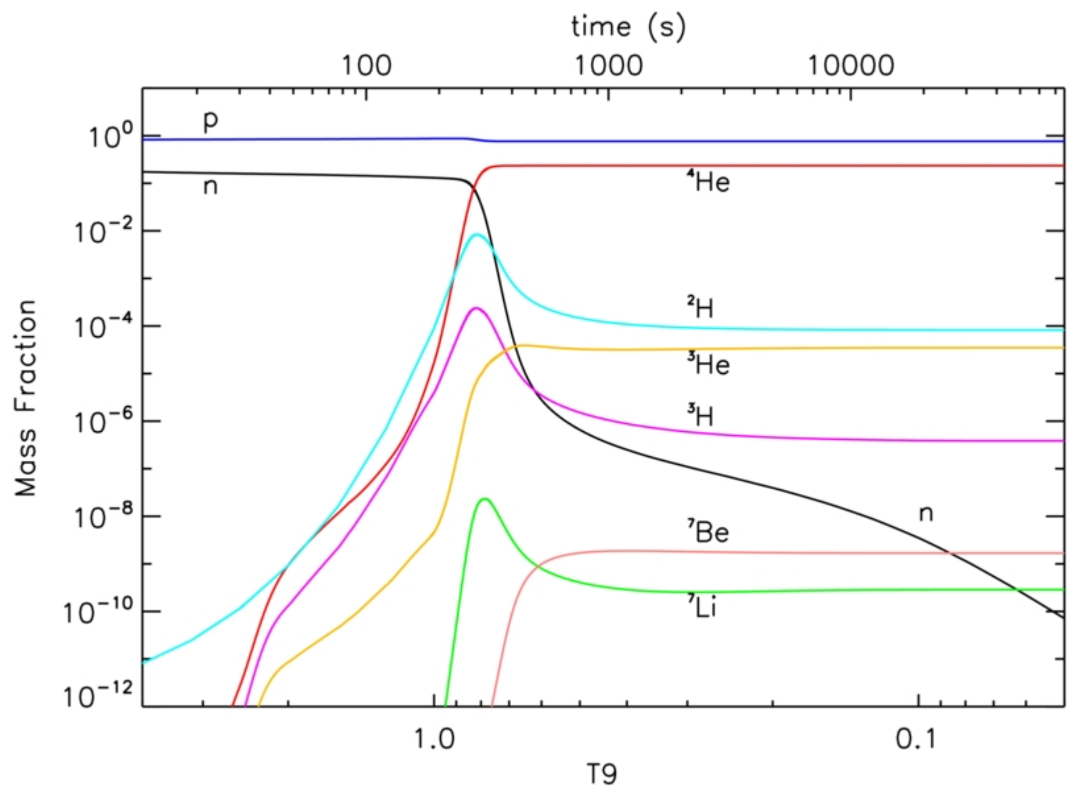
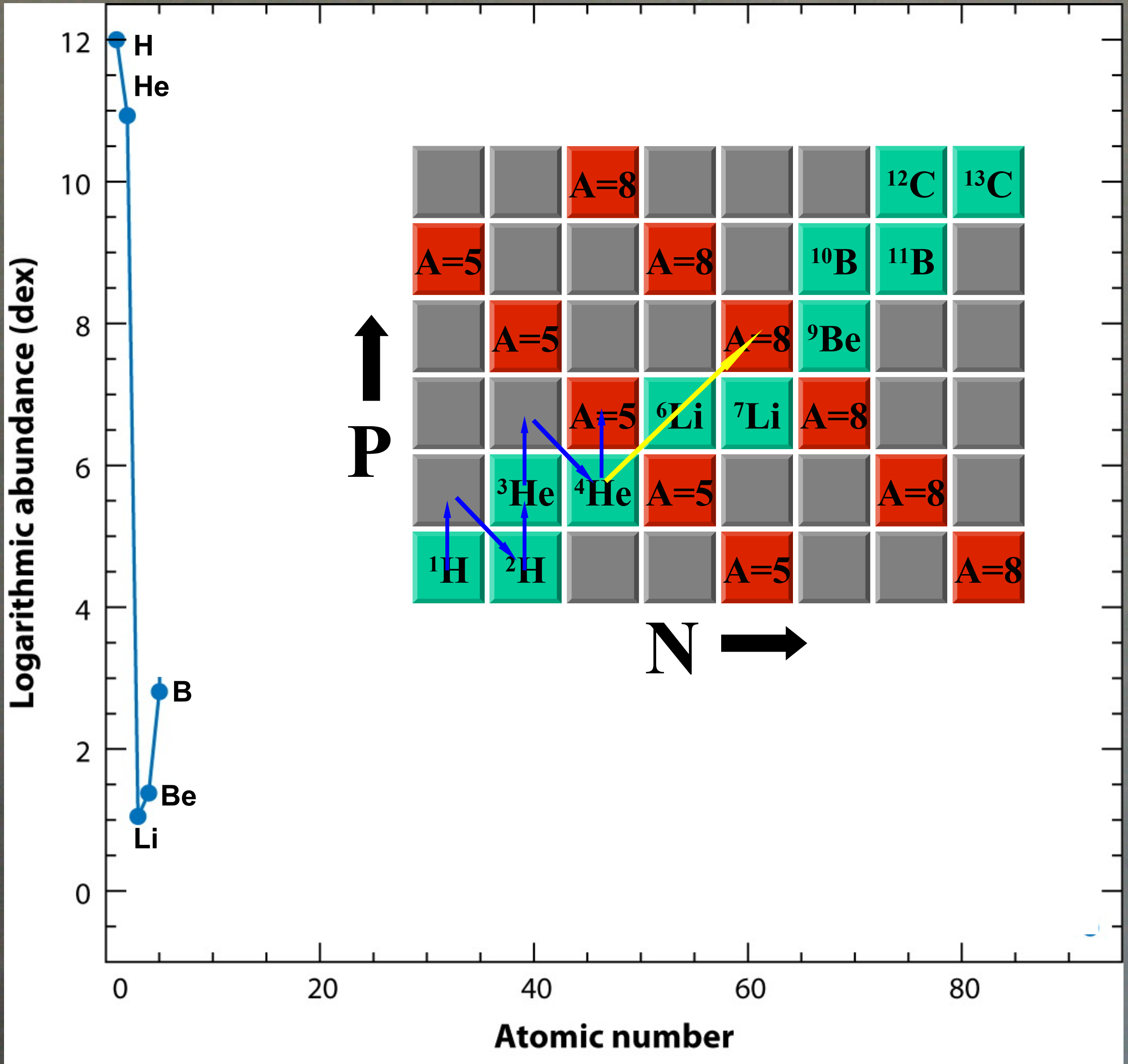

time (s)
100
1000
10000
Mass Fraction
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
p
n
^{4}He
^{2}H
^{3}He
^{3}H
n
^{7}Be
^{7}Li
1.0
0.1
T9



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Evidence

The **Coulomb barrier** prevents an easy fusion between charged particles: only a combination of **high temperatures**, **high densities** and **long timescales** may lead to a substantial amount of fusion.

Even the fusion of the lightest nuclei, protons, requires

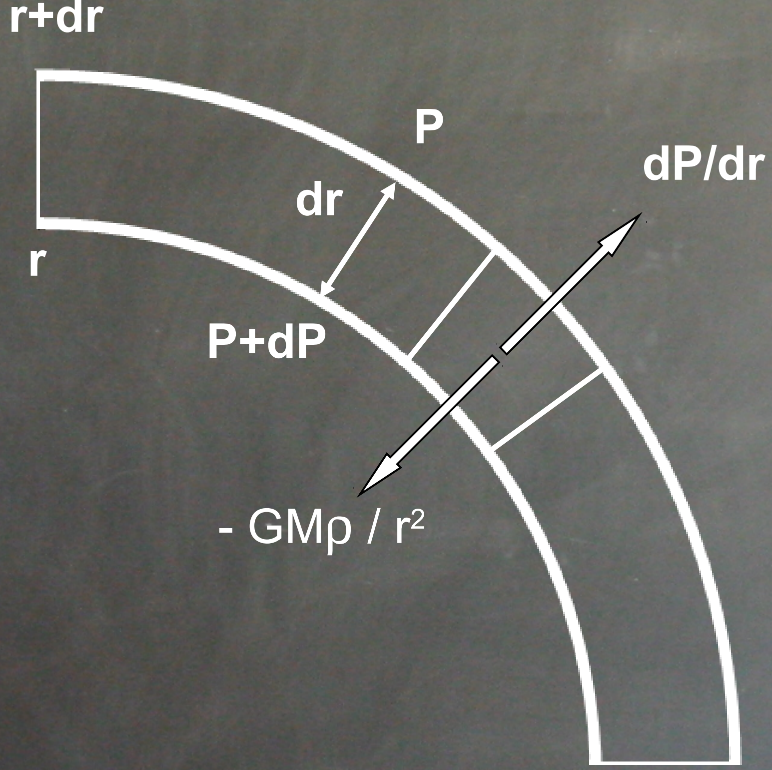
$T >$ several 10^6 K
$\rho >$ several grams / cm^3

to burn a significant amount of nuclei on a timescale shorter than the age of the Universe

These conditions are met only in stars

A star is formed by a gas cloud that contracts under its own gravity and whose luminosity is produced in its interior

In many cases the contraction occurs on "long" timescales because matter naturally settles on a quasi equilibrium configuration in which the various forces acting on each element of matter tend to counterbalance each other:



Hydrostatic equilibrium:

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

Equation of continuity:

Mass conservation:

$$\frac{dM}{dr} = 4\pi r^2 \rho$$

$$\frac{dP}{dr} = -\frac{Gm\,\rho}{r^2}$$

Hydrostatic equilibrium

$$\int_0^M \frac{dP}{dr}\frac{r}{\rho}\,dm = -\int_0^M \frac{Gm}{r}\,dm$$

$$-\int_0^M \frac{Gm}{r}\,dm = \Omega$$

Gravitational potential energy

Ω may be regarded as the total amount of gravitational energy liberated in the contraction from "infinity" to the present configuration.

$$\int_0^M \frac{dP}{dr}\frac{r}{\rho}\,dm = \int_0^M \frac{dP}{dm}\frac{dm}{dr}\frac{r}{\rho}\,dm = \int_0^M \frac{dP}{dm}4\pi r^2 \rho \frac{r}{\rho}\,dm = \int_0^M \frac{dP}{dm}4\pi r^3\,dm$$

This can be integrated by parts

$$\left(P\,4\pi r^3\right)_0^M - \int_0^M P\,4\pi \frac{dr^3}{dm}\,dm = -\int_0^M P\,4\pi\,3r^2\frac{dr}{dm}\,dm = -\int_0^M P\frac{3}{\rho}\,dm$$

$$\frac{dP}{dr} = -\frac{Gm\,\rho}{r^2}$$ ⬅ **Hydrostatic equilibrium**

$$\int_0^M \frac{dP}{dr}\frac{r}{\rho}\,dm = -\int_0^M \frac{Gm}{r}\,dm$$

$$-\int_0^M 3\frac{P}{\rho}\,dm = -\int_0^M \frac{Gm}{r}\,dm = \Omega$$

Gravitational potential energy

Ω may be regarded as the total amount of gravitational energy liberated in the contraction from "infinity" to the present configuration.

At this point we need an equation of state, i.e. a relation between pressure and density

Let us firstly consider a perfect gas; in this case we can write:

$$\left.\begin{array}{l} E = \frac{3}{2}NKT \\ P = NKT \end{array}\right\} P = \frac{2}{3}E \;\Rightarrow\; \frac{P}{\rho} = \frac{2}{3}u$$

Where *u* represents the energy per unit mass

Virial Theorem (perfect gas)

$$-\int_0^M 3\frac{2}{3}u\,dm = \Omega \;\Rightarrow\; -2\int_0^M u\,dm = \Omega \;\Rightarrow\; -2E_i = \Omega$$

$= E_i$ <= *total internal energy*

Virial theorem (perfect gas)

$$2E_i + \Omega = 0$$

What does it mean?

$$\Delta E_i = -\frac{1}{2}\Delta\Omega$$

$\Delta\Omega$ is negative! hence a contraction implies necessarily an increase of the internal energy E_i. However only 50% of the energy gained by the gravitational field remains locked in the star, the other 50% must be lost!

The requirement that some energy must be lost in a contraction introduces the idea that the contraction requires some finite timescale to occur, it cannot occur instantaneously. Since energy is basically lost through photons from the surface, this timescale is dictated by the efficiency of the outward photon flux. In other words no additional contraction may occur until the energy losses required by the virial theorem have been effectively lost!

What about the total energy of the system?

$$E_{TOT} = E_i + \Omega \qquad E_{TOT} = -\frac{1}{2}\Omega + \Omega \qquad E_{TOT} = \frac{1}{2}\Omega \qquad \Delta E_{TOT} = \frac{1}{2}\Delta\Omega$$

Once again, Ω is negative! Hence a contraction ($\Delta\Omega<0$) implies a reduction of the total energy.

The system is more bound!

$$\frac{dP}{dr} = -\frac{Gm\rho}{r^2}$$ ⬅ **Hydrostatic equilibrium**

$$\int_0^M \frac{dP}{dr}\frac{r}{\rho}\,dm = -\int_0^M \frac{Gm}{r}\,dm$$

$$-\int_0^M 3\frac{P}{\rho}\,dm = -\int_0^M \frac{Gm}{r}\,dm = \Omega$$

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$$-\int_0^M 3\frac{2}{3}u\,dm = \Omega \;\Rightarrow\; -2\int_0^M u\,dm = \Omega \;\Rightarrow\; -2E_i = \Omega$$

$\int_0^M u\,dm = E_i$ <= *total internal energy*

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

Hydrostatic equilibrium

$$-\int_0^M 3\frac{P}{\rho}\,dm = -\int_0^M \frac{Gm}{r}\,dm = \Omega$$

Gravitational potential energy

Ω may be regarded as the total amount of gravitational energy liberated in the contraction from "infinity" to the present configuration.

Generalized Virial Theorem

$$-\int_0^M 3(\gamma-1)U\,dm = \Omega \qquad 3(\gamma-1)E_i + \Omega = 0$$

$$\gamma = \frac{4}{3}$$ **is very "special" because in this case** $$E_i + \Omega = 0 \qquad \Delta E_i = -\Delta\Omega$$

All the energy gained by the gravitational field is stored in the star (as internal energy) and no energy is lost outward.

$$\Delta E_{TOT} = \Delta E_i + \Delta\Omega = -\Delta\Omega + \Delta\Omega = 0$$

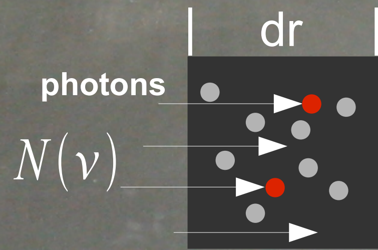
For γ=4/3 a contraction does not increase the binding energy but leaves E_{TOT} constant!

Since the contraction does not require the ejection of any energy no "delay" is necessary for a further contraction to occur. This is an unstable situation that leads to the collapse of the structure

The second basic equation necessary to describe a stellar structure is the one that controls the energy transport through the star.

Let us firstly assume that the energy is transported by radiation only:

The momentum (*dq*) transferred by a flux N of photons of frequency ν per unit time is given by:



λ mean free path

$$\lambda = \frac{1}{\kappa \rho}$$

Opacity coefficient

Mean number of interactions

$$dq = N(\nu)\frac{h\nu}{c}\frac{dr}{\lambda}dS\,dt = \frac{L\kappa\rho}{4\pi R^2 c}dr\,dS\,dt$$

Momentum per photon

But, the momentum transferred may be also expressed as the variation of the radiation pressure:

$$dq = -dP_r\,dS\,dt = -\frac{1}{3}a\,dT^4\,dS\,dt = -\frac{4}{3}a\,T^3\,dT\,dS\,dt$$

By equating the two:

$$\frac{4}{3}aT^3\frac{dT}{dr} = -\frac{L\kappa\rho}{4\pi R^2 c} \quad \Longrightarrow \quad \frac{dT}{dr} = -\frac{3}{16\pi a c}\frac{\kappa\rho L}{R^2 T^3}$$

2nd basic equation

Associated continuity equation:

$$\frac{dL}{dM} = \epsilon = \epsilon_{nuc} + \epsilon_{grav} - \epsilon_{\nu}$$

SUMMARIZING

The set of equations that describe the structure of a star is given by:

$$\frac{dP}{dr} = -\frac{Gm\rho}{r^2}$$ **Hydrostatic equilibrium**

$$\frac{dM}{dr} = 4\pi r^2 \rho$$ **Mass conservation**

$$\frac{dT}{dr} = -\frac{3}{16ac\pi}\frac{\kappa\rho L}{r^2 T^3}$$ **Energy transport (radiative case)**

$$\frac{dL}{dr} = 4\pi r^2 \rho \epsilon$$ **Energy conservation**

\+ Equation Of State, i.e. P (ρ, T, c.c.)
Opacity coefficient, i.e. κ (ρ, T, c.c.)
Energy generation coefficient, i.e. ε (ρ, T, c.c.)

The solution of this system of equations is very difficult and requires COMPUTERS!

but...

...we can try to be clever!

$$\frac{dP}{dr} = -\frac{Gm\rho}{r^2} \Rightarrow \frac{P}{R} \propto \frac{M\rho}{R^2} \Rightarrow P \propto \frac{M\rho}{R}$$

$$\frac{dM}{dr} = 4\pi r^2 \rho \Rightarrow \frac{M}{R} \propto R^2 \rho \Rightarrow R \propto \left(\frac{M}{\rho}\right)^{\frac{1}{3}}$$

$$\Rightarrow P \propto M^{\frac{2}{3}} \rho^{\frac{4}{3}}$$

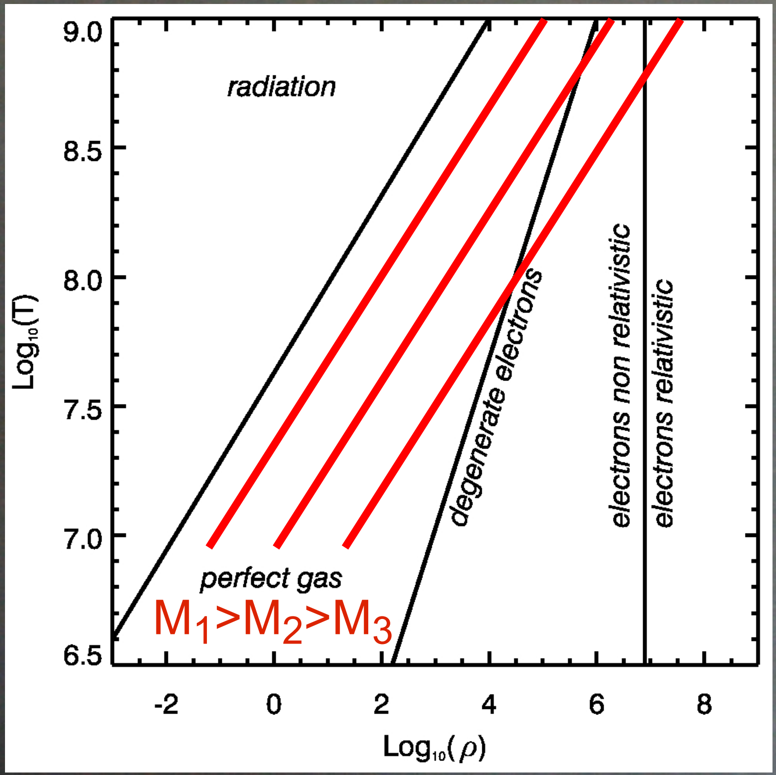
Perfect gas

$$P \propto \rho T \qquad \frac{T^3}{\rho} \propto M^2$$

Pure radiation

$$P \propto T^4 \qquad \frac{T^3}{\rho} \propto M^{0.5}$$

$$\log(T) = K(M) + \frac{1}{3}\log(\rho)$$



Interesting!

Just the hydrostatic equilibrium + perfect gas imply that the centre of a star must evolve along a straight line in the $Log(T_c)$-$Log(\rho_c)$ plane.

What else?

The constant k scales inversely with the mass, so that the density increases as the mass decreases (for each fixed T)

We found that stars naturally separate in two basic groups: stars less massive than a critical value enter the region of electron degeneracy while the more massive ones don't!

$$\frac{dP}{dr} = -\frac{Gm\rho}{r^2} \Rightarrow \frac{P}{R} \propto \frac{M\rho}{R^2} \Rightarrow P \propto \frac{M\rho}{R}$$

$$\frac{dM}{dr} = 4\pi r^2 \rho \Rightarrow \frac{M}{R} \propto R^2 \rho \Rightarrow R \propto \left(\frac{M}{\rho}\right)^{\frac{1}{3}}$$

$$\Rightarrow P \propto M^{\frac{2}{3}} \rho^{\frac{4}{3}}$$

Perfect gas

$$P \propto \rho T$$

$$TR \propto M$$

Pure radiation

$$P \propto T^4$$

$$TR \propto M^{0.5}$$

$$\frac{dT}{dr} = -\frac{3}{16\, a c \pi} \frac{k\rho L}{r^2 T^3} \Rightarrow \frac{T}{R} \propto \frac{\rho L}{R^2 T^3} \Rightarrow T^4 R^4 \propto ML$$

Perfect gas $\Rightarrow L \propto M^3$

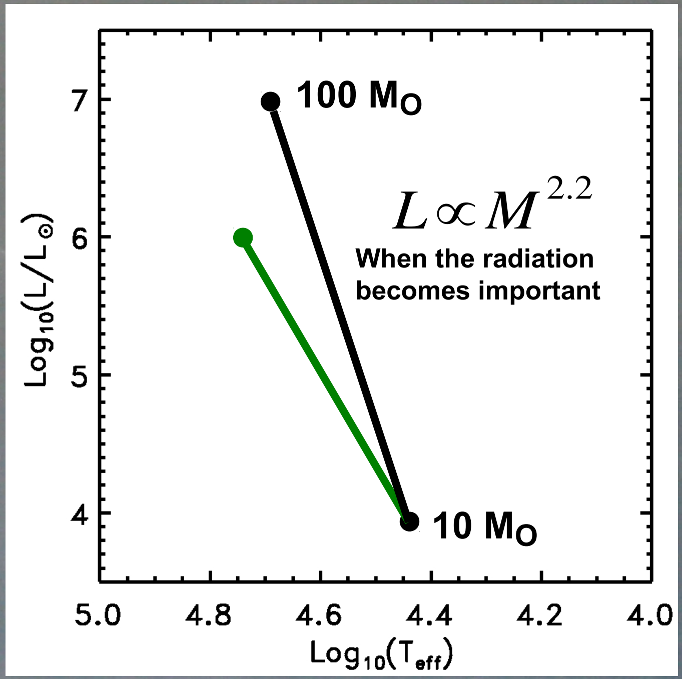
Pure radiation $L \propto M$

What about the surface temperature of the star?

If we assume a black body: $L = 4\pi R^2 \sigma T_{eff}^4$

and also that the central temperature is roughly independent on the mass : $R \propto M$

$$M^3 \propto R^2 T_{eff}^4 \Rightarrow T_{eff}^4 \propto M \Rightarrow T_{eff} \propto M^{\frac{1}{4}}$$



Perfect gas

$$P \propto \rho T$$

$$TR \propto M$$

$$\frac{dP}{dr} = -\frac{Gm\rho}{r^2} \Rightarrow \frac{P}{R} \propto \frac{M\rho}{R^2} \Rightarrow P \propto \frac{M\rho}{R}$$

$$\frac{dM}{dr} = 4\pi r^2 \rho \Rightarrow \frac{M}{R} \propto R^2 \rho \Rightarrow R \propto \left(\frac{M}{\rho}\right)^{\frac{1}{3}}$$

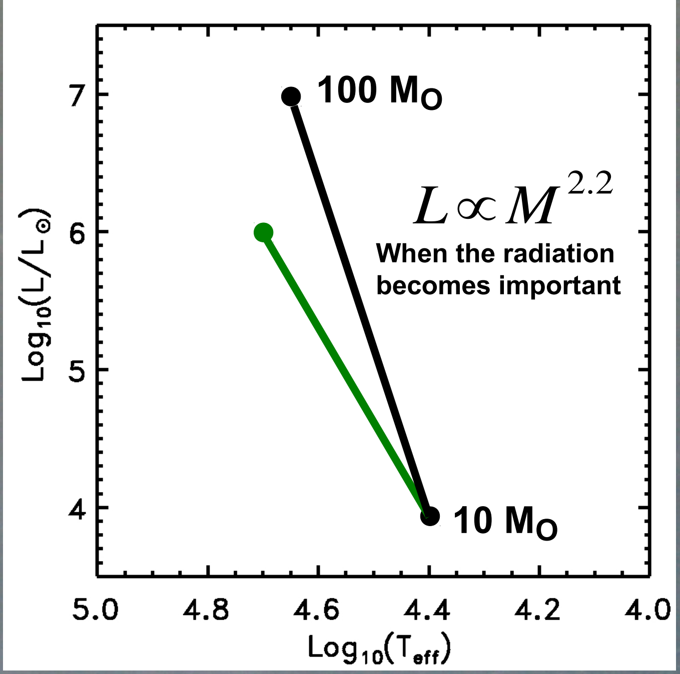
$$\Bigg\} \; P \propto M^{\frac{2}{3}} \rho^{\frac{4}{3}}$$

$$\frac{dT}{dr} = -\frac{3}{16\,a\,c\,\pi}\frac{k\rho L}{r^2 T^3} \Rightarrow \frac{T}{R} \propto \frac{\rho L}{R^2 T^3} \Rightarrow T^4 R^4 \propto ML \Rightarrow L \propto M^3$$

What about the lifetime of the stars?

$$\tau \propto \frac{E}{L} \qquad \tau \propto \frac{qM}{L} \qquad \tau \propto \frac{qM}{M^3} \approx \frac{1}{M^2}$$

When radiation contributes significantly to the EOS $\Rightarrow$ $\tau \propto \frac{qM}{M^{2.2}} \approx \frac{1}{M^{1.2}}$



We learned a lot of things up to now (without really solving any equation!)

If the EOS is dominated by a perfect gas:

hydrostatic equlibrium is “stable” because γ > 4/3

the evolution of the core follows a straight line in the $Log(T_c)$-$Log(\rho_c)$ plane

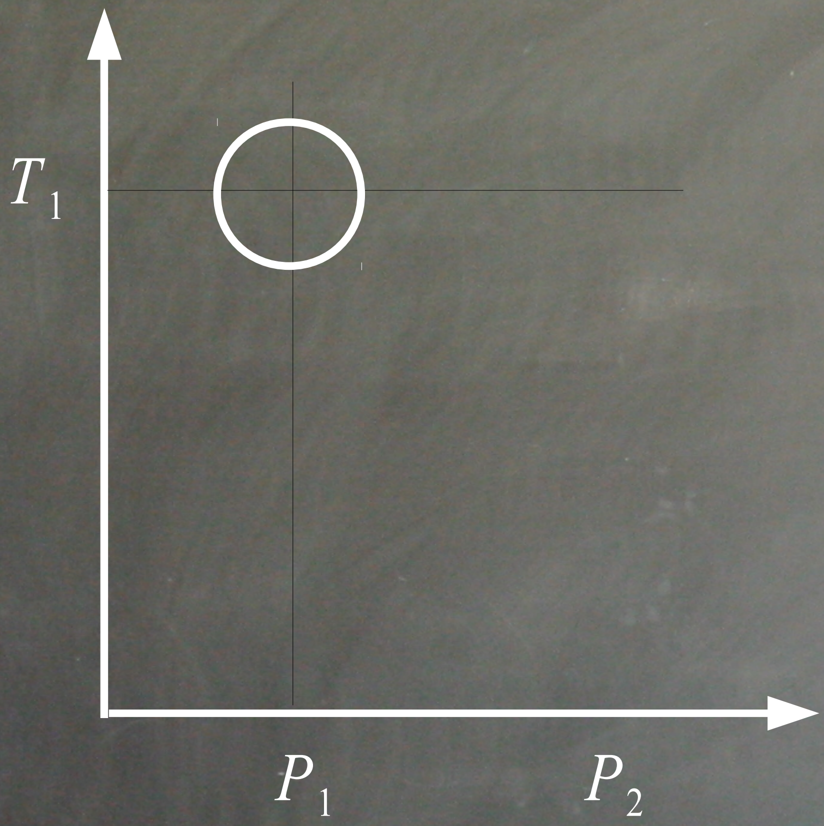
Star less massive than a critical value enter the region where degenerate electrons count

Star more massive than a critical value do not enter the region where degenerate electrons count (at least until the central temperature does not exceed a few billions of K)

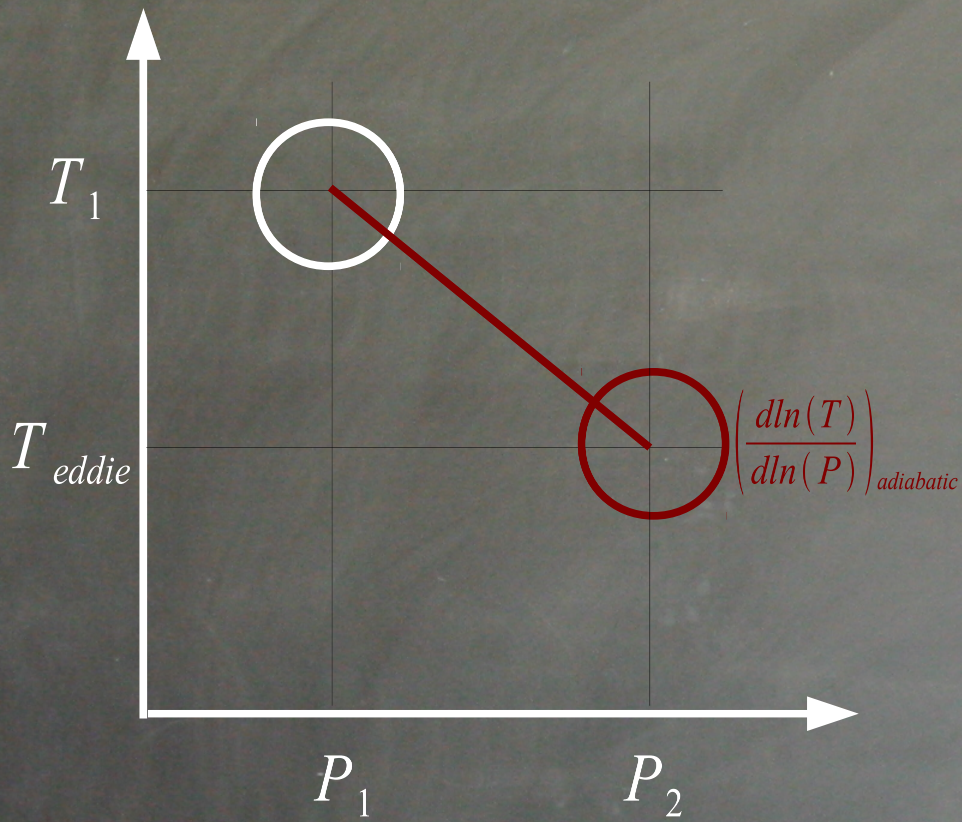
The energy losses from the surface (L) scale as M^3 (perfect gas) or as M (pure radiation)

The lifetime of a star (t) scales as M^{-2}

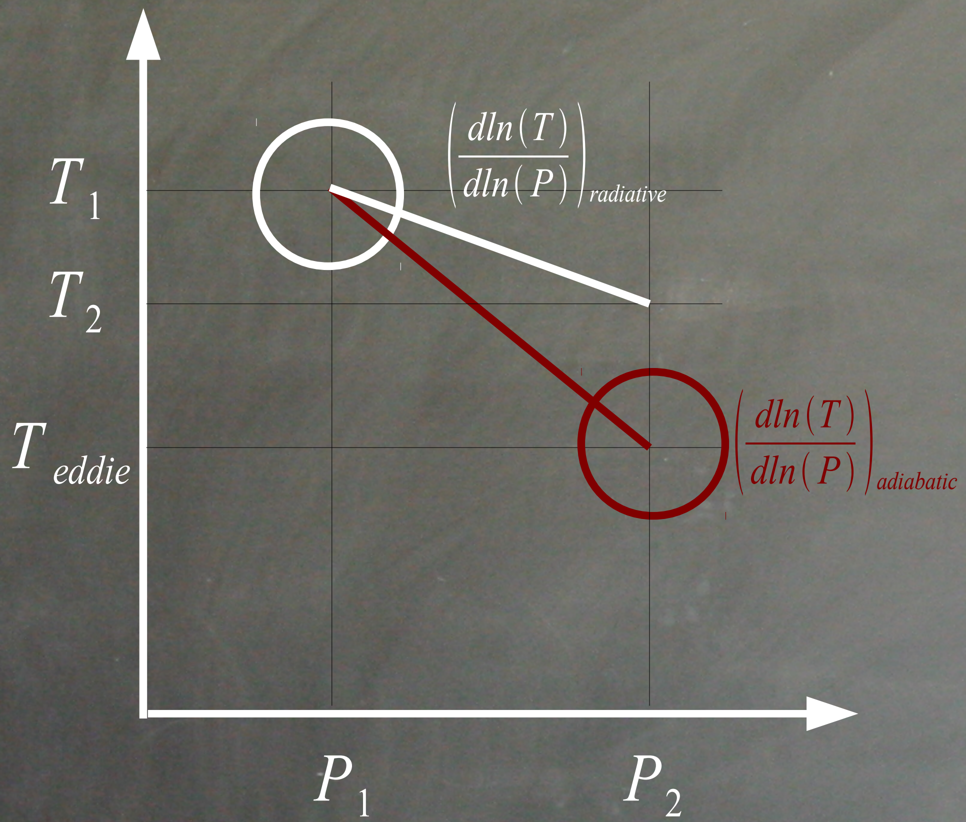
Unfortunately this is not enough ... it's time to introduce CONVECTION



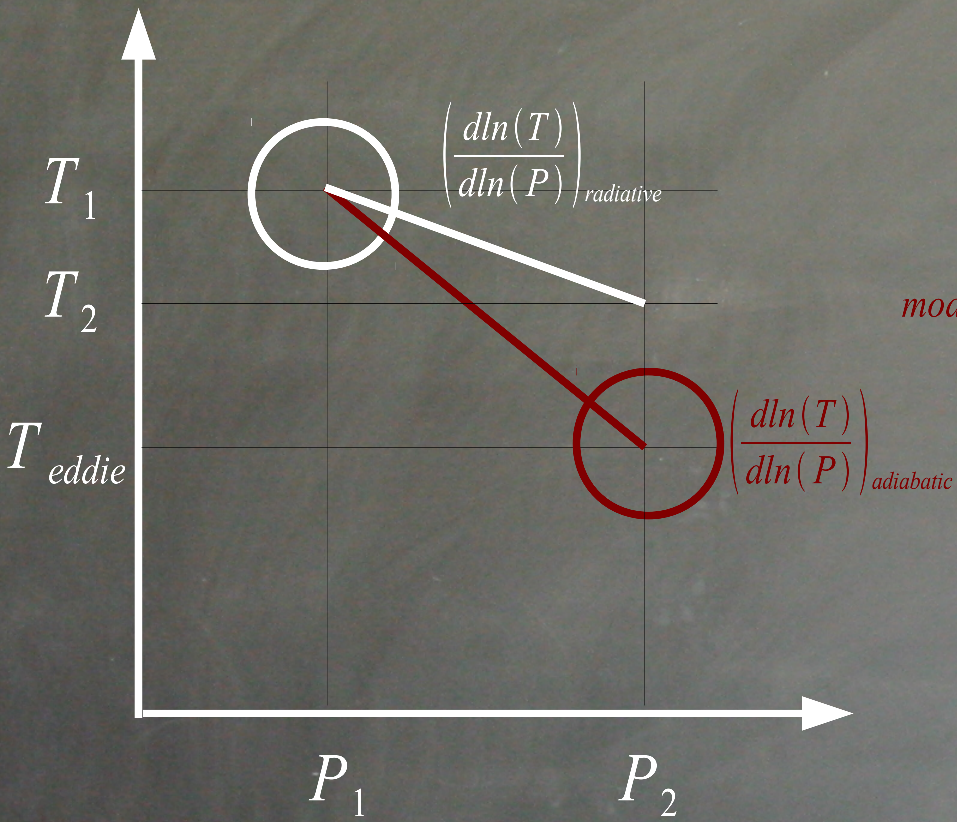
T_1
P_1
P_2



T_1
T_{eddie}
$\left(\frac{d\ln(T)}{d\ln(P)}\right)_{adiabatic}$
P_1
P_2



T_1
T_2
T_{eddie}
P_1
P_2
$\left(\frac{dln(T)}{dln(P)}\right)_{radiative}$
$\left(\frac{dln(T)}{dln(P)}\right)_{adiabatic}$



$$mod\left(\frac{dln(T)}{dln(P)}\right)_{adiabatic} > mod\left(\frac{dln(T)}{dln(P)}\right)_{radiative}$$

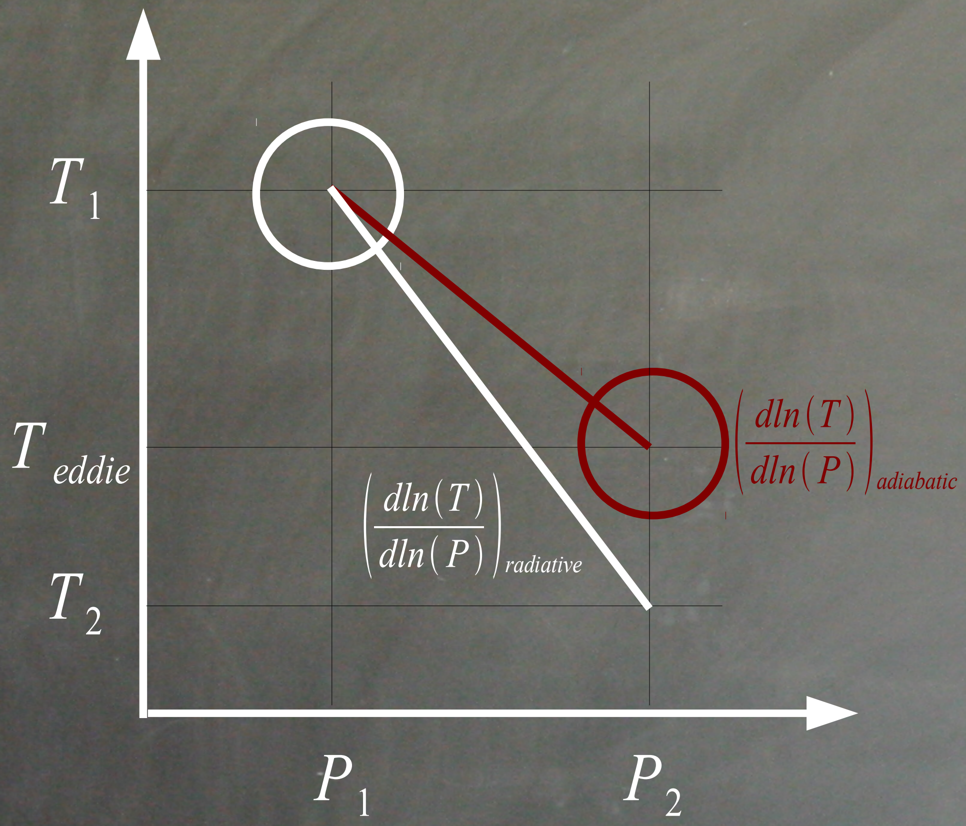
$$P \propto \rho T = const$$

$$T_{eddie} < T_2$$

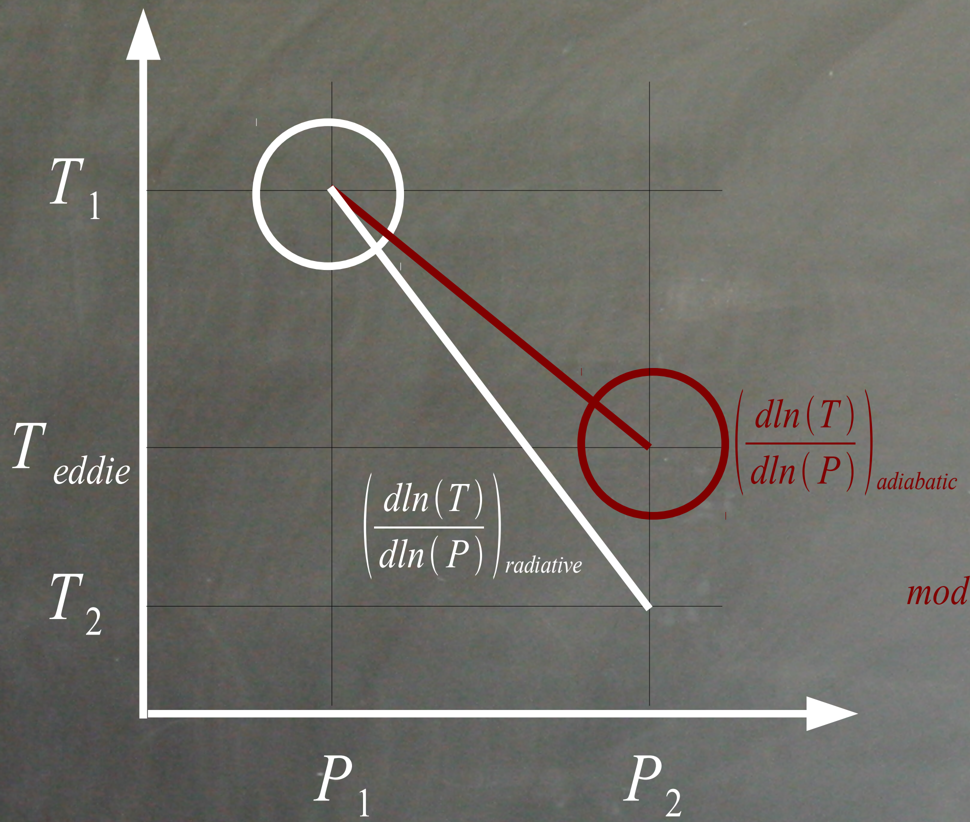
$$\rho_{eddie} > \rho_2$$

The buoyancy force $f \approx -\frac{g}{\rho}\frac{\delta \rho}{\delta r}\Delta r$

is negative and pushes back the eddie



T_1
T_{eddie}
T_2
P_1
P_2
$\left(\frac{dln(T)}{dln(P)}\right)_{adiabatic}$
$\left(\frac{dln(T)}{dln(P)}\right)_{radiative}$



$$mod\left(\frac{dln(T)}{dln(P)}\right)_{adiabatic} < mod\left(\frac{dln(T)}{dln(P)}\right)_{radiative}$$

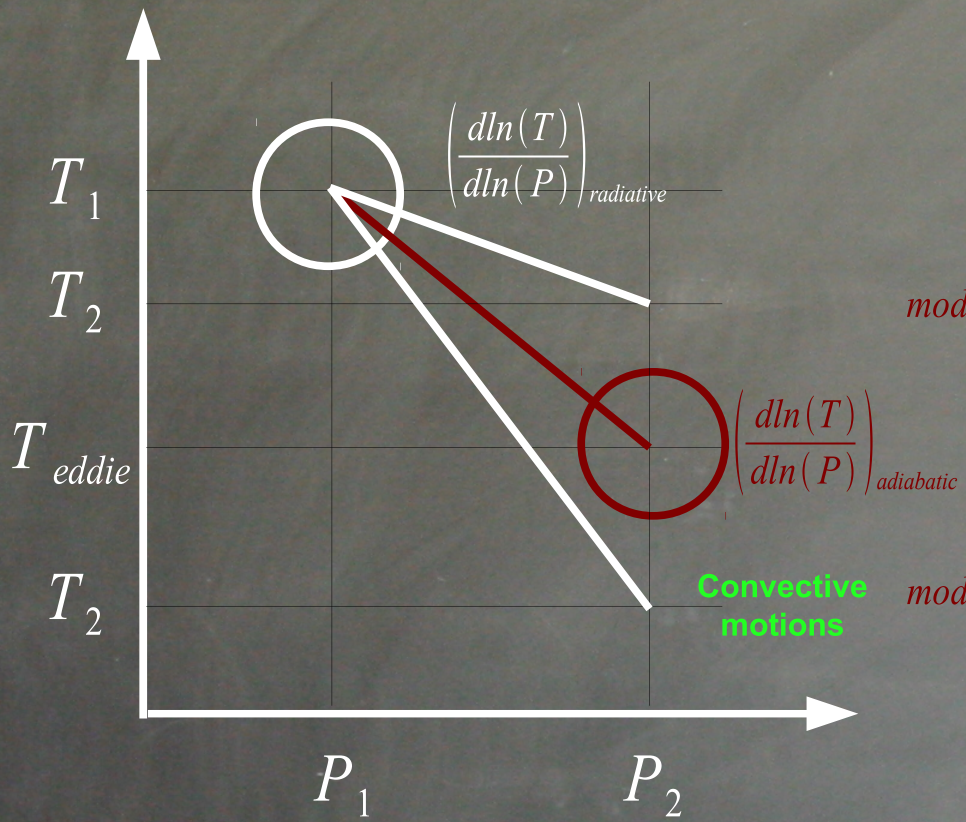
$$T_{eddie} > T_2$$

$$\rho_{eddie} < \rho_2$$

The eddie is accelerated outward.
Large scale motions activate.

The buoyancy force $f \approx -\frac{g}{\rho}\frac{\delta\rho}{\delta r}\Delta r$ **is now positive**

Schwarzschild criterion!



$$P \propto \rho T = const$$

$$mod\left(\frac{dln(T)}{dln(P)}\right)_{adiabatic} > mod\left(\frac{dln(T)}{dln(P)}\right)_{radiative} \qquad T_{eddie} < T_2 \qquad \rho_{eddie} > \rho_2$$

$$mod\left(\frac{dln(T)}{dln(P)}\right)_{adiabatic} < mod\left(\frac{dln(T)}{dln(P)}\right)_{radiative} \qquad T_{eddie} > T_2 \qquad \rho_{eddie} < \rho_2$$

Both the temperature gradient and the mass extension of the convective regions are very difficult to compute properly and still constitute one of the major uncertainties in the stellar modelling.

Which are the basic consequences of the growth of convective motions?

Matter is mixed.

1st side effect: new fuel pulled inward – products of burning pushed outward

2nd side effect: change of the mean molecular weight in the whole convective region

The temperature gradient can't become steeper than the adiabatic one in most of the interior of a star; only in the outer region it can raise towards the radiative one because of the inefficiency of the eddies in carrying the energy.

At this point we are ready to follow the evolution of a star, but...

...first a “stupid” question...

Why should a star “evolve”?

because...

...stars lose energy (e.g. from the surface: the Luminosity)

that must be replaced in order to mantain the hydrostatic equilibrium!

Energy may be gained by either:

contraction (energy is extracted from the gravitational field)

Side effect => the interior heats (Virial theorem)

and / or

Nuclear reactions (energy is extracted from the fusion of nuclei)

Side effect => mean molecular weight increases (P decreases)

Critical masses:

H ignition (4P => ^{4}He)	0.1 $M_{\odot}$	Low mass stars: RGB, He white dwarfs
He ignition (off center, degenerate) (3 ^{4}He => ^{12}C)	0.5 $M_{\odot}$	
He ignition (central, not degenerate)	2.3 $M_{\odot}$	Intermediate mass stars: AGB, CO white dwarfs
C ignition (off center, degenerate) (2 ^{12}C => $^{20}Ne+\alpha$)	7 $M_{\odot}$	Intermediate-High mass stars: Super – AGB, O,Ne,Mg white dwarfs
C ignition (central, not degenerate)	8 $M_{\odot}$	Intermediate –High mass stars: Super - AGB, Electron capture supernovae
All burnings up to the NSE	10 $M_{\odot}$	Massive stars: Go through all burnings up to the Nuclear Statistical Equilibrium

Hydrostatic evolution

H-burning

He-burning

C-burning

Ne-burning

O-burning

Si-burning

Hydrodynamic evolution

Core collapse

Bounce at nuclear densities

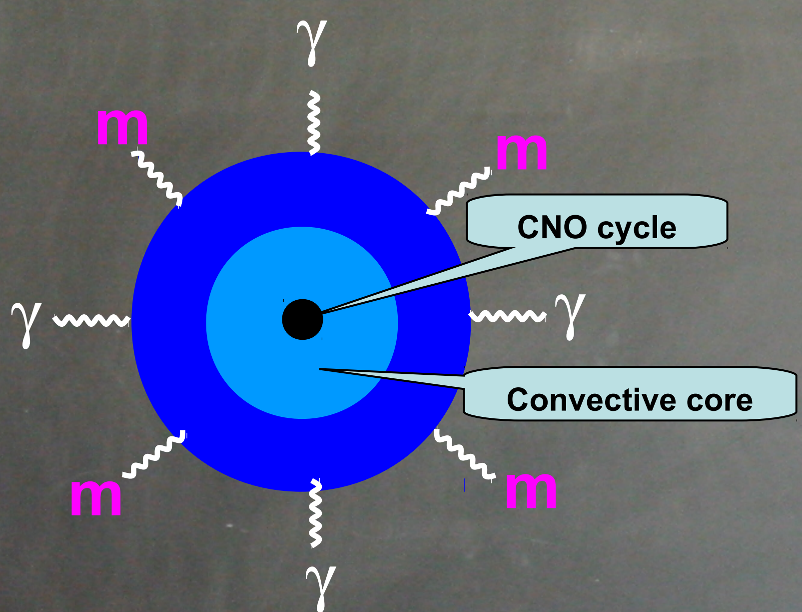
Formation of the shock wave

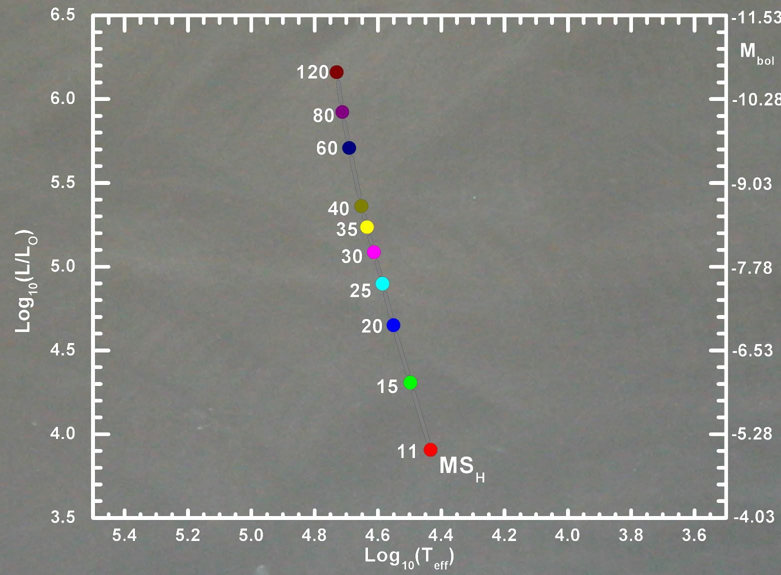
Explosive nucleosynthesis

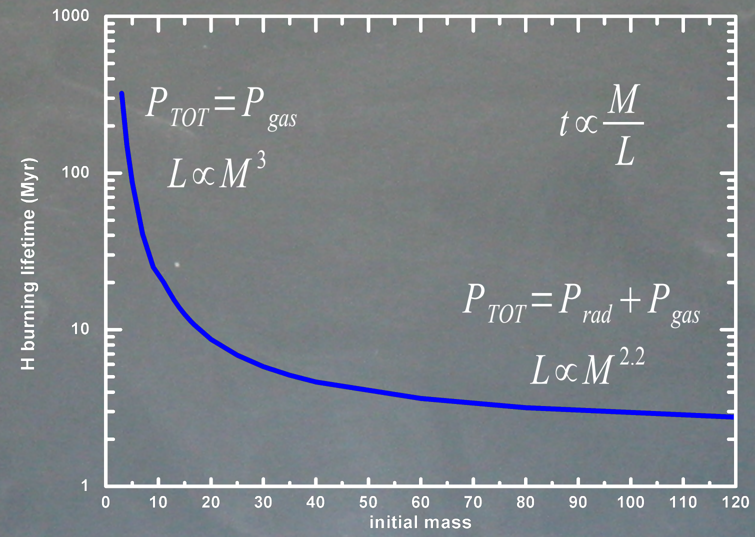
yields

T

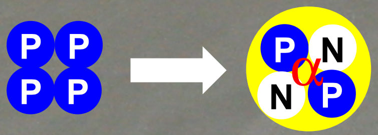
H – burning: luminosity and lifetime







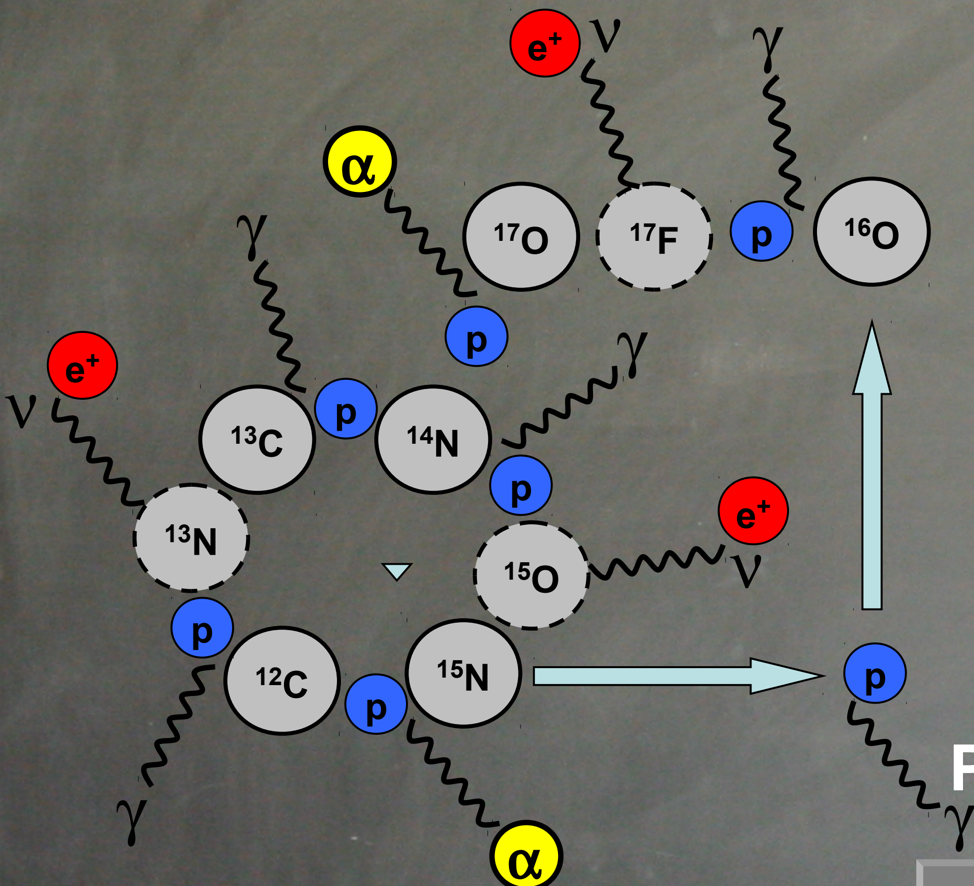
Energy budget

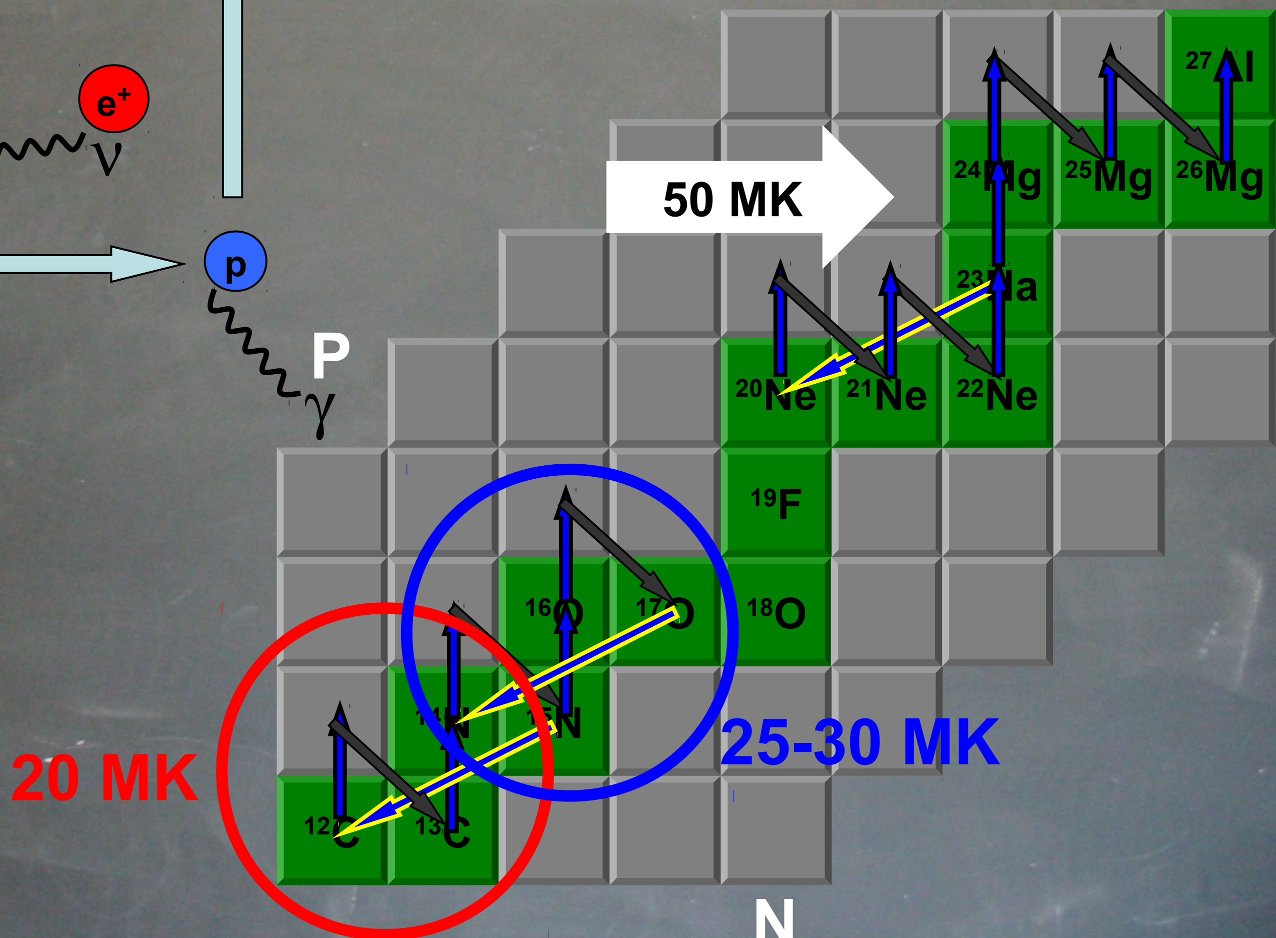


+ 26.73 MeV

2 ν per α carry away part of the energy

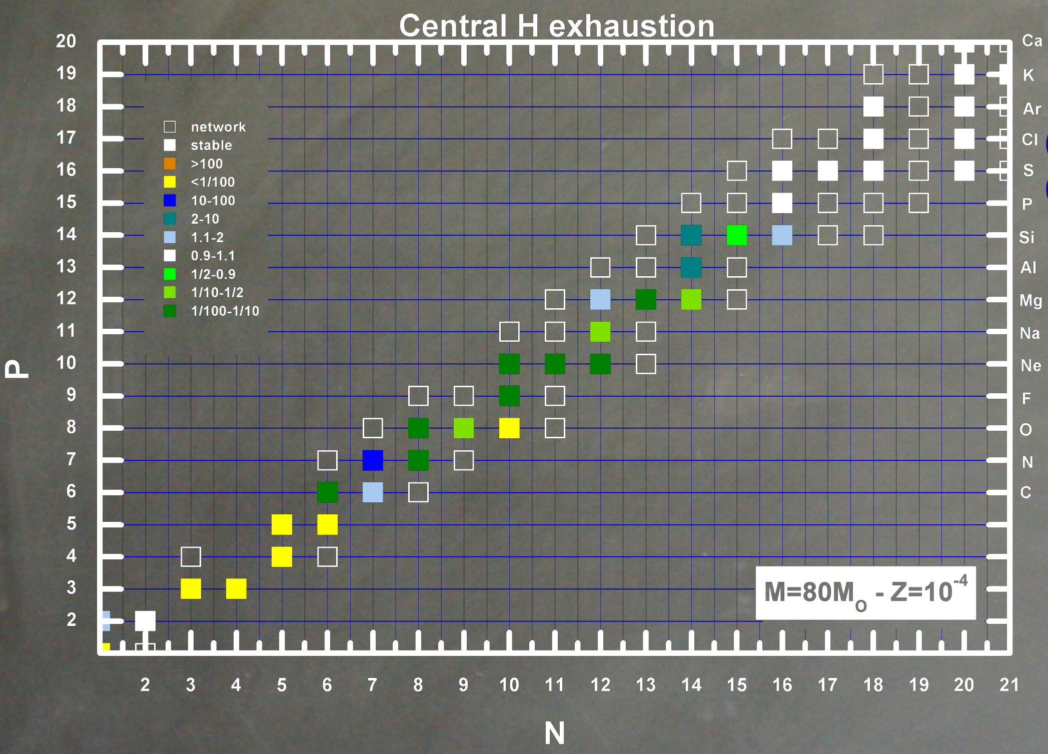
$$6.44\,10^{18}\ erg\ g^{-1}$$



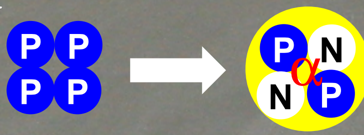


Trailer time!

H burning movie



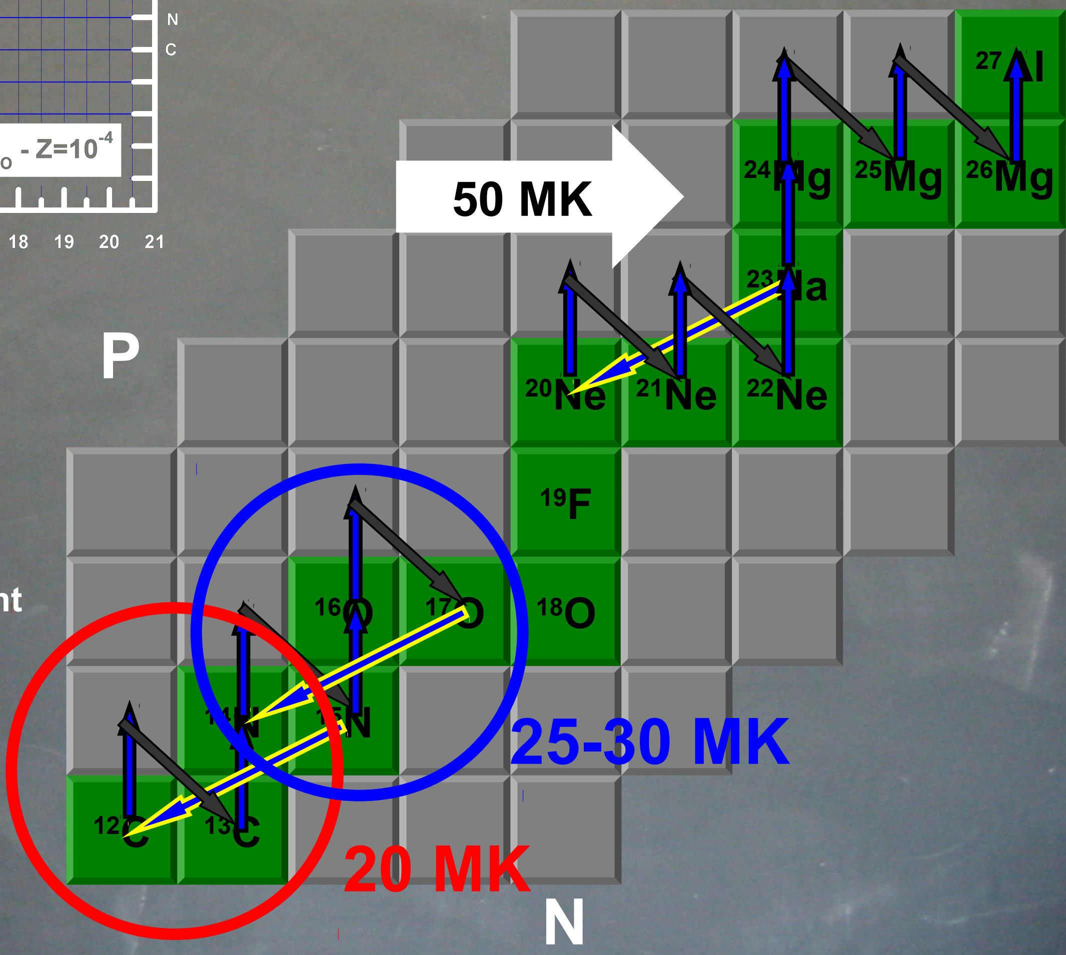
Energy budget



+ 26.73 MeV

2 ν per α carry away part of the energy

$$6.44\,10^{18}\ erg\ g^{-1}$$



Basic effects of the H burning on the elemental abundances:

H converted in He (strong neutronization)

O & C converted in N (becomes the most abundant element after H and He!)

Redistribution among Ne – Na – Mg – Al

F destroyed

H – burning: mass loss

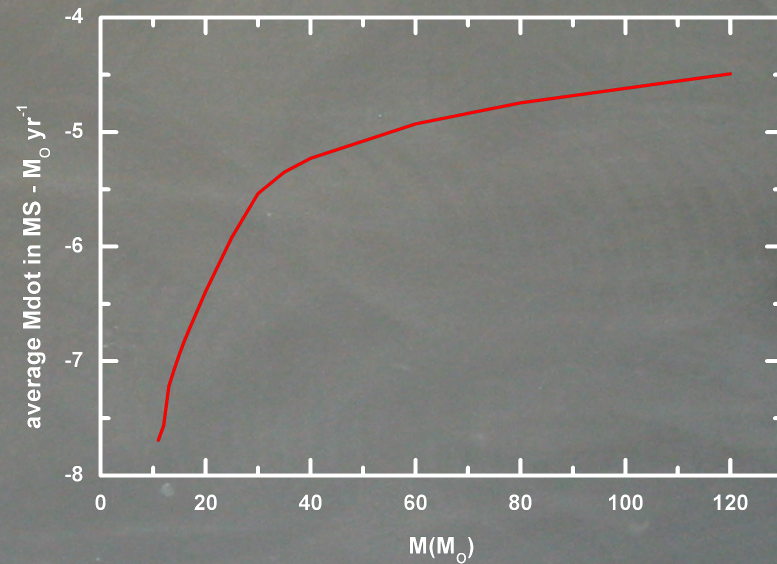
Astron. Astrophys. 362, 295–309 (2000)

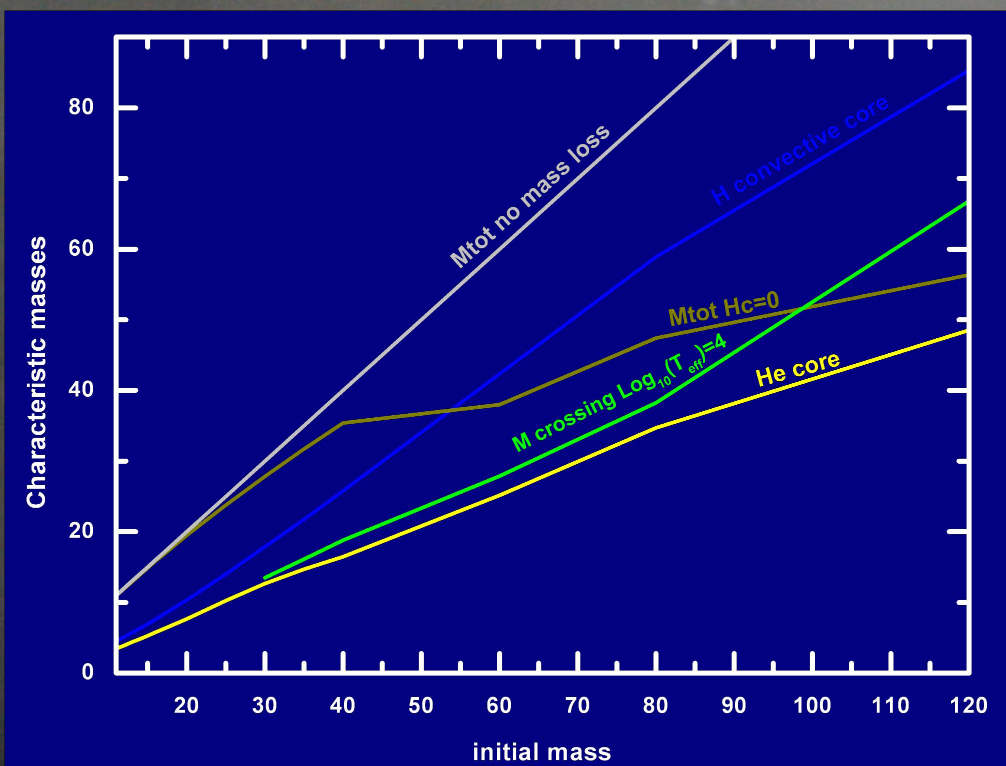
ASTRONOMY AND ASTROPHYSICS

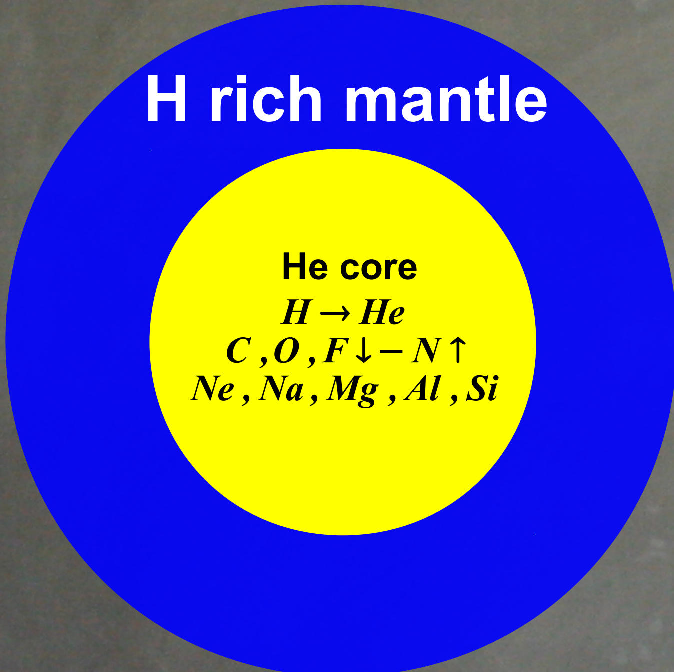
New theoretical mass-loss rates of O and B stars

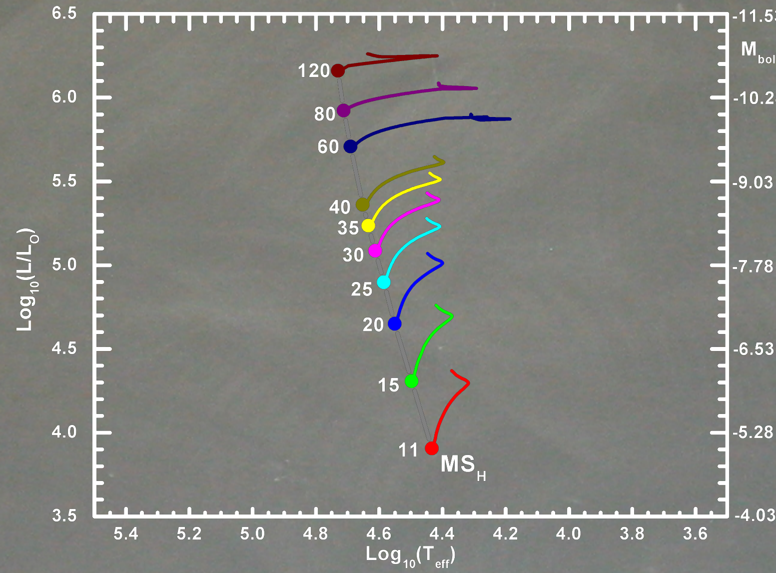
J.S. Vink[1], A. de Koter[2], and H.J.G.L.M. Lamers[1,3]

$$\dot{M}\,(\mathrm{O\ B\ stars}) \propto \frac{L^{2.2}}{M^{1.3}} \quad \& \; (T_{eff},\, V_{inf}/V_{esc})$$

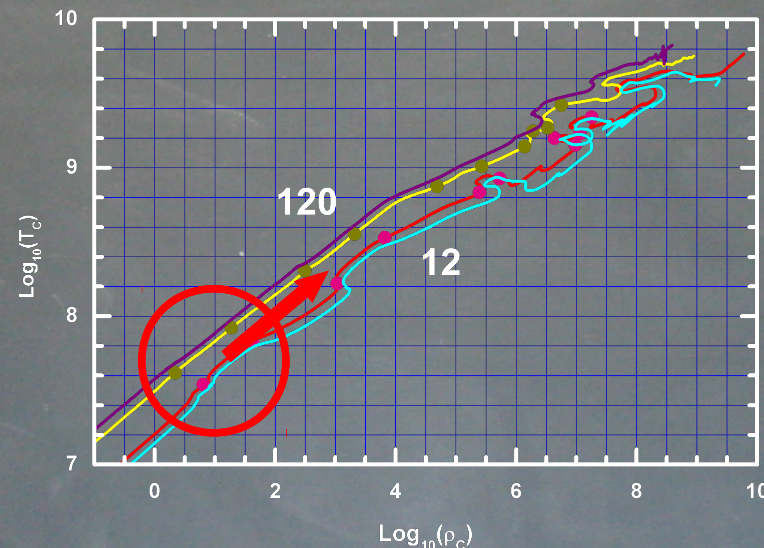




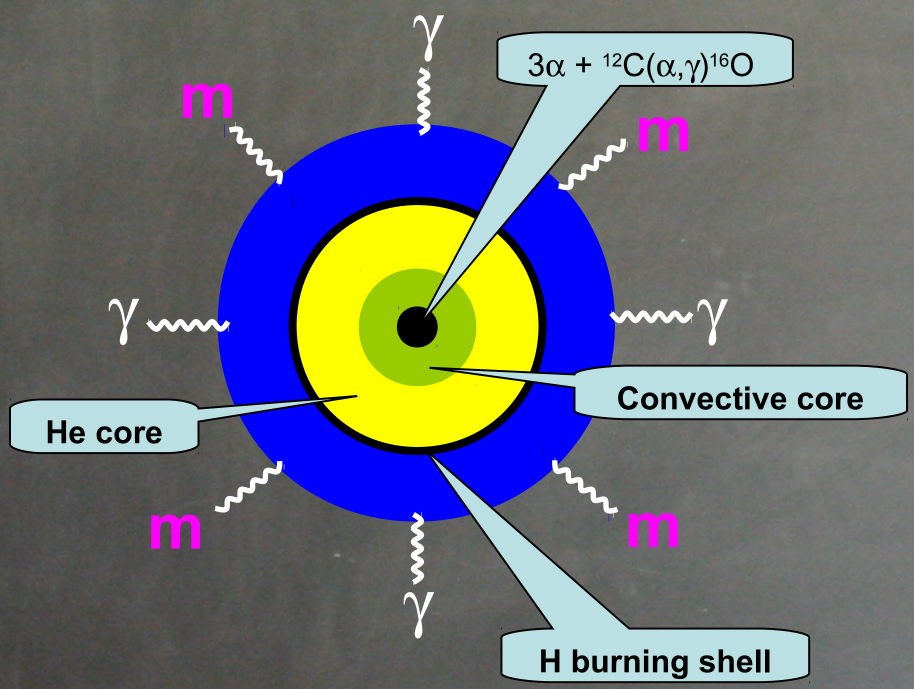

H rich mantle
He core
$H \rightarrow He$
$C, O, F \downarrow - N \uparrow$
Ne, Na, Mg, Al, Si


120
80
60
40
35
30
25
20
15
11
MS_H
$Log_{10}(L/L_{\odot})$
$Log_{10}(T_{eff})$
M_{bol}
6.5
6.0
5.5
5.0
4.5
4.0
3.5
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
-11.53
-10.28
-9.03
-7.78
-6.53
-5.28
-4.03


He core
$H \rightarrow He$
$C, O, F \downarrow - N \uparrow$
Ne, Na, Mg, Al, Si


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

The central He burning



All stars form a convective core

The physical evolution of the star requires the inclusion of just 2 processes:

$$\alpha(2\alpha,\gamma)^{12}C \quad \text{and} \quad {}^{12}C(\alpha,\gamma)^{16}O$$

The chemical evolution of the star requires the inclusion of many, many processes because an efficient n producing chain activates:

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

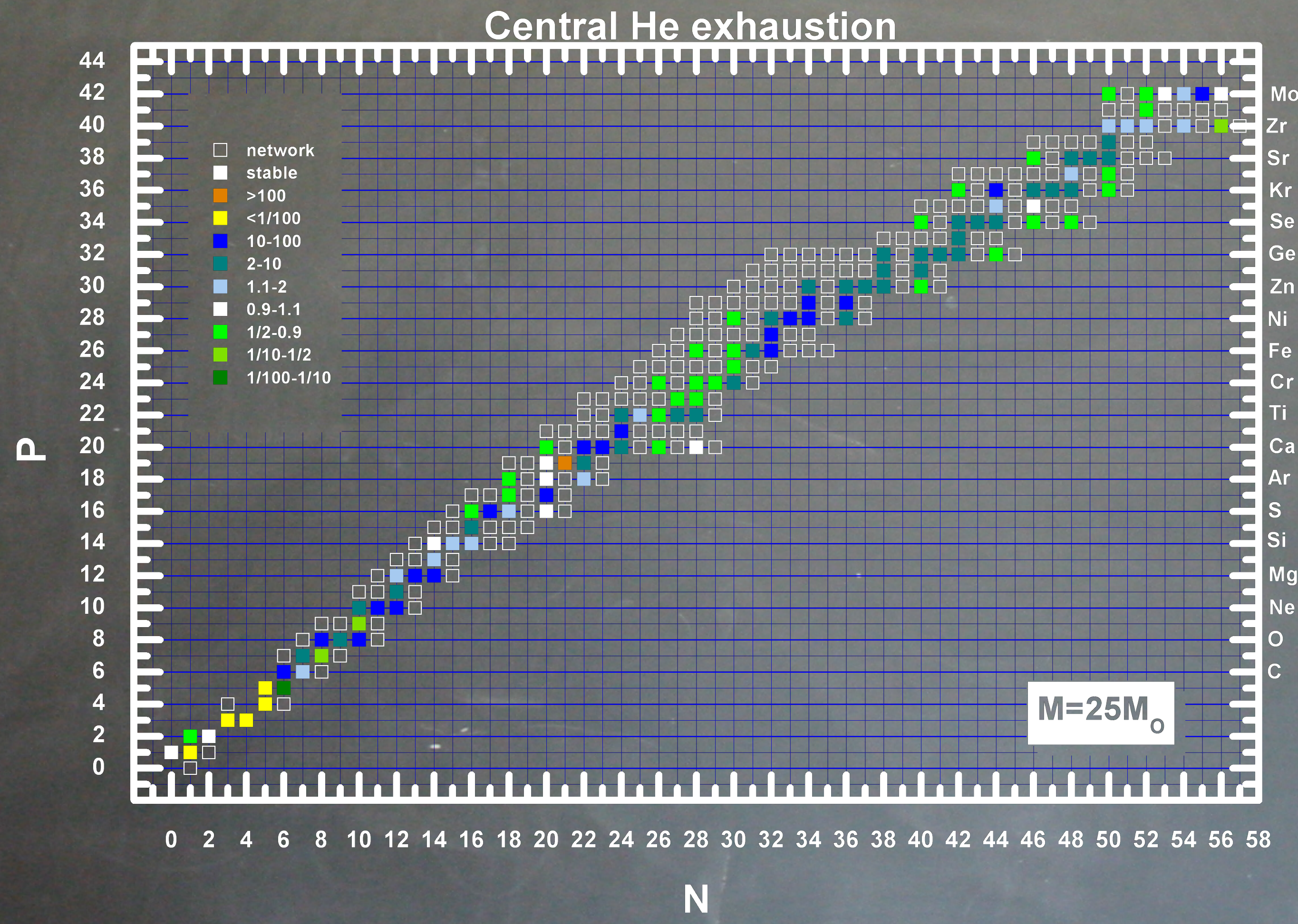
Note that the ^{14}N abundance is roughly equal to the initial abundance of the sum of the CNO nuclei that are more than 70% of the initial metallicity of the star!

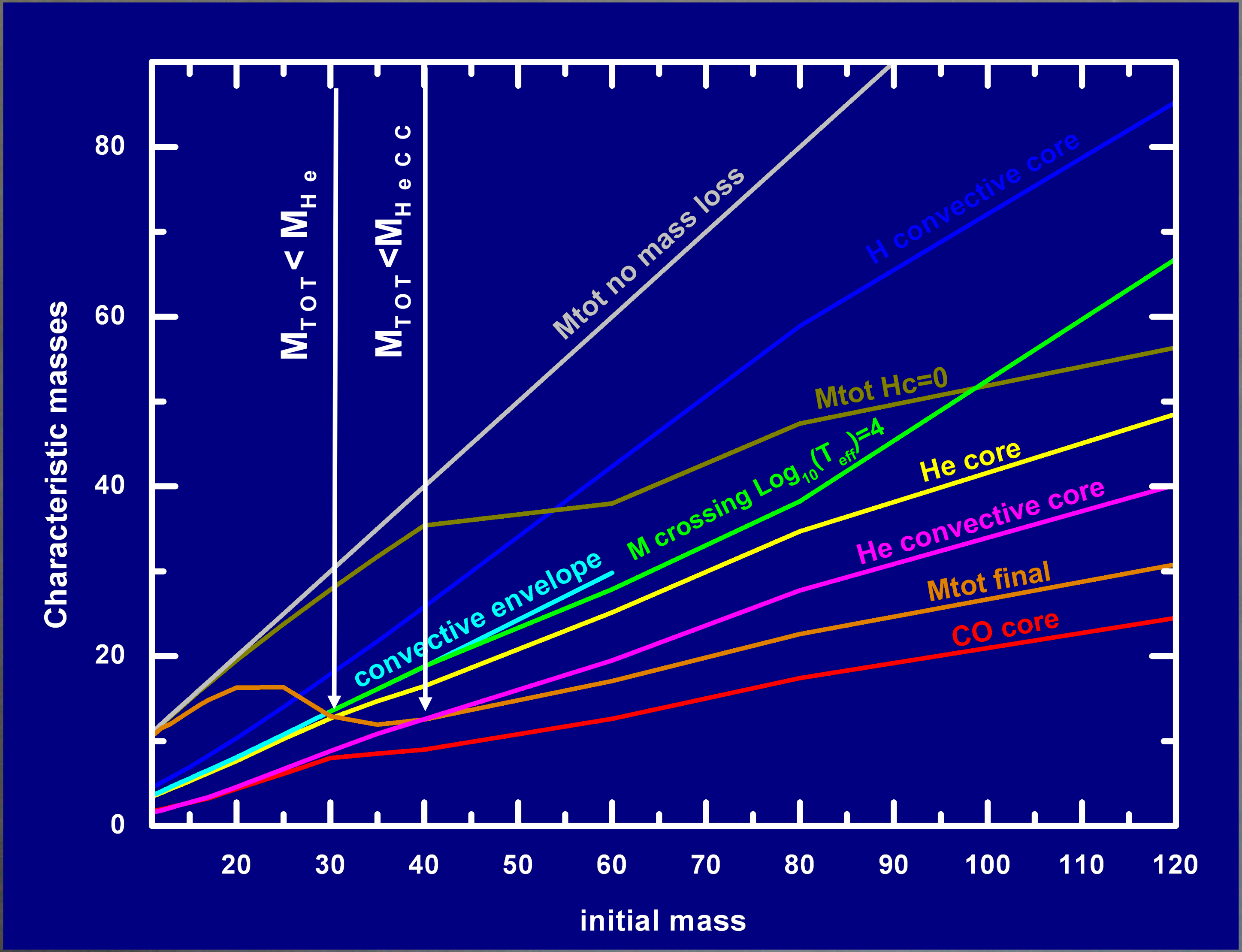
Trailer time!

He burning movie

The central He burning

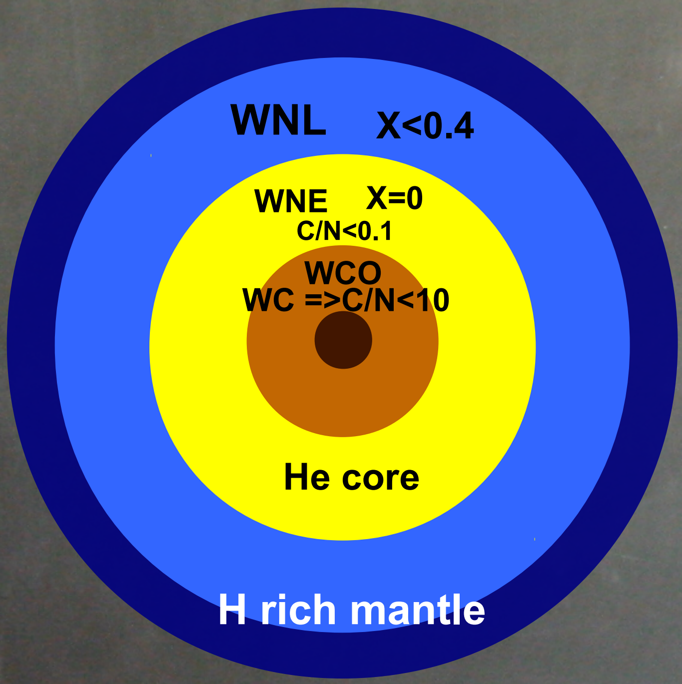
The n emitted by the $^{22}Ne(\alpha,n)^{25}Mg$ process are mainly captured by the Fe peak nuclei so that nuclei up to A=90 (S weak-component) are produced

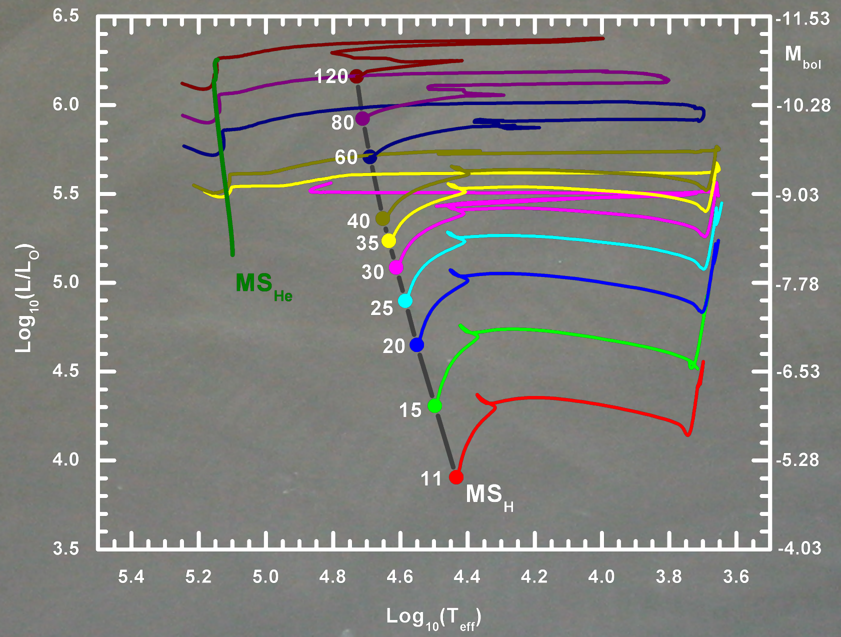


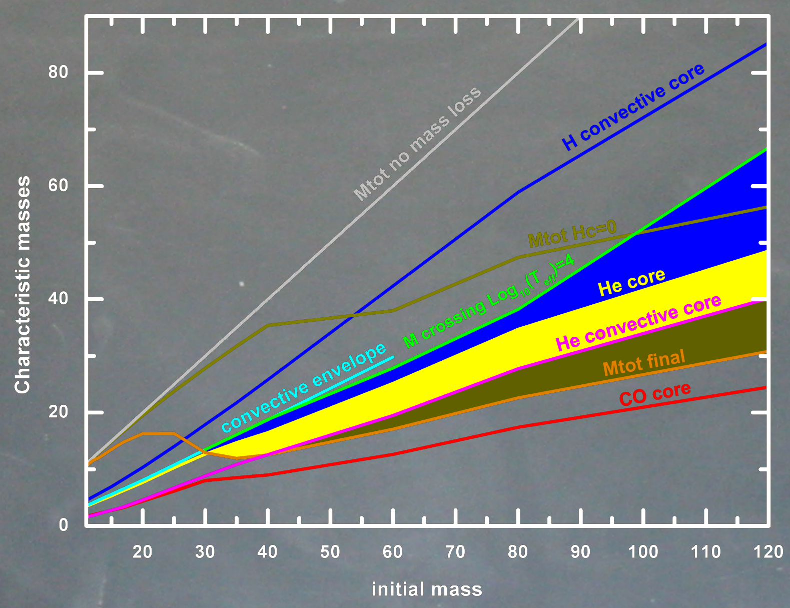


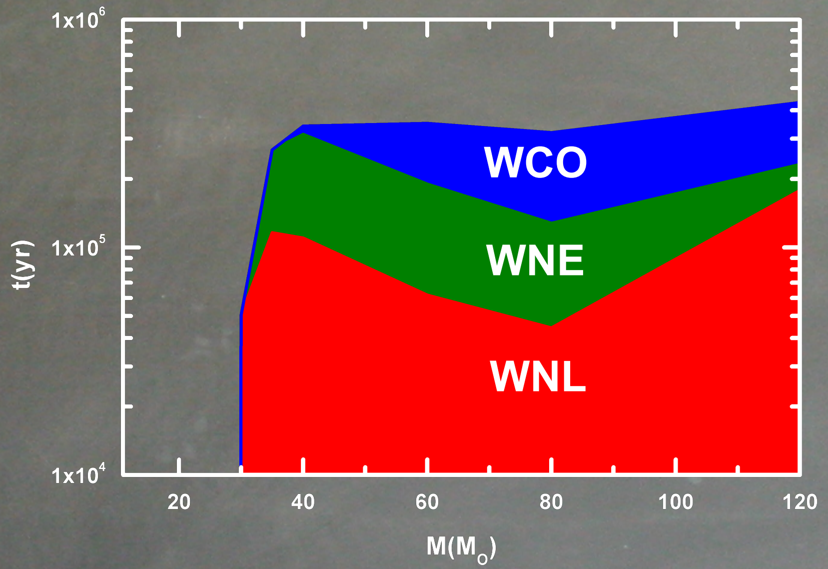
Characteristic masses
initial mass
0
20
40
60
80
20
30
40
50
60
70
80
90
100
110
120
Mtot no mass loss
H convective core
Mtot Hc=0
M crossing Log10(Teff)=4
He core
He convective core
Mtot final
CO core
convective envelope
MTOT < MHe
MTOT <MHeCC

$Log_{10}(T_{eff})$>4.0









Summarizing:

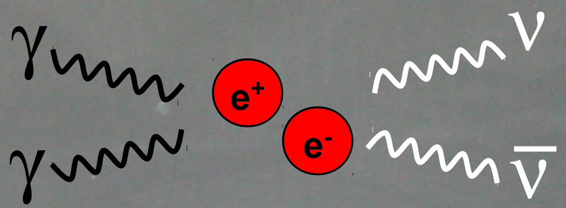
RSG	$< 30\ M_O <$	RSG WNL WNE	$< 40\ M_O <$	RSG WNL WNE WCO	$< 60\ M_O <$	WNL WNE WCO

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, γ+γ begin to efficiently produce electrons-positron pairs.



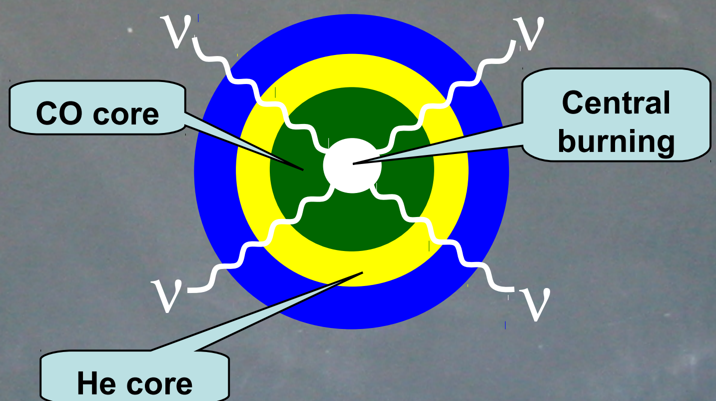
A blackbody radiation has its maximum wavelenght at : λ_{MAX}=2.898 10^{-3} T^{-1} [m / K]

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: $L_\gamma + L_\nu$

$M=80\ M_\odot$ $t = E / 10^6$

- 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...

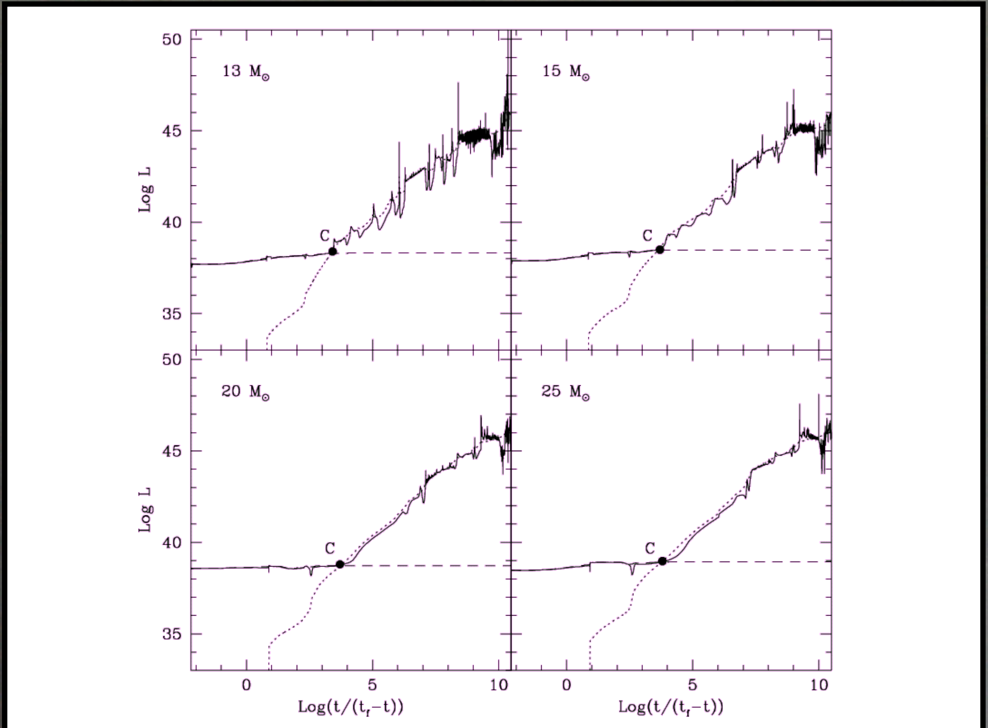
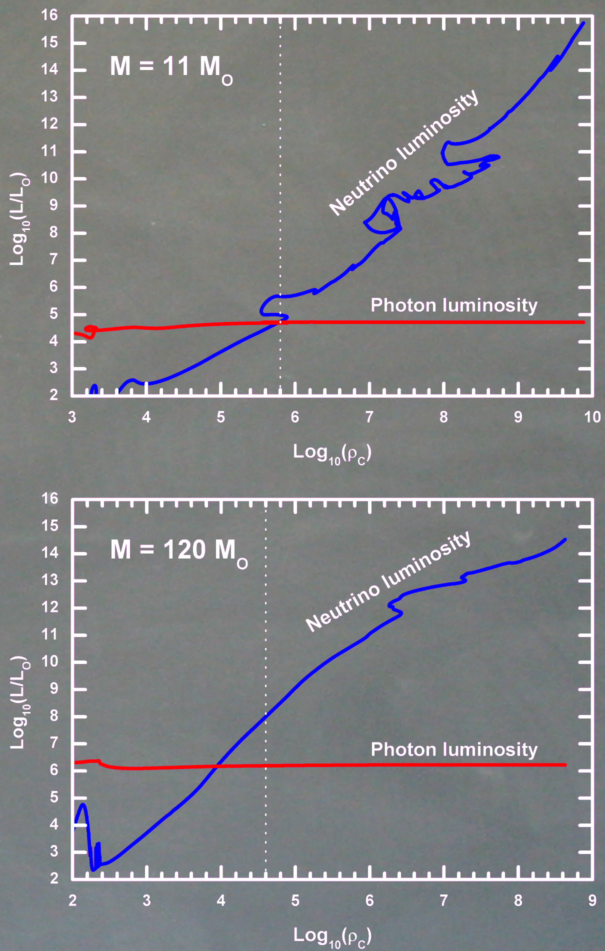
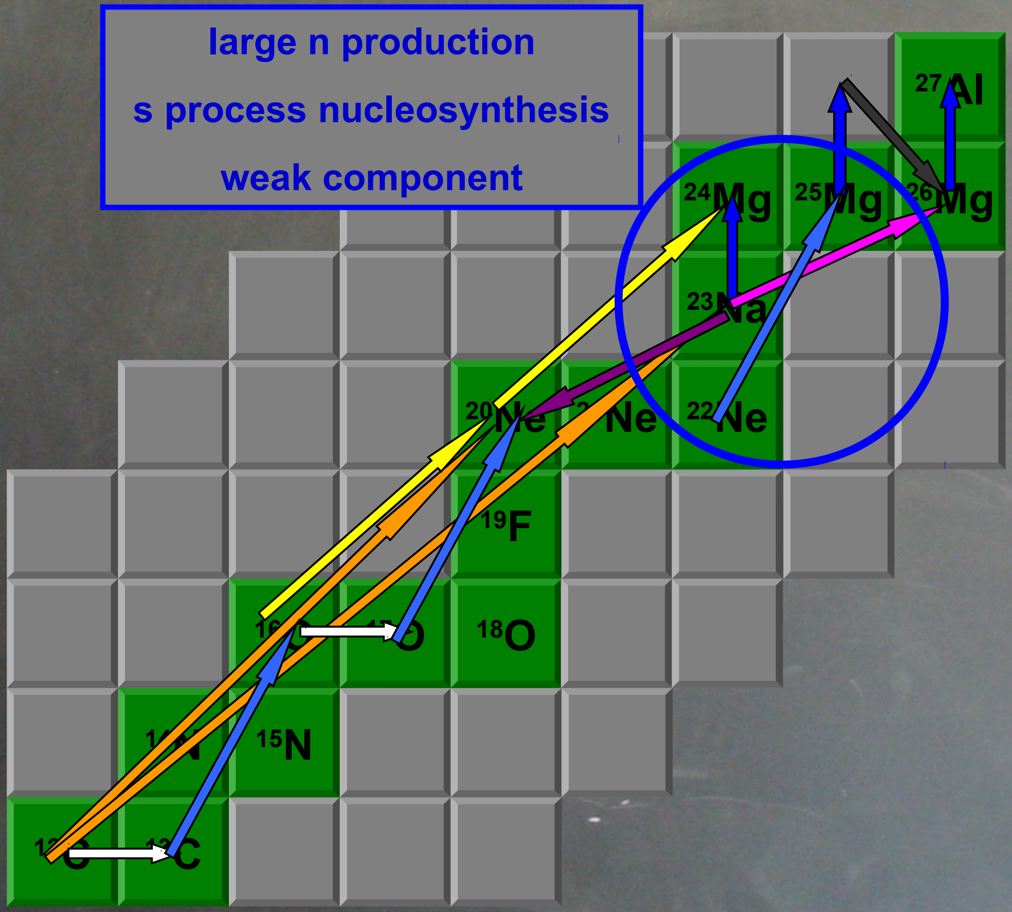


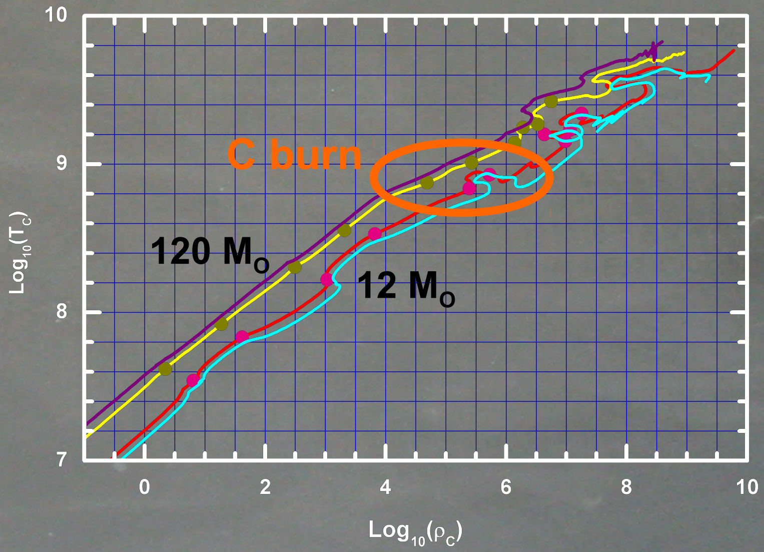
FIG. 7.—Temporal behavior of the various luminosities: photons (*dashed lines*), neutrinos (*dotted lines*), and nuclear (*solid lines*). The carbon-burning ignition is indicated in each panel by the big filled dot labeled "C."

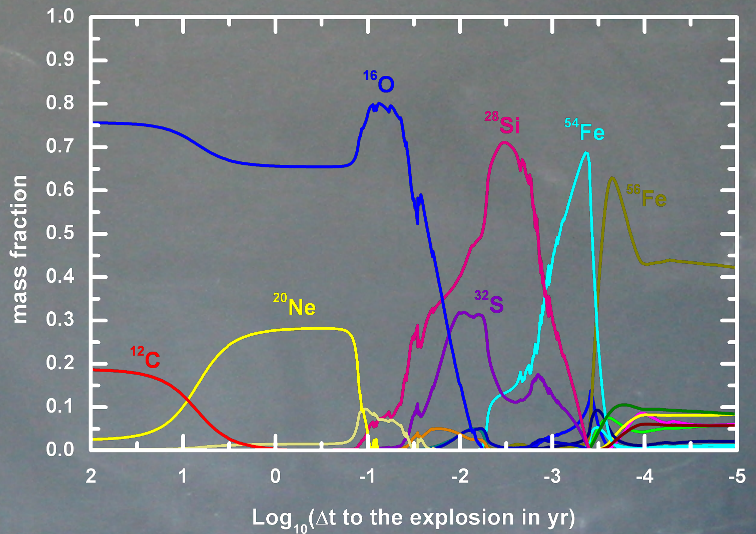


C burning

Typical temperature: 0.8-1.0 BK







Just the main processes in ...

C burning

Panel a)

$^{12}C(^{12}C,\alpha)^{20}Ne$
$^{12}C(^{12}C,p)^{23}Ne$

$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(\alpha,n)^{16}O$ $^{12}C(n,\gamma)^{13}C(\alpha,n)^{16}O$
$^{25}Mg(n,\gamma)^{26}Mg(p,\gamma)^{27}Al$
$^{16}O(\alpha,\gamma)^{20}Ne$
$^{20}Ne(n,\gamma)^{21}Ne$

Panel b)

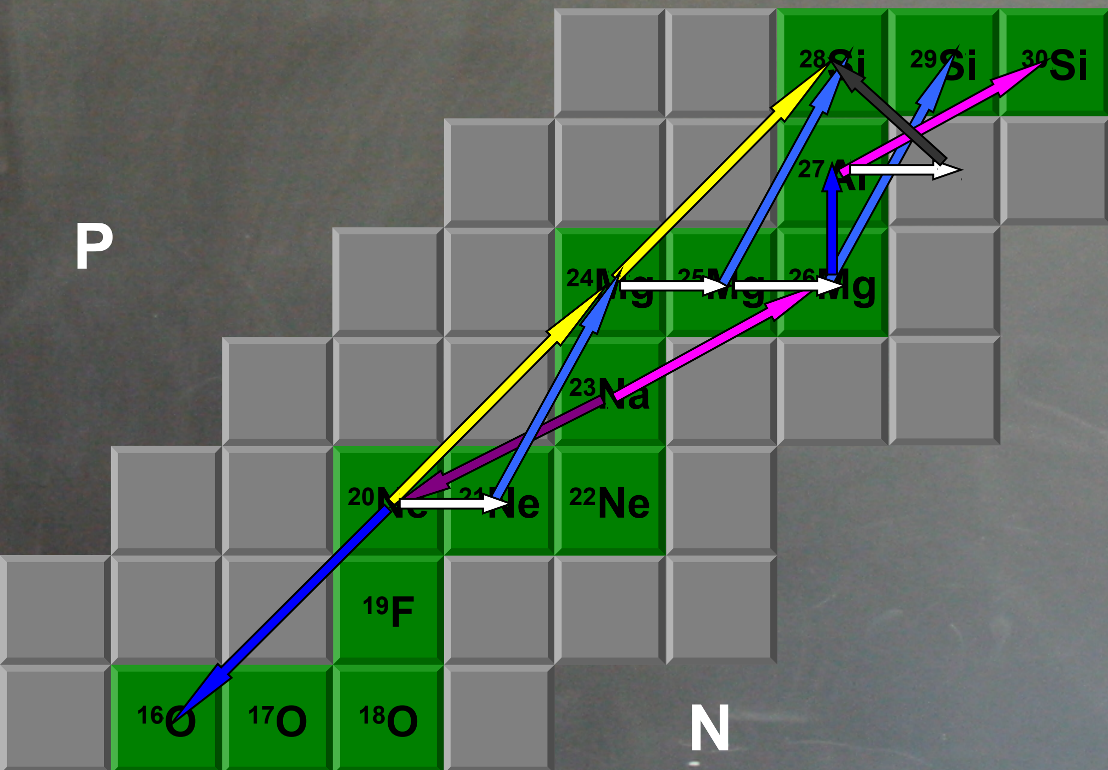
$^{16}O(\alpha,\gamma)^{20}Ne$
$^{12}C(^{12}C,\alpha)^{20}Ne$
$^{12}C(^{12}C,p)^{23}Na$
- $(p,\alpha)^{20}Ne$
- $(p,\gamma)^{24}Mg$
- $(\alpha,p)^{26}Mg$

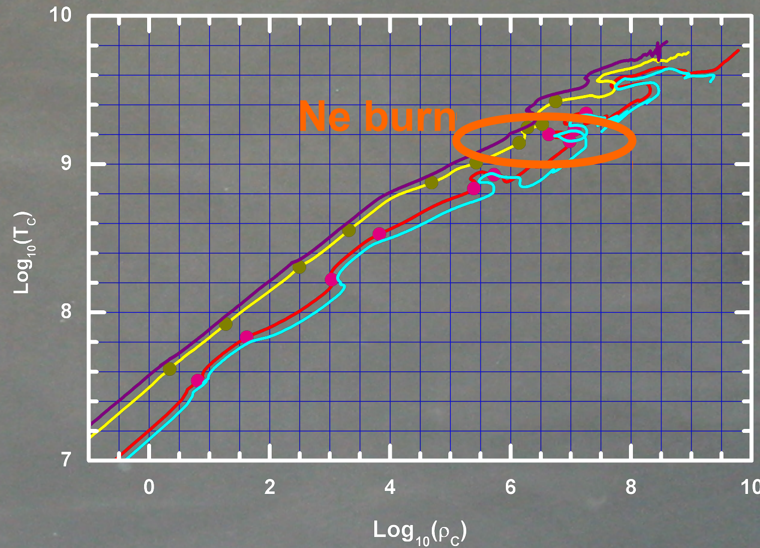
$^{22}Ne(\alpha,n)^{25}Mg(p,\gamma)^{26}Al(\beta^+)^{26}Mg(p,\gamma)^{27}Al$
$^{22}Ne(p,\gamma)^{23}Na$
$^{20}Ne(n,\gamma)^{21}Ne(\alpha,n)^{24}Mg$
$^{20}Ne(\alpha,\gamma)^{24}Mg$
$^{12}C(n,\gamma)^{13}C(\alpha,n)^{16}O$

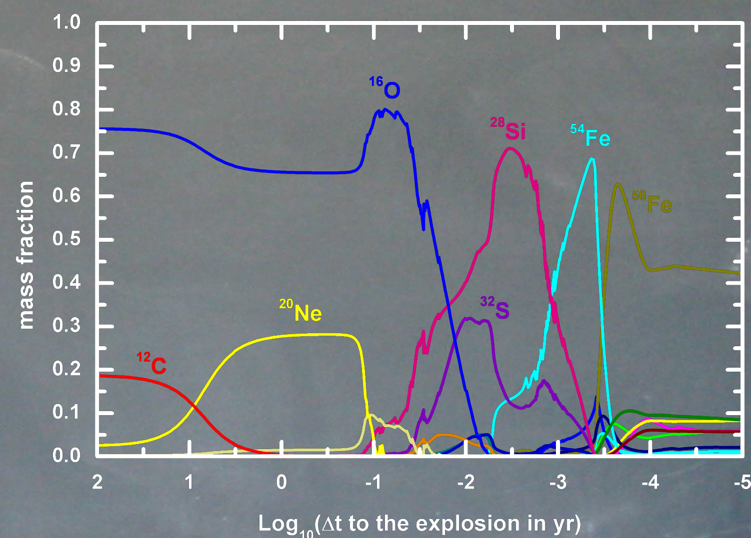
FIG. 6.—Most efficient nuclear processes during the central carbon burning. (*a*) The first part of the carbon burning; (*b*) the second part of carbon burning.

Ne burning

Typical temperature: 1.3-1.6 BK







Just the main processes in ...

Ne burning

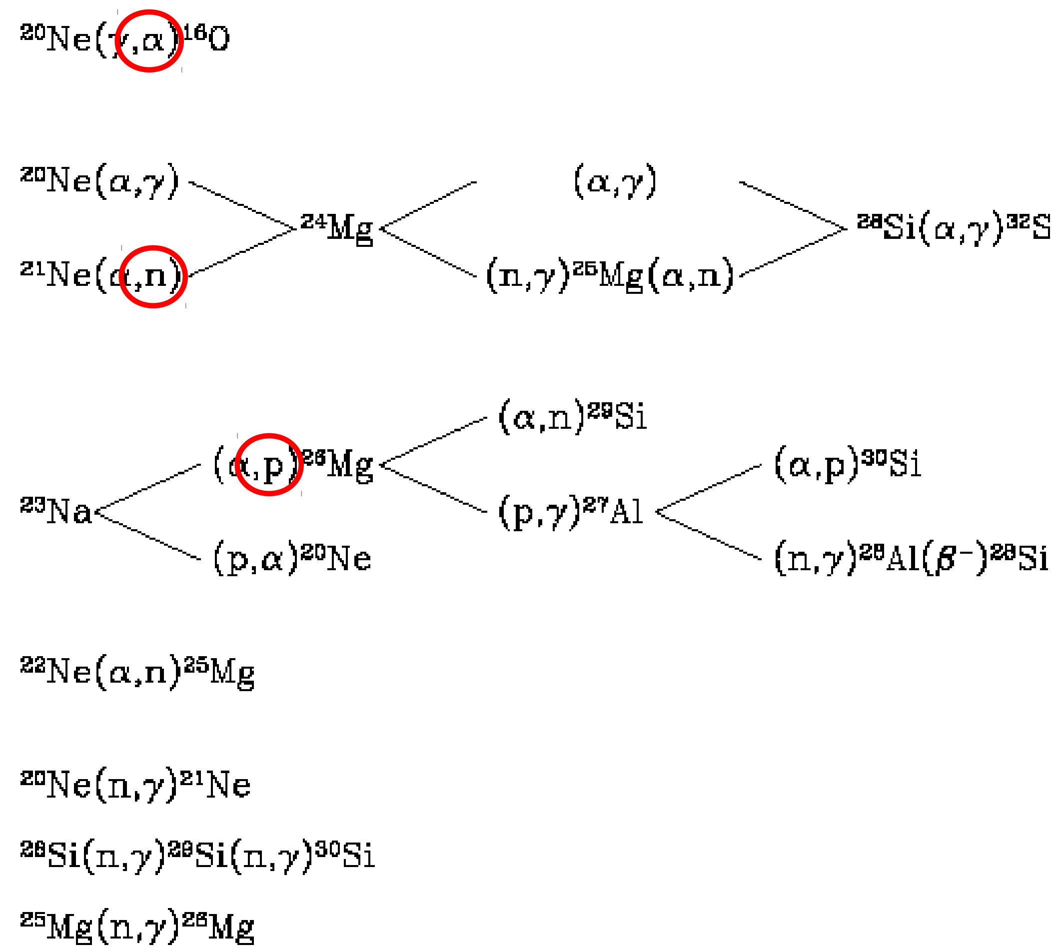
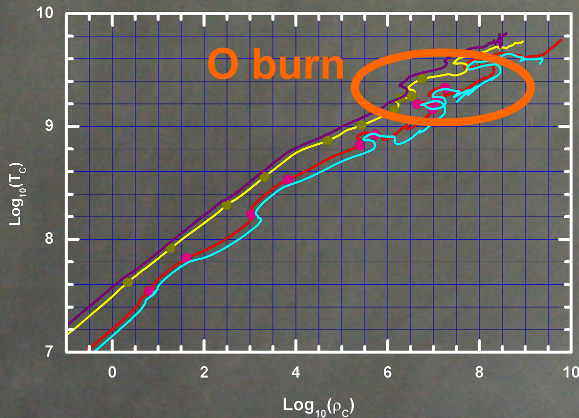
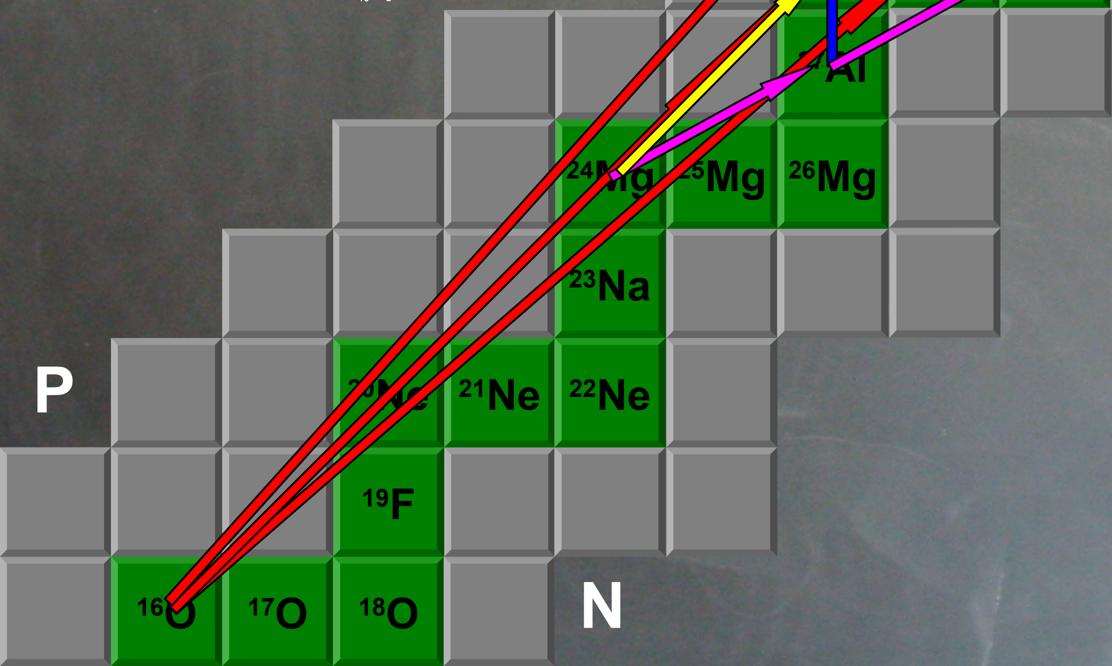


FIG. 8.—Most efficient nuclear processes during the central neon burning

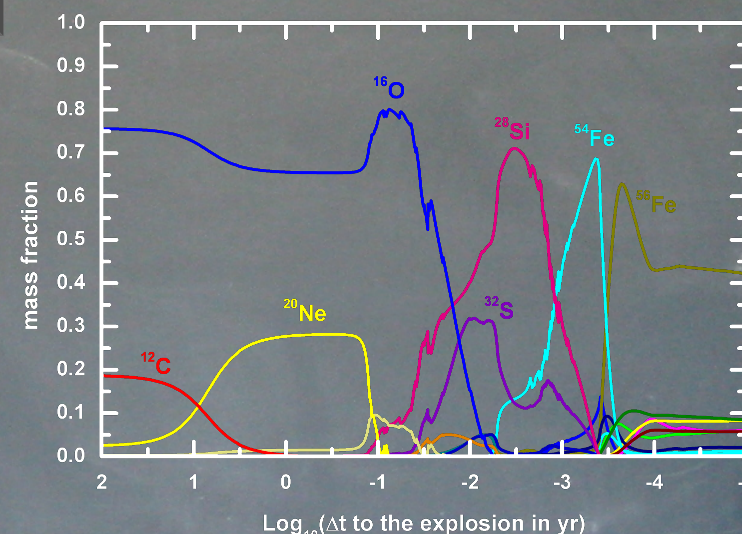
O burning

Typical temperature: 2.-2.5 BK



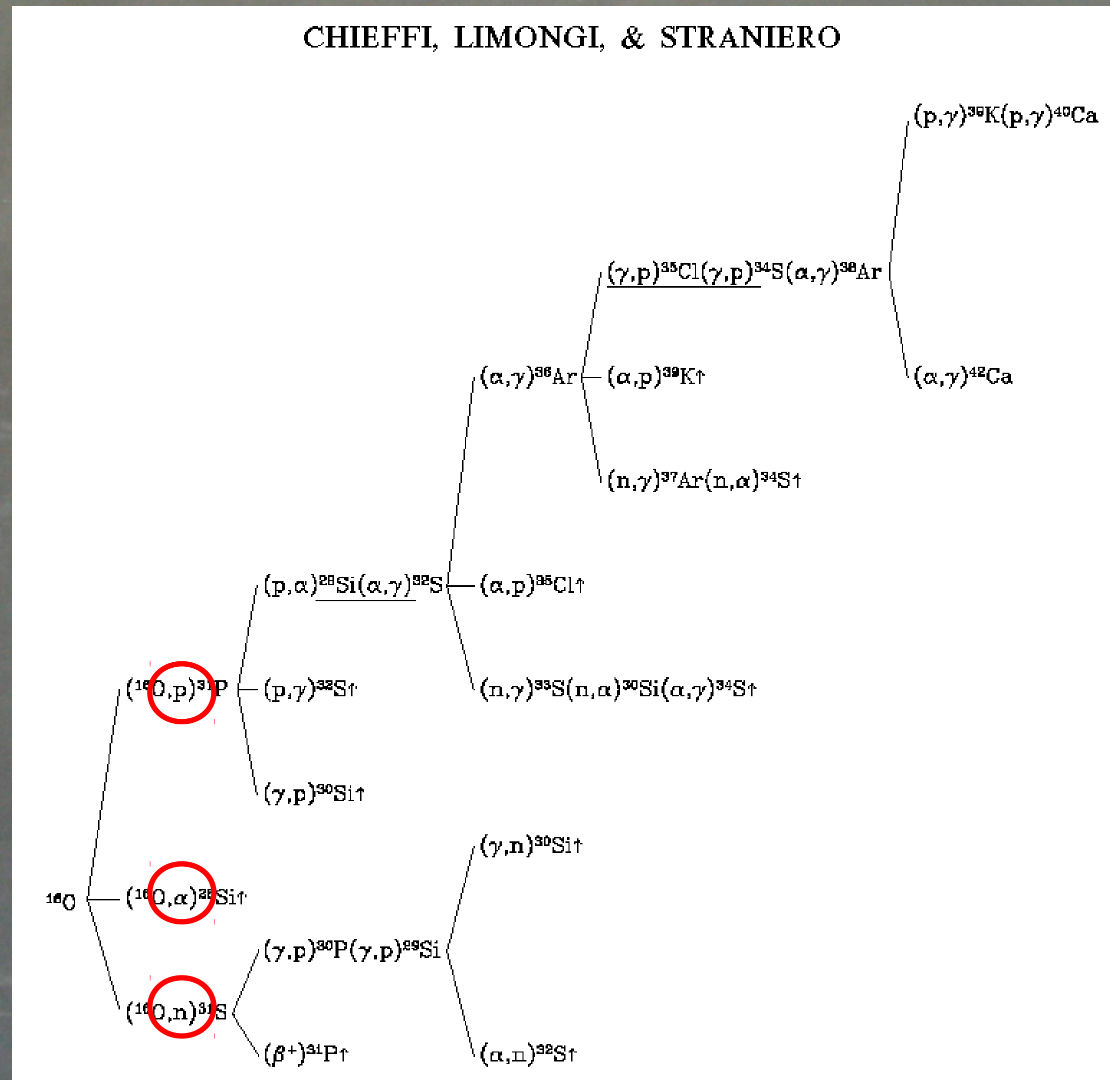


Convective core always of the order of 1-1.5 M_O



Just the main processes in ...

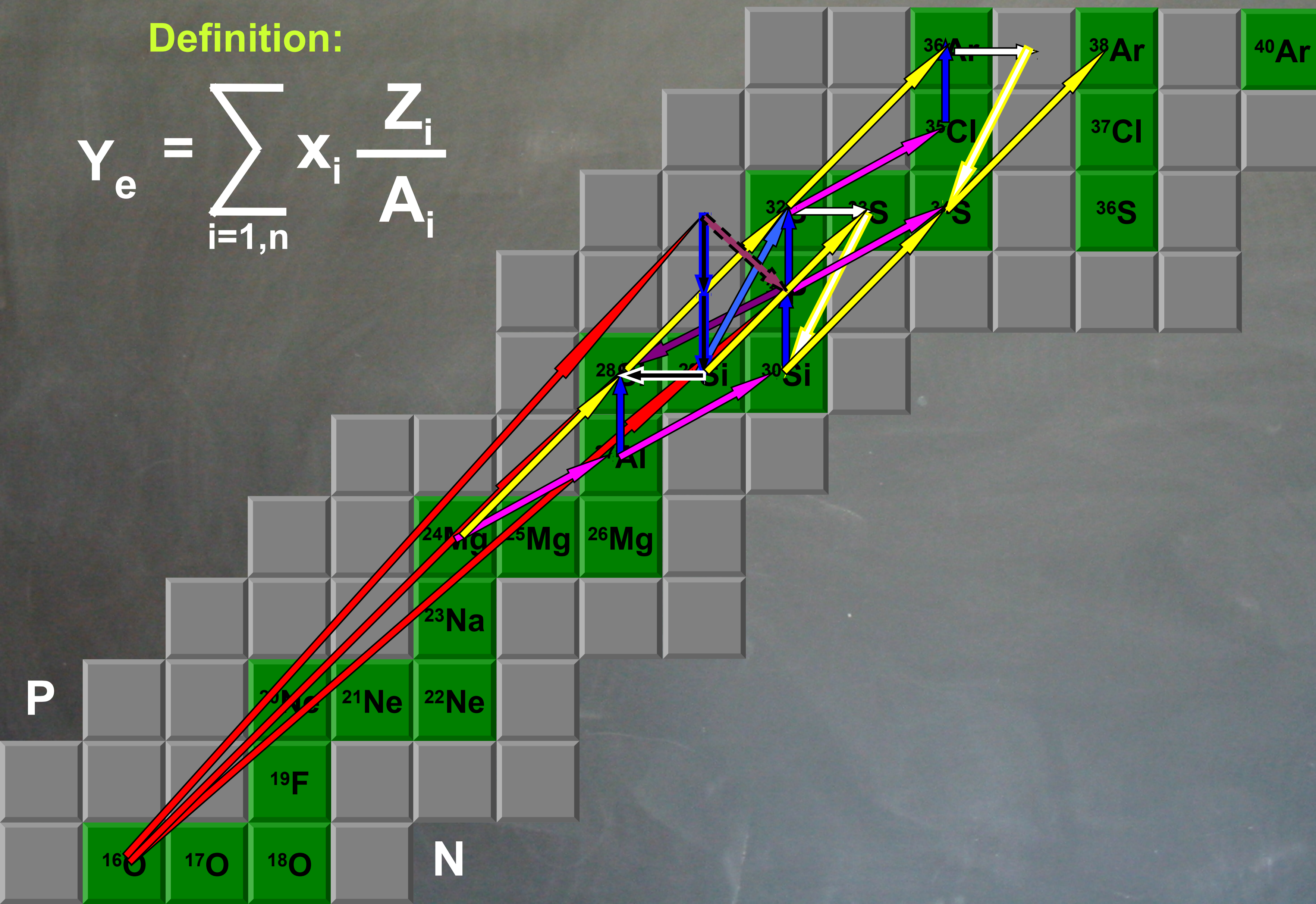
O burning



neutronization

Definition:

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

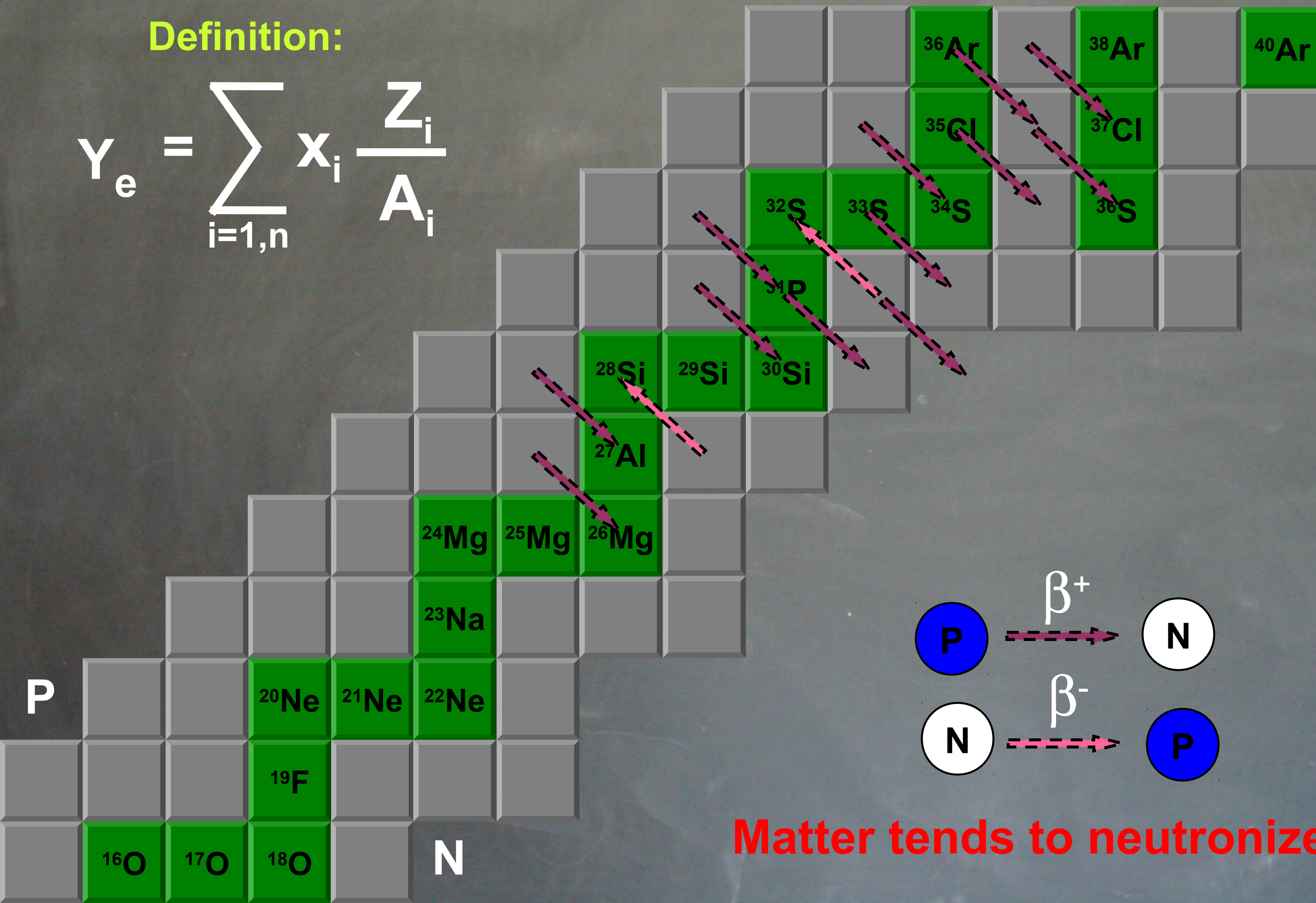


neutronization

Definition:

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

Main weak processes in O burning



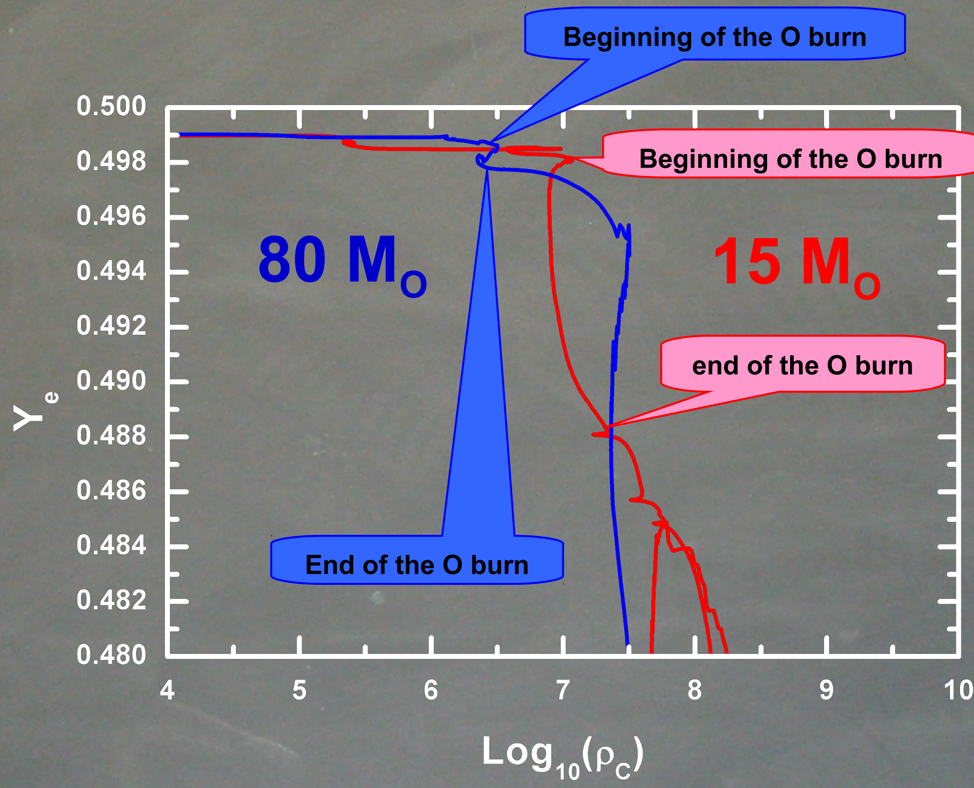
Matter tends to neutronize !

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

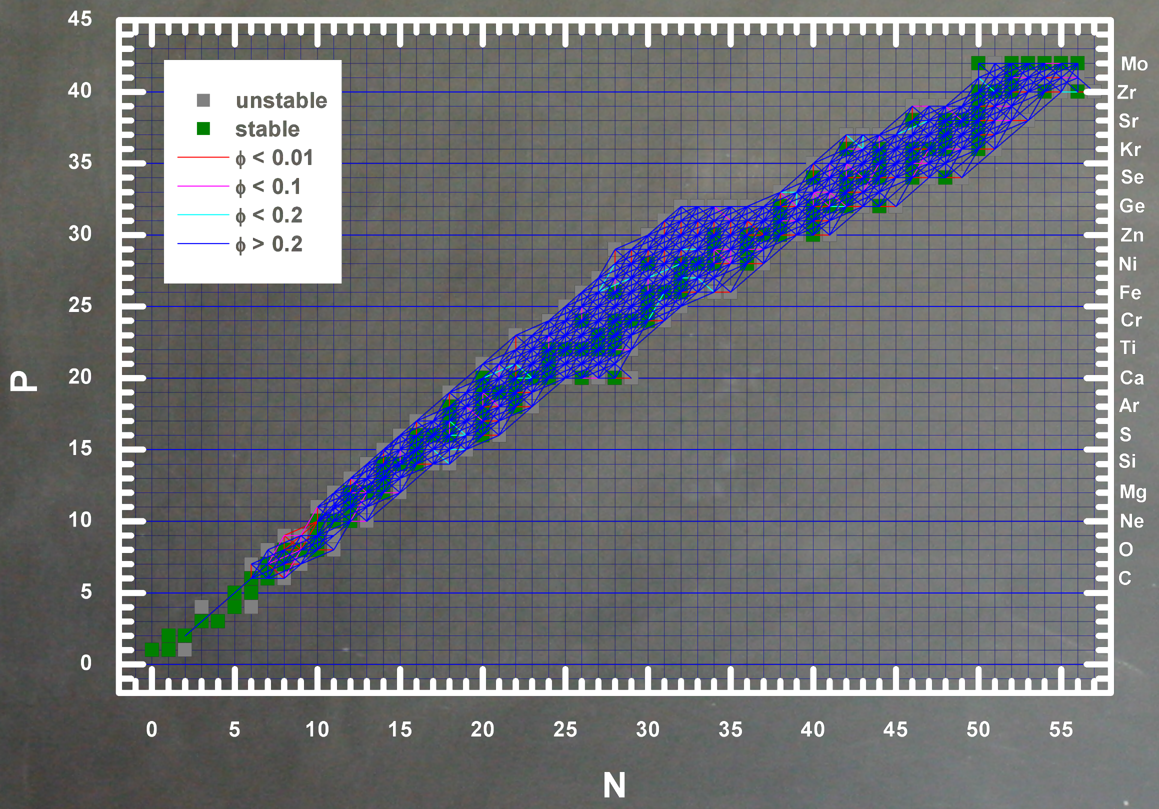
R_{mk} → Rate of the m(k,j)i process

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

Φ= 0 means perfect equilibrium

Φ =1 means one process dominates over the other

The approach to the Nuclear Statistical Equilibrium



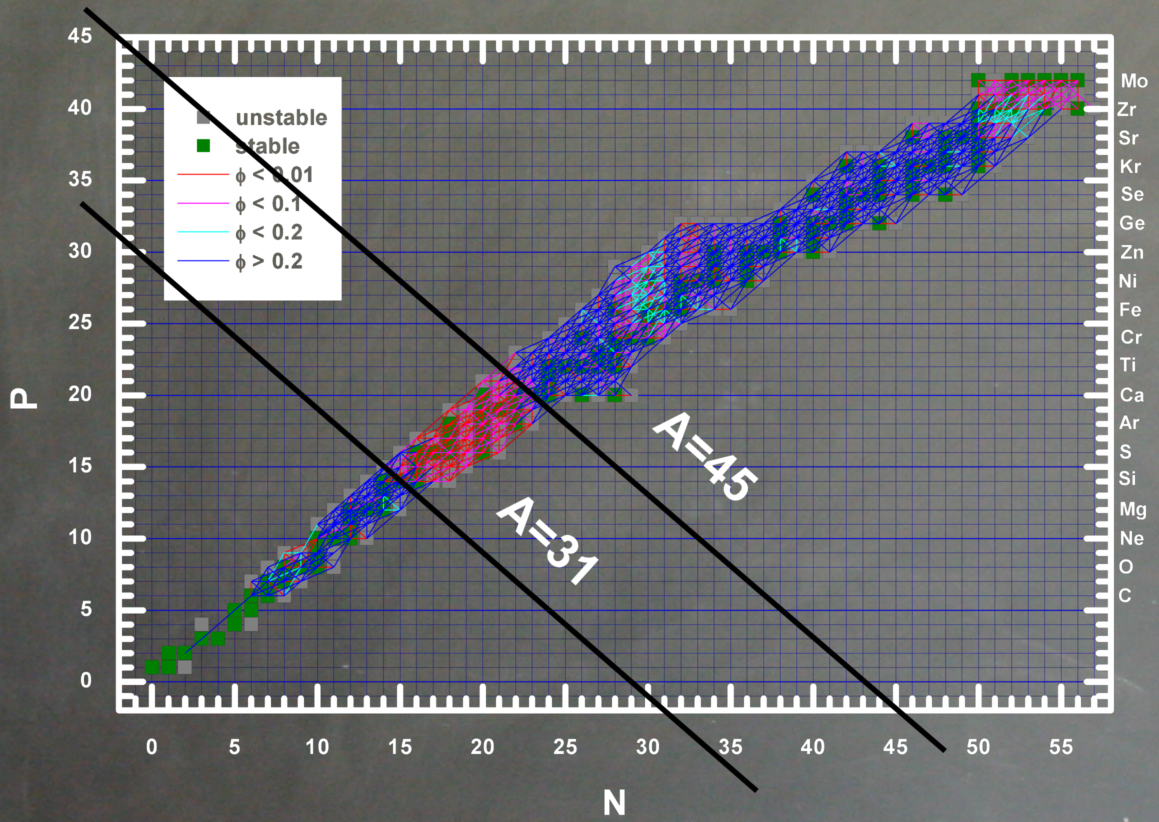
T=1.9 BK

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



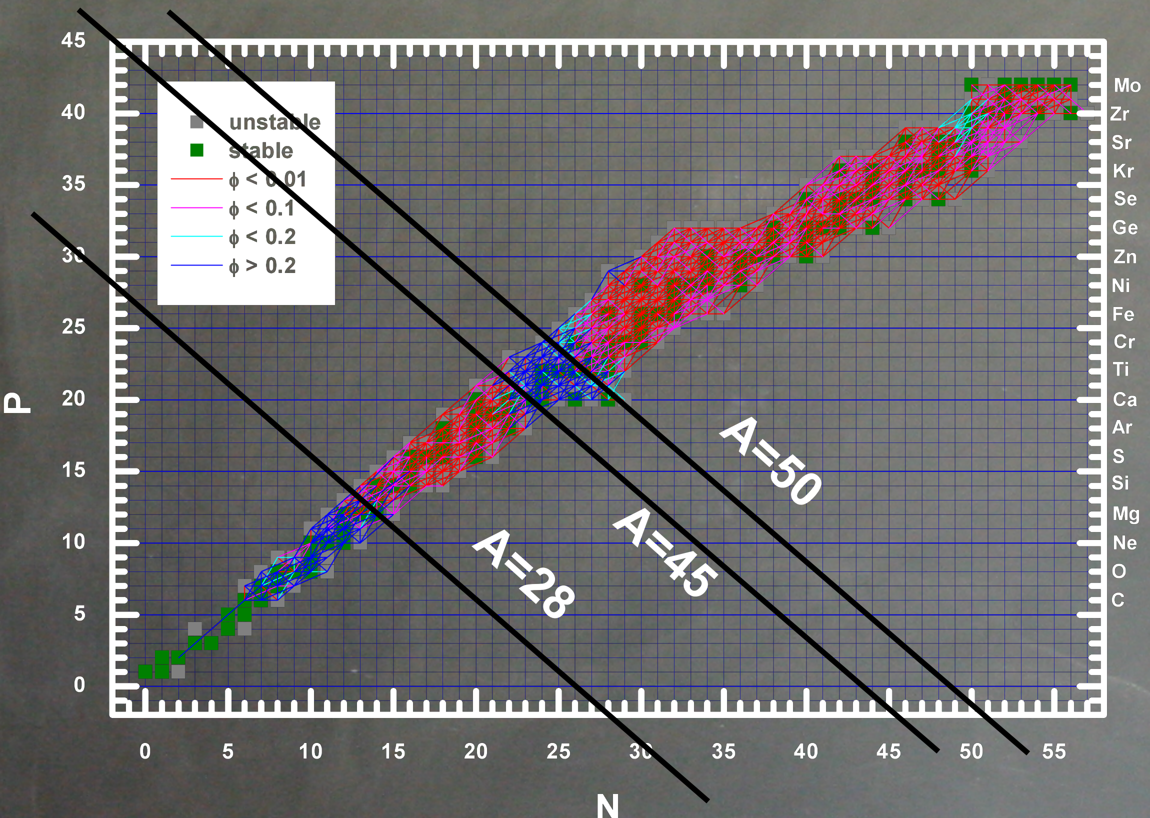
T=2.7 BK

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

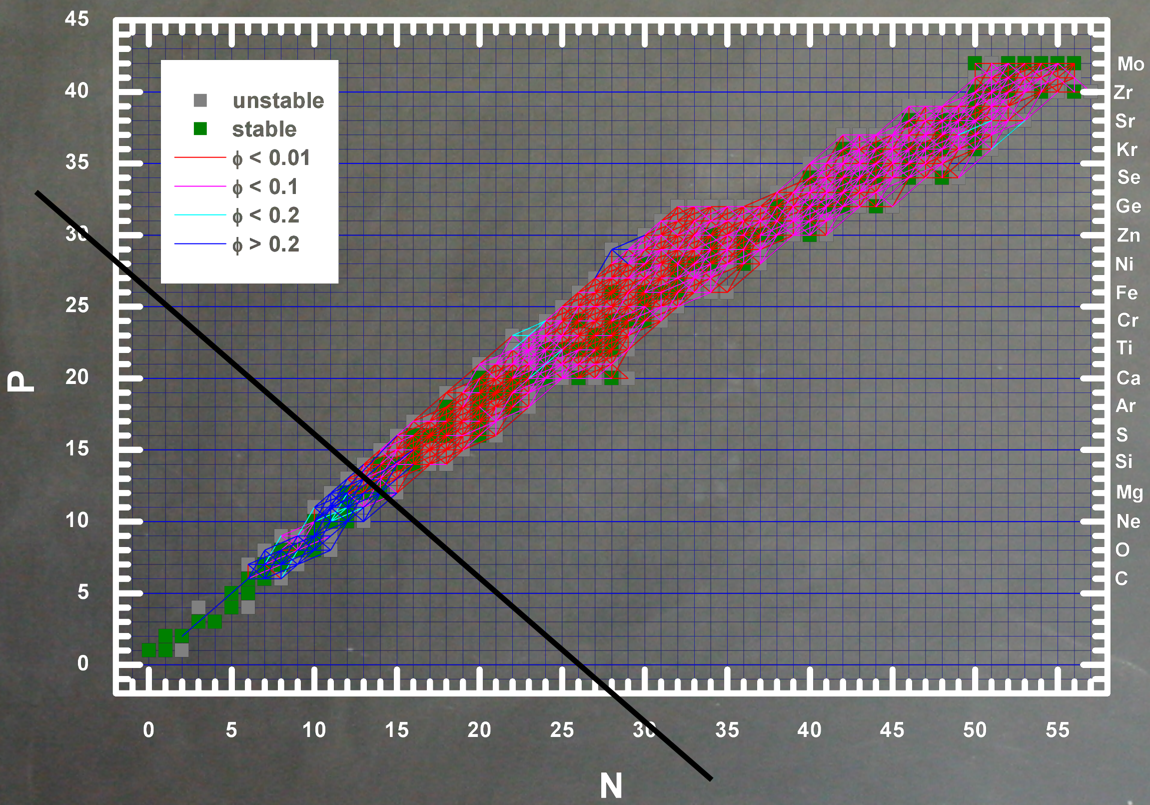
A little bit before the Si burning
Y_e=0.4976

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 equilibrium 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



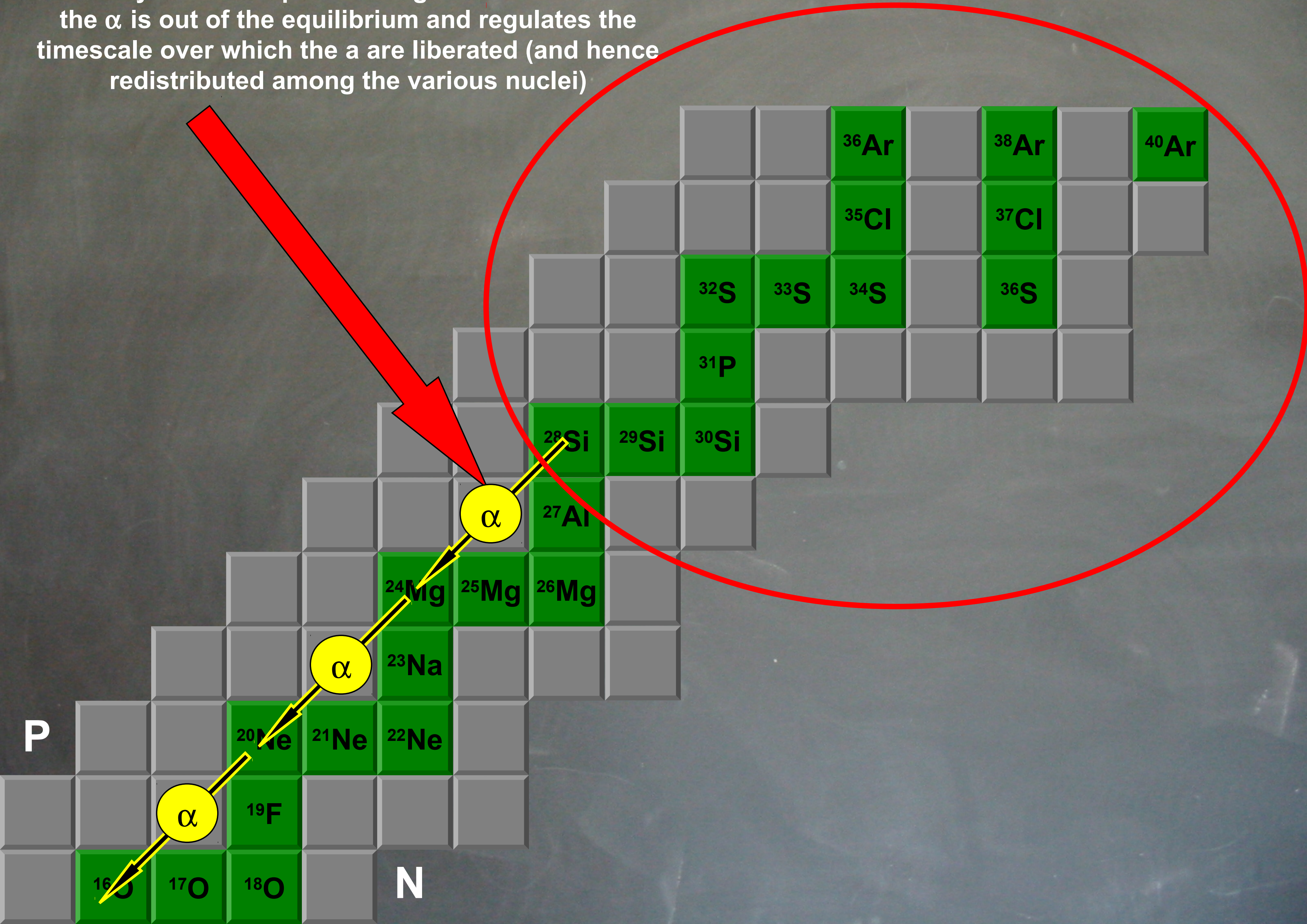
T=3.4 BK

Beginning of the Si burning
Y_e=0.4955

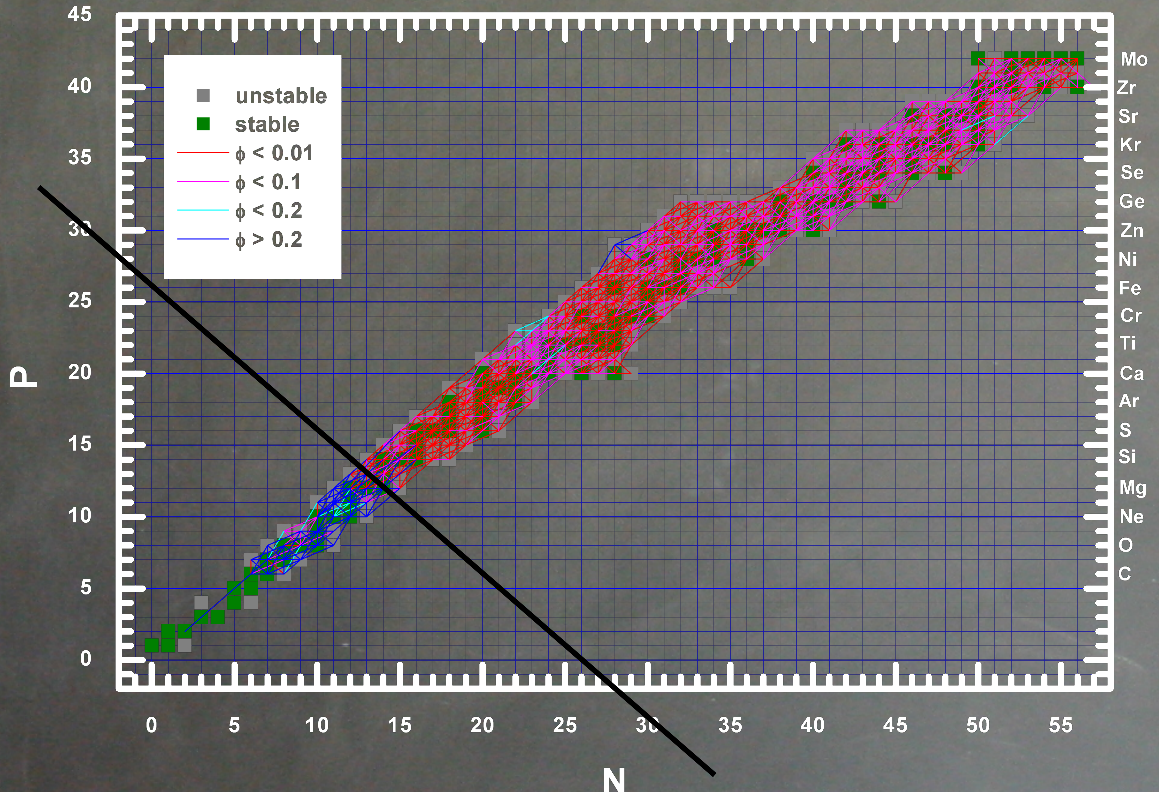
The two clusters begin to merge and form an unique cluster that starts at A=28

^{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



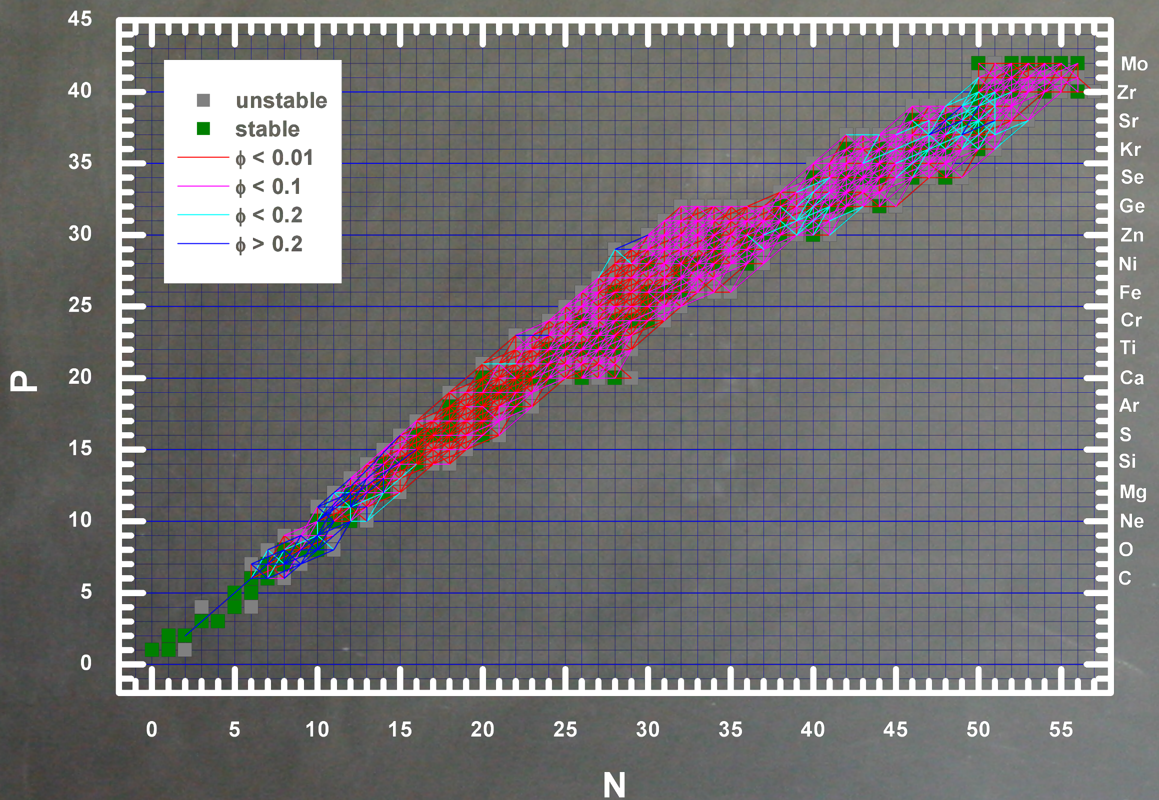
T=3.4 BK

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

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:

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

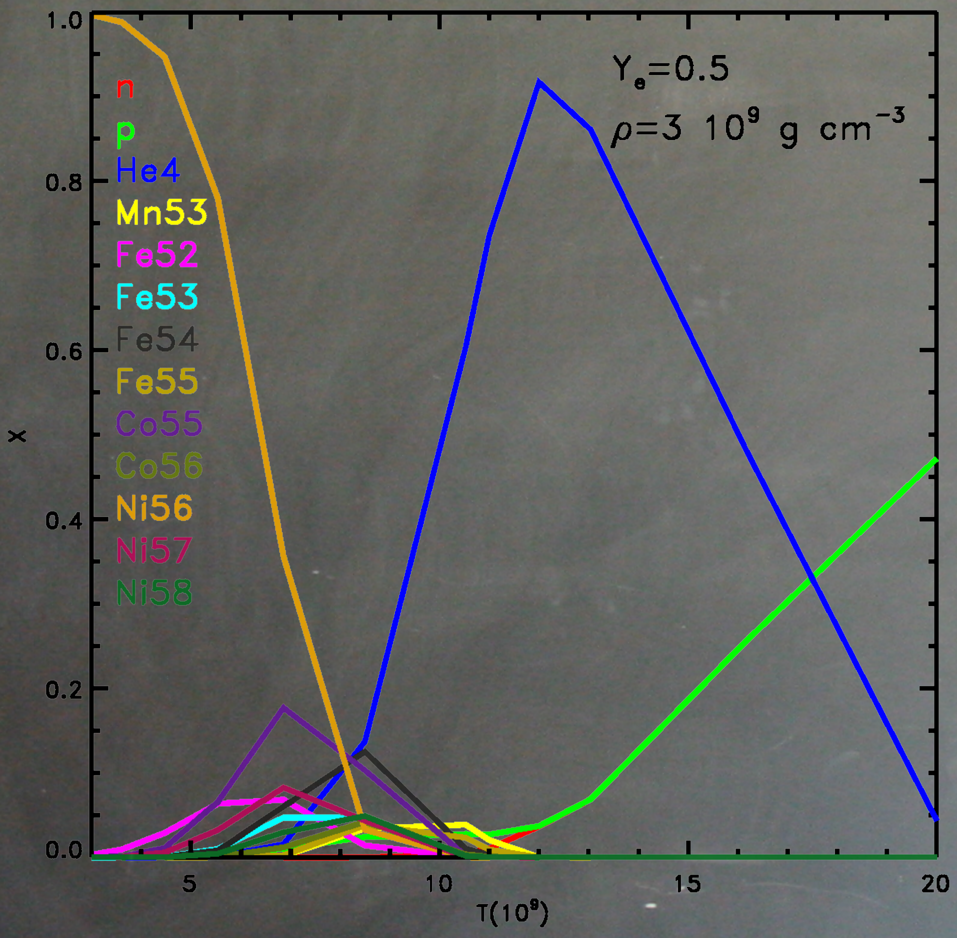
The system is closed by the conditions:

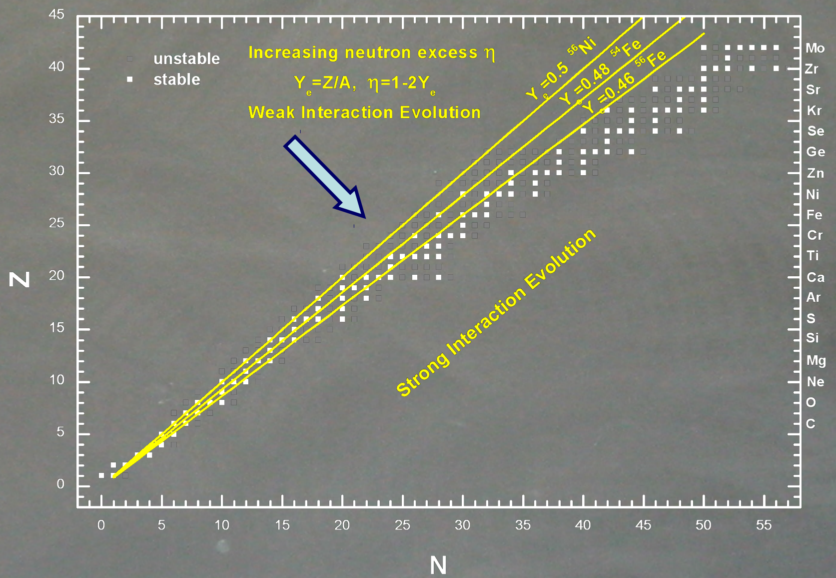
Mass conservation → $$\frac{\sum Y_i \cdot A_i}{\sum Y_i} = 1$$

Electron mole number conservation → **Ye = constant (at each time)**

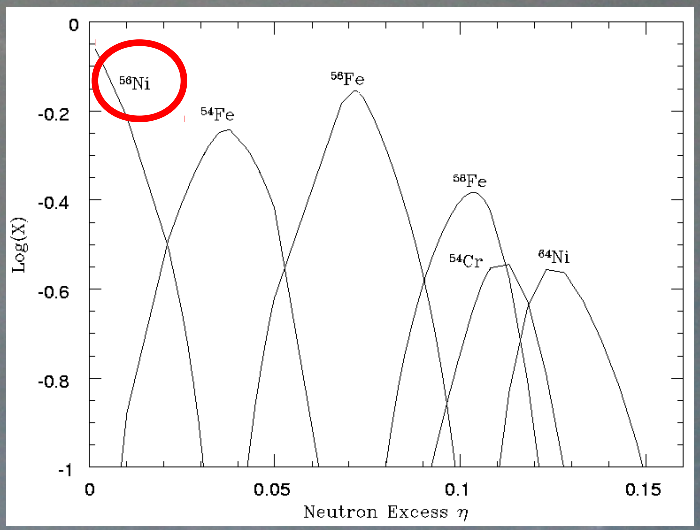
The abundances of all nuclei depend only on ρ , T and Y_e

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



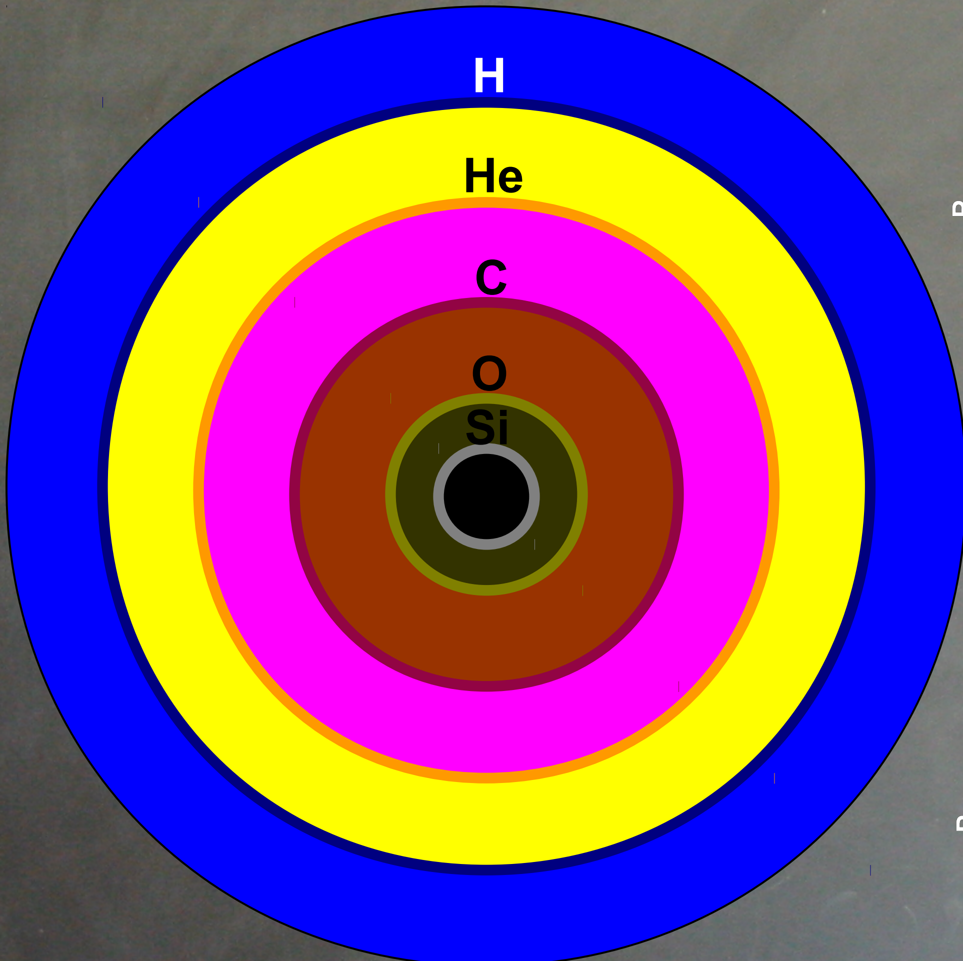


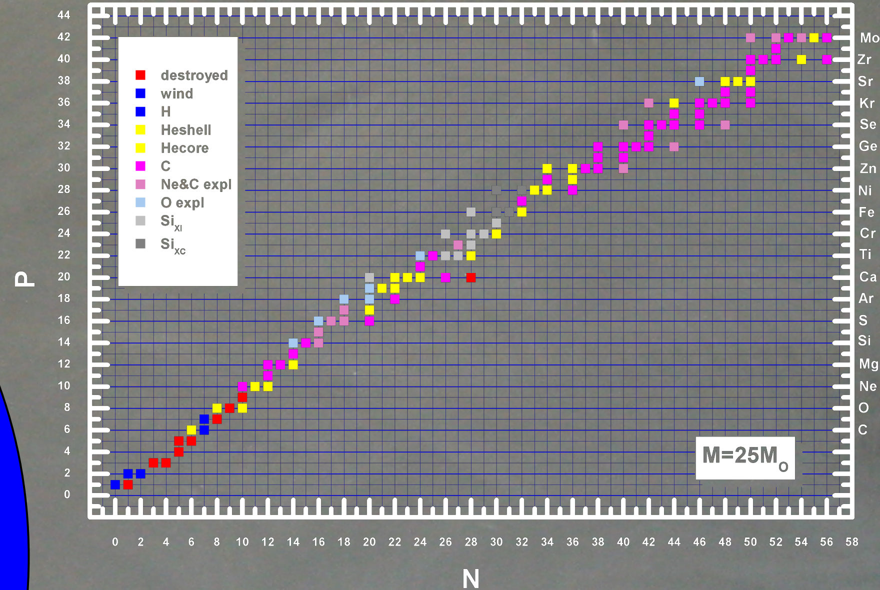
$T = 5 \cdot 10^9$ K $\rho = 10^8$ g/cm^3

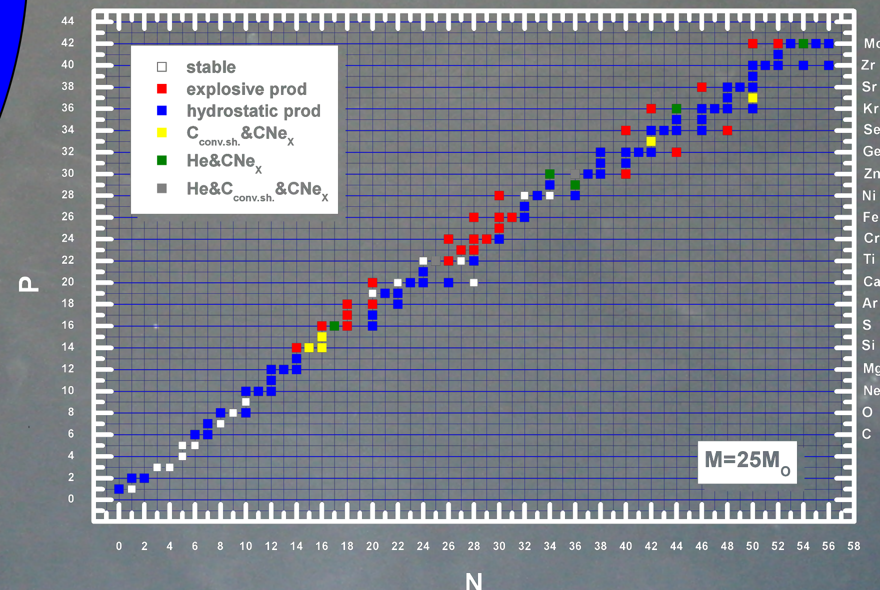


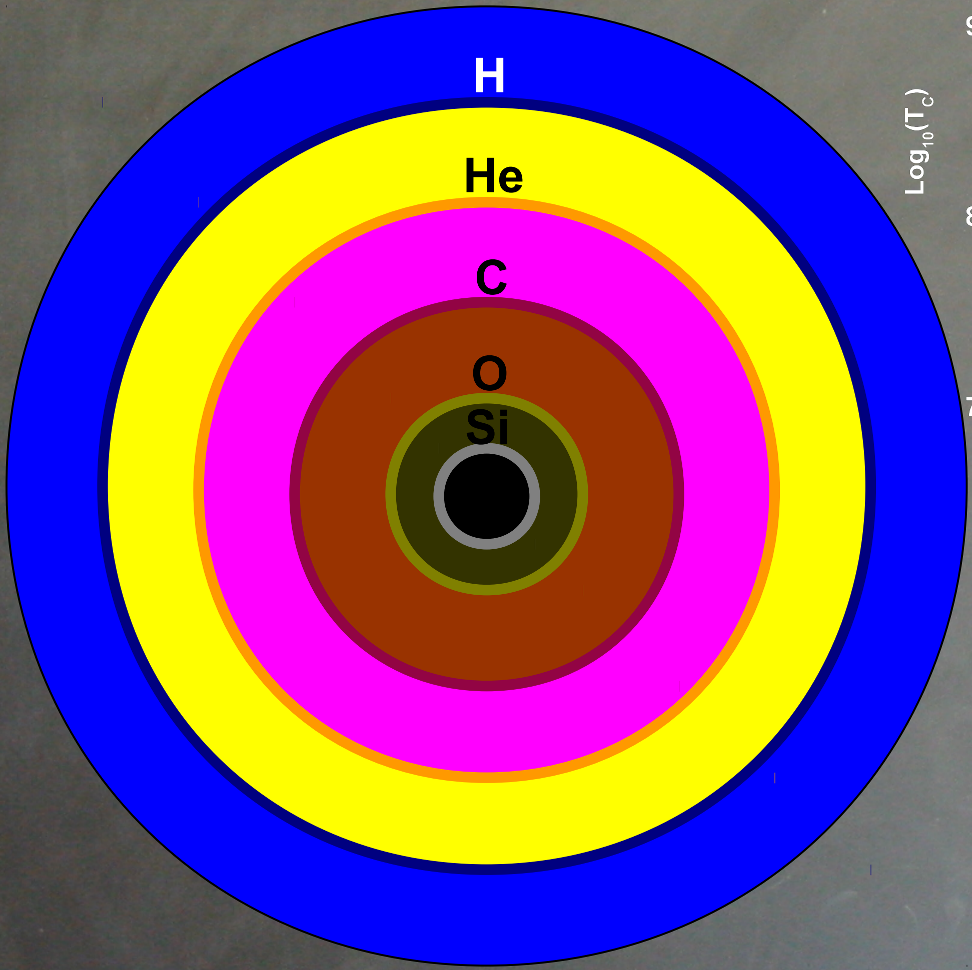
Trailer time!

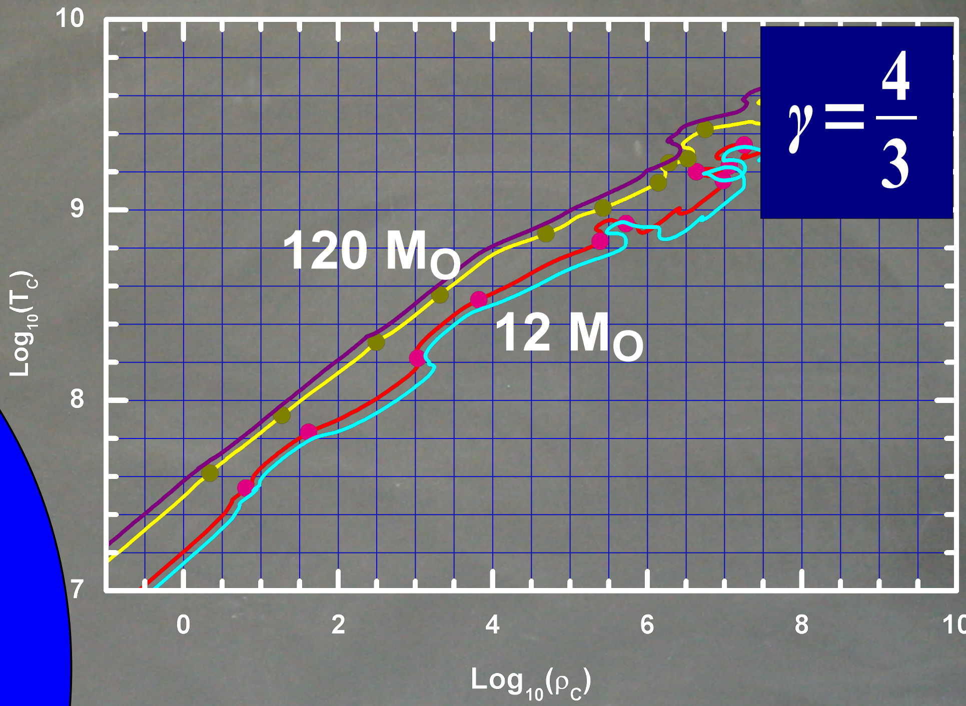
C, Ne, O & Si burning movie


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 Zr Sr Kr Se Ge Zn Ni Fe Cr Ti Ca Ar S Si Mg Ne O C





Virial theorem

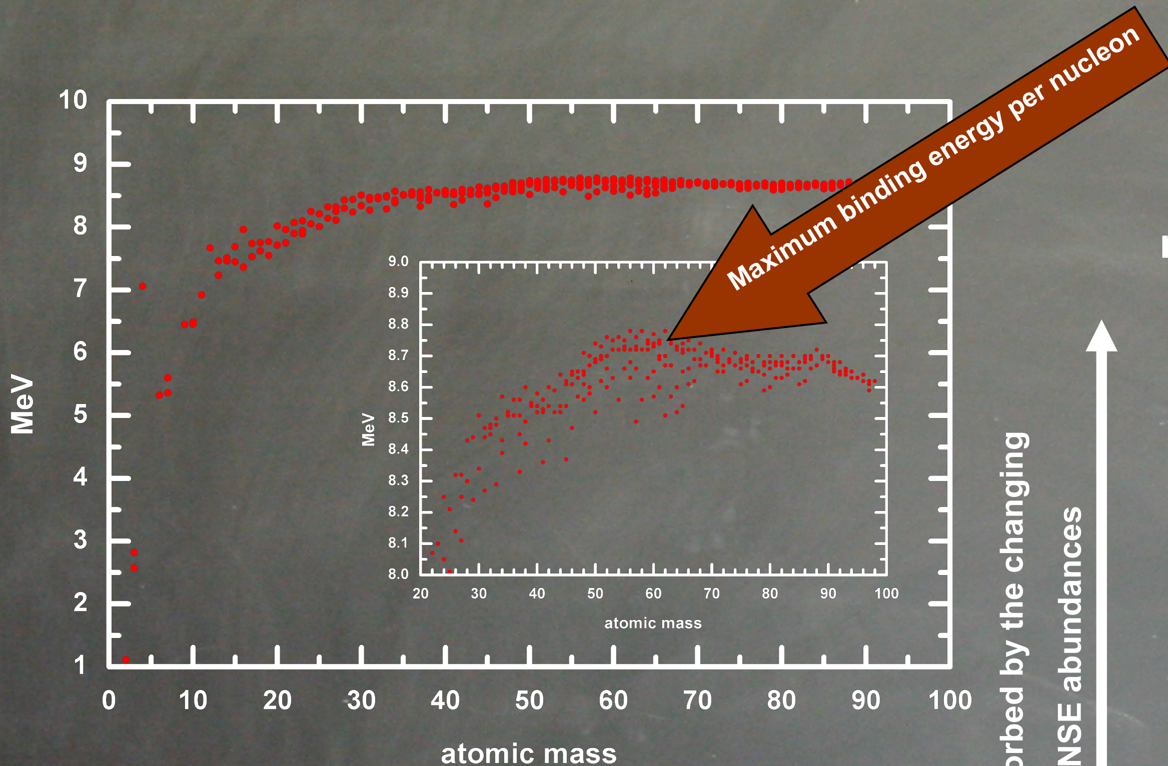
$$3(\gamma-1)U+\Omega=0$$

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

$$\Delta E_{TOT} \equiv 0$$

NO delay is required for a contraction, the structure is only marginally stable

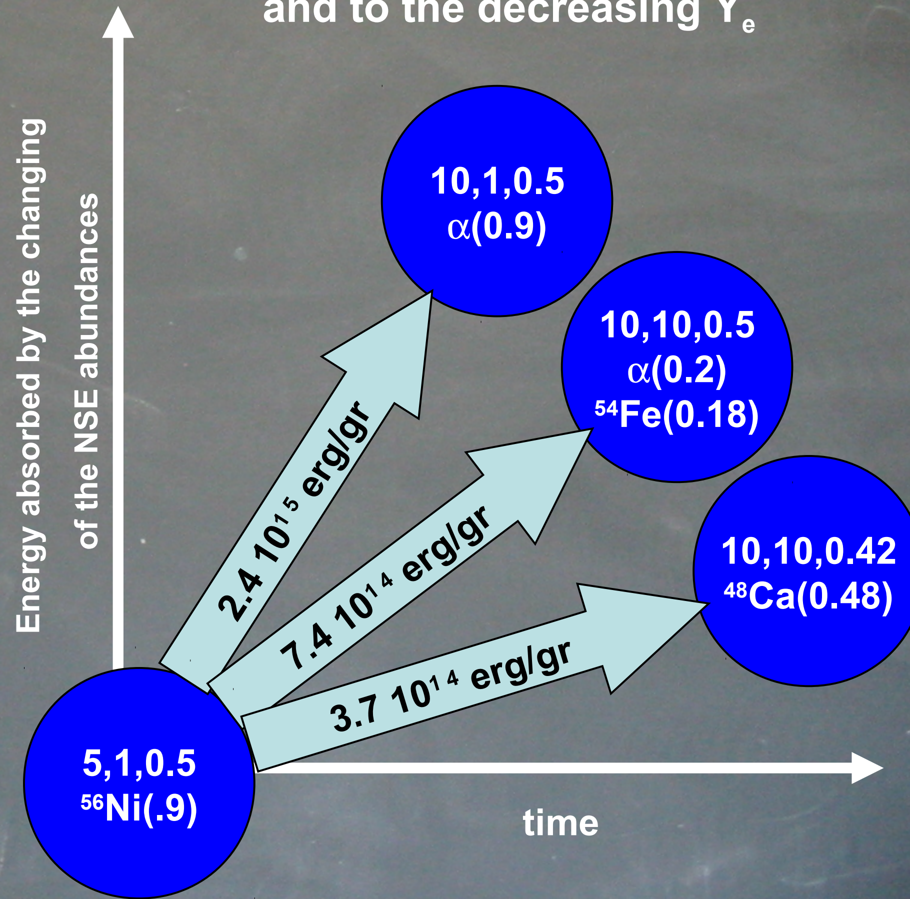
What happens to the inner core after the central Si burning?

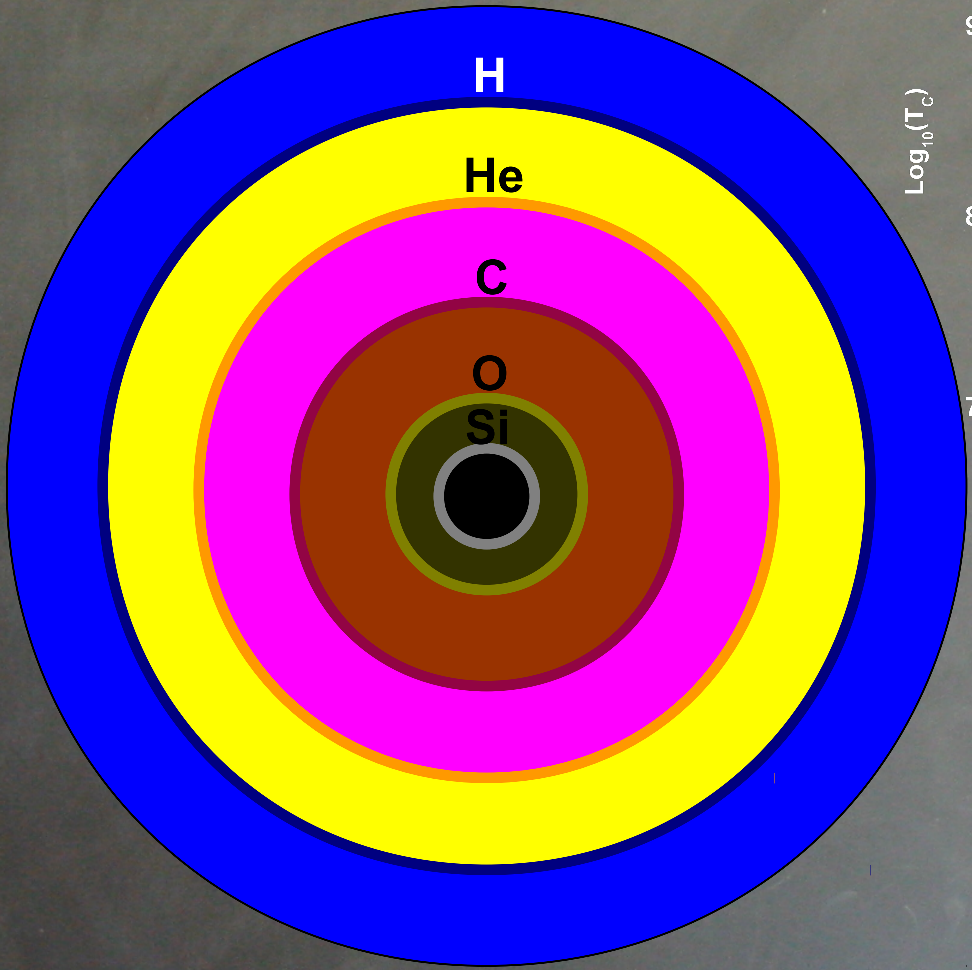


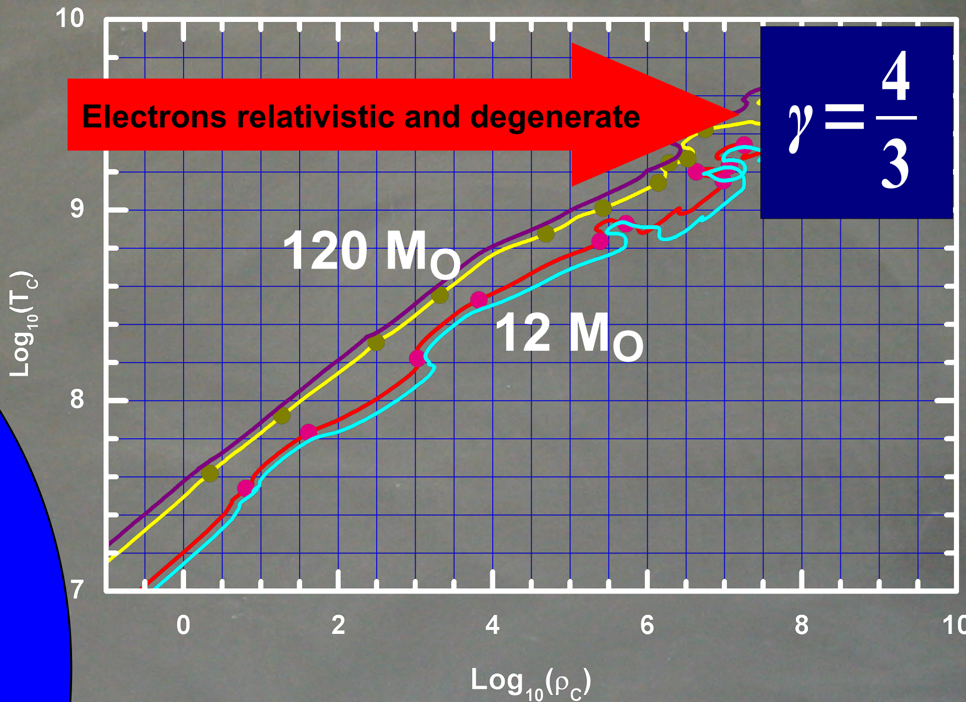
NSE abundances

readjust to the increasing T and ρ

and to the decreasing Y_e







Virial theorem

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

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

$$\Delta E_{TOT}\equiv 0$$

NO delay is required for a contraction,

the structure is only marginally stable

Sequence of events that lead to the collapse

T

The passage from an NSE configuration to another one of higher T,ρ and lower Ye absorbes energy and hence speeds up the contraction.

Electrons become relativistic degenerate, so that $\gamma=4/3$

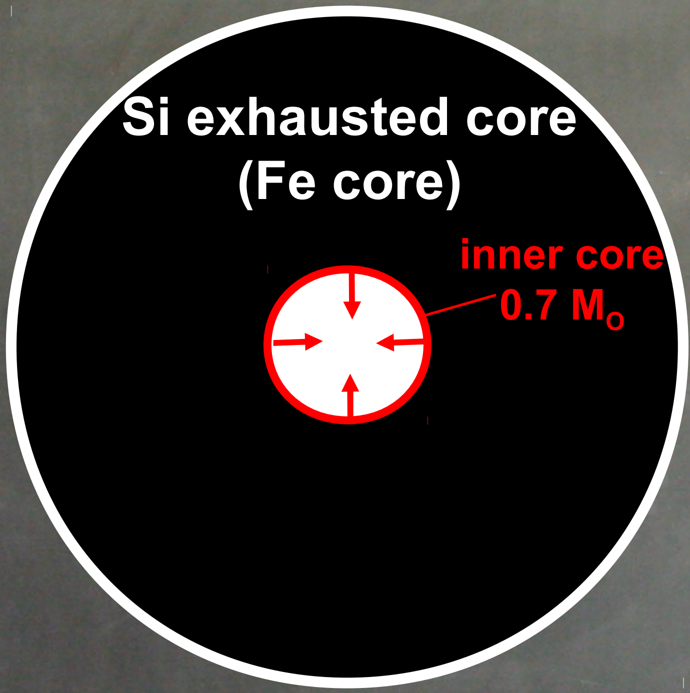
The weak processes substract electrons and hence pressure.

The reduction of the pressure worsens the problem because it translates in a further contraction, electron more relativistically degenerate and stronger weak processes.

The Chandrasekhar mass reduces because $M_{CH}= 5.76\ (Y_e)^2$

No configuration equilibrium exists any more and the collapse starts

Basic core collapse scenario



The inner 0.7-1 M_O starts collapsing

The collapse stops only when matter reaches the nuclear densities:

$$\rho \simeq 10^{14}\, g\, cm^{-3}$$

because at this stage matter becomes incompressible

If we assume that the density is constant throughout the collapsing core, we can easily estimate the final radius of a giant “NUCLEUS” of 1 M_O:

$$M = \frac{4}{3}\pi R^3 \rho \;\Rightarrow\; R = \left(\frac{3}{4\pi}\frac{M}{\rho}\right)^{1/3} \simeq 17\, Km$$

If, for simplicity, we assume constant density: $\Omega = -\int_0^M \frac{G M}{R}\, dm = -\frac{3}{5}\frac{G M^2}{R}$

$$\Delta\Omega = \Omega_{final} - \Omega_{initial} = -\frac{3}{5} G M^2 \left(\frac{1}{R_{final}} - \frac{1}{R_{initial}}\right) \simeq -1.58\, 10^{59} \left(\frac{1}{R_{final}}\right)$$

$$\simeq 1.6\, 10^{53}\, erg$$

(assuming a radius of 10 Km)

Is this energy enough to drive a successful explosion?

Inventory:

Initial pot: $1.6 \cdot 10^{53}\, erg\, M_O^{-1}$

As T and ρ increase, NSE favors P and N so we must consider the energy required to dissociate nuclei in P and N:

$$\Delta E = \left(28 \mathrm{M}_P + 28 \mathrm{M}_N - M\left({}^{56}Ni\right)\right) 1.49 \cdot 10^{-3} \frac{6.022 \cdot 10^{23}}{56} 1.989 \cdot 10^{33} = 1.7 \cdot 10^{52}\, erg\, M_O^{-1}$$

Most of the P tend to convert in N as nucleons begin to feel their fermion soul:

$$\Delta E = (M_N - M_P - M_e) 1.49 \cdot 10^{-3} \frac{6.022 \cdot 10^{23}}{1} 1.989 \cdot 10^{33} = 1.5 \cdot 10^{51}\, erg\, M_O^{-1}$$

But in this process also neutrinos are emitted:

$$\Delta E = (20) 1.6 \cdot 10^{-6} \frac{6.022 \cdot 10^{23}}{1} 1.989 \cdot 10^{33} = 3.8 \cdot 10^{52}\, erg\, M_O^{-1} \qquad assuming\ E_\nu = 20\ MeV$$

The energy available to drive the explosion is therefore given by:

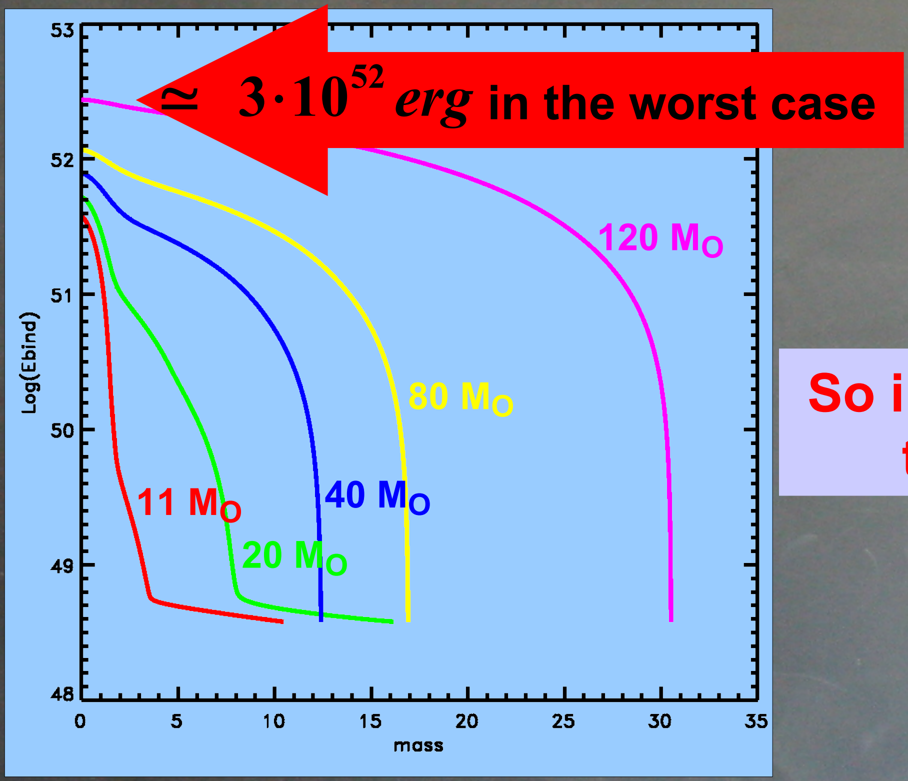
$$1.6 \cdot 10^{53} - 1.7 \cdot 10^{52} - 1.5 \cdot 10^{51} - 3.8 \cdot 10^{52} \simeq 10^{53}\ erg\, M_O^{-1}$$

Is this energy enough to drive a successful explosion?

Inventory:

… so we are left with $\simeq \quad 10^{53} \quad erg\, M_o^{-1}$

Binding energy of the mantle as a function of the mass coordinate



Observations show that some kinetic energy is provided to the ejecta and it ranges, roughly, between:

$$10^{50} - 10^{52} \quad erg$$

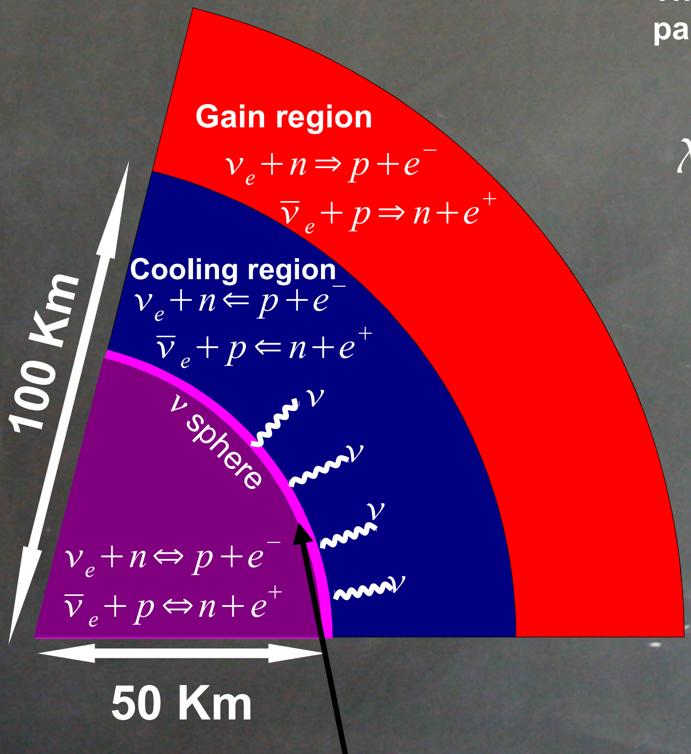
So in principle there is plenty of energy to drive a successful explosion!

Basic core collapse scenario

Unfortunately most of the energy gained during the collapse is emitted as ν and not as γ!

The reason is that, the relative proportions between P and N in the giant “nucleus” are kept at their equilibrium value by the two very efficient processes :

$$\nu_e + n \Leftrightarrow p + e^- \qquad \bar{\nu}_e + p \Leftrightarrow n + e^+$$



The mean free path λ between two successive interactions between the particles i and j is given by:

$$\lambda = \frac{1}{\kappa \rho}$$

Where κ, the “opacity”, may be expressed in terms of the probability σ_{ij} that an interaction between the particles i and j occurs:

$$\kappa = \frac{N_A}{A} \sigma_{\nu A}$$

The basic interaction between ν and a nucleus A is given by the neutral current coherent scattering , whose cross section is given by:

$$\sigma_{\nu A} \simeq 10^{-44} N^2 \left(\frac{E_\nu}{MeV} \right)^2 \quad cm^2$$

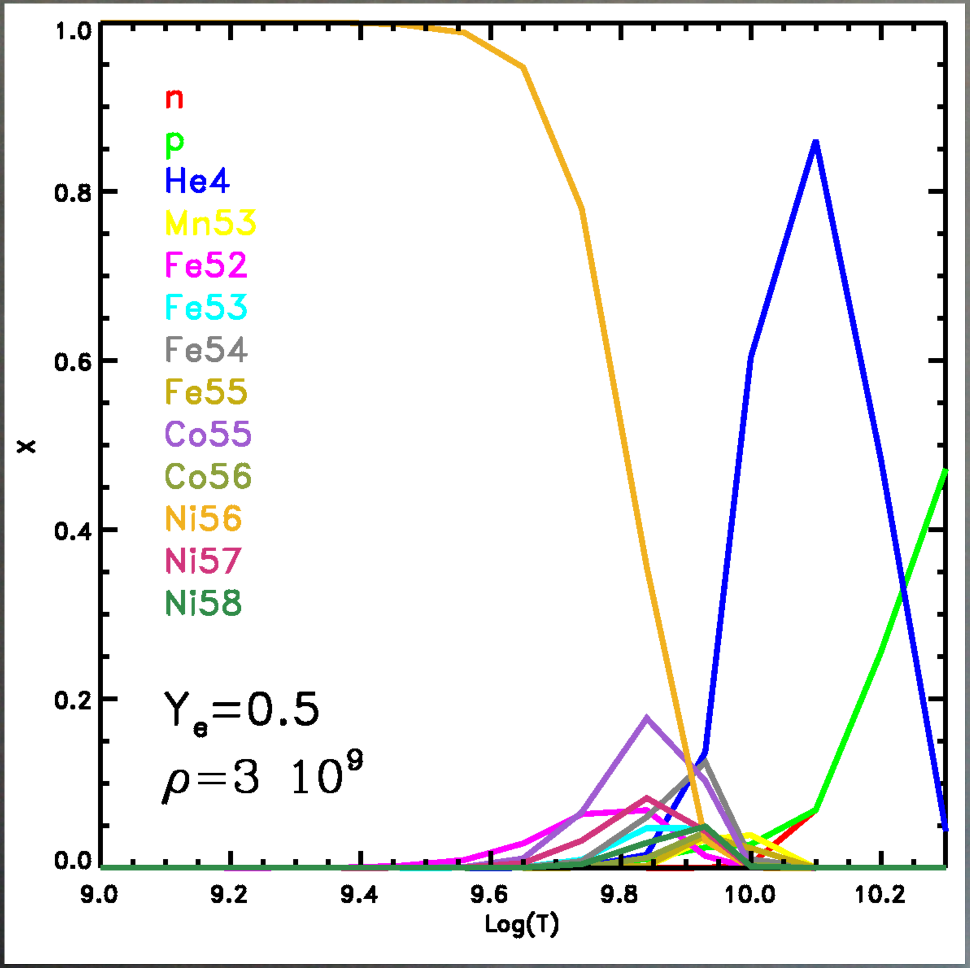
$$\lambda = \frac{A}{N_A \sigma_{\nu A} \rho} = \frac{1}{6.022 \cdot 10^{23} \, 10^{-44} \, 10^2 \rho} \simeq \frac{1.7\, 10^{18}}{\rho} cm$$

Basic core collapse scenario

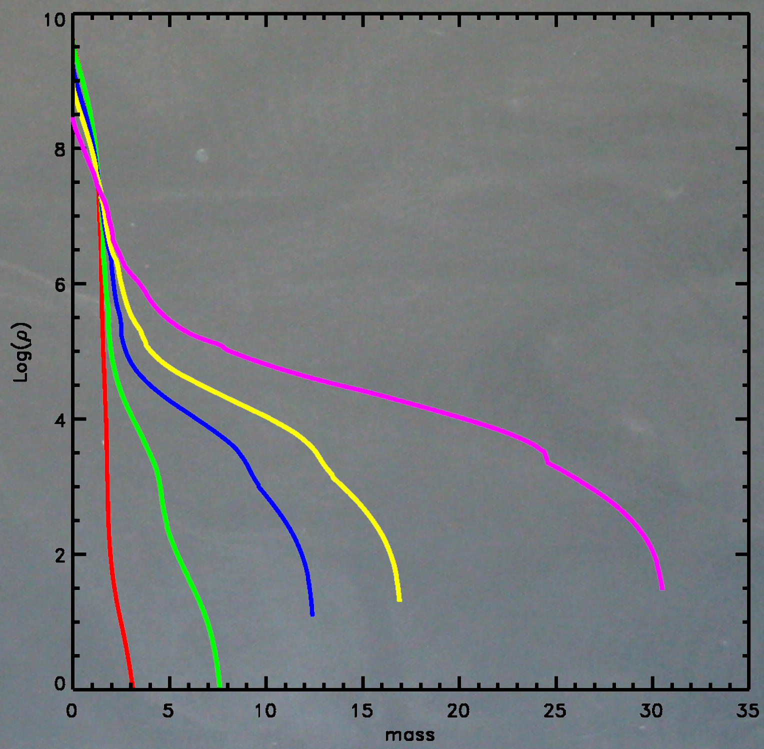
What it is even worst is that the shock wave lose a large amount of energy on its way out:

The reason is that it fully photodisintegrates matter as it advances in mass.

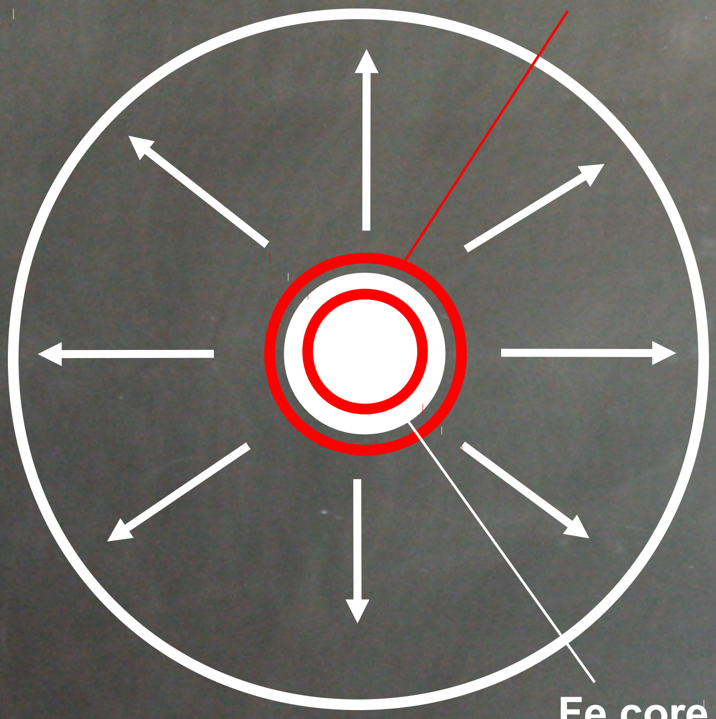
For example: $^{56}Fe \Rightarrow 30\ n + 26\ p$ requires the absorbtion of 7.87 10^{-4} erg (492 MeV)



8.47 10^{18} erg/gr => 10^{51} erg / 0.1 M_{O}



In spite of the many efforts, no successful explosion has been obtained yet



Escamotage:

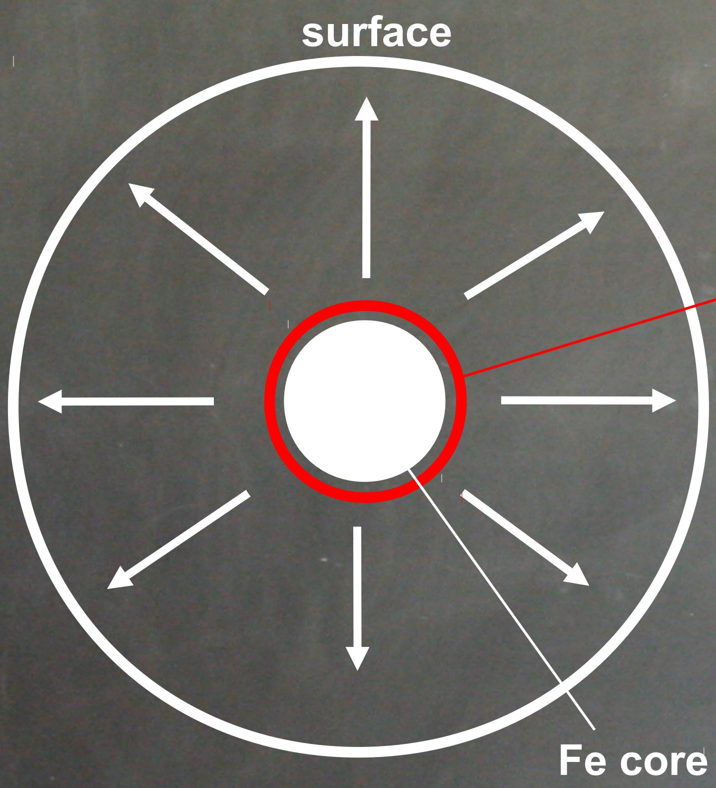
Assume that the shock wave escapes the dense core (roughly the Fe core)

Since the explosion is not obtained "naturally" a few assumptions are unavoidable:

1) **Energy deposited in the shock front**

2) **Formation of a shock driven convective zone**

Three different tecniques have been used up to now:



The piston (Woosley and coworkers)

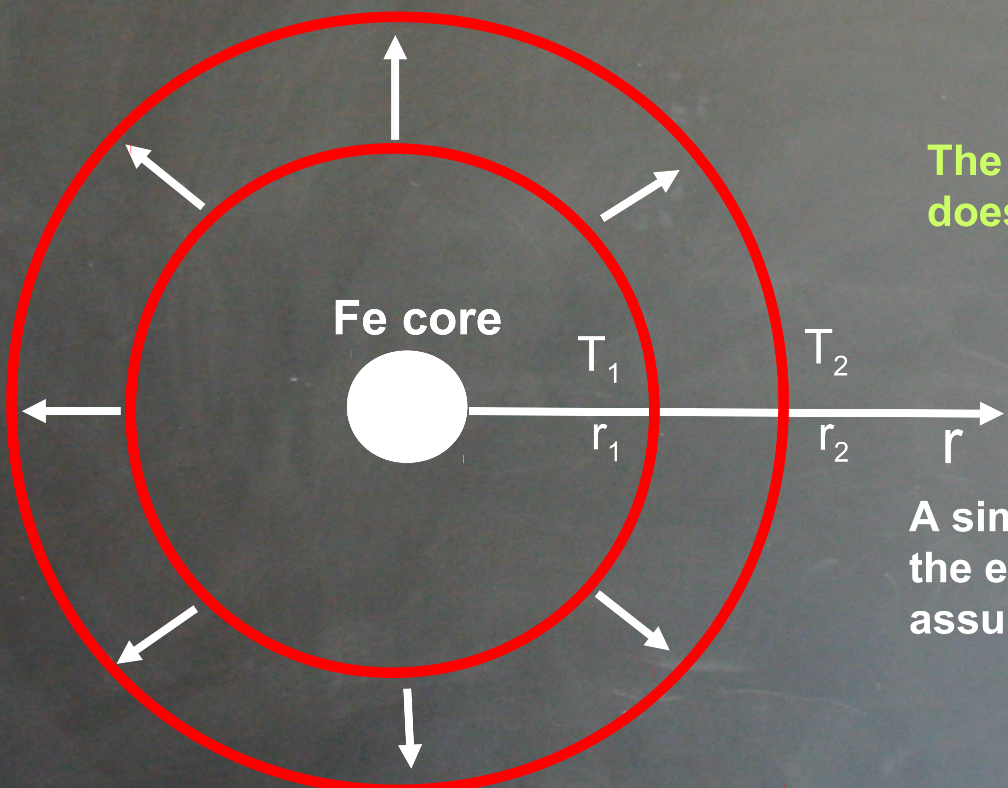
The thermal bomb (Nomoto and coworkers)

The kinetic bomb (Limongi and Chieffi)

BASIC PROPERTIES OF THE SHOCK WAVE AFTER IT HAS ESCAPED THE DENSE FE CORE:

RADIATION DOMINATED: → $$E = \frac{4}{3}\pi r^3 a T^4$$

ADIABATIC EXPANSION: → $$T = const \cdot r^{\frac{3}{4}}$$



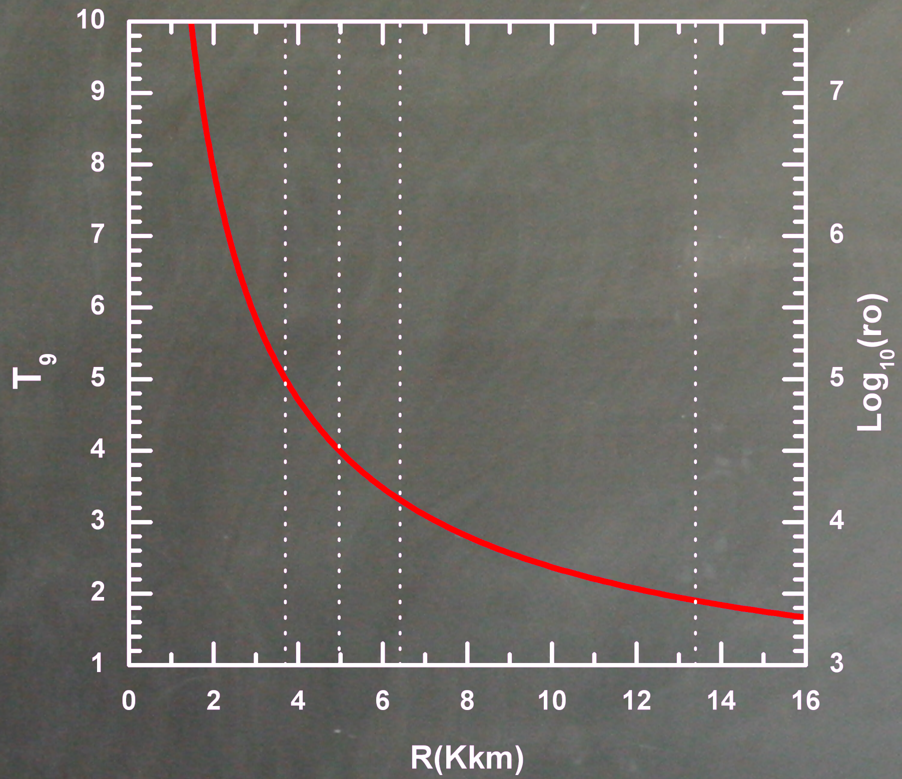
CONSEQUENCE:

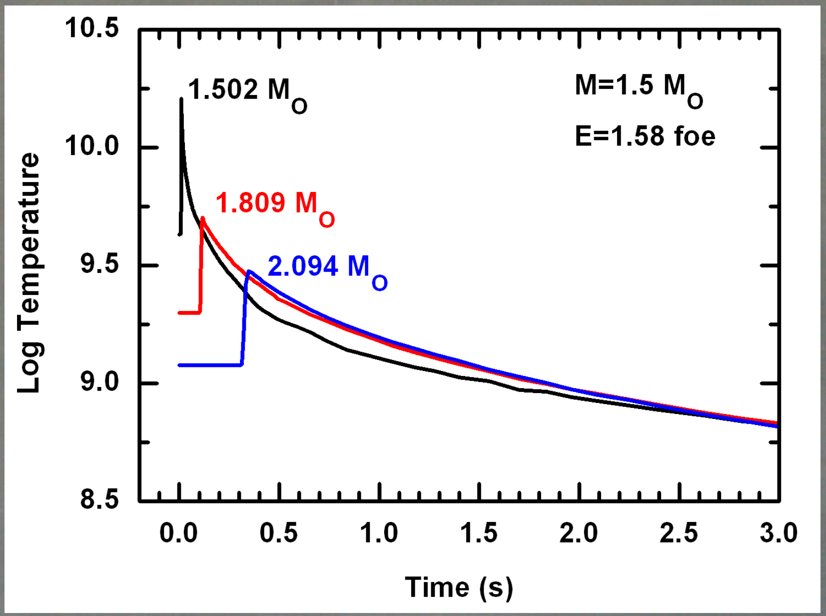
The peak temperature of the blast wave does not depend on the stellar structure.

A simple but quite effective computation of the explosive yields may be obtained by assuming:

$$T(t) = T_{peak}\, e^{-t/\tau}$$

Basic properties of the explosive burnings





$$\dot{Y}_i = \sum_j c_i(j)\lambda_j Y_j + \sum_{j,k} c_i(j,k)\rho N_A \langle\sigma v\rangle_{j,k} Y_j Y_k + \sum_{j,k,l} c_i(j,k,l)\rho^2 N_A^2 \langle\sigma v\rangle_{j,k,l} Y_j Y_k Y_l$$

The typical burning timescale for the destruction of any given nuclear specie is given by: $\tau_i \simeq \left| \frac{Y_i}{\dot{Y}_i} \right|$

CHARACTERISTIC EXPLOSIVE BURNING TEMPERATURES

The timescales for the destruction of H, He, C, Ne, O and Si are determined by these nuclear reactions:

He burning: $\alpha(2\alpha,\gamma)^{12}\mathrm{C}$

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

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

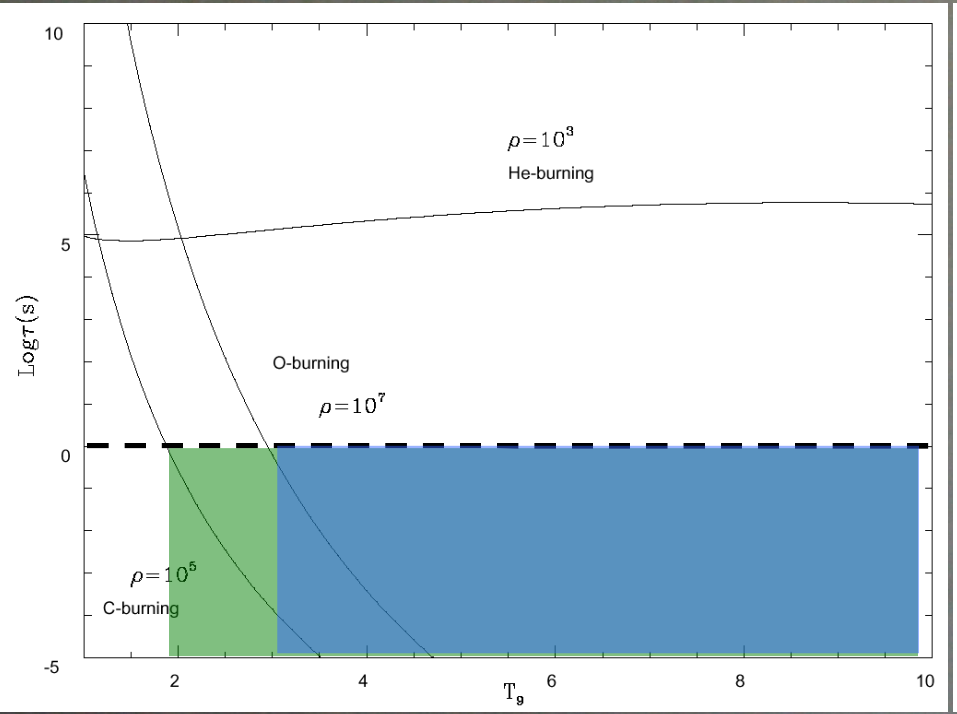
O burning: $^{16}\mathrm{O}(^{16}\mathrm{O},\alpha)^{28}\mathrm{Si}$

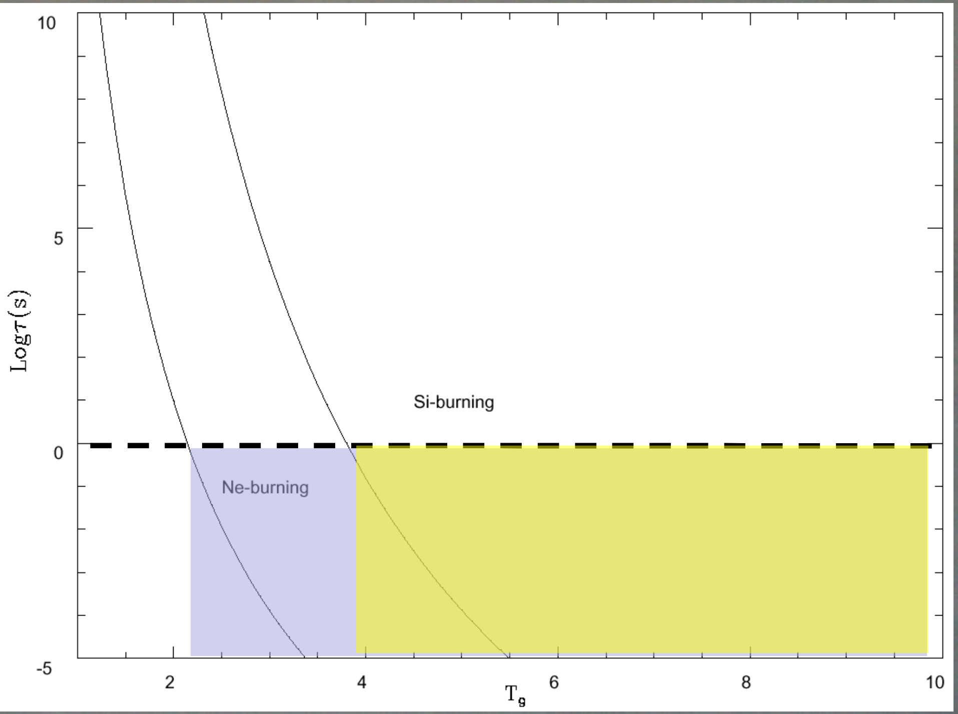
Si burning: $^{28}\mathrm{Si}(\gamma,\alpha)^{24}\mathrm{Mg}$

and in general are functions of temperature and density: $\tau_i = f(T,\rho)$

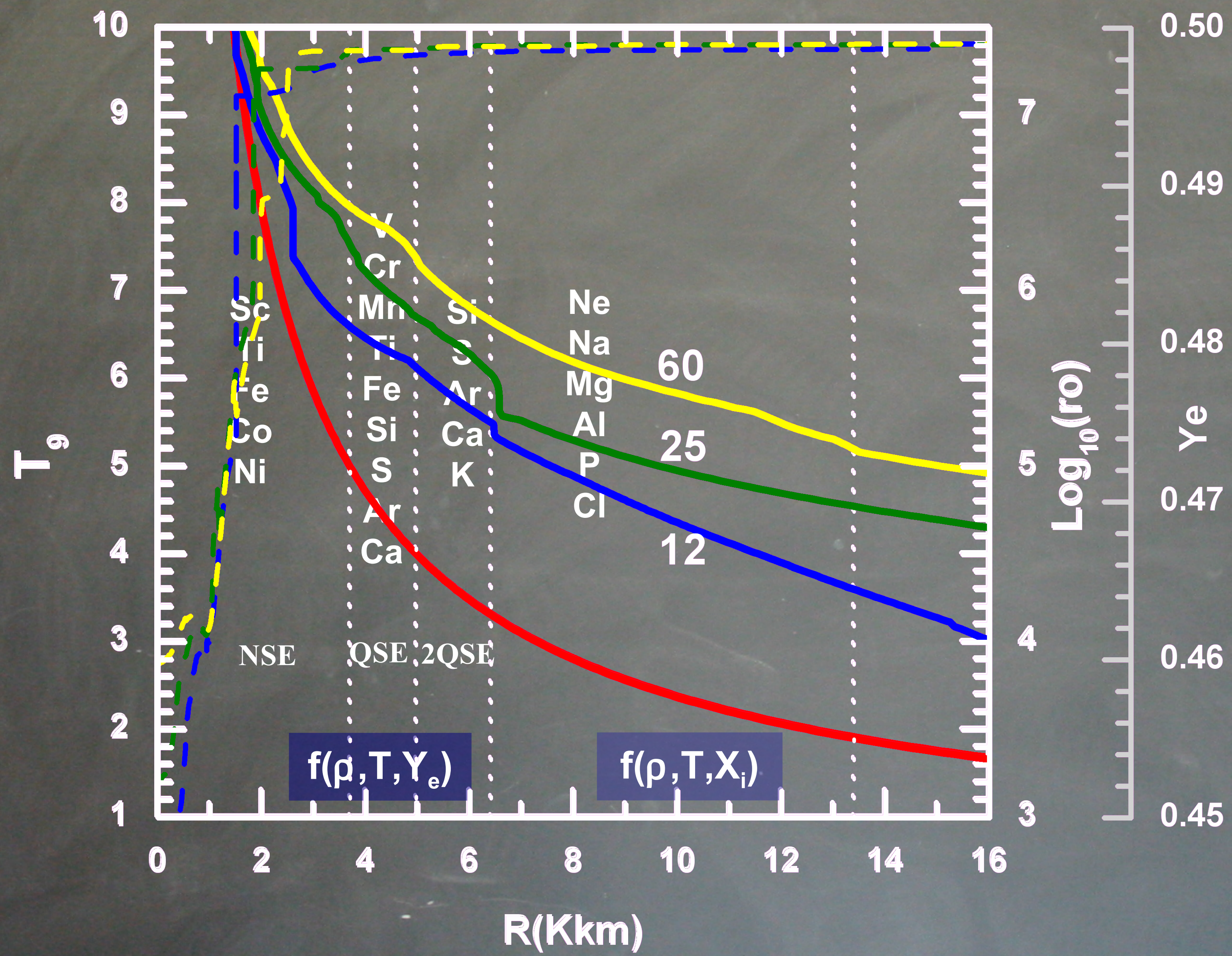
CHARACTERISTIC EXPLOSIVE BURNING TEMPERATURES

If we take typical explosive burning timescales of the order of 1s

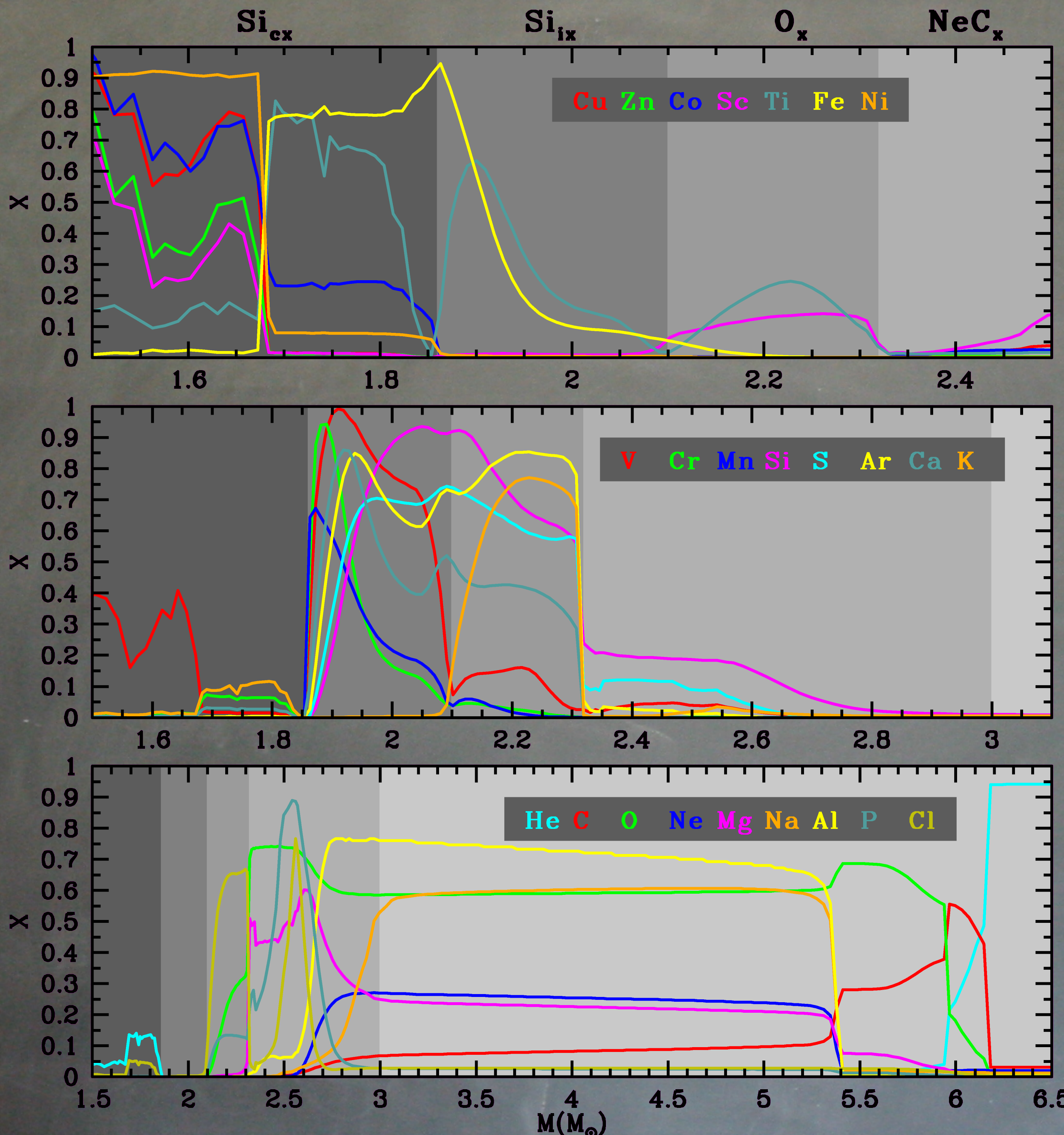




$T_{9,\text{peak}} \gtrsim 1.9$	Explosive C burning
$T_{9,\text{peak}} \gtrsim 2.1$	Explosive Ne burning
$T_{9,\text{peak}} \gtrsim 3.3$	Explosive O burning
$T_{9,\text{peak}} \gtrsim 4.0$	Explosive Si burning



T9
R(Kkm)
Log10(ro)
Ye
Sc
Ti
Fe
Co
Ni
V
Cr
Mn
Ti
Fe
Si
S
Ar
Ca
Si
S
Ar
Ca
K
Ne
Na
Mg
Al
P
Cl
60
25
12
NSE
QSE
2QSE
f(ρ,T,Ye)
f(ρ,T,Xi)

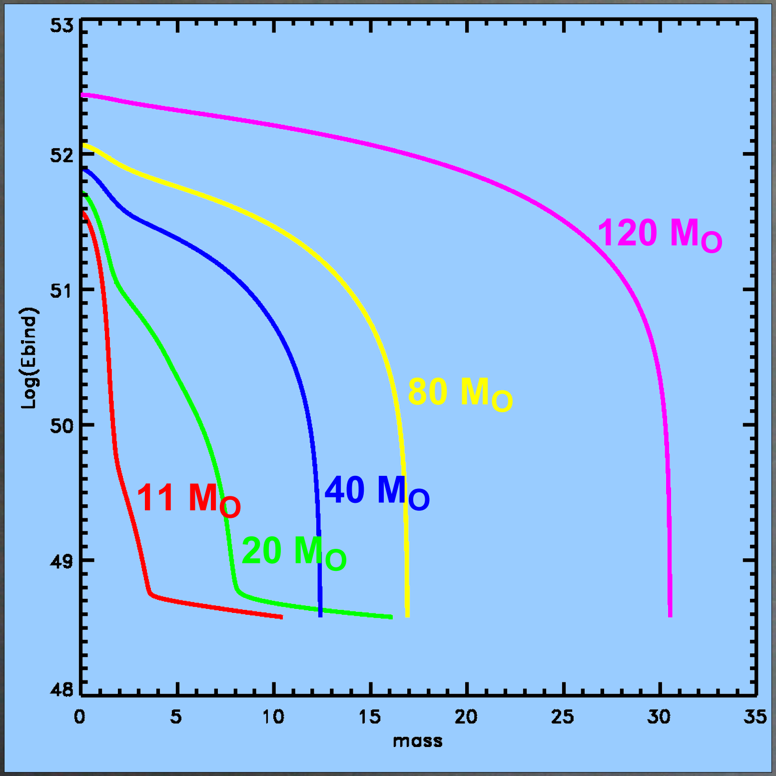


Si$_{cx}$
Si$_{ix}$
O$_x$
NeC$_x$
Cu Zn Co Sc Ti Fe Ni
V Cr Mn Si S Ar Ca K
He C O Ne Mg Na Al P Cl
X
M(M$_\odot$)

Let's come back to the exploding star. Since a self consistent determination of the energy escaping the Fe core is not yet available, we are forced to fix “by hand” a value.

The energy of the shock wave is fixed by imposing that some “observable” is reproduced:
usually
the kinetic energy of the ejecta
and/or
the amount of ^{56}Ni ejected

General considerations



If the energy assumed to escape the Fe core is too low, all the star will fall back in to the remnant (no matter will be ejected).

If the energy assumed to escape the Fe core is high, all the mantle will be ejected.

In the intermediate cases part of the mantle will fall back on the remnant and part will be ejected in the interstellar medium.

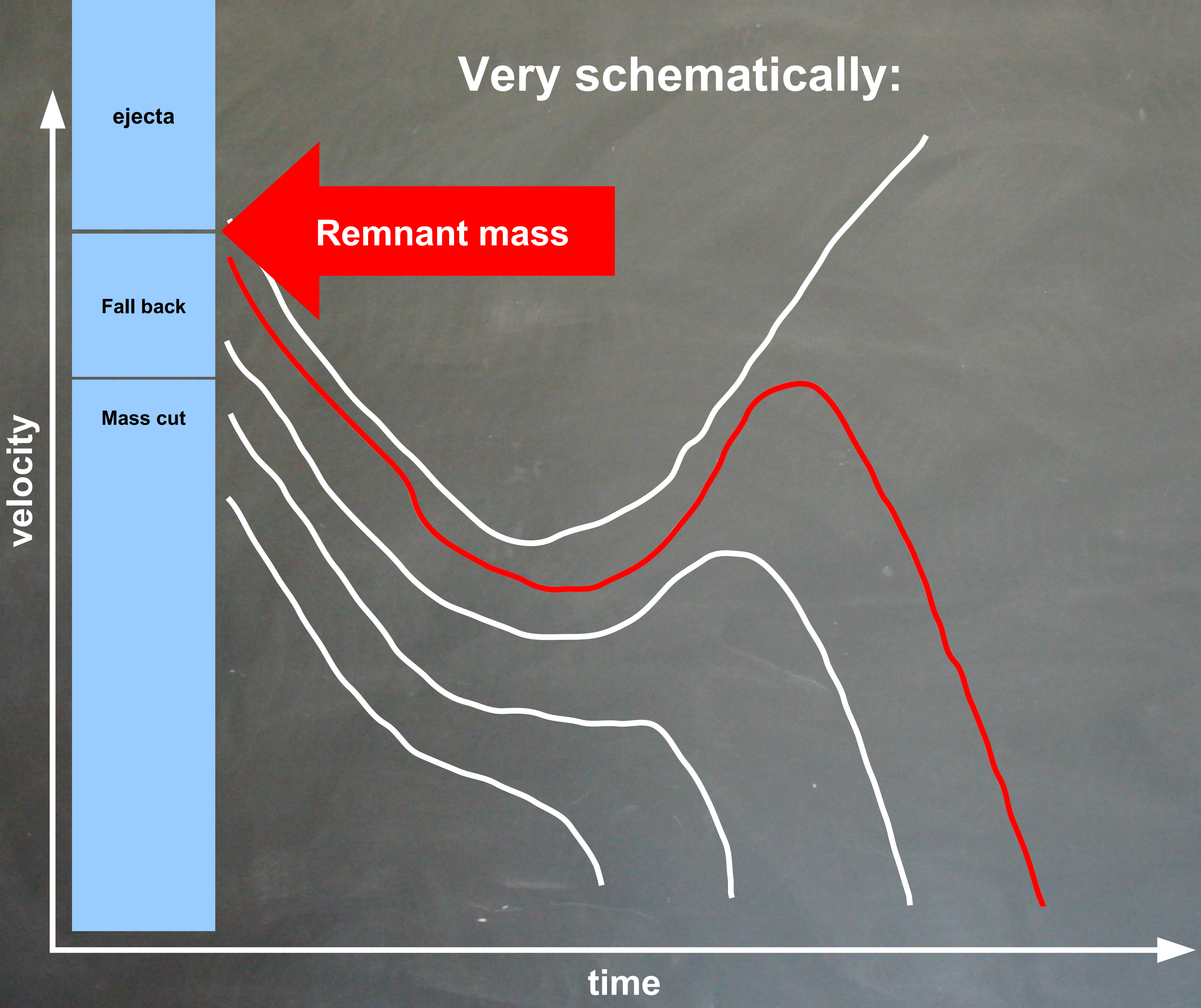
Basic definitions:

Mass cut: maximum mass that will always move inward

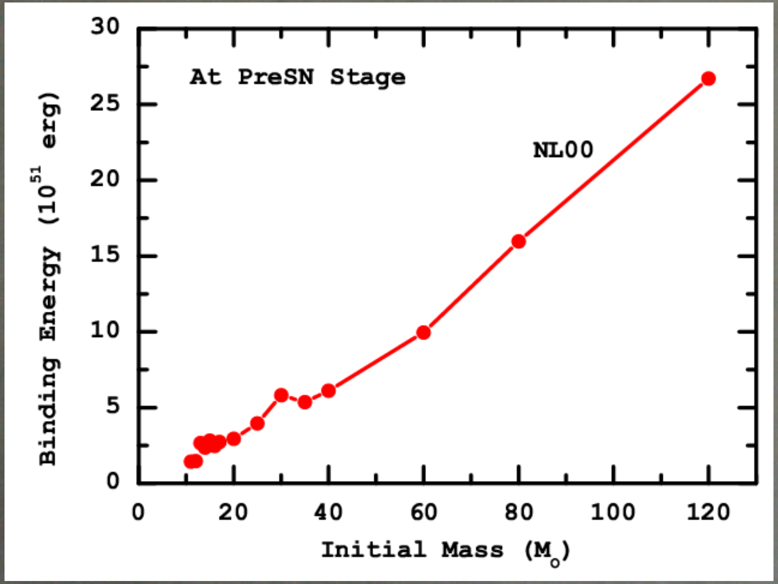
Fall back: mass that initially is kicked off but that then falls back on the collapsed core.

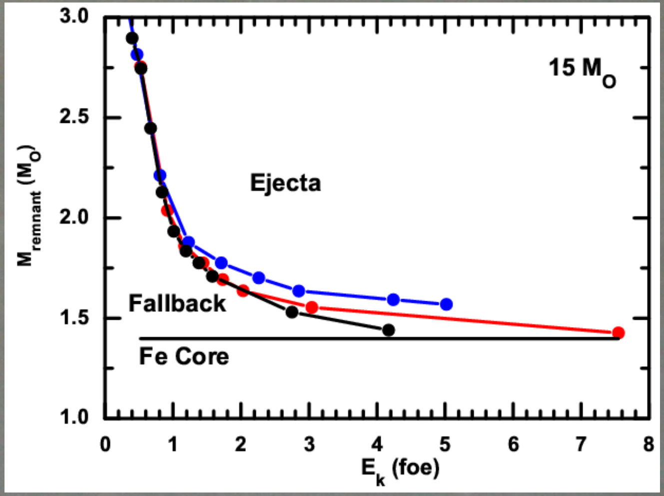
Remnant mass: mass cut + fall back (final mass size of the collapsed core).

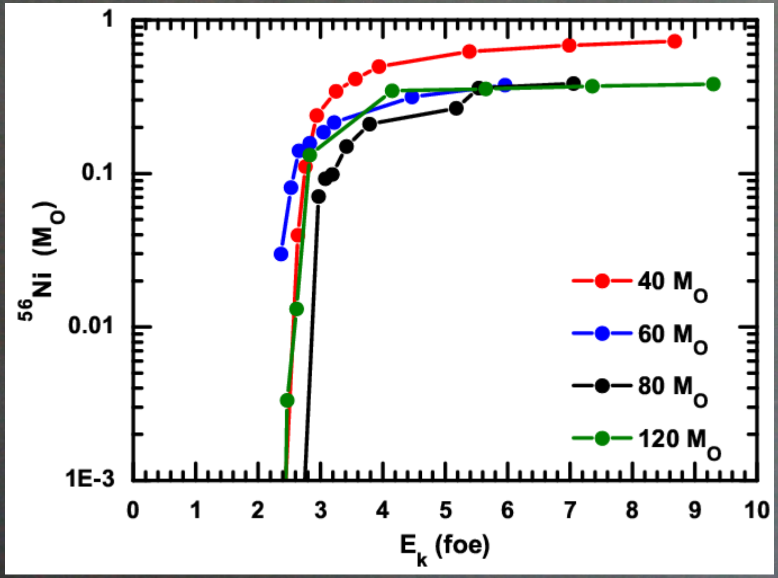
Very schematically:

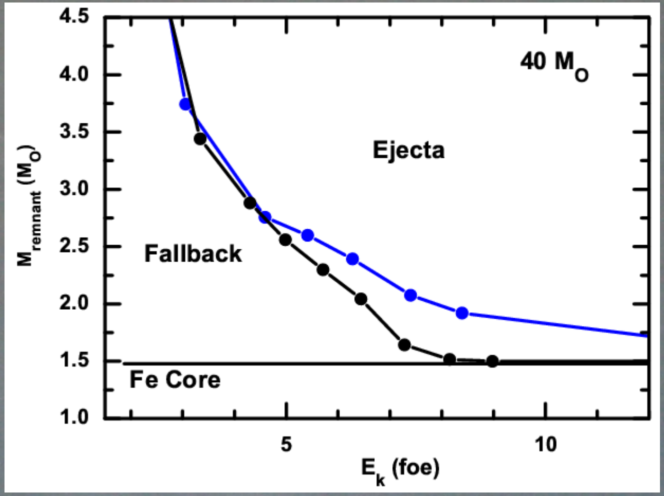


FALL BACK AND FINAL REMNANT

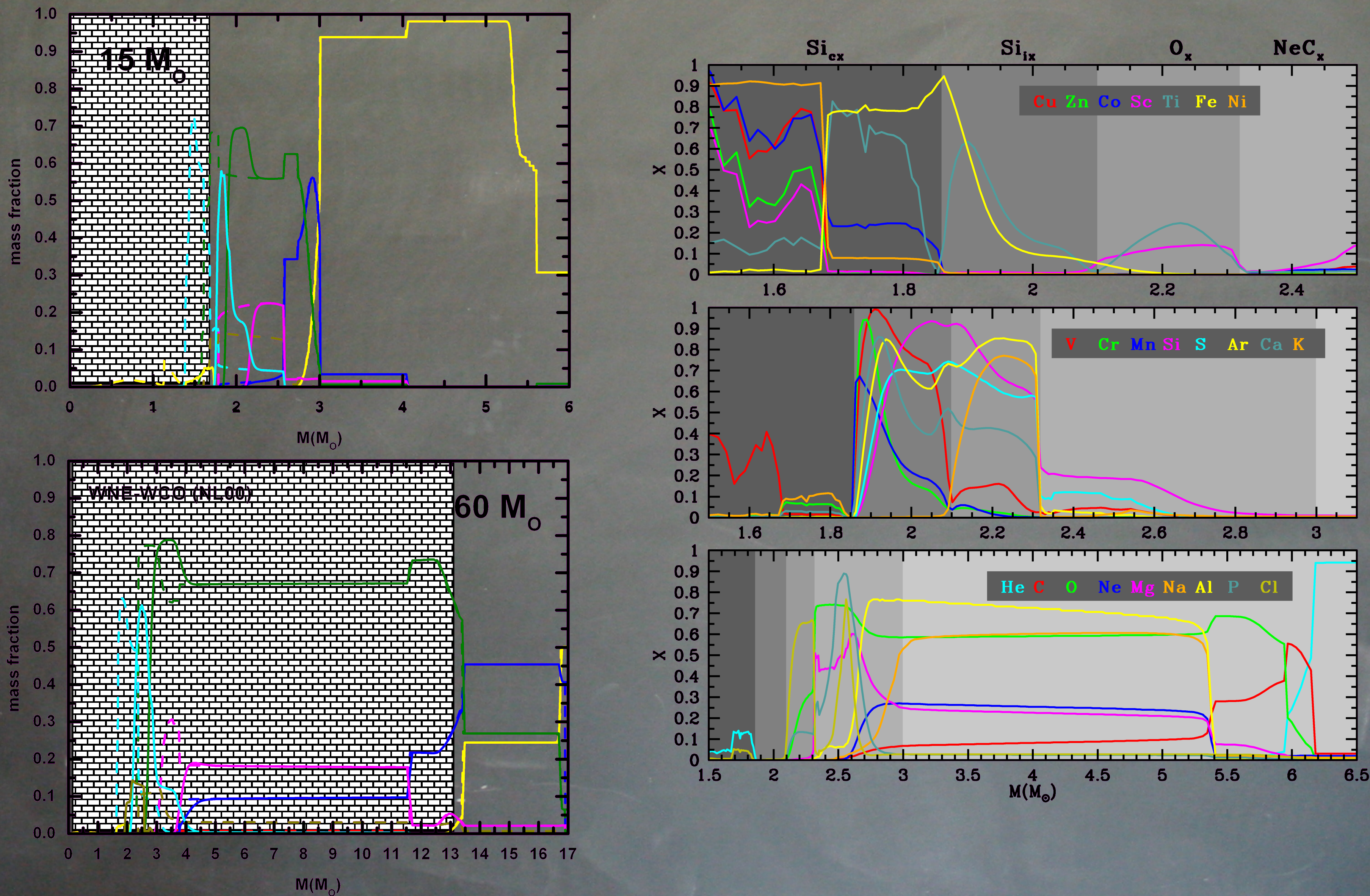


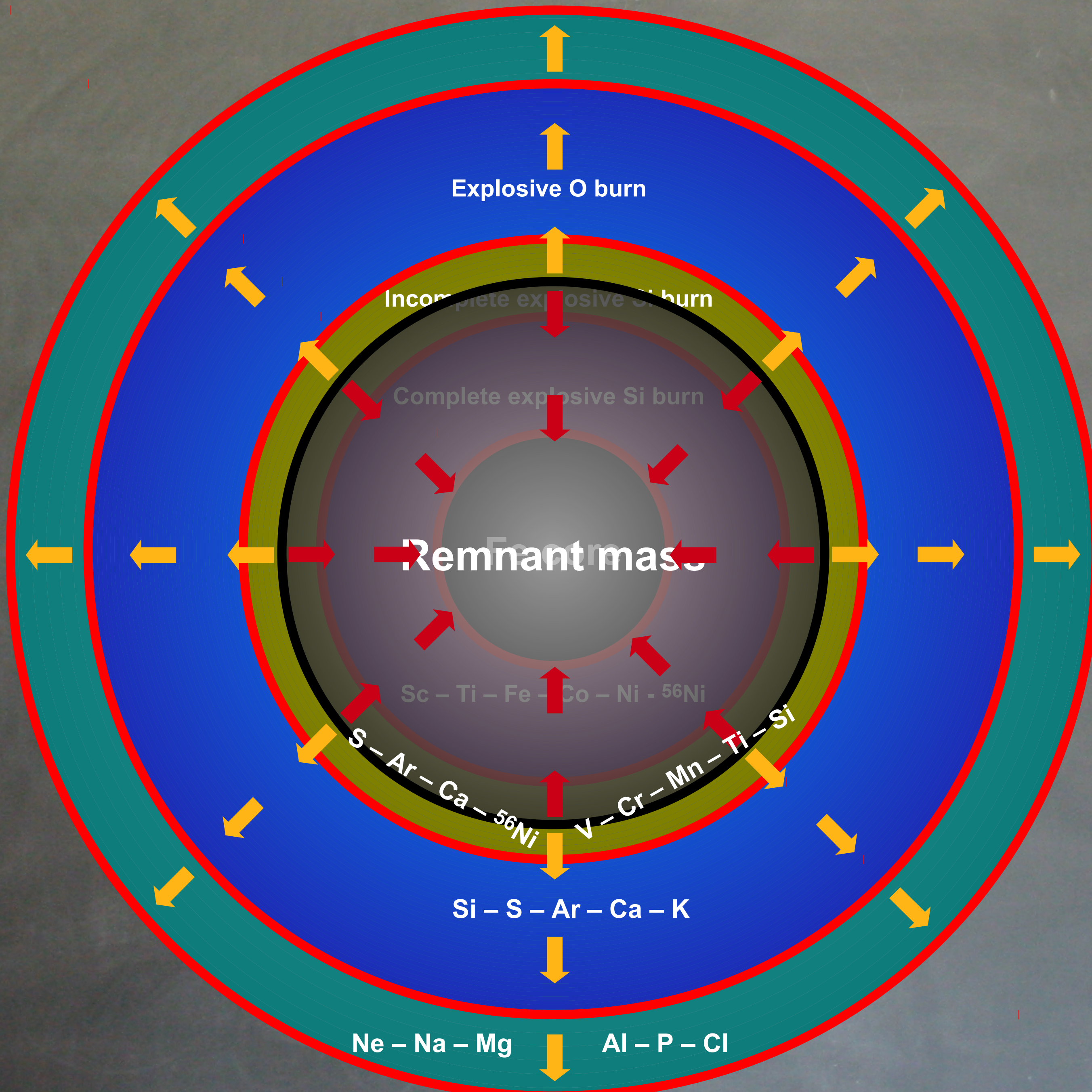




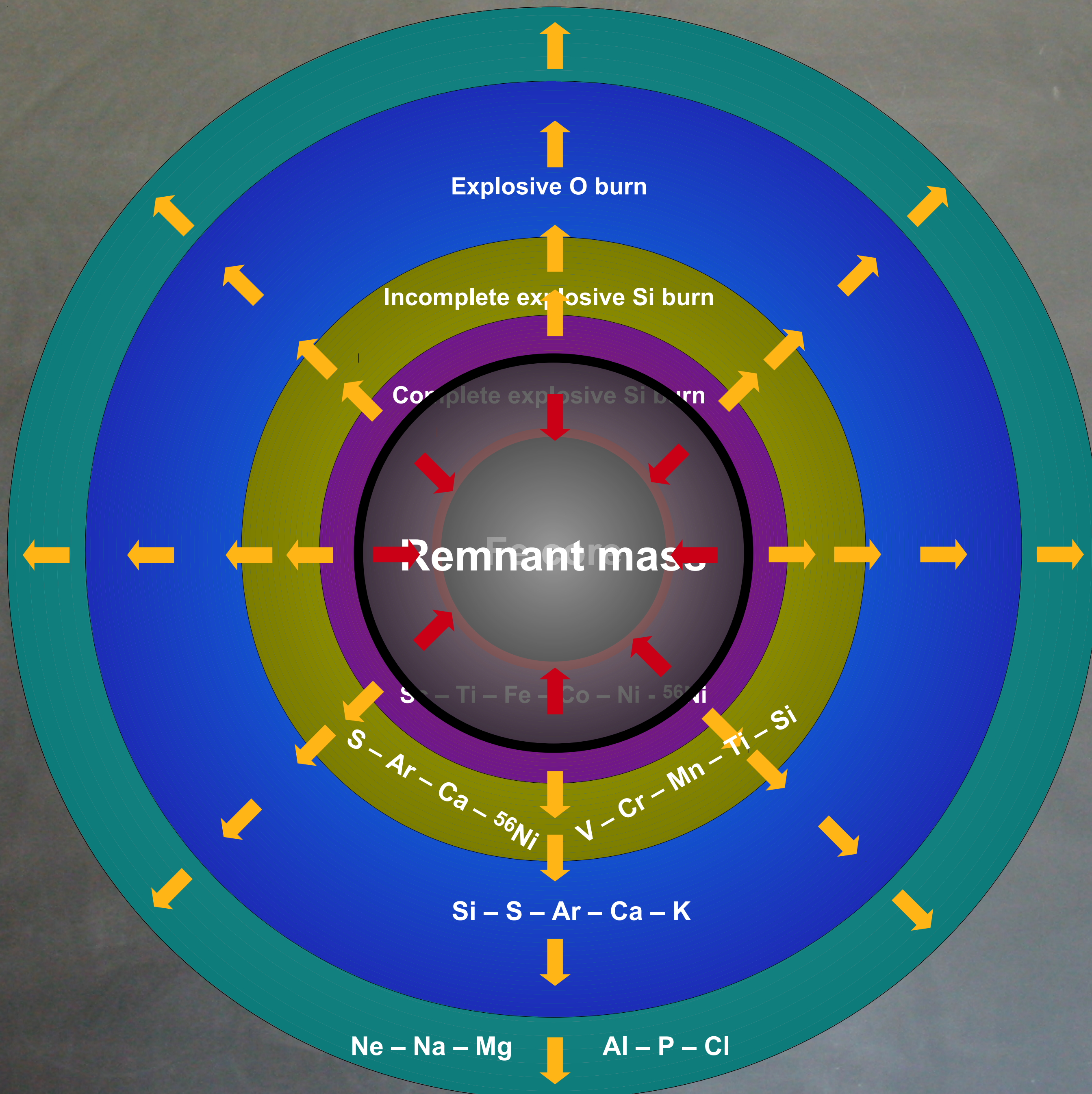


Final kinetic energy = 1 foe (10^{51} erg)

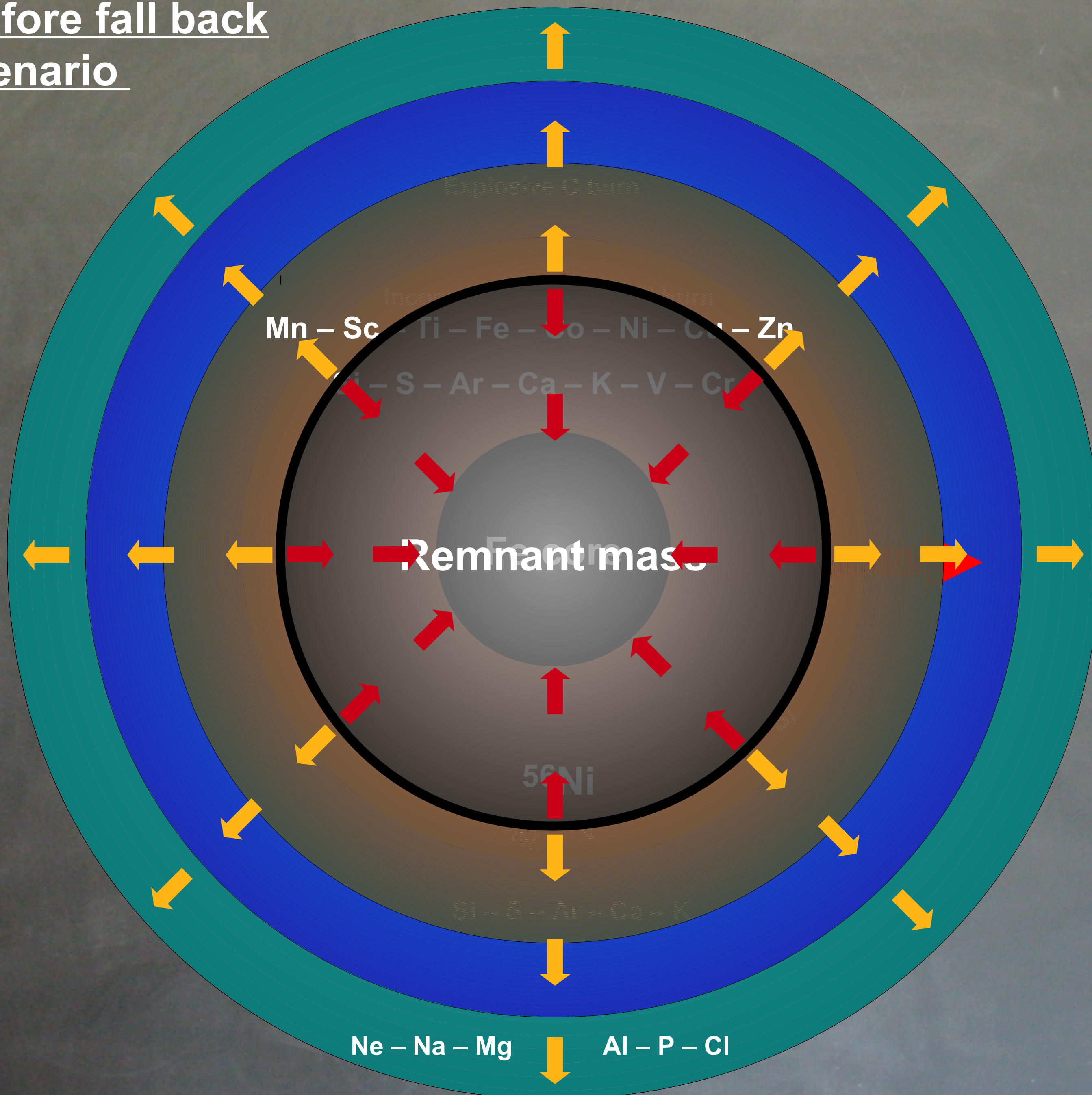




Explosive O burn
Incomplete explosive Si burn
Complete explosive Si burn
Remnant mass
Sc – Ti – Fe – Co – Ni - 56Ni
S – Ar – Ca – 56Ni
V – Cr – Mn – Ti – Si
Si – S – Ar – Ca – K
Ne – Na – Mg
Al – P – Cl

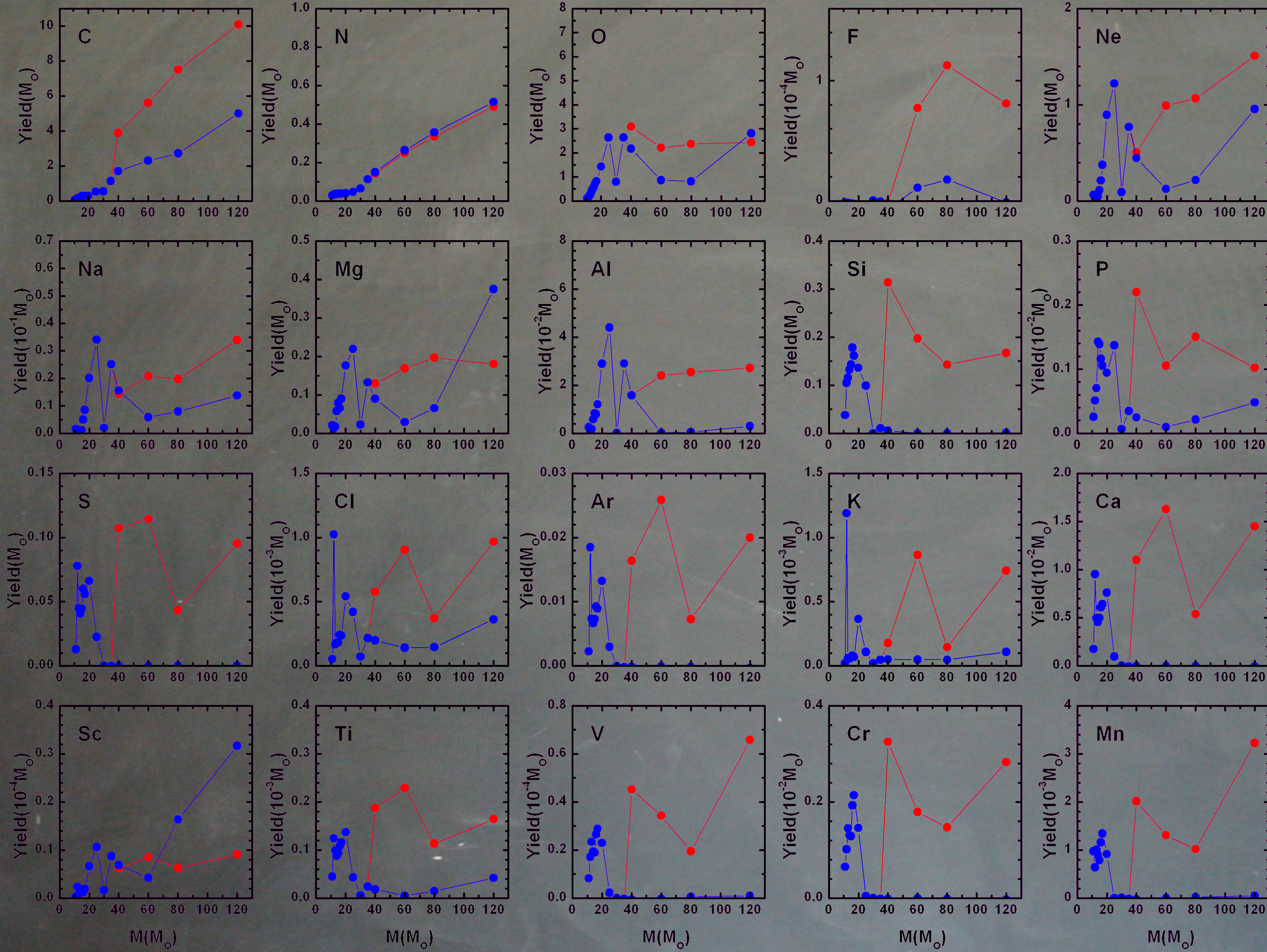

Explosive O burn
Incomplete explosive Si burn
Complete explosive Si burn
Remnant mass
Sc – Ti – Fe – Co – Ni - ⁵⁶Ni
S – Ar – Ca – ⁵⁶Ni
V – Cr – Mn – Ti – Si
Si – S – Ar – Ca – K
Ne – Na – Mg
Al – P – Cl

Mixing before fall back scenario



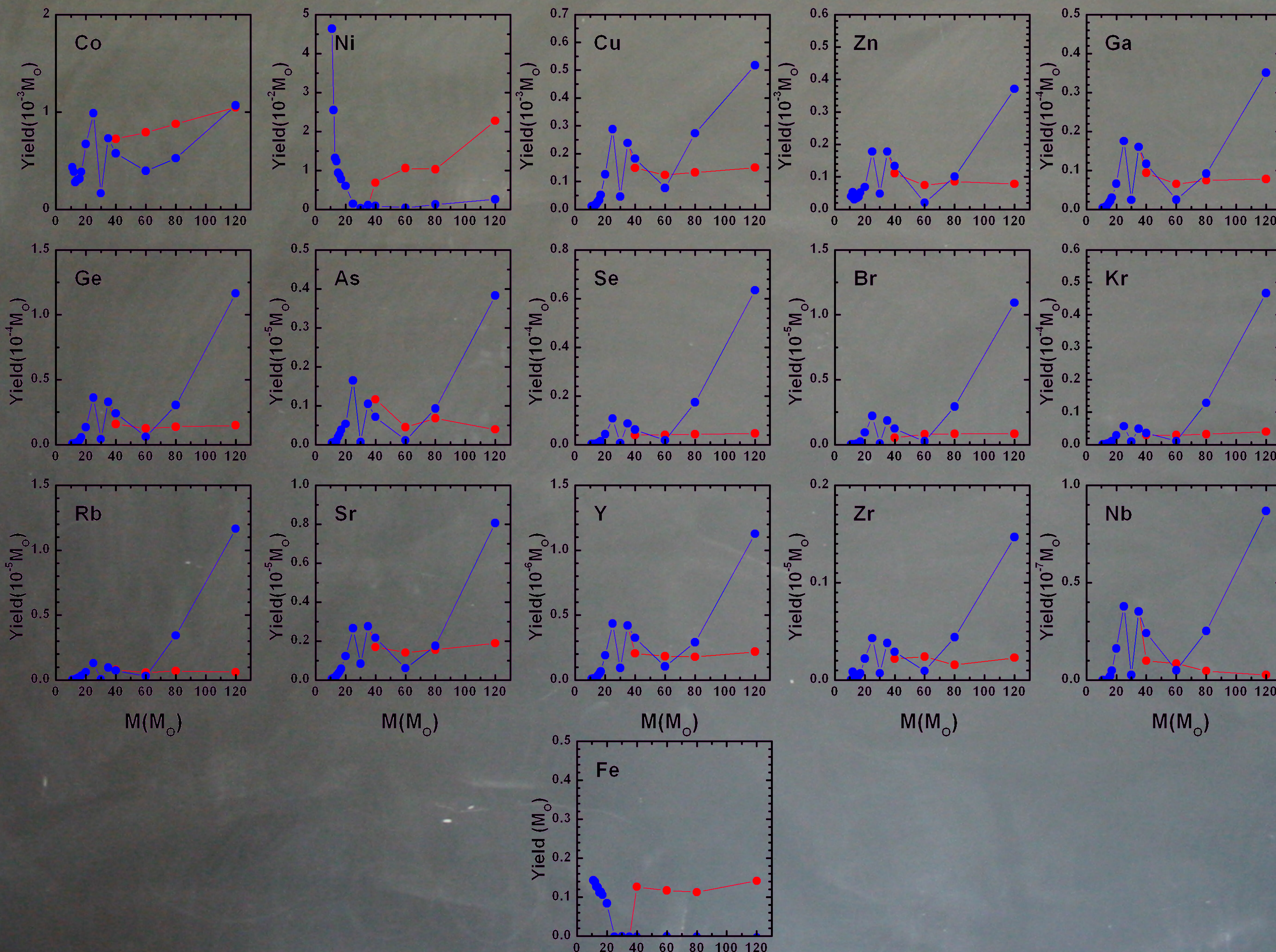
1 foe

Mass Loss in the WNE / WCO phases: Langer89 - Nugis & Lamers 00



1 foe

Mass Loss in the WNE / WCO phases: Langer89 - Nugis & Lamers 00



Yields produced by a generation of massive stars

$$\frac{dN}{dm} = km^{-(1+x)}$$

Salpeter initial mass function

X=1.35 classical

X=1.7-1.8 Kroupa (for massive stars)

M_1 < massive stars < M_2

$$Y_i = k \int_{m_1}^{m_2} Y_i(m) \frac{dN}{dm} dm$$

total yield

Normalization:

$$N_{m_1}^{m_2} = k \int_{m_1}^{m_2} \frac{dN}{dm} dm = k \frac{(m_2^{-x} - m_1^{-x})}{-x}$$

$$N_{m_1}^{m_2} = 1 \Rightarrow k = \frac{-x}{(m_2^{-x} - m_1^{-x})}$$

$$M_{m_1}^{m_2} = k \int_{m_1}^{m_2} m \frac{dN}{dm} dm = k \frac{(m_2^{-x+1} - m_1^{-x+1})}{-x+1}$$

$$M_{m_1}^{m_2} = 1 \Rightarrow k = \frac{-x+1}{(m_2^{-x+1} - m_1^{-x+1})}$$

Production factor

$$PF = \frac{Yield}{X_{initial} M_{ejected}}$$

PF>1 (produced) **PF< 1 (destroyed)** **PF=1 (untouched)**

A flat PF factor implies that the initial relative scaling among the various nuclei is preserved

This means that an initial scaled solar distribution is preserved if the PF is flat

Since the solar chemical composition mainly reflects the ejecta of star having “quasi” solar c.c.,

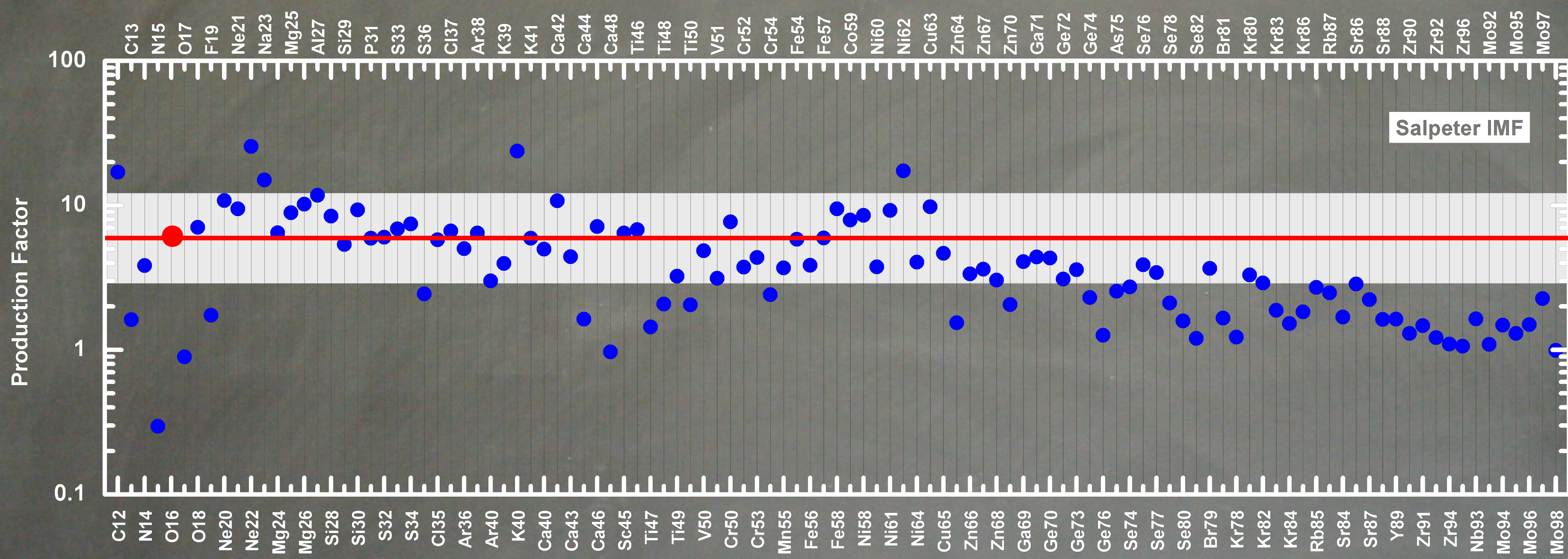
a “roughly” flat PF should be typical of a generation of stars having a solar metallicity

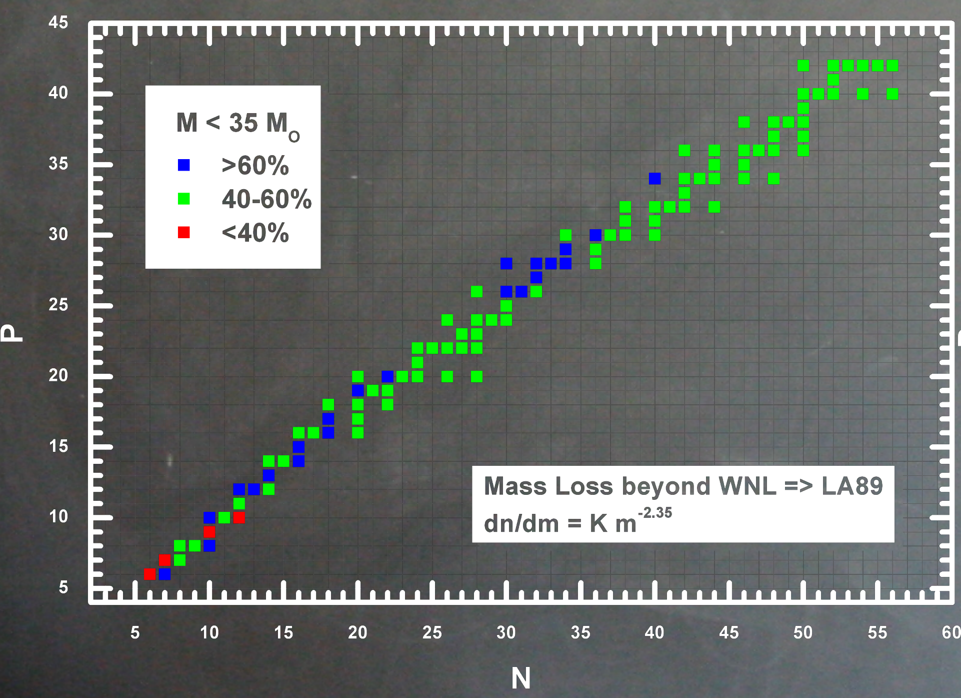
A natural, robust “leader” nucleus is ^{16}O because it is certainly produced only by massive stars and it is also the most abundant nucleus in nature (beyond H and ^{4}He)

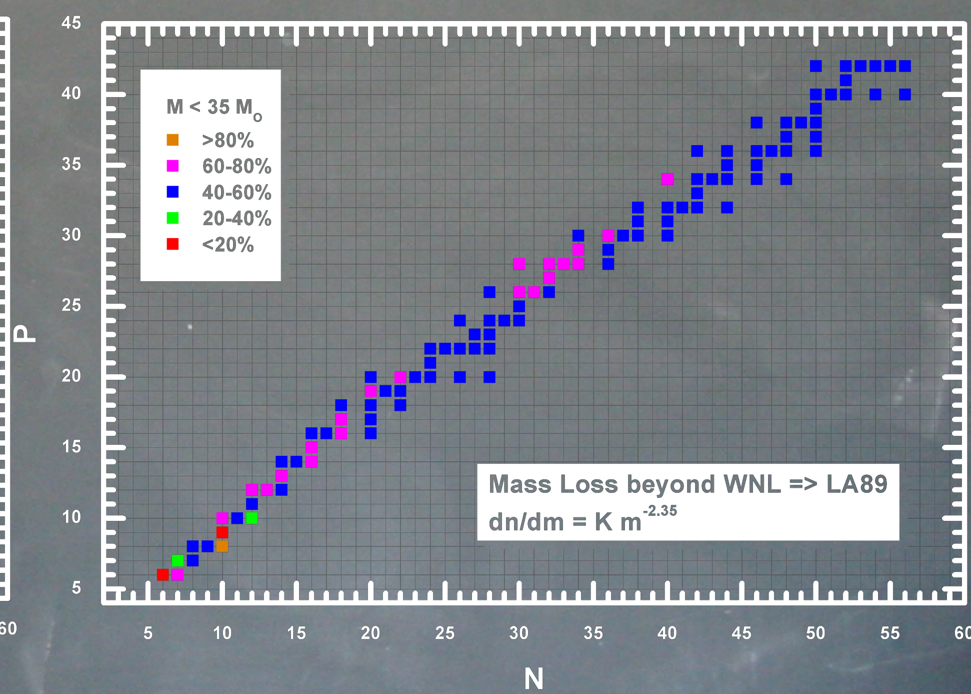
If a nucleus has a PF at same level of that of the O, this means that it comes from massive stars only

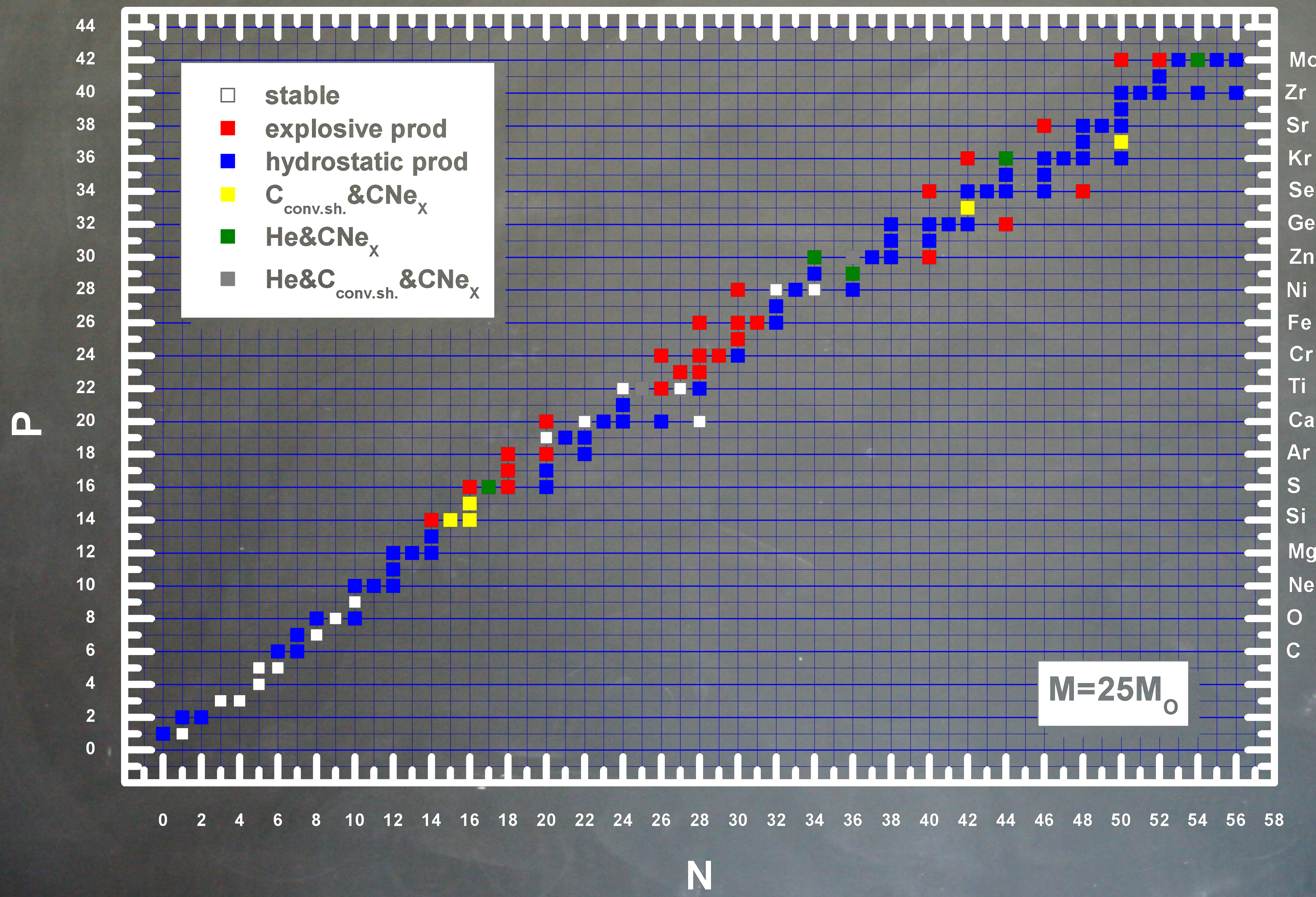
If a nucleus has a PF larger than that of the O, this could be a problem since it would imply that it is overproduced (note however that “secondary” nuclei must be slightly overproduced)

If a nucleus has a PF lower than that of the O, in principle this would simply mean that massive stars are not the main producers of that nucleus

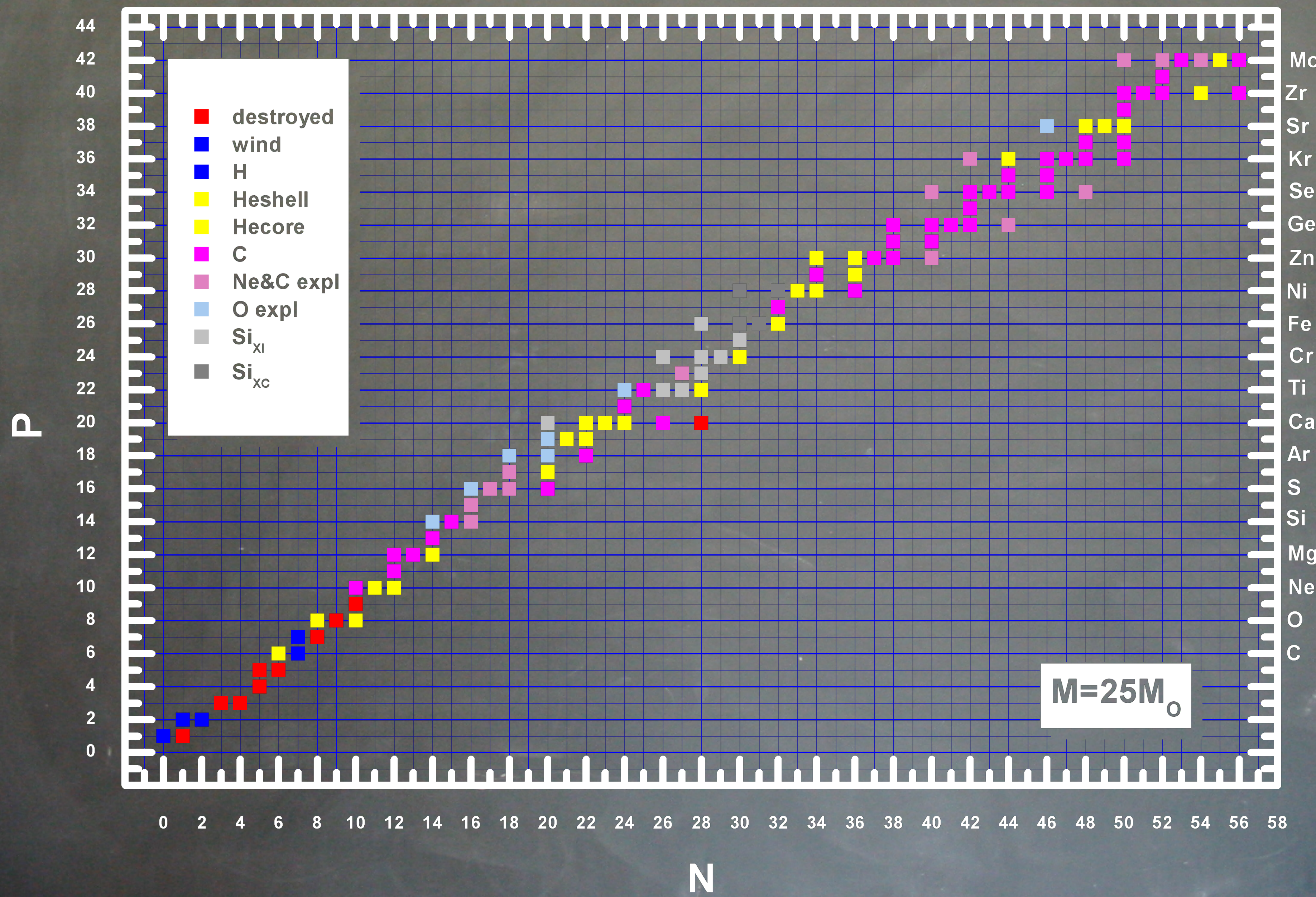

Production Factor
Salpeter IMF
100
10
1
0.1
C12 N14 O16 O18 Ne20 Ne22 Mg24 Mg26 Si28 Si30 P31 S32 S34 Cl35 Ar36 Ar40 K40 Ca40 Ca43 Ca46 Sc45 Ti47 Ti49 V50 Cr50 Cr53 Mn55 Fe56 Fe58 Ni58 Ni61 Ni64 Cu65 Zn66 Zn68 Ga69 Ge70 Ge73 Ge76 Se74 Se77 Se80 Br79 Kr78 Kr82 Kr84 Rb85 Sr84 Sr87 Y89 Zr91 Zr94 Nb93 Mo94 Mo96 Mo98
C13 N15 O17 F19 Ne21 Na23 Mg25 Al27 Si29 P31 S33 S36 Cl37 Ar38 K39 K41 Ca42 Ca44 Ca48 Ti46 Ti48 Ti50 V51 Cr52 Cr54 Fe54 Fe57 Co59 Ni60 Ni62 Cu63 Zn64 Zn67 Zn70 Ga71 Ge72 Ge74 As75 Se76 Se78 Se82 Br81 Kr80 Kr83 Kr86 Rb87 Sr86 Sr88 Zr90 Zr92 Zr96 Mo92 Mo95 Mo97


M < 35 M$_O$
>60%
40-60%
<40%
Mass Loss beyond WNL => LA89
dn/dm = K m$^{-2.35}$
P
N


M < 35 M$_O$
>80%
60-80%
40-60%
20-40%
<20%
Mass Loss beyond WNL => LA89
dn/dm = K m$^{-2.35}$
P
N



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
Zr
Sr
Kr
Se
Ge
Zn
Ni
Fe
Cr
Ti
Ca
Ar
S
Si
Mg
Ne
O
C


destroyed
wind
H
Heshell
Hecore
C
Ne&C expl
O expl
Si_{XI}
Si_{XC}
P
N
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52
54
56
58
Mo
Zr
Sr
Kr
Se
Ge
Zn
Ni
Fe
Cr
Ti
Ca
Ar
S
Si
Mg
Ne
O
C
$M=25M_O$

$He\,(^{4}He) - H$

$C\,(^{12}C) - He$

$N\,(^{14}N) - H$

$O\,(^{16}O) - He$

$F\,(^{19}F)\ \text{Destroyed by } H$

$Ne\,(^{20}Ne) - C$

$Na\,(^{23}Na) - C$

$Mg\,(^{24}Mg) - C$

$Al\,(^{27}Al) - C$

$Si\,(^{28}Si) - O_X, Si_{Xi}$

$P\,(^{31}P) - C_X, Ne_X$

$S\,(^{32}S) - O_X, Si_{Xi}$

$Cl\,(^{35}Cl) - C_X, Ne_X$

$Ar\,(^{36}Ar) - O_X, Si_{Xi}$

$K\,(^{39}K) - O_X$

$Ca\,(^{40}Ca) - O_X, Si_{Xi}$

$Sc\,(^{45}Sc) - C, Si_X$

$Ti\,(^{48}Ti) - Si_{Xi}$

$V\,(^{51}V) - Si_{Xi}$

$Cr\,(^{52}Cr) - Si_{Xi}$

$Mn\,(^{55}Mn) - Si_{Xi}$

$Fe\,(^{56}Fe) - Si_{Xi}, Si_X$

$Co\,(^{59}Co) - C, Si_X$

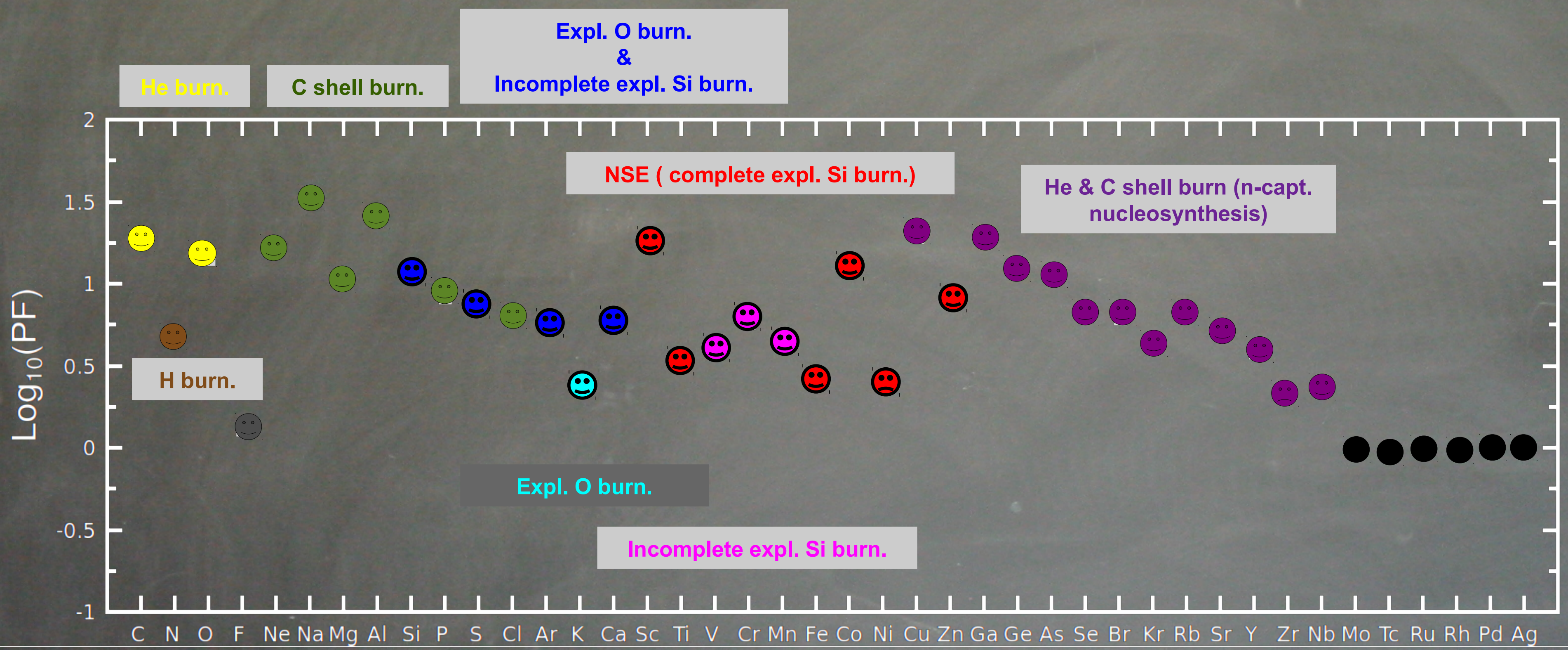
$Ni\,(^{58}Ni) - Si_X$

$Cu\,(^{63}Cu) - C, Si_X$

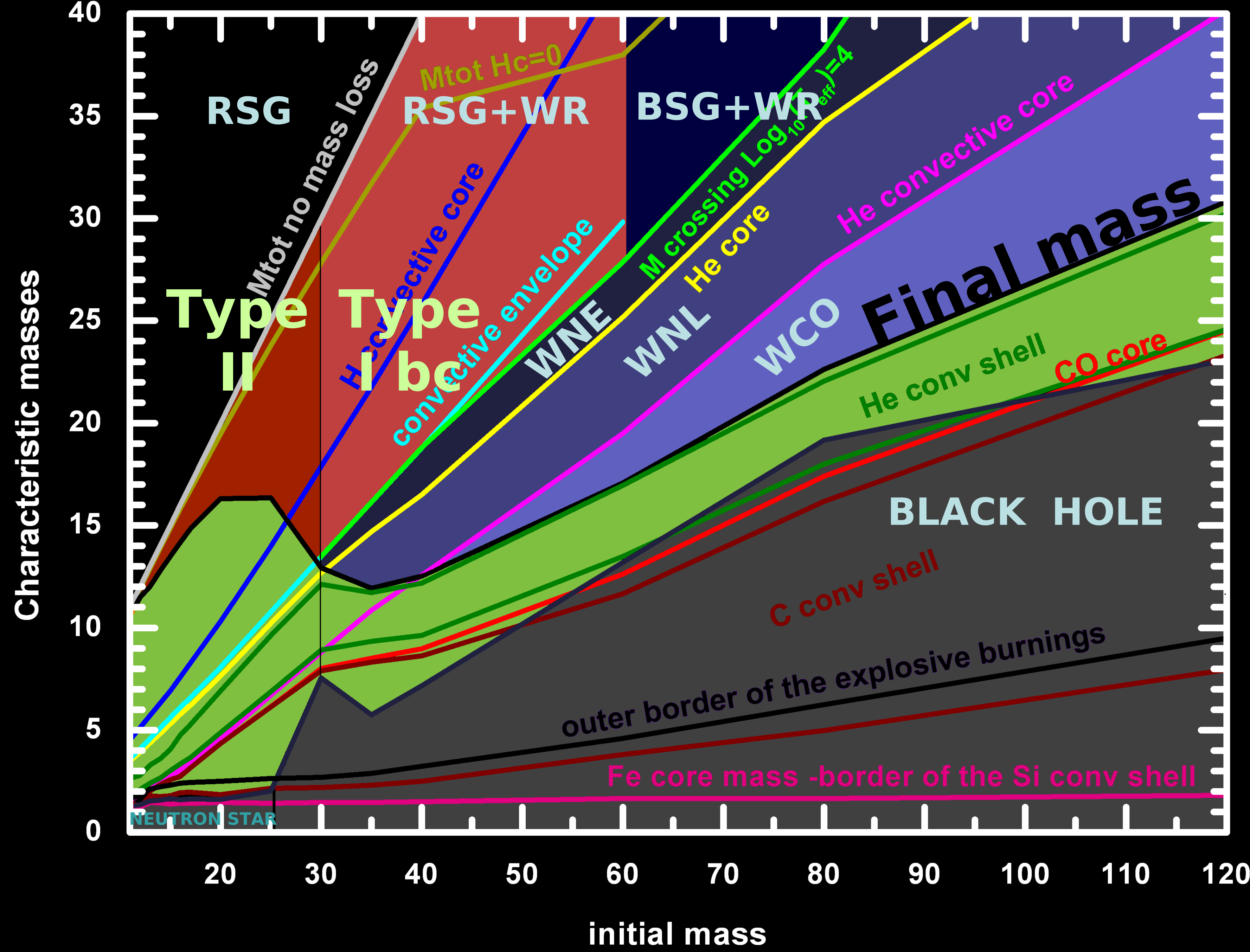
$Zn\,(^{64}Zn) - He, Si_X$

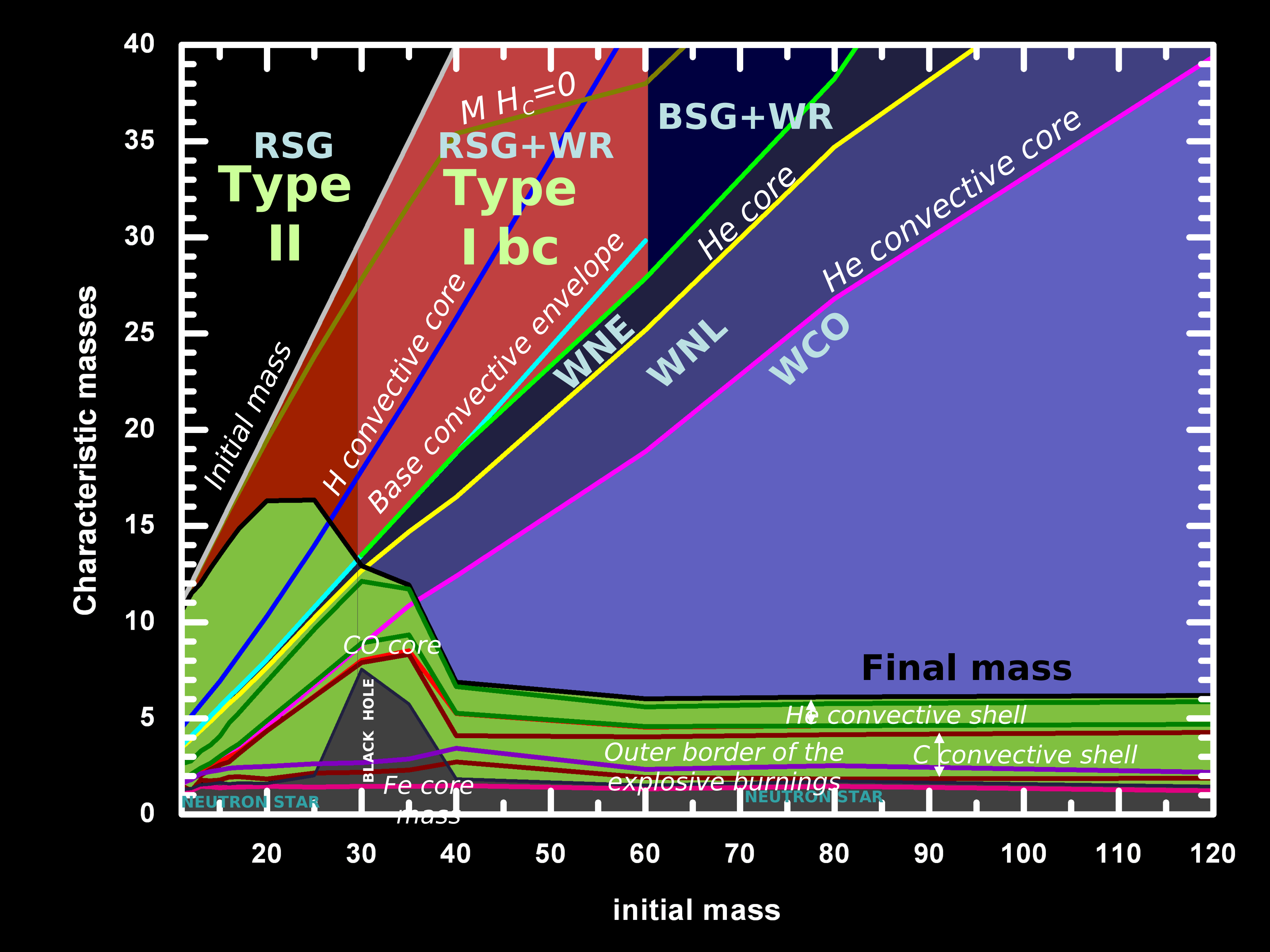
WARNING

The production site of many elements depends on the mass of the star and the initial chemical composition.

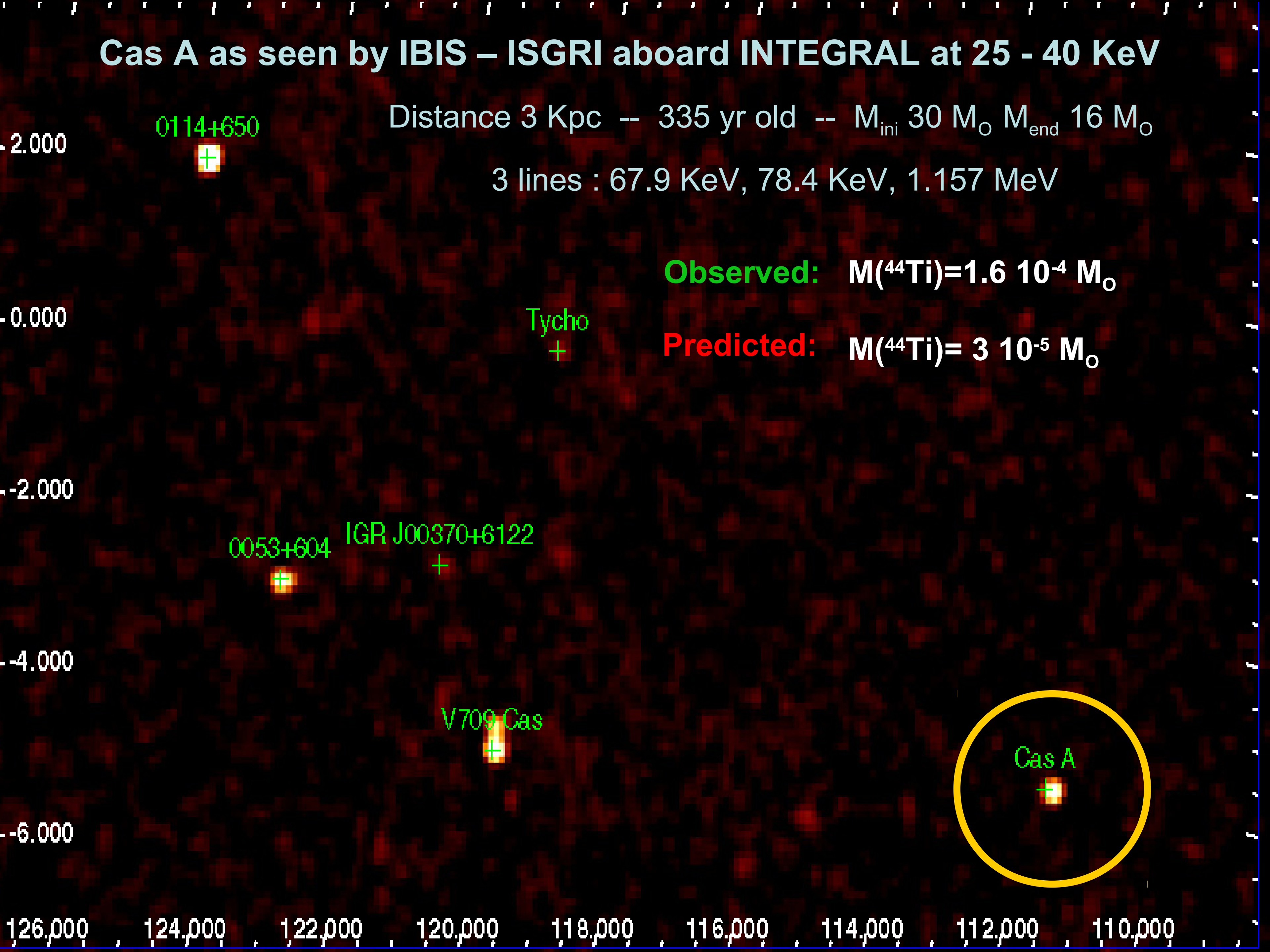


He burn.
C shell burn.
Expl. O burn. & Incomplete expl. Si burn.
NSE (complete expl. Si burn.)
He & C shell burn (n-capt. nucleosynthesis)
H burn.
Expl. O burn.
Incomplete expl. Si burn.
Log10(PF)
2
1.5
1
0.5
0
-0.5
-1
C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag


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
BLACK HOLE
C conv shell
outer border of the explosive burnings
Fe core mass -border of the Si conv shell
NEUTRON STAR
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
Type II
RSG+WR
Type I bc
BSG+WR
M H_C=0
Initial mass
H convective core
Base convective envelope
He core
He convective core
WNE
WNL
WCO
CO core
BLACK HOLE
Fe core mass
Final mass
He convective shell
Outer border of the explosive burnings
C convective shell
NEUTRON STAR
NEUTRON STAR
Characteristic masses
initial mass
0
5
10
15
20
25
30
35
40
20
30
40
50
60
70
80
90
100
110
120



Cas A as seen by IBIS – ISGRI aboard INTEGRAL at 25 - 40 KeV
Distance 3 Kpc -- 335 yr old -- M$_{ini}$ 30 M$_O$ M$_{end}$ 16 M$_O$
3 lines : 67.9 KeV, 78.4 KeV, 1.157 MeV
Observed: M(^{44}Ti)=1.6 10^{-4} M$_O$
Predicted: M(^{44}Ti)= 3 10^{-5} M$_O$
0114+650
Tycho
0053+604
IGR J00370+6122
V709 Cas
Cas A
2.000
0.000
-2.000
-4.000
-6.000
126.000
124.000
122.000
120.000
118.000
116.000
114.000
112.000
110.000

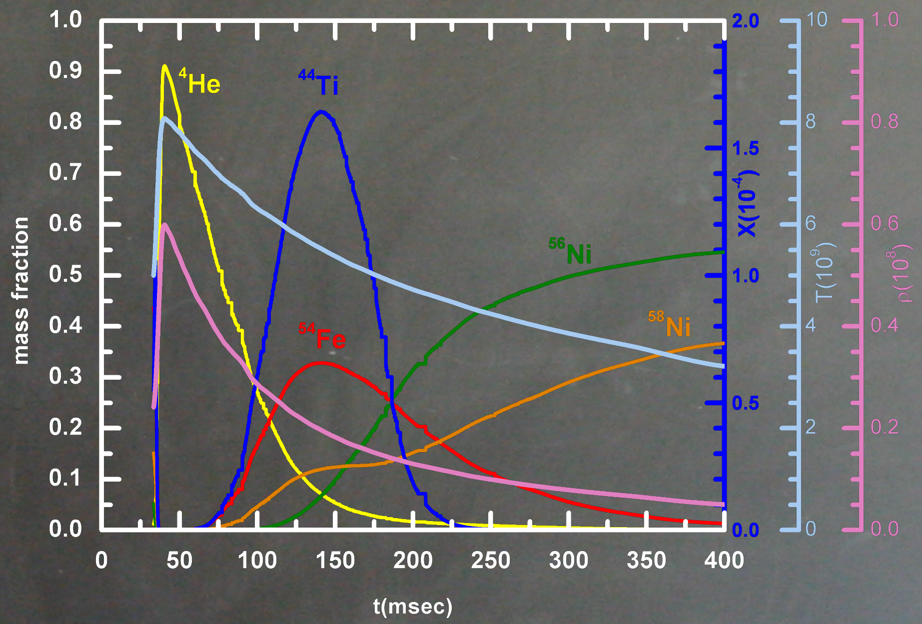
					<105 NS ε P	<70 NS P	34 MS ε: 100.00% εp: 22.00%	100 MS ε: 100.00% εp ≥ 3.40%	158.1 MS ε: 100.00% εp: 0.28%	382 MS ε: 100.00%	283.29 MS ε: 100.00%	46.2 M ε: 100.00%	5.591 D ε: 100.00%	3.74E+6 Y ε: 100.00%	312.12 D ε: 100.00% β- < 2.9E-4%	STABLE 100%
				42Cr 13 MS ε	43Cr 21.6 MS ε: 100.00% εp: 23.00%	44Cr 53 MS ε: 100.00% εp > 7.00%	45Cr 50 MS ε: 100.00% εp > 27.00%	46Cr 0.26 S ε: 100.00%	47Cr 500 MS ε: 100.00%	48Cr 21.56 H ε: 100.00%	49Cr 42.3 M ε: 100.00%	50Cr >1.3E+18 Y 4.345% 2ε	51Cr 27.7025 D ε: 100.00%	52Cr STABLE 83.789%	53Cr STABLE 9.501%	54Cr STABLE 2.365%
			40V P	41V P	42V <55 NS P	43V >800 MS ε: 100.00%	44V 111 MS ε: 100.00% εα	45V 547 MS ε: 100.00%	46V 422.50 MS ε: 100.00%	47V 32.6 M ε: 100.00%	48V 15.9735 D ε: 100.00%	49V 329 D ε: 100.00%	50V 1.4E+17 Y 0.250% ε: 83.00% β-: 17.00%	51V STABLE 99.750%	52V 3.743 M β-: 100.00%	53V 1.60 M β-: 100.00%
			39Ti 31 MS ε: 100.00% εp: 100.00%	40Ti 53.3 MS ε: 100.00% εp: 100.00%	41Ti 80.4 MS εp ≈ 100.00% ε: 100.00%	42Ti 199 MS ε: 100.00%	43Ti 509 MS ε: 100.00%	44Ti 60.0 Y ε: 100.00%	45Ti 184.8 M ε: 100.00%	46Ti STABLE 8.25%	47Ti STABLE 7.44%	48Ti STABLE 73.72%	49Ti STABLE 5.41%	50Ti STABLE 5.18%	51Ti 5.76 M β-: 100.00%	52Ti 1.7 M β-: 100.00%
	36Sc P	37Sc P		39Sc <300 NS P: 100.00%	40Sc 182.3 MS ε: 100.00% εp: 0.44%	41Sc 596.3 MS ε: 100.00%	42Sc 681.3 MS ε: 100.00%	43Sc 3.891 H ε: 100.00%	44Sc 3.97 H ε: 100.00%	45Sc STABLE 100%	46Sc 83.79 D β-: 100.00%	47Sc 3.3492 D β-: 100.00%	48Sc 43.67 H β-: 100.00%	49Sc 57.2 M β-: 100.00%	50Sc 102.5 S β-: 100.00%	51Sc 12.4 S β-: 100.00%
34Ca <35 NS P	35Ca 25.7 MS ε: 100.00% εp: 95.70%	36Ca 102 MS ε: 100.00% εp: 54.30%	37Ca 181.1 MS ε: 100.00% εp: 82.10%	38Ca 440 MS ε: 100.00%	39Ca 859.6 MS ε: 100.00%	40Ca >3.0E+21 Y 96.94% 2ε	41Ca 1.02E+5 Y ε: 100.00%	42Ca STABLE 0.647%	43Ca STABLE 0.135%	44Ca STABLE 2.09%	45Ca 162.61 D β-: 100.00%	46Ca >0.28E+16 Y 0.004% 2β-	47Ca 4.536 D β-: 100.00%	48Ca 2.3E19 Y 0.187% 2β-: 84.00% β- < 25.00%	49Ca 8.718 M β-: 100.00%	50Ca 13.9 S β-: 100.00%
33K <25 NS P	34K <25 NS P	35K 178 MS ε: 100.00% εp: 0.37%	36K 342 MS ε: 100.00% εp: 0.05%	37K 1.226 S ε: 100.00%	38K 7.636 M ε: 100.00%	39K STABLE 93.2581%	40K 1.248E+9 Y 0.0117% β-: 89.28% ε: 10.72%	41K STABLE 6.7302%	42K 12.321 H β-: 100.00%	43K 22.3 H β-: 100.00%	44K 22.13 M β-: 100.00%	45K 17.3 M β-: 100.00%	46K 105 S β-: 100.00%	47K 17.50 S β-: 100.00%	48K 6.8 S β-: 100.00% β-n: 1.14%	49K 1.26 S β-: 100.00% β-n: 86.00%
32Ar 98 MS ε: 100.00% εp: 43.00%	33Ar 173.0 MS ε: 100.00% εp: 38.70%	34Ar 844.5 MS ε: 100.00%	35Ar 1.775 S ε: 100.00%	36Ar STABLE 0.3365%	37Ar 34.95 D ε: 100.00%	38Ar STABLE 0.0632%	39Ar 269 Y β-: 100.00%	40Ar STABLE 99.6003%	41Ar 109.61 M β-: 100.00%	42Ar 32.9 Y β-: 100.00%	43Ar 5.37 M β-: 100.00%	44Ar 11.87 M β-: 100.00%	45Ar 21.48 S β-: 100.00%	46Ar 8.4 S β-: 100.00%	47Ar 1.23 S β-: 100.00% β-n < 0.20%	48Ar 0.48 S β-
31Cl 150 MS ε: 100.00% εp: 0.70%	32Cl 298 MS ε: 100.00% εα: 0.05%	33Cl 2.511 S ε: 100.00%	34Cl 1.5264 S ε: 100.00%	35Cl STABLE 75.77%	36Cl 3.01E+5 Y β-: 98.10% ε: 1.90%	37Cl STABLE 24.23%	38Cl 37.24 M β-: 100.00%	39Cl 56.2 M β-: 100.00%	40Cl 1.35 M β-: 100.00%	41Cl 38.4 S β-: 100.00%	42Cl 6.8 S β-: 100.00%	43Cl 3.13 S β-: 100.00%	44Cl 0.56 S β-: 100.00% β-n < 8.00%	45Cl 400 MS β-: 100.00% β-n: 24.00%	46Cl 232 MS β-: 100.00% β-n: 60.00%	47Cl 101 MS β-: 100.00% β-n > 0.00%
30S 1.178 S ε: 100.00%	31S 2.572 S ε: 100.00%	32S STABLE 95.02%	33S STABLE 0.75%	34S STABLE 4.21%	35S 87.51 D β-: 100.00%	36S STABLE 0.02%	37S 5.05 M β-: 100.00%	38S 170.3 M β-: 100.00%	39S 11.5 S β-: 100.00%	40S 8.8 S β-: 100.00%	41S 1.99 S β-: 100.00% β-n	42S 1.013 S β-: 100.00%	43S 0.28 S β-: 100.00% β-n: 40.00%	44S 100 MS β-: 100.00% β-n: 18.00%	45S 68 MS β-: 100.00% β-n: 54.00%	46S 50 MS β-: 100.00%
29P 4.142 S ε: 100.00%	30P 2.498 M ε: 100.00%	31P STABLE 100%	32P 14.262 D β-: 100.00%	33P 25.34 D β-: 100.00%	34P 12.43 S β-: 100.00%	35P 47.3 S β-: 100.00%	36P 5.6 S β-: 100.00%	37P 2.31 S β-: 100.00%	38P 0.64 S β-: 100.00%	39P 0.28 S β-: 100.00%	40P 125 MS β-: 100.00%	41P 100 MS β-: 100.00%	42P 48.5 MS β-: 100.00%	43P 36.5 MS β-: 100.00%	44P 18.5 MS β-n	45P >200 NS β-

^{44}Ti

Not produced in a normal freeze out

$\tau_{cooling} >> \tau_{build\ up}$

(3α ^{12}C(α,γ)^{16}O(α,γ) ... NSE)



Produced in the α-rich freeze-out of zones exposed to the complete explosive Si burning

$\tau_{cooling} << \tau_{build\ up}$