Massive stars

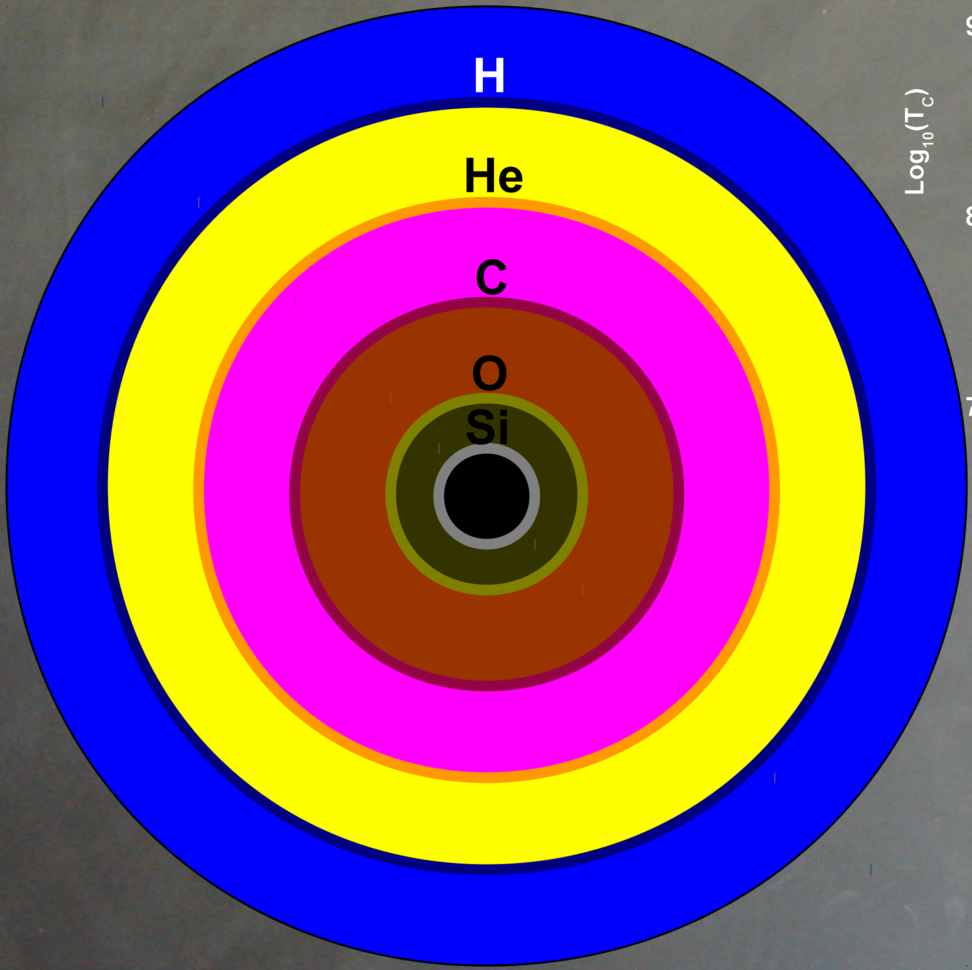
School on "The synthesis of the elements"

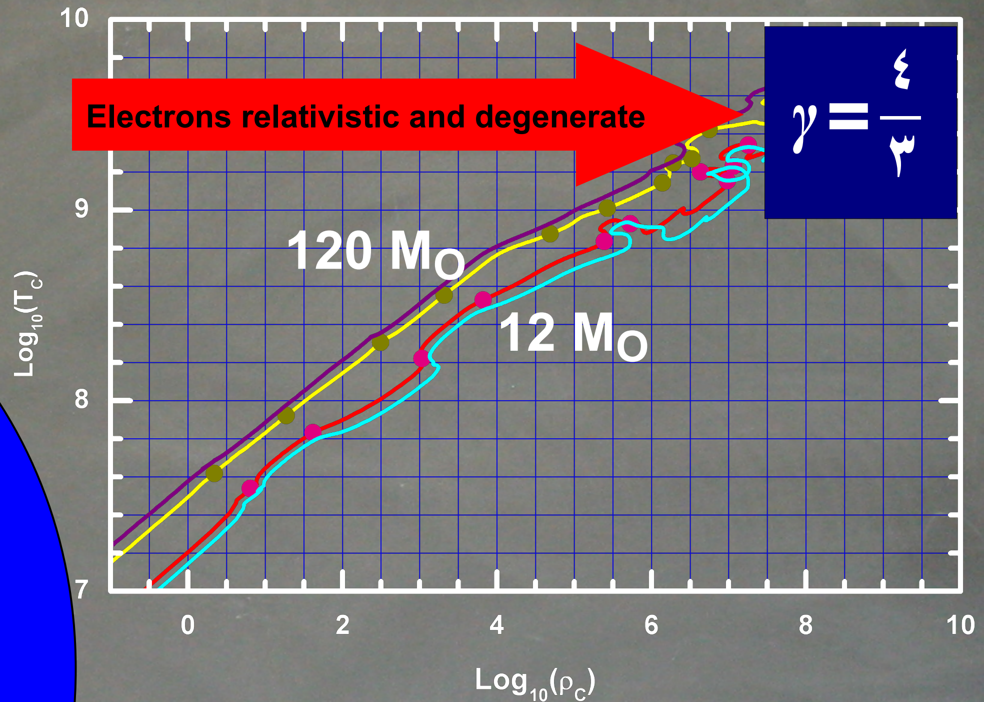
Granada (12-16 April 2010)

Alessandro Chieffi

Email: alessandro.chieffi@iasf-roma.inaf.it

Part 4





Virial theorem

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

$$U+\Omega\equiv E_{TOT}=\text{٠}$$

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

NO delay is required for a contraction,

the structure is only marginally stable

Sequence of events that lead to the collapse

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.

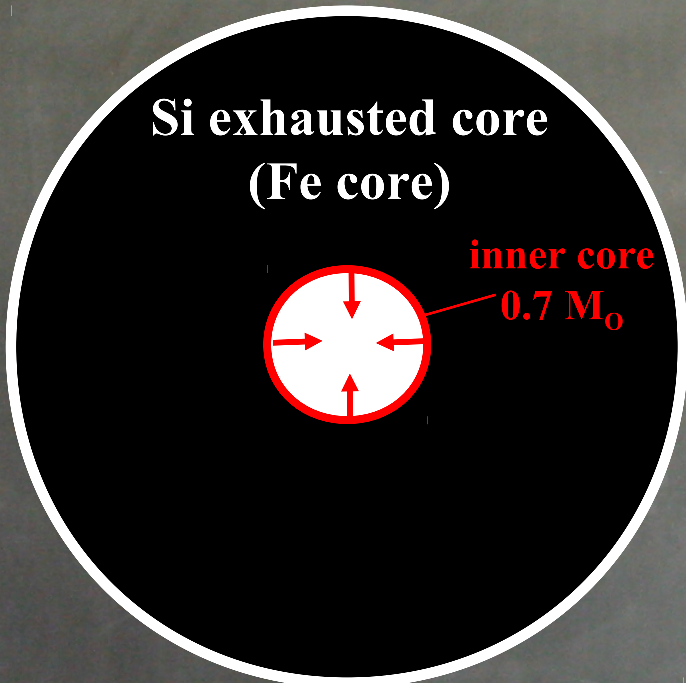
T

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:

$$\Omega = -\int_0^M \frac{G\,M}{R}\,dm = -\frac{3}{5}\frac{G\,M^2}{R}$$

$$\Delta\Omega = \Omega_{final} - \Omega_{initial} = -\frac{3}{5} G\,M^2 \left(\frac{1}{R_{final}} - \frac{1}{R_{initial}}\right) \simeq -1.58\, 10^{59} \left(\frac{1}{R_{final}}\right) \quad \boxed{\simeq 1.6\, 10^{53}\ erg}$$

(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:

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

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:

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

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

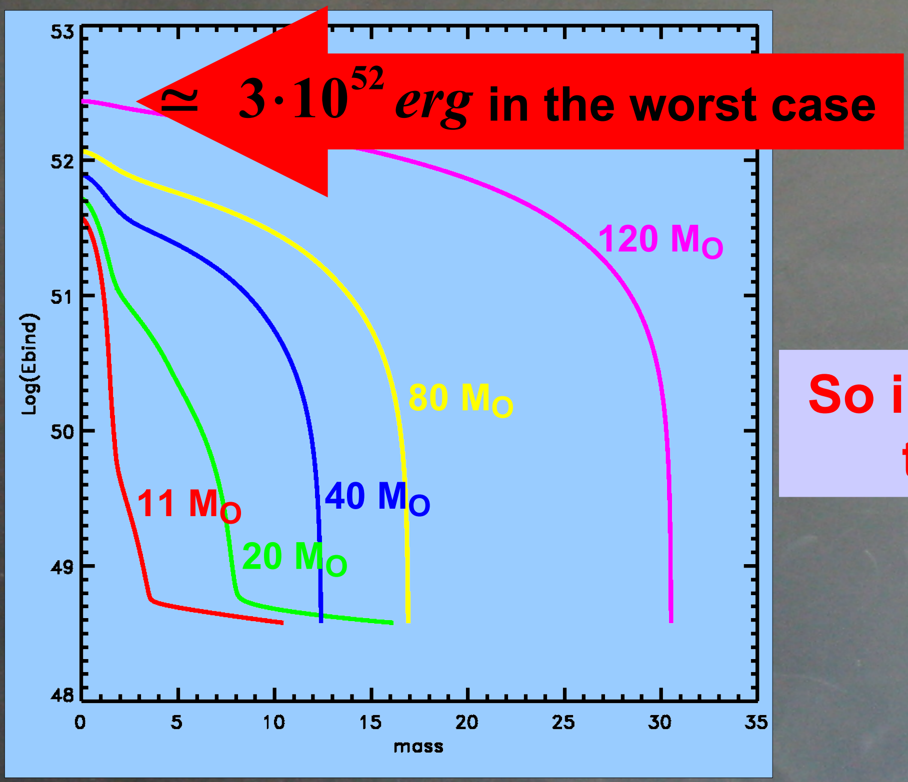
$$1.6\cdot 10^{53} - 1.7\cdot 10^{52} - 1.5\cdot 10^{51} - 3.8\cdot 10^{52} \simeq 10^{53}\ erg\, M_O^{-1}$$

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:

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

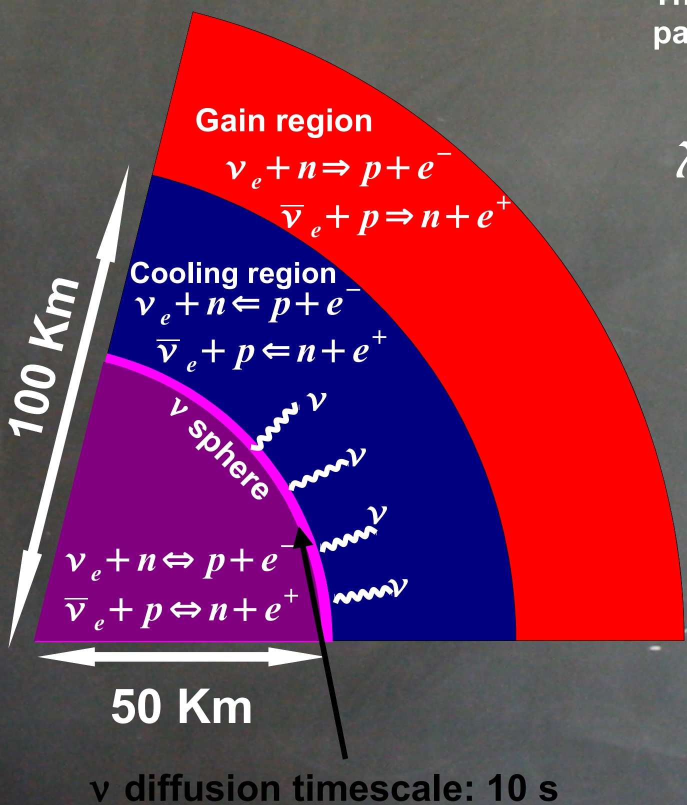
Where κ, the "opacity", may be expressed in terms of the probability σ_{ij} that an interaction between the particles i and j occurs:

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

The basic interaction between n and nuclei A is given by the neutral current coherent scattering , whose cross section is given by:

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

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

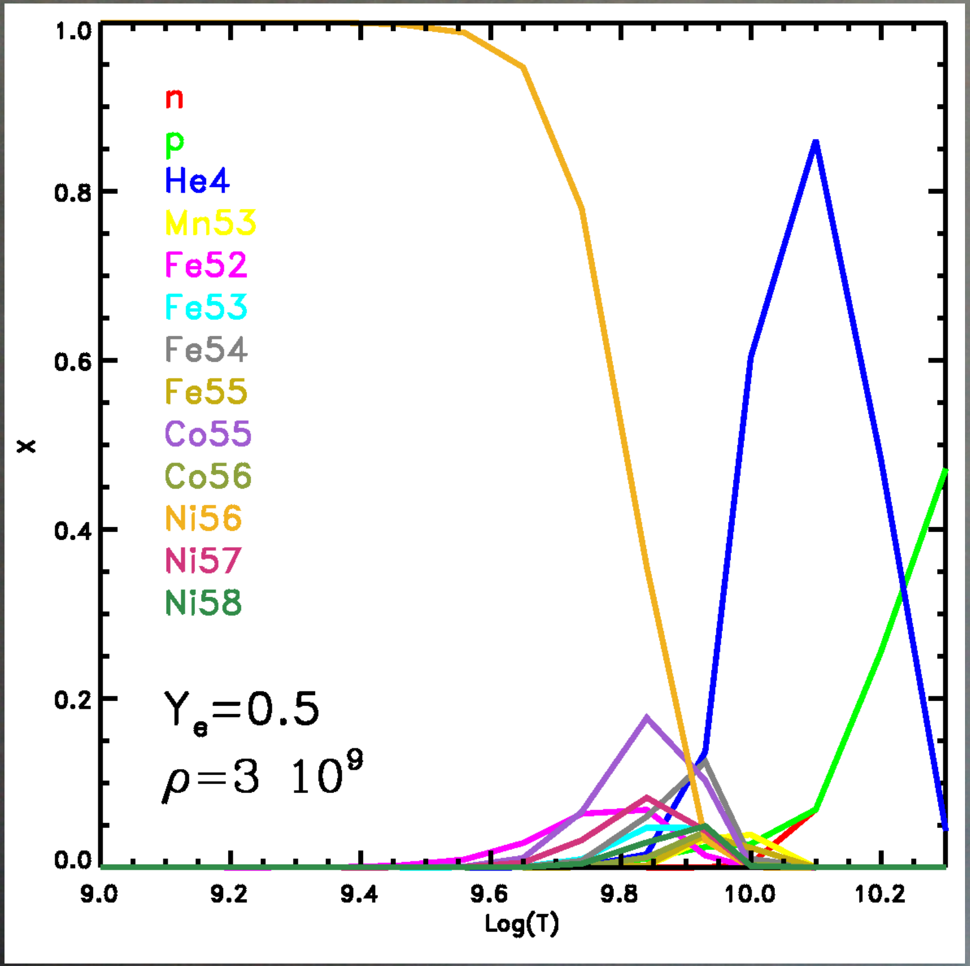


Basic core collapse scenario

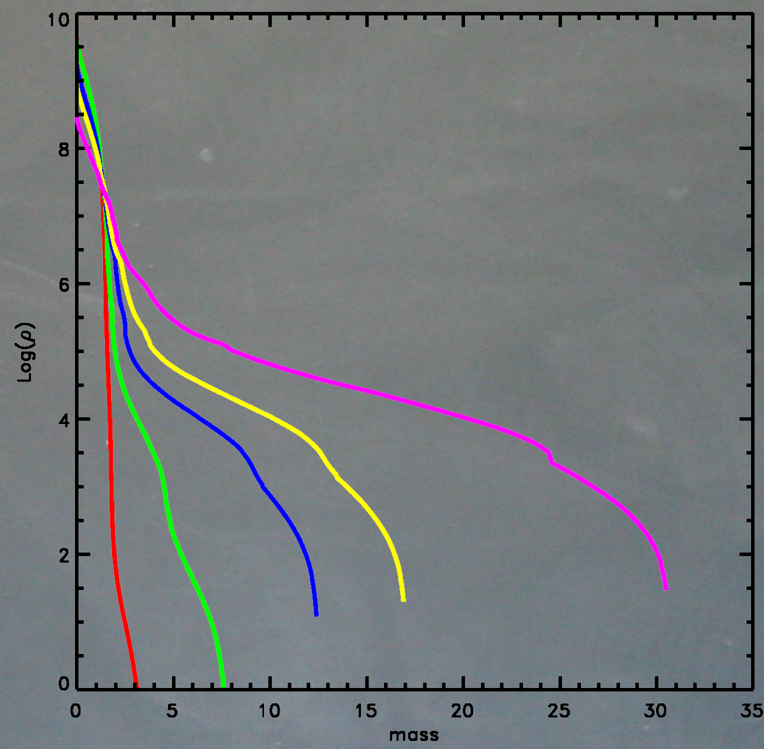
What it is even worst is that the shock wave lose a large amount of energy on its way out:

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

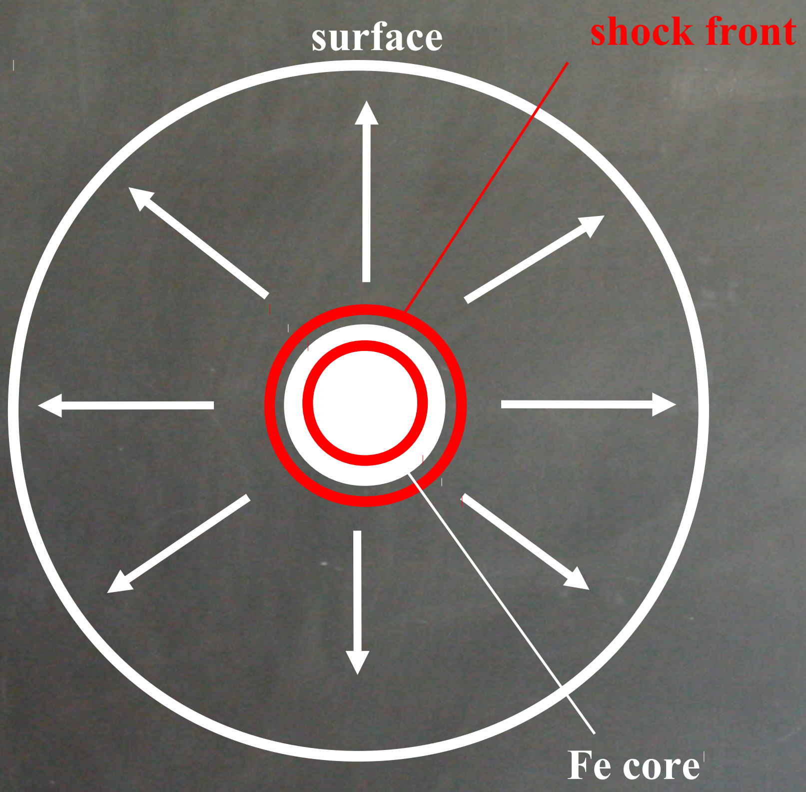
For example: $^{56}Fe \Rightarrow 30\ n + 26\ p$ requires the absorbtion of $7.87\ 10^{-4}$ erg (492 MeV)



$8.47\ 10^{18}$ erg/gr => 10^{51} erg / 0.1 M_O



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



Escamotage:

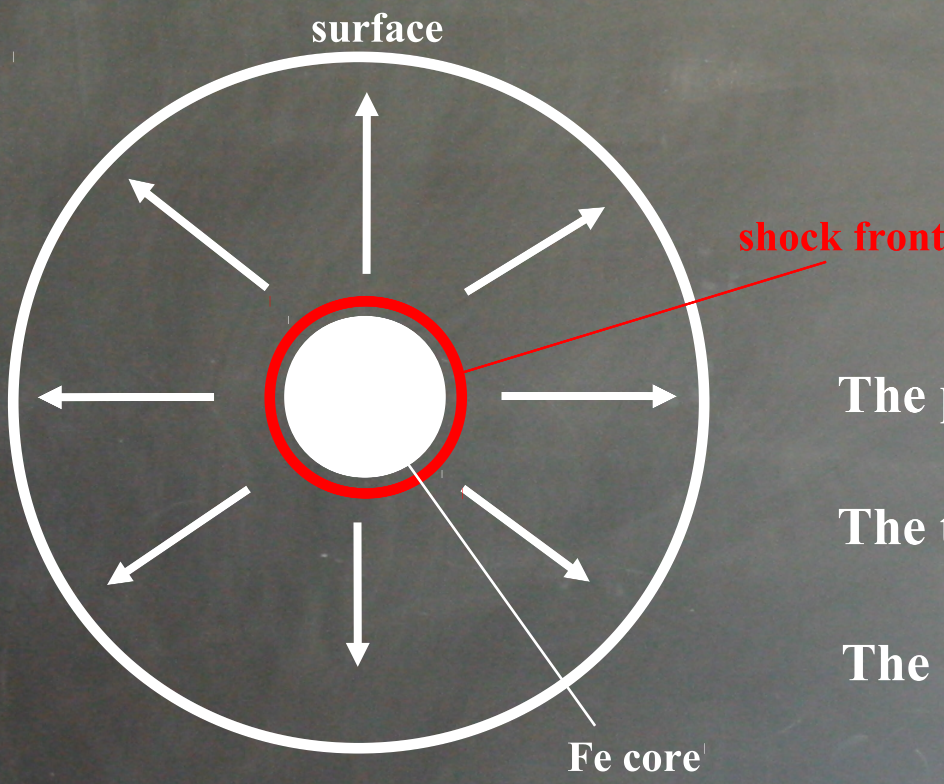
Assume that the shock wave escapes the dense core (roughly the Fe core)

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)

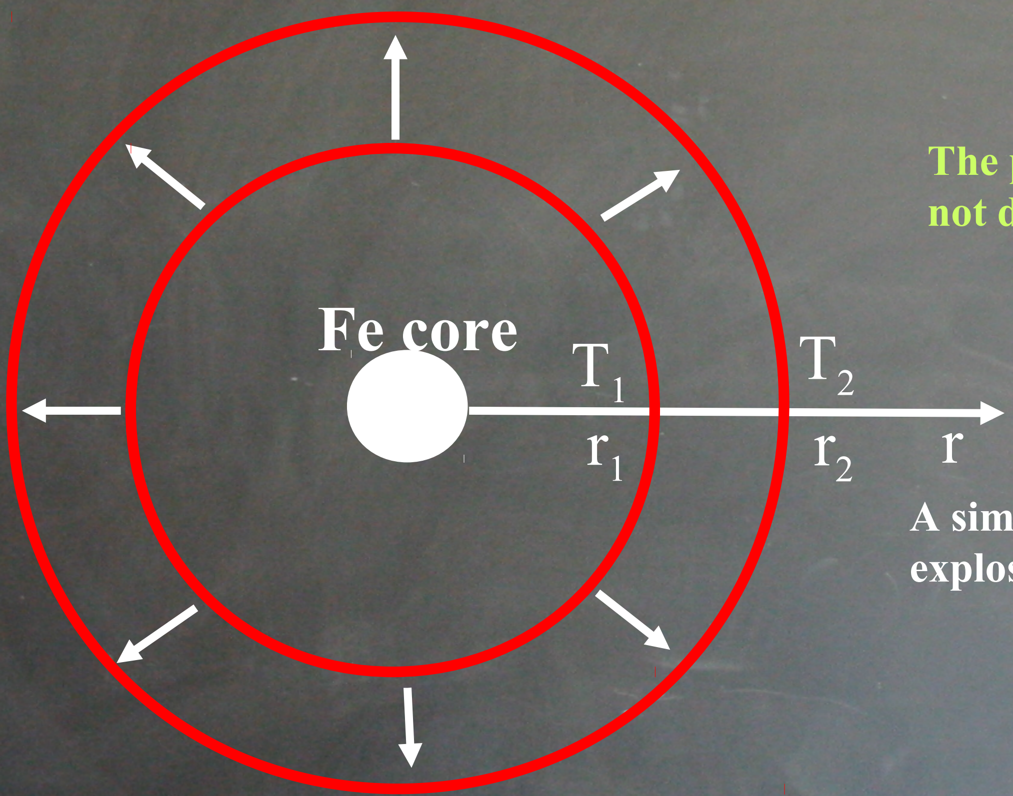
The thermal bomb (Nomoto and coworkers)

The kinetic bomb (Limongi and Chieffi)

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

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

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



CONSEQUENCE:

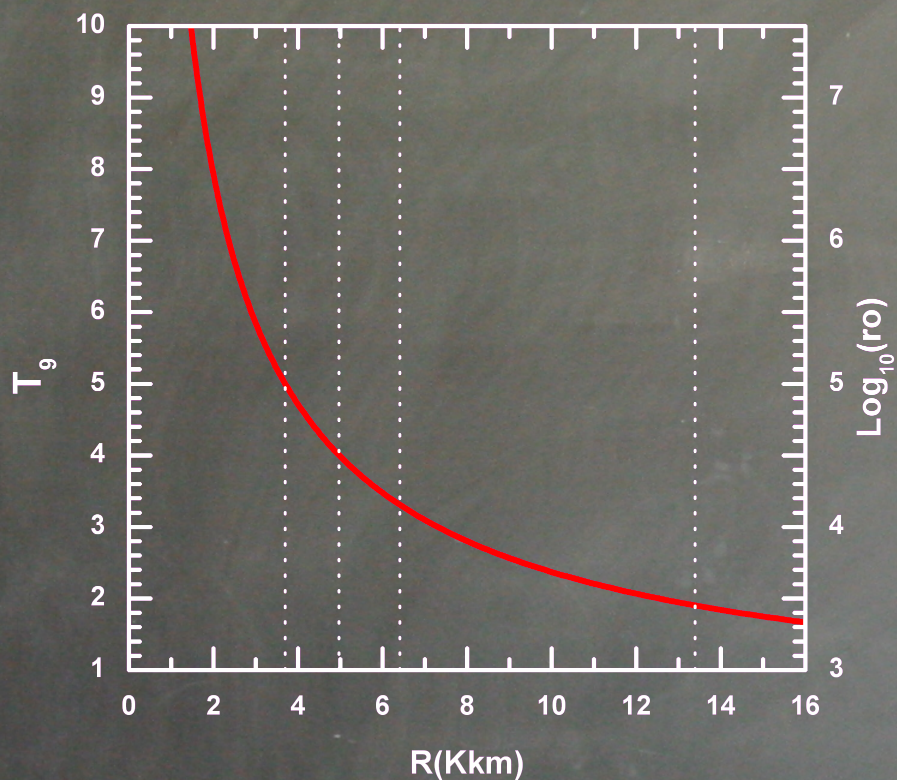
The peak temperature of the blast wave does not depend on the stellar structure.

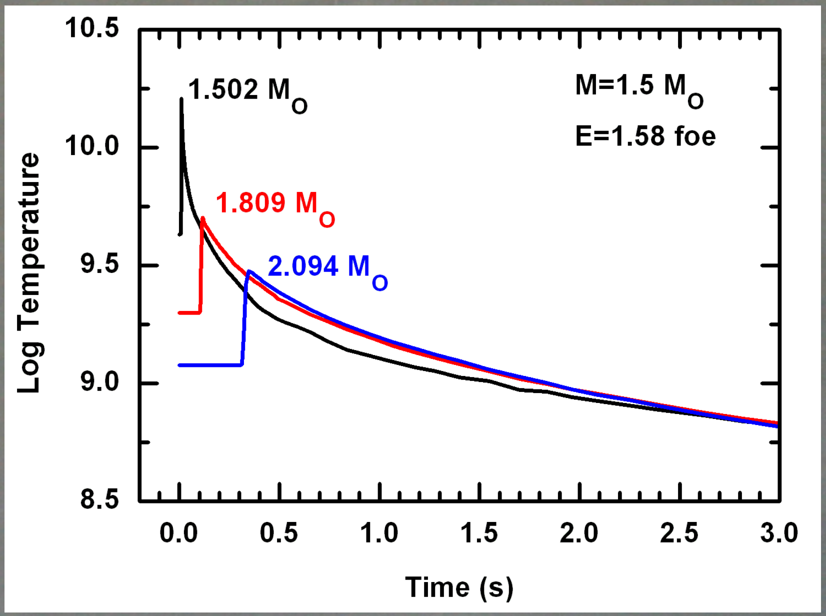
A simple but quite effective computation of the explosive yields may be obtained by assuming:

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

$$\tau = (24 \alpha \pi G)^{-0.5} \rho_{peak}^{-0.5}$$

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

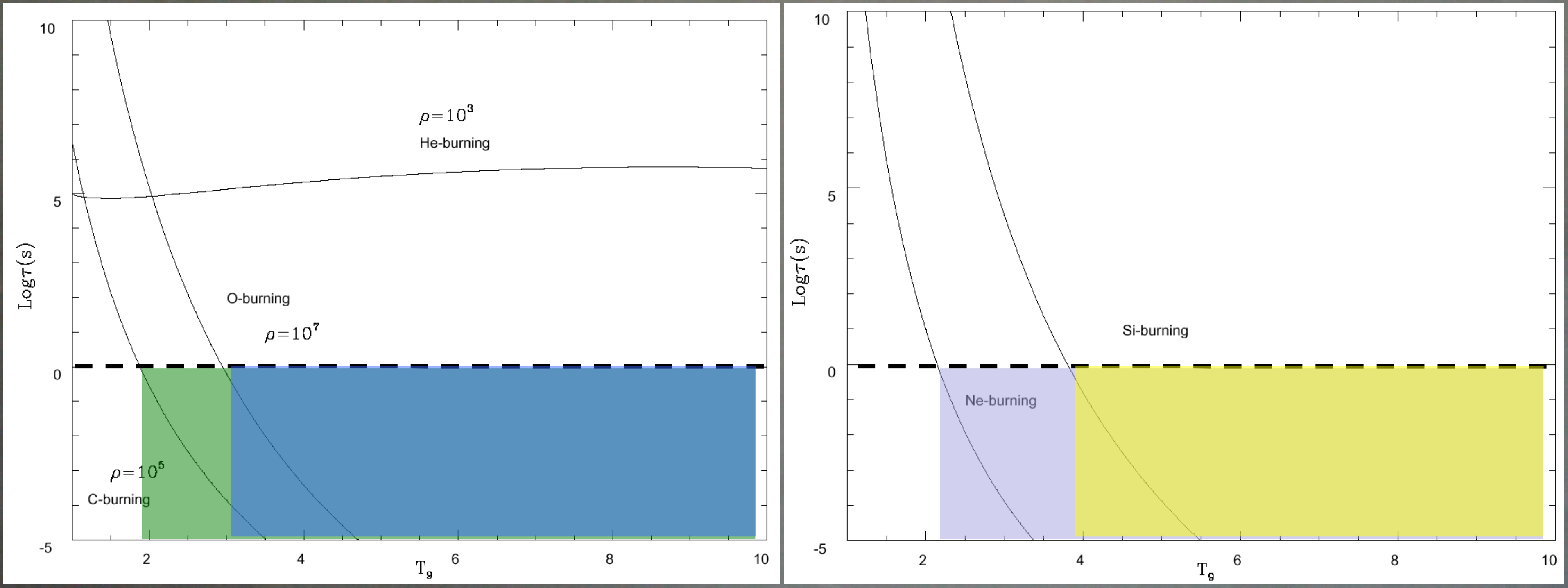
O burning: $^{16}\mathrm{O}(^{16}\mathrm{O},\alpha)^{28}\mathrm{Si}$

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

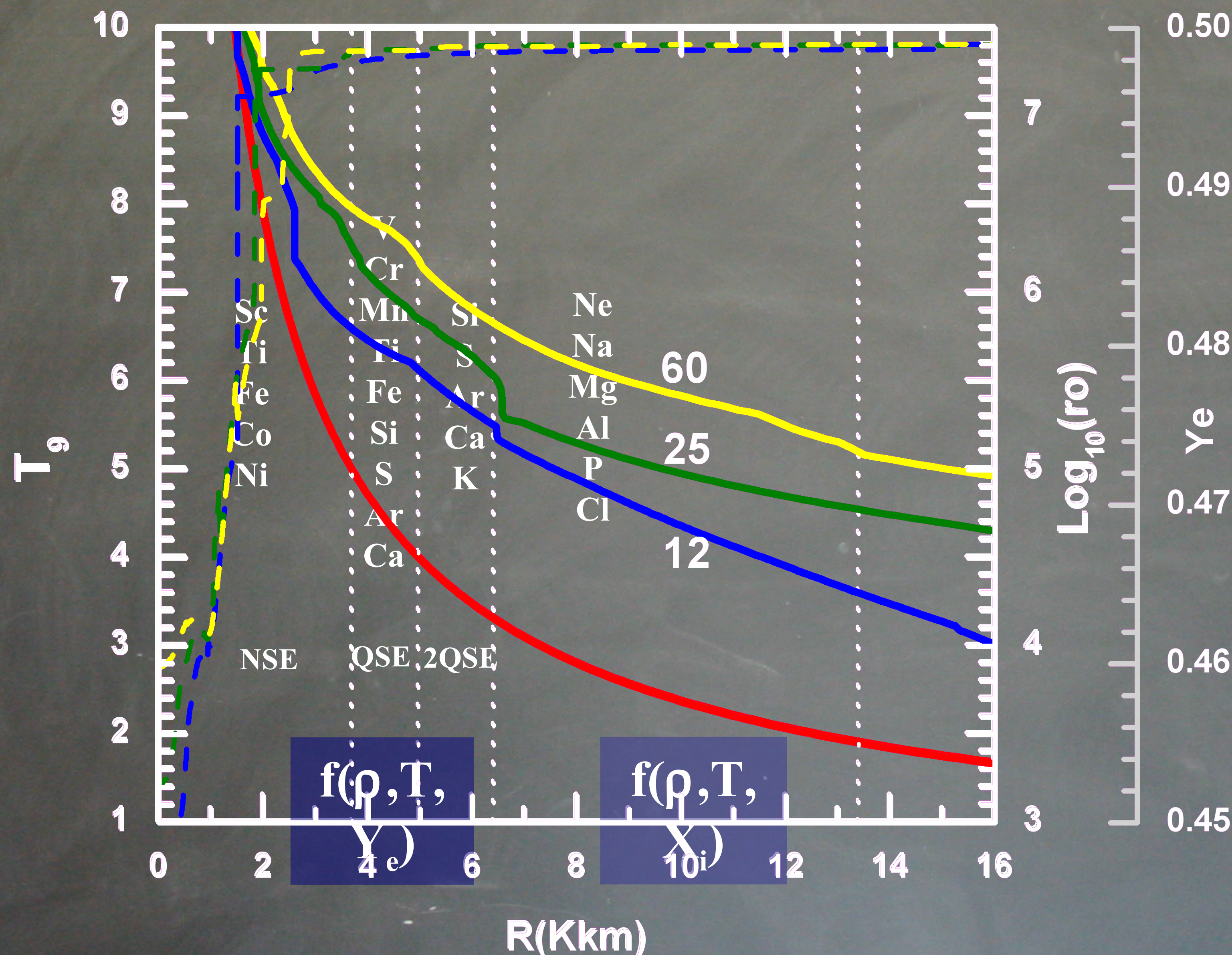
and in general are functions of temperature and density: $\tau_i = f(T,\rho)$

CHARACTERISTIC EXPLOSIVE BURNING TEMPERATURES

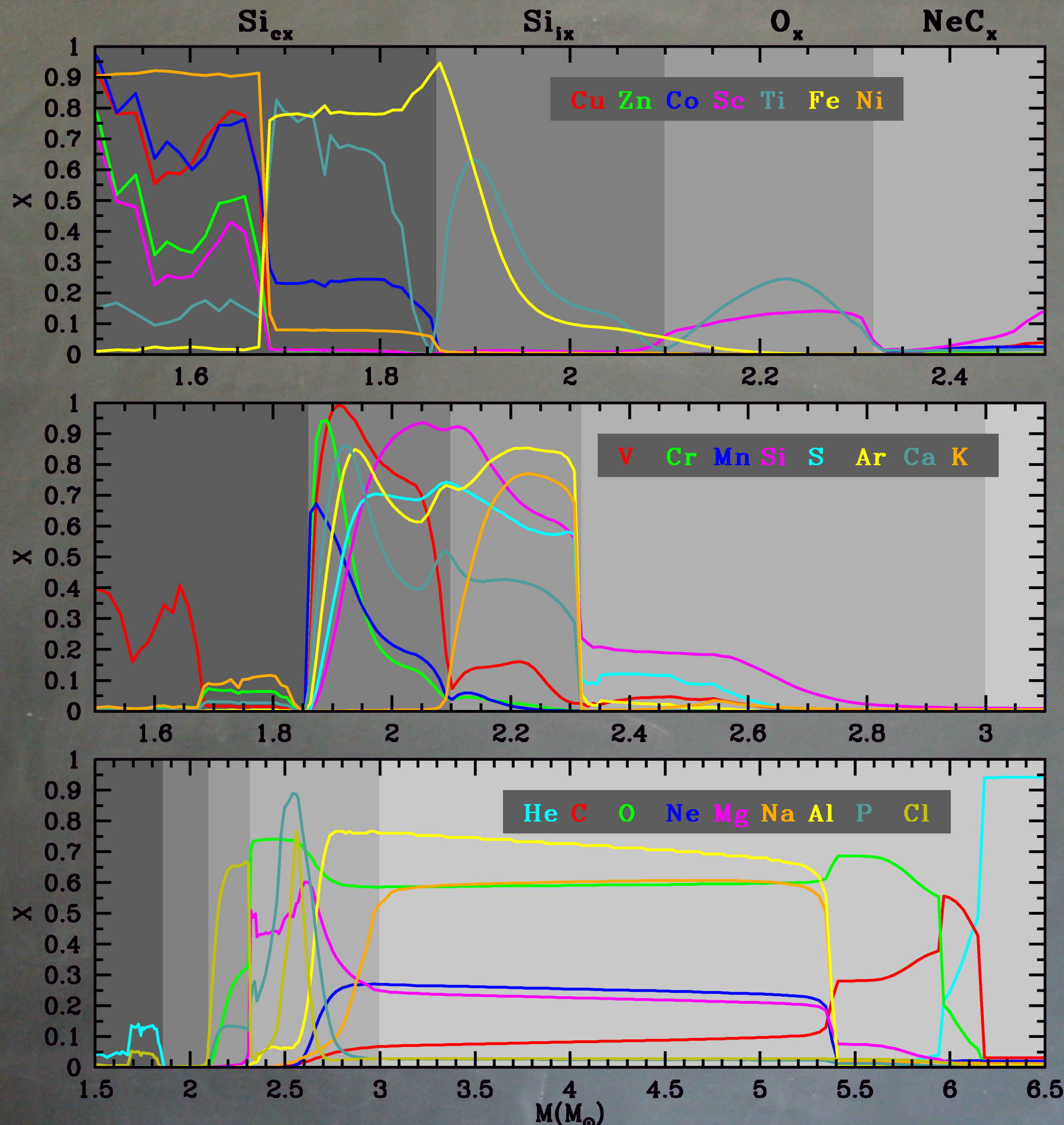
If we take typical explosive burning timescales of the order of 1s



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



T9
R(Kkm)
Log10(ro)
Ye
NSE
QSE
2QSE
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
f(ρ,T,Ye)
f(ρ,T,Xi)

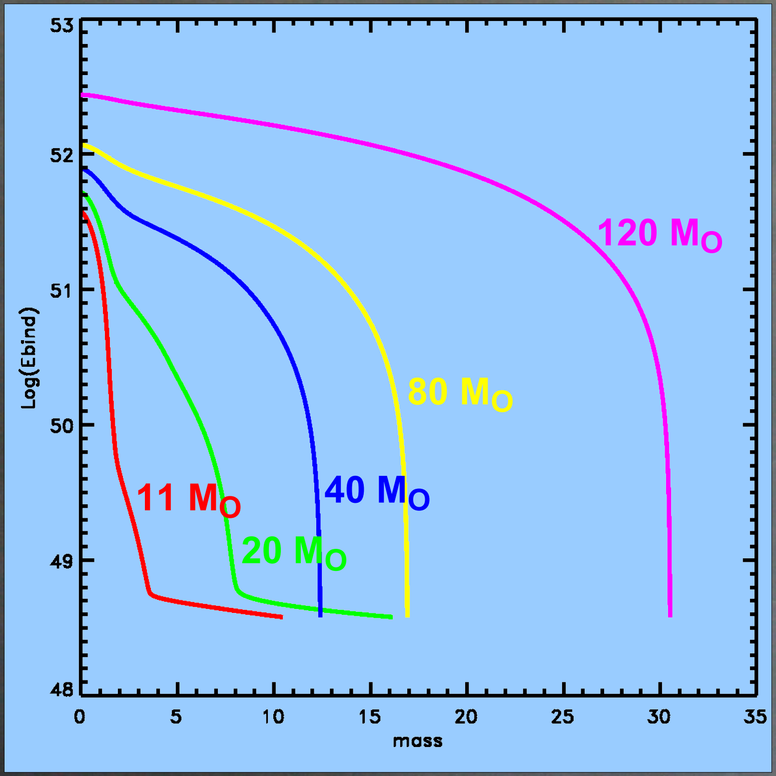


Si$_{cx}$
Si$_{ix}$
O$_x$
NeC$_x$
Cu Zn Co Sc Ti Fe Ni
V Cr Mn Si S Ar Ca K
He C O Ne Mg Na Al P Cl
X
M(M$_\odot$)

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.

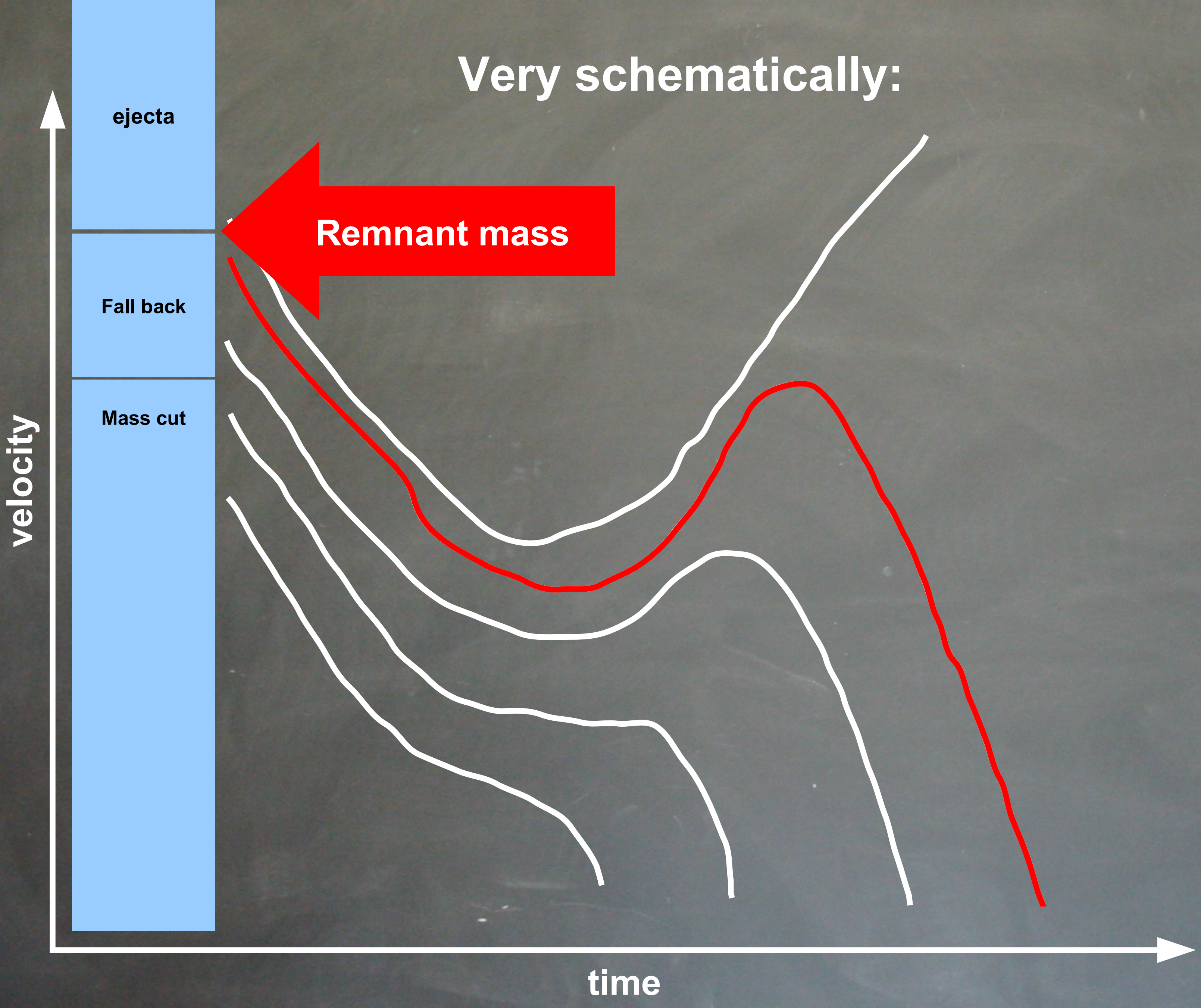
Basic definitions:

Mass cut: maximum mass that will always move inward

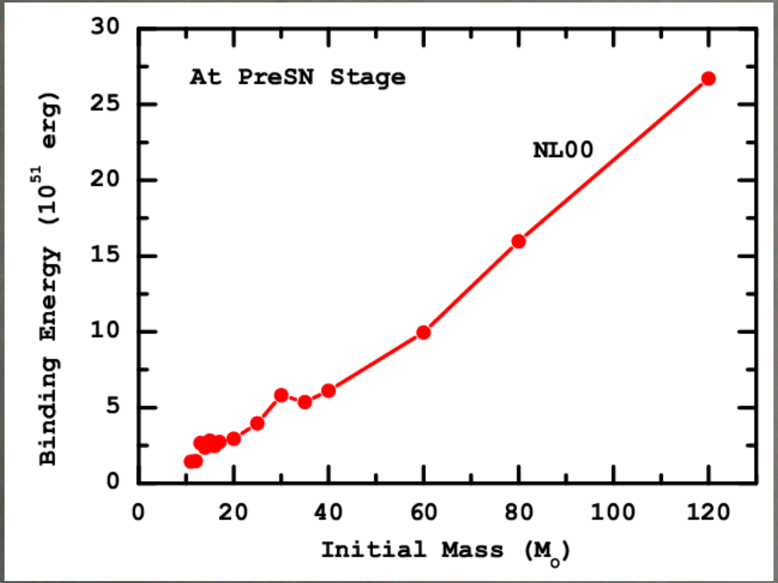
Fall back: mass that initially is kicked off but that then falls back on the collapsed core.

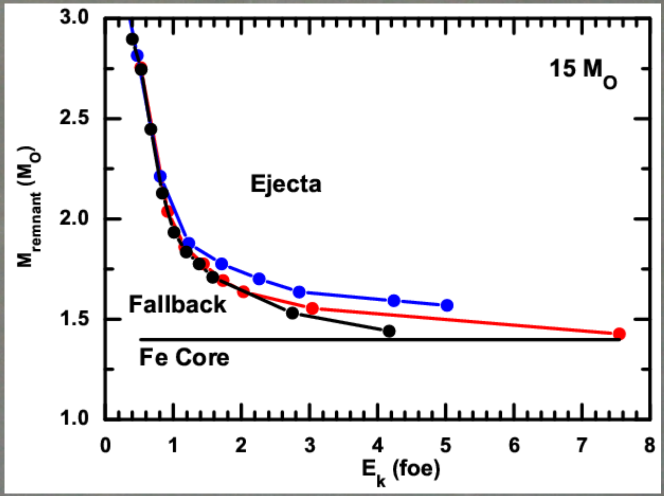
Remnant mass: mass cut + fall back (final mass size of the collapsed core).

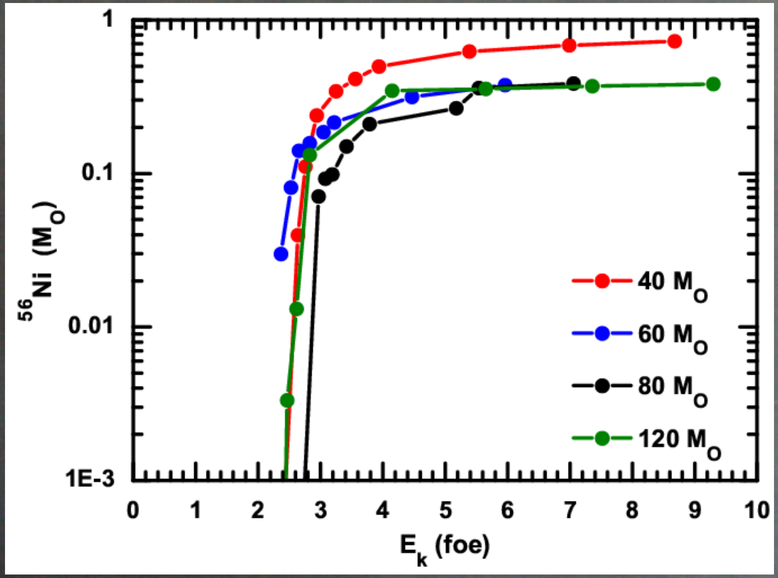
Very schematically:

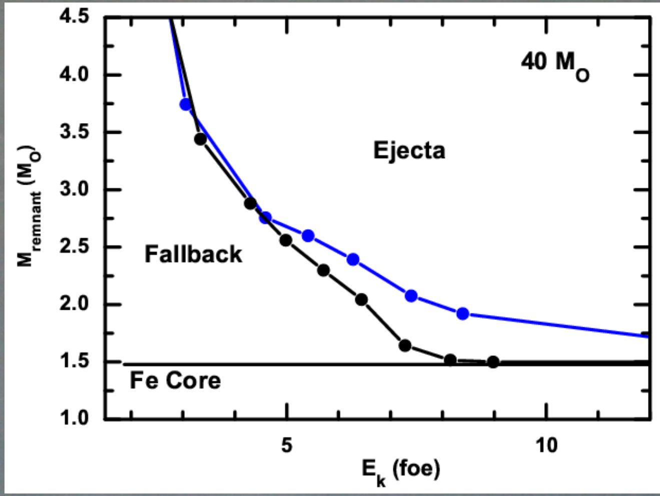


FALL BACK AND FINAL REMNANT

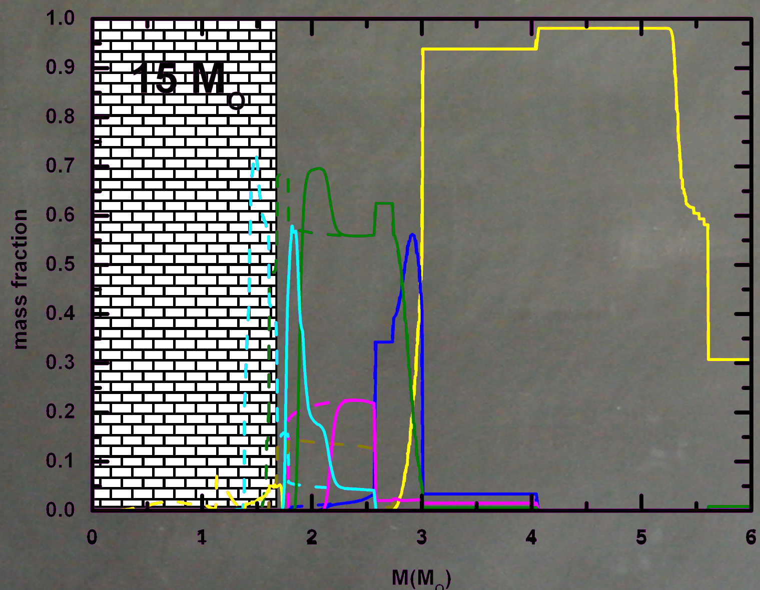


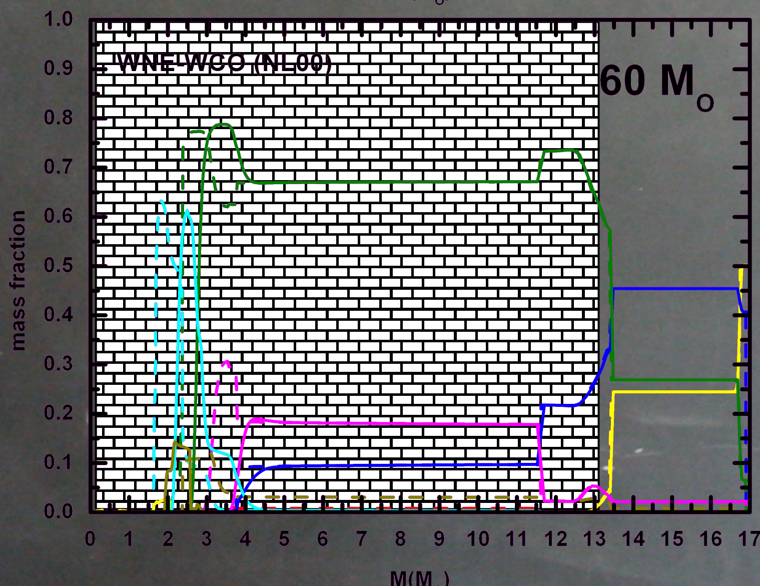


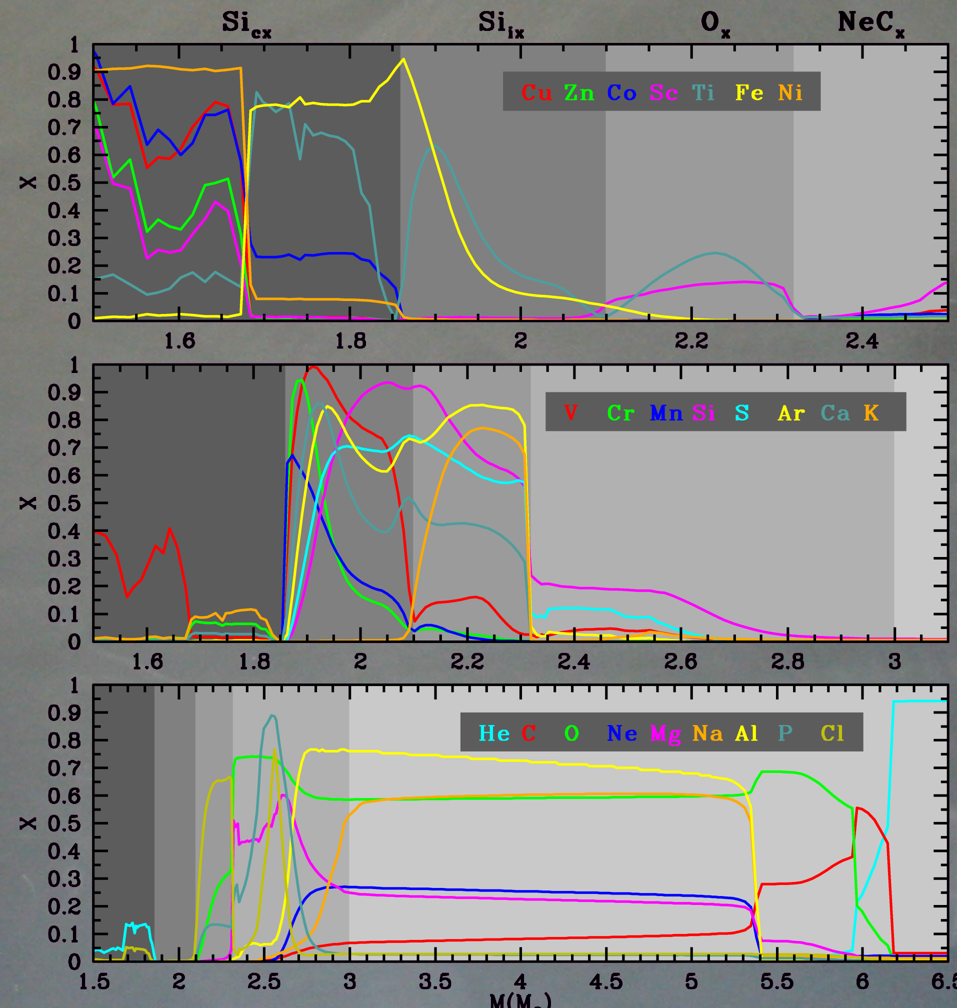


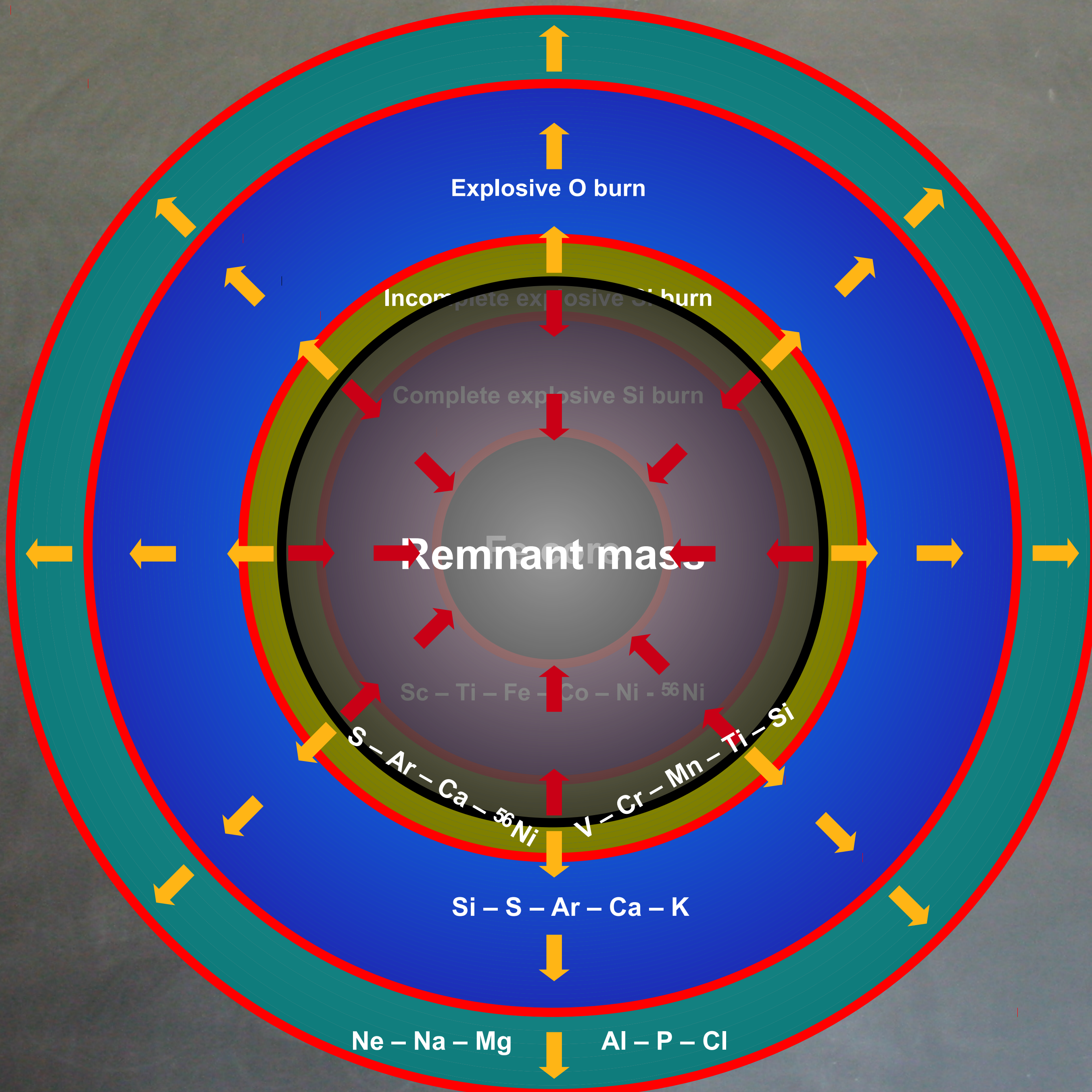


Final kinetic energy = 1 foe (10^{51} erg)

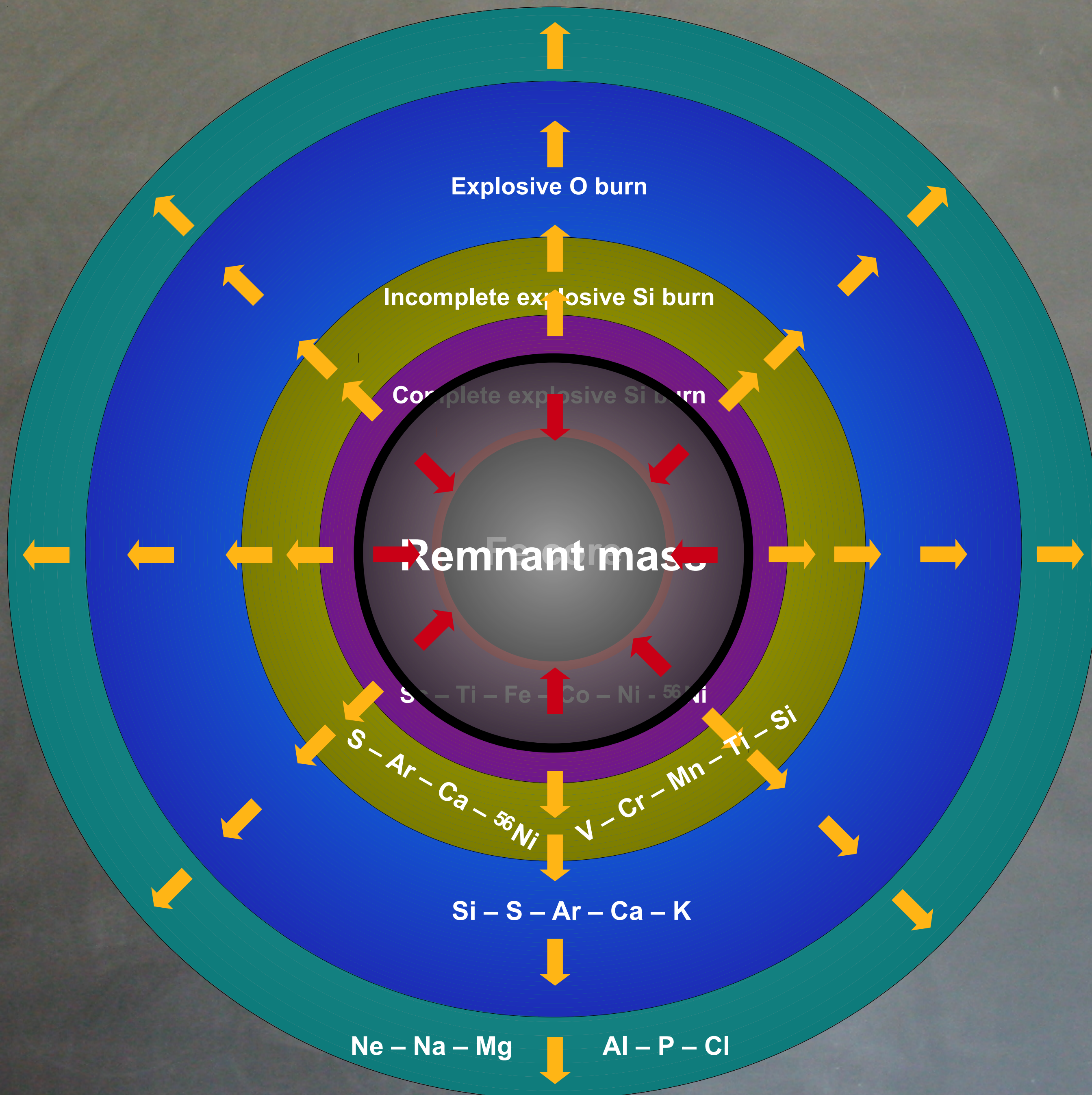




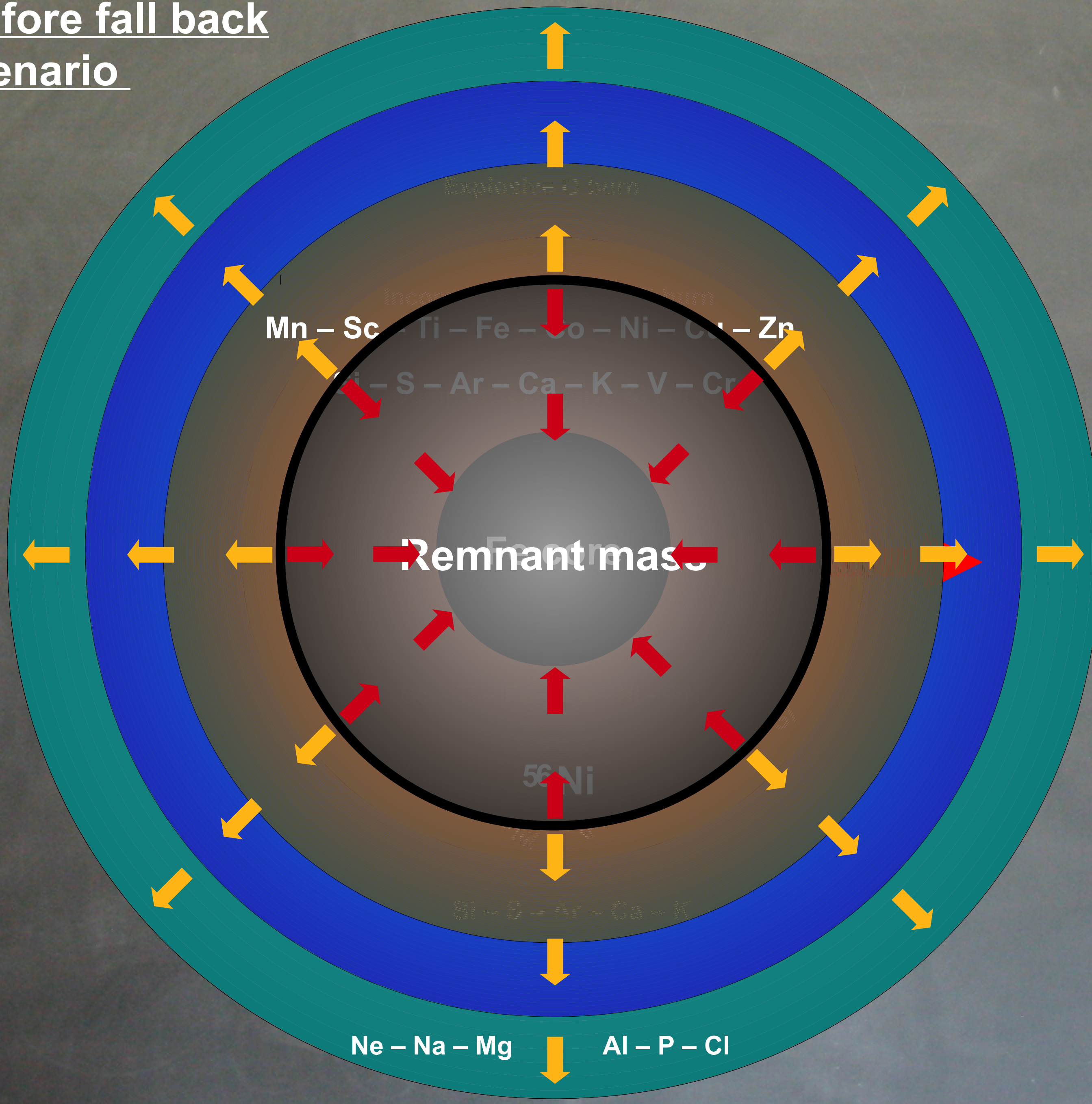




Explosive O burn
Incomplete explosive Si burn
Complete explosive Si burn
Remnant mass
Fe core
Sc – Ti – Fe – Co – Ni - 56Ni
S – Ar – Ca – 56Ni
V – Cr – Mn – Ti – Si
Si – S – Ar – Ca – K
Ne – Na – Mg
Al – P – Cl

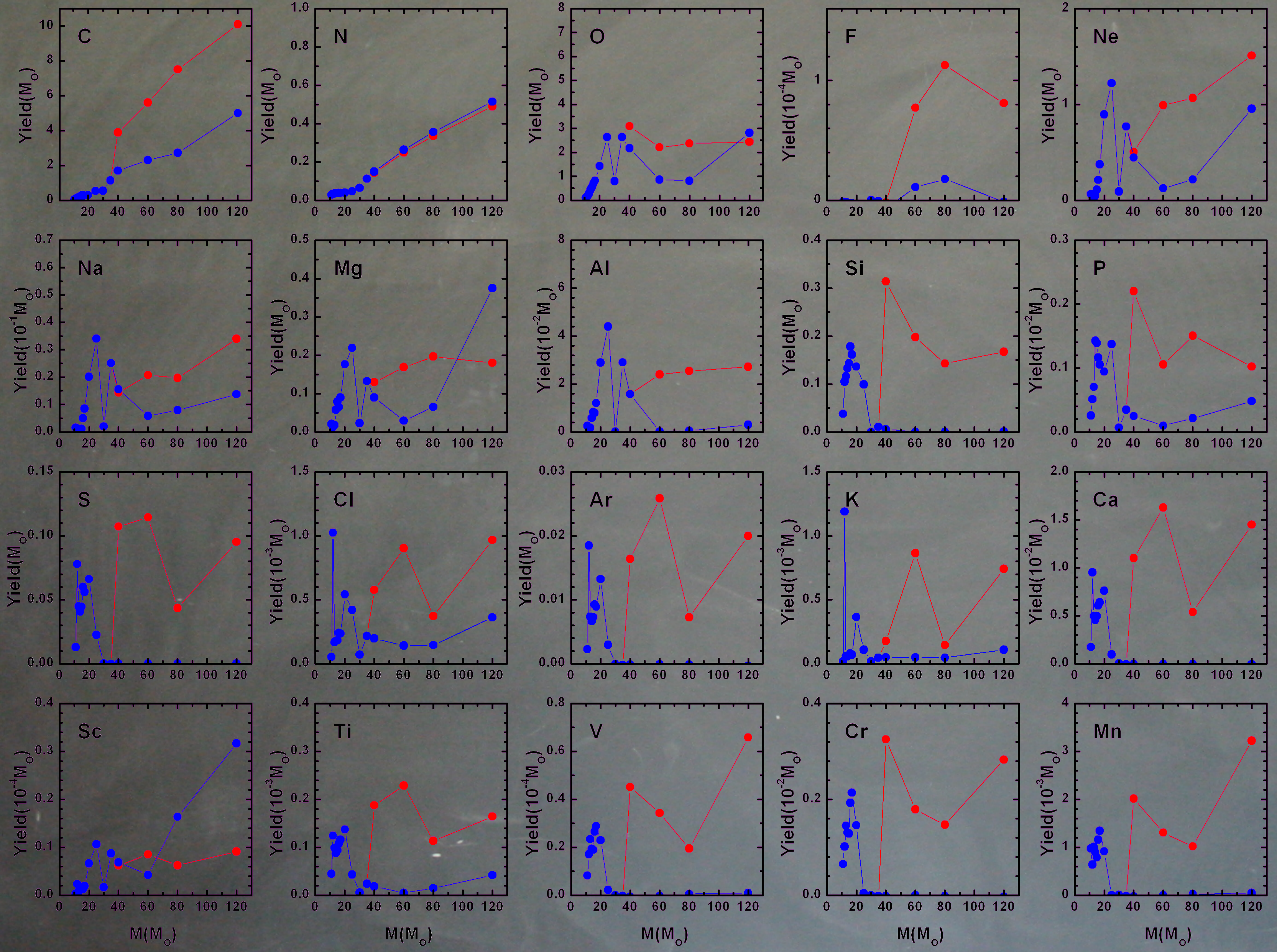

Explosive O burn
Incomplete explosive Si burn
Complete explosive Si burn
Remnant mass
S – Ar – Ca – 56Ni
V – Cr – Mn – Ti – Si
Si – S – Ar – Ca – K
Ne – Na – Mg
Al – P – Cl

Mixing before fall back scenario



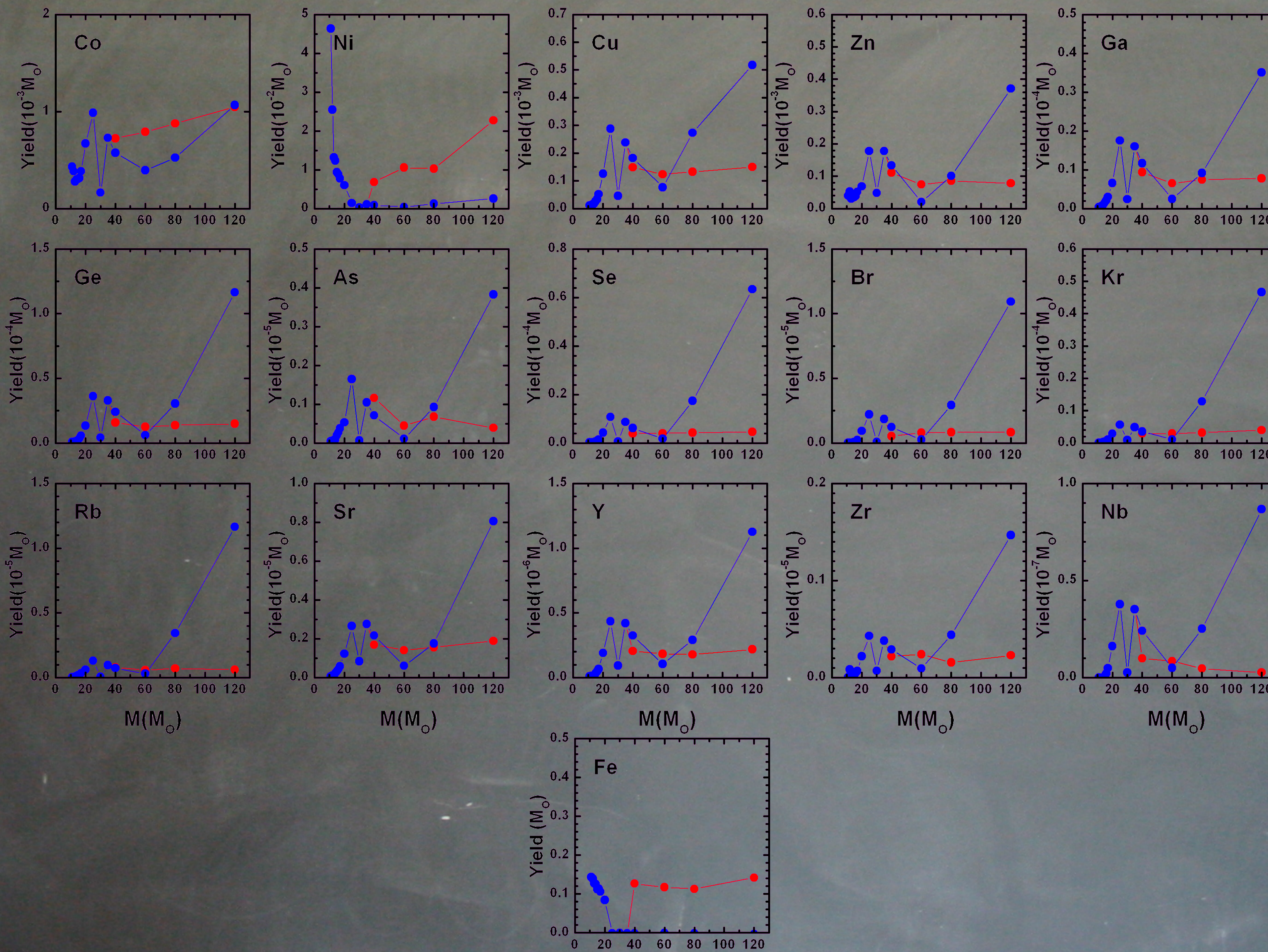
Mass Loss in the WNE / WCO phases: Langer89 - Nugis & Lamers 00

1 foe



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

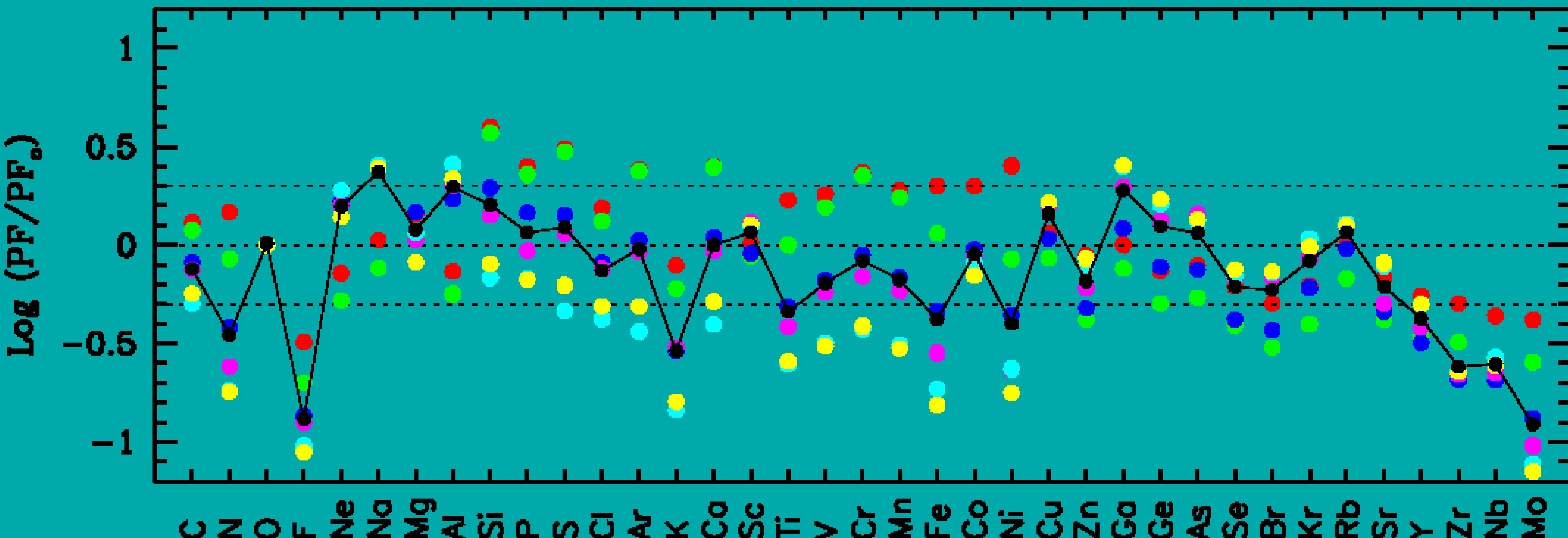
A natural, robust “leader” nucleus is ^{16}O because it is certainly produced only by massive stars and it is also the most abundant nucleus in nature (beyond H and ^{4}He)

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

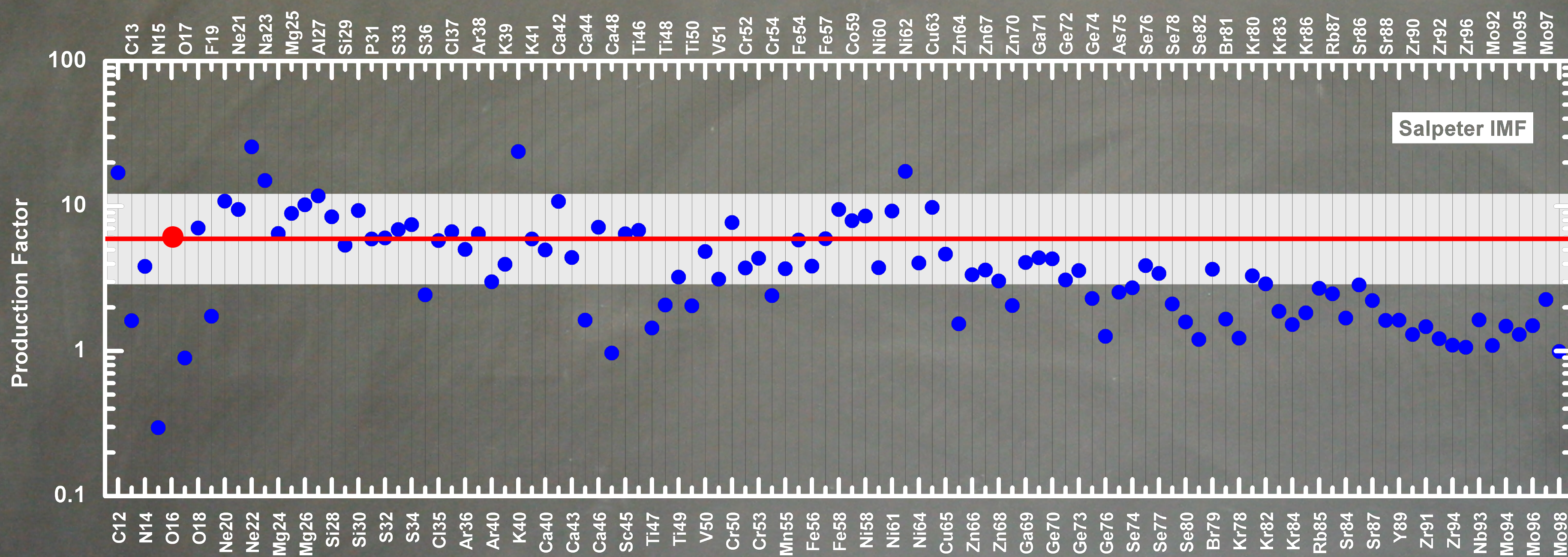
$\mathrm{Log}(PF_O)$ = 0.378 – 0.599 – 0.878 – 1.03 – 1.15 – 1.19 – 0.932



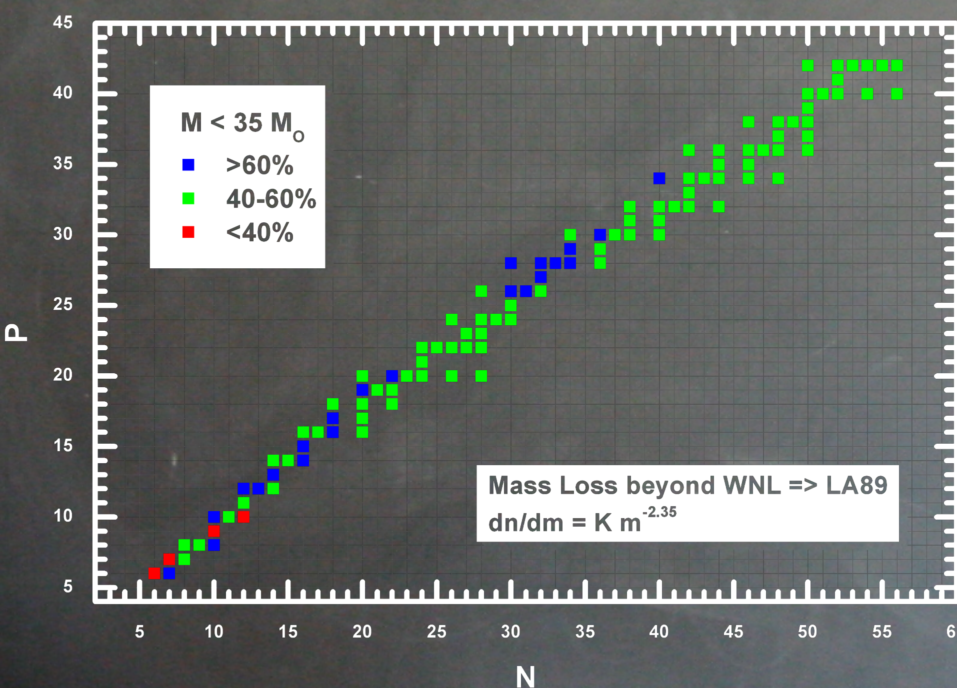
Dots: 13 – 15 – 20 – 25 – 30 – 35 Msun

Solid line: Salpeter Mass Function

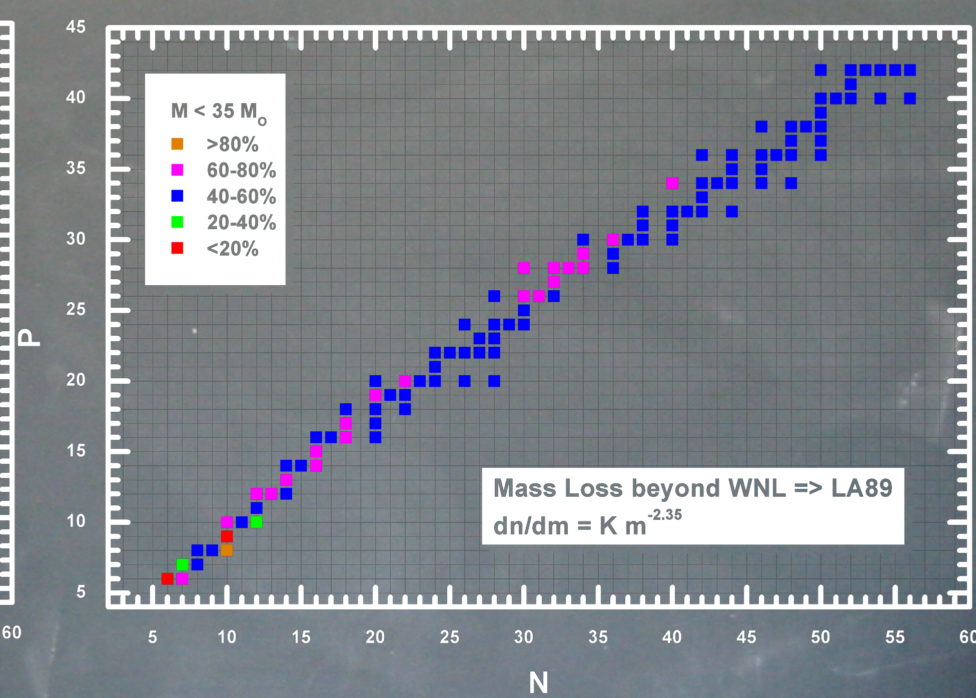
Flat ^{56}Ni => 0.05 $M_\odot$



Production Factor
Salpeter IMF
100
10
1
0.1
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
C12 N14 O16 O18 Ne20 Ne22 Mg24 Mg26 Si28 Si30 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

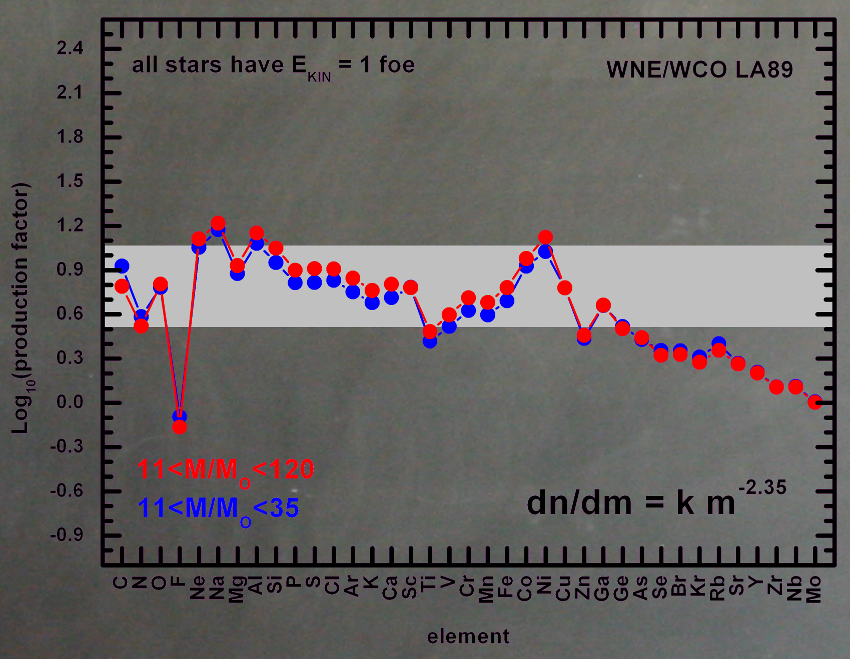


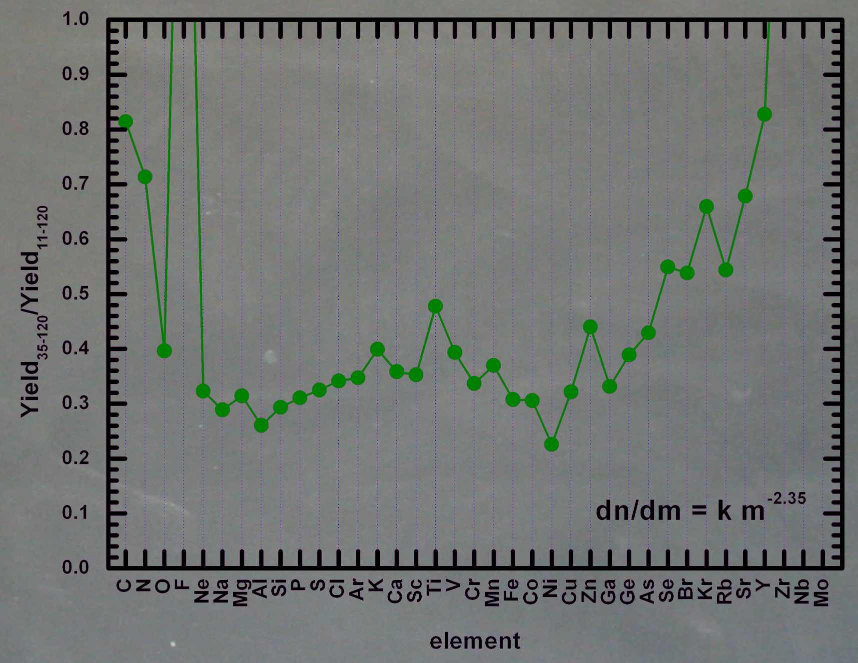
M < 35 M_{O}
>60%
40-60%
<40%
Mass Loss beyond WNL => LA89
$dn/dm = K\ m^{-2.35}$
P
N
5 10 15 20 25 30 35 40 45
5 10 15 20 25 30 35 40 45 50 55 60

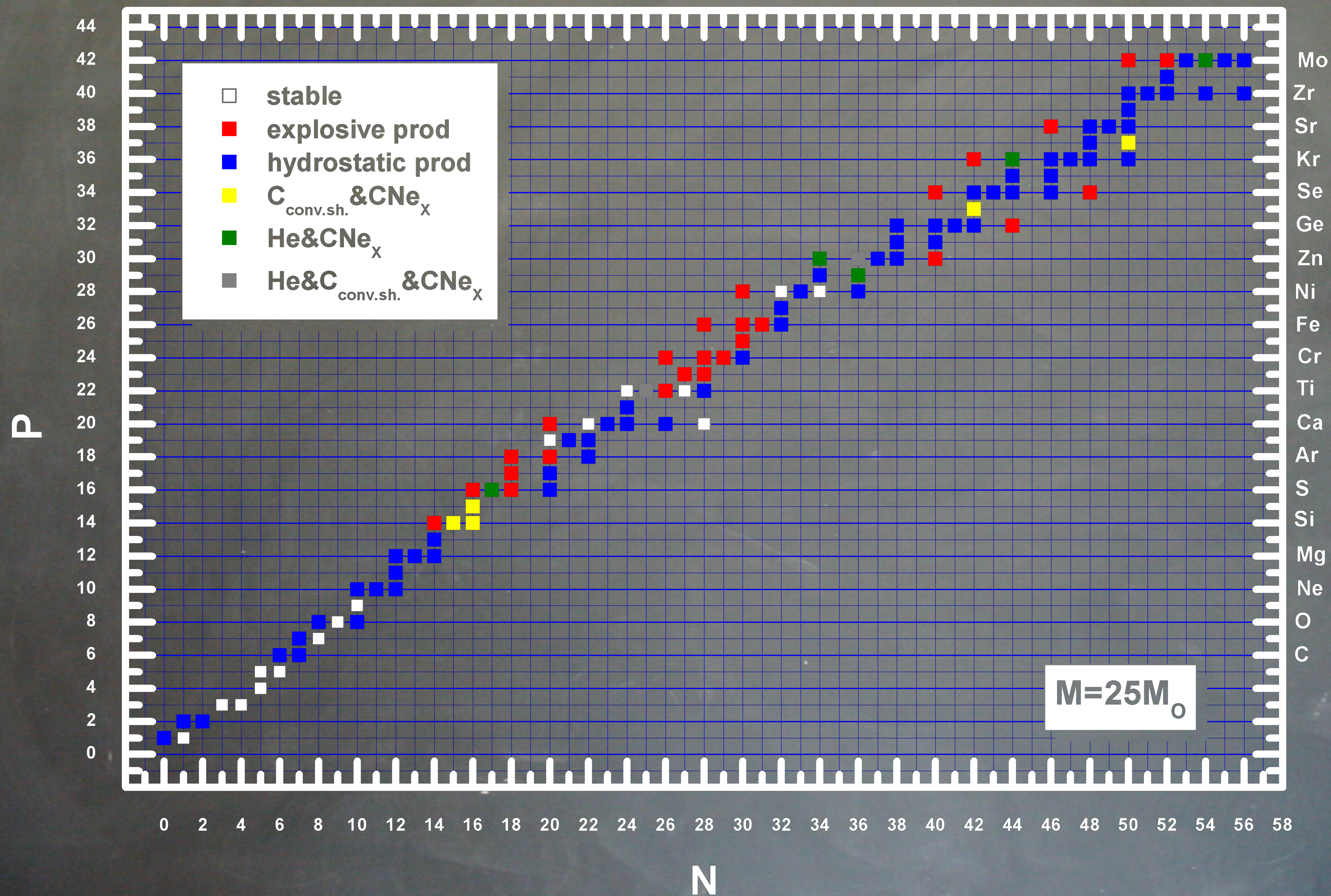


M < 35 M_{O}
>80%
60-80%
40-60%
20-40%
<20%
Mass Loss beyond WNL => LA89
$dn/dm = K\ m^{-2.35}$
P
N
5 10 15 20 25 30 35 40 45
5 10 15 20 25 30 35 40 45 50 55 60

$PF = \text{yield} / (M_{ejected} * X_{initial})$ - >1 (produced) - < 1 (destroyed) - =1 (untouched)







stable
explosive prod
hydrostatic prod
$C_{conv.sh.}$&CNe_x
He&CNe_x
He&$C_{conv.sh.}$&CNe_x
$M=25M_o$
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
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
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Ar
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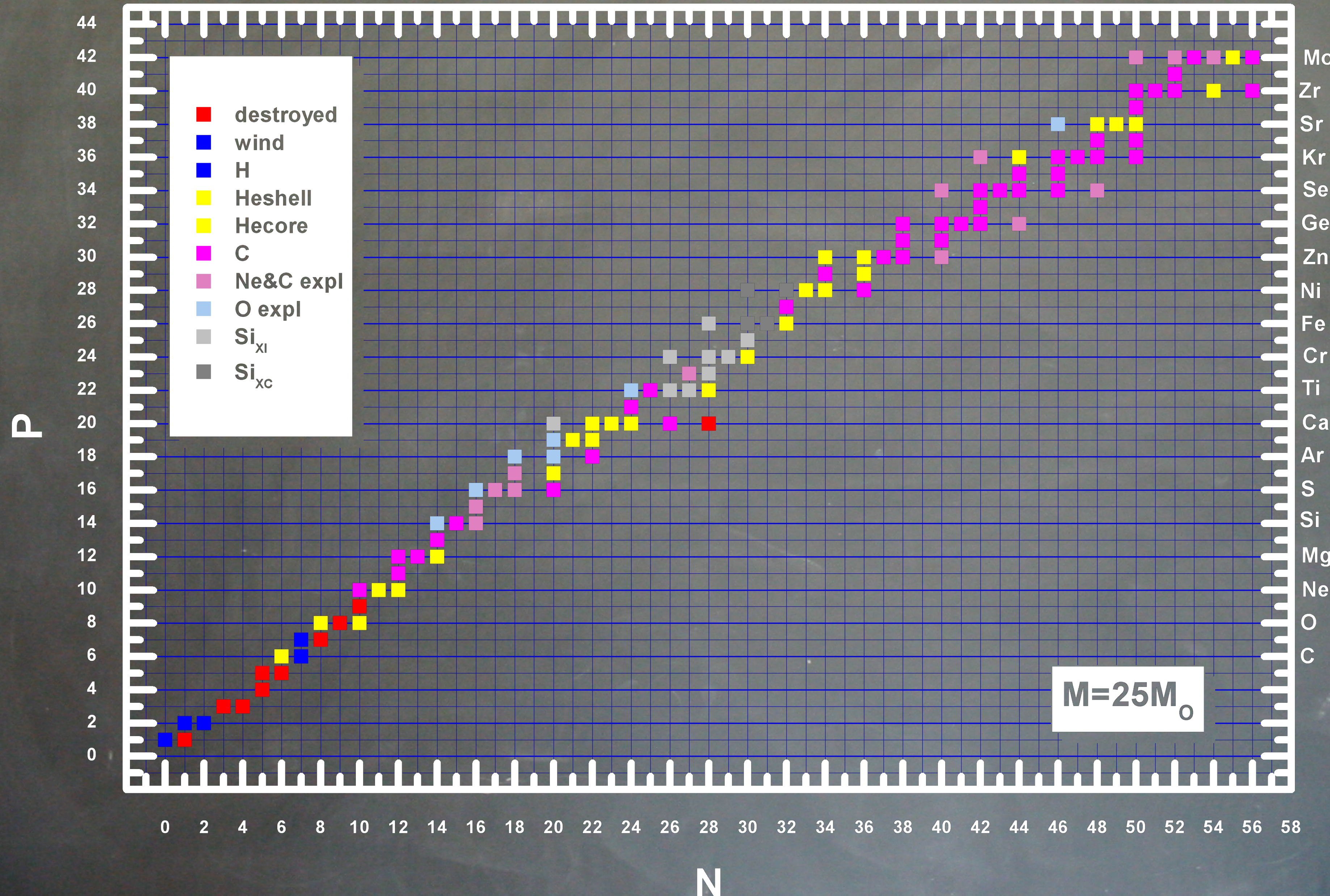
Si
Mg
Ne
O
C



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

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

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

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

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

$F(^{19}F)$ *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.