Explosive Nucleosynthesis in Massive Stars

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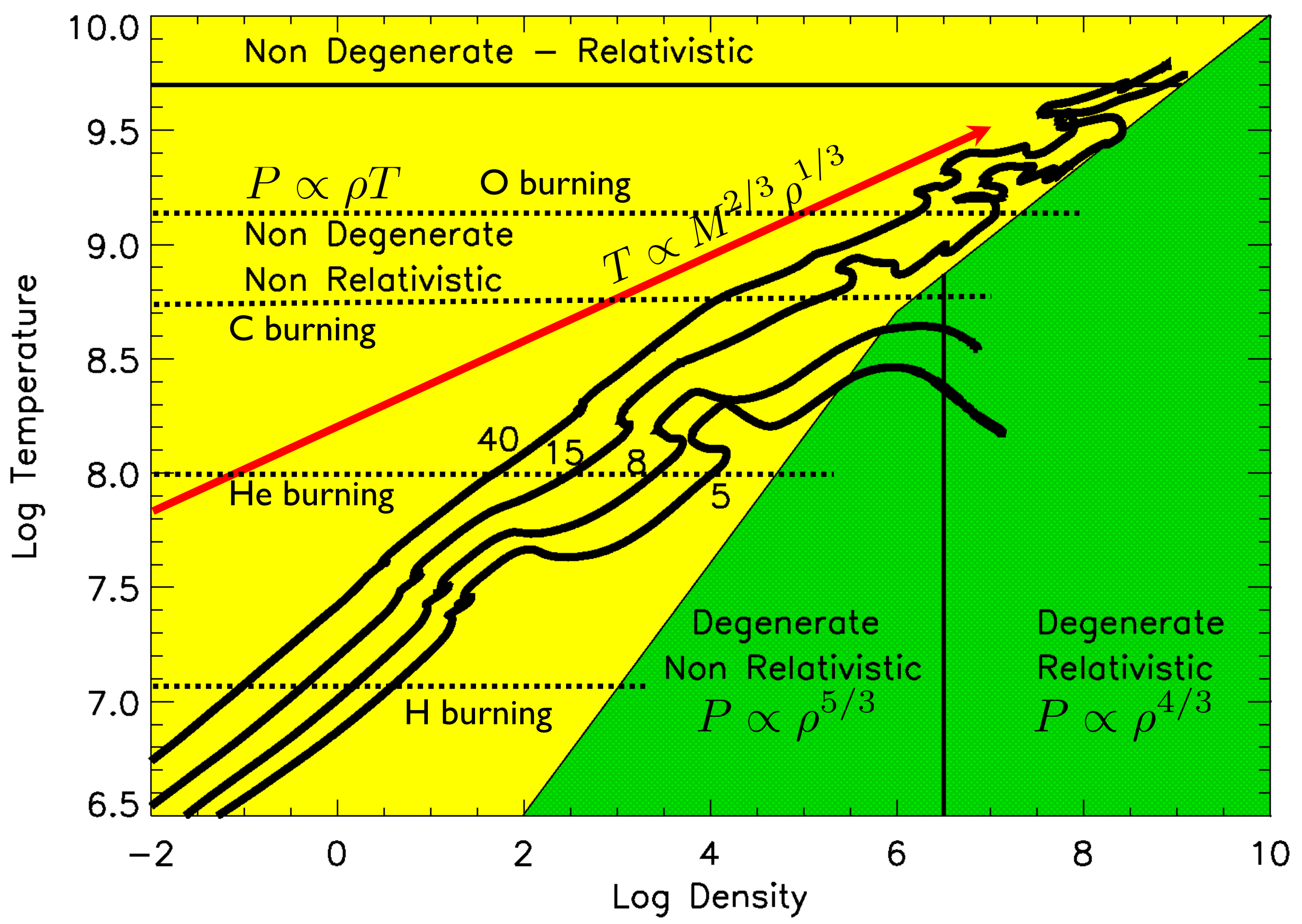
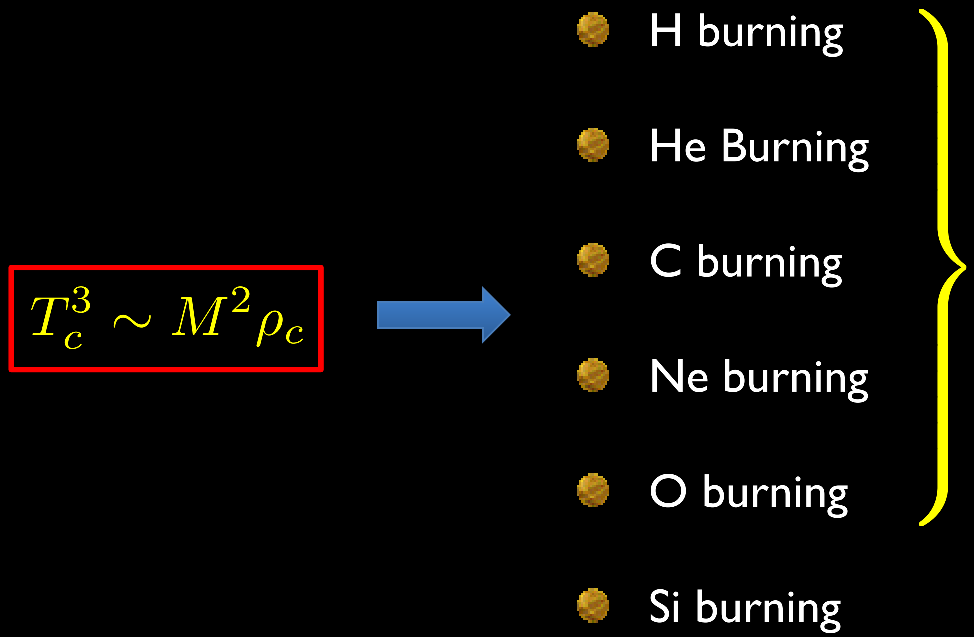
Massive Stars

Massive stars ($M>9\ M_\odot$) go through all the nuclear burning stages in a non degenerate environment and eventually explode as Core Collapse Supernovae



Massive Stars: Nuclear Burning Stages

During its progressive contraction and heating a massive star evolves through a series of nuclear burning stages, either at the center or in a shell, using the products of the previous one as a fuel. Six major (core and/or shell) nuclear burning stages, characterized by their principal fuel, can be identified during all the evolution:



$$\boxed{T_c^3 \sim M^2 \rho_c}$$

- H burning
- He Burning
- C burning
- Ne burning
- O burning
- Si burning

Occurring through well defined sequences of leading reactions

Massive Stars: Nuclear Burning Stages

He burning

$T \sim 2 \cdot 10^8$ K

$\rho \sim 1 \cdot 10^3$ g cm^{-3}

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

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

$\Rightarrow$ ^{12}C, ^{16}O

s-process

C burning

$T \sim 8 \cdot 10^8$ K

$\rho \sim 8 \cdot 10^5$ g cm^{-3}

$^{12}\mathrm{C}(^{12}\mathrm{C},\alpha)^{20}\mathrm{Ne} \rightarrow {}^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}$

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

$^{12}\mathrm{C}(^{12}\mathrm{C},p)^{23}\mathrm{Na} \rightarrow {}^{23}\mathrm{Na}(p,\gamma)^{24}\mathrm{Mg}$

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

+ several hundreds

$\Rightarrow$ ^{20}Ne, ^{23}Na, ^{24}Mg, ^{27}Al

^{25}Mg, ^{26}Mg, s-process

Ne burning

$T \sim 1.5 \cdot 10^9$ K

$\rho \sim 5 \cdot 10^6$ g cm^{-3}

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

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

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

$^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg} \rightarrow {}^{24}\mathrm{Mg}(\alpha,p)^{27}\mathrm{Al}(\alpha,p)^{30}\mathrm{Si}$

$^{23}\mathrm{Na}(\alpha,p)^{26}\mathrm{Mg}(\alpha,n)^{29}\mathrm{Si}$

+ several thousands

$\Rightarrow$ ^{16}O, ^{24}Mg , ^{28}Si

^{25,26}Mg, ^{27}Al, ^{29,30}Si, ^{31}P

O burning

$T \sim 2 \cdot 10^9$ K

$\rho \sim 7 \cdot 10^6$ g cm^{-3}

$^{16}\mathrm{O}(^{16}\mathrm{O},\alpha)^{28}\mathrm{Si}$ $\sim 25\%$

$^{16}\mathrm{O}(^{16}\mathrm{O},p)^{31}\mathrm{P}$ $\sim 60\%$

$^{16}\mathrm{O}(^{16}\mathrm{O},p)^{31}\mathrm{P} \nearrow {}^{31}\mathrm{P}(p,\alpha)^{28}\mathrm{Si}$

$^{16}\mathrm{O}(^{16}\mathrm{O},p)^{31}\mathrm{P} \nearrow {}^{31}\mathrm{P}(\gamma,p)^{30}\mathrm{Si}$

$^{16}\mathrm{O}(^{16}\mathrm{O},p)^{31}\mathrm{P} \searrow {}^{31}\mathrm{P}(p,\gamma)^{32}\mathrm{S}$

$^{31}\mathrm{P}(p,\gamma)^{32}\mathrm{S} \nearrow {}^{32}\mathrm{S}(\alpha,p)^{35}\mathrm{Cl}(e^-,\nu)^{35}\mathrm{S}(\gamma,n)^{34}\mathrm{S}$

$^{31}\mathrm{P}(p,\gamma)^{32}\mathrm{S} \rightarrow {}^{32}\mathrm{S}(\alpha,\gamma)^{36}\mathrm{Ar}(n,\gamma)^{37}\mathrm{Ar}(e^-,\nu)^{37}\mathrm{Cl}$

$^{16}\mathrm{O}(^{16}\mathrm{O},p)^{31}\mathrm{P} \searrow {}^{31}\mathrm{P}(\alpha,p)^{34}\mathrm{S}(\alpha,\gamma)^{38}\mathrm{Ar}(p,\gamma)^{39}\mathrm{K}$

+ several thousands

$\Rightarrow$ ^{28,30}Si, ^{32,34}S

^{35,37}Cl, ^{36,38}Ar, ^{39}K

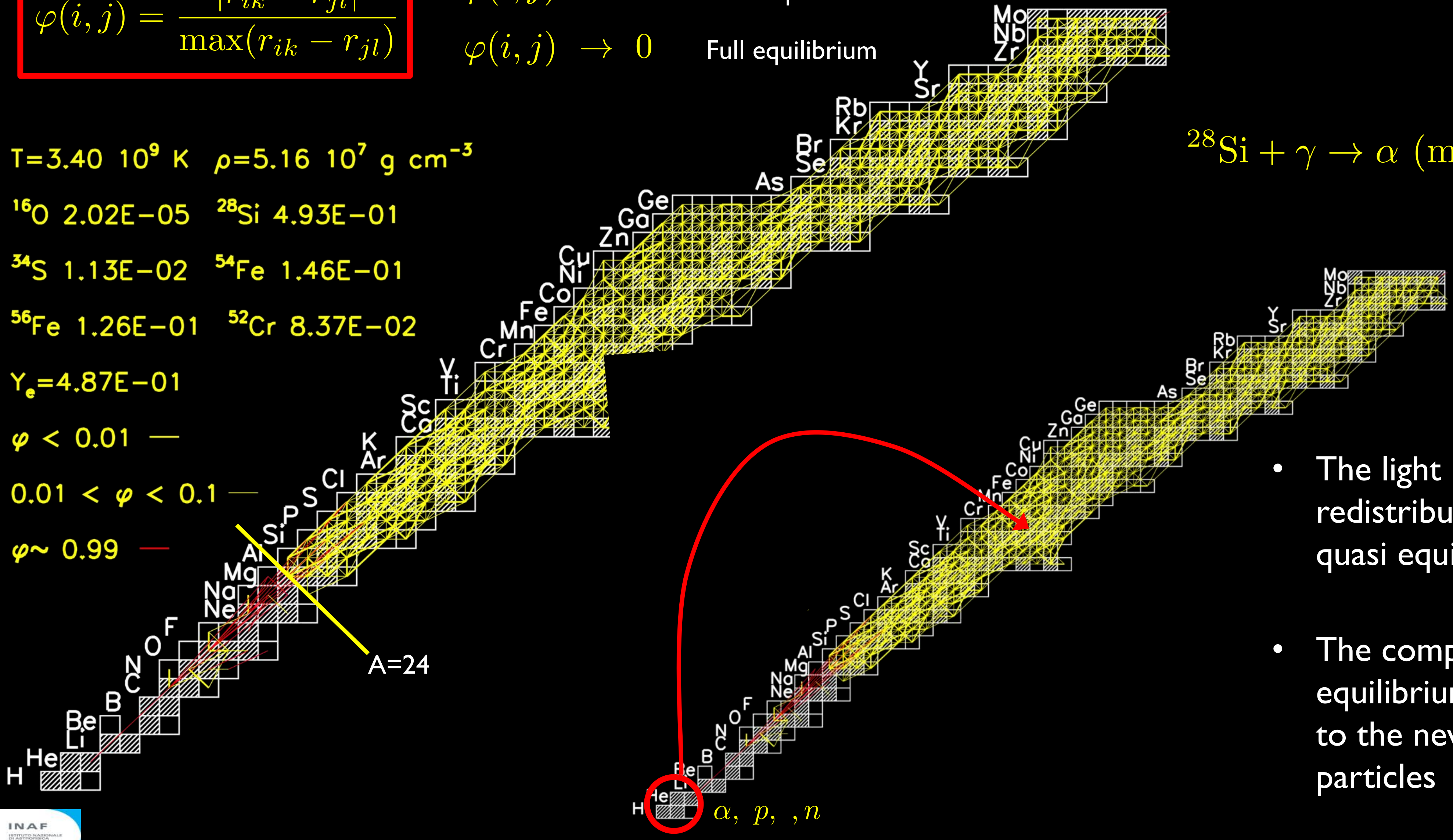
Massive Stars: Silicon Burning

At the beginning of Si burning there exists a large quasi equilibirum clusters of isotopes with A>24

$$\boxed{\varphi(i,j) = \frac{|r_{ik} - r_{jl}|}{\max(r_{ik} - r_{jl})}}$$

$\varphi(i,j) \ \to \ 1$ Non equilibrium

$\varphi(i,j) \ \to \ 0$ Full equilibrium



$$^{28}\text{Si} + \gamma \to \alpha\ (\text{mostly}),\ p,\ n$$

- The light particles can be redistributed within the large quasi equilibrium cluster

- The composition of the quasi equilibrium cluster “readjusts” to the new abundance of light particles

Massive Stars: Silicon Burning

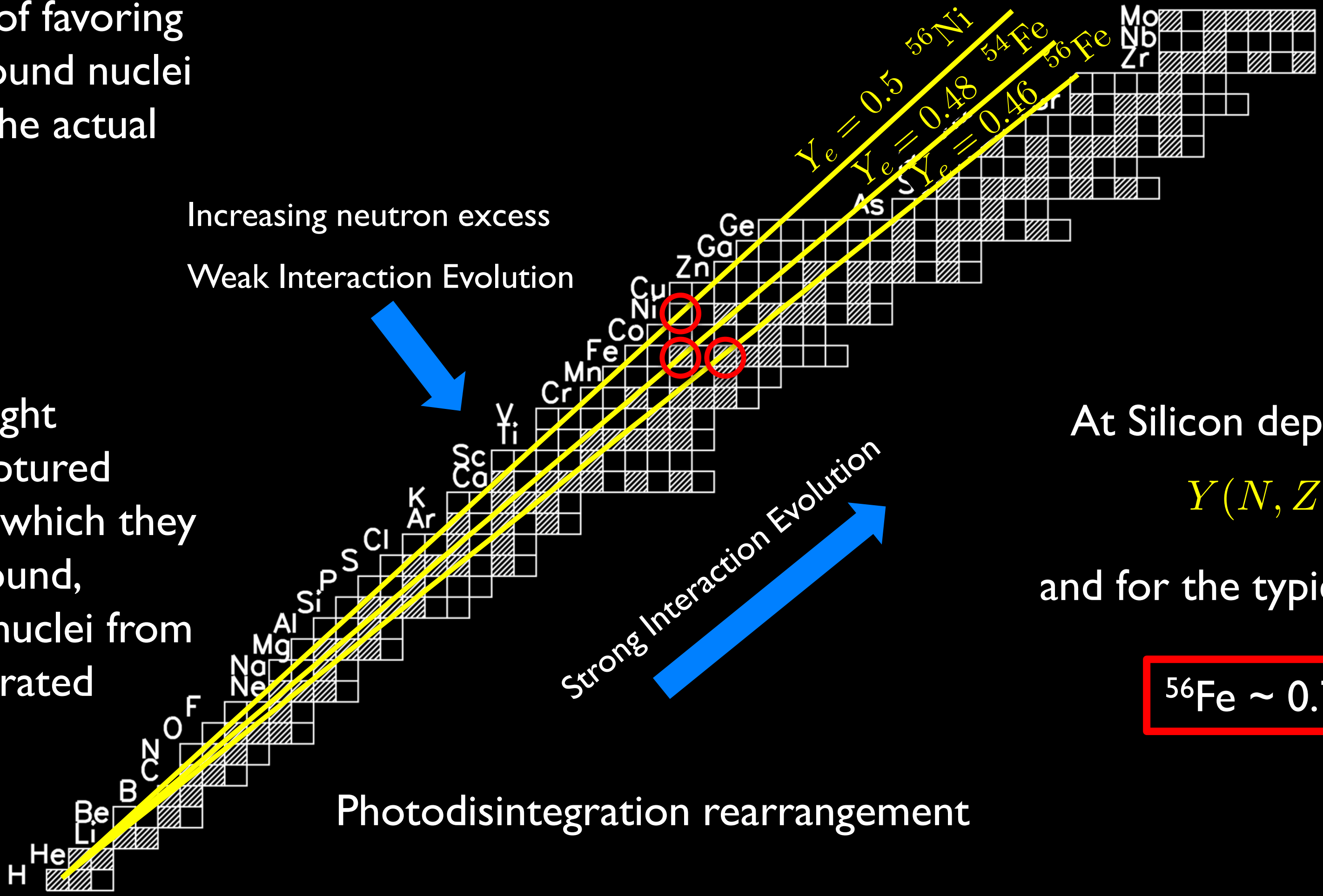
As the temperature rises and the ^{28}Si abundance decreases, the equations

$$Y(N,Z) = C(N,Z,\rho,T)\; Y(^{28}\mathrm{Si})\; Y_\alpha^{\delta_\alpha}\; Y_p^{\delta_p}\; Y_n^{\delta_n}$$

have the property of favoring the more tightly bound nuclei corresponding to the actual neutron excess

$$\eta = 1 - 2Y_e$$

the photoejected light particles will be captured mainly by nuclei in which they are more tightly bound, rather than in the nuclei from which they are liberated



Increasing neutron excess

Weak Interaction Evolution

Strong Interaction Evolution

Photodisintegration rearrangement

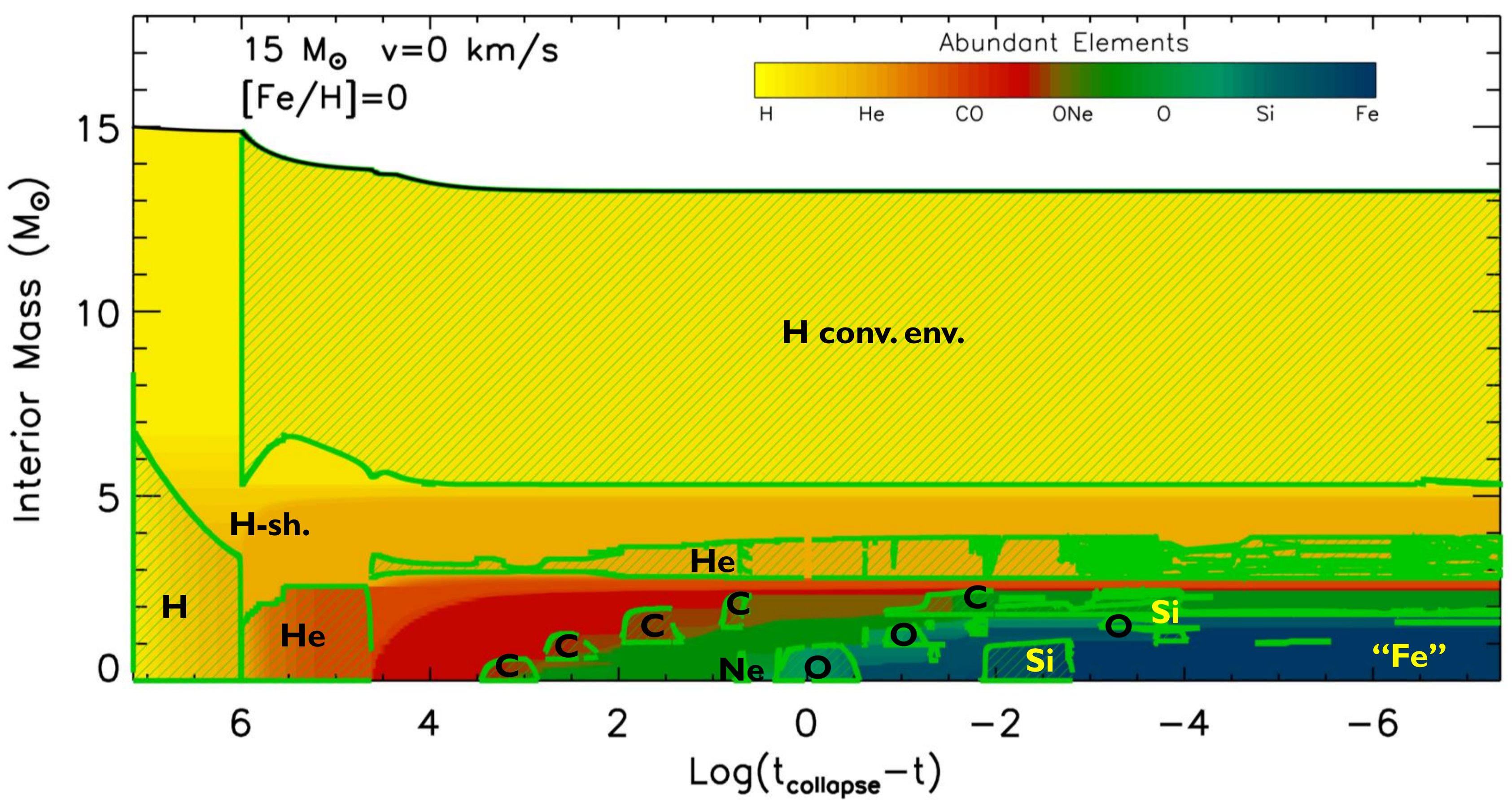
At Silicon depletion the matter is at NSE

$$Y(N,Z) = B(N,Z,\rho,T)\; Y_P^{Z}\; Y_n^{N}$$

and for the typical Y_e values it is dominated by

^{56}Fe ~ 0.70 %   and ^{52}Cr ~ 0.15 %

Presupernova Evolution of a Massive Star: Chemical and Convective Hystory



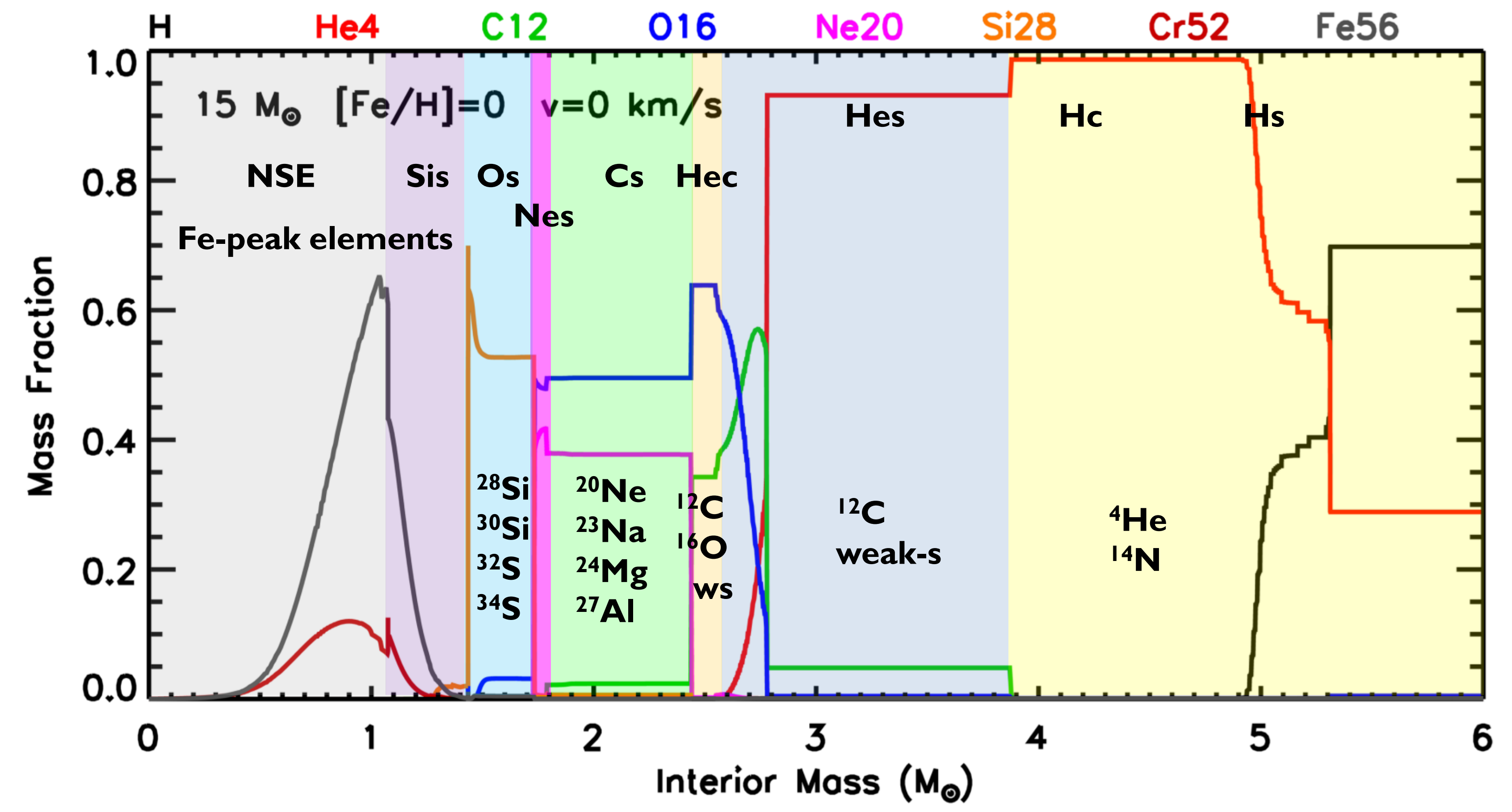
Central burning → formation of a convective core

Central exhaustion → shell burning → convective shell

Local exhaustion → shell burning shifts outward in mass → convective shell

Chemical Stratification @ PreSN Stage

The complex interplay among shell nuclear burning, timing and overlap of the convective zones determines in a direct way the final distribution of the chemical composition and the physical structure of the star @ presupernova stage



Core Collapse Supernova Explosion and Nucleosynthesis

- The Fe core becomes unstable, collapses to nuclear density, rebounces and through a sequence of events a shock wave is launched that drives the explosion of the star

- The propagation of the shock wave through the mantle of the star induces compression and heating → some modification of the chemical composition produced during the hydrostatic burning stages is expected

- Such a modification is called Explosive Nucleosynthesis

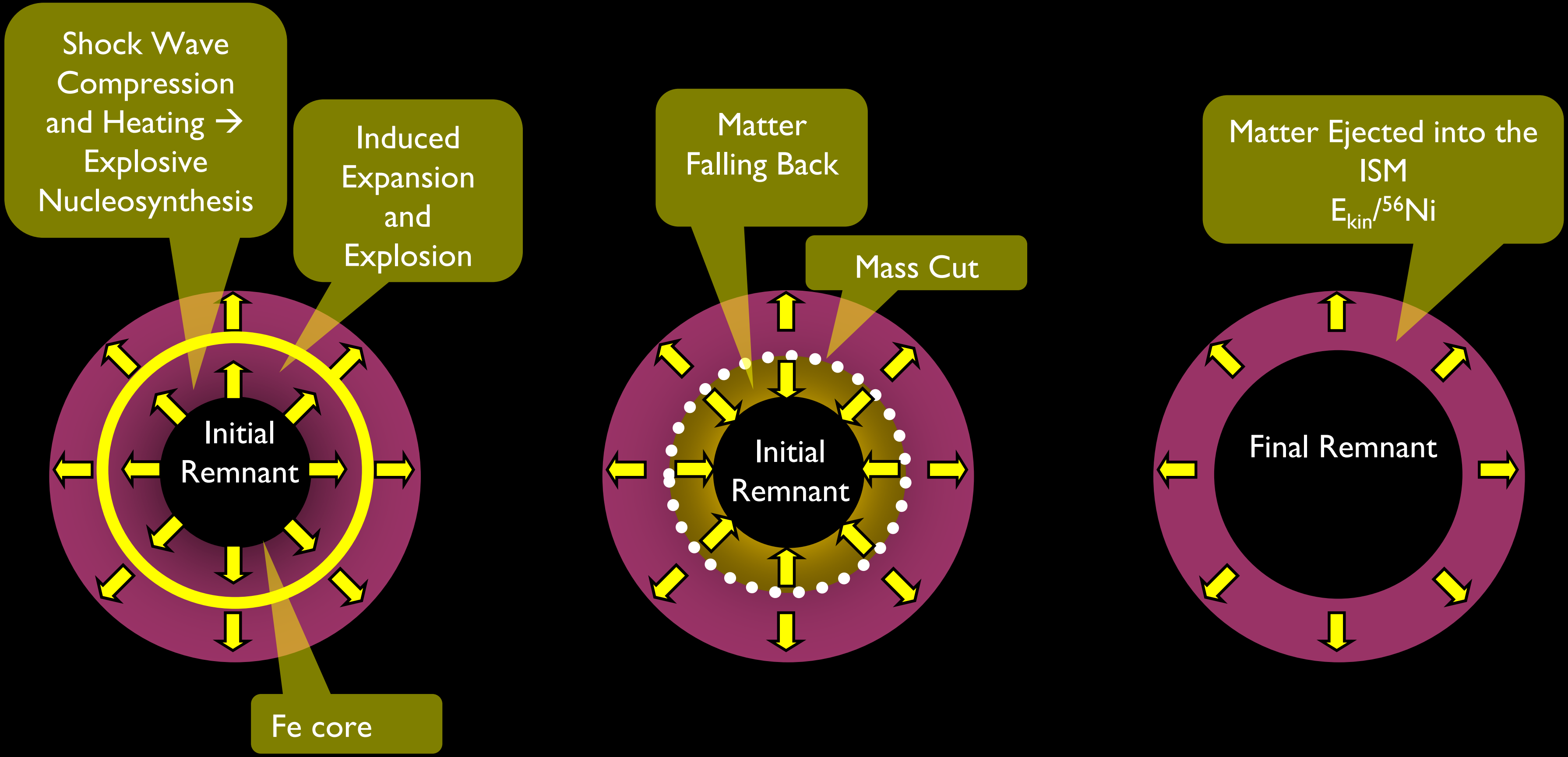
- The modeling of the explosion of the star is mandatory to have information on:
  - The chemical composition of the ejected matter (chemical yields)
  - The initial mass-remnant mass relation

- At present detailed explosive nucleosynthesis calculations for core collapse supernovae are mainly based on artificially induced explosions

Induced Explosion

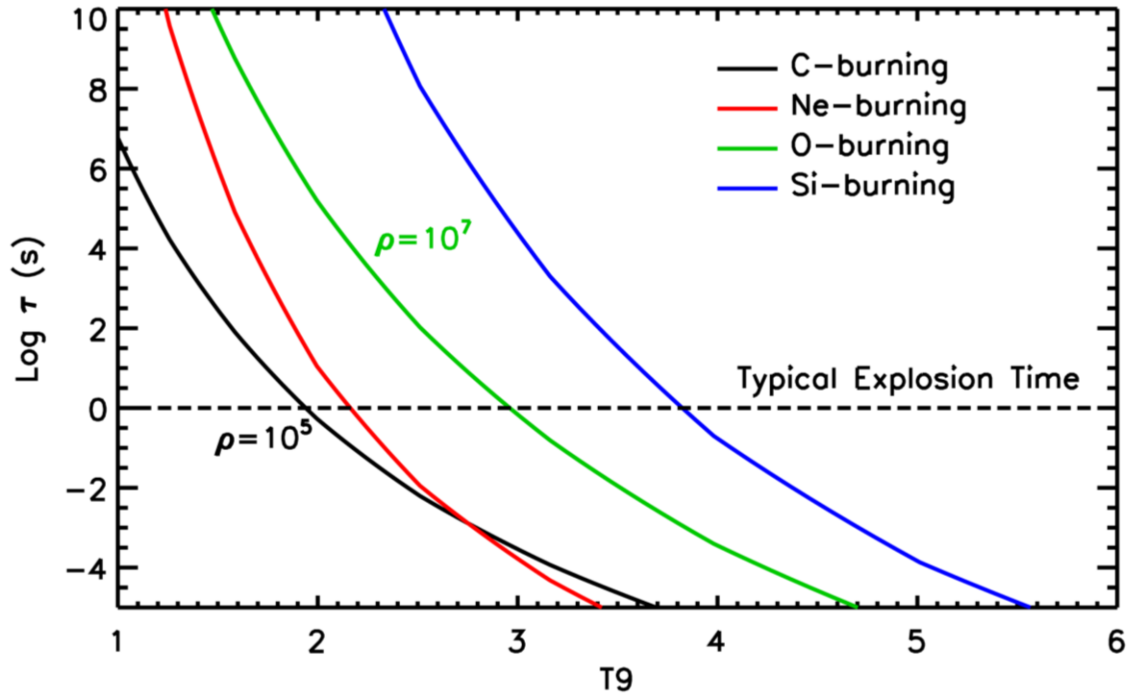
Different ways of inducing the explosion →

- Piston (Woosley, Weaver and coll.)
- Thermal Bomb (Nomoto, Umeda and coll.)
- Kinetic Bomb (Chieffi & Limongi)
- Calibrated Neutrino Luminosity (Fryer, Janka)



Explosion and Nucleosynthesis: Basics

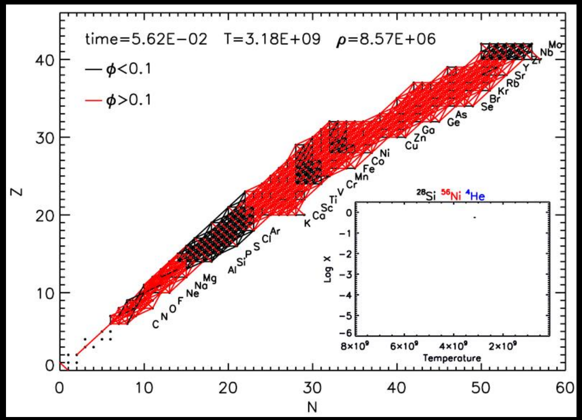
The typical burning timescale $\tau \sim \dfrac{1}{r_{i,j}}$ where $r_{ij} = n_i n_j < \sigma v >_{i,j}$ for fuel destruction of C-, Ne-, O- and Si-burning



For the typical explosion times (~1 s), there exists a typical burning Temperature for any given nuclear burning to occur

Explosive Burning	Temperature
Si burning	$T \gtrsim 4 \cdot 10^9$ K
O burning	$T \gtrsim 3.3 \cdot 10^9$ K
Ne burning	$T \gtrsim 2.1 \cdot 10^9$ K
C burning	$T \gtrsim 1.9 \cdot 10^9$ K

Explosive Nucleosynthesis



Explosive Complete Si burning

$$T \;>\; 5 \cdot 10^9 \text{ K}$$

NSE $$Y_i = f(T, \rho, Y_e)$$

$$Y_e \;>\; 0.49$$

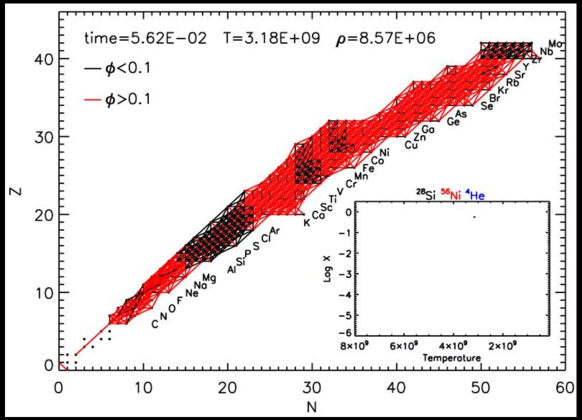
$$(\eta \;<\; 0.02)$$

^{56}Ni

$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$ ~90 days

Sc Ti Co Ni Zn

Explosive Nucleosynthesis



Explosive Complete Si burning

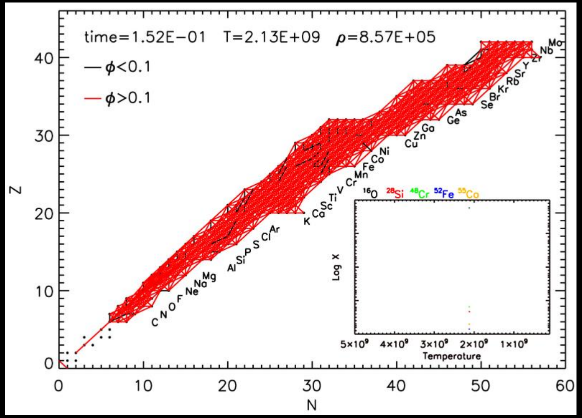
$$T \;>\; 5\cdot 10^9\ \mathrm{K}$$

NSE $Y_i = f(T, \rho, Y_e)$ $\quad Y_e \;>\; 0.49$ $\quad (\eta \;<0.02)$

^{56}Ni

$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$ ~90 days

Sc Ti Co Ni Zn



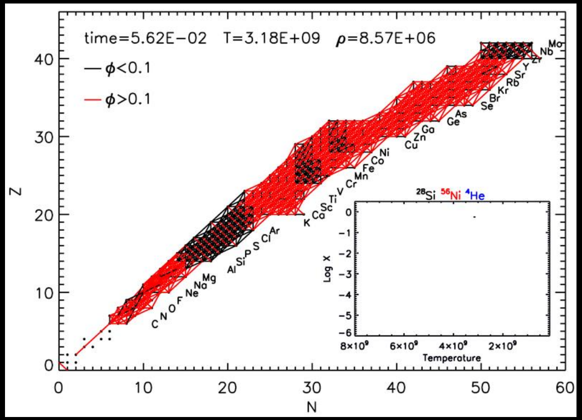
Explosive Incomplete Si burning

$$5\cdot 10^9\ \mathrm{K} \;>\; T \;>\; 4\cdot 10^9\ \mathrm{K}$$

QSE $Y_i = f(T, \rho, Y_e)$ $\quad Y_e \;>\; 0.49$ $\quad (\eta \;<0.02)$

V Cr Mn

Explosive Nucleosynthesis



Explosive Complete Si burning

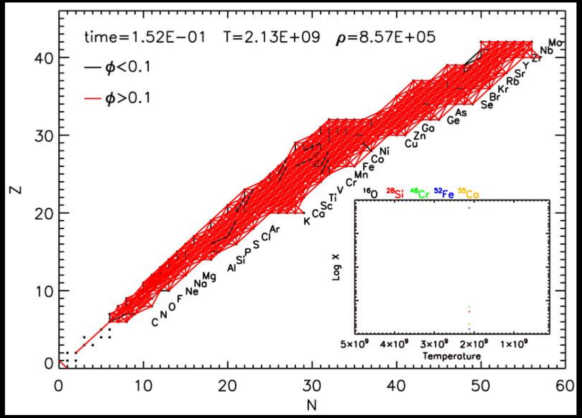
$$T > 5 \cdot 10^9 \text{ K}$$

NSE $Y_i = f(T, \rho, Y_e)$ $Y_e > 0.49$ $(\eta < 0.02)$

^{56}Ni

$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$ ~90 days

Sc Ti Co Ni Zn

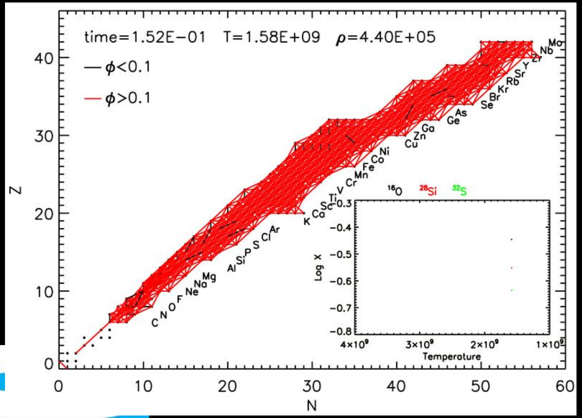


Explosive Incomplete Si burning

$$5 \cdot 10^9 \text{ K} > T > 4 \cdot 10^9 \text{ K}$$

QSE $Y_i = f(T, \rho, Y_e)$ $Y_e > 0.49$ $(\eta < 0.02)$

V Cr Mn



Explosive Oxygen burning

$$4 \cdot 10^9 \text{ K} > T > 3.3 \cdot 10^9 \text{ K}$$

QSE $Y_i = f(T, \rho, Y_e)$ $Y_e > 0.49$ $(\eta < 0.02)$

Si S Ar K Ca

Explosive Nucleosynthesis

$$3.3 \cdot 10^9 \text{ K} > T > 1.9 \cdot 10^9 \text{ K}$$

In these range of temperatures the processes are far from the equilibrium and nuclear processing occur through a well defined sequences of nuclear reactions

Elements preferrentially synthesized in these conditions over the typical explosion timescales:

Explosive Neon burning	$T > 2.1 \cdot 10^9 \text{ K}$	Mg Al P Cl
Explosive Carbon burning	$T < 2.1 \cdot 10^9 \text{ K}$	Ne Na

$$Y_i = f(T, \rho, \sum_j X_j)$$

$T < 1.9 \cdot 10^9 \text{ K}$ No nuclear processing occur over the typical explosion timescales

Explosion and Nucleosynthesis: Basics

Explosion energy radiation dominated

$$E_{\rm expl} = 1\ {\rm foe}\quad (1\ {\rm foe} = 10^{51}\ {\rm erg})$$

$$\boxed{T_{\rm shock} = \left(\frac{3E_{\rm expl}}{4a\pi R^3_{\rm shock}}\right)^{1/4}}$$

$R_{\rm shock}$ spatial location of the shock

$T_{\rm shock}$ temperature at shock location

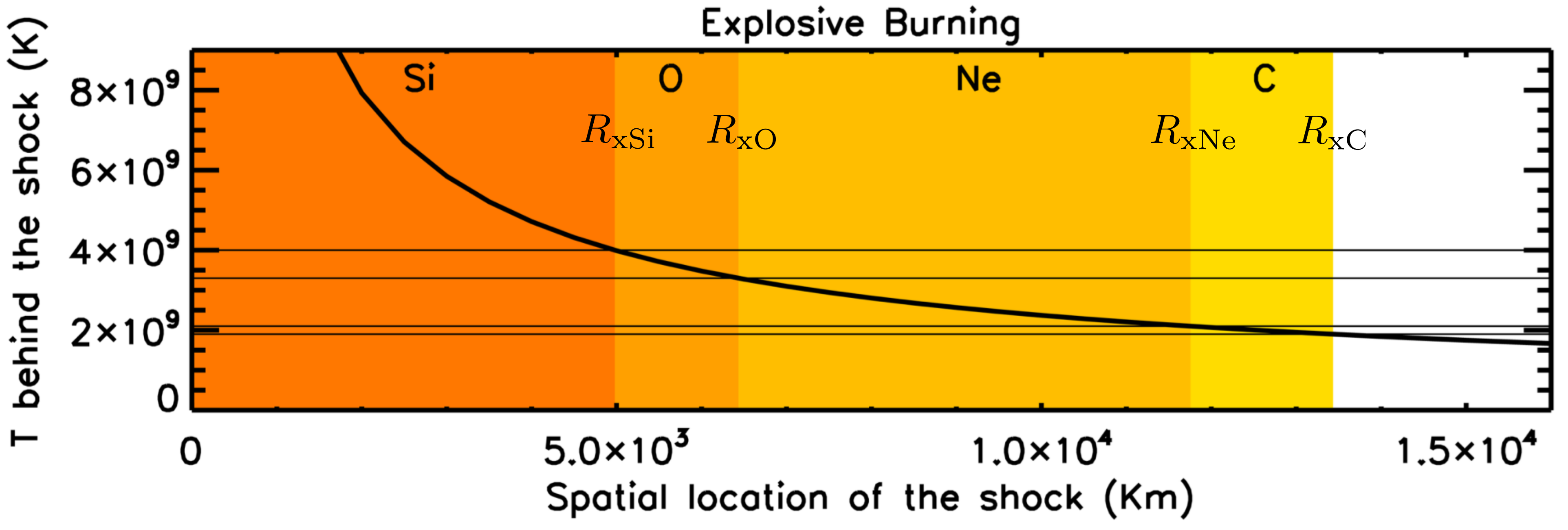
Explosive Burning

Si burning $T \gtrsim 4 \cdot 10^9\ {\rm K} \longrightarrow R_{\rm xSi} \lesssim 5000\ {\rm Km}$

O burning $T \gtrsim 3.3 \cdot 10^9\ {\rm K} \longrightarrow R_{\rm xO} \lesssim 6400\ {\rm Km}$

Ne burning $T \gtrsim 2.1 \cdot 10^9\ {\rm K} \longrightarrow R_{\rm xNe} \lesssim 11750\ {\rm Km}$

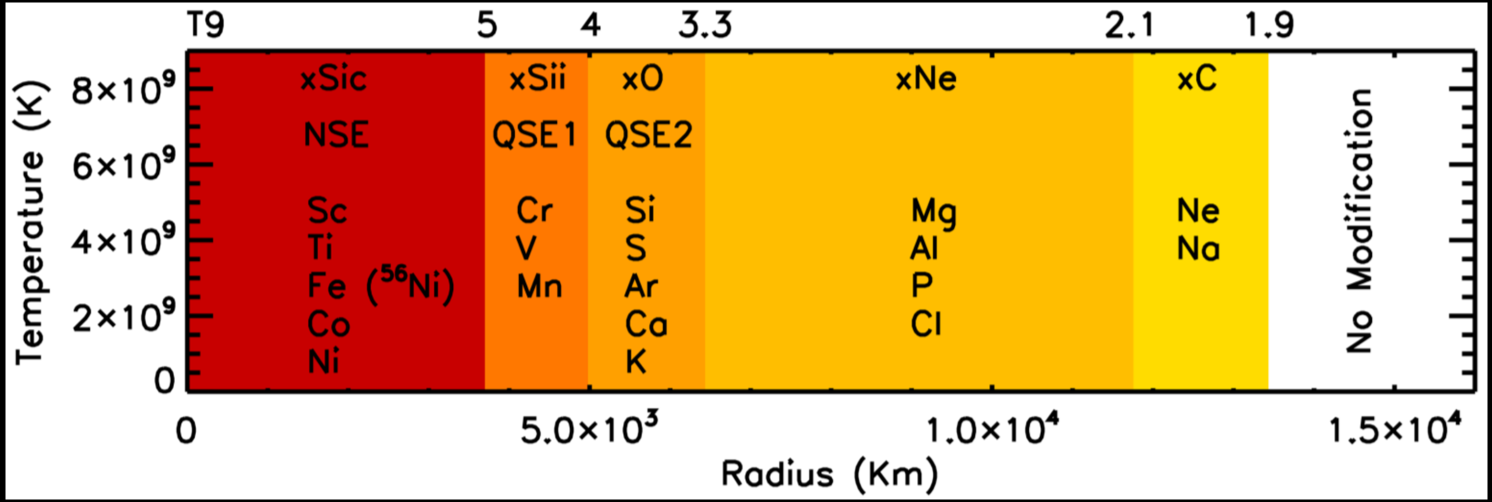
C burning $T \gtrsim 1.9 \cdot 10^9\ {\rm K} \longrightarrow R_{\rm xC} \lesssim 13400\ {\rm Km}$



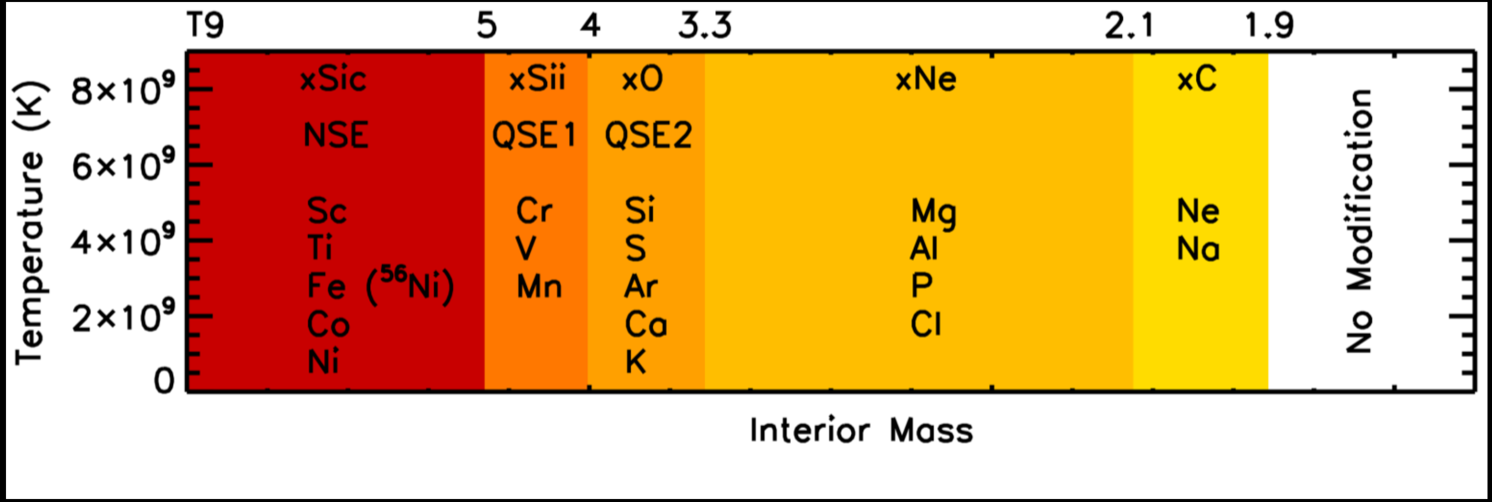
We can identify "volumes" in the star within which the various explosive burning can occur
This is independent of the properties of the presupernova star

Explosion and Nucleosynthesis: Basics

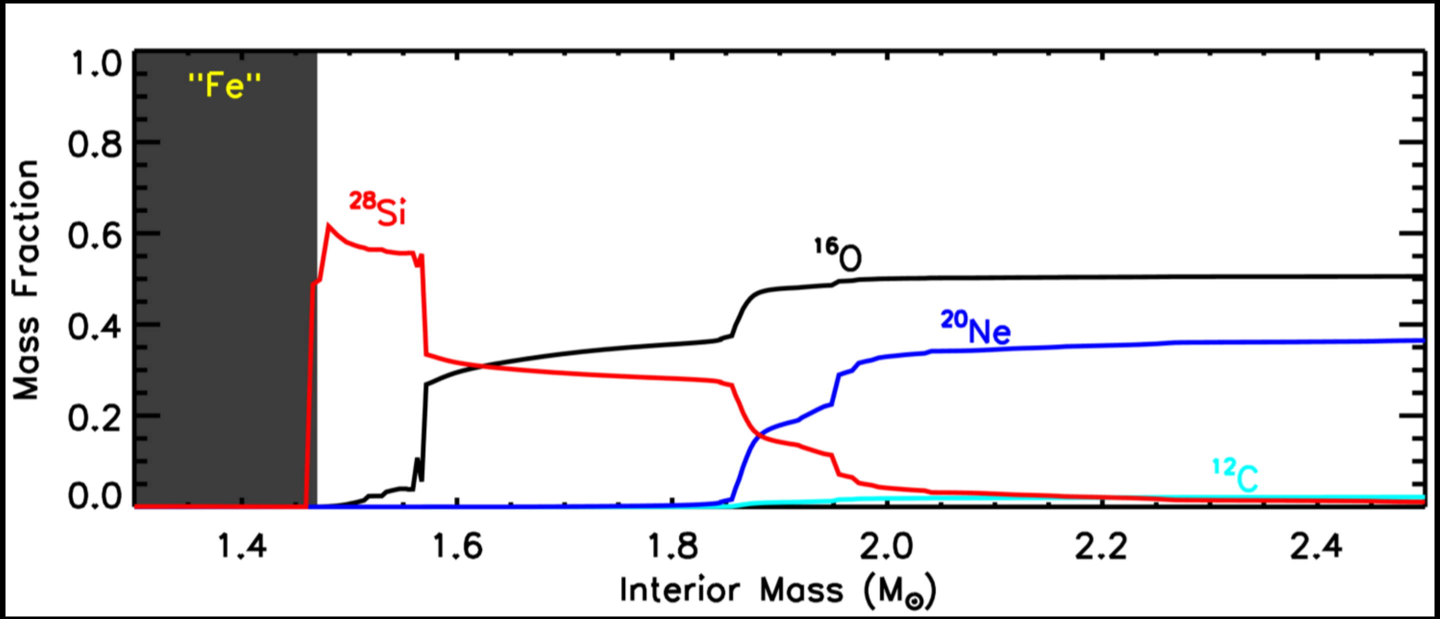
$$T_{\rm max} = \left(\frac{3E_{\rm expl}}{4\pi a R^3_{\rm preSN}} \right)^{1/4} \qquad E_{\rm expl} = 1\ {\rm foe} \quad (1\ {\rm foe} = 10^{51}\ {\rm erg})$$



Mass-Radius relation, Y_e profile, Chemical Stratification @ Presupernova Stage

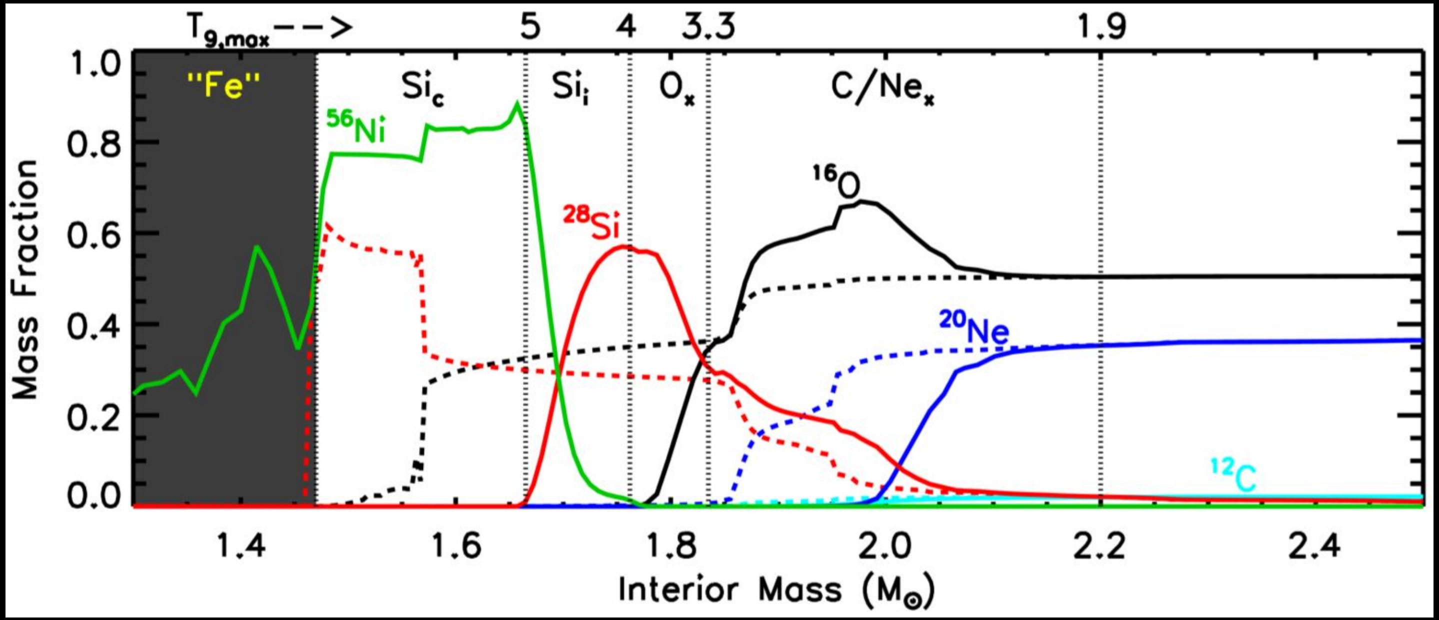


Composition of the Ejecta



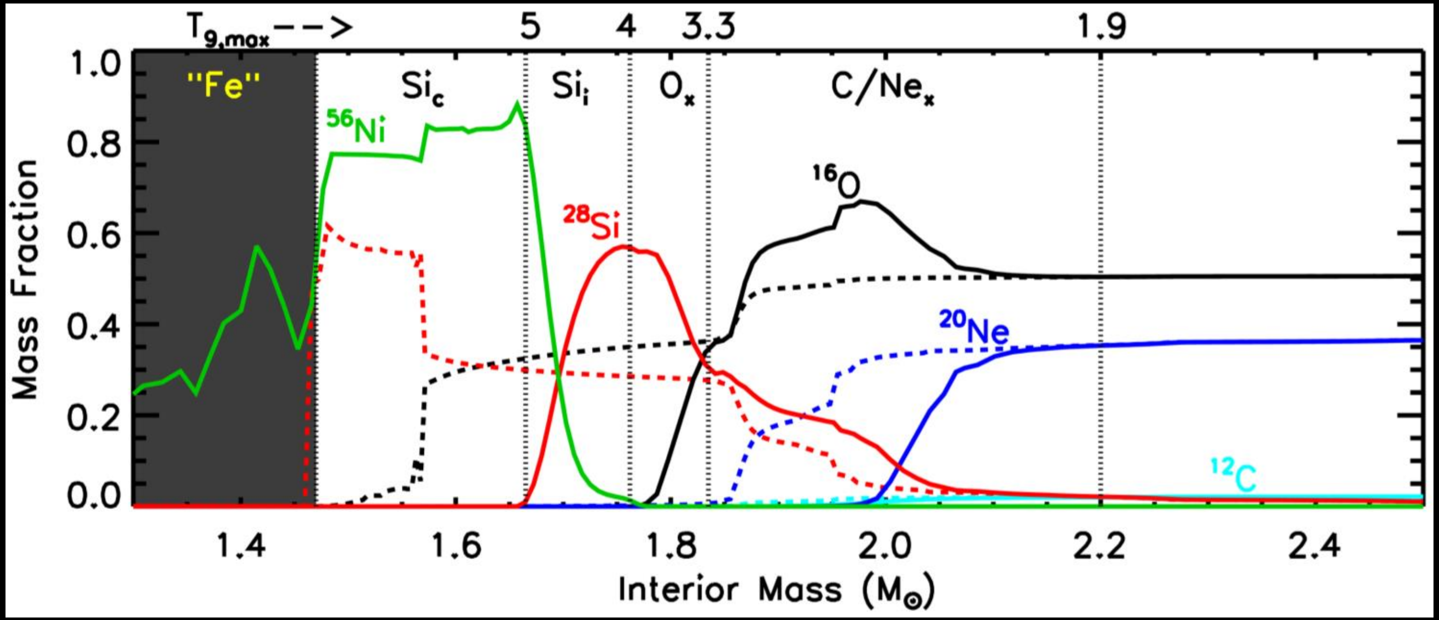
Composition of the Ejecta

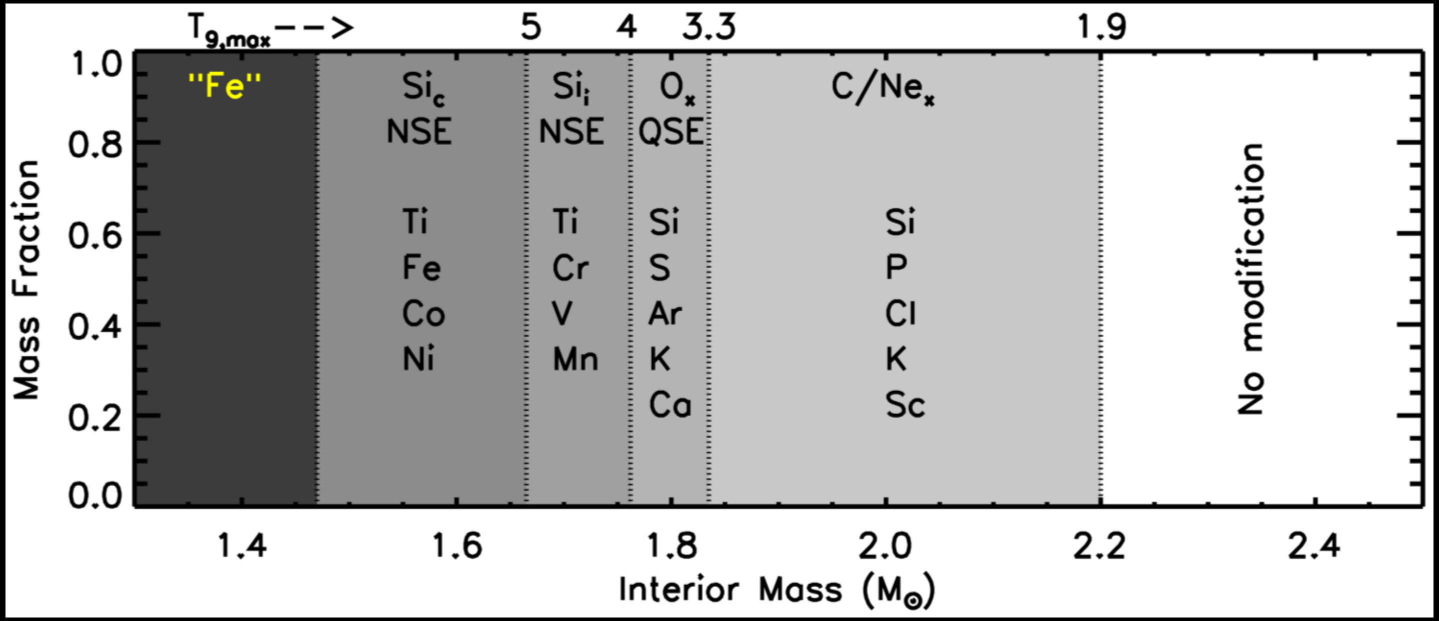
← EXPLOSIVE BURNING →



Composition of the Ejecta

← EXPLOSIVE BURNING →





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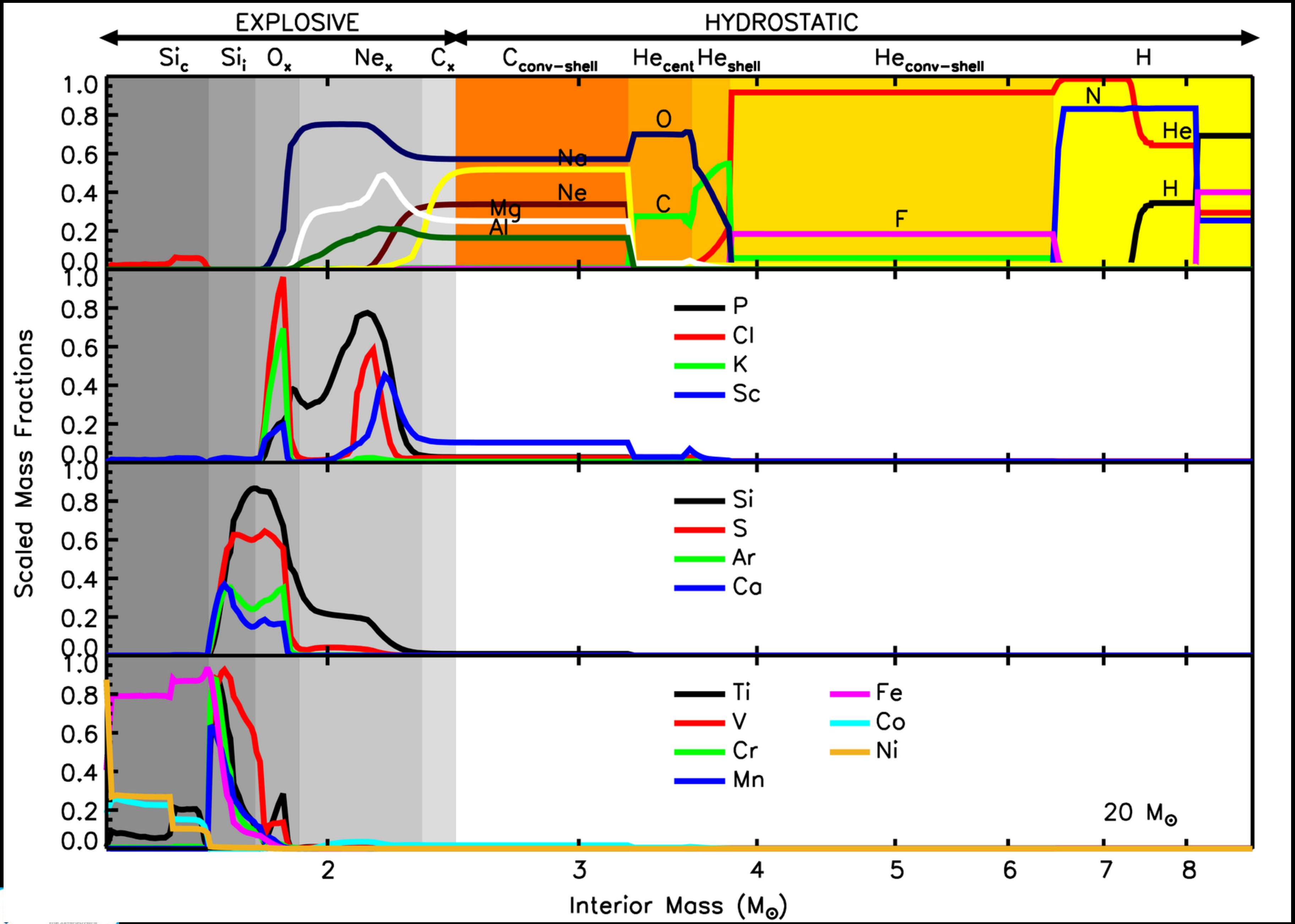
Composition of the Ejecta



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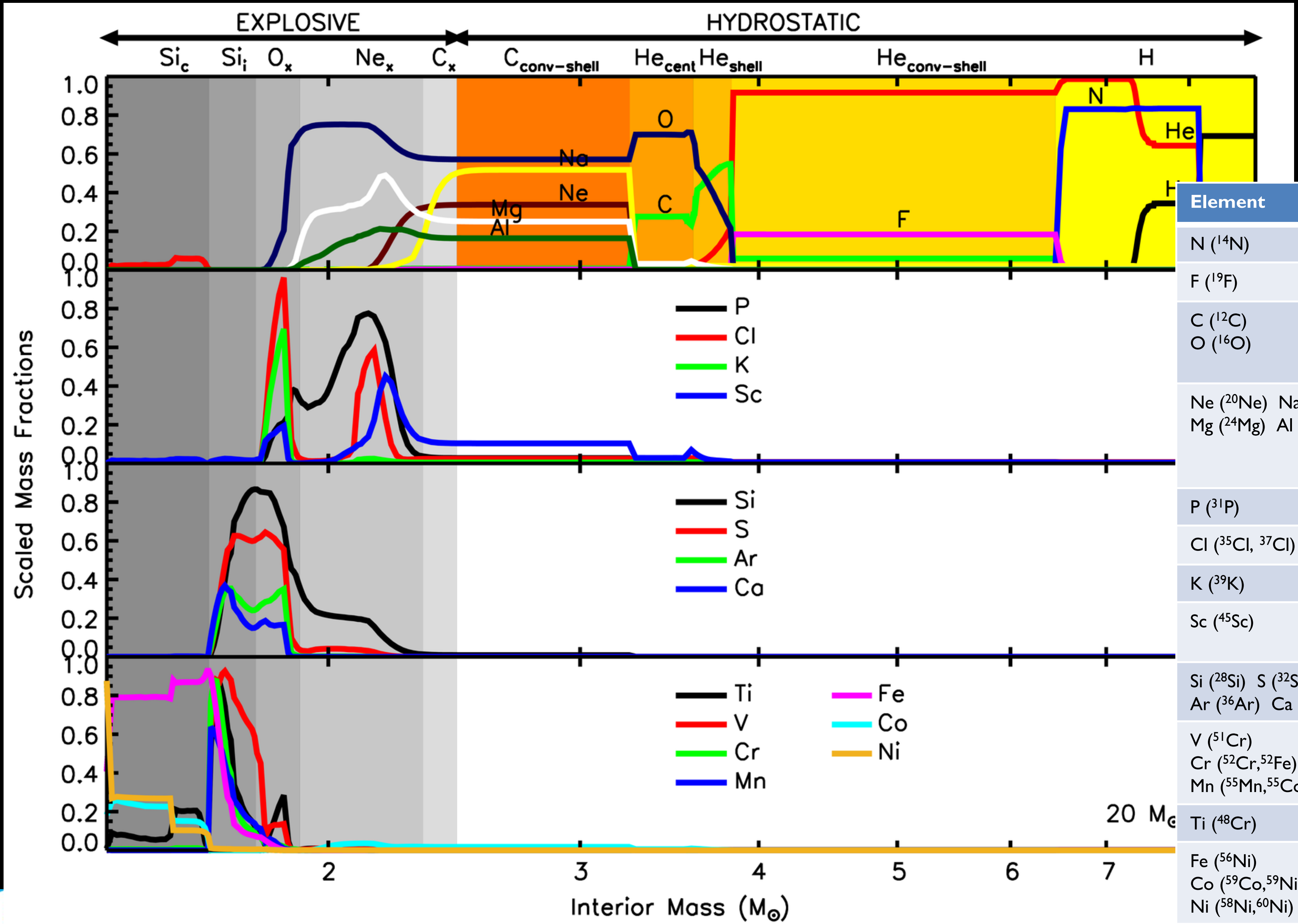
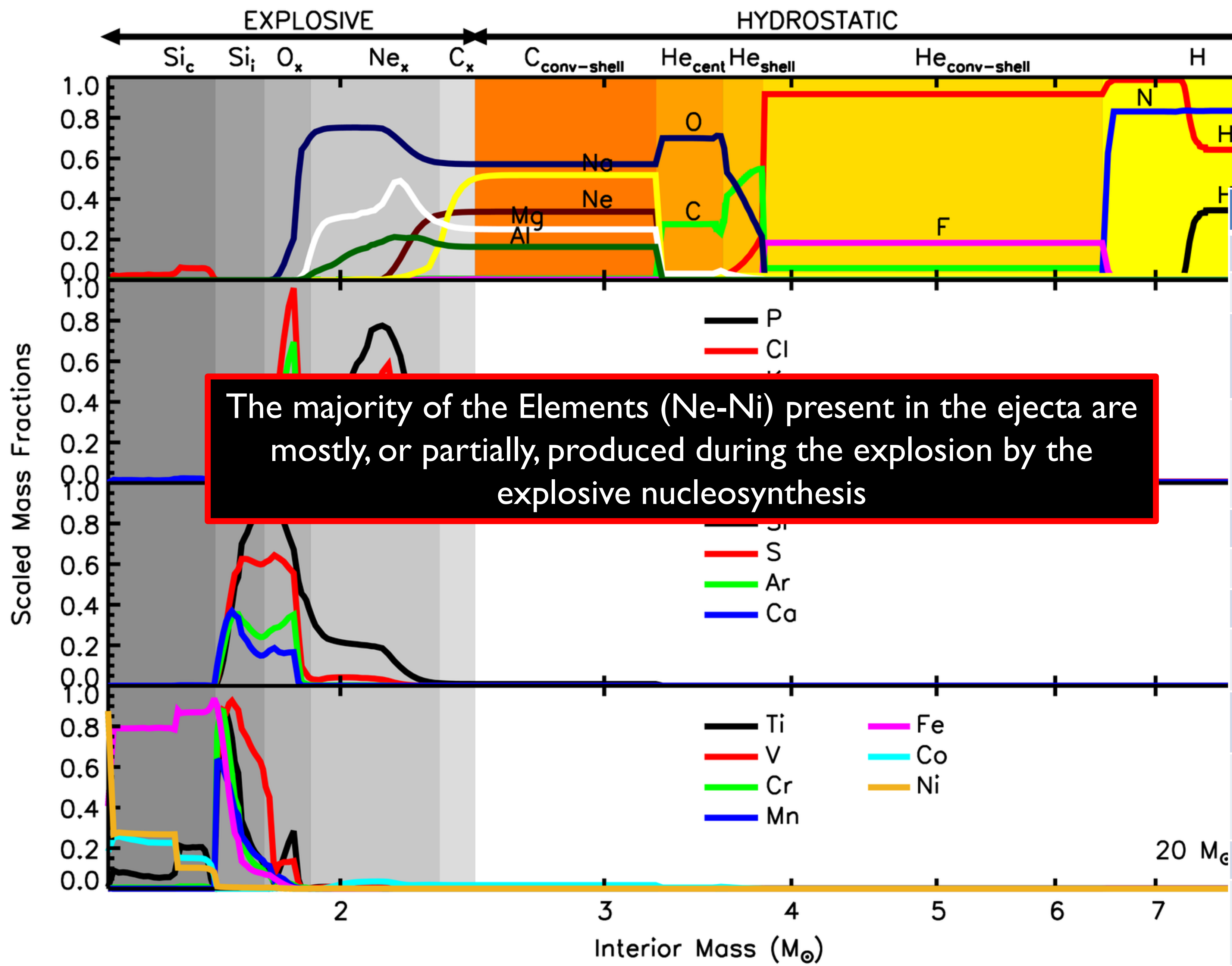


Element	Production Site
N (^{14}N)	Hydrostatic H burning
F (^{19}F)	Hydrostatic He convective shell
C (^{12}C) O (^{16}O)	Hydrostatic core He burning (^{16}O partially modified by Cshell and Ne$_x$)
Ne (^{20}Ne) Na (^{23}Na) Mg (^{24}Mg) Al (^{27}Al)	Hydrostatic C convective shell Partially destroyed by C$_x$ (^{23}Na) and Ne$_x$ (^{20}Ne) Partially produced by Ne$_x$ (^{24}Mg,^{27}Al)
P (^{31}P)	Ne$_x$
Cl (^{35}Cl, ^{37}Cl)	Ne$_x$+O$_x$
K (^{39}K)	O$_x$
Sc (^{45}Sc)	Hydrostatic C convective shell Ne$_x$+O$_x$
Si (^{28}Si) S (^{32}S) Ar (^{36}Ar) Ca (^{40}Ca)	O$_x$+Si$_i$
V (^{51}Cr) Cr (^{52}Cr,^{52}Fe) Mn (^{55}Mn,^{55}Co)	Si$_i$
Ti (^{48}Cr)	O$_x$+Si$_i$+Si$_c$
Fe (^{56}Ni) Co (^{59}Co,^{59}Ni) Ni (^{58}Ni,^{60}Ni)	Si$_c$

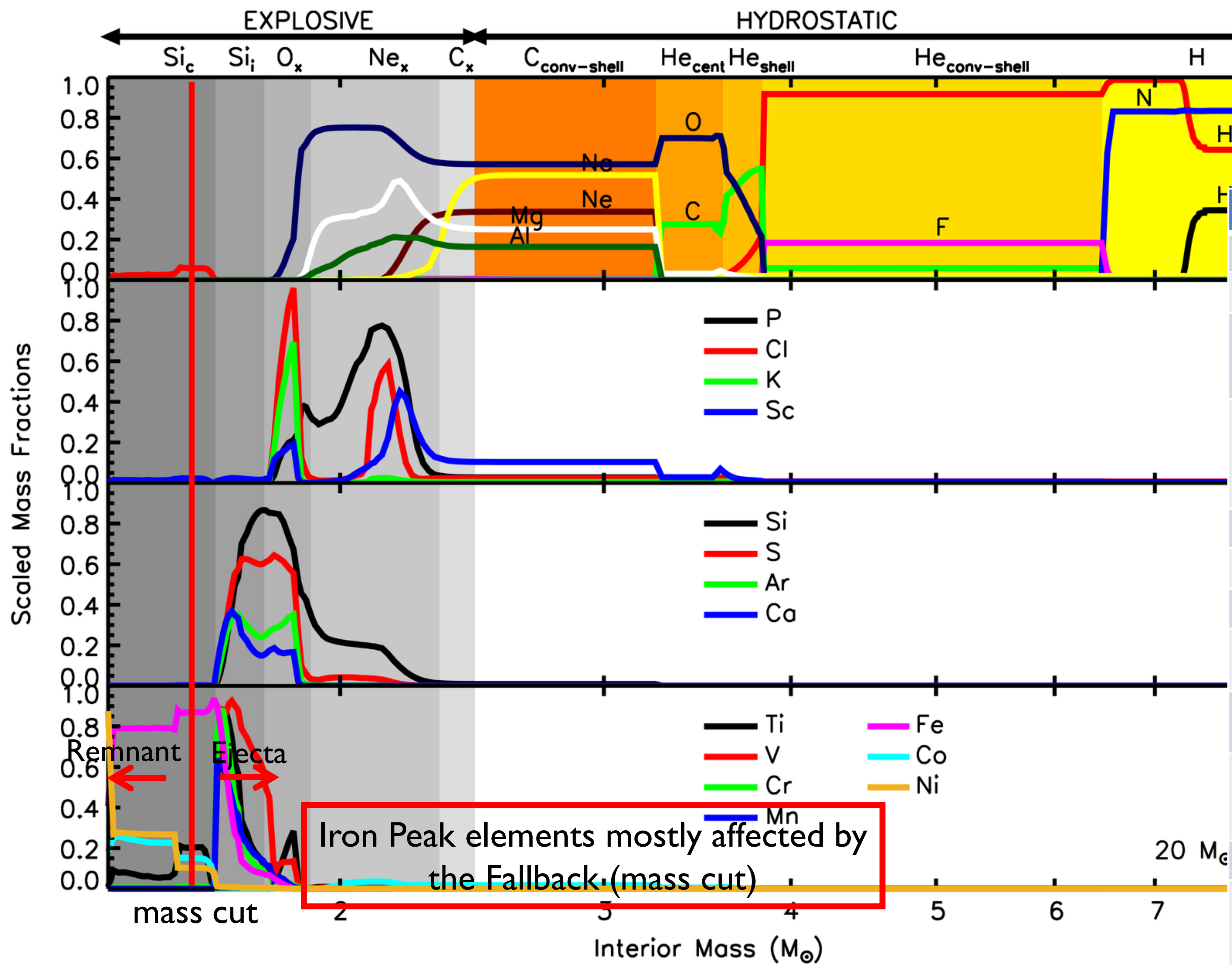
Composition of the Ejecta



The majority of the Elements (Ne-Ni) present in the ejecta are mostly, or partially, produced during the explosion by the explosive nucleosynthesis

Element	Production Site
N (^{14}N)	Hydrostatic H burning
F (^{19}F)	Hydrostatic He convective shell
C (^{12}C) O (^{16}O)	Hydrostatic core He burning (^{16}O partially modified by Cshell and Ne$_x$)
Ne (^{20}Ne) Na (^{23}Na) Mg (^{24}Mg) Al (^{27}Al)	Hydrostatic C convective shell Partially destroyed by C$_x$ (^{23}Na) and Ne$_x$ (^{20}Ne) Partially produced by Ne$_x$ (^{24}Mg,^{27}Al)
P (^{31}P)	Ne$_x$
Cl (^{35}Cl, ^{37}Cl)	Ne$_x$+O$_x$
K (^{39}K)	O$_x$
Sc (^{45}Sc)	Hydrostatic C convective shell Ne$_x$+O$_x$
Si (^{28}Si) S (^{32}S) Ar (^{36}Ar) Ca (^{40}Ca)	O$_x$+Si$_i$
V (^{51}Cr) Cr (^{52}Cr,^{52}Fe) Mn (^{55}Mn,^{55}Co)	Si$_i$
Ti (^{48}Cr)	O$_x$+Si$_i$+Si$_c$
Fe (^{56}Ni) Co (^{59}Co,^{59}Ni) Ni (^{58}Ni,^{60}Ni)	Si$_c$

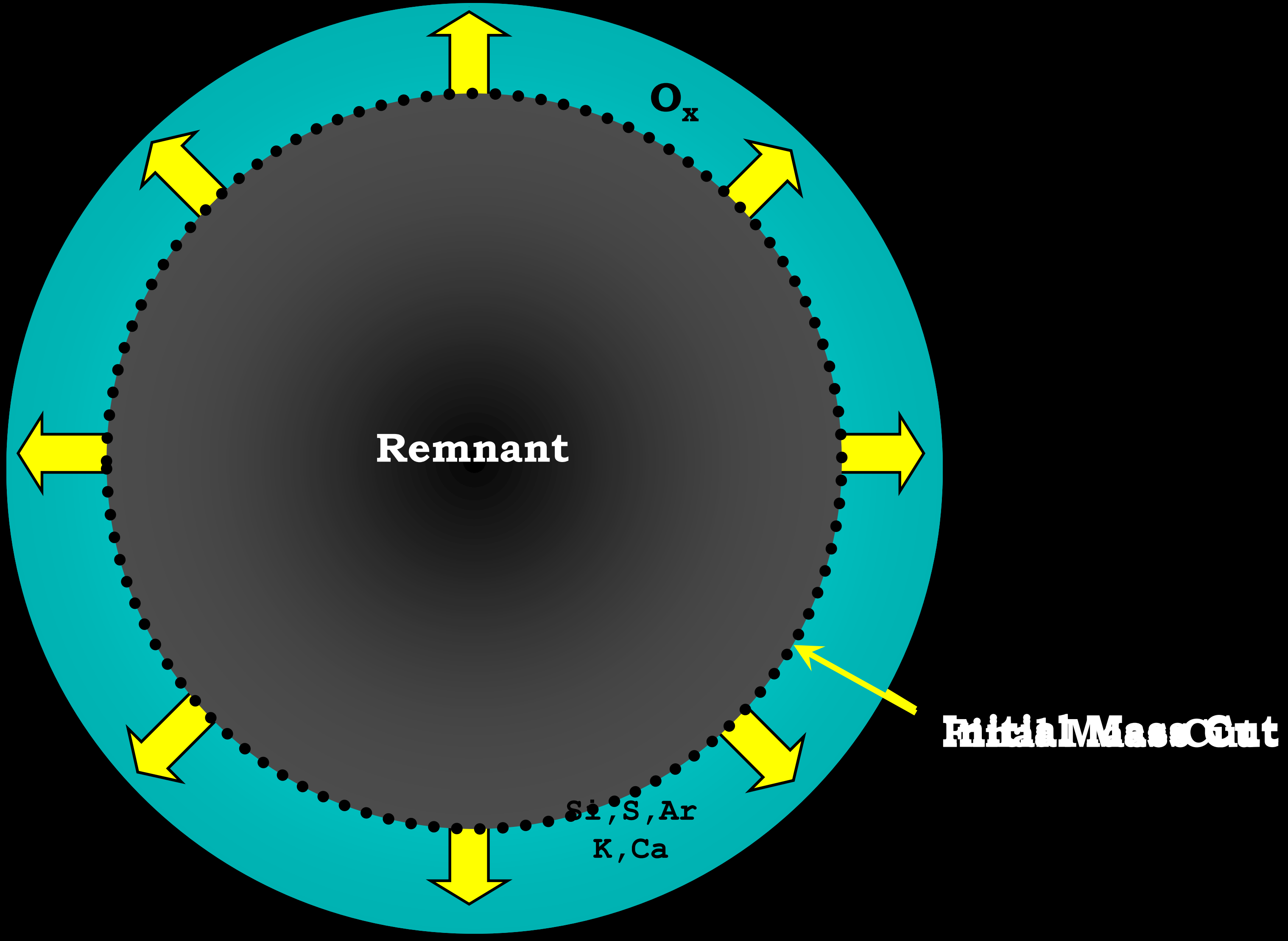
Composition of the Ejecta



Iron Peak elements mostly affected by the Fallback (mass cut)

Element	Production Site
N (^{14}N)	Hydrostatic H burning
F (^{19}F)	Hydrostatic He convective shell
C (^{12}C) O (^{16}O)	Hydrostatic core He burning (^{16}O partially modified by Cshell and Ne_x)
Ne (^{20}Ne) Na (^{23}Na) Mg (^{24}Mg) Al (^{27}Al)	Hydrostatic C convective shell Partially destroyed by C_x (^{23}Na) and Ne_x (^{20}Ne) Partially produced by Ne_x (^{24}Mg,^{27}Al)
P (^{31}P)	Ne_x
Cl (^{35}Cl, ^{37}Cl)	Ne_x+O_x
K (^{39}K)	O_x
Sc (^{45}Sc)	Hydrostatic C convective shell Ne_x+O_x
Si (^{28}Si) S (^{32}S) Ar (^{36}Ar) Ca (^{40}Ca)	O_x+Si_i
V (^{51}Cr) Cr (^{52}Cr,^{52}Fe) Mn (^{55}Mn,^{55}Co)	Si_i
Ti (^{48}Cr)	$O_x+Si_i+Si_c$
Fe (^{56}Ni) Co (^{59}Co,^{59}Ni) Ni (^{58}Ni,^{60}Ni)	Si_c

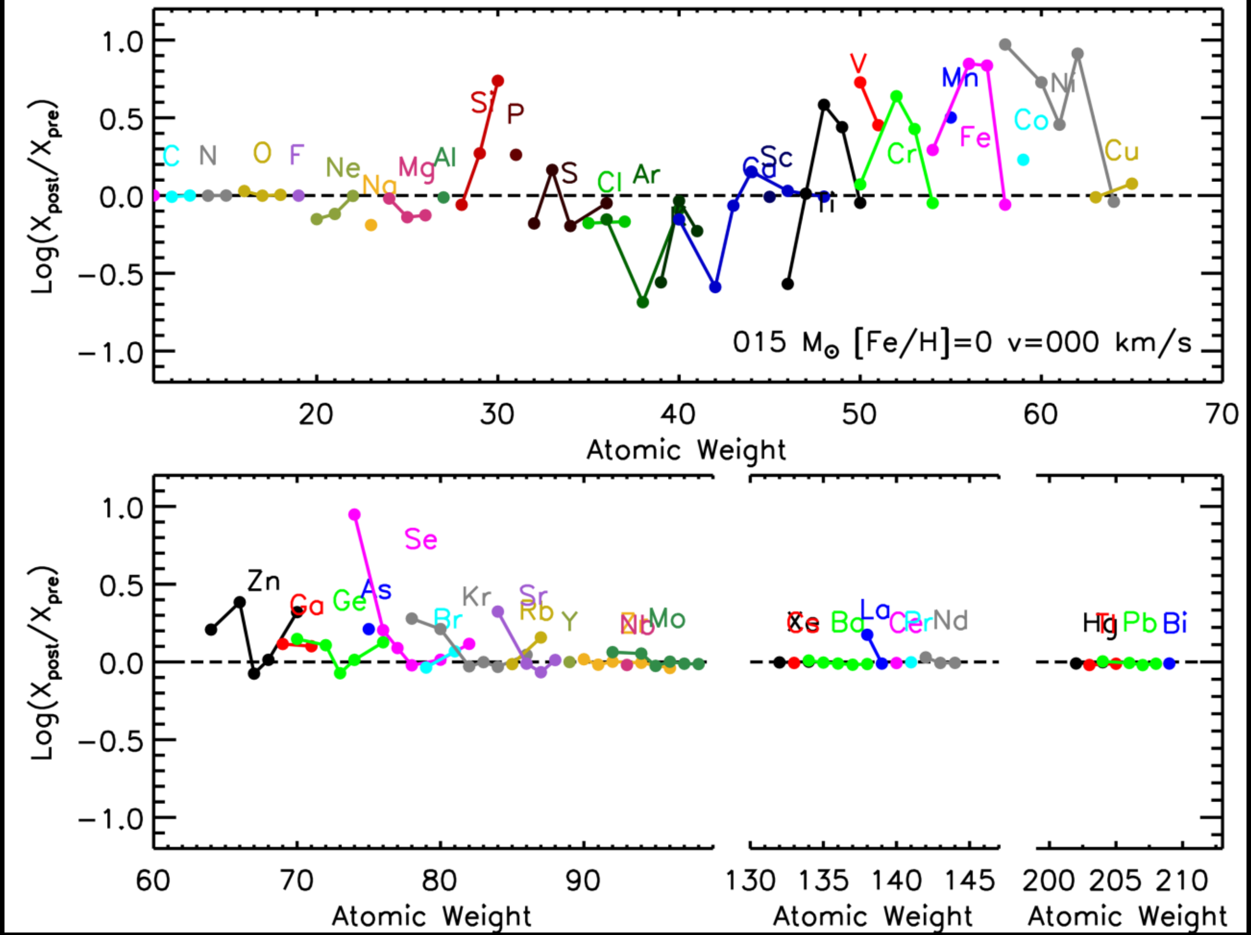
The ejection of ^{56}Ni and heavy elements

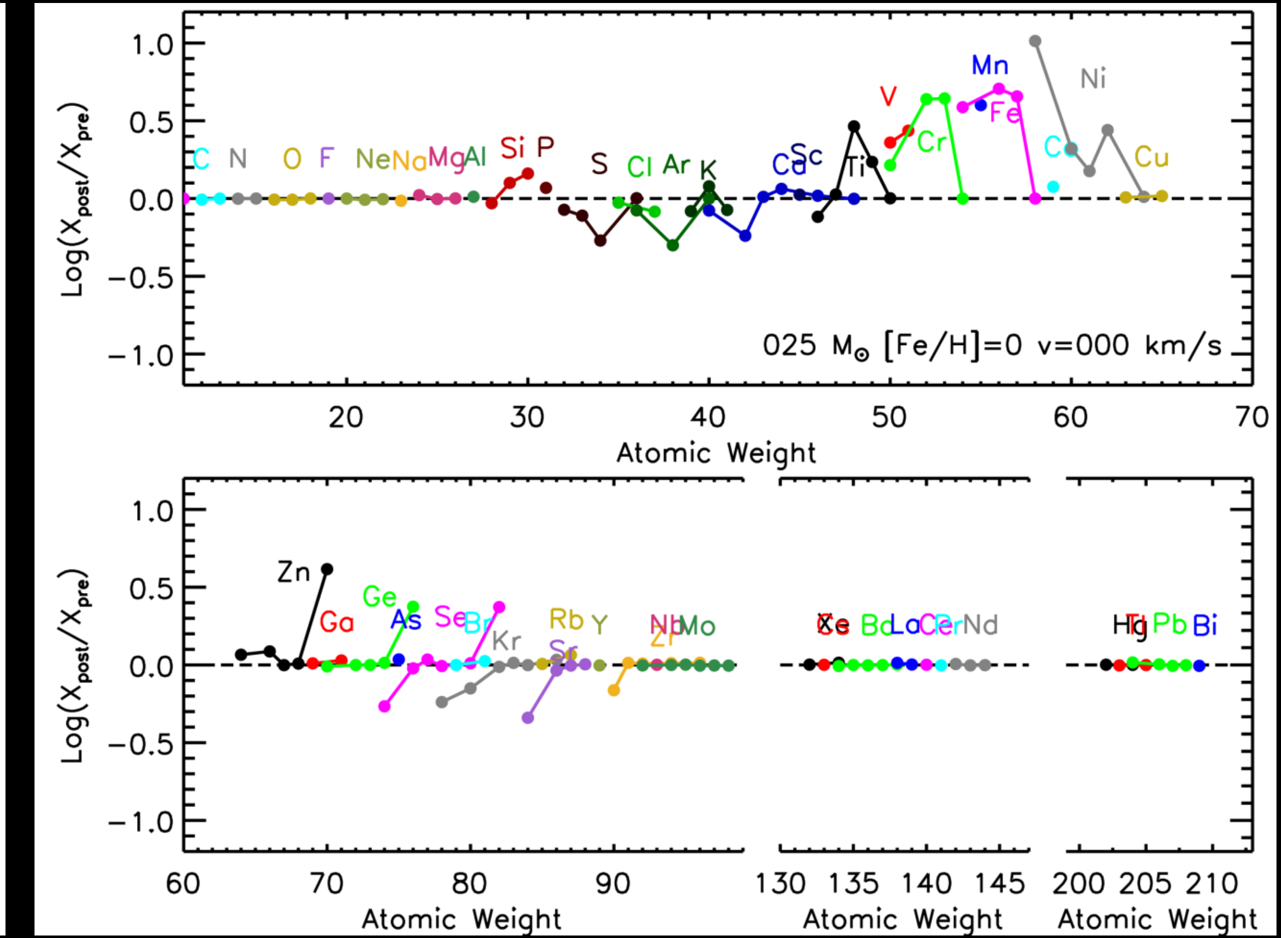


The amount of ^{56}Ni and heavy elements strongly depends on the Mass Cut

Composition of the Ejecta

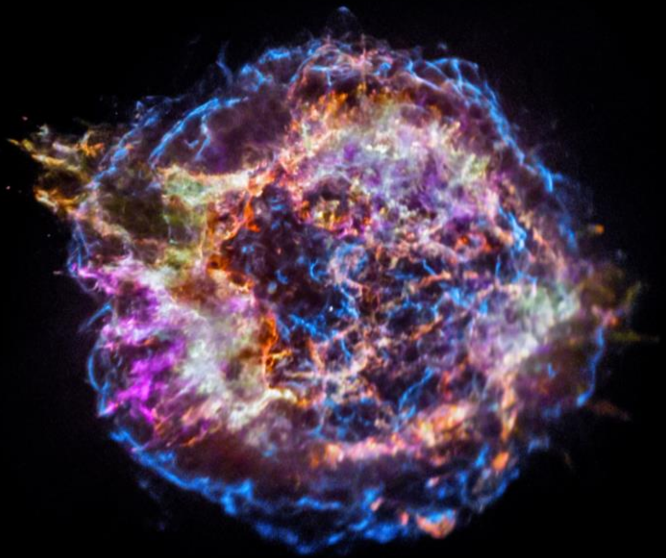
The effect of the explosive nucleosynthesis is higher for lower mass stars





The explosive nucleosynthesis cannot be neglected for the majority of the elements

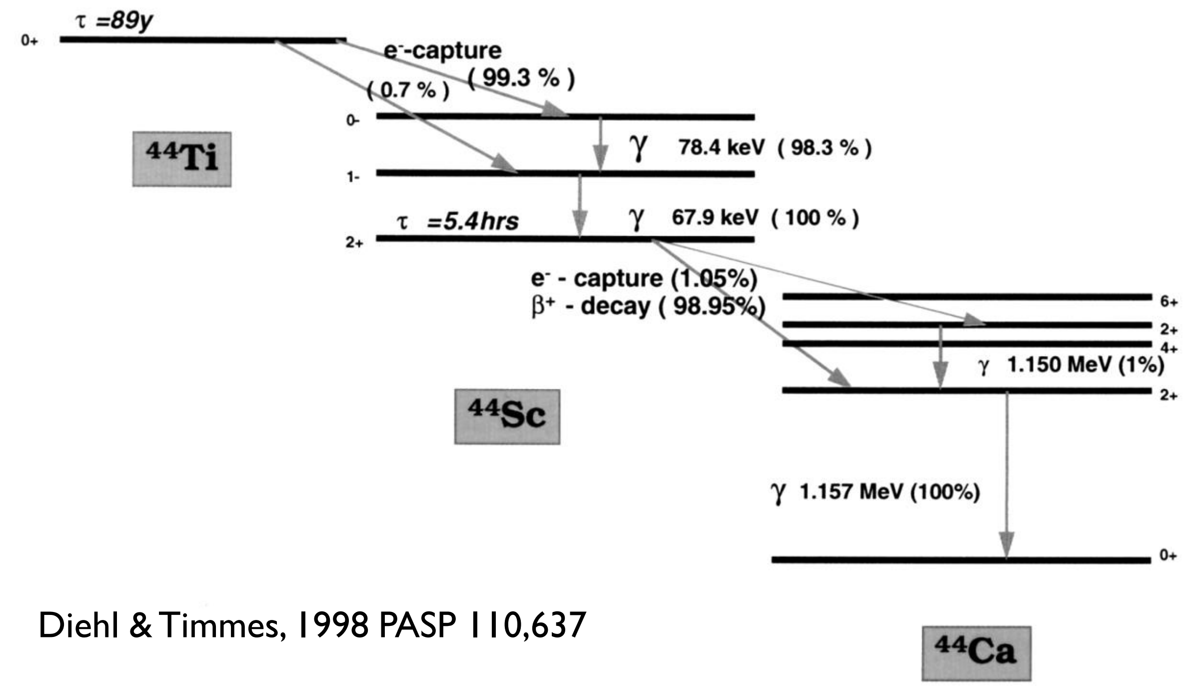
Gamma-ray detection of ^{44}Ti from Cas A SNR



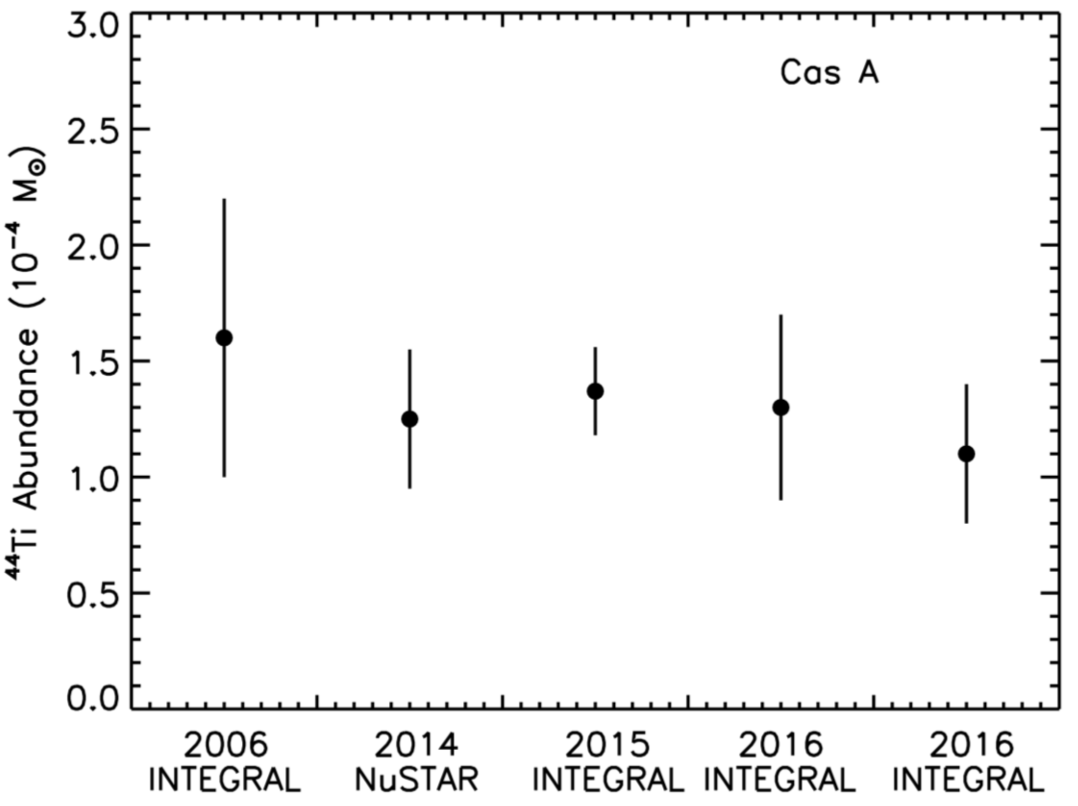
Age ~340 yr   Distance ~3.4 kpc

Possibly a Core Collapse Supernova without a H-rich envelope (Type IIb/Ib SN)

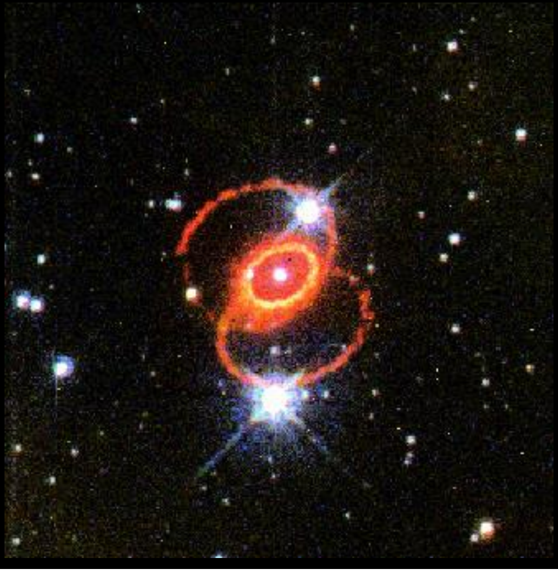
Gamma-ray detection of ^{44}Ti



Diehl & Timmes, 1998 PASP 110,637



Gamma-ray detection of ^{44}Ti from SN1987A

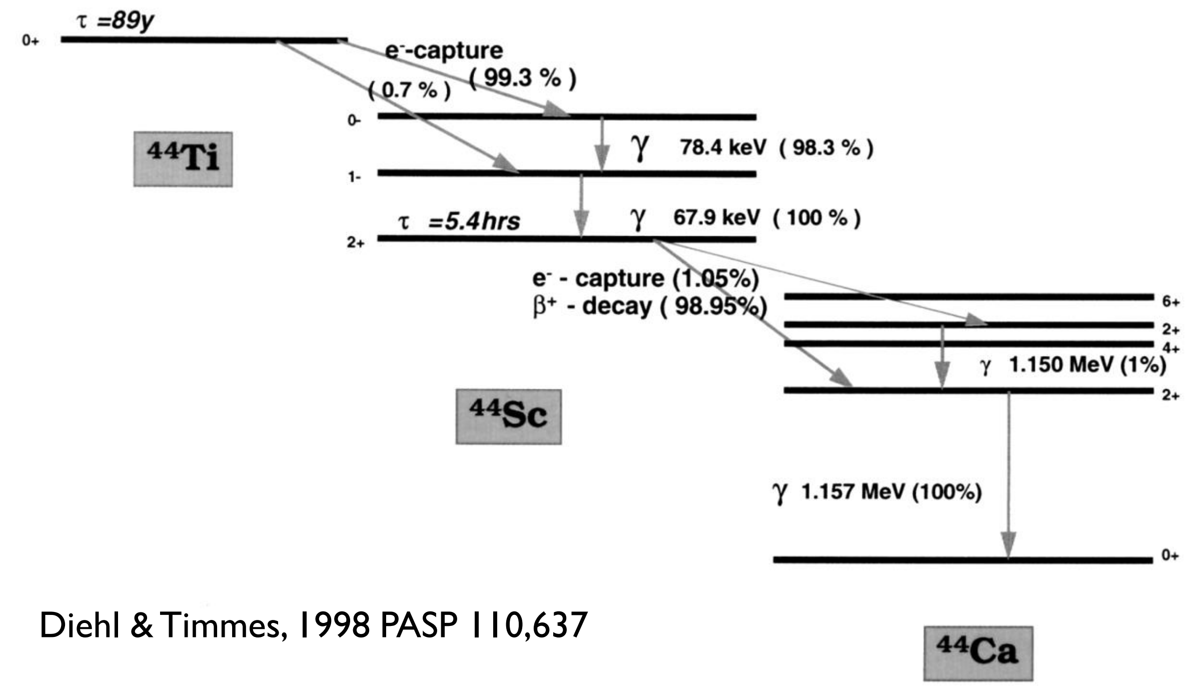


Age 35 yr Distance ~50 kpc

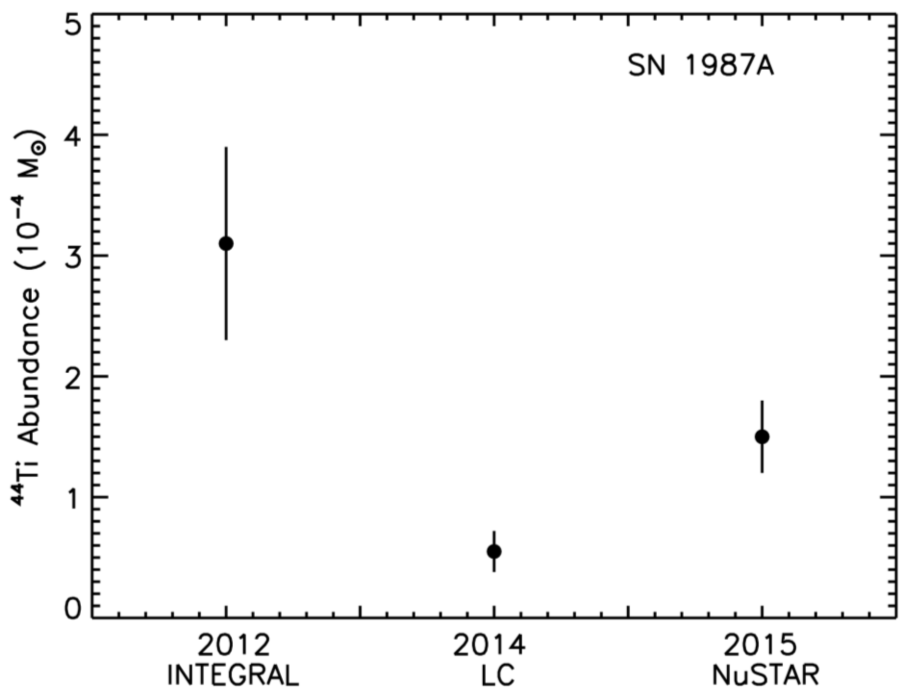
Blue Supergiant Core Collapse Supernova

Mass of the progenitor star ~ 18-20 $M_{\odot}$

Gamma-ray detection of ^{44}Ti

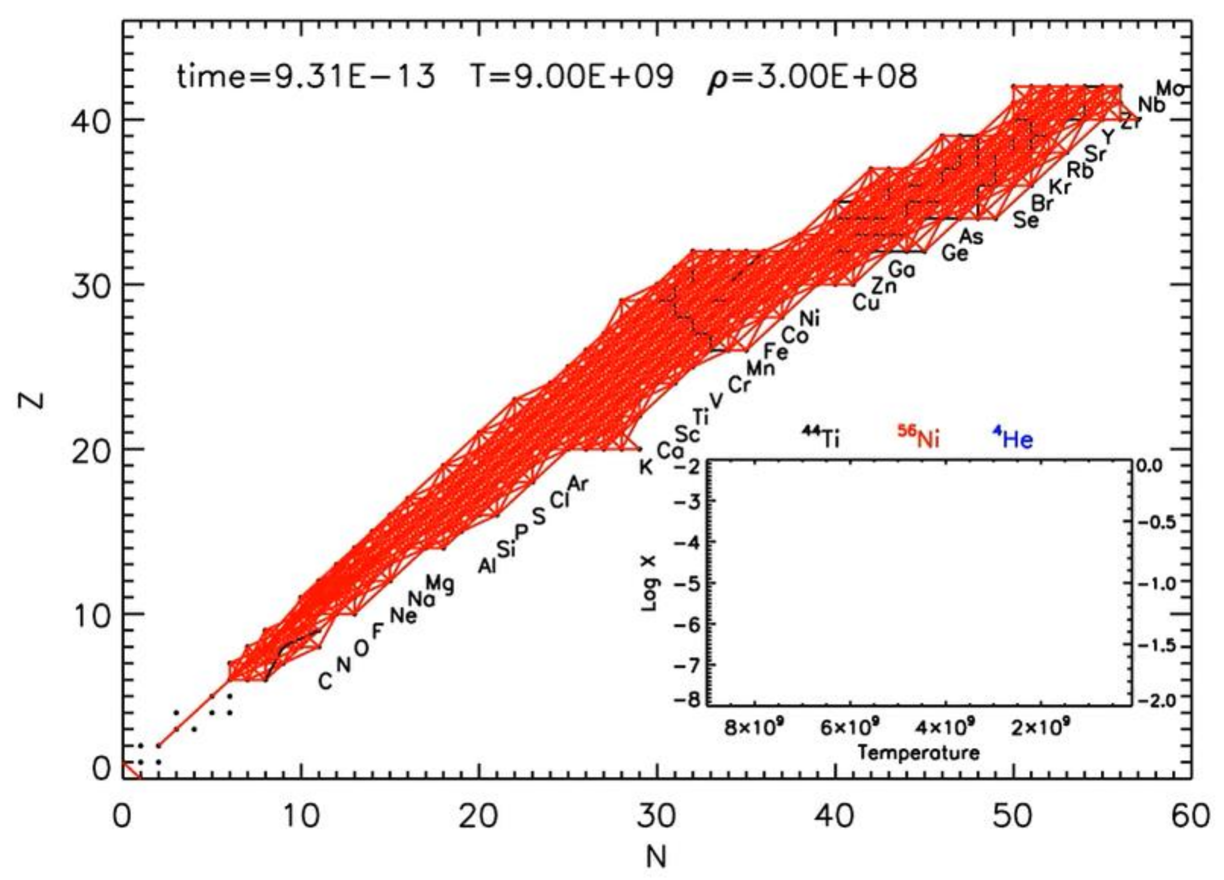


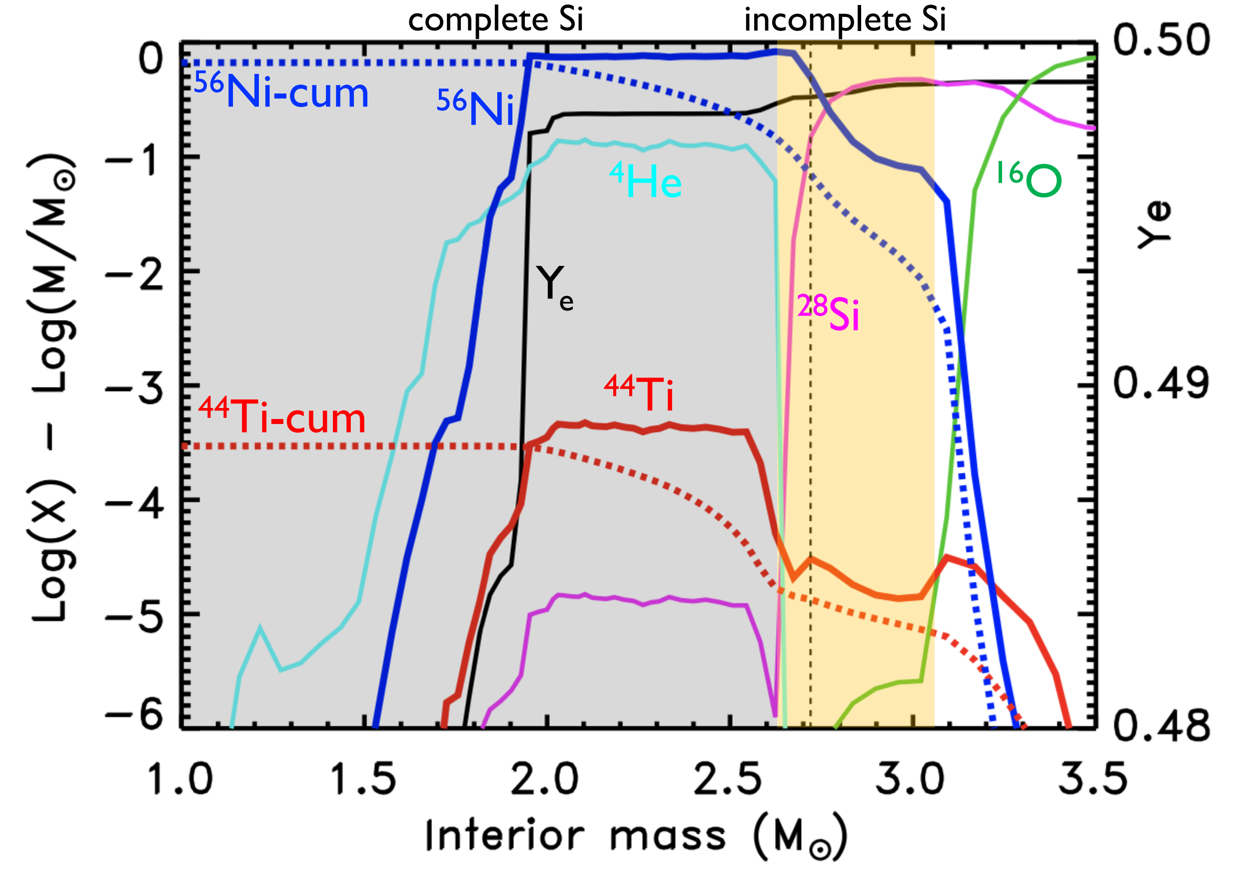
Diehl & Timmes, 1998 PASP 110,637



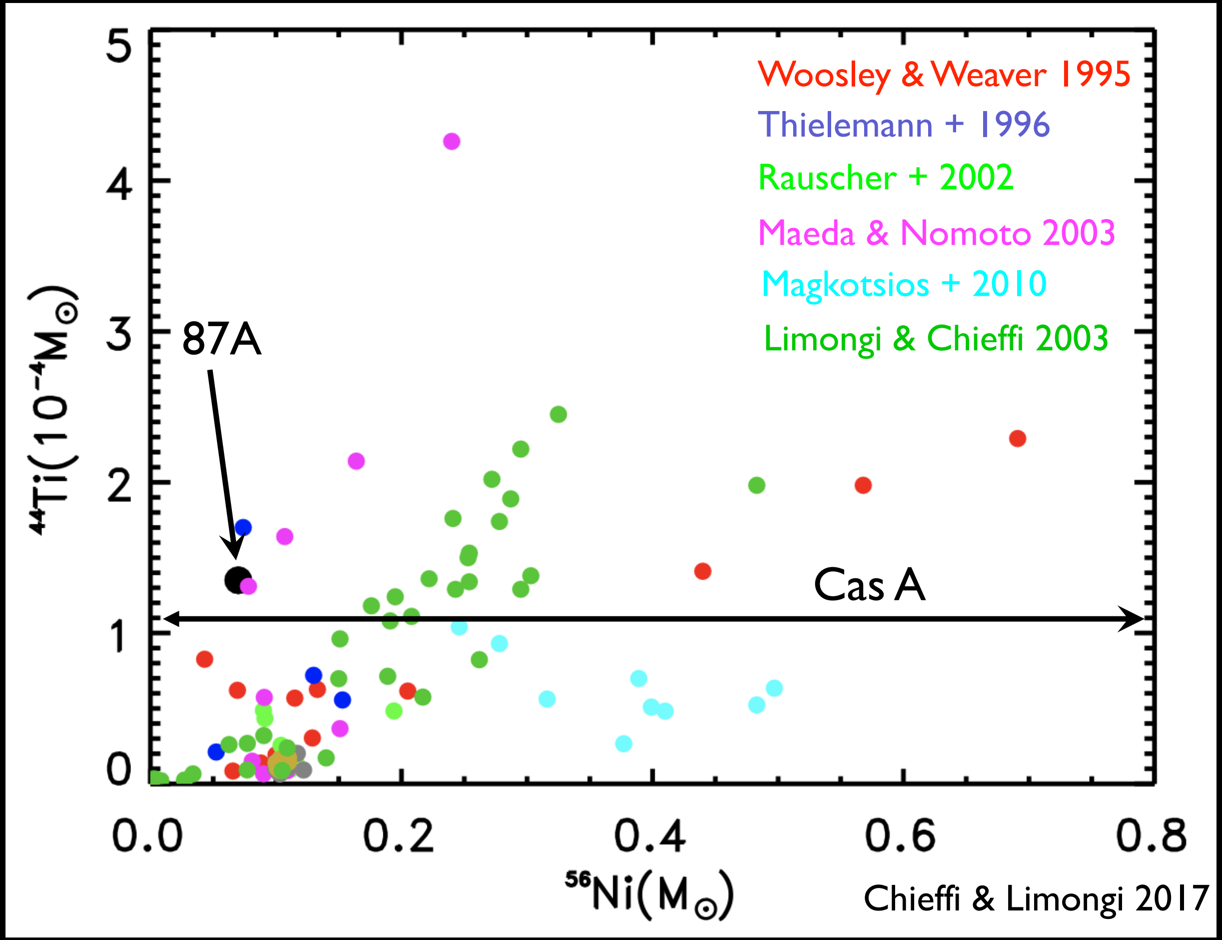
The Synthesis of ^{44}Ti and ^{56}Ni in Massive Stars

^{44}Ti synthesized by the explosive Si burning





The Synthesis of ^{44}Ti and ^{56}Ni in Massive Stars

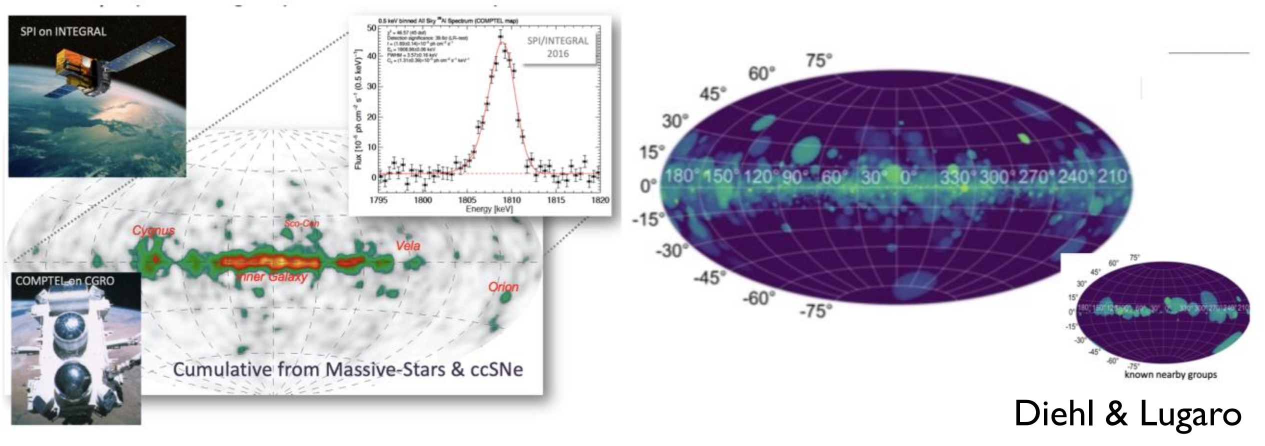


Chieffi & Limongi 2017

No model is compatible with the observed value for 87A (the only exception is an aspherical explosion of a pure He core)

The observed value for CasA implies an ejected amount of ^{56}Ni larger than ~0.15 $M_\odot$
→ data for ^{56}Ni are needed

Gamma-ray detection of ^{26}Al in the Galaxy

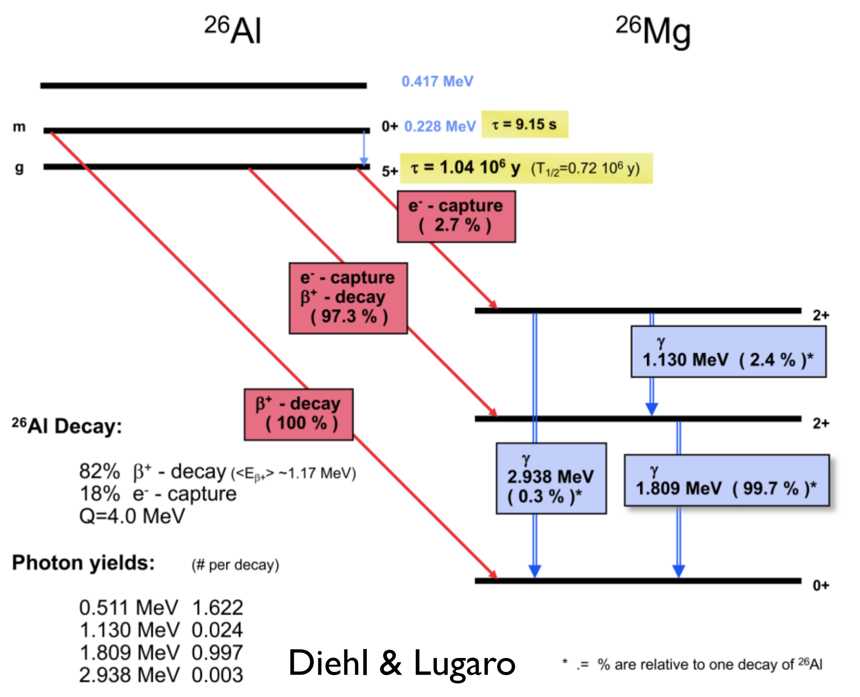


Diehl & Lugaro

Mostly produced by massive stars

~1-3 $M_\odot$ of ^{26}Al present in the Galaxy

^{26}Al/^{60}Fe flux ratio ~0.14 toward the galactic center



^{26}Al Decay:

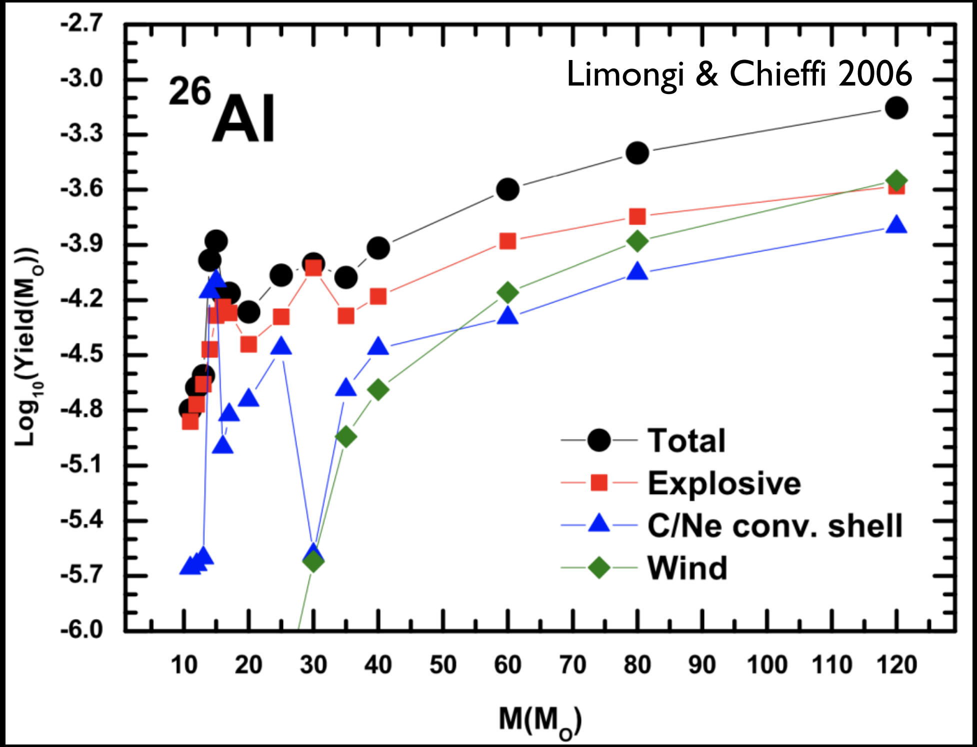
82% β^+ - decay ($<E_{\beta+}>$ ~1.17 MeV)
18% e^- - capture
Q=4.0 MeV

Photon yields: (# per decay)

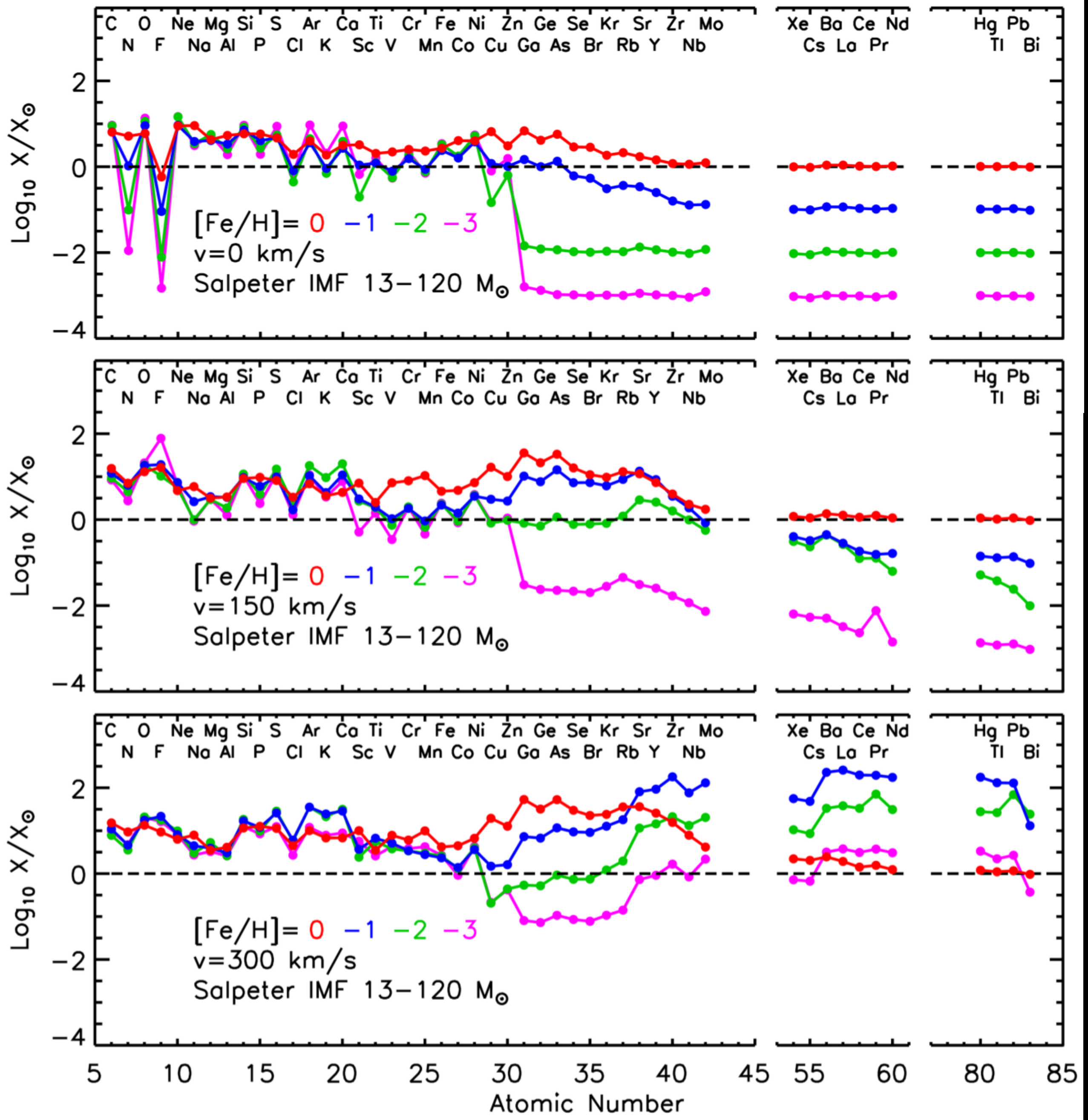
0.511 MeV	1.622
1.130 MeV	0.024
1.809 MeV	0.997
2.938 MeV	0.003

Diehl & Lugaro

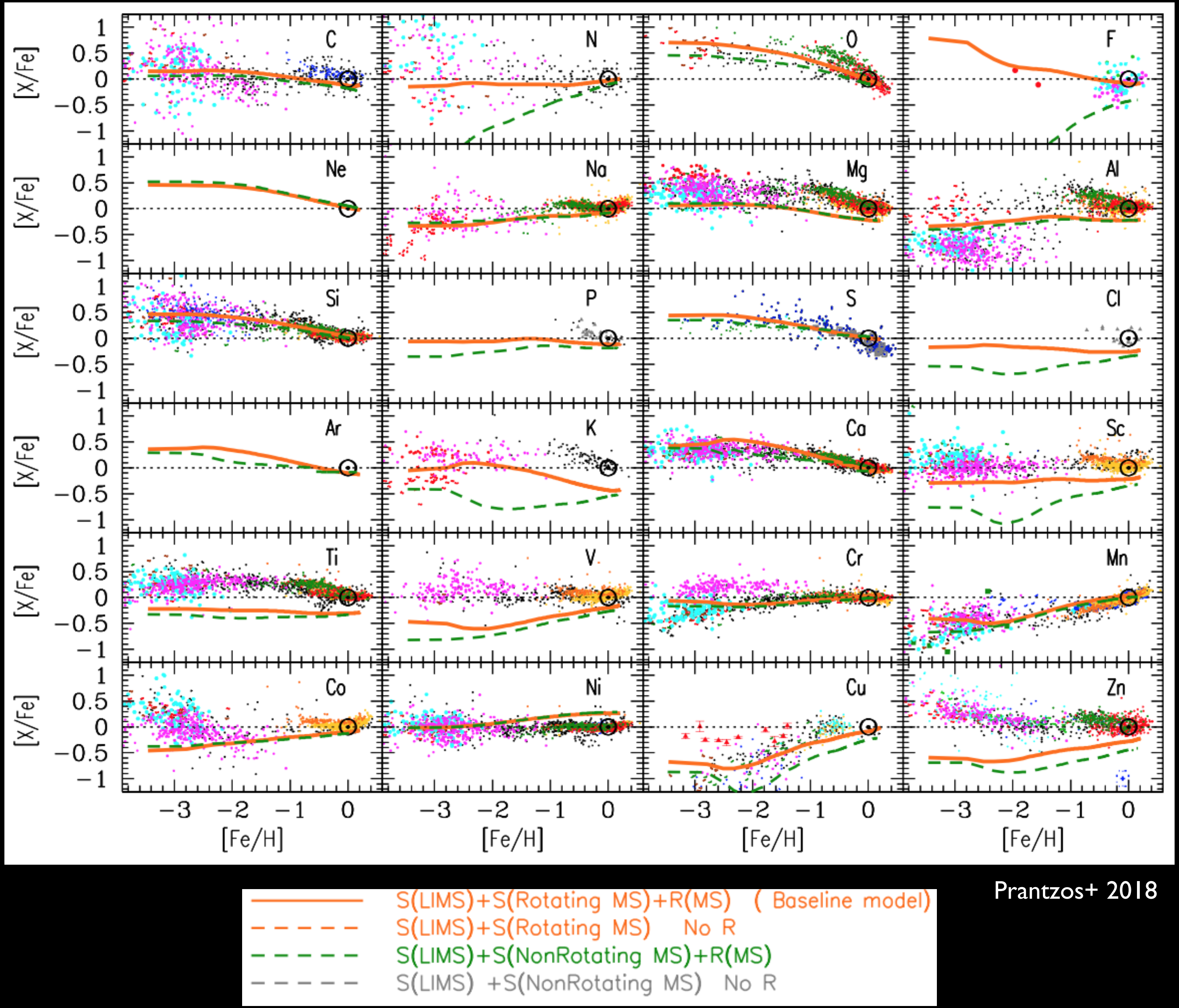
* .= % are relative to one decay of ^{26}Al



Chemical Composition of the Ejecta of Massive Stars

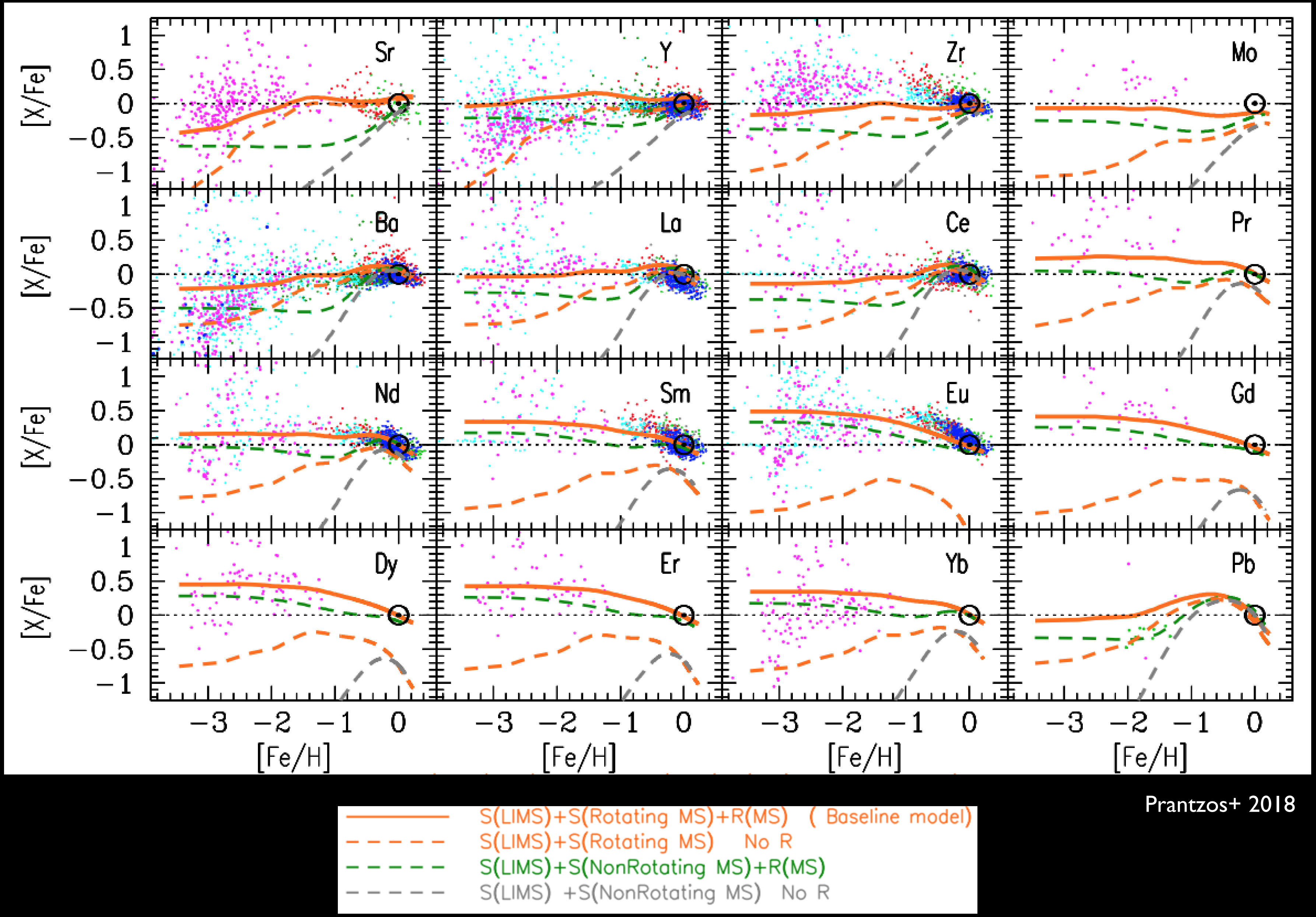


Chemical Evolution of the Milky Way



Prantzos+ 2018

Chemical Evolution of the Milky Way



Prantzos+ 2018

Conclusions

Explosive nucleosynthesis in core collapse supernovae occurs during the explosion of massive stars

It is responsible for the production/destruction of most of the elements Si-Ni

Isotopes like ^{56}N, ^{44}Ti and ^{26}Al are produced only or mostly during the explosion.

Most of the elements heavier than Ni are also partially affected by explosive nucleosynthesis

The effect of explosive nucleosynthesis is higher in massive stars of lower mass

Taking into account the explosive nucleosynthesis is necessary in order to the determine the chemical composition of the ejecta of core collapse supernovae