MASSIVE STARS: PRESUPERNOVA EVOLUTION AND EXPLOSIVE NUCLEOSYNTHESIS

Marco Limongi
INAF – Osservatorio Astronomico di Roma

Massive Stars, those massive enough to explode as supernovae, play a key role in many fields of astrophysics:

Evolution of galaxies:

- Light up regions of stellar birth → induce star formation
- Production of most of the elements (those necessary to life)
- Mixing (winds and radiation) of the ISM
- Production of exotic objects as remnant → neutron stars and black holes
- Anticorrelations [Na/O], [Mg/Al] observed in Globular Clusters

Cosmology (PopIII):

- Reionization of the Universe at z>5
- Massive Remnants (Black Holes) → AGN progenitors
- Pregalactic Chemical Enrichment → Lyα forest at z=3-3.5 con $Z \sim 10^{-3} - 10^{-2}\ Z_u$, extremely metal poor stars [Fe/H]<-3.5

High Energy Astrophisics:

- Production of long-lived radioactive isotopes: (^{26}Al, ^{56}Co, ^{57}Co, ^{44}Ti, ^{60}Fe)
- GRB progenitors (Collapsars o "Failed Supernovae", Supranove)

The understanding of these stars, i.e., their presupernova evolution, their explosion as supernovae and especially their nucleosynthesis, is crucial for the interpretation of many astrophysical objects

In spite of this astrophysical relevance there are only few groups producing theoretical presupernova models of massive stars and associated explosive nucleosynethsis (Limongi, Chieffi, Straniero – Nomoto, Hashimoto, Umeda – Woosley, Weaver, Heger)

NUCLEAR NETWORK

NUCLEAR NETWORK:

Very extended nuclear network including lots of isotopes and nuclear reactions (captures of p, n, α, photodisintegrations, e^+ e^- captures, β decays)

- Limongi, Chieffi, Straniero (LSC): 300 isotopes from neutrons to ^{98}Mo (fully automeated)
- Nomoto, Hashimoto, Umeda (NHU): 240 isotopes from neutrons to ^{71}Ge
- Woosley, Weaver, Heger (WWH): up to 700~2200 (hydrostatic-explosive) from neutron to Polonium (adaptive)

COUPLING OF PHYSICAL AND CHEMICAL SYSTEMS OF EQUATIONS:

$$\frac{\partial P}{\partial M} = -\frac{GM}{4\pi R^4}$$

$$\frac{\partial R}{\partial M} = \frac{1}{4\pi R^2 \rho(P,T,Y_i)}$$

$$\frac{\partial L}{\partial M} = \varepsilon_{nuc}(P,T,Y_i) + \varepsilon_\nu(P,T,Y_i) + \varepsilon_{grav}(P,T,Y_i)$$

$$\frac{\partial T}{\partial M} = -\frac{GMT}{4\pi R^2 P}\nabla(P,T,Y_i)$$

$+$

$$\frac{\partial Y_i}{\partial t} = \sum_j c_i(j)\lambda_j Y_j + \sum_{j,k} c_i(j,k)\rho N_A <\sigma v>_{j,k} Y_j Y_k + \sum_{j,k,l} c_i(j,k,l)\rho^2 N_A^{\ 2} <\sigma v>_{j,k,l} Y_j Y_k Y_l$$

$$i = 1,\dots\dots,N$$

H/He burnings:

$\rho = \rho(P,T)$; $\varepsilon = \varepsilon(P,T)$; $\nabla = \nabla(P,T)$

Systems Solved Separately

Adv. burnings:

$\varepsilon_{nuc} = \varepsilon_{nuc}(P,T,Y_i)$

- LSC: Fully coupling of the two systems adopting the larg network
- NHU: Separated Systems + tabulated nuclear energy generation assuming QSE/NSE + Post Processing with large network
- WWH: Separated Systems + 128-isotope QSE/NSE network for energy generation + Post Processing with large network

CONVECTION

CONVECTION:

- **Time dependent convection** $\tau_{mix} \approx \Delta t$ → Inability of convection to fully mix the matter in a timestep

LCS, NHU, WWH → $\left(\frac{\partial Y_i}{\partial t}\right)_{conv} = \frac{\partial}{\partial m}\left(4\pi r^2 \rho D \frac{\partial Y_i}{\partial m}\right)$ $D = \frac{1}{3} v_{conv} l$ (mixing-length)

- **Interaction Mixing+Nuclear Burning** $\tau_{mix} \approx \tau_{nuc}$ → During the late stages of evolution, convective and nuclear burning timescales become comparable
  - **LSC**: Fully coupling of convection with the systems decsrbing the physical structure and the chemical evolution of the matter due to nuclear burning (one single huge matrix)
  - **NHU**: Nuclear burning carried out first, then stellar zones mixed as a separate step aftewards in the converged model
  - **WWH**: Same as NHU

- **Stability Criterion for Convection**

Schwarzschild $\nabla_{ad} < \nabla_{rad}$

Semiconvection $\nabla_{rad} < \nabla_{ad} < \nabla_{rad} + k\nabla_{\mu}$

Ledoux $\nabla_{ad} < \nabla_{rad} + k\nabla_{\mu}$

- **LSC**: Schwarzschild, No Semiconvection, No mechanical overshooting. Ledoux for H convective shell
- **NHU**: Same as LSC, No Mechanical Overshooting
- **WWH**: Semiconvection + Mechanical Overshooting

INPUT PHYSICS

INPUT PHYSICS:

EOS:

- **Electrons** → **Perfect gas of arbitrary degeneracy and relativity**
- **Ions** → **Ideal gas**
- **Radiation** → **Black Body**

The electric interaction between ions and among ions and electrons (Coulomb corrections) cannot be neglected (→ act to decrease the final iron core mass)

- **LSC: Montecarlo technique (taking into account the partial degeneration o the electron component)**
- **NHU: Approximated formula (Clayton 1968)**
- **WWH: Same as NHU**

$$P_{coul} = -0.3\left(\frac{4\pi}{3}\right)^{1/3} N_A^{4/3} e^2 Y_e^{1/3} \rho^{4/3} \sum_i \frac{Z_i^{5/3} X_i}{A_i}$$

$$\approx -5.5 \cdot 10^{12} Y_e^2 \overline{A}^{2/3} \rho^{4/3} \quad \mathrm{dyne/cm}^2$$

Nuclear Cross Sections:

$^{12}C(\alpha,\gamma)^{16}O$ plays a crucial role for the evolution and nuclesynthaeis of massive stars

- **LSC: Kunz et al. 2002 (adopted rate)**
- **NHU: Cauglhan & Fowler 1985**
- **WWH: Buchmann 1996,2000 x 1.2 (calibrated on the Solar System distribution)**

Other uncertainties:

Rotation (mixing and angular momentum transport) – Mass Loss (single and binaries)

COMPUTER TIME:

Typically a full evolution requires ~20000 models, ~1500 zones, ~300 isotopes, ~3000 nuclear reactions

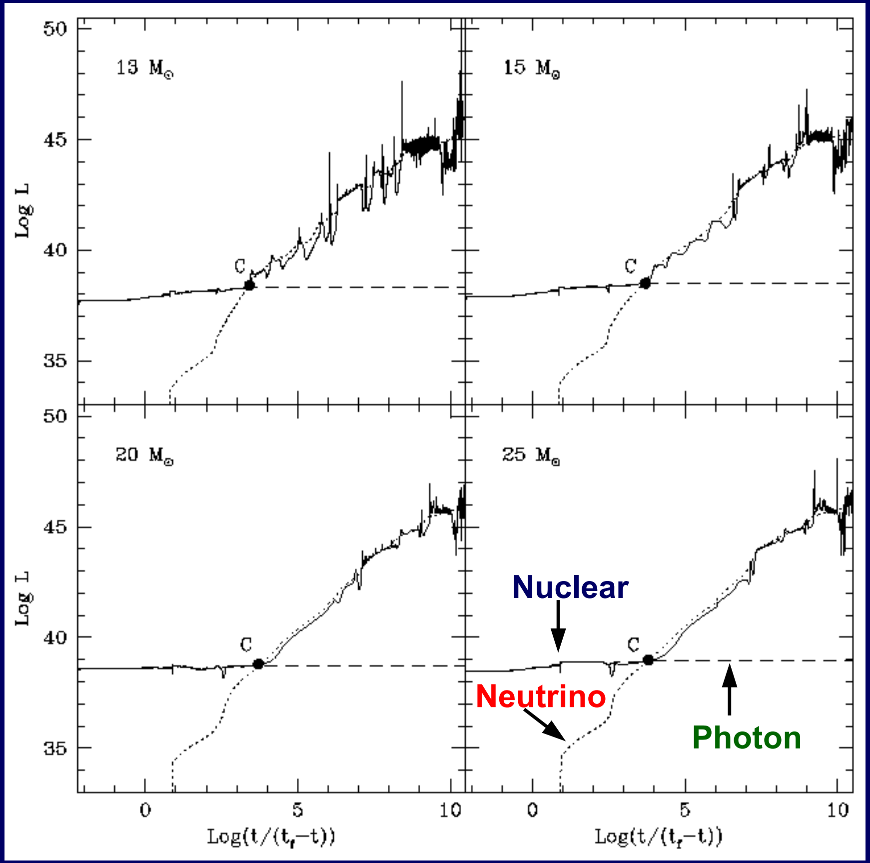
ROLE OF NEUTRINOS

Neutrino losses are a critical aspect of the evolution of massive stars

At high temperature ($T>10^9$ K) neutrino emission from pair production become very efficient

$$\gamma \leftrightarrow e^+ + e^- \rightarrow \nu_e + \overline{\nu}_e$$

The main energy losses occur from the surface (photons) up to C ignition and from the center (neutrinos) in the more advanced phases



$$t_{nuc} \cong E_{nuc} \frac{M}{L}$$

H burning: $4\,{}^1H \rightarrow {}^4He$ $\Delta M = 0.007$ AMU/nucleon

$E_{nuc} = 6.44 \times 10^{18}$ erg/g

He burning: $4\,{}^4He \rightarrow {}^{16}O$ $\Delta M = 0.0009$ AMU/nucleon

$E_{nuc} = 8.70 \times 10^{17}$ erg/g

O burning: $2\,{}^{16}O \rightarrow {}^{32}S$ $\Delta M = 0.0009$ AMU/nucleon

$E_{nuc} = 4.98 \times 10^{17}$ erg/g

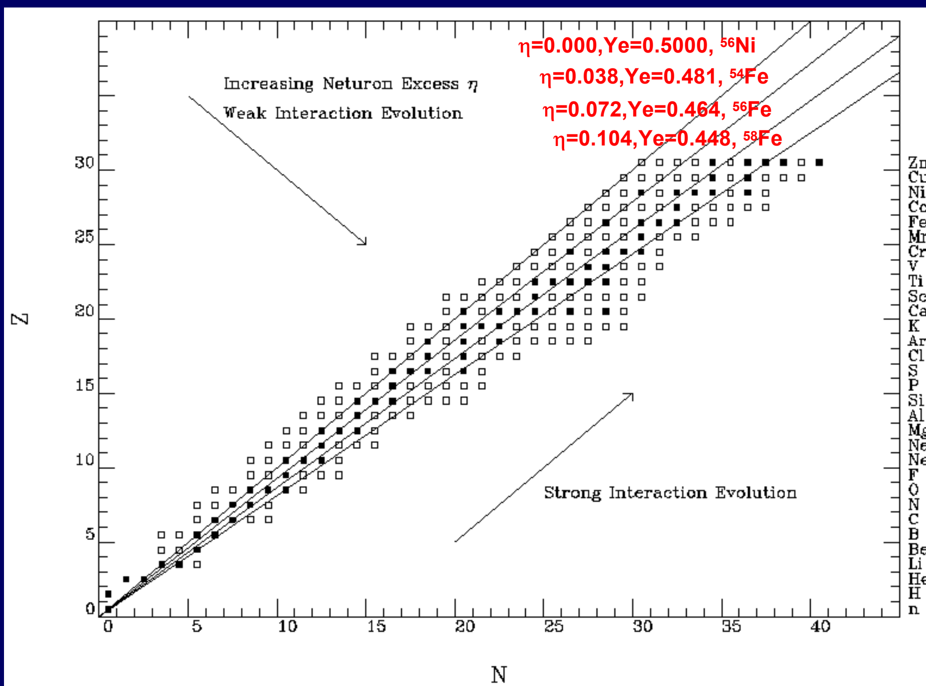
$$\frac{t_{He}}{t_H} \simeq 0.13 \quad \frac{t_O}{t_H} \simeq 0.08$$

From the models: $\frac{t_{He}}{t_H} \simeq 0.11 \quad \frac{t_O}{t_H} \simeq 5.56 \cdot 10^{-8}$

ROLE OF WEAK INTERACTIONS

Though the stars are powered chiefly by fusion reactions (i.e. Strong interactions) from start to finish, weak interactions play an important role in determining the final nucleosynthesis

Weak interactions affect the nucleosynthesis because the production of all nuclei except those for which $N \approx Z$ is sensitive to the electron fraction or, equivalently, the neutron excess



$$Y_e = \sum_i \frac{Z_i}{A_i} X_i \qquad \eta = 1 - 2Y_e$$

The change in neutron excess prior to Oxygen buring has only a slight effect on the stellar structure

After Oxygen burning a large number of excited states with uncertain properties becom populated that their decay must be dealt with statistically

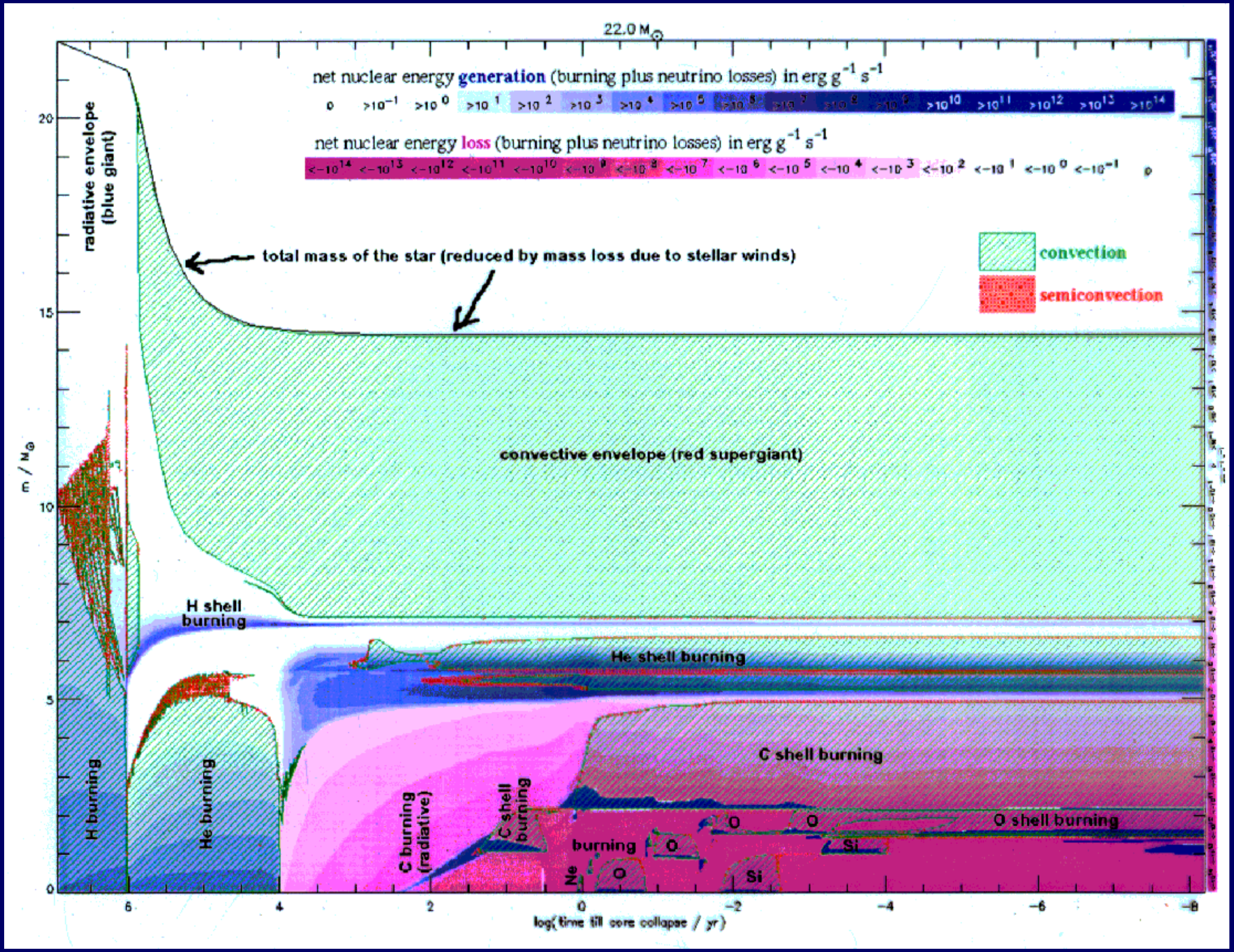
- LSC: Experimental (Terrestrial), Theoretical + Experimental (Oda et al. 1994), Theoretical (Fuller Fowler & Newmann 1985, Langanke & Pinedo 2000, Takahashi & Yokoi 1987)
- NHU: Experimental (Terrestrial), Theoretical (Fuller Fowler & Newmann 1985)
- WWH: Experimental (Terrestrial), Theoretical (Möller et al 1997, Fuller Fowler & Newmann 1985, Langanke & Pinedo 2000)

PRESUPERNOVA EVOLUTION

All stars more massive than ~12 M$_{\text{À}}$ complete all the nuclear burning stages (from H to Si burning) in hydrostatic equilibrium and in non degenerate conditions prior to collapse

The evolution of a massive star is characterized by a complex interplay among:

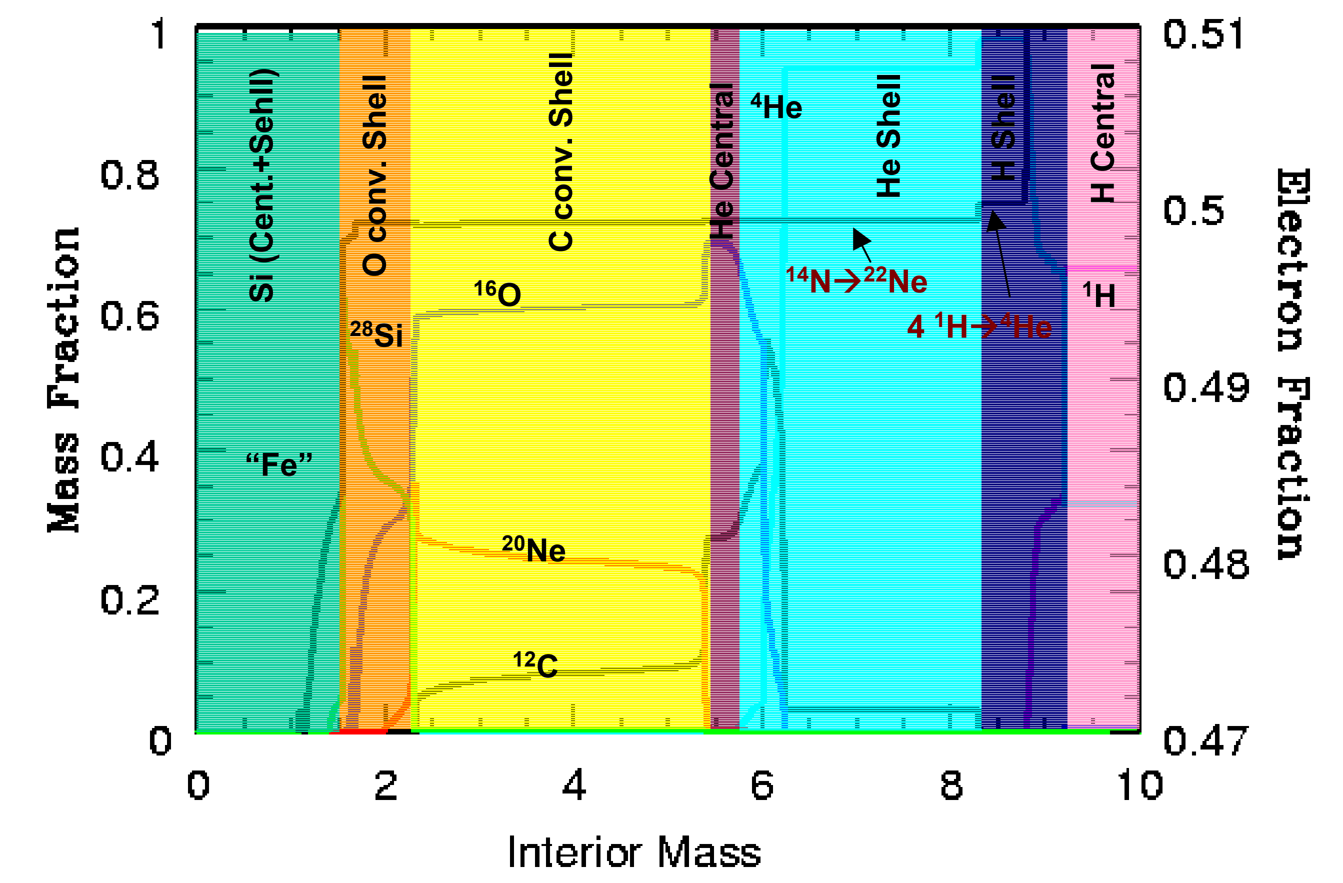
- Nuclear energy generation
- Neutrino losses
- Location and timing of numerous episodes of convective burnings



MAIN EVOLUTIONARY PROPERTIES

Fase	Time	L_ν	M_{cc}/M_{tot}	T_c(K)	ρ_c (g/cm^3)	Fuel	Main Prod.	Sec. Prod.	Main Uncertainties
H	~10^7 yr		0.3-0.5	~7 10^7	~10	^{1}H	^{4}He	^{13}C,^{14}N, ^{17}O,^{23}Na, ^{26}Al,	Extension of the Convective Core (Semiconvection)
He	~10^6 yr		0.13-0.2	~2 10^8	~2 10^3	^{4}He	^{12}C, ^{16}O	^{18}O, ^{22}Ne, *s*-proc.	Convection (Semiconvection) ^{12}C(α,γ)^{16}O, ^{12}C/ ^{16}O
C	~10^3 yr	~L_{ph}	$M_{tot} \geq 20$ ~0.4 $M_{\text{À}}$	~8 10^8	~10^6	^{12}C	^{20}Ne, ^{23}Na, ^{24}Mg, ^{27}Al	^{25}Mg, *s*-proc.	Abundance of ^{12}C $\rightarrow$ ^{12}C(α,γ)^{16}O
Ne	~3 yr	~$10^3 L_{ph}$	~0.6 $M_{\text{À}}$	~1.6 10^9	~10^7	^{20}Ne	^{20}Ne, ^{24}Mg	^{29}Si, ^{30}Si	Abundance of ^{12}C $\rightarrow$ ^{12}C(α,γ)^{16}O
O	~0.3 yr	~$10^5 L_{ph}$	~1 $M_{\text{À}}$	~1.8 10^9	~10^7	^{16}O	^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca,	Cl, Ar, K, Ca	Weak Interactions Coupl. Systems Time dep. Conv.
Si	~5days	~$10^5 L_{ph}$	~1 $M_{\text{À}}$	~2.5 10^9	~10^8	^{28}Si	^{54}Fe, ^{56}Fe, ^{55}Fe	Ti, V, Cr, Mn, Co, Ni	Weak Interactions Coulomb Corr. Coupl. Systems Time Dep. Conv.

PRESUPERNOVA MODEL

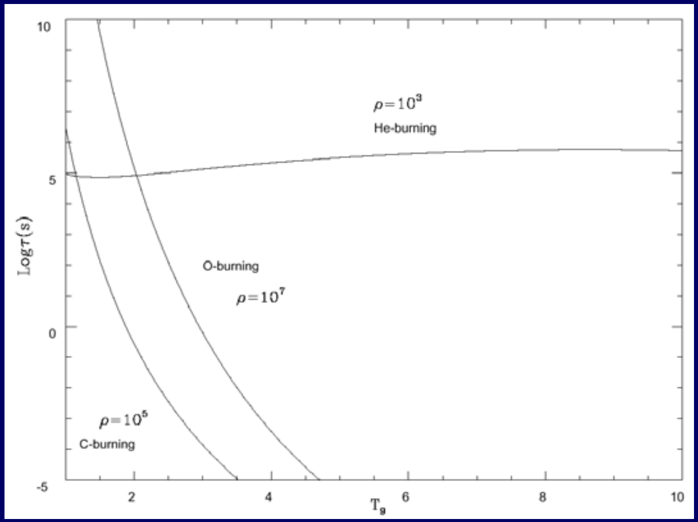


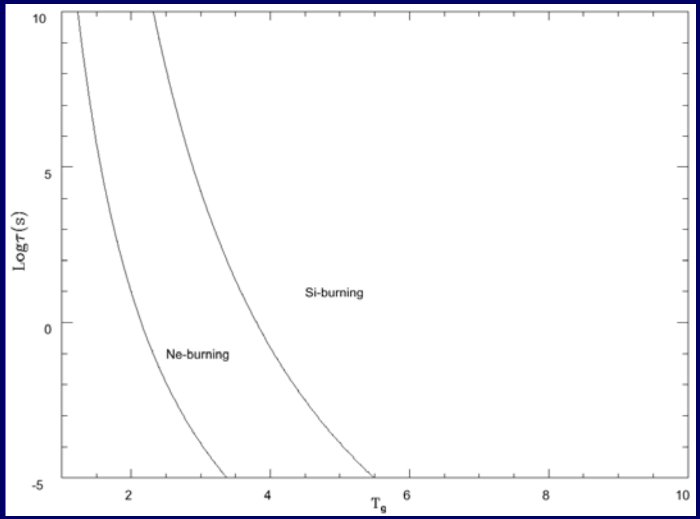
Burning Site	Main Products
Si Burning	^{54}Fe, ^{56}Fe, ^{55}Fe, ^{58}Ni, ^{53}Mn
O Conv. Shell	^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca, ^{34}S, ^{38}Ar
C Conv. Shell	^{20}Ne, ^{23}Na, ^{24}Mg,^{25}Mg, ^{27}Al + *s*-process
He Centrale	^{12}C, ^{16}O, ^{22}Ne, + *s*-process
He Shell	^{12}C, ^{16}O, ^{18}O, ^{22}Ne
H Centrale+Shell	^{13}C, ^{14}N, ^{17}O, ^{26}Al

EXPLOSIVE NUCLEOSYNTHESIS

As the shock wave propagates through the expanding mantle it induces explosive nucleosynthesis

The burning timescale for the destruction of a given fuel nuclei is → $\tau_i = \left|\frac{Y}{\dot{Y}}\right|$ ⟹ $\tau_i = f(T, \rho)$





If we take typical explosive burning timescales to be of the order of seconds

NSE/QSE (freez-out)

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

$T > 4 \cdot 10^9$ K Si burning

$T > 3.3 \cdot 10^9$ K O burning

Normal Burning

$Y_i = f(T, \rho, Y_{i,pre})$

$T > 2.1 \cdot 10^9$ K Ne burning

$T > 1.9 \cdot 10^9$ K C burning

Explosive He burning not efficient

$\rho > 10^5$ g/cm^3 He burning

Except very near the neutron star, the explosion happens too quickly for Y_e to be changed

The ejecta are characterized by the the neutron excess of the presupernova model

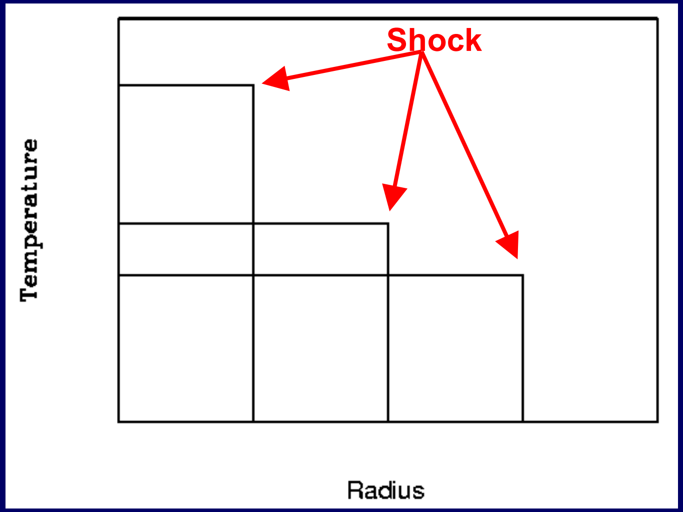
EXPLOSIVE NUCLEOSYNTHESIS

The **conditions for explosive nucleosynthesis** are characterized by the **peak temperature** and by the time for which that temperature persists → the **expansion time**

Except for small radii the peak temperature at radius r can be obtained by assuming that **the energy of the matter behind the shock is dominated by radiation** and that expansion and pressure waves are capable of maintaining nearly **isotermal conditions**.

$$E_{expl} = \frac{4}{3}\pi R^3 a T^4$$

R, T = posizione e temperatura dello shock



The **shock temperature at which any given radius of the presupernova model** is heated up is given to good accuracy by

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

- **The medium within which the shock front moves does not enter in the determination of the peak temperature**: its progressive reduction as the shock front moves outside is a simple consequence of the adiabatic expansion (a "geometrical“ effect), independent on the properties (physical and chemical) of the presupernova model
- **the peak temperature** left by the shock at the various radii **has a very mild dependence on the shock energy**

EXPLOSIVE NUCLEOSYNTHESIS

The existence of the critical temperatures for the various explosive burnings (and related chemical composition)

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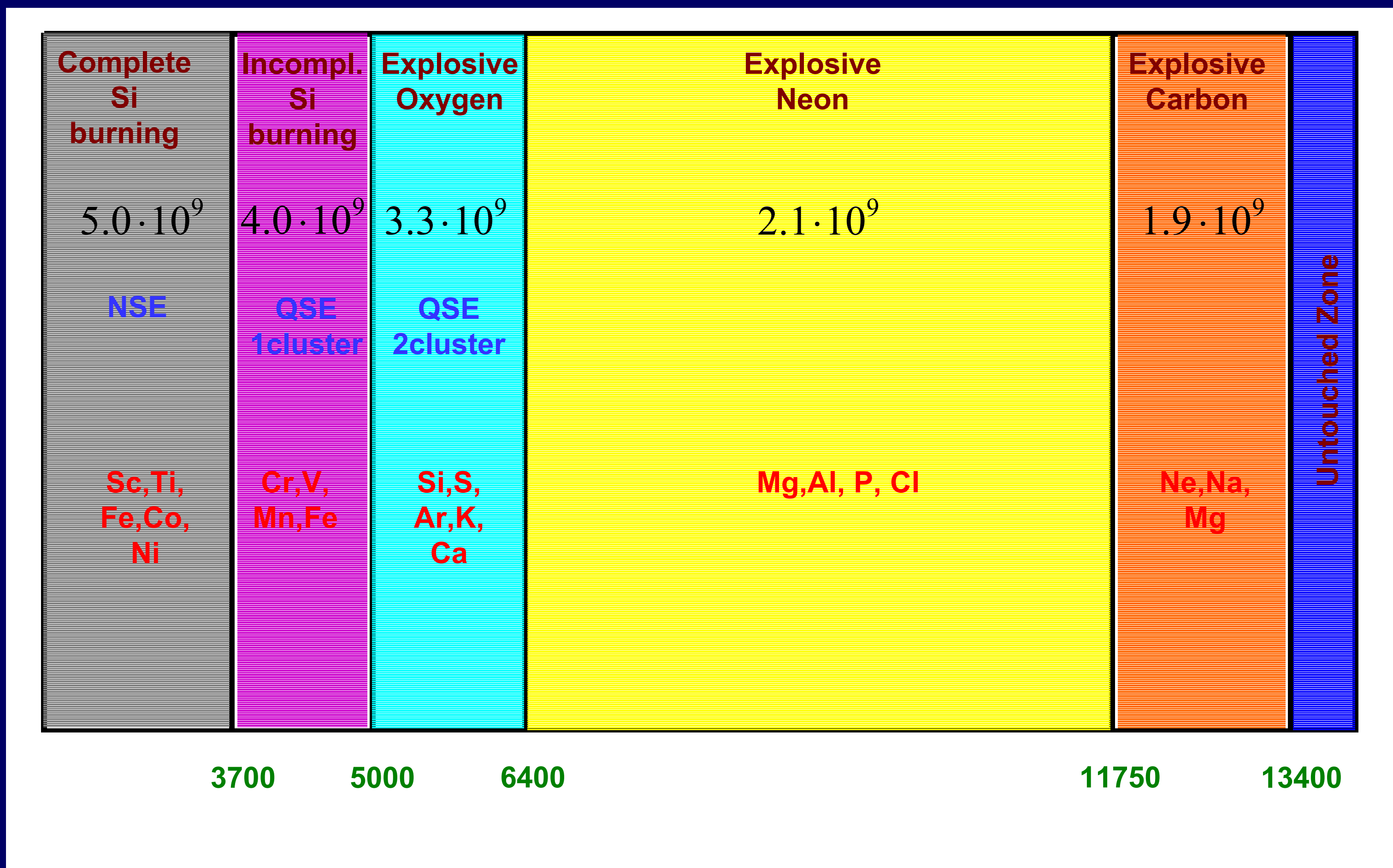
The fact that the shock wave cools simply as a consequence of the self expansion and does not depend on the structure within which it moves

We can define rather carefully and independently on the stellar structure the "volumes" within which the various nuclear conditions occur:



ROLE OF THE PRESUPERNOVA PROGENITOR

1) **MASS-RADIUS RELATION** :

- Fixes the total amount of mass which will be located in each of the volumes and hence the total amount of mass which will by processed by each explosive burnings
- Influences the kind of freez-out (normal or α-rich) of the innermost zones

The final M-R relation is the result of the superimposition of many successive (central and shell, radiative and convective) hydrostatic burnings that regulate the progressive contraction and heating of the core.

➡ any uncertainty present in the computation of the various burning phases may reflect on the final M-R relation.

Es. $^{12}C/^{16}O$ at He exhausiton → Efficiency of C convective shell → Rate of contraction of the C exhausted core → M-R relation of the C exhausted core

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2) Y_e (electron fraction):

- Influences the final chemical composition of the zones reaching NSE/QSE conditions
- Induce the production of neutron rich nuclei in the normal burning zones

The final Y_e profile is sensitive to the inteprplay among the various burning convective zones (times, overlaps), as well as the efficiency of the weak interactions

➡ any uncertainty related to the treatment of convection (especially the time dependent convection and the interaction convection-nuclear burning) may reflect on the final Y_e profile.

Es. The Y_e profile in the innermost zones is the result of the overlap of the O and Si convective shells

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3) **Hydrostatic composition** :

- Fixes the total amount of fuel available for the normal (no NSE/QSE) explosive burnings
- Defines the chemical composition (yields) of the matter not affected by the explosion

EXPLOSIVE NUCLEOSYNTHESIS: KEY QUANTITIES

By combining the properties of the presupernova models to those of the explosion it is possible to to identify which are the key quantities, and their related uncertainties, that influence the chemical composition of each zone of the presupernova model

Complete Si burning	Incompl. Si burning	Explosive Oxygen	Explosive Neon	Explosive Carbon	Untouched Zone
$5.0 \cdot 10^9$	$4.0 \cdot 10^9$	$3.3 \cdot 10^9$	$2.1 \cdot 10^9$	$1.9 \cdot 10^9$	
NSE	QSE 1cluster	QSE 2cluster			
Sc,Ti, Fe,Co, Ni	Cr,V, Mn,Fe	Si,S, Ar,K, Ca	Mg,Al, P, Cl	Ne,Na, Mg	
M-R (freeze-out)	M-R	M-R	M-R	M-R	
Y_e	Y_e	Y_e	Presupernova Composition	Presupernova Composition	

3700 5000 6400 11750 13400

INDUCED EXPLOSIONS

INAF

A more quantitative prediction of the chemical composition of the ejecta (yields of each isotope) should rely on a self consistent treatment of the core collapse, the bounce and then the propagation of the outoging shock through the exploding mantle.

Unfortunately the present modelling of core collapse supernovae does not yield to successful explosions yet

The explosive nucleosynthesis calculations for core collapse supernovae are still based on explosions induced by injecting an arbitrary amount of energy in a (also arbitrary) mass location of the presupernova model and then following the development of the blast wave by means of an hydro code.

Some choices have to be made

1 - Prompt vs Delayed Explosion (this may alter both the M-R relation and Y_e of the presupernova model)

Prompt: the shock front moves within layers that do not experience any collapse

Delayed: the mantle of the star is allowed to collapse for a given delay time (~0.5 s)

2 - How to kick the blast wave:

2a: Thermal Bomb - Kinetic Bomb - Piston

2b: Mass location where the energy is injected

3 - The final kinetic energy at the infinity (i.e. the amount of energy to be injected): usually ~10^{51} erg

4 - Artificial Mass Cut:

Usually chosen, after the explosion, in order to have a given amount of ^{56}Ni

INDUCED EXPLOSIONS

INAF

Limongi, Chieffi & Straniero:

- **Prompt Explosion (no collapse of the mantle is allowed before explosion)**
- **Piston of initial velocity v_0, located at 1 $M_{\odot}$ (within the Fe core)**
- v_0 **tuned in order to have a given** E_{kin}
- **No Artificial mass cut**

Nomoto, Hashimoto & Umeda:

- **Delayed Explosion (collapse before explosion on τ_{delay}~$0.5\ s$)**
- **Thermal Bomb, located at the edge of the Fe core**
- E_{int} **tuned in order to have a given** E_{kin}
- **Artificial mass cut (usully chosen to have ^{56}Ni=0.05 $M_{\odot}$**

Woosley, Weaver & Heger:

- **Delayed Explosion (τ_{delay}~$0.45\ s$ at $500\ Km$)**
- **Piston, located at the edge of the Fe core**
- v_0 **tuned in order to have a given** E_{kin}
- **No Artificial mass cut**

PISTON INDUCED EXPLOSION

Time history of the shock propagation in a 25 MÀ model: v_0=1.555 10^9 cm/s

- Once the shock forms it propagates outward in mass increasing locally both T and ρ → inducing explosive nucleosynthesis
- Behind the shock front T is farily flat (isothermal core) and progressively lower as the shocked matter expand and cool down
- In ~4s → shock at CO core (~6 MÀ) → $T<10^9$ K → explosive nucleosynethsis stops
- After ~100s fall back begins – shock within He core
- After ~370s shock at H/He discontinuity → high ρR^3 → reverse shock forms
- The reverse shock propagates inward in mass and decelerates the previously shocked matter
- After ~2$\times 10^5$ s → shock breakout
- The reverse shock escapes from the interior after ~6$\times 10^6$ s
- Homologous expansion with velocity ~1000)3000 Km/s
- Final kinetic energy of the ejecta $E_{kin}=1.144\times 10^{51}$ erg (1.144 foe, 1 foe = 10^{51} erg)
- Final M_{cut}=1.89 MÀ

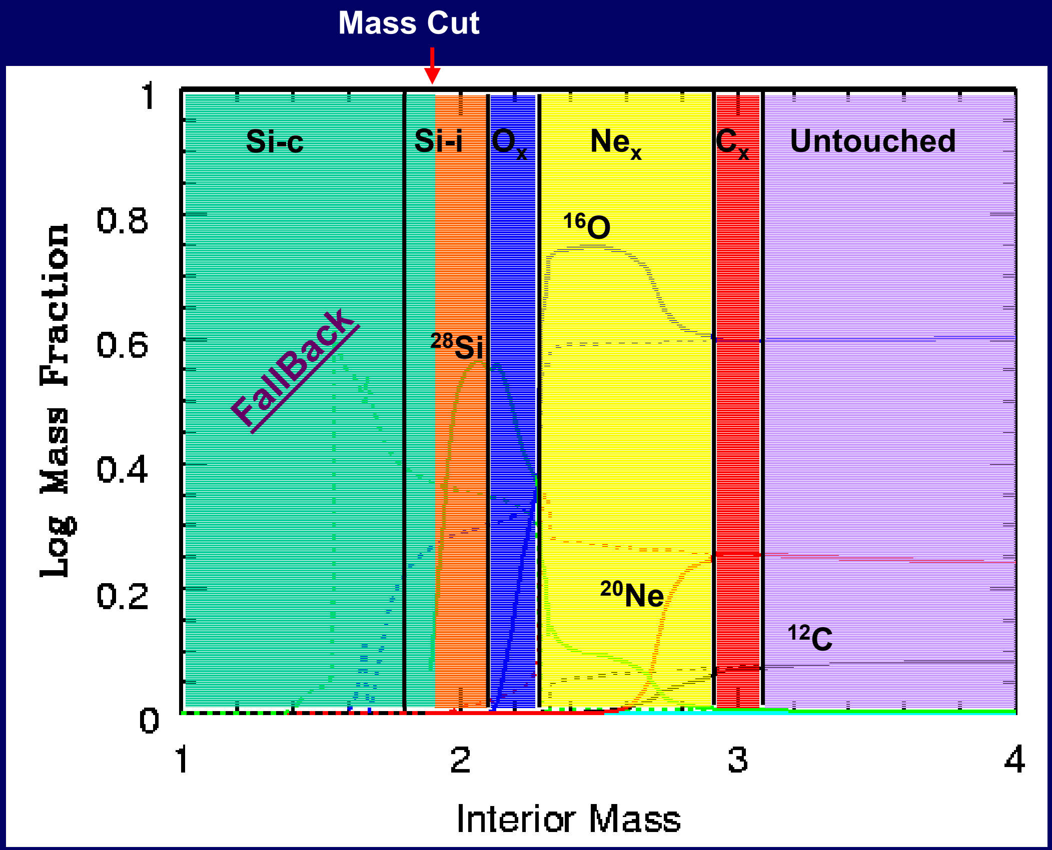
eplxosion 1D movie

explosion 2D movie

CHEMICAL COMPOSITION AFTER THE EXPLOSION

Chemical composition in a 25 M$_{\text{À}}$ model of solar metallicity after the piston induced explosion:

v_0=1.5550 10^9 cm/s M_{cut}=1.89 M$_{\text{À}}$ E_{kin}=1.144 foe



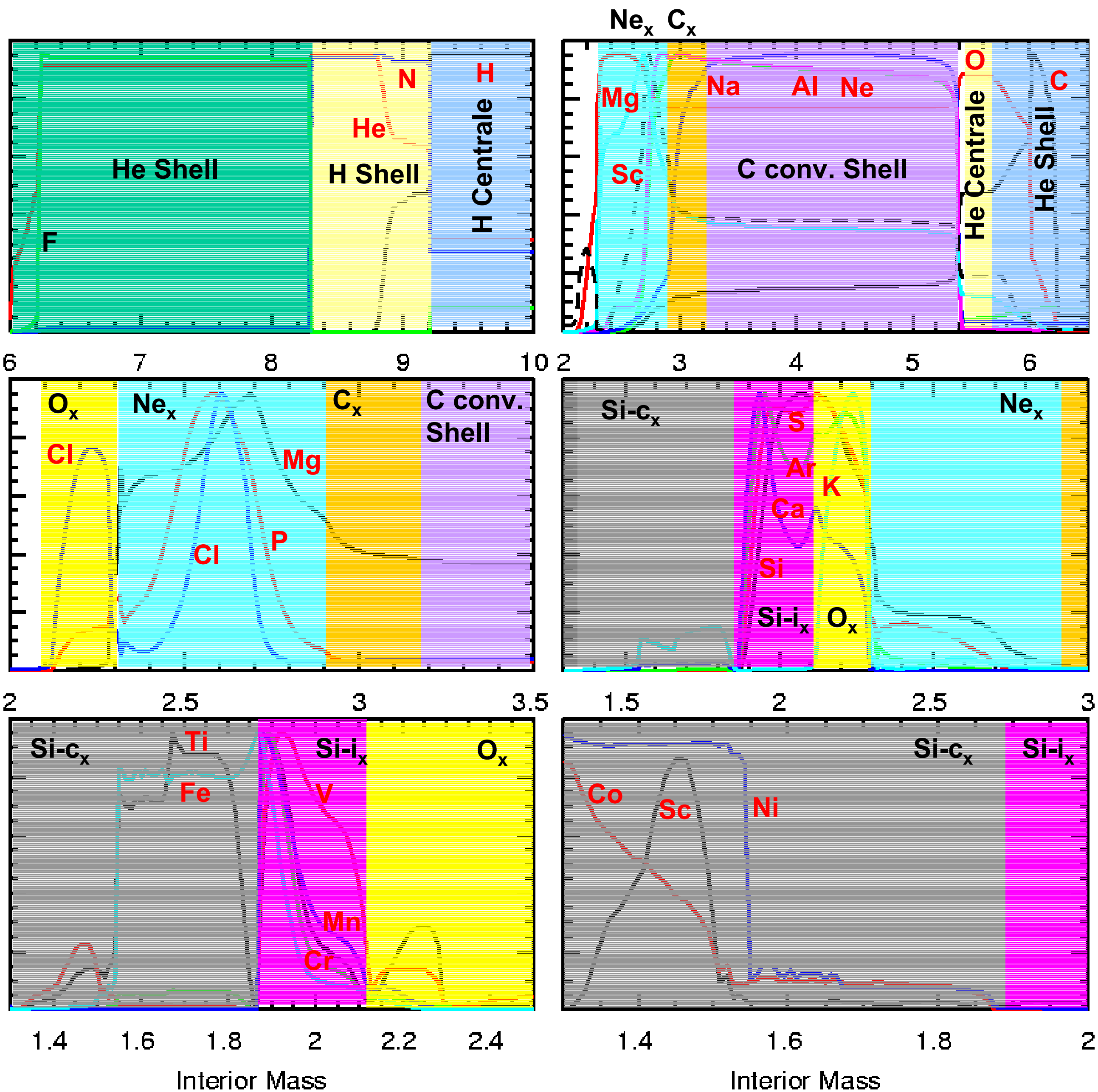
Dotted = Pre-explosive

Solid = Post-explosive

- **The explosion alters the presupernova composition within the inner ~3.1 M$_{\text{À}}$, i.e., well within the C convective shell**
- **Outside ~3.1 M$_{\text{À}}$ the chemical composition is the one of the presupernova model**
- **The zone undergoing explosive complete Si burning, and part of the one exposed to explosive incomplete Si burning, falls back onto the compact remnant**

CHEMICAL COMPOSITION AFTER A MORE ENERGETIC EXPLOSION

v_0=1.5658 10^9 cm/s
E_{kin}=1.263 foe
M_{cut}=1.23 MÀ



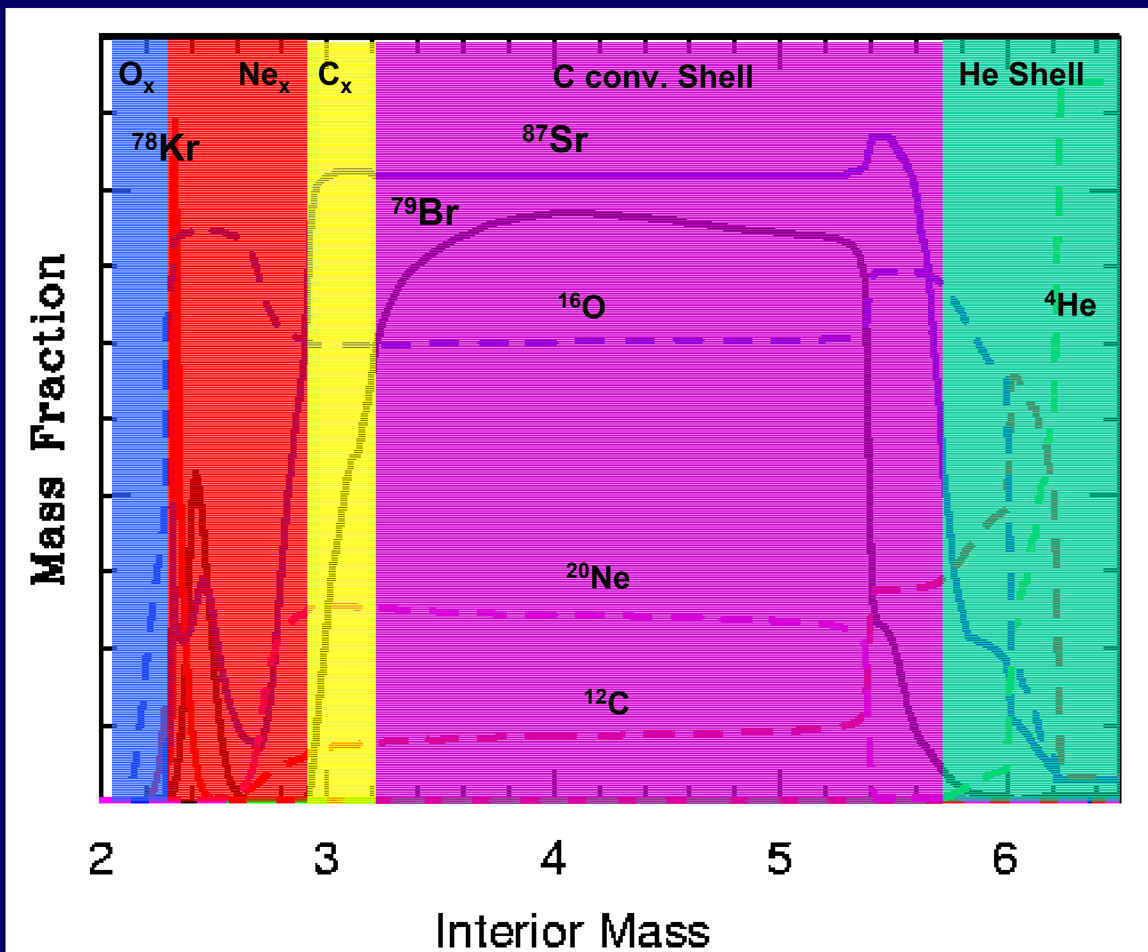
N (^{14}N)	H$_{shell}$
F (^{19}F)	He$_{conv\text{-}shell}$
C (^{12}C)	He$_{cent+shell}$
O (^{16}O)	He$_{cent}$
Na (^{23}Na)	C$_{shell}$ (C$_x$↓)
Al (^{27}Al) Ne (^{20}Ne)	C$_{shell}$ (Ne$_x$↓)
Mg (^{24}Mg)	C$_{shell}$ + Ne$_x$
P (^{31}P)	Ne$_x$
Cl (^{35}Cl,^{37}Cl)	Ne$_x$+ O$_x$
Si (^{28}Si),S (^{32}S), Ar (^{36}Ar),Ca (^{40}Ca)	O$_x$+ Si-i$_x$
K (^{39}K)	O$_x$
V [^{51}V (^{51}Cr)], Cr [^{52}Cr (^{52}Fe)], Mn [^{55}Mn (^{55}Co)]	Si-i$_x$
Ti [^{48}Ti (^{48}Cr)], Fe [^{56}Fe (^{56}Ni)]	Si-c$_x$ + Si-i$_x$
Co [^{59}Co (^{59}Ni)], Ni [^{58}Ni]	Si-c$_x$
Sc [^{45}Sc]	C$_{shell}$ + Ne$_x$ + Si-c$_x$

ELEMENTS BEYOND THE IRON PEAK

Nuclear burnings contributing to the synthesis of the elements heavier than iron

- He centrale
- Shell Convettiva di Carbonio
- Esplosione

Different contribution depending on the isotope:



Isotope	(Hec)	(Csh) 25	(Expl)
Cu63	30	60	10
Cu65	70		30
Zn64	70		30
Zn66	70		30
Zn67	40	60	
Zn68	30	50	20
Zn70		20	80
Ga69	40	40	20
Ga71	30	30	40
Ge70	40	40	20
Ge72	40	40	20
Ge73	10	90	
Ge74	20	50	30
Ge76		30	70
As76	10	50	40
Se74			100
Se76	40	40	20
Se77	10	40	50
Se78	20	60	20
Se80		60	40
Se82			100
Br79	10	90	
Br81	20	60	20
Kr78			100
Kr80	40	40	20
Kr82	30	70	
Kr83	10	70	20
Kr84	30	70	
Kr86		60	40
Rb85	10	80	10
Rb87		40	60
Sr84			100
Sr86	90		10
Sr87	100		
Sr88	50	50	20

EXISTING SET OF PRESUPERNOVA MODELS AND EXPLOSIVE NUCLESYNTHESIS

Authors	Mass Range	Z	Network	Mass Loss	Rot.	$^{12}C(\alpha,\gamma)^{16}O$	Convection	Explosion
LC (2002)	15-80	0.0	179 itosopes Fully Coup.	NO	NO	CF85/CF88	Schwarz. Semi NO Not Coupled	Radiation Dominated
LC (2003)	13-35	0.02	300 itosopes Fully Coup.	NO	NO	Kunz 2001	"	Hydro/Piston Prompt
LC (2003)	15-80	0	"	NO	NO	"	Schwarz. Semi NO Fully Coupled	"
WW (1995)	11-40	0-0.02	19 (ε_{nuc}) + 240 post	NO	NO	CF88@1.7	Ledoux Semiconv. Not Coupled	Hydro/Piston Delayed
WWH (2002)	15-25	0.02	19 (ε_{nuc}) + 700-2000 post	YES	NO	Buch @1.2	"	"
HW (2002)	140-260	0	19 (ε_{nuc}) + 300-477 post	NO	NO	"	"	"
UN (2002)	13-30 150-270	0	240 coupl.	NO	NO	CF85	Schwarz. Semi NO Not Coupled	Hydro/Thermal Bomb Delayed
NH (1988)+ TNH(1996)	13-25	0.02	?	NO	NO	CF85	"	"

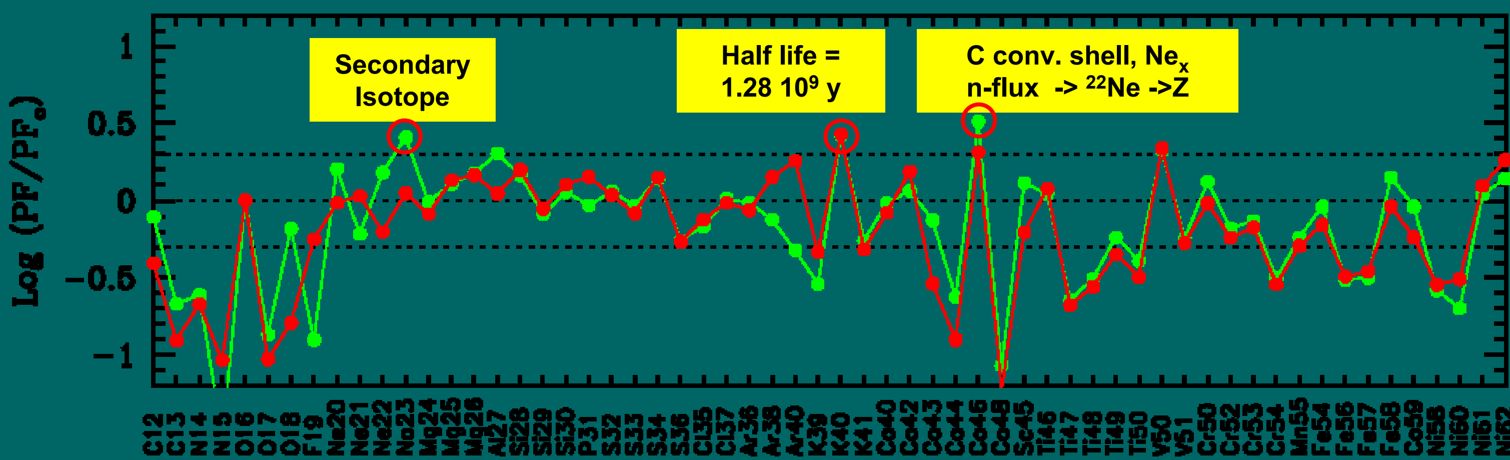
The most interesting models are the ones for initial solar and zero metallicity composition

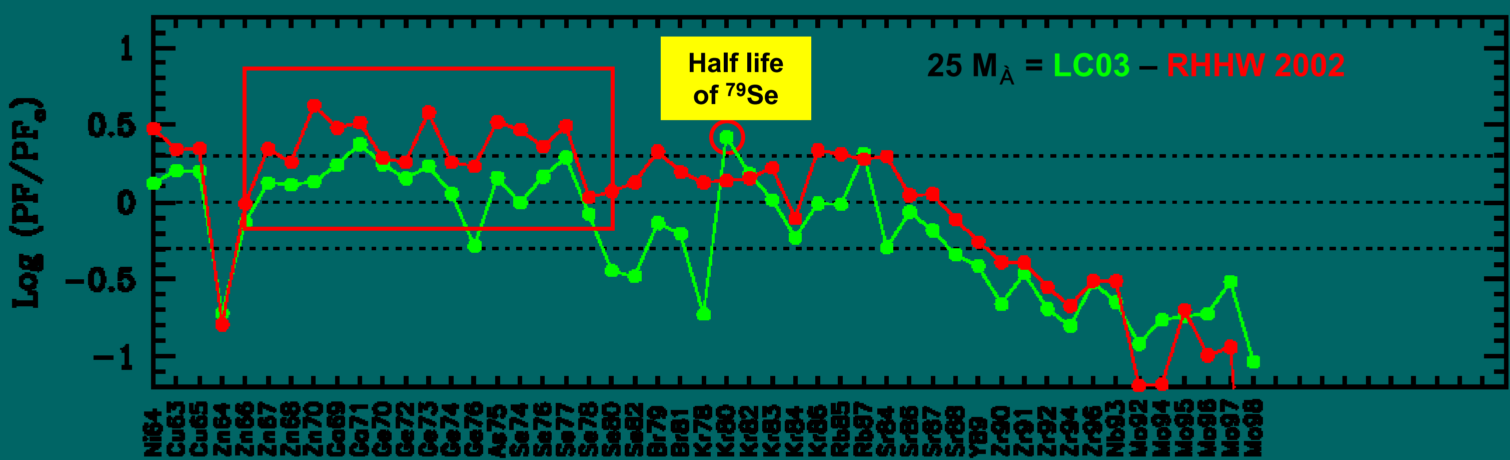
- They are the only models for which we know in detail the initial composition
- There are observational diagnostics for their explosive yields

OBSERVATIONAL DIAGNOSTICS FOR SOLAR METALLICITY MODELS

Under assumption that the average metallicity Z grows slowly and continuously compared to the evolutionary timescales of the stars that contribute to the environment enrichment

It is desirable that a generation of solar metallicity massive stars provides yields in roughly solar proportions (Production Factors almost flat).





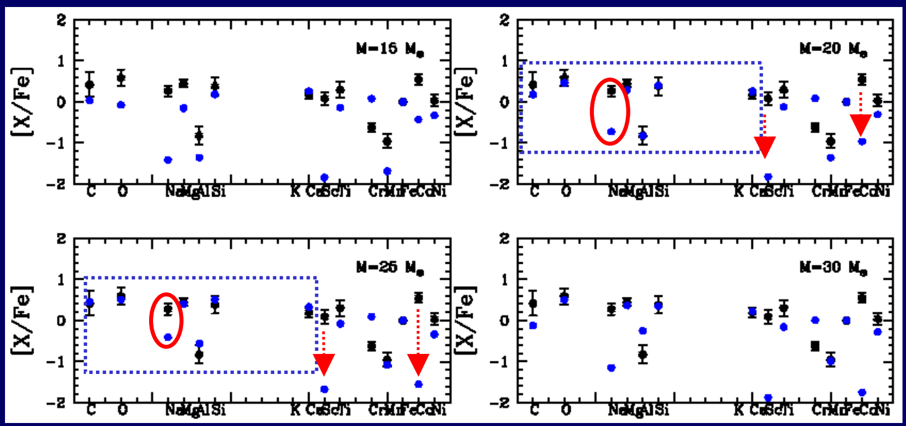
OBSERVATIONAL DIAGNOSTICS FOR POPIII MODELS

If extremely metal poor stars ([Fe/H]<-3.5) formed from clouds enriched by few, at least one, primordial core collapse supernovae,

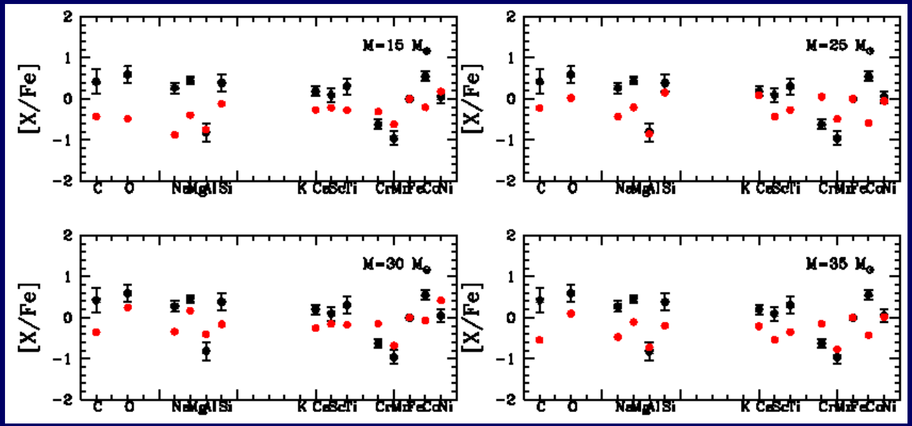
element abundance ratios observed in EMPS can be directly compared with theoretical yields of zero metallicity core collapse supernovae of different masses to constrain the nucleosynthesis

Observations = AVG star that represent 6 stars having [Fe/H]<-3.3 and showing very similar abundance pattern

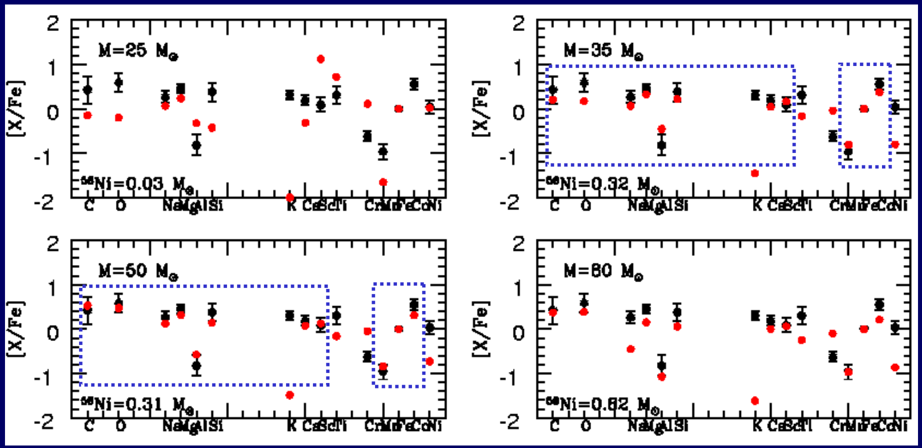
Umeda & Nomoto 2002 (ApJ 460, 408) (UN02)



Woosley & Weaver 1995 (ApJS 101, 181) (WW95)



Chieffi & Limongi 2002 (ApJ 577, 281) (CL02)



WW95 yields do not provied a good fit to the observatons

UN02 yields provide a good fit of the light elements (below Ca) except Na. No fit is found for the iron peak elements

CL02 yields allow for a good fit to 10 of 13 observed element abundance ratios. Among the iron peak elements no fit is found to Ti, Cr and Ni

CONCLUSIONS AND FUTURE DIRECTIONS

The evolution of massive stars and their explosion is qualitatively understood

→ Origin of the elements - Nature of SNII light curves and spectra - Expected masses of neutron stars - how SNII explode (?)

HOWEVER

There remain many uncertainties that prevent a full understanding of these objects:

- **Convection**:

  The greatest uncertainty still affecting our understanding of the presupernova evolution of massive stars. A quantitative theory of convection is still missing. Neither the strict Ledoux nor the Schwarzschild criterion is capable of explaining the observations

- **Supernova explosion mechanism**:

  Despite 50 years of intensive investigation, we still do not understand how massive stars explode. Models of increasing complesity (2D-3D) still do not adequately predict the explosion energies and the mass cut → uncertainty in the final yields especially the products of explosive complete Si burning

- **Uncertain nuclear reactions rate**:

  Key nuclear quantities still have unacceptable errors. Chief among these are the reaction rates for $^{12}C(\alpha,\gamma)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$

- **Mass Loss**:

  The rate at which mass is lost from luminous blue variable stars, red and blue supergiants, and Wolf-Rayet stars is still uncertain. Particularly highly uncertain is how all these mass loss rates scale with the metallicity, especially for very metal poor composition

- **Rotation**:

  Rotation is a typical multidimensional phenomenon → the present 1D rotating models suffer of a large uncertainties related to both the rotation and the associated mixing