PRESUPERNOVA EVOLUTION AND EXPLOSION OF MASSIVE STARS WITH MASS LOSS

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WHY ARE MASSIVE STARS IMPORTANT IN THE GLOBAL EVOLUTION OF OUR UNIVERSE?

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 neutron stars and black holes

Cosmology (PopIII):

Reionization of the Universe at $z>5$

Massive Remnants (Black Holes) → AGN progenitors

Pregalactic Chemical Enrichment

High Energy Astrophysics:

Production of long-lived radioactive isotopes:
(^{26}Al, ^{56}Co, ^{57}Co, ^{44}Ti, ^{60}Fe)

GRB progenitors

The understanding of these stars, is crucial for the interpretation of many astrophysical events

OVERVIEW OF MASSIVE STARS EVOLUTION

Grid of 15 stellar models: 11, 12, 13, 14, 15, 16, 17, 20, 25, 30, 35, 40, 60, 80 and 120 $M_\odot$

Initial Solar Composition (A&G89)

All models computed with the FRANEC (Frascati RAphson Newton Evolutionary Code) release 5.050419

(Limongi & Chieffi 2006, ApJ, 647, 483)

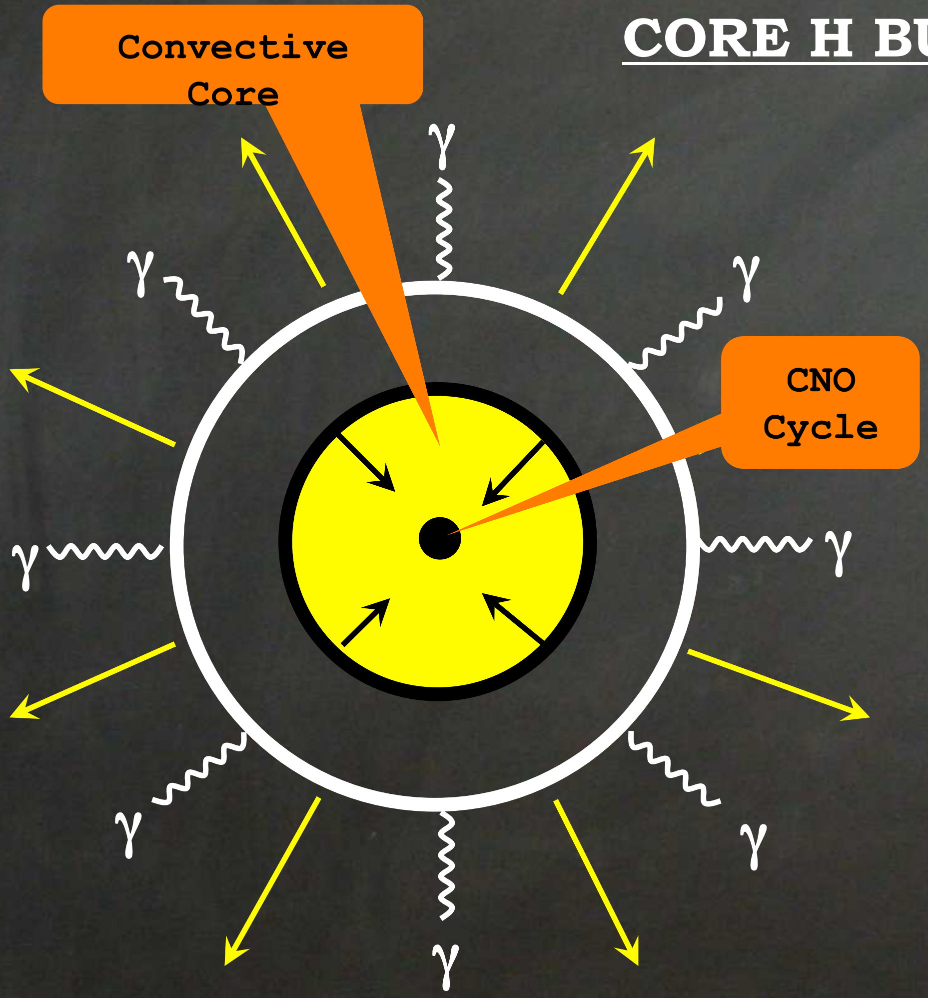
- **Evolution followed from the Pre Main Sequence up to the beginning of the core collapse**
- **4 physical + N chemical equations (nuclear burning) fully coupled and solved simultaneously (Henyey)**
- **Nuclear network very extended**

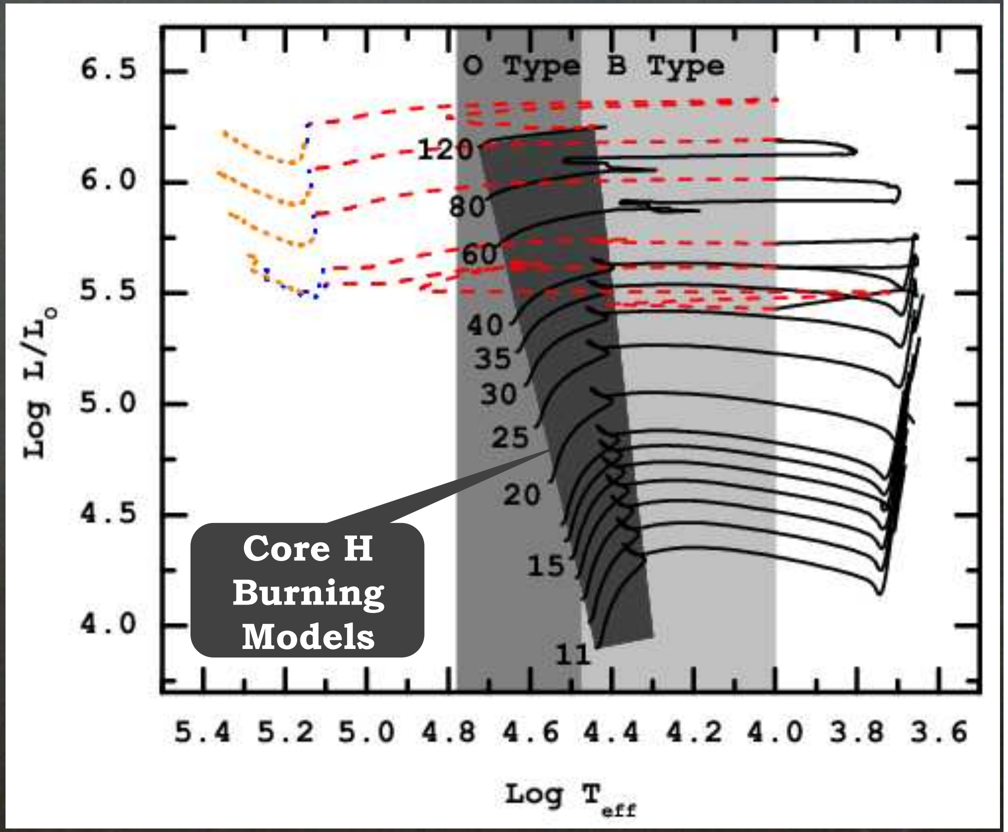
282 nuclear species (H to Mo) and ~ 3000 processes (Fully Automated)

(NO Quasi (QSE) or Full Nuclear Statistical Equilibrium (NSE) approximation)

- **Convective Core Overshooting: $d=0.2\ H_p$**
- **Mass Loss: Vink et al. (2000,2001) (Teff>12000 K), De Jager (1988) (Teff<12000 K), Nugis & Lamers (2000) (Wolf-Rayet)/Langer 1898 (WNE/WCO)**

CORE H BURNING



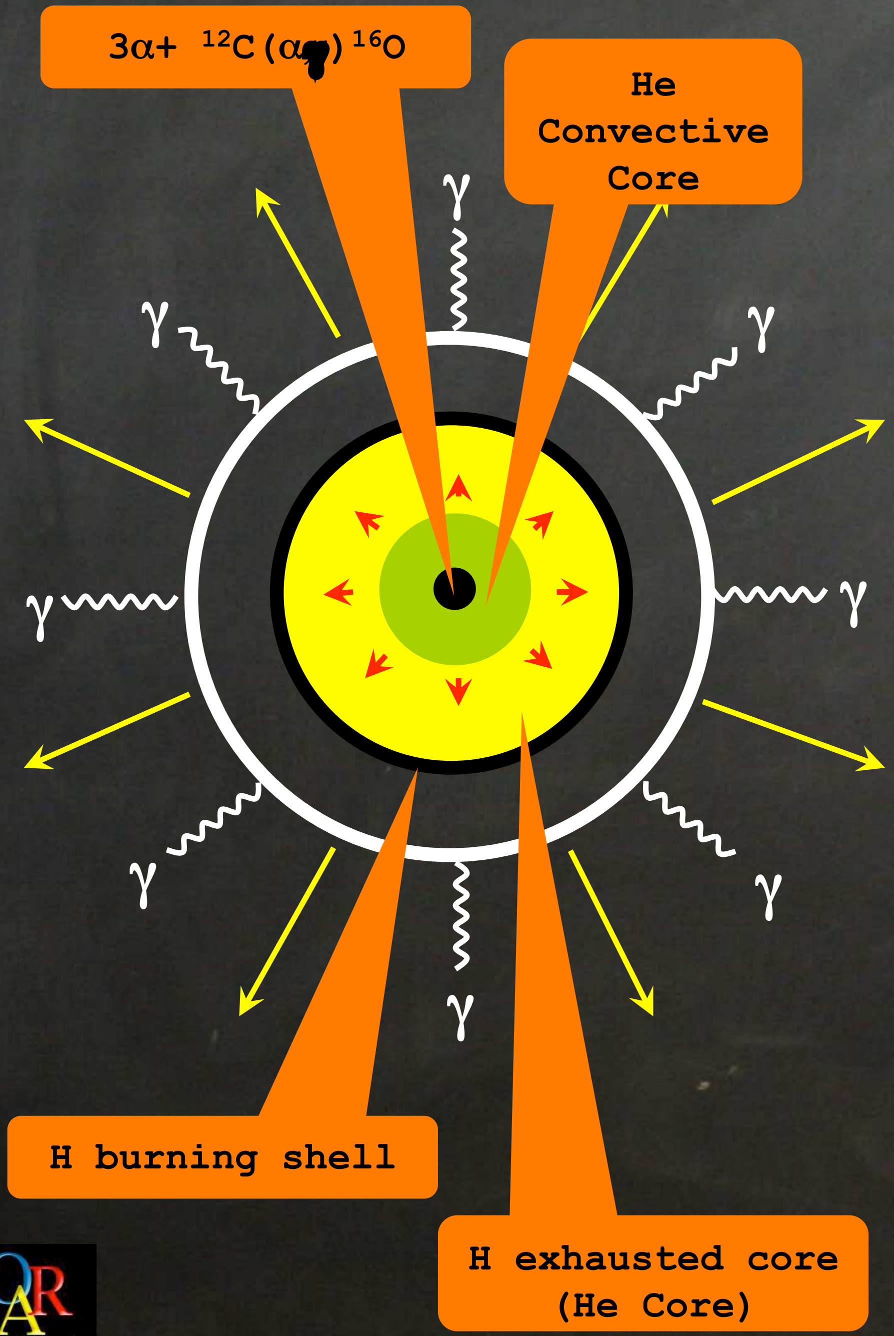


$M_{min}(O) = 14\ M_\odot$

t(O)/t(H burning): 0.15 (14 $M_\odot$) – 0.79 (120 $M_\odot$)

MASS LOSS

CORE HE BURNING

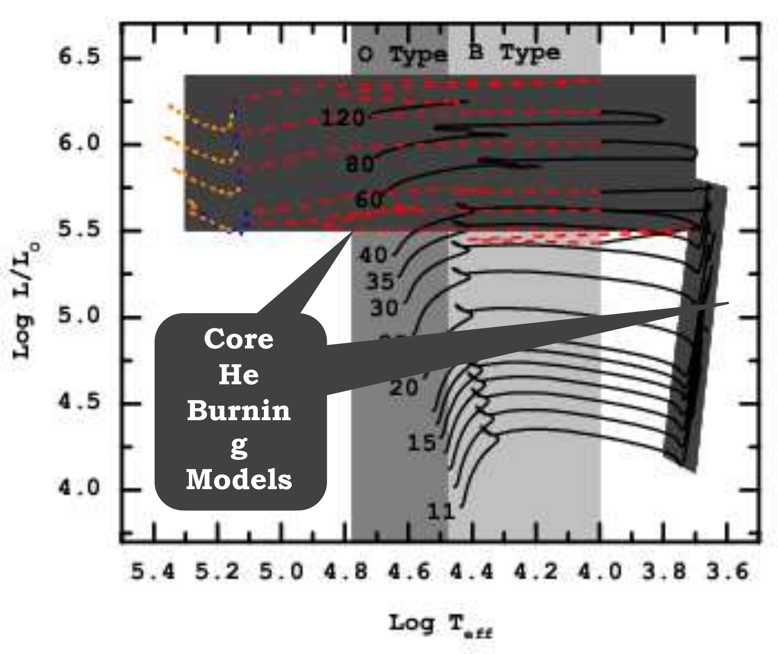


$3\alpha + {}^{12}C(\alpha,\gamma){}^{16}O$

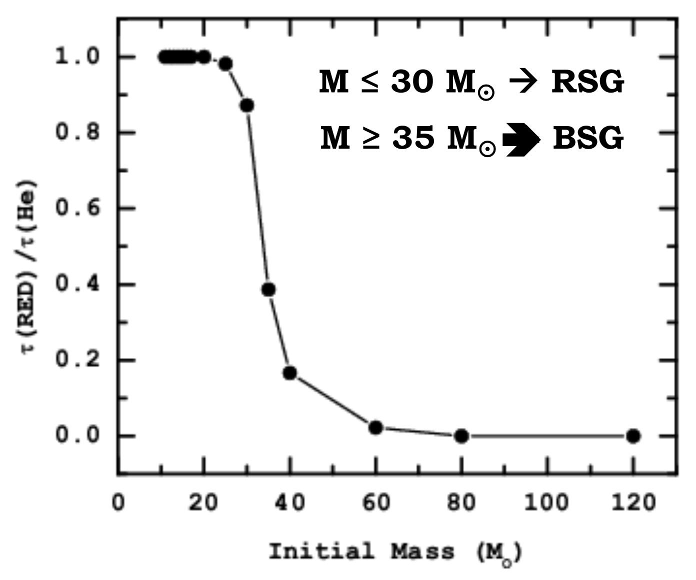
He Convective Core

H burning shell

H exhausted core (He Core)



Core He Burning Models

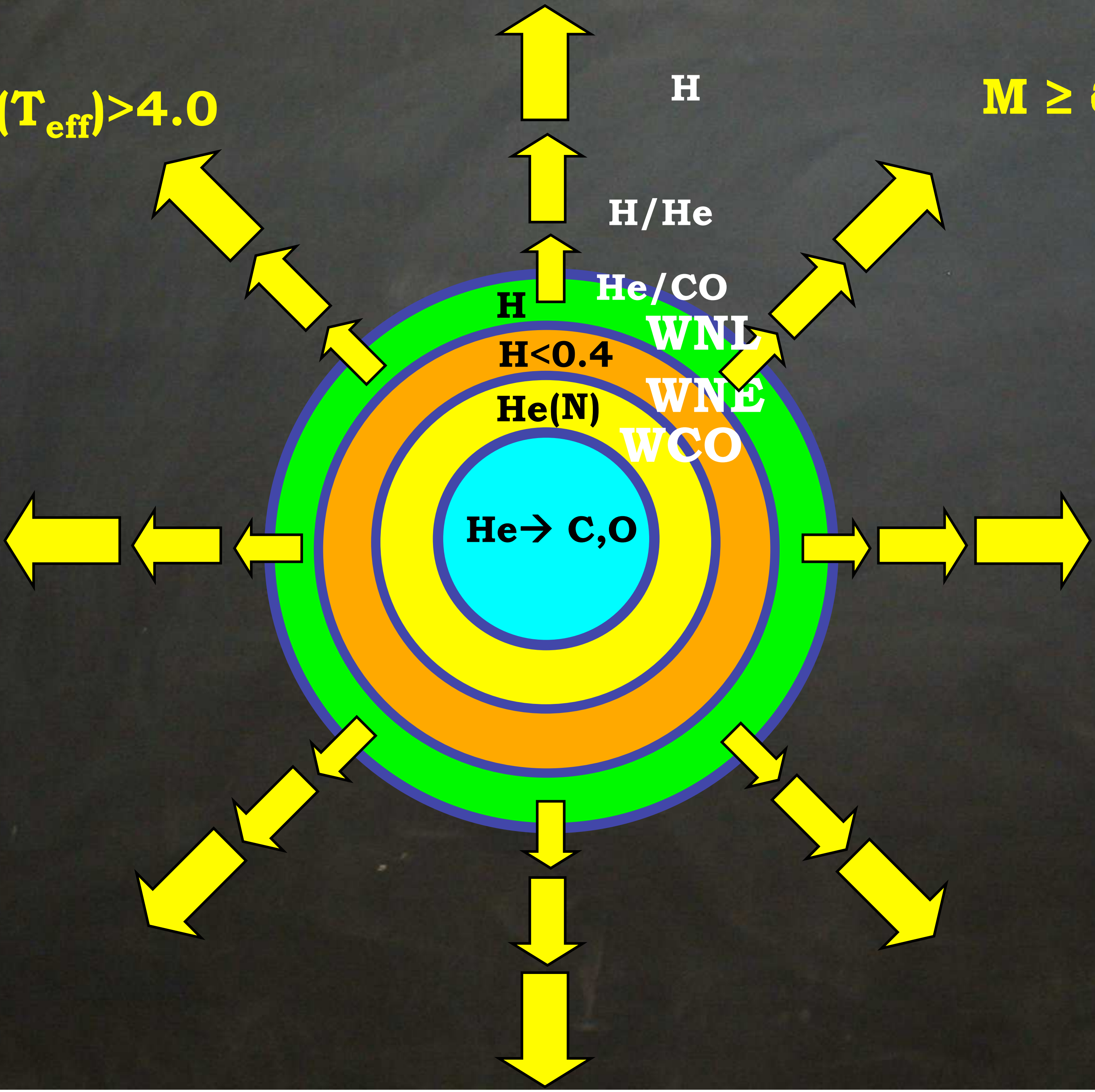


M ≤ 30 $M_\odot$ → RSG

M ≥ 35 $M_\odot$ → BSG

$\log (T_{eff}) > 4.0$

$M \geq 40\ M_\odot$



H

H/He

He/CO

WNL

WNE

WCO

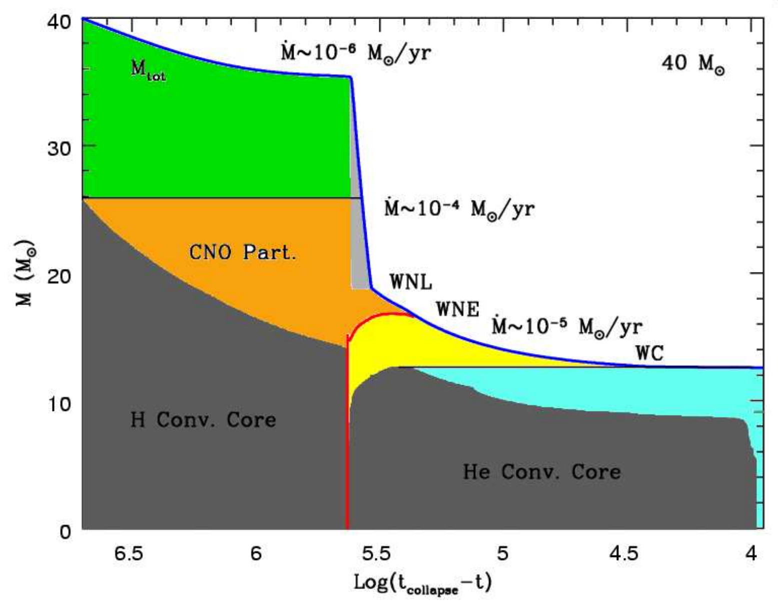
H

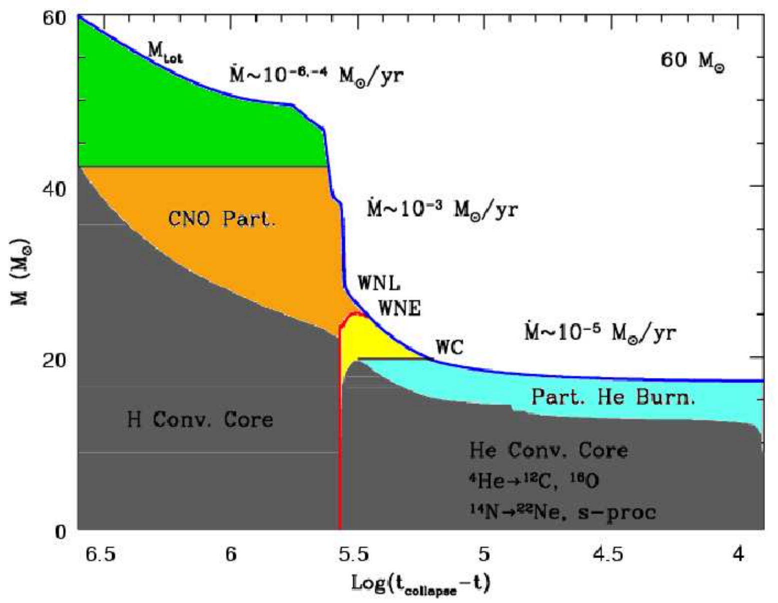
H<0.4

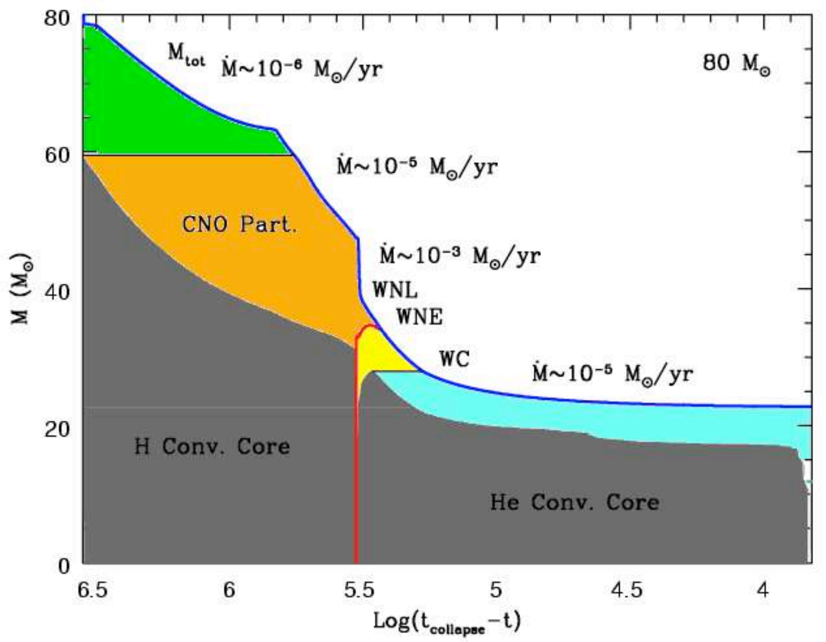
He(N)

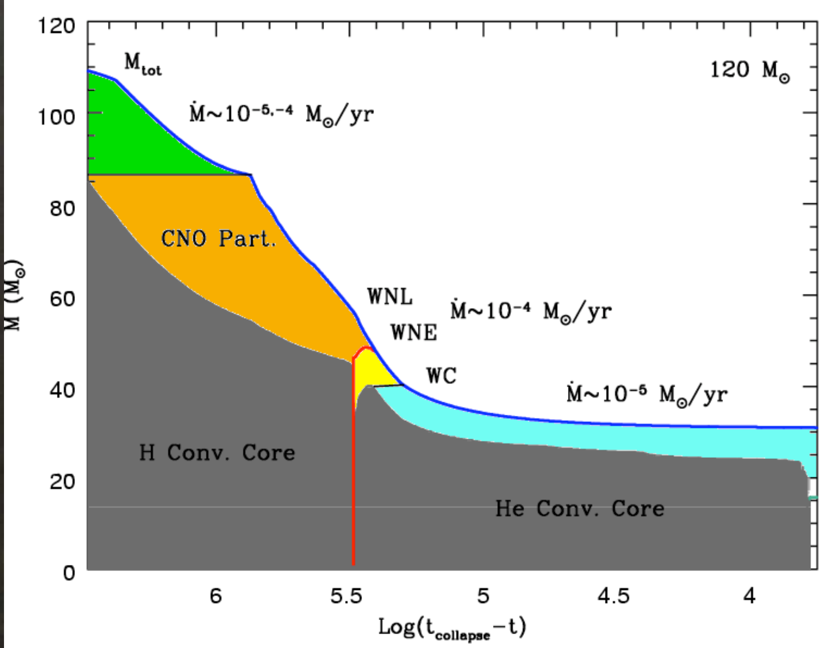
He→ C,O

MASS LOSS HISTORY IN MASSIVE STARS









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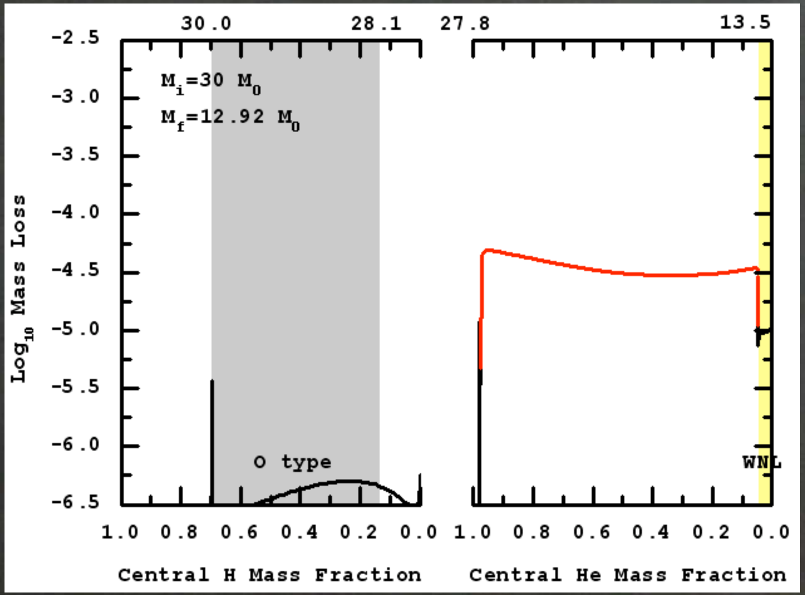
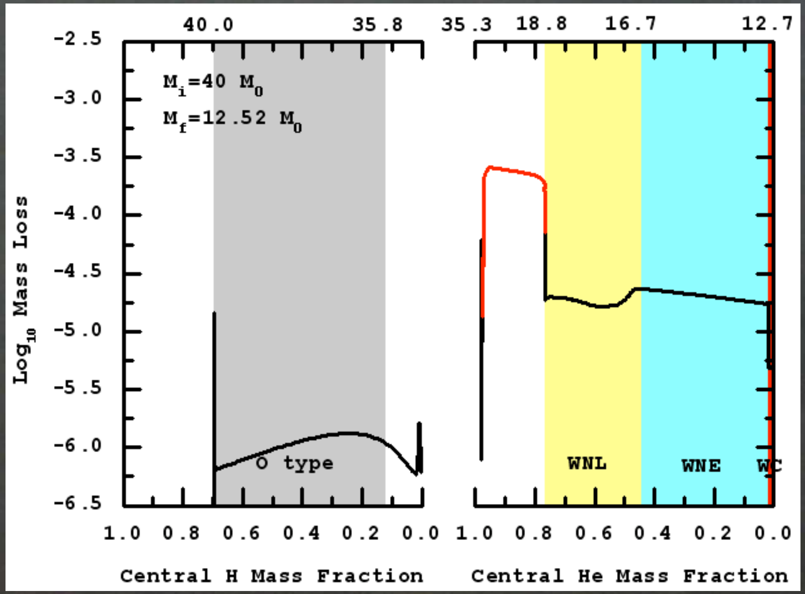
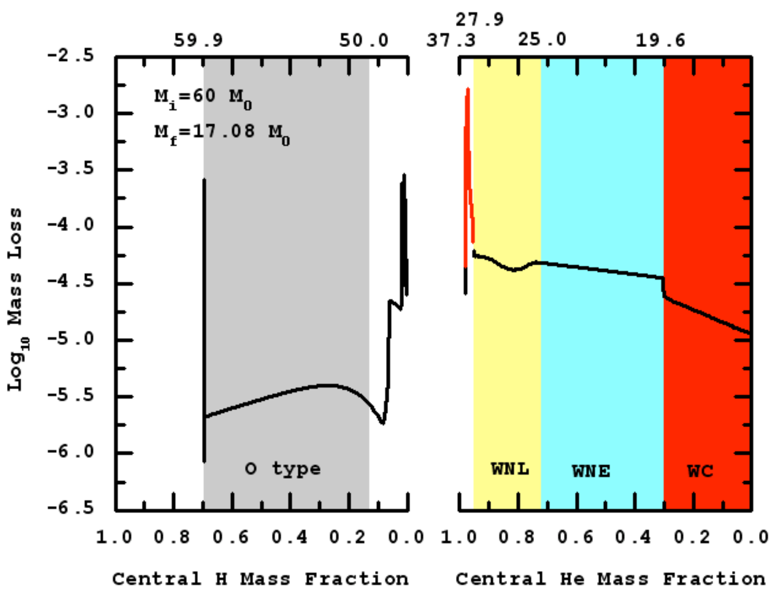
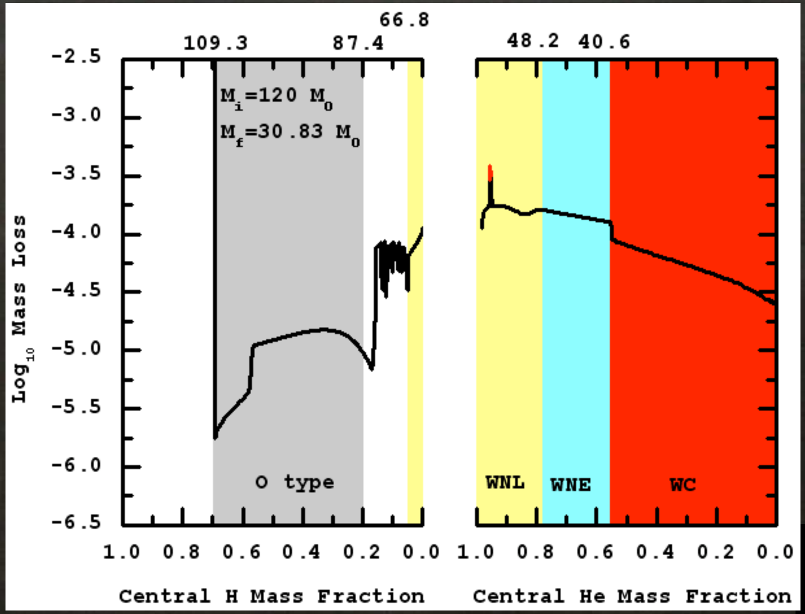
MASS LOSS HISTORY IN MASSIVE STARS

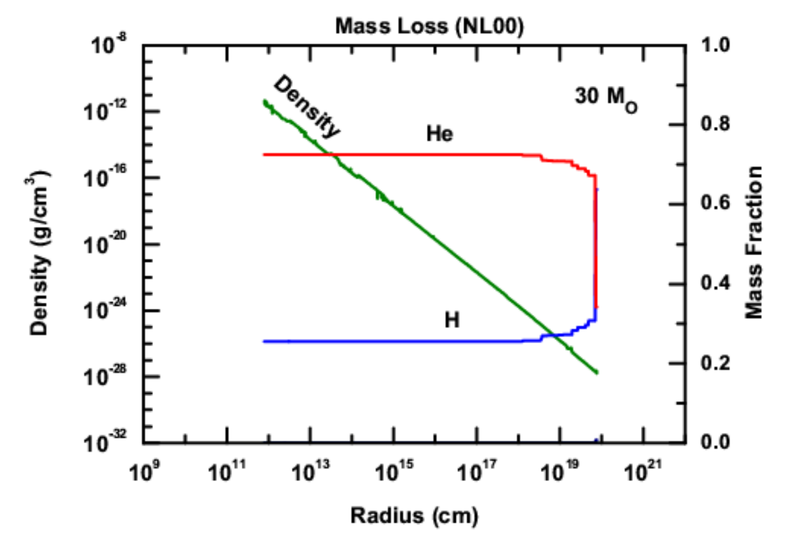


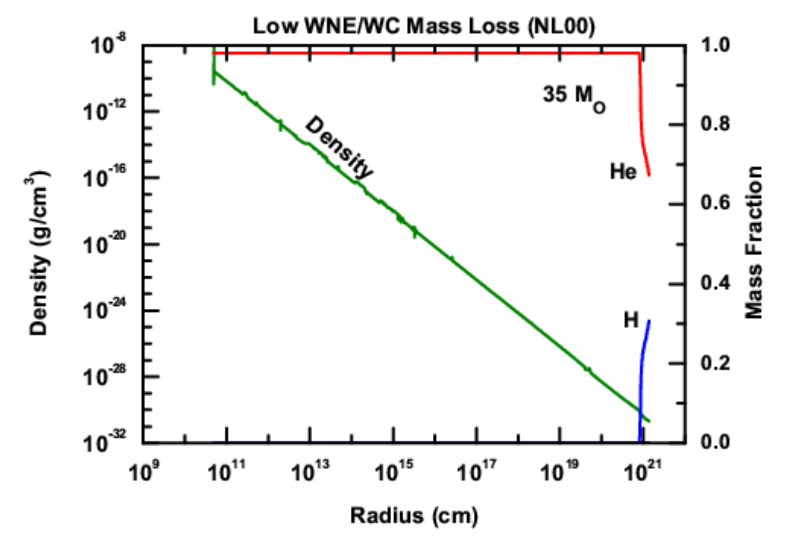


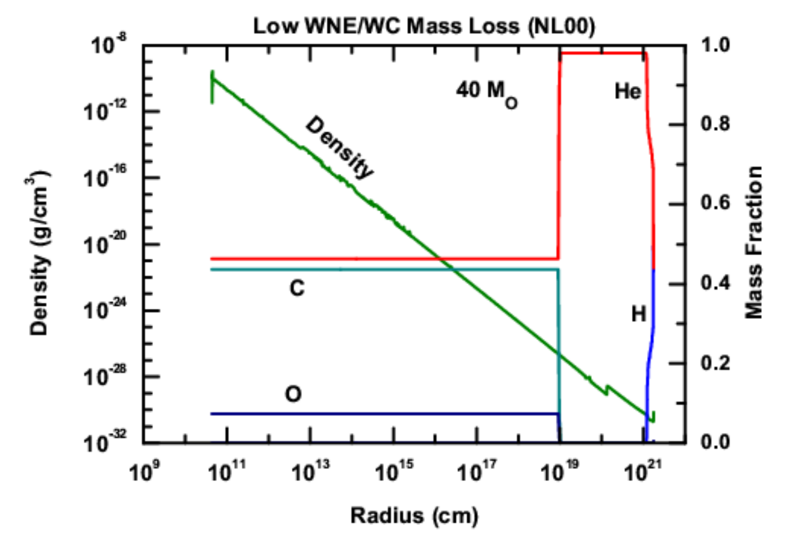


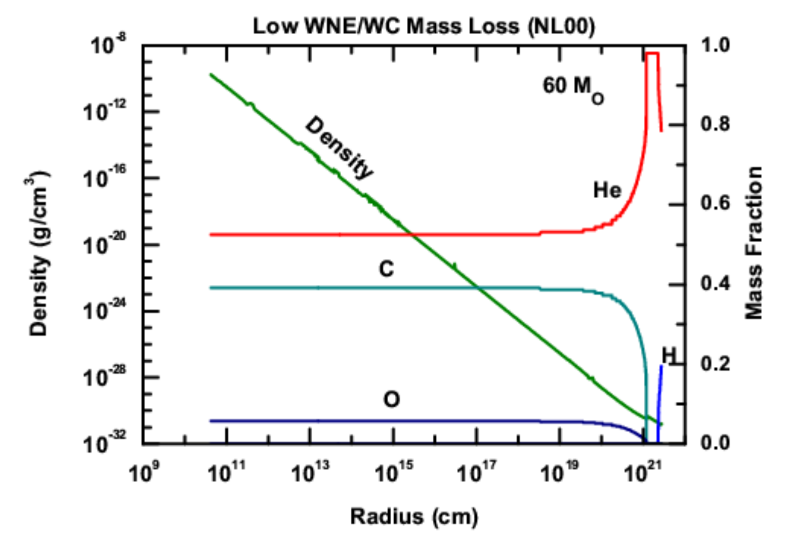


CSM STRUCTURE AND COMPOSITION









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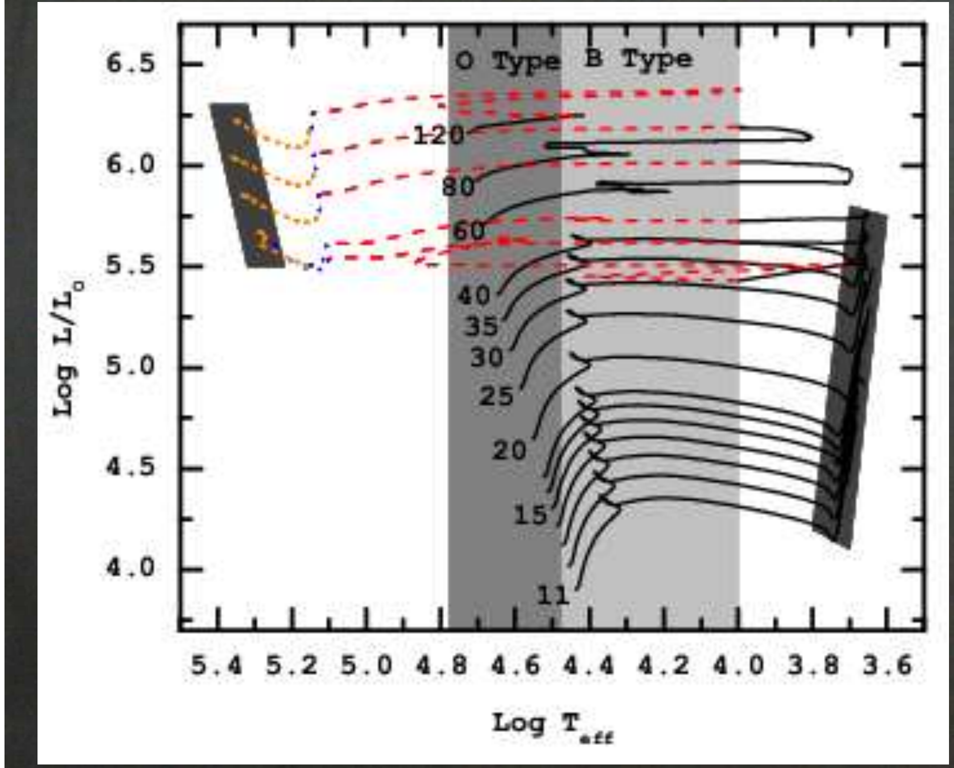
MASSIVE STARS: MASS LOSS DURING H-He BURNING



$30 \leq M/M_o < 35$ RSG → WNL

$35 \leq M/M_o < 40$ RSG → WNL → WNE

$40 \leq M/M_o < 60$ RSG → WNL → WNE → WCO

$60 \leq M/M_o$ WNL → WNE → WCO

O-Type: 60000 > T(K) > 33000

WR : $\mathrm{Log}_{10}(T_{eff}) > 4.0$

- **WNL: $10^{-5} < H_{sup} < 0.4$ (H burning, CNO, products)**
- **WNE: $H_{sup} < 10^{-5}$ (No H)**
- **WN/WC: 0.1 < X(C)/X(N) < 10 (both H and He burning products, N and C)**
- **WC: X(C)/X(N) > 10 (He burning products)**

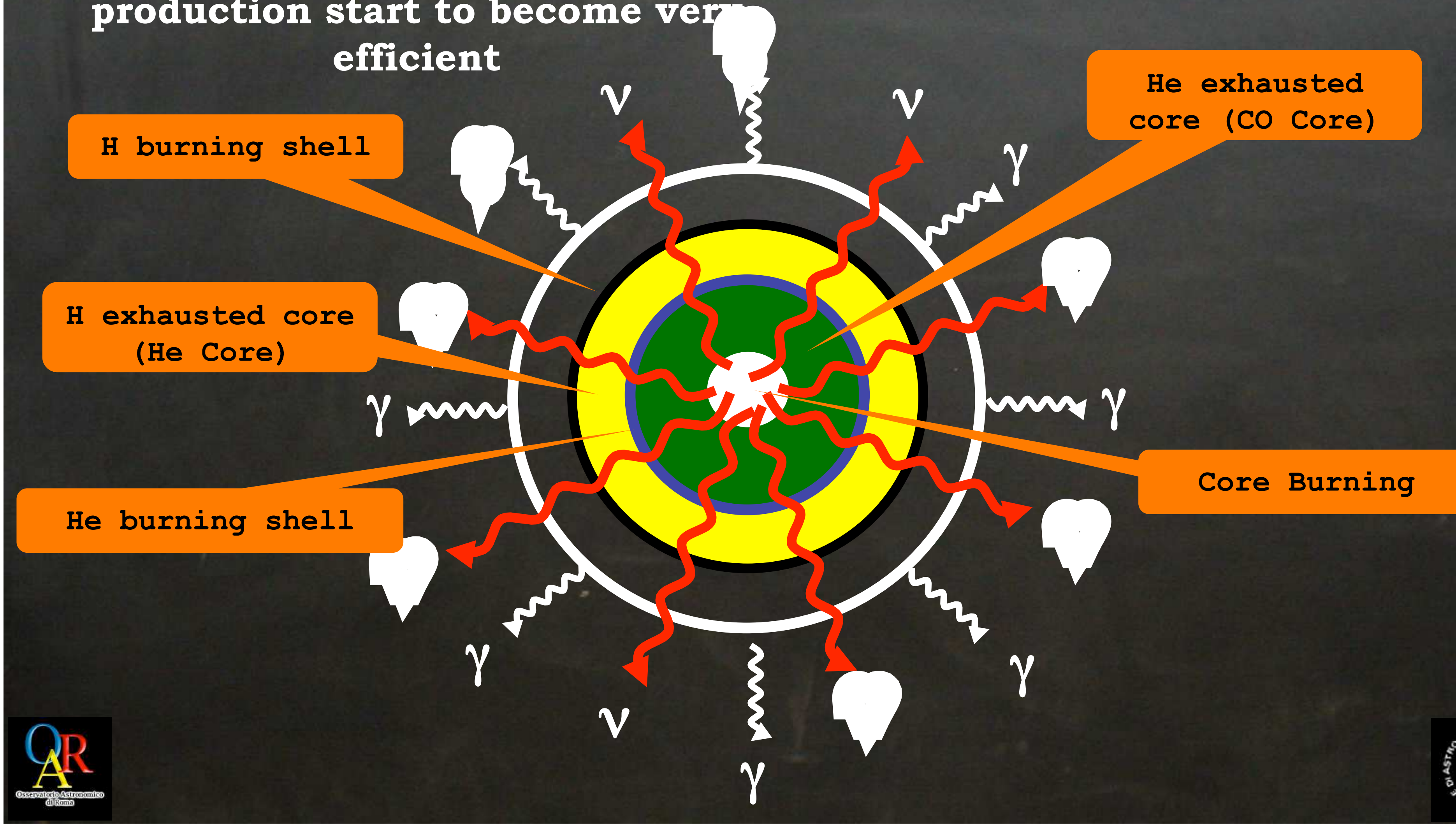
- **M < 30 M_o explode as Red SuperGiant (RSG)**
- **M ≥ 30 M_o explode as Blue SuperGiant (BSG)**

ADVANCED BURNING STAGES

Neutrino losses play a dominant role in the evolution of a massive star beyond core He burning

At high temperature (T>10^9 K ~0.08 MeV) neutrino emission from pair production start to become very efficient

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



H burning shell

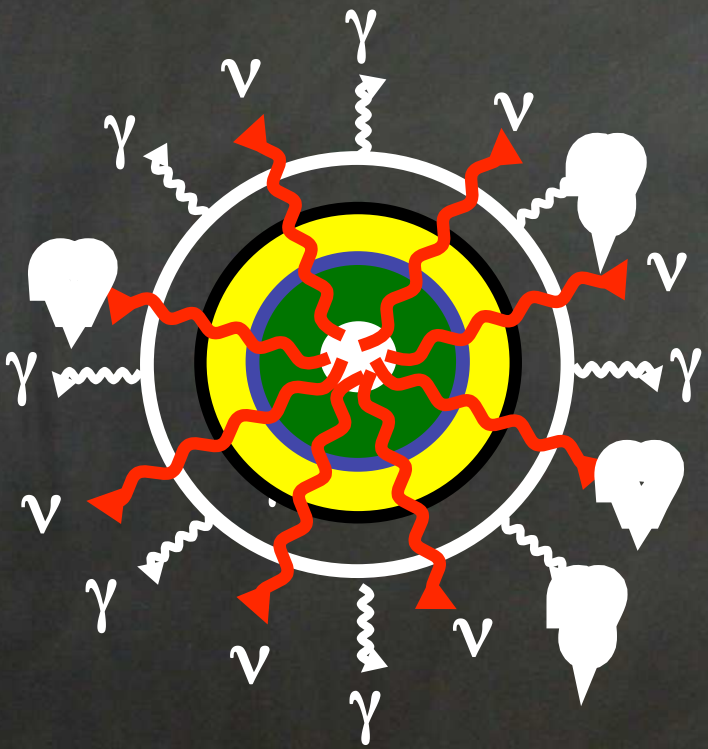
H exhausted core (He Core)

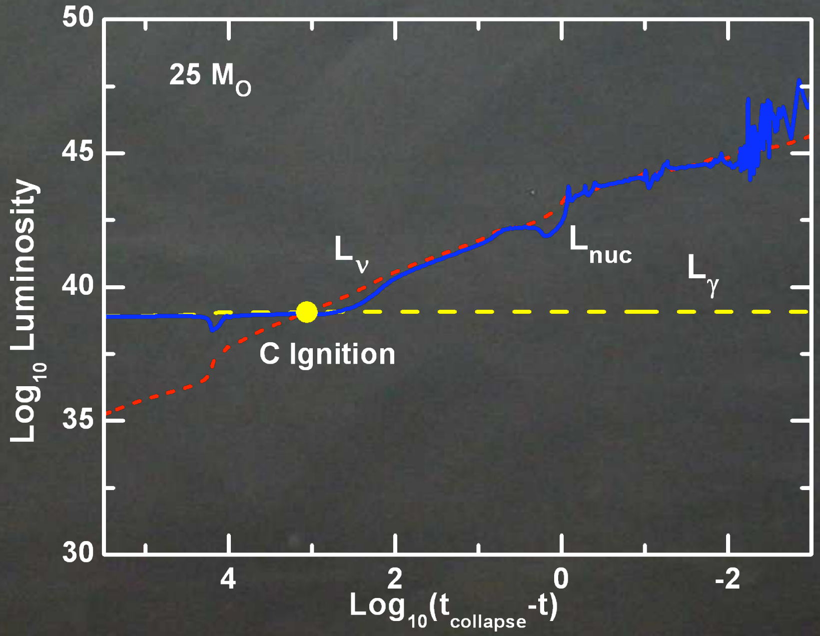
He burning shell

He exhausted core (CO Core)

Core Burning

MASSIVE STARS: NEUTRINO LOSSES





The Nuclear Luminosity (L_{nuc}) closely follows the energy losses

Each burning stage gives about the same E_{nuc}

$$L \cong \frac{E_{nuc}}{t_{nuc}} \cdot M \quad \Rightarrow \quad t_{nuc} \cong E_{nuc} \frac{M}{L}$$

Evolutionary times of the advanced burning stages reduce dramatically

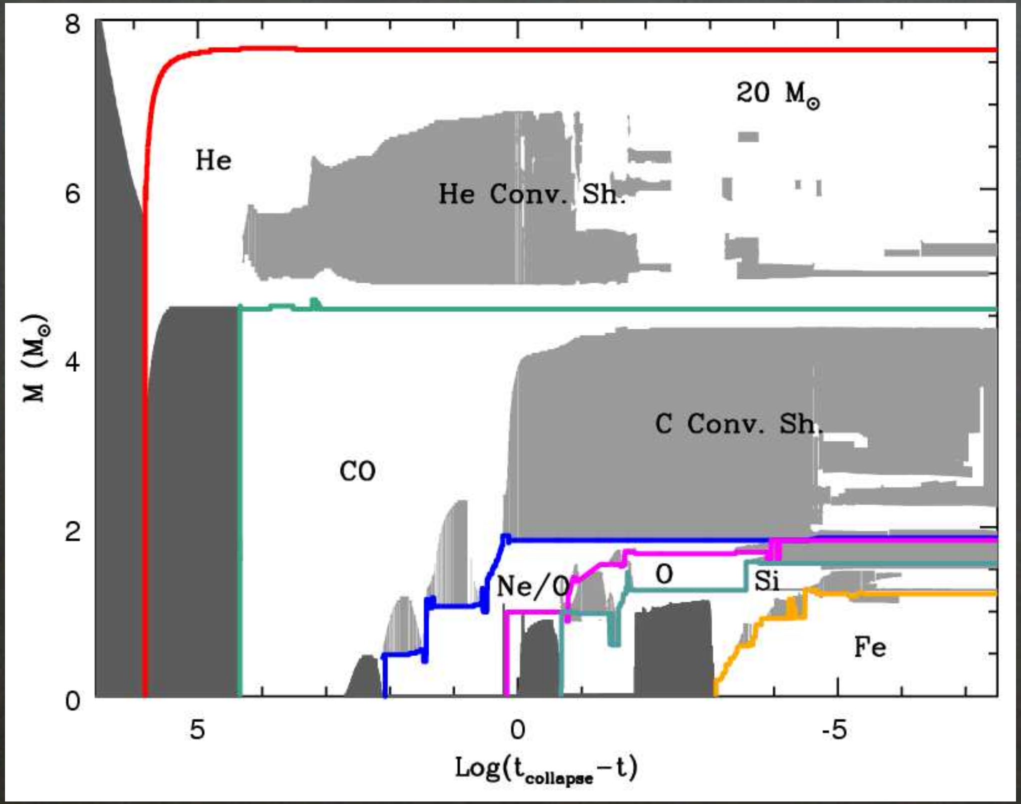
MASSIVE STARS: LIFETIMES

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

Fuel	T_c (K)	ρ_c (g/cm^3)	E_{nuc} (erg/g)	Estimated Lifetime (no ν)	Real Lifetime
H	4.1(7)	4.7	6.44(18)	2.2(7) yr ($L_{\gamma}=5\cdot10^{38}$)	6.87(6) yr ($L_{tot}=5\cdot10^{38}$)
He	2.1 (8)	7.2(2)	8.70(17)	1.6(6) yr ($L_{\gamma}=9\cdot10^{38}$)	5.27(5) yr ($L_{tot}=9\cdot10^{38}$)
C	8.3(8)	1.7(5)	4.00(17)	6.3(5) yr ($L_{\gamma}=1\cdot10^{39}$)	6.27(3) yr ($L_{tot}=8\cdot10^{40}$)
Ne	1.6(9)	2.5(6)	1.10(17)	1.7(5) yr ($L_{\gamma}=1\cdot10^{39}$)	190 days ($L_{tot}=2\cdot10^{43}$)
O	2.1(9)	5.8(6)	4.98(17)	7.9(5) yr ($L_{\gamma}=1\cdot10^{39}$)	243 days ($L_{tot}=9\cdot10^{43}$)
Si	3.5(9)	3.7(7)	1.90(17)	3.0(5) yr ($L_{\gamma}=1\cdot10^{39}$)	19 days ($L_{tot}=2\cdot10^{45}$)

ADVANCED BURNING STAGES: ANATOMY OF A MASSIVE STAR

Four major burnings, i.e., carbon, neon, oxygen and silicon.



Central burning → formation of a convective core

Central exhaustion → shell burning → convective shell

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

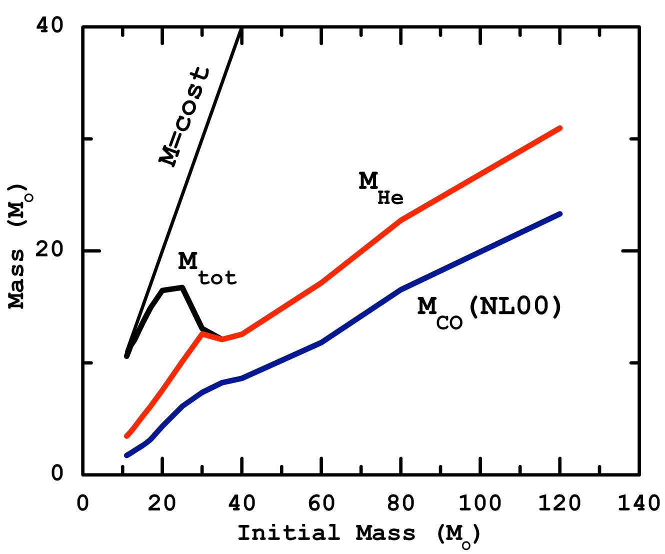
ADVANCED BURNING STAGES

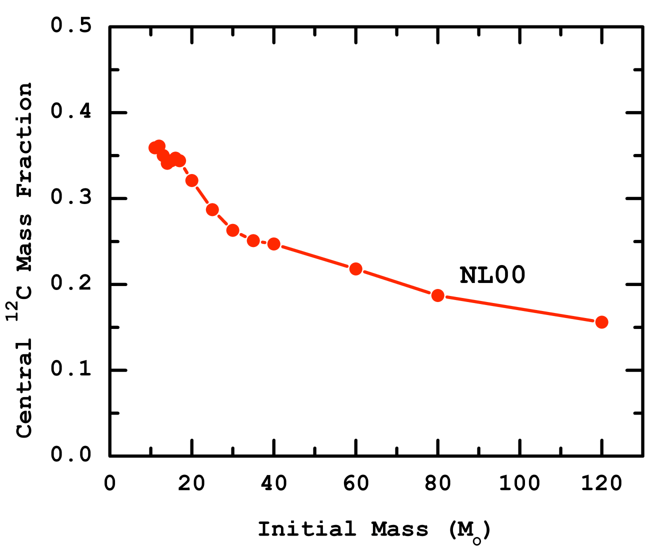
The details of this behavior (number, timing, overlap of convective shells) is mainly driven by the CO core mass and by its chemical composition (^{12}C, ^{16}O)

CO core mass → **Thermodynamic history**

^{12}C, ^{16}O → **Basic fuel for all the nuclear burning stages after core He burning**

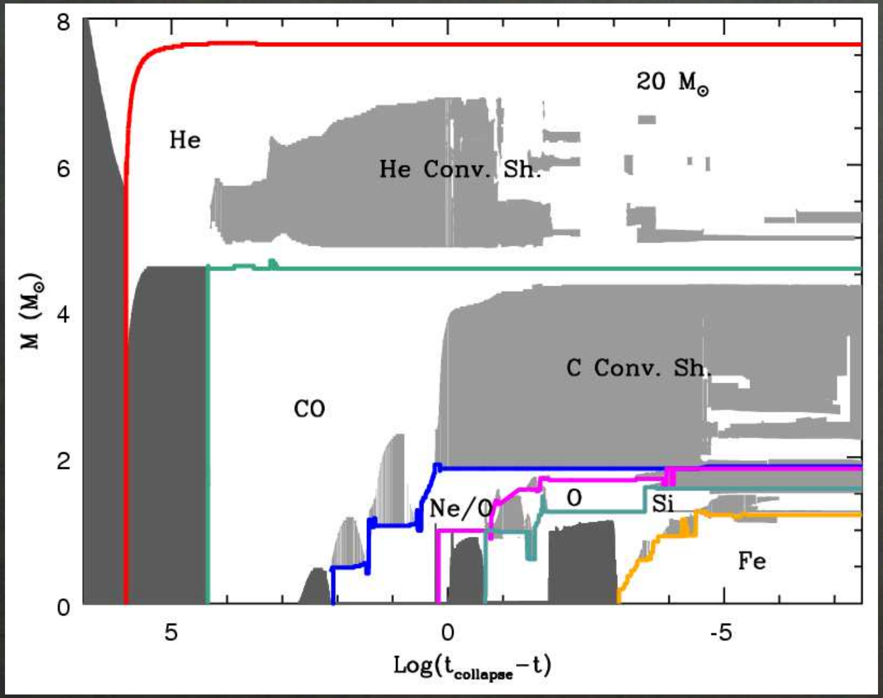
At core He exhaustion both the mass and the composition of the CO core scale with the initial mass

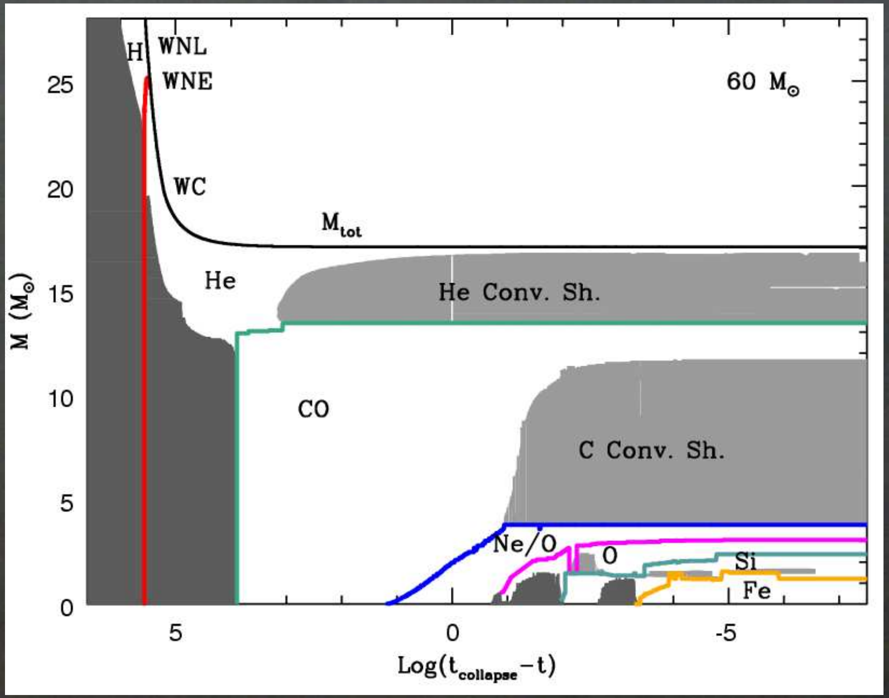




ADVANCED BURNING STAGES

...hence, the evolutionary behavior scales as well



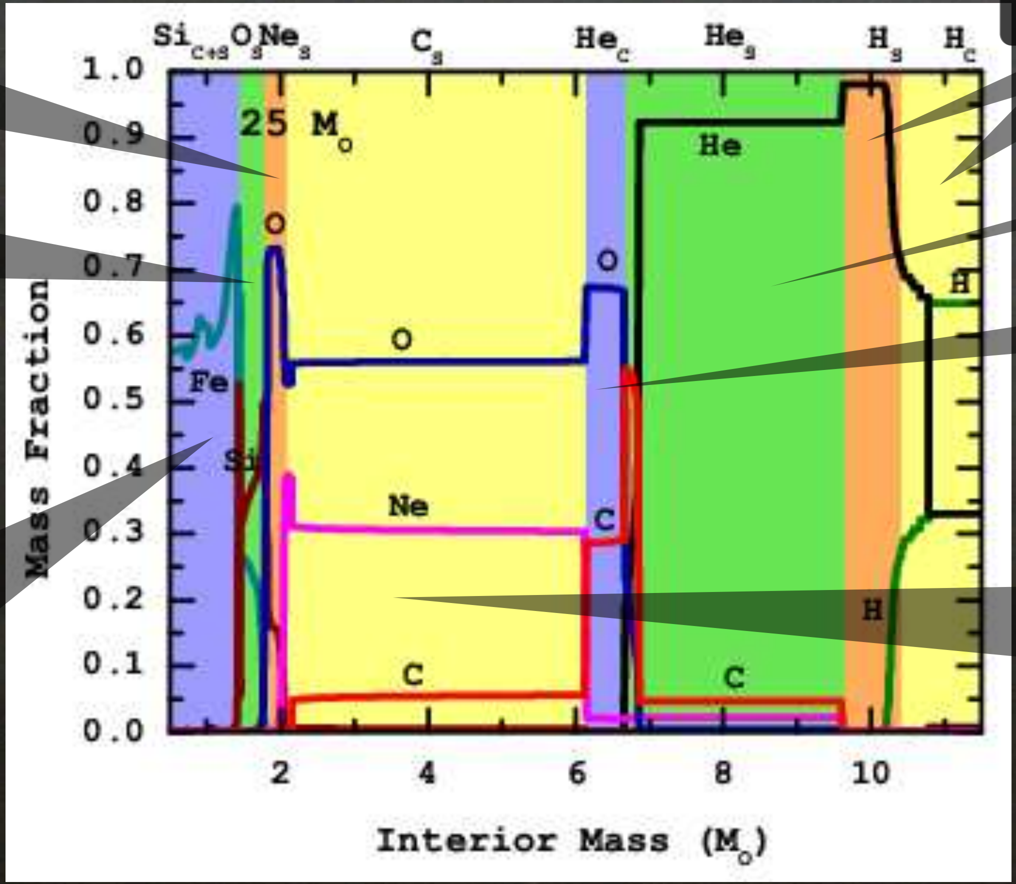


In general, one to four carbon convective shells and one to three convective shell episodes for each of the neon, oxygen and silicon burnings occur.

The number of C convective shells decreases as the mass of the CO core increases (not the total mass!).

PRESUPERNOVA STAR

The complex interplay among the shell nuclear burnings and the timing of the convective zones determines in a direct way the final distribution of the chemical composition…



^{16}O, ^{24}Mg, ^{28}Si, ^{29}S, ^{30}Si

^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca, ^{34}S, ^{38}Ar

^{56,57,58}Fe, ^{52,53,54}Cr, ^{55}Mn, ^{59}Co, ^{62}Ni

NSE

^{14}N, ^{13}C, ^{17}O

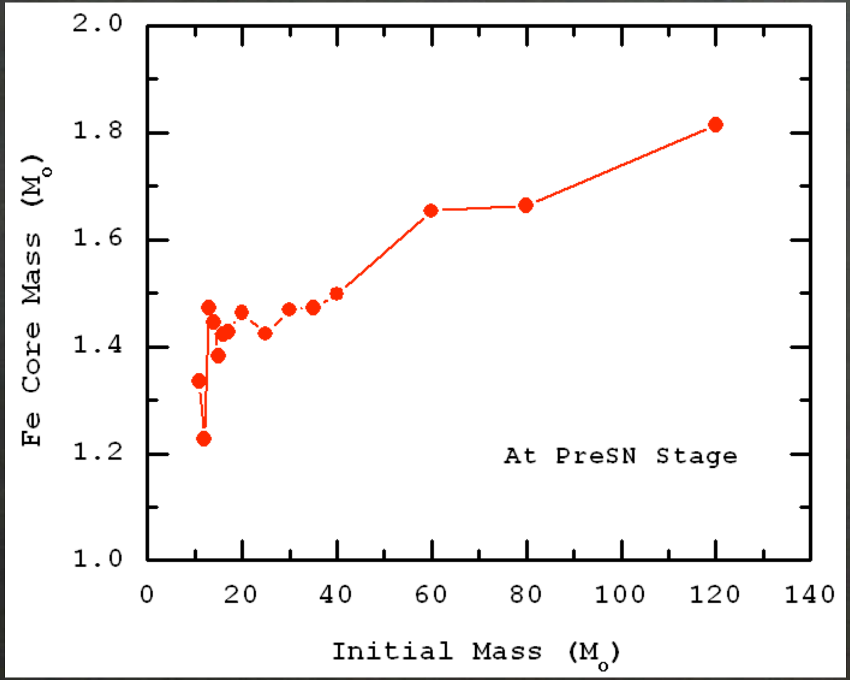
^{12}C, ^{16}O

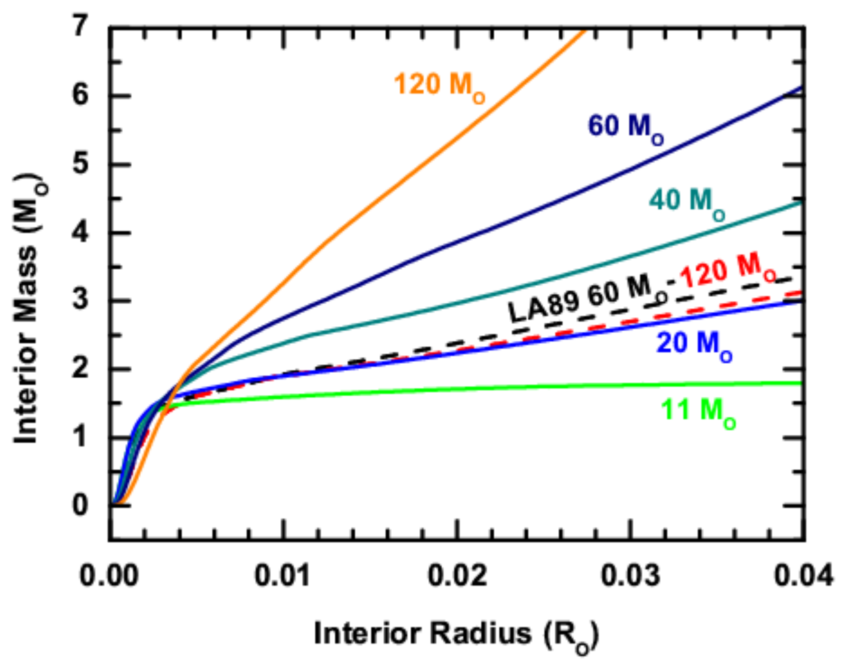
^{12}C, ^{16}O s-proc

^{20}Ne, ^{23}Na, ^{24}Mg, ^{25}Mg, ^{27}Al, s-proc

PRESUPERNOVA STAR

…and the density structure of the star at the presupernova stage





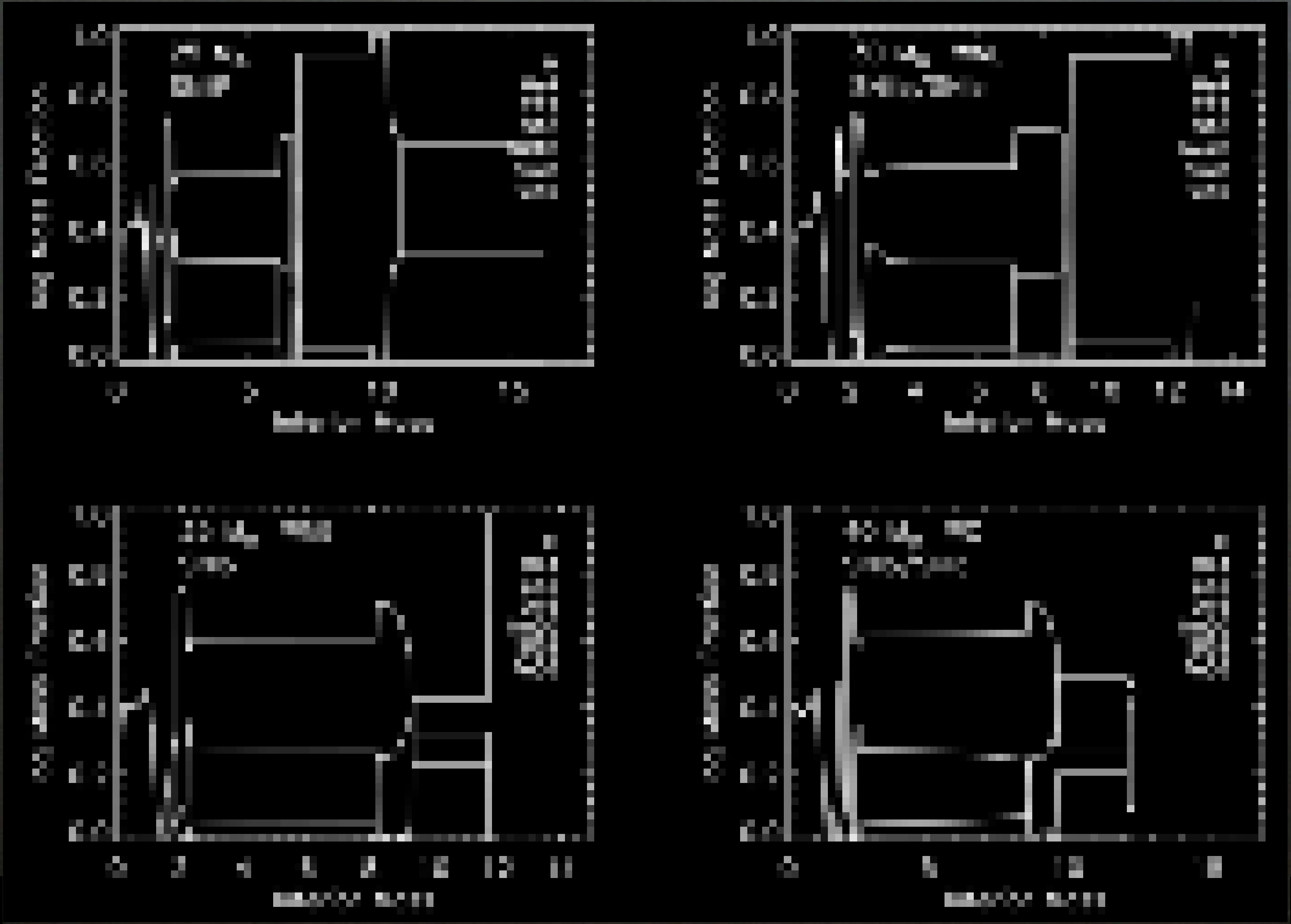
The final Fe core Masses range between:

M_{Fe}=1.20-1.45 $M_\odot$ for $M \leq 40\ M_\odot$
M_{Fe}=1.45-1.80 $M_\odot$ for $M > 40\ M_\odot$

In general the higher is the mass of the CO core, the more compact is the structure at the presupernova stage

PRESUPERNOVA STAR

....also the mass loss history plays a crucial role



INDUCED EXPLOSION

The simulation of the explosion of the envelope is needed to have information on:

- the chemical yields (propagation of the shock wave → compression and heating→ explosive nucleosynthesis)
- the initial mass-remnant mass relation

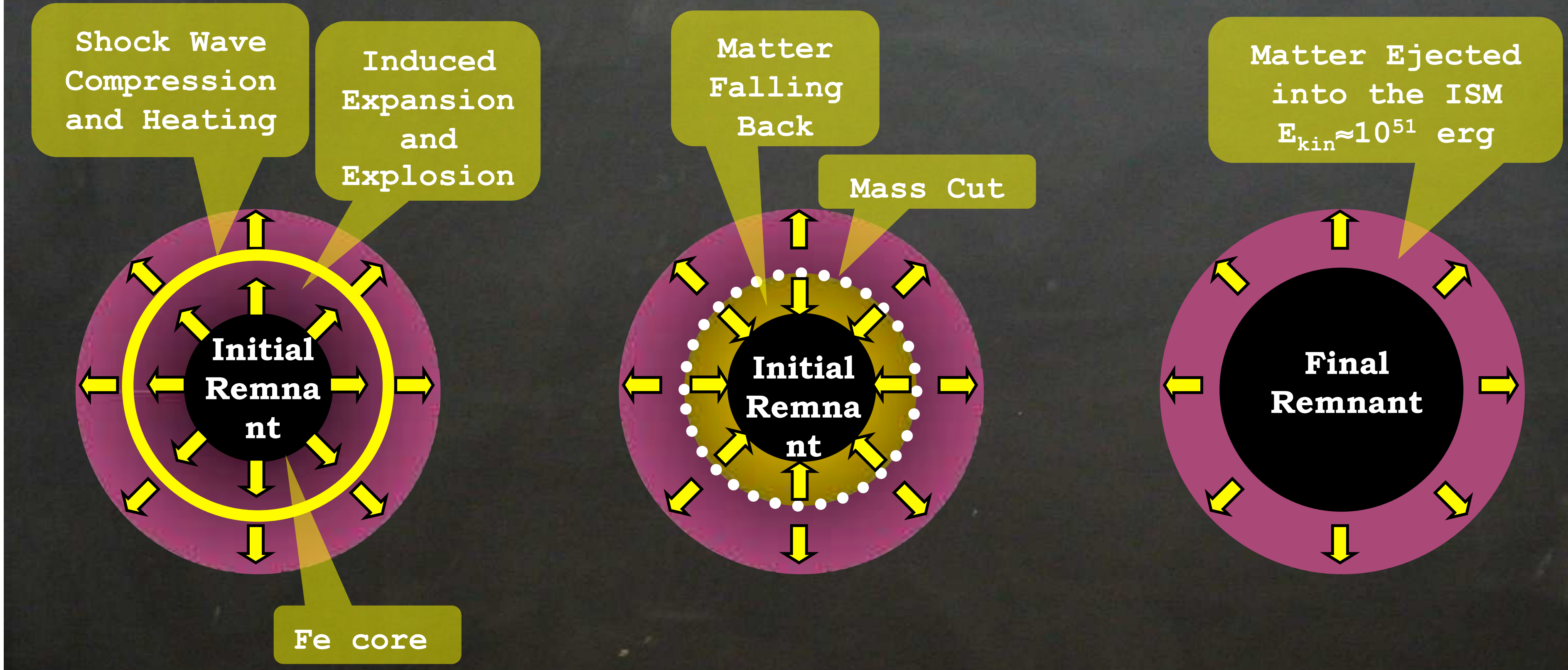
In spite of the big progresses in the simulation of the core collapse explosion (see Bruenn's talk) at the moment the multi-D calculations cannot provide these information yet

At present explosive nuclosynthesis calculations for core collapse supernovae are based on artificially induced explosions

EXPLOSION AND FALLBACK

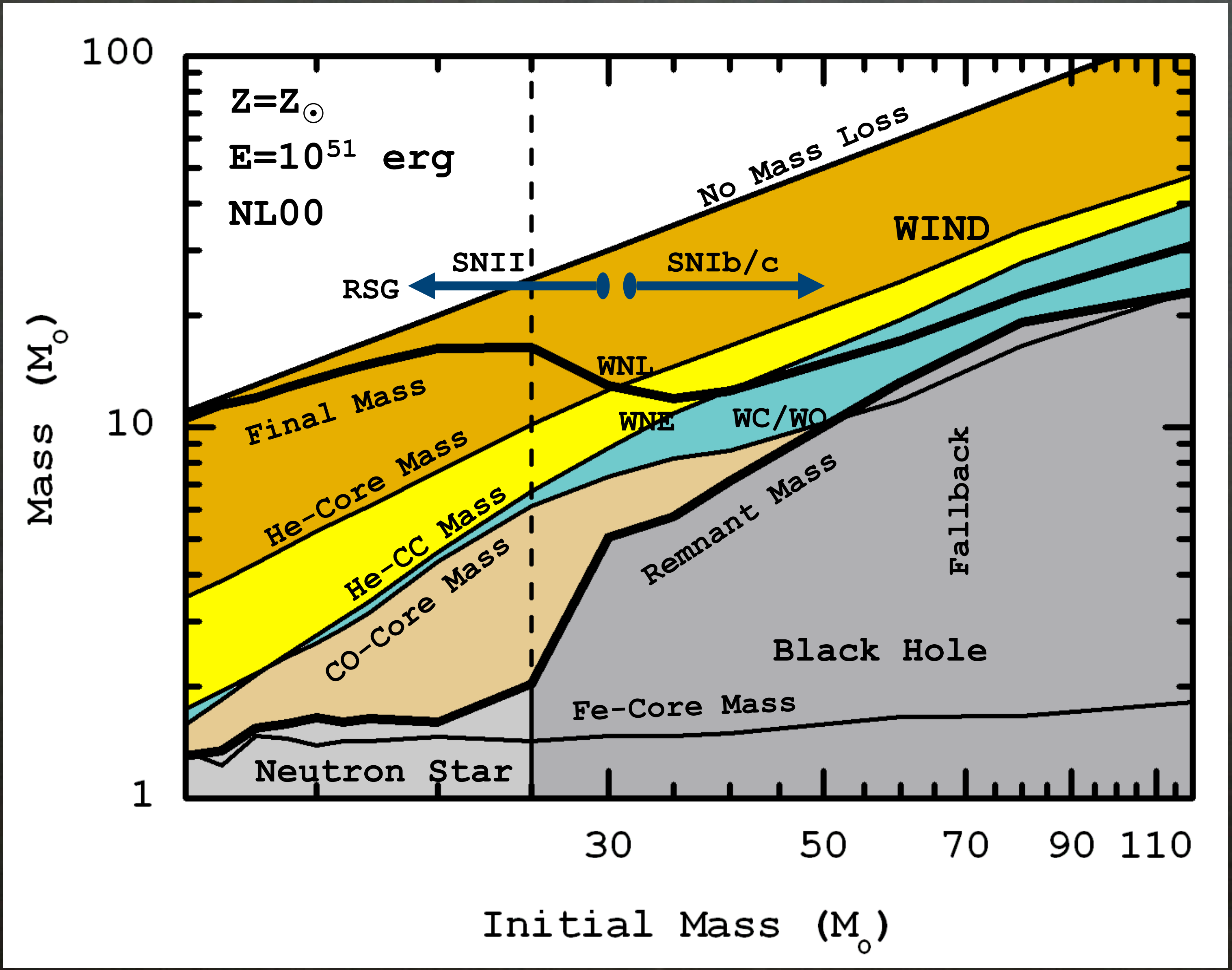
Different ways of inducing the explosion →

- Piston (Woosley & Weaver)
- Thermal Bomb (Nomoto & Umeda)
- Kinetic Bomb (Chieffi & Limongi)

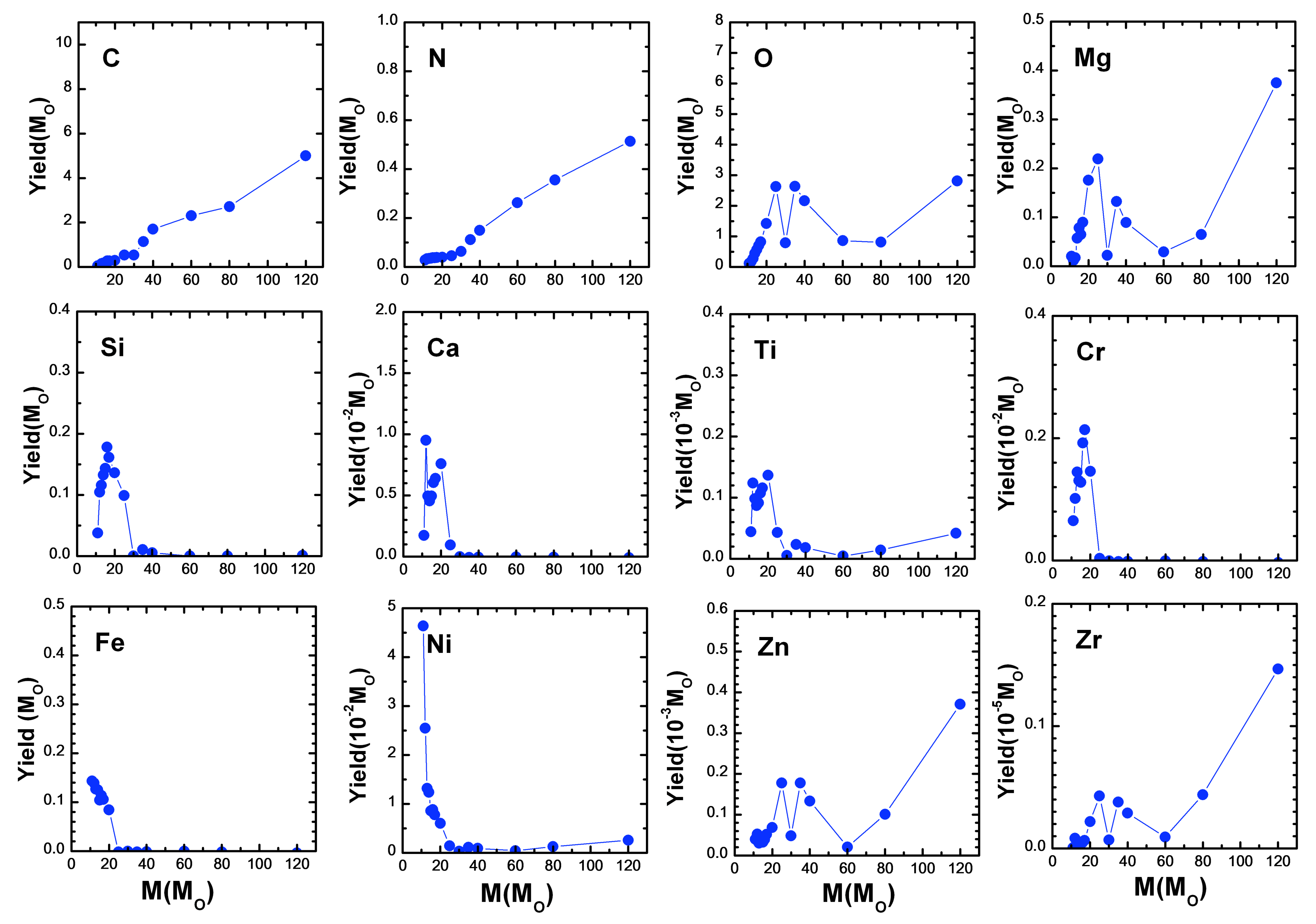


FB depends on the binding energy: the higher is the initial mass the higher is the binding energy

THE FINAL FATE OF A MASSIVE STAR



THE YIELDS OF MASSIVE STARS



CONCLUSIONS. I

- **Stars with $M<30\ M_\odot$ explode as RSG**
  Stars with $M\geq30\ M_\odot$ explode as BSG
- **The minimum masses for the formation of the various kind of Wolf-Rayet stars are:**
  WNL: $25\text{-}30\ M_\odot$
  WNE: $30\text{-}35\ M_\odot$
  WNC: $35\text{-}40\ M_\odot$
- **The final Fe core Masses range between:**
  $M_{Fe}=1.20\text{-}1.45\ M_\odot$ for $M \leq 40\ M_\odot$
  $M_{Fe}=1.45\text{-}1.80\ M_\odot$ for $M > 40\ M_\odot$
- **The limiting mass between SNII and SNIb/c is:**
  $30\text{-}35\ M_\odot$
  SNII | | SNIb/c

  Salpeter IMF → $\frac{SNIb/c}{SNII} \cong 0.22$
- **The limiting mass between NS and BH formation is:**
  $25\text{-}30\ M_\odot$
  NS | | BH
- **$M>35\ M_\odot$ (SNIb/c) do not contribute to the intermediate and heavy elements (large fallback)**

**Models available @ web sites: http://orfeo.iasf-roma.inaf.it,
http://www.mporzio.astro.it/~limongi/data.html**

MAIN UNCERTAINTIES

PRESUPERNOVA EVOLUTION:

- **Mass Loss during Blue and Red supergiant phases, and Wolf-Rayet stages**
- **Treatment of Convection: extension of the convective zones (overshooting, semiconvection), interaction mixing-nuclear burning**
- **$^{12}C(\alpha,\gamma)^{16}O$ cross section**
- **Rotation**

EXPLOSION:

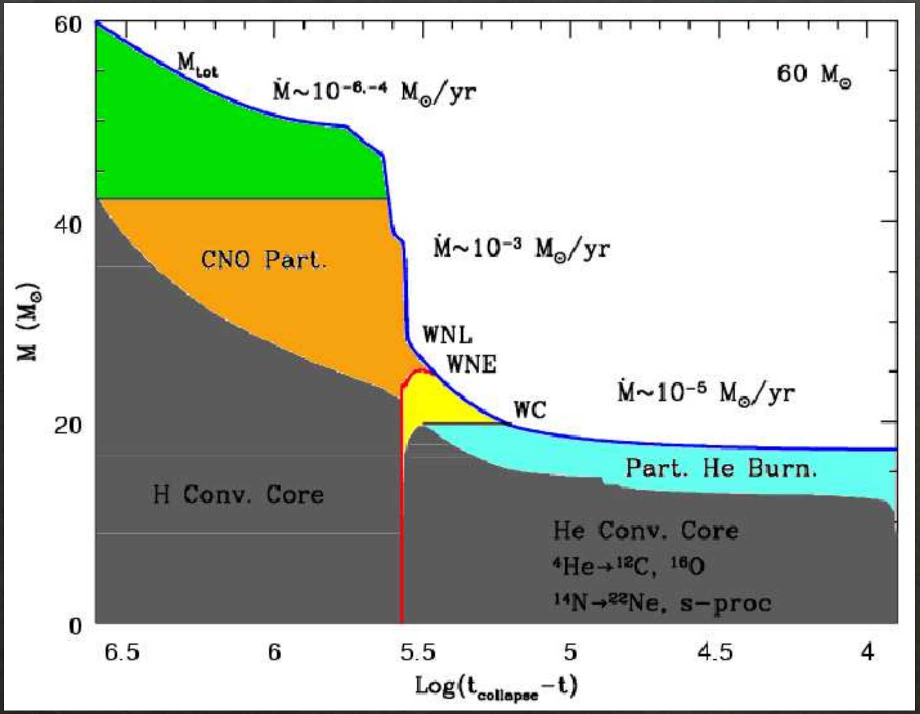
- **Induced explosion [Explosion energy (where and how), time delay, fallback and mass cut (boundary conditions), mixing (inner and outer borders), extra-fallback, Y_e variation, aspherical explosions]**

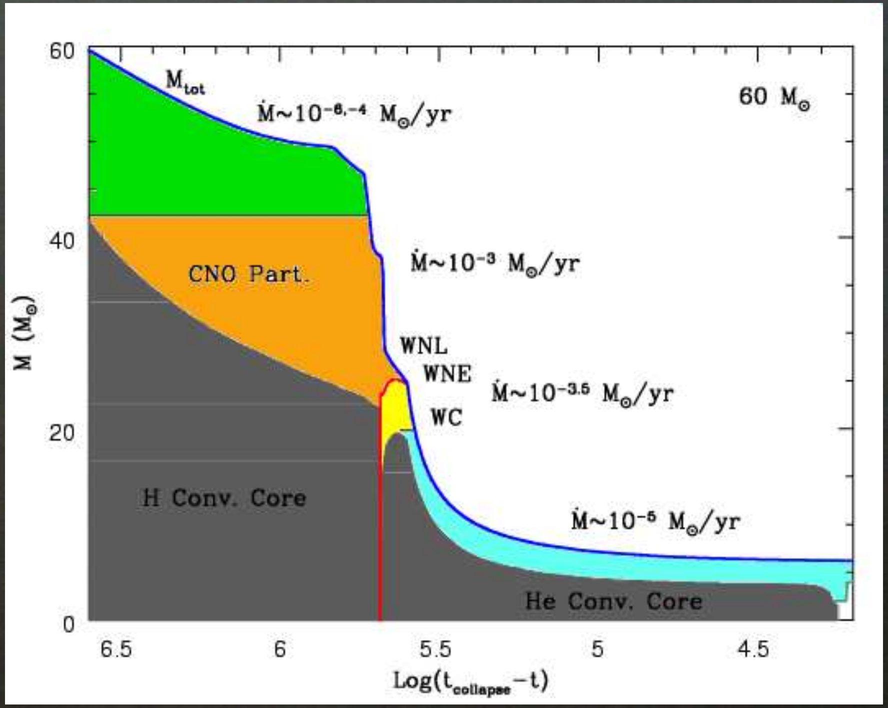
THE ROLE OF THE MASS LOSS FOR WNE/WCO IN THE ADVANCED BURNING PHASES

Nugis & Lamers (2000) (NL00)

Langer (1989) (LA89)

$$M_{dot} = 10^{-11}(L/L_\odot)^{1.29} Y^{1.7} Z^{0.5} \ M_\odot/\mathrm{yr} \quad < \quad M_{dot} = 10^{-7}(M/M_\odot)^{2.5} \ M_\odot/\mathrm{yr}$$





Strong reduction of the He core during early core He burning

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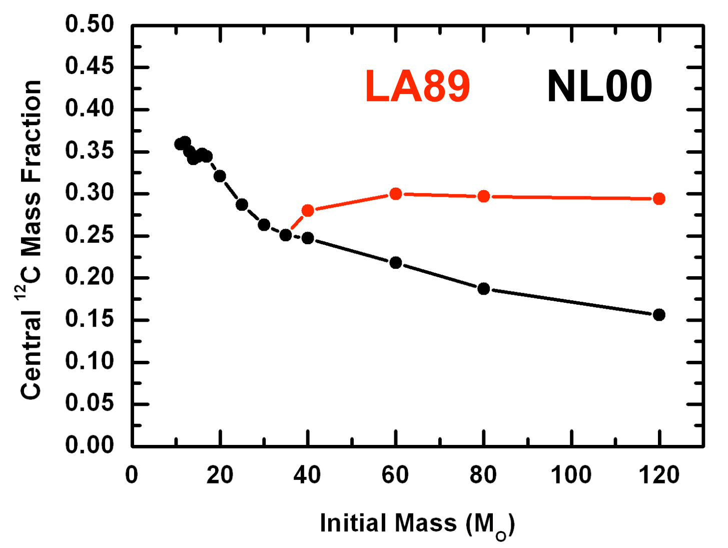
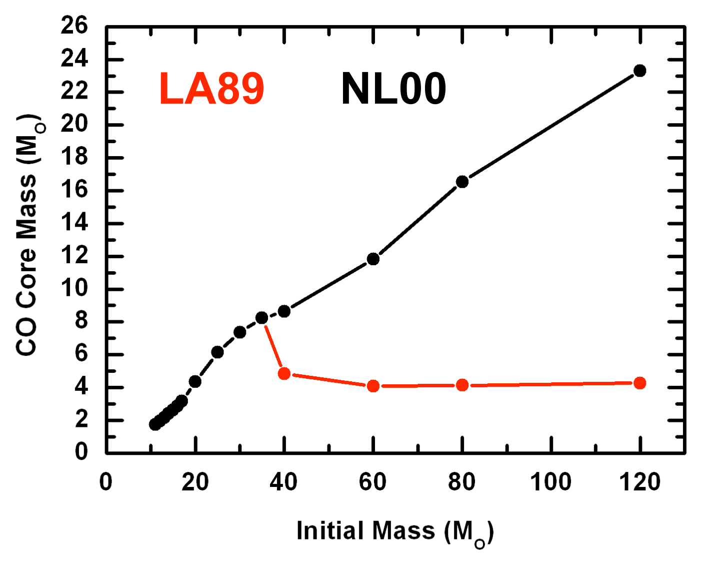
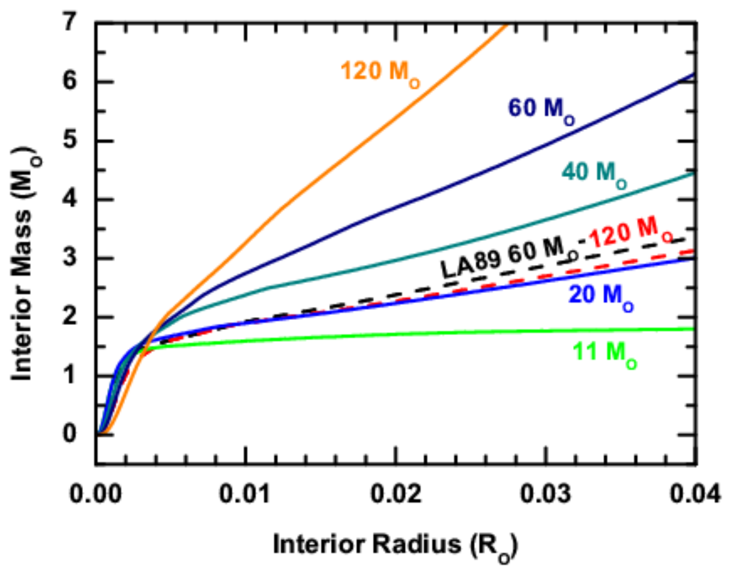
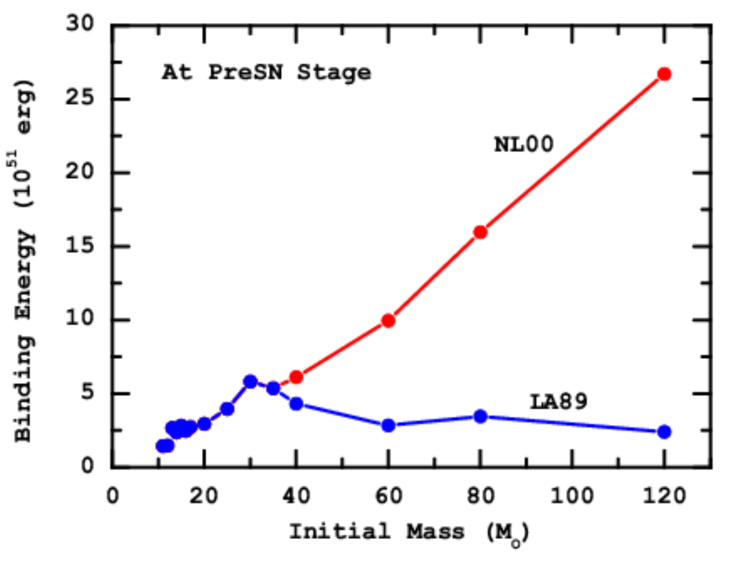
THE ROLE OF THE MASS LOSS FOR WNE/WCO IN THE ADVANCED BURNING PHASES









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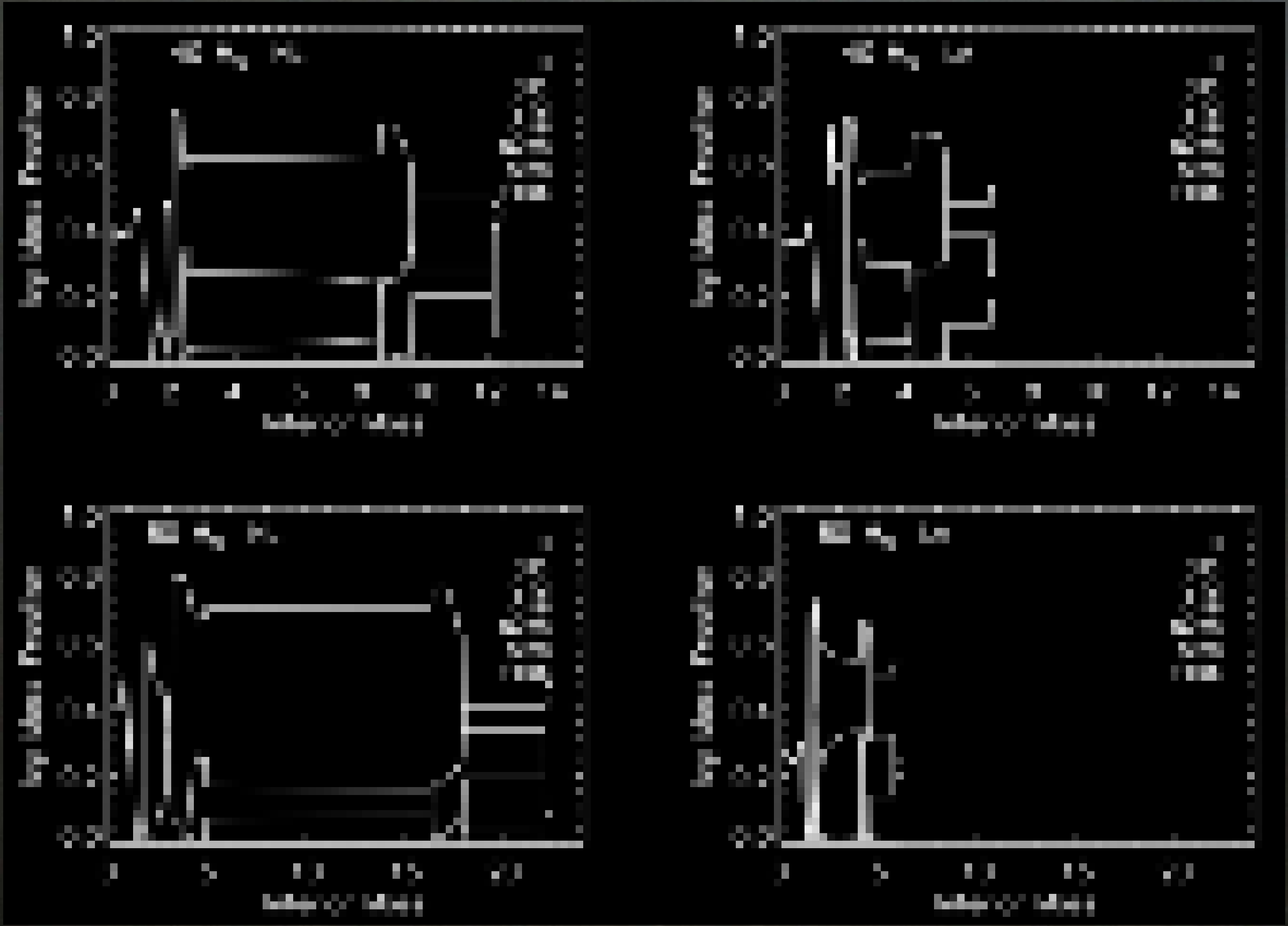
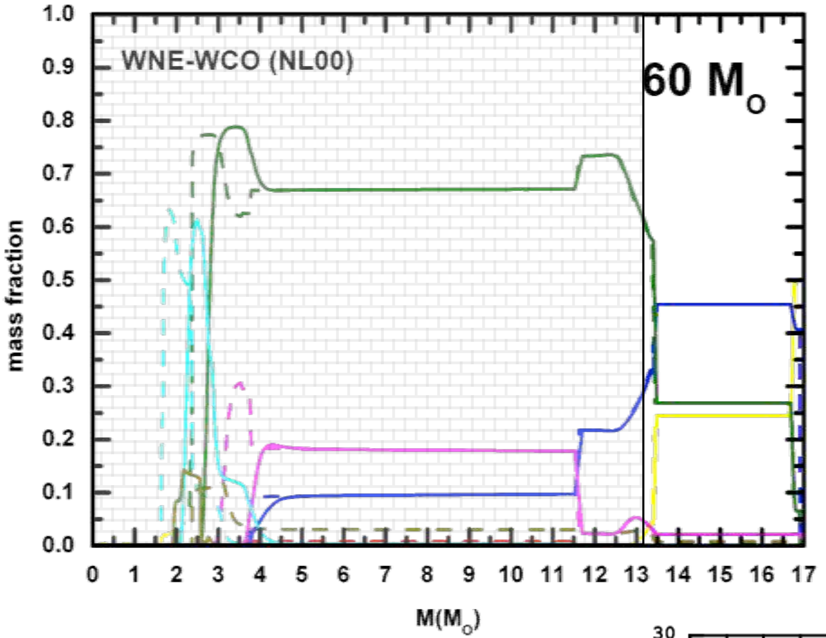
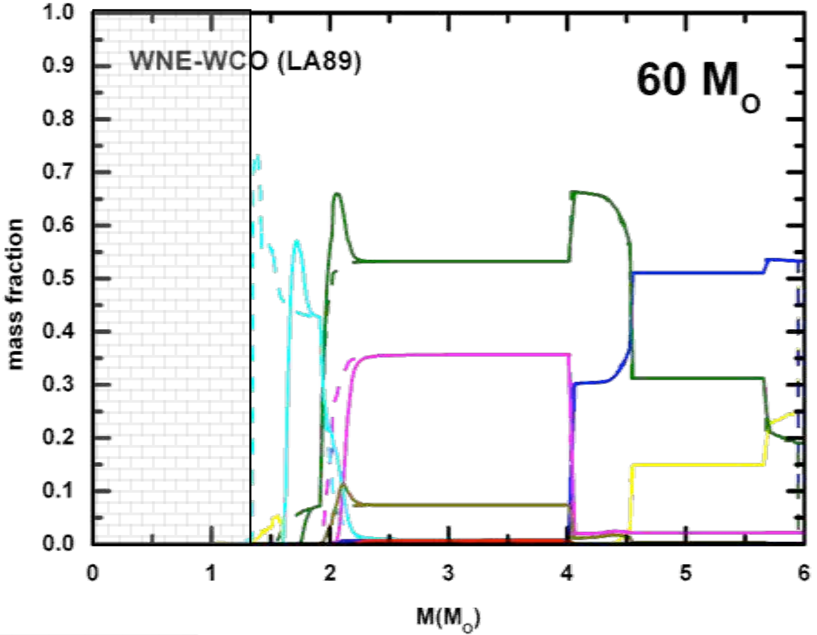
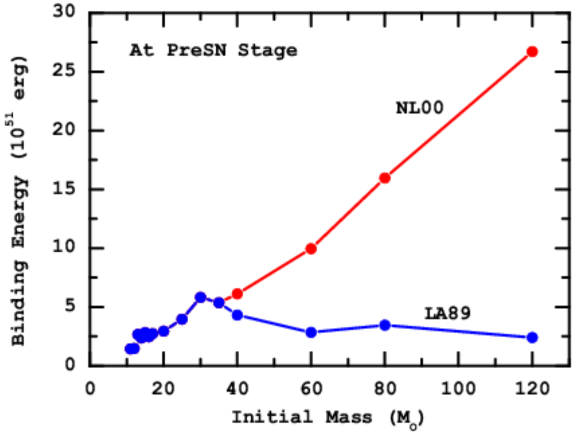


CONSEQUENCES ON THE FALLBACK

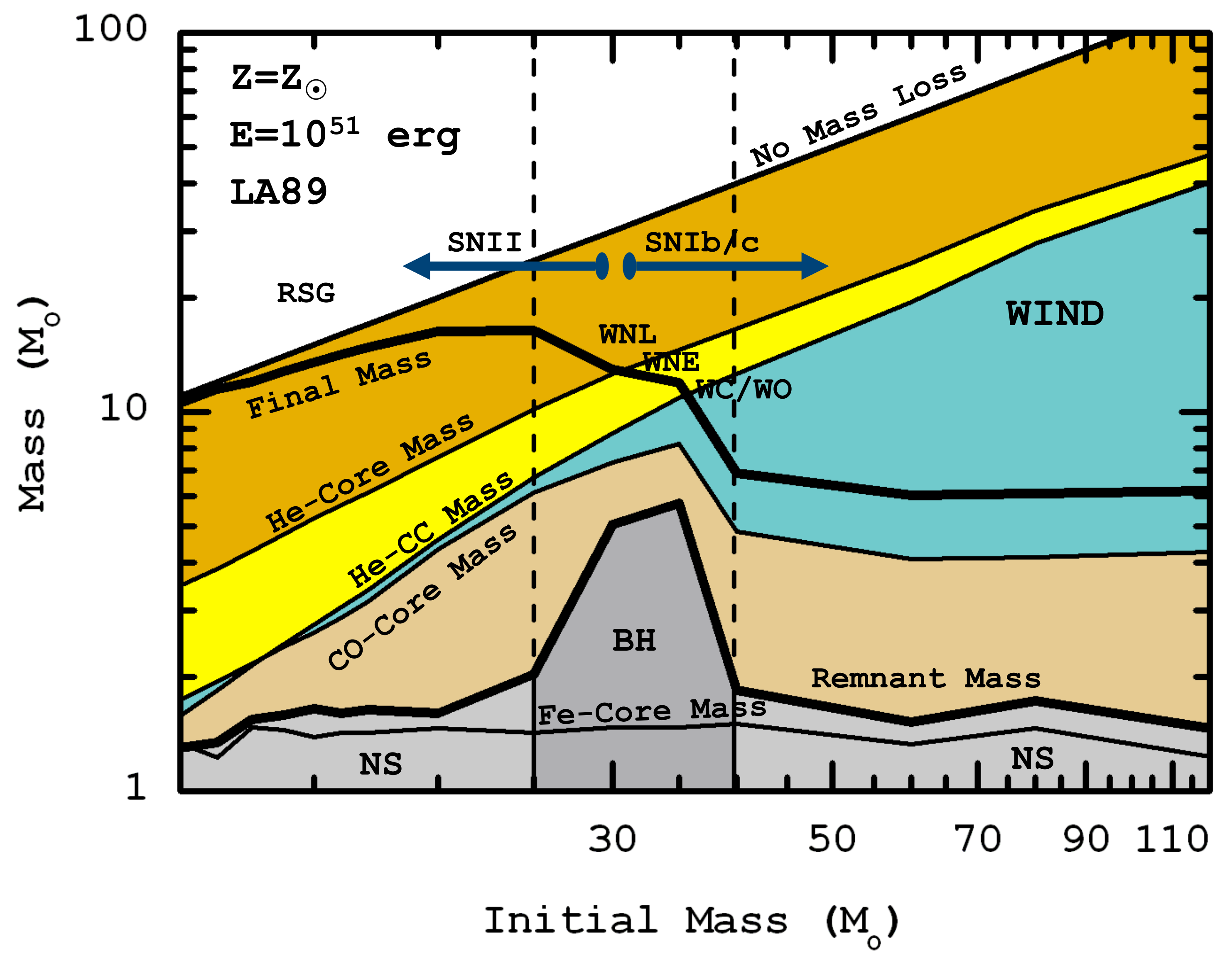
Final kinetic energy = 1 foe (10^{51} erg)



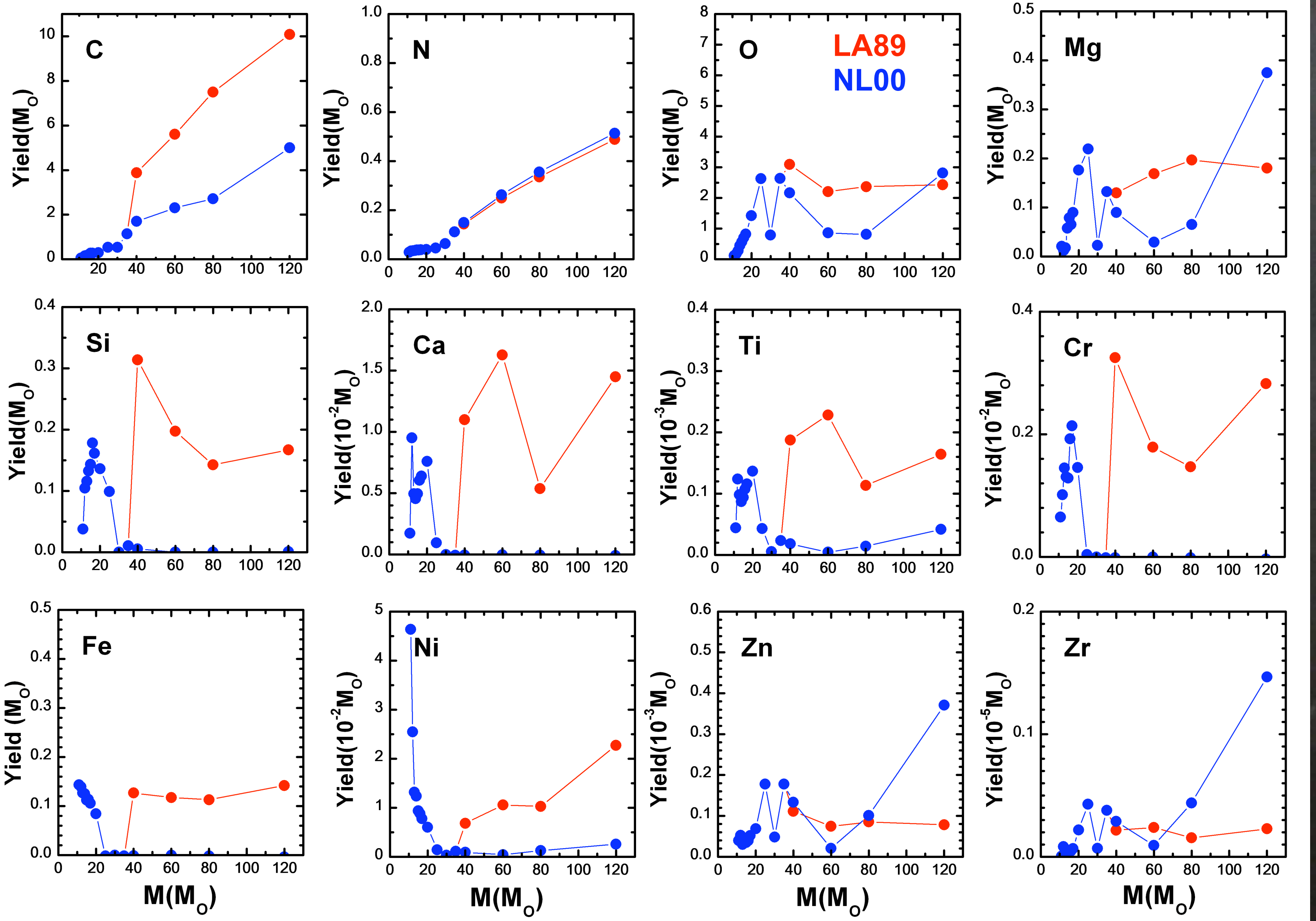




THE FINAL FATE OF “LA89” MASSIVE STARS



THE YIELDS OF “LA89” MASSIVE STARS



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TREATMENT OF CONVECTION

Convection is, in general, a hydrodynamical multi-D phenomenon → its inclusion in a hydrostatic 1-D stellar evolution code consititutes a great source of uncertainty

Mixing-Length theory:

- **Extension of the convective zones (stability criterion, overshooting, semiconvection)?**
- **Temperature Gradient?**
- **Interaction between nuclear burning and convective mixing?**

What about Mixing-Length theory for advanced burning stages of massive stars?

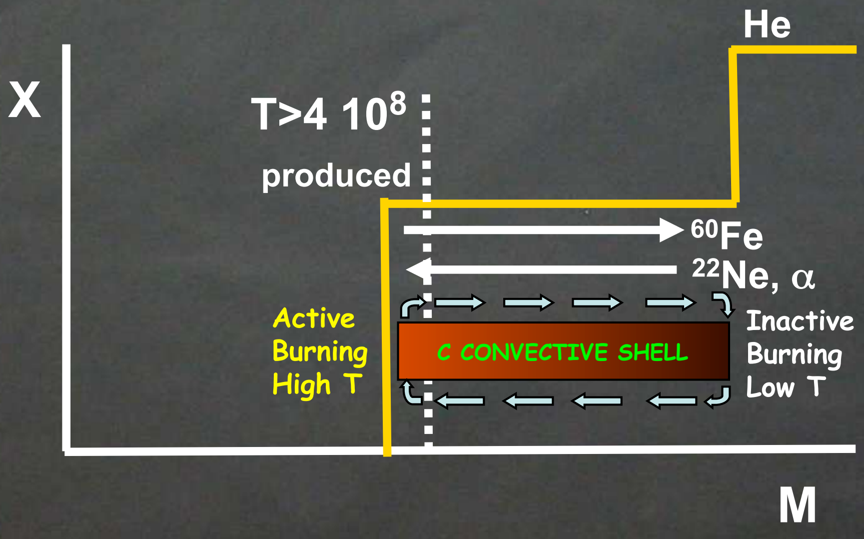
$$\frac{dY_i}{dt} = \left(\frac{\partial Y_i}{\partial t}\right)_{nuc} + \left(\frac{\partial Y_i}{\partial t}\right)_{conv} = \left(\frac{\partial Y_i}{\partial t}\right)_{nuc} + \frac{\partial}{\partial m}\left[\left(4\pi r^2 \rho\right)^2 D \frac{\partial Y_i}{\partial m}\right]$$

It does make sense?

TREATMENT OF CONVECTION

PRODUCTION OF ^{60}Fe IN MASSIVE STARS:

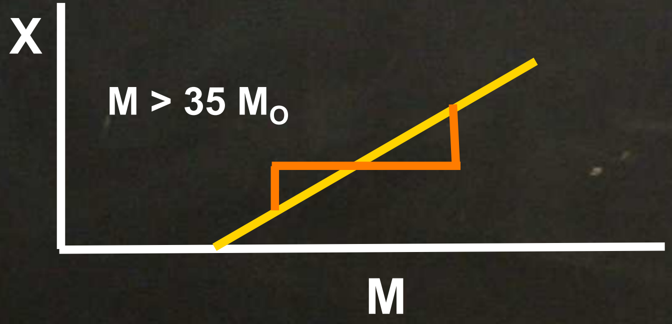
^{60}Fe is synthesized within the He convective shell

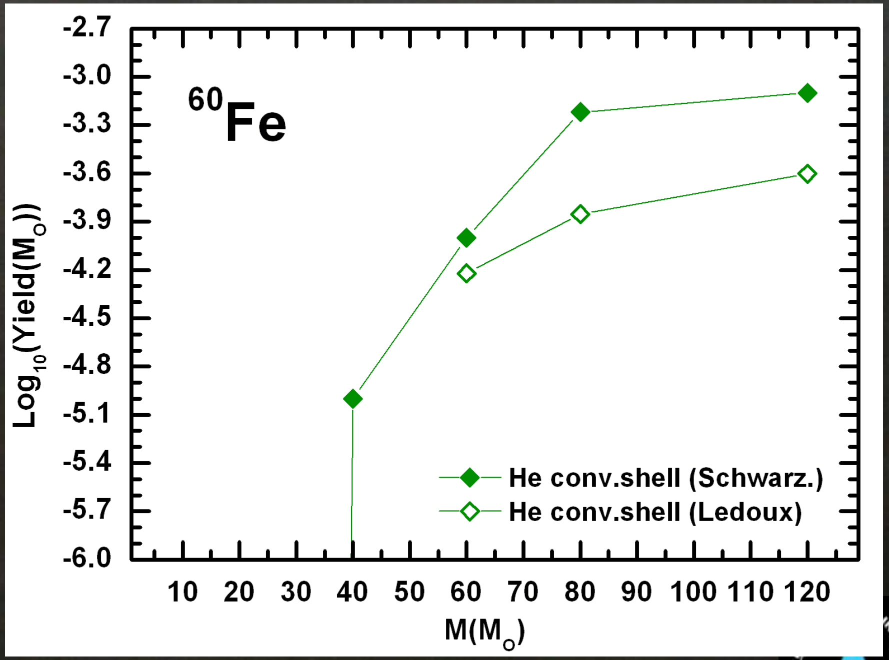


Convection

- **Preserves ^{60}Fe from destruction**
- **Brings new fuel (α, ^{22}Ne)**

He convective shell forms in a zone with variable composition

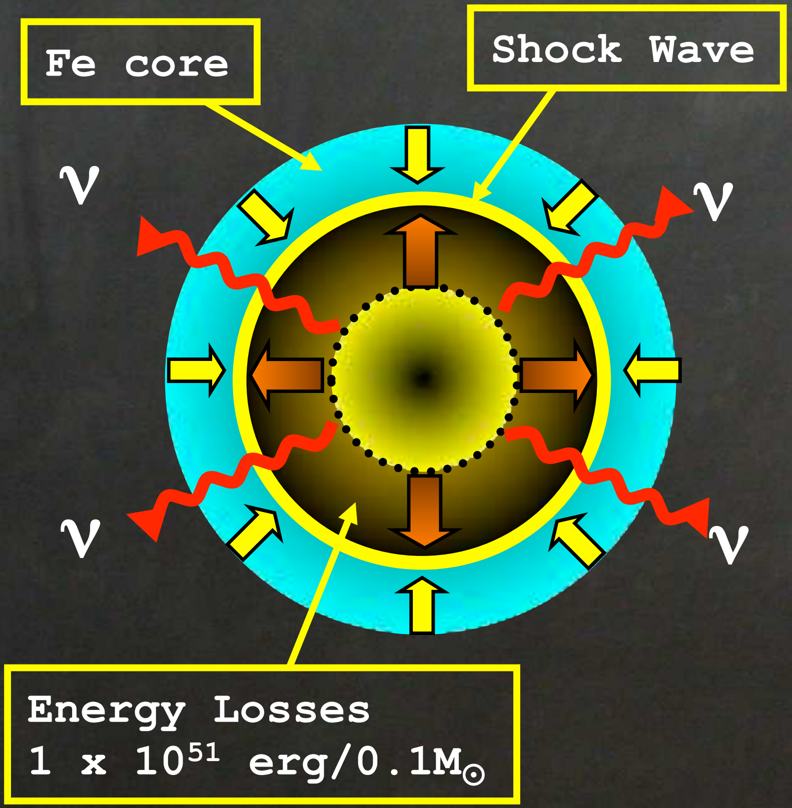


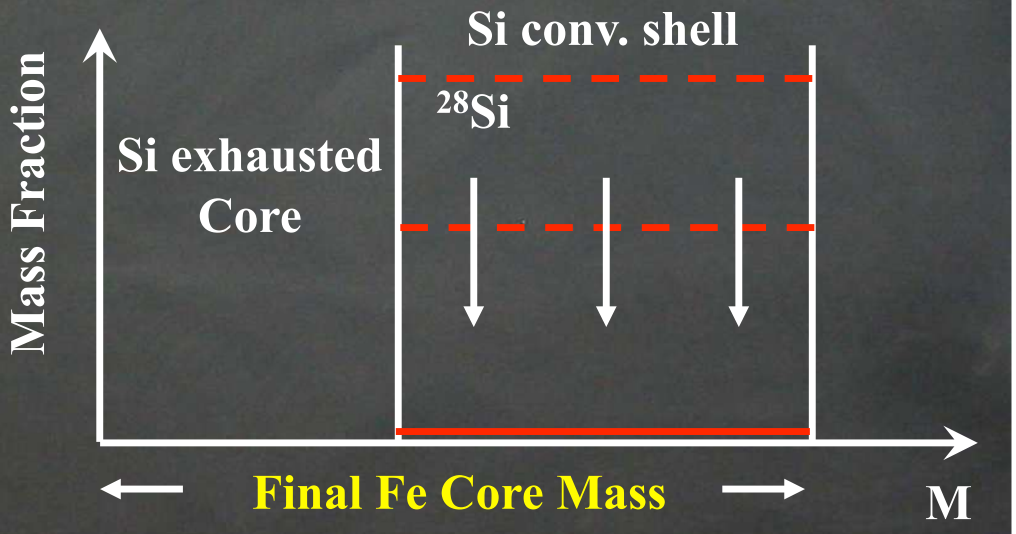


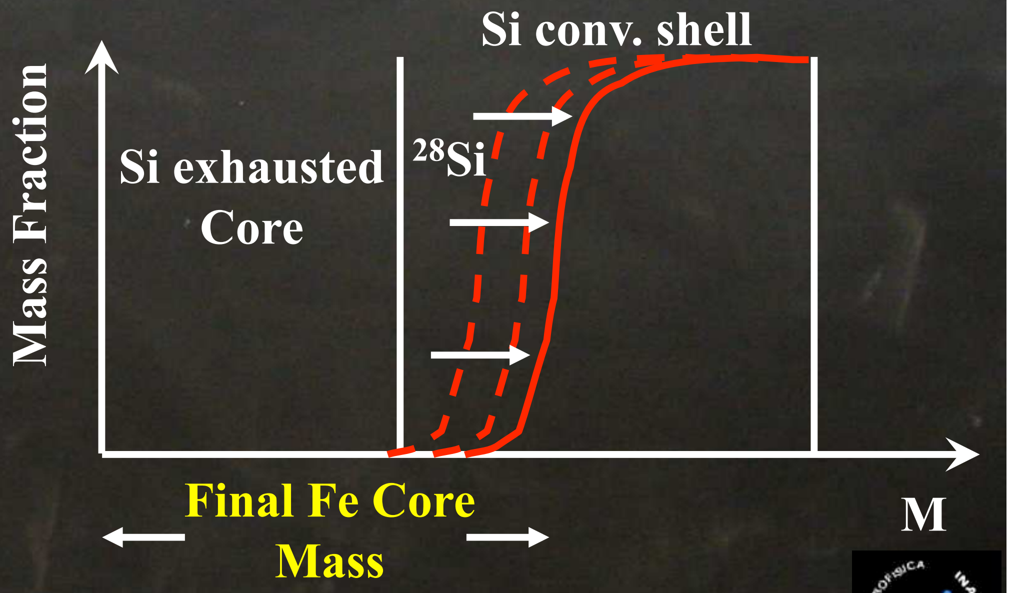
TREATMENT OF CONVECTION

THE MASS OF THE Fe CORE:

Core Collapse and Bounce







UNCERTAINTY ABOUT $^{12}C(\alpha,\gamma)^{16}O$

$C_{0.2}$ → $X(^{12}C)=0.2$

$C_{0.4}$ → $X(^{12}C)=0.4$

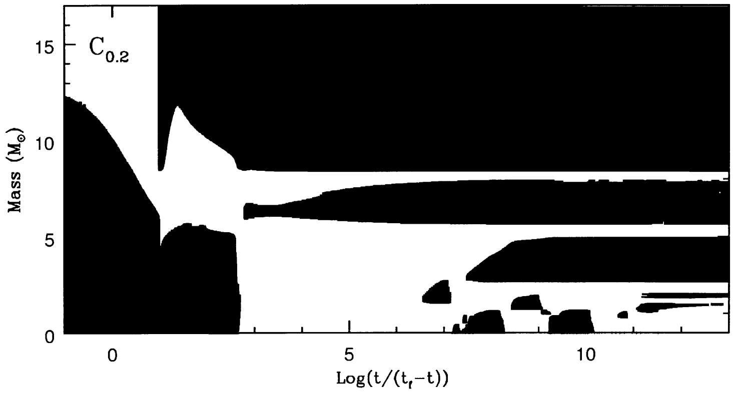
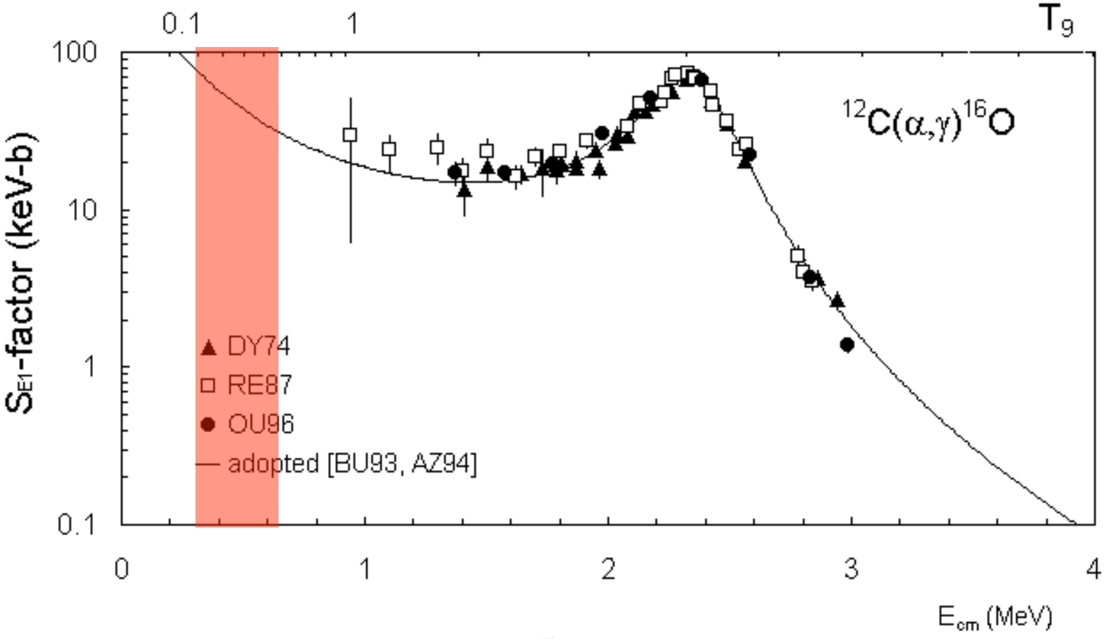


FIG. 8.—Temporal (properly adapted) behavior of the convective zones that form during the evolution of the 25 $M_\odot$ stellar model in the $C_{0.2}$ case.

FIG. 9.—Temporal (properly adapted) behavior of the convective zones that form during the evolution of the 25 $M_\odot$ stellar model in the $C_{0.4}$ case.

(Imbriani et al. ApJ 2001)



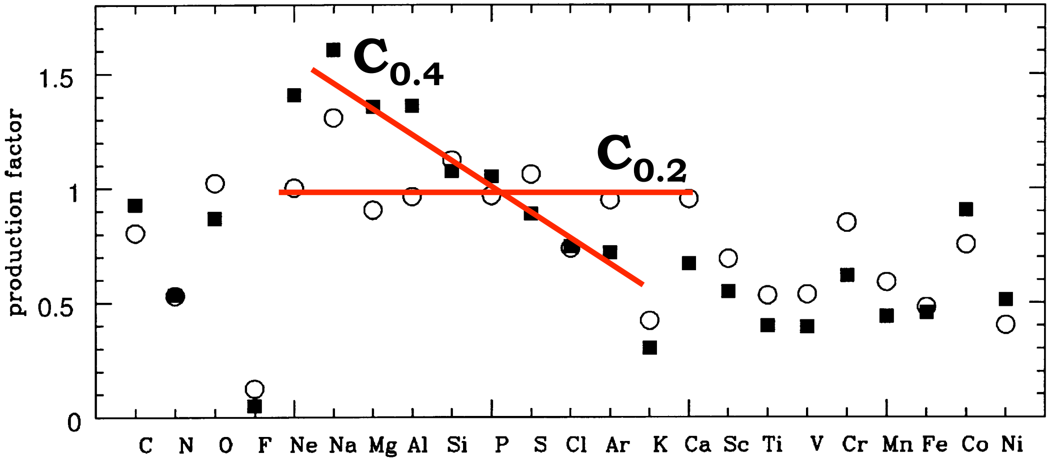


FIG. 16.—Comparison between the production factors obtained in the $C_{0.4}$ case (*filled squares*) and those produced in the $C_{0.2}$ case (*open circles*).

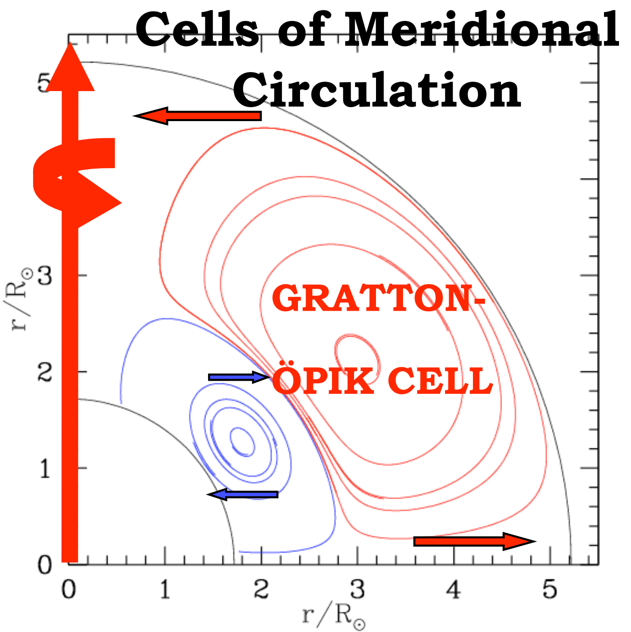
THE ROLE OF ROTATION

Increasing rotation →

OBLATENESS

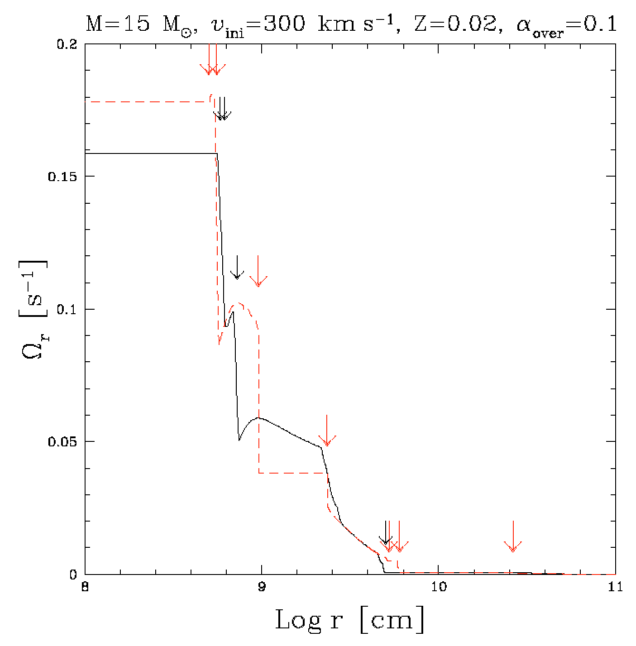
Von Zeipel Theorem

$$F_{rad} \propto g_{eff}$$



Cells of Meridional Circulation

Advection of Angular Momentum



Shear Instabilities:

- **Mixing of chemical species**
- **Transport (diffusion) of angular momentum**

THE ROLE OF ROTATION

How include this multi-D phenomenon in a 1-D code?

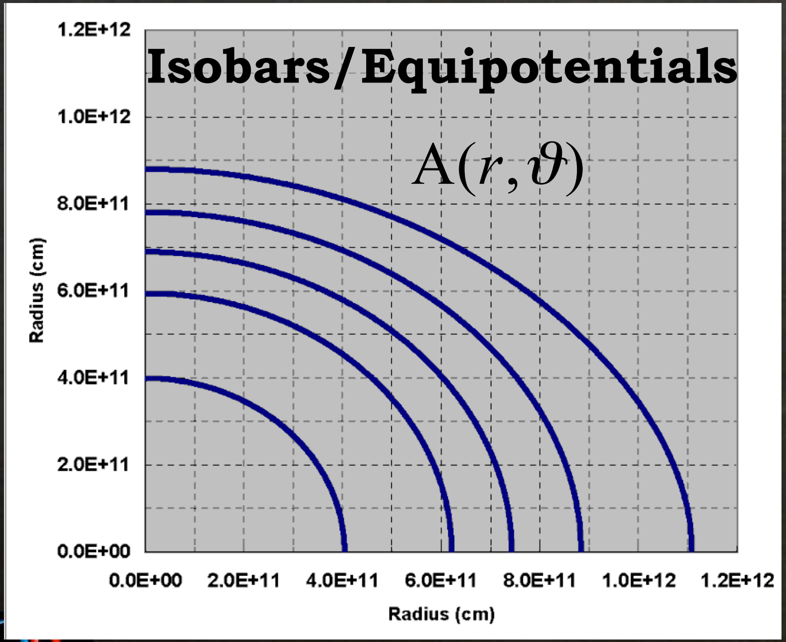
Cylidrical Symmetry: $A(r,\vartheta,\varphi) \to A(r,\vartheta)$

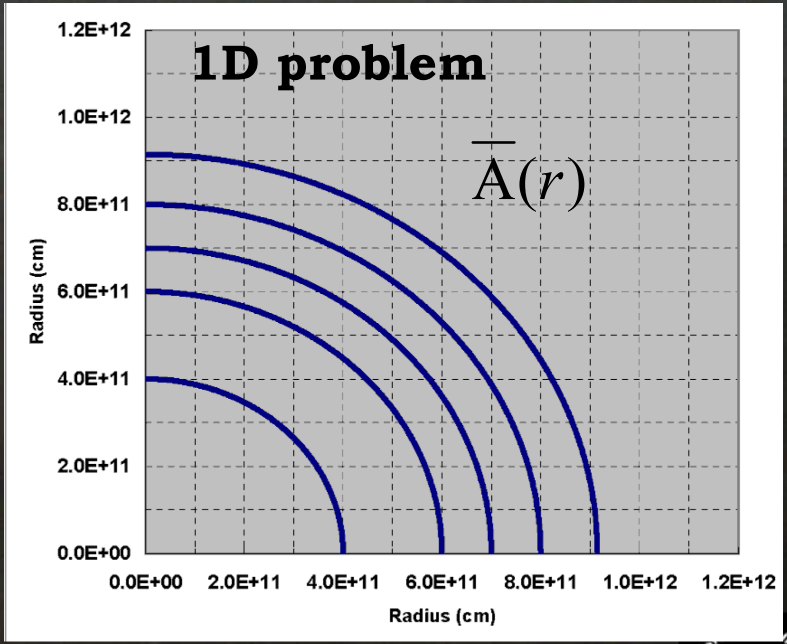
$$A(r,\vartheta) = \overline{A}(r) + \widehat{A}(r)P_2(\cos\vartheta)$$

$$\overline{A}(r) \gg \widehat{A}(r)$$

$$A(r,\vartheta) \simeq \overline{A}(r) \equiv \frac{\int_0^\pi A \sin\vartheta d\vartheta}{\int_0^\pi \sin\vartheta d\vartheta}$$

Average values over characteristic surfaces





STRATEGIES FOR IMPROVEMENTS

- **Convection** : hydrodynamical simulations in 3D → derive simple prescriptions to be used in 1D hydrostatic models (Arnett)
- **Rotation** : implementation of 3D stellar models
- **$^{12}C(\alpha,\gamma)^{16}O$** : ask to nuclear physicists
- **Explosive Nucleosynthesis and Stellar Remnants** : link progenitor stellar models and detailed nucleosynthesis with hydrodynamical simulations of core collapse and explosion

THE NEW VERSION OF THE FRANEC CODE
(release 6)

The most important updates compared to release 5 are:

Full coupling and simultaneously solving of all the equations describing the physical structure, chemical evolution and convective mixing (improvement of the solution of extremely large sparse systems)

Inclusion of rotation: oblateness and chemical mixing

Update of the solar composition (Asplund et al. 2007)

Update of nuclear cross sections and beta decays

Update of mass loss rates: inclusion of the mass loss driven wind during the RSG phase

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INCLUSION OF ROTATION

1. In order to take into account the oblateness of star induced by rotation the two basic equations for the hydrotatic equilibrium and radiative flux transfer have been properly modified (Kippenhahn & Thomas 1974) under the following assumptions:

- The angular velocity has cilindrical symmetry
- The equipotential surfaces have been derived in the Roche approximation
- The angular veolcity is an average over the equipotentials
- The chemical composition is constant over the equipotentials

INCLUSION OF ROTATION

2. The rotational induced mixing has been included as a diffusive process by defining a proper diffusion coefficient (Pinsonneault et al. 1989). Five different instabilities have been considered:

    - The Eddington-Sweet circulation (Von Zeipel theorem)
    - The secular shear
    - The dynamical shear
    - The Goldreich-Frick-Schubert instability
    - The Solberg-Høiland instability

3. The transport of the angular momentum has been treated as a diffusive process (Endal & Sofia 1978, Pinsonneault et al. 1989)

CALIBRATING THE NON ROTATING SSM

The new solar abundances are lower than previously recommended values and the present solar metallicity decrease to Z=0.0122 and Z/X=0.0165 (Asplund et al. 2007)

A new calibration of the non rotating SSM is required

Z_{ini} = Initial metallicity

Y_{ini} = Initial He content

α = Mixing Lenght

$R_\odot = 6.951\times10^{10}$ cm

$L_\odot = 3.844\times10^{32}$ erg s^{-1}

Z/H = 0.0165

@ $t = 4.57\times10^{9}$ yr

We obtain

$Z_{ini} = 0.014$; $Y_{ini} = 0.253$; [illegible] = 2.0

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CALIBRATING THE ROTATING SSM

The calibration of the rotating SSM involves 5 parameters:

Z_{ini} = Initial metallicity

Y_{ini} = Initial He content

α = Mixing Lenght

f_c = Efficiency of composition transport relative to angular momentum transport

K = Efficiency of angular momentum loss due to magnetic bracking and stellar wind

$R_\odot = 6.951\times10^{10}$ cm

$L_\odot = 3.844\times10^{32}$ erg s^{-1}

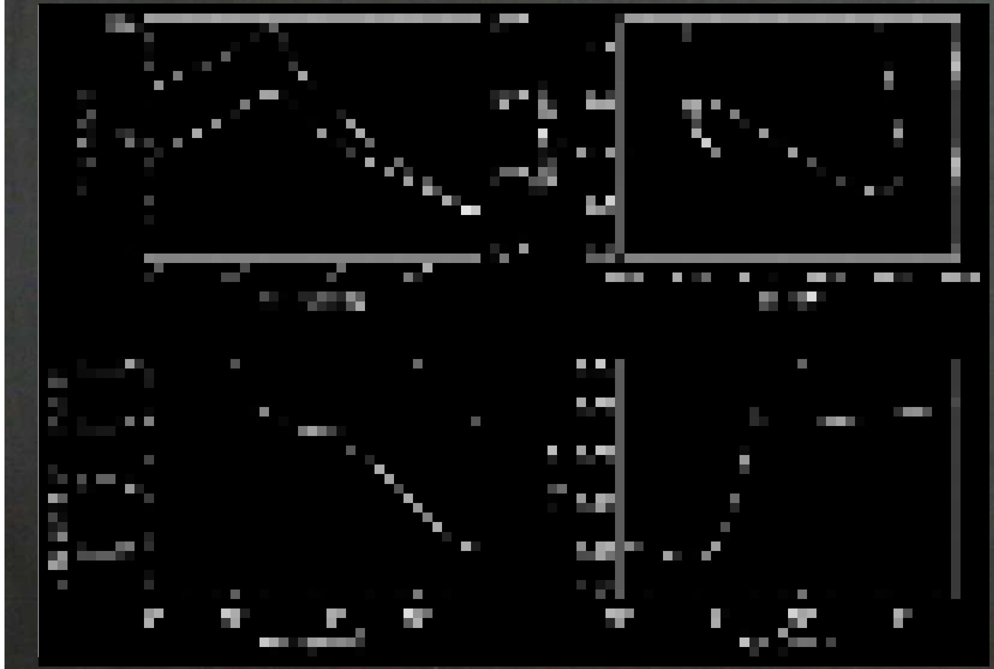
Z/H = 0.0165

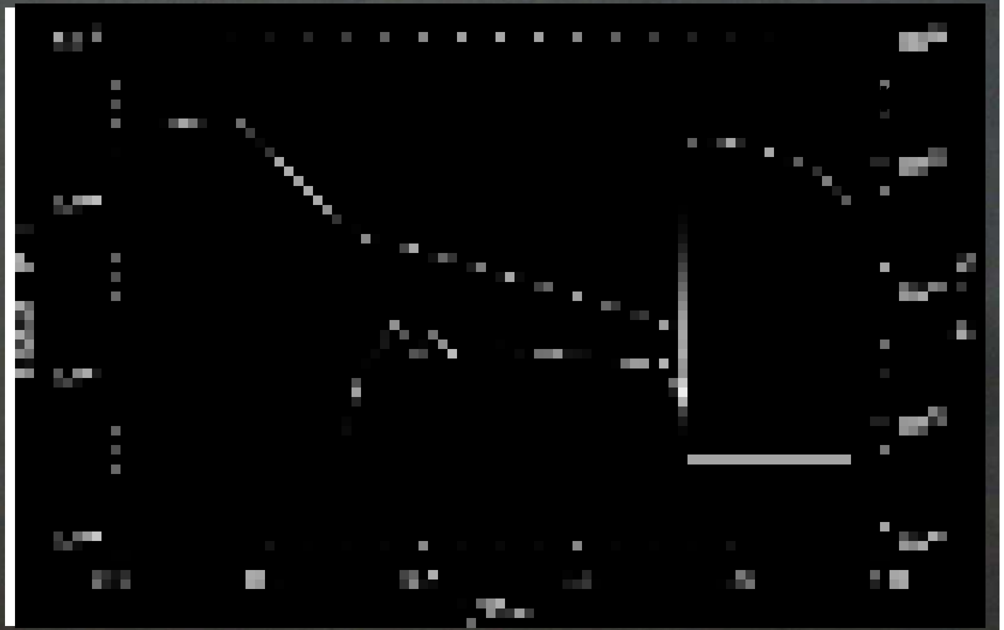
● $= 3\times10^{-6}$ s^{-1}

$^7Li/^7Li_{ini}=0.01$

@ $t = 4.57\times10^9$ yr

CALIBRATING THE ROTATING SSM





The best rotation SSM is obtained for

$Z_{ini} = 0.0133$; $Y_{ini} = 0.253$; [illegible] $= 2.0$; $f_c = 0.15$

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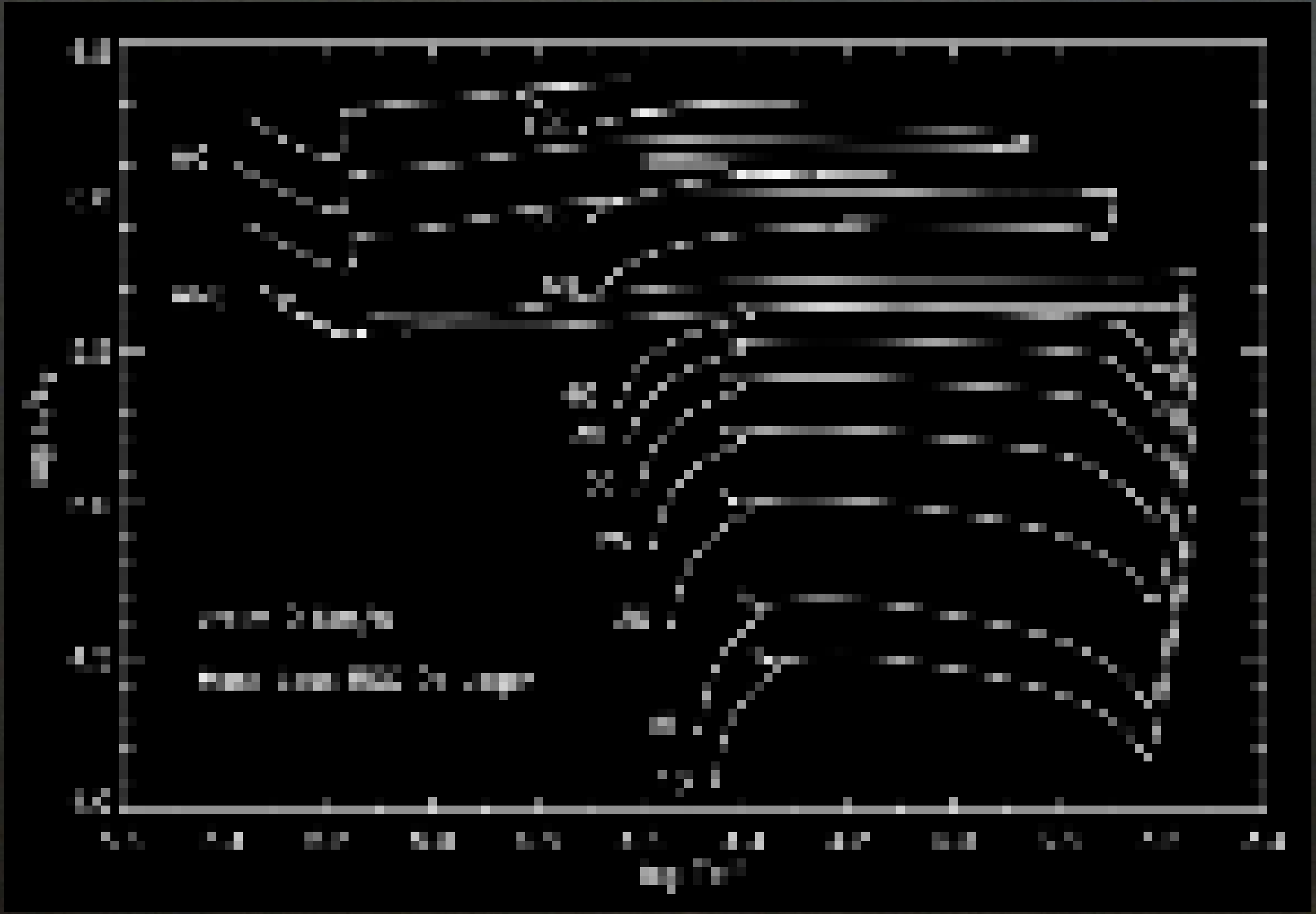
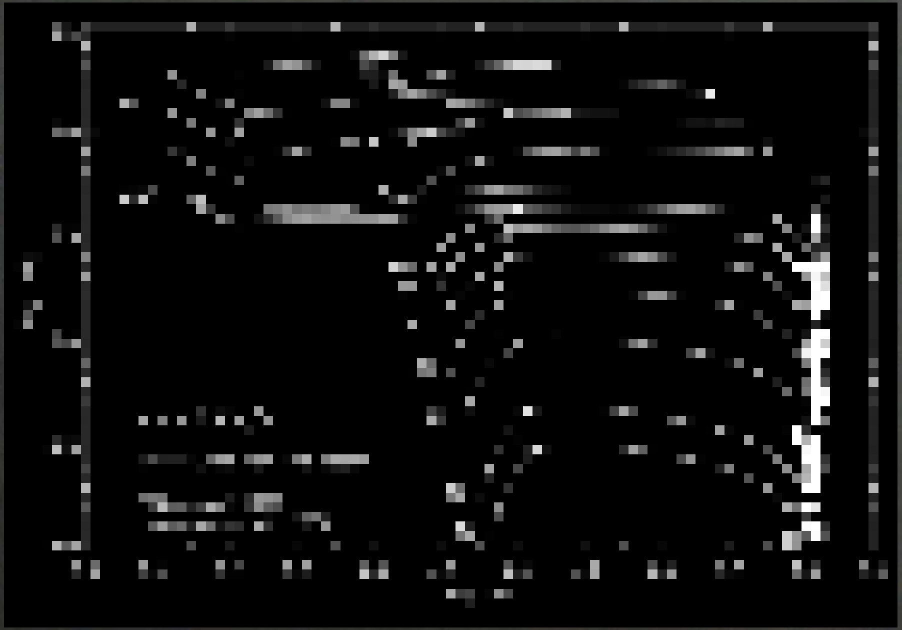
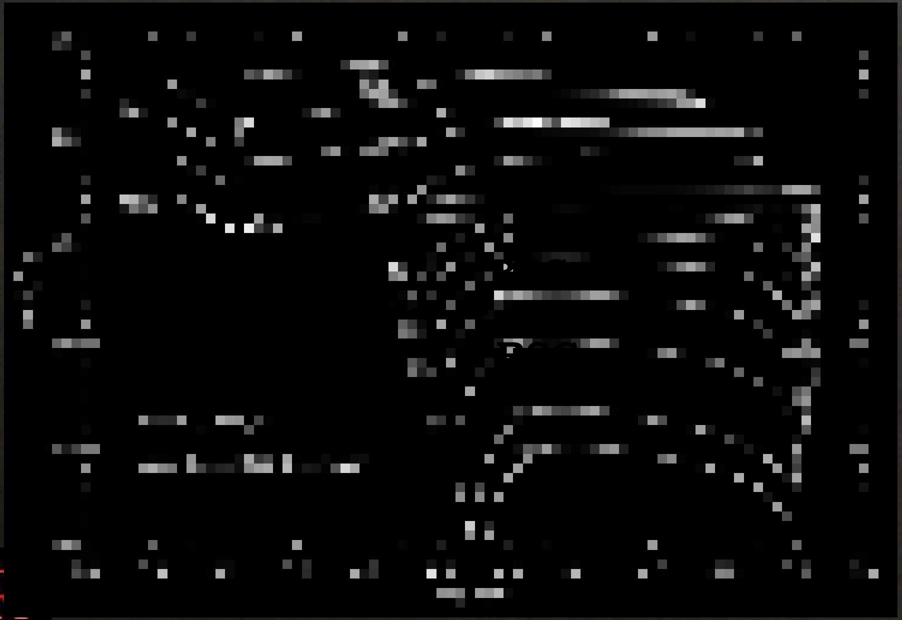
THE NEW SET OF MASSIVE STAR MODELS. SET 1

Mass Loss: Vink et al. (2000,2001) (Teff>12000 K), De Jager (1988) (Teff<12000 K), Nugis & Lamers (2000) (Wolf-Rayet)



THE NEW SET OF MASSIVE STAR MODELS. SET 1



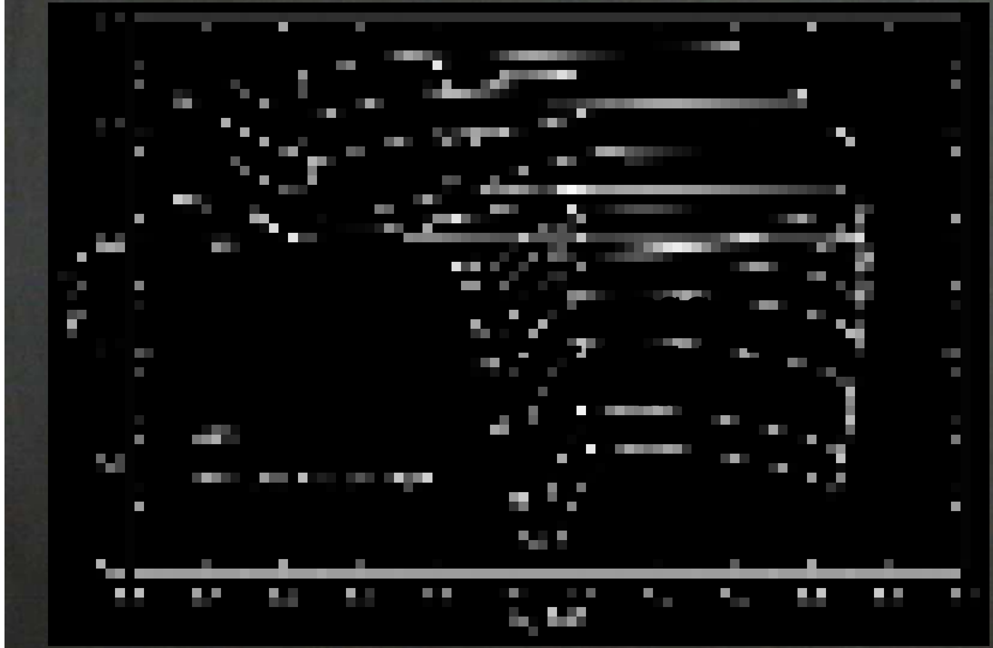


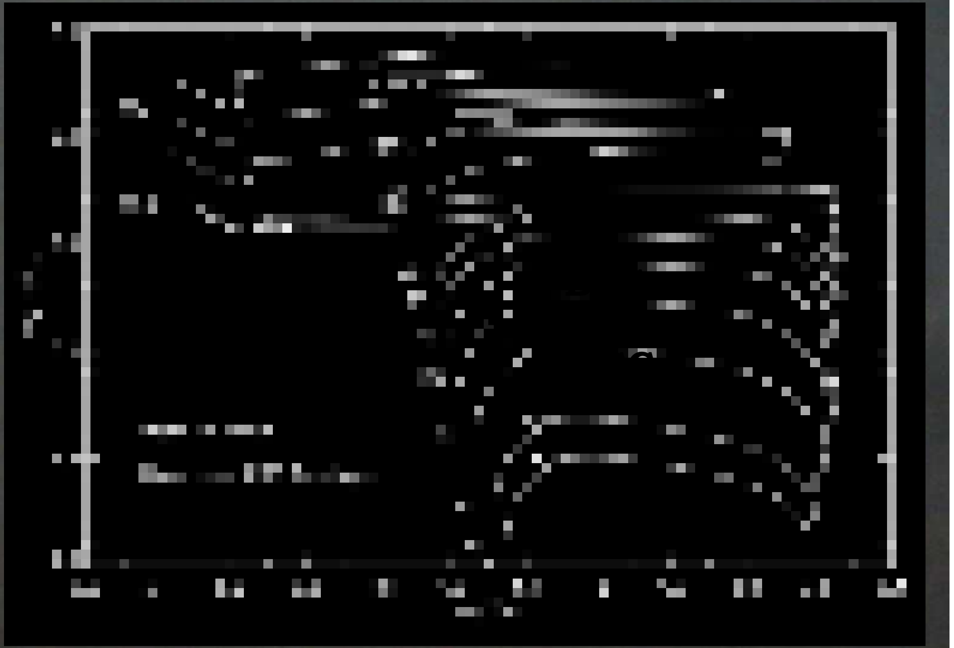
1. Very good agreement between evolutionary tracks and “observed” location of the galactic RSG (Levesque et al. 2006)

2. Stars with $M \leq 30\ M_\odot$ explode as RSG while stars with $M > 30\ M_\odot$ explode as BSG

3. Stars with $M > 30\ M_\odot$ become WR stars. Stars with $M > 40\ M_\odot$ become WC stars

COMPARISON WITH LC06 MODELS
(THE EFFECT OF CHANGING THE METALLICITY)

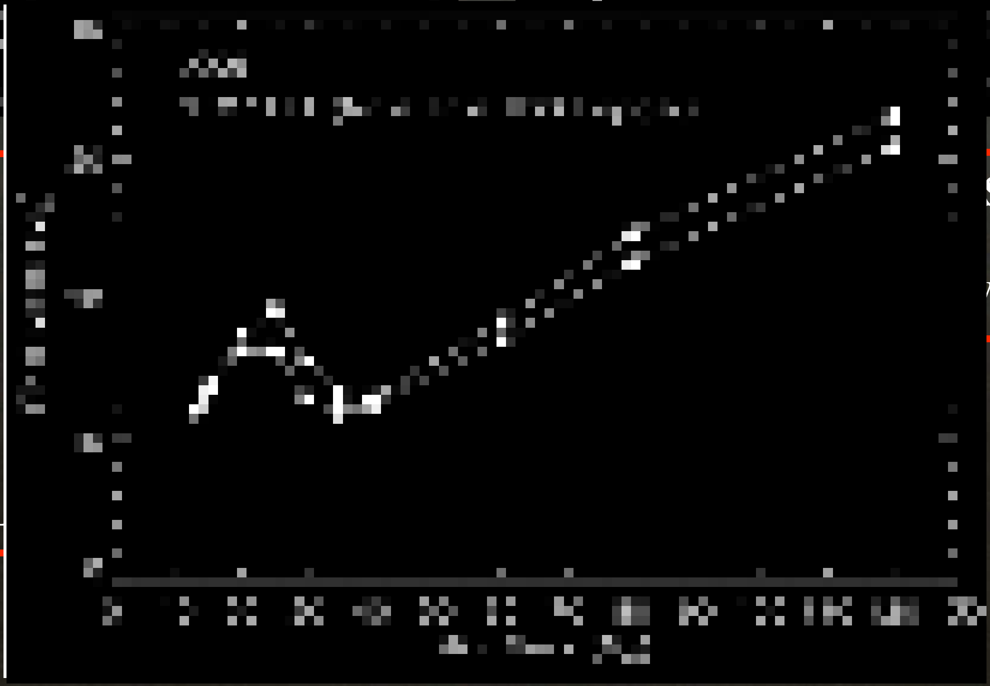




$30 \leq M/M_{\odot} < 35$	RSG → WNL
$35 \leq M/M_{\odot} < 40$	RSG → WNL → WNE
$40 \leq M/M_{\odot} < 60$	RSG → WNL → WNE → WC
$60 \leq M/M_{\odot}$	WNL → WNE → WC

$35 \leq M/M_{\odot} < 60$	RSG → WNL → WNE
$60 \leq M/M_{\odot}$	WNL → WNE → WC

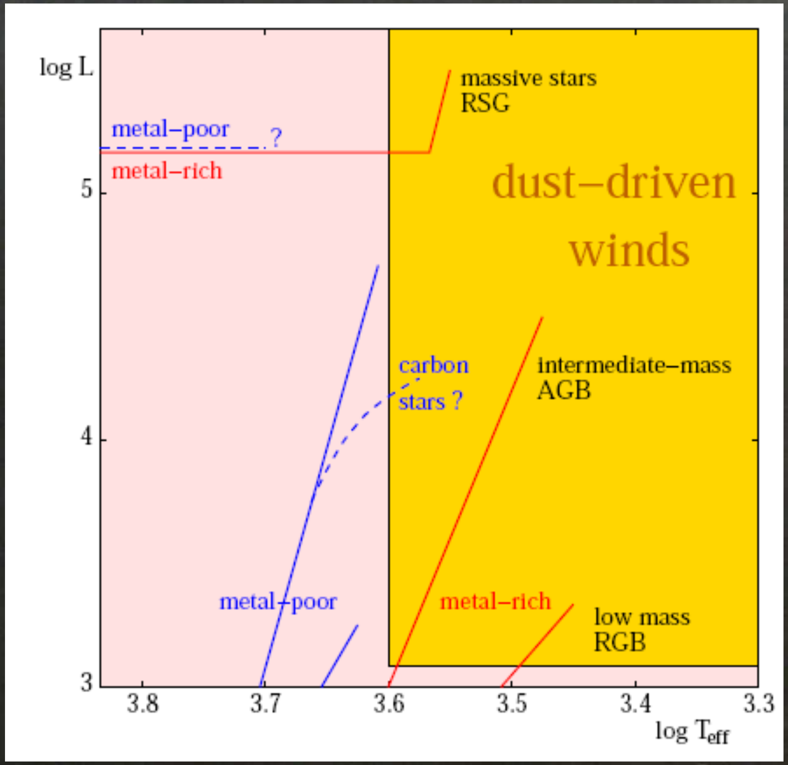
COMPARISON WITH LC06 MODELS
(THE EFFECT OF CHANGIN THE METALLICITY)



$30 \leq M/M_\odot < 35$	RSG	SG → WNL → WNE
$35 \leq M/M_\odot < 40$	RSG	NL → WNE → WC
$40 \leq M/M_\odot < 60$	RSG	
$60 \leq M/M_\odot$	WNL	

THE EFFECT OF DUST DRIVEN WIND

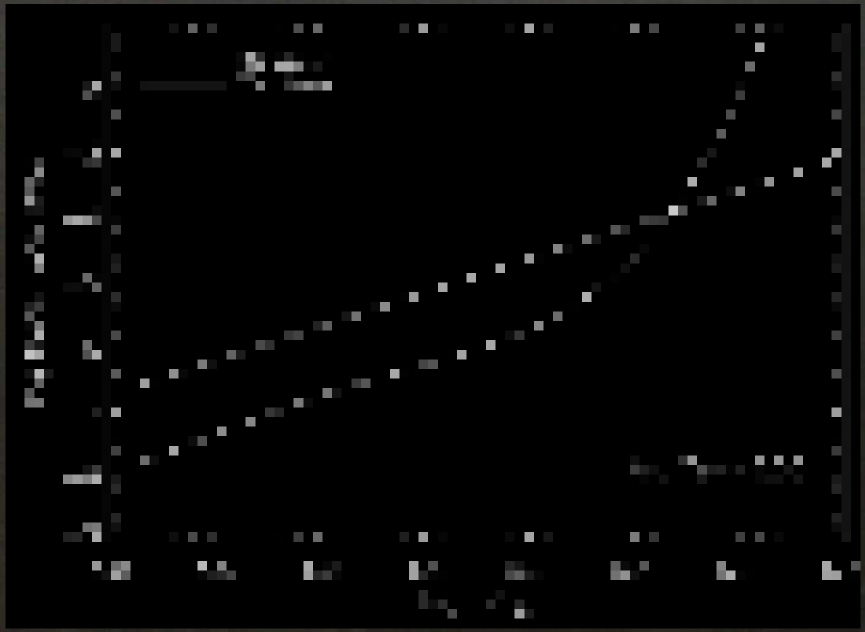
During the RSG phase massive stars become luminous and cool and may be able to produce dust in an atmosphere undergoing strong radial pulsation → drive a wind



(Van Loon et al. 2005)

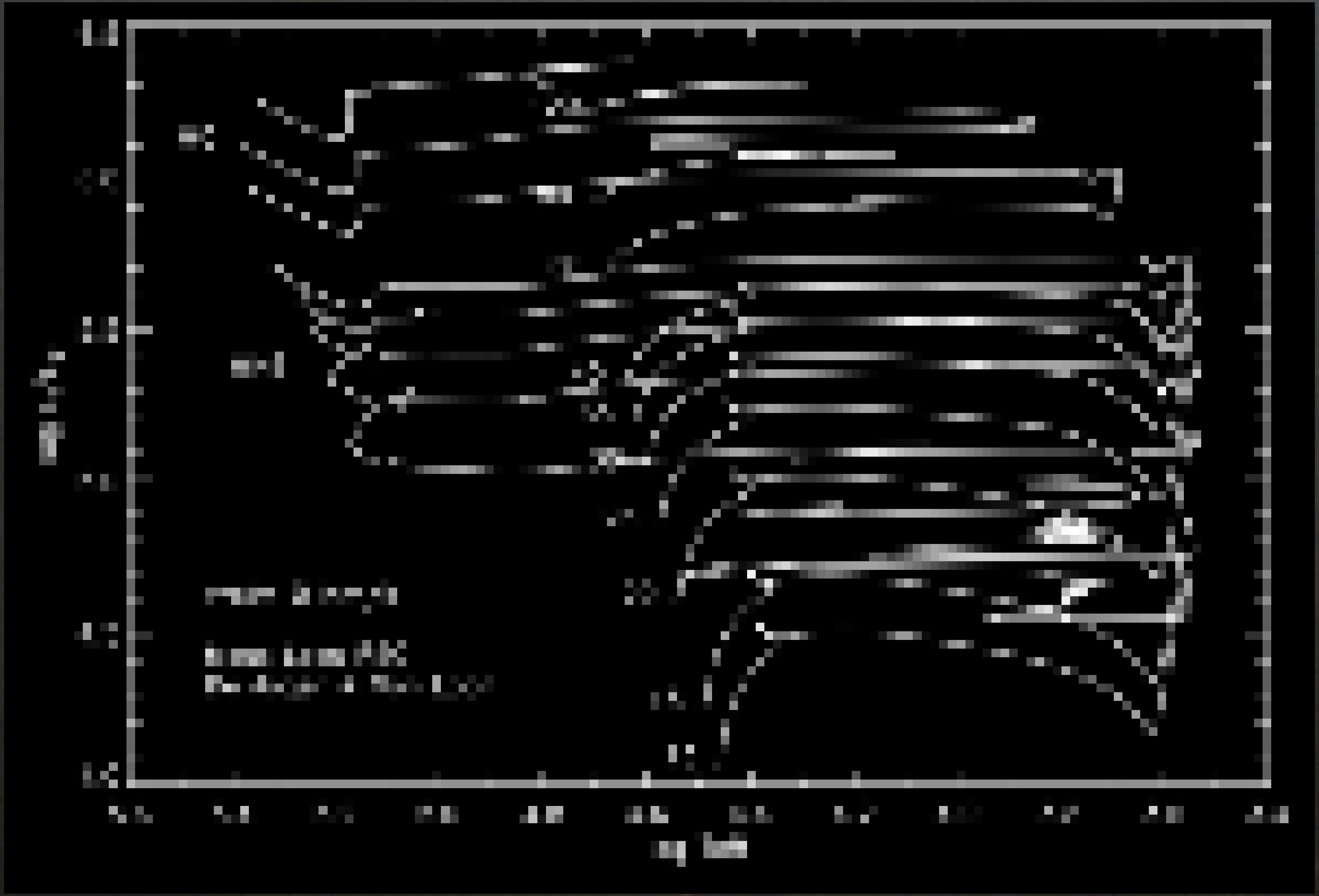
Van Loon et al. (2005) derived an empirical formula for the mass loss rate in this regime:

$$M_{dot} = -5.65 \log(L/10000\ L_{\odot}) - 6.3 \log(T_{eff/}3500\ K)$$

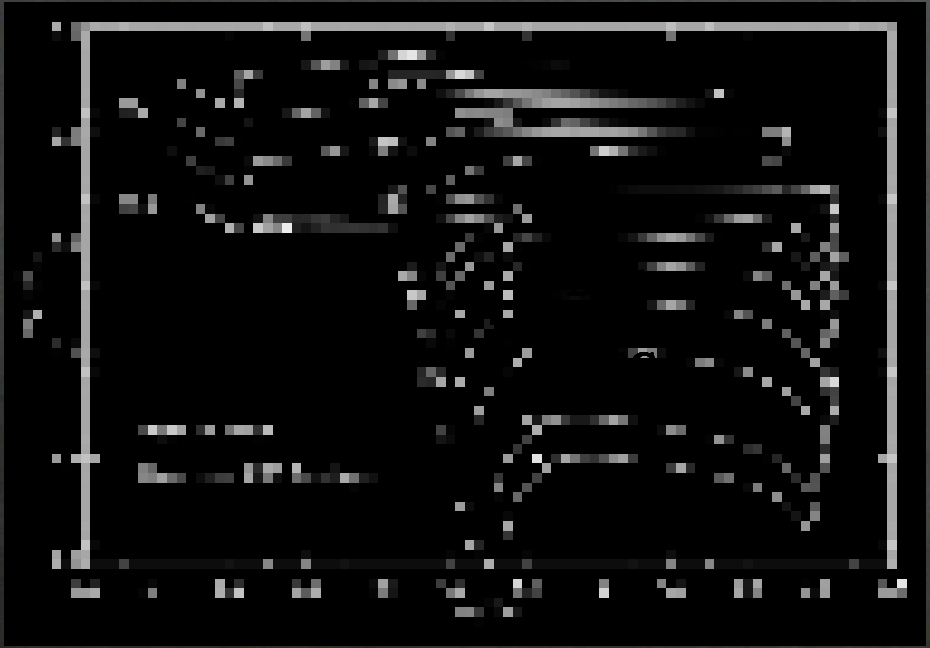


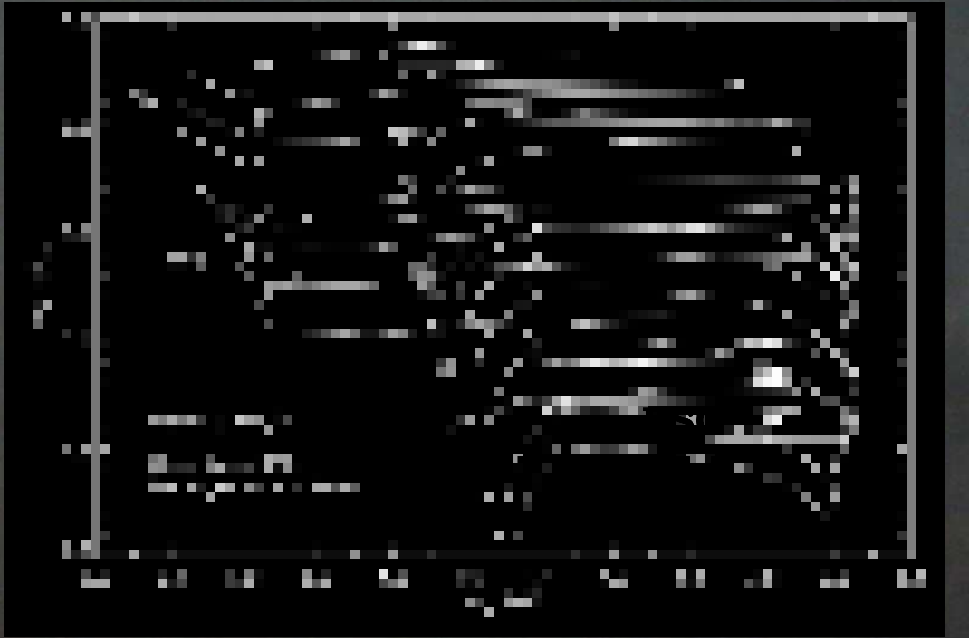
THE NEW SET OF MASSIVE STAR MODELS. SET 2

Mass Loss: Vink et al. (2000,2001) (Teff>12000 K), De Jager (1988) (Teff<12000 K), Van Loon et al. (2005) (Teff<3980 K), Nugis & Lamers (2000) (Wolf-Rayet)



COMPARISON BETWEEN SET1 AND SET2
(THE EFFECT OF DUST DRIVEN WIND)





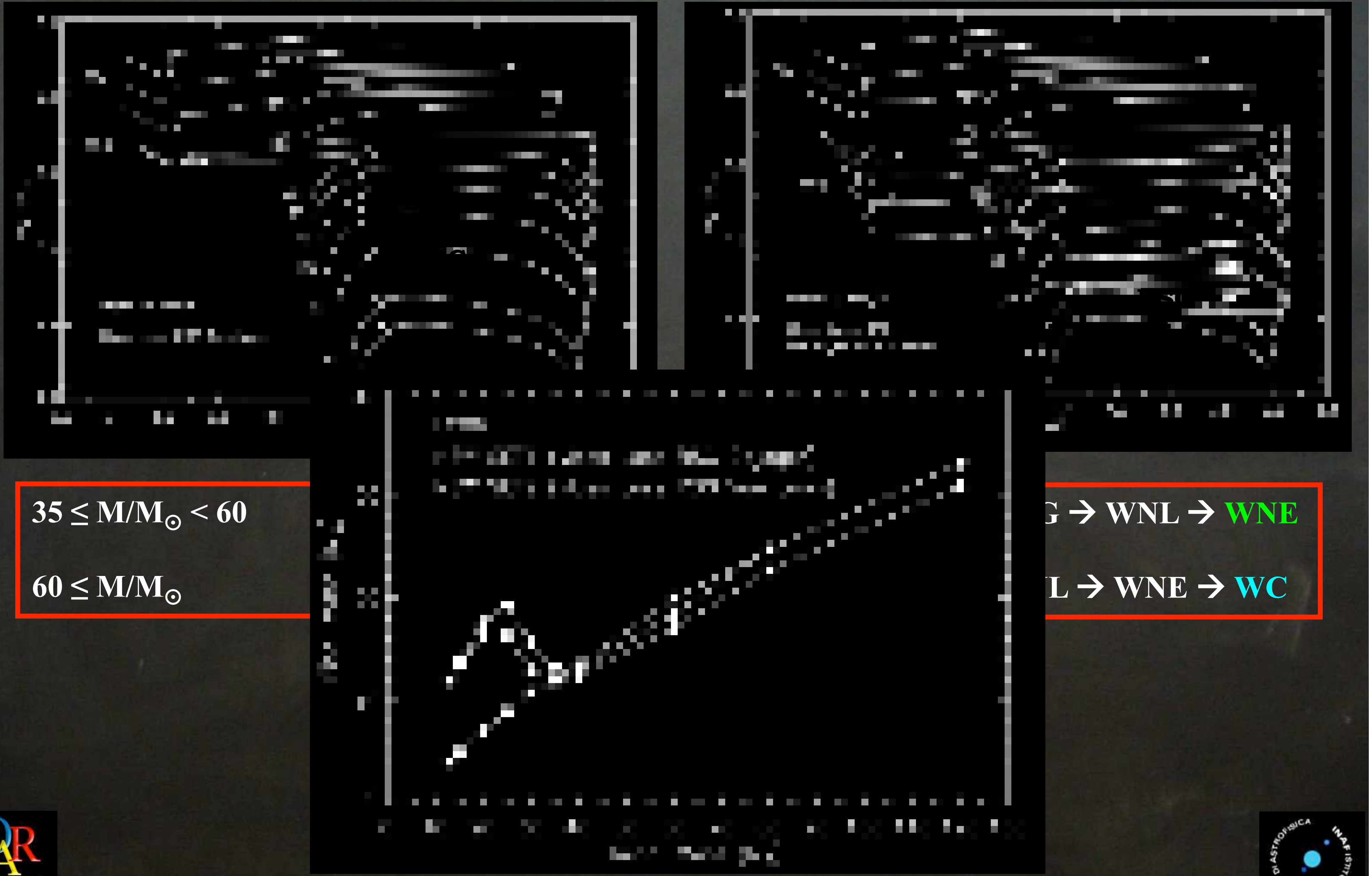
$35 \leq M/M_{\odot} < 60$ RSG → WNL → WNE

$60 \leq M/M_{\odot}$ WNL → WNE → WC

$20 \leq M/M_{\odot} < 60$ RSG → WNL → WNE

$60 \leq M/M_{\odot}$ WNL → WNE → WC

COMPARISON BETWEEN SET1 AND SET2
(THE EFFECT OF DUST DRIVEN WIND)



$35 \leq M/M_{\odot} < 60$

$60 \leq M/M_{\odot}$

G → WNL → **WNE**

L → WNE → **WC**

THE FINAL FATE OF MASSIVE STARS

LC06

SNII SNIb/c

RSG WNL WNE WC

13 15 20 25 30 35 40 60 80 120

SET 1

SNII SNIb/c

RSG WNL/WNE WC

13 15 20 25 30 35 40 60 80 120

SET 2

SNII SNIb/c

YSG WNL/WNE WC

13 15 20 25 30 35 40 60 80 120