PRESUPERNOVA EVOLUTION AND EXPLOSION OF MASSIVE STARS

Marco Limongi
INAF – Osservatorio Astronomico di Roma, ITALY
Institute for the Physics and Mathematics of the Universe, JAPAN
marco.limongi@oa-roma.inaf.it

and

Alessandro Chieffi
INAF – Istituto di Astrofisica e Planetologia Spaziali, Italy
Centre for Stellar and Planetary Astrophysics, Monash University, Australia
alessandro.chieffi@iasf-roma.inaf.it
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:
$(^{26}\text{Al}, ^{56}\text{Co}, ^{57}\text{Co}, ^{44}\text{Ti}, ^{60}\text{Fe})$
GRB progenitors

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

Distribution in HR diagram (location of RSG, BSG/RSG)

Relative number of O-type and WR stars and WR/WNE/WNL/WCO stars (mass limits for the formation of the various WR stars)

Relative number of Type II and Type Ibc SNe (mass limits for the formation of the various kind of SNe)

Luminosities of the WR stars

Mass of the remnant and relation with the progenitor mass

Average mass of the pulsars

Production factors of the chemical yields scaled solar

\(^{26}\text{Al}, \, ^{60}\text{Fe}\) in the Galaxy

Surface abundances in B-type stars (N)

Rotational velocity (period) neutron star remnant

Relative number of Type Ibc/GRB
OVERVIEW OF PRESUPERNOVA EVOLUTION OF MASSIVE STARS

Grid of models: 13, 15, 20, 25, 30, 40, 60, 80 and 120 M☉

Initial Solar Composition (Asplund et al. 2009)

All models computed with the FRANEC (Frascati RAphson Newton Evolutionary Code) 6.0

Major improvements compared to the release 4.0 (ML & Chieffi 2003) and 5.0 (ML & Chieffi 2006)

- FULL COUPLING of: Physical Structure - Nuclear Burning - Chemical Mixing (convection, semiconvection, rotation)

- INCLUSION OF ROTATION:
  - Conservative rotation law/Shellular Rotation (Meynet & Maeder 1997)
  - Transport of Angular Momentum (Advection/Diffusion, Maynet & Maeder 2000)
  - Coupling of Rotation and Mass Loss

- TWO NUCLEAR NETWORKS:
  - 163 isotopes (448 reactions) H/He Burning
  - 282 isotopes (2928 reactions) Advanced Burning

- MASS LOSS:
  - RSG: de Jager 1988+Van Loon 2005 (Dust driven wind)
  - WR: Nugis & Lamers 2000/Langer 1989
\[
\begin{align*}
\frac{\partial P}{\partial M} &= -\frac{GM}{4\pi R^4} f_P \\
\frac{\partial R}{\partial M} &= \frac{1}{4\pi \rho R^2} \\
\frac{\partial T}{\partial M} &= -\frac{GMT}{4\pi R^2 P} \nabla f_T \\
\frac{\partial L}{\partial M} &= \varepsilon \\
\frac{\partial Y_i}{\partial t} &= \left( \frac{\partial Y_i}{\partial t} \right)_{\text{nuc}} + \frac{\partial}{\partial m} \left[ \left( 4\pi \rho r^2 \right)^2 \left( D_{\text{mix}} + D_{\text{semi}} + D_{\text{rot}} \right) \left( \frac{\partial X_i}{\partial m} \right) \right]
\end{align*}
\]

(Coupled and solved simultaneously)

\[
\rho \frac{d}{dt} \left( r^2 \omega \right) = \frac{1}{5r^2} \frac{\partial}{\partial r} \left( \rho r^4 \omega U \right) + \frac{1}{r^2} \frac{\partial}{\partial r} \left( \rho D_{\text{shear}} r^4 \frac{\partial \omega}{\partial r} \right)
\]

(4th order \(\rightarrow\) 4 ODE solved by means of a relaxation method)

or

\[
\rho \frac{d}{dt} \left( r^2 \omega \right) = \frac{1}{r^2} \frac{\partial}{\partial r} \left( \rho D r^4 \frac{\partial \omega}{\partial r} \right)
\]

(Chieffi & ML in prep.)
MASSIVE STARS: CORE H BURNING

- **Convective Core**
- **CNO Cycle**

### Equations

- \( t \propto \frac{M}{L} \)

- \( P \propto \rho T \quad \Rightarrow \quad L \propto M^3 \)

- \( P \propto T^4 \quad \Rightarrow \quad L \propto M \)

### Graphs

- Core H burning models
- Initial mass vs. H burning lifetime (Myr)
  \( t \propto M^{-2} \)
  \( t \propto \text{cost} \)
The location of a core He burning star in the HR diagram depends on the mass of its H envelope.

The Mass Loss rate during the RSG phase is crucial in determining if and when (at which stage of core He burning) such a transition occurs and if and when the star enters the Wolf-Rayet stage or becomes a YSG.
15 \leq M/M_\odot \leq 20 \quad O \rightarrow \text{RGB}

20 < M/M_\odot \leq 30 \quad O \rightarrow \text{RGB} \rightarrow \text{WNL} \rightarrow \text{YSG}

30 < M/M_\odot \leq 40 \quad O \rightarrow \text{RGB} \rightarrow \text{WNL} \rightarrow \text{WNE}

40 < M/M_\odot \quad O \rightarrow \text{WNL} \rightarrow \text{WNE} \rightarrow \text{WNC} \rightarrow \text{WCO}

M_{\text{min, WNL, WNE, WCO}} \simeq 23, 35, 45M_\odot

M_{\text{max, II-P}} \simeq 17M_\odot

M_{\text{min, Ib}} \simeq 30M_\odot \quad N_{Ibc}/N_{II} \simeq 0.29

18 - 30M_\odot

Live a substantial fraction of time as RSG and explode as as IIb/Ib

\begin{tabular}{|c|c|c|c|c|c|}
\hline
\text{Initial Mass} & \text{Final Mass} & \text{M}_H & \text{M}_{\text{He}} & \text{Progenitor} & \text{SN} \\
\hline
13 & 12.0 & 5.46 & 4.49 & \text{RSG} & \text{II-P} \\
15 & 13.4 & 5.75 & 4.90 & \text{RSG} & \text{II-P} \\
20 & 8.1 & 0.25 & 3.81 & \text{RSG} & \text{IIb} \\
25 & 10.4 & 0.14 & 4.42 & \text{YSG} & \text{IIb} \\
30 & 12.6 & 0.03 & 4.35 & \text{YSG} & \text{IIb/Ib} \\
30 & 16.0 & 0.00 & 4.22 & \text{WNE} & \text{Ib/c} \\
60 & 16.8 & 0.00 & 0.93 & \text{WC} & \text{Ib/c} \\
80 & 22.6 & 0.00 & 1.07 & \text{WC} & \text{Ib/c} \\
120 & 30.8 & 0.00 & 1.02 & \text{WC} & \text{Ib/c} \\
\hline
\end{tabular}
COMPARISON WITH WOLF-RAYET STARS POPULATION

- Too few WR-stars predicted compared to O-type stars
- WNC/WR in good agreement with observations (semiconvection during core He burning) – MM03 claimed that such an agreement could be achieved only with the inclusion of rotation
- Too many WN predicted compared to WCO
- WR predicted masses higher than the observed ones
PROGENITORS OF CORE COLLAPSE SUPERNOVAE

Log\(\frac{L}{L_\odot}\)\(_{SN,\text{max}}\) = 5.1

Log\(\frac{L}{L_\odot}\)\(_{RSG,\text{max}}\) = 5.6

The RSG problem (Smartt et al. 2009)
PROGENITORS OF CORE COLLAPSE SUPERNOVAE

$M_{\text{max, II-P}} \simeq 17M_\odot$

Compatible observations (Smartt et al. 2009): $16.5 \pm 1.5M_\odot$

$18 - 30M_\odot$ Live a substantial fraction of time as RSG and explode as as IIb/Ib → possible solution to the RSG problem (Smartt et al. 2009)
SN RATES

Compatible with the observed rates (Cappellaro & Turatto 99)

\[ M_{\text{min,Ib}} \simeq 30 M_\odot \quad N_{Ibc}/N_{II} \simeq 0.29 \]

\[ N_{II} \simeq 0.78\% \quad N_{Ibc} \simeq 0.22\% \]
Neutrino losses play a dominant role in the evolution of a massive star beyond core He burning.

The Nuclear Luminosity ($L_{\text{nuc}}$) closely follows the energy losses. Each burning stage gives about the same $E_{\text{nuc}}$.

$$L \approx \frac{E_{\text{nuc}}}{t_{\text{nuc}}} \cdot M$$

Evolutionary times of the advanced burning stages reduce dramatically.

$$t_{\text{nuc}} \approx \frac{E_{\text{nuc}}}{L} \cdot \frac{M}{L}$$

Surface properties (Mass Loss, Teff, L) do not change anymore till the explosion.
ADVANCED BURNING STAGES: INTERNAL EVOLUTION

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

Central burning $\rightarrow$ formation of a convective core

Central exhaustion $\rightarrow$ shell burning $\rightarrow$ convective shell

Local exhaustion $\rightarrow$ shell burning shifts outward in mass $\rightarrow$ convective shell
ADVANCED BURNING STAGES: INTERNAL EVOLUTION

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

- **CO core mass** → **Thermodynamic history**
- $^{12}\text{C, }^{16}\text{O}$ → **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: INTERNAL EVOLUTION

...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!) or as the $^{12}$C left over by core He burning decreases.
PRESUPERNova STAR

...and also the density structure of the star at the presupernova stage

The final Fe core Masses range between: \( M_{Fe} = 1.14 - 1.80 \, M_\odot \)

In general the higher is the mass of the CO core (the lower is the \(^{12}\text{C}\) left over by the core He burning), the more compact is the structure at the presupernova stage.
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. The mass loss history (RSG/WR) determines in a direct way the kind of CCSN.
INDUCED 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.
Hydrodynamical simulations based on induced explosions for $E_{\text{expl}} = 10^{51}$ erg
SUMMARY

- Maximum mass evolving as a RSG on a substantial fraction of core He burning:
  \[M_{max,\text{RSG}} \sim 35 \, M_\odot\]

- Consistent with the maximum luminosity of galactic RSG stars.

- The minimum masses for the formation of the various kind of Wolf-Rayet stars are:
  \[M_{\text{WNL}} \sim 23 \, M_\odot, \quad M_{\text{WNE}} \sim 35 \, M_\odot, \quad M_{\text{WC}} \sim 45 \, M_\odot\]

- WR/O significantly underestimated compared to observations.
- WNC/WR in good agreement with observations.
- Too many WN predicted compared to WCO.
- WR predicted masses higher than the observed ones.

- RSG/YSG/BSG SNe as a function of the initial mass:
  \[M \leq 22 \, M_\odot \rightarrow \text{RSG-SN}, \quad 22 \, M_\odot < M \leq 35 \, M_\odot \rightarrow \text{YSG-SN}, \quad 35 \, M_\odot < M \rightarrow \text{BSG-SN}\]
SUMMARY

- Maximum mass for SNII-P: \( M_{\text{max,II}P} \approx 17 M_{\odot} \)
  - Consistent with the recent observational estimates (Smartt et al. 2009)

- Minimum mass for SNIIb/c: \( M_{\text{SNII/SNIbc}} \approx 35 M_{\odot} \)
  - In principle compatible with the observed rates

\( N_{\text{Ibc}} / N_{\text{II}} \approx 0.29 \)

- The final Fe core Masses range between: \( M_{\text{Fe}} = 1.14 - 1.80 M_{\odot} \)

- The limiting mass between NS and BH froming SNe: \( M_{\text{NS/BH}} \approx 22 M_{\odot} \)

\(< M_{\text{NS}} >_{\text{theo}} = 1.40 \pm 0.02 M_{\odot} \text{ in agreement with } < M_{\text{NS}} >_{\text{obs}} = 1.35 \pm 0.04 M_{\odot}\)
PHYSICS OF ROTATION

STRUCTURE
- Oblateness (interior, surface)
- New structure equations

Von Zeipel Theorem
\[ F_{\text{rad}} \propto g_{\text{eff}} \]

Meridional Circulation

Local conservation

Advection of angular momentum

Increase the gradient of angular velocity

Transport of Angular Momentum
\[ \rho \frac{d}{dt} (r^2 \omega) = \frac{1}{5r^2} \frac{\partial}{\partial r} (\rho r^4 \omega U) + \frac{1}{r^2} \frac{\partial}{\partial r} \left( \rho D_{\text{shear}} r^4 \frac{\partial \omega}{\partial r} \right) \]

Transport of Chemical Species
\[ \frac{\partial Y_i}{\partial t} = \left( \frac{\partial Y_i}{\partial t} \right)_{\text{nuc}} + \frac{\partial}{\partial m} \left[ (4\pi \rho r^2)^2 D_{\text{rot}} \left( \frac{\partial X_i}{\partial m} \right) \right] \]
INFLUENCE OF ROTATION ON CORE H BURNING
INFLUENCE OF ROTATION ON CORE H BURNING

![Graphs showing mass fraction vs. interior mass for different core masses and rotation velocities.](image-url)
INFLUENCE OF ROTATION ON CORE H BURNING

- Almost same H exhausted core @ core H depletion (exception for M=120 $M_\odot$)
- Shallower chemical profiles in rotating models due to rotationally induced mixing
- H-rich envelope enriched by core H burning products
- Different path in the HR diagram $\rightarrow$ different mass loss history $\rightarrow$ Mass Loss does not scale monotonically with rotation
INFLUENCE OF ROTATION ON CORE AND SHELL He BURNING

M≤60 M_☉ : Rotational mixing dominates

- Rotational induced mixing beyond the He convective core
- Reduced μ-gradient barrier → larger convective cores
M ≤ 60 M_☉: Rotational mixing dominates

- Rotational induced mixing beyond the He convective core
  - Reduced μ-gradient barrier \(\rightarrow\) larger convective cores
  - Larger CO cores
  - Continuous inward mixing of fresh $^4$He fuel \(\rightarrow\) Lower $^{12}$C left over at core He depletion
INFLUENCE OF ROTATION ON CORE AND SHELL He BURNING

\( M \leq 60 \, M_\odot \): Rotational mixing dominates

- Rotational induced mixing beyond the He convective core
  - Reduced \( \mu \)-gradient barrier \( \rightarrow \) larger convective cores
  - Larger CO cores
  - Continuous inward mixing of fresh \(^4\text{He}\) fuel \( \rightarrow \) Lower \(^{12}\text{C}\) left over at core He depletion
  - Formation of He convective shell in the region of variable He \( \rightarrow \) He convective shell hotter \( \rightarrow \) more \(^{12}\text{C}\) and \(^{16}\text{O}\) produced locally

Rotating and Non Rotating models show completely different structures
INFLUENCE OF ROTATION ON CORE AND SHELL He BURNING

M$>60$ $M_\odot$: Mass Loss dominates

Mass Loss uncovers the He core at the beginning of Core He burning
\[ M > 60 \, M_\odot : \text{Mass Loss dominates} \]

- Mass Loss uncovers the He core at the beginning of Core He burning
- He convective core progressively recedes in mass and leaves a region of variable He

\[ \text{INFLUENCE OF ROTATION ON CORE AND SHELL He BURNING} \]

\[ v = 0 \, \text{km/s} \]

\[ v = 300 \, \text{km/s} \]
INFLUENCE OF ROTATION ON CORE AND SHELL He BURNING

M>60 M_☉ : Mass Loss dominates

- Mass Loss uncovers the He core at the beginning of Core He burning
- He convective core progressively recedes in mass and leaves a region of variable He
- In these stars this region is not due to the rotationally induced mixing but to the efficient mass loss that progressively erodes the He core
M>60 M\(_{\odot}\) : Mass Loss dominates

- Mass Loss uncovers the He core at the beginning of Core He burning
- He convective core progressively recedes in mass and leaves a region of variable He
- In these stars this region is not due to the rotationally induced mixing but to the efficient mass loss that progressively erodes the He core
- Formation of He convective shell in the region of variable He in both rotating and non rotating models

Rotating and Non Rotating models show similar structures
Properties of the CO core at Core C-ignition

Rotating models show larger CO cores and smaller $^{12}$C mass fractions at core He depletion compared to the non rotating ones

Differences progressively reduce with the initial mass
THE EFFECT OF ROTATION ON THE HRD

- Progressive reduction of the effective gravity from the pole to the equator
- Mixing of core nuclear burning products outward and fresh material inward
- Different path in the HRD diagram
- Increase of the nuclear burning lifetimes
- Increase of the mean molecular weight of the envelope
- Different mass loss history
- Early entrance in the WR phase → Different mass limits and lifetimes for the various WR stages
THE EFFECT OF ROTATION

- Progressive reduction of the effective gravity from the pole to the equator
- Mixing of core nuclear burning products outward and pristine material inward
- Different path in the HRD diagram
- Increase of the nuclear burning lifetimes
- Different mass loss history
- Early entrance in the WR phase
- Various WR stages

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<th>No Rotation</th>
<th>Rotation</th>
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<td>$M_{\text{min}}$(WNL)</td>
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<td>17</td>
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<tr>
<td>$M_{\text{min}}$(WNE)</td>
<td>35</td>
<td>100</td>
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<tr>
<td>$M_{\text{min}}$(WNC)</td>
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<td>17</td>
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<td>$M_{\text{min}}$(WCO)</td>
<td>45</td>
<td>35</td>
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</table>
- Good fit to WR/O
- Discrepancies between predicted and observed WR ratios
- Good fit to the WR luminosities
THE EFFECT OF ROTATION

<table>
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<tr>
<th>Initial Mass</th>
<th>Final Mass</th>
<th>$M_H$</th>
<th>$M_{He}$</th>
<th>Progenitor</th>
<th>SN</th>
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<td>12.0</td>
<td>5.46</td>
<td>4.49</td>
<td>RSG</td>
<td>II-P</td>
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$M_{\text{max, II-P}} \simeq 17M_\odot$  
$M_{\text{min,Ib}} \simeq 35M_\odot$  
$N_{Ibc}/N_{II} \simeq 0.29$  
OK

<table>
<thead>
<tr>
<th>Initial Mass</th>
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<td>0.63</td>
<td>WC</td>
<td>Ib/c</td>
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</table>

$M_{\text{max, II-P}} \simeq 17M_\odot$  
$M_{\text{min,Ib}} \simeq 17M_\odot$  
$N_{Ibc}/N_{II} \simeq 1.16$  
Too many SN Ib/c predicted
Properties of the CO core at Core C-ignition

Rotating models show larger CO cores and smaller $^{12}$C mass fraction at core He depletion compared to the non rotating ones.

Differences progressively reduce with the initial mass.
PRESUPERNOVA MODELS: ROTATING vs NON ROTATING STARS

....hence the behavior of any given rotating star during the more advanced burning stages will resemble that of a non rotating star having a higher mass (80-120 exceptions)

Presupernova rotating models appear much more compact compared to the non rotating ones and with larger Fe cores

Rotating models have a larger binding energy compared to the non rotating ones
PRESUPERNOVA MODELS: ROTATING vs NON ROTATING STARS

[Graphs showing mass fraction distribution for different masses and velocities]
THE FINAL FATE

Hydrodynamical simulations based on induced explosions for $E_{\text{expl}} = 10^{51}$ erg

(ML & Chieffi 2003, Chieffi & ML 2012 in prep)

Larger binding energies $\rightarrow$ Larger fallback masses after the explosion $\rightarrow$ Rotating models less efficient in polluting the ISM with heavy elements

In both cases no, or very few, heavy elements ejected for models with $M > 20 \, M_\odot$

Difficult to compare the ejected masses in this case
Comparison made for a fixed amount of $^{56}\text{Ni}$ ejected

- Differences confined with a factor of 2 for the majority of the elements

EJECTED MASSES: COMPARISON
Comparison made for a fixed amount of $^{56}$Ni ejected

- Differences confined with a factor of 2 for the majority of the elements
- Overproduction of C and O in low-mass rotating models
Comparison made for a fixed amount of $^{56}\text{Ni}$ ejected

- Differences confined with a factor of 2 for the majority of the elements
- Overproduction of C and O in low-mass rotating models
- Overproduction of F in rotating models with mass 20-40 $M_\odot$
Comparison made for a fixed amount of $^{56}\text{Ni}$ ejected

- Differences confined with a factor of 2 for the majority of the elements
- Overproduction of C and O in low-mass rotating models
- Overproduction of F in rotating models with mass 20-40 $M_\odot$
- Overproduction of Si-Sc elements in rotating models with mass ~ 20-25 $M_\odot$
Comparison made for a fixed amount of $^{56}\text{Ni}$ ejected

- Differences confined with a factor of 2 for the majority of the elements
- Overproduction of C and O in low-mass rotating models
- Overproduction of F in rotating models with mass 20-40 $M_\odot$
- Overproduction of Si-Sc elements in rotating models with mass $\sim$ 13-25 $M_\odot$
- Overproduction of s-process elements in rotating models with mass 20-40 $M_\odot$
<table>
<thead>
<tr>
<th>Element</th>
<th>Production Site</th>
<th>Ejected Mass Ratio (Rot/No Rot)</th>
<th>Reason</th>
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<tbody>
<tr>
<td>C</td>
<td>Hydrostatic Core and Shell He burning</td>
<td>~3-2 for M&lt;30 $M_\odot$</td>
<td>Larger CO cores/Hotter He convective shells (In spite of the lower $^{12}$C left by core He burning)</td>
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<tr>
<td>O</td>
<td>Hydrostatic Core He burning</td>
<td>~5-2 for M&lt;25 $M_\odot$</td>
<td>Larger CO cores/Larger $^{16}$O left by Core He burning</td>
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<tr>
<td>F</td>
<td>Hydrostatic He convective shell</td>
<td>~20 around M=30 $M_\odot$</td>
<td>Hotter He convective shell</td>
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<td>Si-Sc</td>
<td>Explosive burning</td>
<td>~2 for M&lt;30 $M_\odot$</td>
<td>More compact PreSN structure → more mass synthesized by all the explosive burning</td>
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<tr>
<td>s-process</td>
<td>Hydrostatic Core He burning and Hydrostatic Convective C burning</td>
<td>~7 around M=30 $M_\odot$</td>
<td>Longer He burning lifetimes Larger He convective cores Hotter C convective shell</td>
</tr>
</tbody>
</table>
Rotating models produce more metals compared to the non rotating ones because of the larger CO cores and more compact structures.

Differences reduce with the mass.
PRODUCTION FACTORS
EVOLUTION OF THE ANGULAR MOMENTUM

During core H burning the angular momentum transport is dominated by the meridional circulation and by mass loss – the relative efficiency depending on the initial mass.

From Core He exhaustion onward the evolution of the angular momentum is dominated by the local conservation and by the convective mixing.
IMPLICATIONS FOR YOUNG PULSARS AND GRBs

If the hydrodynamical simulations are wrong and we assume that all the stars would collapse to a NS with a mass corresponding roughly to the Iron Core Mass and a Radius of 12 Km

These models have even much more angular momentum in the collapsing iron core than a neutron star can possibly carry

Treatment of angular momentum transport still highly uncertain (advection/diffusion, transport mechanisms and their efficiency) → should be revised

Important the role of magnetic field (see Heger et al. 2005)
If the large angular momenta obtained for the iron cores in this work may pose a problem for pulsars, they are very favorable for the GRBs.

These models imply that all WR stars can retain enough angular momentum to produce GRBs, either by magnetar or collapsar formation depending on the final mass. This gives a nearly 1000 times higher ratio of GRBs to SNe than the observationally implied value.
The inclusion of a more efficient mass loss during the RSG phase (dust driven wind) lowers the maximum mass for SN-IIP from $\sim 30 \, M_\odot$ (old models) to $\sim 17 \, M_\odot$ without changing the maximum mass evolving as RSG, independent of rotation.

The inclusion of rotation reduces the minimum mass that becomes a WR star from $\sim 22 \, M_\odot$ (non rotating models) to $\sim 17 \, M_\odot$ and the minimum masses for all the various WR stages and also the minimum mass for SNIIb/c from $\sim 30 \, M_\odot$ (non rotating models) to $\sim 17 \, M_\odot$.

- Improve the fit to WR/O and to WR luminosities
- Discrepancies between predicted and observed WR ratios still remain
- Sharp transition from SNIIIP to SNIIb - too many SNIIb/c predicted

Rotating models are much more compact and with larger iron cores than the non rotating ones (due to larger CO cores and lower $^{12}$C mass fractions @ core He depletion).

- Larger binding energies
- Implications for CCSN explosion simulations
- Average mass of NS remnant larger than observed
- Larger fallback masses $\rightarrow$ Lowering of the $M_{NS/BH}$ from 22 to $14 \, M_\odot$

The angular momentum of the core of rotating models is too large:

- NS remnants rotating too fast
- GRB/SN ratio severely overestimated

SUMMARY
SUMMARY

- Differences in the final yields confined within a factor of ~2 for the majority of the elements
- Overproduction of C and O more pronounced in the low-mass models
- Overproduction of Si-Sc elements in models with mass ~ 20-25 M\(_{\odot}\)
- Overproduction of F and s-process elements in models with mass ~ 20-40 M\(_{\odot}\)
- F and s-process elements distribution closer to the solar one in stars with mass ~ 25-40 M\(_{\odot}\)