Mass and Luminosity of type II Sne progenitors

OSCAR STRANIERO

ITALIAN NATIONAL INSTITUTE OF ASTROPHYSICS

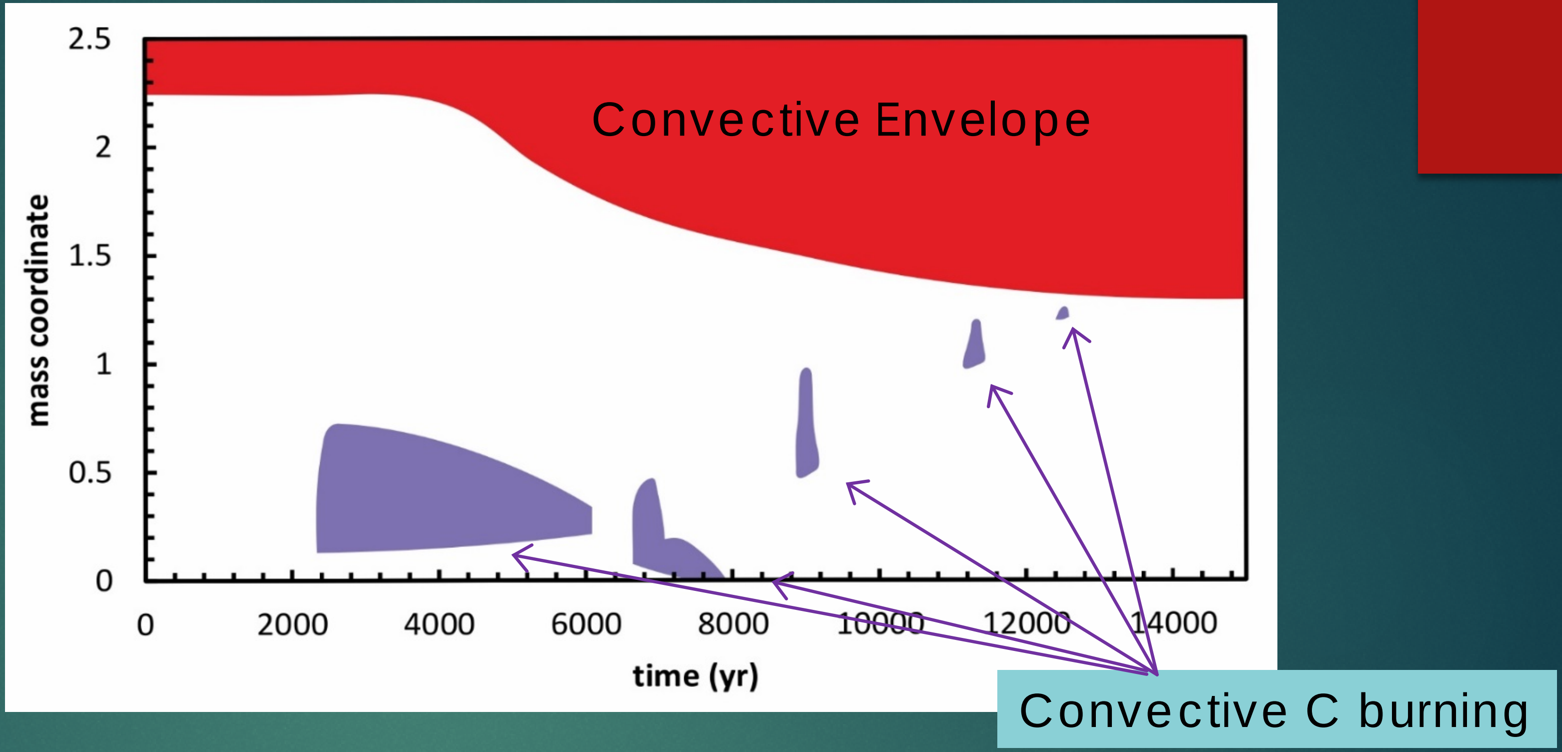
Do we really know the core-collapse progenitors ?

Mass ($M_\odot$)

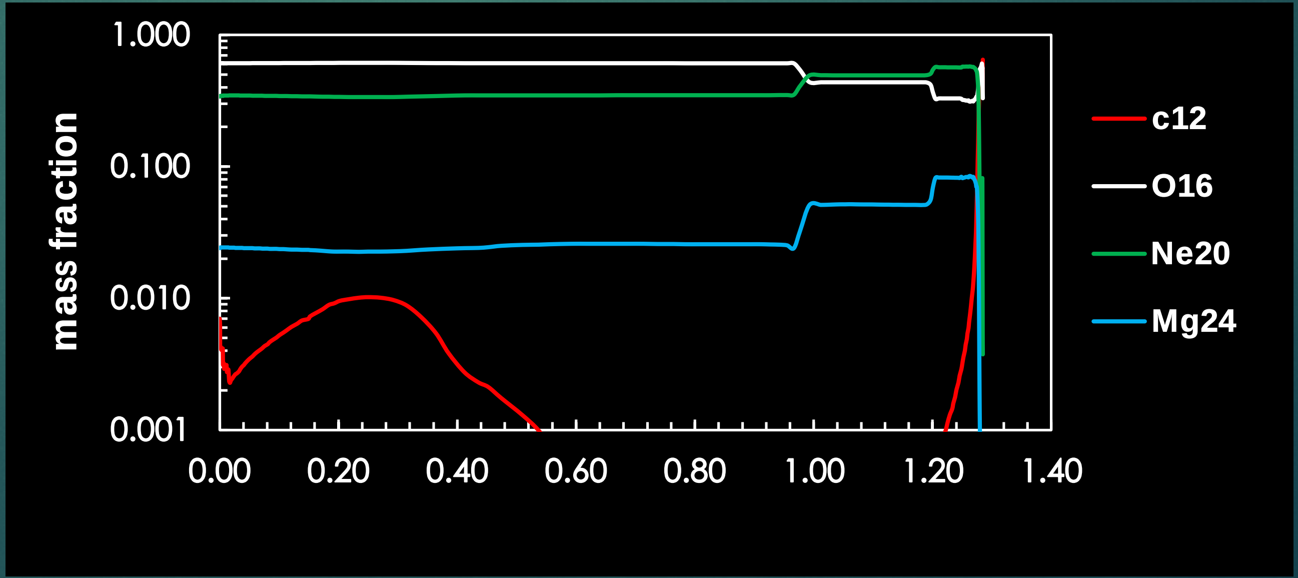
No C	7.5	Off center	9	Off center	10	Off center	12	Central Ne/O/Si	30	SNe
AGB		degenerate C		degenerate C		degenerate		Core collapse		Ib/c
CO WD		SAGB		SAGB		Ne/O/Si		SNe IIP		
		CONe WD		SAGB		Core collapse				
				One WD		SNe IIP?				
				or						
				EC SNe?						

ROTATION ←

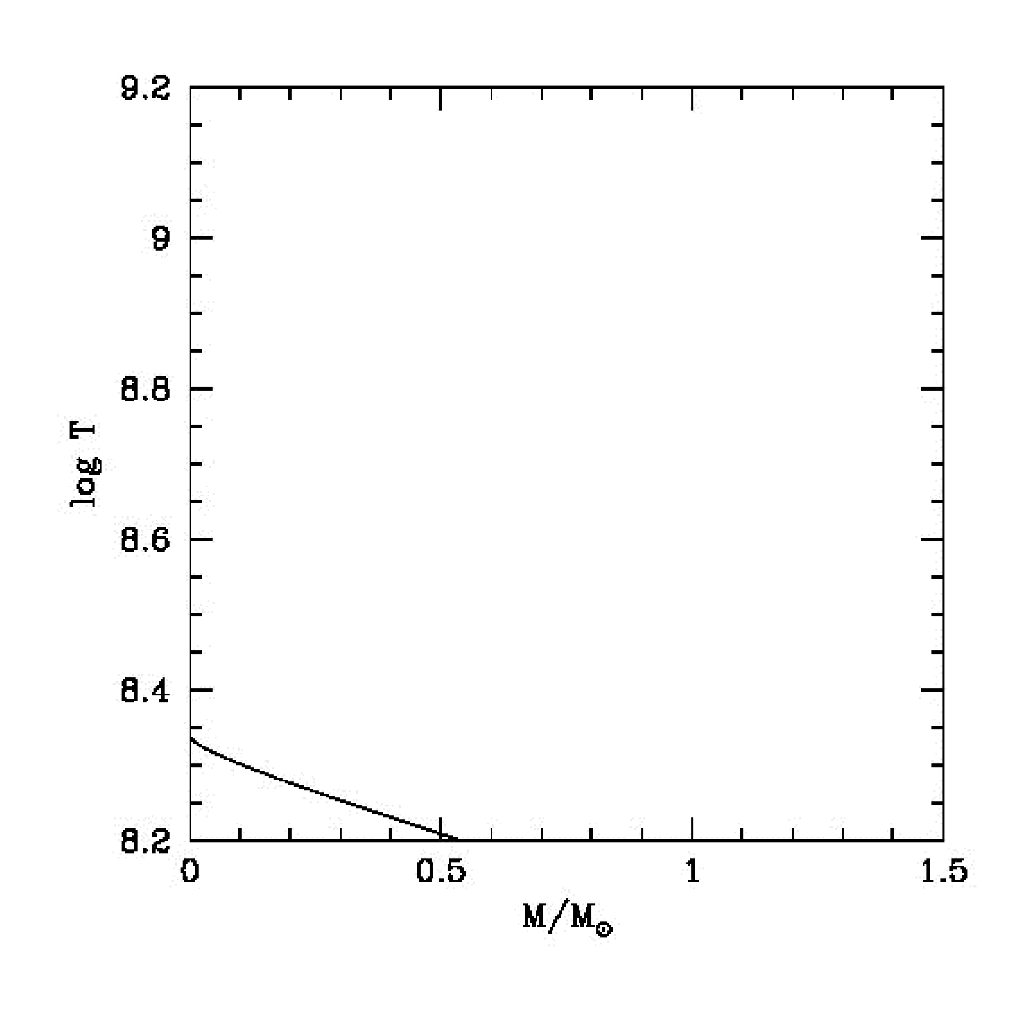
C burning
9 M⊙
Z=0.02
Y=0.27

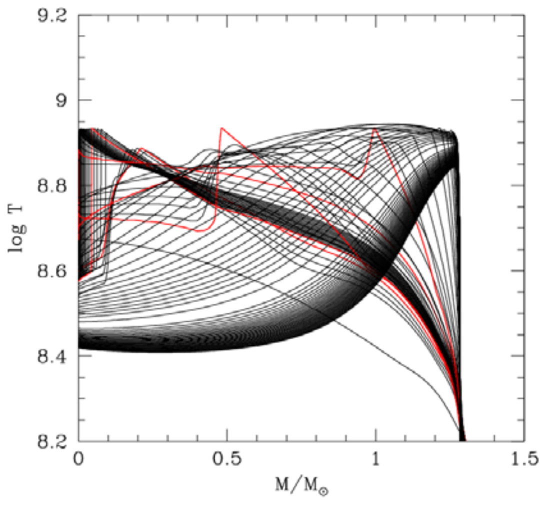


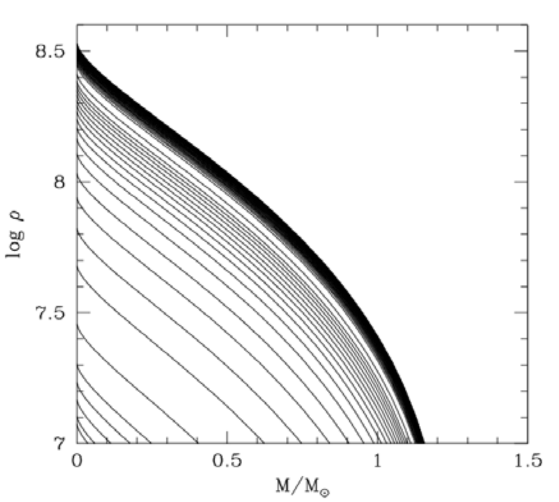
Final core composition



Evolution of the temperature within the core

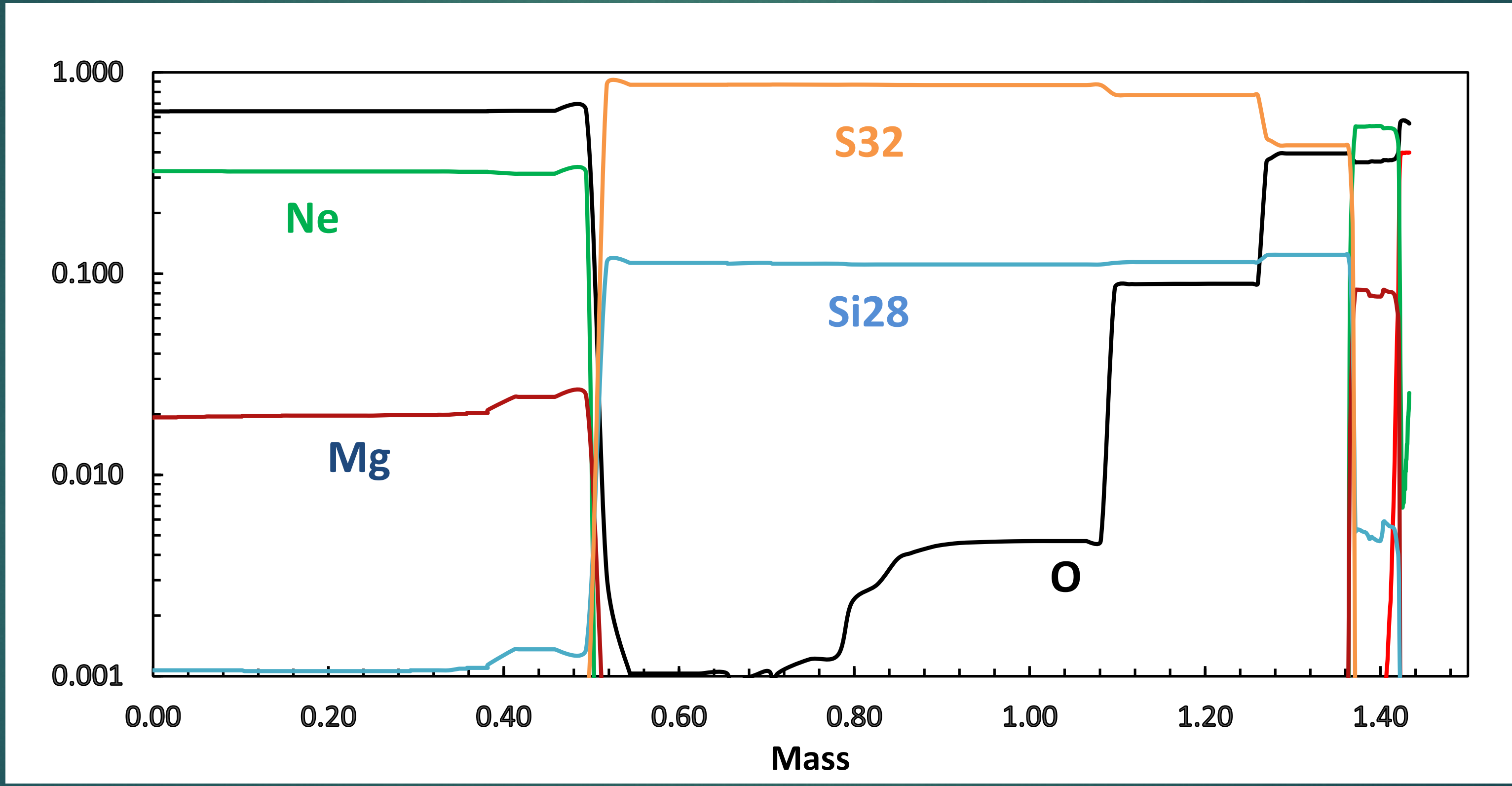






A slightly higher mass: 10 M☉ (the CRAB progenitor)

Off-center Ne, O, Si ignitions



More than 10^6 stellar structures to complete the evolution (up to the core collapse).

Burning flame

More massive stars

- 12-30 $M_\odot$, central ignitions of C-O-Ne-Si.
  Expected **progenitors of type II SNe**.

- More massive objects, $M>30\ M_\odot$, H-rich envelope eroded by stellar wind before the final collapse.
  Expected **progenitors of Ib and Ic SNe**

Extant estimates of the progenitor (initial) masses are based on:

1. Pre-explosive luminosity
2. Properties of the light curves
3. Nucleosynthesis yields (Oxygen)

All these estimates are model dependent and the uncertainties affecting the stellar physics introduce systematic errors !!

For a few nearby type II SNe , the progenitors have been discovered in pre-explosive photometric frames.

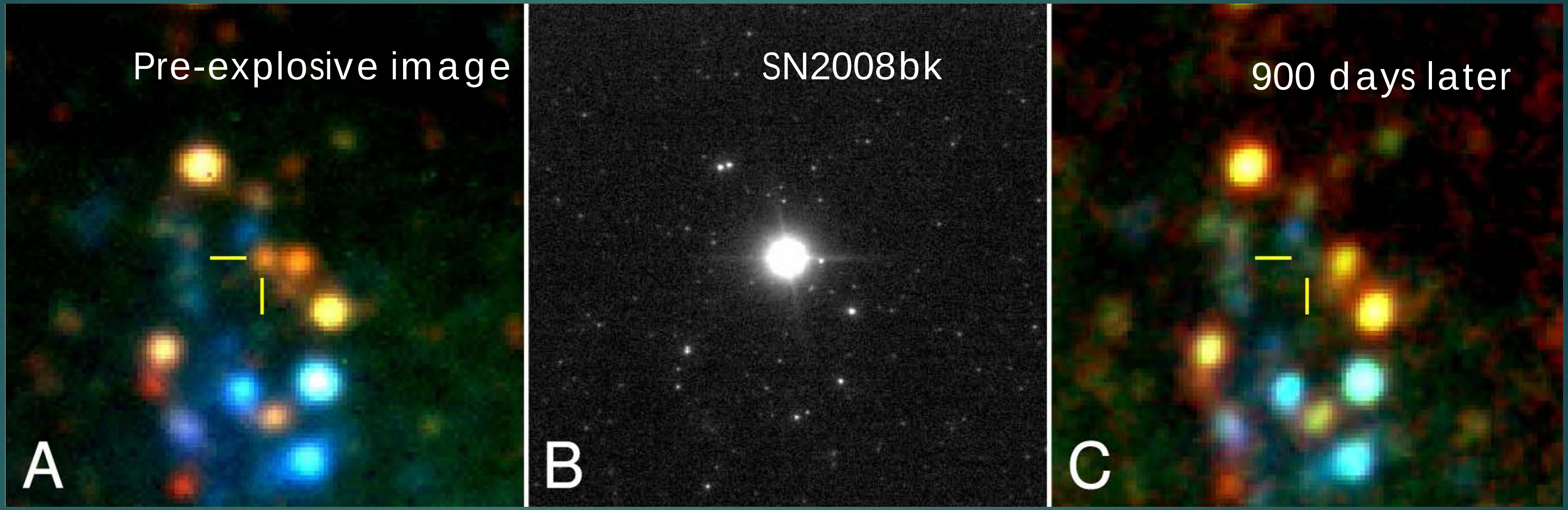


Figure 8. Upper: The visually striking illustration of the disappearance of the red supergiant progenitor of SN2008bk, from Mattila et al. (2010). Panel A shows the VLT colour image of the progenitor (marked). Panel B shows the VLT NACO image of SN2008bk and the surrounding population at high resolution. Panel C shows an NTT colour image at approximately 940 days after explosion illustrating the disappearance of the red source. The quantitative mass estimates of the progenitor are in Maund et al. (2014a).

from Smartt 2015

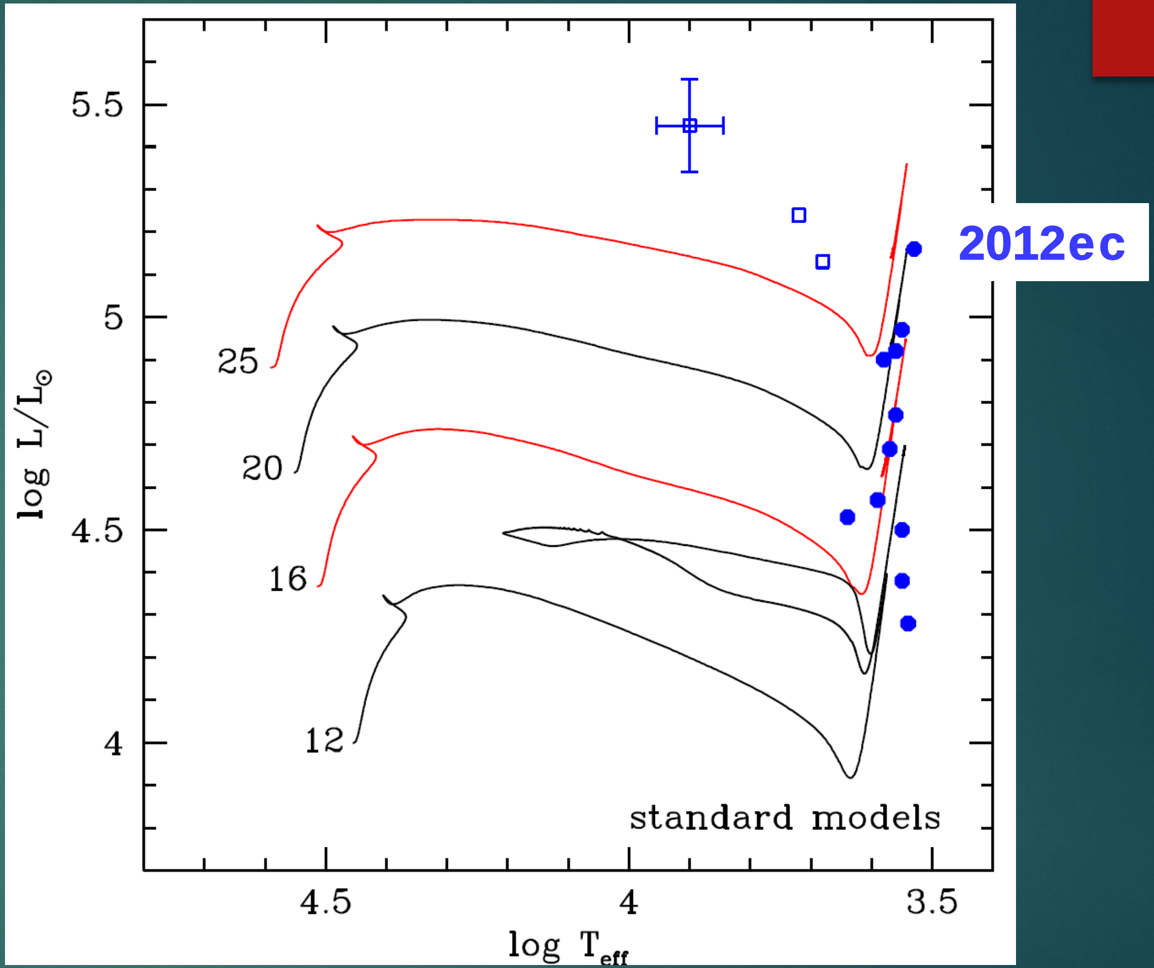
By comparing the observed pre-explosive luminosities (blue dots) to extant evolutionary tracks, one gets for the initial progenitor masses:

$$9 \leq M \leq 20$$

or

$$9 \leq M \leq 17$$

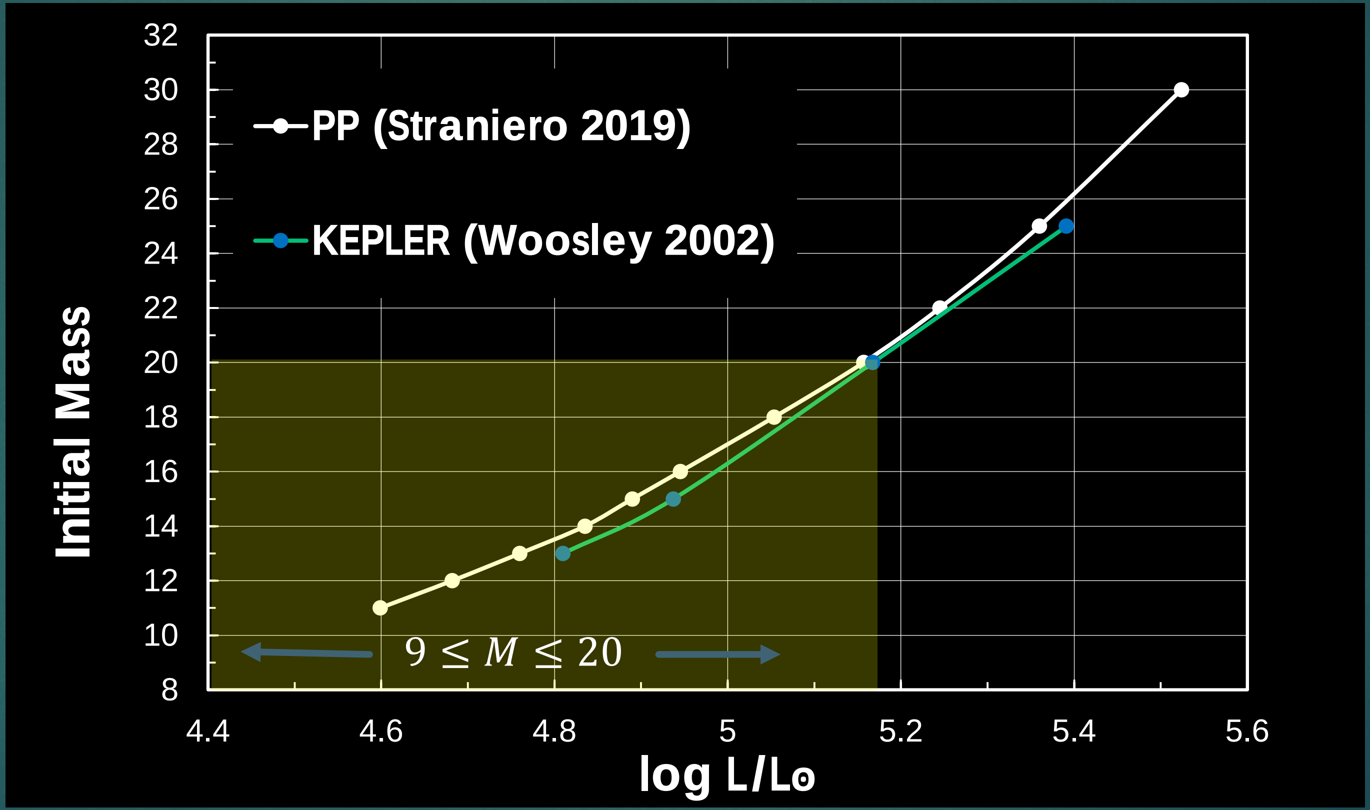
(IIP only-SN 2012ec)



L/T_{eff} SN II progenitors from Davies+ 2018
FuNS models from Straniero+ 2019.

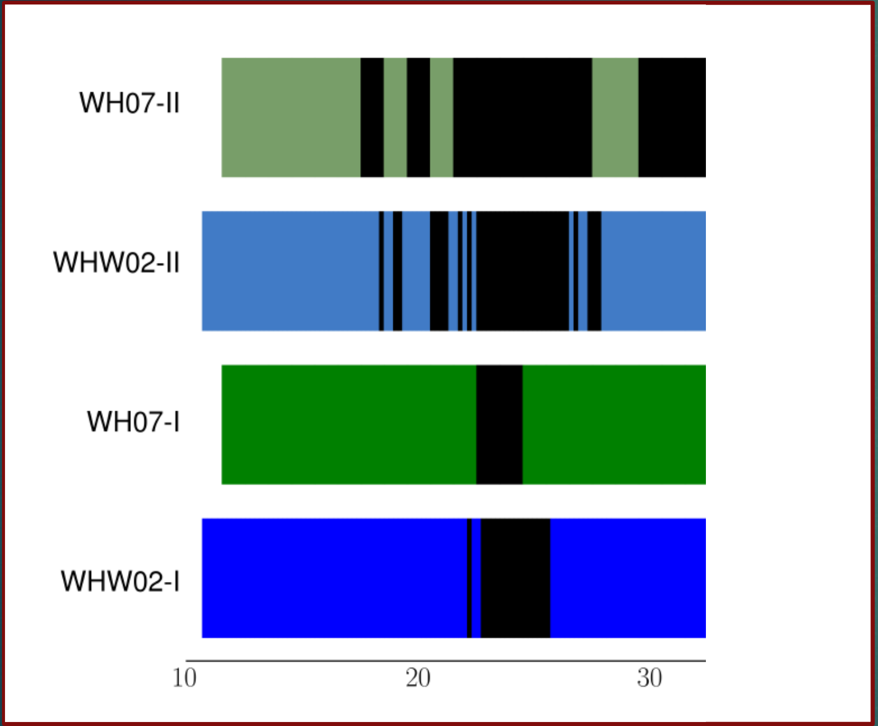
INITIAL MASSS vs FINAL LUMINOSITY

NON-rotating models (solar composition)



Explodability

All the red supergiants undergo a core-collapse, but only some of them explode!



adapted from Ebinger et al. 2018

Parametric studies 1d explosions

- All the models with $M \leq 15\ M_\odot$ give rise to successful SN IIP, but weak explosion for $M \leq 12\ M_\odot$.
- There exists islands of explodability, for $15 < M < 22\ \ and\ 25 < M < 27$.

O'Connor & Ott 2011; Ugliano et al. 2012; Horiuchi et al. 2014; Pejcha & Thompson 2015; Sukhbold et al. 2016; Ertl et al. 2016; Ebinger et al. 2018. **CARLA FROHLICH talk**

L is not a monotonic function of M

$$L = f(M_{He}) \qquad \textit{but} \qquad M_{He} = g(M, v, Y, Z)$$

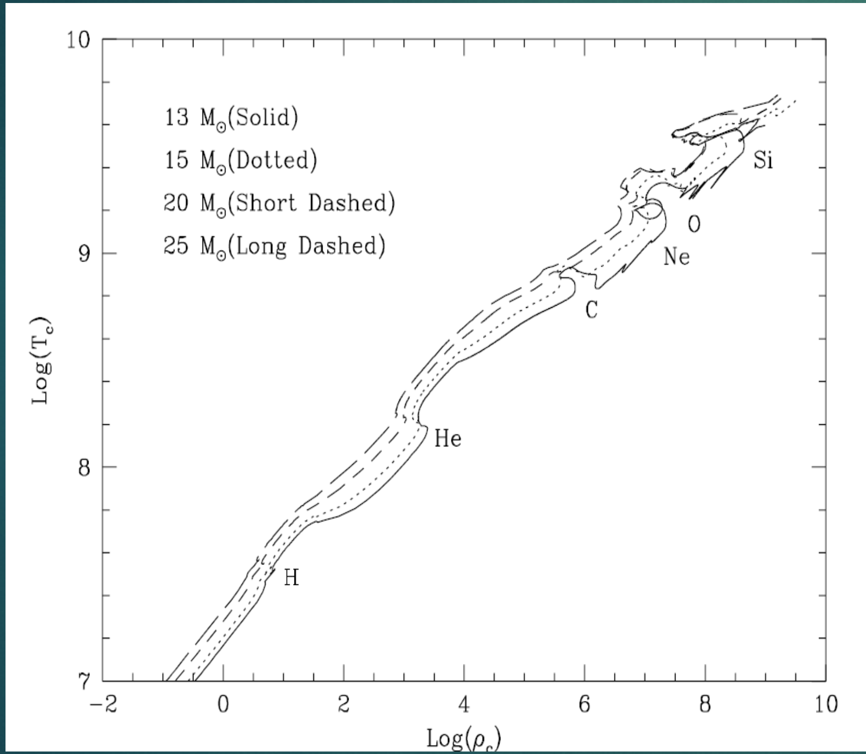
The pre-explosive luminosity depends on the initial values of: mass, rotational velocity, He mass fraction, metallicity

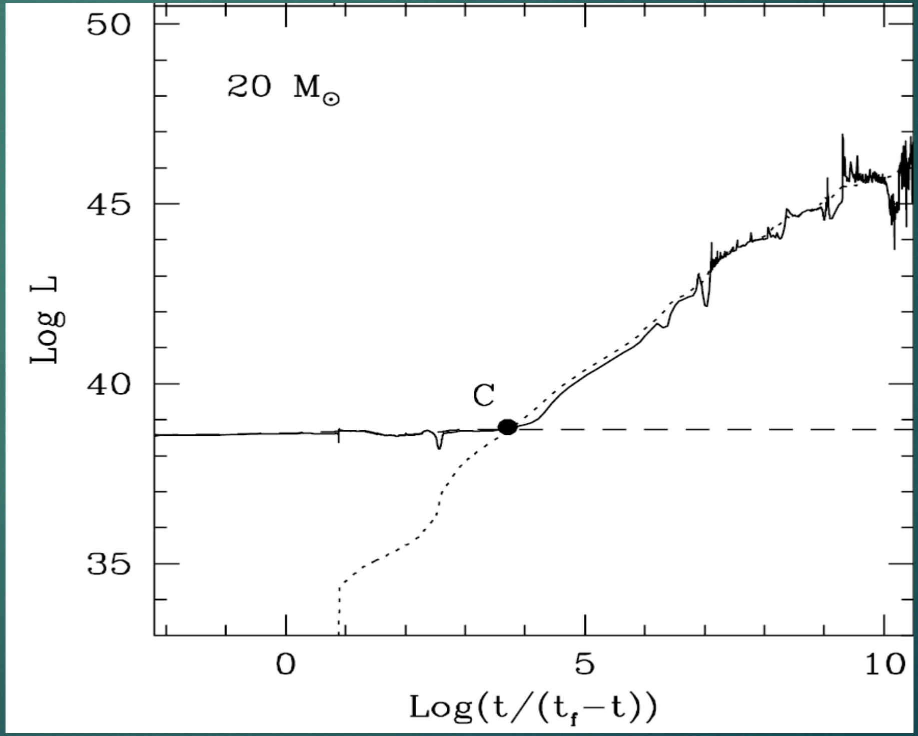
The luminosity of a red supergiant depends on its He-core mass!

- On the red giant branch the **electromagnetic power** (luminosity) is supplied by the **shell-H burning**.
- On the other hands, T and ρ at the shell depend on the He-core mass.
- **The larger the core mass, the hotter (and thinner) the shell and, in turn, the brighter the star.**

He-core (and L) freeze-out. During the late evolution, the temperature within the core becomes > 100 keV (like in BBN era). Neutrinos productions (Compton+pair) is the dominant energy-loss process:

$$\epsilon_{neutrinos} \gg \epsilon_{photons}$$





Nuclear (solid)
Photons (dashed)
Neutrinos (dotted)

Limongi, Chieffi & Straniero 1998

Rotation

The lifting due to rotation affects the hydrostatic equilibrium and the temperature gradient. The equipotential surface do not coincide with the isobars:

$$\Psi = -\frac{GM}{r} - \frac{1}{2}\omega^2 r^2 \sin^2\vartheta = \text{constant}$$

Von Zeipel paradox: thermal and hydrostatic equilibrium cannot be simultaneously satisfied. This occurrence induces **meridional circulation** that implies **transport of angular momentum and mixing.**

Rotation, initially uniform, naturally evolves into **differential rotation**, which may induce turbulence and, in turn, further instabilities:

- Eddington-Sweet (ES)
- Goldreich-Schubert-Fricke
- Secular shear
- Dynamical shear
- Solberg-Hoiland

According to Kippenhahn 1974:

$$v_{\mathrm{ES}} = \frac{\nabla_{ad}}{\delta(\nabla_{ad} - \nabla)} \frac{\omega^2 r^3 L}{(Gm)^2} \left[\frac{2\varepsilon r^2}{L} - \frac{2r^2}{m} - \frac{3}{4\pi \rho r} \right]$$

Meridional circulation is inhibited by a molecular weight gradient. It is like an anti-circulation whose velocity is given by:

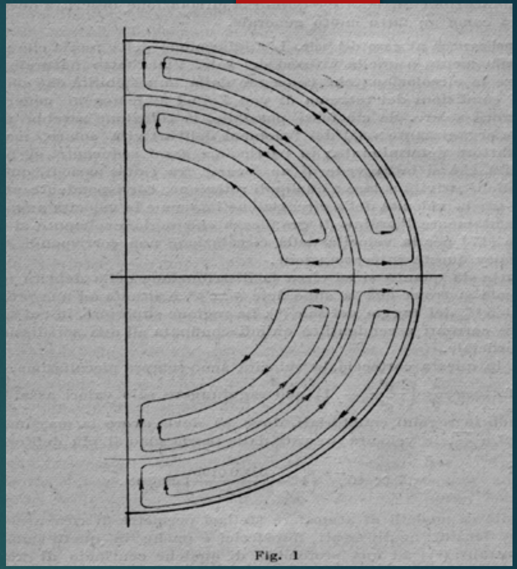
$$v_{\mu} = f_{\mu} \frac{H_P}{\tau_{\mathrm{th}}} \frac{\varphi \nabla_{\mu}}{\nabla - \nabla_{ad}},$$

so that:

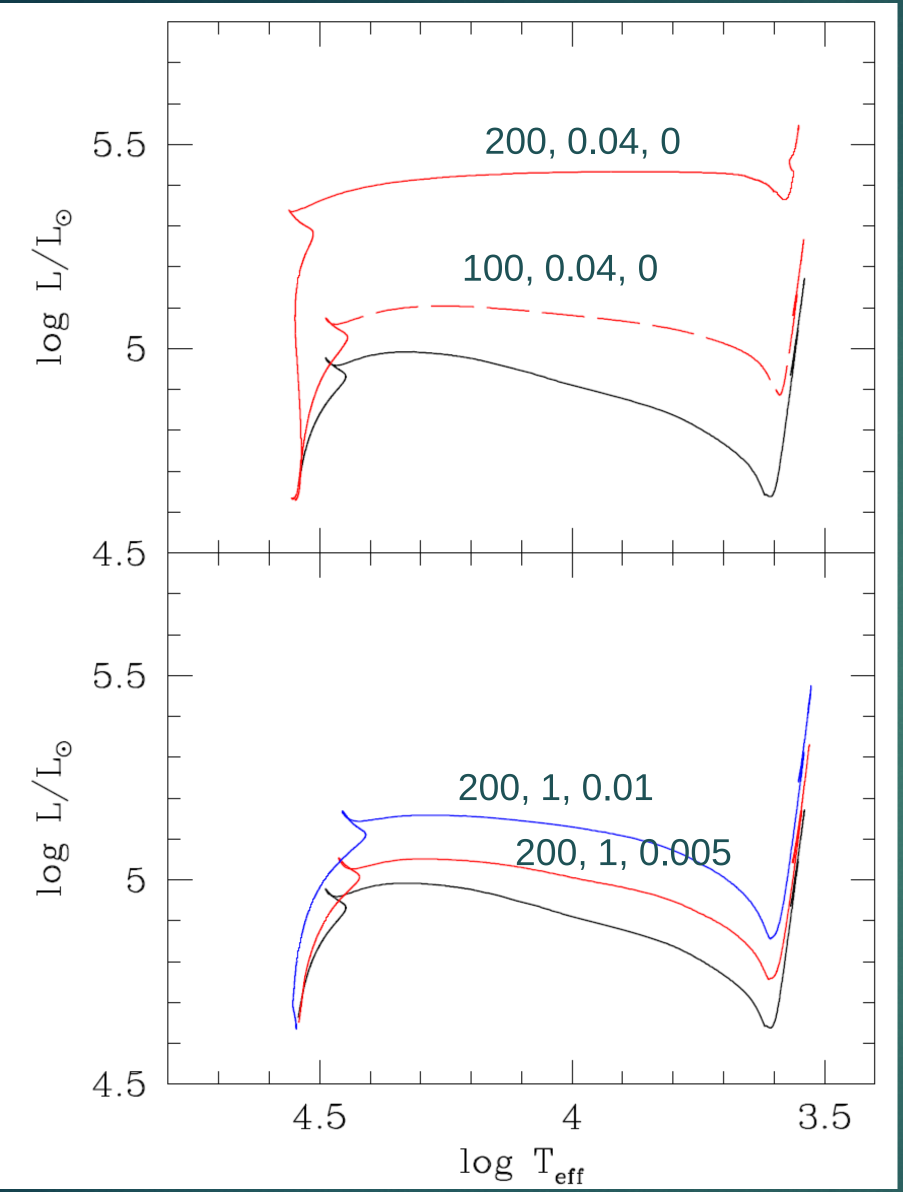
$v_{circ} = |v_{ES}| - |v_{\mu}|$ ← **angular momentum redistribution**

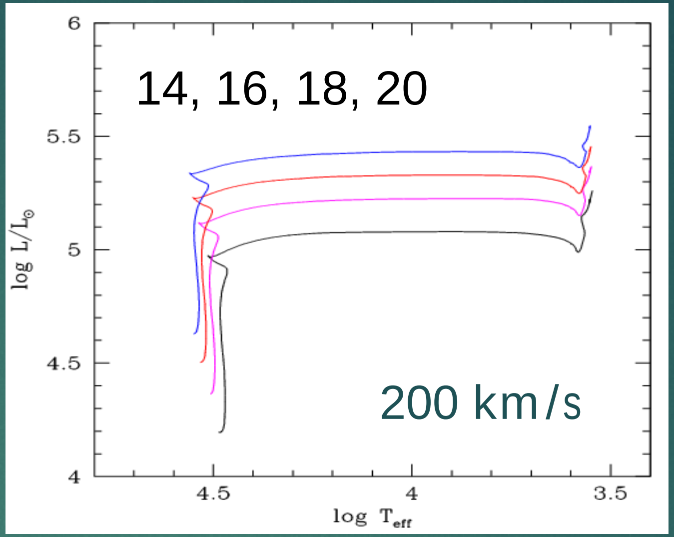
The mixing velocity, is proportional to v_{circ}:

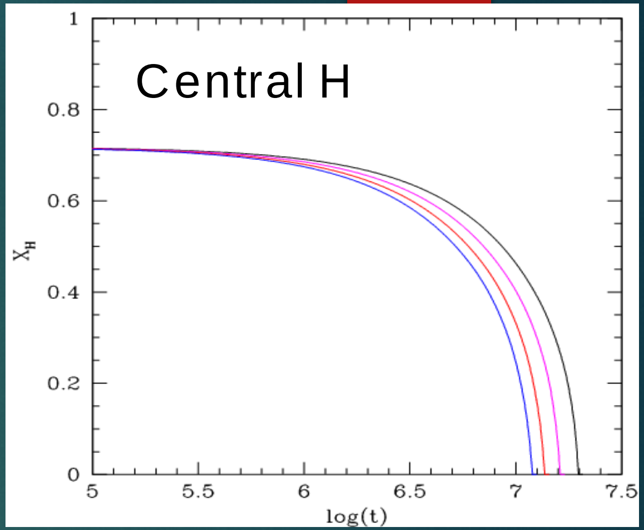
$v_{mixing} = f_C v_{circ}$ ← **mixing**

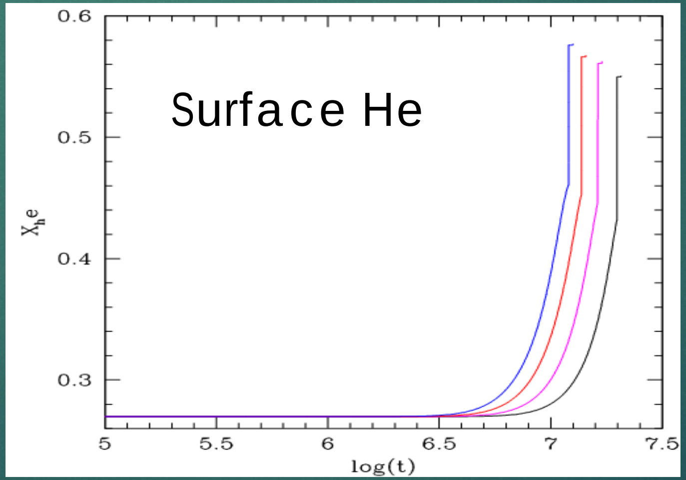


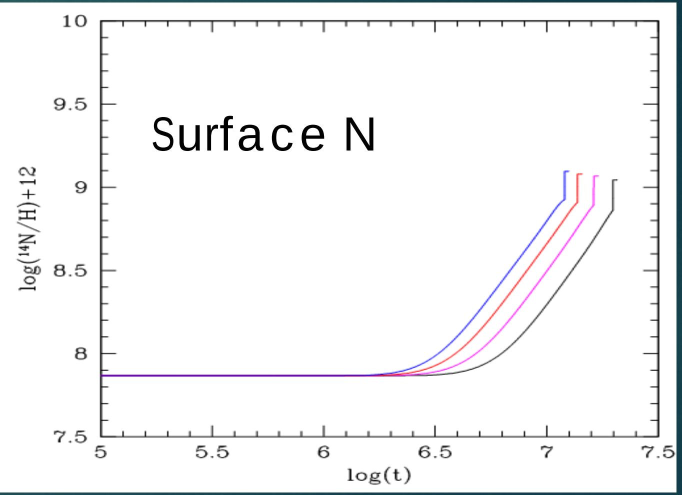
Livio Gratton 1944





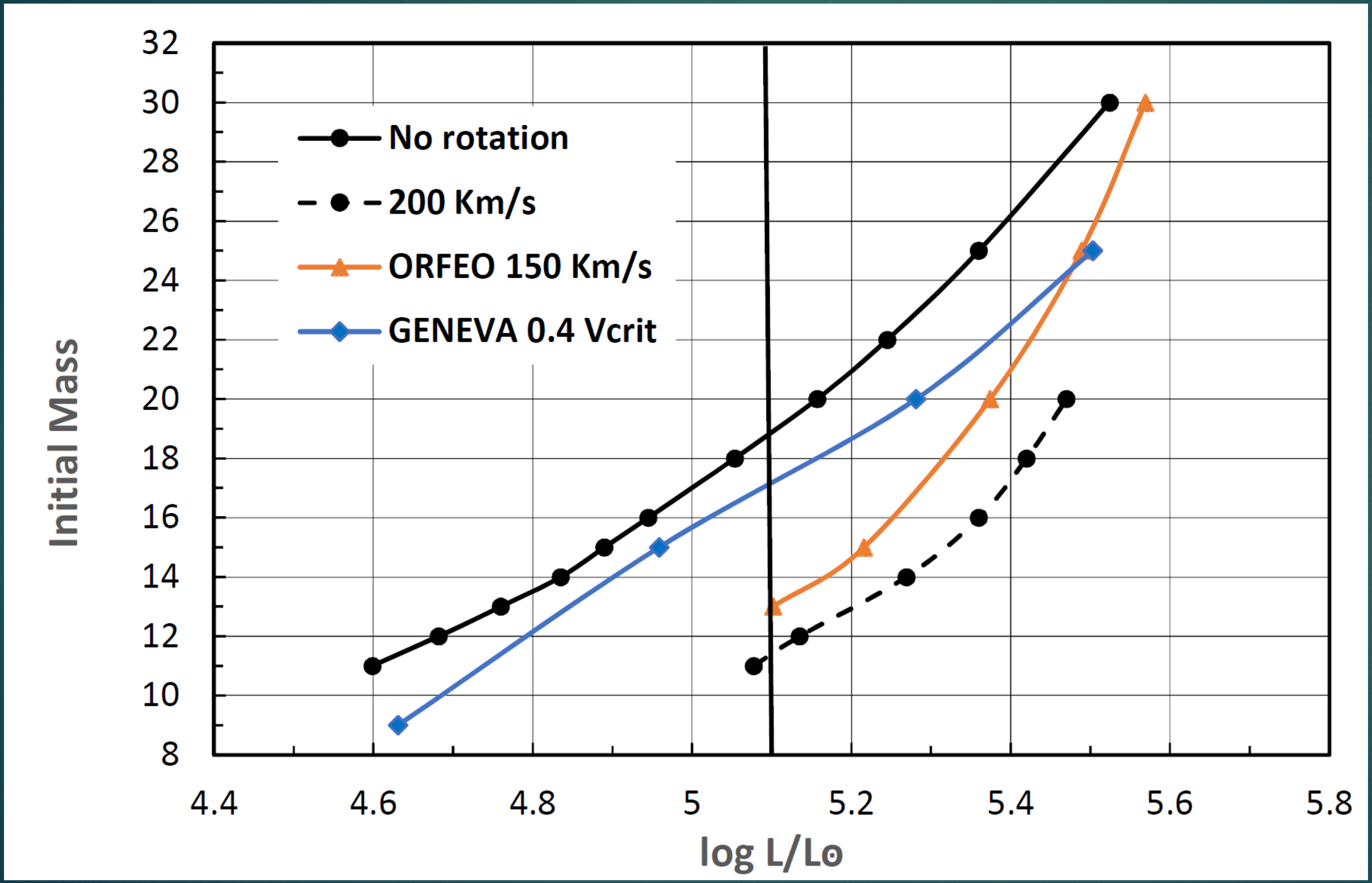






...but the effect depends on f_C , f_μ and v_{ini} !!

Rotation → Larger He-core → Higher Final Luminosity !



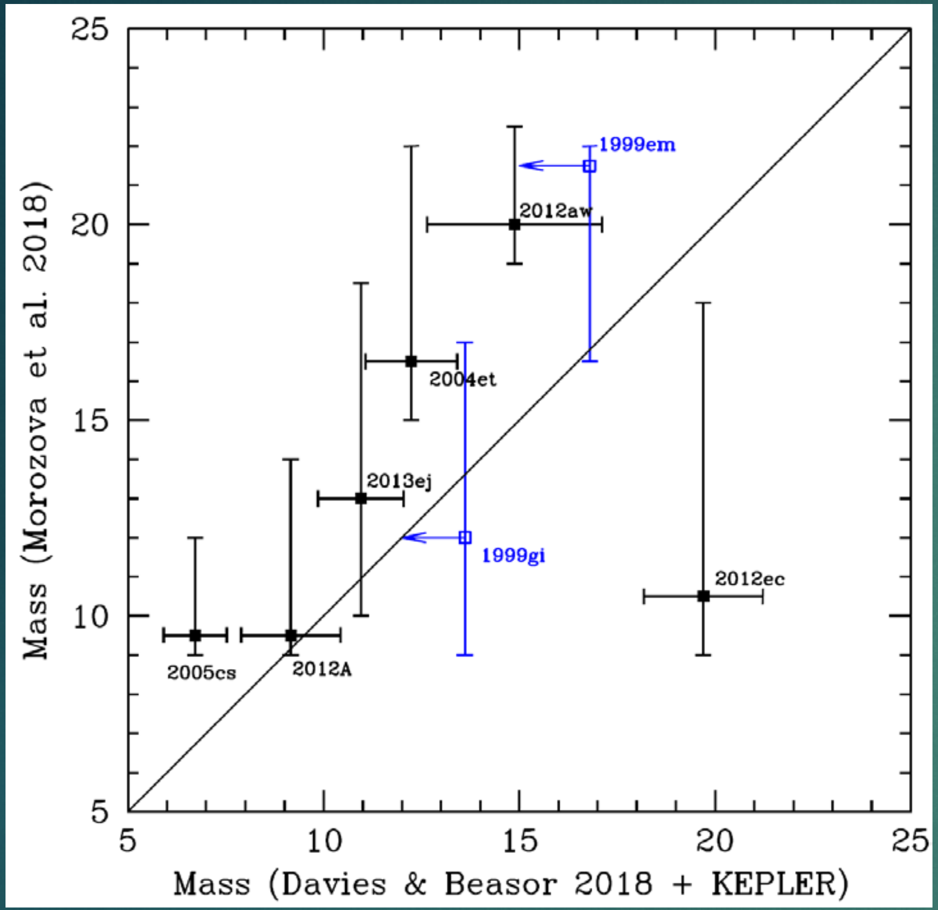
GENEVA (Meynet et al. 2015)
ORFEO (Limongi & Chieffi 2018)

Same final luminosity, but different Initial mass !

Table 1. Initial Mass of type II SN progenitors with final luminosity $\log L/L_{\odot} = 5.1$.

Name	$M/M_{\odot}$	Reference
Standard non-rotating Models		
FuNS	18.9	present work
KEPLER	18.5	Woosley et al. (2002)
with convective overshoot		
$\beta = 0.01$	17.0	present work
$\beta = 0.02$	13.8	present work
GENEVA	18.9	Meynet et al. (2015)
ORFEO	17.4	Limongi & Chieffi (2018)
STARS	15.6	Eldridge & Tout (2004)
with rotation		
$V_{ini} = 200 km/s$	11.8	present work
$V_{ini} = 150 km/s$	13.0	Limongi & Chieffi (2018)
$V_{ini} = 0.4 V_{crit}$	17.1	Meynet et al. (2015)
with axion energy loss		
$g_{10} = 0.6, g_{13} = 0$	19.8	present work
$g_{10} = 0.6, g_{13} = 4$	20.9	present work

Both rotation and overshooting reduce the progenitor mass estimated by means of the observed pre-explosive luminosity.



- SN2013ec, with the brightest progenitors and a rather low initial mass, would require high equatorial velocity (>200 km/s).
- SN2004et, SN2012aw e SN1999em, higher masses, but too faint progenitors, appears incompatible with the current theoretical scenario.

Excluding SN 2012ec, the mass estimated from the luminosity curve are ***2.9±0.8 M⊙*** *higher than those derived from the progenitor luminosity !!*

HINTS FOR NEW PHYSICS.

Larger initial masses, or lower final L, can be ONLY obtained by anticipating the *L* freeze-out.

Possible solutions:

- An increase of the thermal neutrinos rate, as due to ***a non-zero neutrino magnetic moment.***
- Strong reduction of the S(E) factor of the $^{12}C+^{12}C$ reaction for $E \leq 2$ MeV (***Hindrance***?)
- An additional energy-loss process, as due to the production WISPS (weak interactive small particles), such as ***Axions or ALPs***.

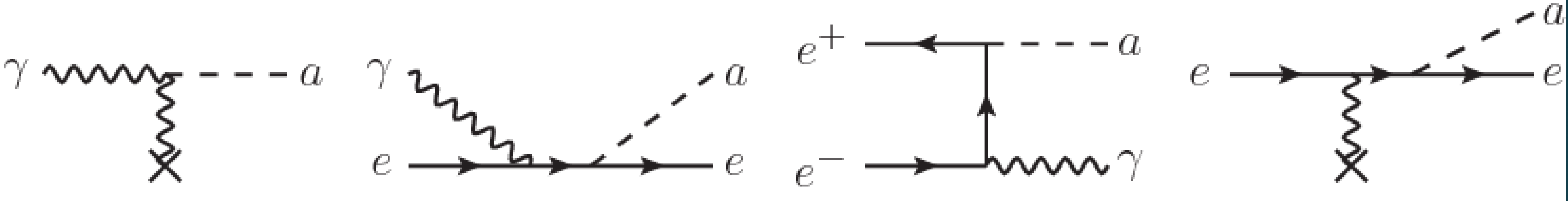
$\boldsymbol{\mu_\nu > 0}$:

by assuming the current upper bound $\mu_\nu = 5 \times 10^{-11} \mu_B$ *(reactor neutrinos, GEMMA, or solar neutrinos Borexino)*, ***we get 2% reduction of the pre-explosive luminosity*** (but more stringent constraint from astrophysics, Viaux et al. 2013).

^{12}C+^{12}C reaction rate:

Hindrance seems to be excluded by the most recent experimental investigations (Zickefoose+ 2018, Tumino+ 2018).

Thermal Axion production in stellar cores



Primakoff Process Compton Process Pair Annihilation Bremsstrahlung

The most important for (non-degenerate) massive stars ($M \geq 11 M_{\odot}$ are Primakoff and Compton Axions

Primakoff:

$$\gamma + Ze \rightarrow a + Ze$$

The axion-photon Lagrangian

$$\mathcal{L} = -\frac{g_{a\gamma}}{4} F\tilde{F} = g_{a\gamma} \mathbf{E} \cdot \mathbf{B}$$

The Primakoff recipes:

The rate depends on the square of the coupling constant $g_{10} = g_{a\gamma}/10^{-10}$ GeV^{-1}, and on the forth power of the temperature.

1. $y_{\rm pl}$ (in the numerical expression, $\rho_{\rm cg}$ is in g cm^{-3} and $T_{\rm K}$ in K)

$$y_{\rm pl} = \frac{\omega_{\rm pl}}{T} = \frac{3.33 \times 10^5}{T_{\rm K}} \frac{(\rho_{\rm cg}/\mu_e)^{1/2}}{(1 + (1.019 \times 10^{-6} \rho_{\rm cg}/\mu_e)^{2/3})^{1/4}}; \tag{46}$$

2. $z = \dfrac{\rho_{\rm cg}}{T_K^{3/2}\,\mu_e}$;

3. $\theta_{\rm deg}$, given by the fit below:

$$\begin{cases} \theta_{\rm deg} = 1\,, & \text{for } \; z \leq 5.45 \times 10^{-11}\,, \\ \theta_{\rm deg} = 0.63 + 0.3 \tan^{-1}\left(0.65 - 9316\, z^{0.48} + \dfrac{0.019}{z^{0.212}}\right)\,, & \text{for } \; 5.45 \times 10^{-11} < z \leq 7.2 \times 10^{-8}\,, \\ \theta_{\rm deg} = 4.78 \times 10^{-6}\, z^{-0.667}\,, & \text{for } \; z > 7.2 \times 10^{-8}\,. \end{cases} \tag{47}$$

4. $y_{\rm S}$ in the following steps:

$$\begin{aligned} y_{\rm ions} &= \frac{\kappa_{\rm ions}}{T} = 2.57 \times 10^{10} \left(\frac{\sum_{\rm ions} Z_j^2 X_j}{A_j}\right)^{1/2} \left(\frac{\rho_{\rm cg}}{T_{\rm K}^3}\right)^{1/2}, \\ y_{\rm el} &= \frac{\kappa_{\rm el}}{T} = 2.57 \times 10^{10}\, \theta_{\rm deg} \left(\frac{\sum_{\rm ions} Z_j X_j}{A_j}\right)^{1/2} \left(\frac{\rho_{\rm cg}}{T_{\rm K}^3}\right)^{1/2}, \\ y_{\rm S} &= \sqrt{y_{\rm ions}^2 + y_{\rm el}^2}\,. \end{aligned} \tag{48}$$

5. The function $g(y_{\rm pl}, y_{\rm S}, y_m)$ by interpolating the table "new_data_g_mass.dat".

6. $f(y_{\rm pl}, y_{\rm S}, y_m)$:

$$f(y_{\rm pl}, y_{\rm S}, y_m) = \frac{100\,(1 + {y_{\rm pl}}^2)\,(1 + {y_m}^2)}{(1 + {y_{\rm S}}^2)\,(1 + e^{y_{\rm pl}})}\, g(y_{\rm pl}, y_{\rm S}, y_m)\,. \tag{49}$$

$$\varepsilon = 4.706 \times 10^{-31} g_{10}^2 T_{\rm K}^4 \frac{\rm erg}{\rm g \cdot s} \left[\sum_{\rm ions} (Z_j^2 + \theta_{\rm deg} Z_j) \frac{X_j}{A_j}\right] f(y_{\rm pl}, y_{\rm S}, y_m)$$

Compton: $\gamma + e \to \gamma +$ [redacted]

The Compton recipes:
The rate depends on the square of the axion-electron coupling, $g_{13} = g_{ae}/10^{-13}$, and on the sixth power of the temperature.

$$\varepsilon_{\mathrm{compton}} = \theta_{\mathrm{deg}} 2.66 \times 10^{-48}\, g_{13}^2 \frac{T^6}{\mu_e} \,\mathrm{erg\,g^{-1}\,s^{-1}}$$

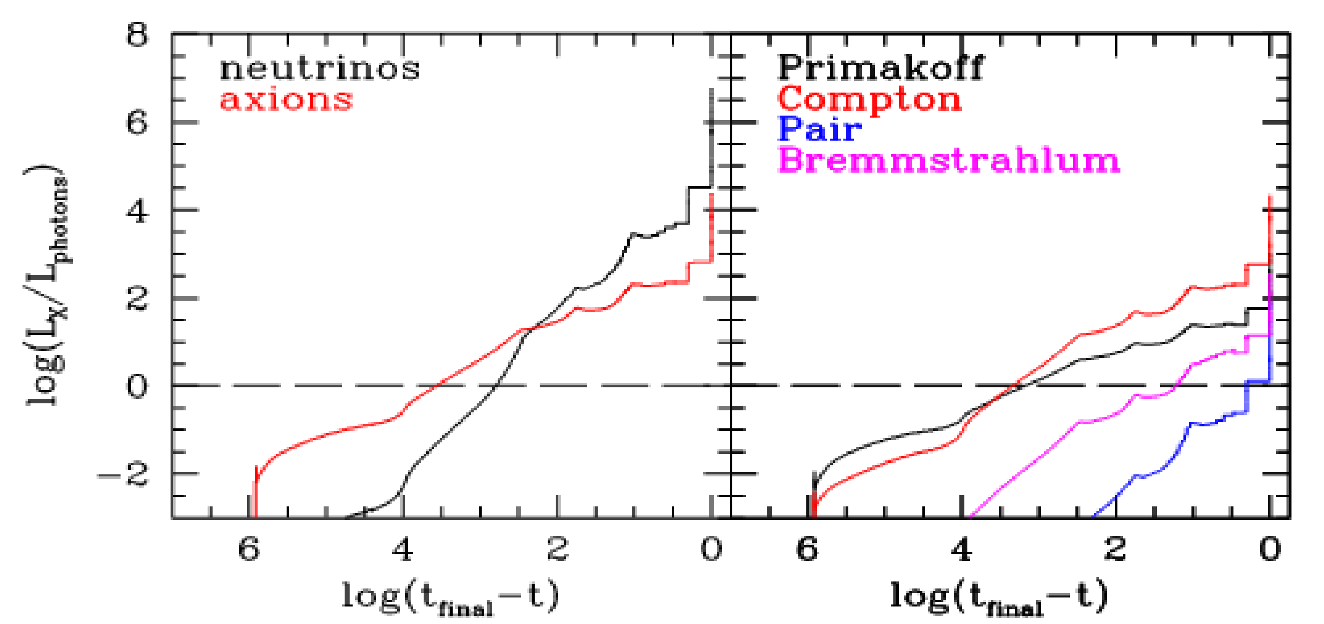
Experimental and astrophysical constraints to the coupling constants.

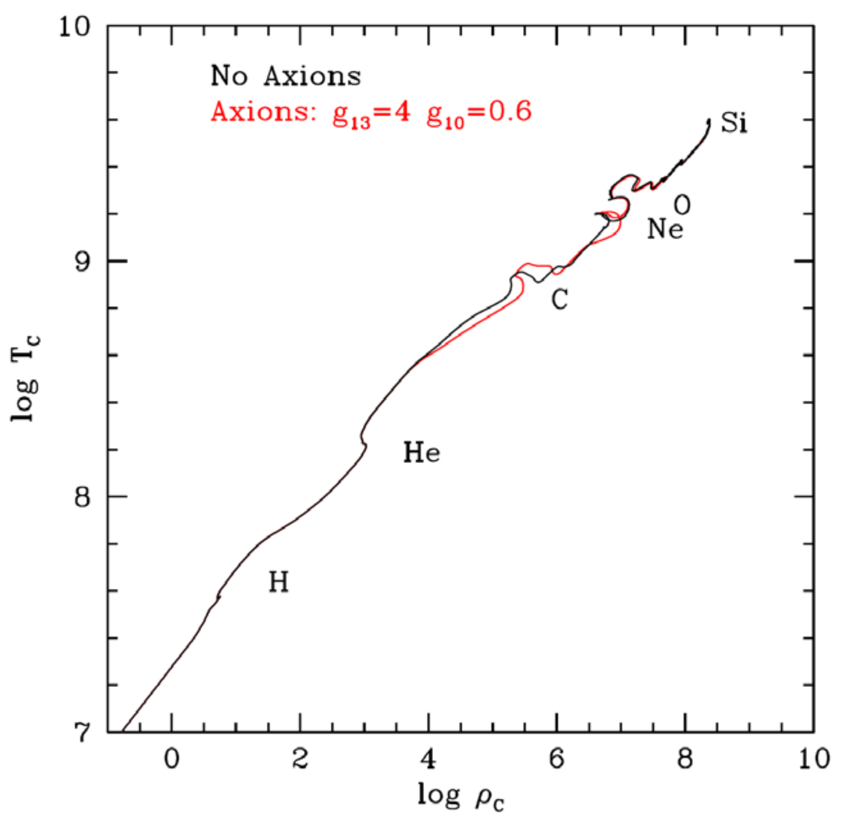
$g_{a\gamma} < 6 \times 10^{-11}$ **GeV^{-1}** : Globular Clusters HB stars (Ayala et al. 2014, Straniero 2016); Solar Axions (CAST collaboration, 2017)

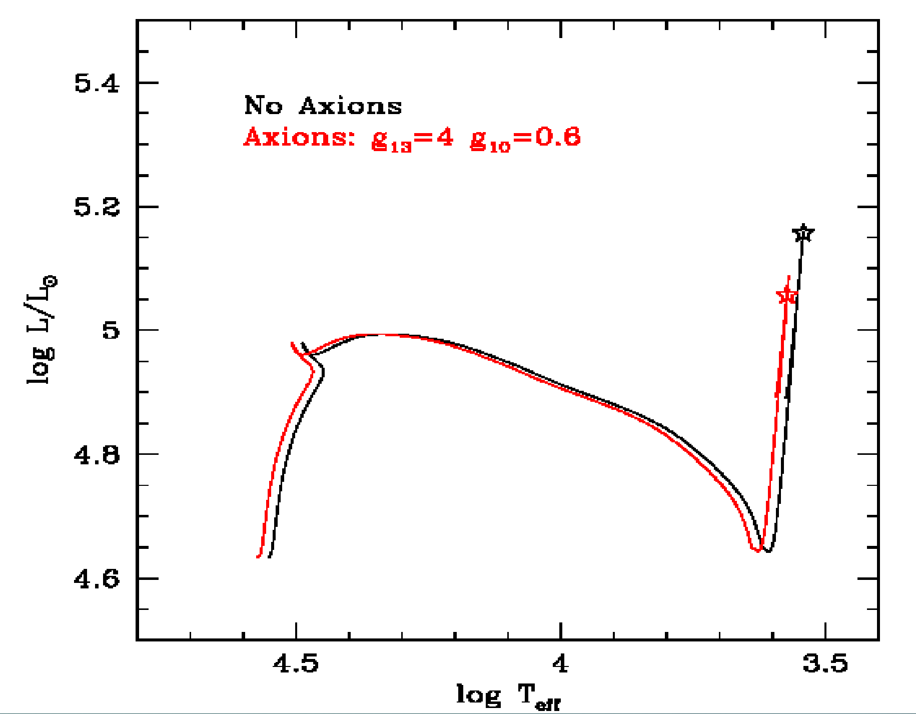
$g_{ae} < 4 \times 10^{-13}$: WDs Luminosity Function (Bertoulani et al. 2014)
Period change of variable WDs (Corsico et al. 2012, Battich et al. 2016)
RGB tip of Globular Clusters (Viaux et al. 2014, Straniero et al. 2017).
XENON100 collaboration (2018)

$$\varepsilon_a > \varepsilon_\nu$$

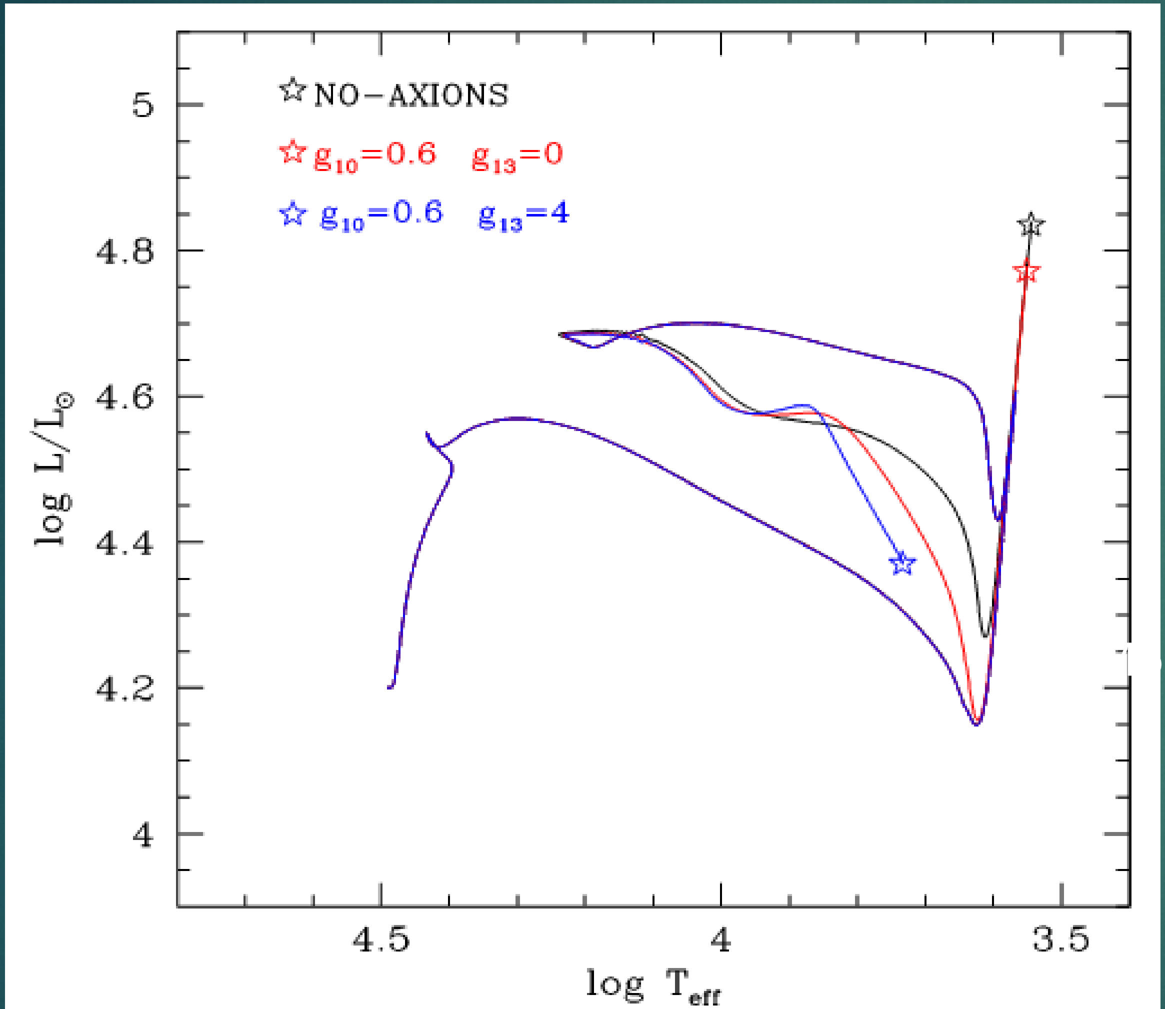
before the end of the C burning





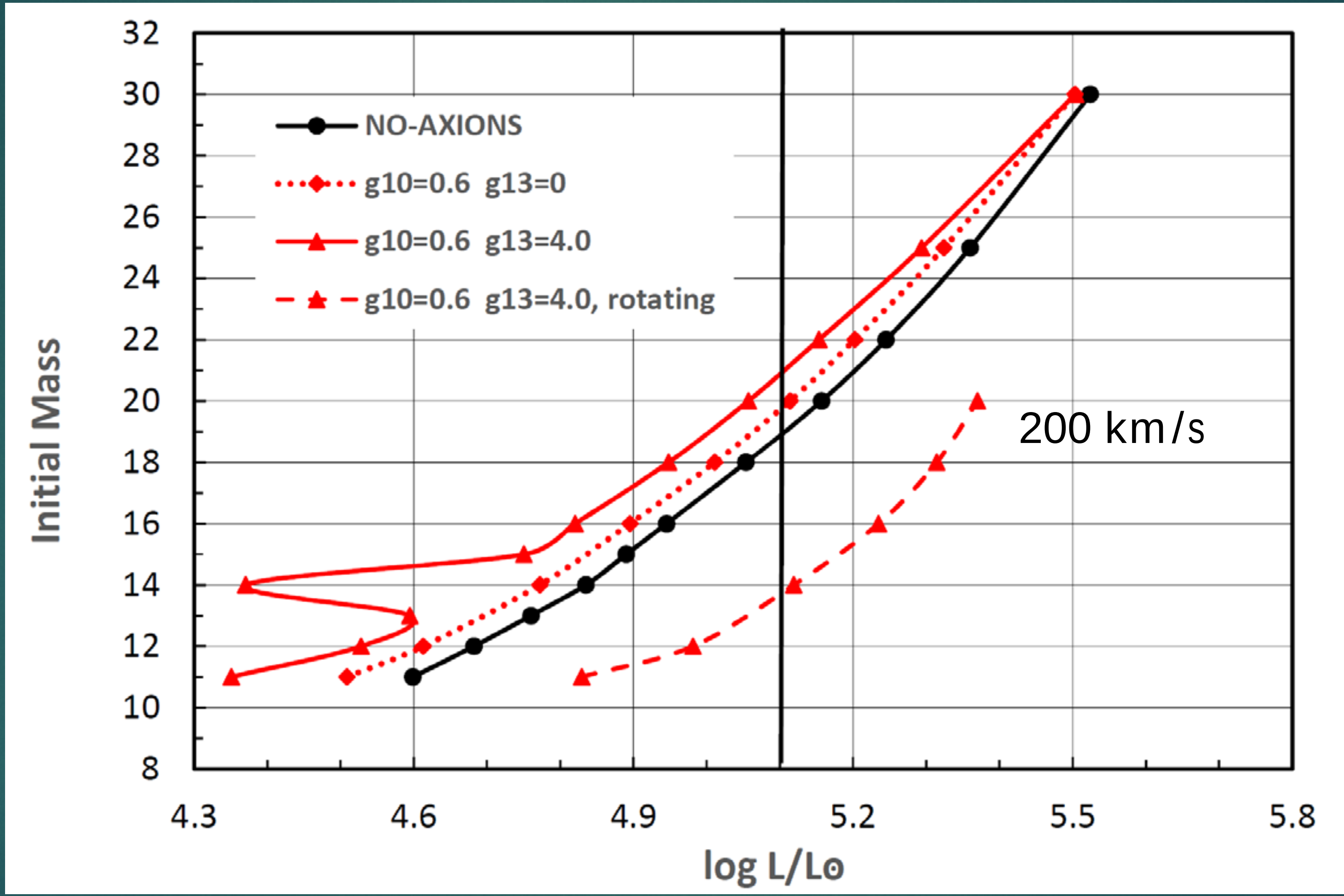


20 Mo



14 Mo
Incomplete blue-loop
Very lo L

Pre-explosive structure non very different….
But lower Luminosity



FAINTER PROGENITORS !!

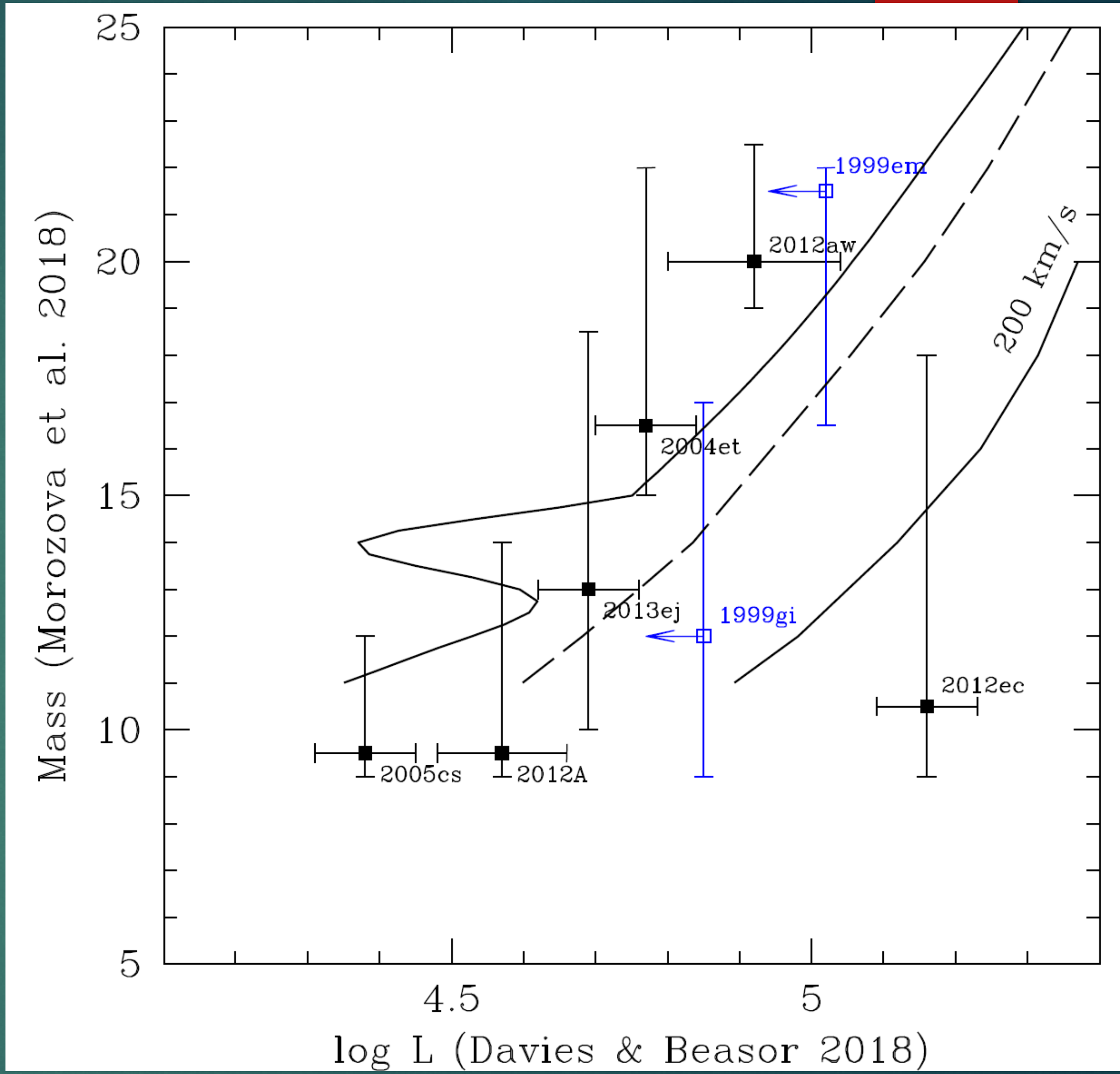
AXIONS

ROTATION

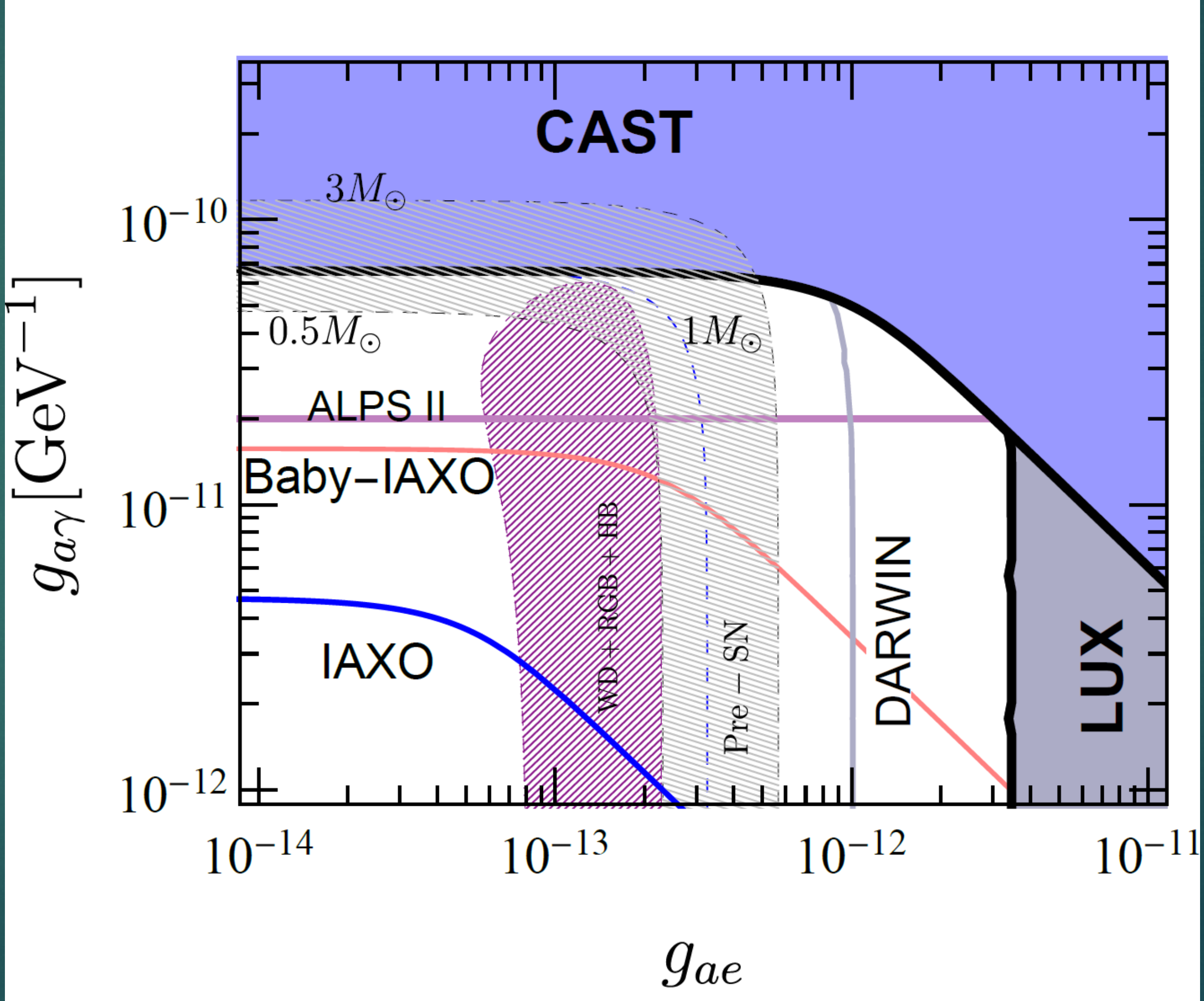
CONCLUDING REMARKS!

- ROTATION explains:
  1. spread in the IMFL relation
  2. Bright but light progenitors

- AXIONS explain:
  1. Faint but massive progenitors



Various astrophysics hints (shaded areas)
Current axion experiments (filled areas)
Next generation axion experiments (lines)



The initial mass-final luminosity relation of type II supernova progenitors. A new evidence of axions?

Oscar Straniero[1,2⋆], Inma Dominguez[3], Luciano Piersanti[1], Maurizio Giannotti[4] and Alessandro Mirizzi[5,6]

ABSTRACT
We revise the theoretical initial mass-final luminosity relation for progenitors of type IIP and IIL supernovae. The effects of the major uncertainties, as those due to the treatment of convection, semiconvection, rotation, mass loss, nuclear reaction rates and neutrinos production rates are discussed in some details. By comparing the theoretical predictions to a sample of type II supernovae for which the initial mass of the progenitors and the pre-explosive luminosity are available, we conclude that stellar rotation is required to explain a few red supergiant progenitors which appear brighter than expected in case of non-rotating models. In the most extreme case, SN2012ec, an initial rotational velocity up to 300 km/s is required. However, most of the observed progenitors appear fainter than expected. This occurrence seems to indicate that the Compton and Pair neutrino energy-loss rates, as predicted by the standard electro-weak theory, are not efficient enough and that an additional negative contribution to the stellar energy balance is required. We show that axions coupled with parameters accessible to currently planned experiments, such as IAXO and, possibly, Baby-IAXO and ALPS II, may account for the missing contribution to the stellar energy-loss.