Red supergiants
in the perspective of stellar evolution

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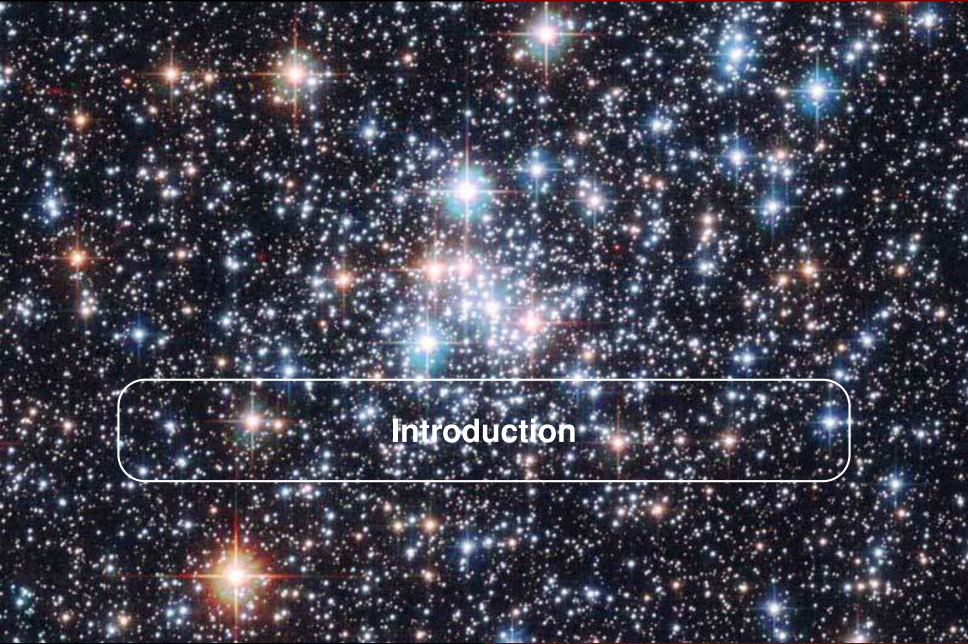
Outline



Introduction

Why are RSGs interesting objects?

if all stars with $M \simeq 8 - 25 M_\odot$ go through a RSG phase:

80% of all massive stars will be a RSG one day!

crucial phase for mass loss

progenitors of type II cc-SNe

Why are RSGs interesting objects?

evolutionary scheme: the (modified) Conti scenario *(Conti, 1975)*

$M > 60\, M_\odot$:	O → Of/WNL → LBV → WNL → WC → WO	→ SNIbc
$M = 40 - 60\, M_\odot$:	O → BSG → LBV → WNL → (WNE) → WC	→ SNIbc
	→ WC → WO	→ SNIbc
$M = 30 - 40\, M_\odot$:	O → BSG → RSG → WNE→ WCE	→ SNIbc
$M = 25 - 30\, M_\odot$:	O → (BSG) → RSG → (YSG?)	→ SNII-L/b
$M = 10 - 25\, M_\odot$:	O → RSG → (Ceph. loop for $M < 15\, M_\odot$) → RSG	→ SNII-P

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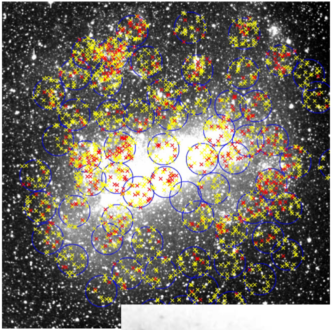
real filiation depends on:

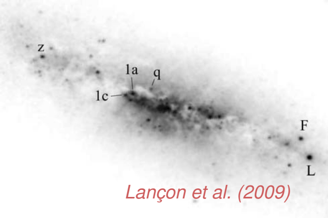
- mass loss
- overshooting
- rotation
- magnetic fields
- interactions in close binaries

Why are RSGs interesting objects?

easily seen in external galaxies

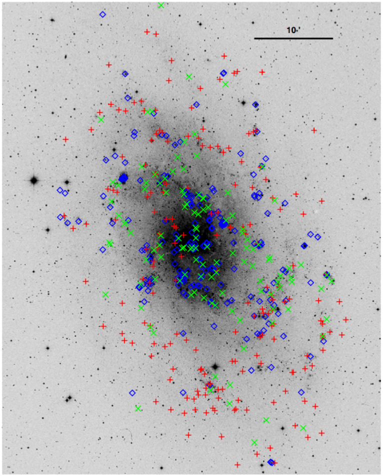


Neugent et al. (2012)



Lançon et al. (2009)

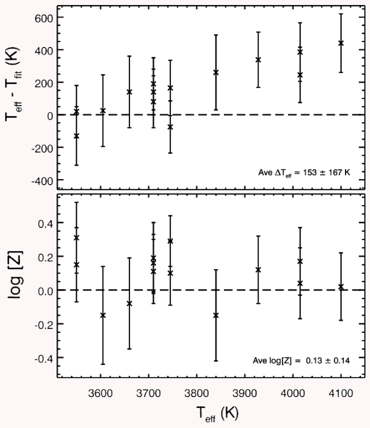
Drout et al. (2012)



Why are RSGs interesting objects?

they can be used as indicators:

Davies et al. (2010)



metallicity indicators

(Davies et al., 2010; Bergemann et al., 2012)

see Rolf Kudritzki's talk

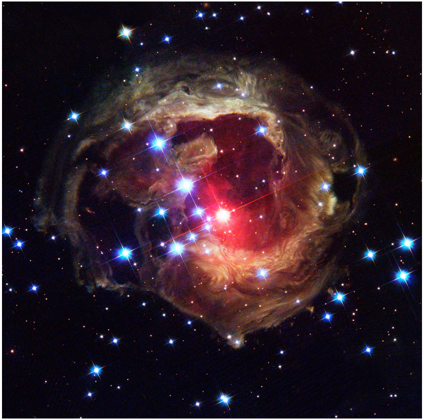
when only modest resolution ($R = 2 - 3000$) is available

Z determination is robust

for $T_{\rm eff}$: needs higher R

Why are RSGs interesting objects?

they can be used as indicators:



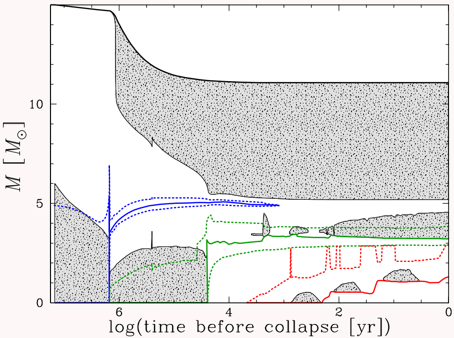
- distance indicators
  (cf. Rolf Kudritzki's or Ben Davies' talks?)
- age indicators
  (Lançon et al., 2009)

  RSG phase limited in mass range

  and to advanced stage of stellar evolution
- important sources of dust in the Universe

Some present-day challenges in the physics of RSGs

rotating 15 $M_\odot$ at $Z_\odot$



$R_{\text{core}} \simeq 0.5\, R_\odot$
$R_{\text{env}} \simeq 800\, R_\odot$

- physics of convection
  - non adiabatic
  - supersonic turbulence

- mass loss
  - rates?
  - steady or bursts?

Some crucial questions for the evolutionists

- when does a massive star enter into the RSG phase?
- how long does this phase last?
- what is the impact of the available physics?
- what types of cc-SNe arise from RSGs?

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  - convection?
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  - multiplicity?
- what types of cc-SNe arise from RSGs?
  - type II-P, II-L?
  - no SN event if black hole?

To be or not to be a RSG

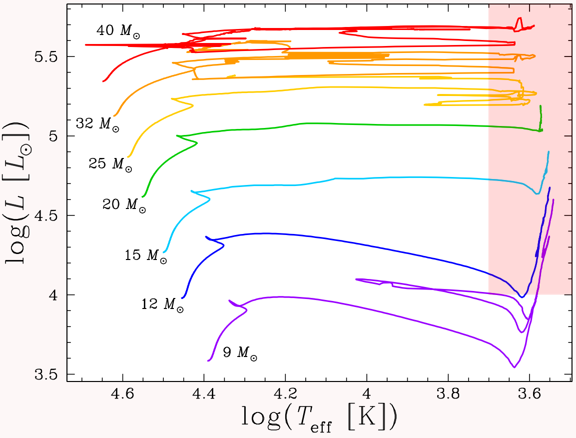
When do massive stars enter into the RSG phase?

New grids of stellar models:

- updated abundances *(Asplund et al., 2005)*, opacities, and reaction rates
- rotation prescriptions from *Maeder (1997)* and *Zahn (1992)*
- improved treatment of rotation with angular momentum conservation
- mass loss
  - *Vink et al. (2001)* for O-stars
  - *de Jager et al. (1988)* for RSGs
  - $\dot{M} \times 3$ if supra-Eddington layers ($M \geq 20\,M_{\odot}$)
    $\rightarrow \dot{M}$ close from *van Loon et al. (2005)* rates

When do massive stars enter into the RSG phase?

non-rotating models at $Z_\odot$, Ekström et al. (2012)



mass range:

$9 - 40\ M_\odot$

age range:

$4.5 \cdot 10^6 - 30 \cdot 10^6$

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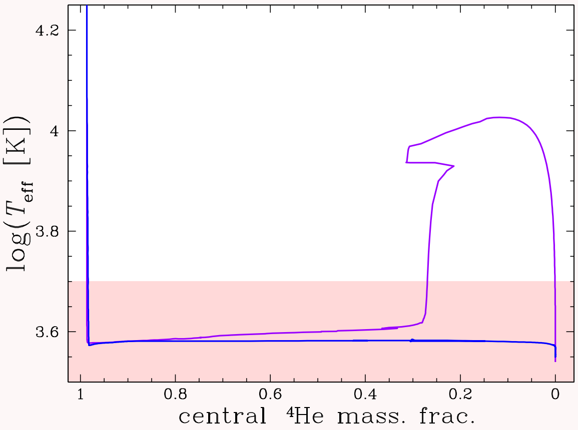

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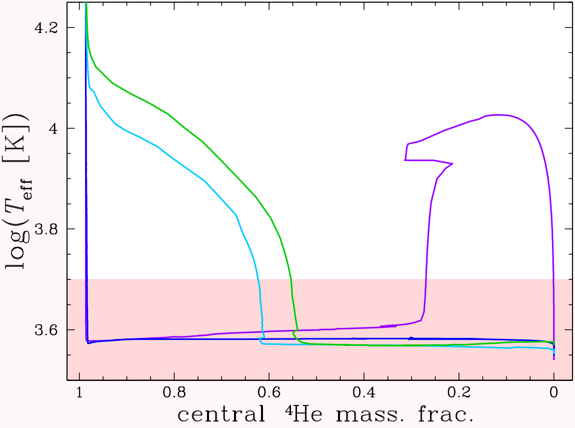

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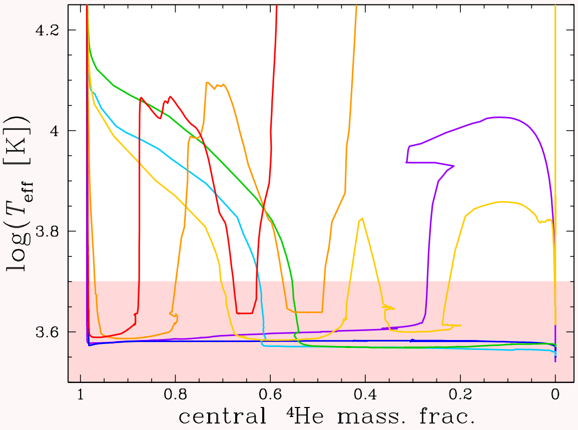

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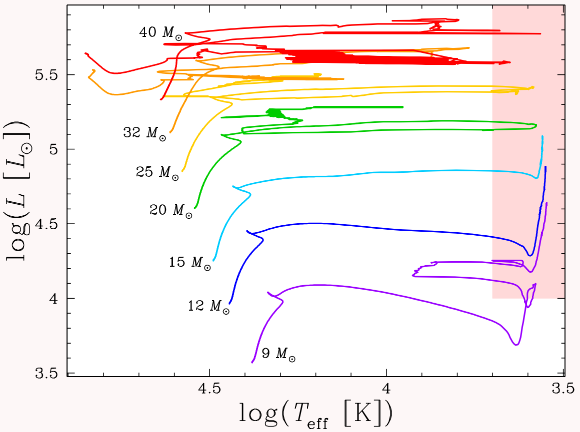
rotating models at $Z_\odot$, Ekström et al. (2012)



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high mass:
rotation mixing
keeps the star in the
blue

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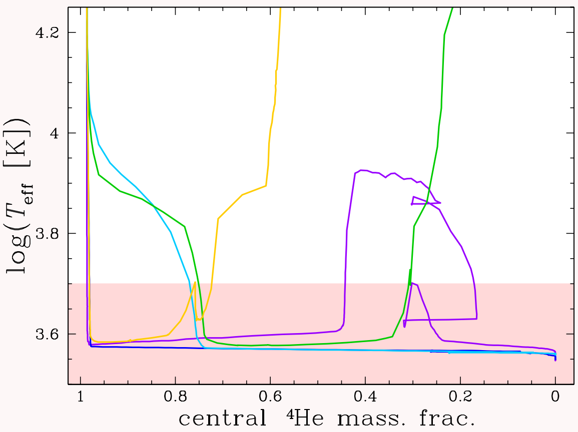

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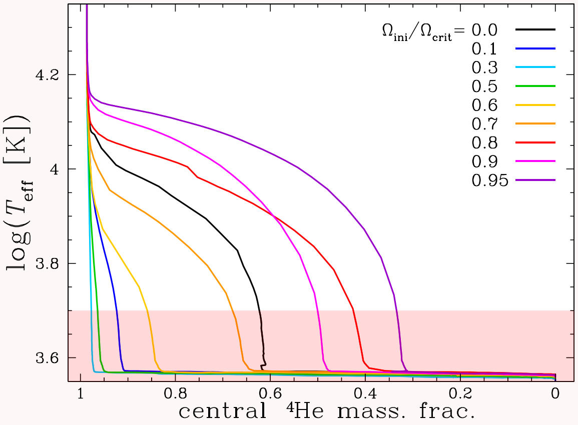
rotating 15 models at $Z_\odot$, Georgy et al. (submitted)



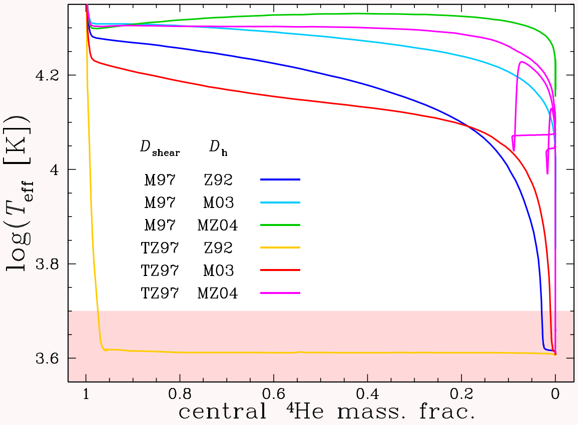
a little rotation favours the crossing to the red

too much rotation keeps the star in the blue

In real stellar populations:
velocity distribution

When do massive stars enter into the RSG phase?

rotating 15 $M_\odot$ models at Z_{SMC}, Meynet et al. (2012)



dependent on the prescription used for rotation

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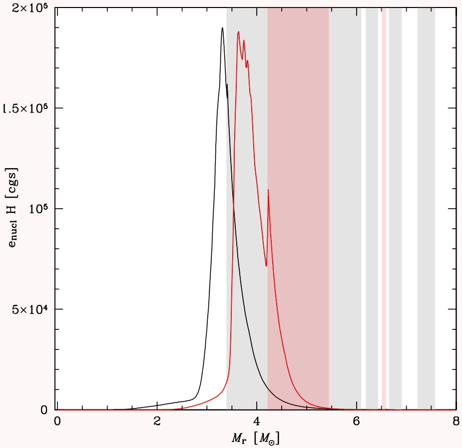


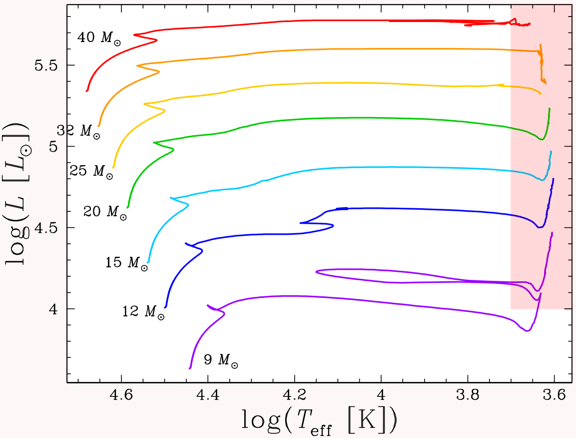
dependent on the prescription used for rotation

lobal trend:

a large core with a H-b shell associated to a narrow conv. z. favours the redward crossing

When do massive stars enter into the RSG phase?

non-rotating models at Z_{SMC}, Georgy et al. (in prep)



effect of metallicity:

- He-b mostly in the blue
- late HRD crossing

short duration of RSG phase!

$Z_\odot$: RSGs are He-b stars
low Z: C-b stars

cf. Jose Groh's poster

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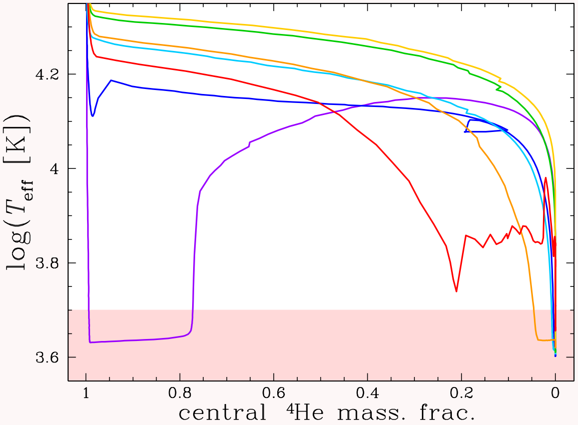

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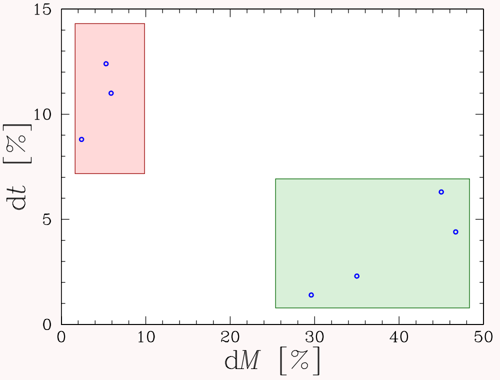
How long does the RSG phase last?

non-rotating models at $Z_{\odot}$, Ekström et al. (2012)



the higher the mass loss,
the shorter the RSG phase

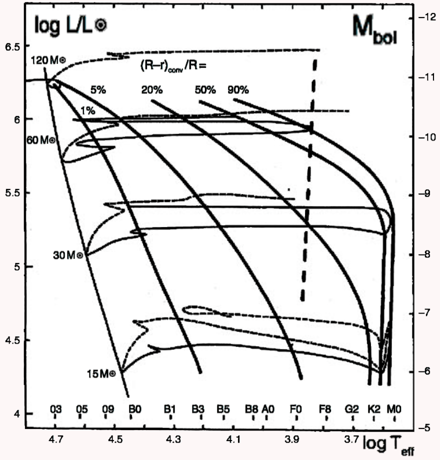
cf. Cyril Georgy's talk

transition around
$18 - 20\ M_{\odot}$

in the models:
due to the treatment of
supra-Eddington layers for
$M \geq 20\ M_{\odot}$

How long does the RSG phase last?

Maeder (2009)



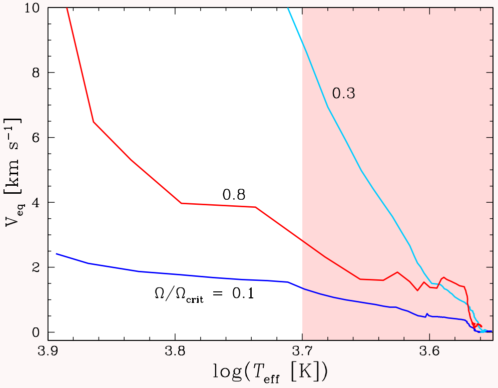
BUT:

- sensitivity to supersonic convection around 20 $M_{\odot}$
- cf. *Smartt (2009)*: no RSG progenitors for SN II-P above 18 $M_{\odot}$

note that most of the RSG observed (80%) would come from the low mass-loss group

Can we distinguish a former rapid-rotator?

15 $M_\odot$ *models at* $Z_\odot$ *from Georgy et al. (2012, submitted)*



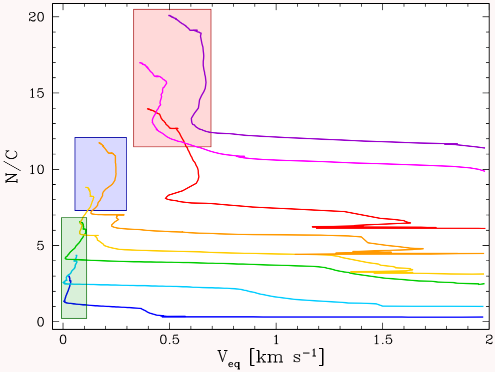
radius inflation:
→ V_{eq} decreases strongly

impact of the time spent in the crossing

higher initial rotation rate: slow crossing
→ angular momentum loss through winds

Can we distinguish a former rapid-rotator?

15 $M_\odot$ models at $Z_\odot$ from Georgy et al. (2012, submitted)



high initial rotation rate:

slow, but not so slow!

surface enrichment by a factor of 50-60 for the former most rapid-rotators

RSG as a population

Universe enrichment through mass loss

the mass lost in the RSG phase is enriched with He and secondary N

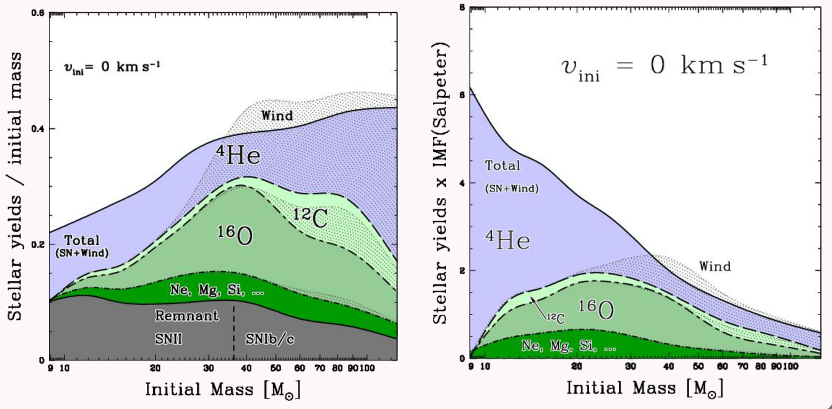
is it significant for the chemical evolution of galaxies?

probably no:
for those elements, most contributors will be intermediate-mass stars

they are important dust producers in the Universe

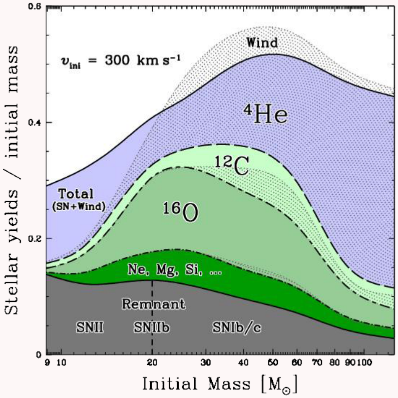
Universe enrichment through mass loss

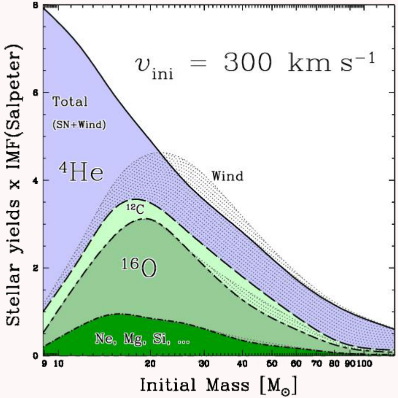
non-rotating models at $Z_\odot$ from Hirschi et al. (2004)



Universe enrichment through mass loss

rotating models at $Z_\odot$ from Hirschi et al. (2004)





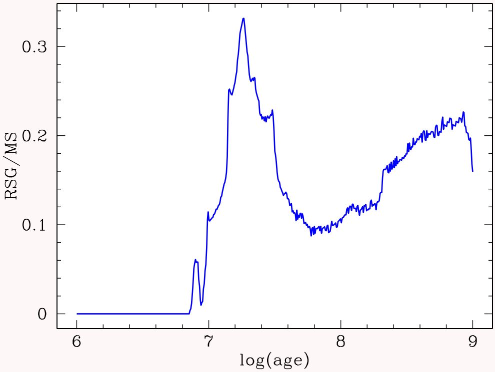
with rotation: for $M < M_{WR}$, ^{12}C and ^{16}O increased by a factor of 2
yields of a 30 $M_\odot$ at 20 $M_\odot$

RSGs in clusters

COEVAL	CONSTANT STAR FORMATION
population ratios can be predicted by:	population ratios can be predicted by:
ratio of IMF integrated over the initial mass range responsible for the type of star considered	ratio of IMF, weighted by the duration of the phase, integrated over the initial mass range responsible for the type of star considered
→ constraints on mass limits	→ constraints on mass limits and durations

RSGs in coeval clusters: the RSG to MS stars ratio

rotating models from (Ekström et al., 2012)



MS stars: 2 mag below TO
R(S)Gs: $T_{\rm eff} \leq 3.70$

Peak of the ratio when high-L RSGs dominate

valley in the age range of large-loop Cepheids

increase again at red giants time

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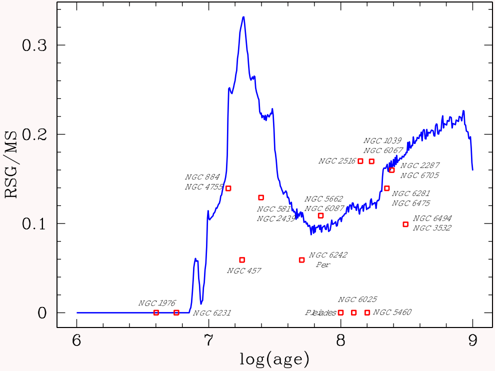

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Peak of the ratio when high-*L* RSGs dominate

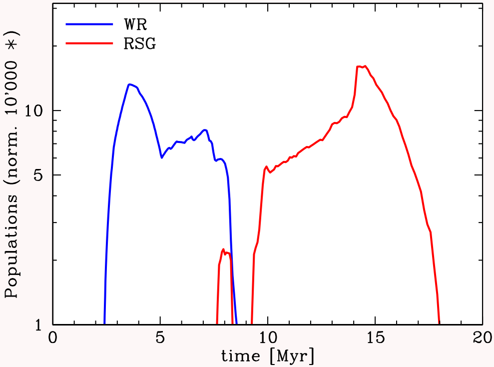
valley in the age range of large-loop Cepheids

increase again at red giants time

stochastic effect in small clusters

RSG and WR populations

rotating models from Ekström et al. (2012)



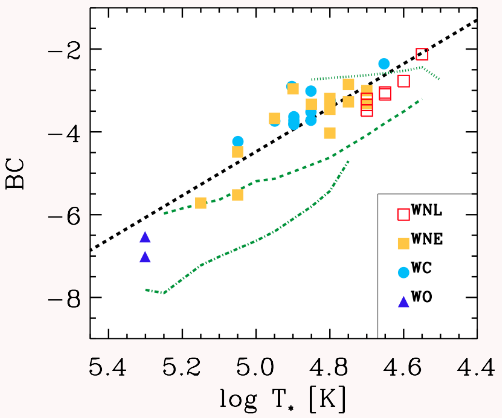
in single star scenario:

almost no overlap between WRs and RSGs populations

test for the binarity channel of WR?

Note on SNe progenitors

Yoon et al. (2012)



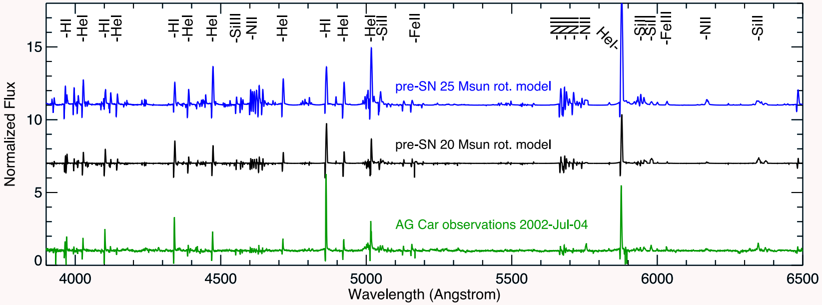
Maund & Smartt (2005), Maund et al. (2005): lack of high-*L* progenitors for type Ibc SNe

interpreted as an indication of low-mass progenitors in binaries

however, *Yoon et al. (2012)* show large BC for massive WR stars

Note on SNe progenitors

Groh et al. (submitted to A&A letters)

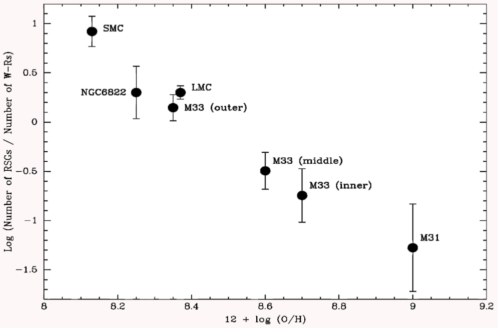


coupling the Geneva stellar evolution models with the CMFGEN atmosphere code:

LBVs as direct SNe progenitors

RSGs in constant star formation regions: the RSG to WR ratio

Massey (2002)



at $Z_\odot$: $N_{\mathrm{RSG}}/N_{\mathrm{WR}} = 0.2$

strong metallicity trend:
$Z \searrow \rightarrow N_{\mathrm{RSG}}/N_{\mathrm{WR}} \nearrow$

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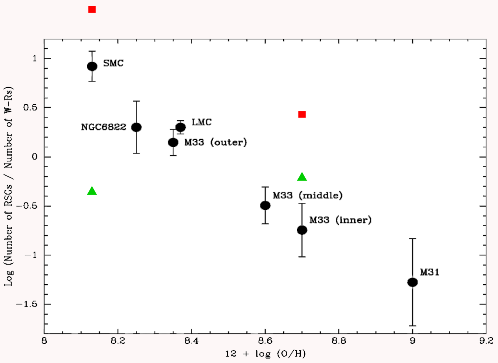

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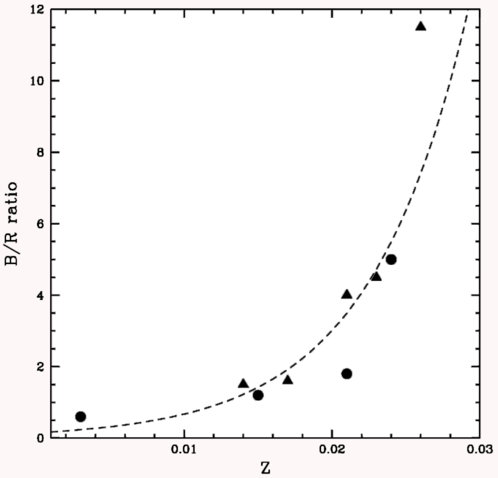
strong metallicity trend:
$Z \searrow \rightarrow N_{\rm RSG}/N_{\rm WR} \nearrow$

non-rotating models: good Z-trend but too high

rotating models: ok at $Z_\odot$, Z-trend not reproduced

The BSG to RSG ratio

Eggenberger et al. (2002)



at $Z_\odot$: $N_{\mathrm{BSG}}/N_{\mathrm{RSG}} \sim 3$

strong metallicity trend:
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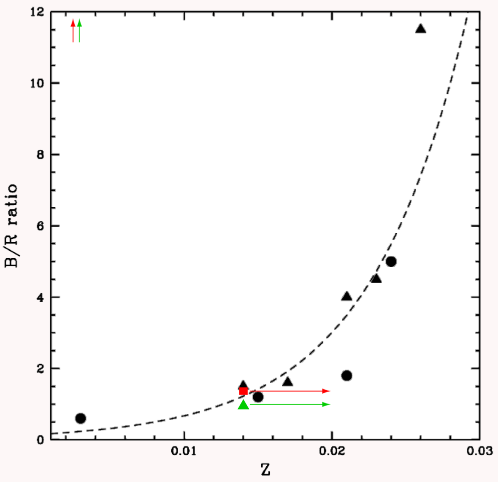

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models: $\pm$ ok at $Z_\odot$
much too high ratio at $Z_{\rm SMC}$:
no rot: 94 - rot: 87

lack of RSGs at low Z

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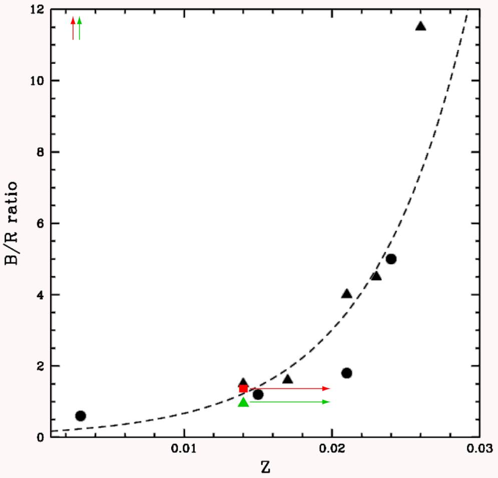

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no rot: 94 - rot: 87

lack of RSGs at low Z

only the rotating 15 $M_\odot$: 65
with a velocity disturb.: 16

The BSG to RSG ratio

We have to conclude that massive star models in the considered mass range still lack some significant physical ingredient. However, we want to emphasize that this does not imply that the results of massive star theory have to be questioned altogether. The B/R-ratio is a quantity which is known to depend extremely sensitive on the model parameters. It is thus a welcome amplifier which can (and finally will) be very useful to constrain the model physics very accurately. Most other results of massive star calculations depend far less on the uncertain assumptions and can thus be used with much more confidence.

Langer & Maeder (1995)

Conclusion

- the mass loss in RSG phase is still not very well constrained
  steady? bursts? rates?

- the detailed physics leading to a RSG is not yet fully understood
  conditions to cross the HRD? loops?

- need for precise observations of RSGs characteristics
  $\dot{M}$ related to L, clusters with RSGs and WRs?

THANK YOU FOR YOUR ATTENTION !

References I

Asplund, M., Grevesse, N., & Sauval, A. J. 2005, in ASPC, Vol. 336, Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, ed. T. G. Barnes, III & F. N. Bash (San Francisco: ASP), p. 25 [ADS]

Bergemann, M., Kudritzki, R.-P., Plez, B., et al. 2012, ApJ, 751, 156 [ADS]

Conti, P. S. 1975, Memoires of the Societe Royale des Sciences de Liege, 9, 193 [ADS]

Davies, B., Kudritzki, R.-P., & Figer, D. F. 2010, MNRAS, 407, 1203 [ADS]

de Jager, C., Nieuwenhuijzen, H., & van der Hucht, K. A. 1988, A&AS, 72, 259 [ADS]

Drout, M. R., Massey, P., & Meynet, G. 2012, ApJ, 750, 97 [ADS]

Eggenberger, P., Meynet, G., & Maeder, A. 2002, A&A, 386, 576 [ADS]

Ekström, S., Georgy, C., Eggenberger, P., et al. 2012, A&A, 537, A146 [ADS]

Georgy, C., Ekström, S., Granada, A., et al. 2012, A&A, (submitted)

Hirschi, R., Meynet, G., & Maeder, A. 2004, A&A, 425, 649 [ADS]

Lançon, A., Gallagher, J. S., Mouhcine, M., et al. 2009, Ap&SS, 324, 241 [ADS]

Langer, N. & Maeder, A. 1995, A&A, 295, 685 [ADS]

Maeder, A. 1997, A&A, 321, 134 [ADS]

Maeder, A. 2009, Physics, Formation and Evolution of Rotating Stars (Berlin Heidelberg: Springer Verlag) [ADS]

Massey, P. 2002, ApJS, 141, 81 [ADS]

Maund, J. R. & Smartt, S. J. 2005, MNRAS, 360, 288 [ADS]

References II

Maund, J. R., Smartt, S. J., & Schweizer, F. 2005, ApJL, 630, L33 [ADS]

Meynet, G., Ekström, S., Maeder, A., et al. 2012, in Seismology for studies of stellar rotation and convection, Lecture Notes in Physics, Berlin Springer Verlag (Berlin: Springer Verlag)

Smartt, S. J. 2009, ARA&A, 47, 63 [ADS]

van Loon, J. T., Cioni, M.-R. L., Zijlstra, A. A., & Loup, C. 2005, A&A, 438, 273 [ADS]

Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 2001, A&A, 369, 574 [ADS]

Yoon, S.-C., Gräfener, G., Vink, J. S., Kozyreva, A., & Izzard, R. G. 2012, A&A, 544, L11 [ADS]

Zahn, J.-P. 1992, A&A, 265, 115 [ADS]