Mass loss of red supergiants: a key ingredient for the final evolution of massive stars

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The physics of evolved stars, Nice, June 9

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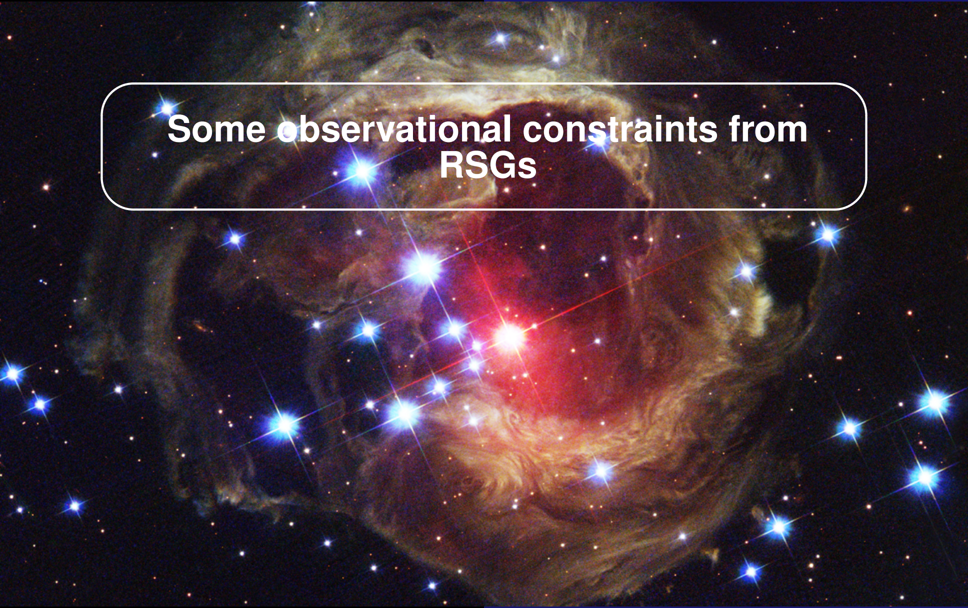
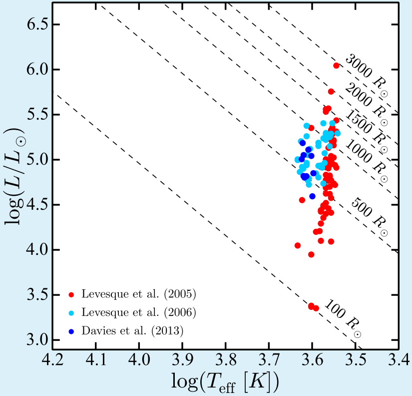
Some observational constraints from RSGs

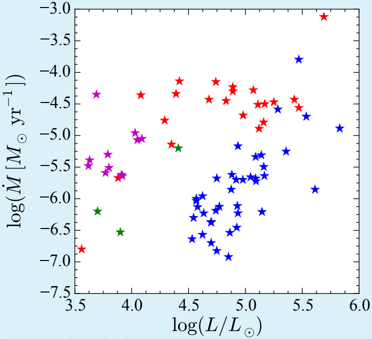


Position of the RSGs in the HRD



RSGs form a relatively thin sequence with $\log(T_{\rm eff}) \sim 3.6$.

Mass-loss rates from RSGs



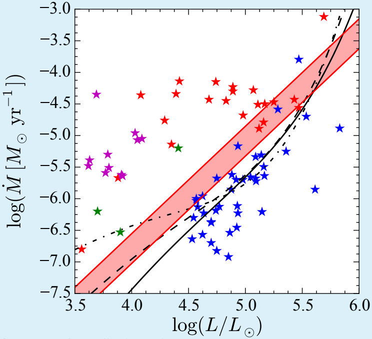
★: *Mauron & Josselin (2011)*

★: M-type, ★: MS- and S-type, ★: carbon RSGs *(van Loon et al. 2005)*

Wide variety of $\dot{M}$ over $\sim$ 3 orders of magnitude.

New set of massive stars models: Implications for RSGs

Mass-loss rates from RSGs



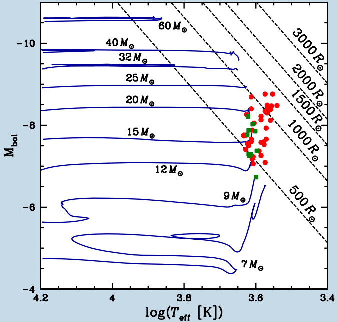
★: *Mauron & Josselin (2011)*
★: M-type, ★: MS- and S-type, ★: carbon RSGs *(van Loon et al. 2005)*
$\dot{M}$ from *de Jager et al. (1988)*: $\log(T_{\rm eff}) = 3.5$ (solid line), 3.6 (dashed), 3.7 (dotted-dashed)

Mass-loss rates in the Geneva code:

- *de Jager et al. (1988)* for $\log(T_{\rm eff}) > 3.7$
- linear fit on data *(Crowther 2001)* for $M < 20\,M_\odot$, 3x for $M > 20\,M_\odot$.

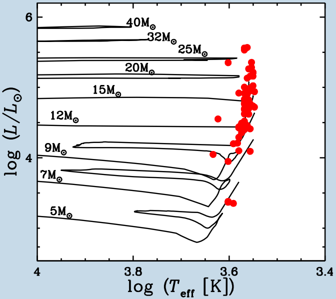
HRD tracks and endpoints

SMC RSGs *Georgy et al. (2013)*



red dots: *Levesque et al. (2006)*
green squares: *Davies et al. (2013)*

Galactic RSGs *Ekström et al. (2013)*



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Good fit of the maximal RSGs luminosities.

HRD tracks and endpoints

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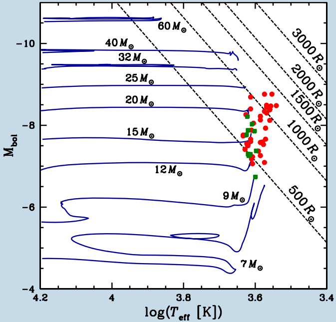

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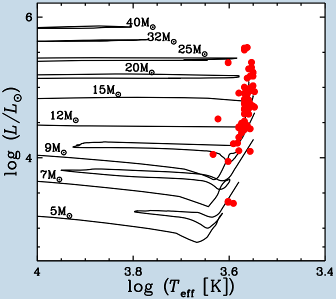

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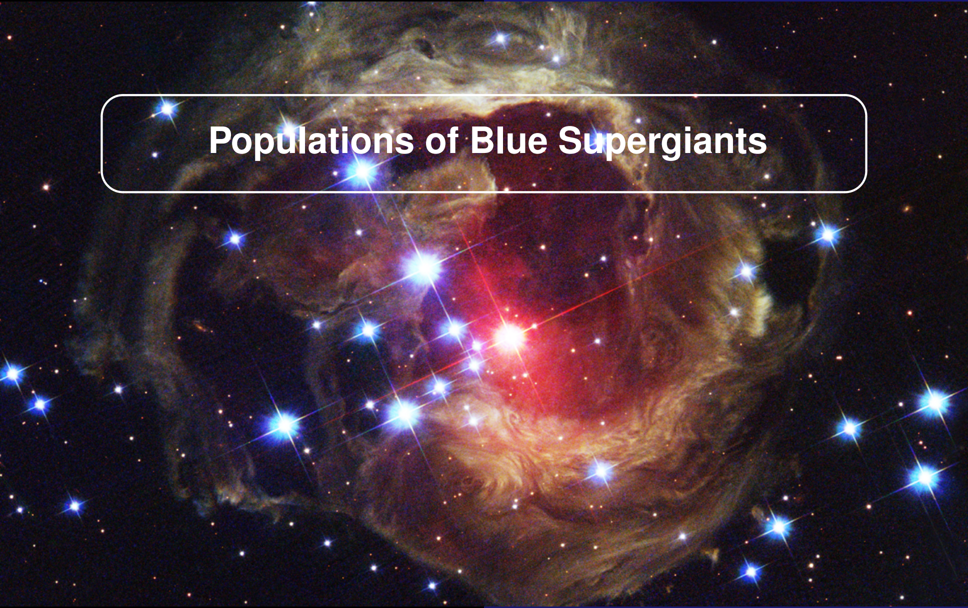
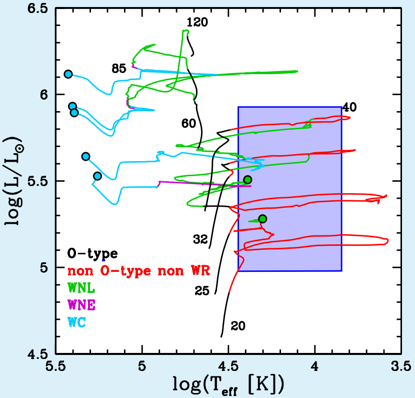
Maximal mass for type IIP SNe of 16 – 19 $M_\odot$ *(Georgy et al. 2012)*, in good agreement with the results of *Smartt et al. (2009)*



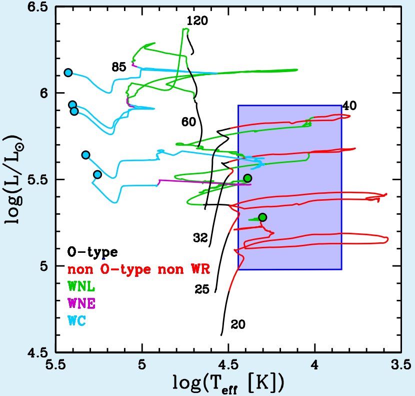
Populations of Blue Supergiants

Bluewards evolution after the RSG phase



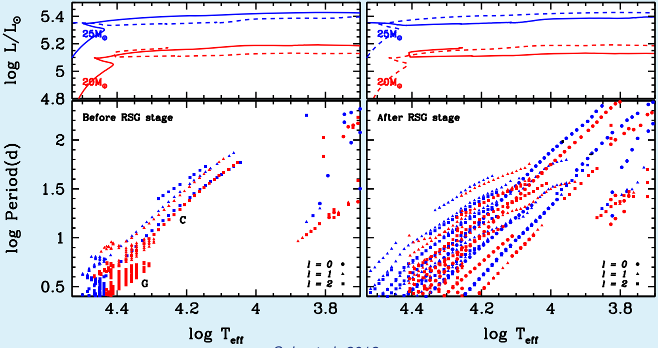
- The strong mass loss and the rotational mixing decrease the surface H abundance.
- The star evolves to the blue side of the HRD.

Bluewards evolution after the RSG phase



- 2 populations of BSGs are thus expected.
- Is there a way to distinguish them?

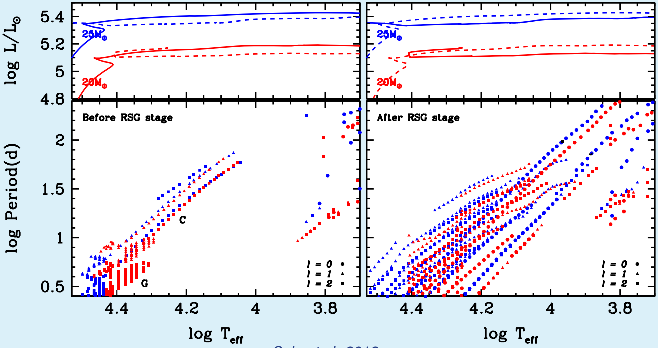
Pulsational properties



Saio et al. 2013

- The crossings occur at $\sim$ constant L.
- However, the star loses a lot of mass during the RSG phase!
- Thus, the L/M ratio strongly increases, favouring pulsations for the stars in their second crossing.

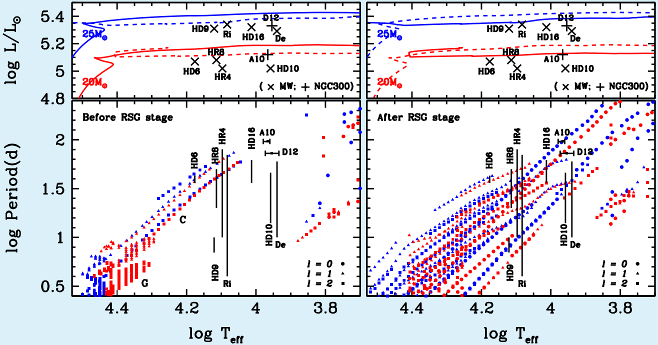
Pulsational properties



Saio et al. 2013

Are they pulsating BSGs? Yes! The α Cygni variables!

Pulsational properties



Saio et al. 2013

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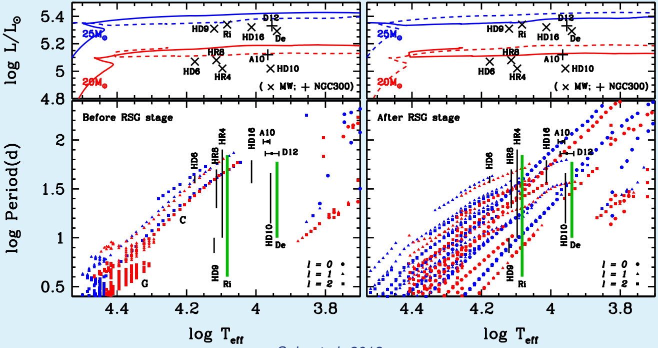
Their variability periods are in much better agreement with the models on their second crossing.

Pulsational properties



Saio et al. 2013

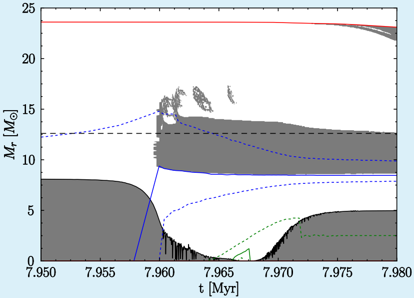
Rigel and Deneb seem to be post-RSG stars

Surface abundances

	BSG before RSG			BSG after RSG		
M_{ini}	Y	N/C	N/O	Y	N/C	N/O
20	0.31	2.46	0.609	0.57	39.7	2.94
25	0.35	3.23	0.877	0.64	60.4	4.22

Models predict a strong increase of N/C during the RSG phase.

Observations *(Przybilla et al. 2010)*:
Rigel : 2.0
Deneb : 3.4



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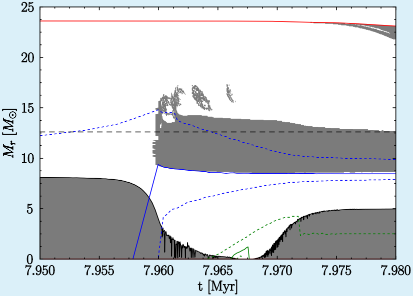

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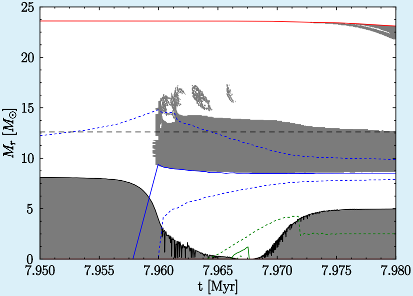
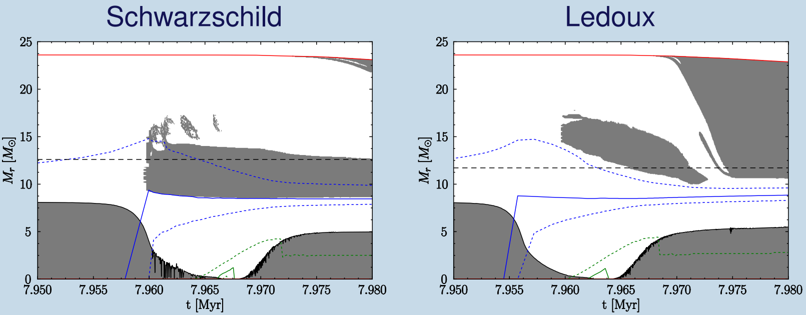


Puzzling??

A way to constrain convection in massive stars?

Kippenhahn diagrams *Georgy et al. 2014*



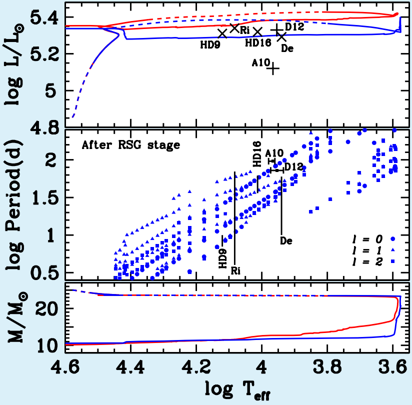
The treatment of the convection plays a key role concerning the intermediate H-burning shell.

A possible solution? Schwarzschild vs. Ledoux

M_{ini}	Y	N/C	N/O
	after RSG, Schw		
25	0.64	60.4	4.22
	after RSG, Led		
25	0.46	6.97	1.61

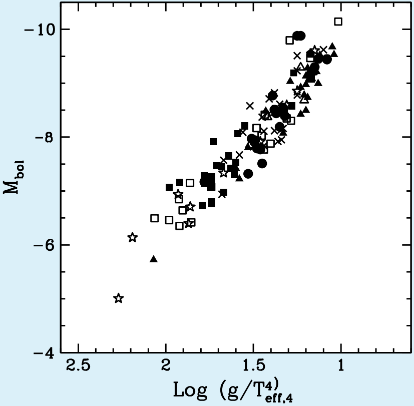
Significantly improves the agreement with the observed surface abundances.

Pulsational properties remain similar.



Georgy et al. 2014

The flux-weighted gravity – luminosity relation

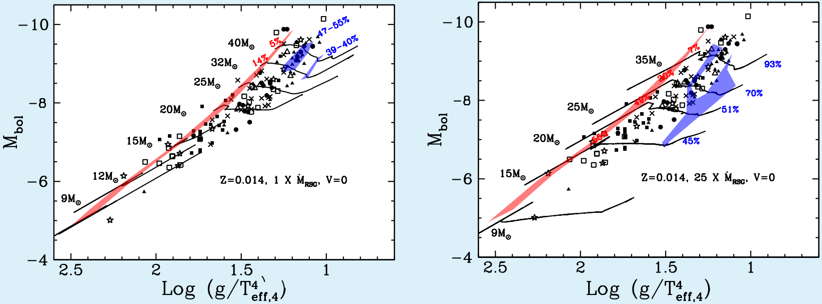


Data from *Kudritzki et al. (2008a,b, 2012, 2013, 2014)*, *U et al. (2009)*, *Urbaneja et al. (2008)*, *Hosek et al. (2014)*

It can be shown analytically that, if the BSGs mass-luminosity relation is a power-law, then the flux-weighted gravity $g/T^4_{\rm eff}$ and the luminosity follows a power-law as well *(Kudritzki et al. 2008)*.

This can open a new way of determining extragalactic distances.

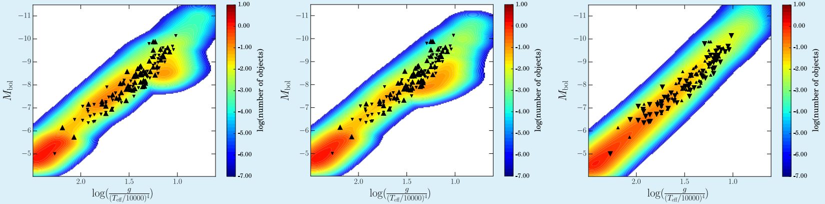
Constraining the RSGs mass-loss rates?



Meynet et al. (2015)

From the tracks, very high RSG $\dot{M}$ seems less probable.

Population synthesis

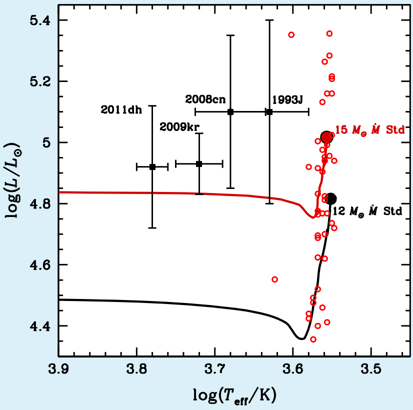


Meynet et al. (2015)

- Indicates that we produce slightly too much group 2 BSG at solar metallicity.
- Low-metallicity predictions matches well the observations.
- Single star models are able to reproduce the FGLR. The next step is to check if binary models produce similar results.

Yellow supergiants as SN progenitors

What happens if the $\dot{M}$ is increased for lower initial mass stars?



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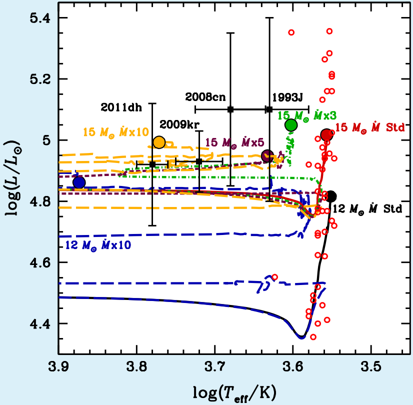

Georgy 2012

- Produces stars that end their life as YSGs.
- Good agreement with the identified YSGs SN progenitors.
- For SN 2011dh, so far no hint of a binary companion *(Maund, priv. comm.)*