Chemically homogeneous evolution of massive stars

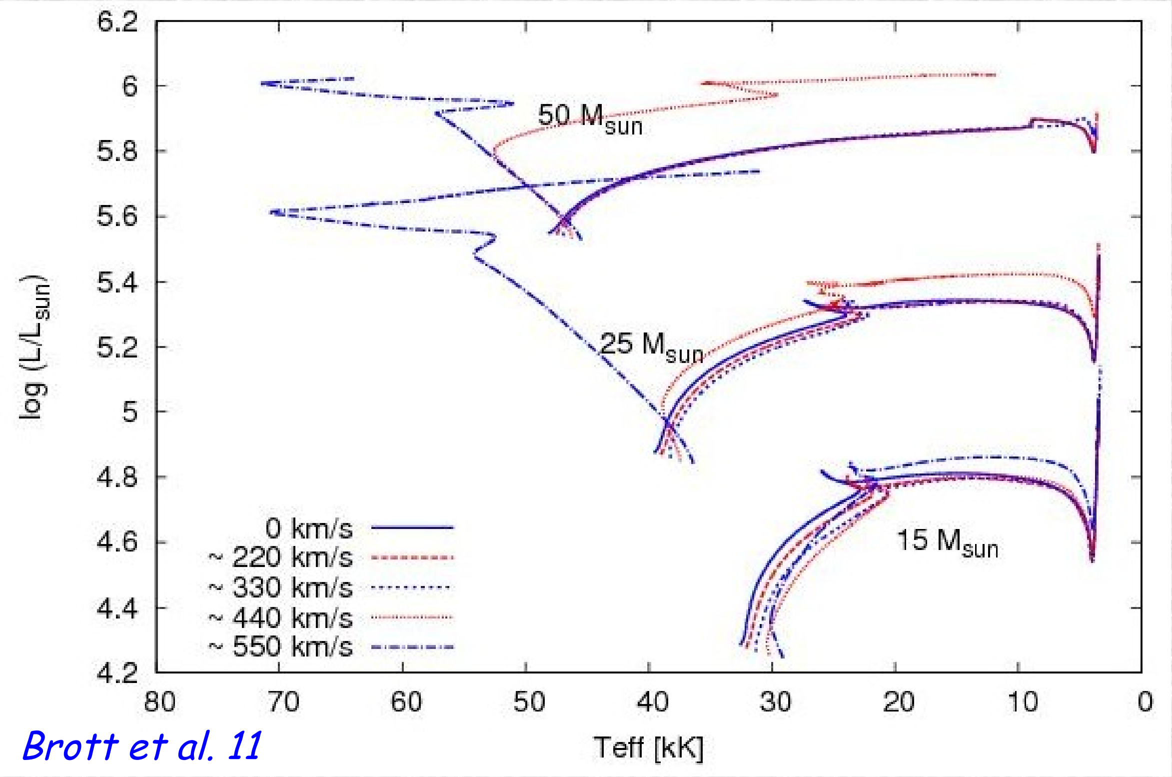
Fabrice Martins

(CNRS & University of Montpellier)

E. Depagne, D.J. Hillier, L. Mahy, D. Russeil, J.C. Bouret, A.J. Moffat, S. Marchenko, C. Foellmi

Martins et al., 2009, A&A, 495, 257
Martins et al., 2013, A&A, 554, 23

What is chemically homogeneous evolution?



Brott et al. 11

Effect of very fast rotation on the evolution of single stars

Mixing timescale shorter than nuclear timescale

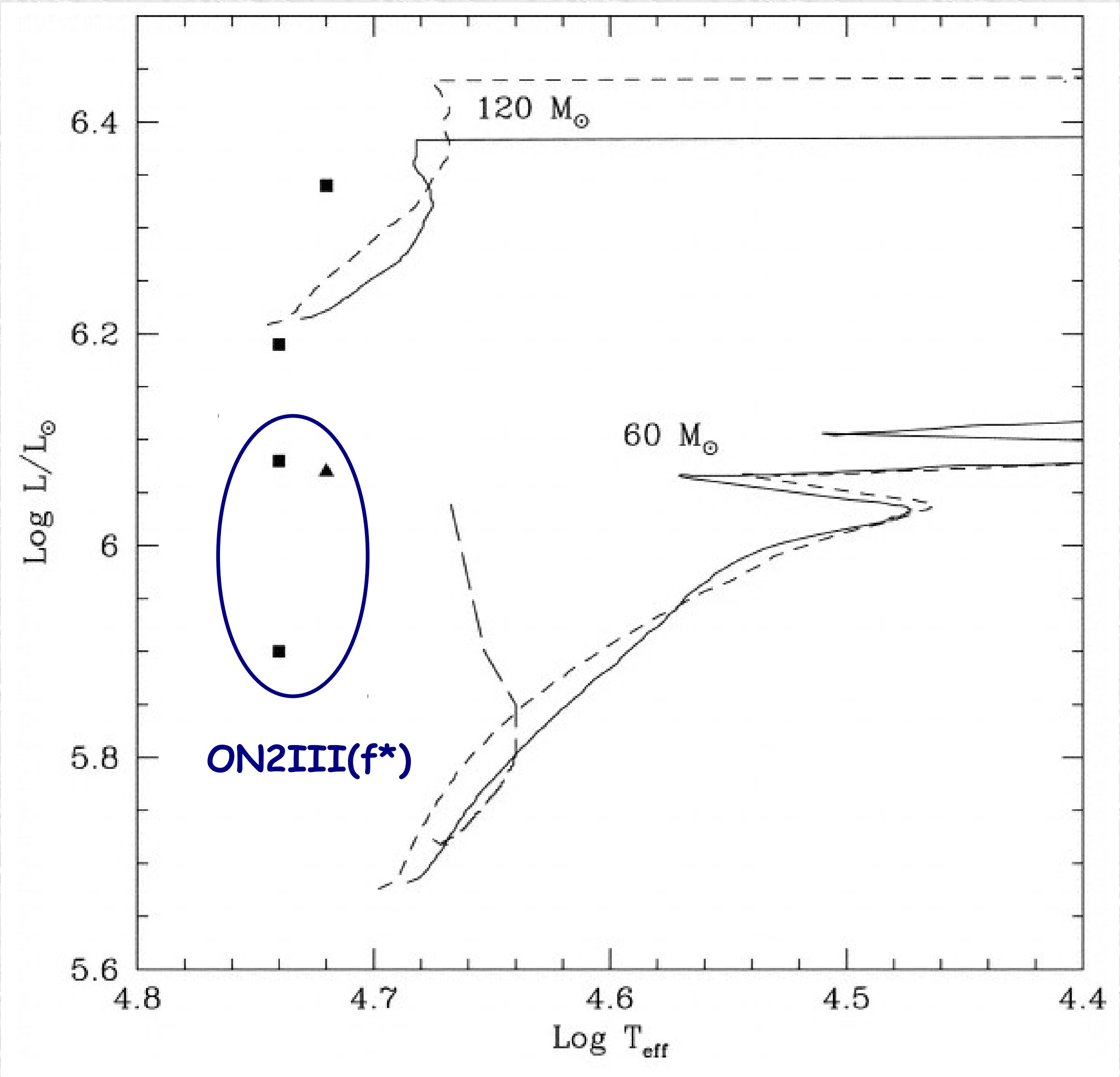
Material produced in stellar core immediately redistributed in the envelope

Maeder 87, Langer 92, Yoon et al. 06, Graefener & Vink 10

- $T_{eff}^4 \propto$ 1/opacity
- $L \propto$ (mean molecular weight)^3

→ Blueward evolution

What about CHE?



Walborn et al. 04

Chemically homogeneous evolution helps understand puzzles in stellar evolution:

- peculiar position in the HRD

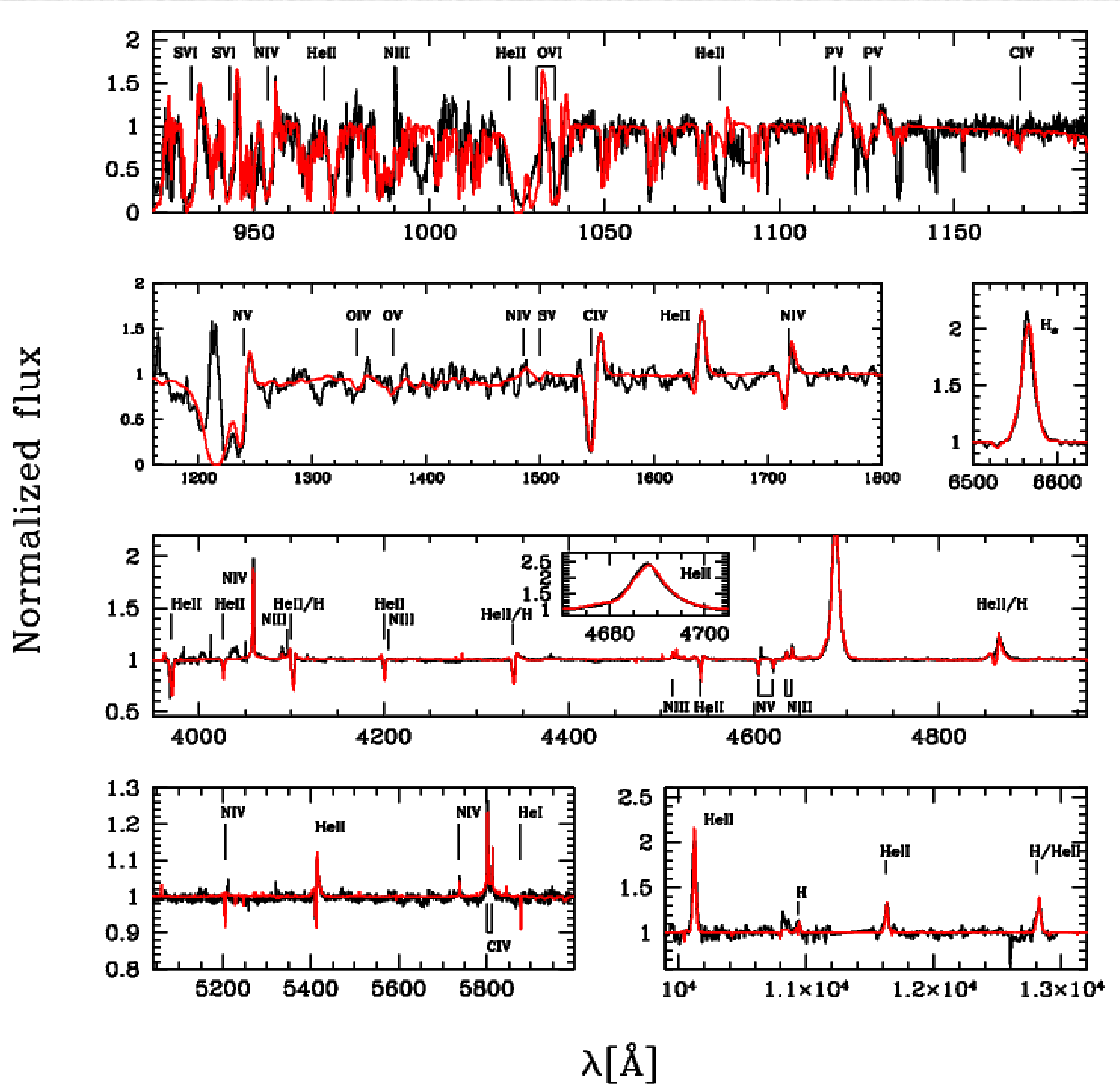
- peculiar abundances

- puzzling mass estimates

e.g. Bouret et al. 03,13, Walborn et al. 04, Mokiem et al. 07, Bestenlehner et al. 11

Posters: Szecsi & Langer
Walborn et al.

Sample stars



CMFGEN model observation

Candidates to follow homogeneous evolution:

- Stars located on the left of the zero age main sequence

- Evolved, but not too much

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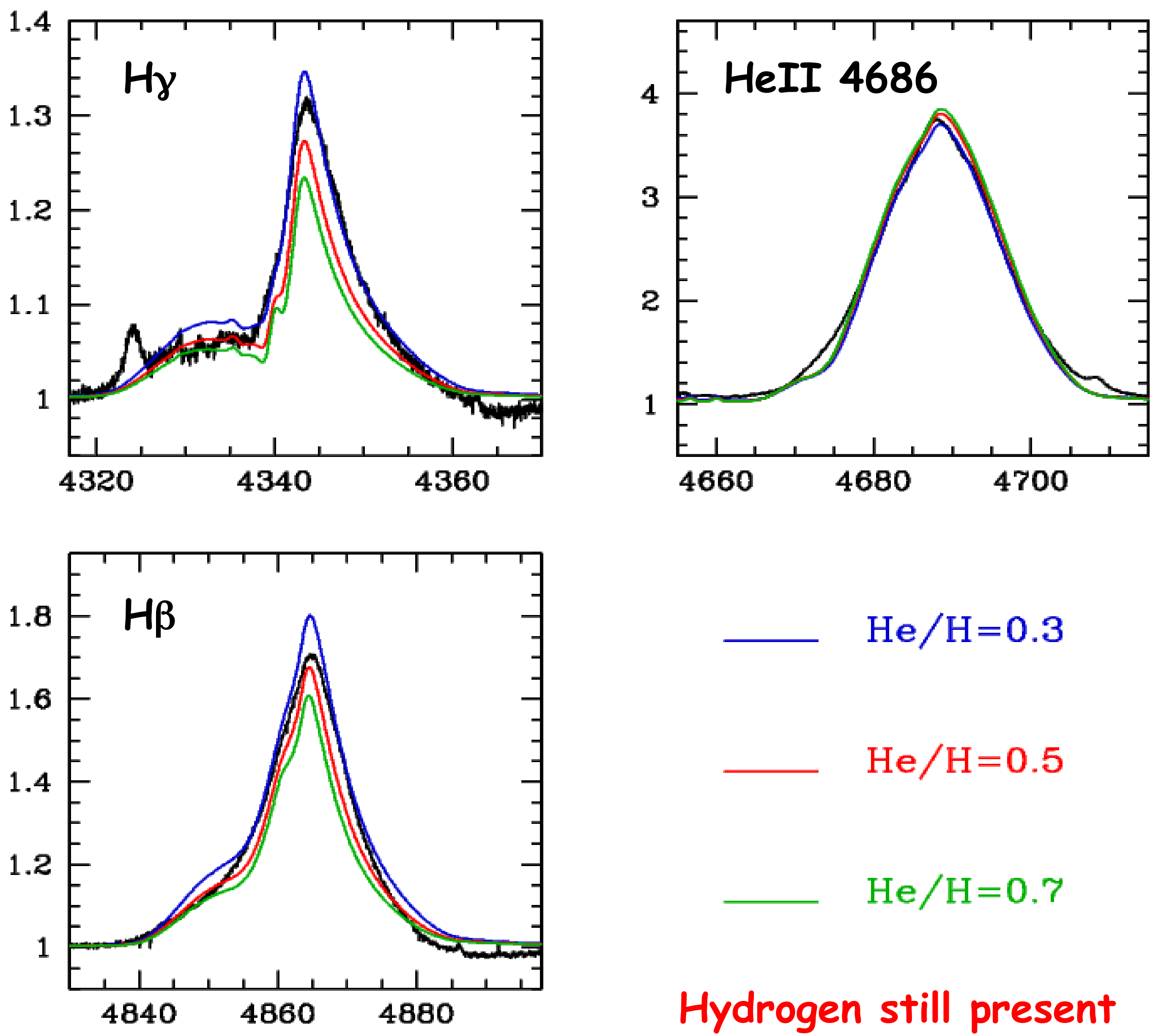
Hot WN stars with indication of hydrogen in their atmosphere:
WN3-5h

No direct indication of binarity (no RV variations)

In the SMC, LMC and Galaxy

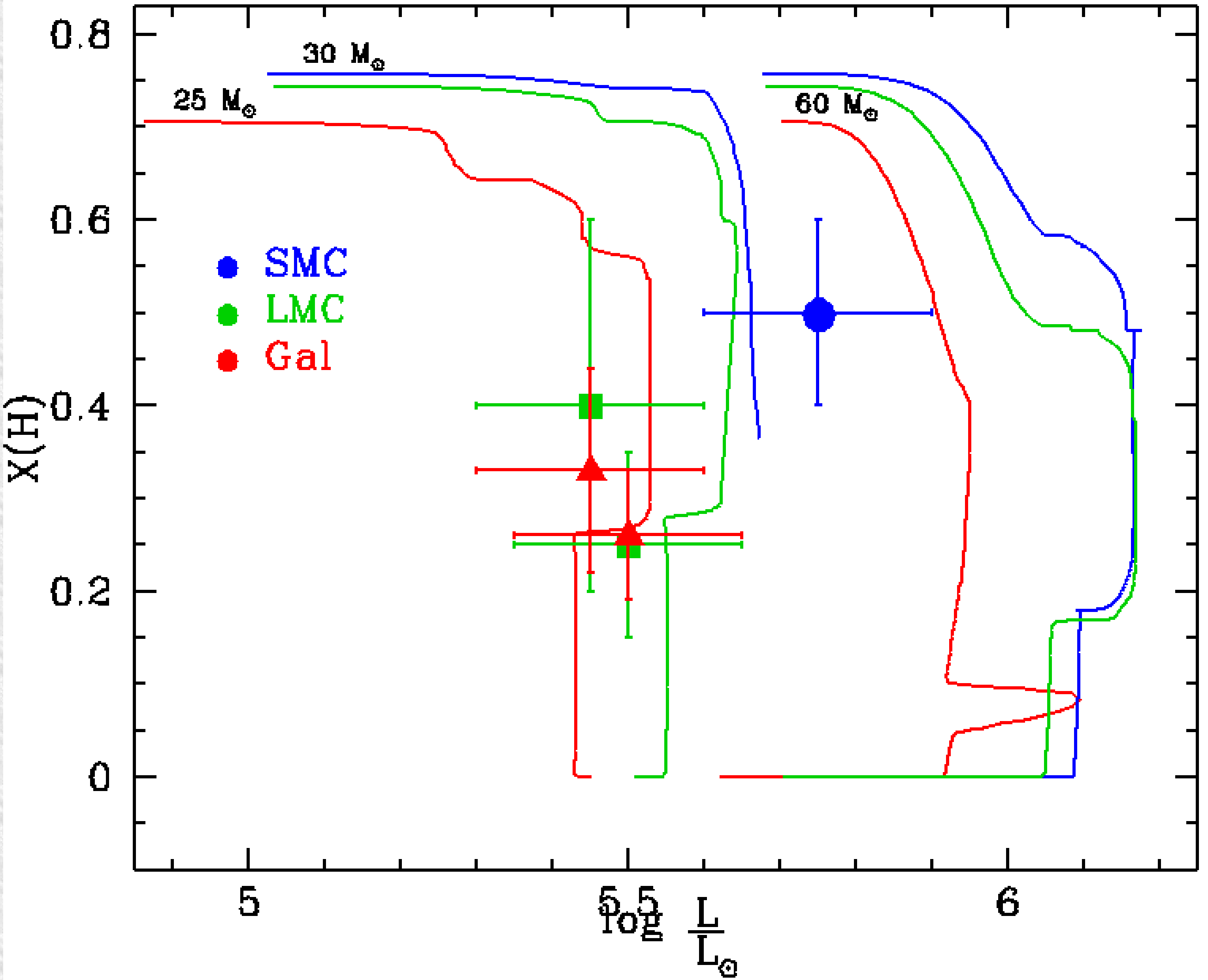
2 WN3h, 2 WN4h, 1 WN5h

Surface abundances: hydrogen / helium



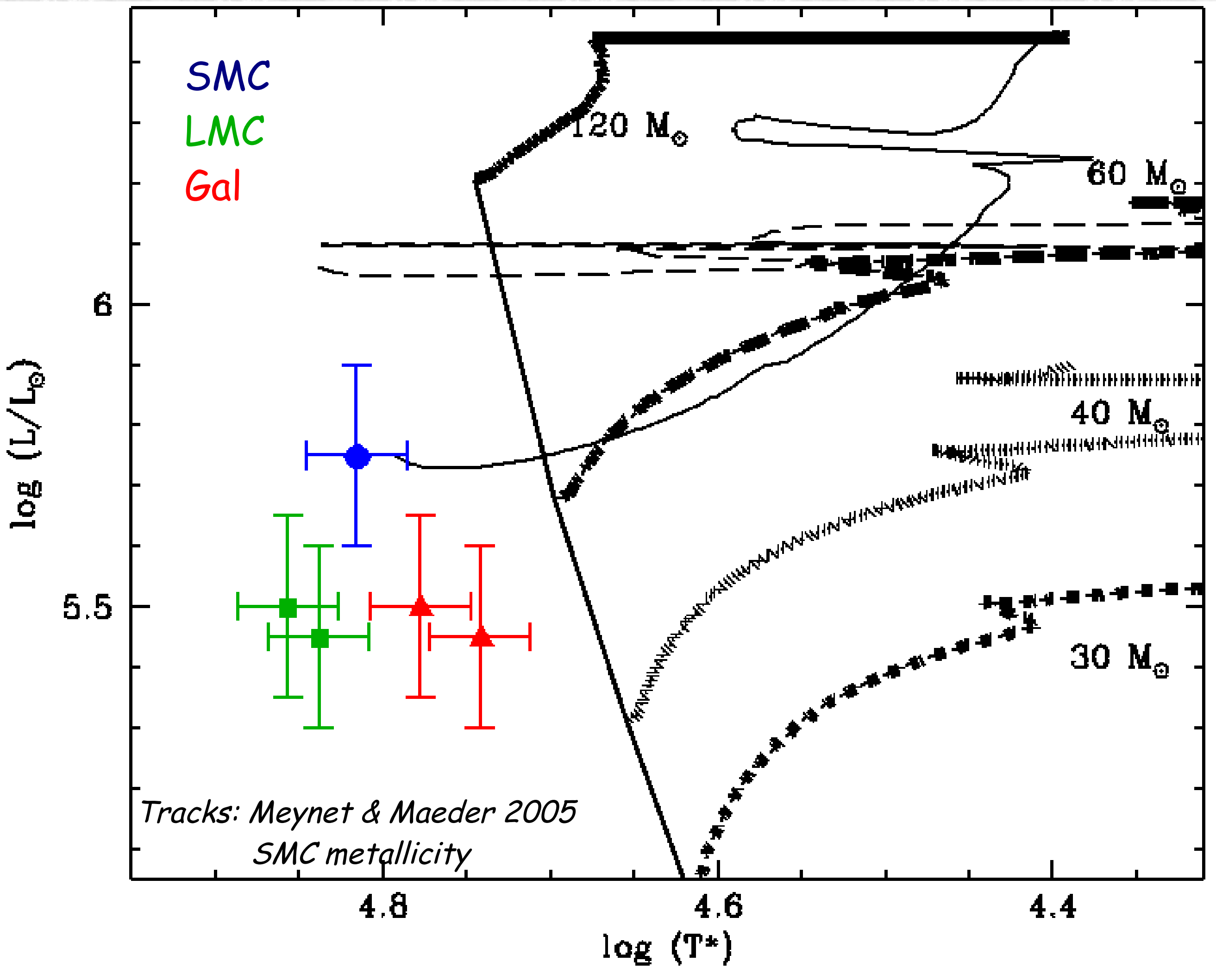
Hydrogen still present

Hydrogen mass fraction



Hydrogen still present in the stellar atmospheres

Evolution



Standard evolutionary tracks with rotation:

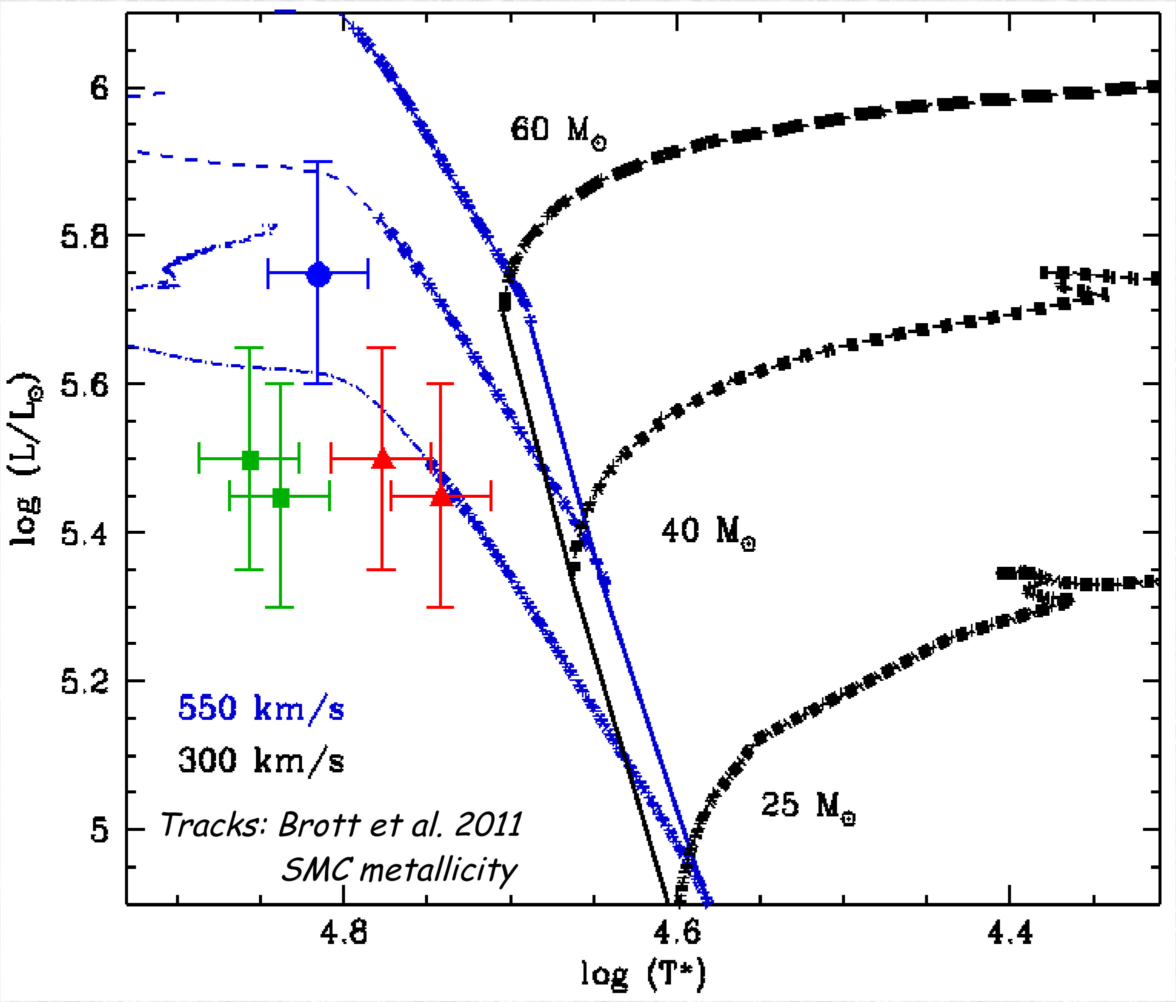
Stars evolve redward

Only come back to the blue part of the HRD when no H anymore

Bold part of the tracks: X(H) > 0.2

X(H) > 0.2 in the sample stars

Evolution



Standard evolutionary tracks with rotation:

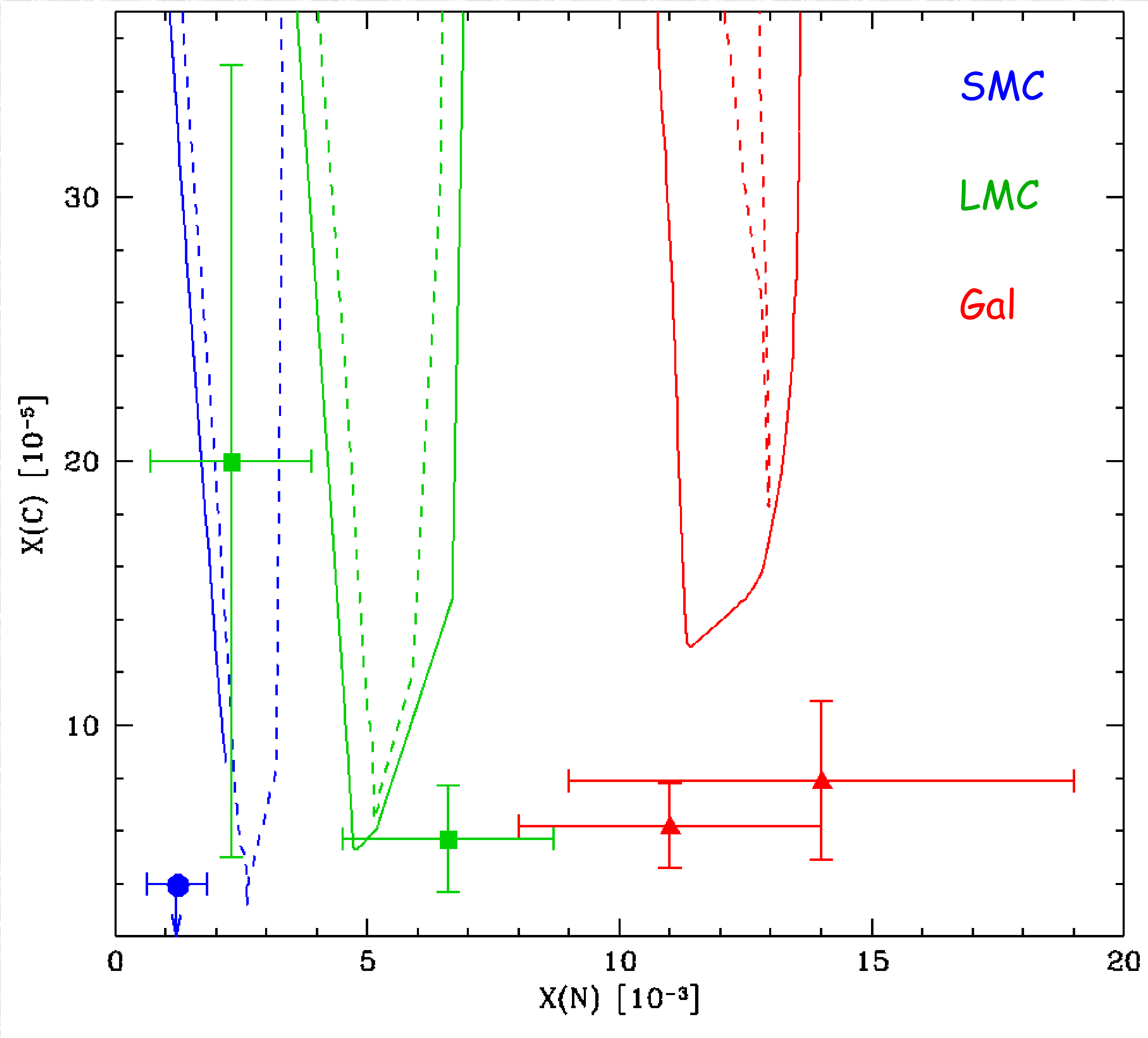
Stars evolve redward
Only come back to the blue part of the HRD when no H anymore

Fast rotation:

Stars evolve blueward
Can keep a large H mass fraction

H-rich early WN stars reasonably explained by quasi chemically homogeneous evolution

Surface abundances: carbon / nitrogen



Surface C and N content consistent with CN equilibrium.

For CHE, surface abundance ~ core abundances

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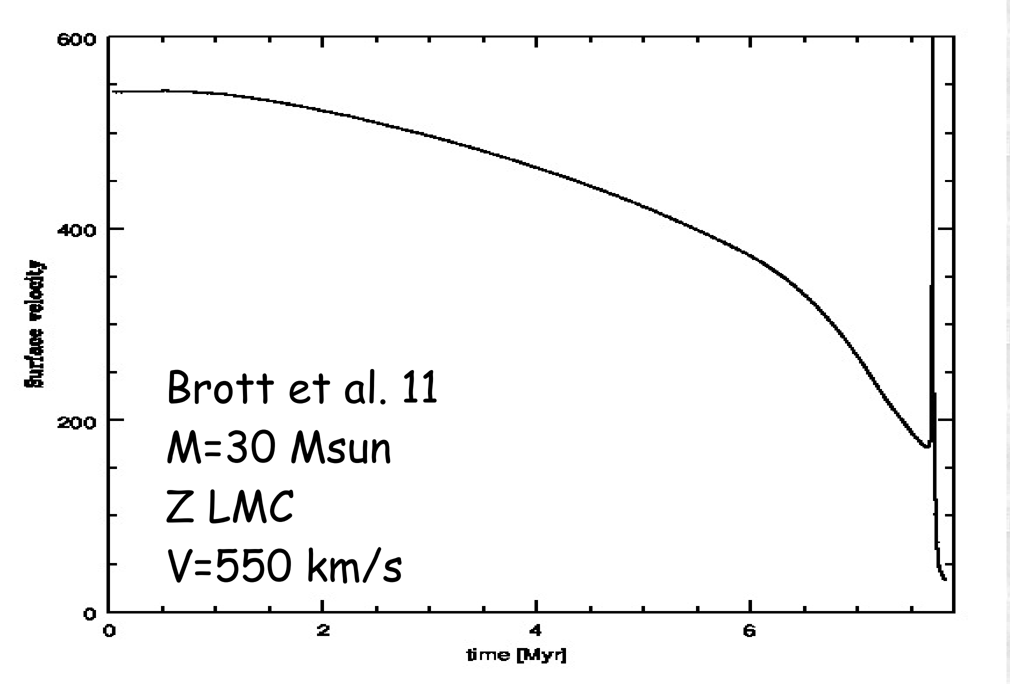
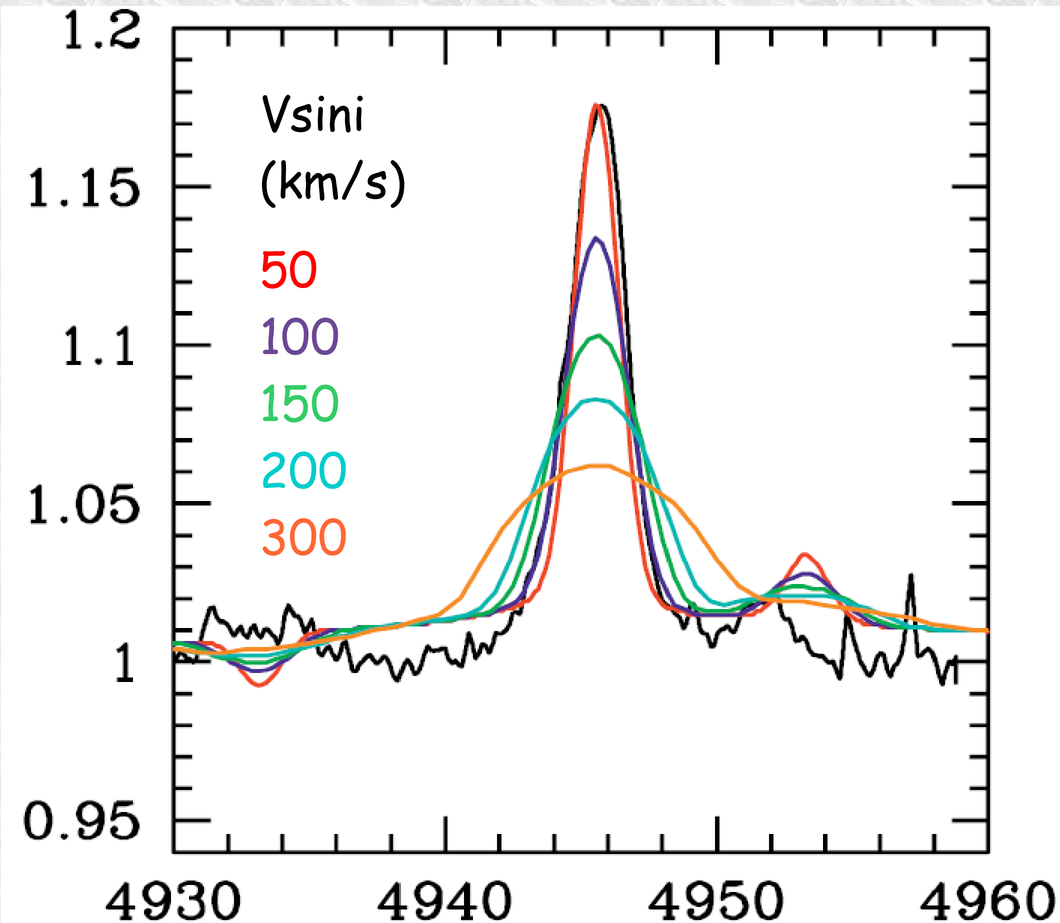
Stars most likely still in the core-H burning phase

Rotational velocity

Present day rotational velocity of 50 to ~ 100 km/s

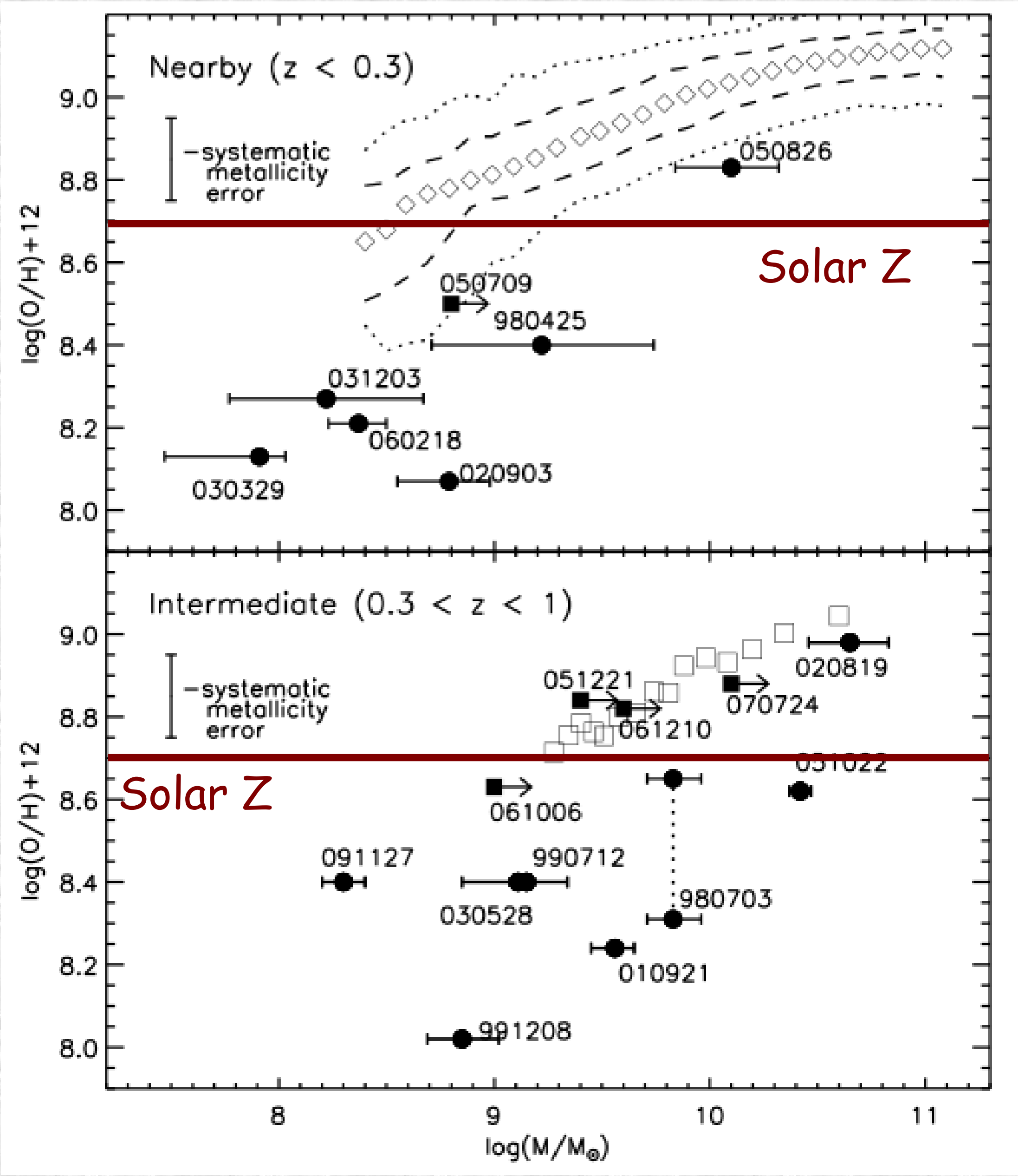




But

- Lines formed above photosphere / in the wind
- braking
- angular momentum coupling between wind/envelope and core

Implication for Long GRBs



Levesque 13

Long GRBs formed through collapsar

High core angular momentum before SN/GRB
→ weaker stellar winds at low metallicity favour LGRB formation

Chemically homogeneous evolution can lead to LGRB

Possibility of CHE at solar metallicity consistent with discoveries of LGRBs in (super) solar metallicity galaxies (*Graham et al. 2009, Levesque et al. 2010*)

Conclusion / open questions

- Early (i.e. WN3-5) H-rich WN stars have properties consistent with chemically homogeneous evolution

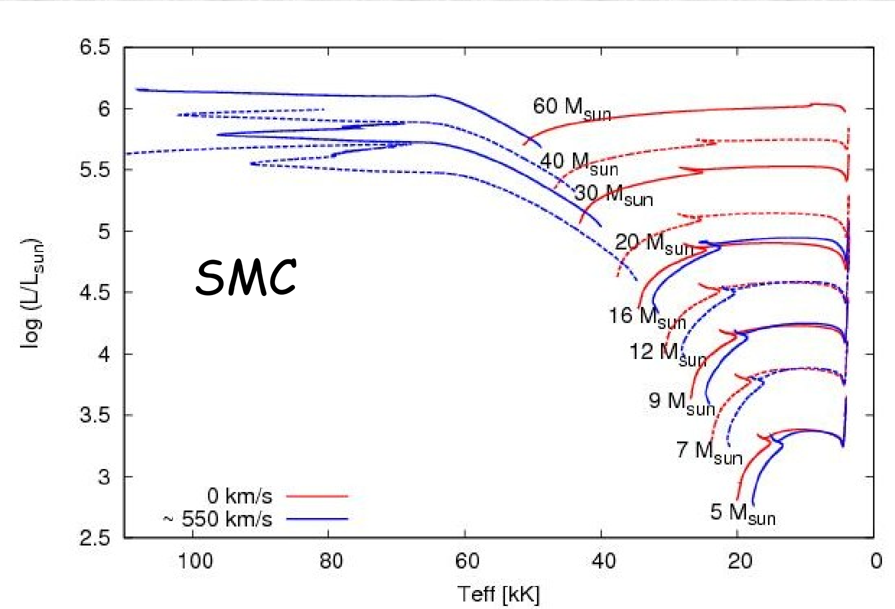
- Chemically homogeneous evolution likely to happen up to solar metallicity (but more difficult at higher Z because of stronger winds)

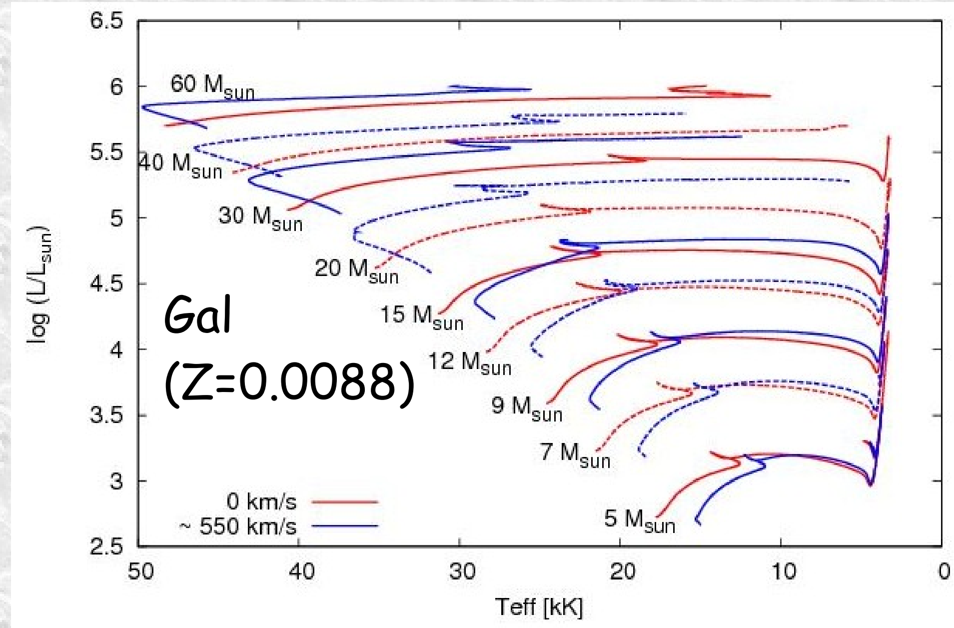
- CHE is rare: only 1-2% of Galactic WR stars are early WN3-5h stars
  Fraction increases when metallicity decreases (role of winds)

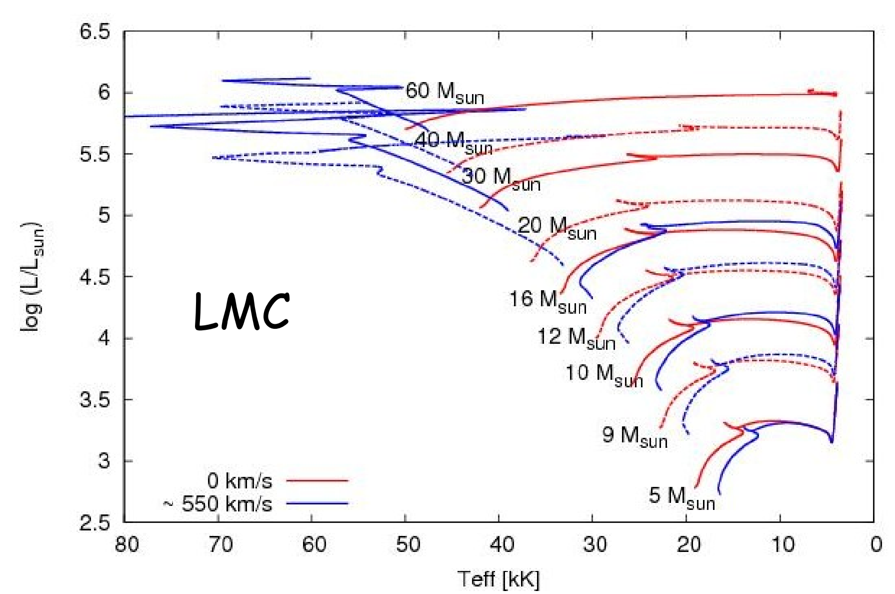
- Present day rotational velocity from wind lines not so large: poor determination of surface velocity? Strong braking? Relation between interior and wind rotational velocity?

- "Blue stragglers/mergers": not excluded, but predictions of merger properties (T, L, surface abundances...) required to test this hypothesis
  Fryer et al. 05: H envelope ejected during merger process

Metallicity threshold ?





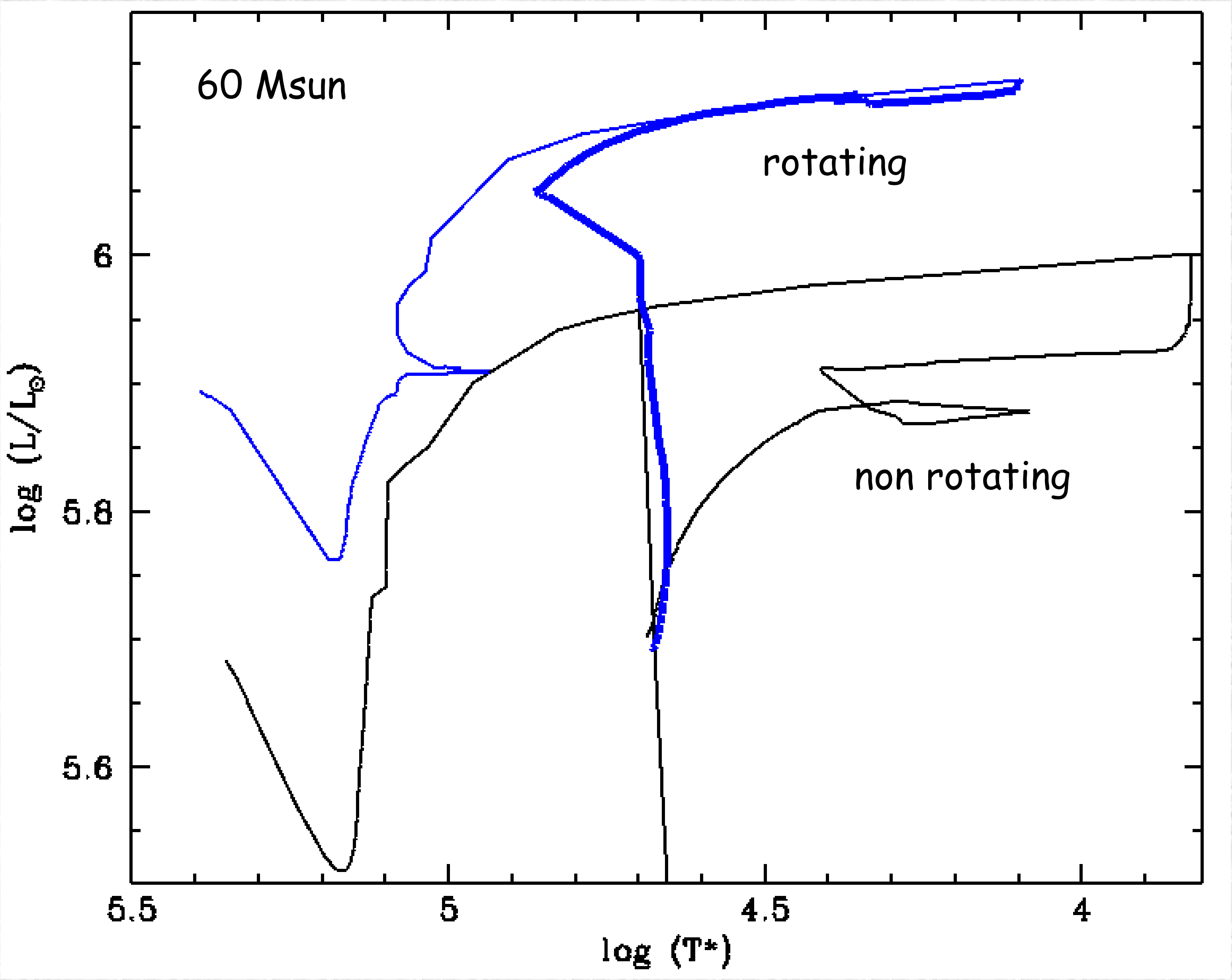


Single star evolutionary models: more difficult to produce quasi homogeneous evolution at high metallicity (e.g. *Brott et al. 2011*)

We find Galactic WNh stars likely following this evolution at Z=0.6-1.0

Brott et al. 11

CHE at Zsun ?



Ekstroem et al. 11

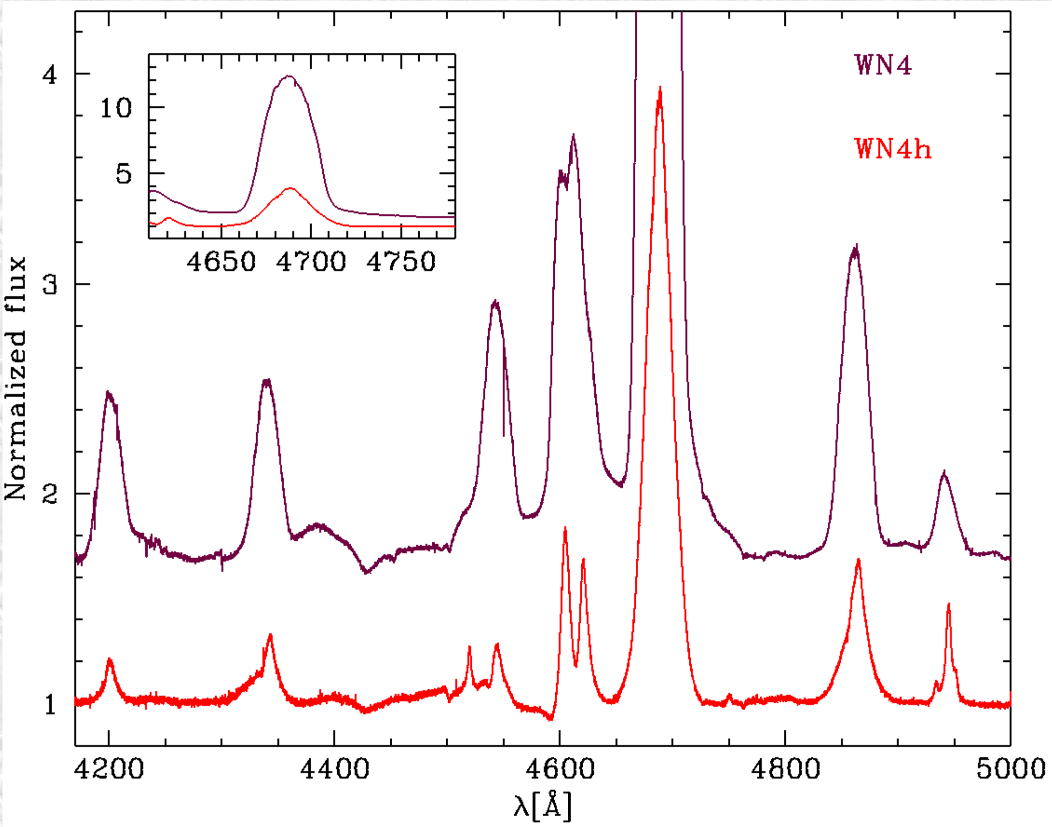
Wind properties

Star	ST	T_{eff} [kK]	T_* [kK]	$\log \frac{L}{L_\odot}$	R_* [$R_\odot$]	$\log(\dot{M})$	v_∞ [km s^{-1}]	f
Galaxy								
WR7	WN4	60.0	80.8	5.40	2.57	–4.80	1600	0.1
WR10	WN5h	53.5	55.2	5.45	5.79	–5.40/–5.45	1400	0.1
WR18	WN4	56.0	74.1	5.30	2.73	–4.60	2200	0.3
WR128	WN4(h)	57.0	59.9	5.50	5.43	–5.30	1800	0.1
LMC								
Bat 18	WN3h	60.0	72.8	5.50	3.54	–5.02	1800	0.3
Bat 63	WN4ha	58.5	68.9	5.45	3.73	–5.45	2000	0.1

Theoretical predictions from Vink et al.: log Mdot ~ -5.5 (Gal) / -5.8 (LMC)

If fast rotation, increase of Mdot by factor ~1.5-2

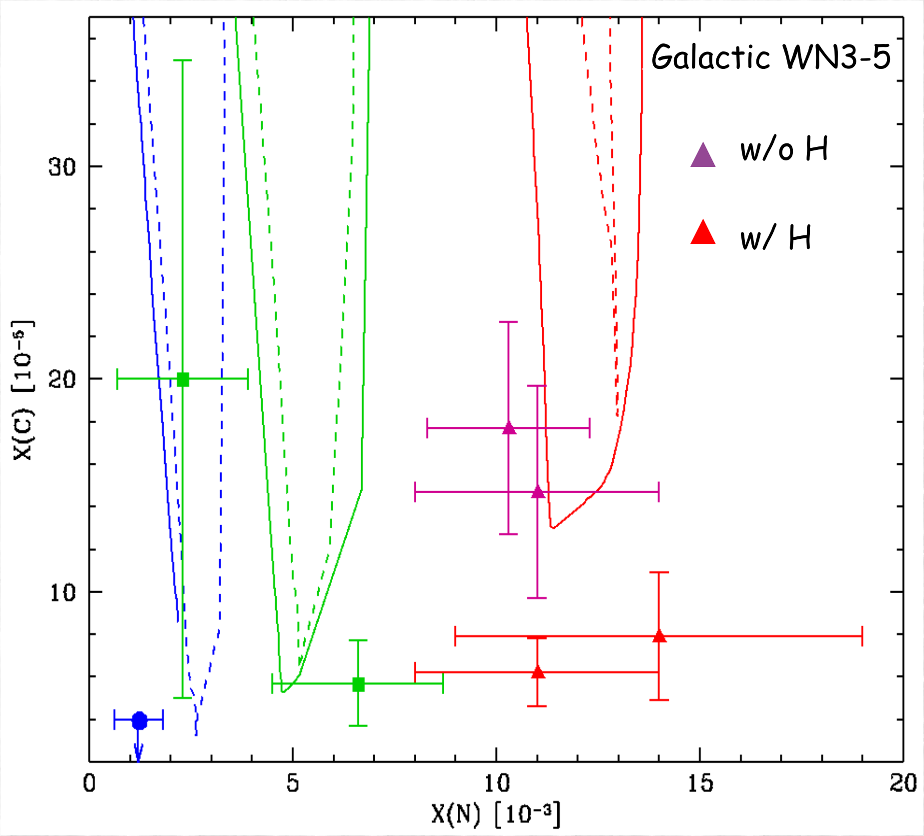
Spectroscopy: comparison to H-free WN4 stars



H-free WN4 have:

- stronger winds
  (mass loss rate 5 to 10 times larger)

- larger C content

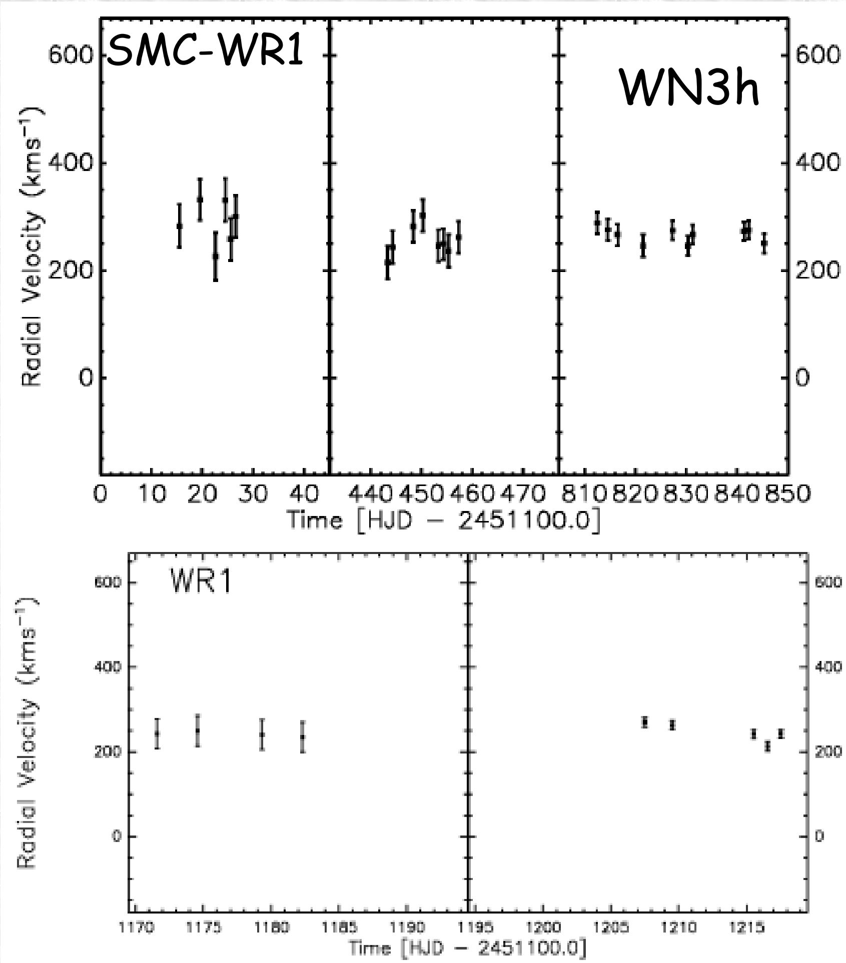


Similar position in the HR diagram but different physical properties

→ Different evolutionary status

See also Hamann et al. 06, Smith & Conti 08

Binarity

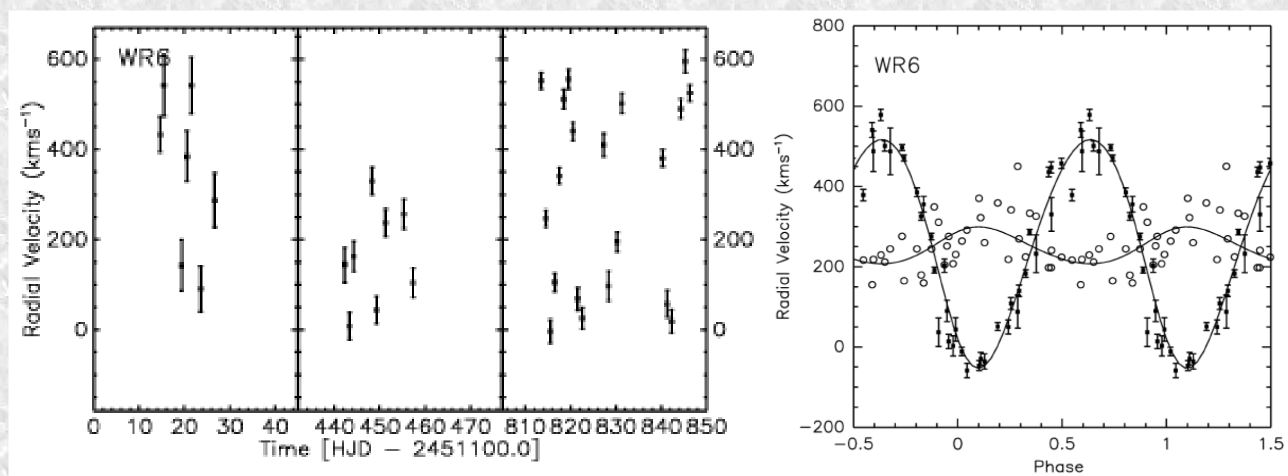


No sign of radial velocity variations
(no frequency detected in time series analysis)
in SMC/LMC targets

No X-ray detection

Foellmi et al. 03a, 03b

RV of binary : SMC-WR6 (WN4+O6.5I)



No clear sign of binarity

Single star scenario preferred