THE EVOLUTION OF MASSIVE STARS

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Stars formed between 0.10 and 120 M_{sol}
Salpeter's IMF

IN A STELLAR GENERATION: 3/1000
with masses between 8 ans 120 M_{sol}

Very low mass stars

$0.1 < M/M_{sol} < 1 \rightarrow 61\%$

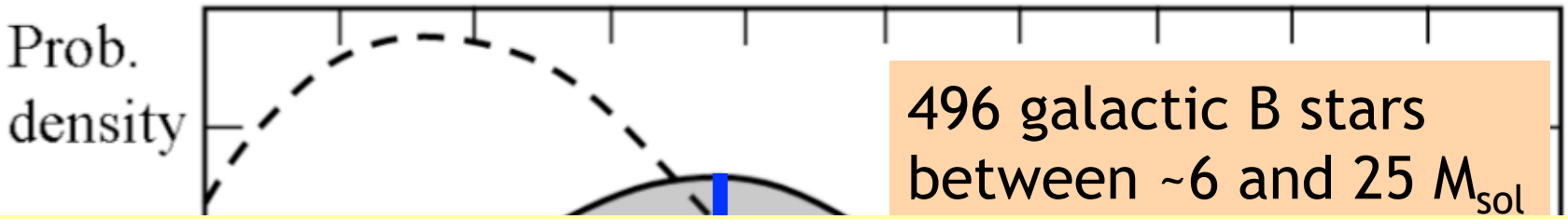
Low and intermediate mass stars

$1 < M/M_{sol} < 8 \rightarrow 25\%$

Mass fraction in massive stars

$M > 8\ M_{sol} \rightarrow 14\%$

AXIAL ROTATION



496 galactic B stars between ~6 and 25 M_{sol}

MIXING WHICH INCREASES

WITH MASS
WITH DECREASING Z

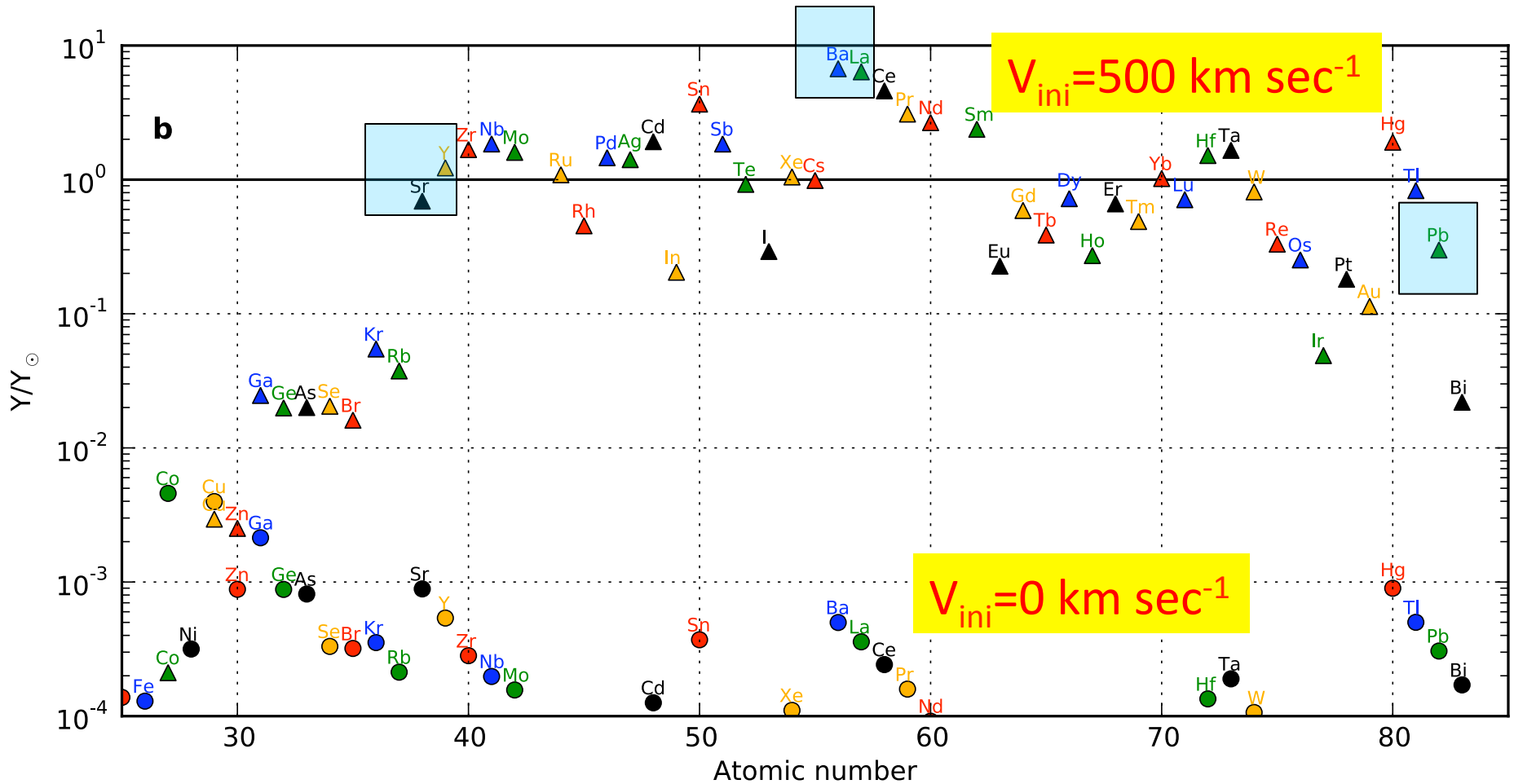
NUCLEOSYNTHESIS

Meynet & Maeder 2002, Meynet et al. 2006, Hirschi 2007, Decressin et al. 2007ab, Decressin et al. 2009, Frischknecht et al. 2012

EARLY CHEMICAL EVOLUTION OF GALAXIES

Chiappini, Matteucci, Ballero 2005, Chiappini et al. 2006, 2008, 2011, 2012, Cescutti et al. 2013

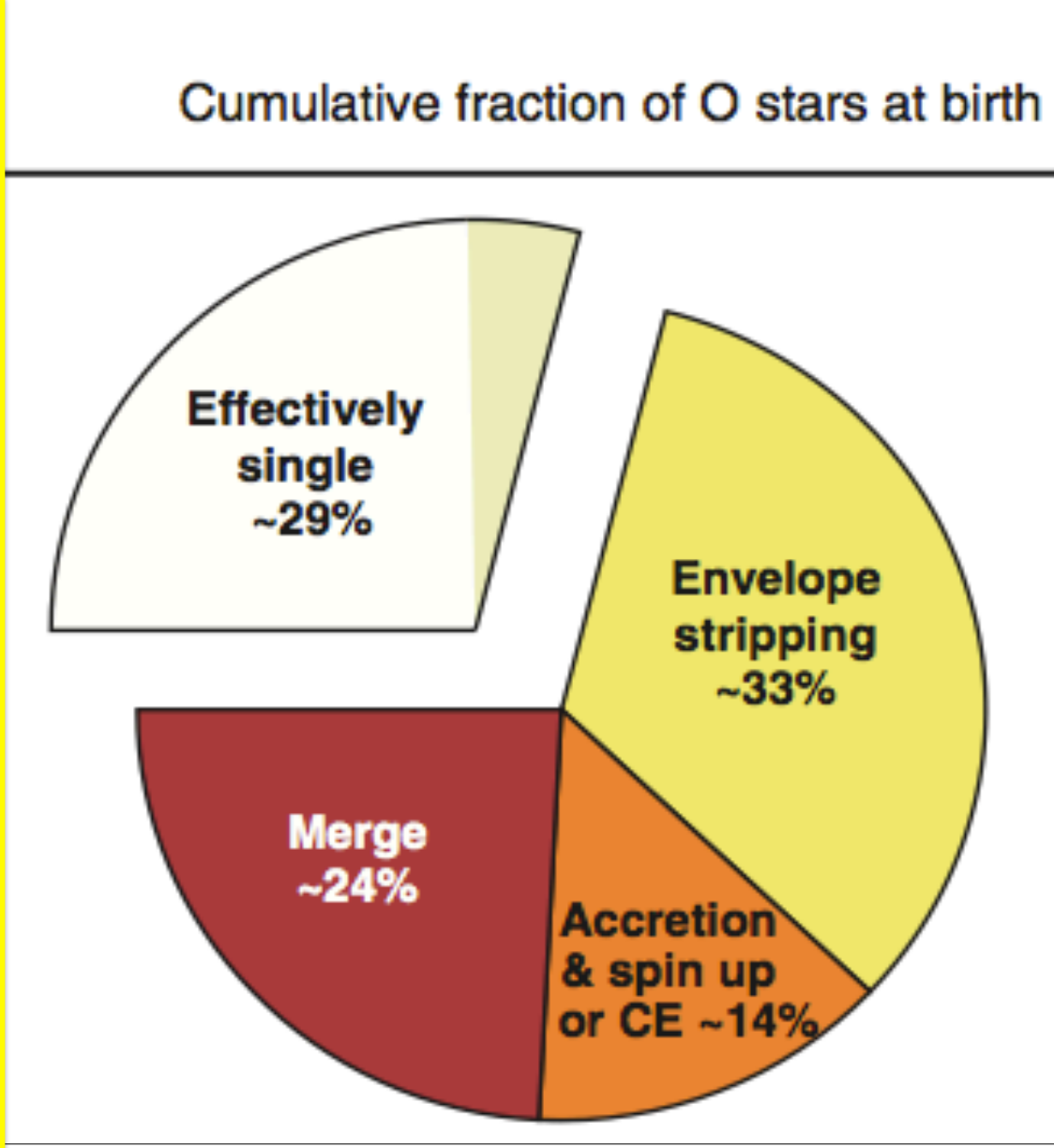
40 M_{sol} $Z=10^{-5}$



Frischknecht et al. 2012, see also Piganatari et al. 2008

BINARITY

- Stars in six nearby galactic open clusters→
- 71 single and multiple O-type objects
- 40 detected binaries



Sana et al. 2012

The VLT-FLAMES Tarantula Survey*

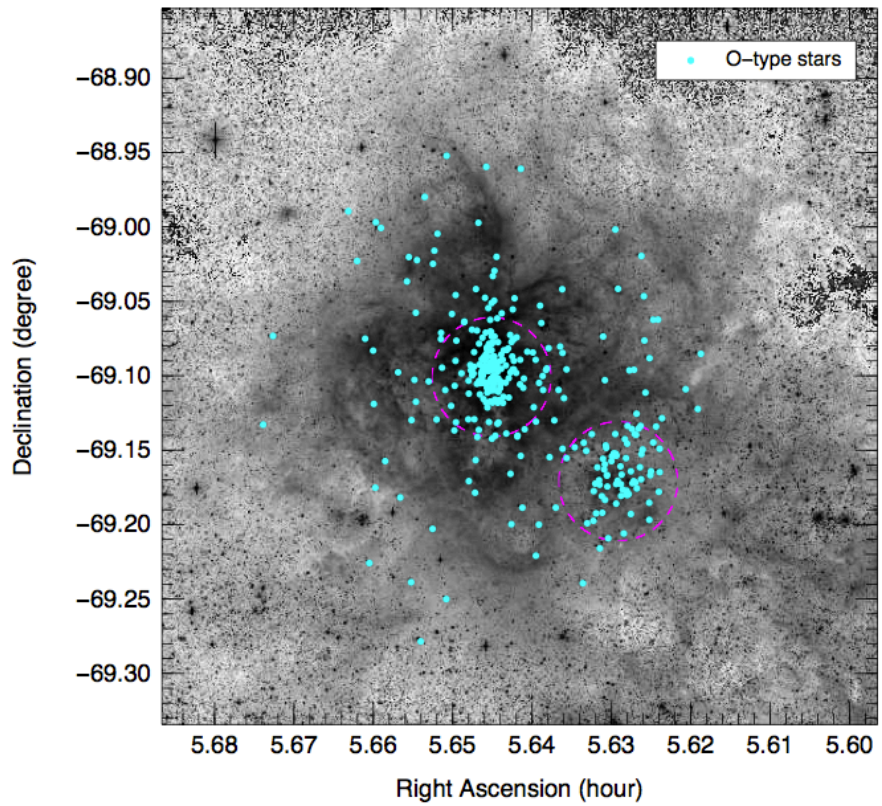
VIII. Multiplicity properties of the O-type star population

H. Sana[1], A. de Koter[1,2], S.E. de Mink[3,4**], P.R. Dunstall[5], C.J. Evans[6], V. Hénault-Brunet[7], J. Maíz Apellániz[8], O.H. Ramírez-Agudelo[1], W.D. Taylor[7], N.R. Walborn[3], J.S. Clark[9], P.A. Crowther[10], A. Herrero[11,12], M. Gieles[13], N. Langer[14], D.J. Lennon[15,3], and J.S. Vink[16]

(Affiliations can be found after the references)

Received May 17, 2012; accepted September 18, 2012

360 O-type stars
Intrinsic binary fraction 51%



THE PHYSICS OF BINARIES
NEEDS THE PHYSICS OF SINGLE STARS
(mass loss, rotation…)

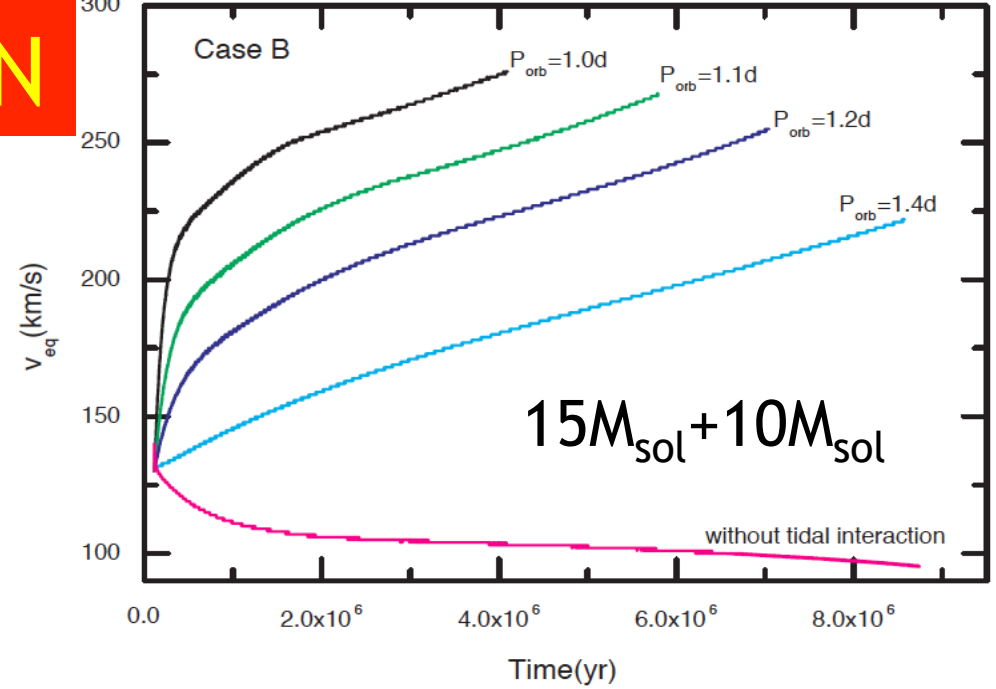
BINARITY & ROTATION

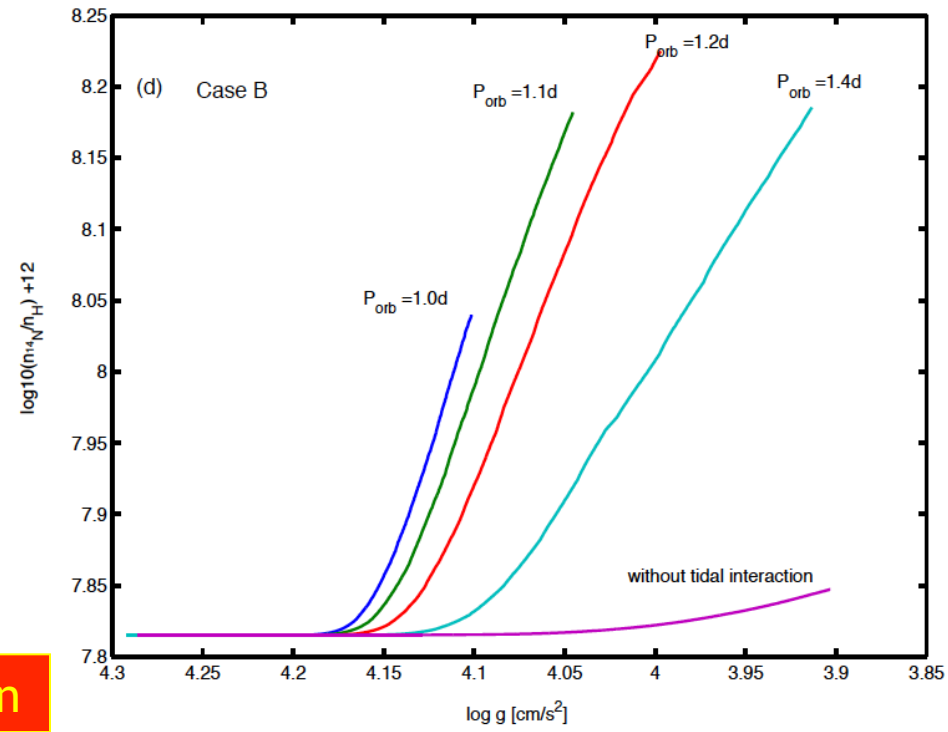
TIDAL INTERACTIONS

CAN BRAKE DOWN
CAN SPIN UP

IN BOTH CASES

TRIGGER MIXING





Song, Maeder, Meynet, Huang, in preparation

SURFACE MAGNETIC FIELDS

Wade et al. 2012, astro-ph 1206.5163V2 (350 OB stars survey)

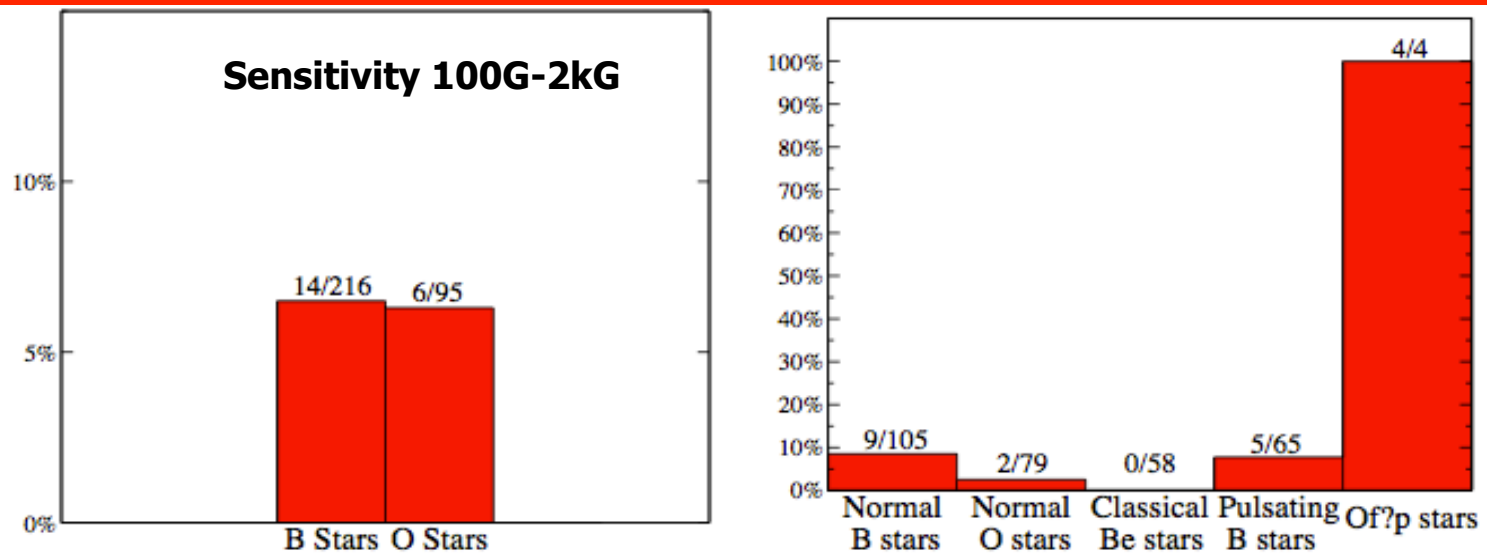


Figure 3. Incidence fraction of magnetic stars relative to the total indicated sample of all stars observed as part of the MiMeS survey. Our statistics indicate a ~ 6.5% incidence rate of magnetism amongst all massive stars in our sample.

(i) ubiquitous **evidence for magnetic wind confinement** in optical spectra of all magnetic O stars,

(ii) the **presence of strong, organized magnetic fields in all known Galactic** Of?p stars,

(iii) a **complete absence of magnetic fields in classical Be stars**.

External magnetic field

$$\eta(r) \equiv \frac{B^2/8\pi}{\rho v^2/2}$$

if $\eta > 1$ → wind channelled by magnetic lines

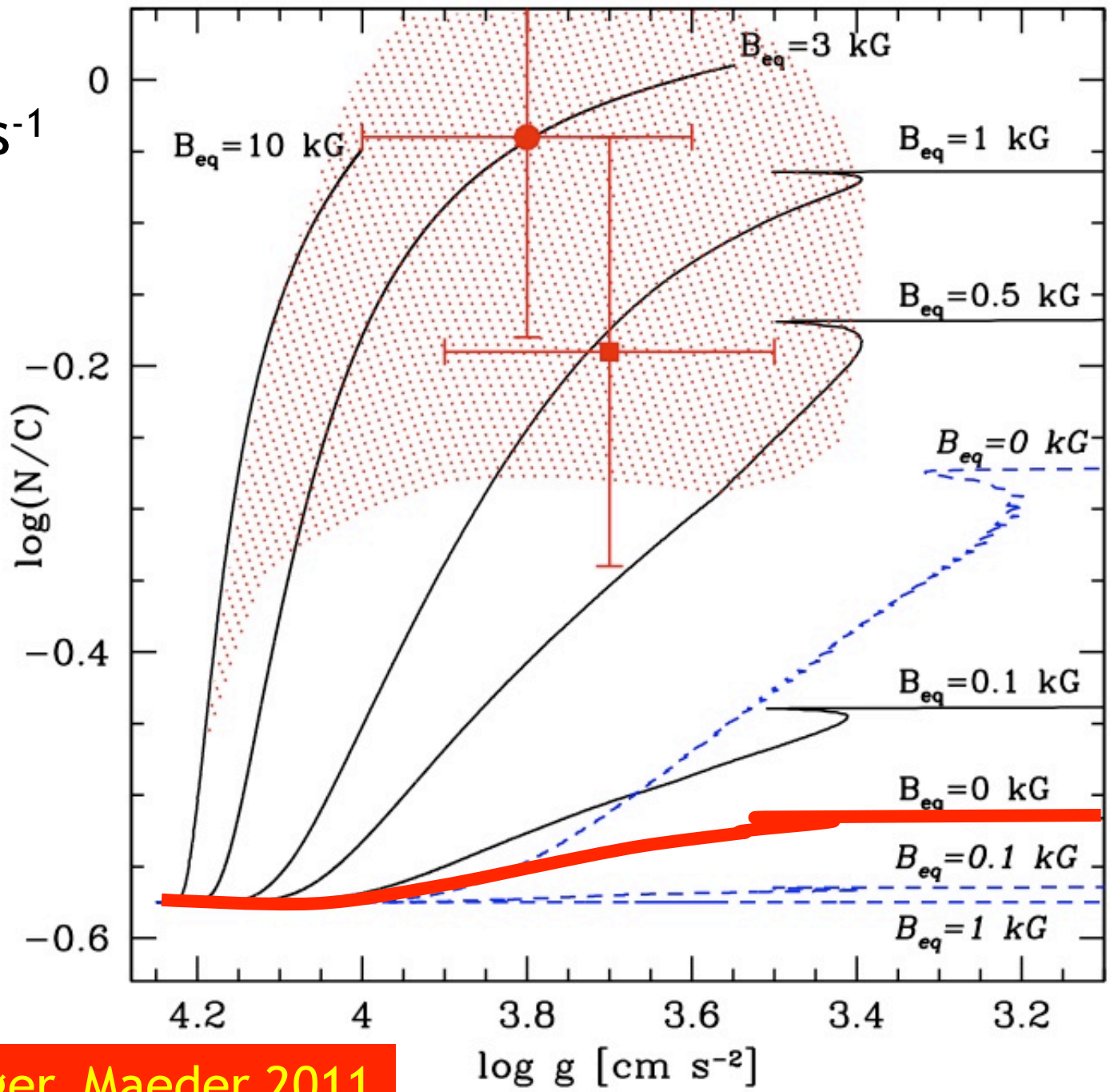
$$\frac{\mathrm{d}J}{\mathrm{d}t} = \frac{2}{3}\dot{M}\Omega R_*^2[0.29 + (\eta_* + 0.25)^{1/4}]^2$$

ud-Doula & Owocki (2002)

10 M_{sol}

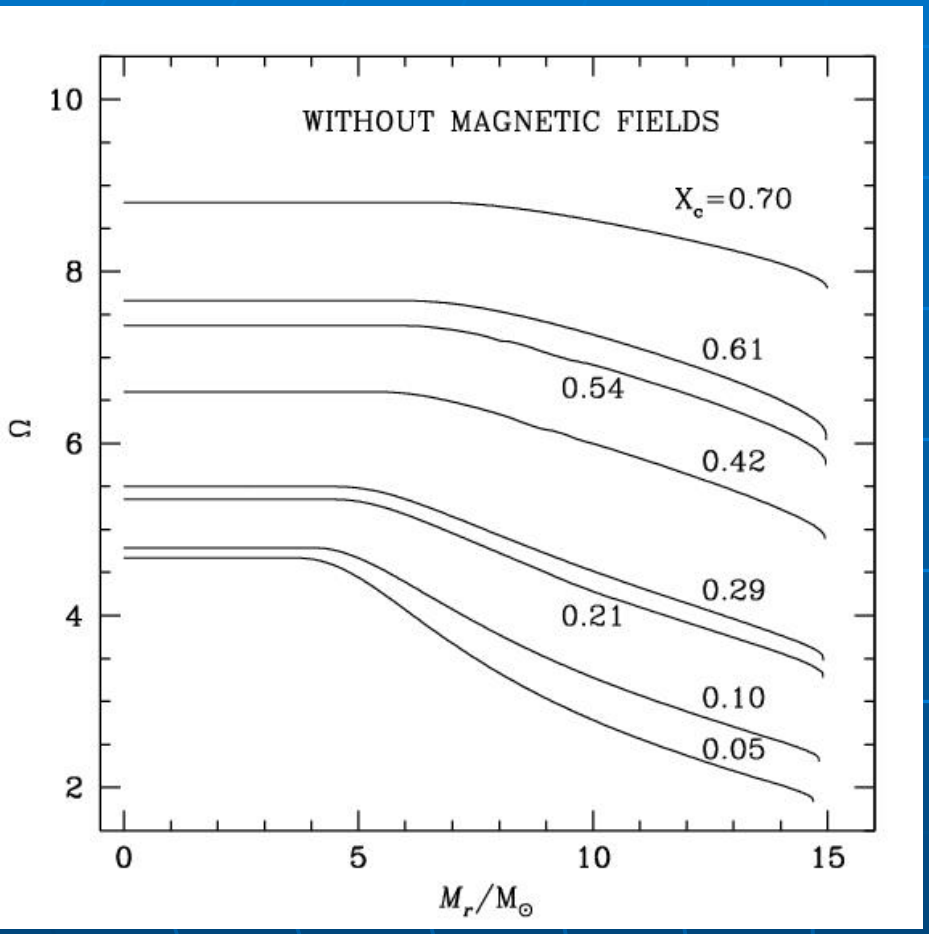
V_{ini}=200 km s^{-1}

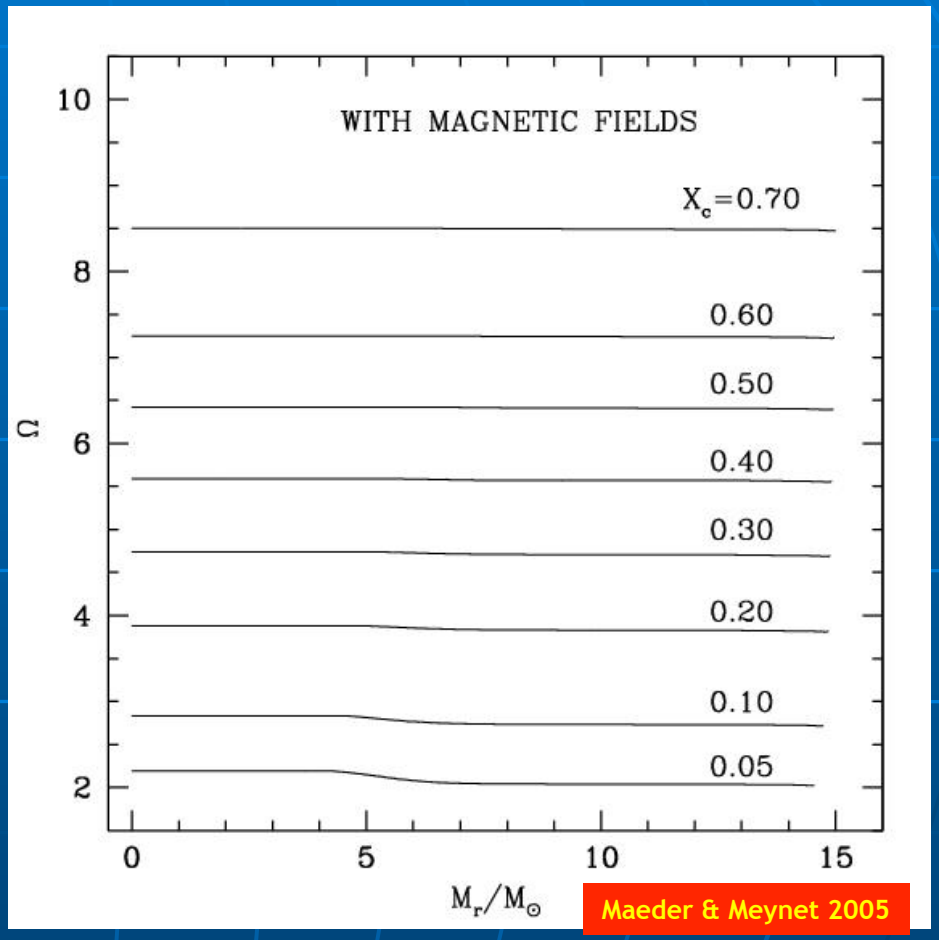
Z=0.014



GM, Eggenberger, Maeder 2011

15 M_{sol}, Z=0.020, V_{ini}=40% V_{crit}





Maeder & Meynet 2005

INTERNAL MAGNETIC FIELDS (10^4-10^5 G)
→ SOLID BODY ROTATION

Rotating models

With and without Dynamo.

TABLE I Grids of rotating massive star models (starting from 2000).

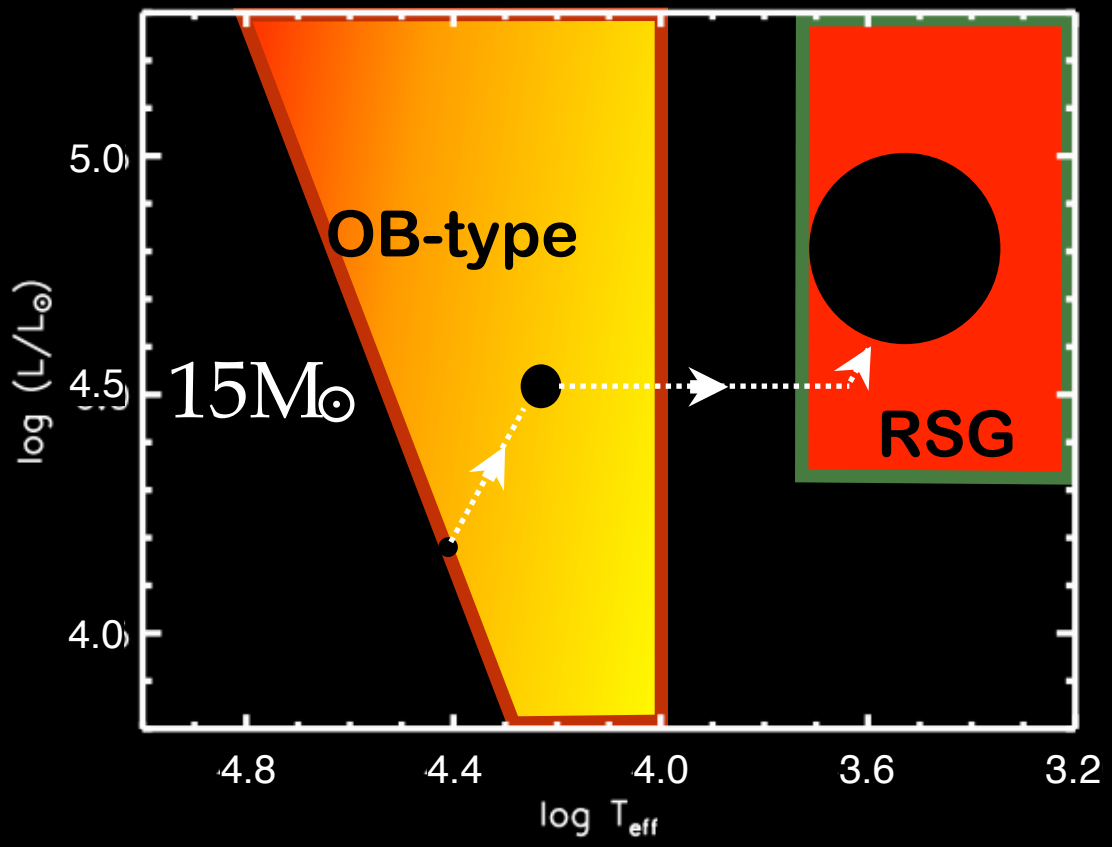
Masses $M_\odot$	Z	Initial rotation km/s	Magnetic field (interior)	Ref.
9- 200	0	0-800	no	Ekström et al. (2008a)
3-60	0	39-1423	no	Ekström et al. (2008b)
9-85	0.00000001	800	no	Hirschi (2007)
2-60	0.00001	0-400	no	Meynet & Maeder (2002a)
20-60	0.00001	230-605	yes	Yoon & Langer (2005)
12-60	0.00001	0 - 936	yes	Yoon et al. (2006)
3-60	0.0001	39-1017	no	Ekström et al. (2008b)
20-200	0.0005	0-800	no	Decressin et al. (2007b)
20-60	0.001	230-605	yes	Yoon & Langer (2005)
12-60	0.001	0-747	yes	Yoon et al. (2006)
3-60	0.002	32-879	no	Ekström et al. (2008b)
12-60	0.002	0-653	yes	Yoon et al. (2006)
5-60	0.0021	0-600	yes	Brott et al. (2011)
9-60	0.004	0-300	no	Maeder & Meynet (2001b)
30-120	0.004	300	no	Meynet & Maeder (2005)
12-60	0.004	0-507	yes	Yoon et al. (2006)
5-60	0.0047	0-600	yes	Brott et al. (2011)
30-120	0.008	300	no	Meynet & Maeder (2005)
5-60	0.0088	0-600	yes	Brott et al. (2011)
8-25	0.020	0-474	no	Heger & Langer (2000)
8-25	0.020	200	no	Heger et al. (2000)
9-120	0.020	0-300	no	Meynet & Maeder (2000)
9-120	0.020	0-300-500	no	Meynet & Maeder (2003)
12-60	0.020	0-300	no	Hirschi et al. (2004)
12-35	0.020	200	yes & no	Heger et al. (2005)
16-40	0.020	210-556	yes	Yoon et al. (2006)
3-60	0.020	28-732	no	Ekström et al. (2008b)
20,25,40,60,85,120	0.040	0-300	no	Meynet & Maeder (2005)

+ Limongi & Chieffi 2013
13-120 $M_{sol,}$ solar Z
No internal magnetic field

Massive star evolution (8 to ~17 $M_\odot$) (Solar Z)

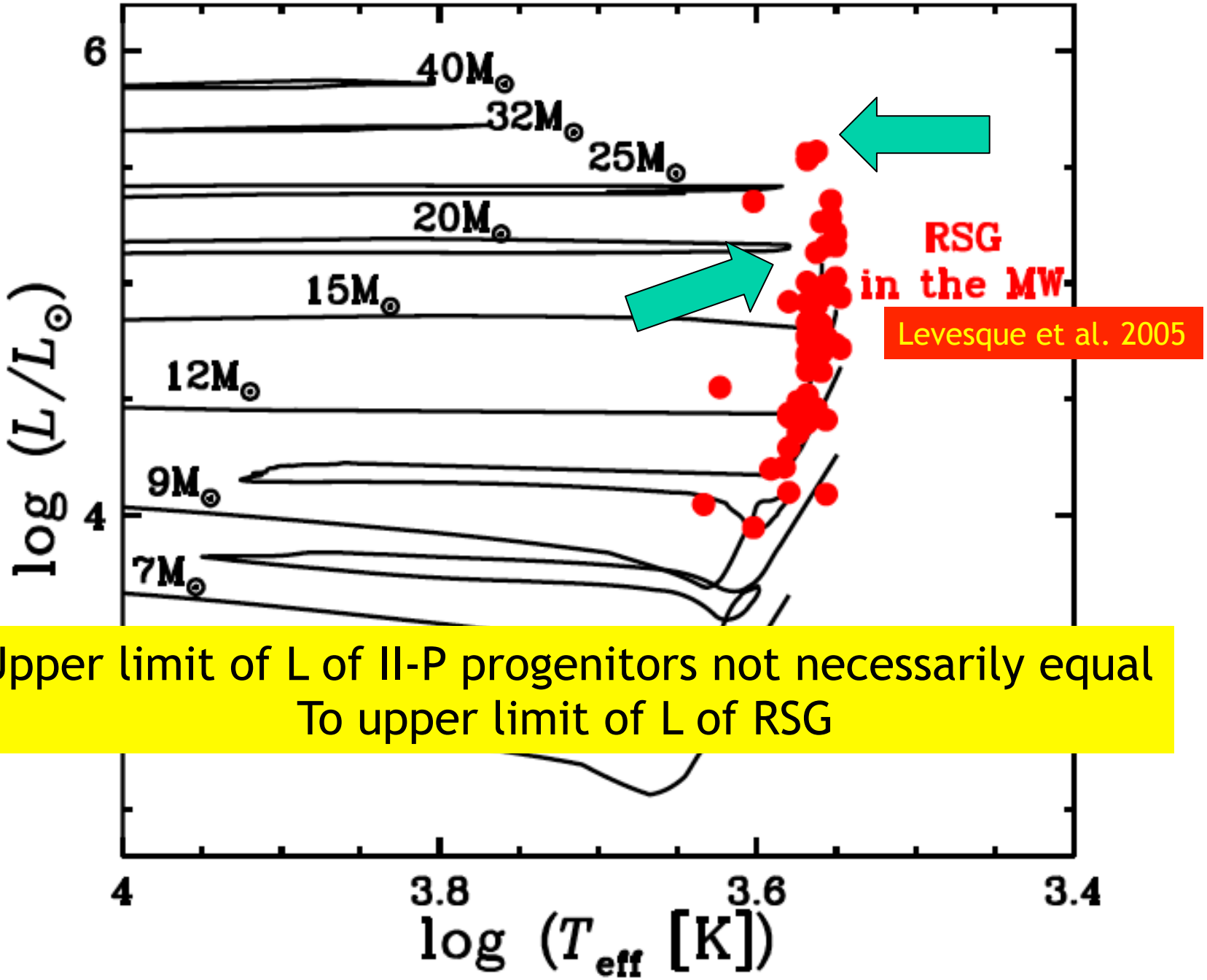
OB-type → RSG → SN IIP

Agrees with observations of SN II progenitors (Smartt 09)



(after evol. tracks from Meynet & Maeder 03, Ekstrom+ 12)

slides of José Groh

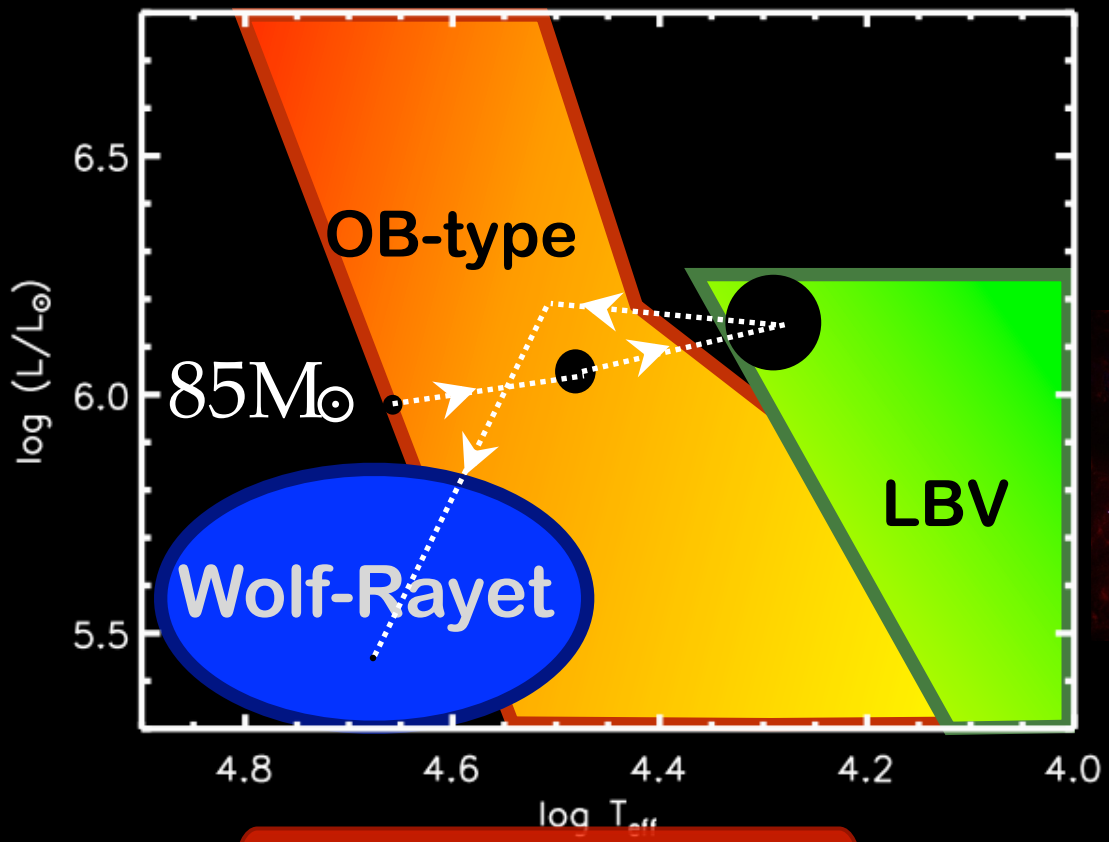


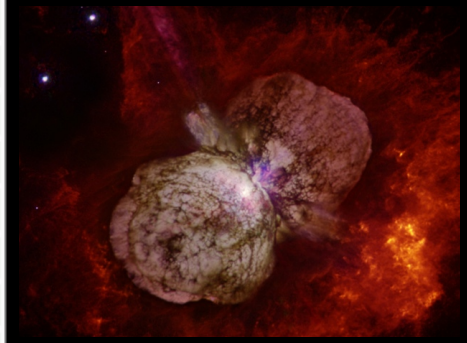
Upper limit of L of II-P progenitors not necessarily equal
To upper limit of L of RSG

Massive star evolution (at solar Z, above 30 $M_\odot$)

OB-type → LBV → WR → SN I_{bc} or BH

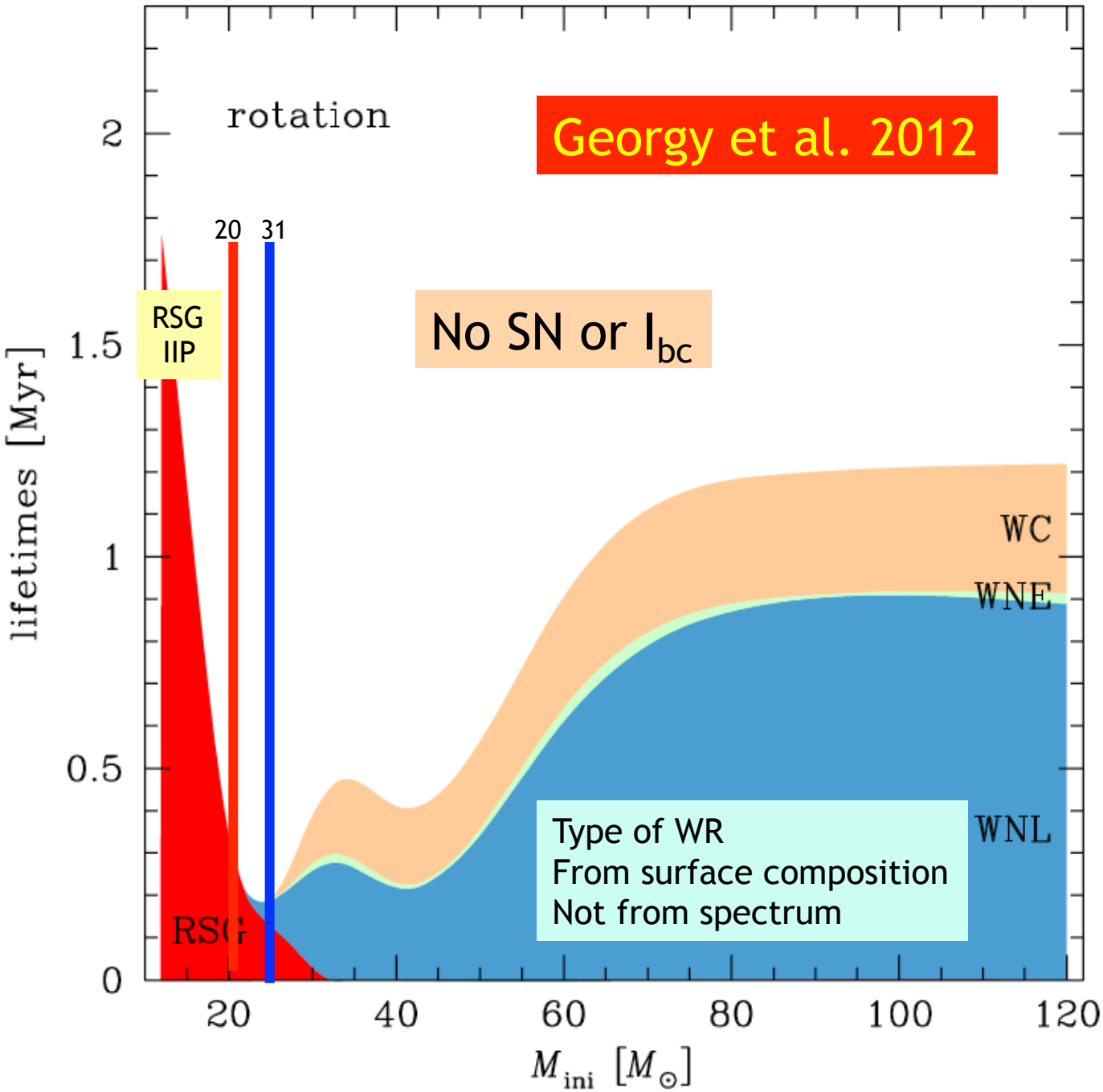
So far, no observations of WRs as SN progenitors (Smartt 09)

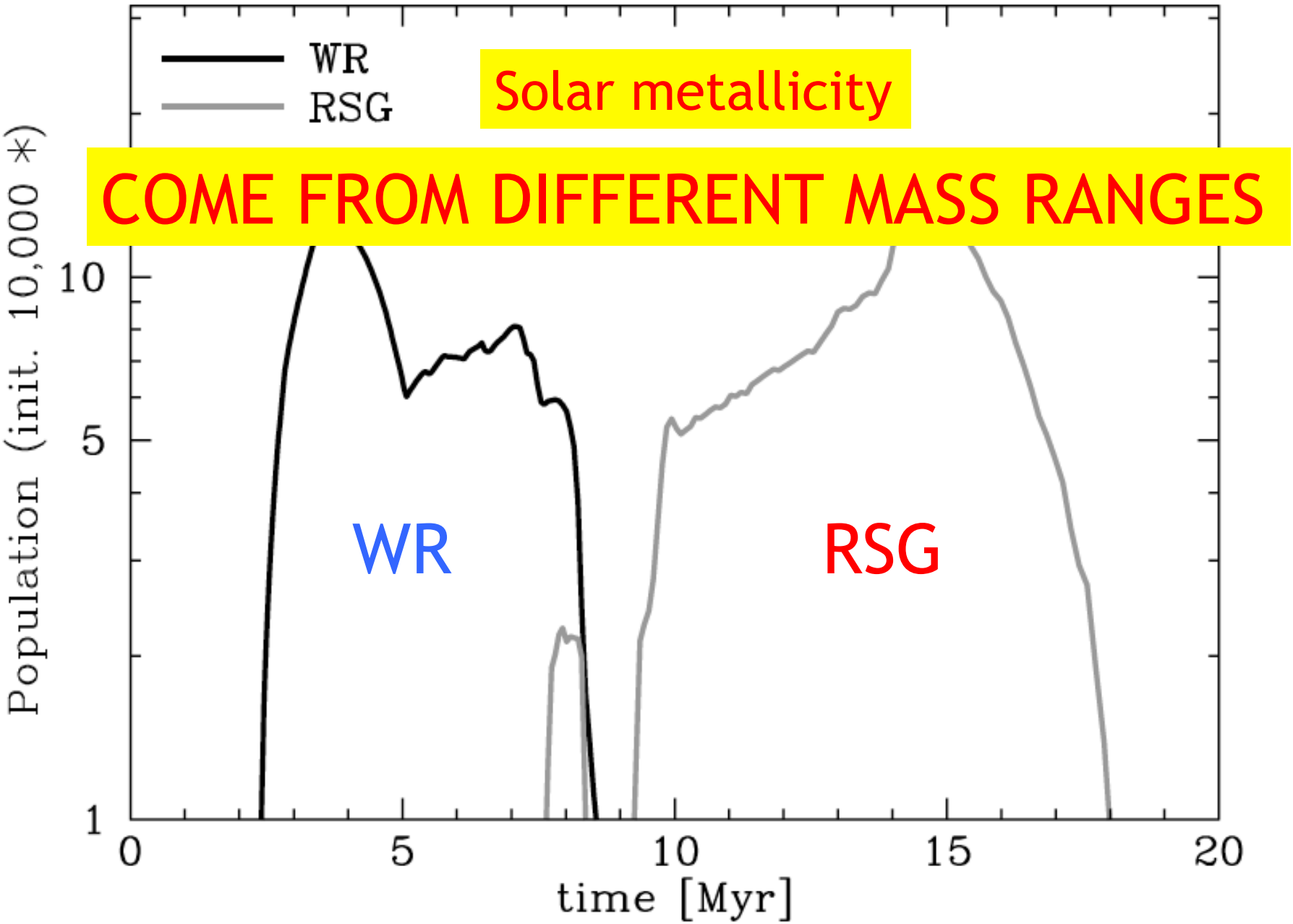


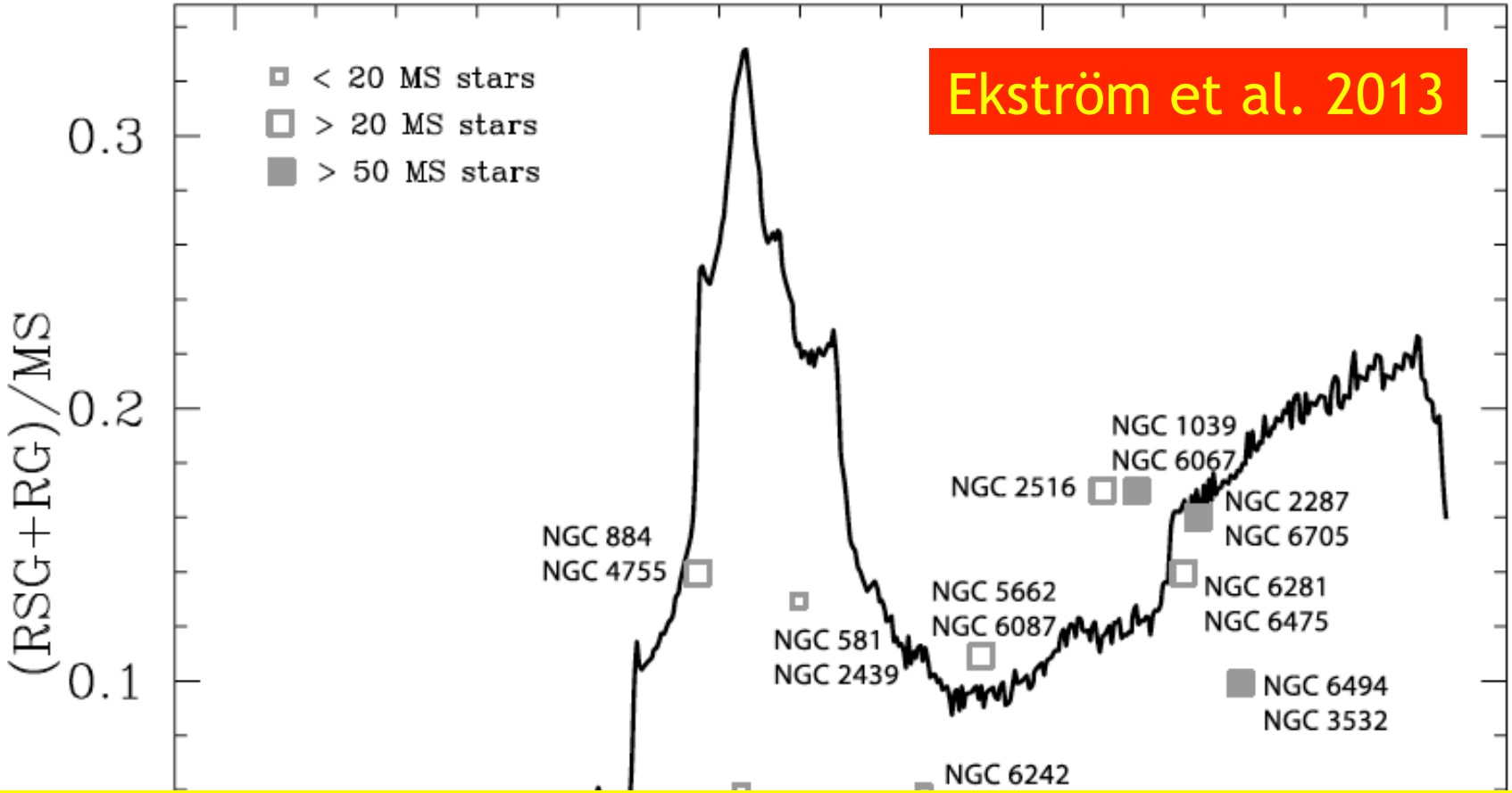


See José Groh's talk

(after evol. tracks from Meynet & Maeder 03, Ekstrom+ 12)


rotation
Georgy et al. 2012
20
31
RSG
IIP
No SN or I_{bc}
WC
WNE
WNL
RSG
Type of WR
From surface composition
Not from spectrum
lifetimes [Myr]
M_{ini} [$M_\odot$]
0
0.5
1
1.5
2
20
40
60
80
100
120


WR
RSG
Solar metallicity
COME FROM DIFFERENT MASS RANGES
WR
RSG
Population (init. 10,000 ⋆)
10
5
1
0
5
10
15
20
time [Myr]



In solar neighbourhood (Constant star formation in the last 10 Myr) one observes N(WR)/N(O)=0.12+-0.03,
the models of single stars: 0.07 **(Georgy et al. 2012)**
Garmany et al. (1982), van der Hucht 2001, Pasquali et al. 2002, Neguerela 2003, Hadfield & Crowther 2007, Shara et al. 2009, Mauerhan et al. 2011, Reed (2011)

Core-collapse SN fraction

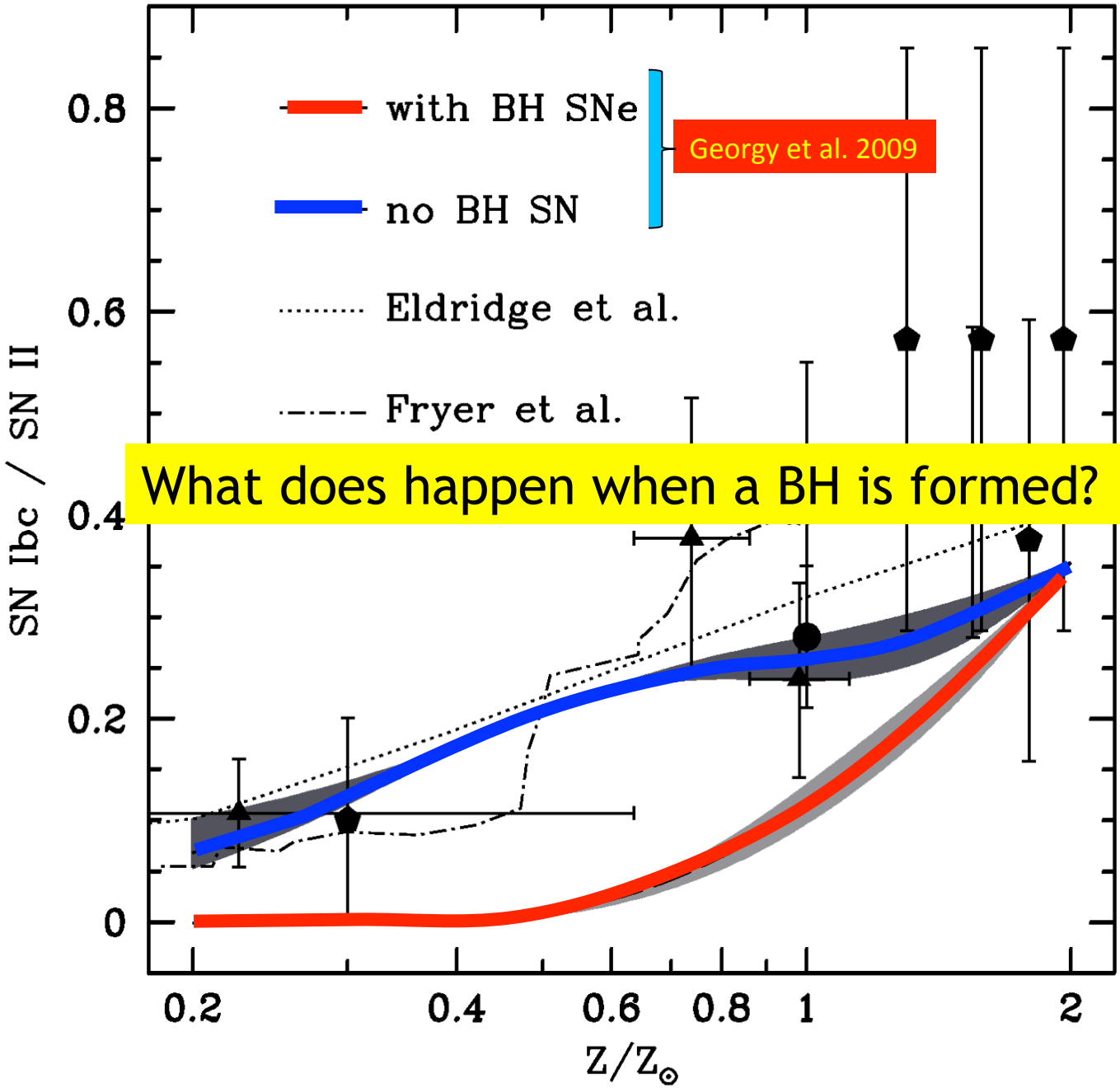
Table 1. Core-collapse SN fractions from our models compared to observed samples

SN Type	Non-rot. model (%)	Rot. model (%)	Obs. E13 (%)	Obs. S11 (%)
			Eldridge et al. 2013	Smith et al. 2011
IIP IIL + IIb IIn IIpec	86.9	78.0	74 +12.3 -12.3	74 +13.6 -12.5
Ib Ic	13.1	22.0	26 +6.4 -6.4	26 +7.3 -6.4

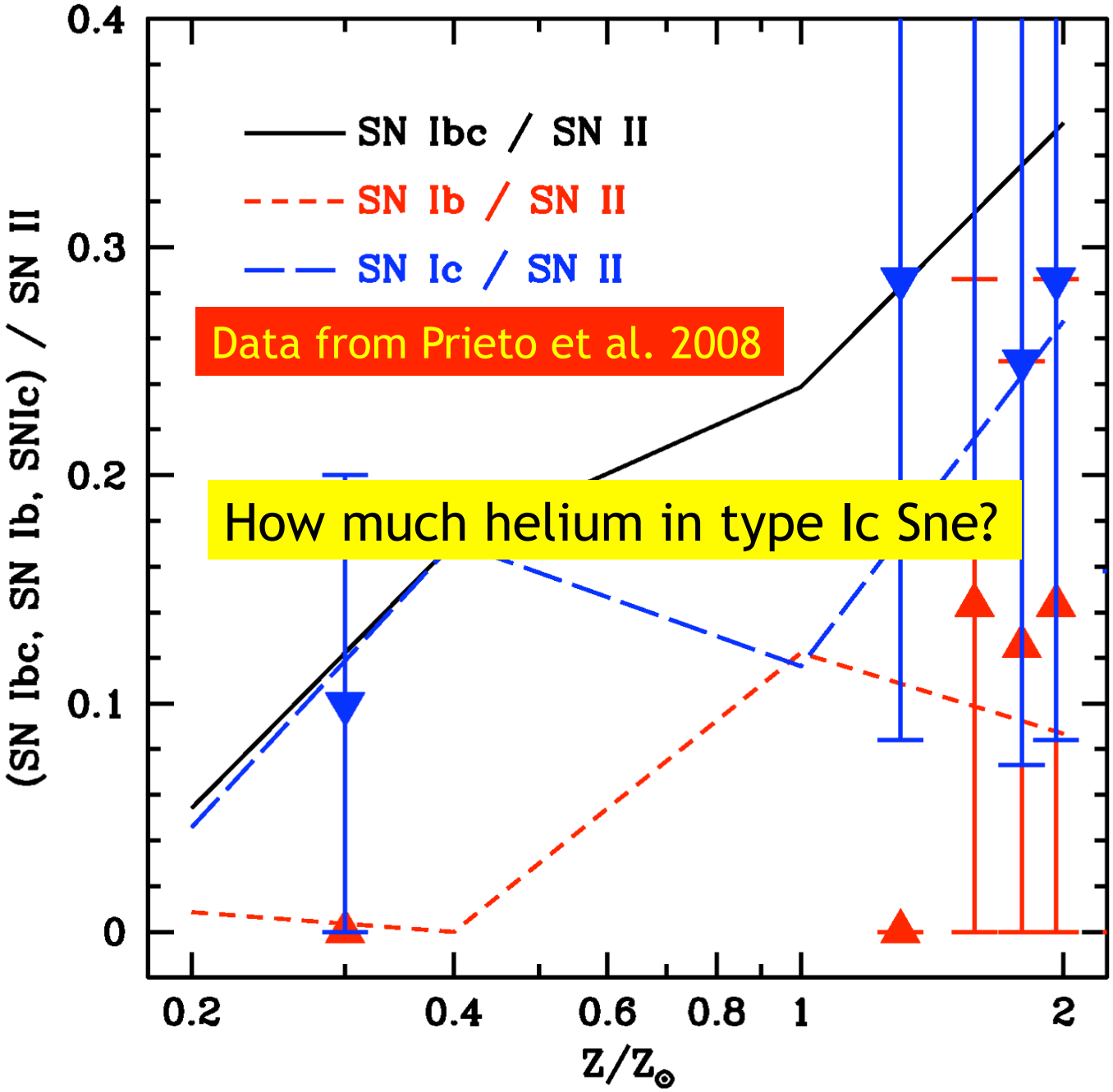
(Groh+ 2013, in prep.)

All massive stars produce Sne→ may be some overestimates

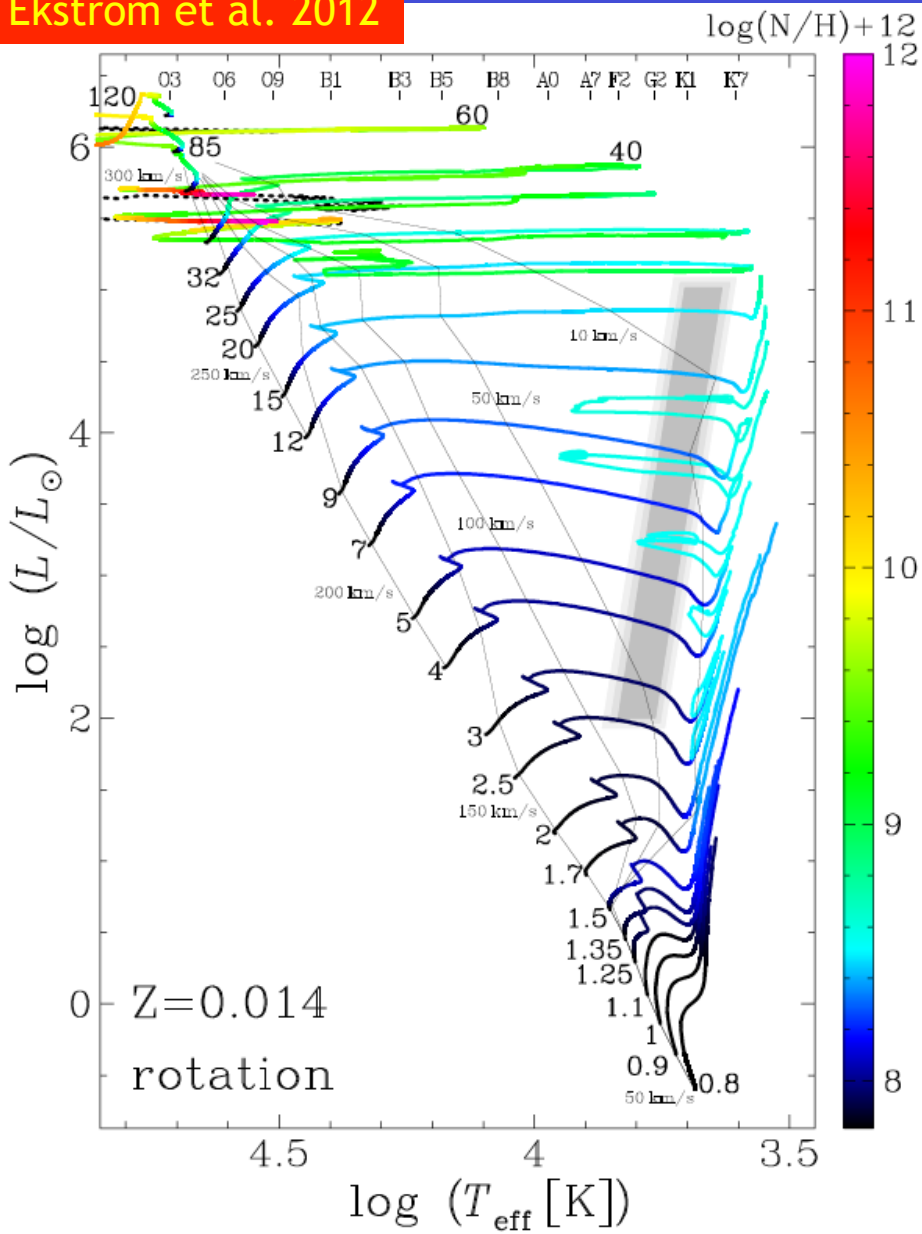
Prieto et al. 2008 (pentagons); Prantzos & Boissier 2003 (triangles); Cappellaro et al. 2009 (circle)



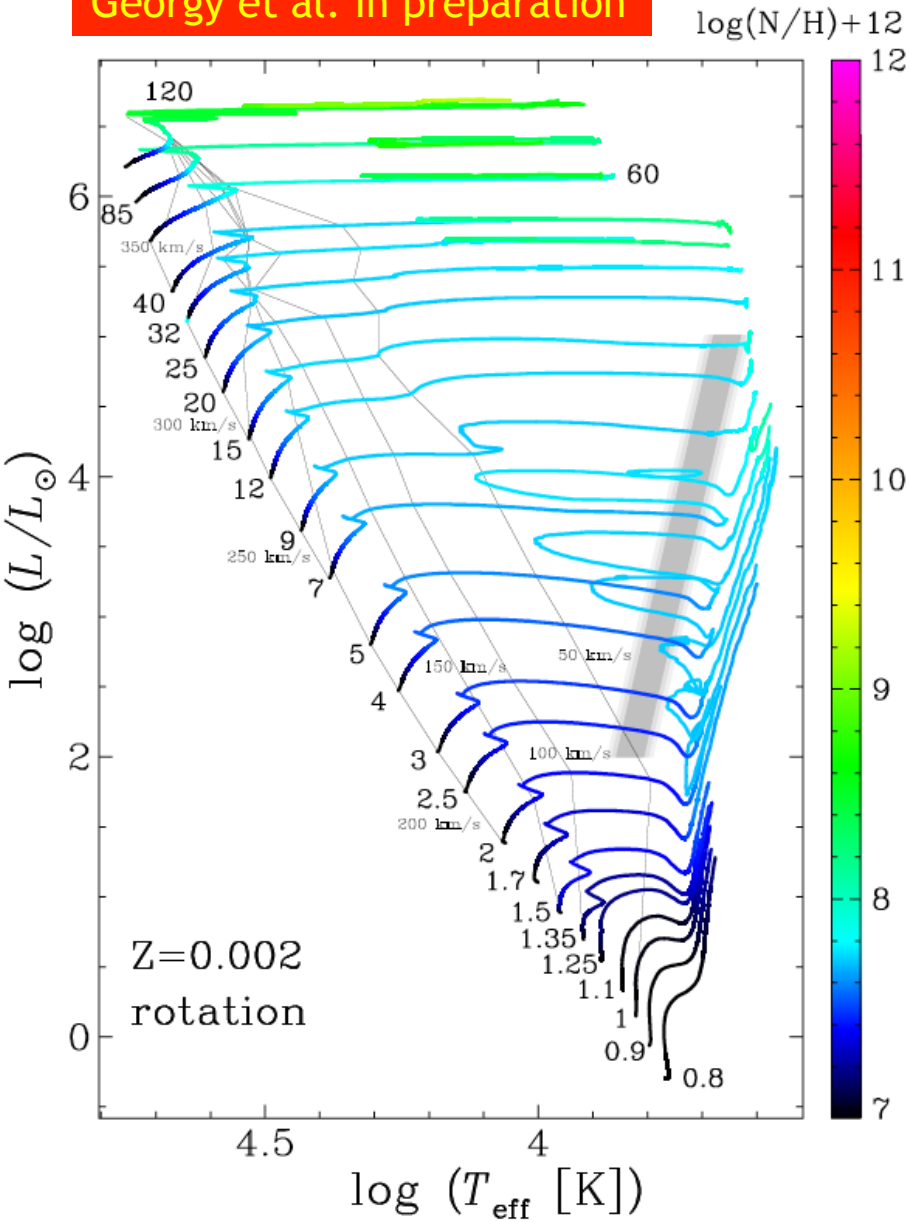
What does happen when a BH is formed?

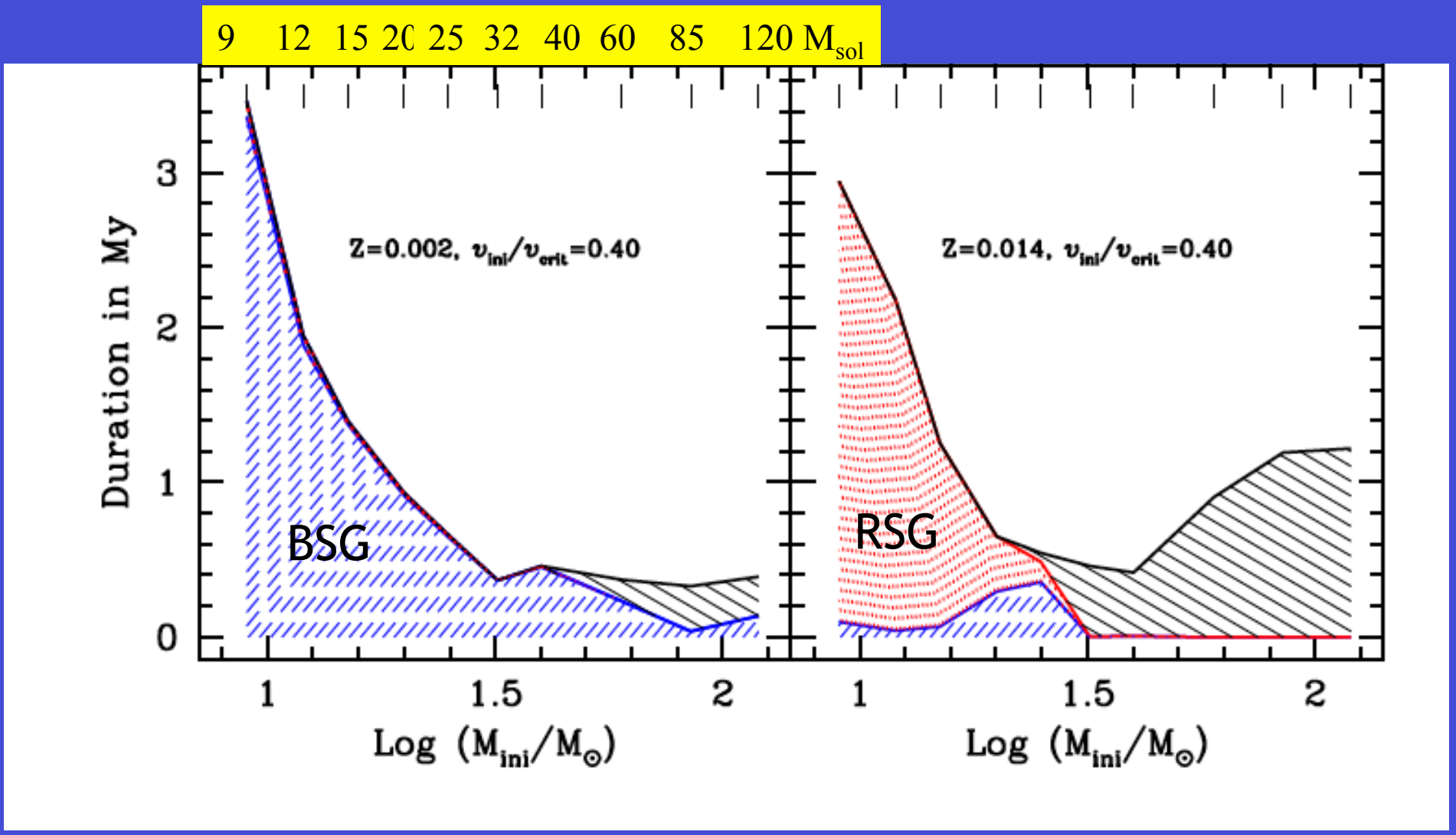

SN Ibc / SN II
SN Ib / SN II
SN Ic / SN II
Data from Prieto et al. 2008
How much helium in type Ic Sne?
(SN Ibc, SN Ib, SNIc) / SN II
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1
2
Z/Z⊙

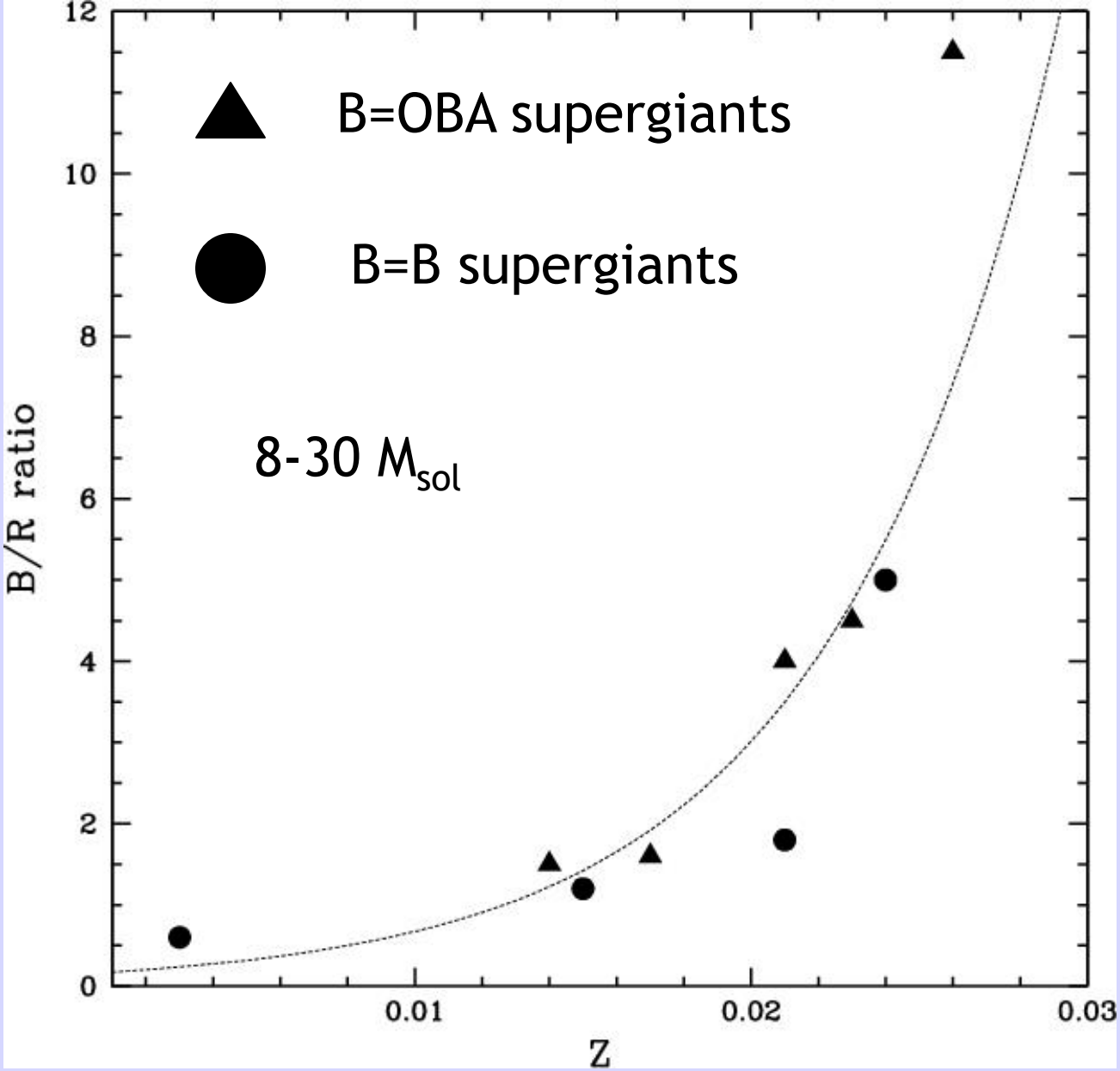
Ekström et al. 2012



Georgy et al. In preparation



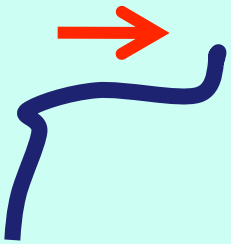

9 12 15 20 25 32 40 60 85 120 M_sol
Duration in My
Z=0.002, v_ini/v_crit=0.40
Z=0.014, v_ini/v_crit=0.40
BSG
RSG
Log (M_ini/M_⊙)
Log (M_ini/M_⊙)



Eggenberger et al. AA, 386, 576 (2002);
Cf discussion in Langer and Maeder AA 373, 555 (1995)

What makes BSG?

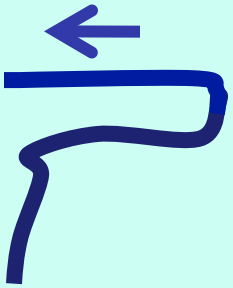
FIRST CROSSING OF THE HR GAP



Fast → He-b. in red → RSG
Slow→ He-b. in blue→ BSG

Z, low → blue
Opacity → blue
Overshoot→ red
Mass loss → red or blue
Mixing → red or blue

SECOND CROSSING OF THE HR GAP



Mass loss→Bluewards evolution
Mixing →Bluewards evolution

The set of physical parameters which can reproduce the general trend has not yet been found

CAN WE DISTINGUISH
A BSG HAVING EVOLVED DIRECTLY FROM MS
FROM A BSG HAVING EVOLVED FROM A RSG PHASE ?

1- Surface composition

Table 3. The surface H abundance and ratios of CNO elements for BSG models at $\log T_{\rm eff} = 4.0$

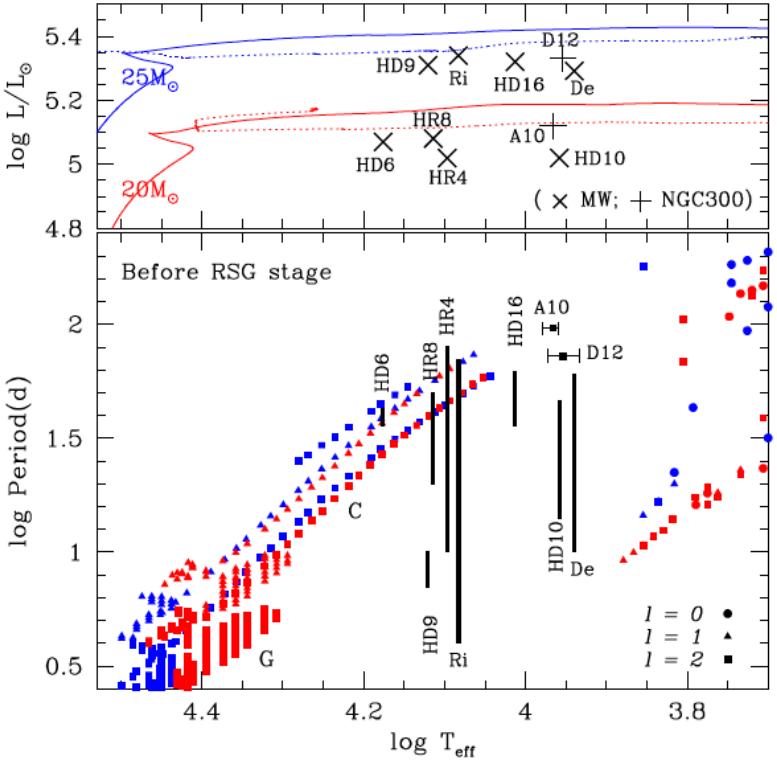
	BSG before RSG			BSG after RSG		
$M_{\rm i}$	$X_{\rm H}$	N/C	N/O	$X_{\rm H}$	N/C	N/O
14 (rot)	0.70	2.27	0.517	0.44	38.0	2.41
20 (rot)	0.68	2.46	0.609	0.42	39.7	2.94
25 (rot)	0.64	3.23	0.877	0.35	60.4	4.22

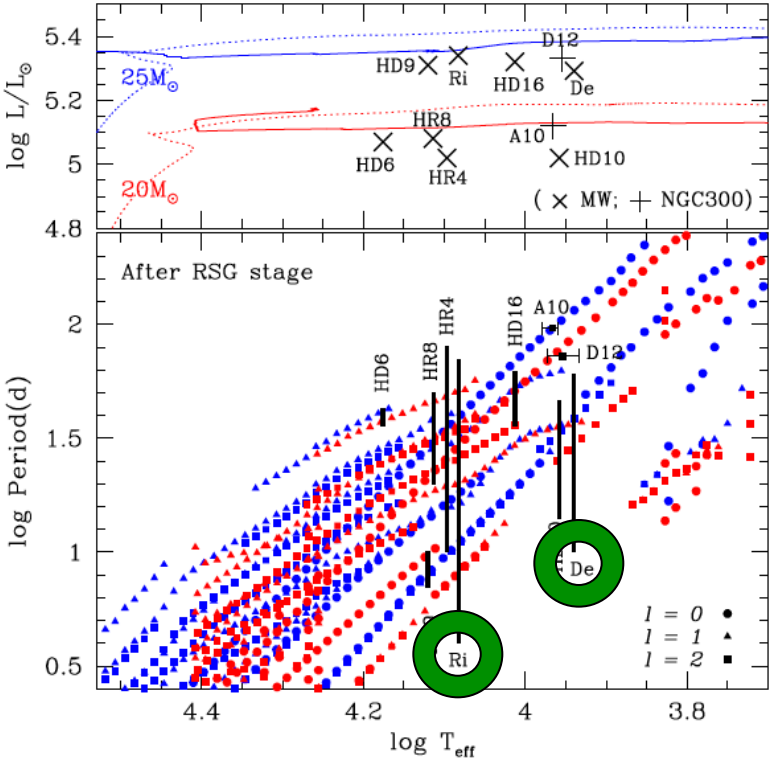
The initial values are N/C$\equiv X_{\rm N}/X_{\rm C} = 0.289$ and N/O$\equiv X_{\rm N}/X_{\rm O} = 0.115$, where $X_{\rm i}$ means mass fraction of element i.

Saio, Georgy, Meynet, submitted to MNRAS

CAN WE DISTINGUISH
A BSG HAVING EVOLVED DIRECTLY FROM MS
FROM A BSG HAVING EVOLVED FROM A RSG PHASE ?

2- Pulsation properties





Saio, Georgy, Meynet, submitted to MNRAS

But....

MASSIVE STARS ARE SELDOM… BUT…

Energy released per solar mass transformed in stars (Salpeter IMF, mass range 0.01-120 solar masses)

1 Bethe $=10^{51}$ ergs (f.o.e.)

1-8 solar masses

0.6 [B=Bethe]

8-120 solar masses

1.70 B

Energy released per solar mass transformed in stars (Salpeter IMF, mass range 0.01-120 solar masses)

1 Bethe $=10^{51}$ ergs (f.o.e.)

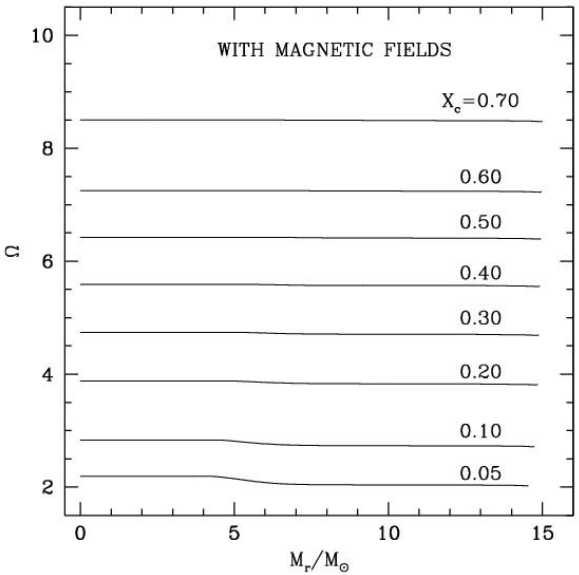
	Nuclear energy	Gravitational Energy
1-8 solar masses	0.6 [B=Bethe]	0.02 B
8-120 solar masses	0.1 B	1.60 B

SNe explosion only for stars with masses between 8 and 30 Msol

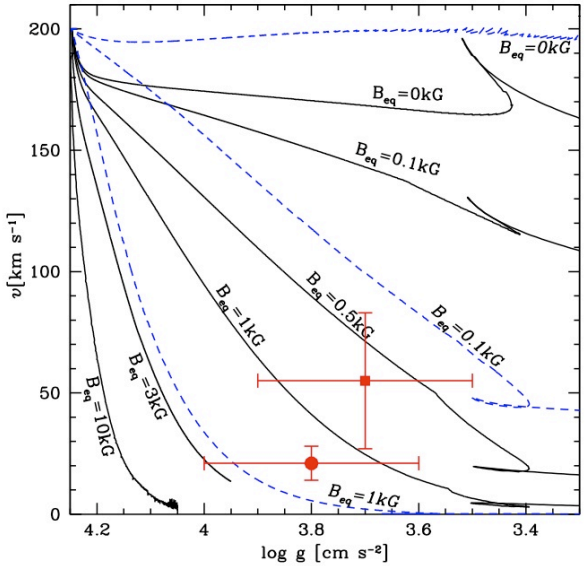
Explain type through composition

MAGNETIC FIELD AND ROTATION

INTERIOR → COUPLE DIFFERENT REGIONS
→ SOLID BODY ROTATION
→ FAST MERIDIONAL CURRENTS
→ MIXING
→ ROTATION RATE OF PULSARS



SURFACE → MAGNETIC BRAKING
→ STRONG Omega GRADIENTS
→ STRONG MIXING
→ ROTATION RATE OF PULSARS



SUPERGIANTS AND SUPERNOVAE

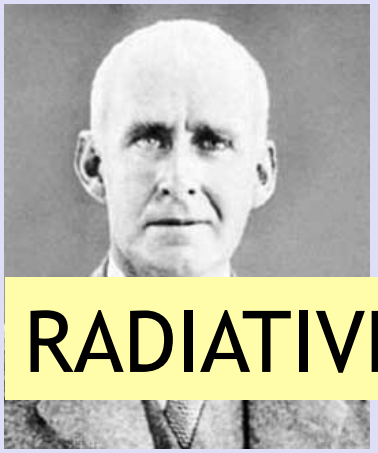
AT SOLAR Z

STARS IN THE MASS RANGE BETWEEN ~20-30 (9-20 Msol→ RSG, IIP or IIL)
→ BSG - 87A type
→ LBV (see Groh's talk) - IIn (see Takahashi's talk)
→ WR?

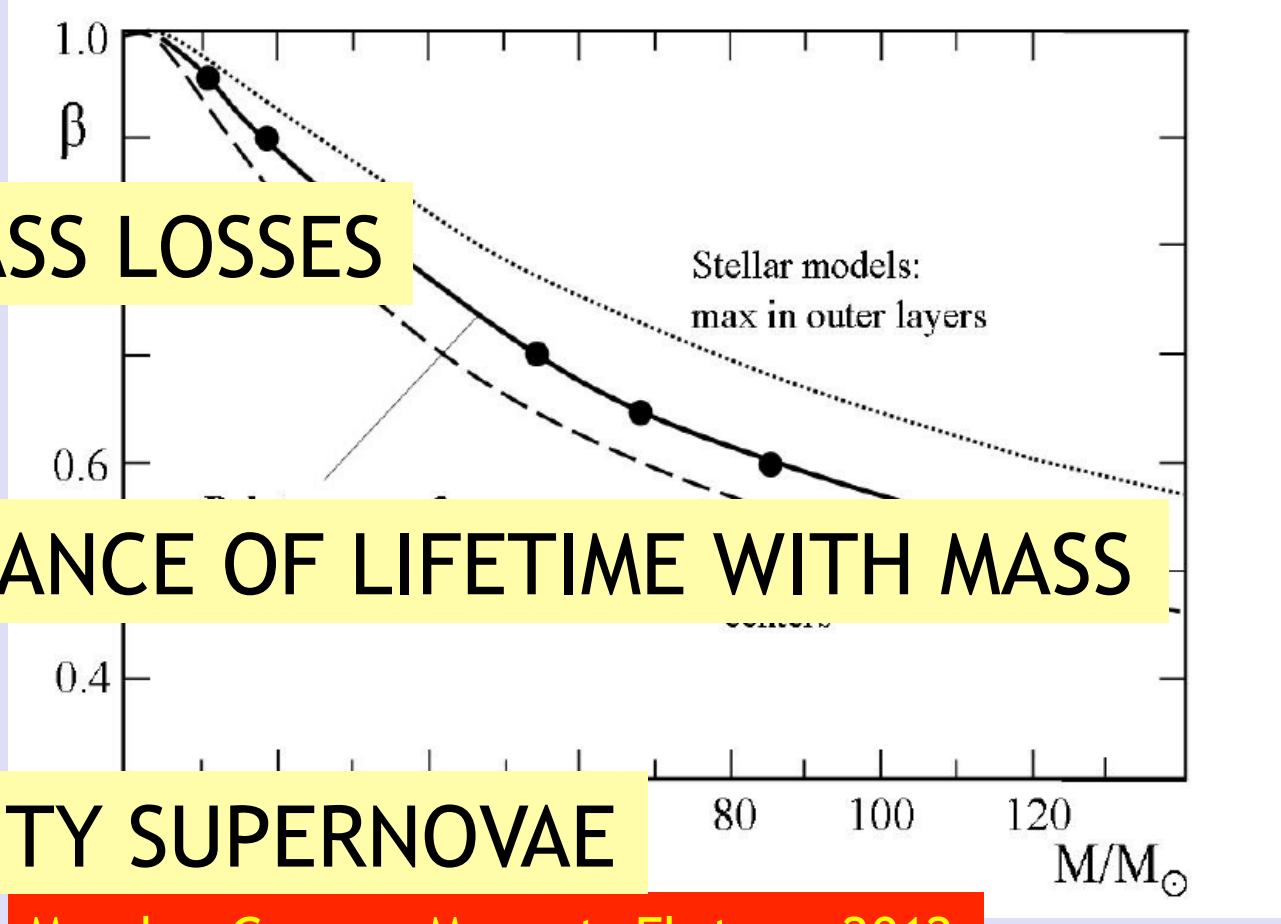
THE FREQUENCY OF THESE DIFFERENT OUTPUTS DEPENDS
ON MASS LOSS
ON MIXING
ON MULTIPLICITY

WOULD BE INTERESTING TO HAVE MORE DATA ON BSG
SURFACE CHEMICAL COMPOSITION
PULSATION PROPERTIES
CIRCUMSTELLAR ENVIRONMENTS

RADIATION PRESSURE



$P_{gaz}/P=$



RADIATIVE MASS LOSSES

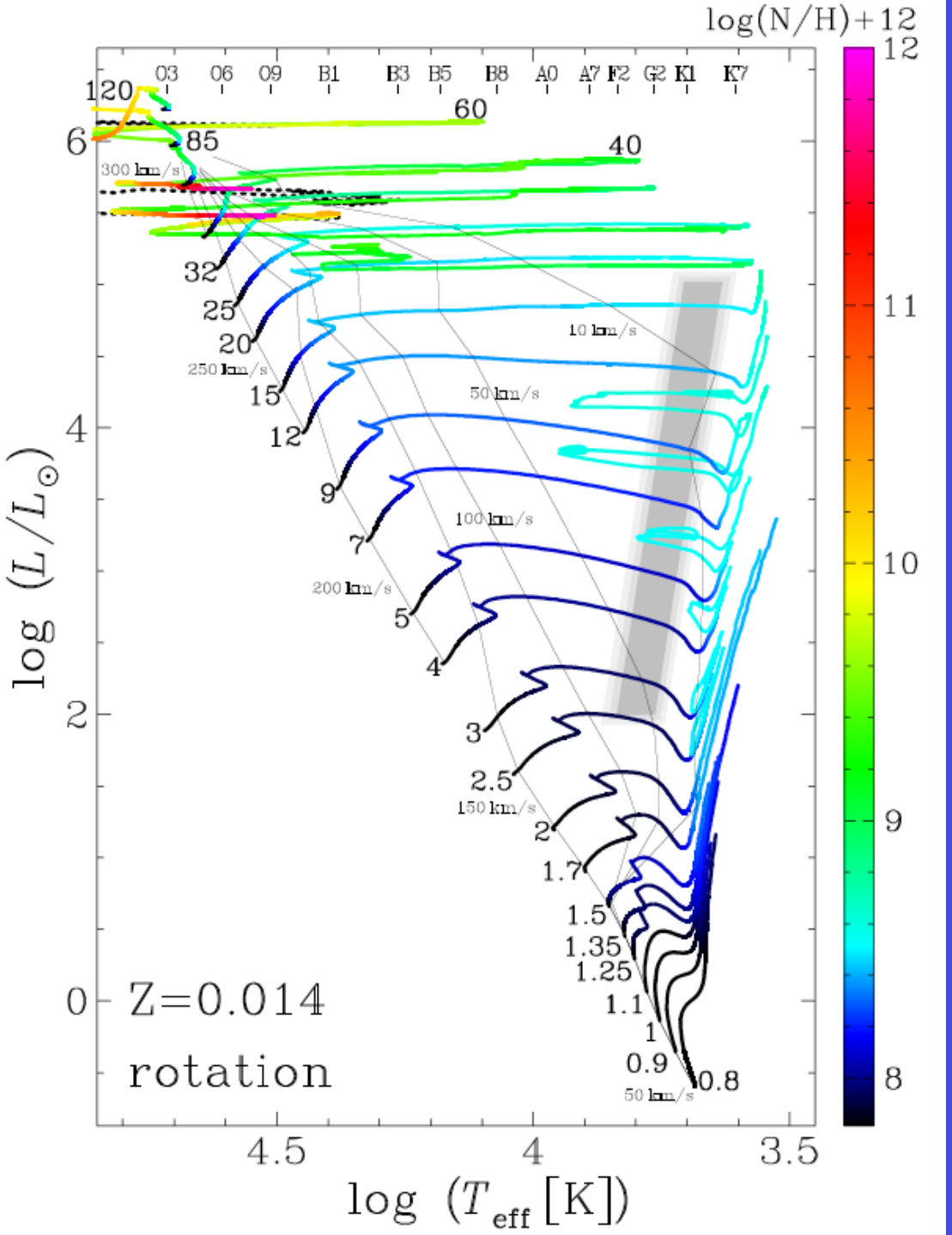
Eddington

WEAK DEPENDANCE OF LIFETIME WITH MASS

PAIR INSTABILITY SUPERNOVAE

Maeder, Georgy, Meynet, Ekstrom 2012

$$P_{rad}/P_{gaz} \sim \mu^4 M^2$$



Ekström et al. 2012

0.8- 120 M_{sol}

Z=0.014

V_{ini}=0 & 0.4 V_{crit}

D_{over}=0.1 H_p

Mass Loss:

Vink et al. 01
Nugis & Lamers 00
Eldridge & Vink 06
Gräfener &Hamman 08
Reimers 75,77
De Jager et al. 88

Core-collapse SN fraction

Table 1. Core-collapse SN fractions from our models compared to observed samples

SN Type	Non-rot. model (%)	Rot. model (%)	Obs. E13 (%)	Obs. S11 (%)
			Eldridge et al. 2013	Smith et al. 2011
IIP	70.7	64.9	55.5 ± 6.6	$48.2^{+5.7}_{-5.6}$
IIL + IIb	16.2	13.1	15.1 ± 3.4	$17.0^{+4.6}_{-4.0}$
IIn	...	....	2.4 ± 1.4	$8.8^{+3.3}_{-2.9}$
IIpec	...	....	1.0 ± 0.9	...
Ib	8.1	7.8	9.0 ± 2.7	$8.4^{+3.1}_{-2.6}$
Ic	5.0	14.2	17.0 ± 3.7	$17.6^{+4.2}_{-3.8}$

(Groh+ 2013, in prep.)

All massive stars produce Sne→ may be some overestimates

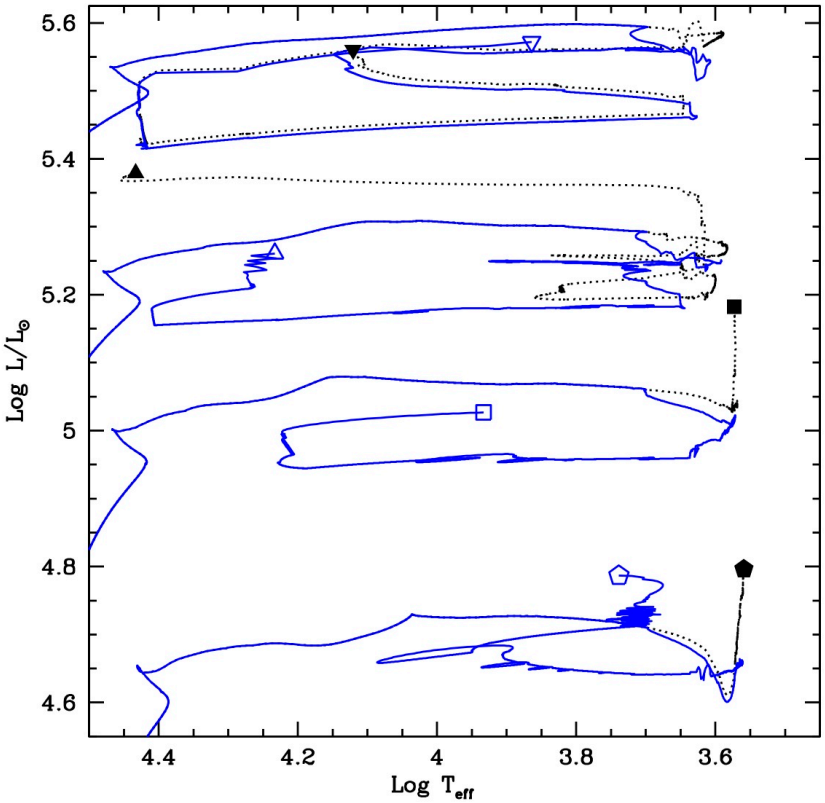
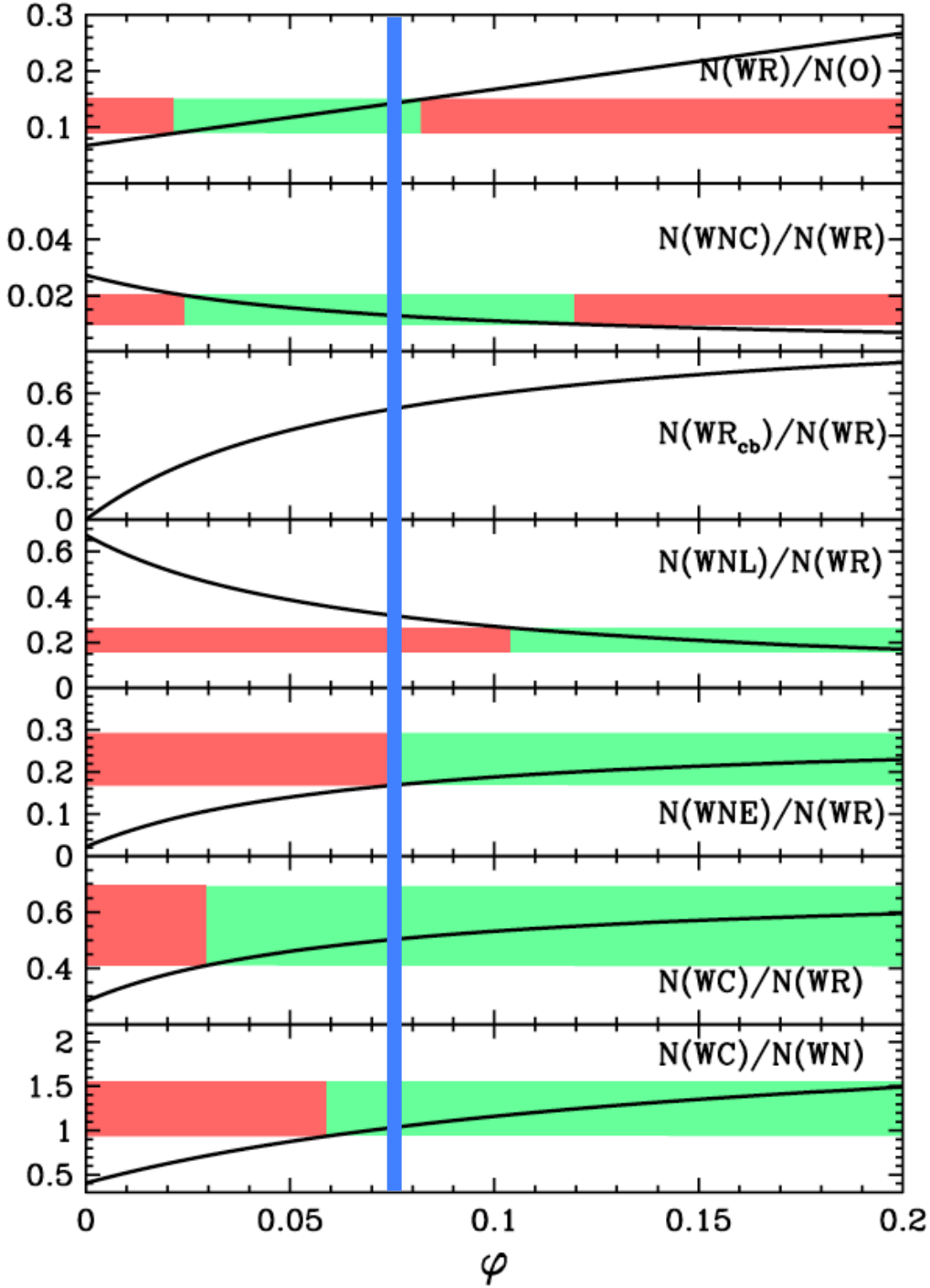


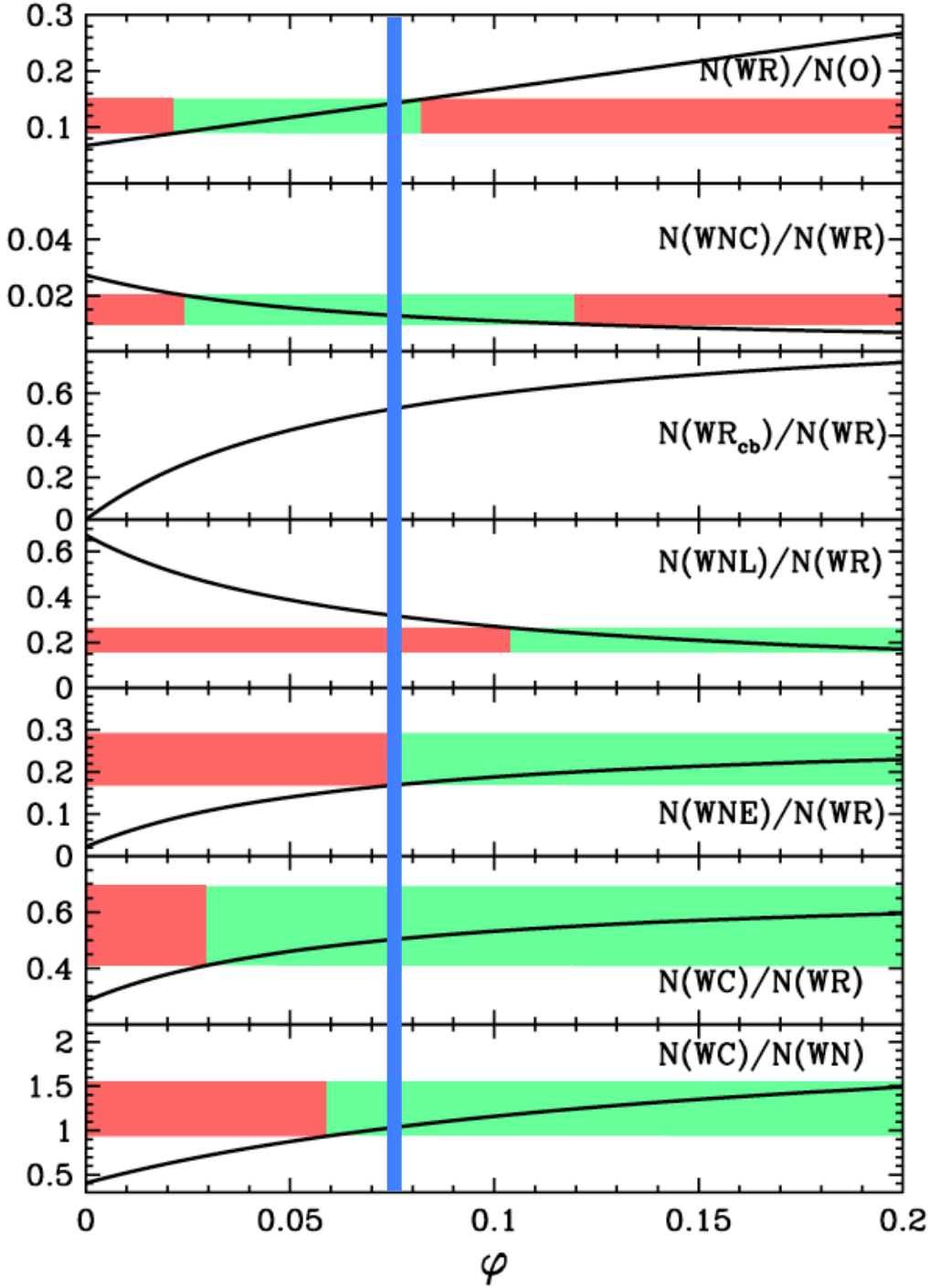
Table 1. Comparison of Wray15-751 and Hen 3-1379.

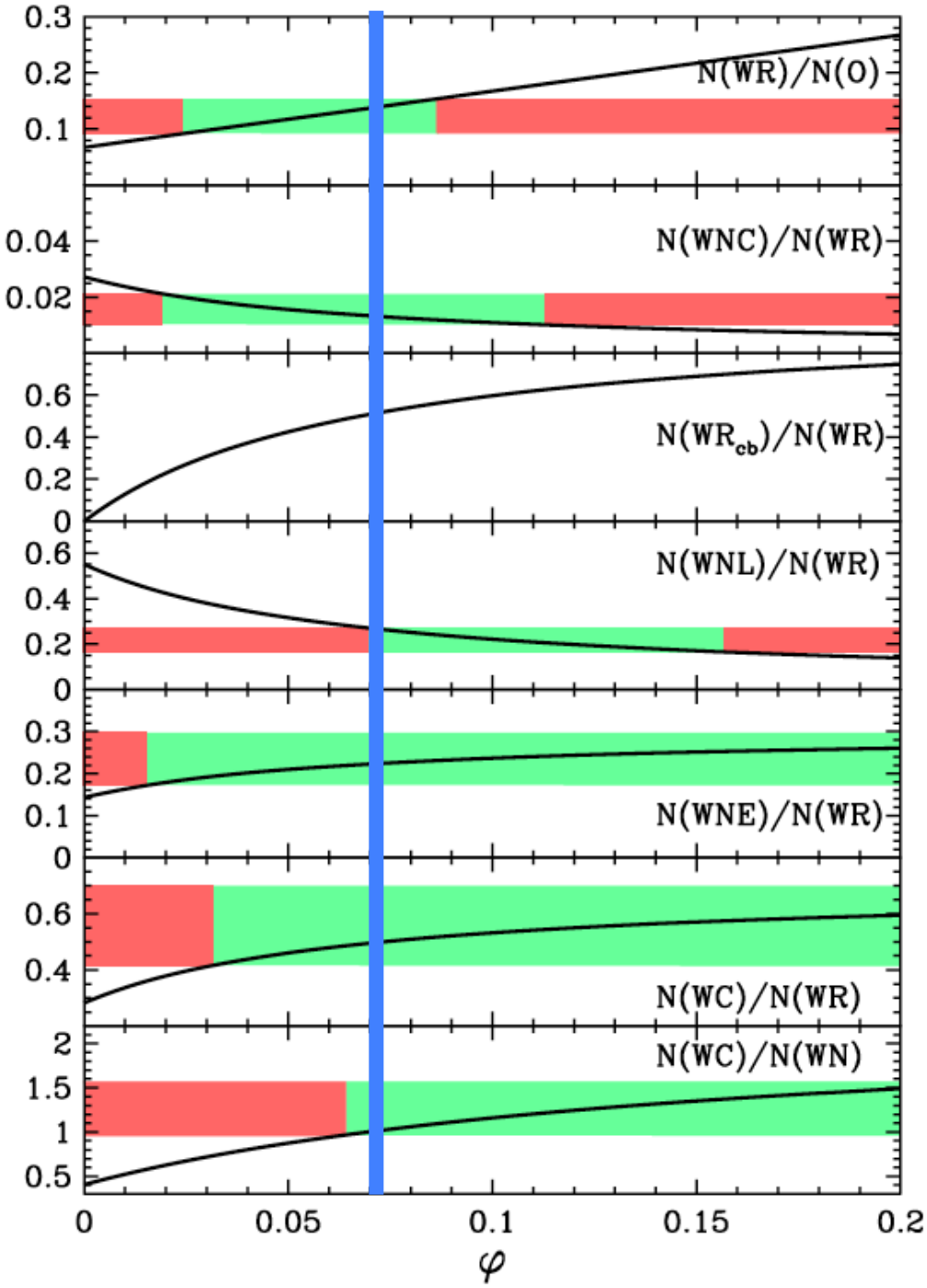
	Wray15-751	Hen 3-1379
$\log L/L_\odot$	5.7 ± 0.2	5.7 ± 0.1
$T_{\rm eff}$ (10^3 K)	$30 \leftrightarrow 9$	8.5 ± 1.0
d (kpc)	6.0 ± 1.0	4.0 ± 0.5
r (inner shell) (pc)	0.5	0.04
r (outer shell) (pc)	2.0	0.5
$v_{\rm exp}$ (km s^{-1})	26	~30
$t_{\rm kin}$ (inner shell) (10^4 yr)	1.9	0.13
$t_{\rm kin}$ (outer shell) (10^4 yr)	7.5	1.6
$M_{\rm d}$ (inner shell) (10^{-2} $M_\odot$)	4.5 ± 0.5	0.21 ± 0.06
$M_{\rm d}$ (outer shell) (10^{-2} $M_\odot$)	5.0 ± 2.0	17 ± 5

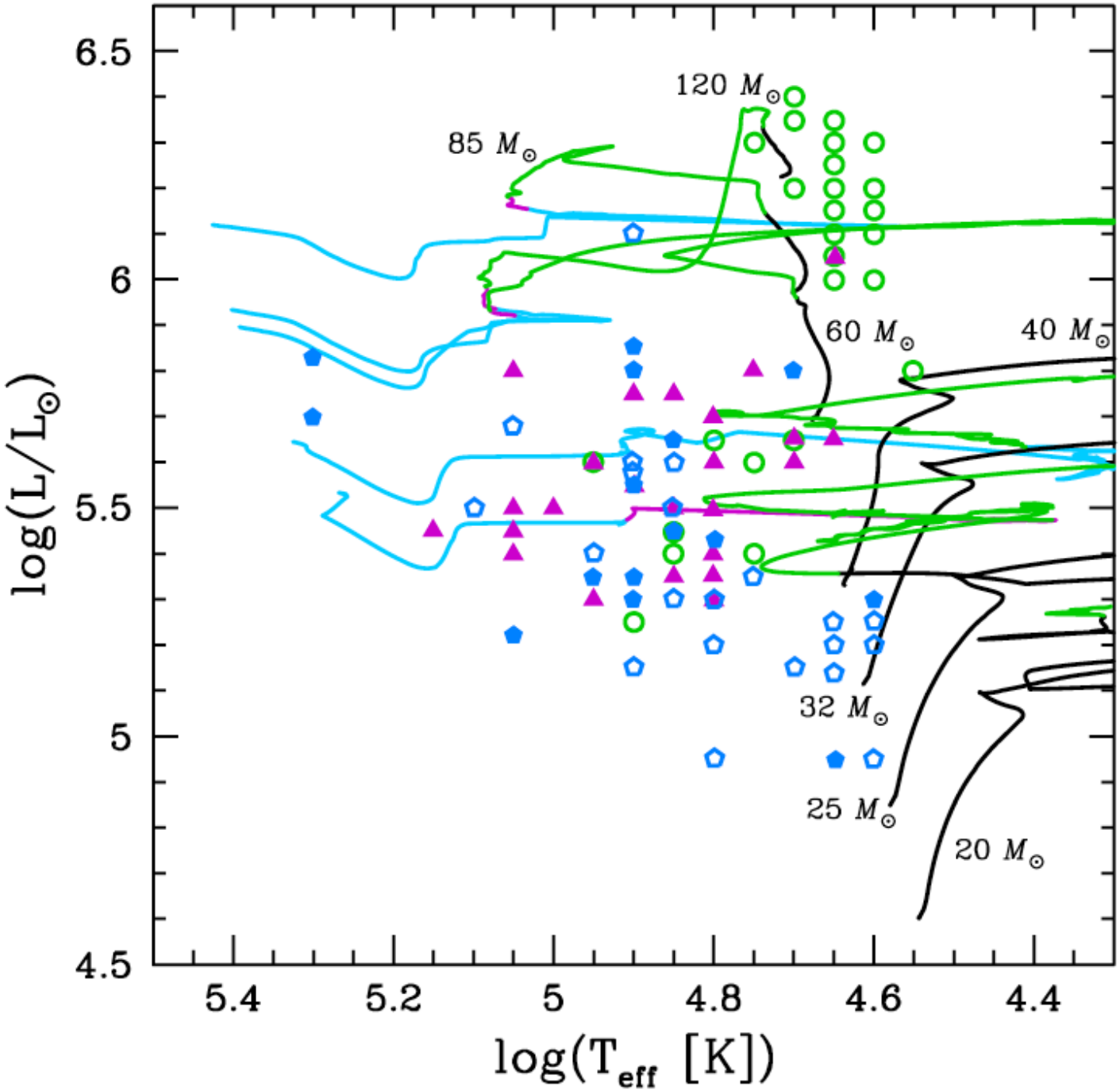
Notes. The expansion velocity of the Hen 3-1379 nebula is assumed similar to the one measured for the shell around yellow hypergiant IRC+10420, i.e., $v_{\rm exp} \simeq 25{-}37$ km s^{-1} (Castro-Carrizo et al. 2007). The inner shell of Hen 3-1379 refers to the whole "Fried Egg" nebula and the outer shell to the large ring nebula.

References. Sterken et al. (2008); Vamvatira-Nakou et al. (in prep.); Lagadec et al. (2011a); this work.


N(WR)/N(O)
N(WNC)/N(WR)
N(WR$_{cb}$)/N(WR)
N(WNL)/N(WR)
N(WNE)/N(WR)
N(WC)/N(WR)
N(WC)/N(WN)
0.3
0.2
0.1
0.04
0.02
0.6
0.4
0.2
0
0.3
0.2
0.1
0
0.6
0.4
2
1.5
1
0.5
0
0.05
0.1
0.15
0.2
φ


N(WR)/N(O)
N(WNC)/N(WR)
N(WR$_{cb}$)/N(WR)
N(WNL)/N(WR)
N(WNE)/N(WR)
N(WC)/N(WR)
N(WC)/N(WN)
0.3
0.2
0.1
0.04
0.02
0.6
0.4
0.2
0
0.3
0.2
0.1
0
0.6
0.4
2
1.5
1
0.5
0
0.05
0.1
0.15
0.2
φ


N(WR)/N(O)
N(WNC)/N(WR)
N(WR$_{cb}$)/N(WR)
N(WNL)/N(WR)
N(WNE)/N(WR)
N(WC)/N(WR)
N(WC)/N(WN)
0.3
0.2
0.1
0.04
0.02
0.6
0.4
0.2
0
0.3
0.2
0.1
0
0.6
0.4
2
1.5
1
0.5
0
0.05
0.1
0.15
0.2
φ


6.5
6
5.5
5
4.5
5.4
5.2
5
4.8
4.6
4.4
log(L/L⊙)
log(T_eff [K])
120 M⊙
85 M⊙
60 M⊙
40 M⊙
32 M⊙
25 M⊙
20 M⊙

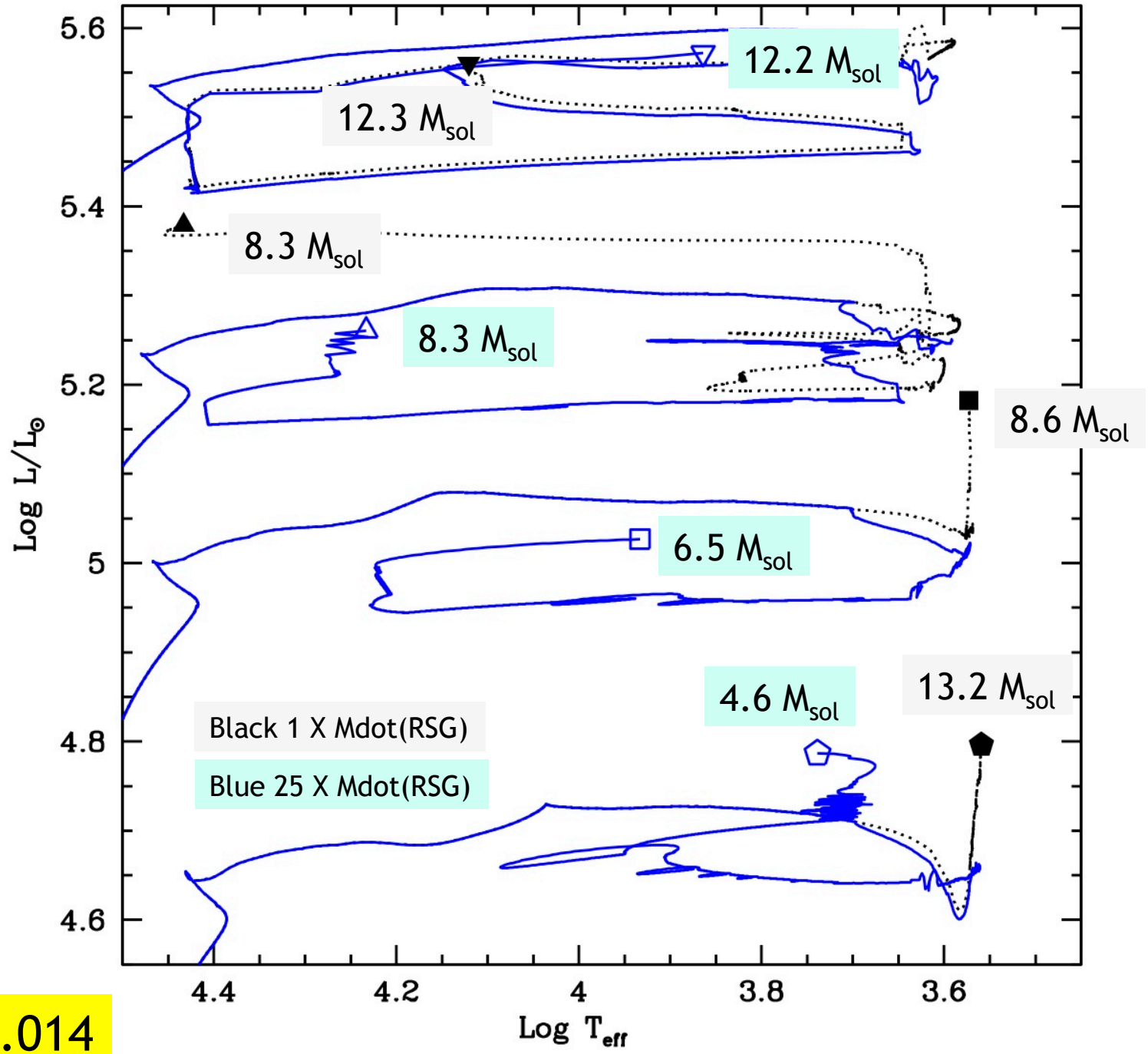
35 M_{sol}

25 M_{sol}

20 M_{sol}

15 M_{sol}

V=0, Z=0.014



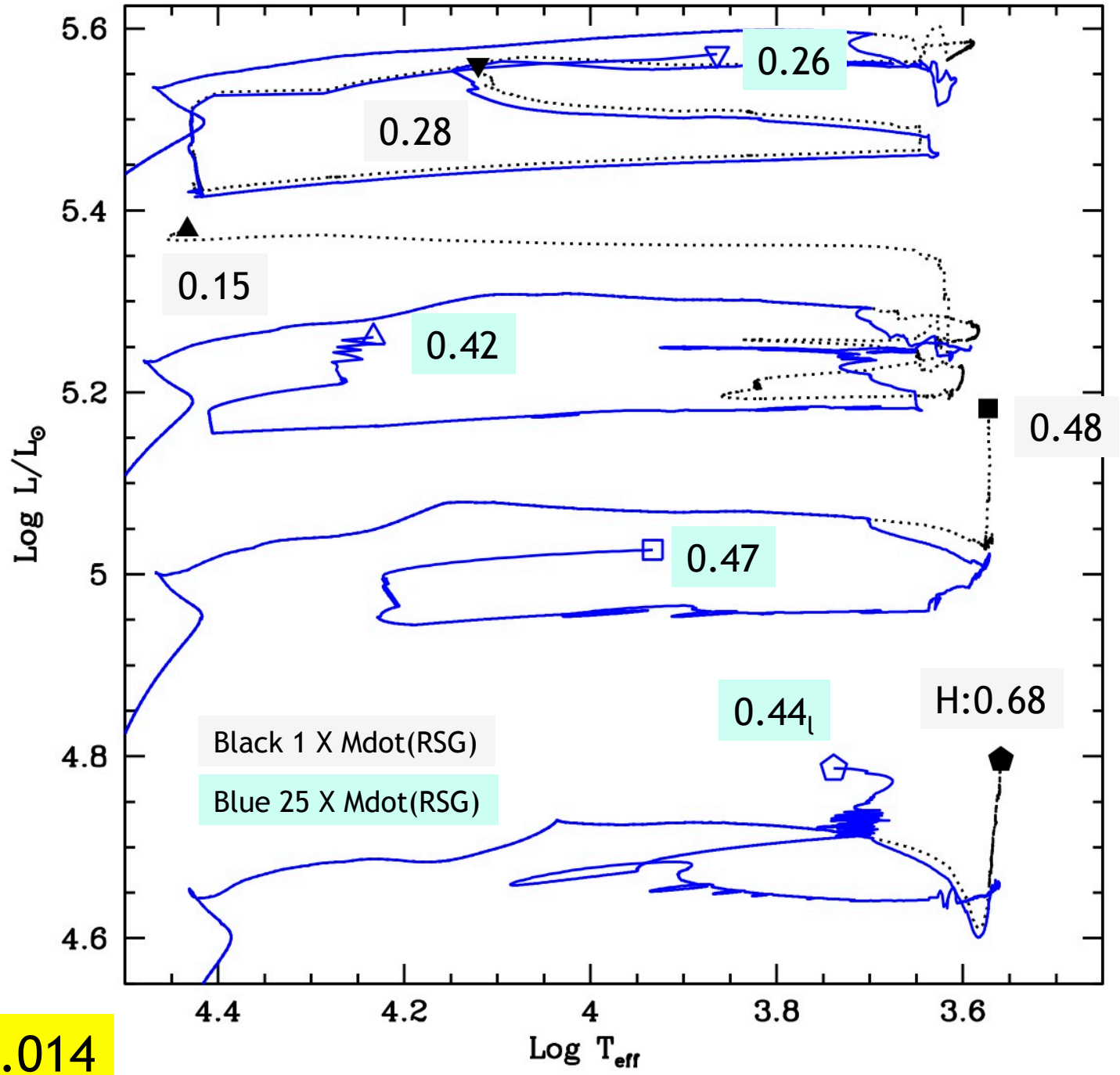
35 M_{sol}

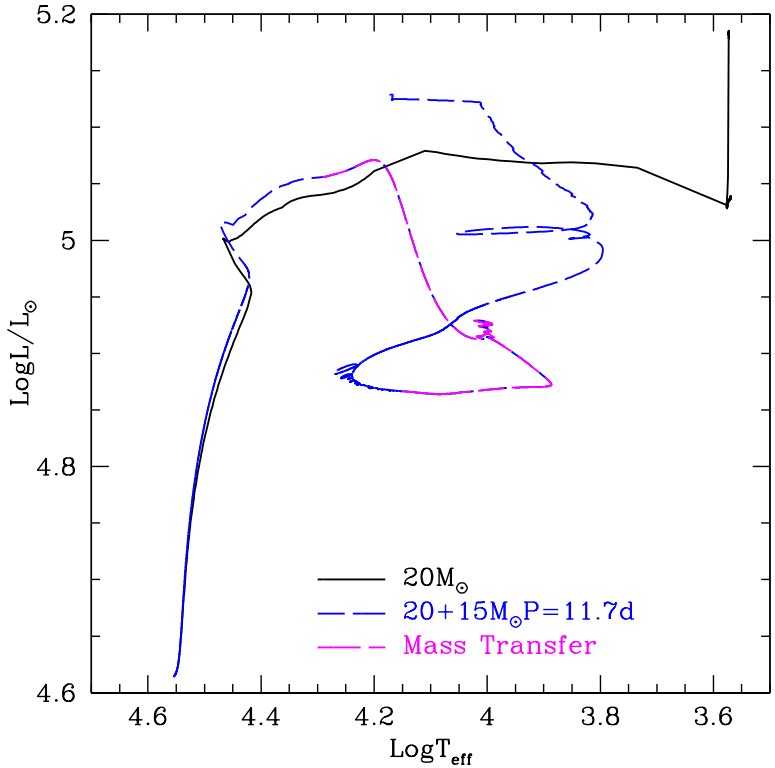
25 M_{sol}

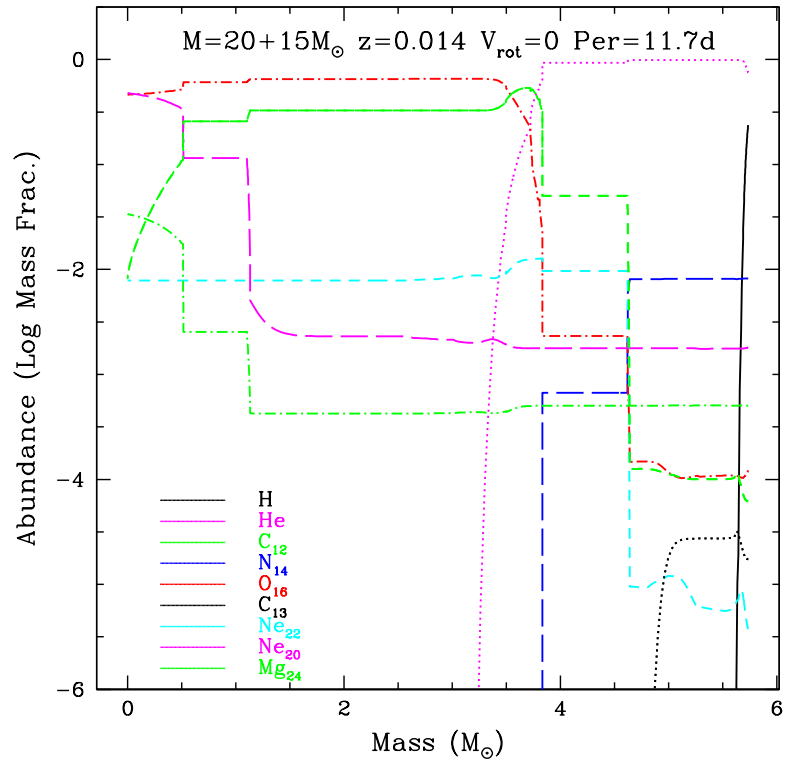
20 M_{sol}

15 M_{sol}

V=0, Z=0.014







Maiuro & Barblan et al. (in preparation)

THE PRIMARY LOSES ~13 M_{sun} DURING THE MASS TRANSFER

NO RED SUPERGIANTS

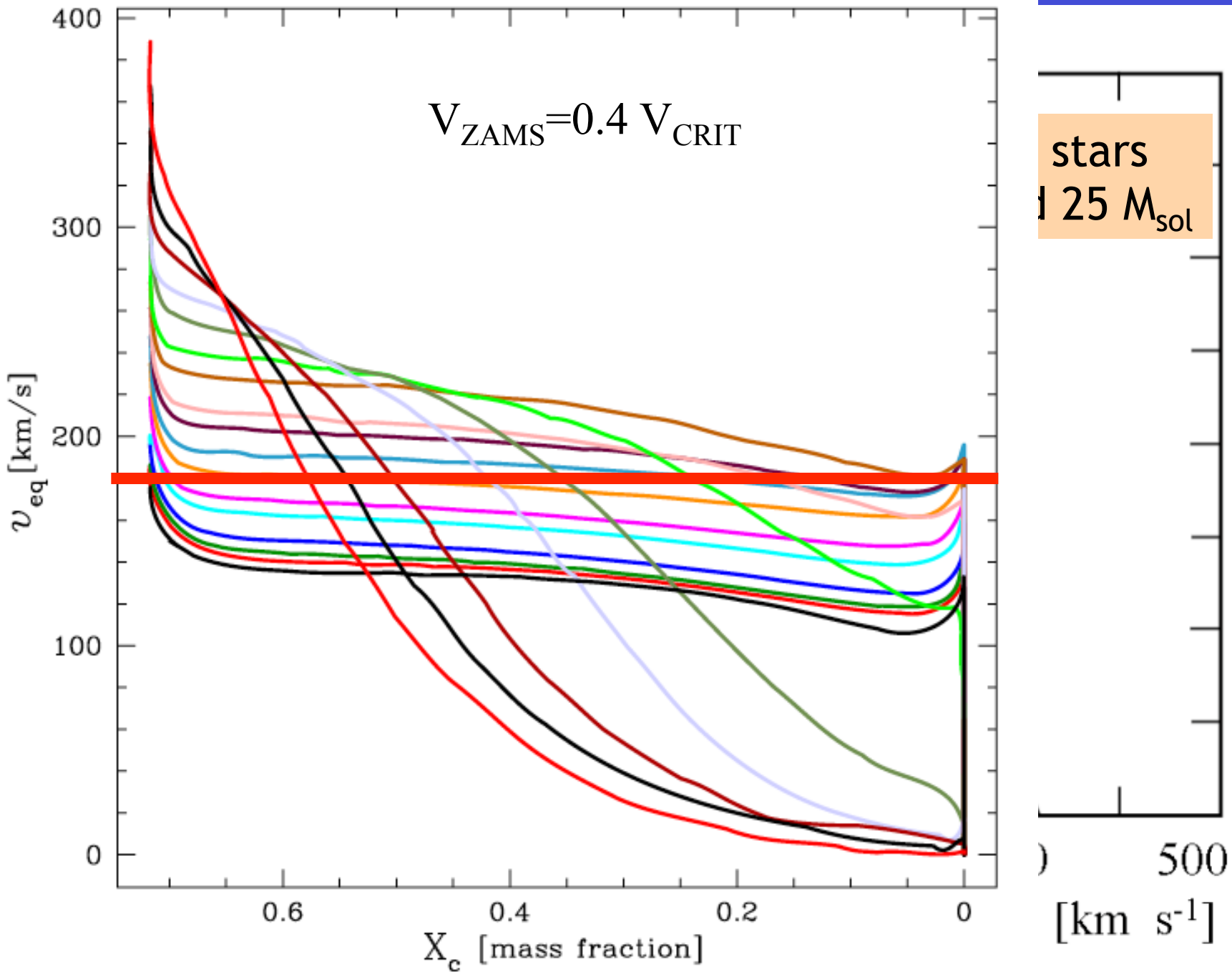
THE MASS TRANSFER LASTS FOR ABOUT 160 000 years

THE STAR WILL EXPLODE AS A TYPE II-L OR TYPE Ib SN

Rotational mixing:Amplitudes of the effects

Age, M, Z, V_{rot} ,…

Mixing	Increases when	
	Age	increases
	V_{rot}	increases
	M	increases
	Z	decreases


V_{ZAMS}=0.4 V_{CRIT}
400
300
200
100
0
υ_{eq} [km/s]
0.6
0.4
0.2
0
X_c [mass fraction]
stars
25 M_{sol}
500
[km s^{-1}]

WOLF-RAYET STARS AND SUPERNOVAE

AT SOLAR Z

WR from single stars: $M > \sim 20\ M_{sol}$ (rotation)

From observed numbers, about 50% WR from single star evolution

Predicted frequency of Ibc depends a lot on what happens when a BH is formed and thus on the limit for BH formation

Predicted frequency of Ic depends a lot on the mass of helium allowed In type Ic Sne.

Single star models, assuming type Ibc comes from WR stars: can account for a significant fraction of type Ibc supernovae

TENTATIVE FILIATIONS:

mass limits function of Z

M > 60 M_O: O- Of/WNL ←→ LBV - WNL(H poor)- WCL-E- SN (SNIbc?))
(slash star SNIIn??)

M: 40-60 M_O: O - BSG - LBV ←→ WNL -(WNE) - WCL-E - SN (SNIb)
- WCL-E - WO - SN (SNIc)

WR

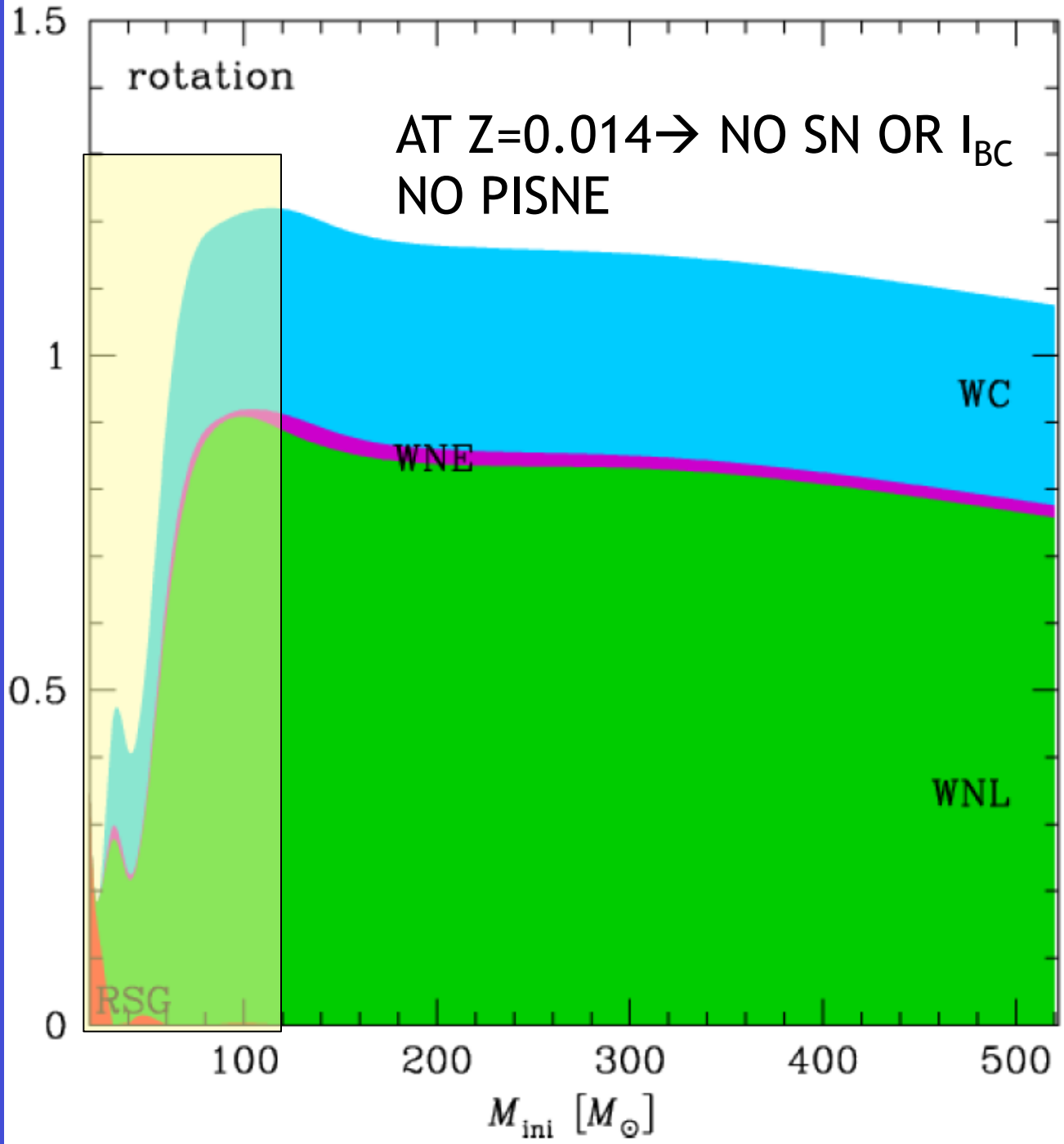
M: 30-40 M_O: O - BSG - RSG -- WNE - WCE - SN (SNIb)
OH/IR ←→ LBV ? (see Humphreys, 2003)

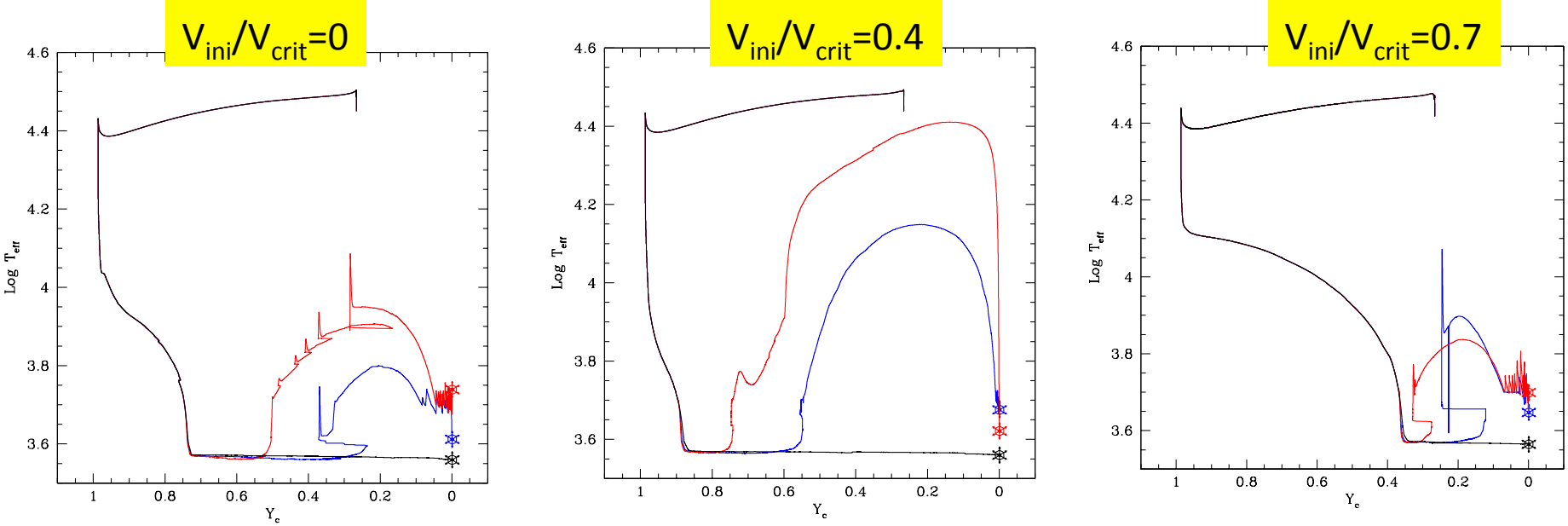
M: 25-30 M_O: O - (BSG) - RSG -- BSG ←→ RSG SNIIL
BLUE LOOP

M: 10-25 M_O: O - RSG - (Cepheid loop for M<15 M_O) - RSG -- SN SNII-P

RSG

Mass loss
Overshooting
Rotation
Magnetic fields
Interactions in close binaries


rotation
AT Z=0.014→ NO SN OR I_{BC}
NO PISNE
WC
WNE
WNL
RSG
1.5
1
0.5
0
100
200
300
400
500
M_{ini} $[M_\odot]$

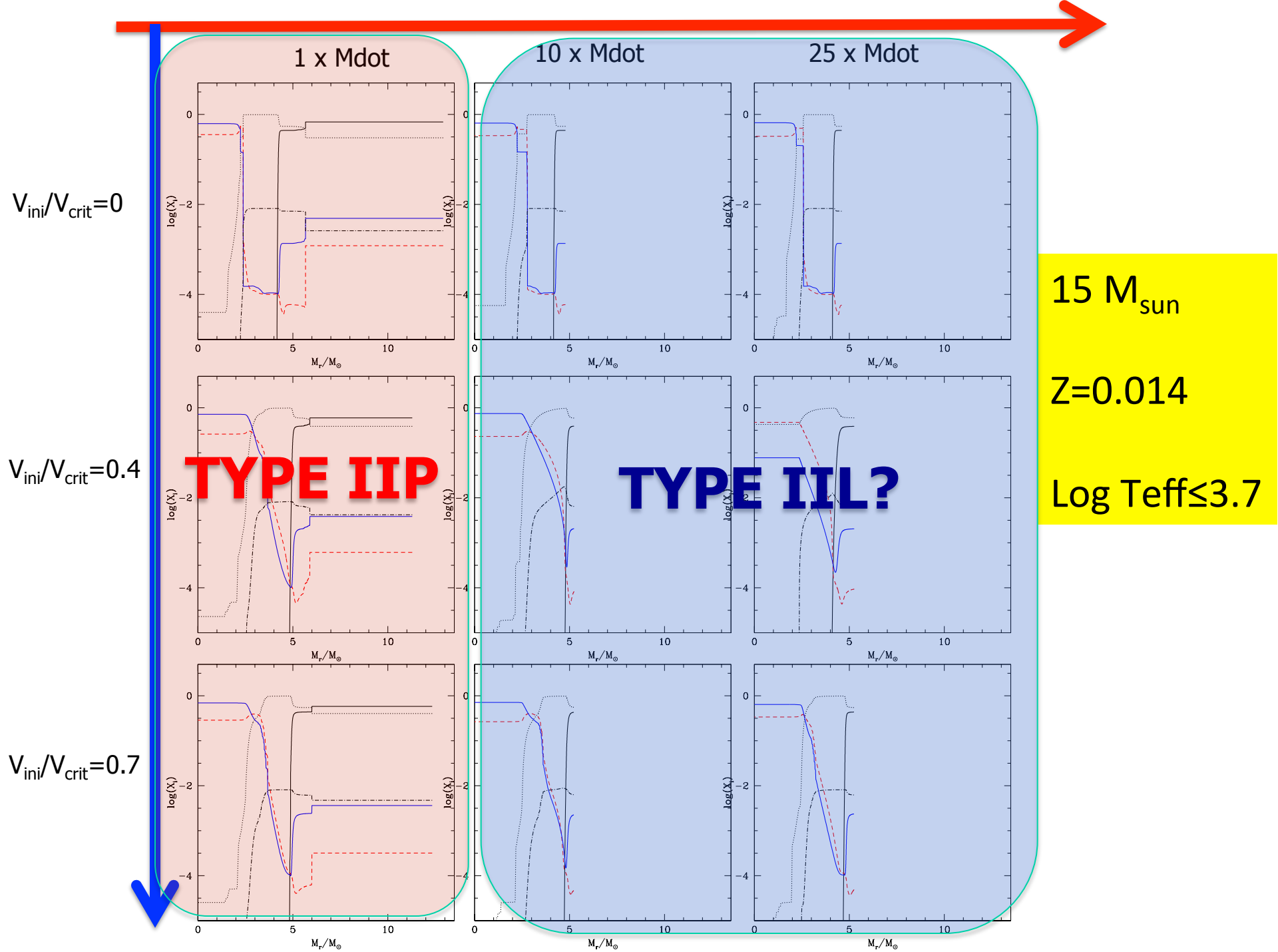


15 M_{sun}, Z=0.014, black 1 x Mdot (RSG),
blue 10 x Mdot (RSG),
red 25 x Mdot (RSG)
(computation by Chomienne)

An increase of mass loss during The RSG favours Blue loops	A not too strong mixing during the MS phase → rapid redwards evolution, more time for high Mdot Favours blue loops	A stronger mixing during the MS phase disfavours blue loops

MASS LOSS IN RSG PHASE AND MIXING HAVE STRONG IMPACT

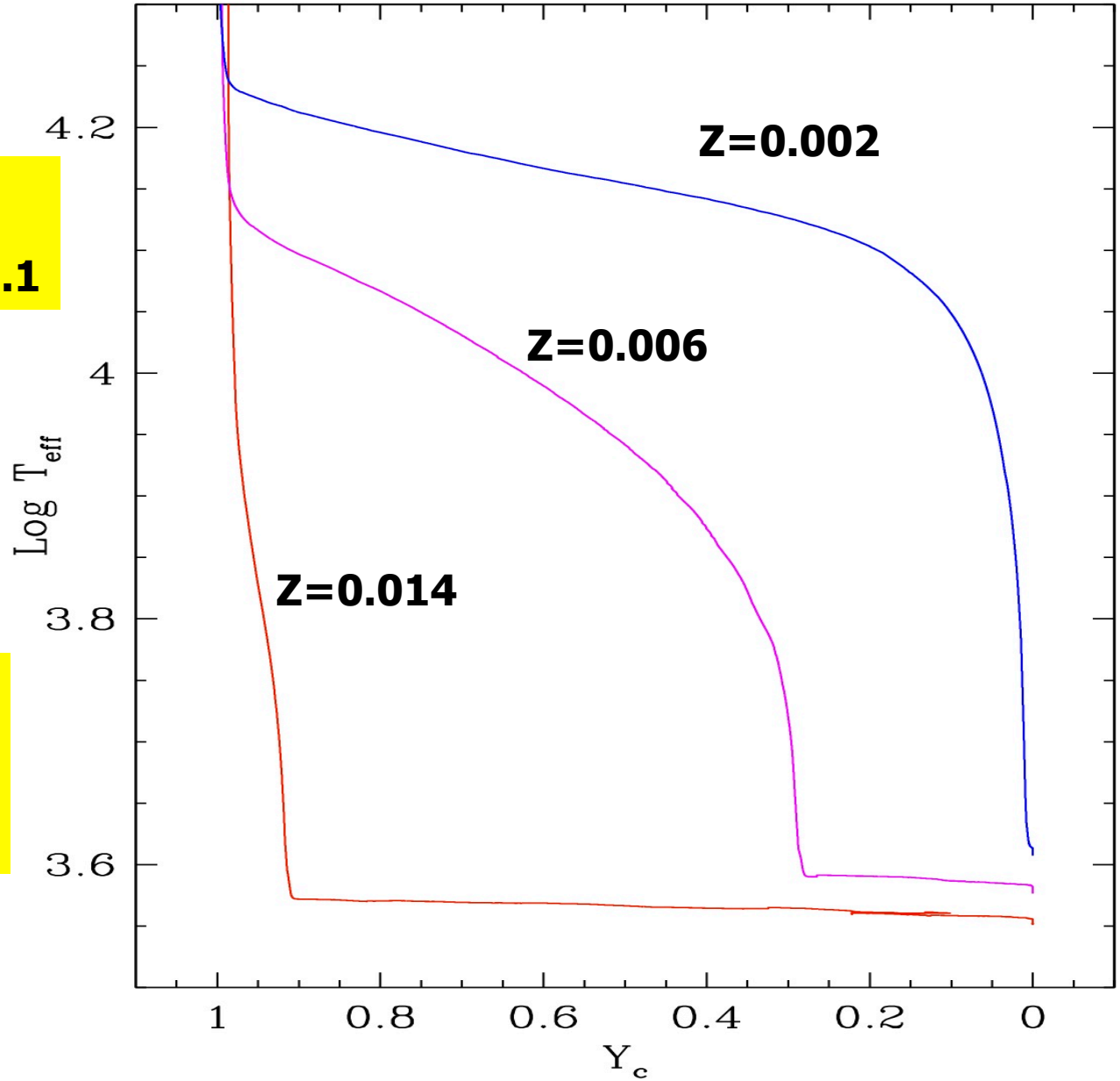
Impact on the number of blue to red supergiants
Impact on the nature of the Core Collapse Supernovae → José Groh's talk


1 x Mdot
10 x Mdot
25 x Mdot
V_{ini}/V_{crit}=0
V_{ini}/V_{crit}=0.4
V_{ini}/V_{crit}=0.7
TYPE IIP
TYPE IIL?
15 M_{sun}
Z=0.014
Log Teff≤3.7
log(X_i)
$M_r/M_\odot$

Effect of Z

15 M_{sun}

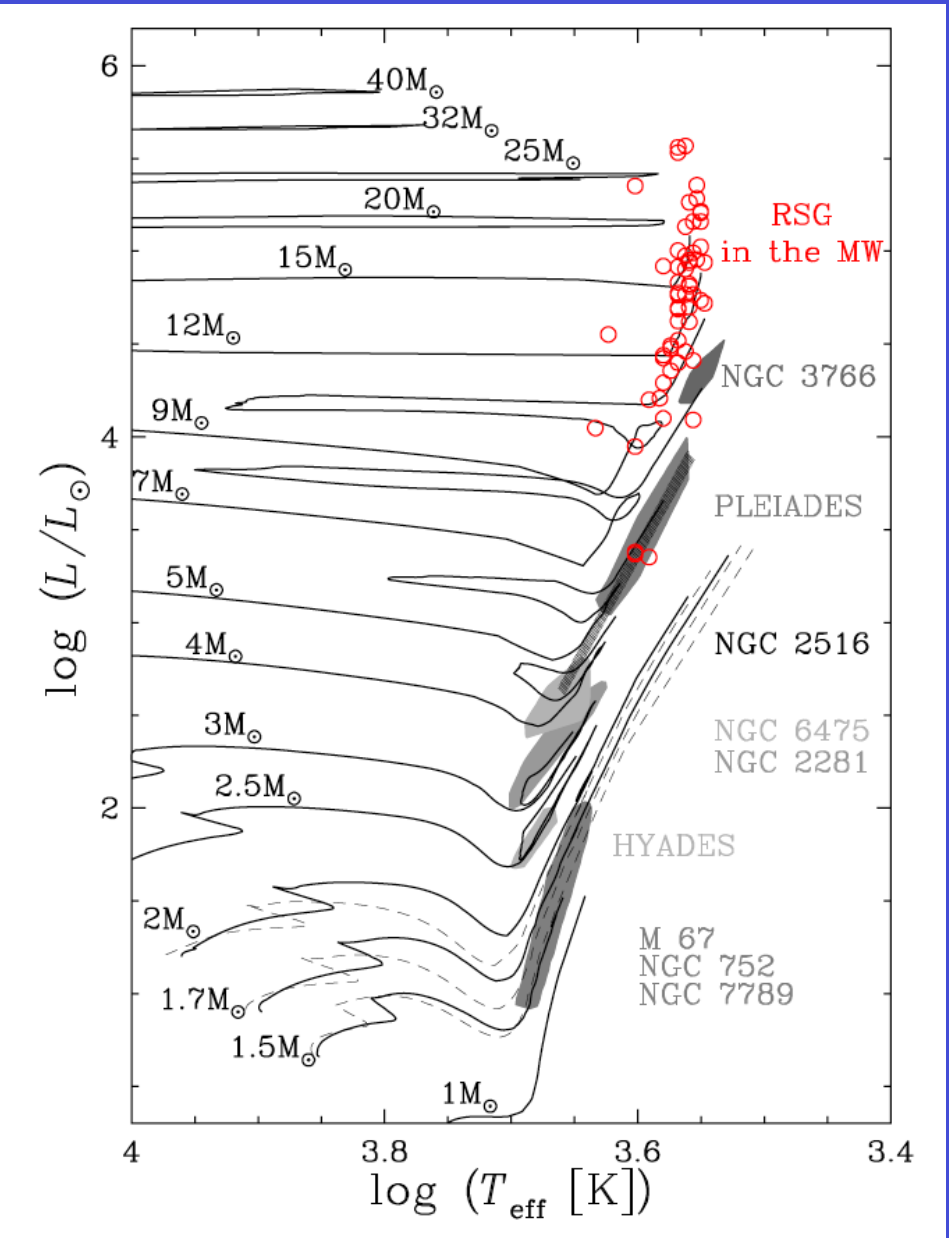
V_{ini}/V_{crit}=0.1

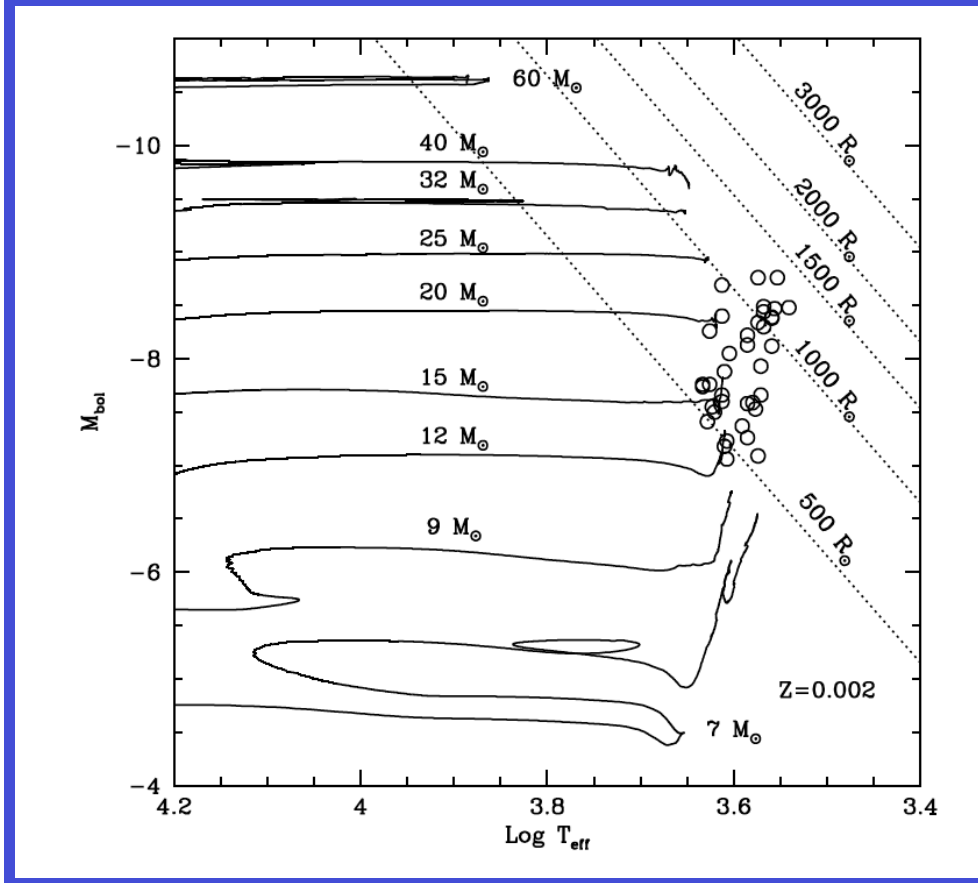


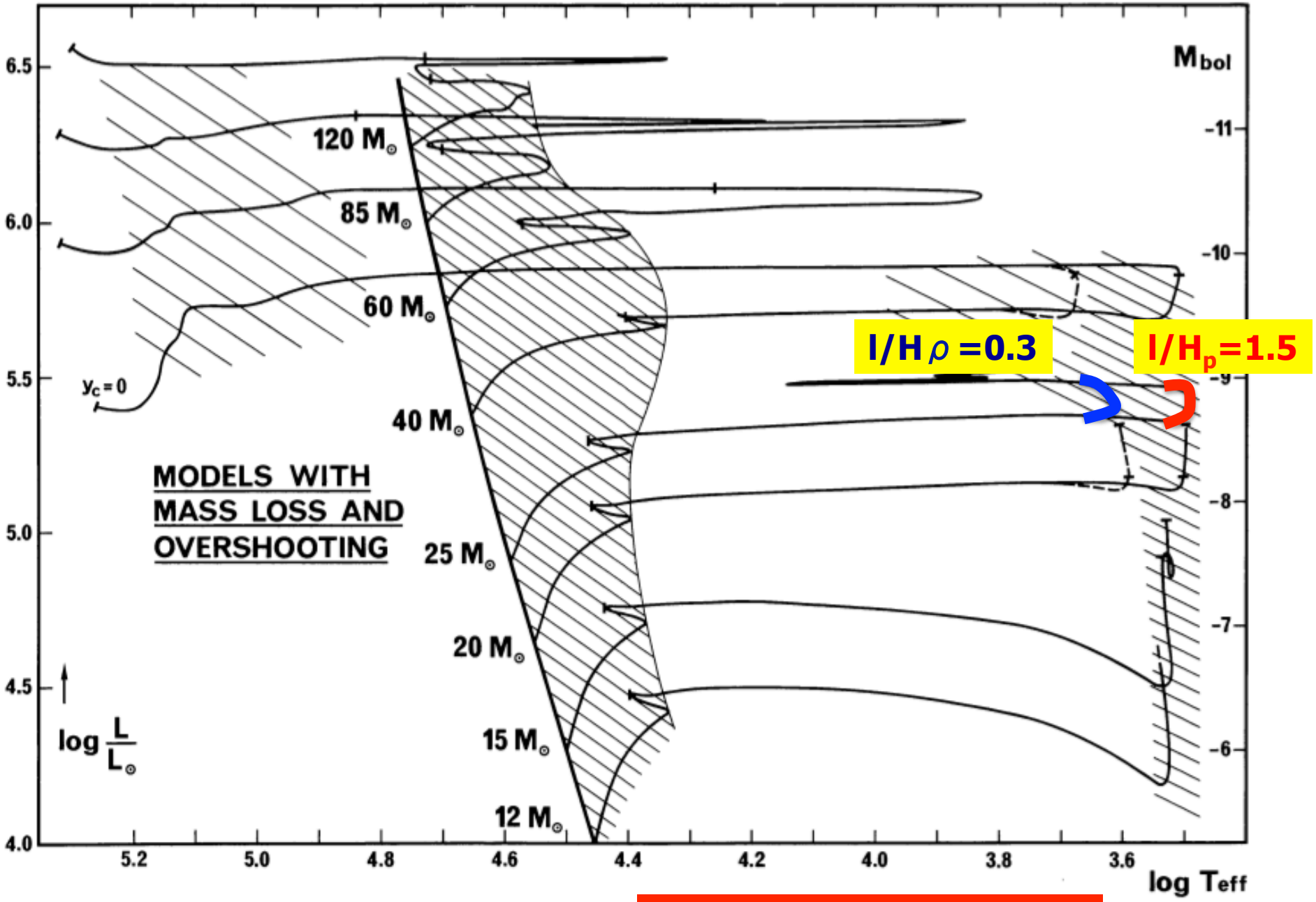
At low Z

Blue SG favoured

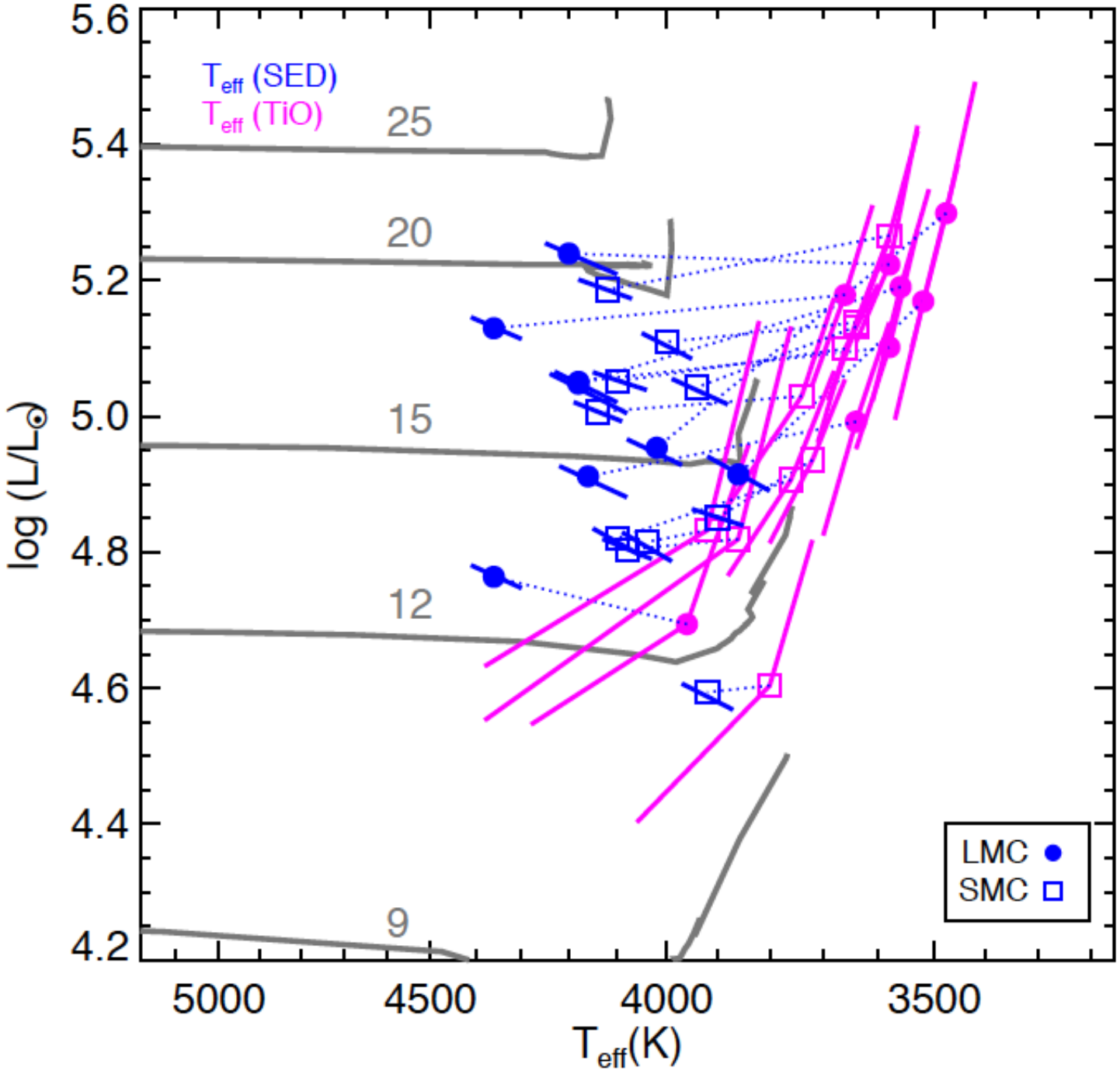
Models from Georgy et al. (2013)

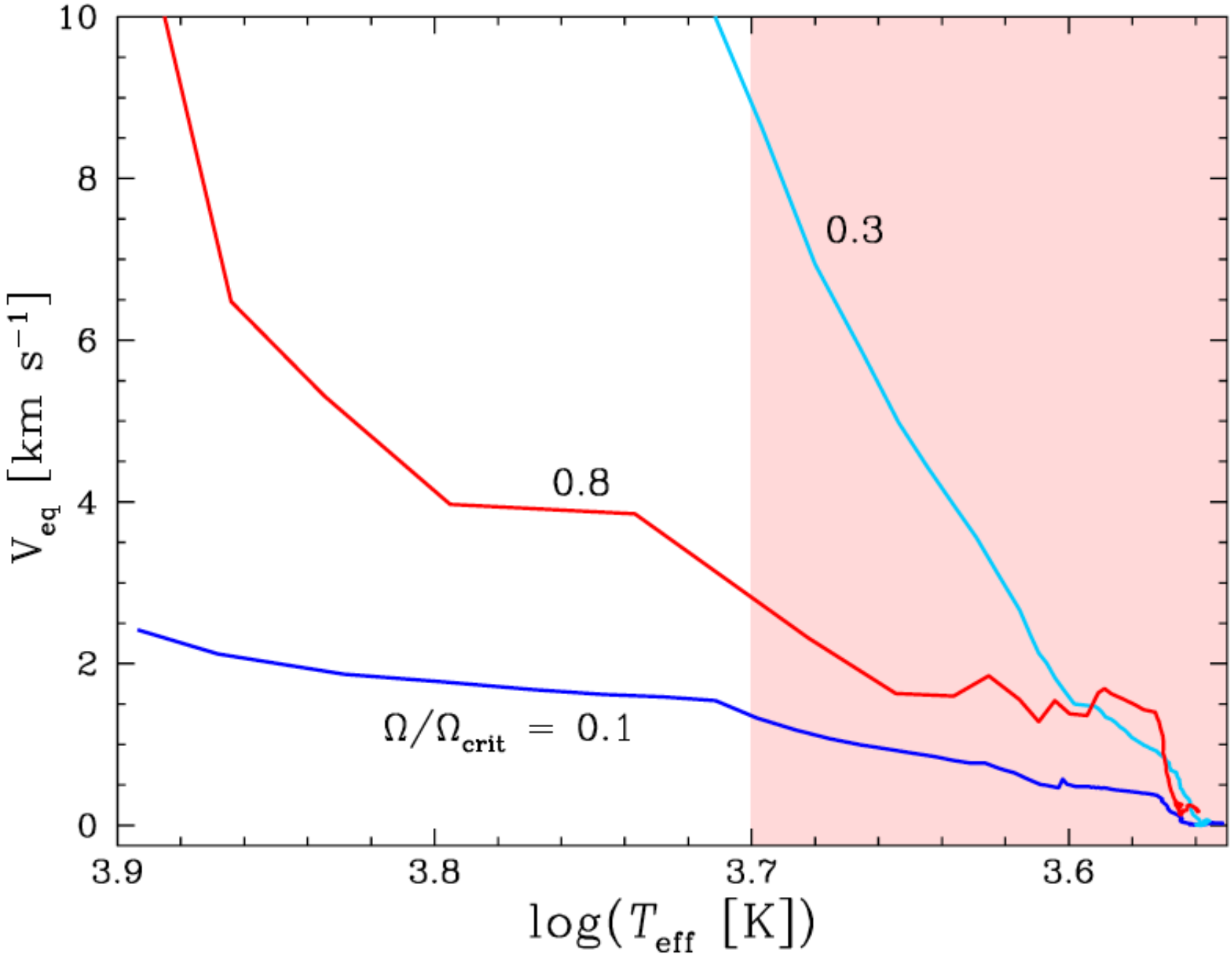

40M⊙
32M⊙
25M⊙
20M⊙
15M⊙
12M⊙
9M⊙
7M⊙
5M⊙
4M⊙
3M⊙
2.5M⊙
2M⊙
1.7M⊙
1.5M⊙
1M⊙
RSG
in the MW
NGC 3766
PLEIADES
NGC 2516
NGC 6475
NGC 2281
HYADES
M 67
NGC 752
NGC 7789
log (L/L⊙)
log (Teff [K])
6
4
2
4
3.8
3.6
3.4

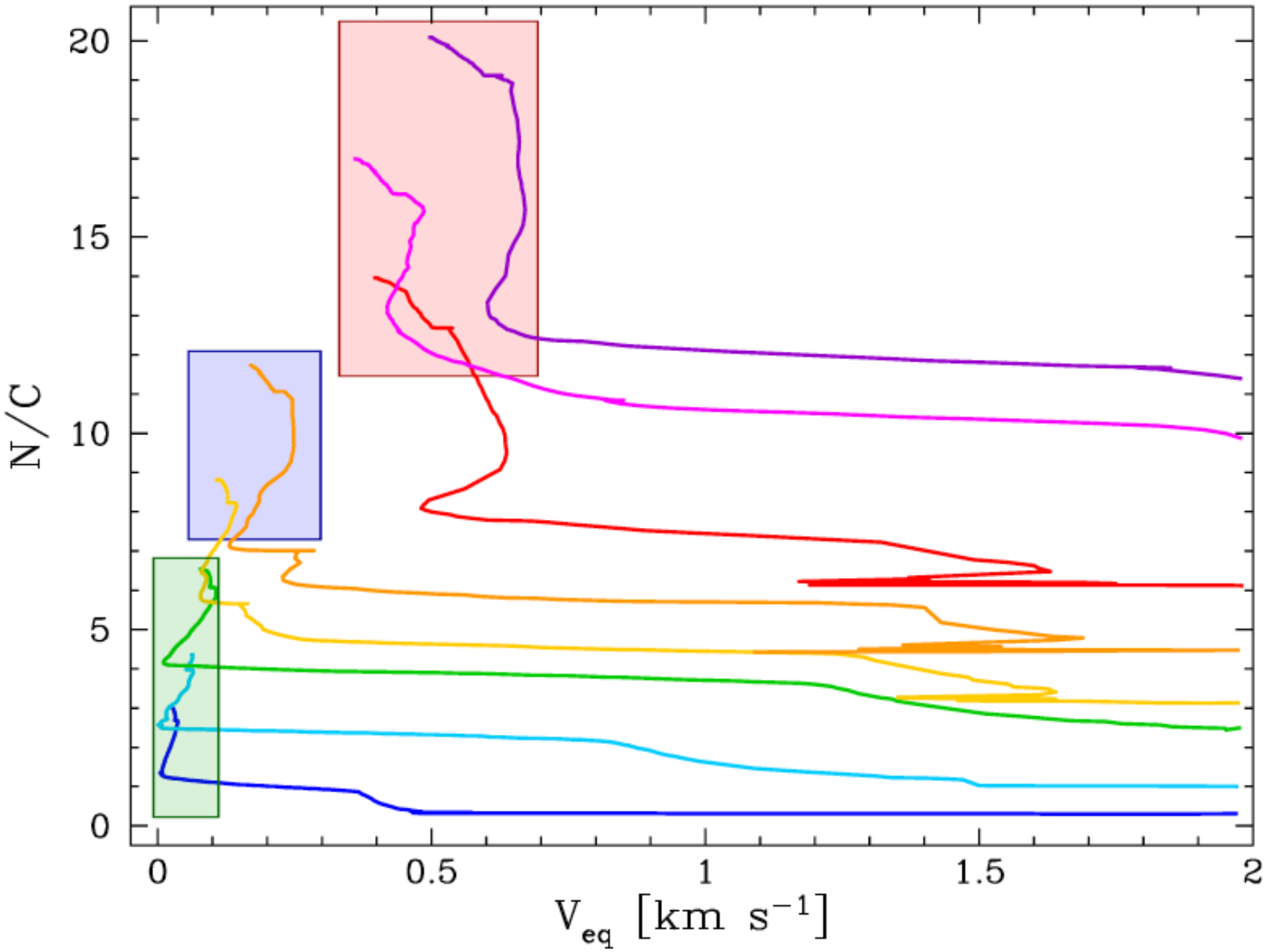

60 M⊙
40 M⊙
32 M⊙
25 M⊙
20 M⊙
15 M⊙
12 M⊙
9 M⊙
7 M⊙
3000 R⊙
2000 R⊙
1500 R⊙
1000 R⊙
500 R⊙
Z=0.002
Mbol
Log Teff
−10
−8
−6
−4
4.2
4
3.8
3.6
3.4



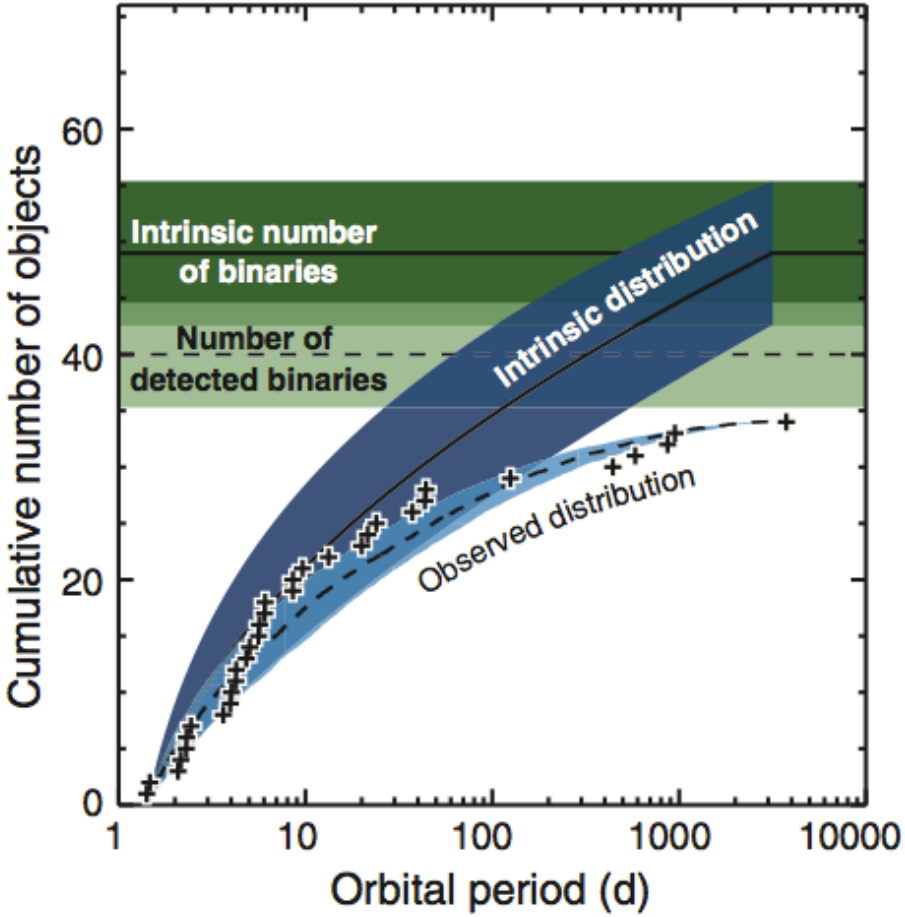
Maeder & Meynet 1987

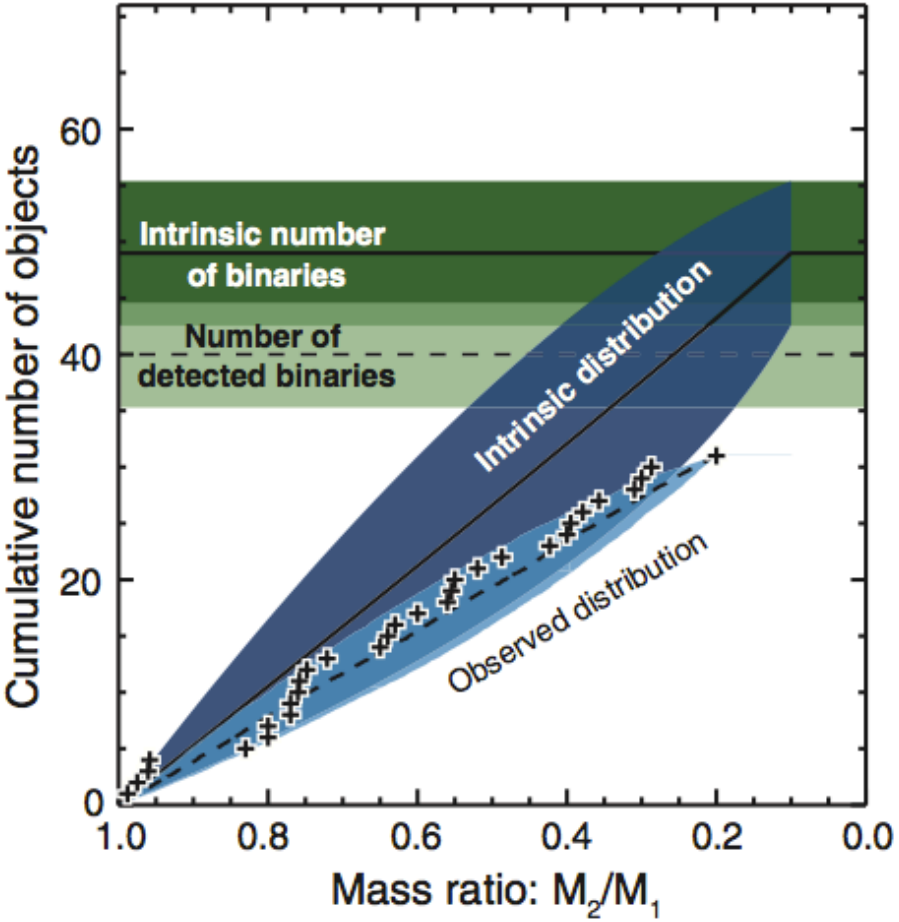

T_{eff} (SED)
T_{eff} (TiO)
25
20
15
12
9
LMC
SMC
log ($L/L_\odot$)
T_{eff}(K)
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
5000
4500
4000
3500


10
8
6
4
2
0
3.9
3.8
3.7
3.6
0.3
0.8
$\Omega/\Omega_{crit} = 0.1$
V_{eq} [km s^{-1}]
$\log(T_{eff}$ [K])

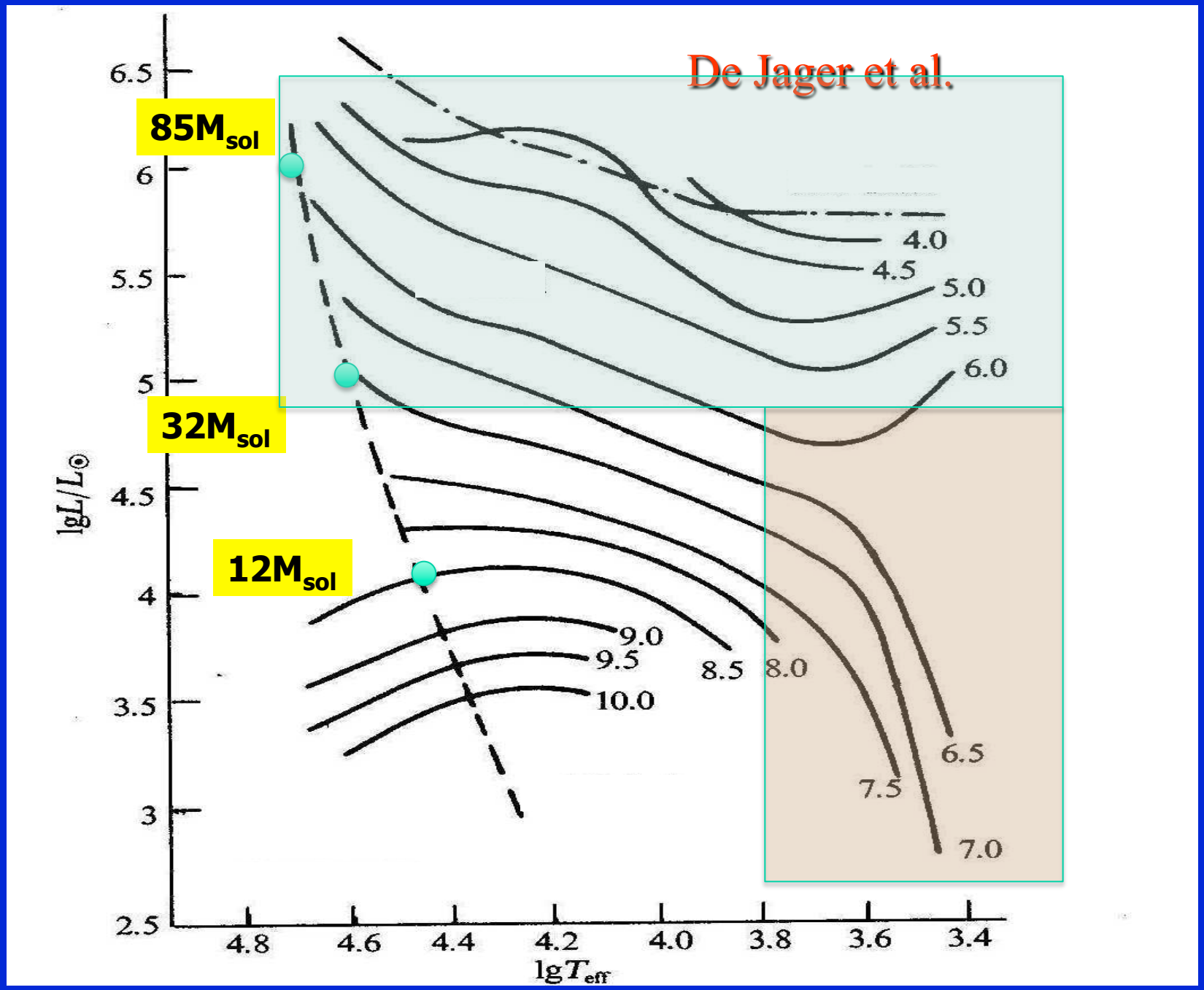

N/C
20
15
10
5
0
0
0.5
1
1.5
2
V_{eq} [km s^{-1}]

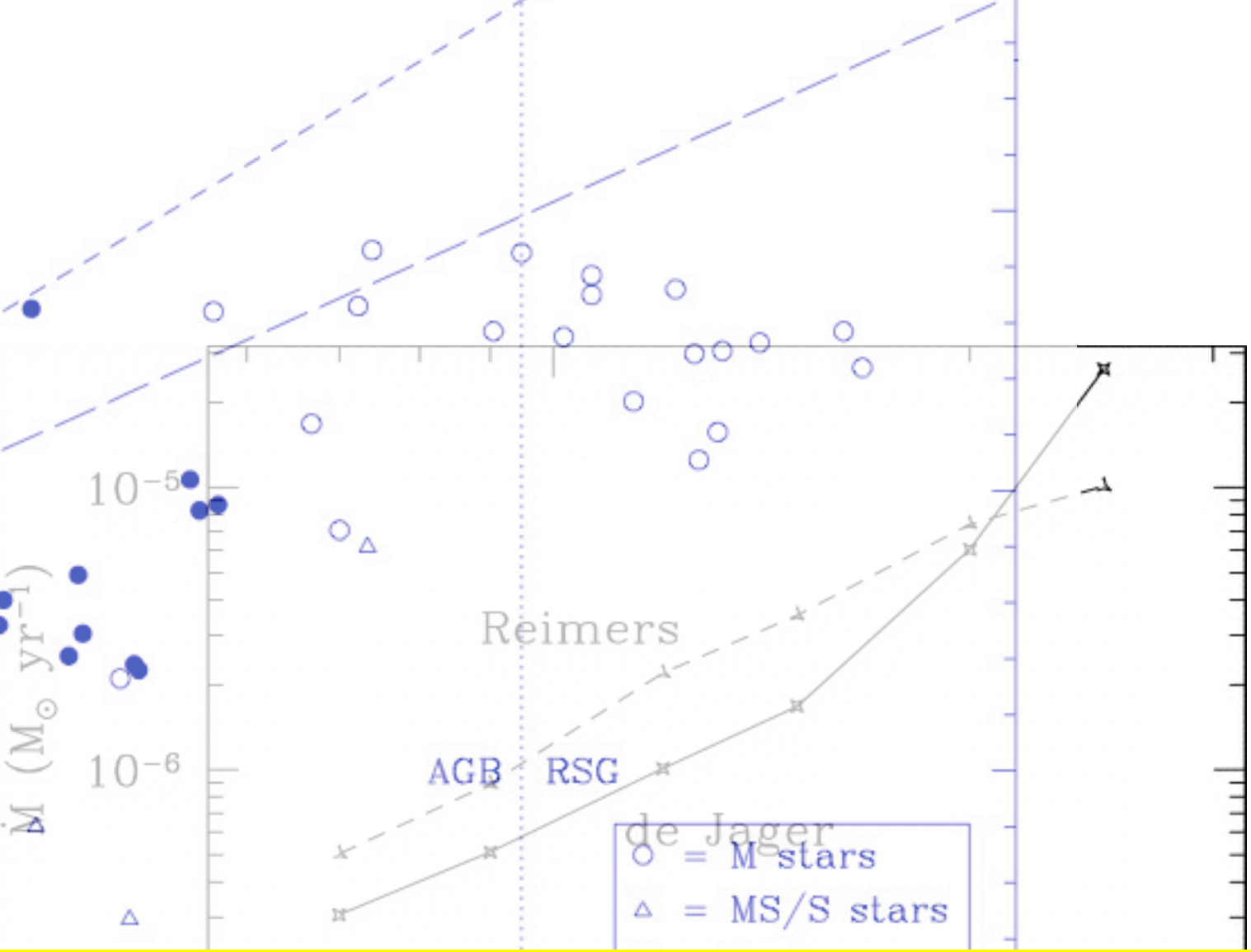
- **Stars in six nearby galactic open clusters→**
- **71 single and multiple O-type objects**
- **40 detected binaries**





Sana et al. 2012


De Jager et al.
85M$_{sol}$
32M$_{sol}$
12M$_{sol}$
6.5
6
5.5
5
4.5
4
3.5
3
2.5
lgL/L⊙
4.0
4.5
5.0
5.5
6.0
9.0
9.5
10.0
8.5
8.0
7.5
6.5
7.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
lgT$_{eff}$



Dust enshrouded red supergiant may have higher mass loss (factor between 3 and 50) van Loon et al. (2005).

Dependence on the metallicity?

VY CMa, Circumstellar material very inhomogeneous

Smith, Hinkle, Ryde, 2009, ApJ, 137, 3558

Current average Mdot ~2-4 10^{-4} M_{sol}/y
Higher Mdot in the past (~1000 y ago)→ 1-2 10^{-3} M_{sol}/y

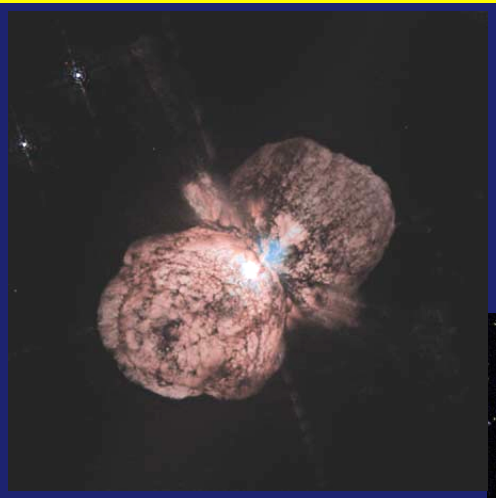
1 Msol of circumstellar material accumulated in the last 1000 y

Might give a type IIn SN type.

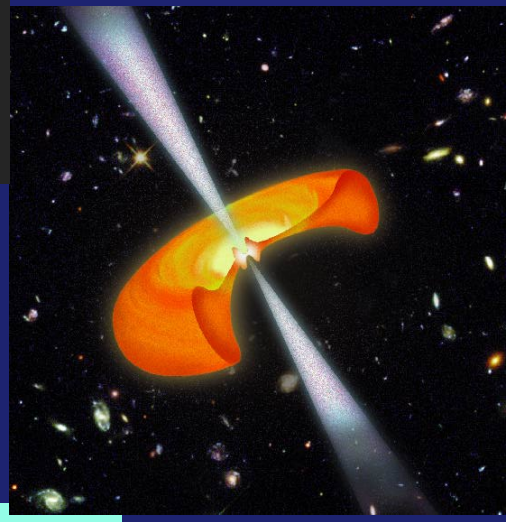
NASA, ESA, and R. Humphreys (University of Minnesota)

SOME CURRENT CHALLENGES

PISN in local Universe?



Can LBV explode as SNe?



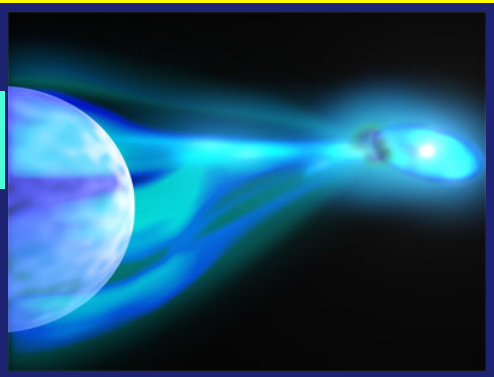
How to explain lack of SN II-P from RSG progenitors between 18 and 25 Msol?

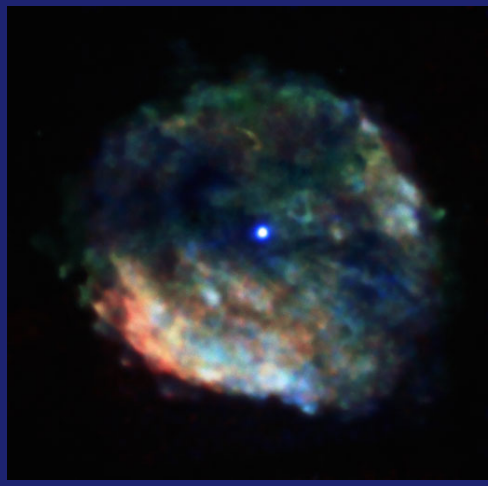
What are the progenitors of Gamma Ray Bursts?

Rotation rate of young pulsars?

SOME OLD STILL CURRENT CHALLENGES

BINARY VERSUS SINGLE STAR?





LINK BETWEEN LIGHT CURVE SPECTRUM OF SN AND NATURE OF THE PROGENITOR?

MASS LIMITS BETWEEN NEUTRON STAR AND BLACK HOLE PROGENITORS (HOW DOES IT DEPEND ON Z)?

WHAT CAN WE SEE WHEN A BLACK HOLE IS FORMED?

1) Energies
2) The evolutionary scenarios
3) Some successes
4) Story 1→ The Blue red ratio
5) Story 2→ the puzzle of BSG
6) Story 3→ the origin of low luminous WC stars
7) conclusion

$$\dot{M} = 4\pi r^2 \rho v \Rightarrow \dot{M} = \frac{L}{c^2} N_{eff} (1 - \varepsilon)$$

Mass loss rates proportional to the number of strong lines

Number of strong lines proprtional to Z

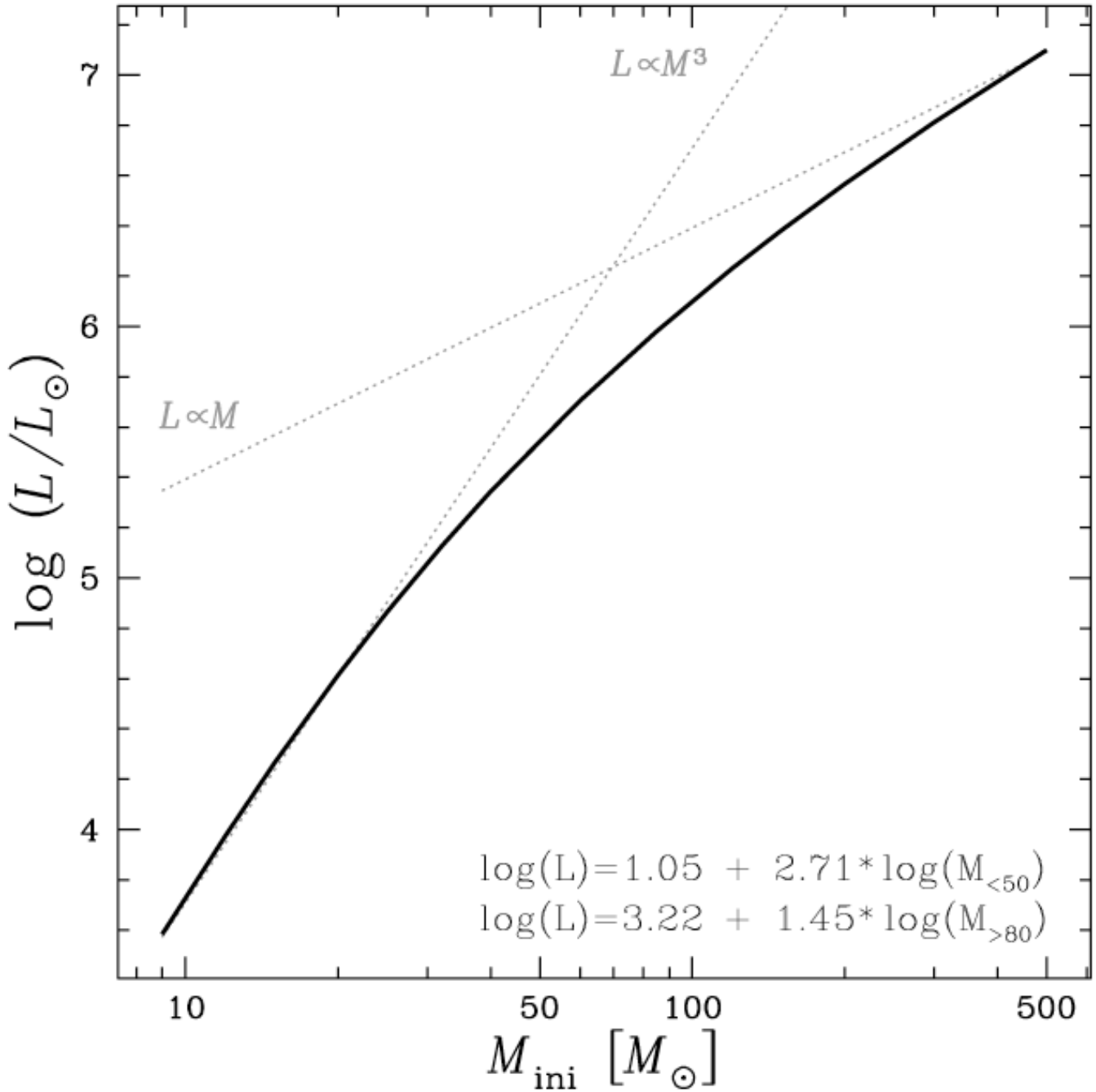
Wind models for hot stars show this effect

O5V
Kudritzki et al 86

Z	Mass loss [10^{-6} M_{sol}/y.]
0.020	2.12
0.006	1.35
0.002	0.72

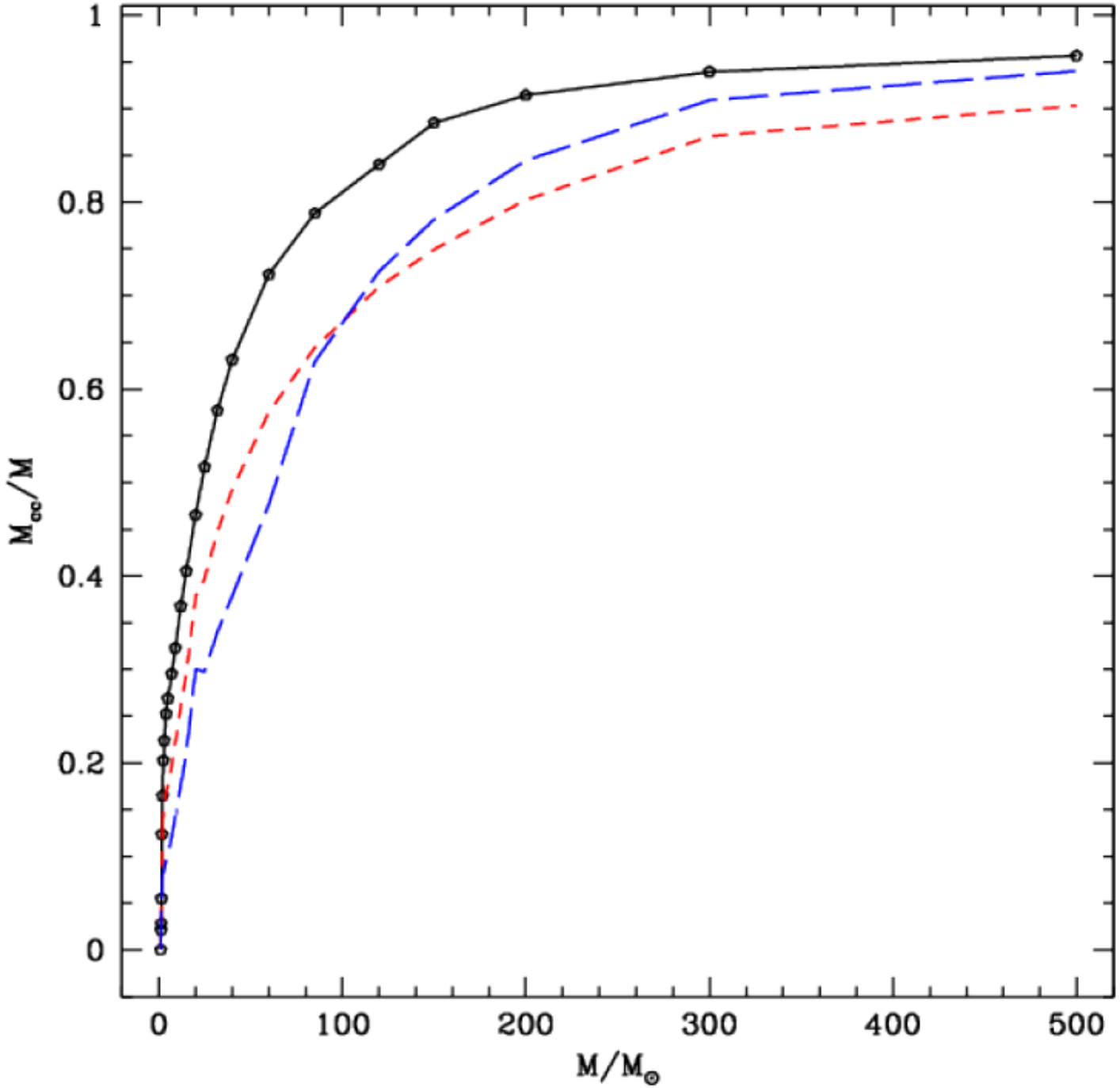
$$\dot{M}_Z = \left(\frac{Z}{Z_{sol}} \right)^{\alpha} \dot{M}_{Z_{sol}}$$

VERY IMPORTANT CONSEQUENCES



Lifetimes

$t_H = M/L$

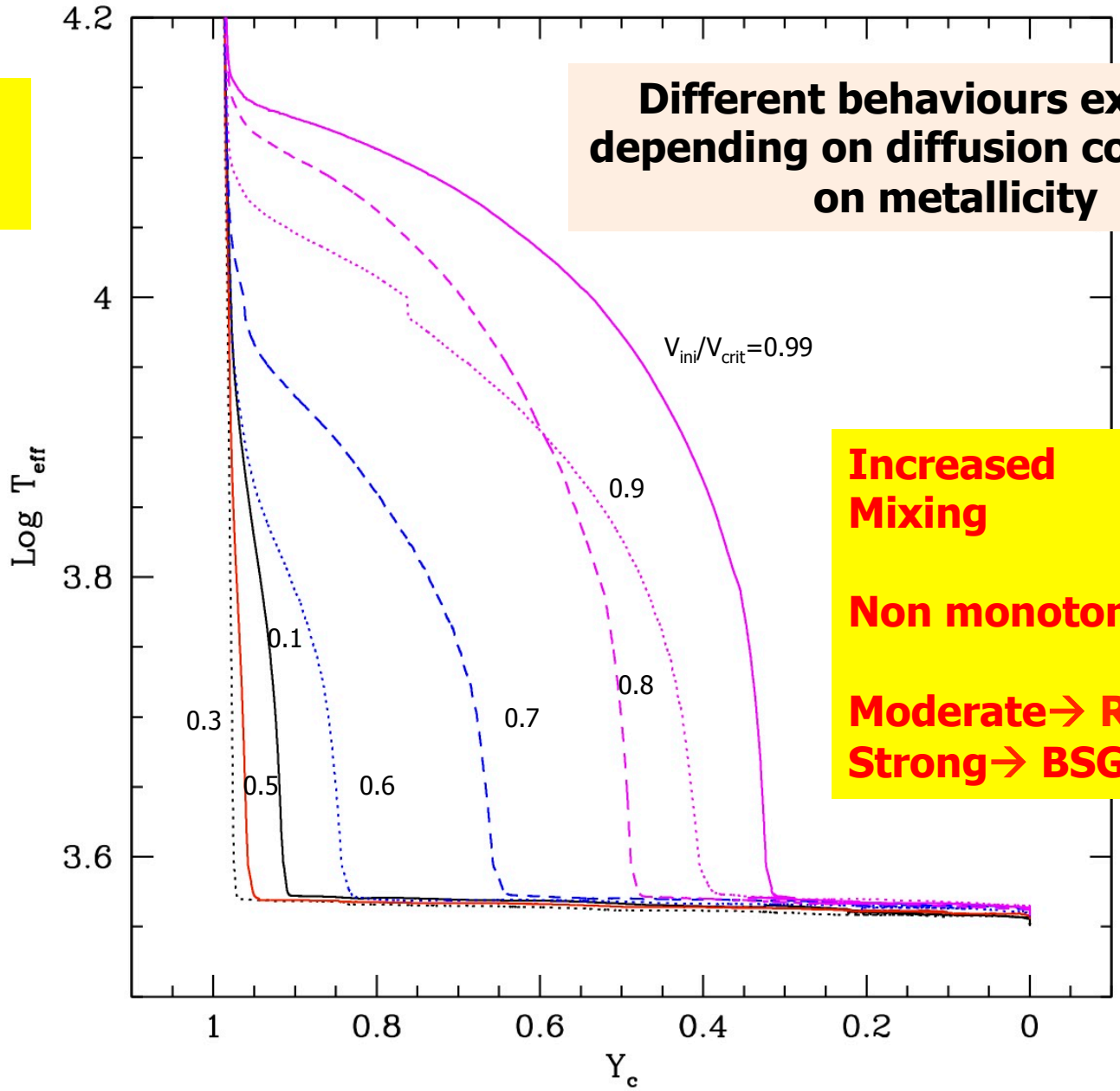

1
0.8
0.6
0.4
0.2
0
M_{cc}/M
0
100
200
300
400
500
$M/M_{\odot}$

H-rich supernova progenitors

Effect of rotational mixing

15 M_{sun}

Z=0.014



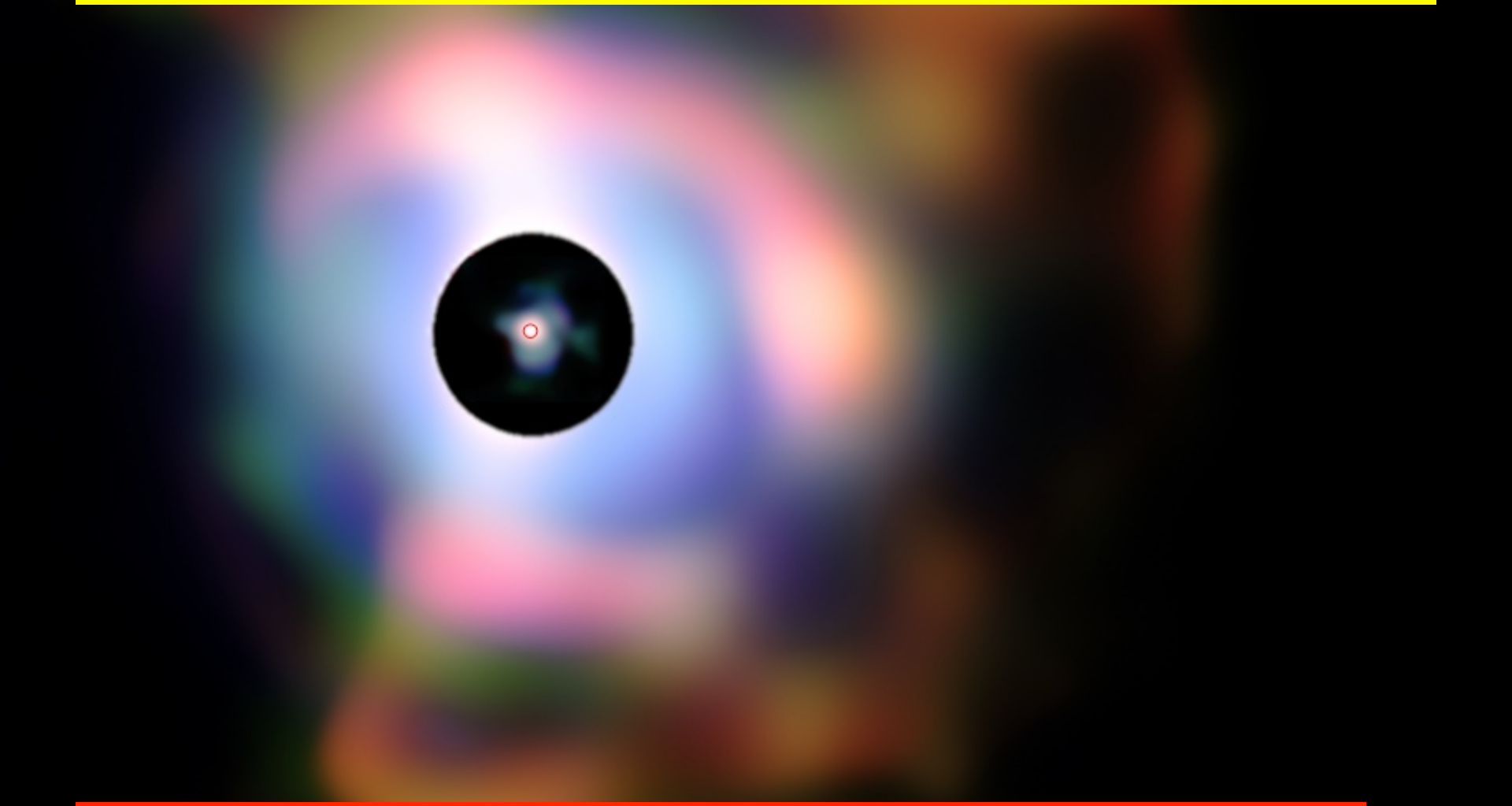
Different behaviours expected depending on diffusion coefficients on metallicity

Increased Mixing

Non monotonic behaviour

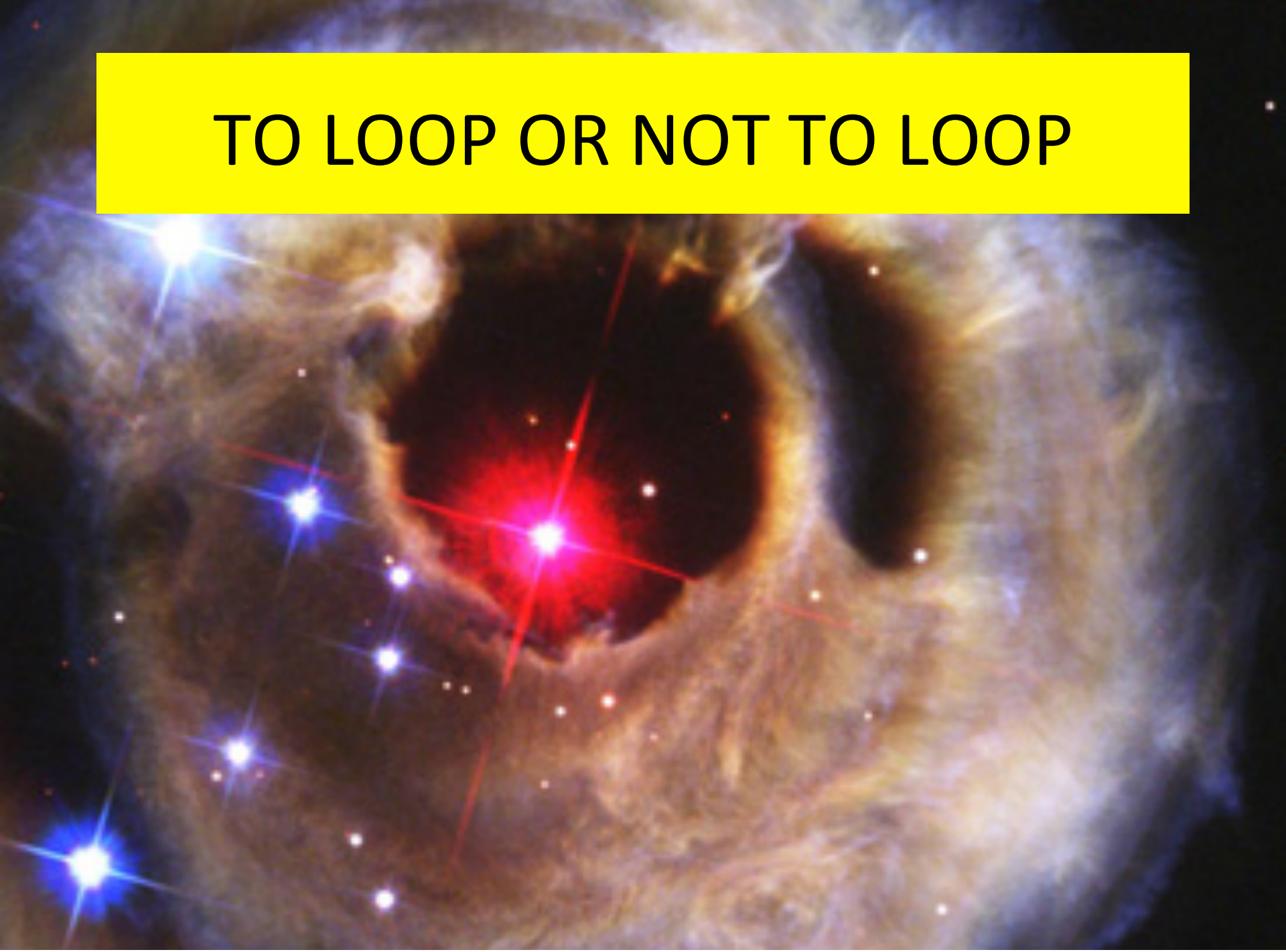
Moderate→ RSG favoured
Strong→ BSG favoured

THE RSG PHASE



ESO, Pierre Kervella (LESIA, Observatoire de Paris), et al.

TO LOOP OR NOT TO LOOP



THE END POINT OF THE EVOLUTION

CONCLUSIONS

ARE YOUNG MASSIVE STARS ROTATING AS SOLID BODIES? *ASTEROSEISMOLOGY*

TO CHECK ROTATIONAL MIXING, MORE WORK STILL NEEDED

ARE RSG IN CLUSTERS WITH A LOT OF FAST ROTATORS DIFFERENT?

THE TIMESCALE FOR THE FIRST REDWARDS EVOLUTION DEPENDS ON MASS LOSS AND MIXING

CAN WE DIFFERENTIATE A BLUE SUPERGIANT EVOLVING FROM BLUE TO RED FROM THOSE EVOLVING FROM RED TO BLUE?

THE UPPER LUMINOSITY OF RSG DEPENDS ON MASS LOSS-MIXING, THE Teff ON CONVECTION TURBULENCE

WHAT IS THE EFFECTIVE TEMPERATURE OF RSG?

A BLUE LOOP CAN BE PRODUCED IN STARS WHERE THE MASS FRACTION OF THE CORE > 70% M

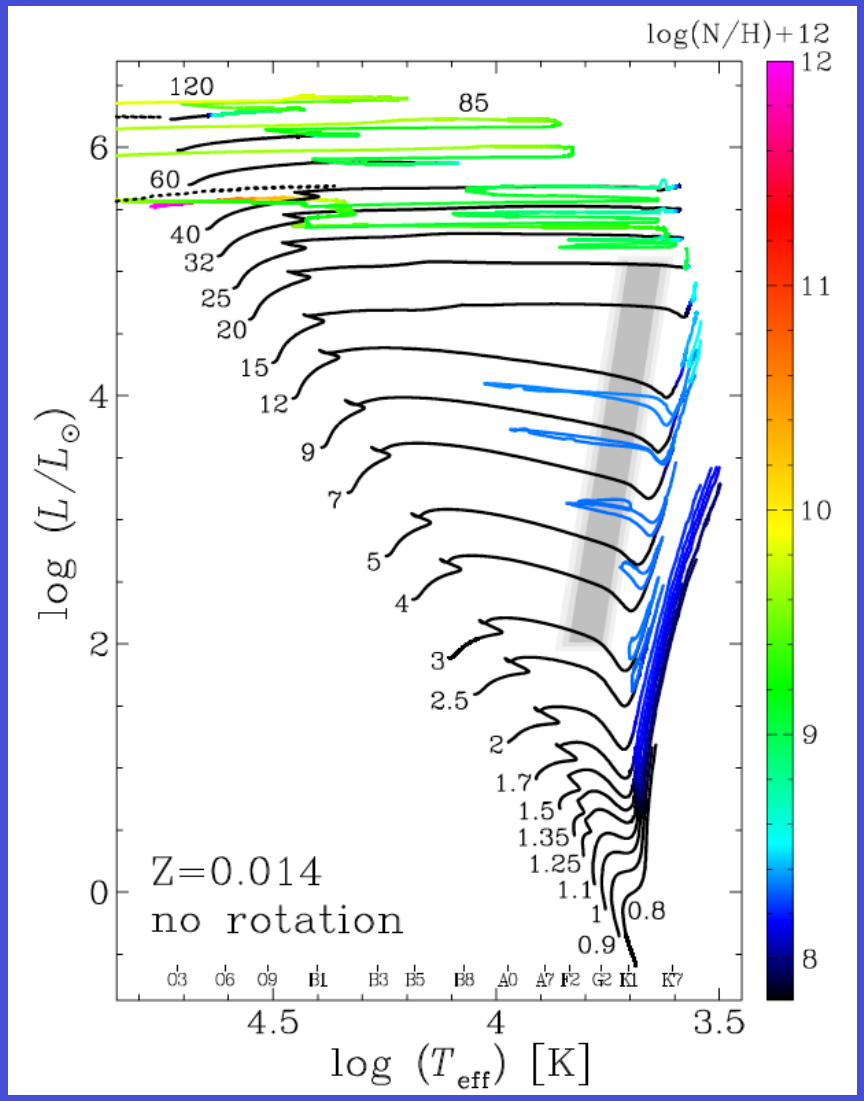
WHAT ARE THE MASS LOSS RATES OF RSG?

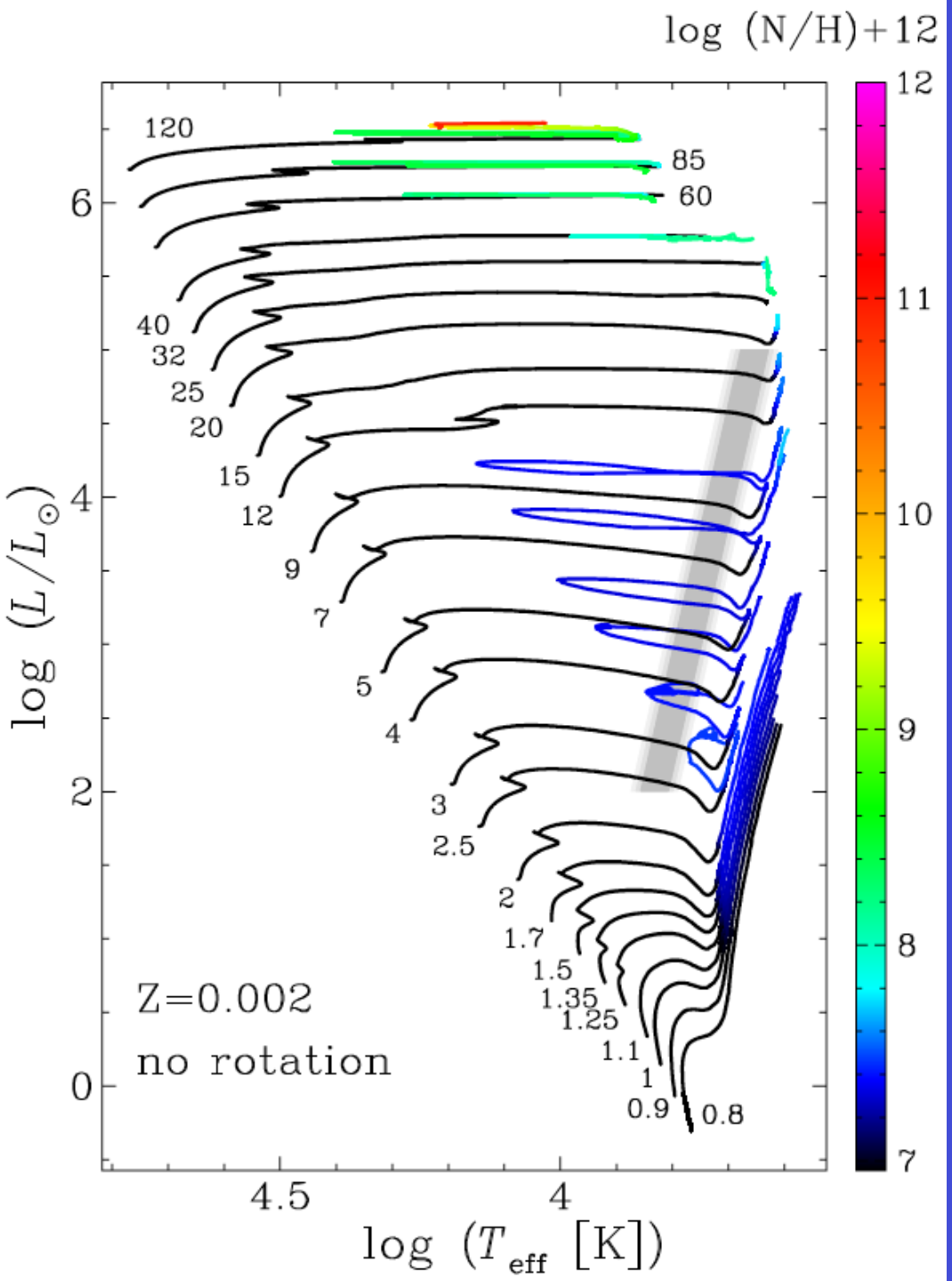
RSG ARE DIRECT PROGENITORS OF TYPE IIP OR TYPE IIL SUPERNOVAE

CHARACTERISTICS OF THE RSG WITH A NON COMPACT COMPANION?

Sharpless 308
Credit & Copyright: Don Goldman

What are their impacts in a stellar generation?


log(N/H)+12
12
11
10
9
8
120
85
60
40
32
25
20
15
12
9
7
5
4
3
2.5
2
1.7
1.5
1.35
1.25
1.1
1
0.9
0.8
Z=0.014
no rotation
O3 O6 O9 B1 B3 B5 B8 A0 A7 F2 G2 K1 K7
6
4
2
0
log (L/L⊙)
4.5
4
3.5
log (Teff) [K]


log (N/H)+12
12
11
10
9
8
7
120
85
60
40
32
25
20
15
12
9
7
5
4
3
2.5
2
1.7
1.5
1.35
1.25
1.1
1
0.9
0.8
Z=0.002
no rotation
6
4
2
0
4.5
4
log (L/L⊙)
log (Teff [K])

The SNe zoo

age < 100 Myr

progenitor mass

8 $M_\odot$

SN Ia

detonation of an accreting white dwarf

no Hydrogen (Si+ absorption)

SN II

IIn IIL IIP IIb

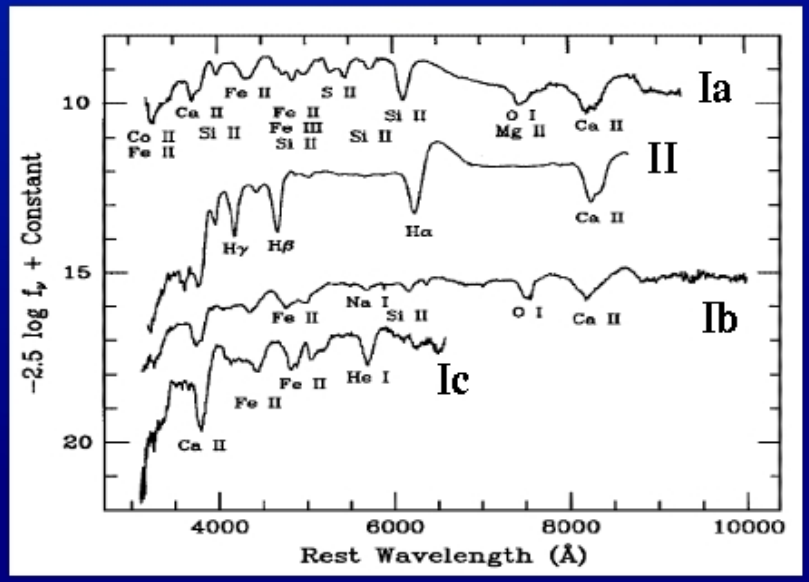
core collapse of a massive star

Hydrogen lines

SN Ib/c

core collapse (outer layers stripped by winds)

no Hydrogen (no Si+)



http://www.arcetri.astro.it/science/SNe/zoo.jpg

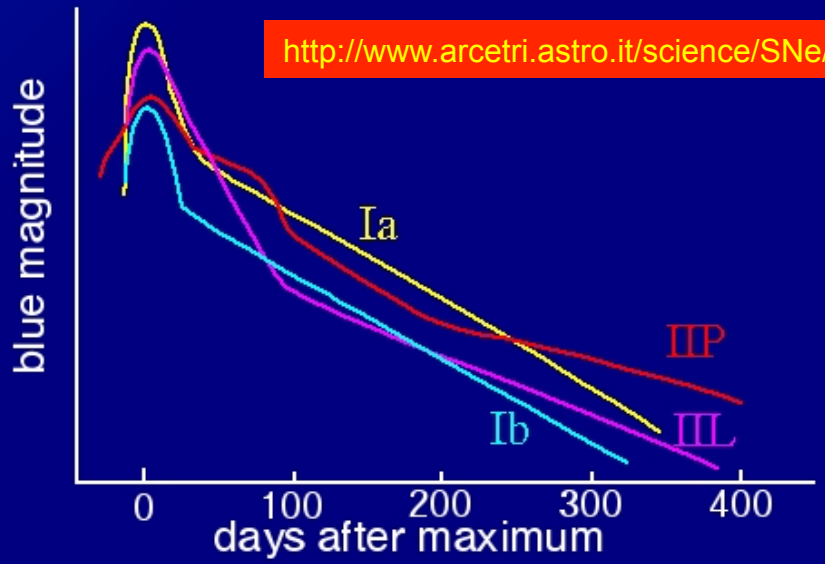
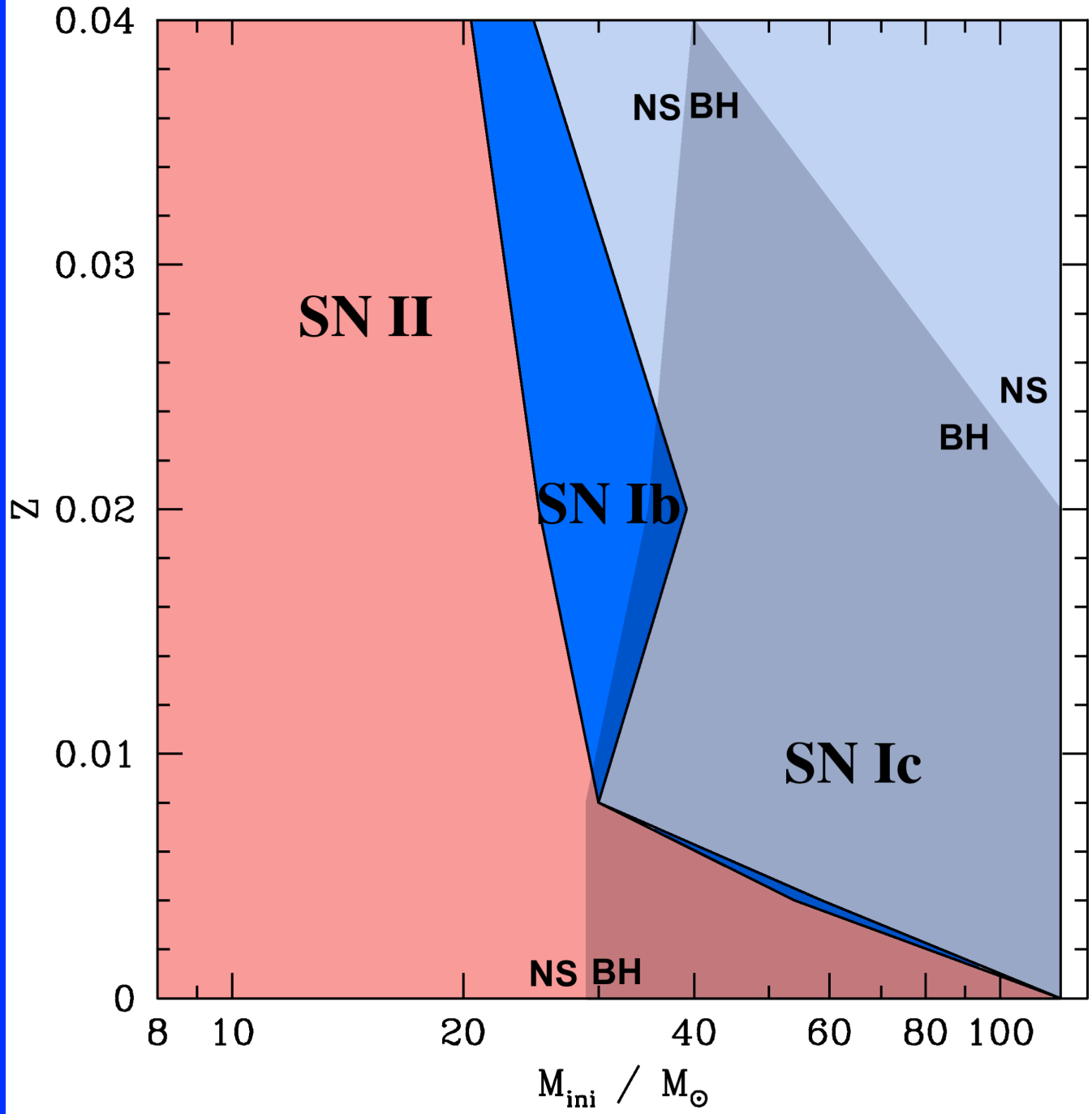


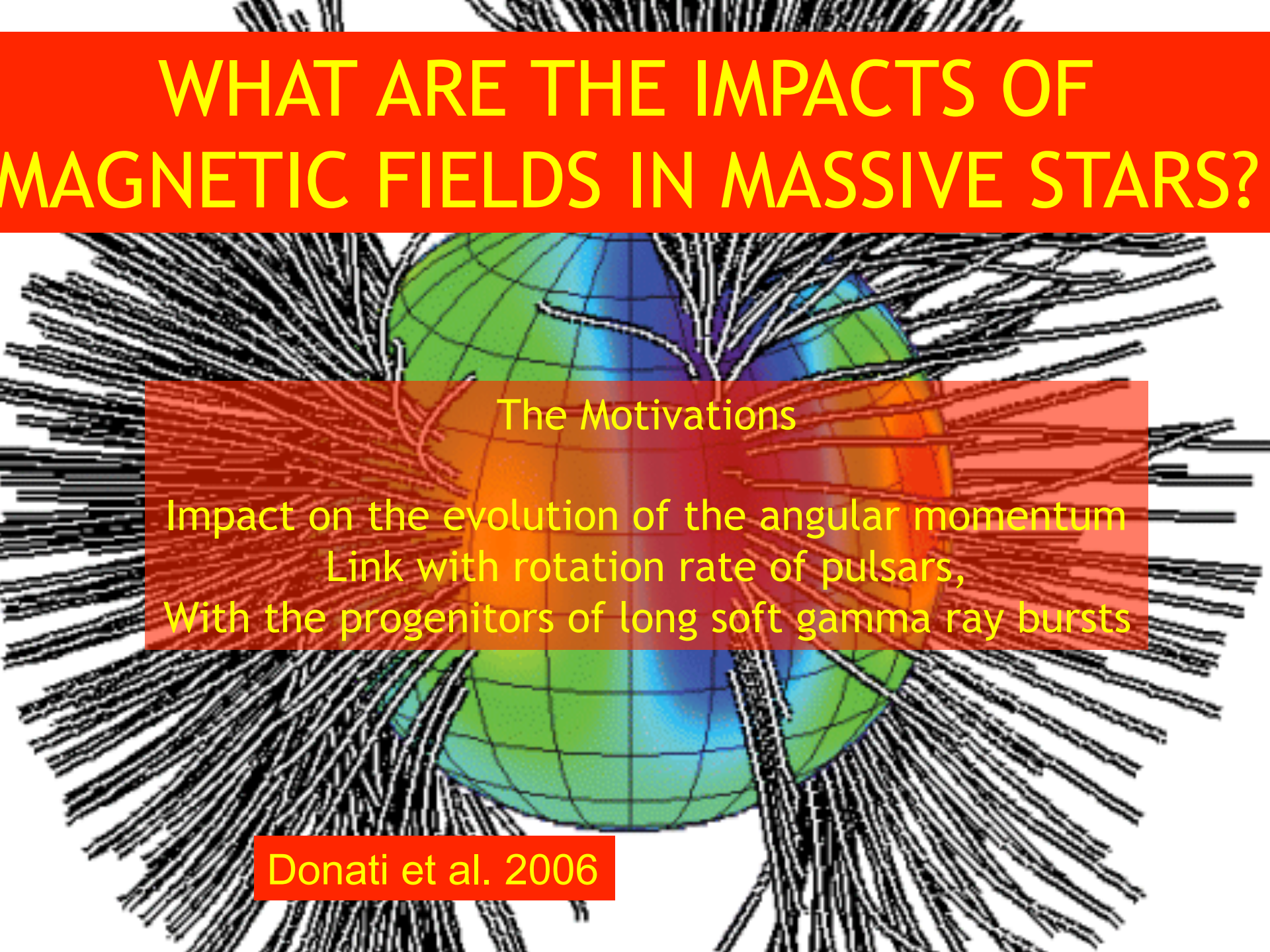
Table 1 The relative frequency of core-collapse supernova types reported in five different studies: SECM (Smartt et al. 2009), LWVetal07 (Li et al. 2007), VLF08 (van den Bergh, Li & Filippenko 2005), PSB08 (Prieto, Stanek & Beacom 2008), and CET99 (Cappellaro, Evans & Turatto 1999). The uncertainties are simple Poissonian errors, and the total number of objects in each survey is listed in the Sample Size row. SECM08 and LWVetal07 are volume-limited estimates with distance limits of 28 Mpc and 30 Mpc, respectively, covering different time periods. VLF05 is based on LOSS discoveries within about 140 Mpc. The PSB08 sample is between about 10–170 Mpc, and CET99 combines various surveys mostly within 100 Mpc

		Sample				
Type		SECM08	LWVetal07	VLF05	PSB08	CET99
II-P	60%	58.7 ± 8.0%	67.6 ± 10%	62.9 ± 4.7%	75.5 ± 9.8%	77.7 ± 10.8%
II-L		2.7 ± 1.7%				
IIn	10%	3.8 ± 2.0%	4.4 ± 2.5%	9.2 ± 1.8%		
IIb		5.4 ± 2.7%	1.5 ± 1.5%	3.2 ± 1.0%		
Ib	30%	9.8 ± 3.3%	26.5 ± 6.2%	24.7 ± 3.0%	24.6 ± 5.6%	22.3 ± 5.8%
Ic		19.6 ± 4.5%				
Sample size		92	68	277	77	67

Smartt 2009


0.04
0.03
0.02
0.01
0
Z
8
10
20
40
60
80
100
M_{ini} / $M_\odot$
SN II
SN Ib
SN Ic
NS BH
NS
BH
NS BH

WHAT ARE THE IMPACTS OF MAGNETIC FIELDS IN MASSIVE STARS?



The Motivations

Impact on the evolution of the angular momentum
Link with rotation rate of pulsars,
With the progenitors of long soft gamma ray bursts

Donati et al. 2006

Stars formed between 0.1 and 120 M_{sol}
Salpeter's IMF

Mass fraction in massive stars

$M > 8\ M_{sol} \rightarrow$ **14%**

~1% in remnants
~13% returned

3.5 – 4.5 % new elements

Low and intermediate mass stars

$1 < M/M_{sol} < 8 \rightarrow$ **25%**

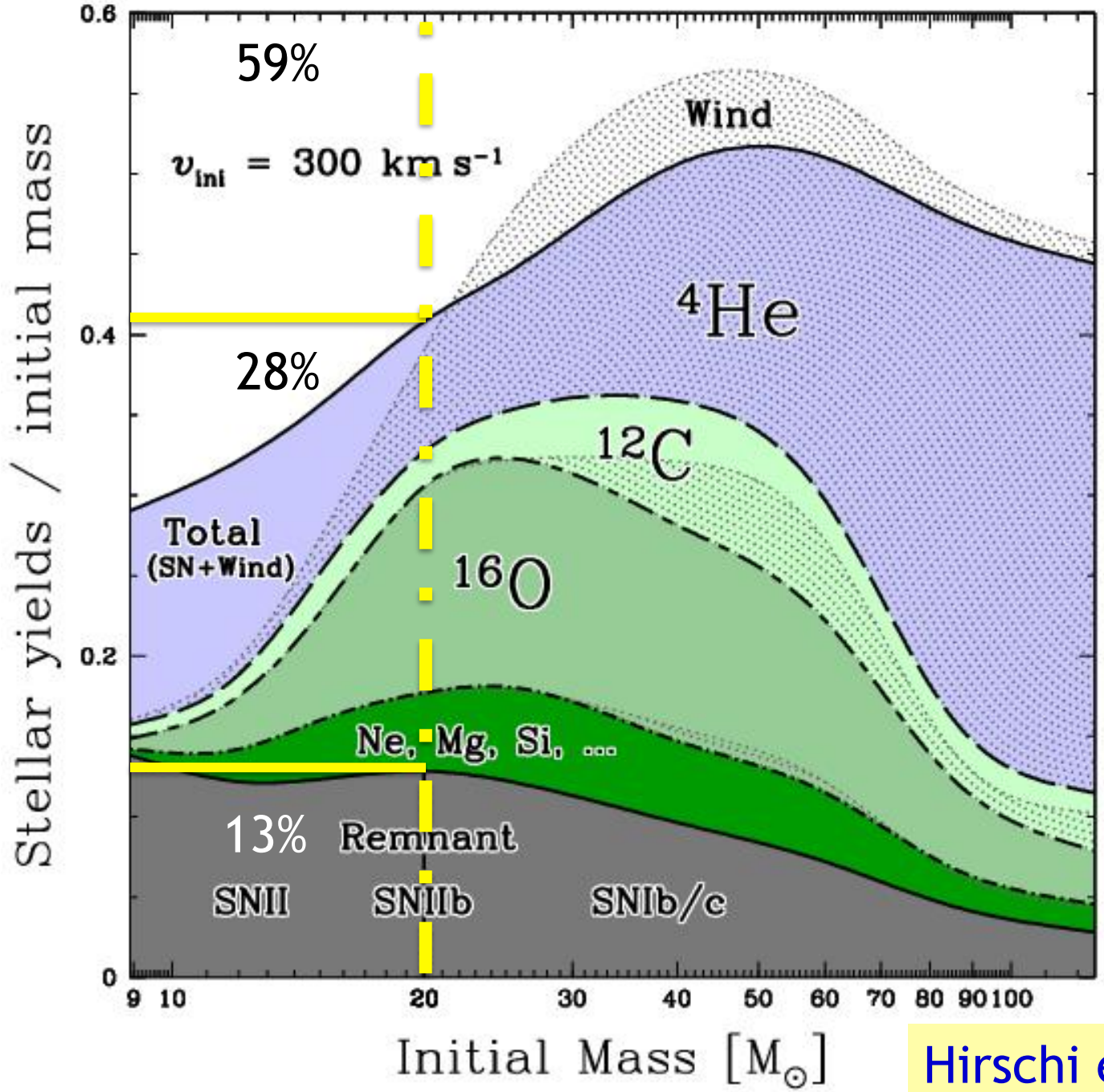
~6.5% in remnants
~18.5% returned

Very low mass stars

$0.1 < M/M_{sol} < 1 \rightarrow$ **61%**

Energy released per solar mass transformed in stars (Salpeter IMF, mass range 0.01-120 solar masses)

1-8 solar masses	41 10^{61} eV
8-120 solar masses	~109 10^{61} eV



Hirschi et al. 2005

50 minutes

40 min. exposé, 10 min questions

First draft plan

- 5 min: 3 viewgraphs

  1) **Massive stars in a broad context**
- V1 generous give a lot and in a short timescale, for this reason
- V2 Their deaths important in the whole cosmic history
- Can probe first stellar generations
- Still important to understand present day Universe
- V3 At the crossroad of many topical questions: reionizations,
- Evolution of galaxies, birth of our own solar system

2) Physics of massive stars 6 V, 10 min (TOT 13V 15min)

- The key role of radiation → impact on M-L relation V4
- on timescale
- on convection (large L/M) V5
- on mass-loss V7

- The key role of rotation → fast rotators V8
- on mixing in rad. Zone V6
- on angular momentum transport
-
- Magnetic field V9

- Multiplicity V10

- Explain how Type is attributed through chemical composition.

3) Evolutionary channels towards preSNe progenitors

- Evolutionary scenarios for single stars, the 3 families V11
- 3a) H-rich progenitors, Case of RSGs 7+1=8V, 10min (21 VT 25min)
- When do a star becomes a RSG?
    - first HR and 2nd crossing V12
    - the properties of RSG proge depends on mixing & mass loss
    - timescale for first crossing V13 (mixing)
    - lifetime of RSG (mixing and mass loss) V14
    - The properties of RSG preSN (mass of H-rich envelope V15
    - Note on Davies work V16
    - Note on Dessart work
    - impact on upper limit for RSG preSNe V17
    - impact of lower limit for RSG preSNe V18

3b He-rich progenitors (6V 10 27 V min TOT=35)

- Lower limit for WR stars depends on Z (through Mdot) and mixing V19
- Properties of WR preSNe depends on when the star enters the WR phase and mass loss during the WR phase V20
- The observed WR populations and single star models WN, WN/C and WC→ WN/C internal mixing only models with rottaion explain them V21
- The number ratios, the abundances, the luminosities V22
- Final fate→ type Ibc Sne, Ib and Ic's dep. On Z, Smartt result cf Yoon, José talk, BH? V23
- Even most massive stars evolve into WR stage V24

3c OTHER CHANNELS 4V 5min (31 V TOT 40)

Inbetween H-rich and He-rich: Yellow (?), Blue, LBV cf Georgy
Single no very massive LBV but ok for 20 M V25

Close binary evolution V26

PISNe V27

Homogeneous evolution V28 (new Mdot)

4 Conclusions 1V 3Min (32 V Tot 43 Min)

- How to improve connection initial conditions with final Outcome (would allow to predict frequencies, from Observations trace back the SFH, impact on our understanding Of chemical evolution of galaxies)

Observations: hunt to progenitors
better understanding of the LC of Sne and how it relates to physics of progenitors

stellar evolution: M, Z, V, H, in single star
multiplicity effects

Résultats de Saio

The blue-supergiant puzzle

What is there behind rotating models? (magnetic field? Different outputs for same rotation dependant on which Dshear/Deff
New diffusion coefficients from last paper by André

Mass loss

RSG mass loss rates
Mdot from homogeneous evolution

Résultat de Martin Krause, de Liza, de Cristina
The low luminous WC stars

Magnetic braking of the surface and of the core

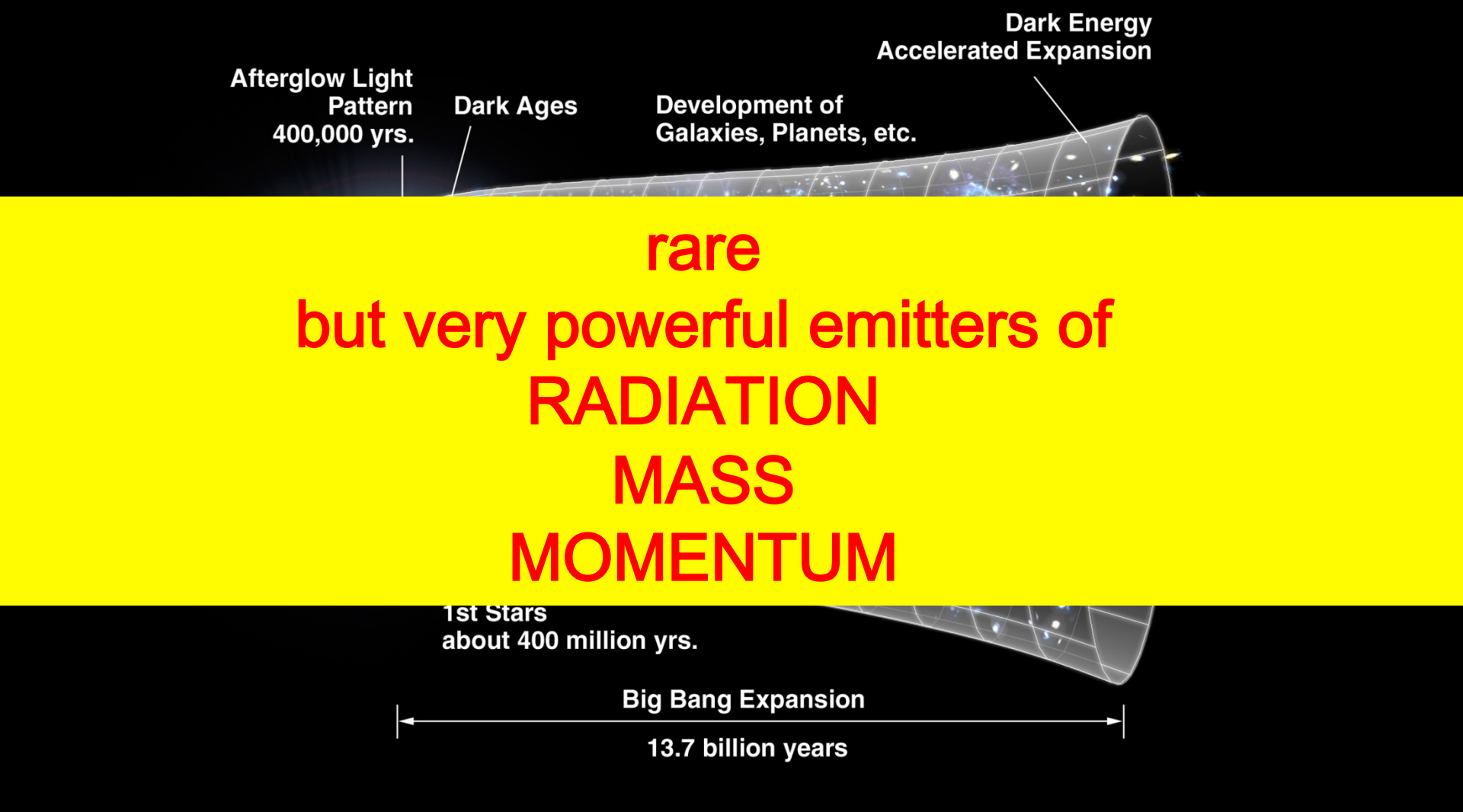
RSG more compact

Origin of fast rotators?

What could tell us the RSG luminosity function?

MASSIVE STARS AS COSMIC ENGINES

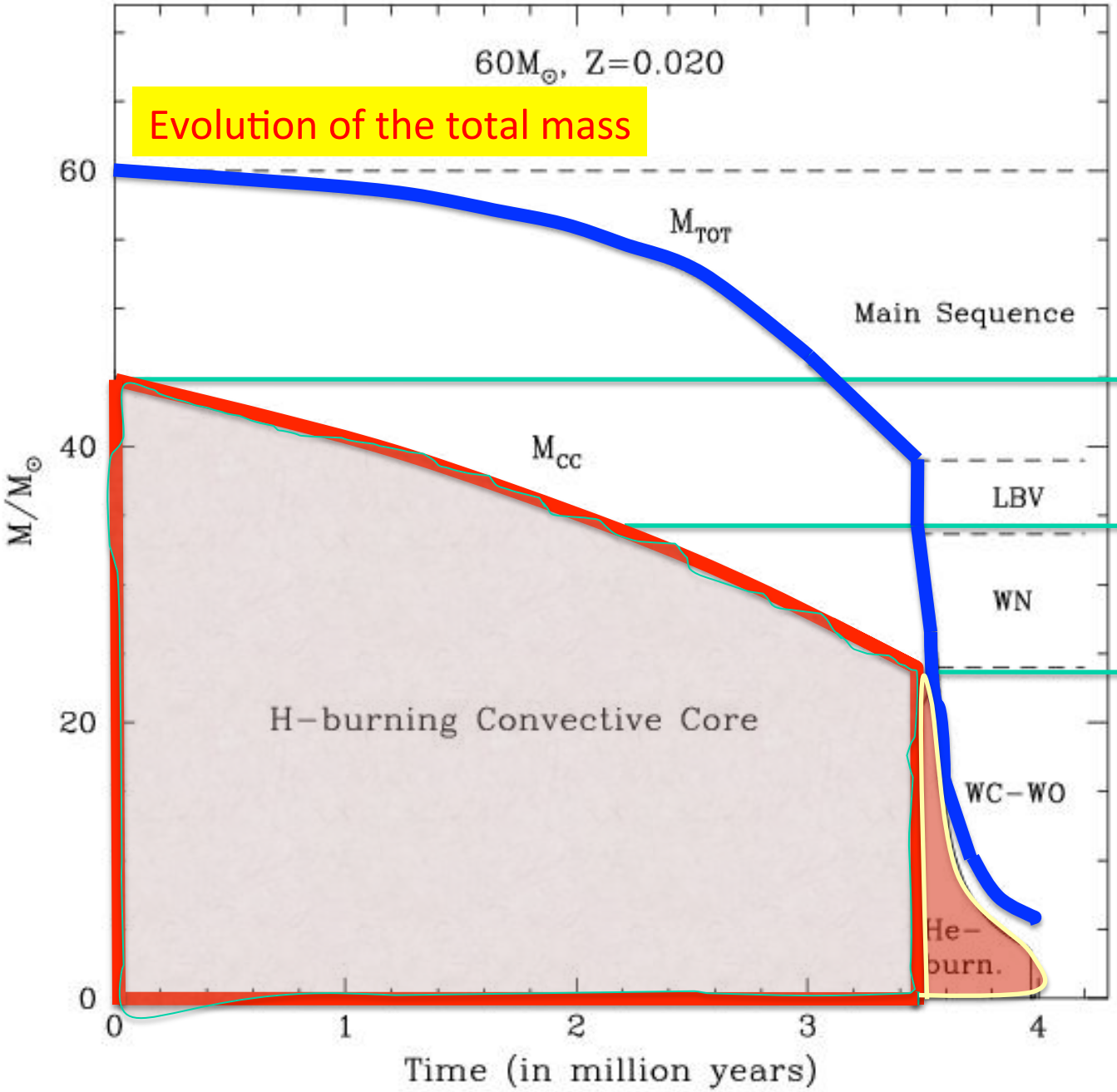
Massive stars plays a key role in many cosmic evolution processes…



rare
but very powerful emitters of
RADIATION
MASS
MOMENTUM

Mass loss through radiative stellar winds

NASA, ESA, Y. Nazé (University of Liège, Belgium) and Y.-H. Chu (University of Illinois, Urbana)



Change of Surface abundances

Change of surface abundances

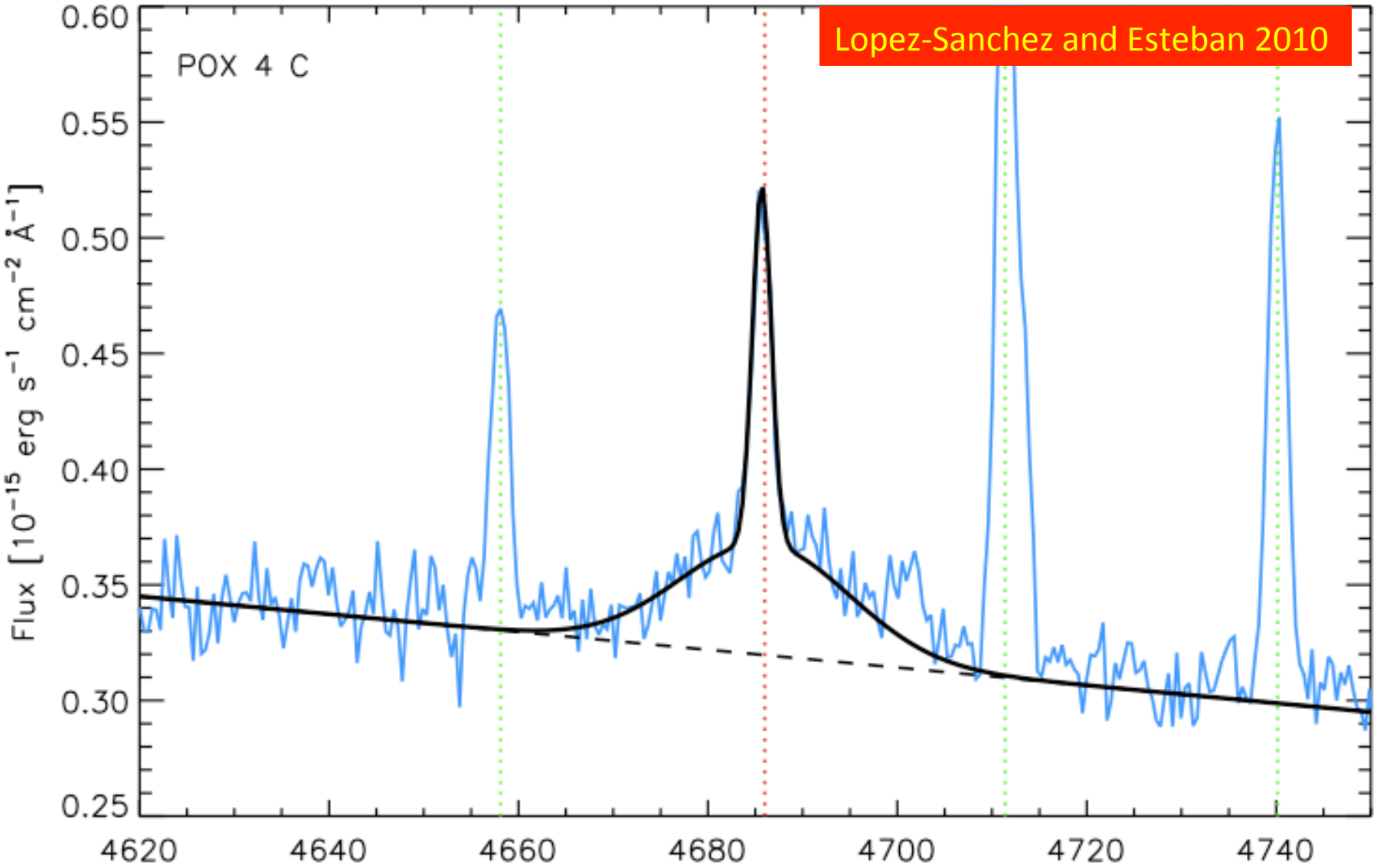
At the surface the mass fraction of H < ~0.4 (initial ~0.70)

WN stars

At the surface He-burning products

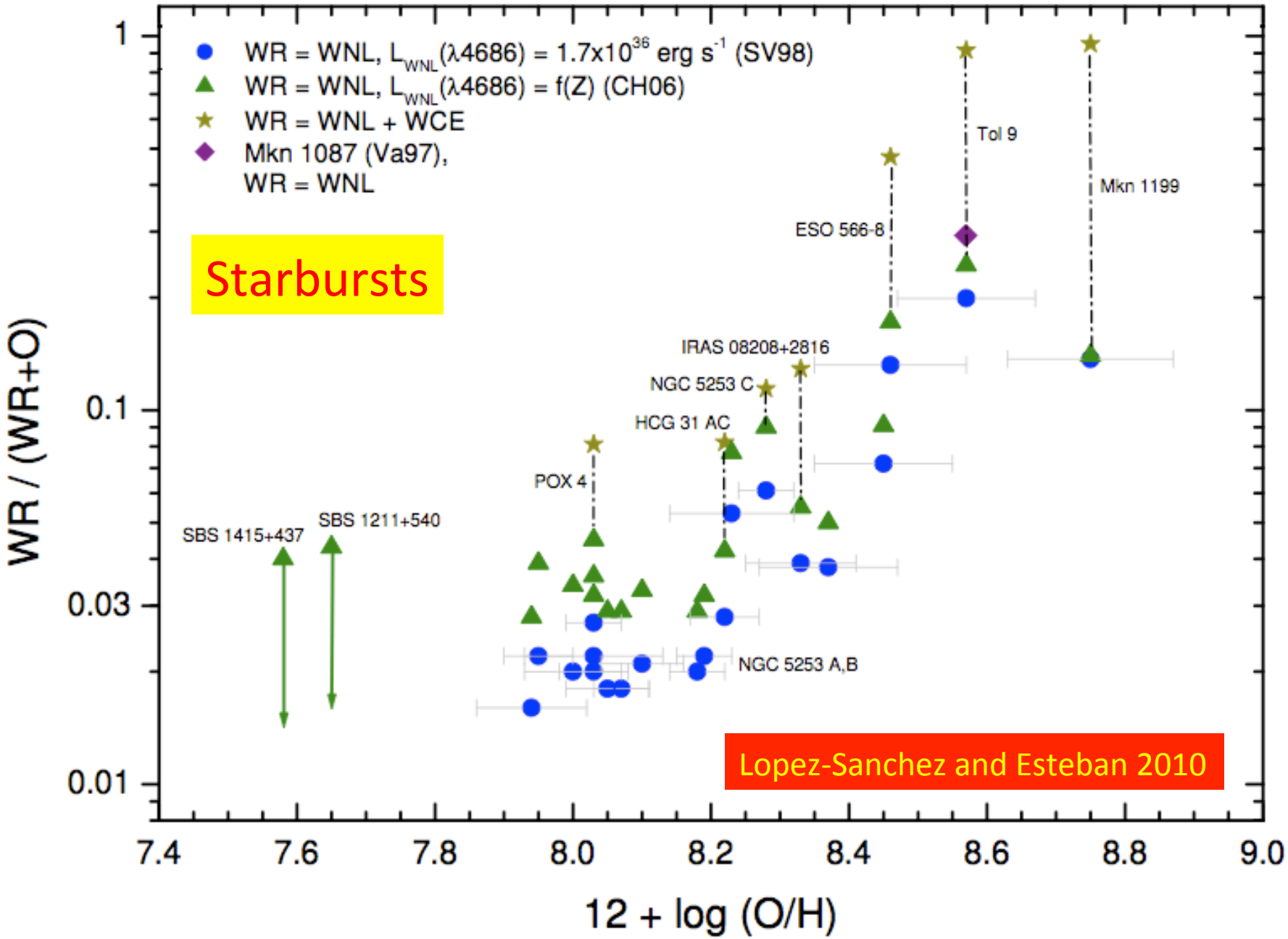
WC-WO stars

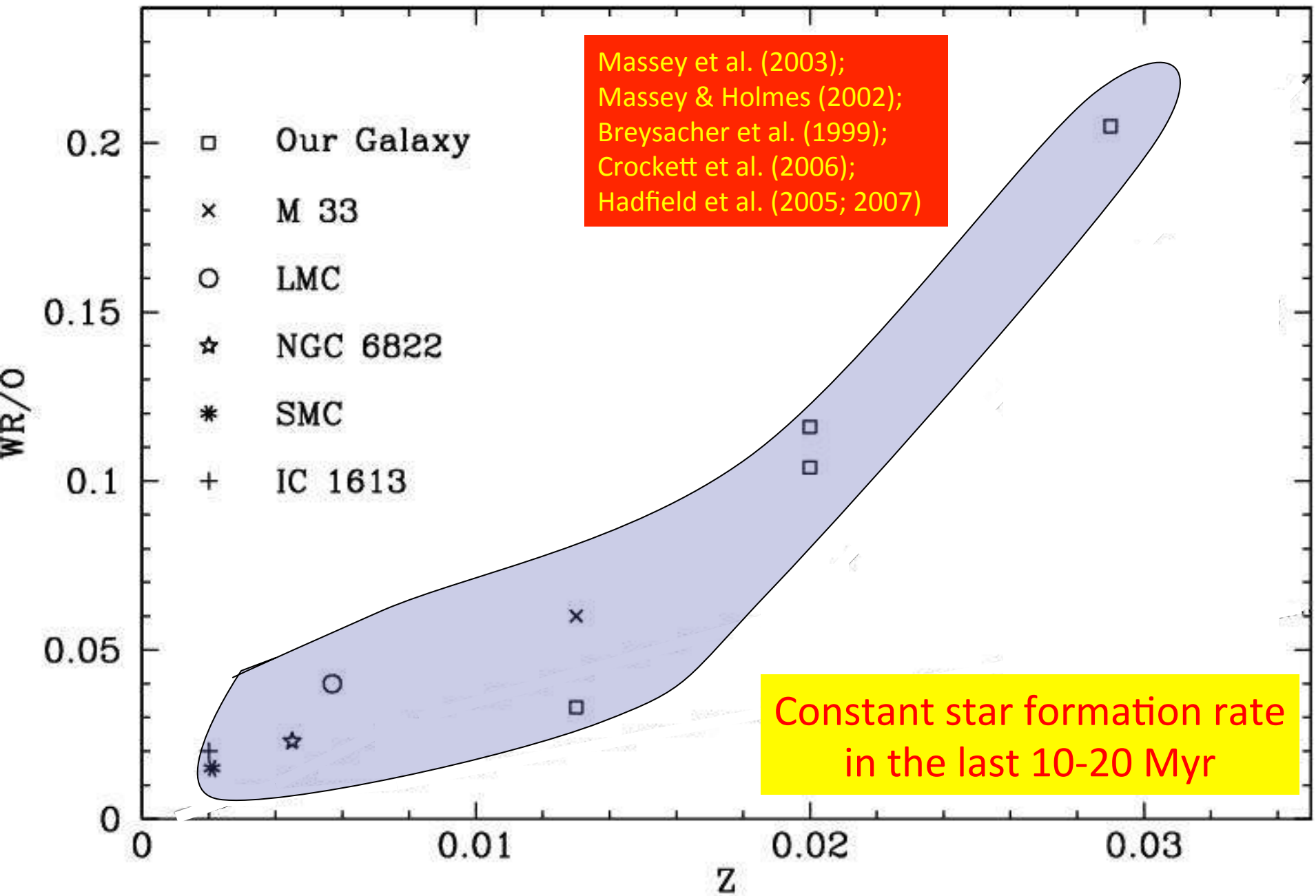
Starburst galaxy Tol 9 within Klemola 13 group



Optical broad-band images show the stellar distribution. The ionized gas is traced by the Hα emission.
Tol 9 (center, right) hosts a huge amount of ionized gas, star formation phenomena and Wolf-Rayet stars.
The beautiful barred spiral ESO 436-46 (center, left) is the main member of the galaxy group known as Klemola 13.
Other two galaxies of this group (one in apparent interaction with Tol 9) are also shown.

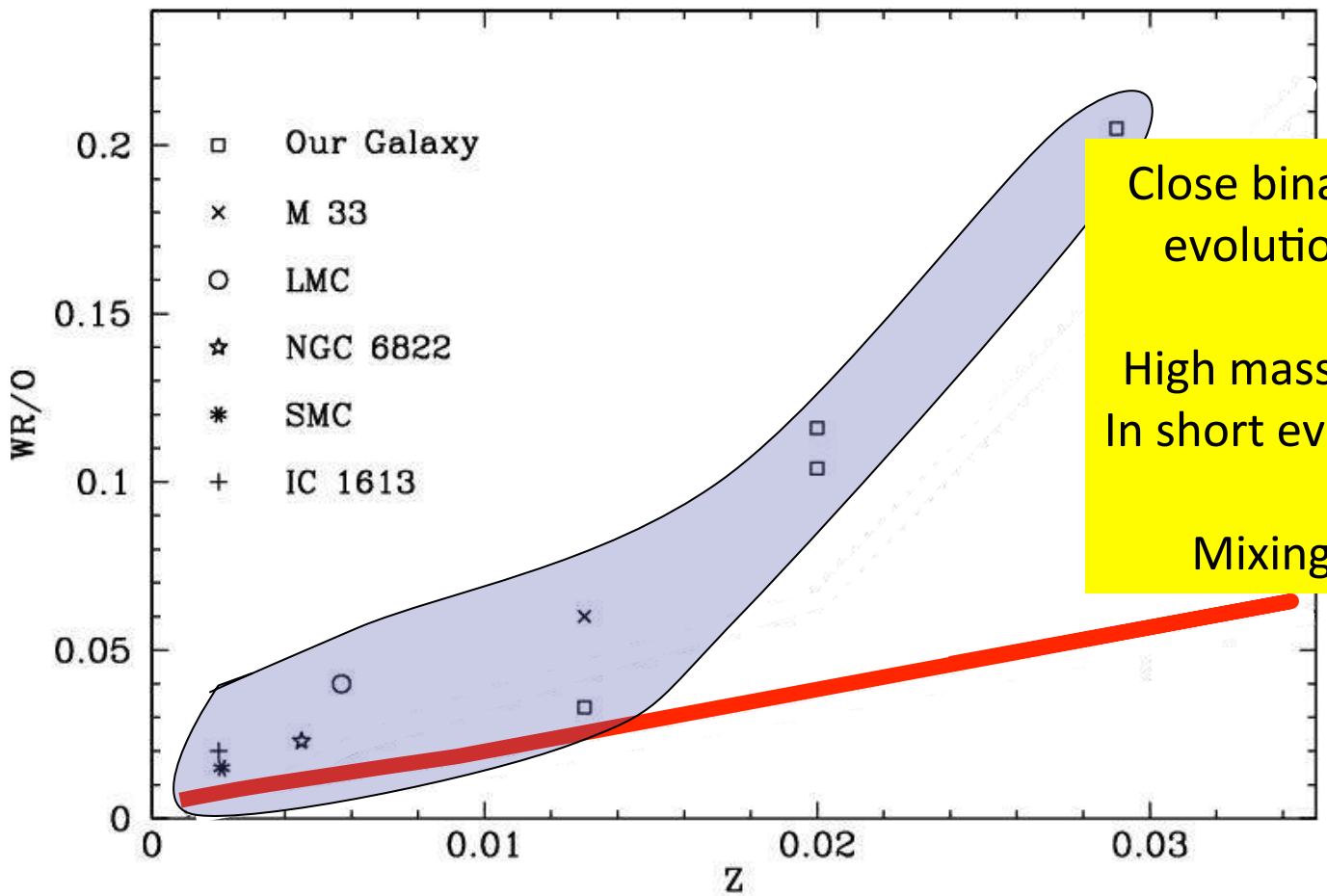
Ángel R. López-Sánchez, César Esteban & Jorge García-Rojas
CSIRO / Australia Telescope National Facility (ATNF), Instituto de Astrofísica de Canarias (IAC)


WR = WNL, $L_{WNL}(\lambda4686) = 1.7\times10^{36}$ erg s^{-1} (SV98)
WR = WNL, $L_{WNL}(\lambda4686) = f(Z)$ (CH06)
WR = WNL + WCE
Mkn 1087 (Va97), WR = WNL
Starbursts
Tol 9
Mkn 1199
ESO 566-8
IRAS 08208+2816
NGC 5253 C
HCG 31 AC
POX 4
SBS 1415+437
SBS 1211+540
NGC 5253 A,B
Lopez-Sanchez and Esteban 2010
WR / (WR+O)
12 + log (O/H)
1
0.1
0.03
0.01
7.4
7.6
7.8
8.0
8.2
8.4
8.6
8.8
9.0


Massey et al. (2003);
Massey & Holmes (2002);
Breysacher et al. (1999);
Crockett et al. (2006);
Hadfield et al. (2005; 2007)
Our Galaxy
M 33
LMC
NGC 6822
SMC
IC 1613
WR/O
Z
0
0.05
0.1
0.15
0.2
0.01
0.02
0.03
Constant star formation rate
in the last 10-20 Myr

A SUCCESS AND AN OPEN QUESTION

Z-effect



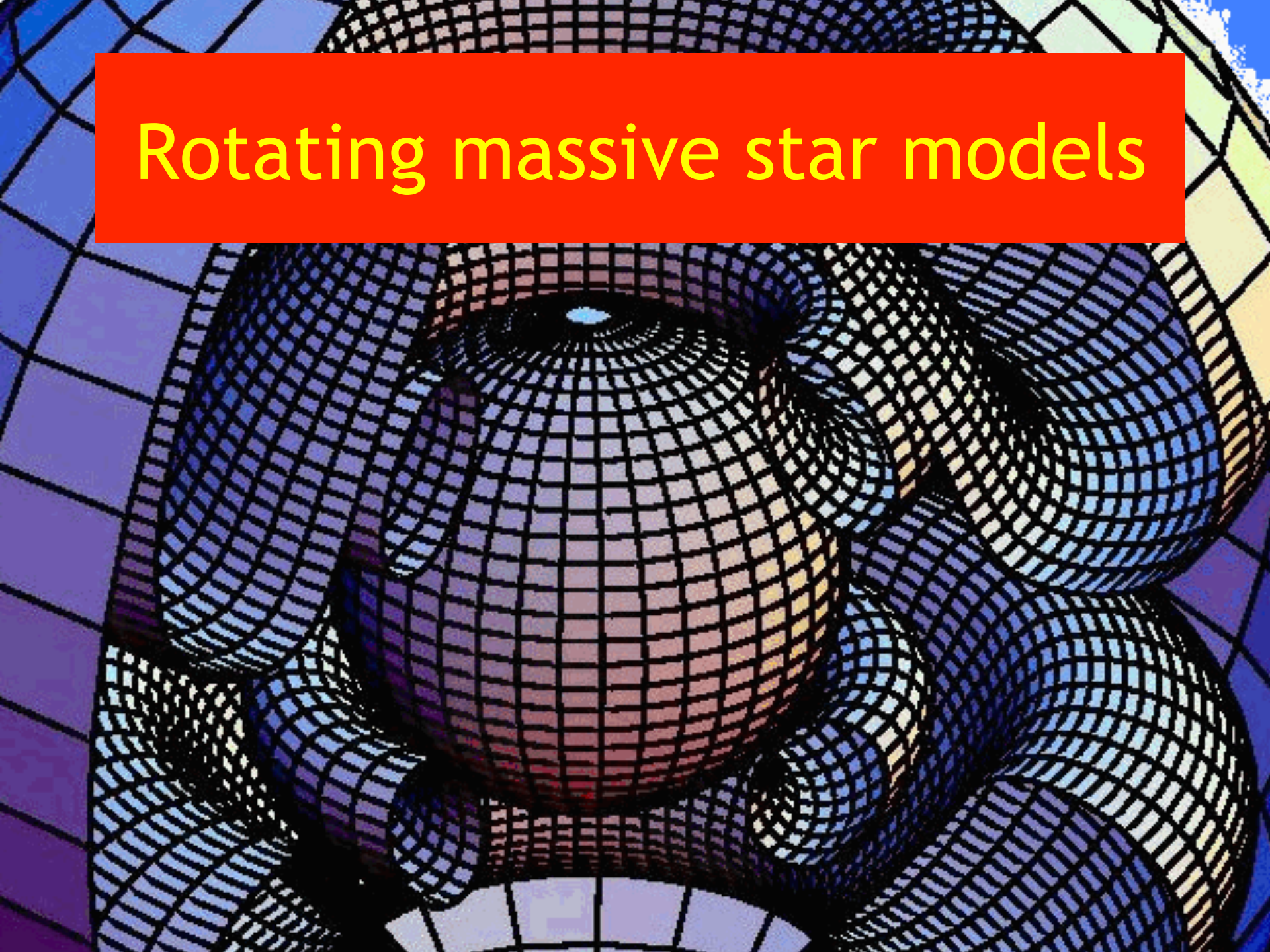
Close binaries evolution?

High mass loss In short events?

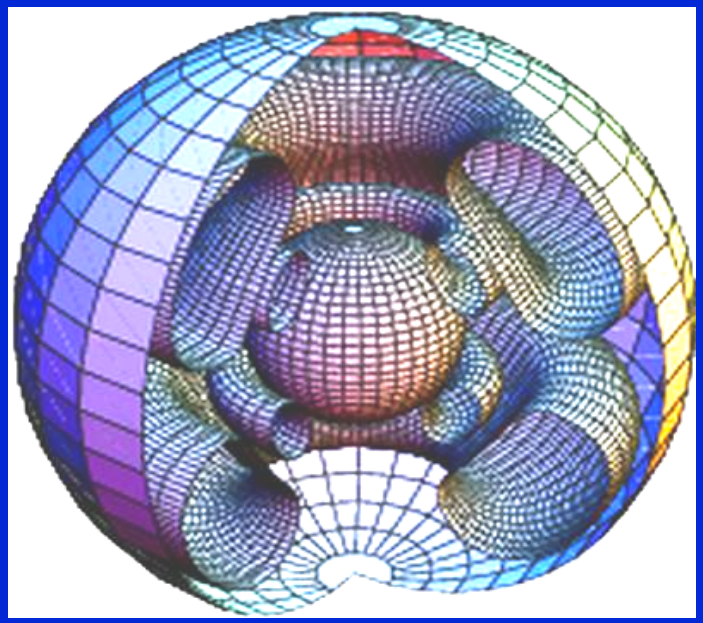
Mixing?

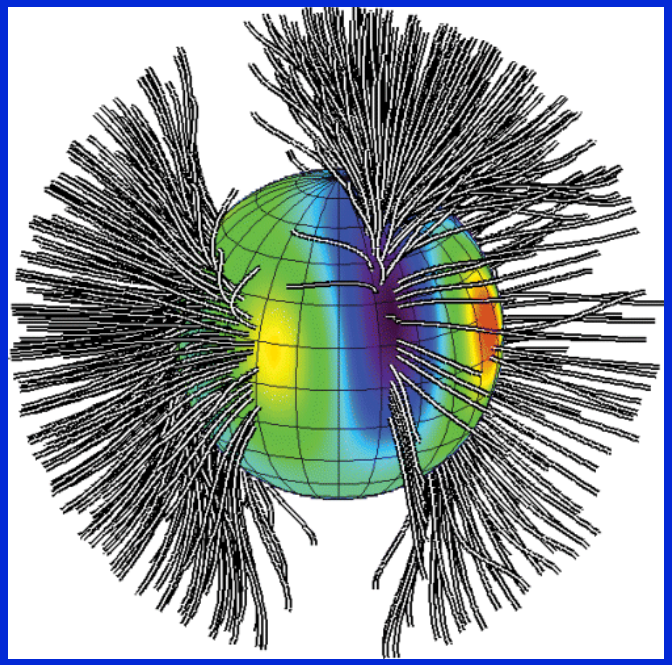
More spectral lines→ more transfer of momentum→ stronger winds→more mass loss

Rotating massive star models



Effects in Asteroseismology





Donati et al. 2006

STRUCTURE

- Oblateness (interior, surface)
- Differential rotation

MASS LOSS

- Stellar winds
- Anisotropic losses of mass and J

MIXING

- **Meridional circulation**
- **Shear instabilities**
- **Turbulence**
- Transport of angular momentum of elements

MAGNETIC FIELD

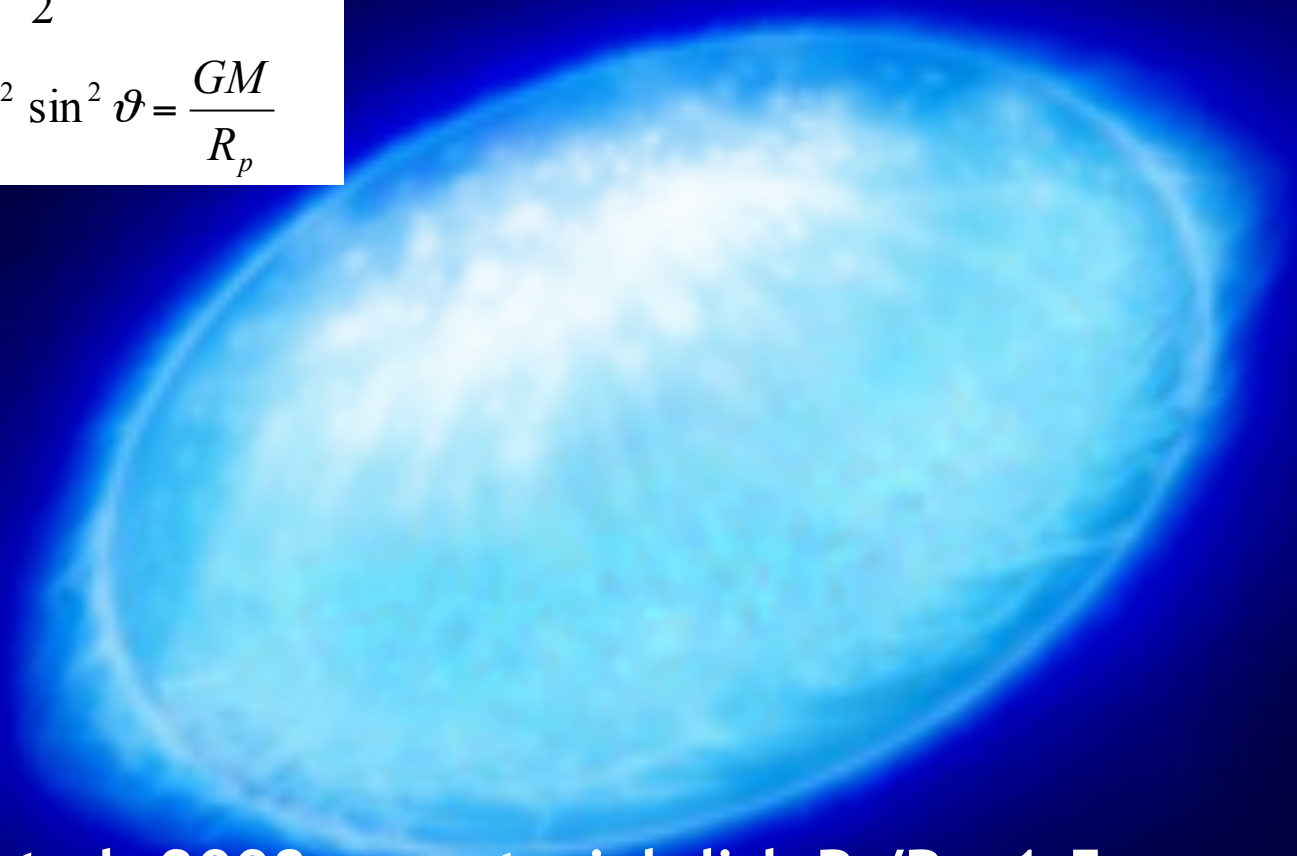
- Dynamo
- Internal coupling
- Effects on element transport

ROTATIONAL DISTORTION

$$\frac{1}{\rho}\nabla P = -\nabla\Phi + \frac{1}{2}\Omega^2\,\nabla(r\sin\vartheta)^2$$

$$\frac{GM}{R} + \frac{1}{2}\Omega^2\,R^2\sin^2\vartheta = \frac{GM}{R_p}$$

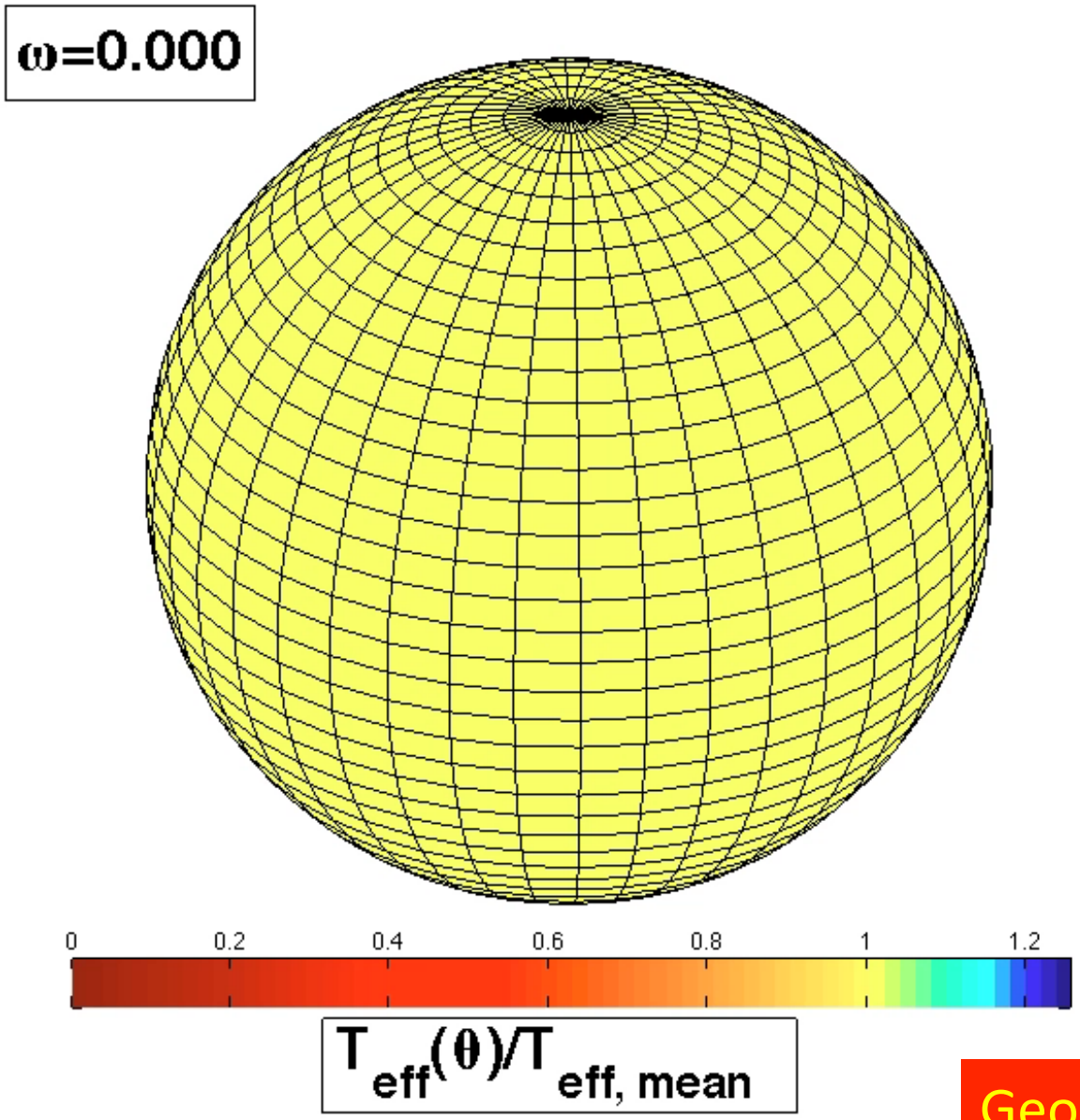
ACHERNAR ~9.6 M_{sol}



Carciofi et al. 2008: equatorial disk R_e/R_p=1.5

ROCHE MODEL OK for ω =0.992

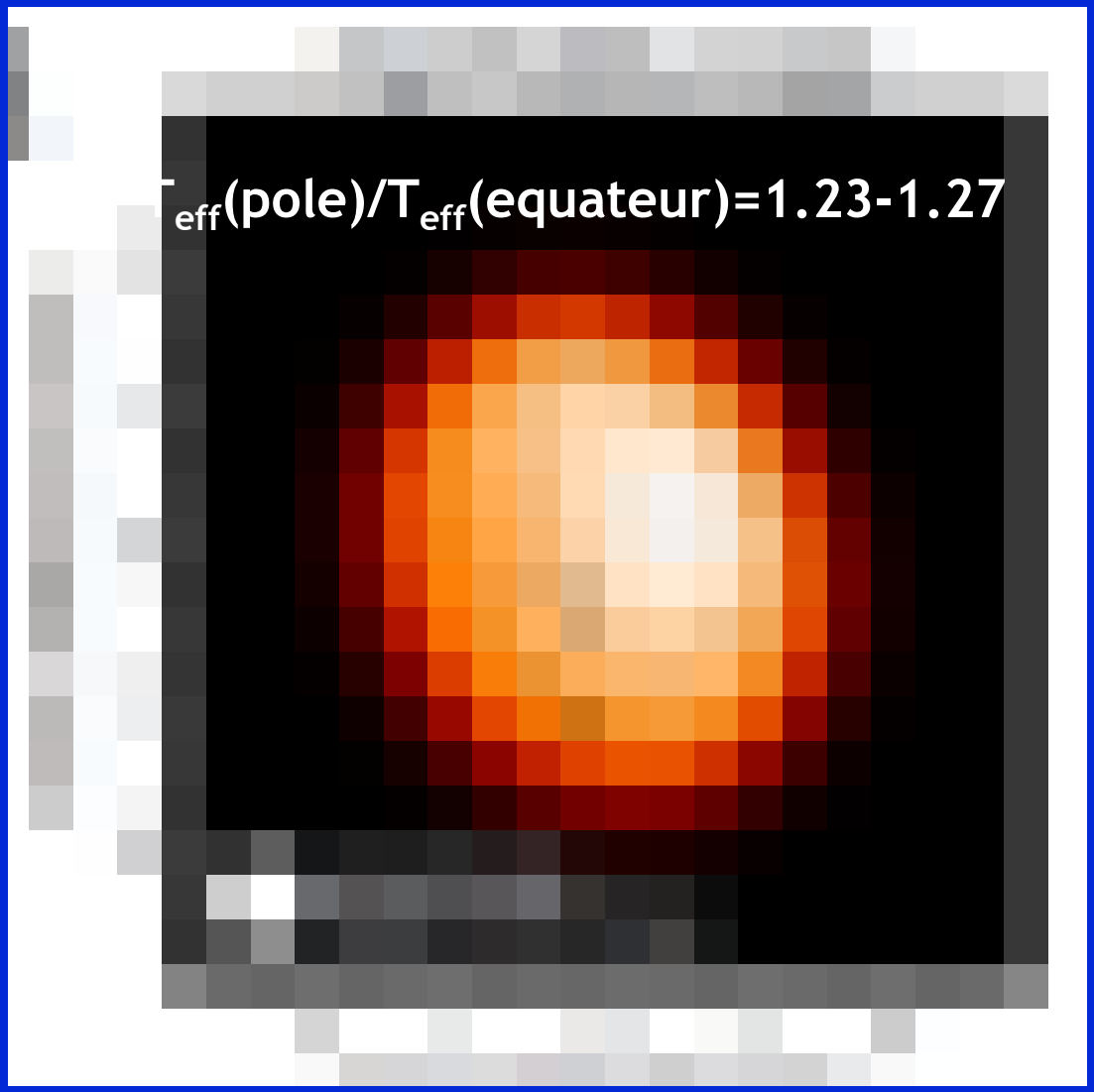
Fraction of the critical velocity



Georgy, phD 2010

GRAVITY DARKENING

Altair 1.8 M_{sol} $\omega = 0.9$



Confirmation of Von Zeipel

Peterson et al. 2006
Monnier et al. 2007

Walder, Georgy et al. in preparation

α Arae HAS POLAR WINDS

9.6 M_{sol} V_e=470 km/s
~91% V_{crit}

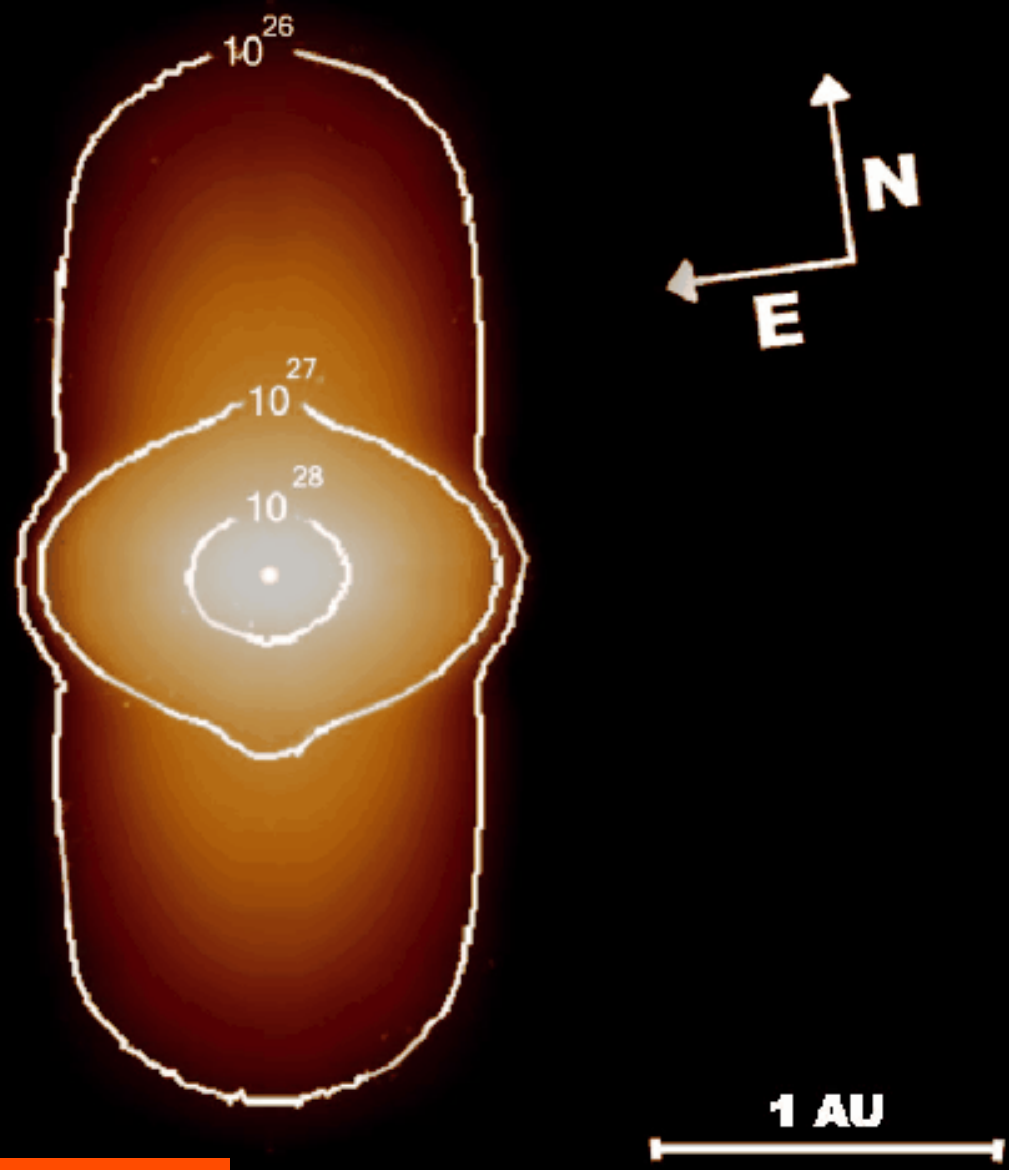
Mass of the disk
=4.1 $10^{-10} M_{sol}$

Mass loss
=1.3 10^{-8} M_{sol}/y

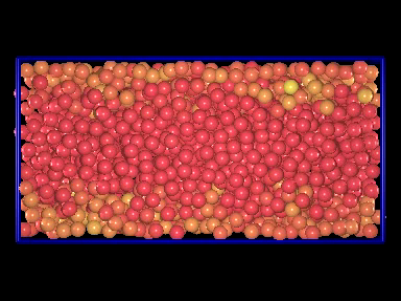
Polar mass flux
7 10^{-9} M_{sol} y^{-1} sr^{-1}

Disk in Keplerian rotation

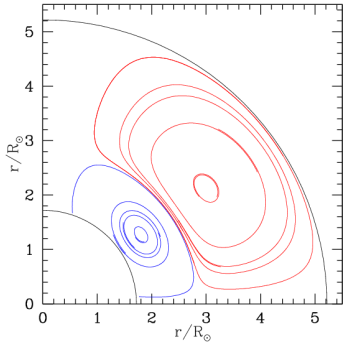
Meilland et al. 2007



Intensity map in the continuum at 2.15 micron (SIMECA code)



INTERIOR EFFECTS



Instabilities→ Transport mechanisms of

Angular momentum

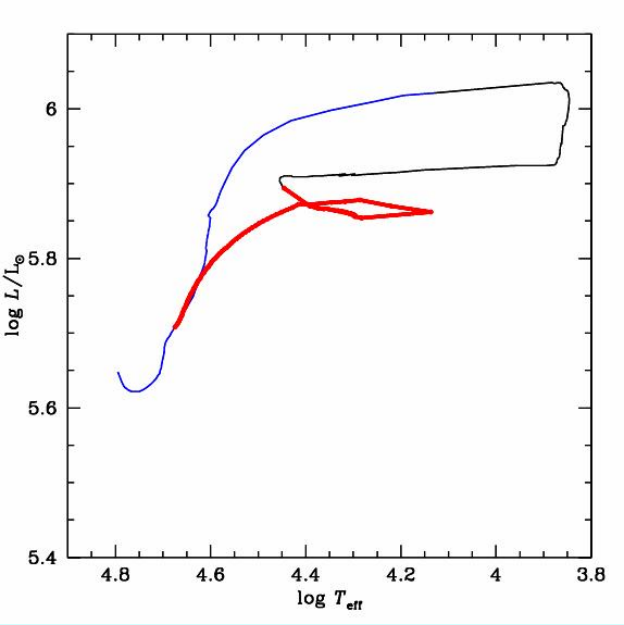
Chemical species

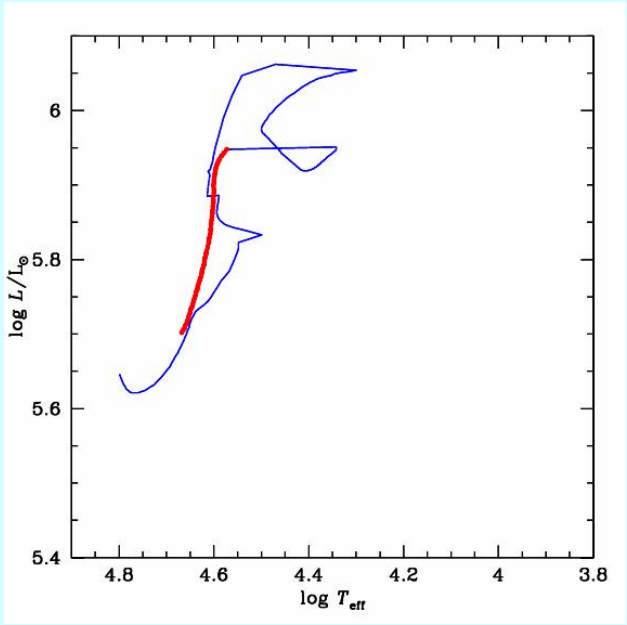
Energy
(weak effect because→ thermal timescale)

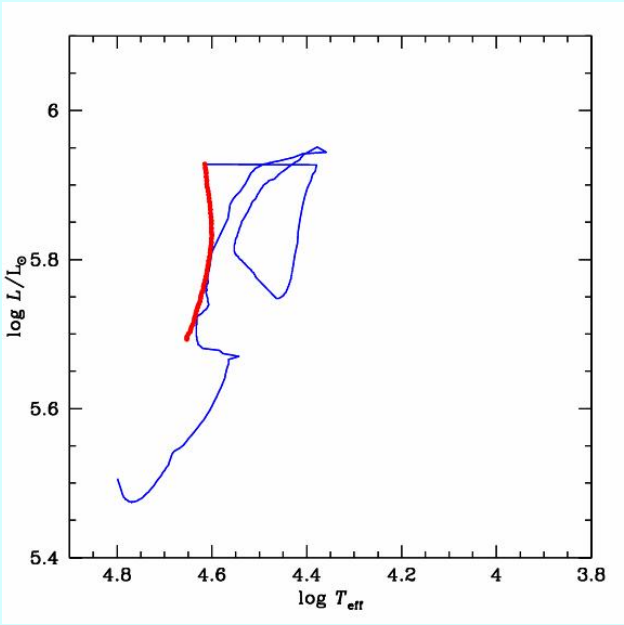
Zahn 1992 meridional circulation and shear instabilities

Meridional circulation→ thermal instability

Shear instability→ Excess of energy in differential rotation



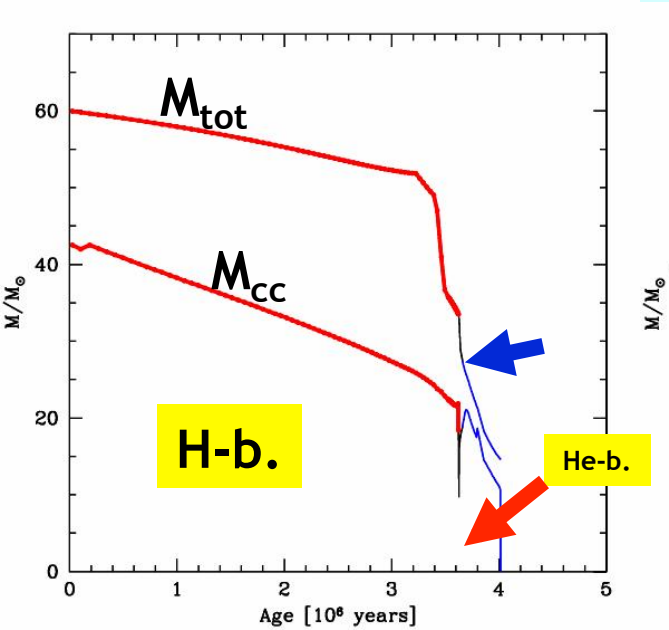


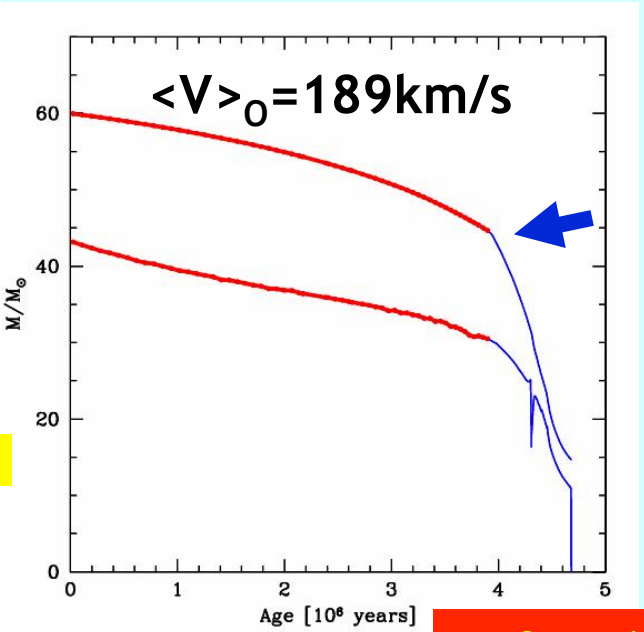


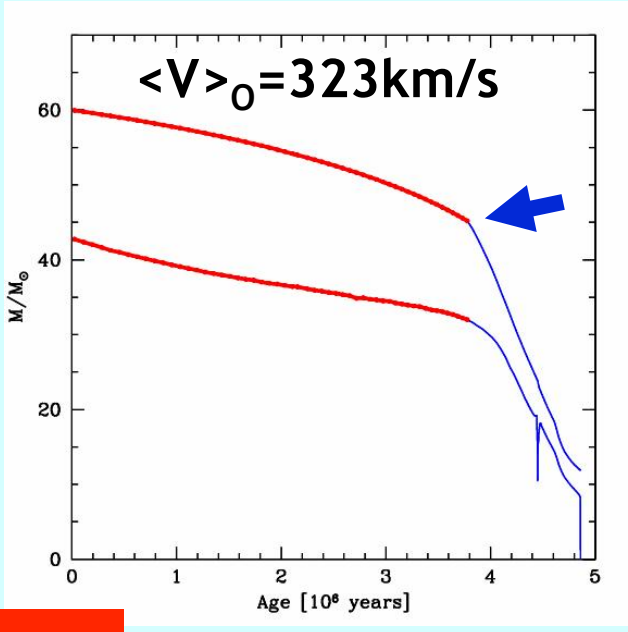
60 Msol, v_{ini}= 0 km s^{-1}

v_{ini}= 300 km s^{-1}

v_{ini}= 500 km s^{-1}

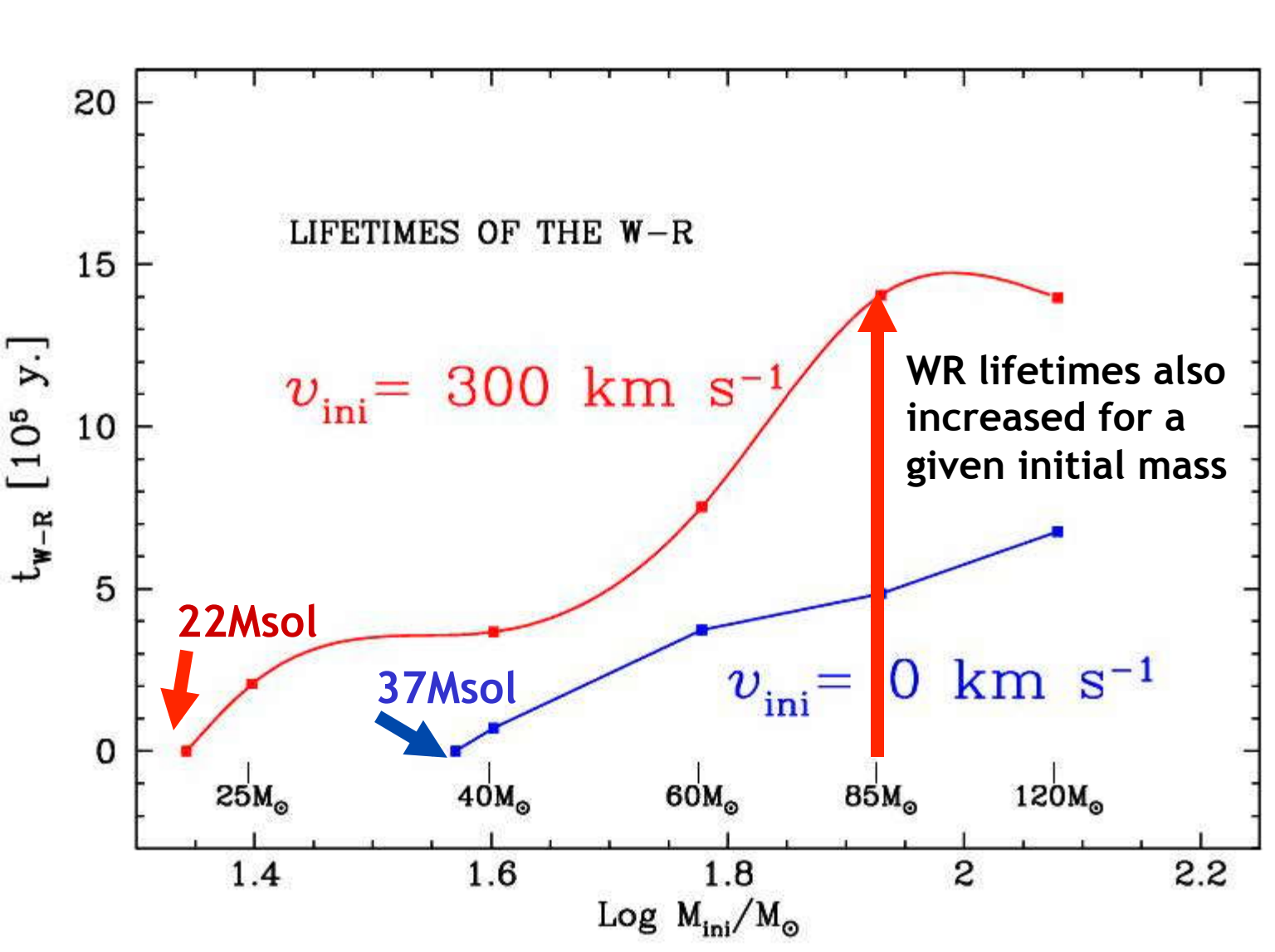


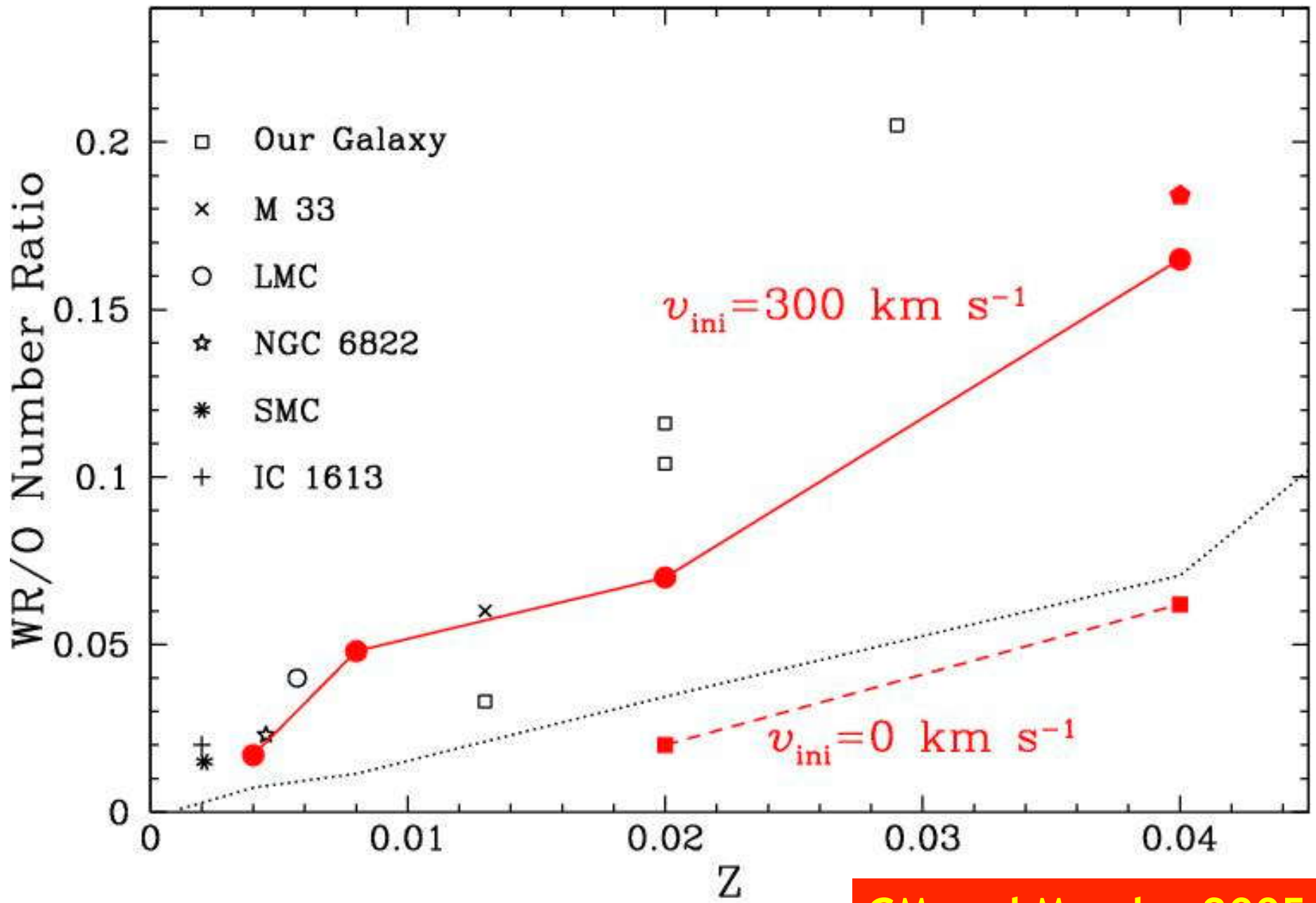




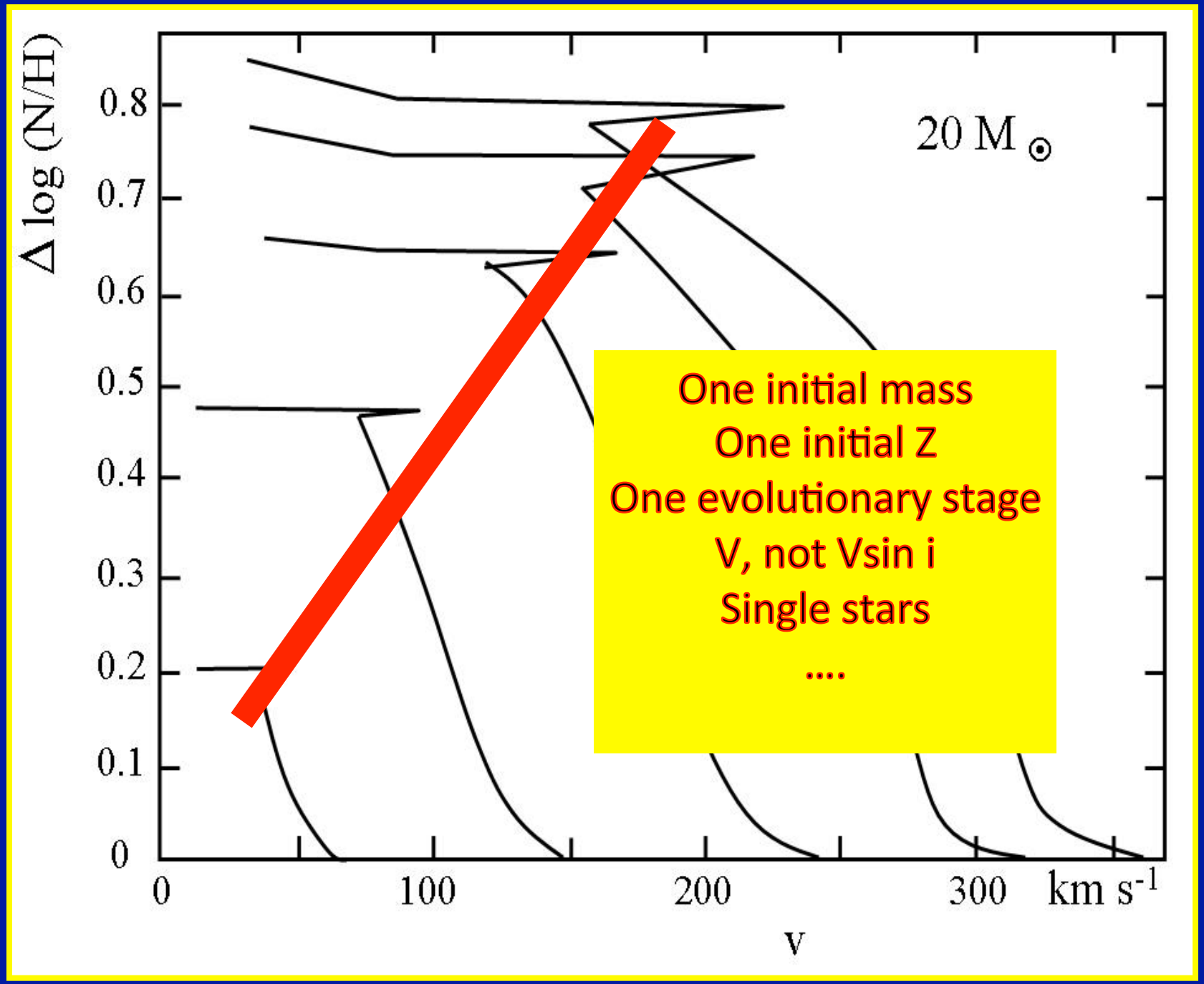
GM & Maeder 2003

For a given metallicity, the minimum initial mass of single stars which become Wolf-Rayet star is decreased for higher rotation velocities



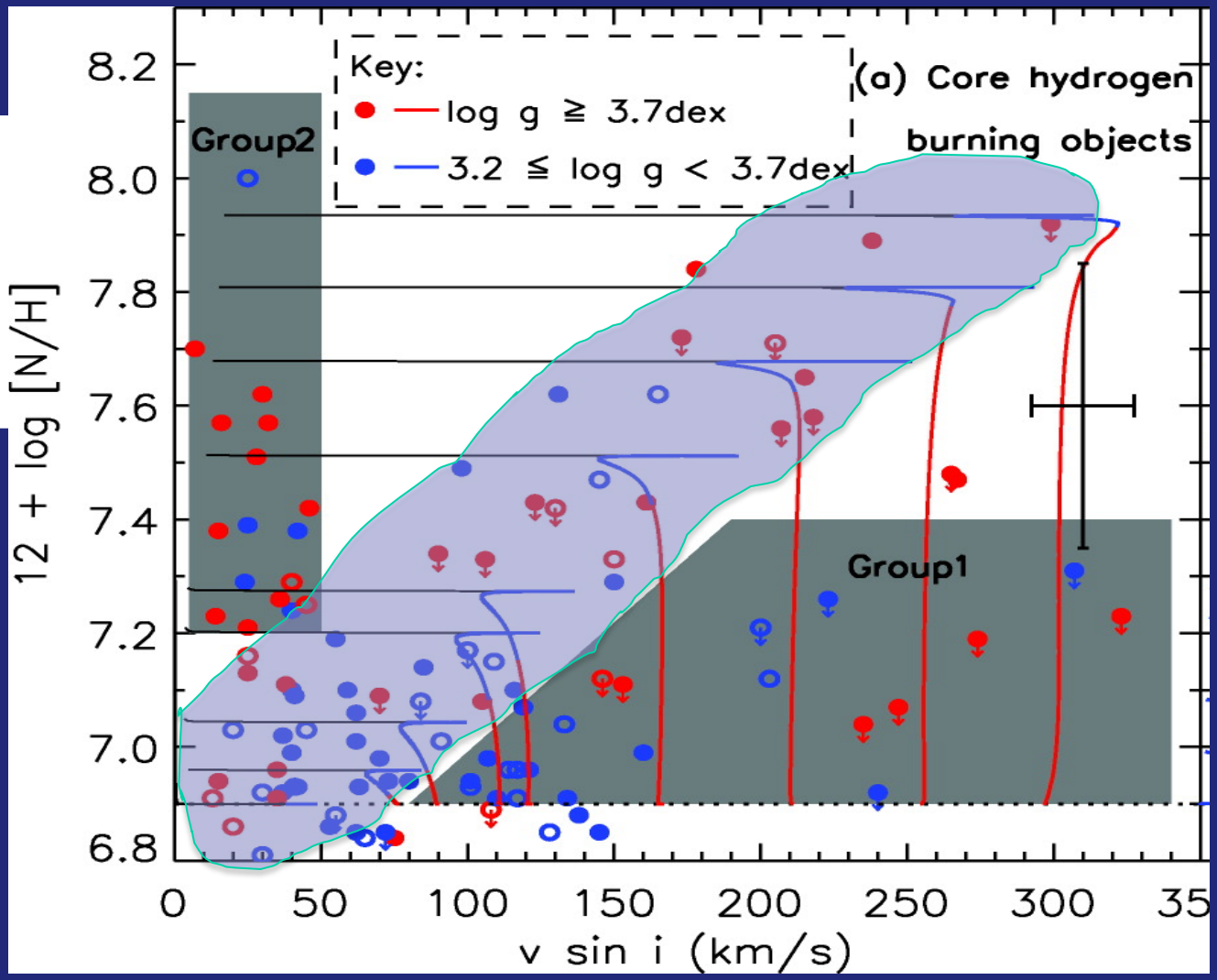


GM and Maeder 2005



One initial mass
One initial Z
One evolutionary stage
V, not Vsin i
Single stars
....

Stars in extended regions around N11 and NGC 2004 in the LMC.



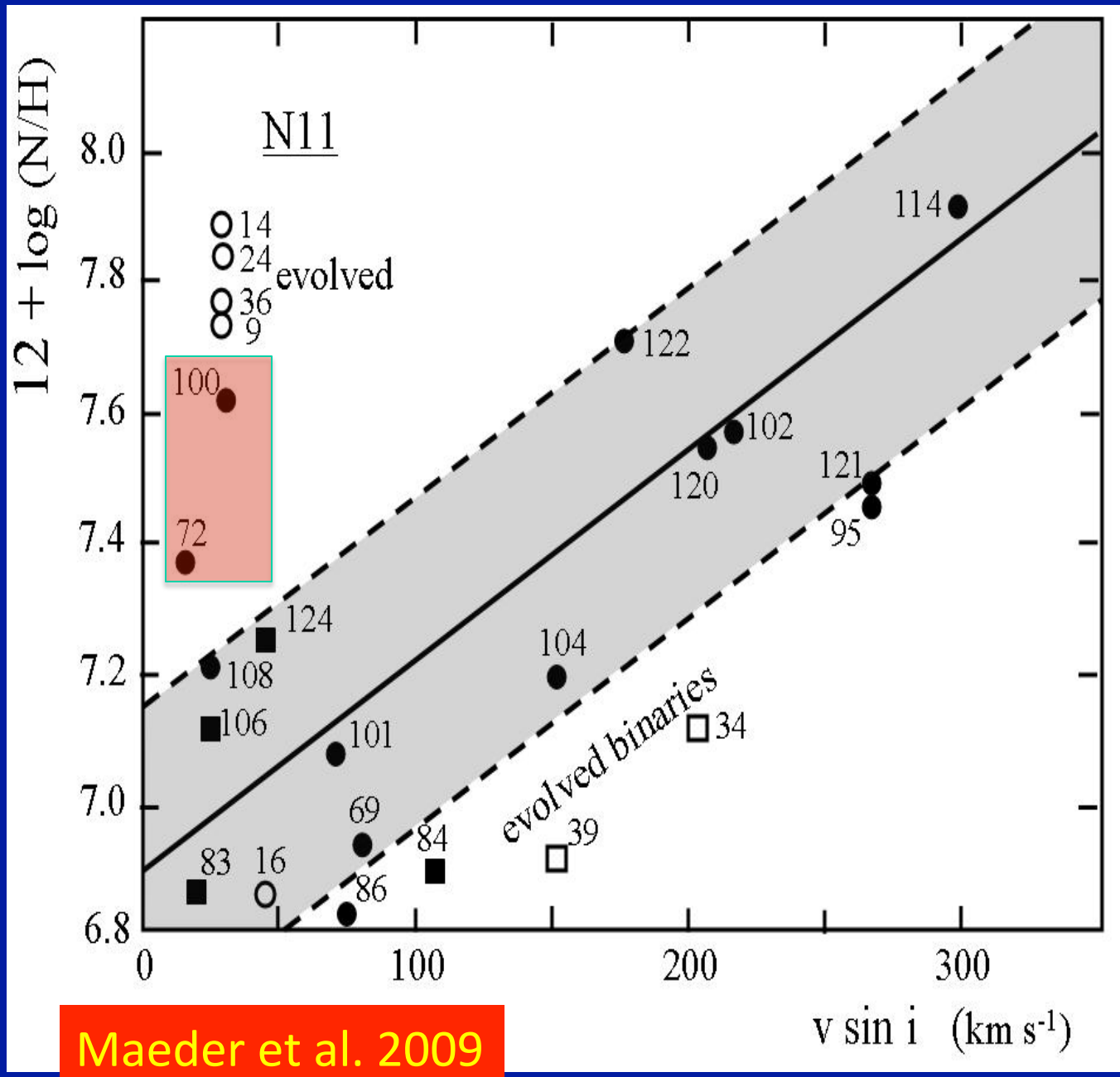
« The observation challenges the concept of rotational mixing »

Hunter et al. 2008

MS stars between 14 and 20 M_{sol} in the list by Hunter et al. 2008

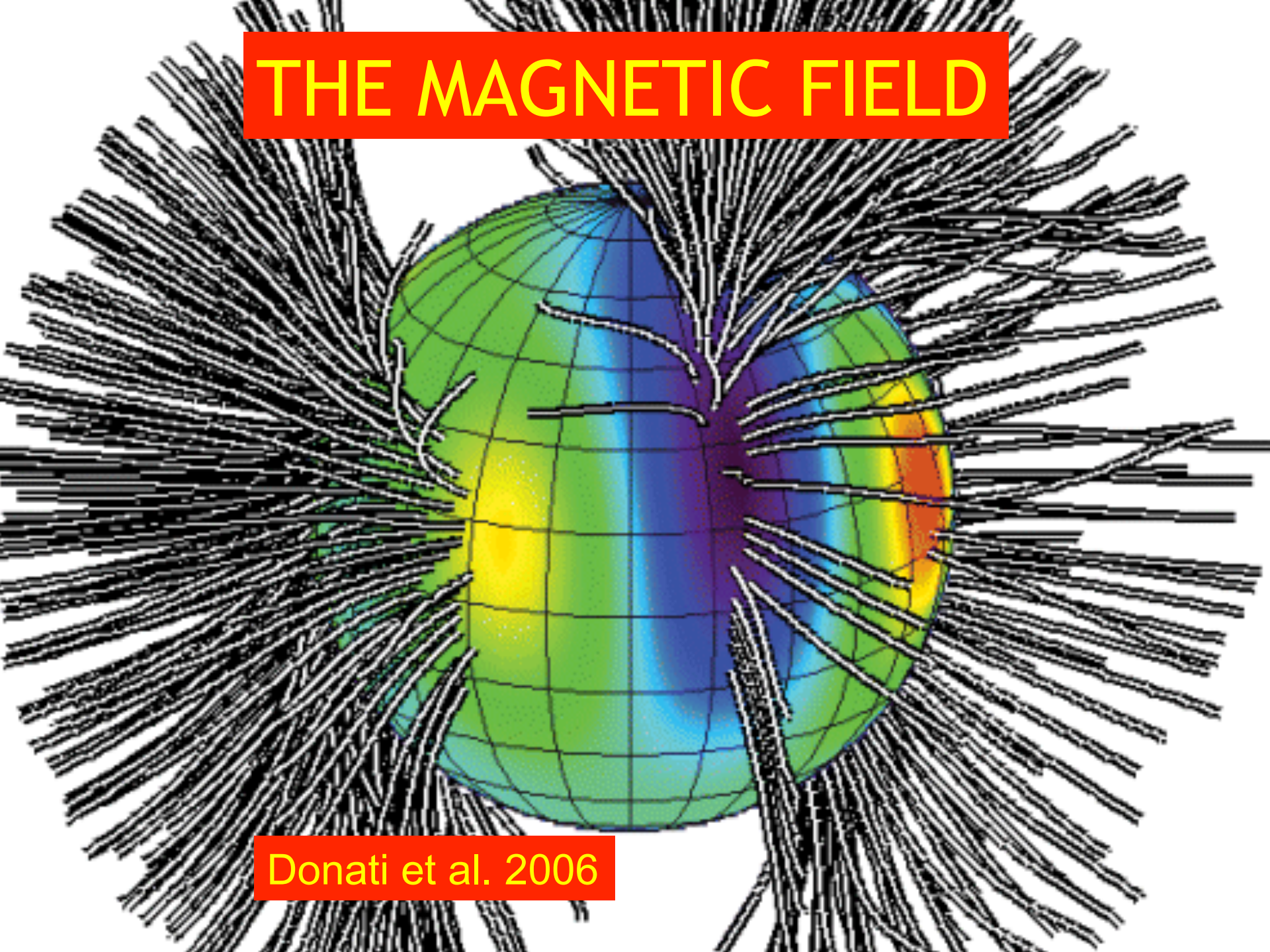
Gr 1 disappeared, except binaries

Gr 2 : mainly evolved stars



Maeder et al. 2009

THE MAGNETIC FIELD



Donati et al. 2006

P= 1.2 days, increases linearly by 77 ms per year

Townsend et al. 2010

External magnetic field

$$\eta(r) \equiv \frac{B^2/8\pi}{\rho v^2/2}$$

if $\eta > 1$ → wind channelled by magnetic lines

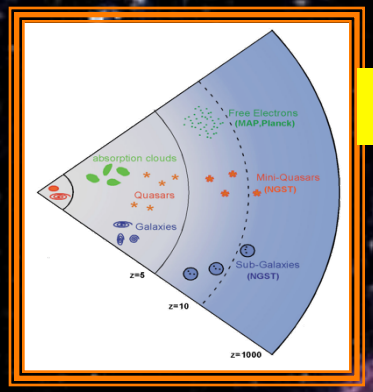
$$\frac{\mathrm{d}J}{\mathrm{d}t} = \frac{2}{3}\dot{M}\Omega R_*^2[0.29 + (\eta_* + 0.25)^{1/4}]^2$$

ud-Doula & Owocki (2002)

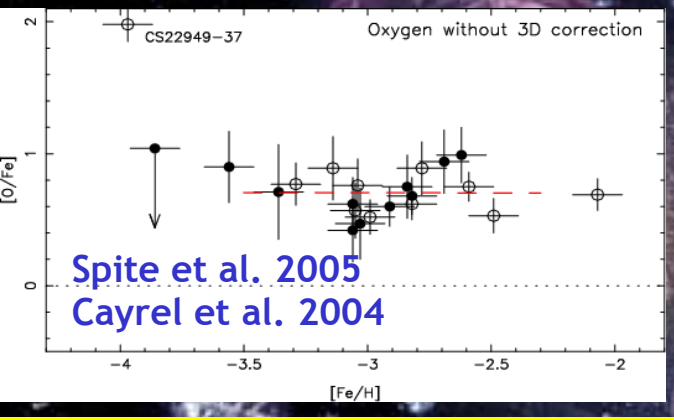
THE FIRST GENERATIONS OF STARS IN THE UNIVERSE

Painting by Adolf Schaller, STScI-PRC02-02

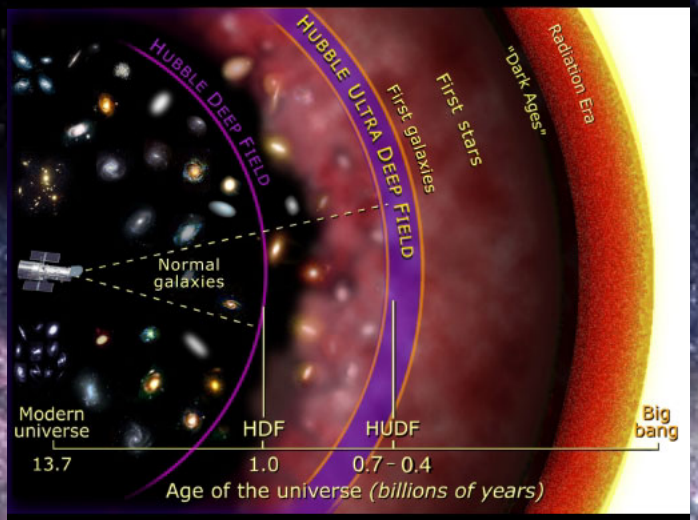
IMPACTS OF FIRST GENERATIONS ON OBSERVABLE PROPERTIES



Reionization at high redshift



Early chemical evolution of galaxies

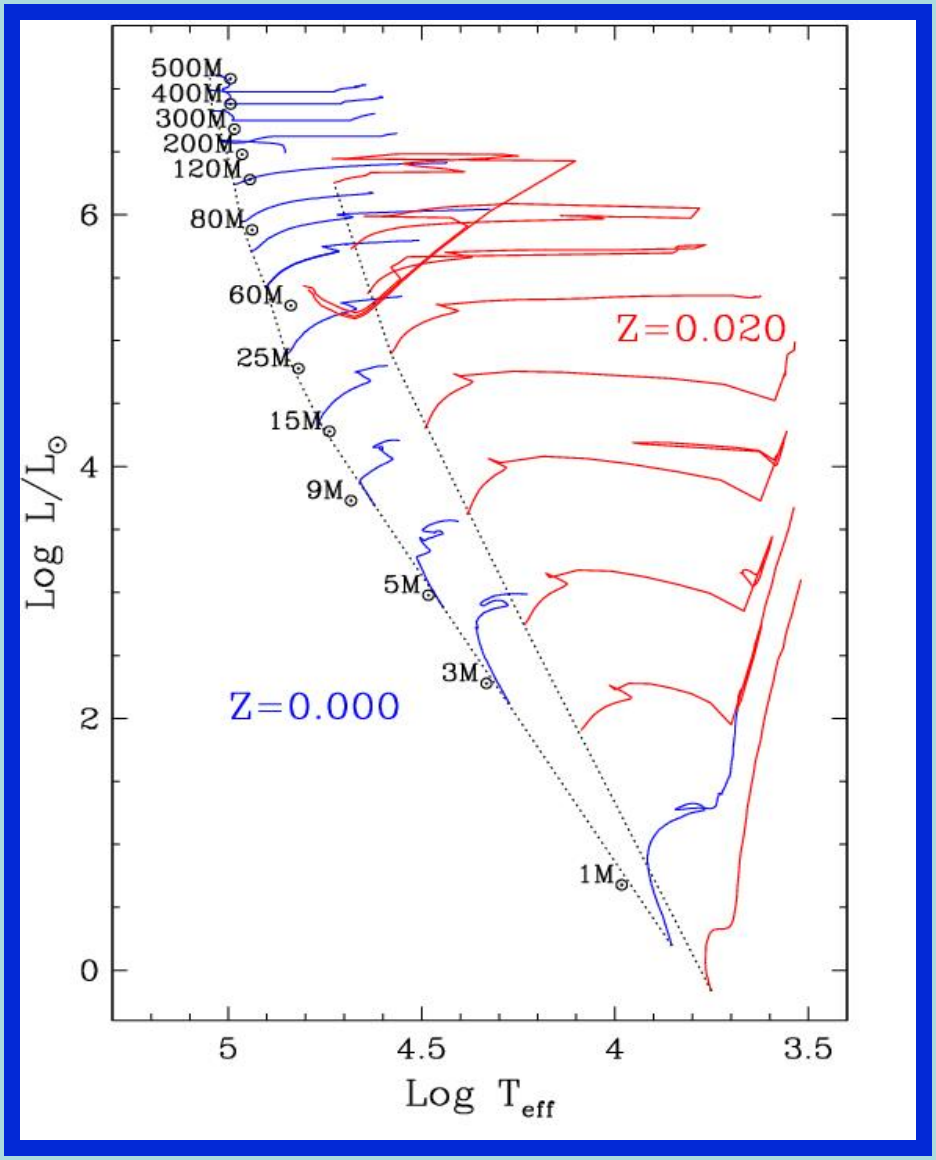


NASA

Stellar population in metal poor and/or high redshifted galaxies

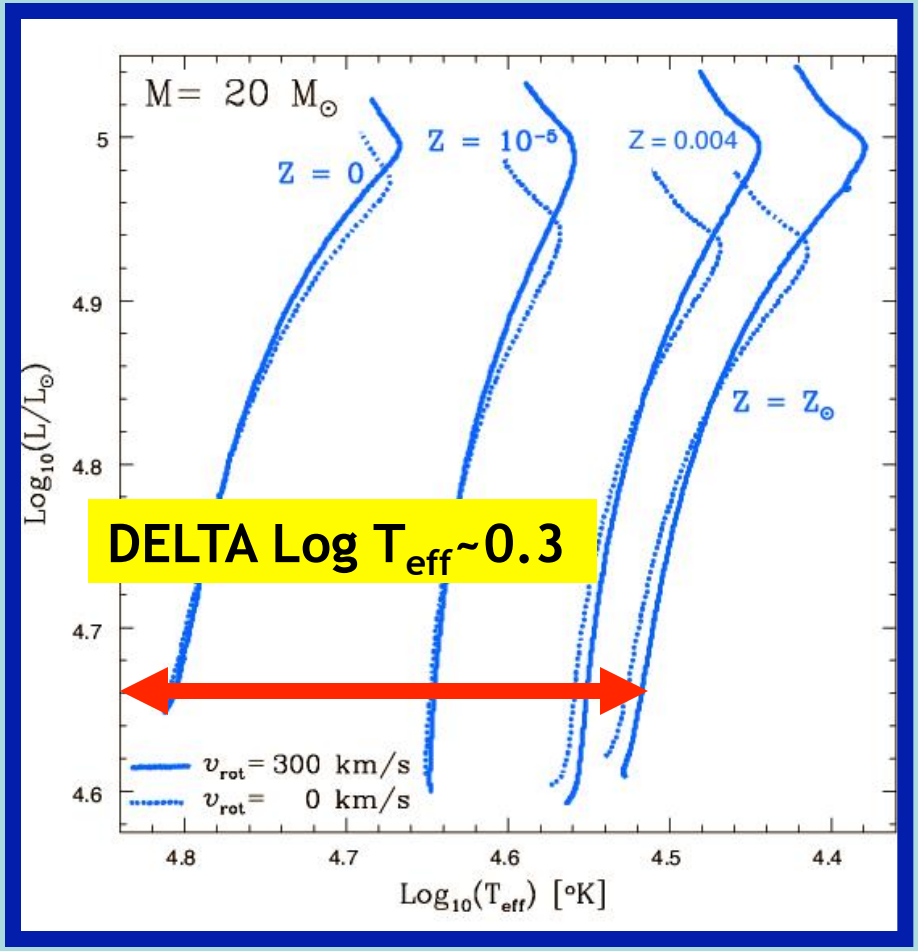
Long soft Gamma Ray Bursts have probably metal poor massive stars as progenitors

At Z= 0, stars are more compact



Feijoo 1999 diploma work

PopIII star: radii decreased by a factor 4



Ekström 2004 diploma work

WHAT CHANGES AT VERY LOW Z FOR ROTATING MODELS ?

Meridional velocities smaller

⇒ MORE ANGULAR MOMENTUM IN THE CORE

Steeper gradients of the angular velocity in the interior and smaller extent of the region to be mixed

⇒ MORE EFFICIENTMIXING+ ENHANCED MASS LOSS IN ADVANCED PHASES

Less angular momentum removed by radiative stellar winds on the Main Sequence

⇒ BREAK-UP LIMIT

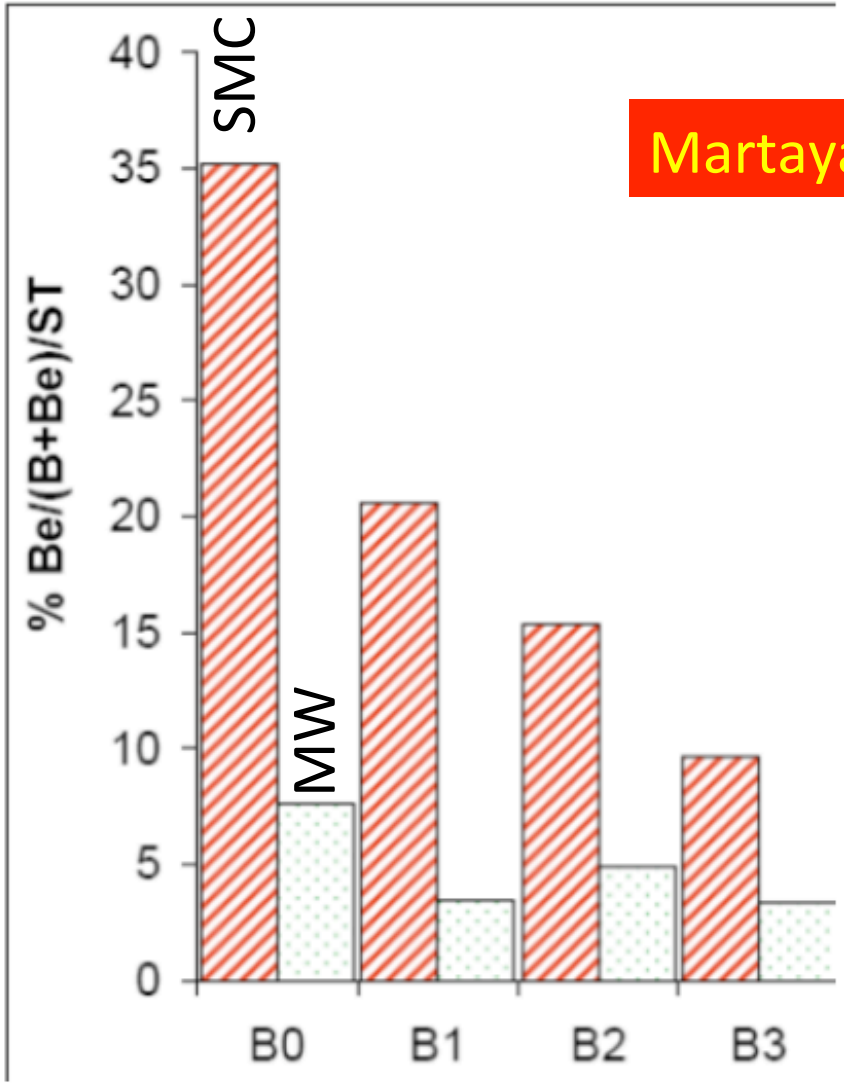
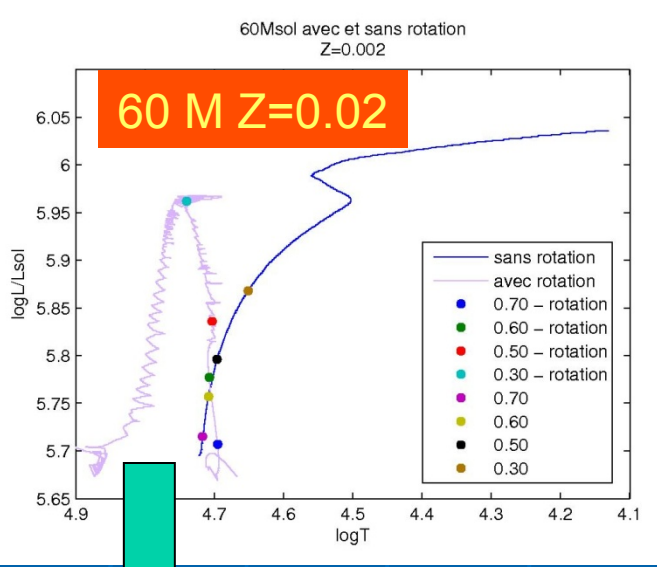
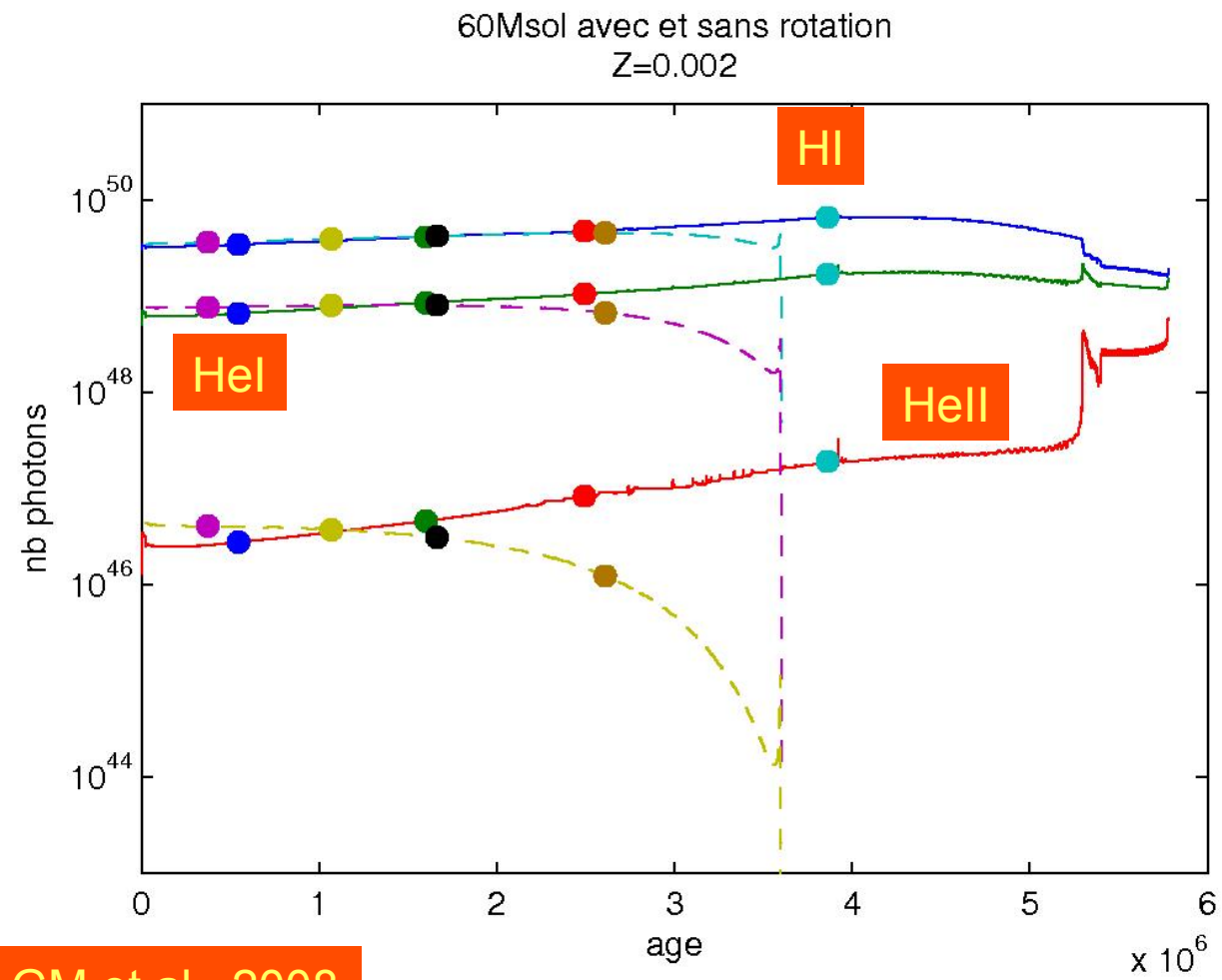


Figure 6. Ratio of Be to B stars by spectral categories in the SMC and MW. Figure adapted from Martayan et al. (2010a).Red dashed bars are for the SMC, white bars for the MW.



IONIZING PHOTONS	HI	HeI	HeII
$\Omega/\Omega_{crit}=0$	1.46E+56	2.4E+55	8.7E+52
$\Omega/\Omega_{crit}=0.75$	2.65E+56	6.7E+55	184E+52
	Hb 98%	Hb 92%	Heb 67%
	X 1.8	X 2.8	X 21

HOMEGENEOUS EVOLUTION
Maeder (1987)



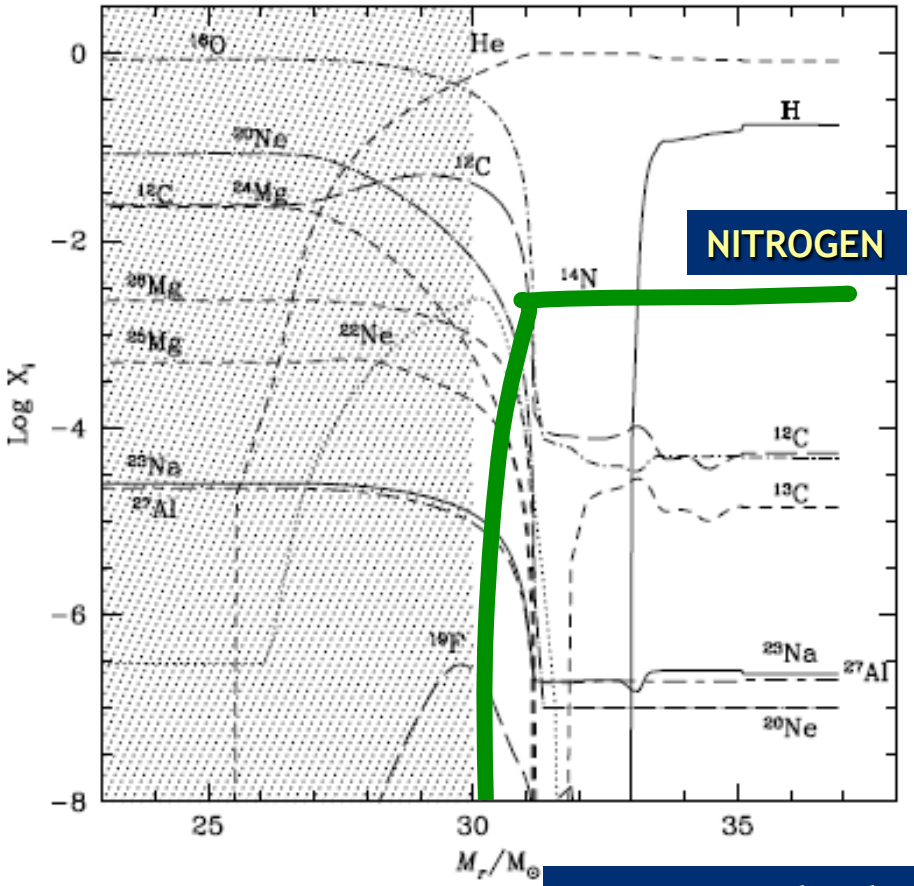
GM et al. 2008

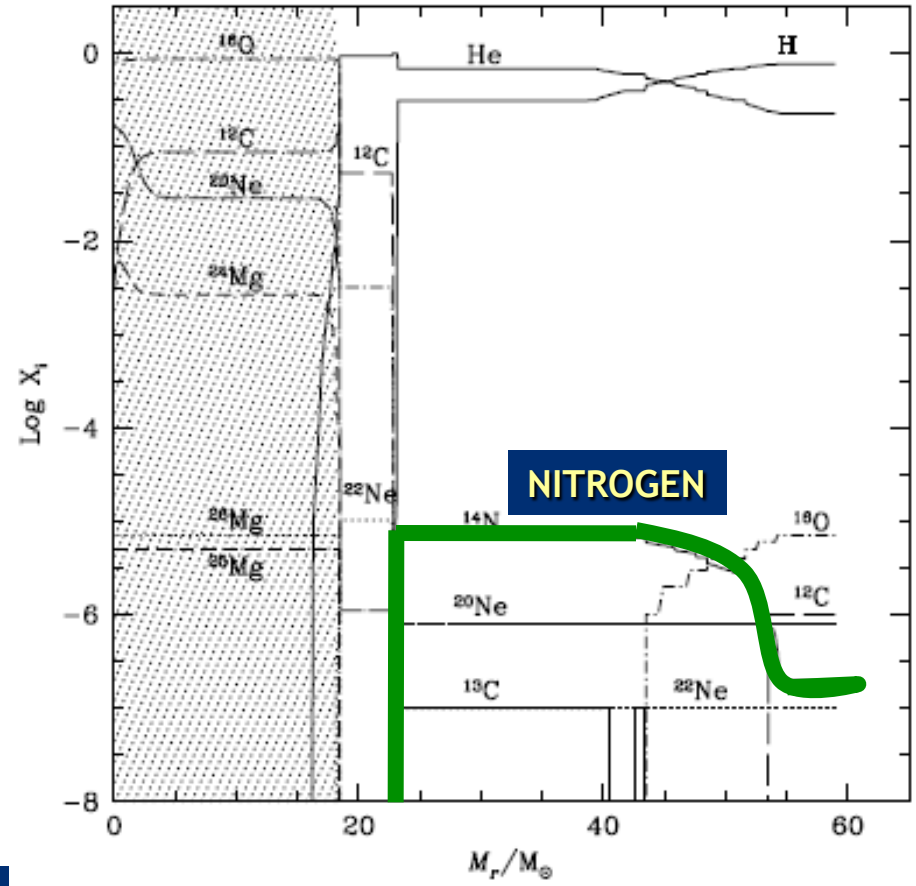
$V/V_{crit}=0.70$

$60\ M_{sun},\ Z=10^{-5}$

$V/V_{crit}=0$

→SIMILAR MIXING IN INTERMEDIATE MASS STARS
→LOW METALLICITY REQUIRED

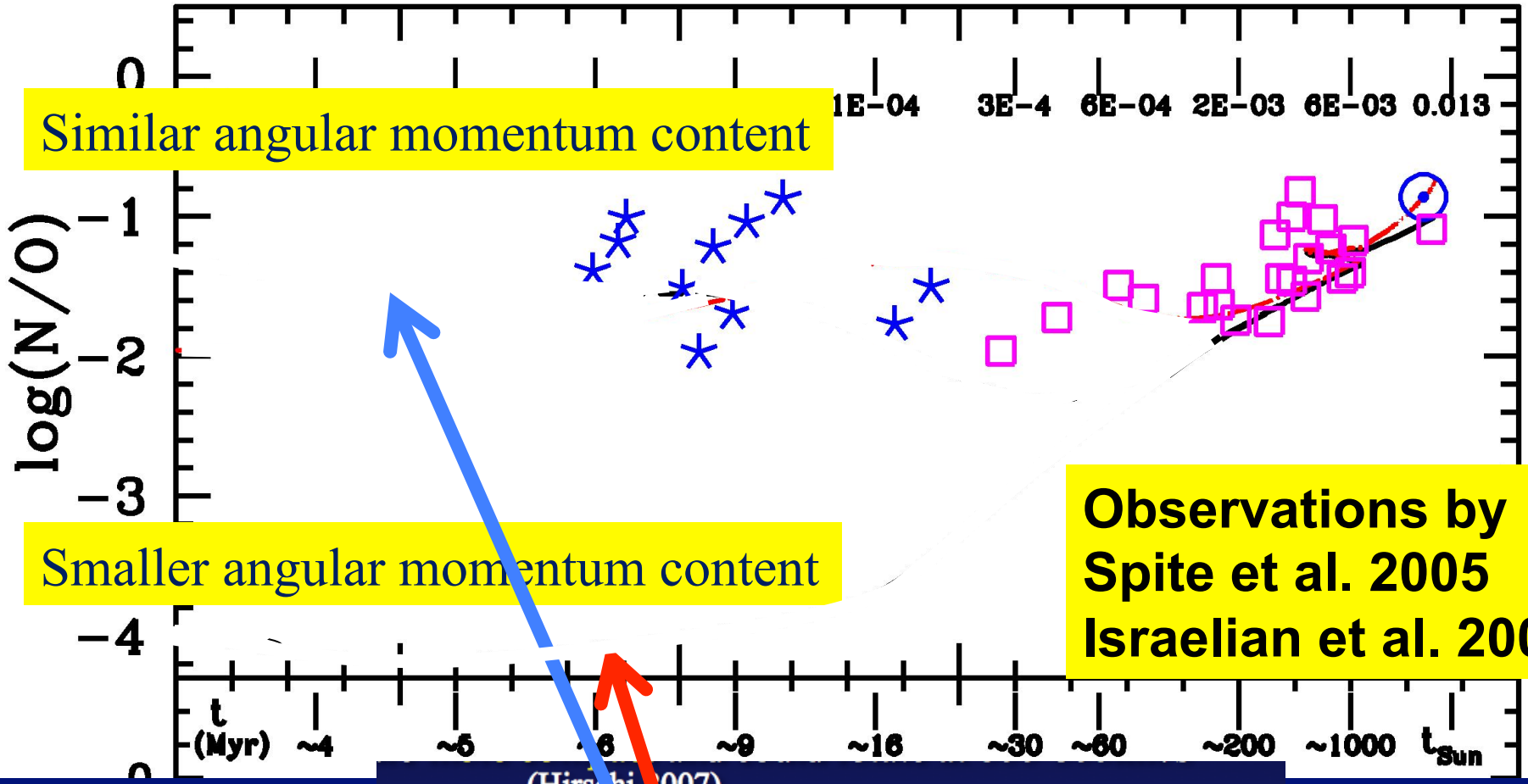




Rotating star has lost
Material through winds

GM et al. 2010

Chiappini, Hirschi, GM, Ekström, Maeder, Matteucci, (2006)



Observations by Spite et al. 2005 Israelian et al. 2004

(Hirschi 2007)

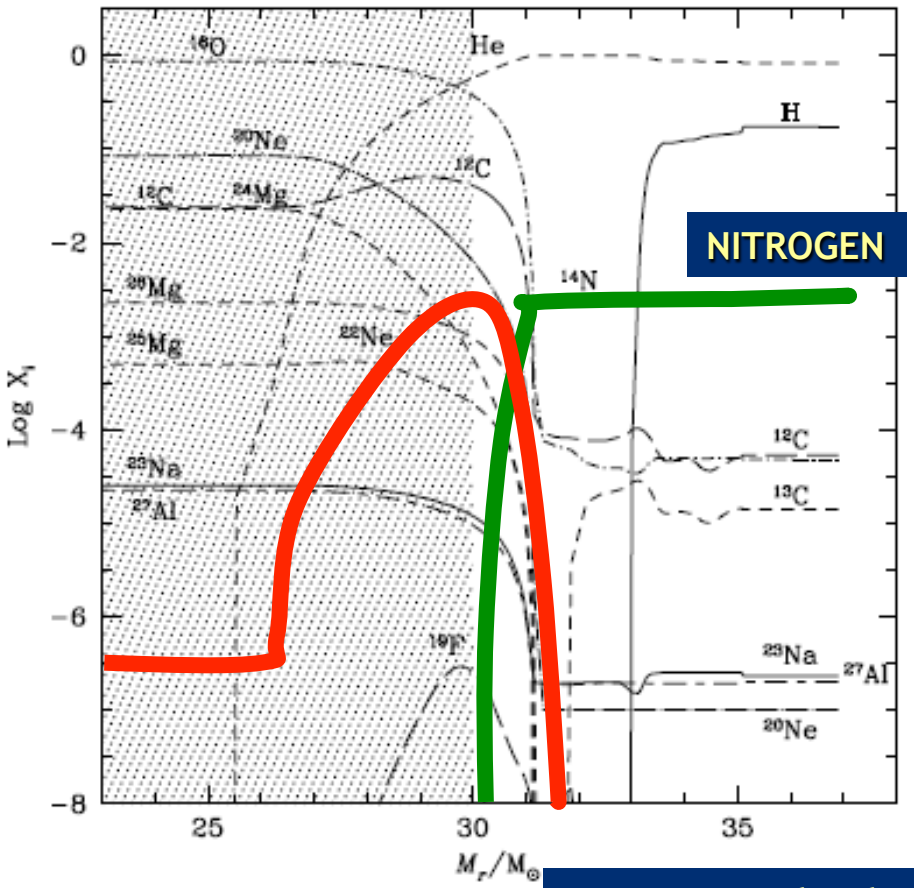
- M_{ini}= 20 M_{sun}:

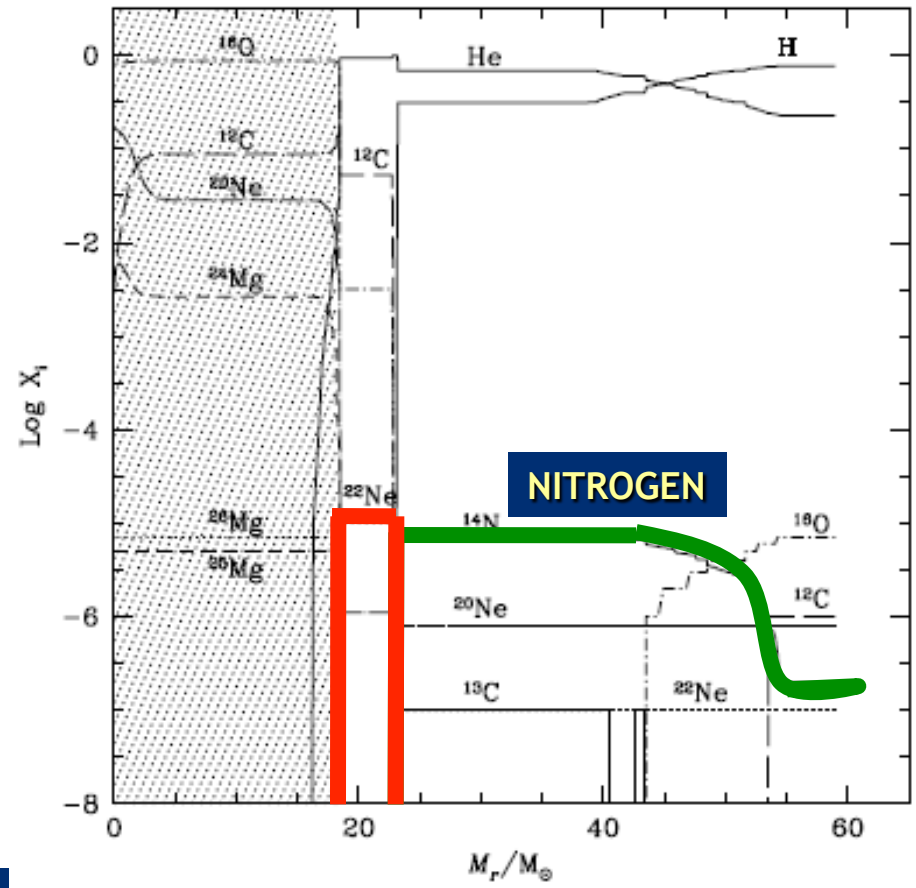
V_{ini}	Z_{ini}	J_{ini} [10^{53} erg s]
300	solar	0.36
300	10^{-8}	0.18
600	10^{-8}	0.33

$V/V_{crit}=0.70$

$60\ M_{sun},\ Z=10^{-5}$

$V/V_{crit}=0$





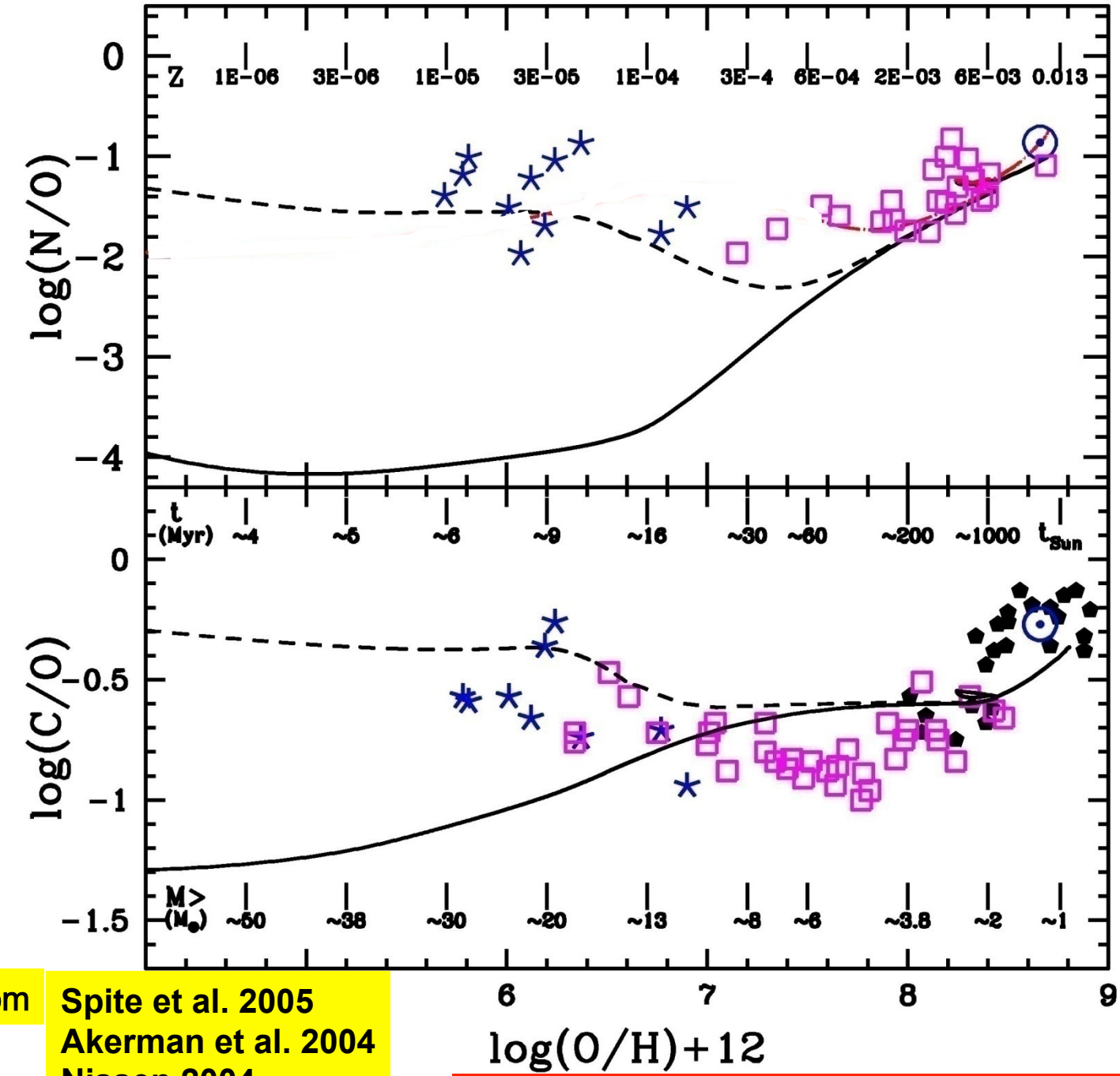
Rotating star has lost
Material through winds

The details are making the perfection and the perfection is not a detail.

Léonard de Vinci

Extrait des carnets

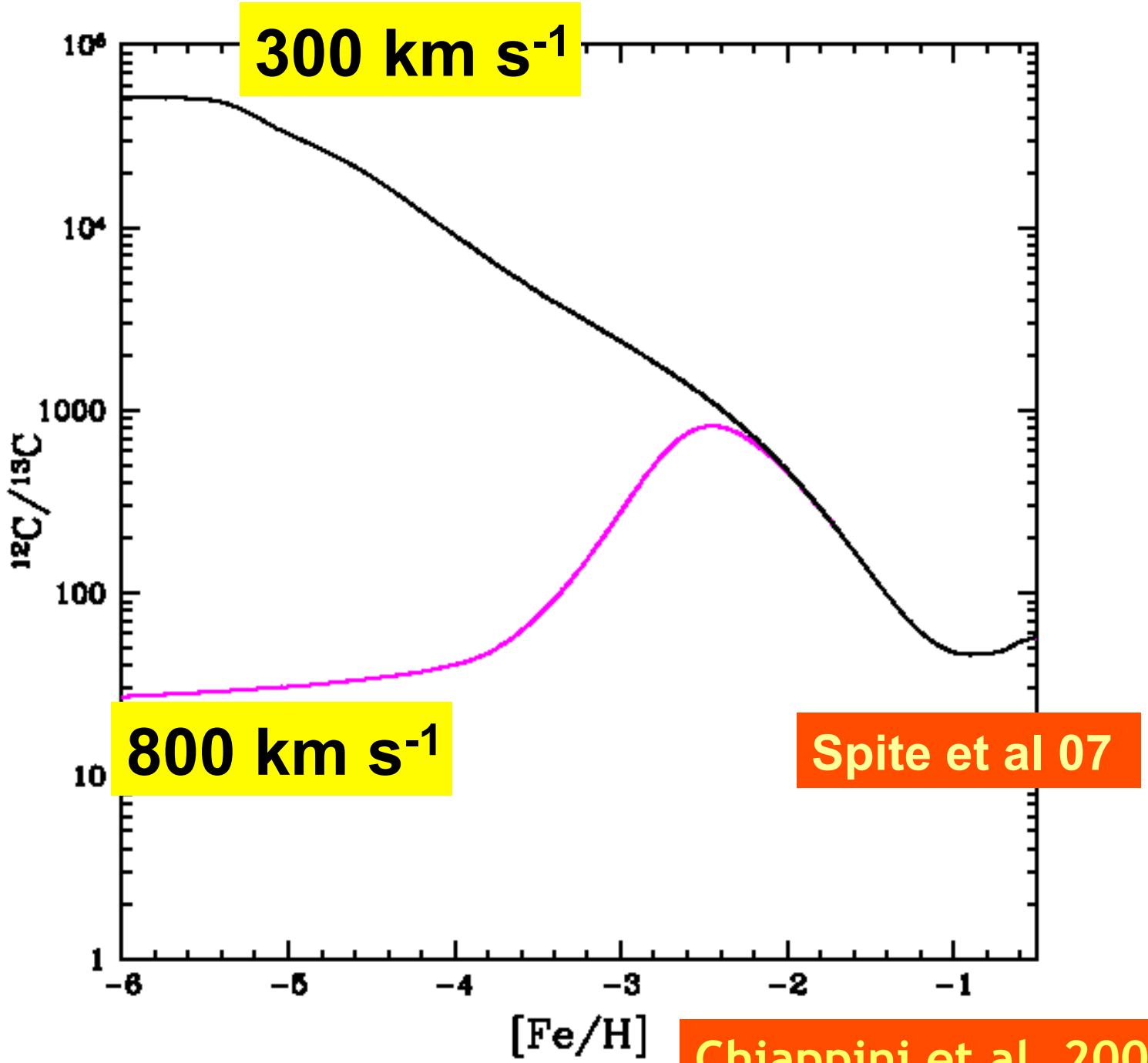
C/O



Observations from

Spite et al. 2005
Akerman et al. 2004
Nissen 2004

Chiappini, Hirschi, Meynet, Ekström, Maeder, Matteucci, 2006


300 km s-1
800 km s-1
Spite et al 07
Chiappini et al. 2008
12C/13C
[Fe/H]
10⁶
10⁴
1000
100
10
1
−6
−5
−4
−3
−2
−1

A few challenging stars

→Low v sin i
→Signs of strong mixing, strong N/H or strong B depletion
→Non evolved stars (high log g)

Could effects of magnetic fields explain these features?

A few challenging stars

→Low v
→Signs of strong mixing, strong N/H or strong B depletion
→Non evolved stars (high log g)

Internal magnetic field only

→Low v sini NO (except inclination effect)
→Fast and strong mixing OK
→ Non evolved stars OK

A few challenging stars

→Low v
→Signs of strong mixing, strong N/H or strong B depletion
→Non evolved stars (high log g)

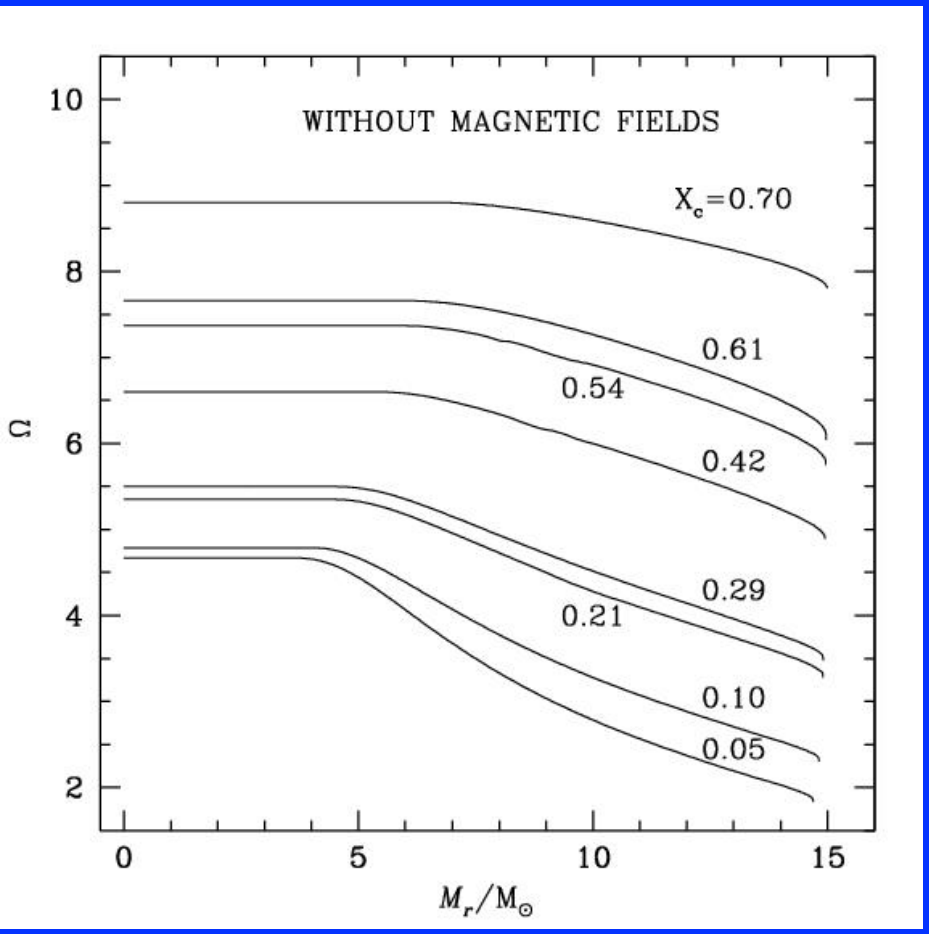
<u>interior magnetic fields</u>
<u>+ magnetic braking</u>
→Low v sini YES
→Fast and strong mixing NO
→ Non evolved stars YES

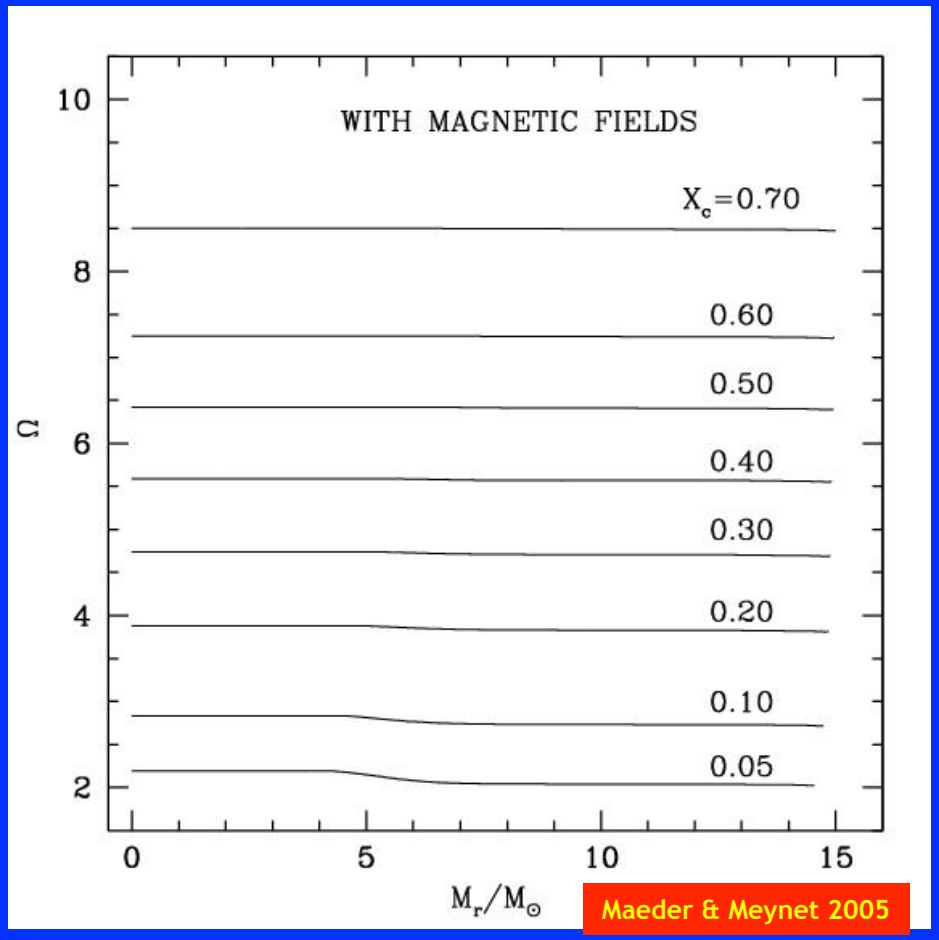
A few challenging stars

→Low v
→Signs of strong mixing, strong N/H or strong B depletion
→Non evolved stars (high log g)

<u>magnetic braking only</u>
(No internal coupling)
→Low v sini YES
→Fast and strong mixing YES
→ Non evolved stars YES

15 M_{sol}, Z=0.020, V_{ini}=300 km s^{-1}





Maeder & Meynet 2005

MAGNETIC FIELDS → SOLID BODY ROTATION

Zahn 1992

Transport of the chemical species

$$\rho \frac{\partial X_i}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[\rho r^2 (D_{eff} + D_{schear})\frac{\partial X_i}{\partial r}\right]$$

Transport of the angular momentum

$$\rho \frac{\partial (r^2 \Omega)}{\partial t} = \frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 U \Omega\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho r^4 D_{schear}\frac{\partial \Omega}{\partial r}\right)$$

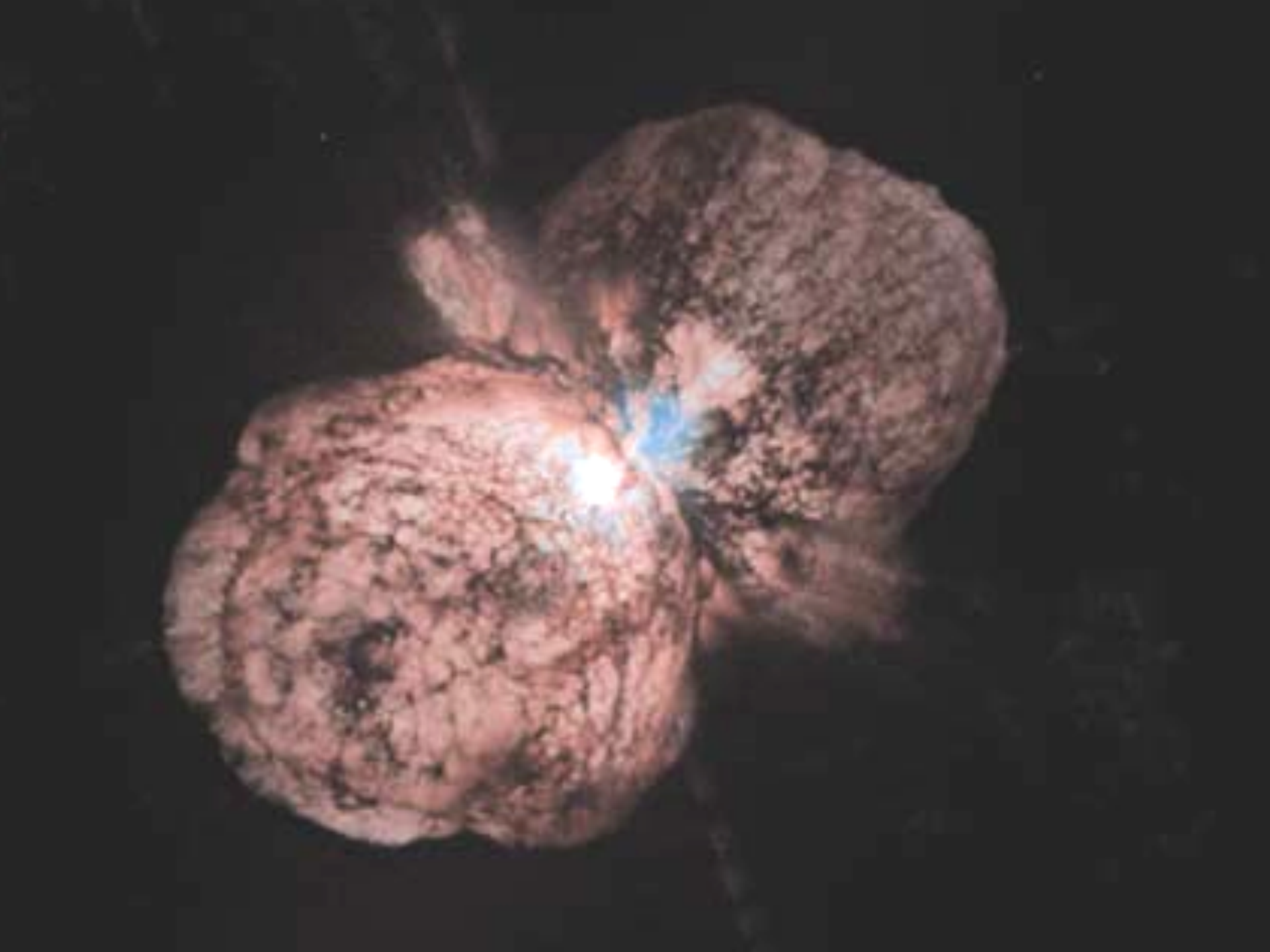
$$D_h \approx |rU(r)| \qquad D_{eff} = \frac{r^2 U^2}{30 D_h}$$

$$D_{shear} = \frac{(K + D_h)}{\left[\frac{\varphi}{\rho}\nabla_\mu (1 + \frac{K}{D_h}) + (\nabla_{ad} - \nabla_{rad})\right]} \times \frac{H_p}{g\delta}\left[\alpha\left(0.8836\Omega \frac{d\ln\Omega}{d\ln r}\right)^2 - 4(\nabla' - \nabla)\right]$$

Maeder 1997,
Talon and Zahn 1997

$$U(r) = \frac{P}{\overline{\rho g} C_p \overline{T}\left[\nabla_{ad} - \nabla + \frac{\varphi}{\delta}\nabla_\mu\right]} \times \left\{\frac{L}{M_*}(E_\Omega + E_\mu) + \frac{C_p}{\delta}\frac{\partial \Theta}{\partial t}\right\}$$

Maeder and Zahn 1998



TENTATIVE FILIATIONS:

mass limits function of Z

M > 60 M_O: O- Of/WNL ←→ LBV - WNL(H poor)- WCL-E- SN (SNIbc?))
(slash star SNIIn??)

M: 40-60 M_O: O - BSG - LBV ←→ WNL -(WNE) - WCL-E - SN (SNIb)
- WCL-E - WO - SN (SNIc)

LBV WR

M: 30-40 M_O: O - BSG - RSG -- WNE - WCE - SN (SNIb)
OH/IR ←→ LBV ? (see Humphreys, 2003)

M: 25-30 M_O: O - (BSG) - RSG -- BSG ←→ RSG SNIIL
BLUE LOOP

M: 10-25 M_O: O - RSG - (Cepheid loop for M<15 M_O) - RSG -- SN SNII-P

RSG

Mass loss
Overshooting
Rotation
Magnetic fields
Interactions in close binaries

$$\dot{M} = 4\pi r^2 \rho v \Rightarrow \dot{M} = \frac{L}{c^2} N_{eff} (1 - \varepsilon)$$

Mass loss rates proportional to the number of strong lines

Number of strong lines proportional to Z

Wind models for hot stars show this effect

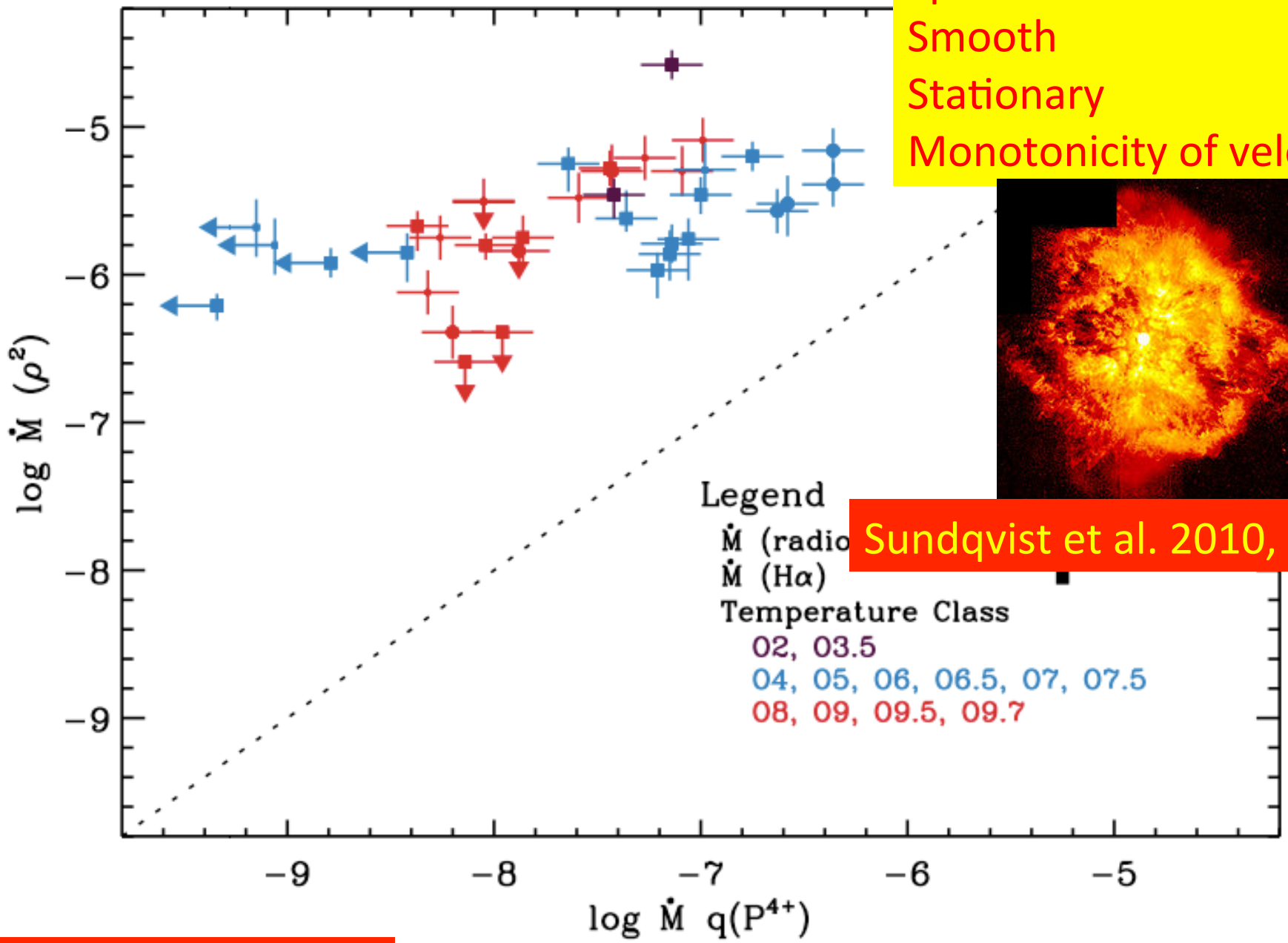
O5V
Kudritzki et al 86

Z	Mass loss [10^{-6} M_{sol}/y.]
0.020	2.12
0.006	1.35
0.002	0.72

$$\dot{M}_Z = \left(\frac{Z}{Z_{sol}}\right)^{\alpha} \dot{M}_{Z_{sol}}$$

VERY IMPORTANT CONSEQUENCES

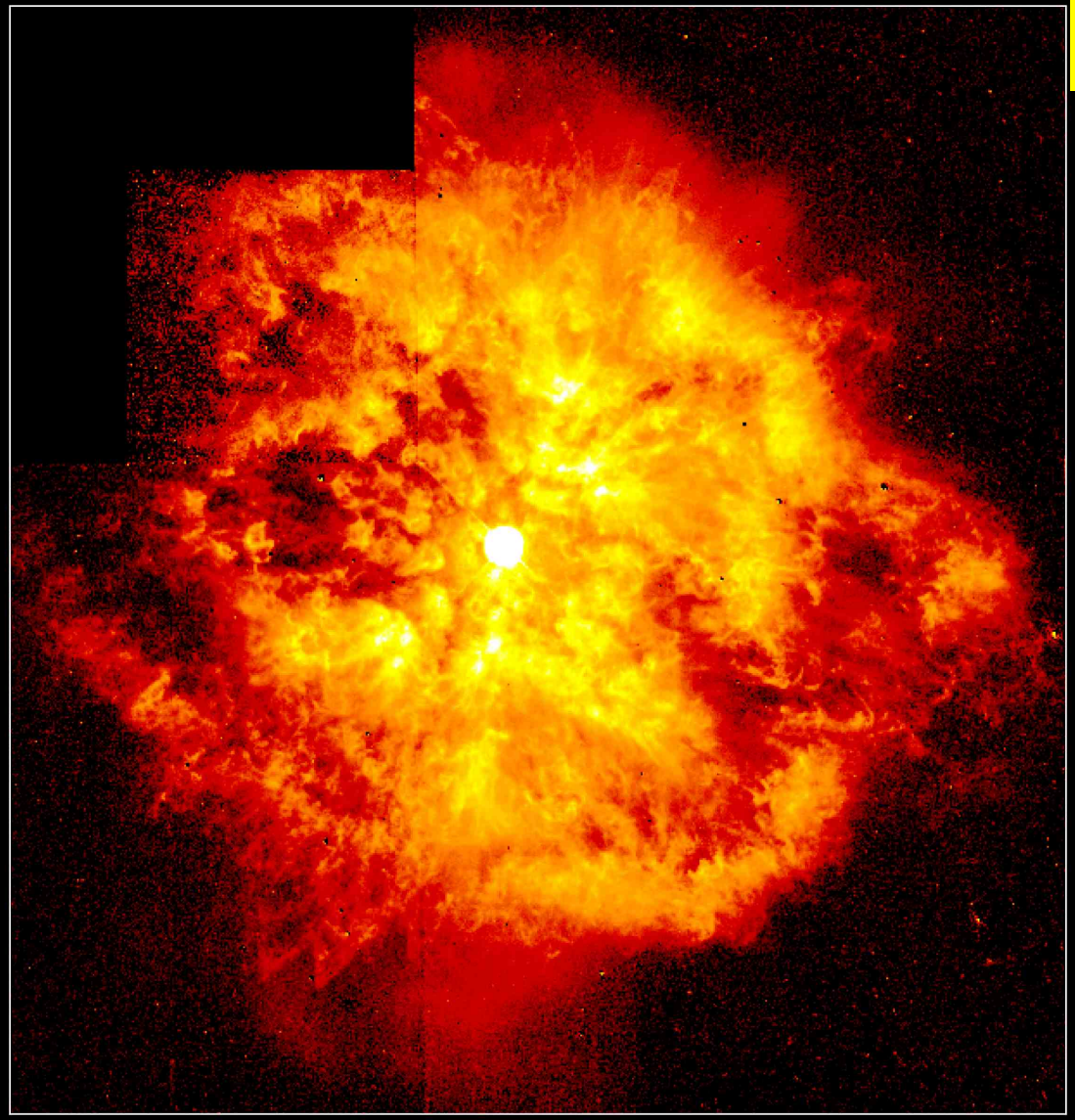
Spherical
Smooth
Stationary
Monotonicity of velocity



Sundqvist et al. 2010, 2011

Fullerton et al. 2006

A 60 Msol



Nebula M1-67 around Star WR224
Hubble Space Telescope • WFPC2

PRC98-38 • STScI OPO • Y. Grosdidier and A. Moffat (University of Montreal) • NASA

Evaporating stars

$60\ M_{sol} \rightarrow 14\ M_{sol}$

The Wolf-Rayet star WR224 is found in the nebula M1-67 which has a diameter of about 1000 AU

The wind is clearly very clumpy and filamentary.

MASSIVE STARS ARE MECHANICAL STARS ($M > 40M_{sol}$ at solar metallicity)

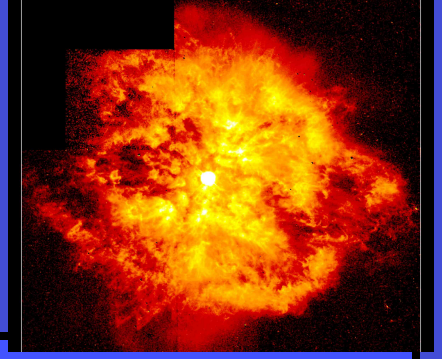
$$L_{mechanic} = \frac{1}{2}\dot{M}\, v_{\infty}^{\ 2}, \qquad v_{\infty} = 3000 \ \text{km/s}$$

$$L_{mechanic} \approx 30000 L_{sol}, \qquad \frac{L}{L_{mechanic}} \approx 0.1$$

During 500 000 years

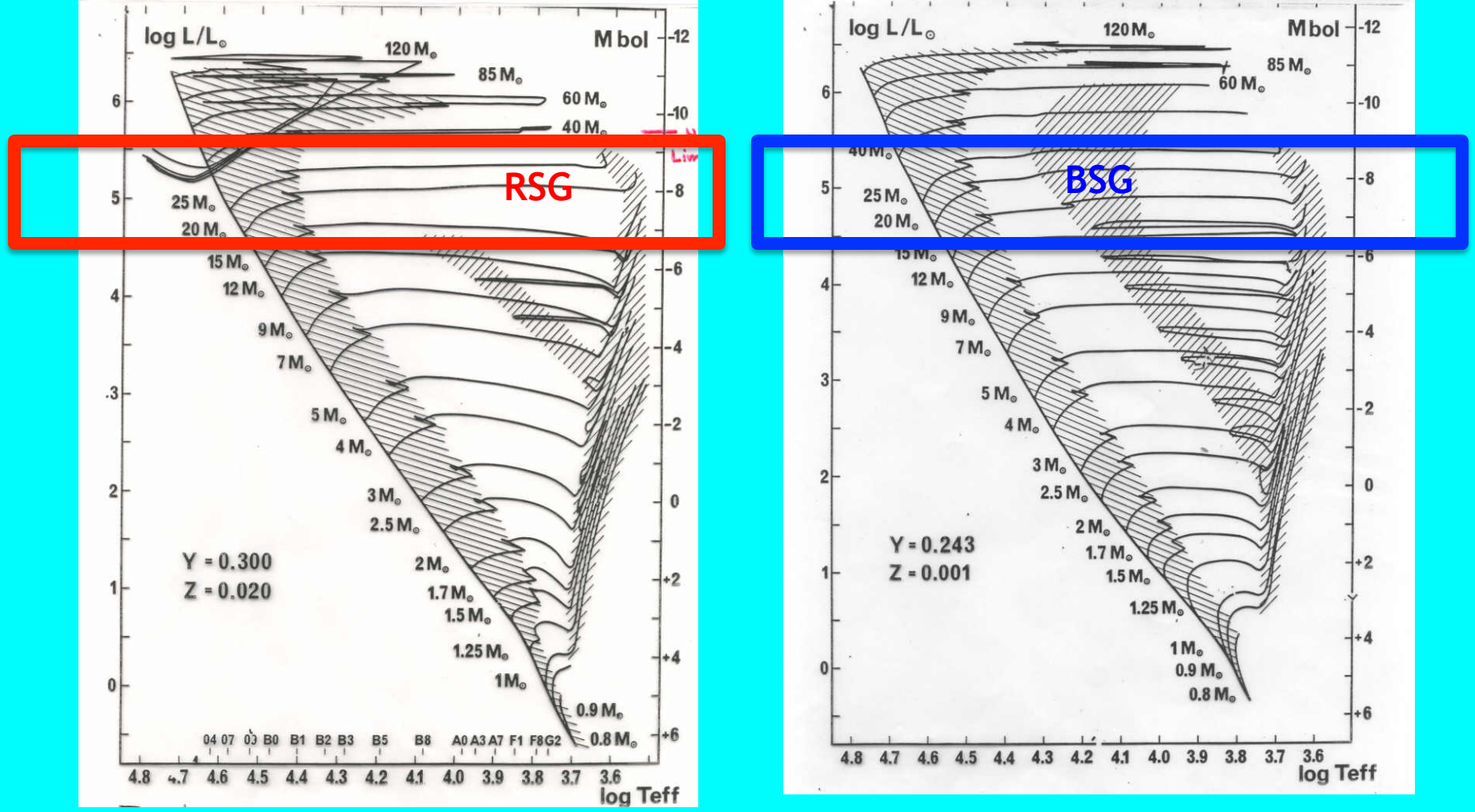
$$E_{mechanic} \approx 2 \ X \ 10^{51} \text{ ergs similar to SNe!}$$

NUMBER RATIOS OF MASSIVE STARS IN NEARBY GALAXIES



GALAXY	Z	WR/O	WC/WR	RSG/WR
M31	0.035	0.24	0.44	1.7
6-7.5	0.029	0.21	0.55	--
7.5-9	0.020	0.104	0.48	~1
9.5-11	0.013	0.033	0.33	--
M33	0.013	0.06	0.52	~4
LMC	0.006	0.04	0.20	--
6822	0.005	0.02	--	8.3
SMC	0.002	0.017	0.11	--
1613	0.002	0.02		

Conti & Maeder'94; Massey '02

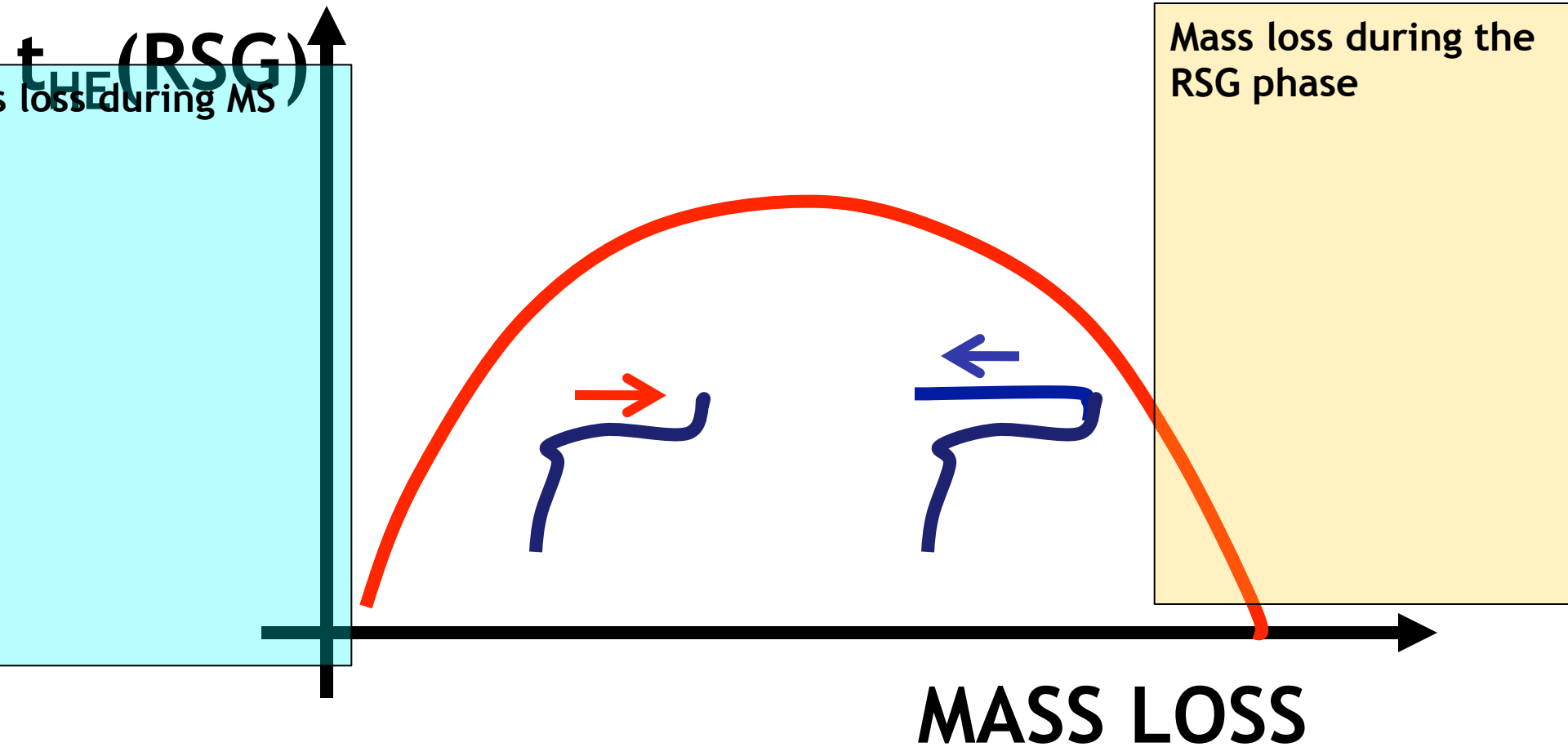


When the metallicity (mass loss) decreases, models predict that a still greater portion of the core He-burning phase occurs in the blue

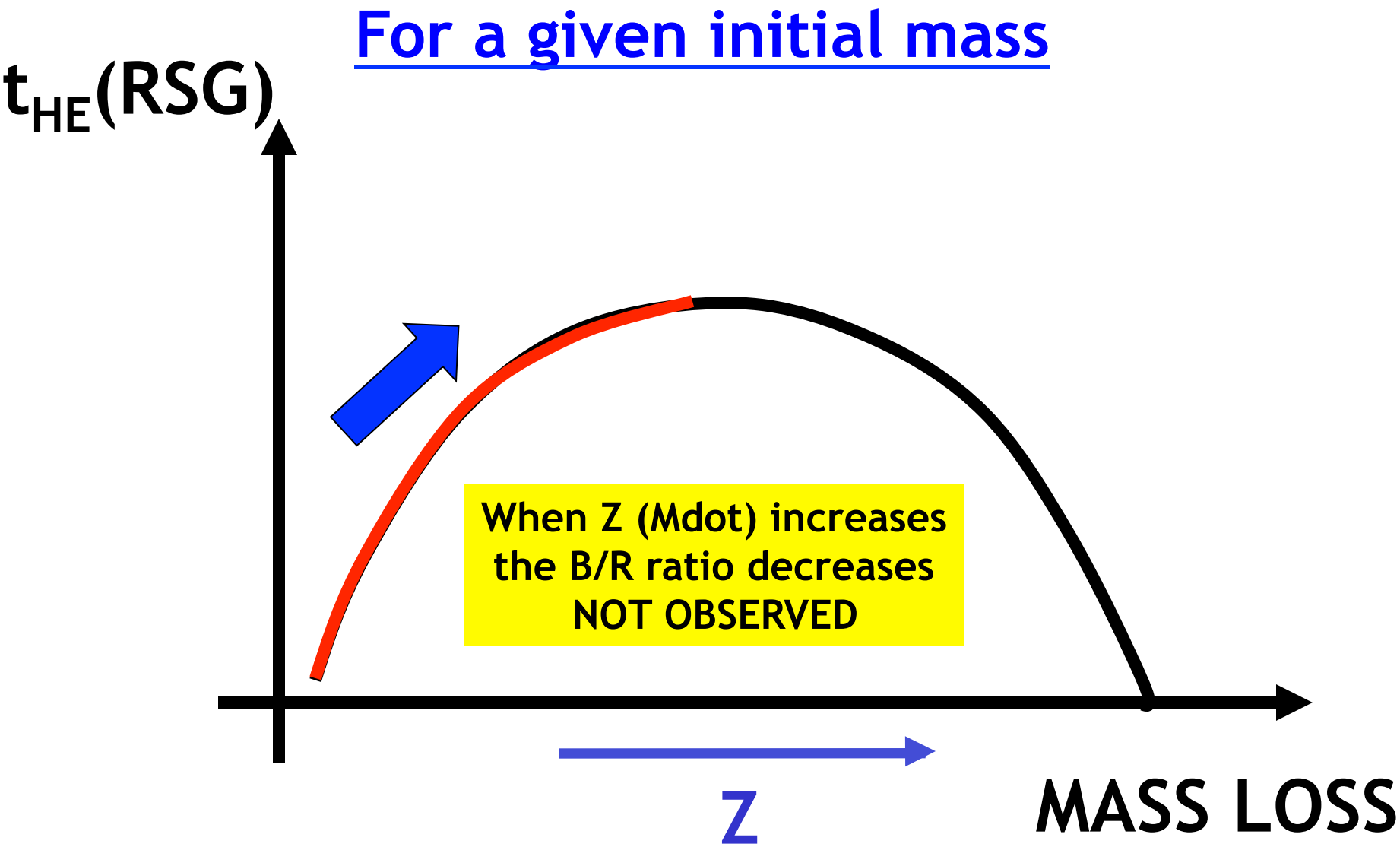
Z decreases→ higher B/R

CHANGE OF MASS LOSS

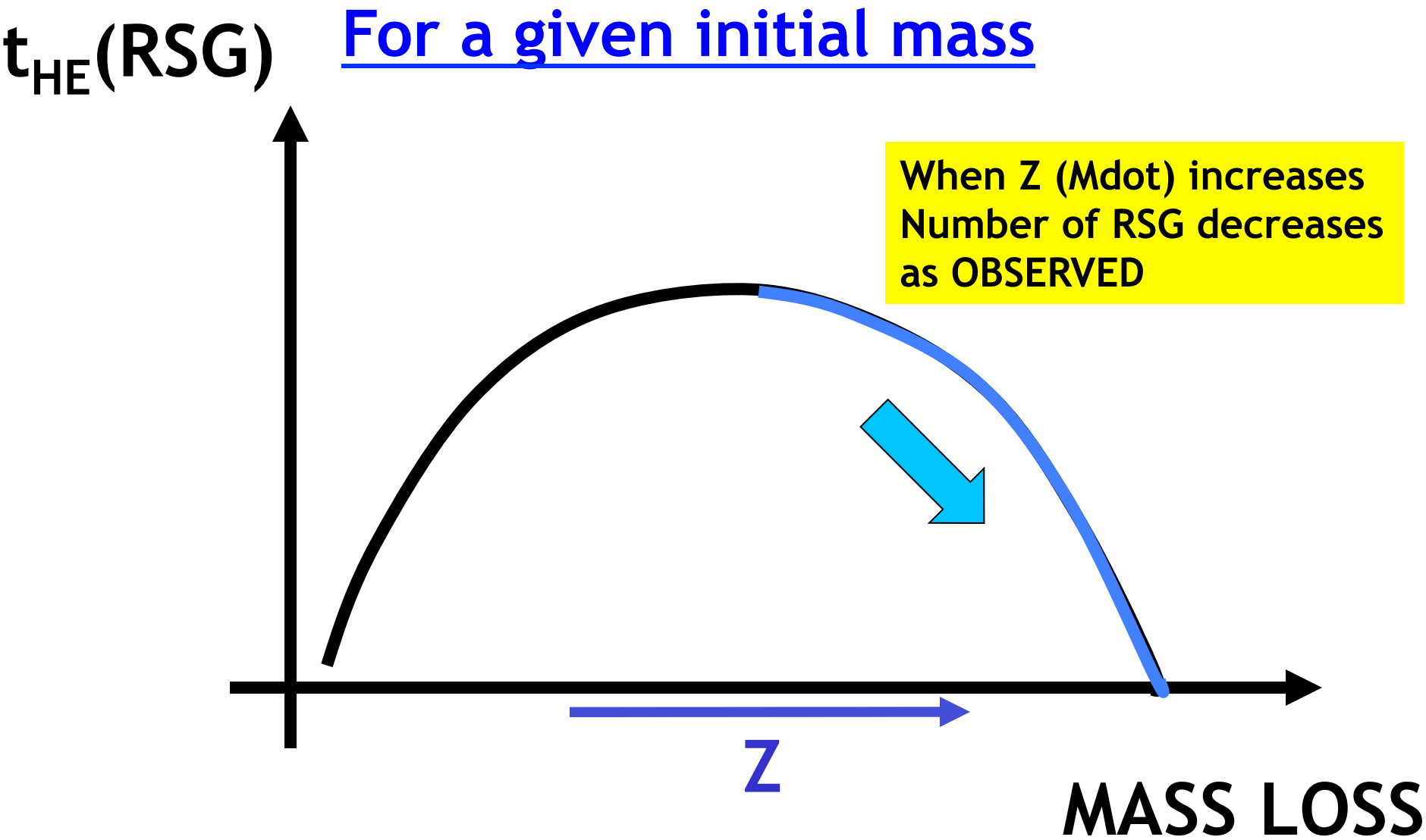
For a given initial mass



INCREASE OF Mdot DURING THE MS?



INCREASE DURING THE RSG PHASE?



VY CMa, Circumstellar material very inhomogeneous

Smith, Hinkle, Ryde, 2009, ApJ, 137, 3558

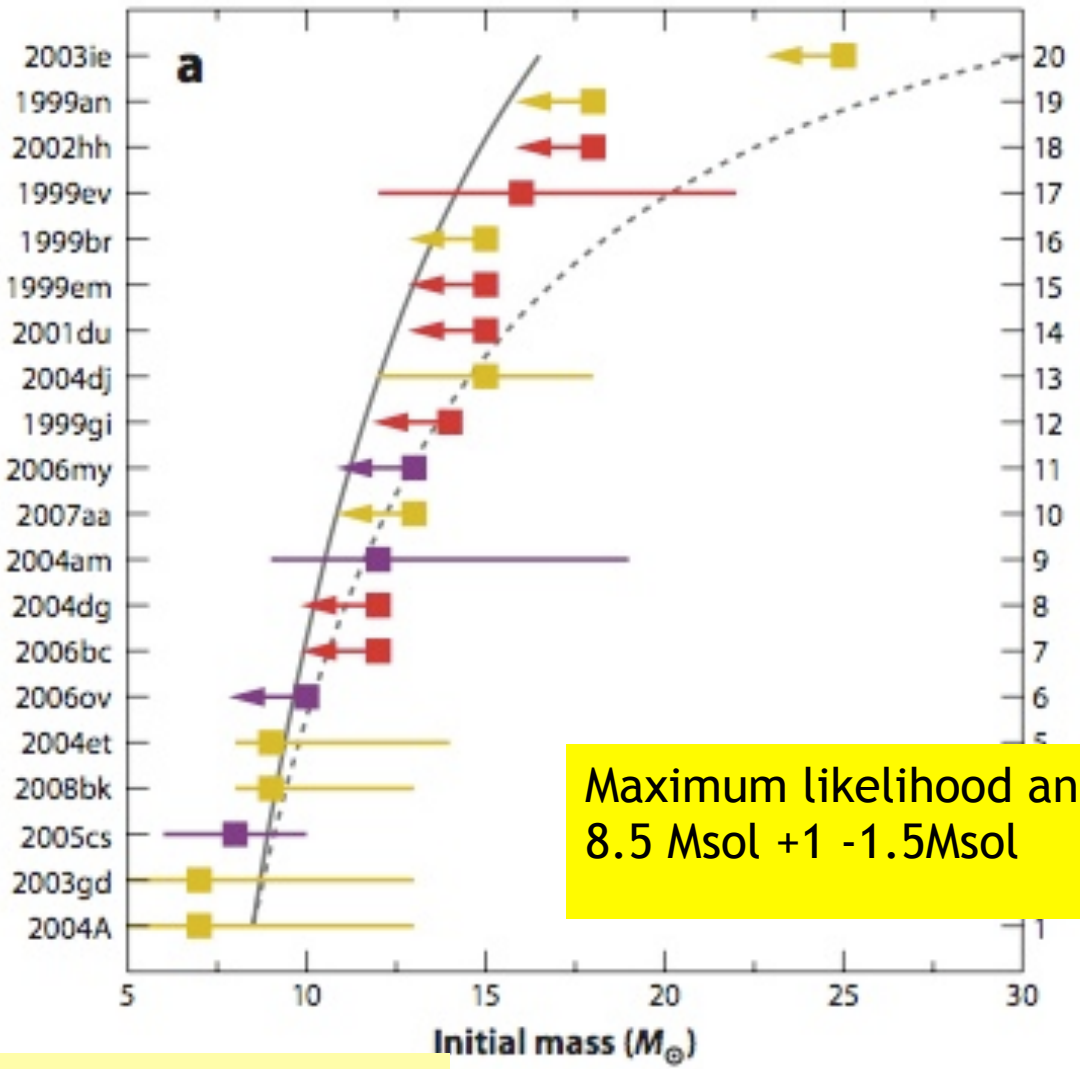
Current average Mdot ~2-4 10^{-4} M_{sol}/y
Higher Mdot in the past (~1000 y ago)→ 1-2 10^{-3} M_{sol}/y

1 Msol of circumstellar material accumulated in the last 1000 y

Might give a type IIn SN type.

NASA, ESA, and R. Humphreys (University of Minnesota)

Minimum mass for the progenitors of type II Sne (IIP)

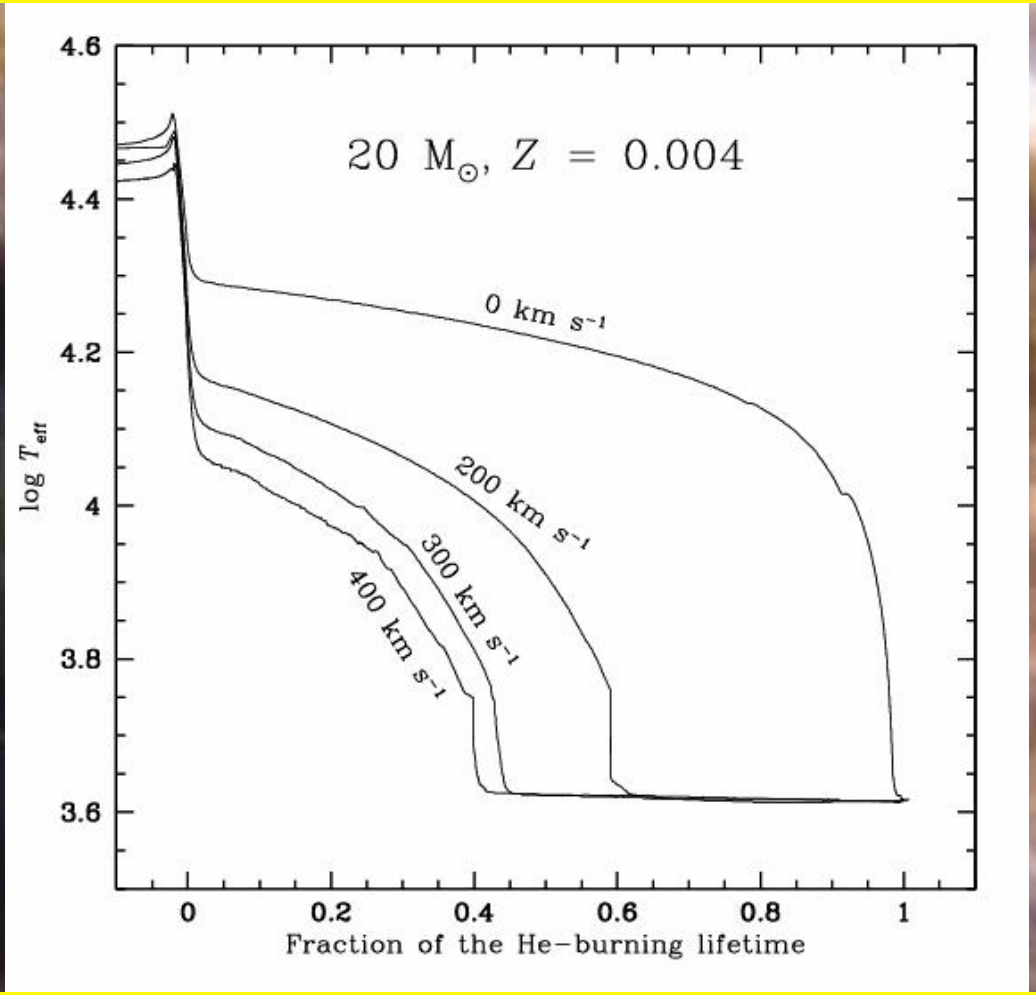


Maximum likelihood analysis
8.5 Msol +1 -1.5Msol

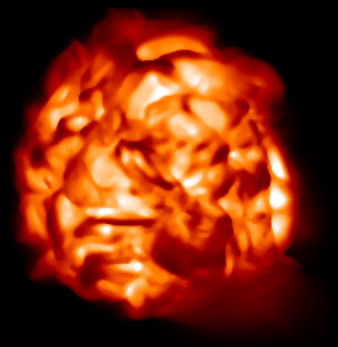
Smartt, 2009, ARAA, 47, 63

B/R PROBLEM

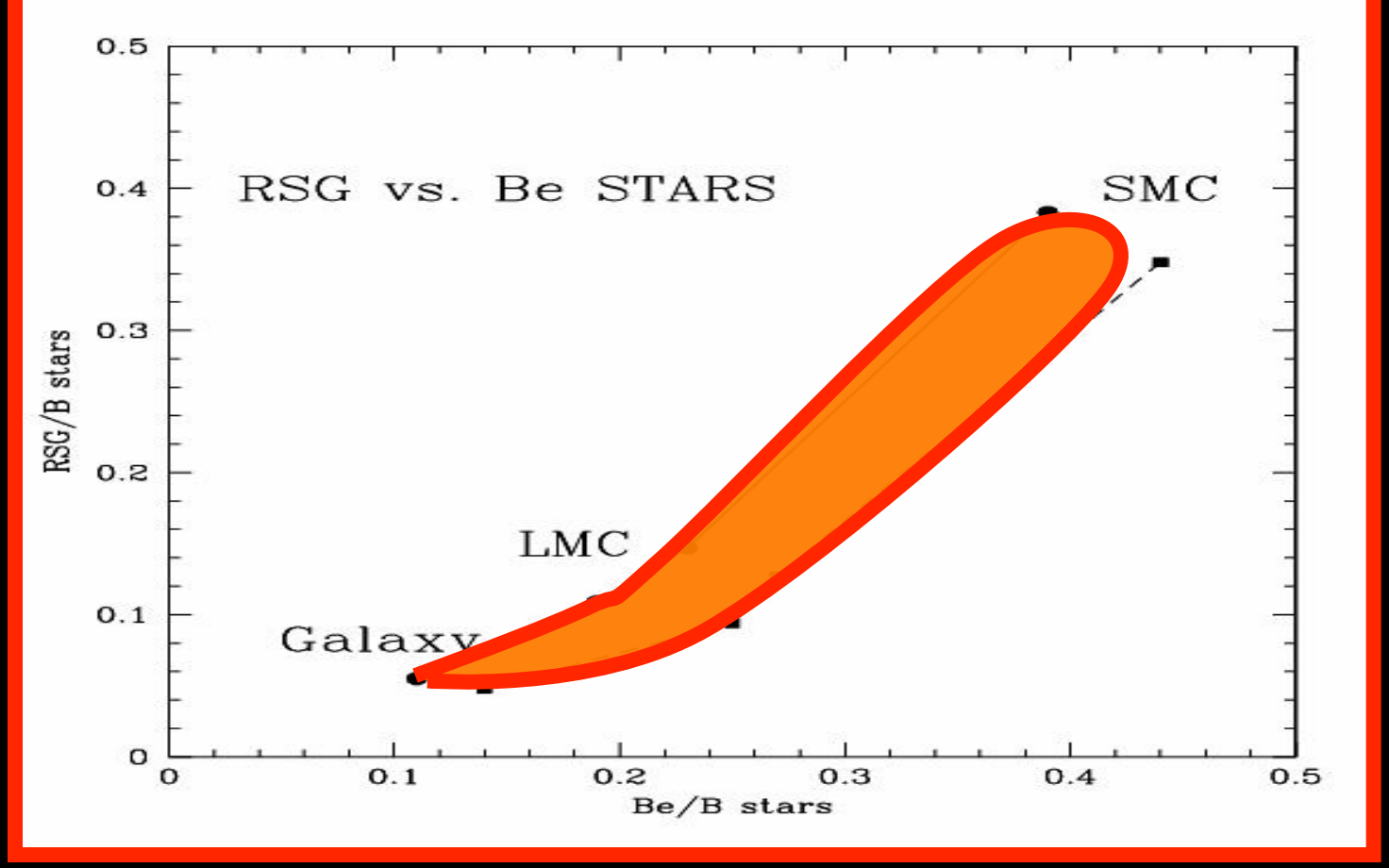
Lots of RSG observed at low Z, B/R~0.5-0.8 in SMC but current models predict none, B/R~50.



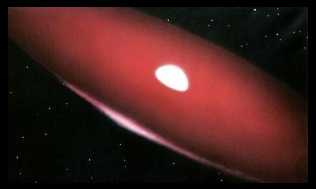
Models with mixing due to rotation are OK with B/R = 0.5-0.8 in SMC cf. Maeder & Meynet 2001



Red SG



Be stars



CONSISTENT WITH MODELS

More fast Rotators → More RSG

CONSEQUENCES

Evolutionary tracks MS width, blue loops, surface abundances

Talon et al. 1997; Heger & Langer 2000; Meynet & Maeder 2000; Ekström et al. 2011

Massive star populations Be, Red and Blue SGs, LBV, WR

Ekstrom et al. 2008; Maeder & Meynet 2001, Meynet & Maeder 2003; 2005; Eldridge & Vink 2005

Supernova types II, Ib, Ic, collapsars

Heger & Woosley 2006; Yoon & Langer 2005; Meynet & Maeder 2007; Georgy et al. 2009

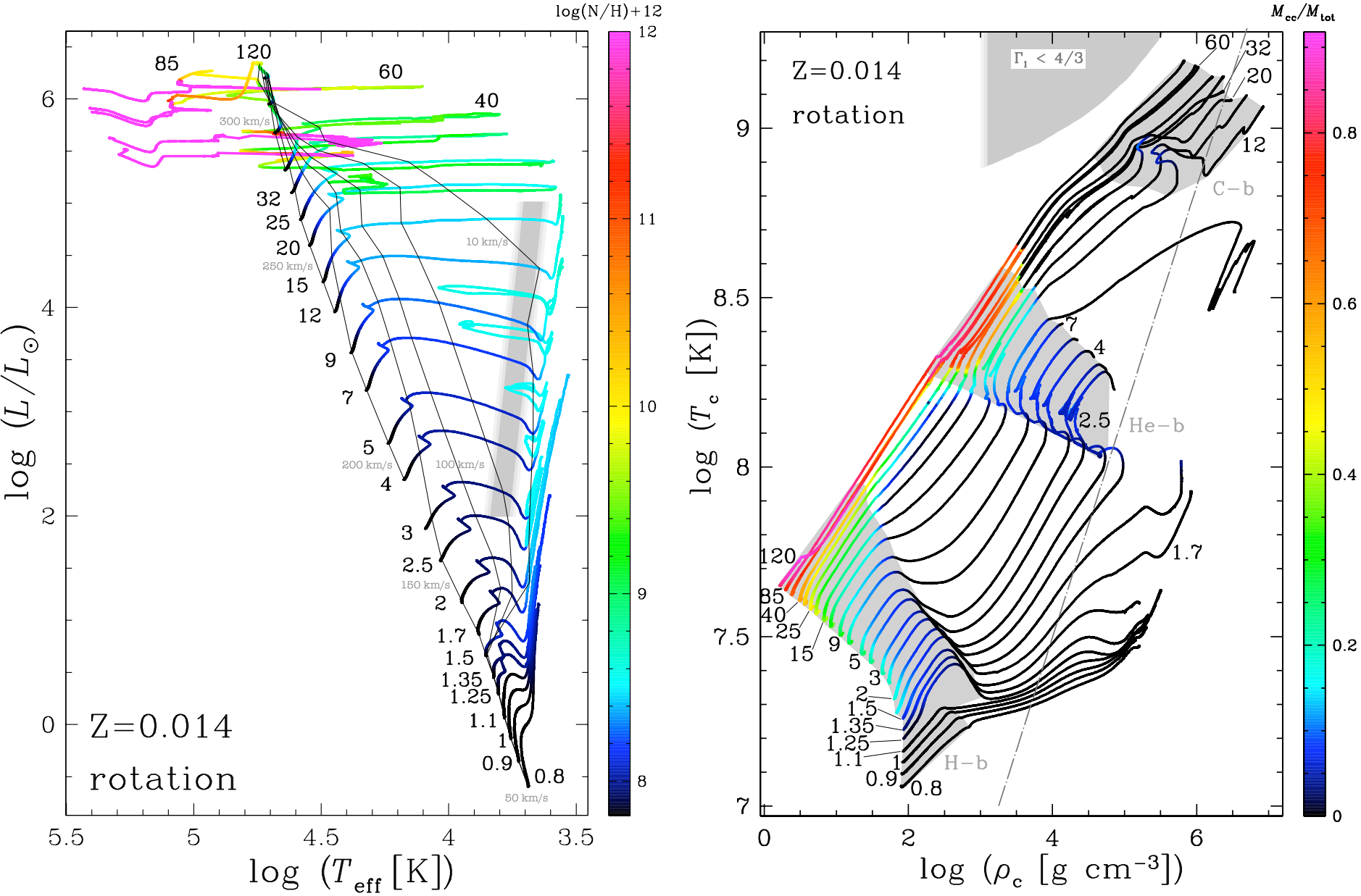
Chemical evolution of globular clusters and of galaxies

He, CNO, Ne, Al, s-process…

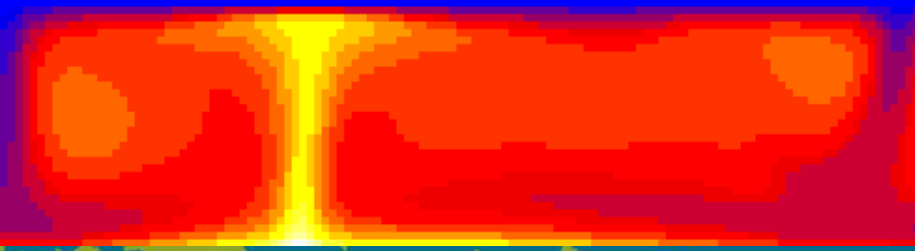
Chiappini et al. 2006, 2008ab, 2011; Decressin et al. 2007; 2008; Meynet et al 2006, 2010; Pignatari et al. 2008

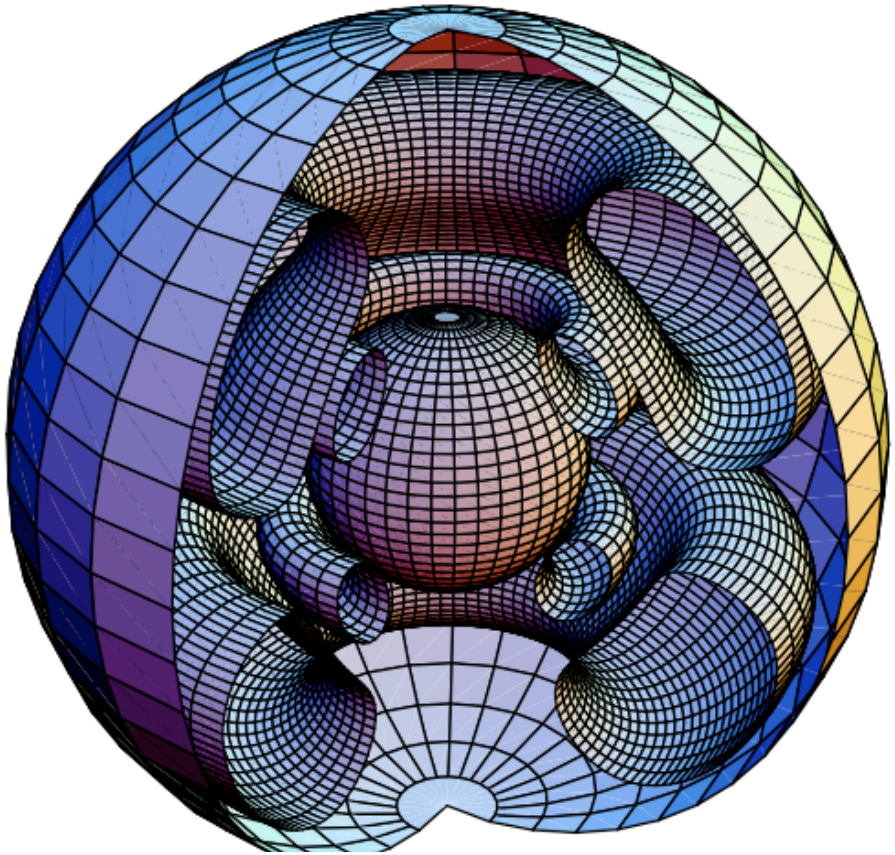
Binary evolution

Langer et al. 2008, IAUS 250, Mink et al. 2009

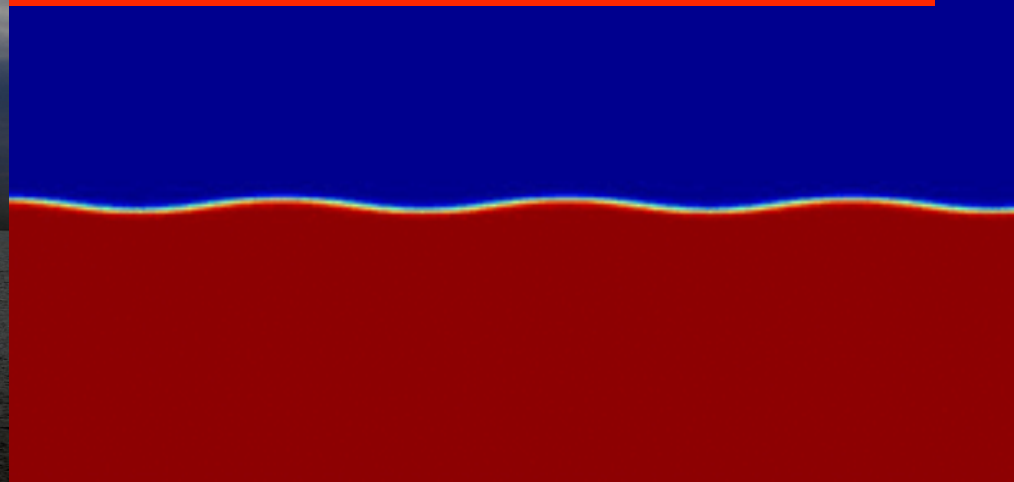


Ekström et al., in preparation





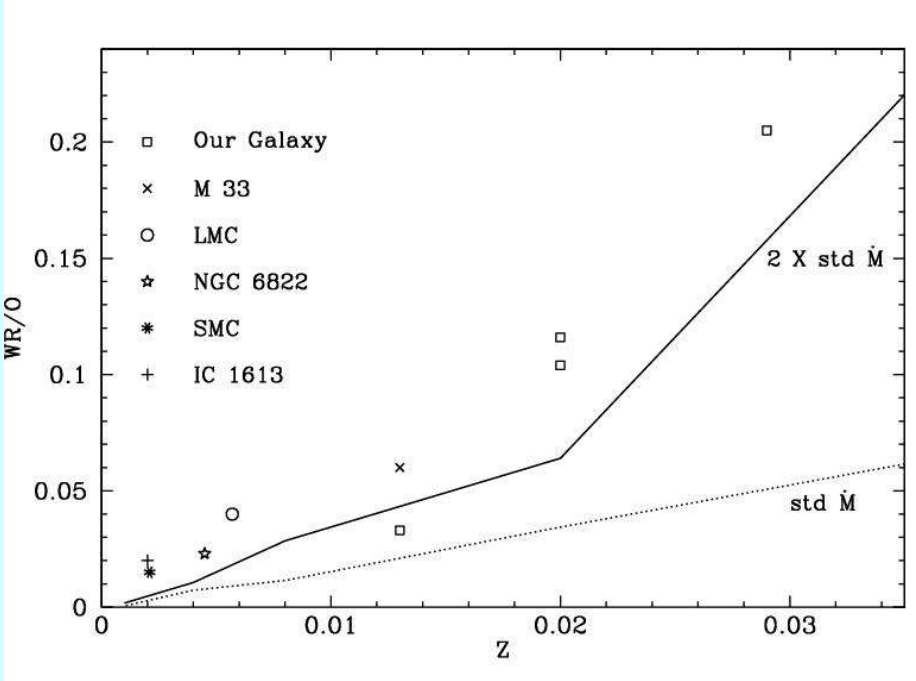
MANY INSTABILITIES-TRANSPORT PROCESSES



Remaining problems with WR stars

Possible to reproduce the WR/O number ratios observed at different Z only using models with enhanced mass loss rates

Maeder and Meynet 94



Not satisfactory ! Clumping in the winds of hot stars tends to reduce the observed mass loss rates by a factor 2 to 3

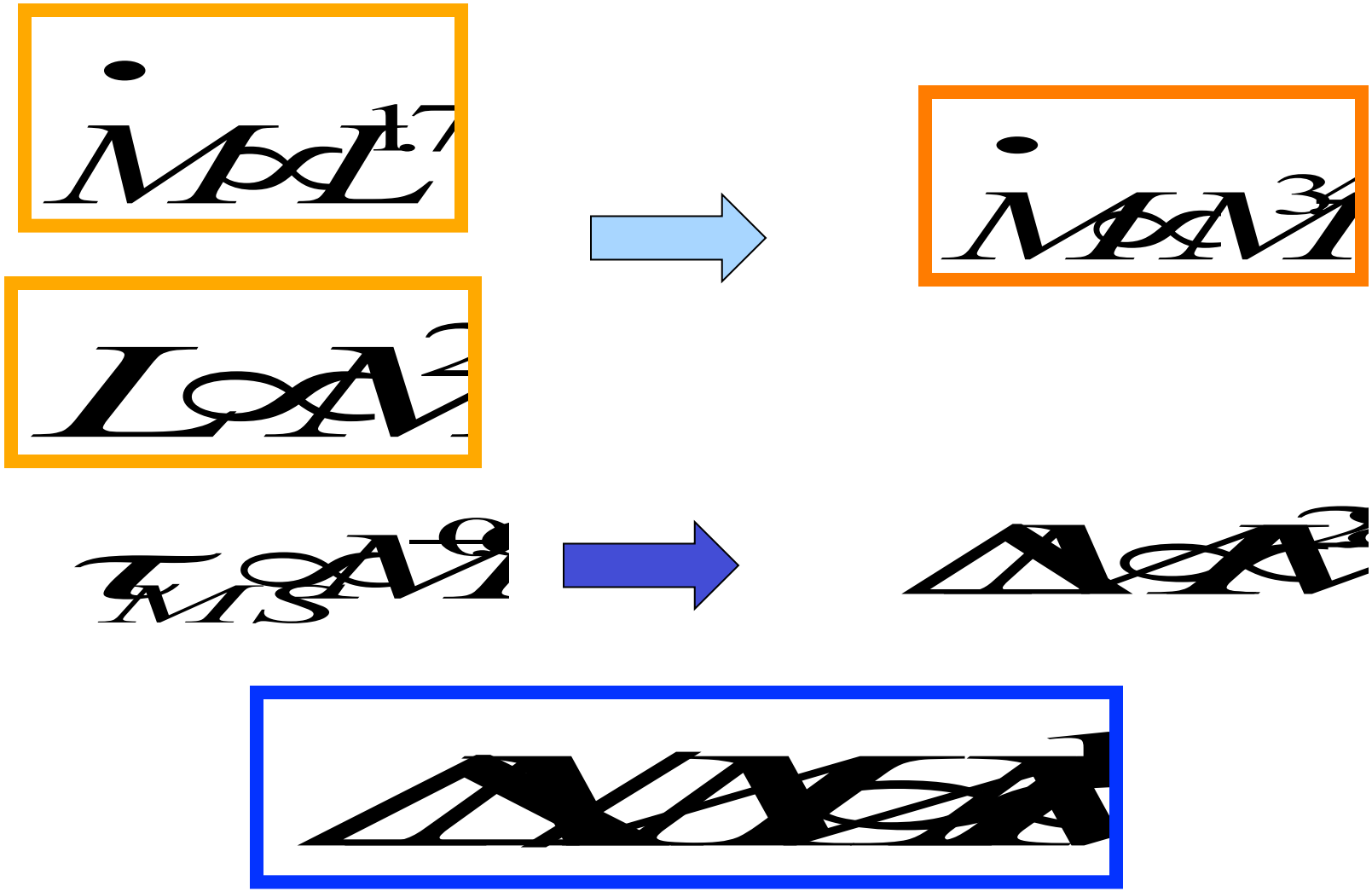
Nugis et al 98; Hamann and Koesterke 98

Other difficulties ⇒ Observation →smooth transition from high surface abundances to H-free atmospheres

⇒ Observed number of stars in the transition WN/WC phase (Conti & Massey 89; Langer 91; Crowther 95,02)

Typical mass-loss rates for galactic O-type stars

0.5-20 x 10^{-6} M_{sol} $year^{-1}$



MASS LOSS BY LINE DRIVEN WINDS

Luminous Stars

$$\dot{M} \propto L^{1.7}$$

Metal rich stars

$$\dot{M}_Z = \left(\frac{Z}{Z_{sol}}\right)^{0.5-0.7} \dot{M}_{Z_{sol}}$$

Impact on populations, nucleosynthesis, SNe type, stellar remnant

ROTATION

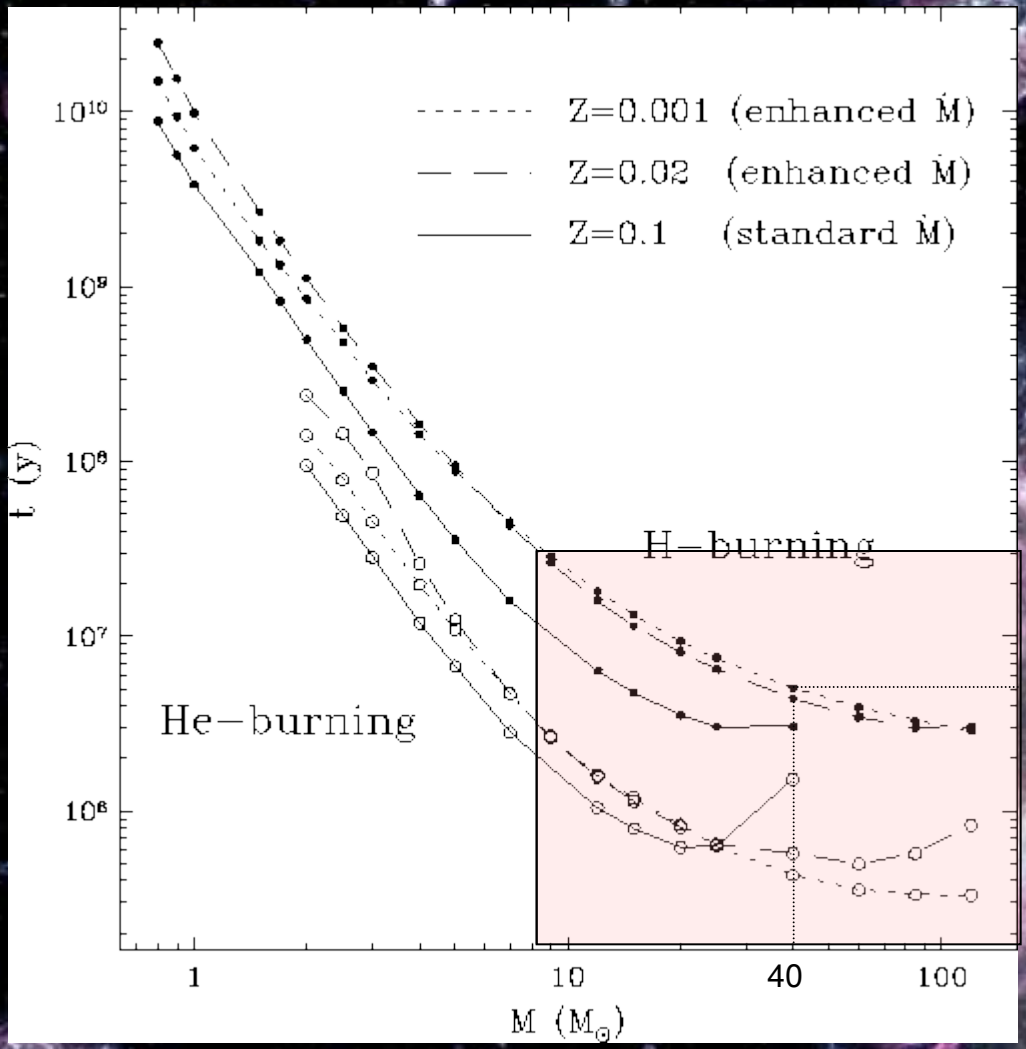
AOB Stars

<V> ~180 -220 km s^{-1}

Metal poor stars

Impact on populations, nucleosynthesis, SN types, stellar remnants

Short lifetimes



30 My

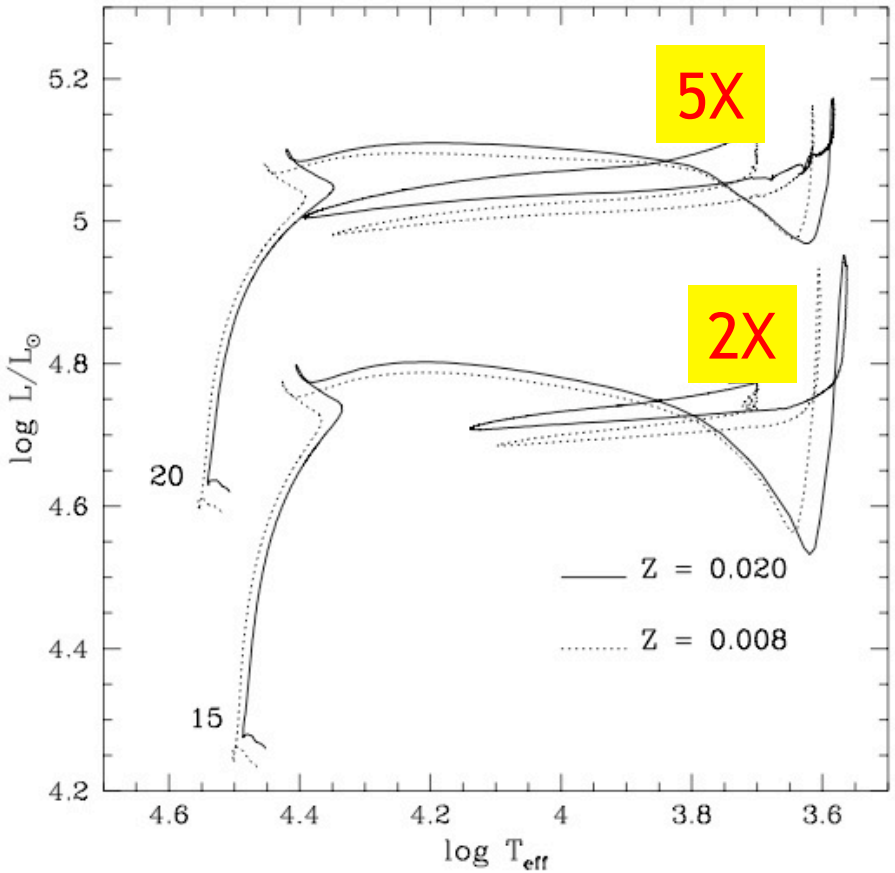
3 My

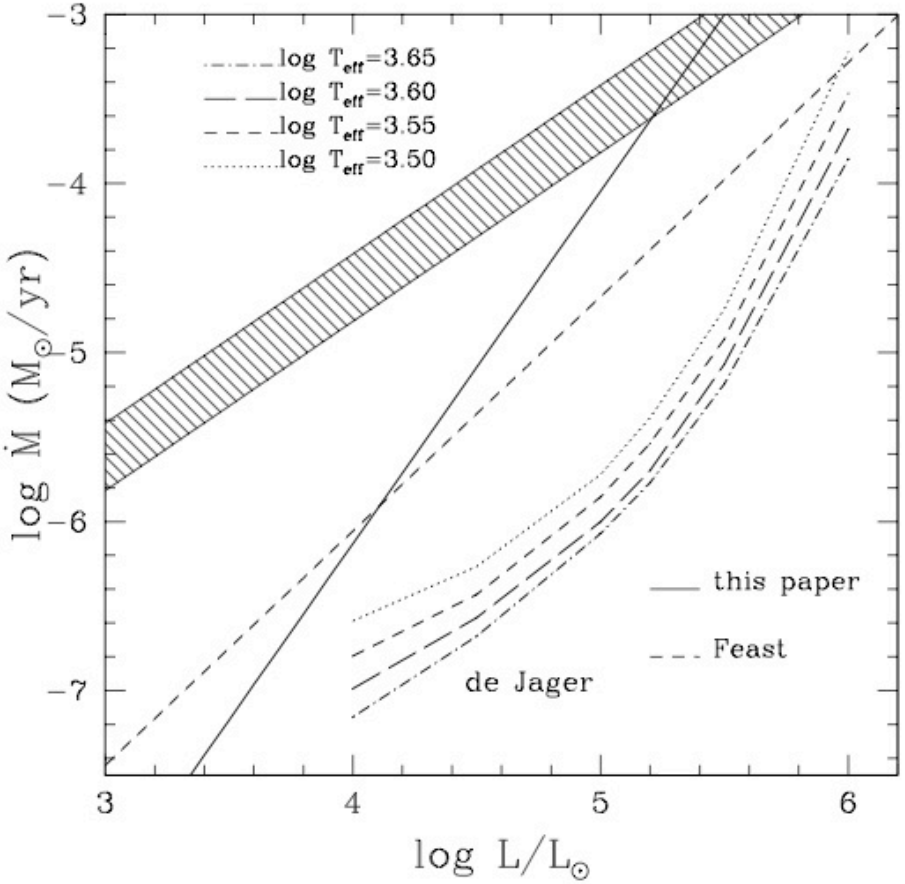
Mowlavi, Meynet , Maeder , Schaerer , Charbonnel , A&A 335, 573 (1998)

Very short lifetimes for advanced phases

Table 28.1. The main parameters in the advanced evolution of a 15 $M_\odot$ star. From S.E. Woosley and Th.Janka [638]

Stage	Timescale	Fuel	Ashes	$T(10^9)$ K	ϱ g cm^{-3}	$L/L_\odot$ photons	$L_\nu/L_\odot$ neutrinos
H	1.1×10^7 yr	H	He	0.035	5.8	2.8×10^4	1.8×10^3
He	2.0×10^6 yr	He	C,O	0.18	1.4×10^3	4.4×10^4	1.9×10^3
C	2.0×10^3 yr	C	Ne,Mg	0.81	2.8×10^5	7.2×10^4	3.7×10^5
Ne	0.7 yr	Ne	O, Mg	1.6	1.2×10^7	7.5×10^4	1.4×10^8
O	2.6 yr	O,Mg	Si,S,Ar,Ca	1.9	8.8×10^6	7.5×10^4	9.1×10^8
Si	18 d	Si,S, Ar,Ca	Fe,Ni, Cr,Ti	3.3	4.8×10^7	7.5×10^4	1.3×10^{11}
Fe core collapse	~ 1 s	Fe,Ni, Cr,Ti	n star	~ 7.1	$> 7.3 \times 10^9$	7.5×10^4	$> 3.6 \times 10^{11}$





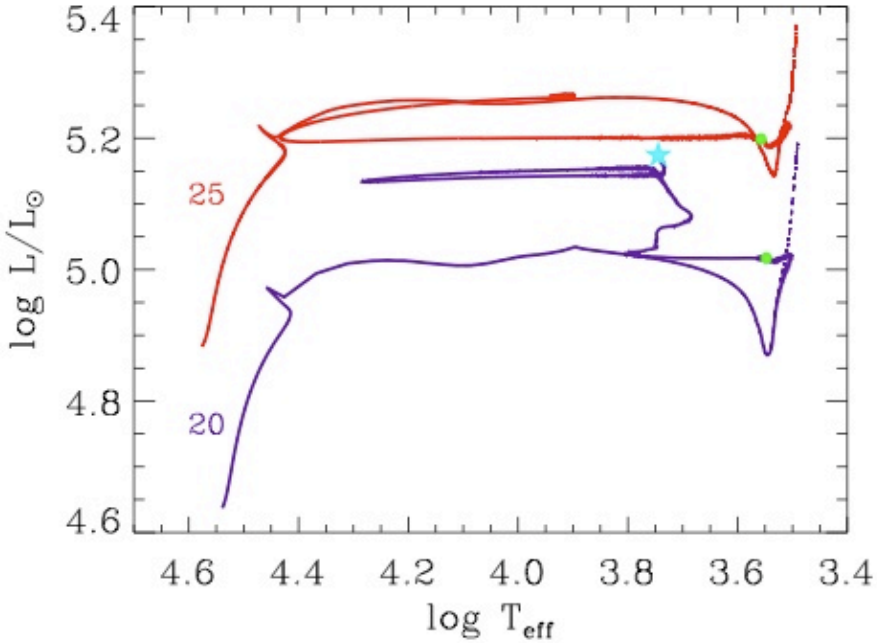
Salasnich, Bressan, Chiosi, 1999, A&A, 342, 131

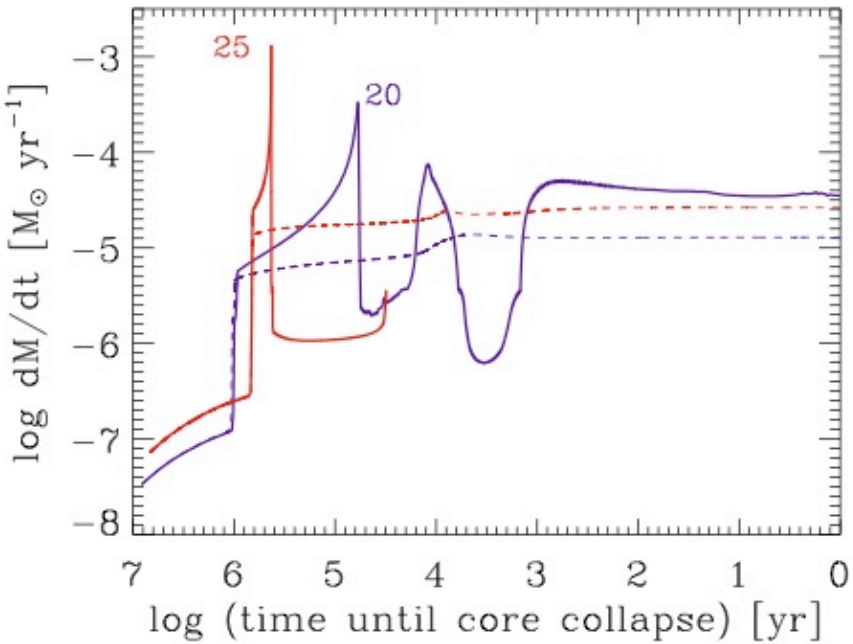
20 M_{sol} 60% He-burning lifetime with log T_{eff} > 4.2
End He-burning surface hydrogen ~0.5.

Reduction inferior mass limit for removal of outer envelope from 25 M_{sol} to ~19 M_{sol}

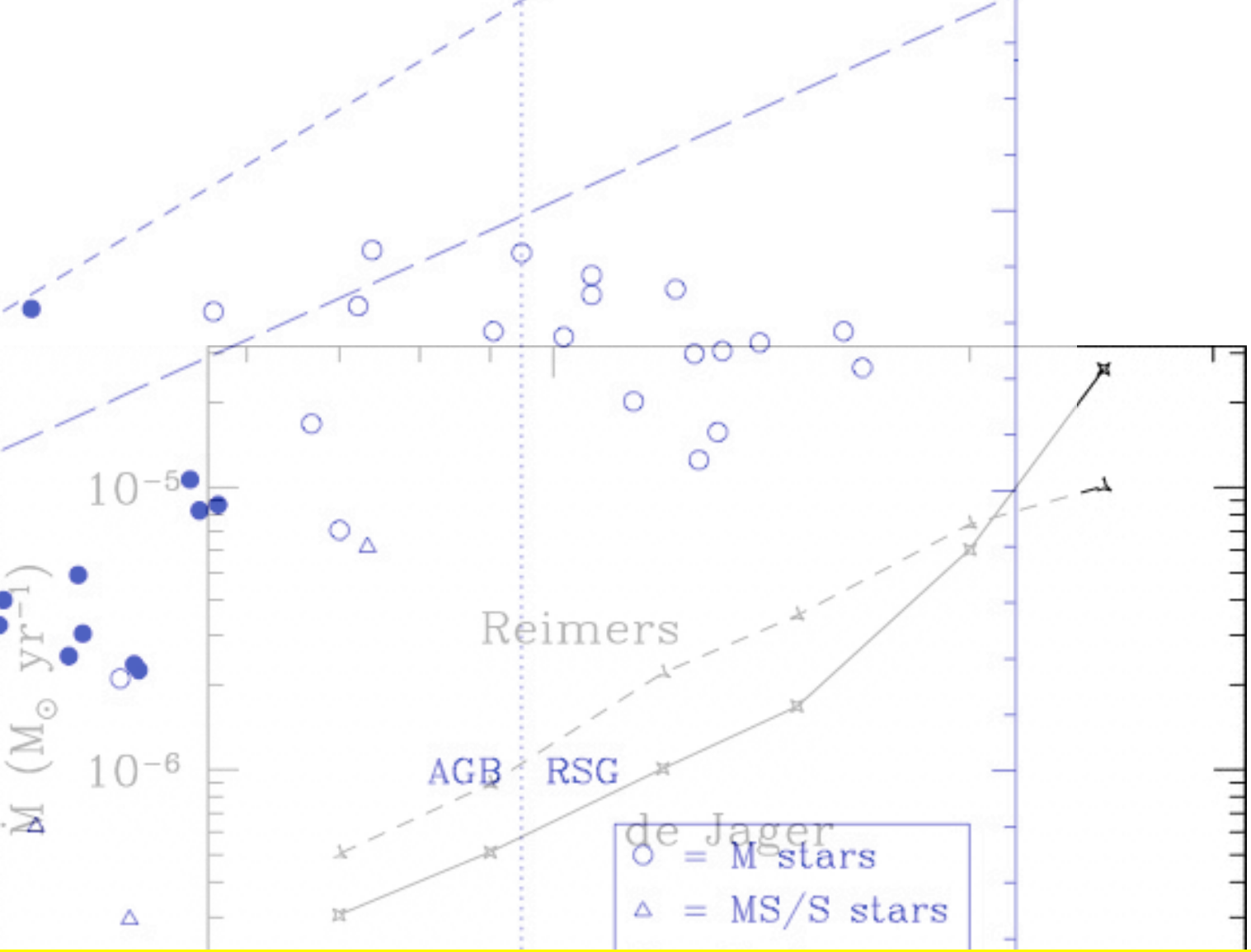
May explain lack of SNII-P progenitors with M > 17 M_{sol}

Progenitors of type IIn with circumstellar envelope of only a few M_{sol}





Yoon & Cantiello , 2010, eprint arXiv:1005.4925

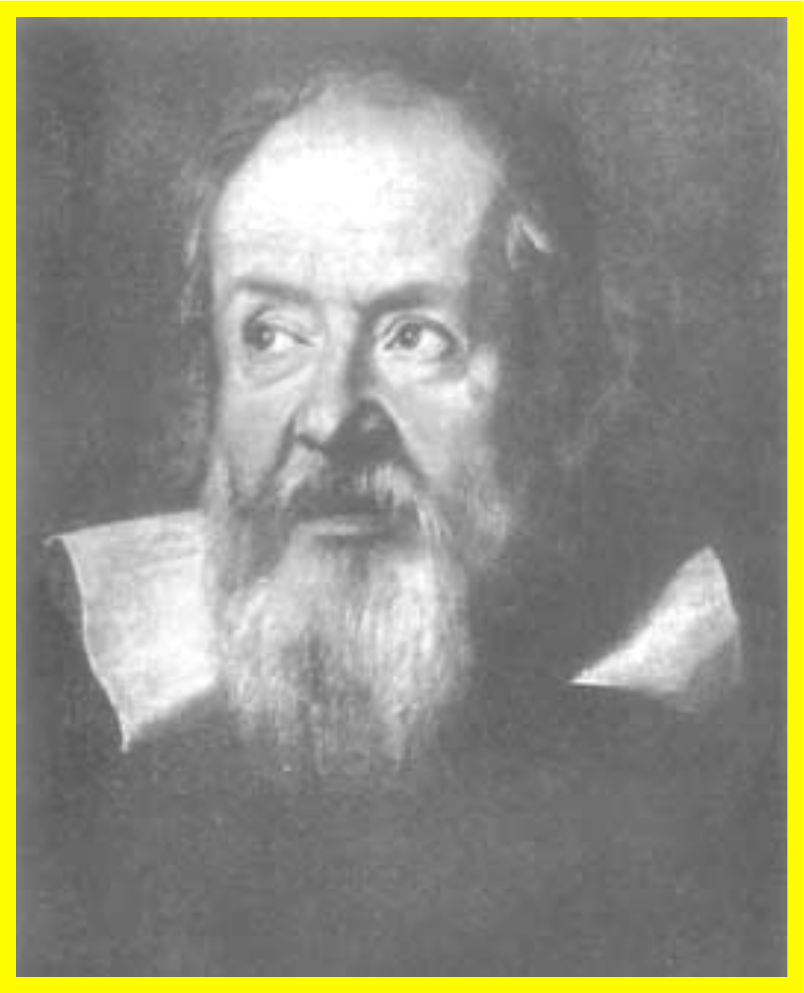


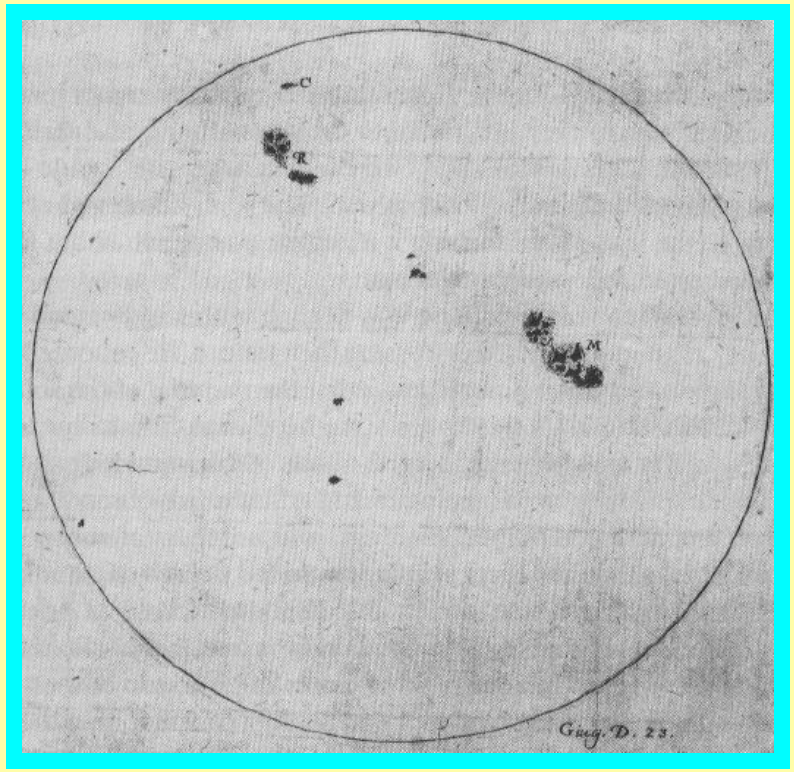
Dust enshrouded red supergiant may have higher mass loss (factor between 3 and 50) van Loon et al. (2005).

Dependence on the metallicity?

ROTATION…

An old topic…

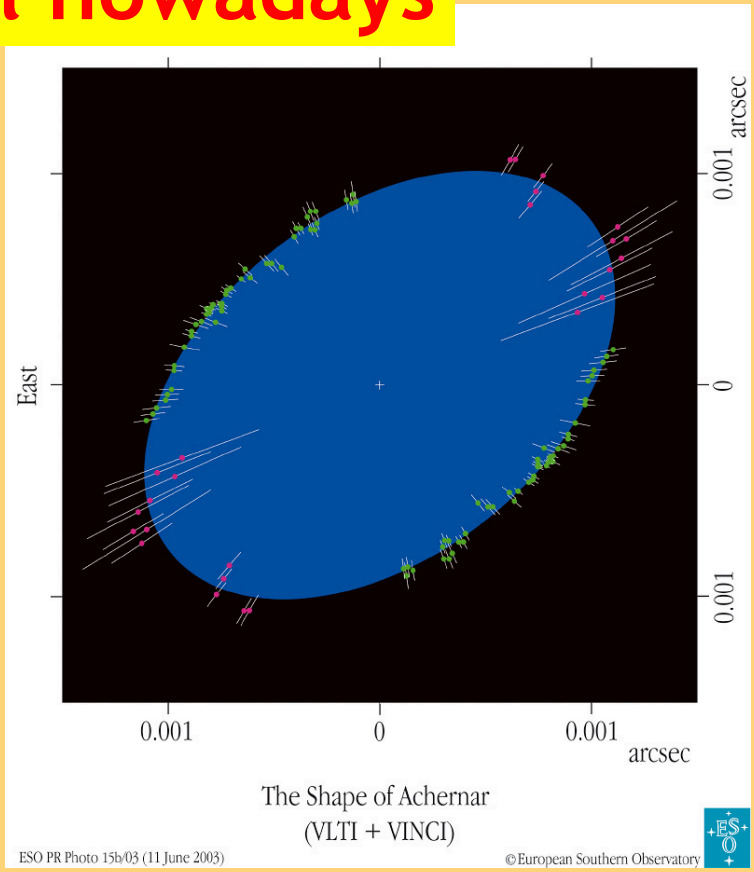




Von Zeipel 1924; Eddington 1925; Vogt 1925

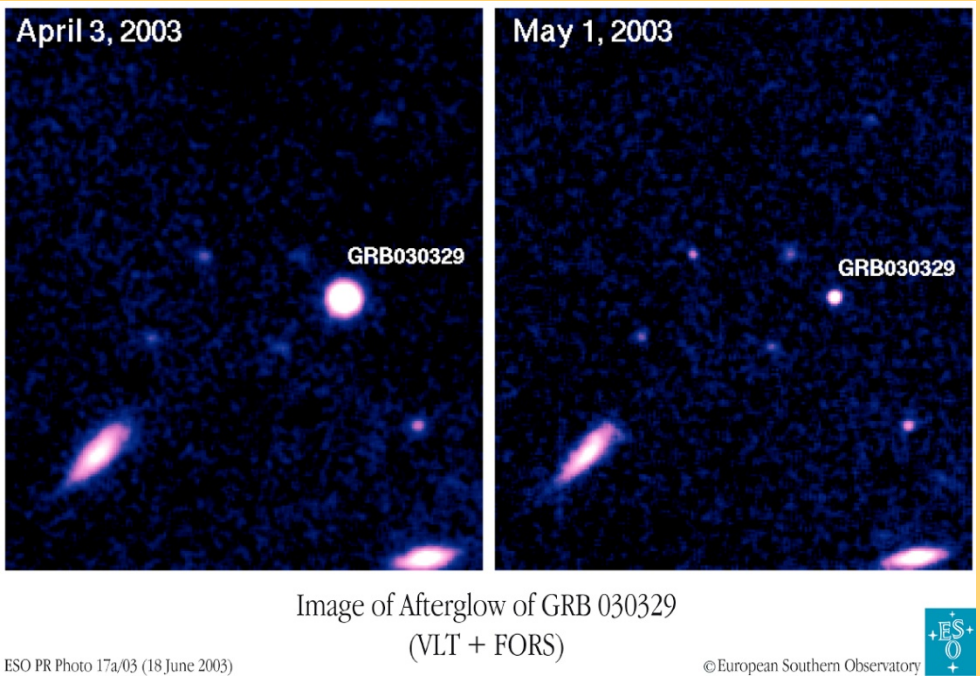
… but quite topical nowadays

Star deformation due to its fast axial rotation



Dominiciano de Souza et al. 2003

Cf also van Belle et al. 2003



Link between Long GRB and Hypernova confirmed

Hjorth et al. 2003

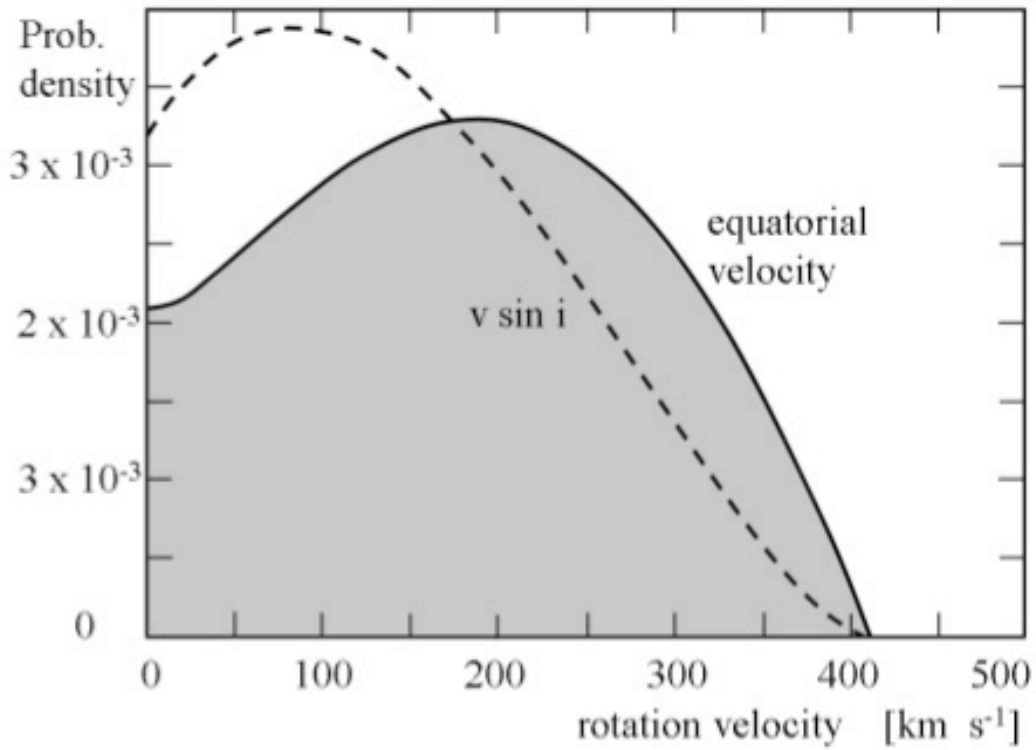
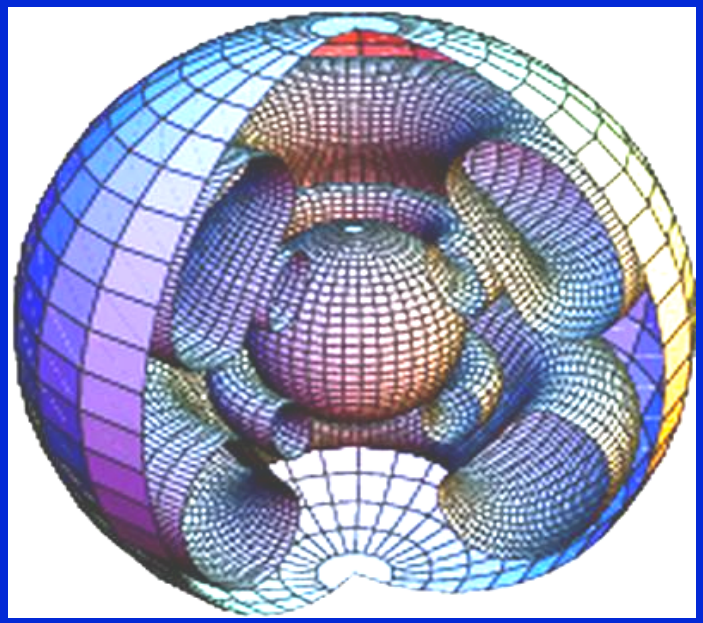
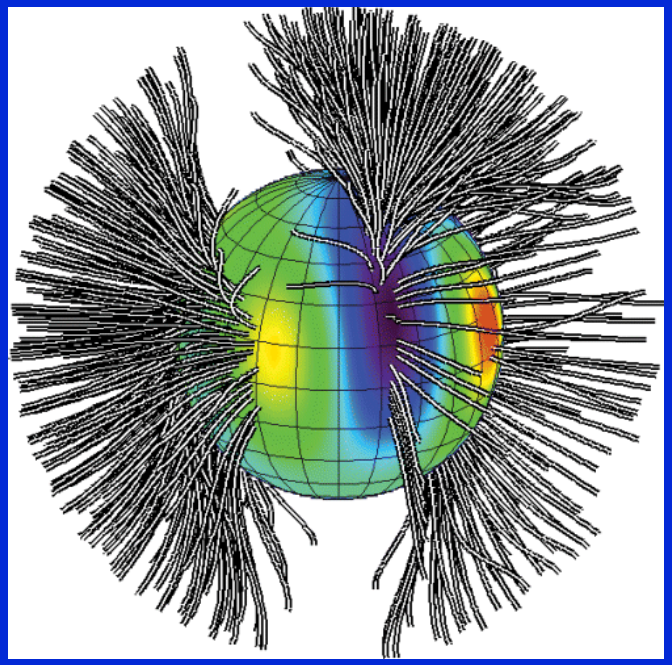


Fig. 27.1. Probability density by km s^{-1} of rotation velocities for 496 stars with types O9.5 to B8. Adapted from W. Huang and D.R.Gies [259]

Huang & Gies 2006





Donati et al. 2006

STRUCTURE

- Oblateness (interior, surface)
- Differential rotation

MASS LOSS

- Stellar winds
- Anisotropic losses of mass and J

MIXING

- **Meridional circulation**
- **Shear instabilities**
- **Turbulence**
- Transport of angular momentum of elements

MAGNETIC FIELD

- Dynamo
- Internal coupling
- Effects on element transport
- Magnetic braking

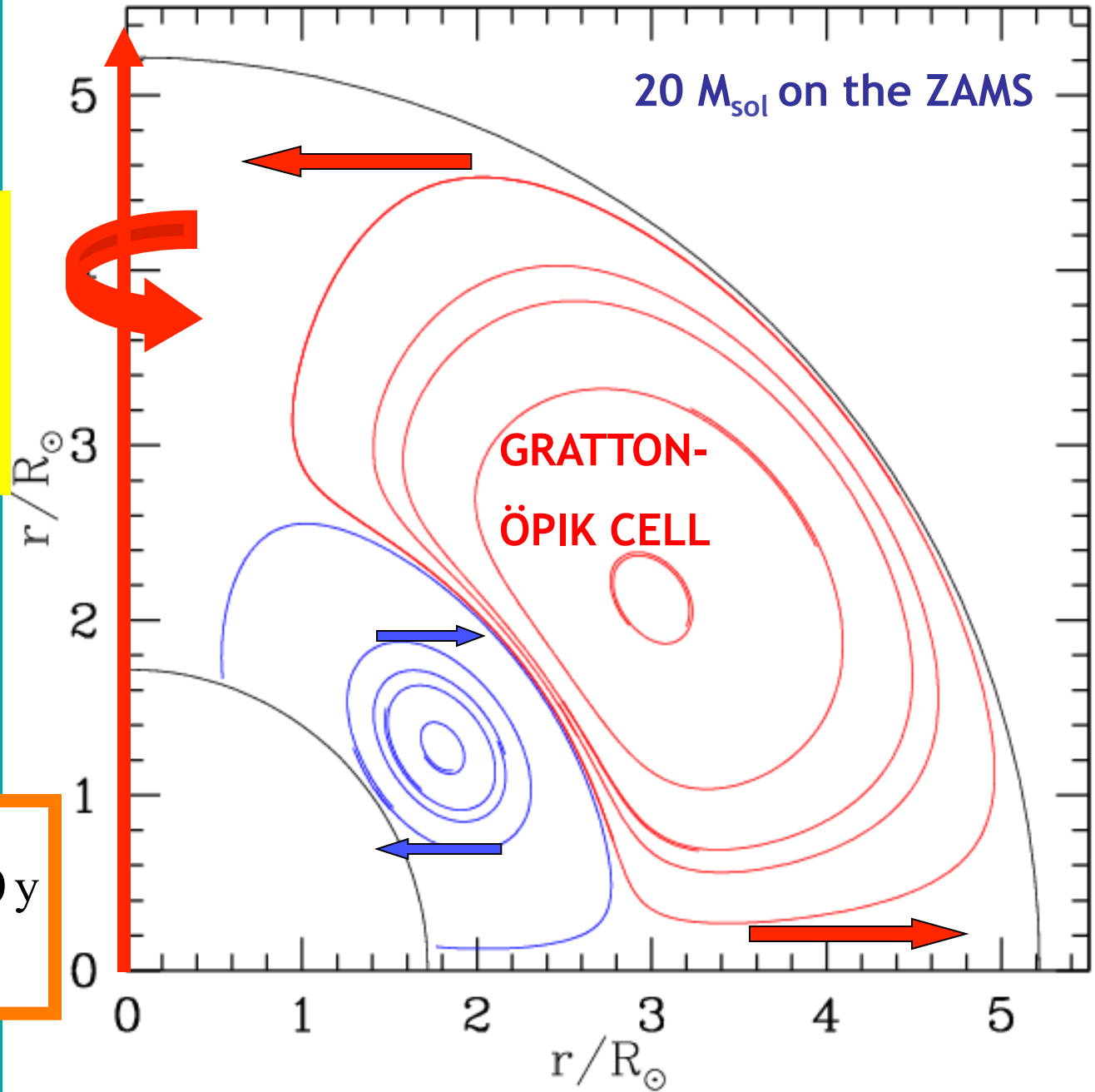
Cells of meridional circulation

Very important process for the transport of the angular momentum

Inner cell → inwards transport of angular momentum
Outer cell → outwards transport of angular momentum

Timescale→ a few times the Kelvin-Helmholtz timescale

$$\underbrace{\left(\frac{\Omega_{KEP}}{\Omega}\right)^2}_{4} \underbrace{\tau_{KH}}_{34000} \approx 140\,000\ \mathrm{y}$$



THE SHEAR INSTABILITY

Where does the energy come from ?

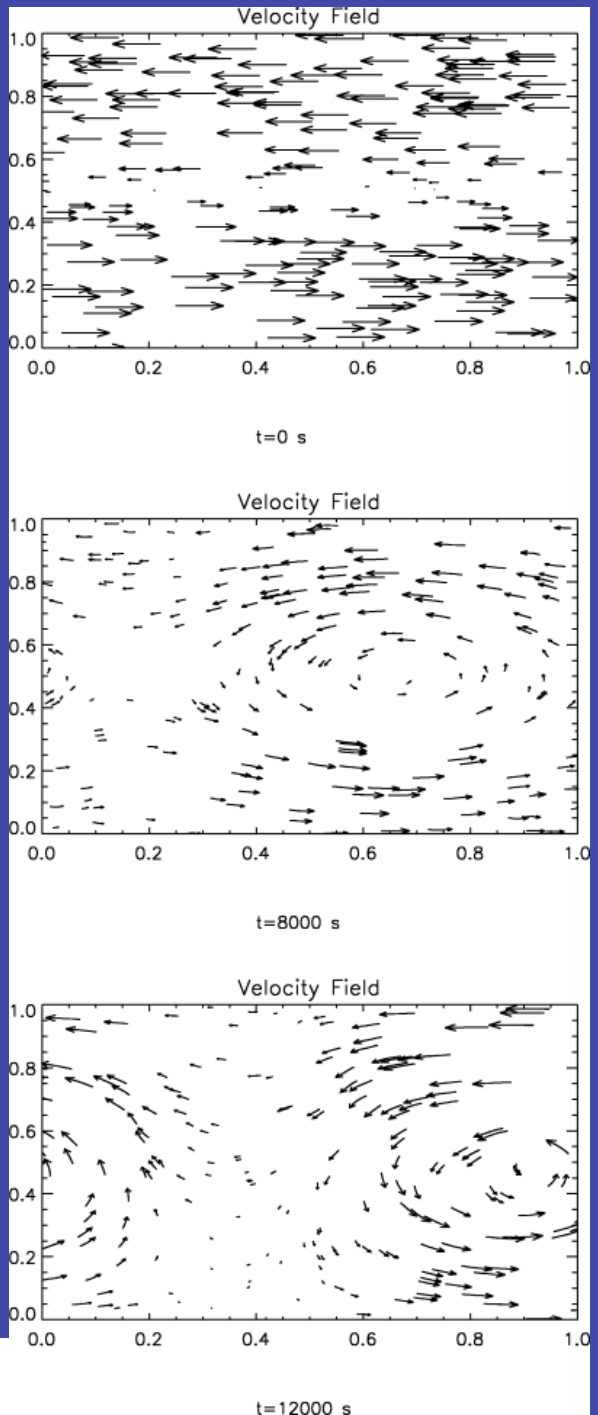
From the excess energy in the shear

When does it occur ?

When the excess energy in the shear can overcome the stable pressure gradients

The timescale

Secular shear → a few times thermal timescale
Dynamical shear → dynamical timescale



Brueggen & Hillebrandt 2001

Meridional circulation → Gradients of Ω

Shear instabilities

Zahn 1992: strong horizontal turbulence, shellular rotation

Transport of the chemical species

$$\rho \frac{\partial X_i}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left[\rho r^2 (D_{eff} + D_{schear}) \frac{\partial X_i}{\partial r} \right]$$

Transport of the angular momentum

$$\rho \frac{\partial (r^2 \Omega)}{\partial t} = \frac{1}{5r^2} \frac{\partial}{\partial r} \left(\rho r^4 U \Omega \right) + \frac{1}{r^2} \frac{\partial}{\partial r} \left(\rho r^4 D_{schear} \frac{\partial \Omega}{\partial r} \right)$$

Grids of single rotating massive stars

Standard Metallicity

Masses	V_{rot}	Magn. Field	Reference
8,10,12,15,20,25	0-474	No	Heger & Langer 2000
8,10,12,15,20,25	200	No	Heger et al. 2000
9,12,15,20,25,40,60,120	0-300	No	Meynet & Maeder 2000 (V)
9,12,15,20,25,40,60,85,120	0,300,500	No	Meynet & Maeder 2003 (X)
12,15,20,25,40,60	0,300	No	Hirschi et al. 2004 (XII)
12,15,20,25,35	200	Yes & No	Heger et al. 2005
16,30,40	210-556	Yes	Yoon et al. 2006
3,9,20,60	28-732	No	Ekstrom et al. 2008

Grids of single rotating massive stars

Non-solar metallicities

Z	Masses	V_{rot}	Magn. Field	Reference
0	9,15,25,40.60,85,200 3,9,20,60	0-800 39-1423	No No	Ekstrom et al. 2009 Ekstrom et al. 2008
0.00001	2,3,5,7,9,15,20,40,60 20,30,40,50,60 12,16,20,25,40,60 3,9,20,60	0,200,300,40 230-605 0-935.80 39-1017	No Yes Yes No	Meynet & Maeder 2002 (VIII) Yoon & Langer 2005 Yoon et al. 2006 Ekstrom et al. 2008
0.0005	20,40,60,120,200	0,600,800	No	Decressin et al. 2007
0.001	20,40,60 12,16,20,25,30,40,60	230-605 0-747.30	Yes yes	Yoon & Langer 2005 Yoon et al. 2006
0.002	3,9,20,60 12,16,20,25,30,40,60	32-879 0-652.76	No Yes	Ekstrom et al. 2008 Yoon et al. 2006
0.004	9,12,15,20,25,40,60 30,40,60,120 12,16,20,25,30,40,60	0,300 300 0-507.43	No No Yes	Maeder & Meynet 2001 (VII) Meynet & Maeder 2005 (XI) Yoon et al. 2006
0.008	30,40,60,120	300	No	Meynet & Maeder 2005 (XI)
0.040	20,25,40,60,85,120	0,300	No	Meynet & Maeder 2005 (XI)

Evolution of Ω(r) during the Main Sequence

Ω decreases inside the star

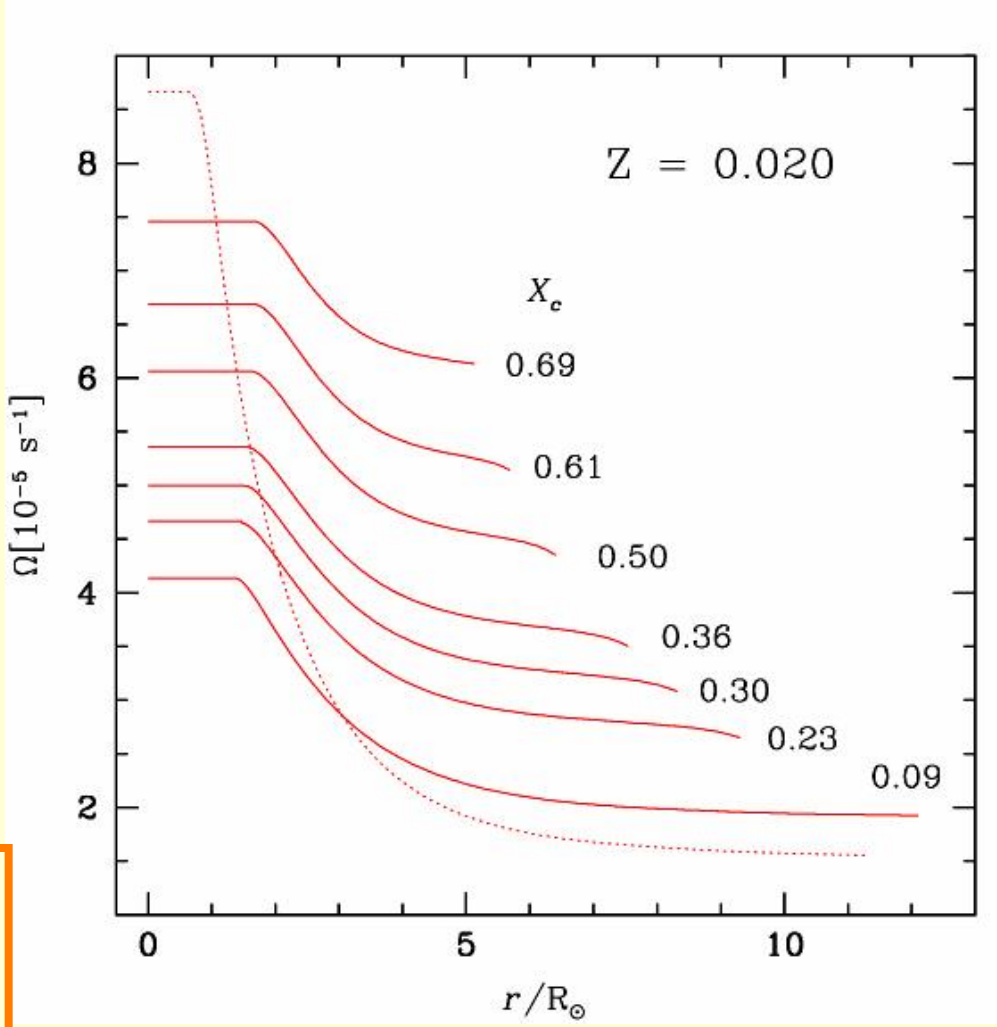
Increase of the radius

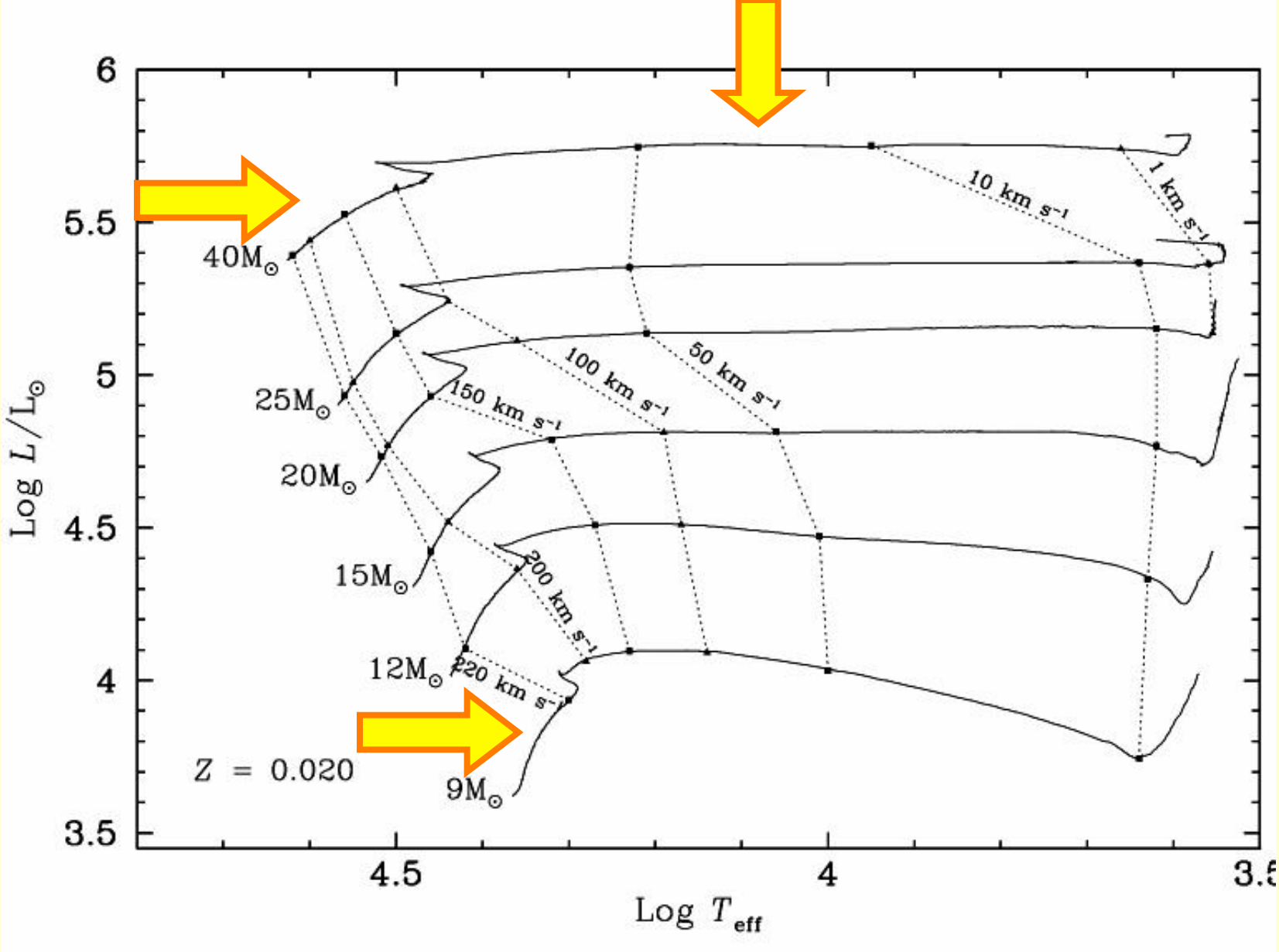
Transport of angular momentum

Removal of angular momentum
at the surface by the stellar winds

Gradients of Ω modest but
essential for chemical mixing

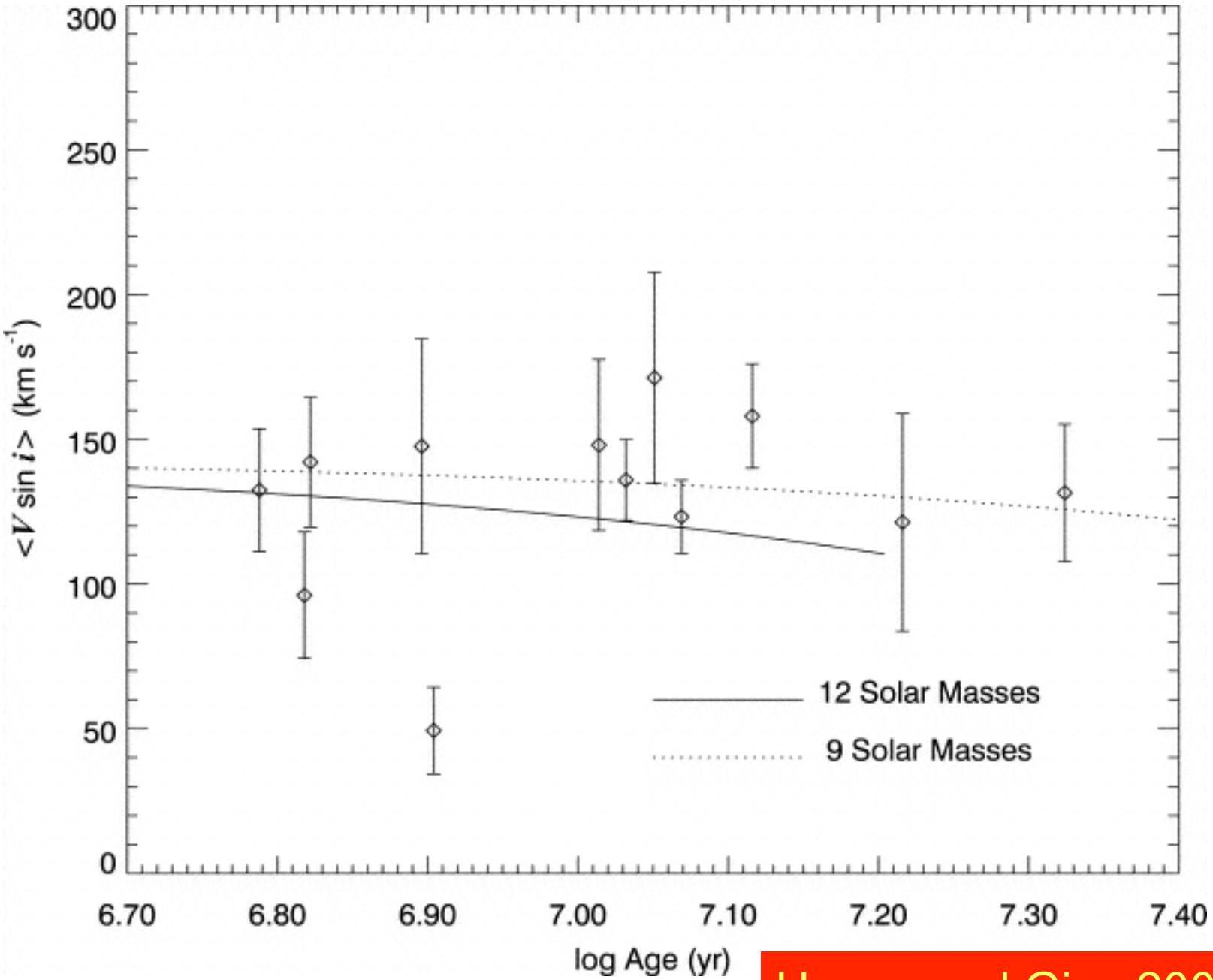
At the end of the MS, dominant
effect is the local conservation
of the angular momentum





V_{ini} (ZAMS)=300 km/s

<V> (MS) ~ 225 km/s



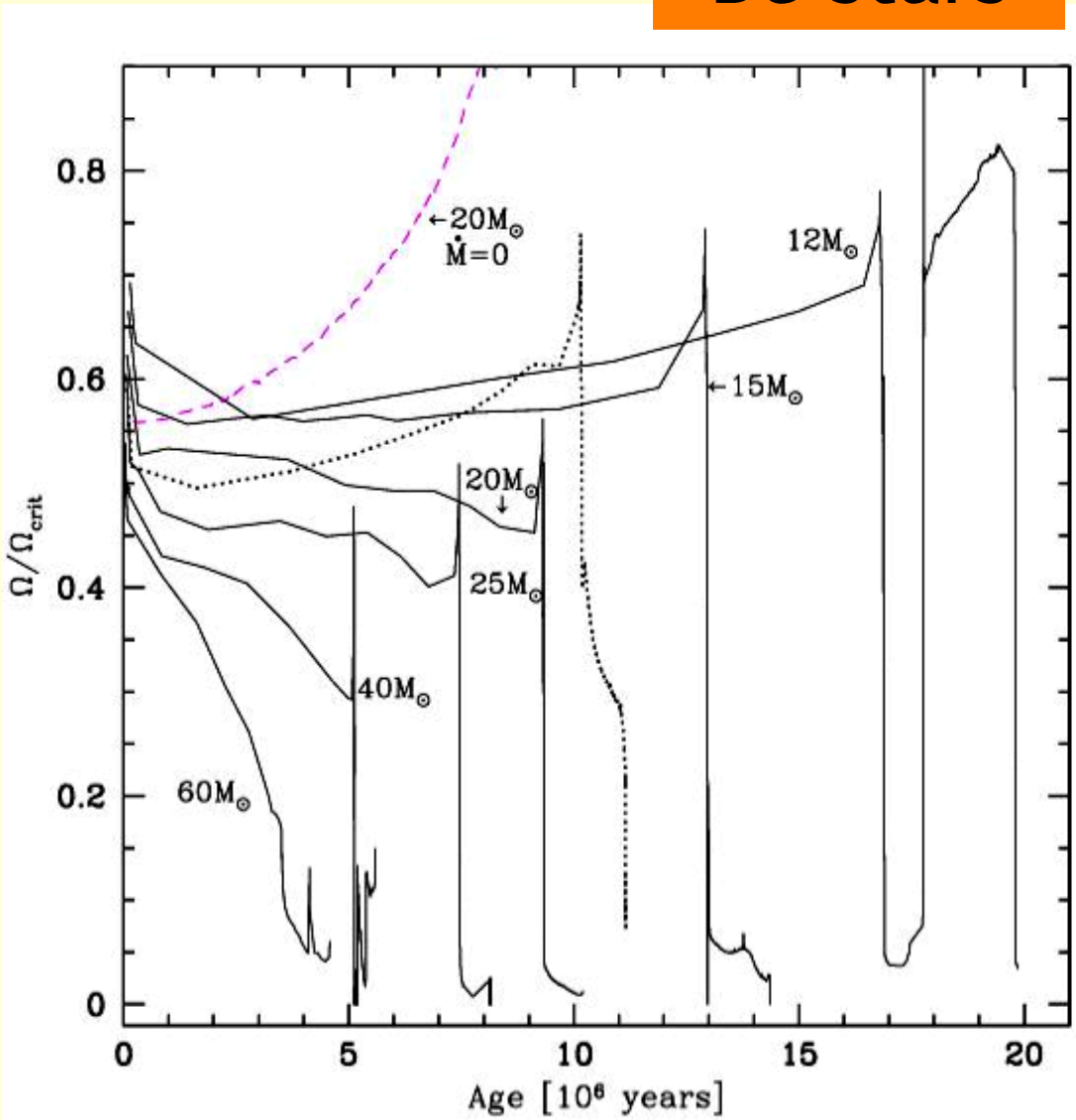
Huang and Gies 2006

Approach of the critical Velocity

Be stars

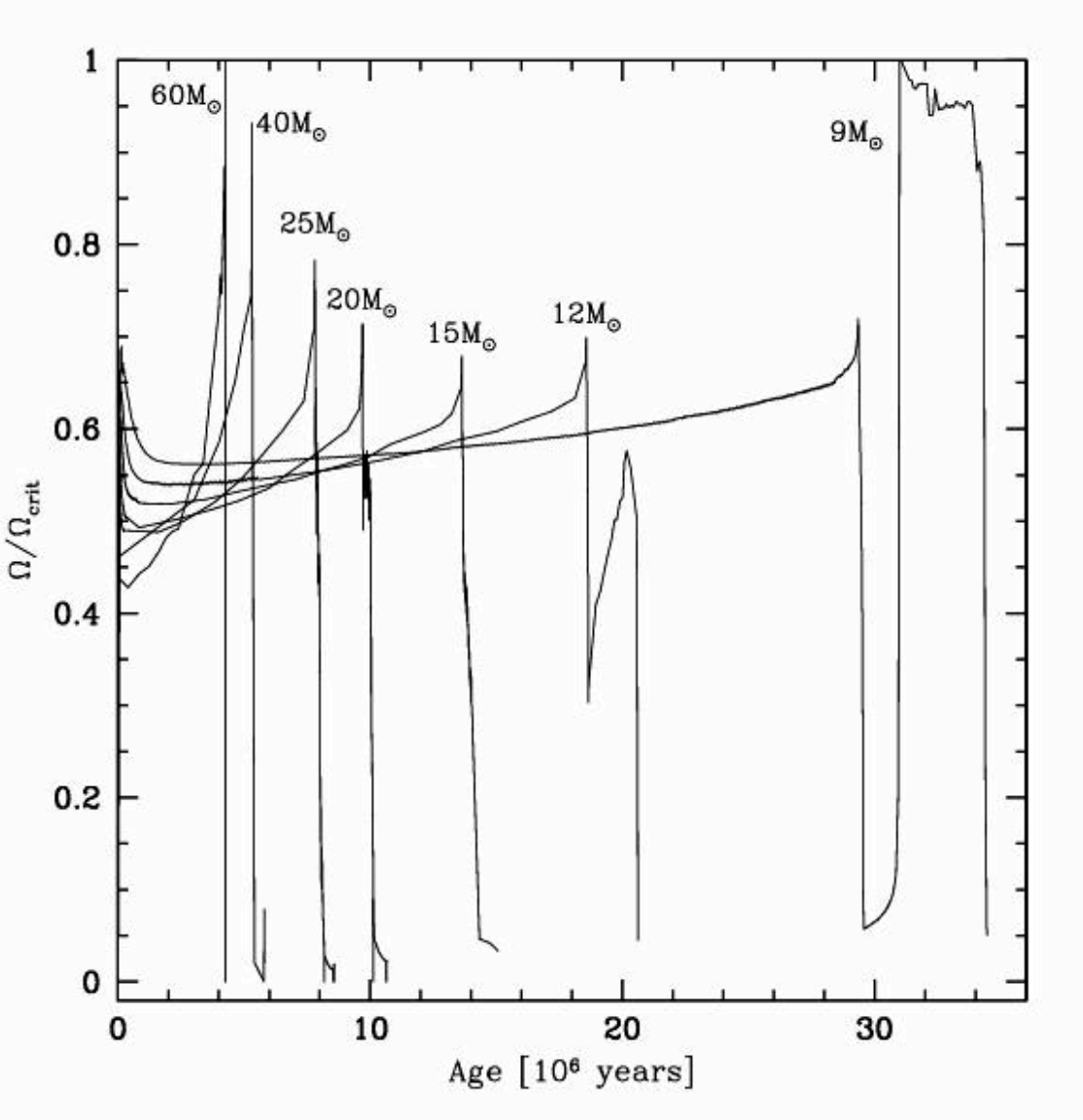
Z=0.02

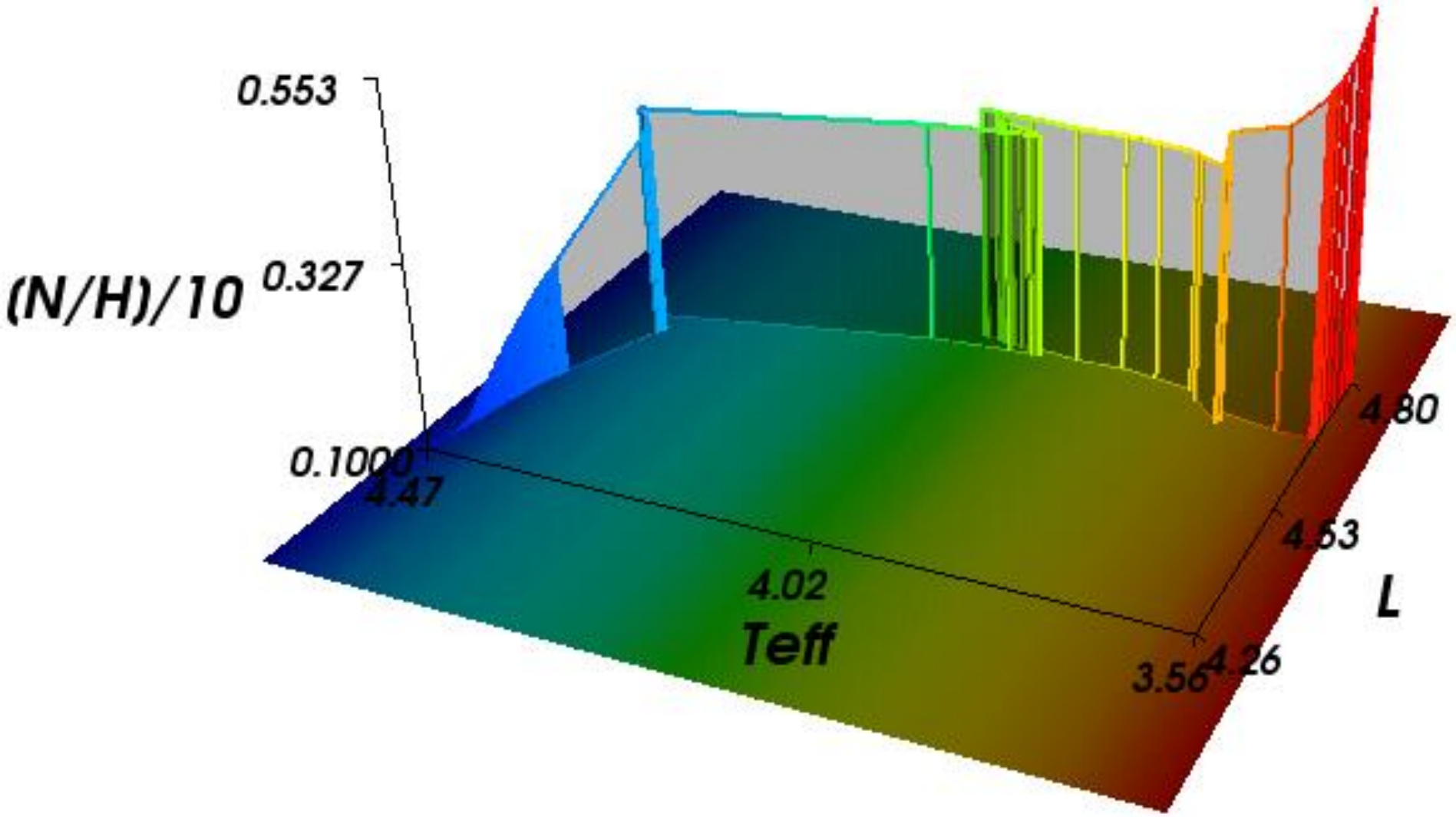
At Z=0.02, drastic decrease of velocity for high masses



Z=0.004

At lower Z, more stars reach break-up velocities.




0.553
(N/H)/10
0.327
0.1000
4.47
4.02
Teff
3.56
4.26
4.53
4.80
L

WHY MIXING IN MASSIVE STARS ?

$$\tau_{mix} = \frac{R^2}{D} = \frac{4K}{\alpha g \Delta\nabla_{ad}} \left[\frac{\nabla_{rad} - \nabla_{ad}}{\nabla_{rad} - \nabla_{ad} + \frac{\varphi}{\delta}\nabla_{\mu}} \right]$$

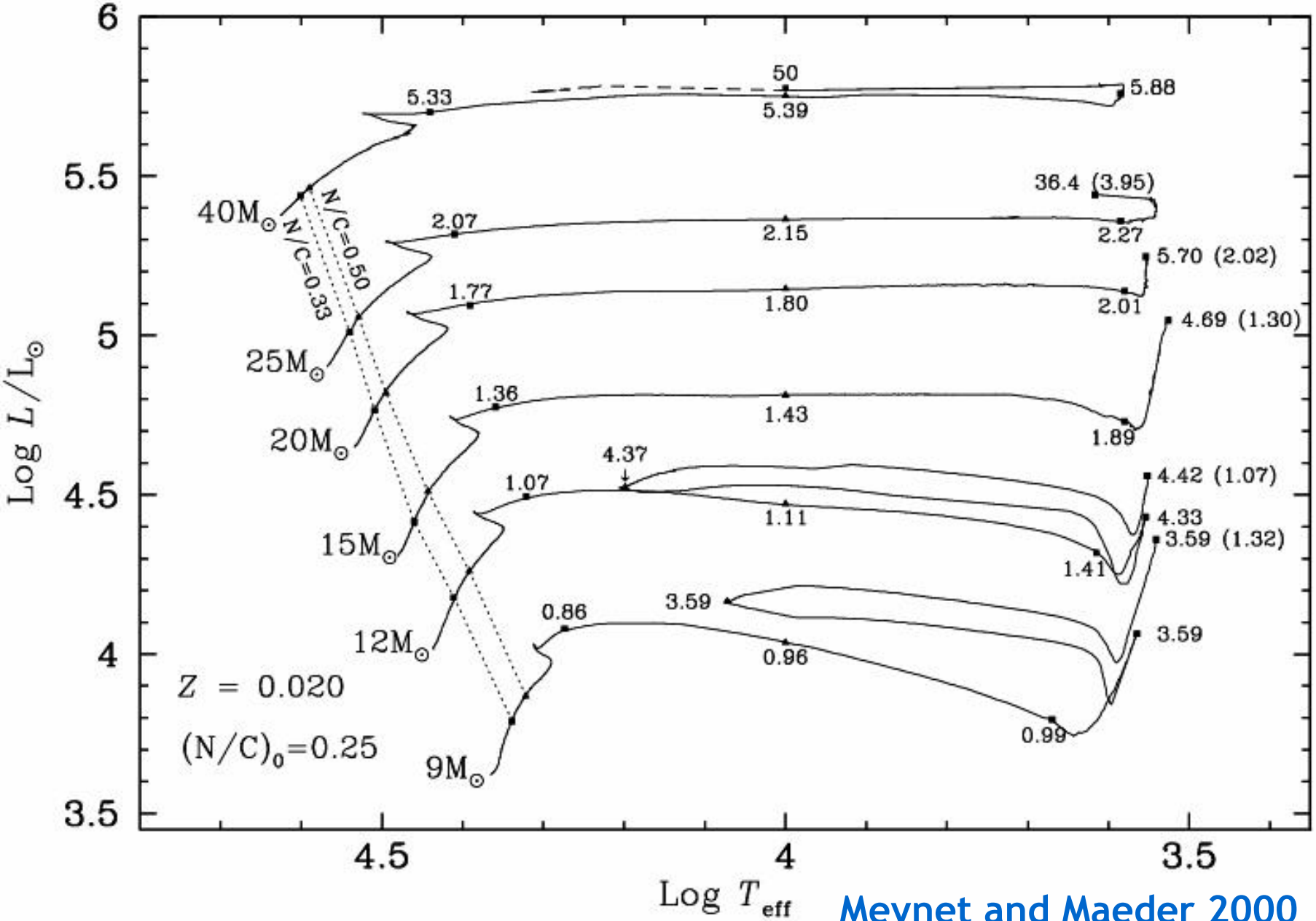
$$K = \frac{4acl^3}{3\kappa\rho c_P}$$

$$\tau_{mix} \approx \frac{1}{\kappa\rho l} \qquad \tau_{MS} \approx \frac{1}{\kappa\rho l}$$

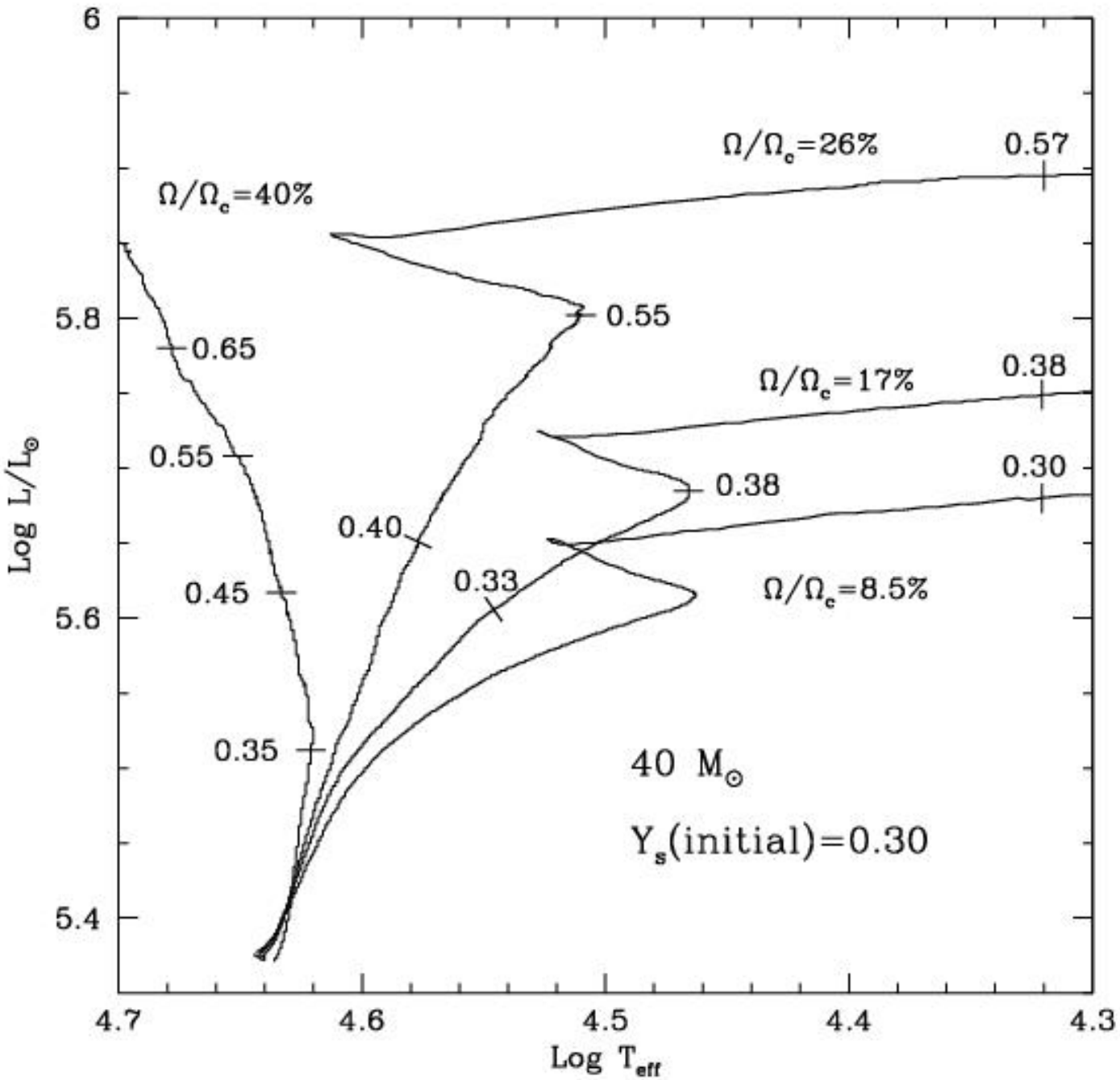
$$\frac{\tau_{mix}}{\tau_{MS}} \approx \frac{1}{M^4}$$

FOR HIGH M

MIXING TIME / MS TIMESCALE SMALL

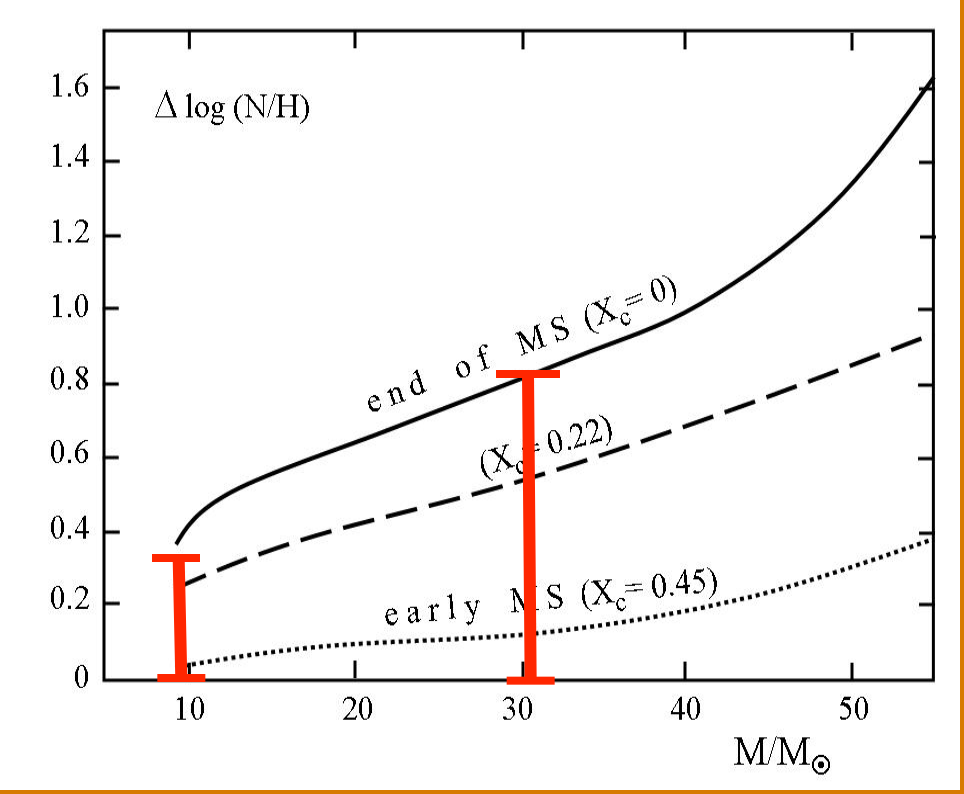


Meynet and Maeder 2000

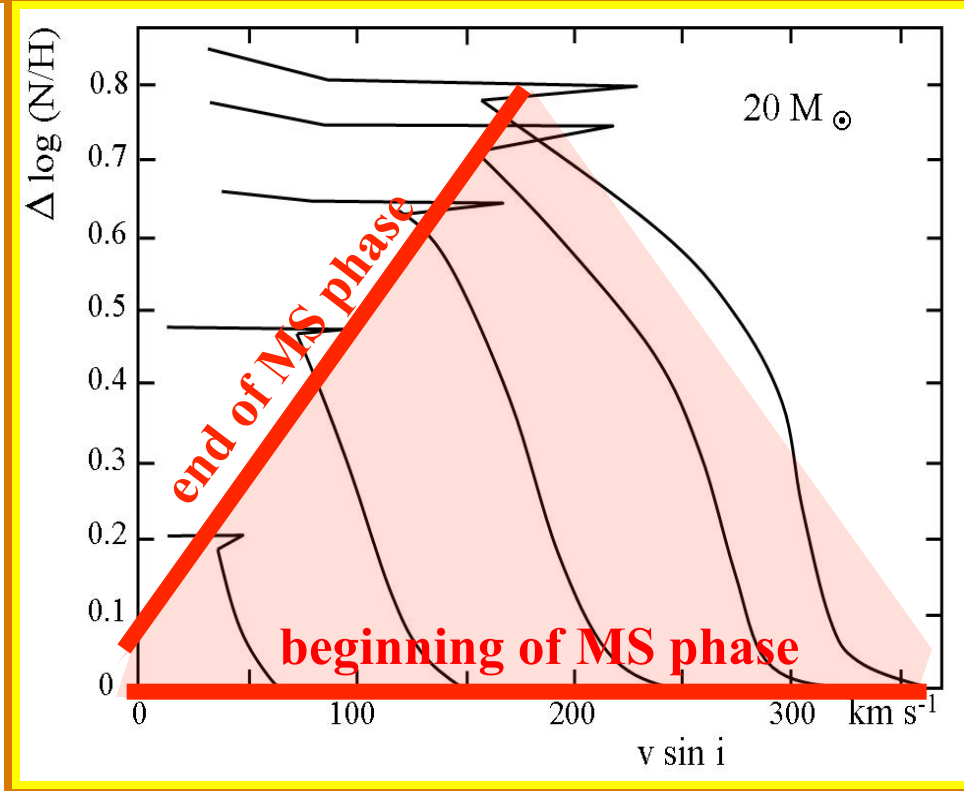

6
5.8
5.6
5.4
4.7
4.6
4.5
4.4
4.3
Log L/L⊙
Log T_eff
Ω/Ω_c=26%
0.57
Ω/Ω_c=40%
0.55
0.65
Ω/Ω_c=17%
0.38
0.55
0.38
0.30
0.40
0.33
0.45
Ω/Ω_c=8.5%
0.35
40 M⊙
Y_s(initial)=0.30

Reality: Δlog (N/H) = f(v sini, M, age, Z, binary, field ….)
not : Δlog (N/H) = f(v sini)

Mass effect

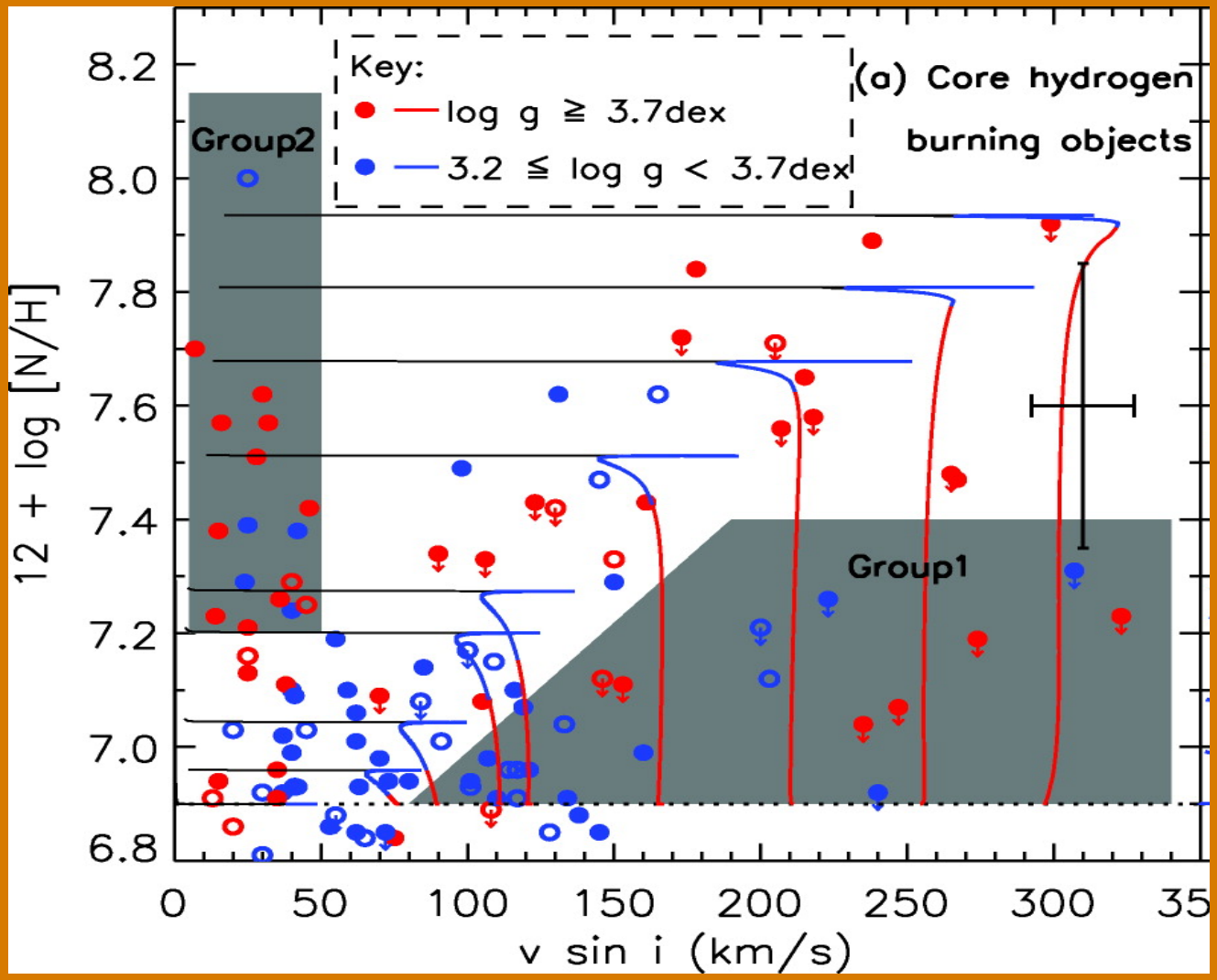


Age effect



Stars in extended regions around N11 and NGC 2004 in the LMC.

Spread in masses and ages.



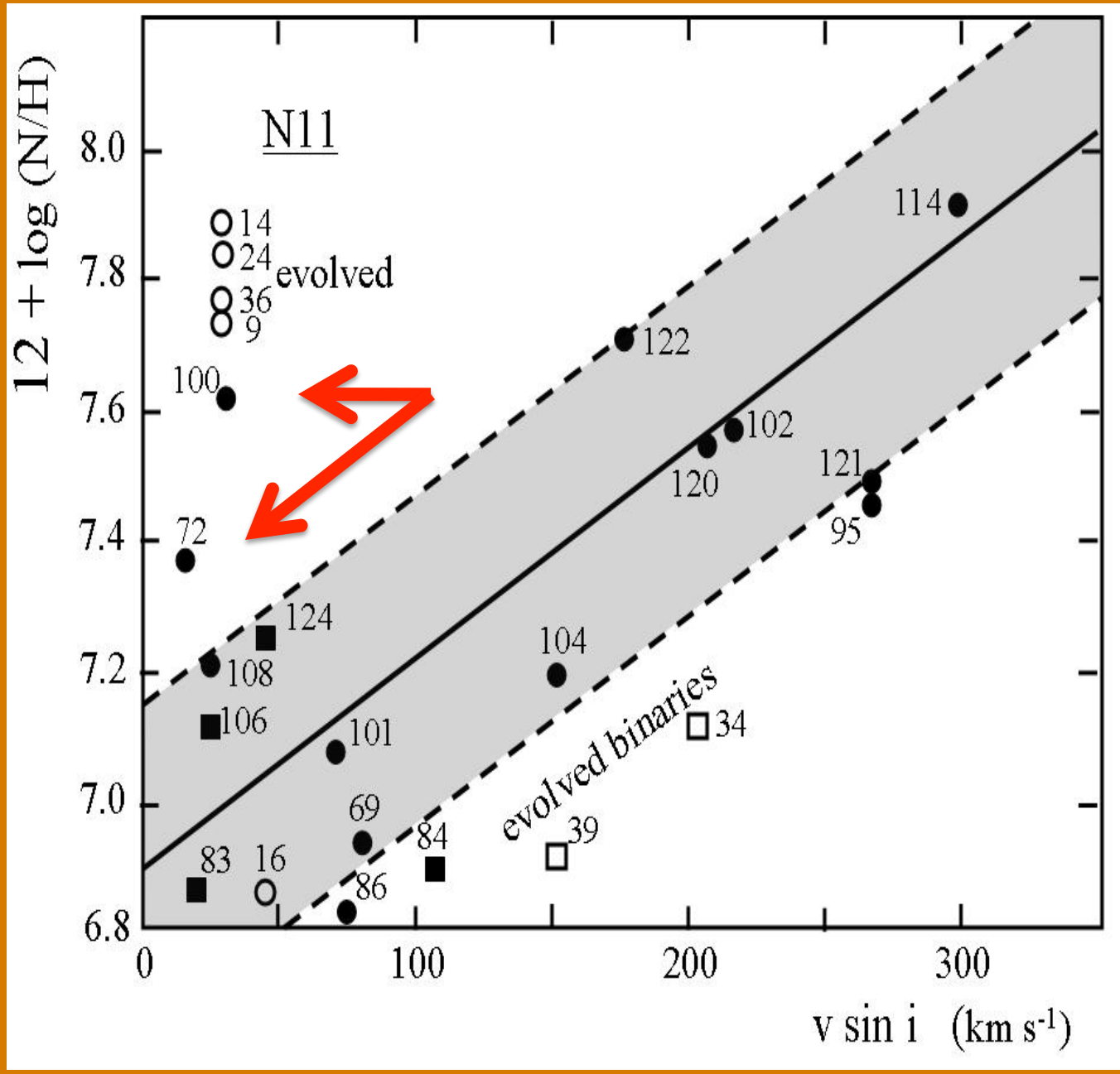
« The observation challenges the concept of rotational mixing »
Hunter et al. 2008

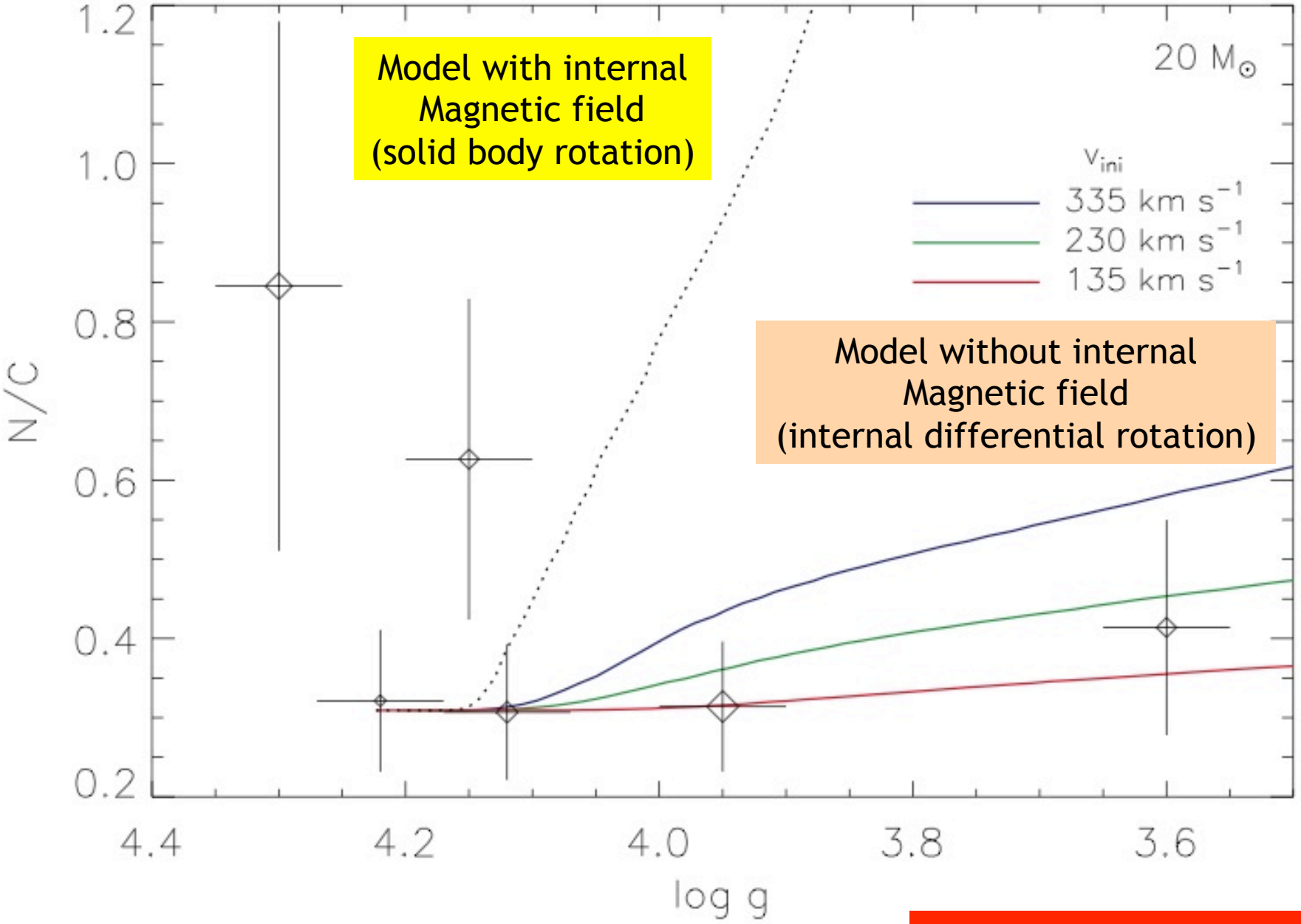
MS stars between 14 and 20 M_{sol} in the list by Hunter et al. 2008

Gr 1 disappeared, except binaries

Gr 2 : mainly evolved stars

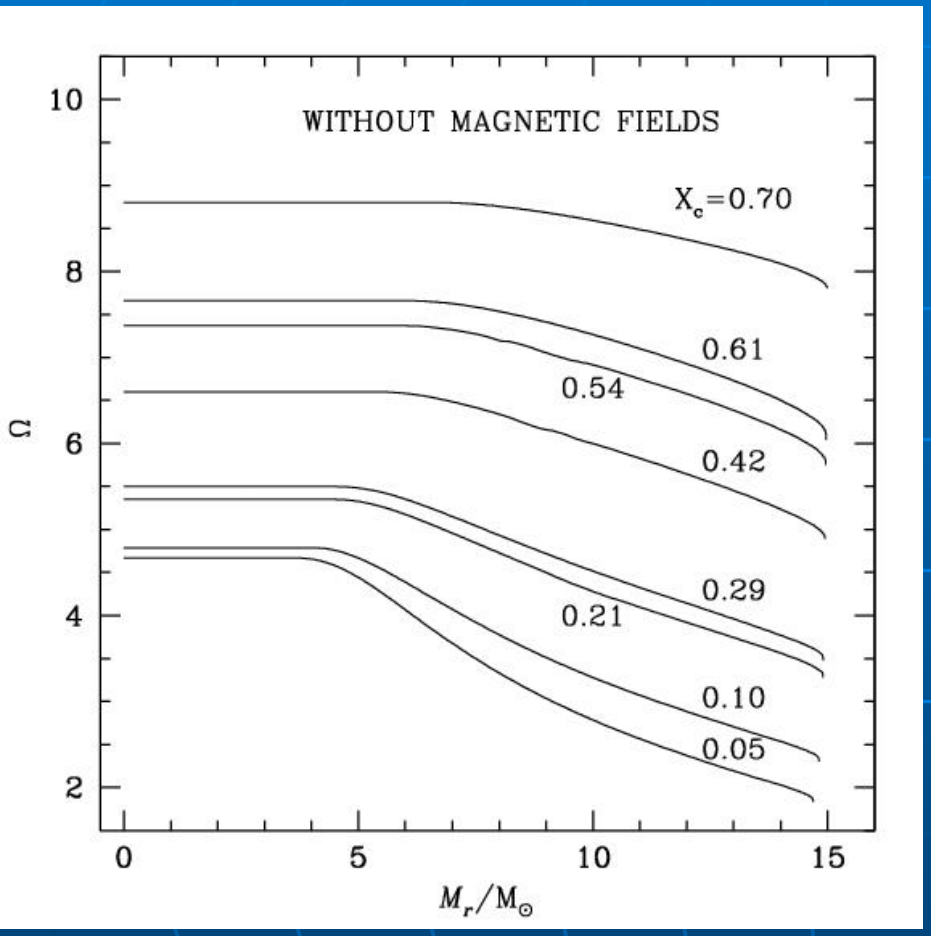
In Hunter et al. '08
- no account of gravity darkening
- no separation of gravity changes due to rotation and evolution

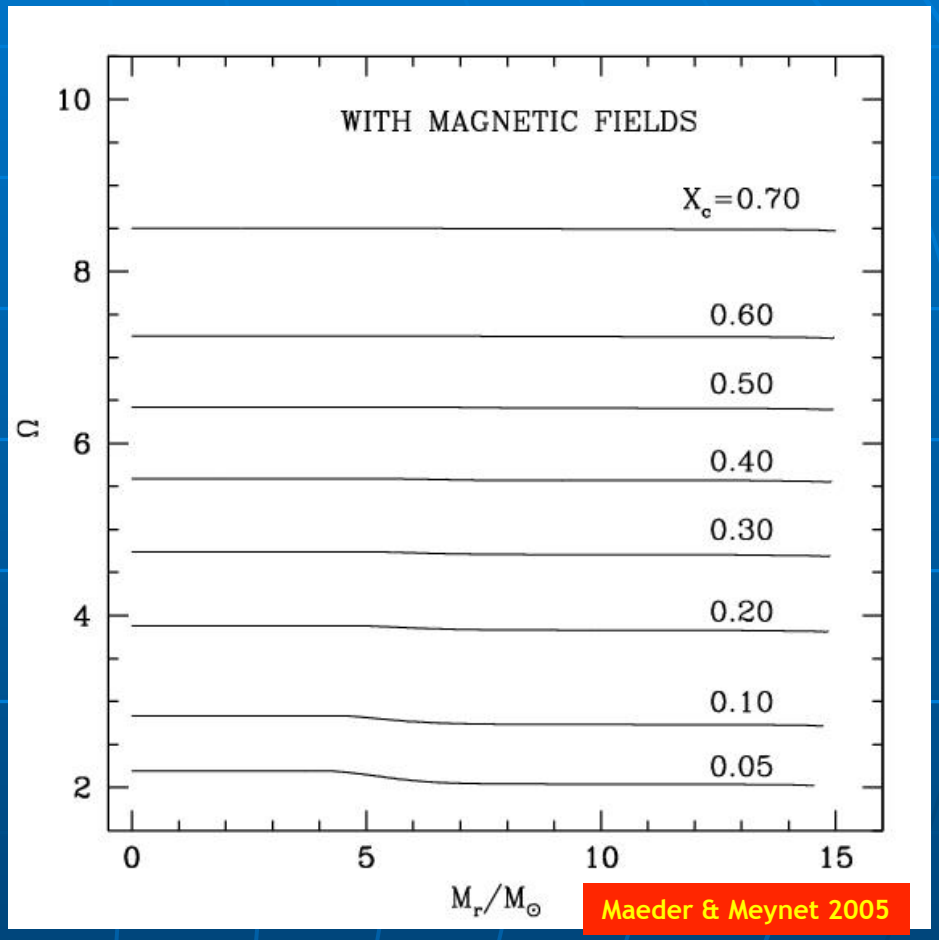




Przybilla et al. 2010

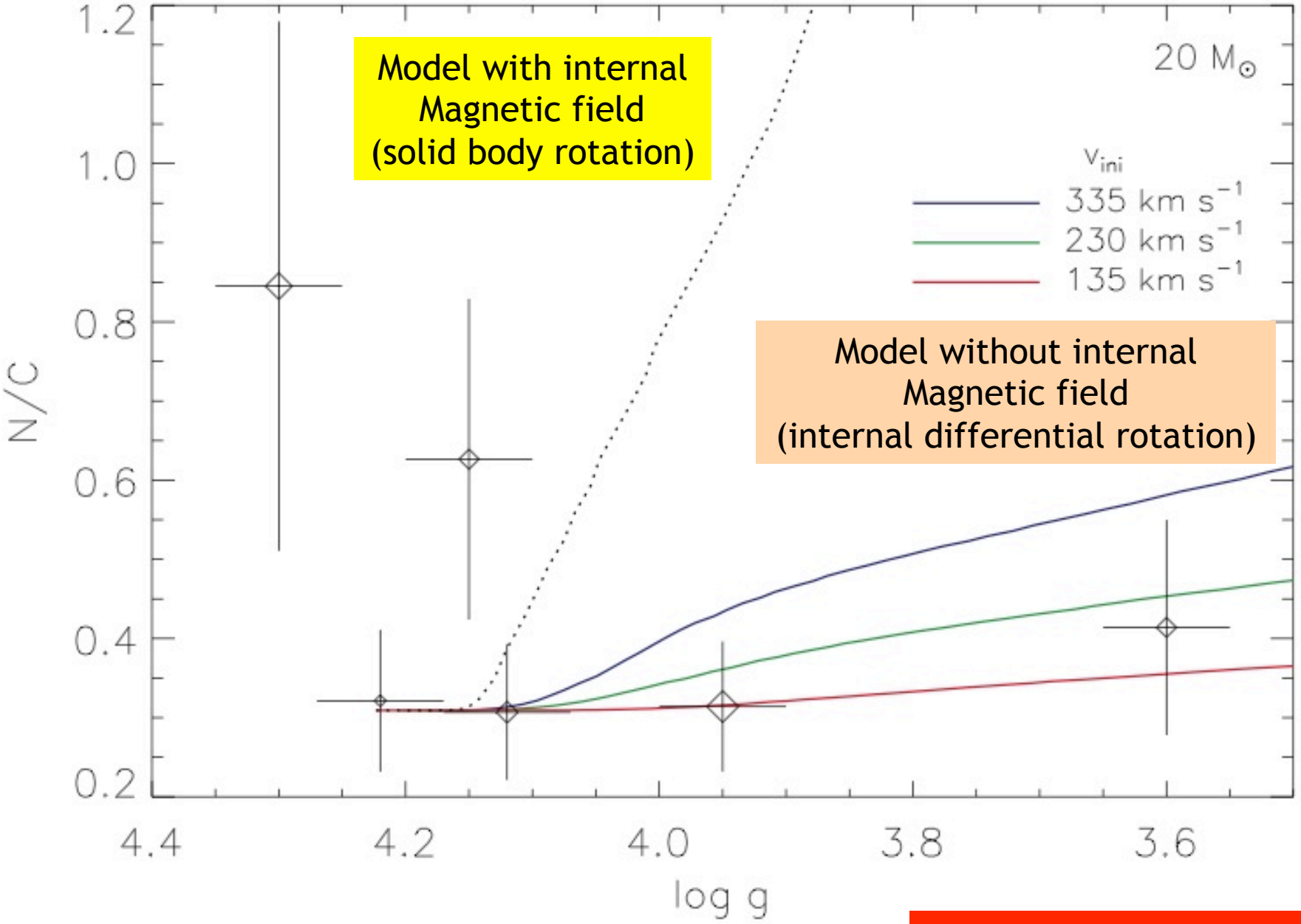
15 M_{sol}, Z=0.020, V_{ini}=300 km s^{-1}





Maeder & Meynet 2005

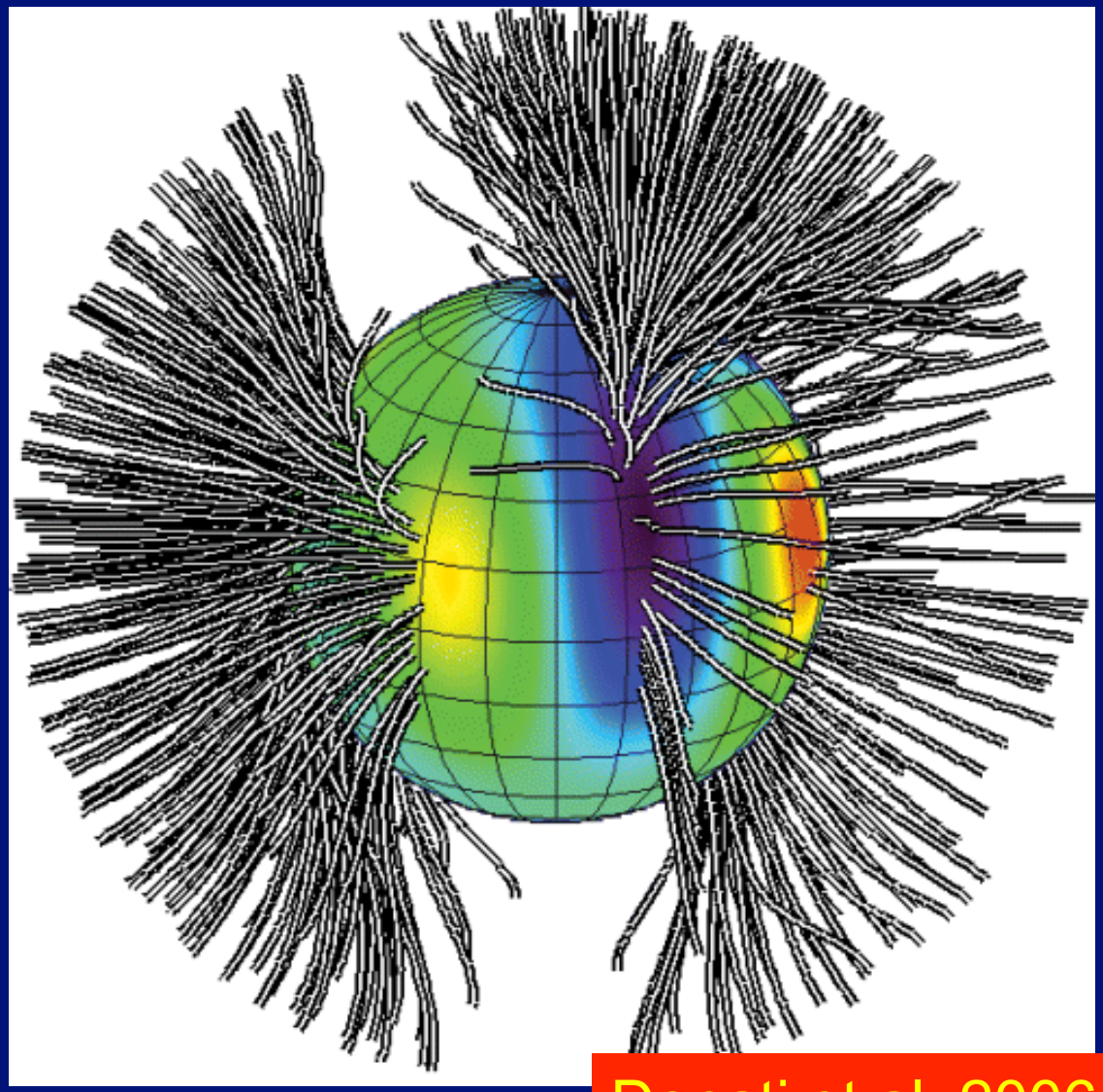
INTERNAL MAGNETIC FIELDS (10^4-10^5 G)
→ SOLID BODY ROTATION



Przybilla et al. 2010

SURFACE MAGNETIC FIELDS

τ Sco



Donati et al. 2006

External magnetic field

$$\eta(r) \equiv \frac{B^2/8\pi}{\rho v^2/2}$$

if $\eta > 1$ → wind behavior

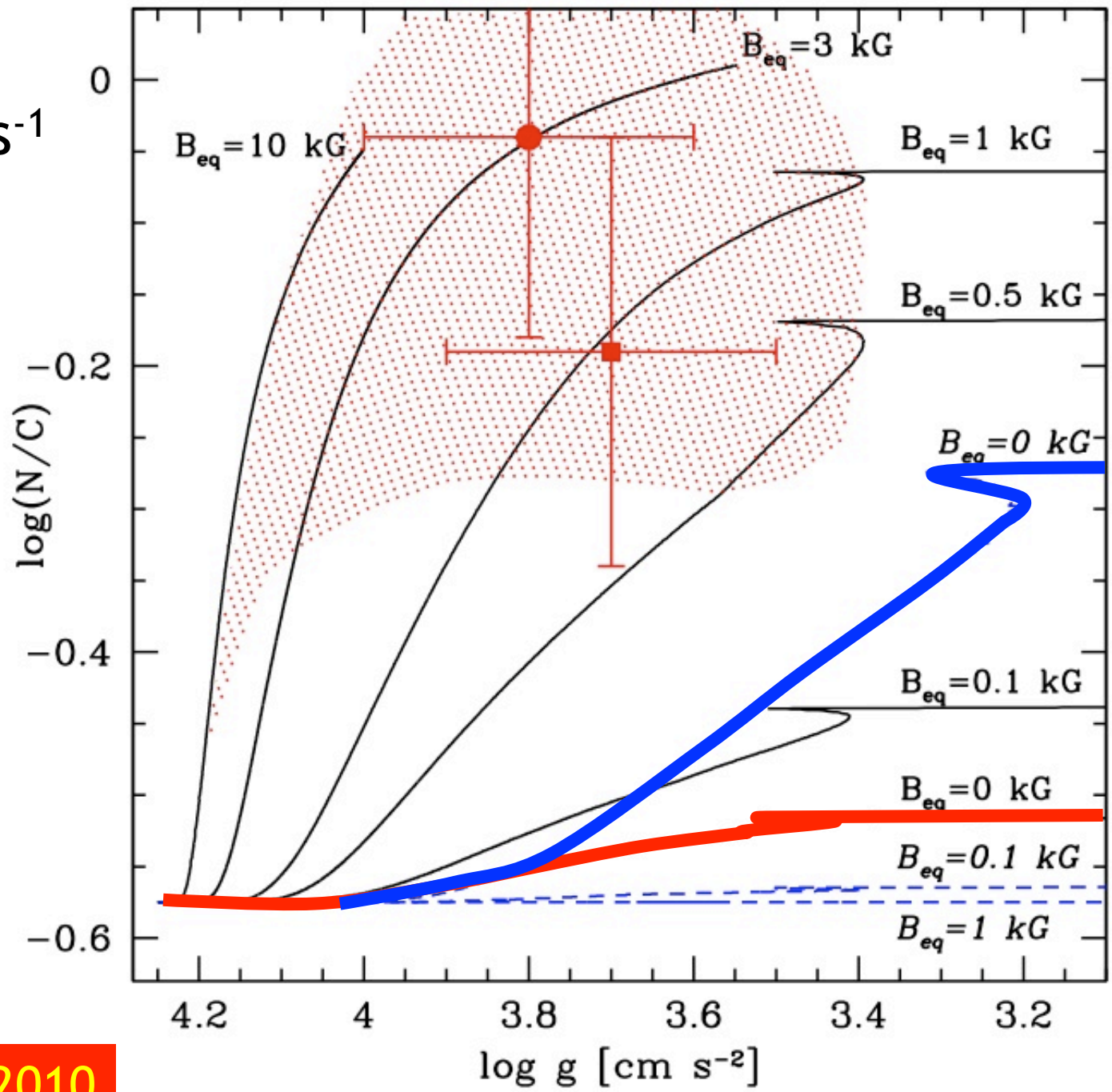
ud-Doula & Owocki (2002)

$$\frac{\mathrm{d}J}{\mathrm{d}t} = \frac{2}{3}\dot{M}\Omega R_*^2[0.29 + (\eta_* + 0.25)^{1/4}]^2$$

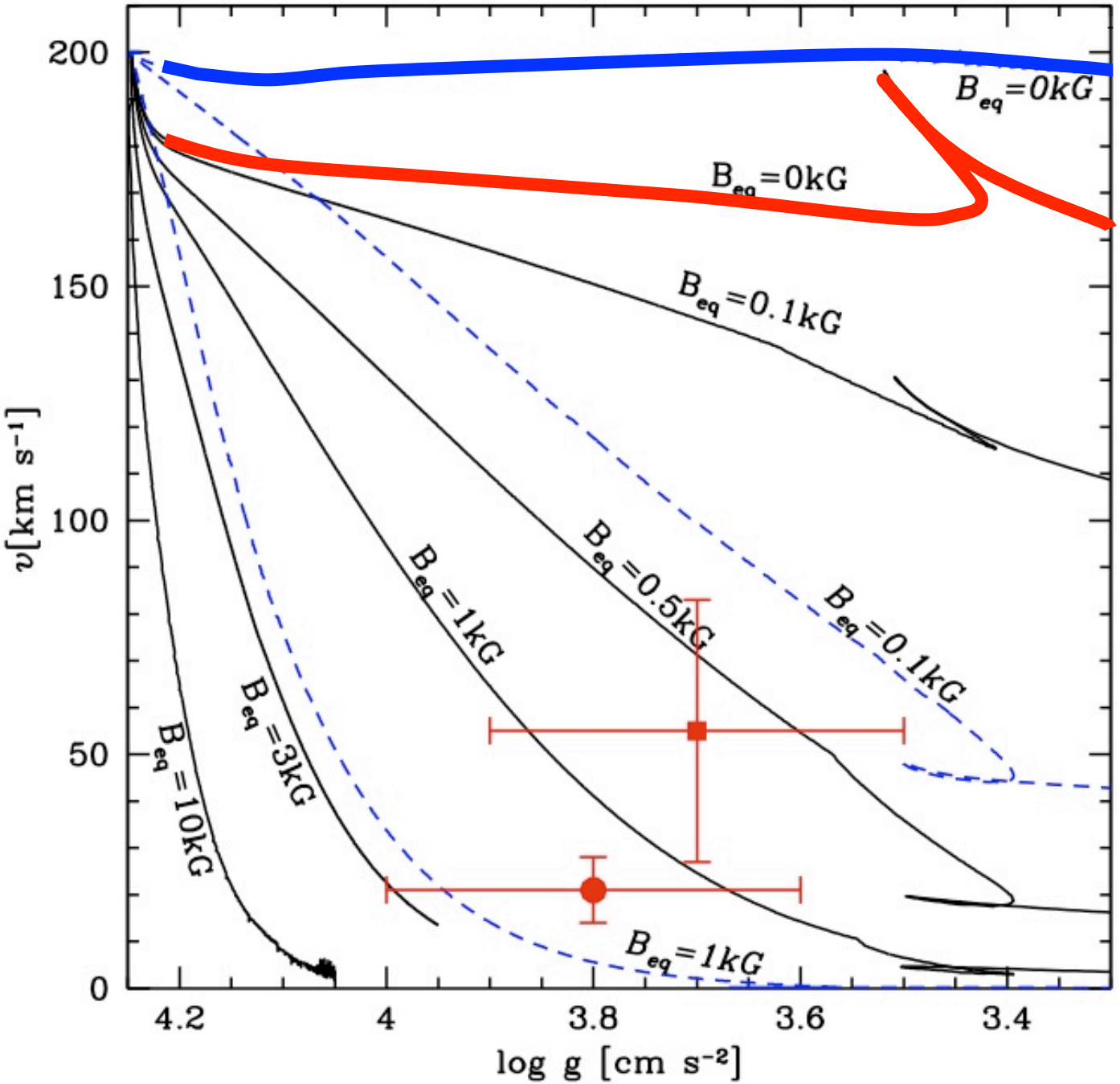
10 M_{sol}

V_{ini}=200 km s^{-1}

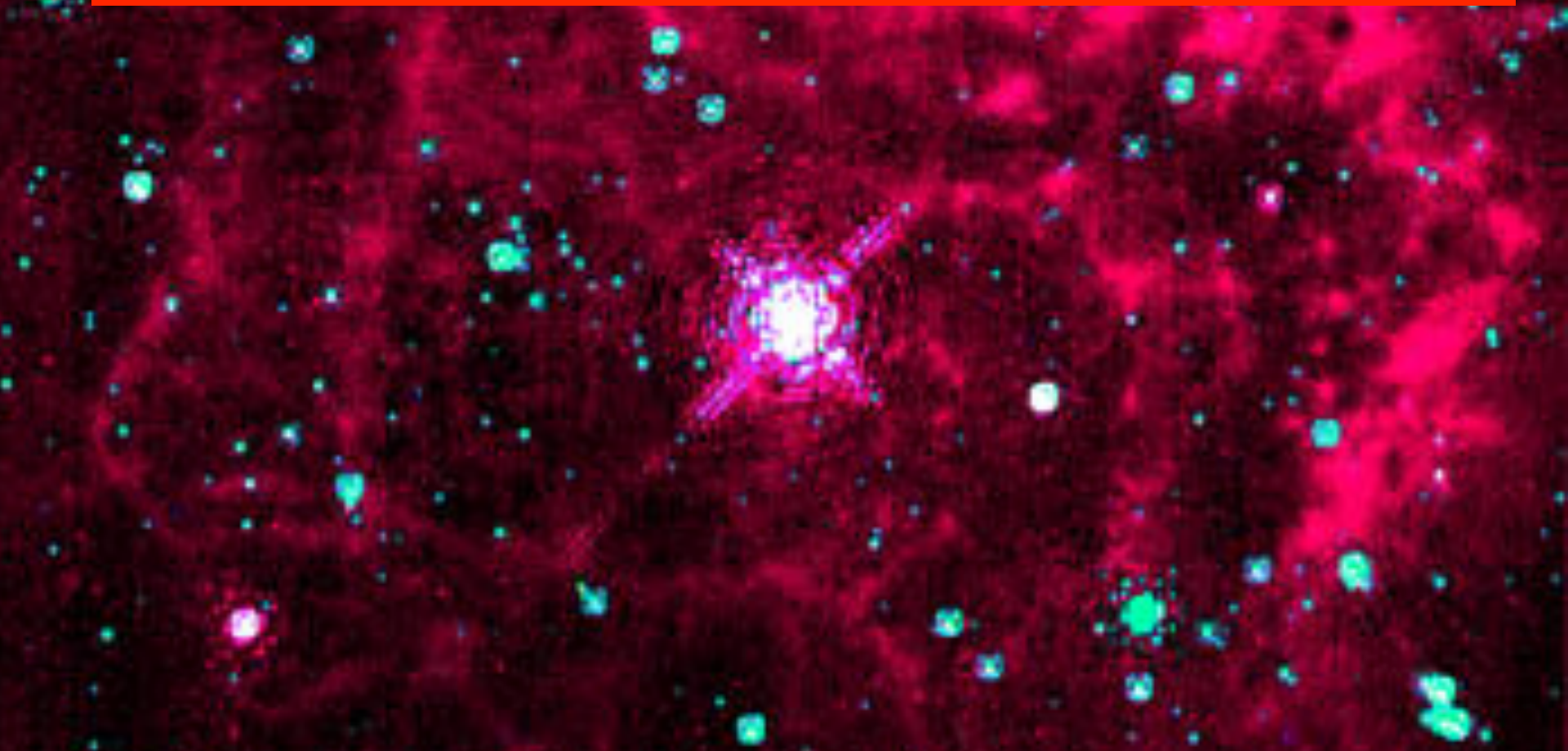
Z=0.014



Meynet et al. 2010


200
150
100
50
0
4.2
4
3.8
3.6
3.4
v[km s⁻¹]
log g [cm s⁻²]
B_eq=0kG
B_eq=0kG
B_eq=0.1kG
B_eq=0.1kG
B_eq=0.5kG
B_eq=1kG
B_eq=1kG
B_eq=3kG
B_eq=10kG

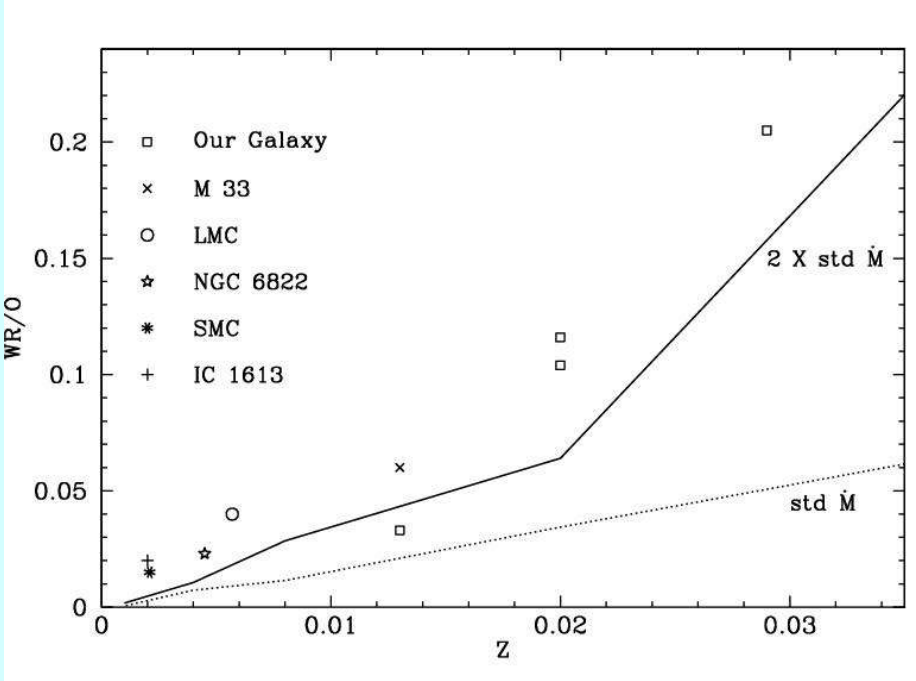
Effect of Rotation on Wolf-Rayet and Supergiant populations



Remaining problems with WR stars

Possible to reproduce the WR/O number ratios observed at different Z only using models with enhanced mass loss rates

Maeder and Meynet 94

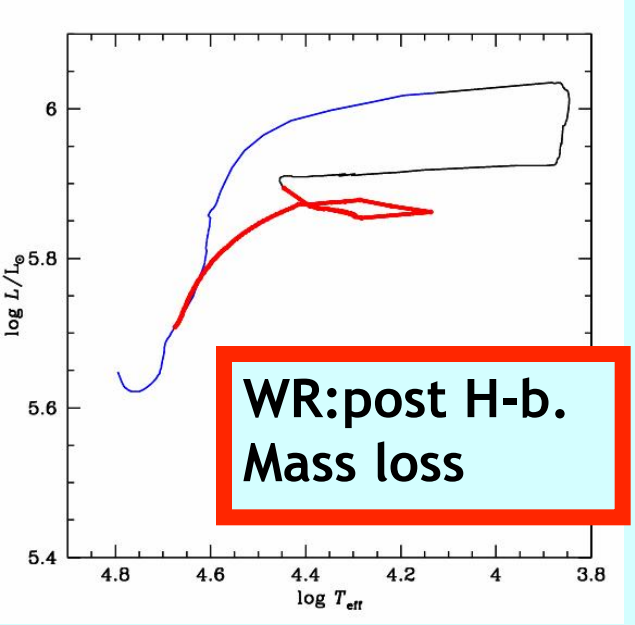


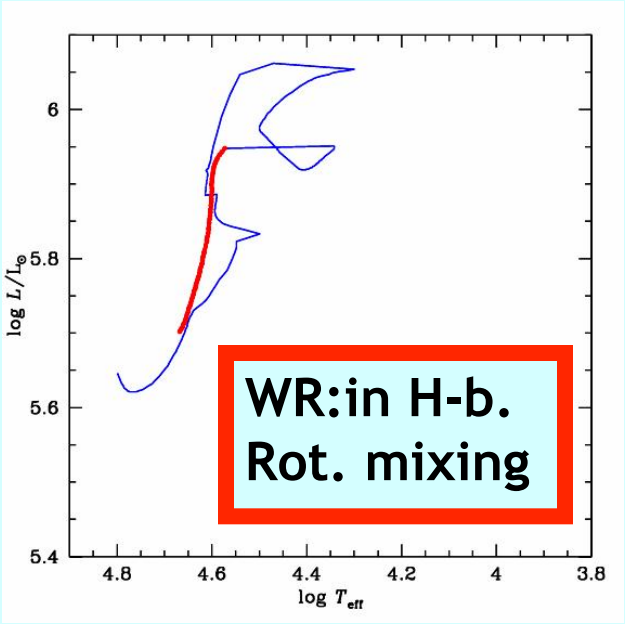
Not satisfactory ! Clumping in the winds of hot stars tends to reduce the observed mass loss rates by a factor 2 to 3

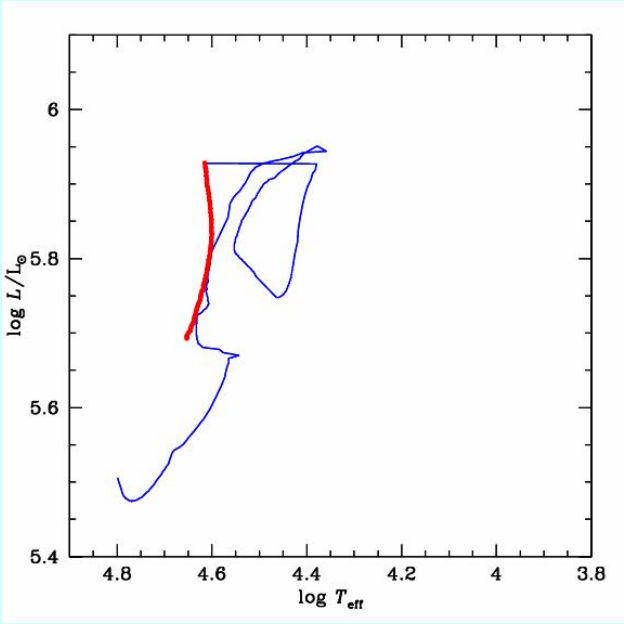
Nugis et al 98; Hamann and Koesterke 98

Other difficulties ⇒ Observation →smooth transition from high surface abundances to H-free atmospheres

⇒ Observed number of stars in the transition WN/WC phase (Conti & Massey 89; Langer 91; Crowther 95,02)



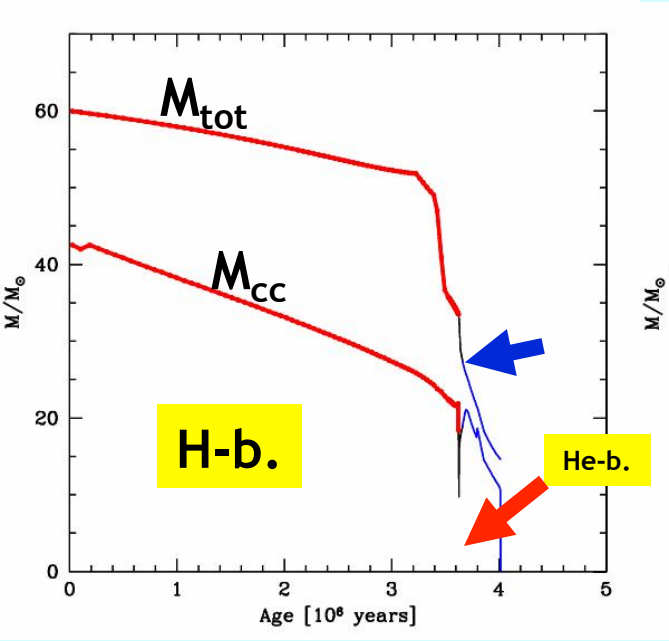


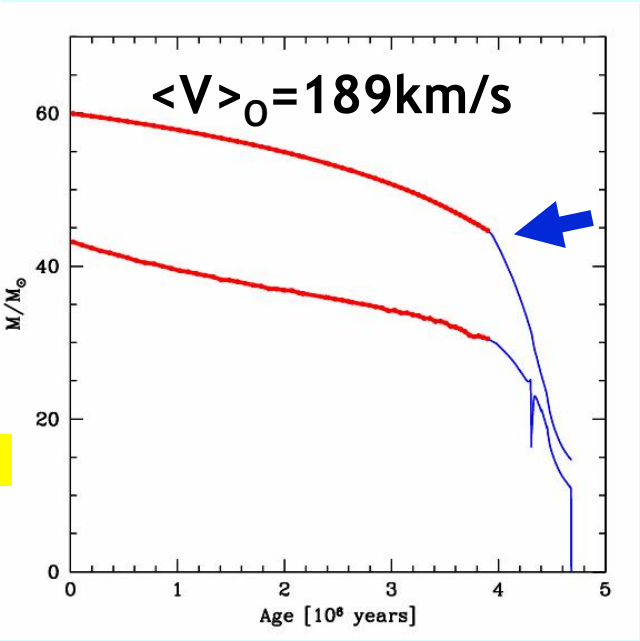


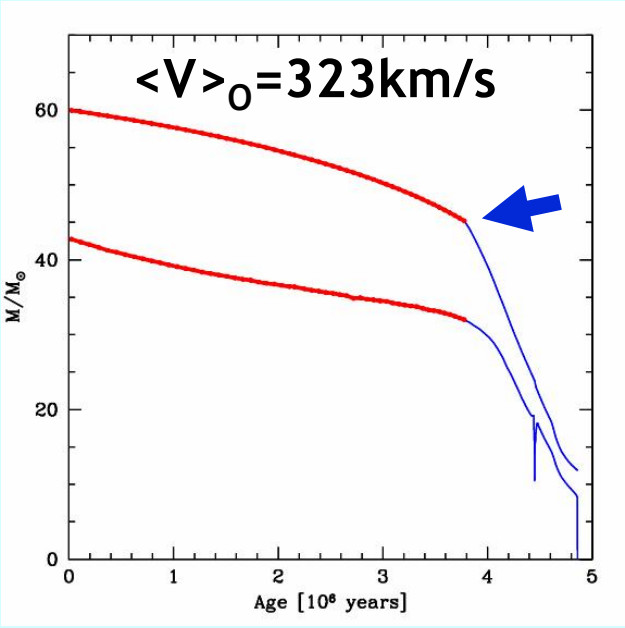
60 Msol, v_{ini}= 0 km s^{-1}

v_{ini}= 300 km s^{-1}

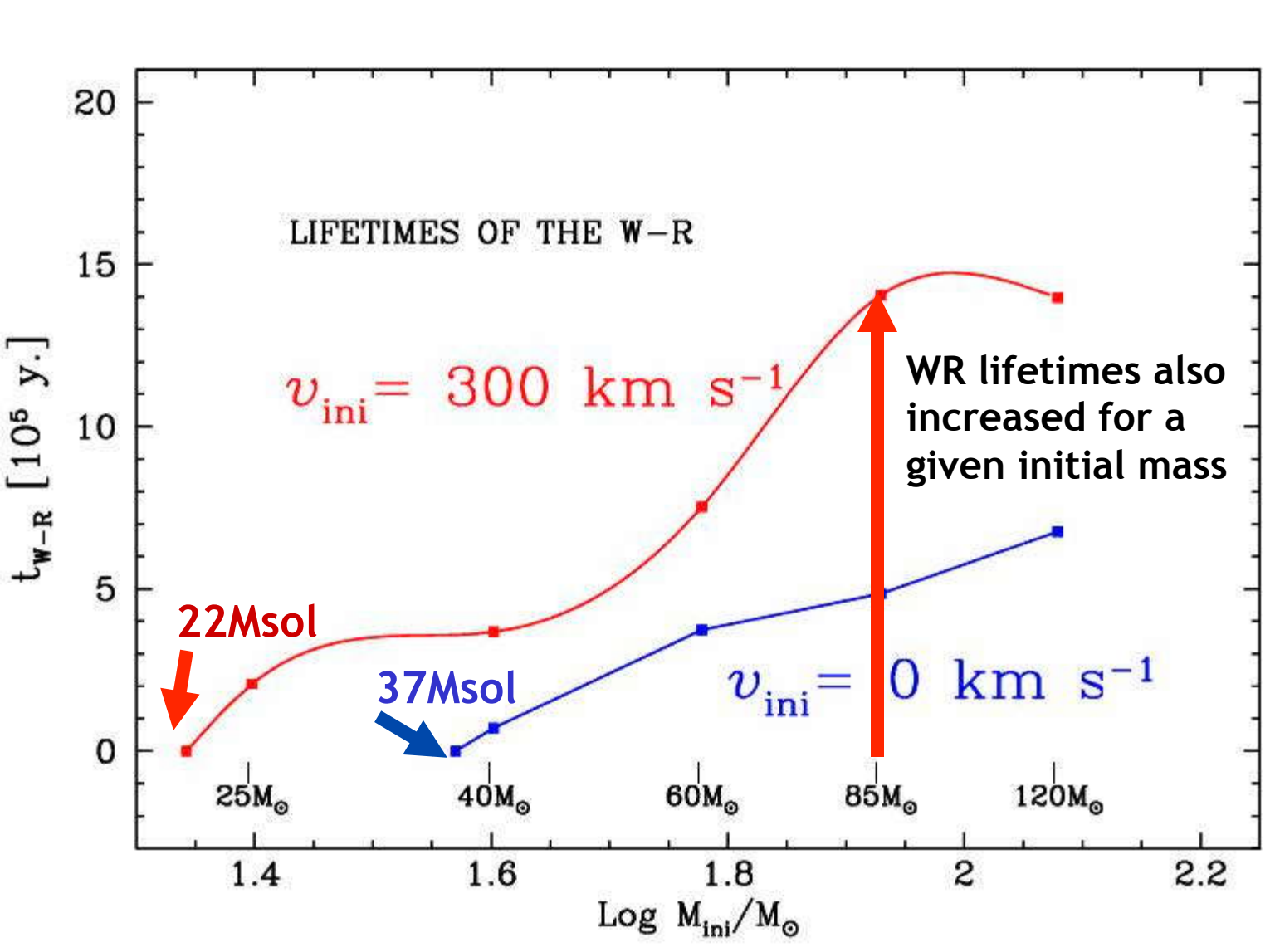
v_{ini}= 500 km s^{-1}

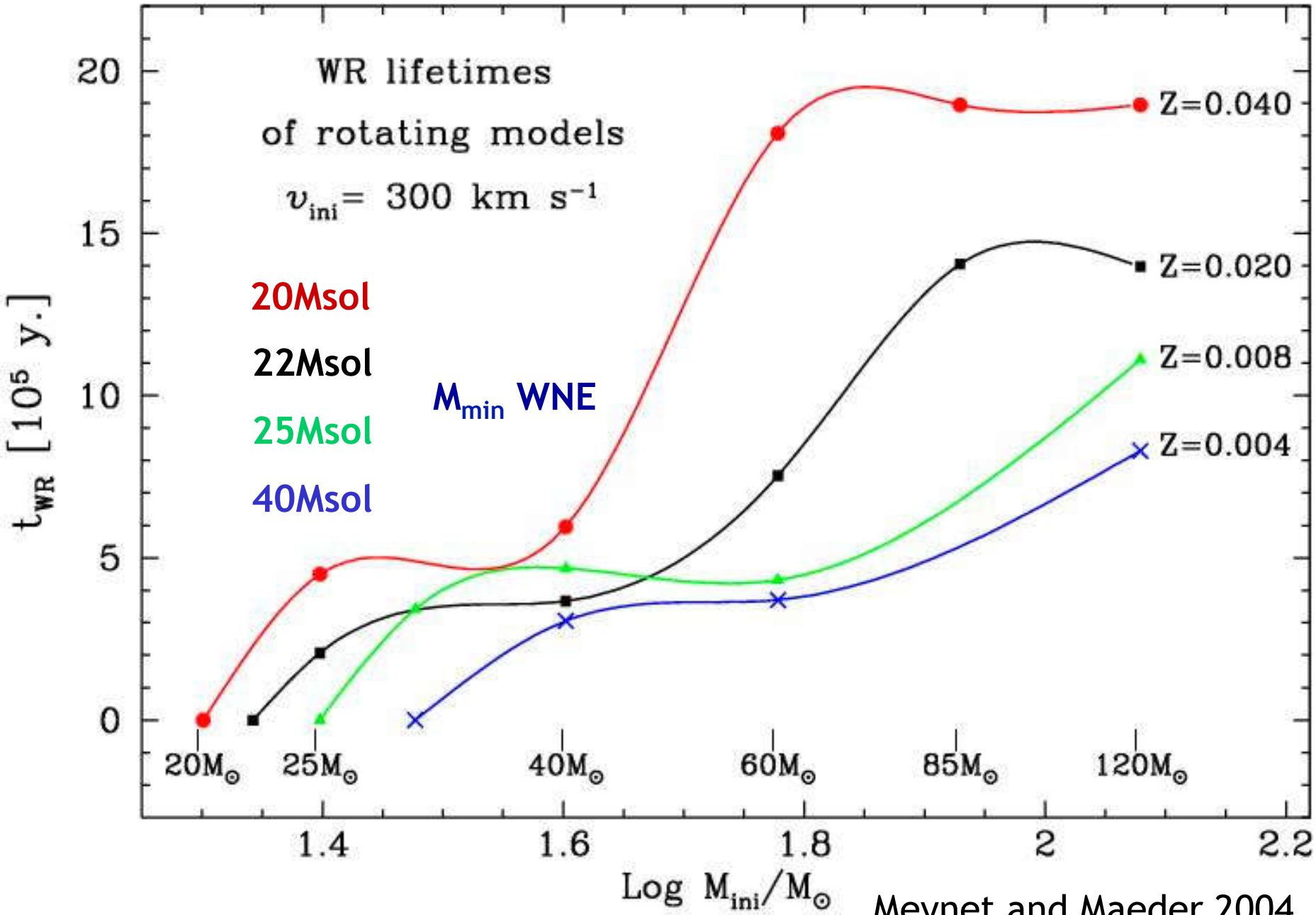




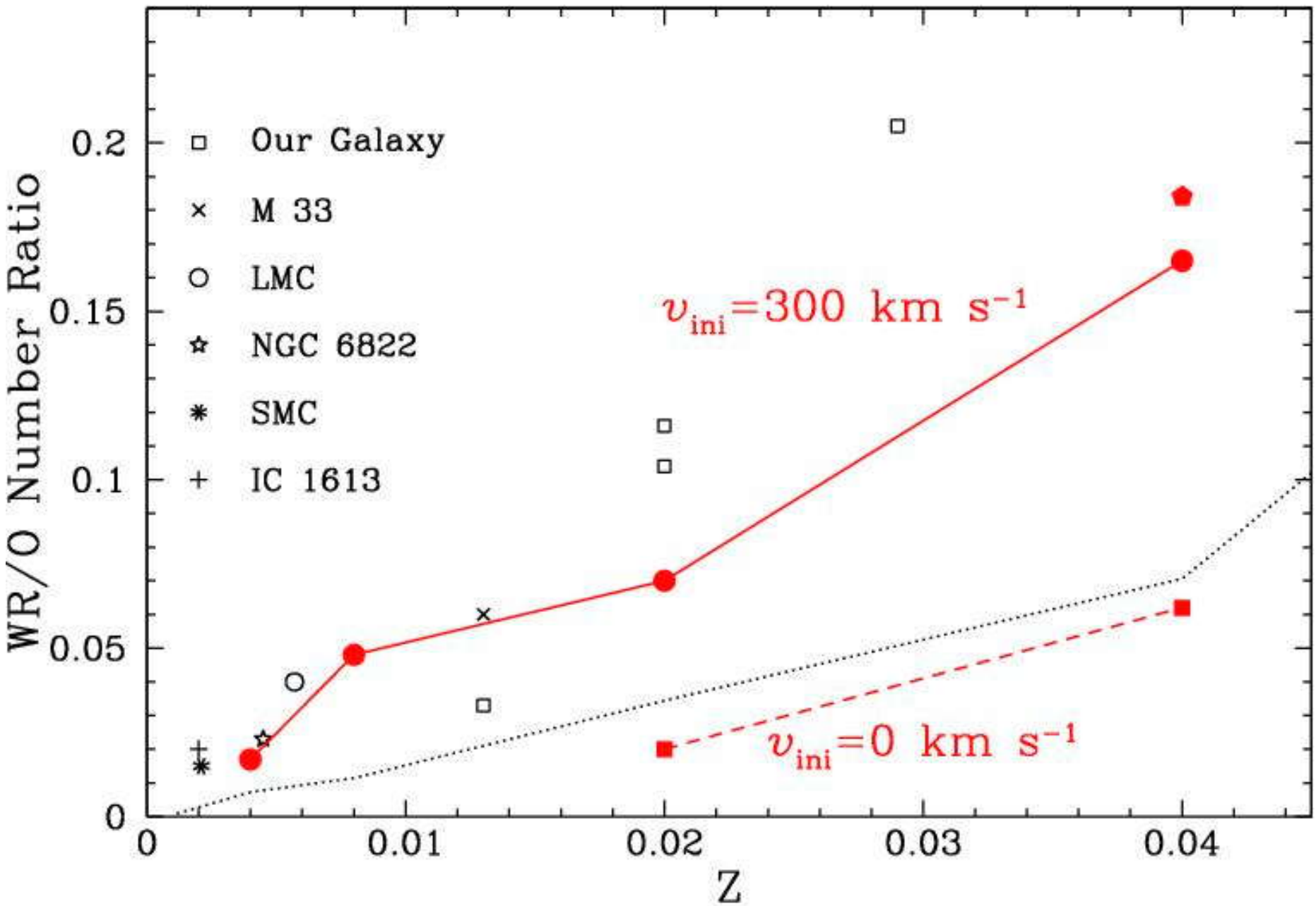


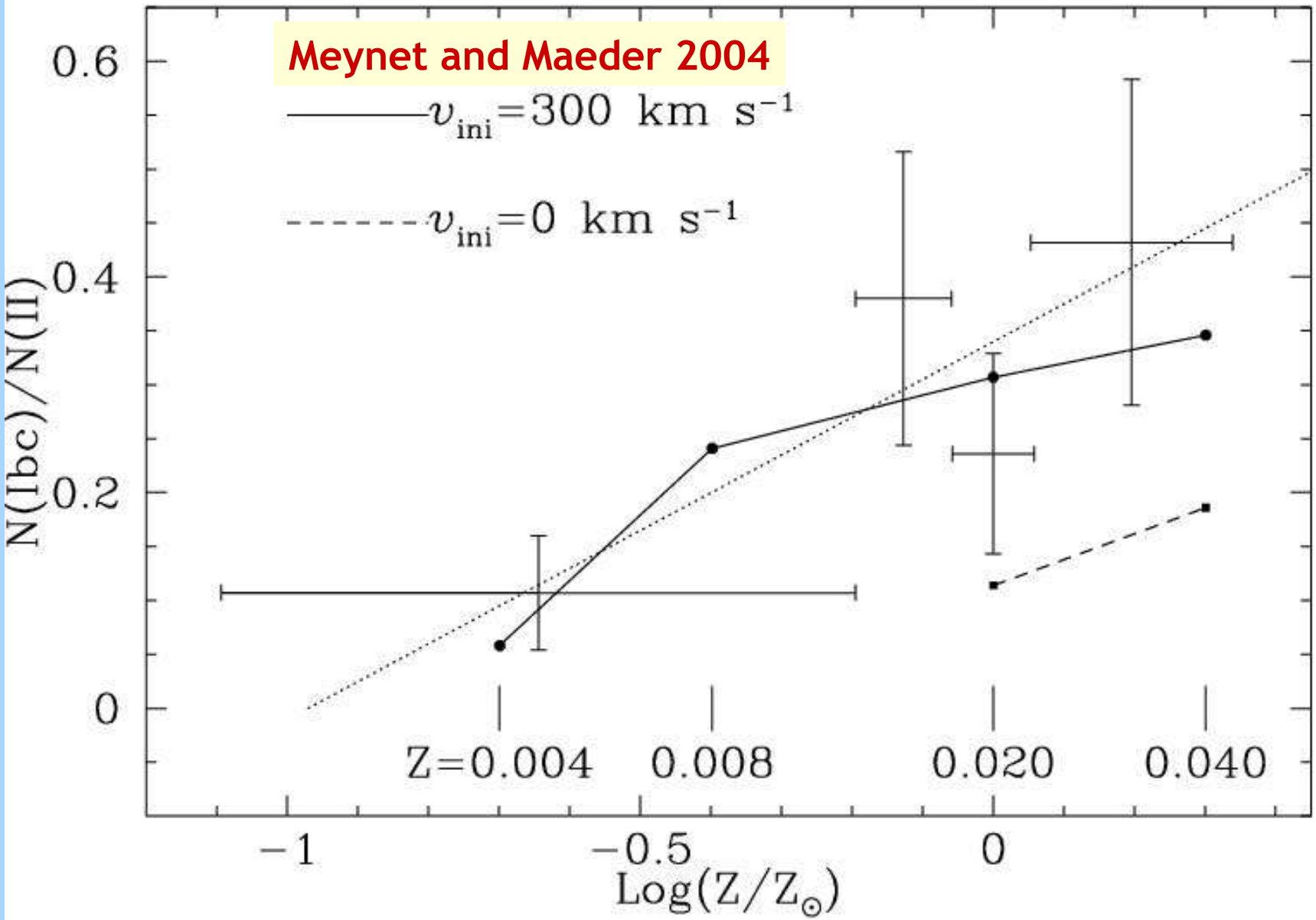
For a given metallicity, the minimum initial mass of single stars which become Wolf-Rayet star is decreased for higher rotation velocities



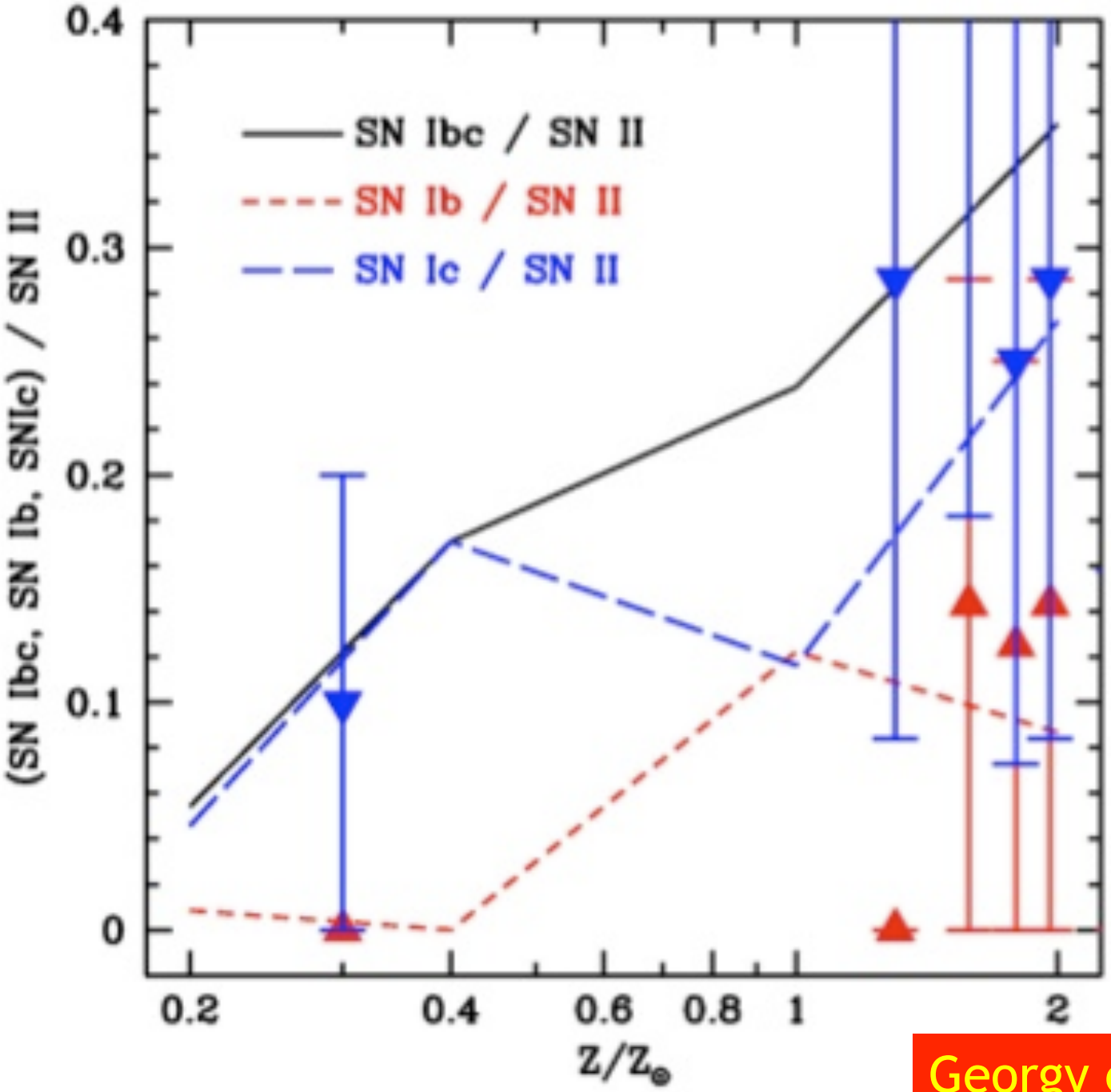


Meynet and Maeder 2004


Our Galaxy
M 33
LMC
NGC 6822
SMC
IC 1613
v_{ini}=300 km s^{-1}
v_{ini}=0 km s^{-1}
WR/O Number Ratio
Z
0
0.05
0.1
0.15
0.2
0.01
0.02
0.03
0.04

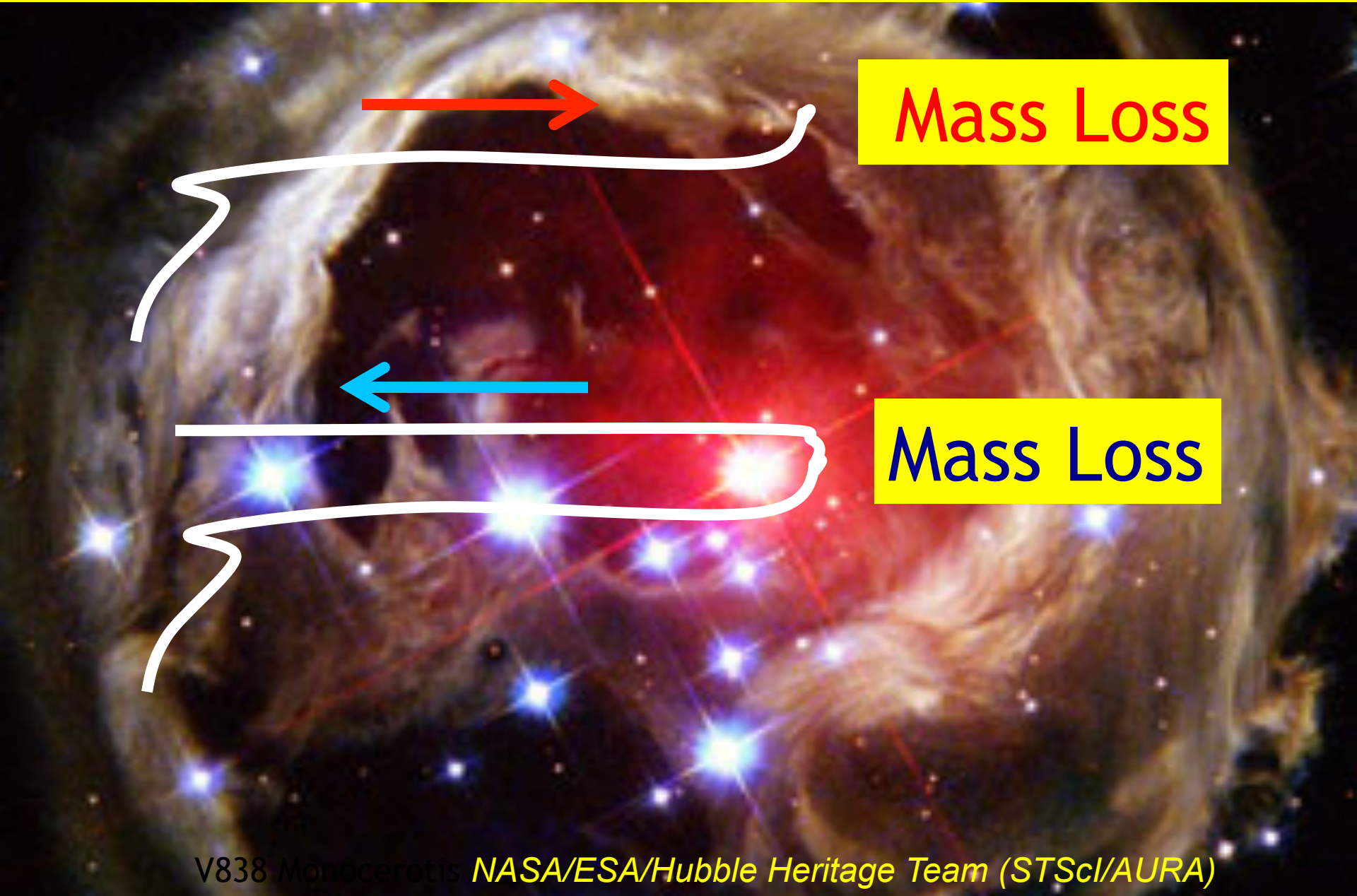


Observed points from Prantzos and Boissier (2003)



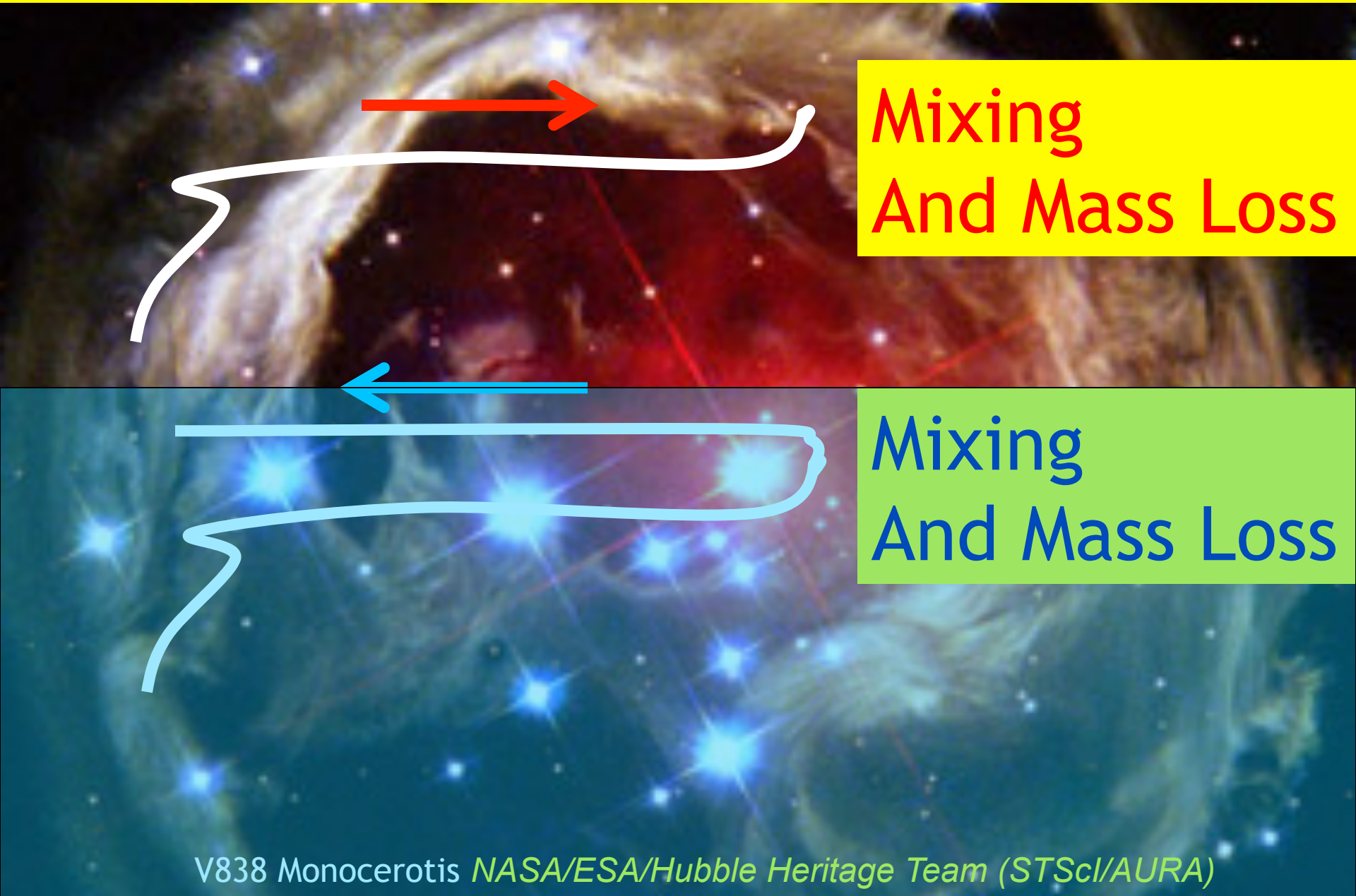
Georgy et al. 2009

WHAT ARE THE FACTORS DETERMINING THE TIME SPENT AS RSG FOR A SINGLE GIVEN INITIAL MASS STAR?



V838 Monocerotis *NASA/ESA/Hubble Heritage Team (STScI/AURA)*

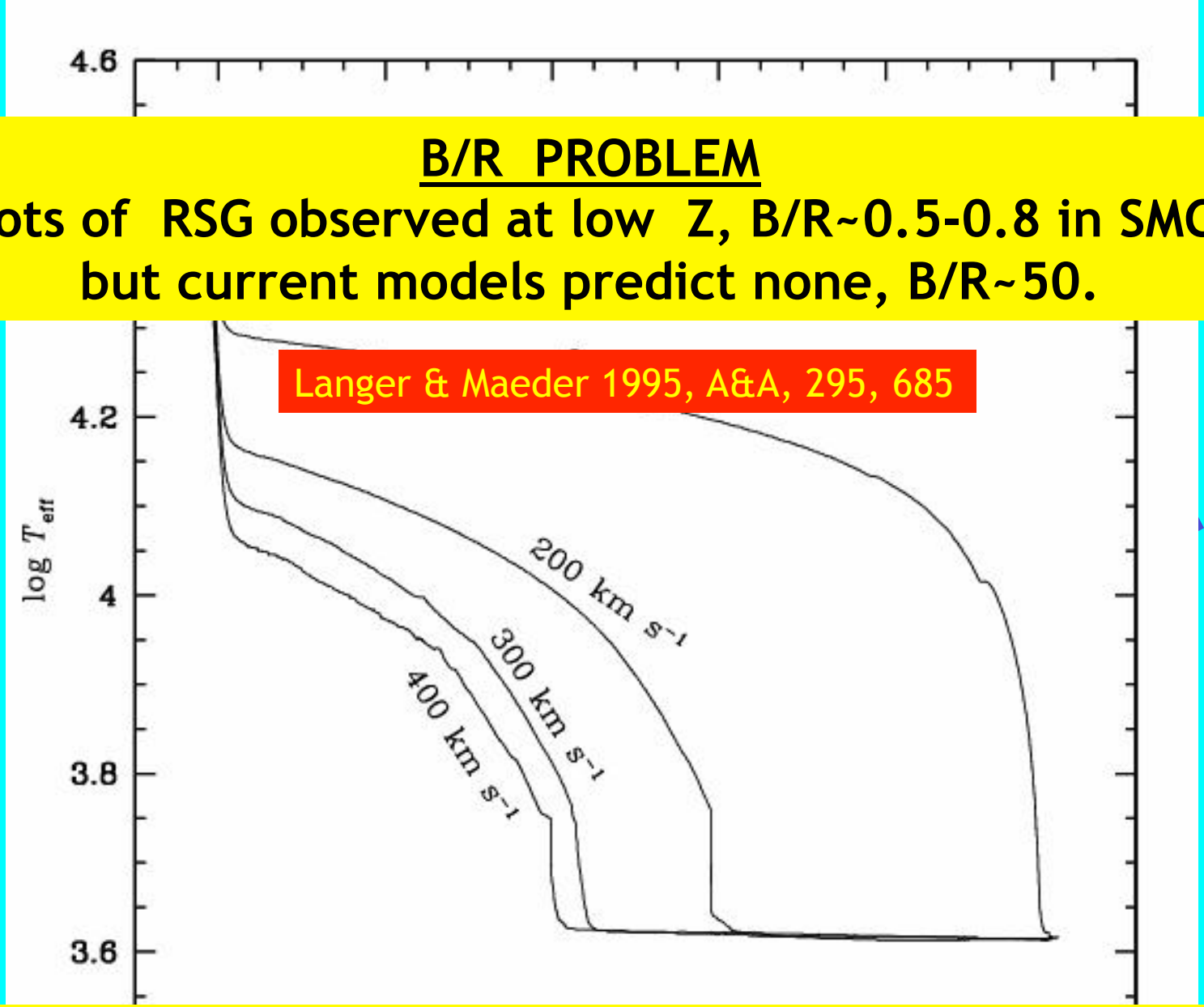
WHAT ARE THE FACTORS DETERMINING THE TIME SPENT AS RSG FOR A SINGLE GIVEN INITIAL MASS STAR?



V838 Monocerotis *NASA/ESA/Hubble Heritage Team (STScI/AURA)*

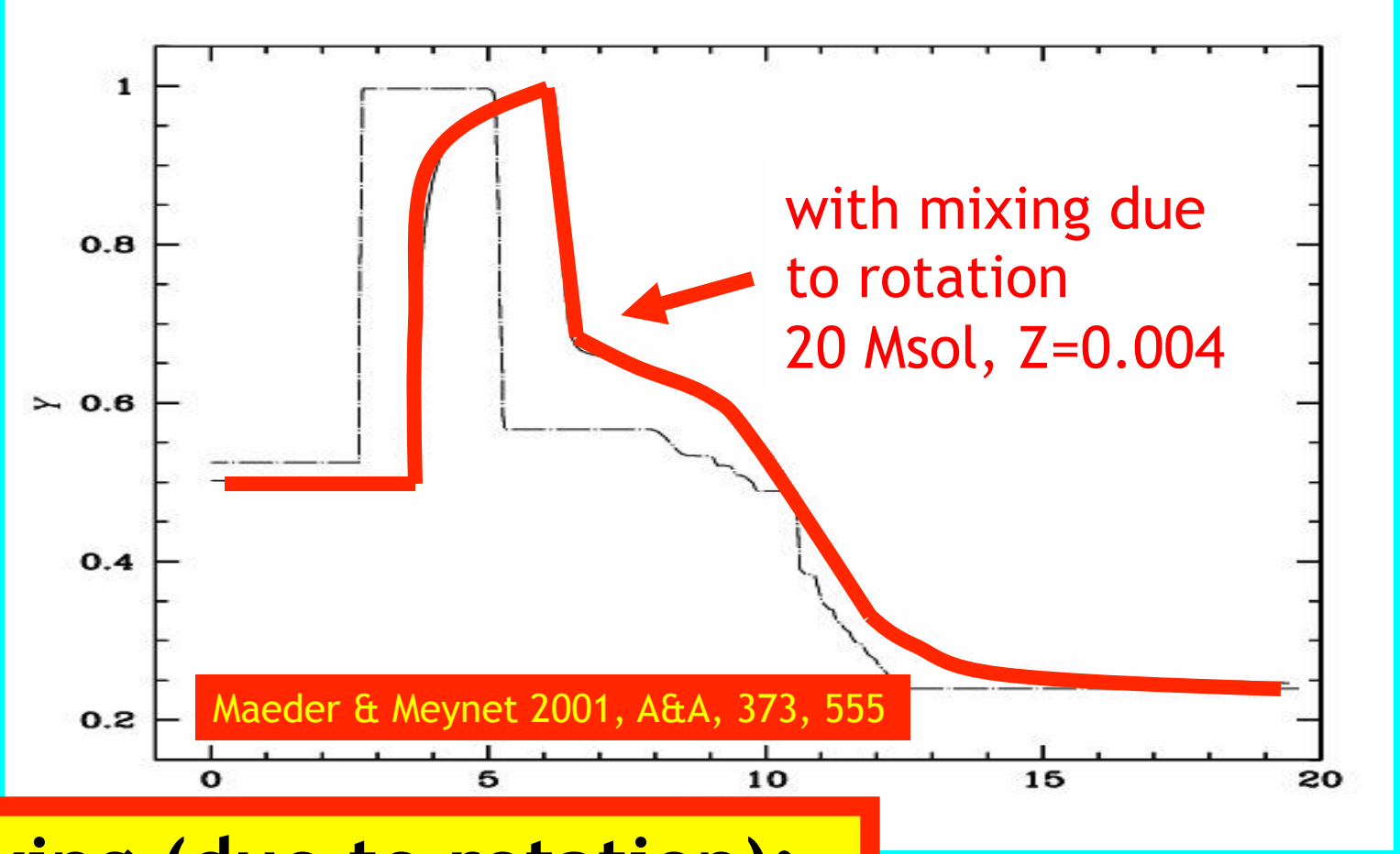
B/R PROBLEM

Lots of RSG observed at low Z, B/R~0.5-0.8 in SMC but current models predict none, B/R~50.



Models with mixing due to rotation are OK with B/R = 0.5-0.8 in SMC cf. Maeder & Meynet 2001

Helium mass fraction

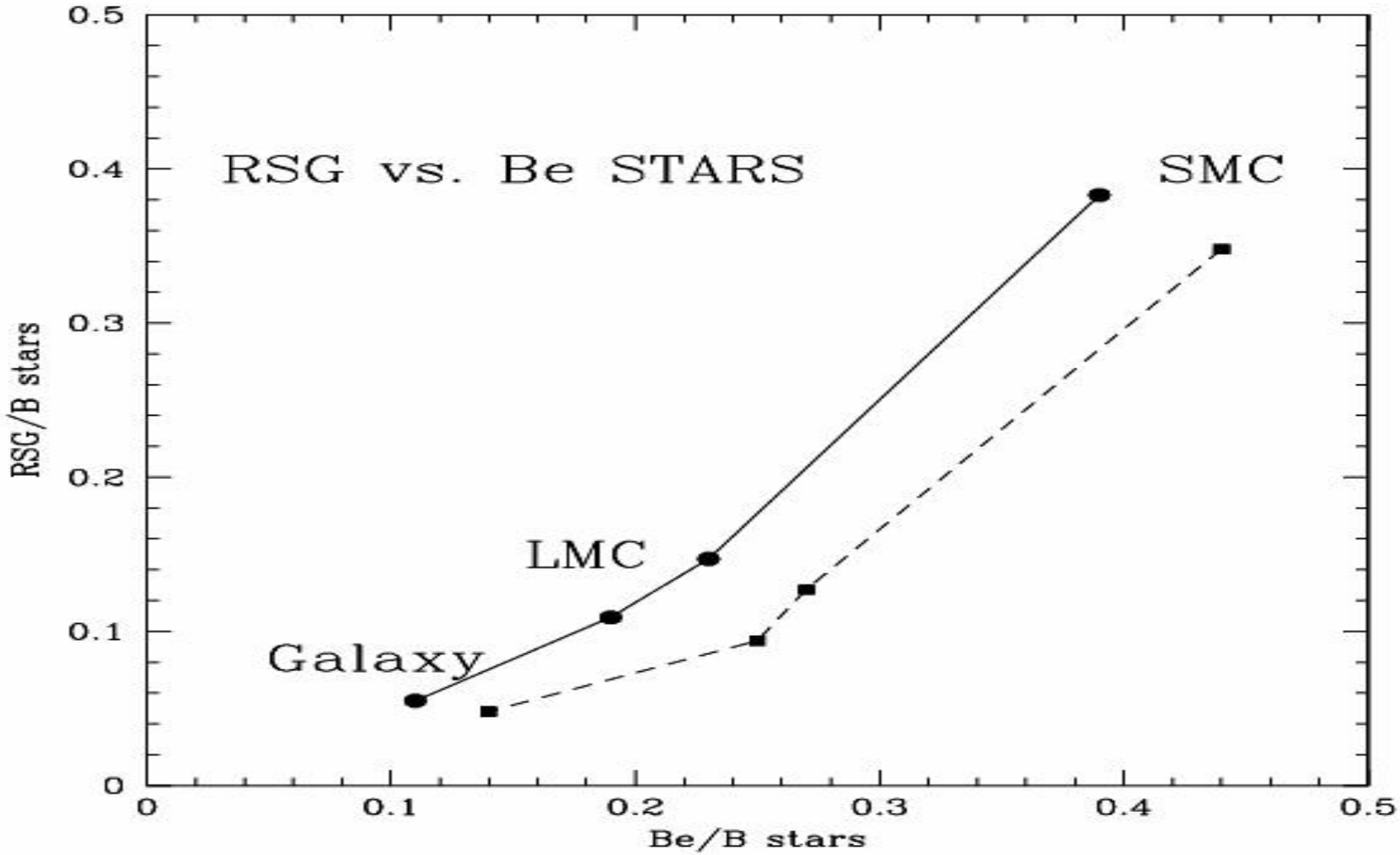


With mixing (due to rotation):

- Larger core
- More He in shell
- H shell less active
- no intermed. conv. zone

M_r/M_{sun}

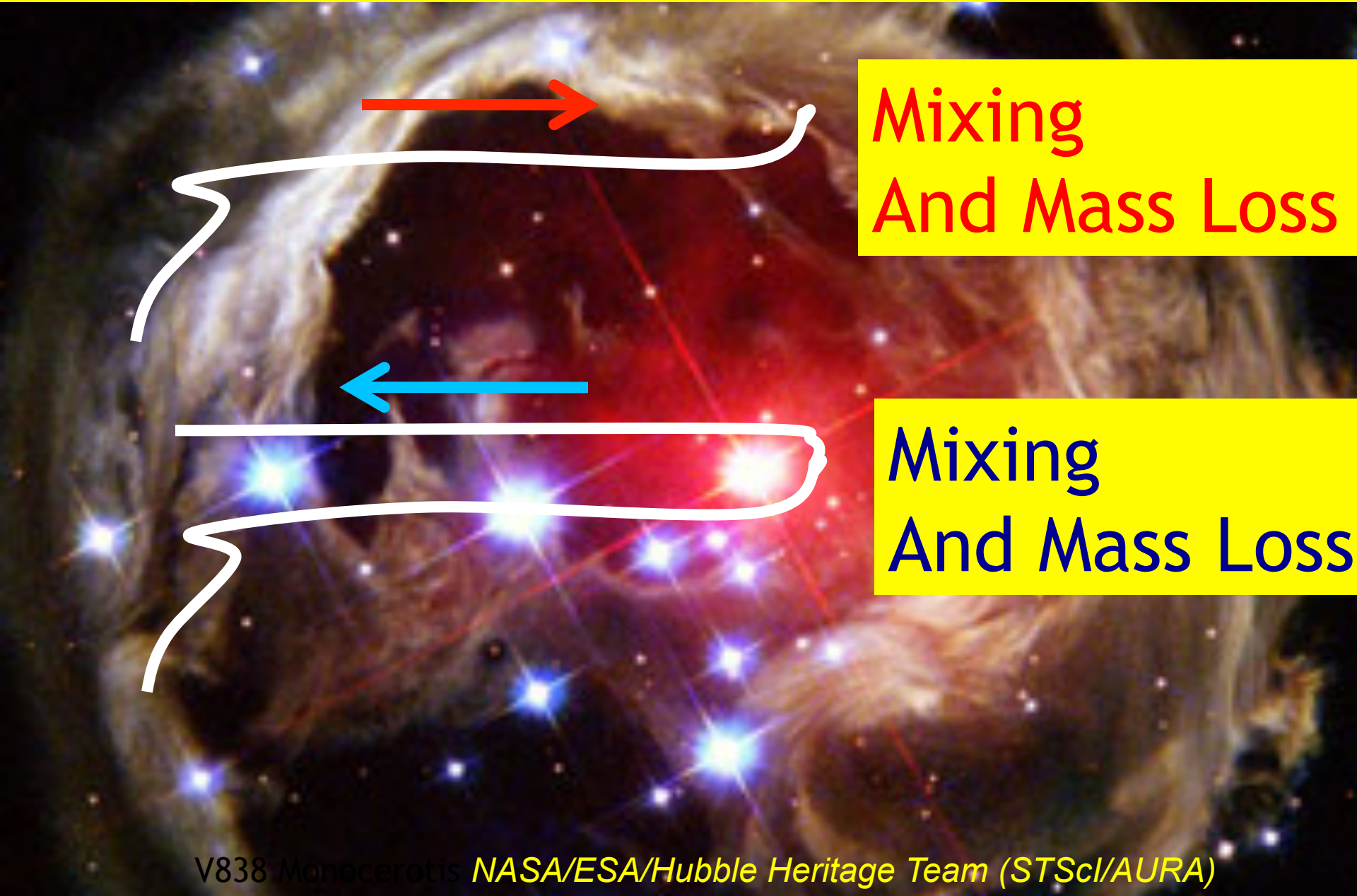
RSG



CONSISTENT WITH MODELS

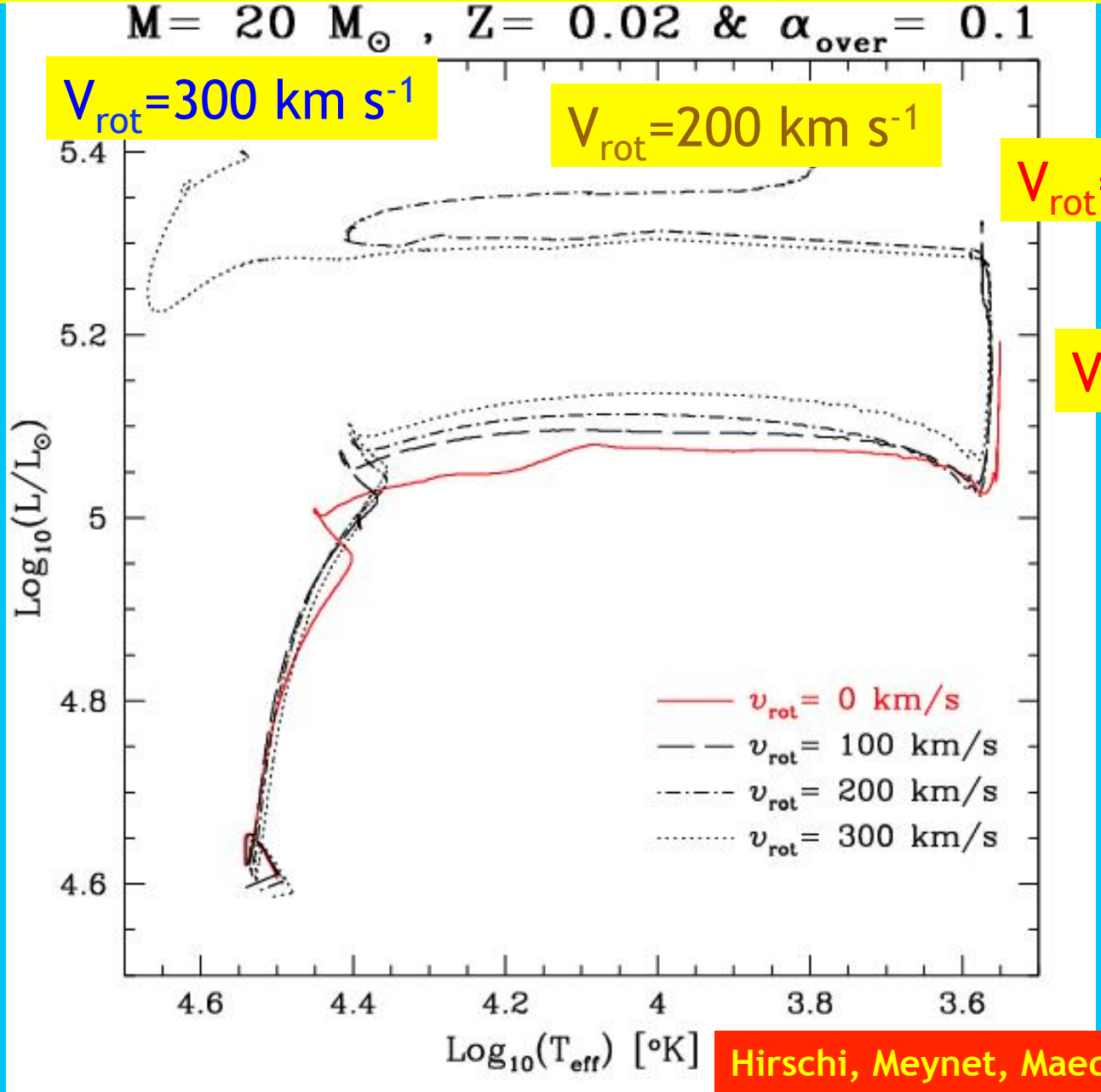
More fast Rotators → More RSG

WHAT ARE THE FACTORS DETERMINING THE TIME SPENT AS RSG FOR A SINGLE GIVEN INITIAL MASS STAR?



V838 Monocerotis *NASA/ESA/Hubble Heritage Team (STScI/AURA)*

Effect of rotation

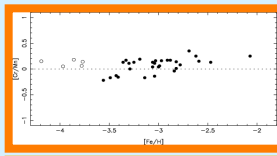


Hirschi, Meynet, Maeder, 2004, A&A, 425, 649

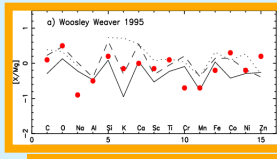
The first stellar generations

STRIKING OBSERVATIONAL FACTS

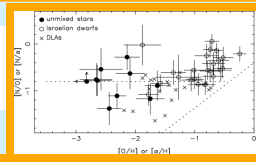
1) Different scatter for different elements



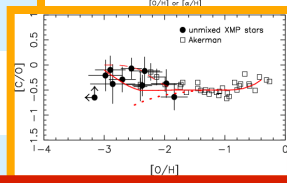
2) No sign of Pair Instability Supernovae



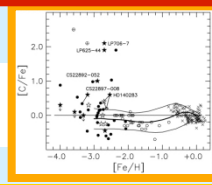
3) Important amount of primary nitrogen



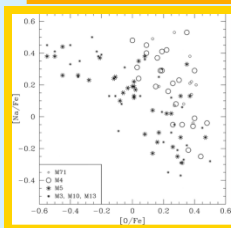
4) More carbon, less oxygen produced at low Z ?



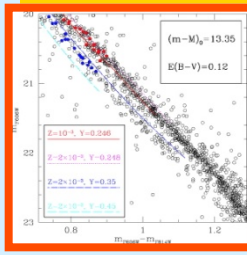
5) C-rich stars



6) The O-Na, Mg-Al anticorrelation in globular cluster stars



7) Very Helium-rich stars in ω Centuri ?



Observations: Cayrel et al. 2004 Spite et al 2005 Israelian et al. 2004, Centurion et al 2003 Norris et al 1997
Mc William et al 95; Barbuy et al. 96; Christlieb et al. 04; Frebel et al. 05; Plez & Cohen 05
Graton et al 2004; Piotto et al 2005

What is different at very low Z ?

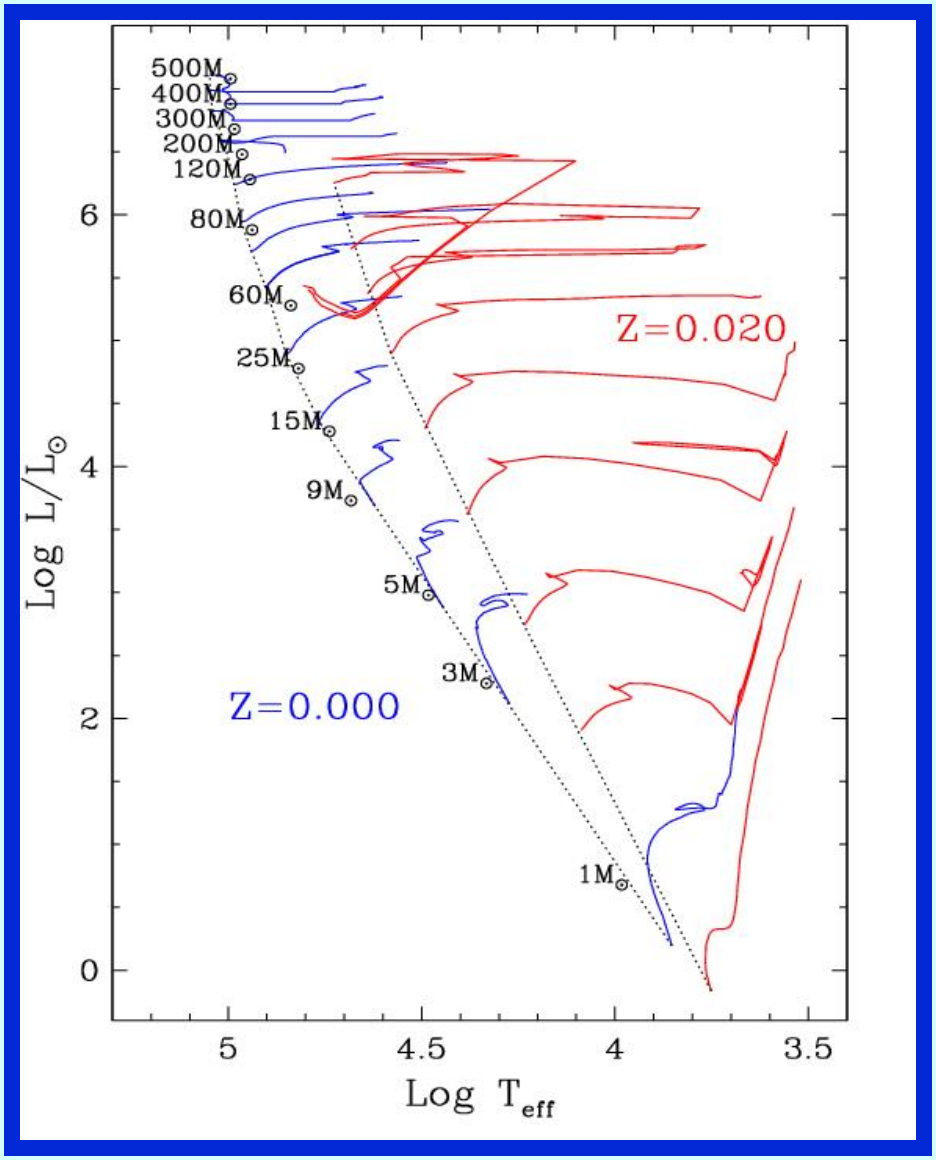
- The initial masses of the stars (?)
- The ignition of H-burning in massive stars (no CNO element catalysts at the beginning)
- The opacities are lower

  → Stars more compact: R(popIII) = $R(Z_{sol})/4$

  → Stellar winds are weaker

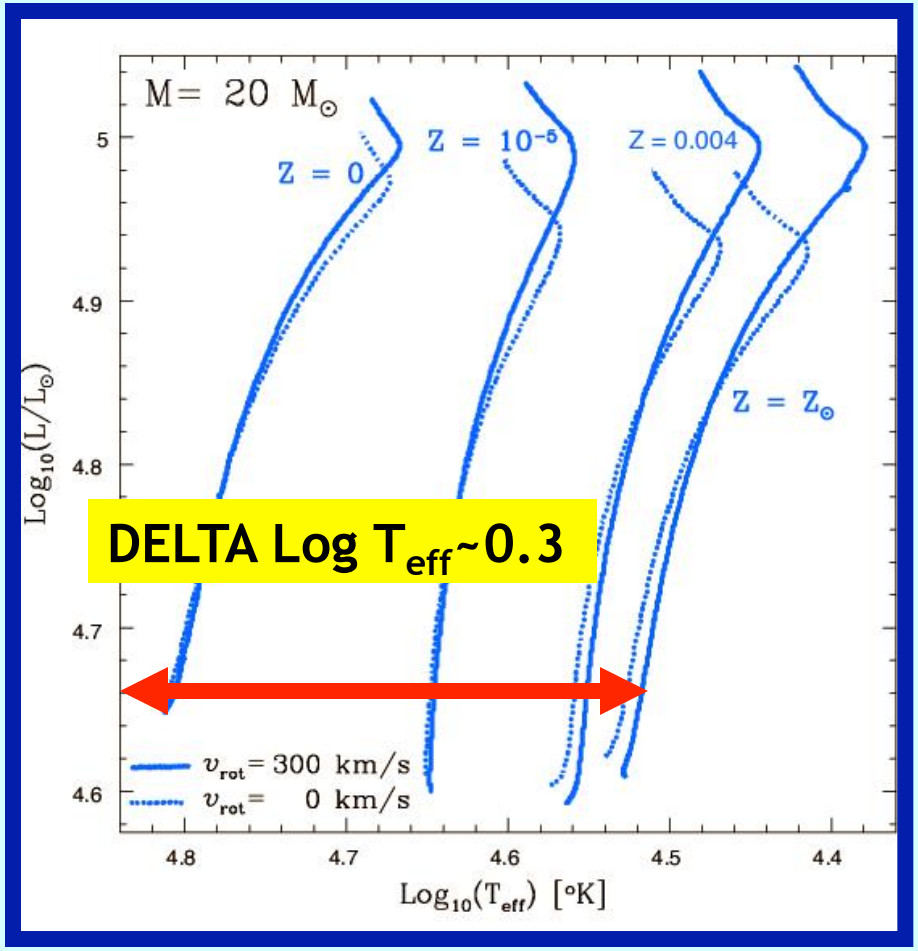
El Eid et al 1983; Ober et al 1983; Bond et al 1984; Klapp 1984; Arnett 1996; Limongi et al. 2000; Chieffi et al. 2000; Chieffi and Limongi 2002; Siess et al. 2002; Heger and Woosley 2002; Umeda and Nomoto 2003; Nomoto et al. 2003; Picardi et al. 2004; Gil-Pons et al. 2005

At Z= 0, stars are more compact



Feijoo 1999 diploma work

PopIII star: radii decreased by a factor 4



Ekström 2004 diploma work

WHAT CHANGES AT VERY LOW Z FOR ROTATING MODELS ?

Meridional velocities smaller

⇒ MORE ANGULAR MOMENTUM IN THE CORE

Steeper gradients of the angular velocity in the interiors

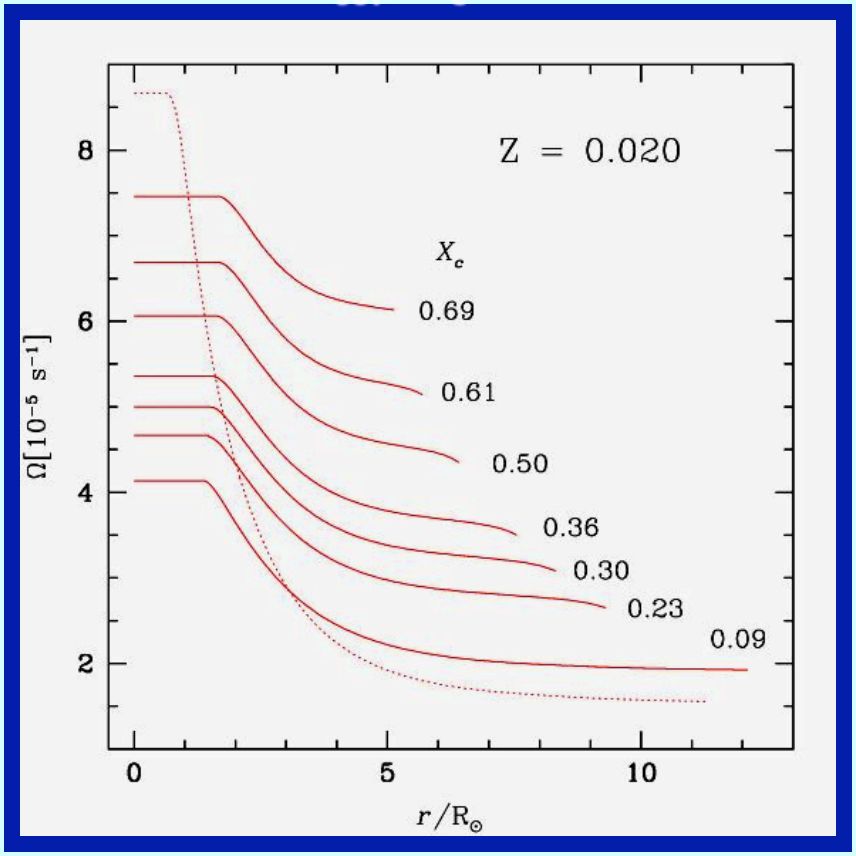
⇒ MORE EFFICIENT MIXING

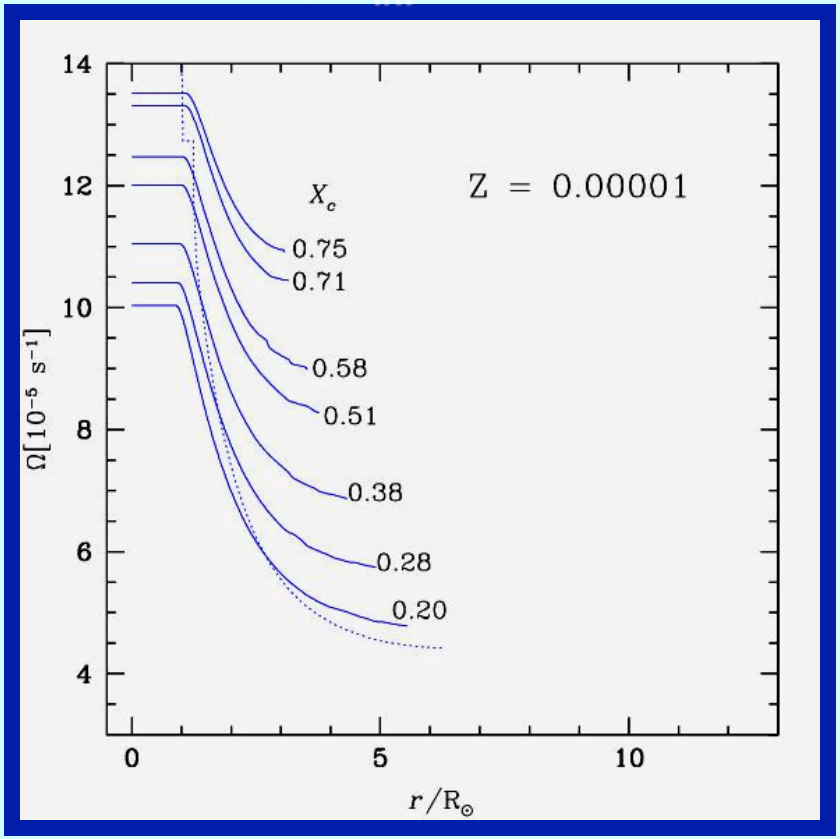
Less angular momentum removed by stellar winds

⇒ BREAK-UP LIMIT

Gradients of Ω steeper at lower metallicity

20 M_{sol}, X_c mass fraction of H at the centre, V_{ini}= 300 km/s





Why ?

Stars more compact, mixing timescale scales with R^2
transport of angular momentum less efficient

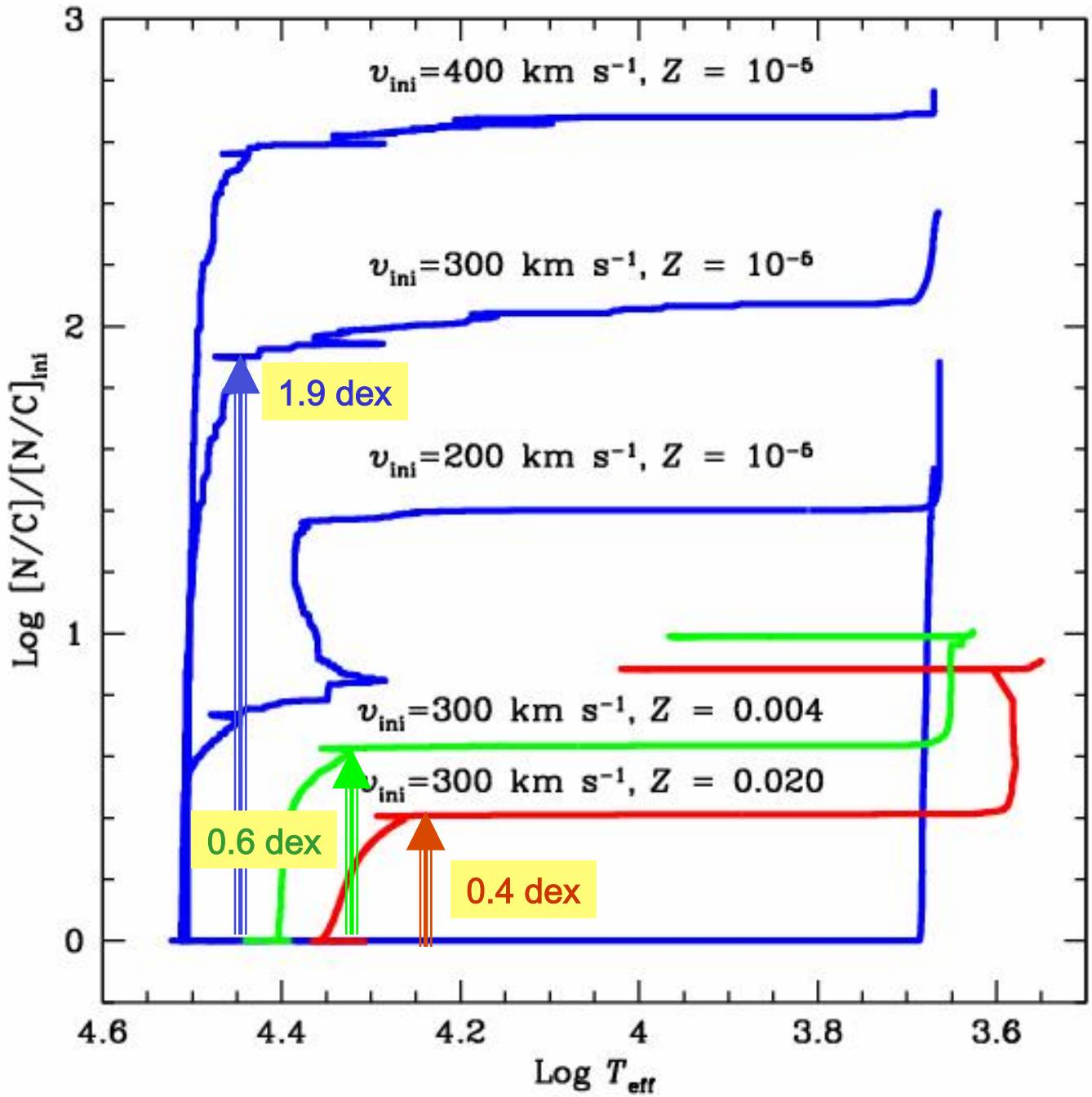
Consequences ?

More efficient mixing of the chemical elements

9 M_{sol}

When Z

Surface enrichments



ABUNDANCES:

Galaxy: [N/H] for O-stars : ~ 0.5 up to 0.8-1.0 dex

< 20 $M_\odot$ B – dwarfs : ~ 0.5 dex

> 20 $M_\odot$ B – giants , supg. : ~0.5 -0.7 dex

Ref: Villamariz & Herrero ’02; Smartt ’02;Herrero’03;Venn & Przybilla03;Trundle et al.’07

LMC: [N/H] for B-supg. : ~ 0.3 - 0.8 dex

< 20 $M_\odot$ B – dwarfs : ~ 0.7- 0.9 dex

B – giants, supg. : → 1.1 -1.2 dex

> 20 $M_\odot$ B – giants , supg. : → 1.3 dex

Ref: Herrero’03;Trundle et al. ’07;Hunter et al.’07

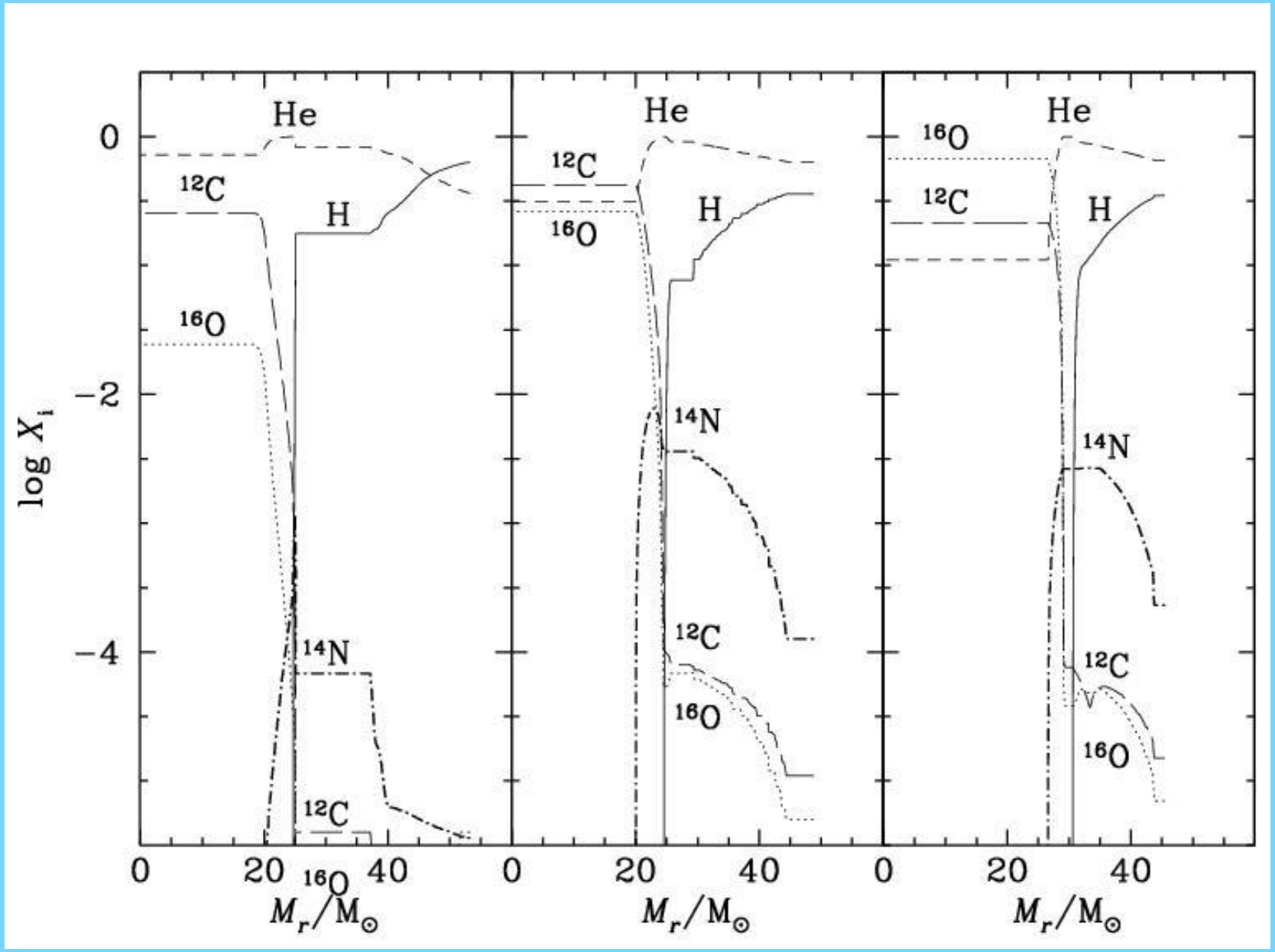
SMC: [N/H] O-stars, A-F supg. : 1.5 -1.7 dex

< 20 $M_\odot$ B – dwarfs : → 1.1 dex

B – giants, supg. : → 1.5 dex

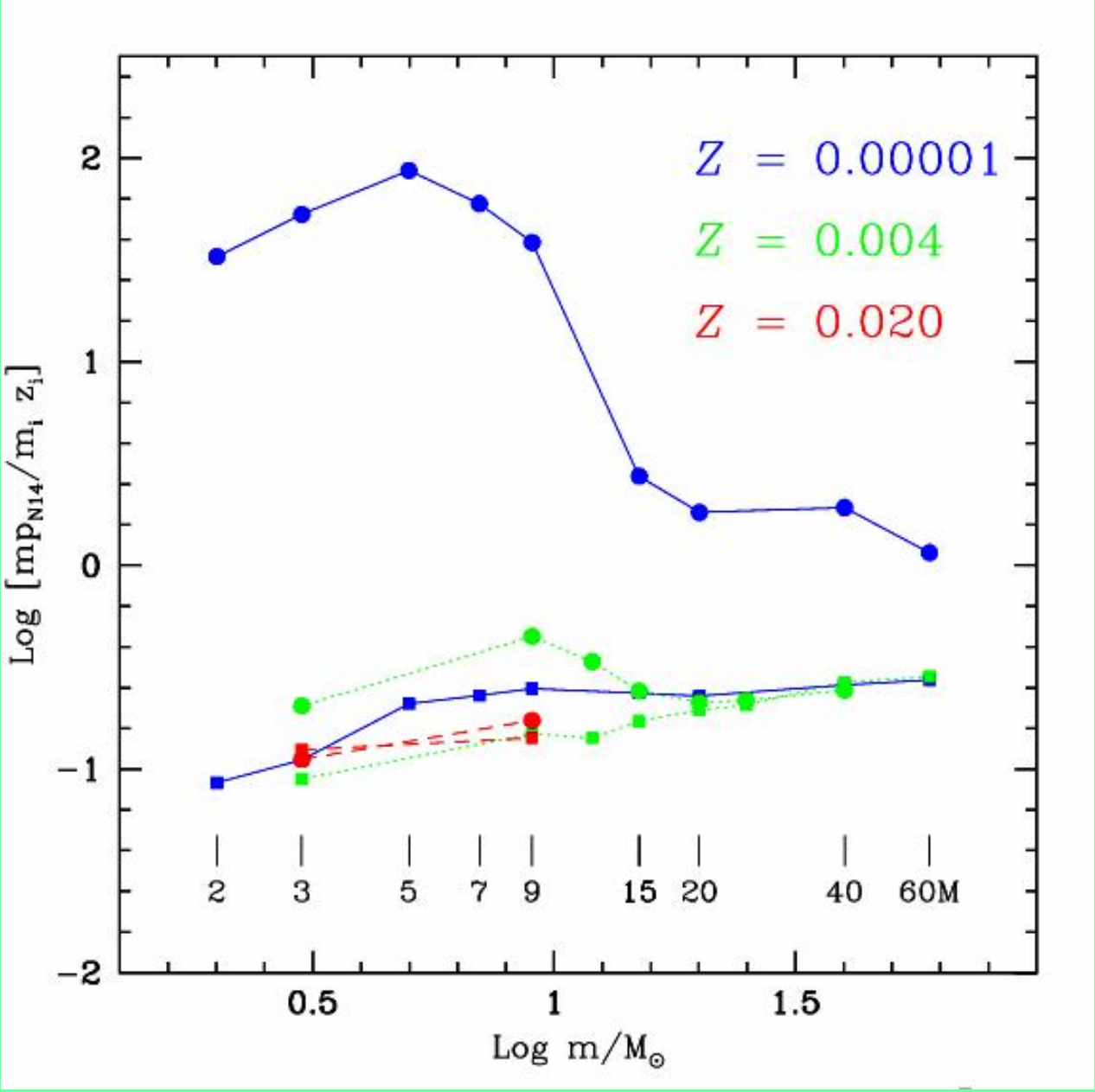
> 20 $M_\odot$ B – giants , supg : → 1.9 dex

Ref: Heap & Lanz’06; Venn & Przybilla’03; Bouret et al.’03;Trundle et al.’07; Hunter et al.’07

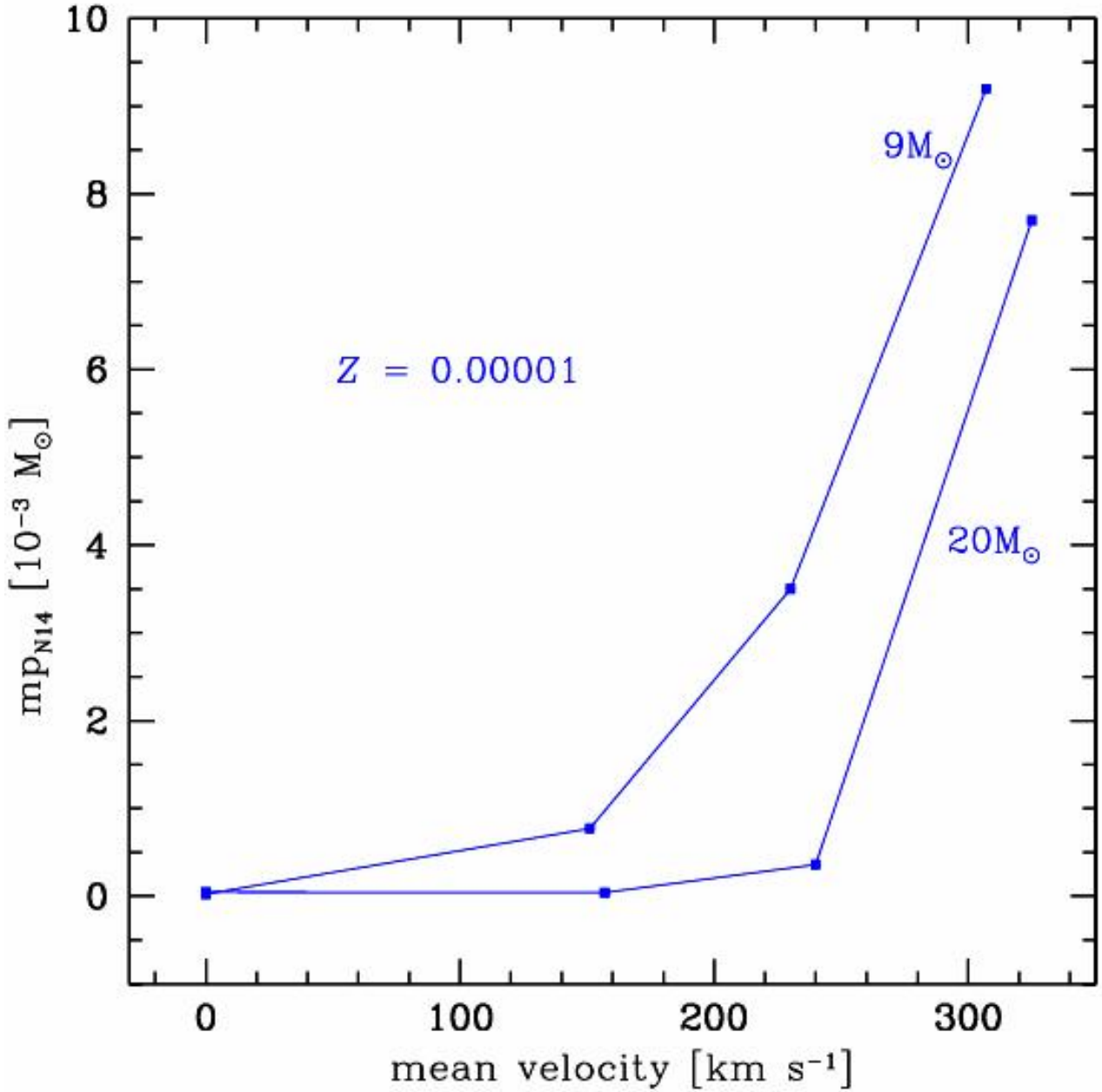


60 M_{sol}, $Z=10^{-5}$, $\Omega_{ini}/\Omega = 0.85$

For Z=0.004 and Z=0.020 , nearly no primary N production



Increase of primary N production when rotation increases



WHAT CHANGES AT LOW Z FOR ROTATING MODELS ?

Steeper gradients of the angular velocity in the interiors

⇒ MORE EFFICIENT MIXING

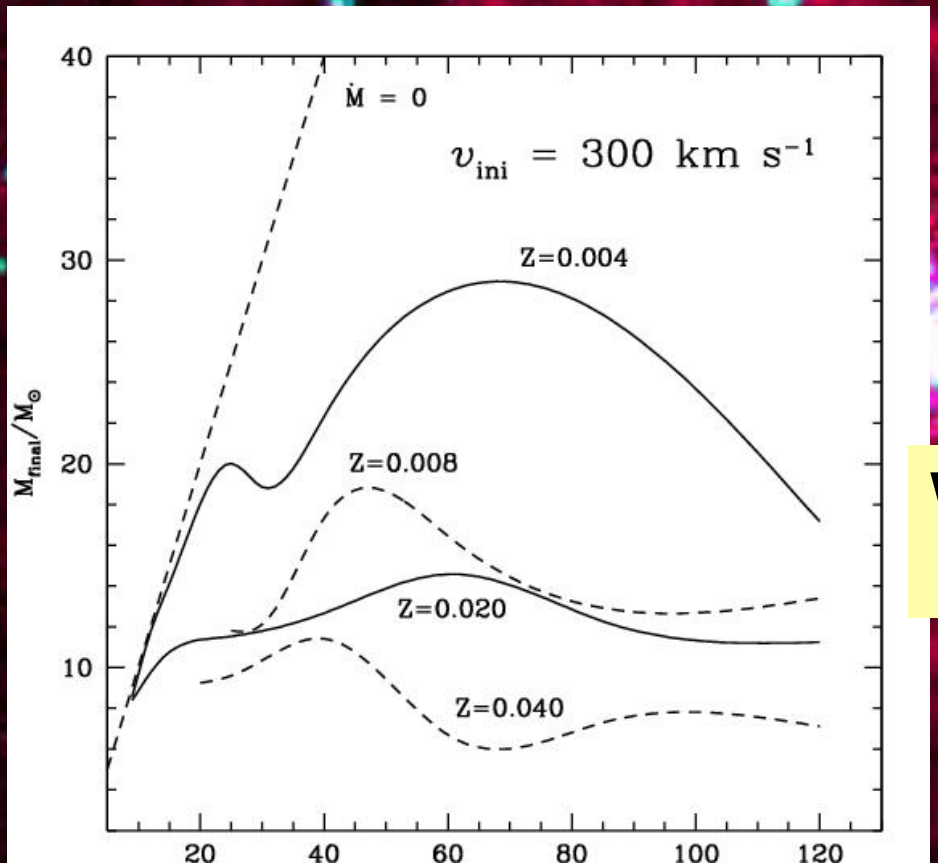
Less angular momentum removed by stellar winds

⇒ BREAK-UP LIMIT

At low metallicity, very weak radiatively driven stellar winds

Mass loss rate

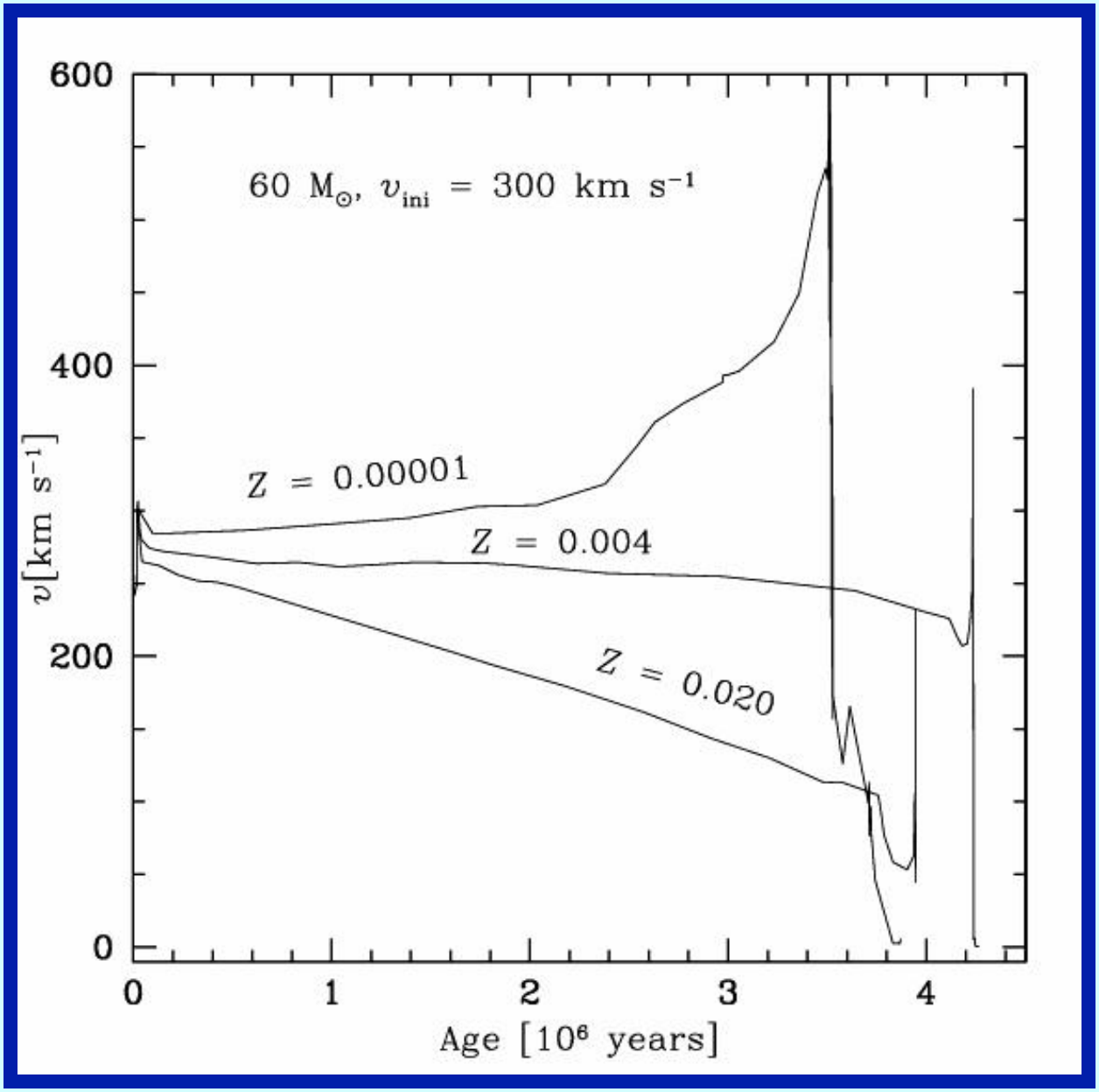
$$\dot{M}_Z = \left(\frac{Z}{Z_{sol}}\right)^{\alpha} \dot{M}_{Z_{sol}}$$

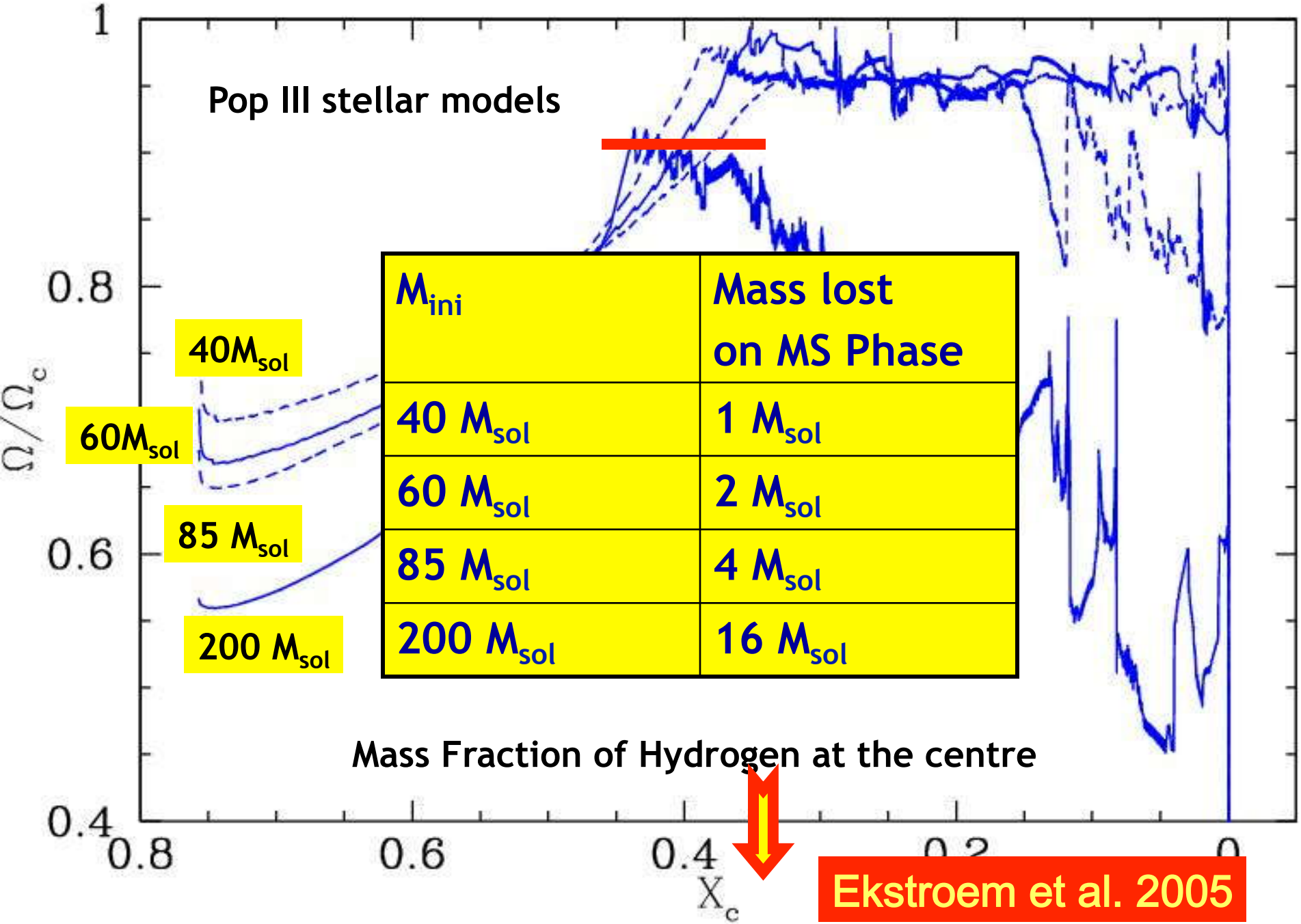


Kudritzki & Puls (2000) → α=0.5
Evans et al. (2005) → α=0.62+ - 0.15

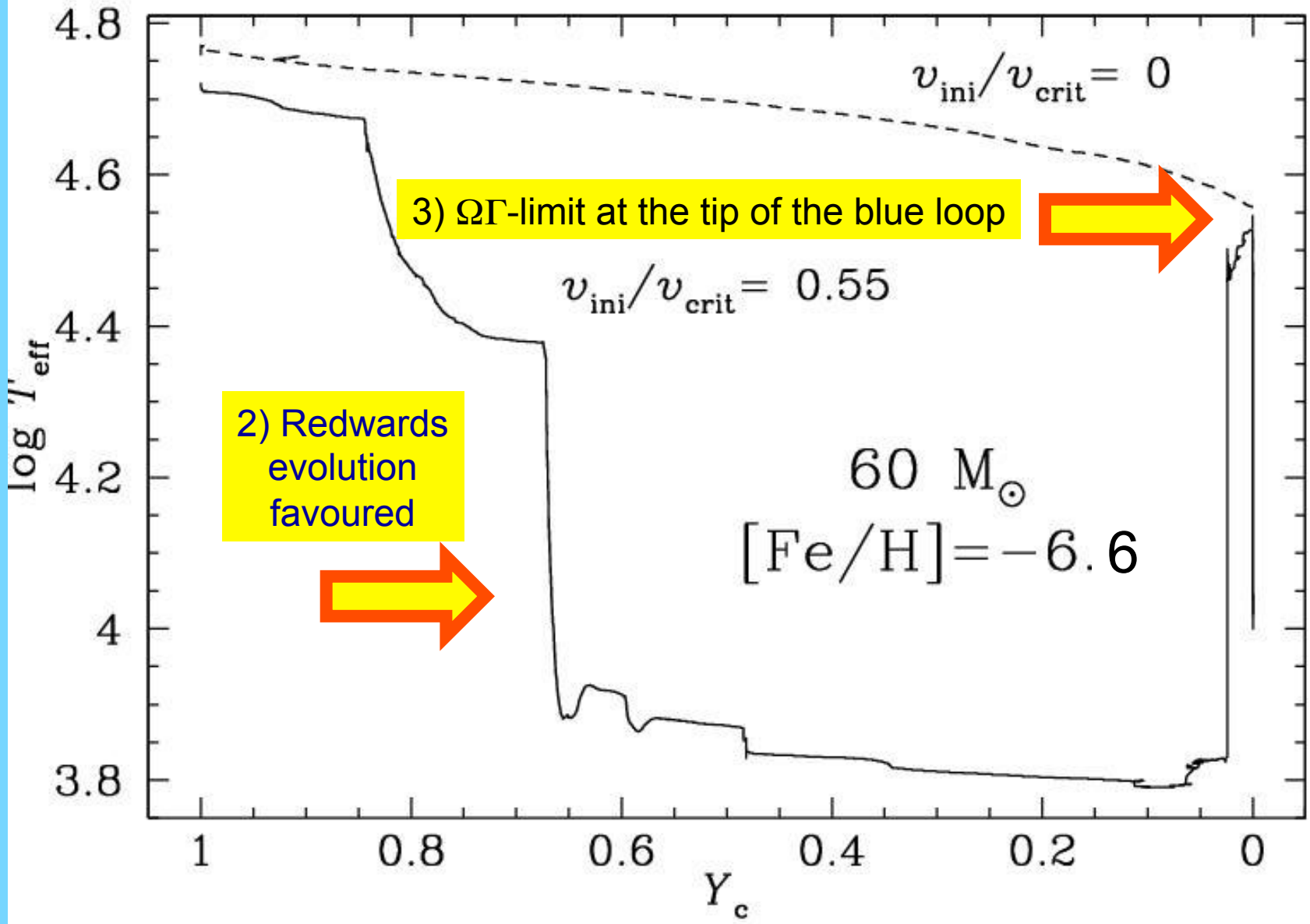
What happens if metal poor stars are fast rotators ?

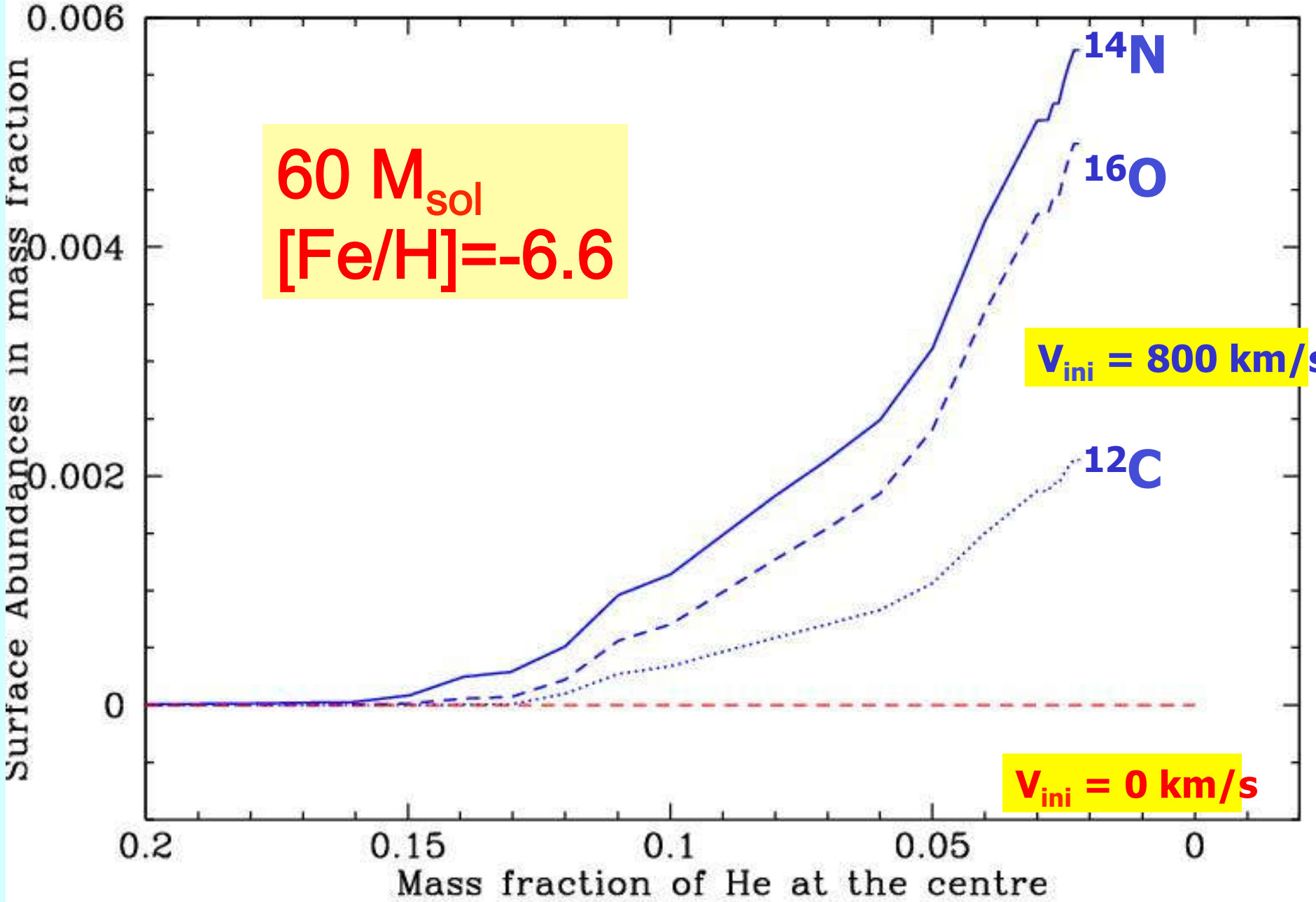
Could very low metallicity stars loose a lot of mass when reaching the break-up ?



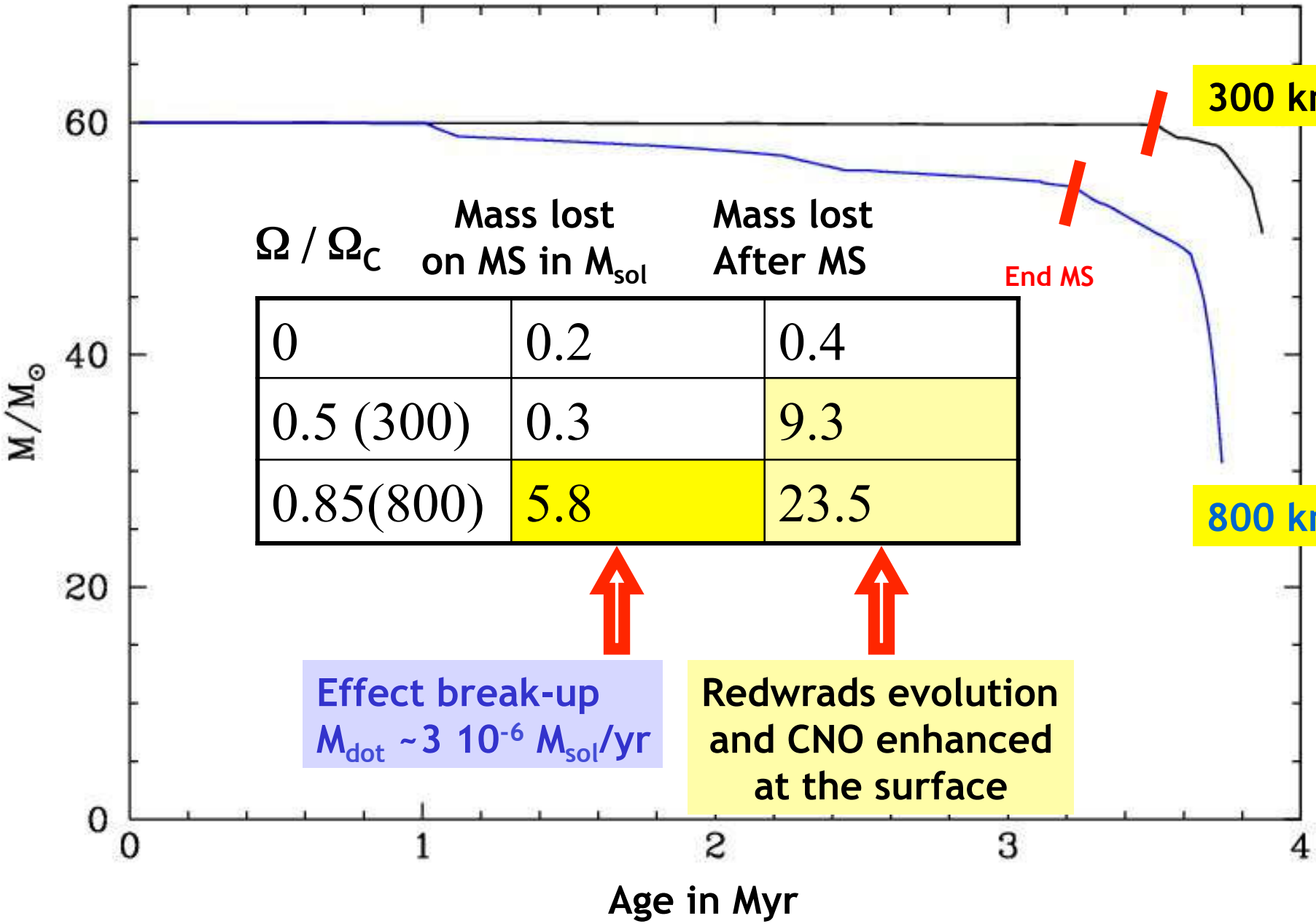


M_{ini}	Mass lost on MS Phase
40 M_{sol}	1 M_{sol}
60 M_{sol}	2 M_{sol}
85 M_{sol}	4 M_{sol}
200 M_{sol}	16 M_{sol}


4.8
4.6
4.4
4.2
4
3.8
log T_eff
1
0.8
0.6
0.4
0.2
0
Y_c
v_ini/v_crit = 0
v_ini/v_crit = 0.55
60 M⊙
[Fe/H]=−6.6
3) ΩΓ-limit at the tip of the blue loop
2) Redwards evolution favoured


60 M_{sol}
[Fe/H]=-6.6
^{14}N
^{16}O
^{12}C
V_{ini} = 800 km/s
V_{ini} = 0 km/s
Surface Abundances in mass fraction
0.006
0.004
0.002
0
0.2
0.15
0.1
0.05
0
Mass fraction of He at the centre

MASS LOST DUE TO THE APPROACH OF THE BREAK-UP LIMIT



Ω / Ω_C	Mass lost on MS in M_{sol}	Mass lost After MS
0	0.2	0.4
0.5 (300)	0.3	9.3
0.85(800)	5.8	23.5

Effect break-up
M_{dot} ~3 10^{-6} M_{sol}/yr

Redwrads evolution and CNO enhanced at the surface

Some Possible Consequences

Origin of primary nitrogen, ^{13}C, ^{22}Ne in the early phases of the chemical evolution of galaxies

Chiappini et al. 2005, 2006, 2008

Origin of the CEMP stars (at least the CEMP-no :no s-elements)

Meynet et al. 2006, 2010

Origin of the O-Na anticorrelation in globular clusters

Decressin et al. 2007ab

Origin of the high He-abundance in some stars in globular clusters

Maeder and Meynet 2006

New s-process in massive metal poor rotating stars

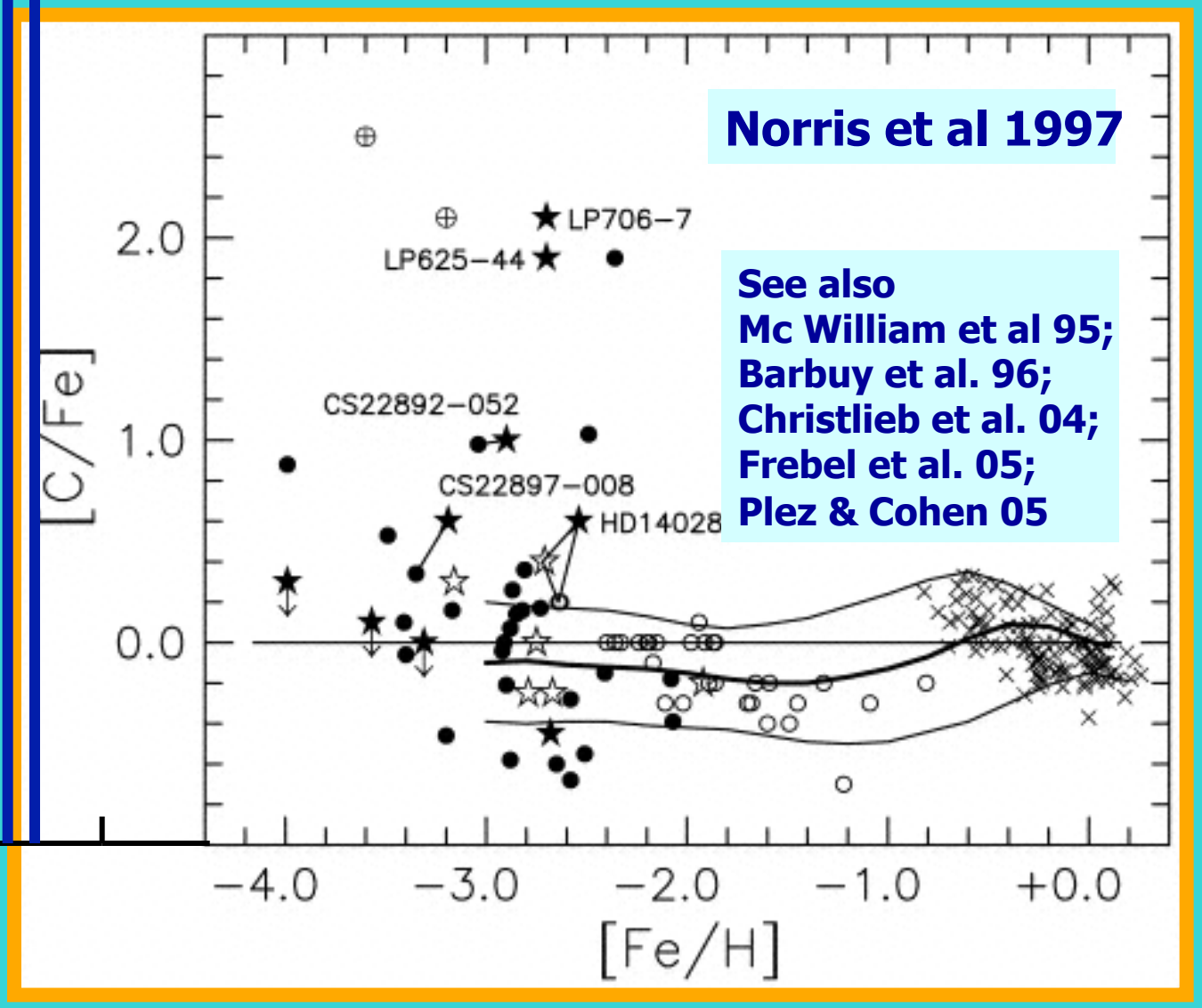
Pignatary et al. 2008

Carbon Rich Ultra Metal Poor Stars (CRUMPS)

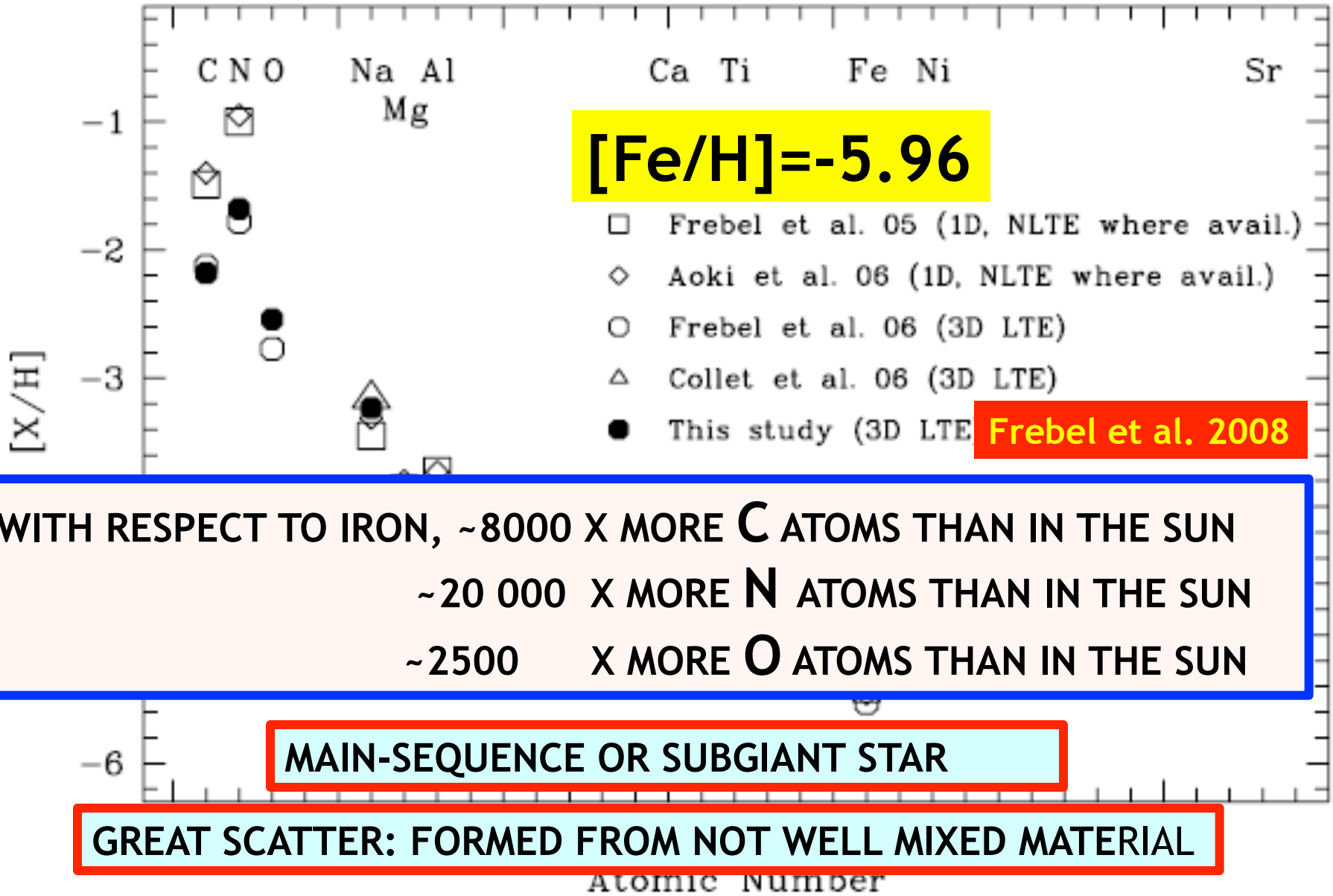
Most metal poor stars

Christlieb et al. 2002

Frebel et al. 2005



THE MOST IRON POOR STAR PRESENTLY KNOWN IN THE UNIVERSE



WITH RESPECT TO IRON, ~8000 X MORE **C** ATOMS THAN IN THE SUN

~20 000 X MORE **N** ATOMS THAN IN THE SUN

~2500 X MORE **O** ATOMS THAN IN THE SUN

MAIN-SEQUENCE OR SUBGIANT STAR

GREAT SCATTER: FORMED FROM NOT WELL MIXED MATERIAL

MODELS FOR THE SOURCE MATERIAL

AGB STARS (Suda et al. 2004)

ACCRETION BY THE NOW CRUMP STAR OF MATERIAL FROM THE AGB

BINARITY NEEDED

SUPERNOVAE (Umeda & Nomoto 2003; Limongi et al. 2003)

CRUMP STARS MADE OF 1-2 SUPERNOVA EJECTA AND ISM MATERIAL

FALLBACK NEEDED

WINDS OF MASSIVE STARS (Meynet et al. 2006; 2010)

CRUMP STARS MADE OF WIND EJECTA OF ONE MASSIVE STAR AND OF ISM MATERIAL

ROTATION NEEDED

WHAT CAN WE LEARN FROM THE HIGH CNO CONTENT?

NITROGEN: H-BURNING, FROM CO

CARBON: He-BURNING, FROM He

OXYGEN: He-BURNING, FROM He

N only FROM CNO-cycle

Δ[N/H]= Δ[N/Fe]~ +1.4 at Maximum

Δ[N/H]= Δ[N/Fe]~ +4.3 needed!

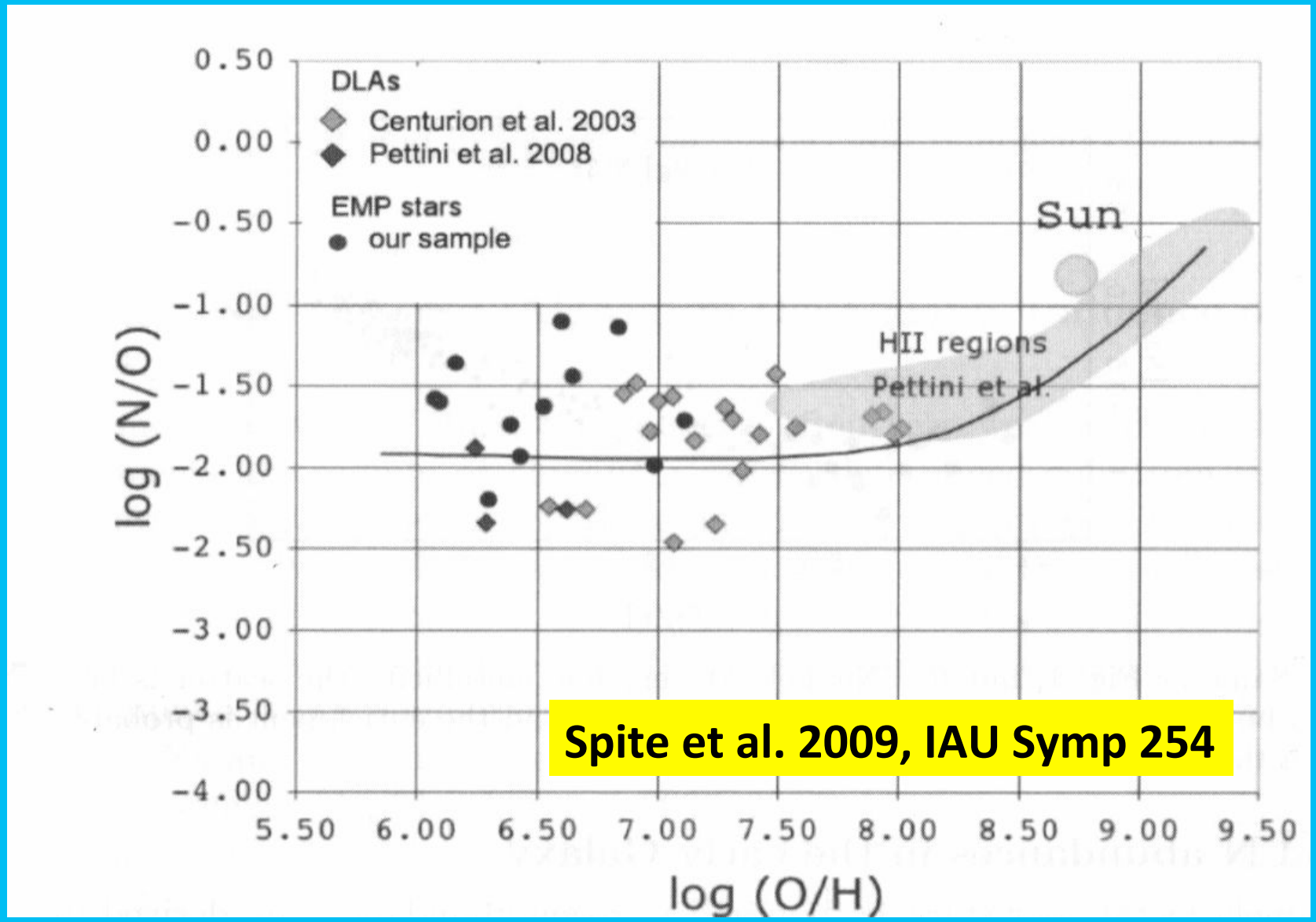
HIGH CNO NEEDS

1) MATERIAL PROCESSED BY BOTH H- AND He-BURNING PROCESSES

2) DIFFUSION BETWEEN THE He-CORE AND THE H-BURNING SHELL

3) NOT TOO HIGH PROPORTION OF He-BURNING MATERIAL→ WINDS OR FAINT SUPERNOVA WITH FALLBACK or ENVELOPE OF AN AGB

IMPORTANT PRODUCTION OF PRIMARY NITROGEN

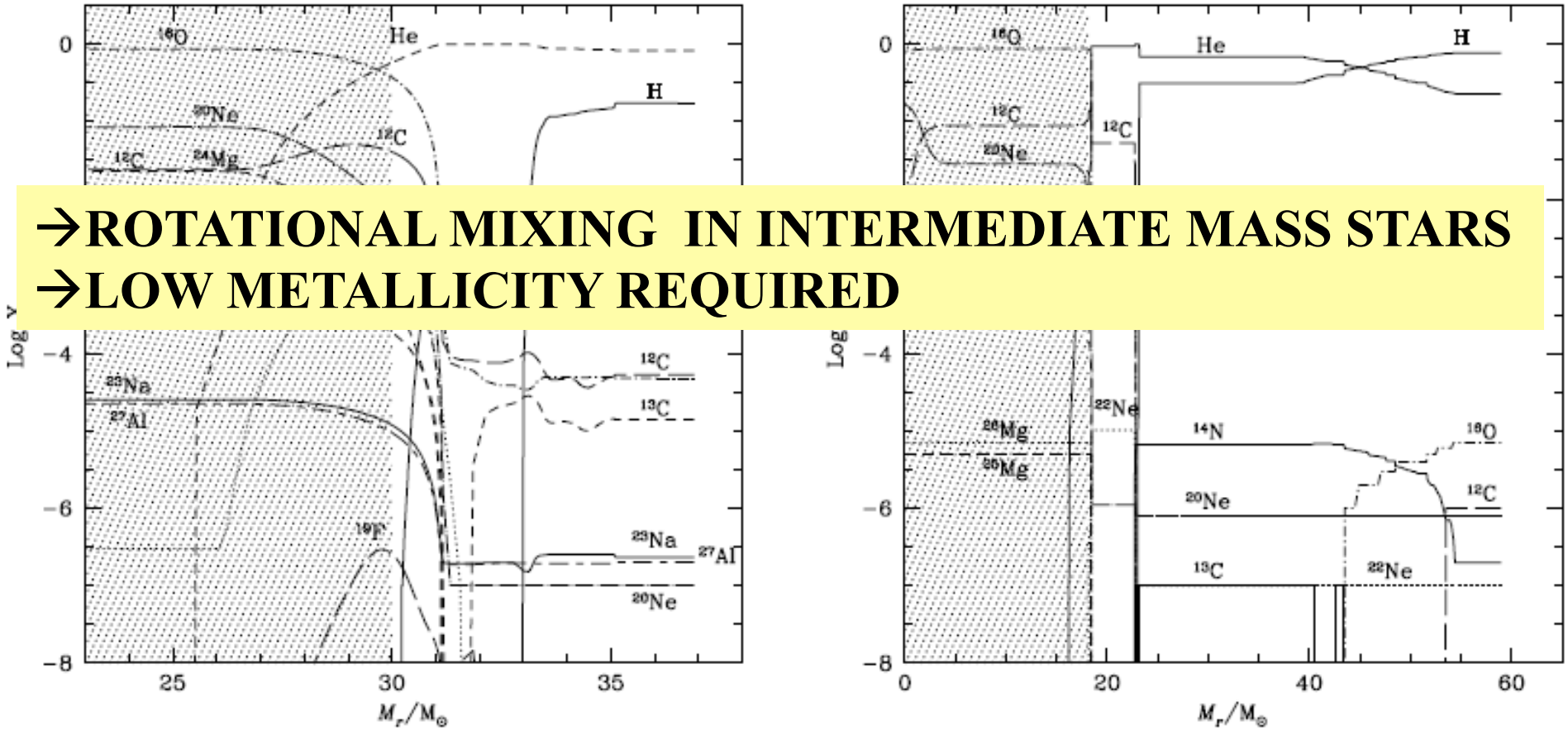


Spite et al. 2009, IAU Symp 254

60 M_{sun}, $Z=10^{-5}$

V=800 km s^{-1}

V = 0 km s^{-1}



→ROTATIONAL MIXING IN INTERMEDIATE MASS STARS

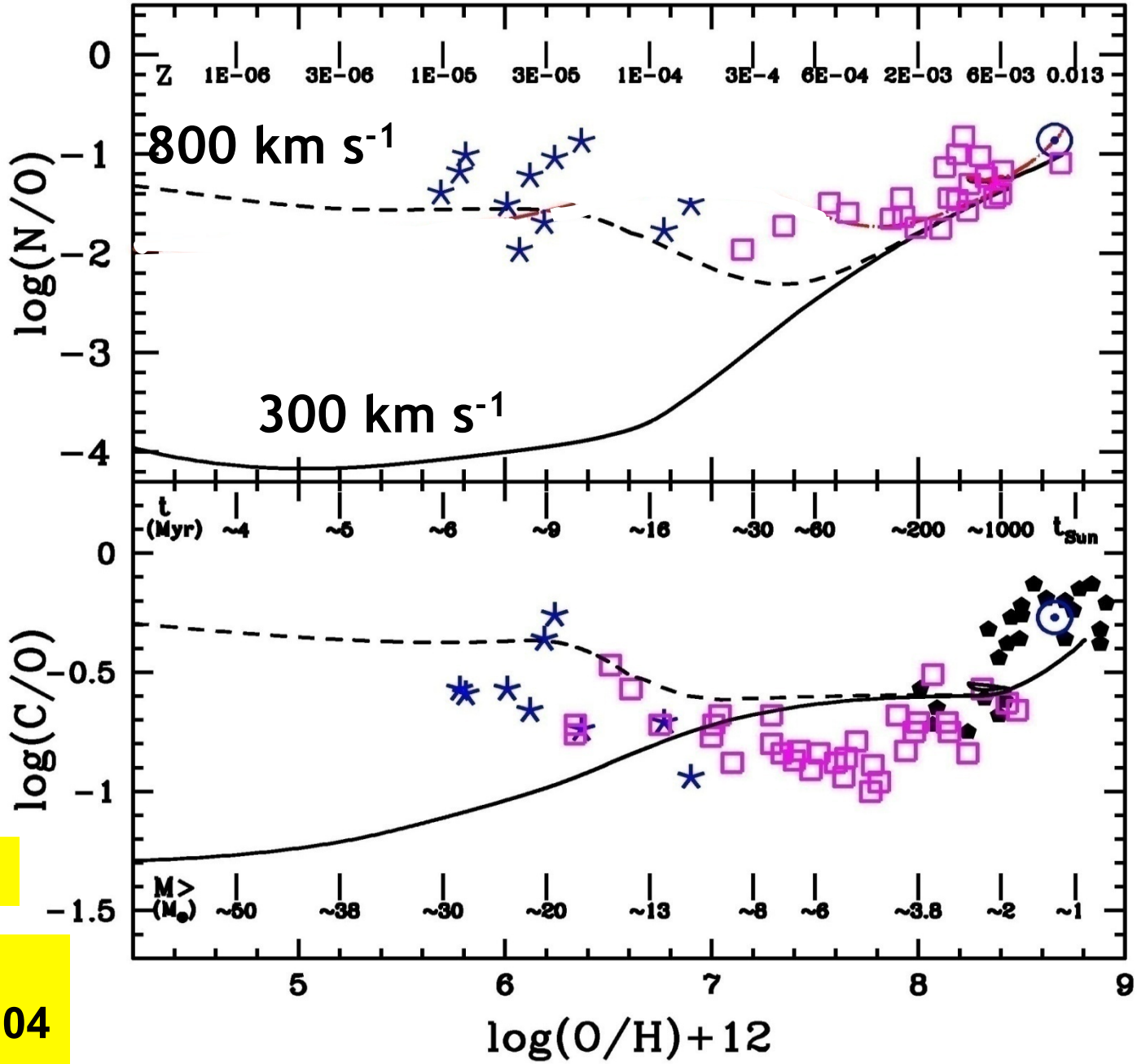
→LOW METALLICITY REQUIRED

NITROGEN

WINDS

N/O

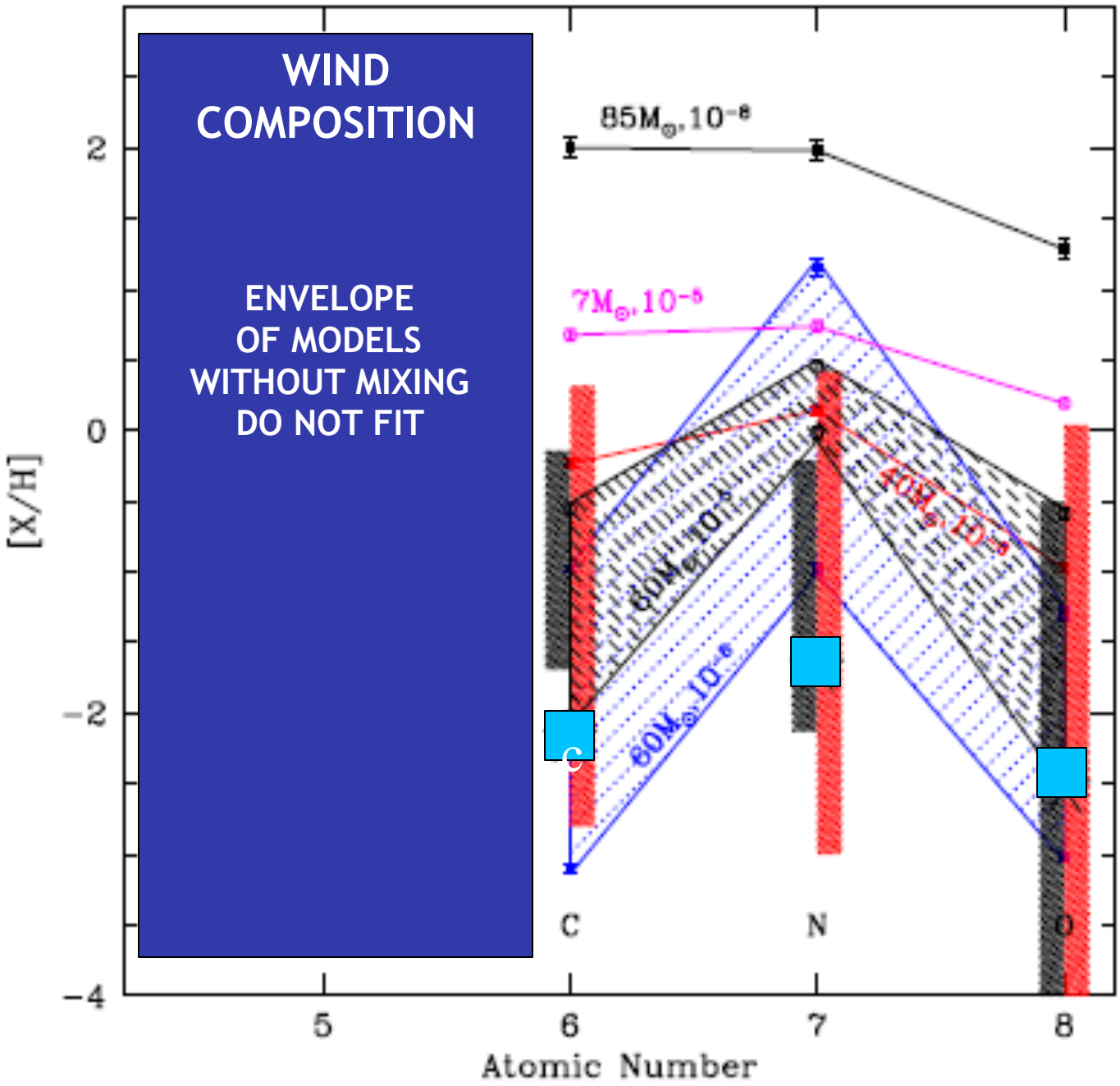
C/O



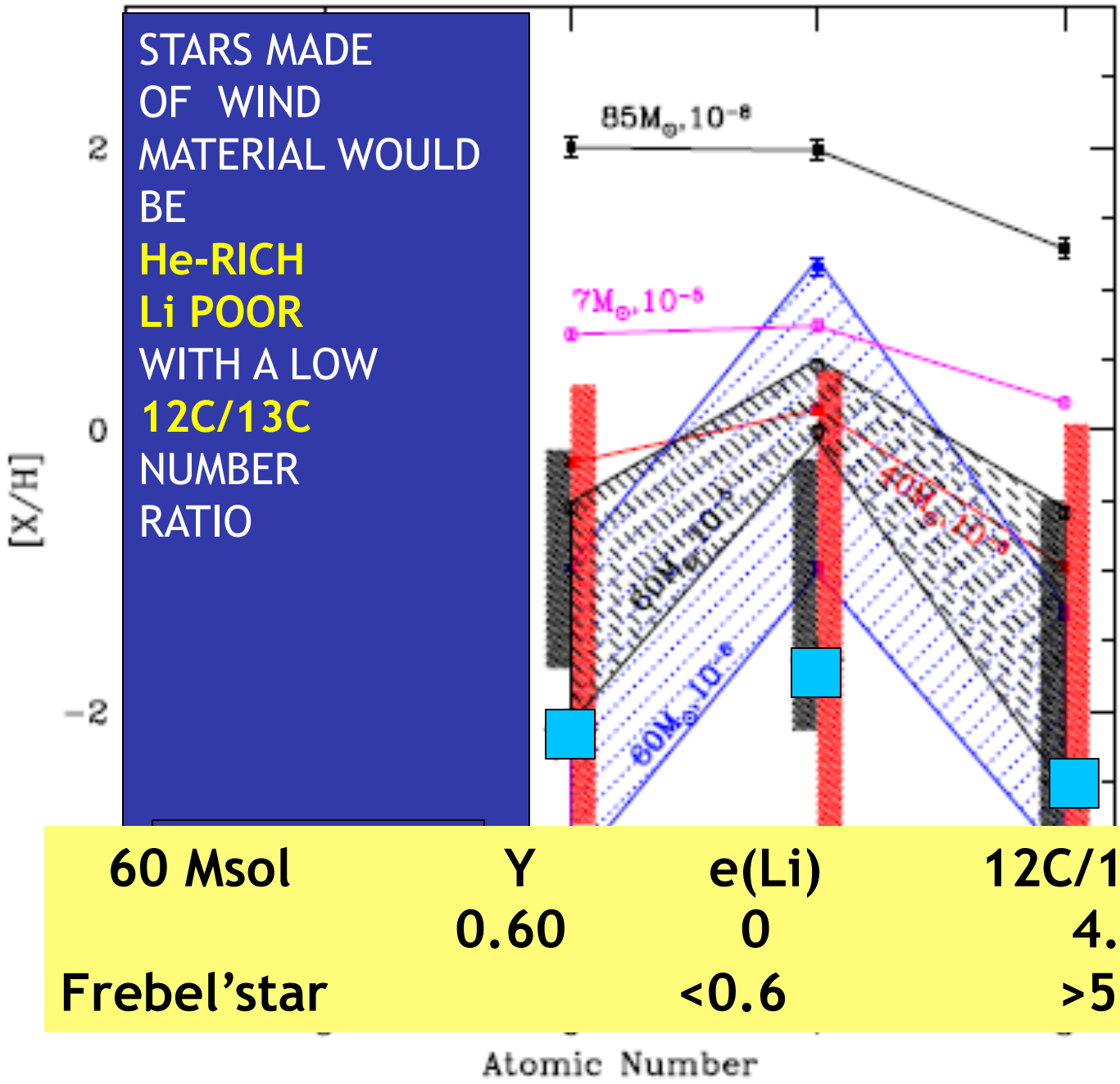
Observations from

Spite et al. 2005
Akerman et al. 2004
Nissen 2004

Chiappini, Hirschi, Meynet, Ekström, Maeder, Matteucci, 2006

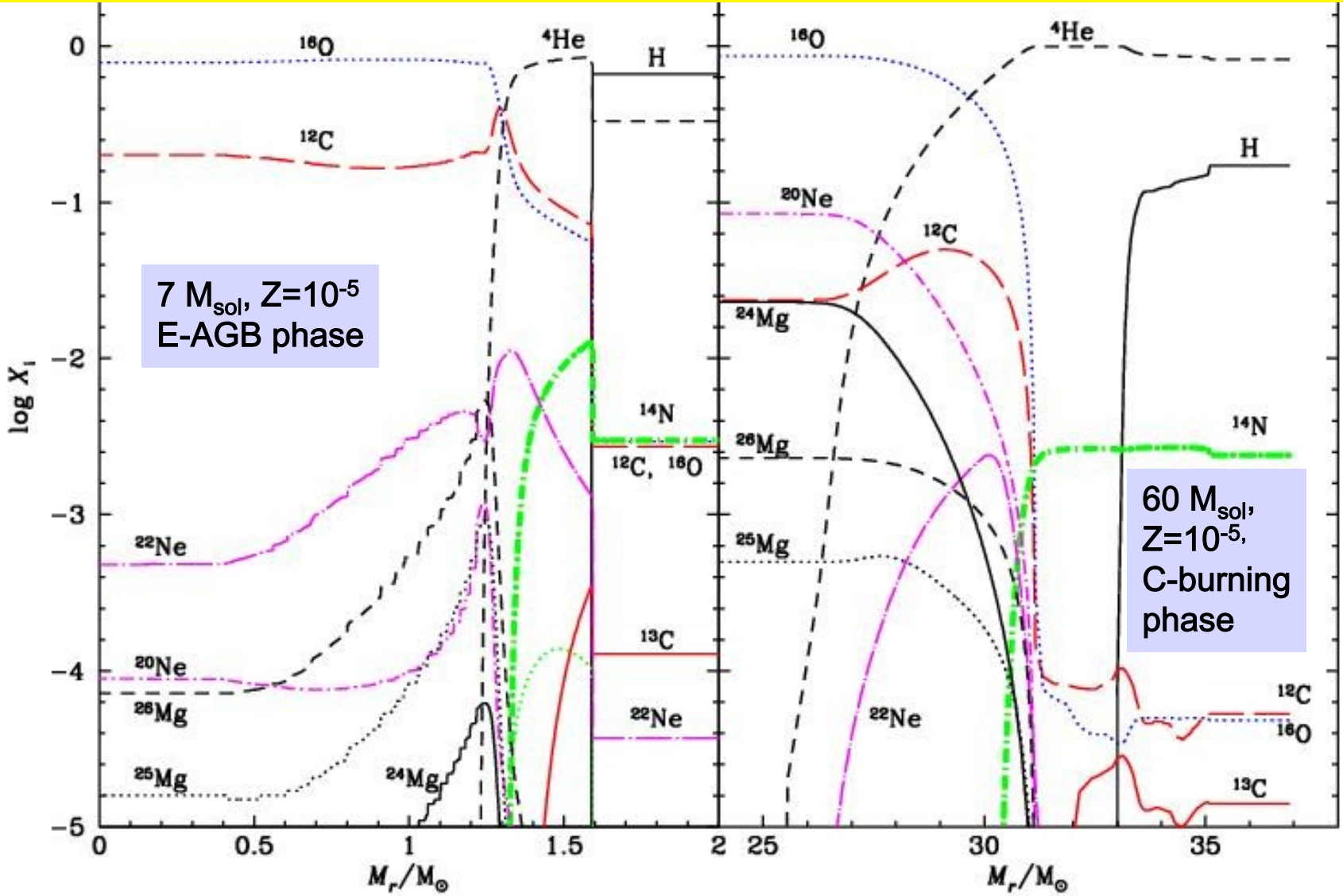

WIND
COMPOSITION
ENVELOPE
OF MODELS
WITHOUT MIXING
DO NOT FIT
85M⊙,10⁻⁶
7M⊙,10⁻⁵
60M⊙,10⁻⁶
60M⊙,10⁻⁶
40M⊙,10⁻⁵
C
N
O
[X/H]
Atomic Number
2
0
−2
−4
5
6
7
8

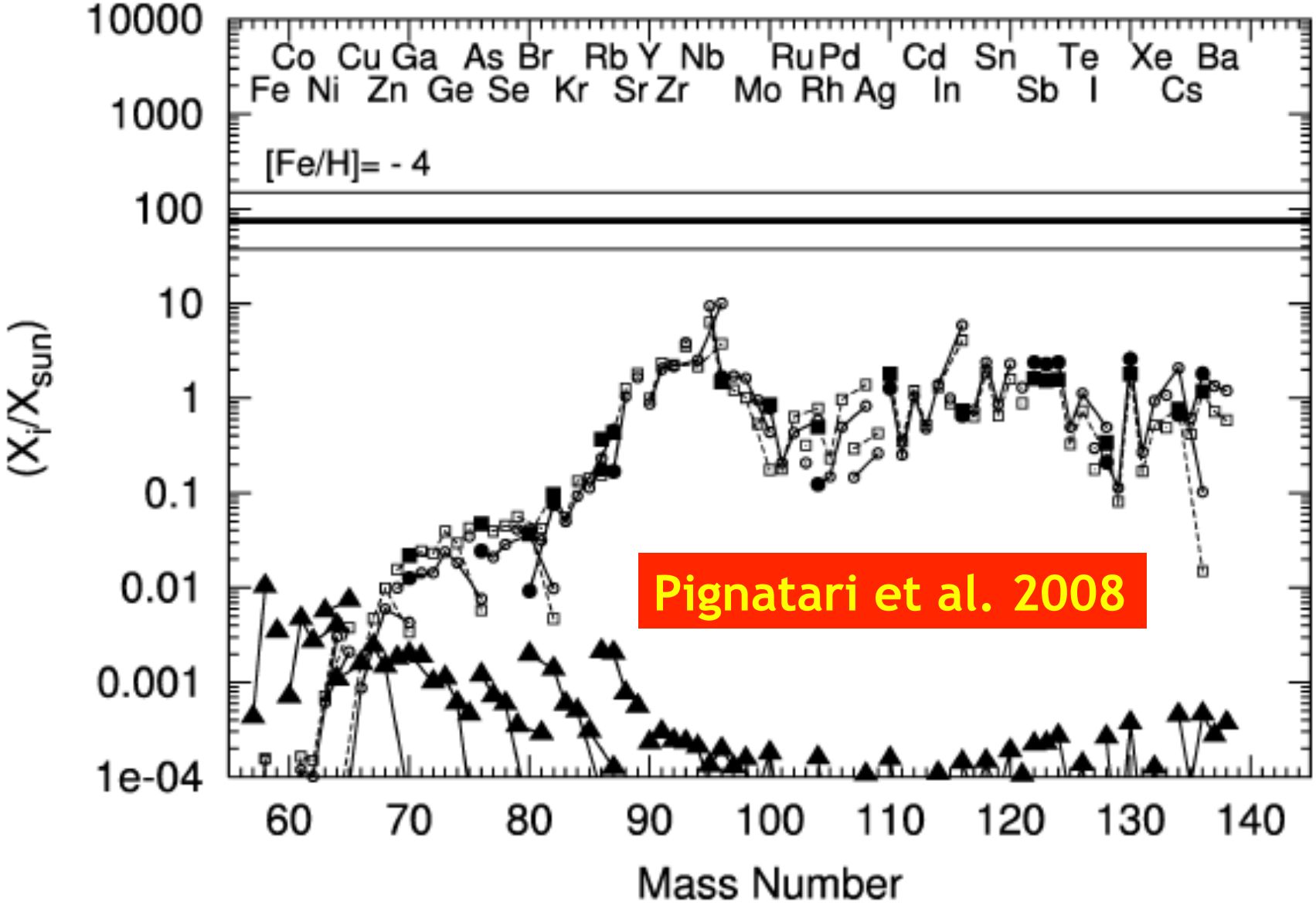
STARS MADE OF WIND MATERIAL WOULD BE **He-RICH** **Li POOR** WITH A LOW **12C/13C** NUMBER RATIO



60 Msol	Y	e(Li)	12C/13C
	0.60	0	4.7
Frebel'star		<0.6	>5

FROM PRIMARY NITROGEN TO ^{19}F, ^{18}O, ^{22}Ne PRIMARY PRODUCTION
FROM PRIMARY 22Ne TO s-procees
^{25}Mg, ^{26}Mg PRODUCTION→ IN H-SHELL→^{26}Al, ^{27}Al




Co Cu Ga As Br Rb Y Nb Ru Pd Cd Sn Te Xe Ba
Fe Ni Zn Ge Se Kr Sr Zr Mo Rh Ag In Sb I Cs
[Fe/H]= - 4
Pignatari et al. 2008
10000
1000
100
10
1
0.1
0.01
0.001
1e-04
(X_i/X_sun)
60
70
80
90
100
110
120
130
140
Mass Number

DOUBLE SEQUENCE.

Blue Sequence

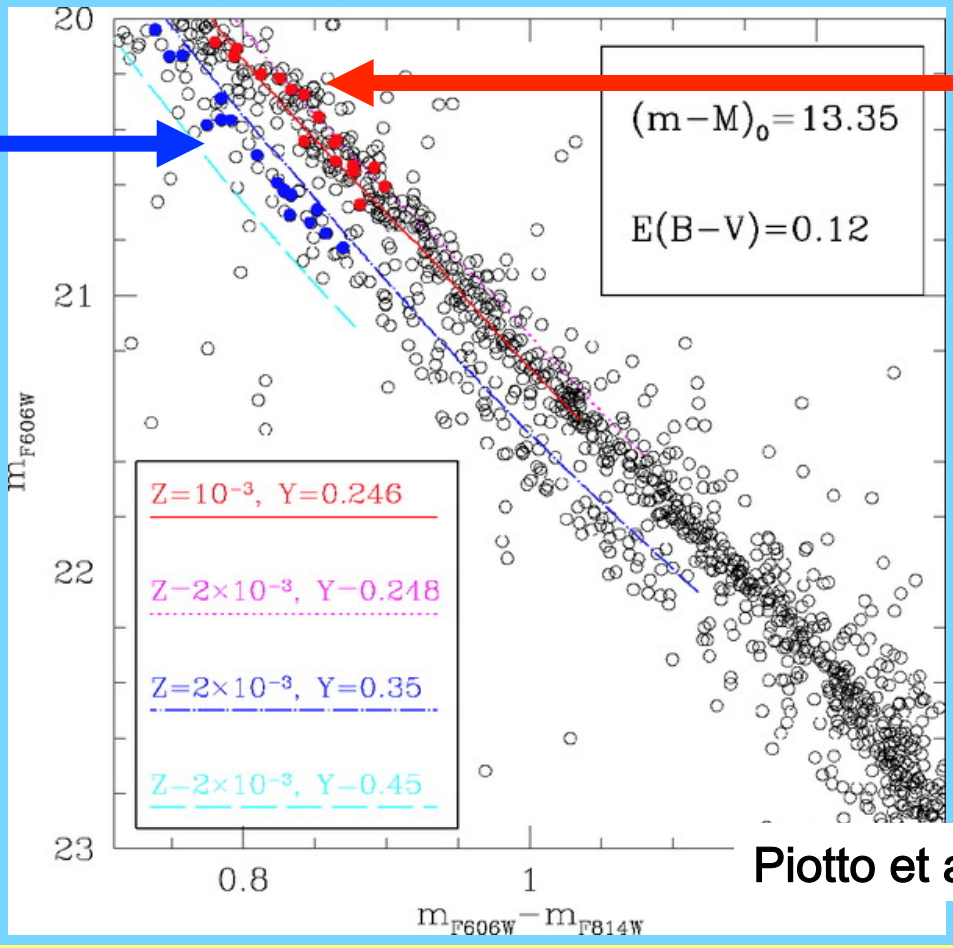
[Fe/H]=-1.26

[C/M]=0

M→ Metals

[N/M]=1-1.5

[Ba/M]=0.7



Piotto et al., ApJ, 621, 777 (2005

Red Sequence

[Fe/H]=-1.57

[C/M]=0

[N/M] < 1.0

[Ba/M]=0.4

Interpretation: Bedin et al. (2004) → blue sequence → pop of super-helium rich stars

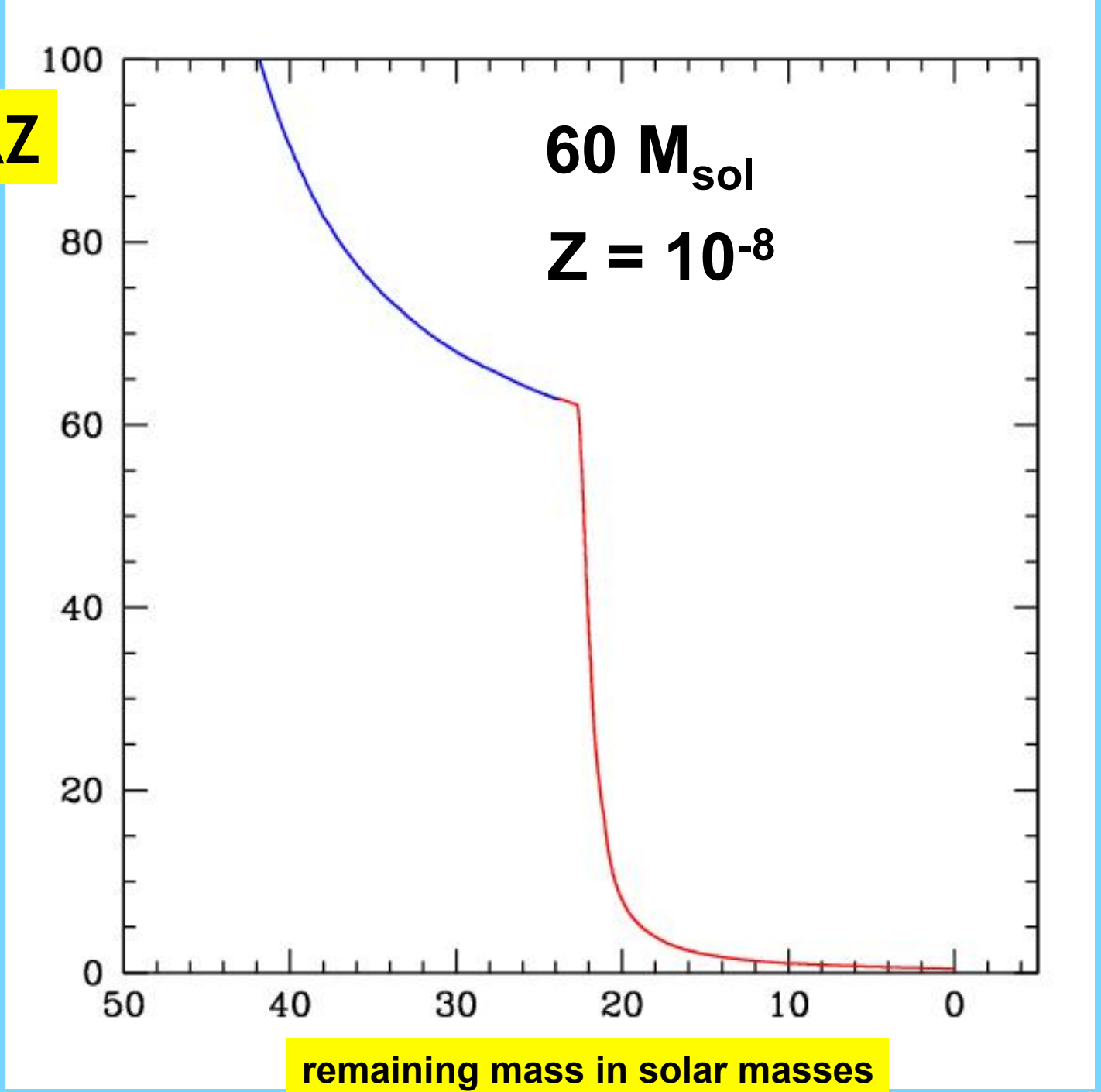
2

Y=0.38

Y=mass fraction of helium which would be necessary to reproduce the position of the blue sequence

Y=0.25

ΔY/ΔZ


60 M_{sol}
$Z = 10^{-8}$
100
80
60
40
20
0
50
40
30
20
10
0
remaining mass in solar masses

MASSIVE STARS AND THE SOLAR SYSTEM FORMATION

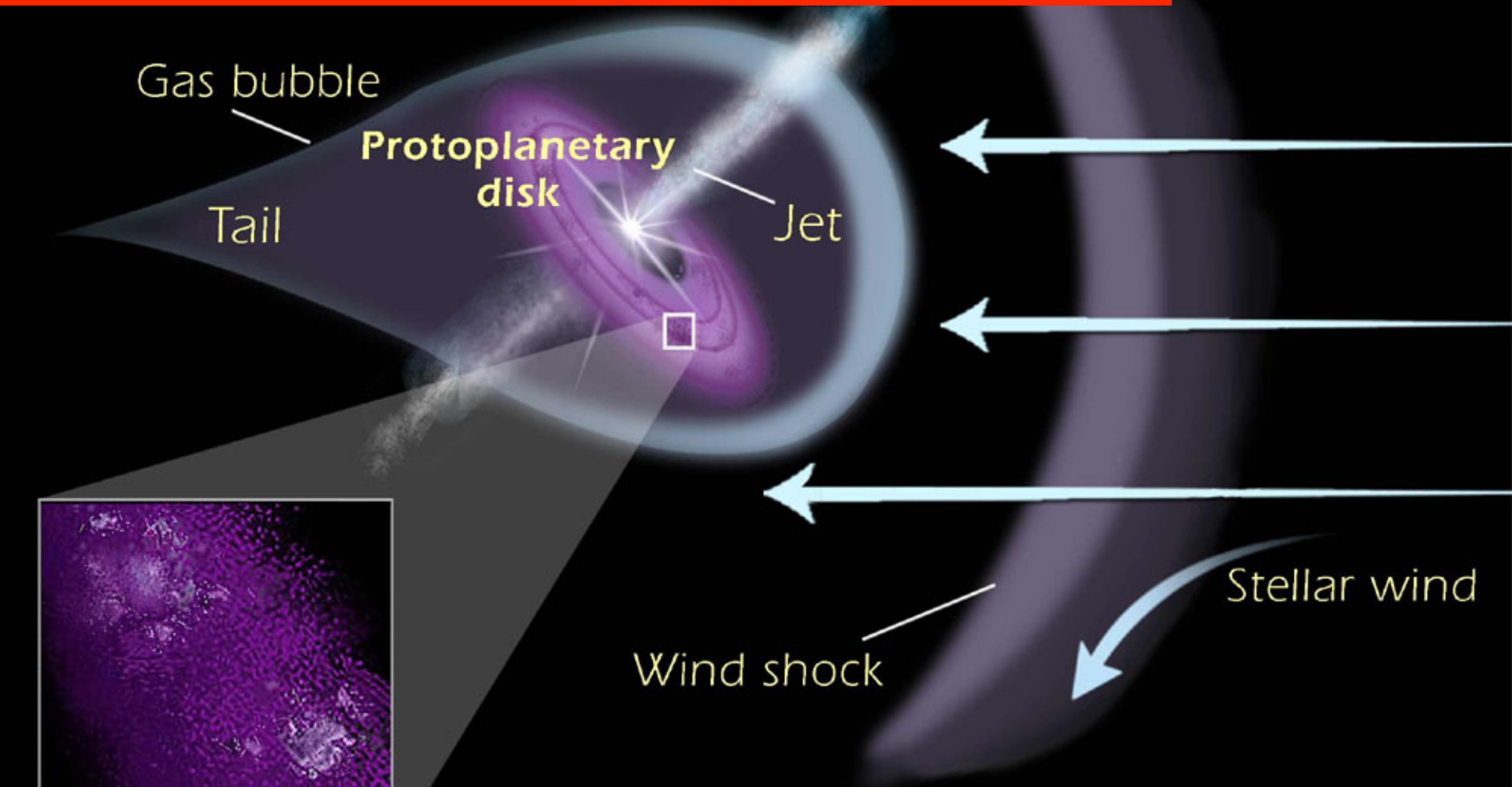
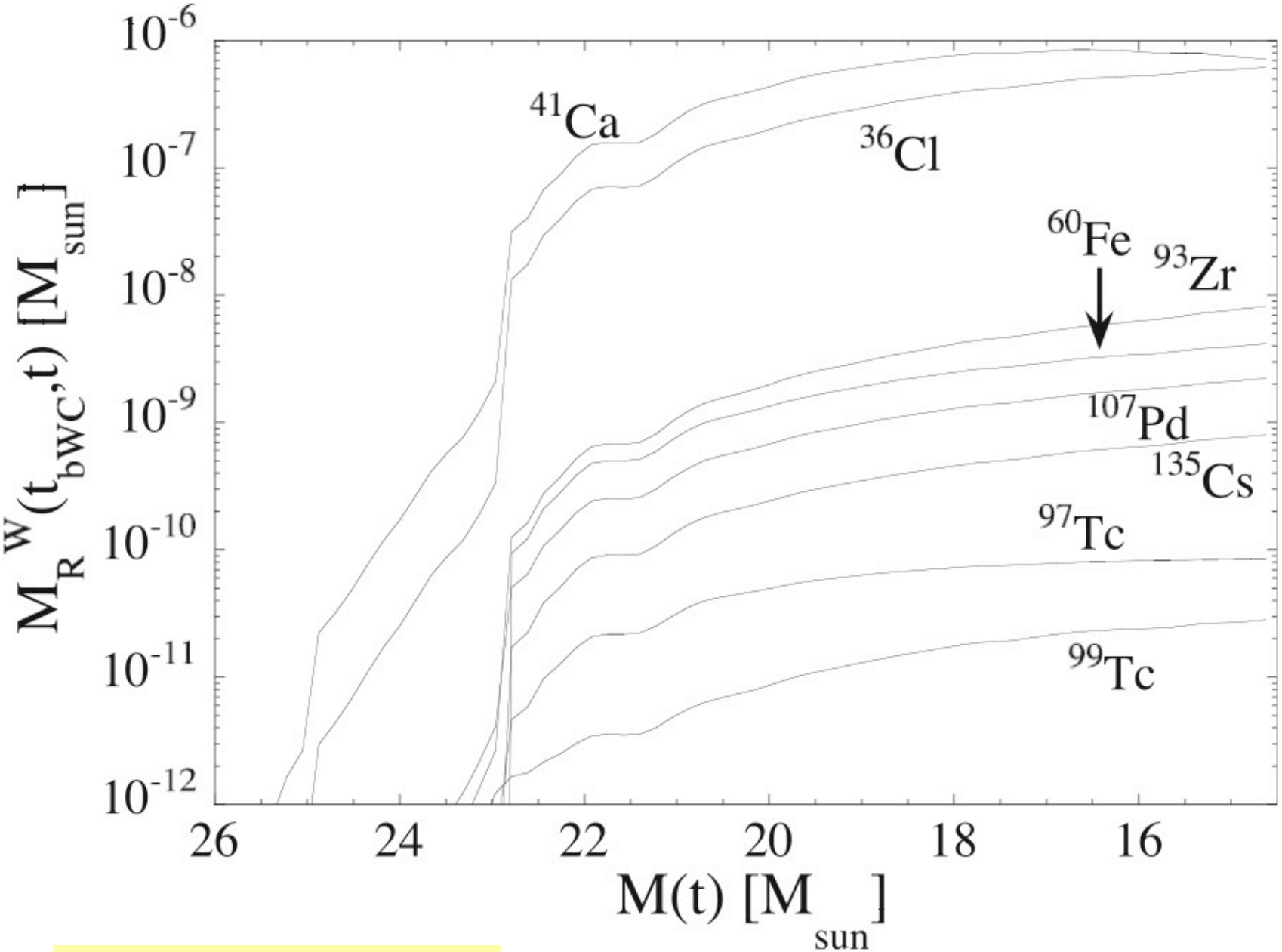


TABLE I

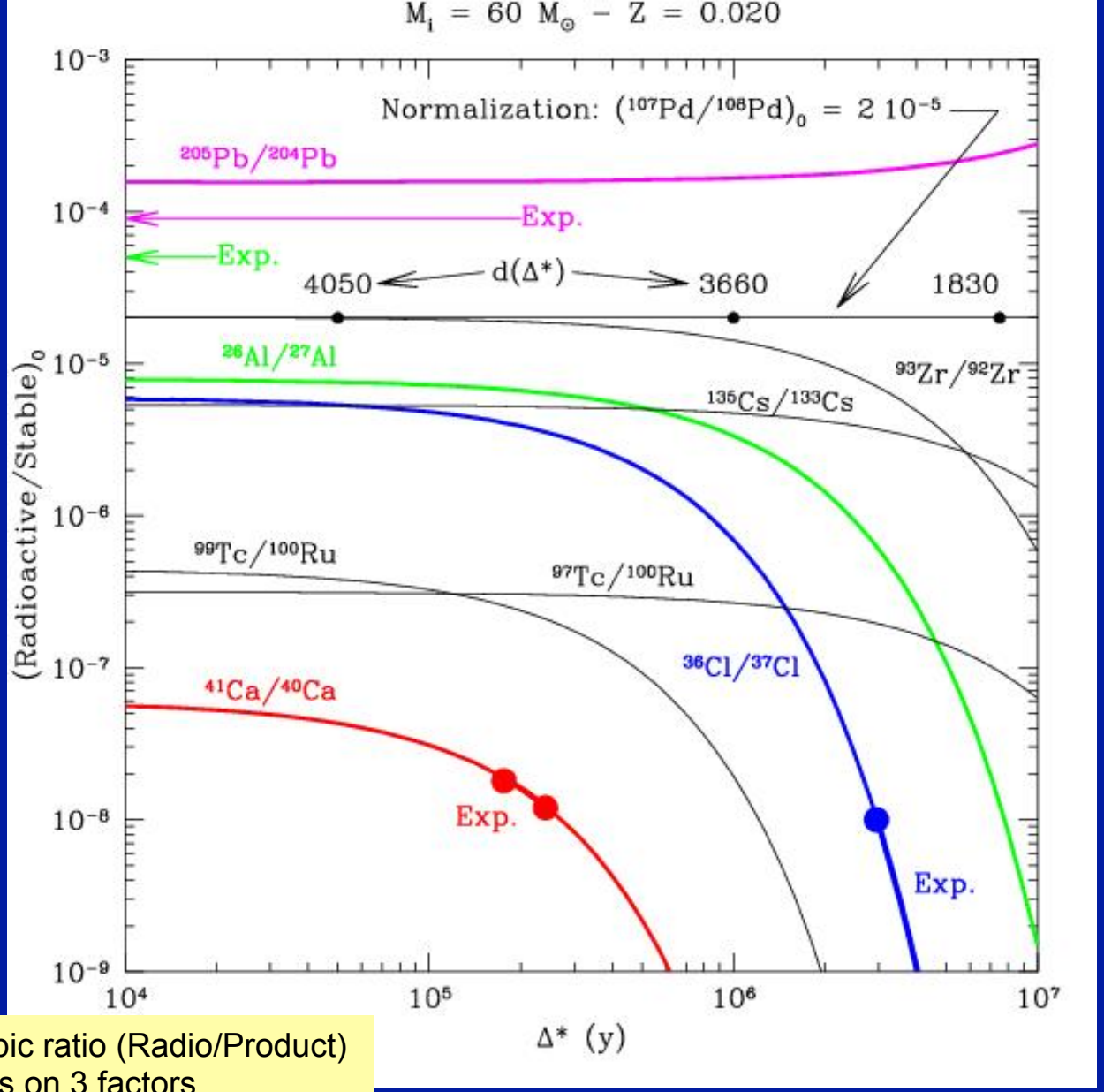
Data on short-lived radioactivities taken from Podosek and Nichols (1997)

Rad. (i)	Ref. (j)	$\tau_{1/2}$ (Myr)	Adopted ratio
^{26}Al	^{27}Al	0.72	5×10^{-5}
^{36}Cl	^{35}Cl	0.30	1.4×10^{-6}
^{41}Ca	^{40}Ca	0.10	1.5×10^{-8}
^{53}Mn	^{55}Mn	3.7	6×10^{-6}
^{60}Fe	^{56}Fe	1.5	4×10^{-9}
^{107}Pd	^{108}Pd	6.5	2×10^{-5}
^{129}I	^{127}I	16	1×10^{-4}
^{146}Sm	^{144}Sm	103	0.005
^{182}Hf	^{180}Hf	9	2×10^{-4}
^{244}Pu	^{238}U	81	0.007

Meyer and Clayton 2000



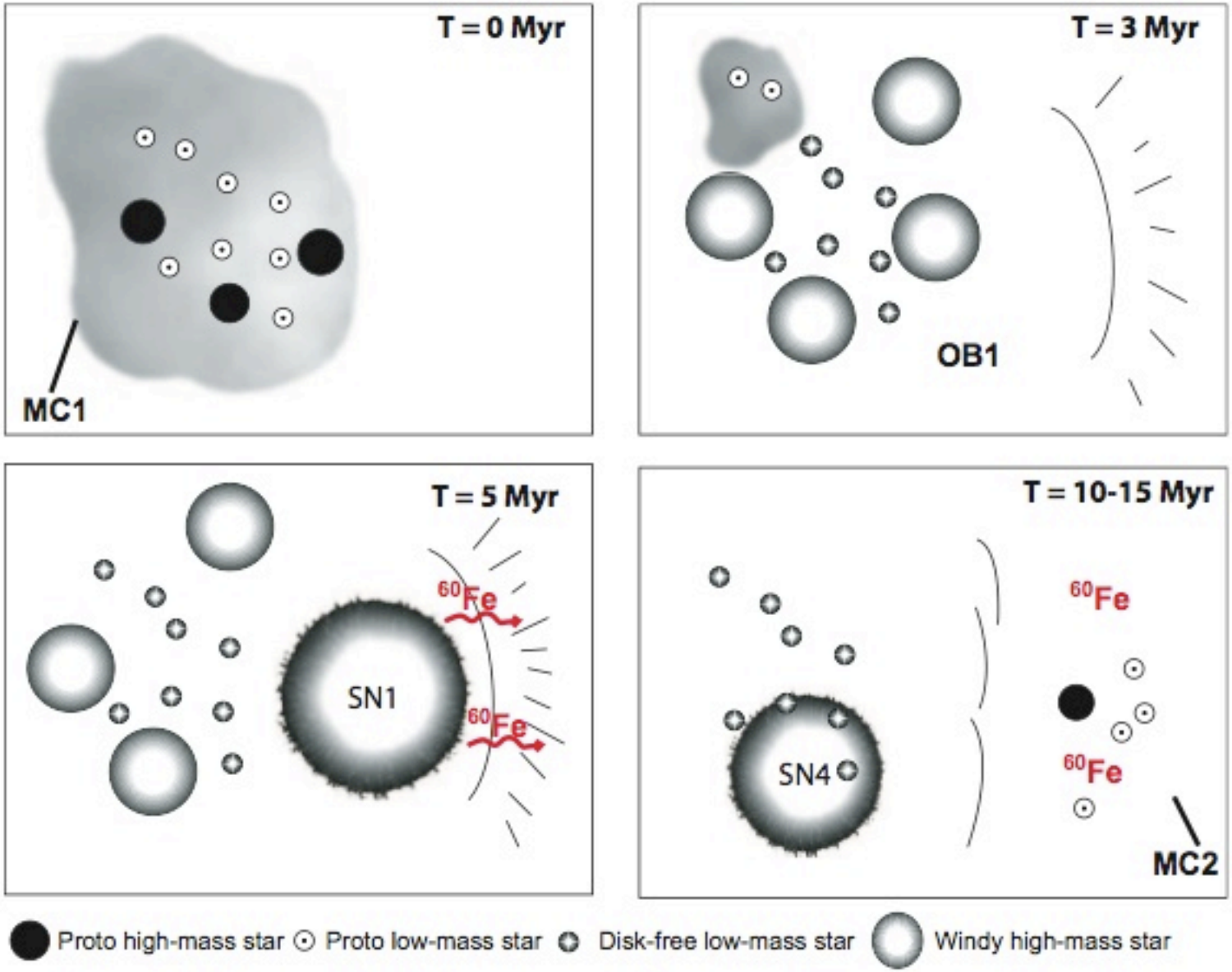
Arnould et al. 2006



Observed isotopic ratio (Radio/Product)
Depends on 3 factors

Initial ratio (in the winf ejected material)
Dilution factor
Time between ejection and incorporation

Arnould et al. 1997, 2006

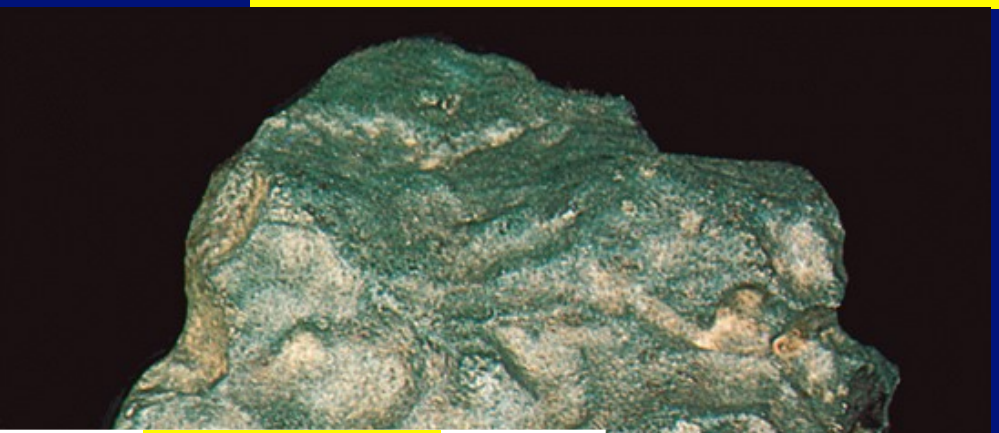


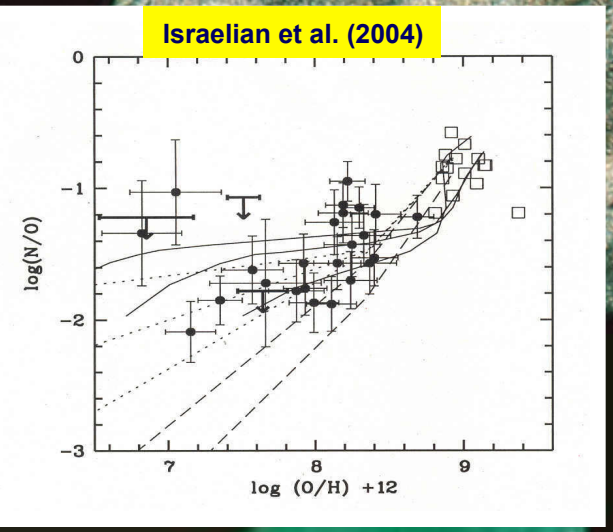
Gounelle et al. 2009

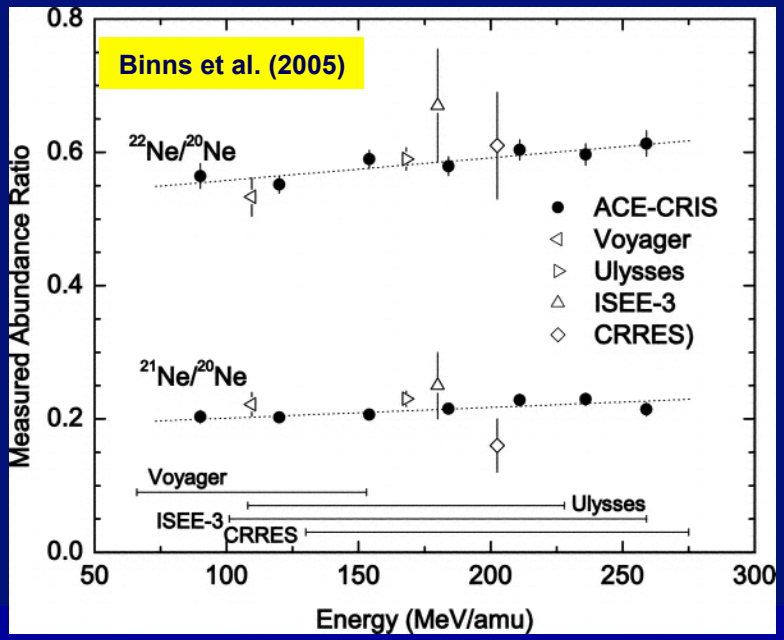
Massive stars are like the flavour of the Universe

So a few
for such a great
emotion

What is the common point ?

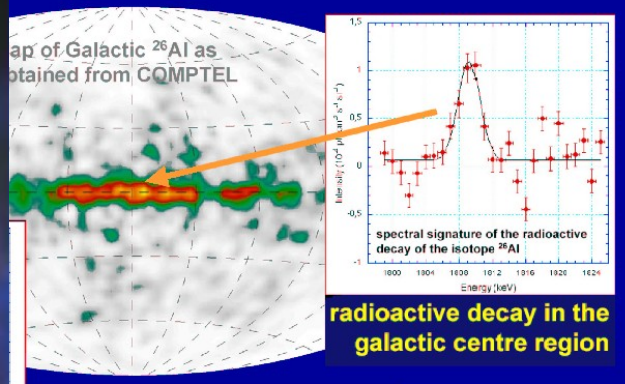






Radioactive ^{26}Al in the Galaxy

... results from SPI/INTEGRAL -



radioactive decay in the galactic centre region

synthesis of new elements by super-massive stars in the Cygnus constellation

© 2003 the SPI collaboration

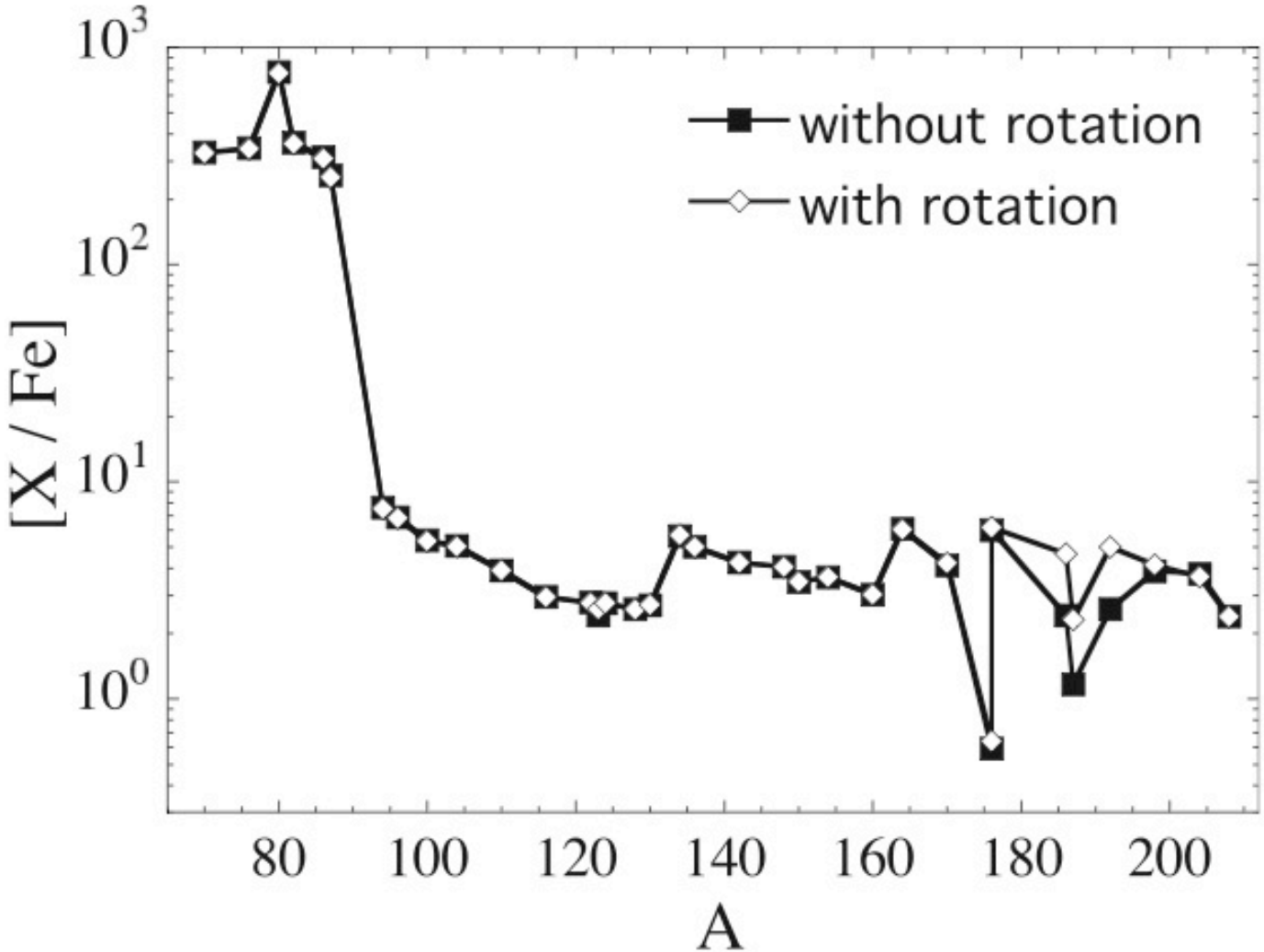
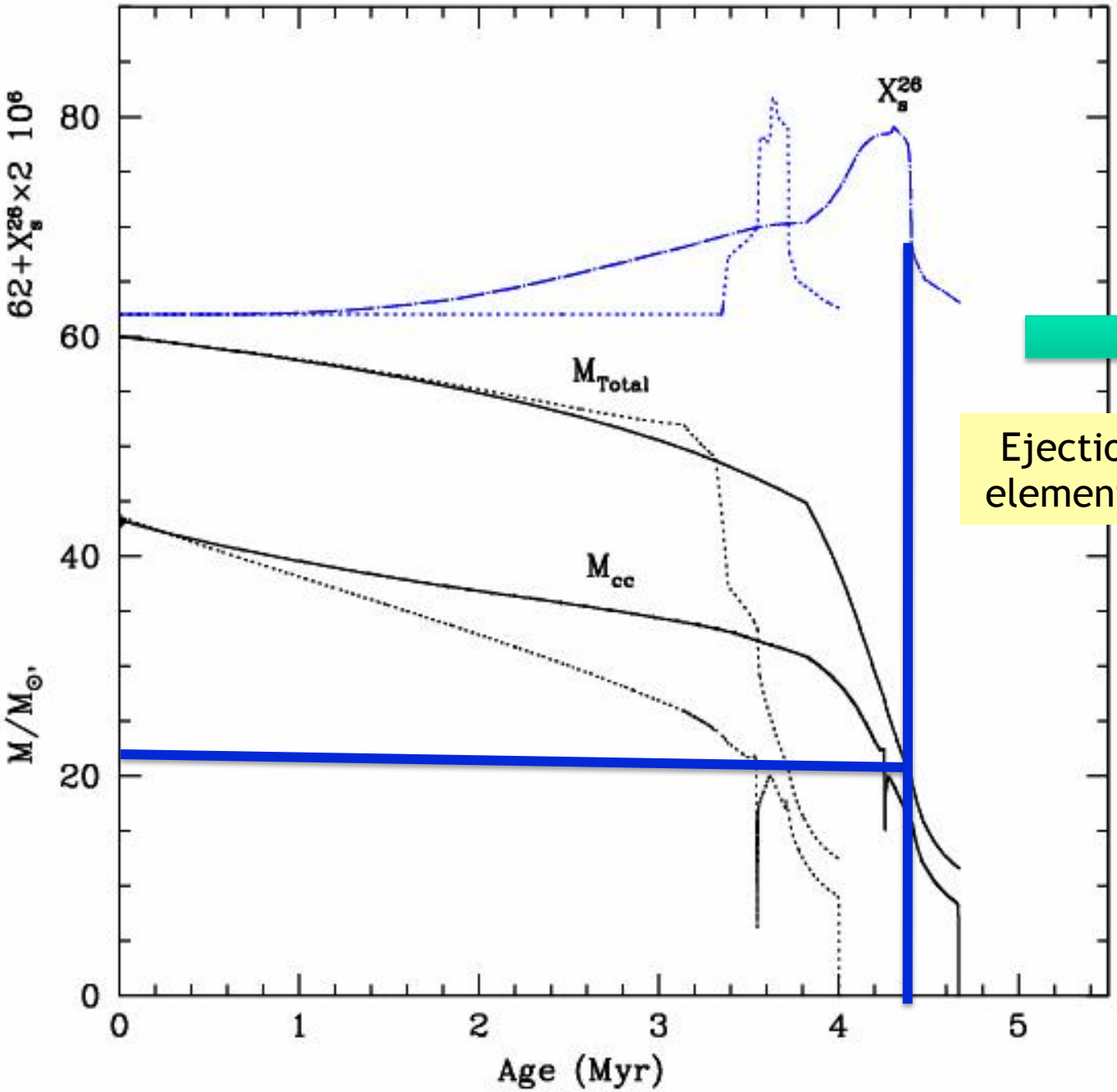


Fig. 2. Mass fractions relative to iron of the (stable) *s*-nuclides (mass number *A*) in the convective core at He exhaustion of the non-rotating and rotating 60 $M_\odot$ stars.

Arnould et al. 2006



Ejection of s-process elements by the winds

Mup

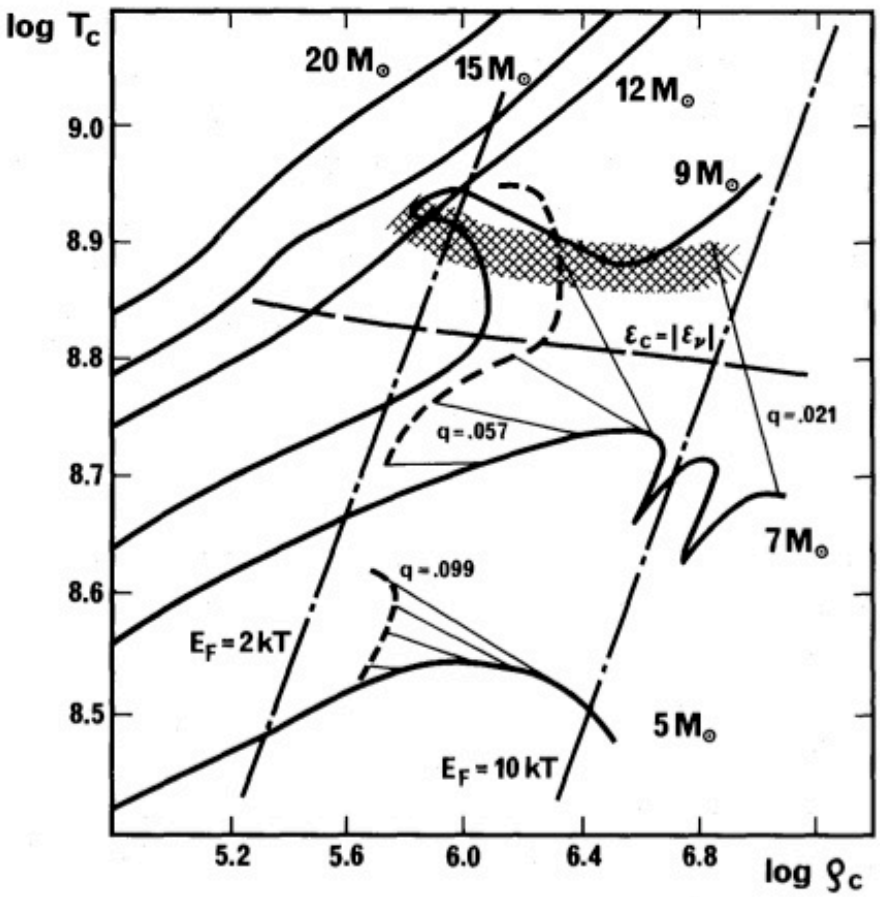


Fig. 12. Detailed part of Fig. 4 for the determination of M_{up}. The evolution of the off-centre maximum of temperature for the models of 7 and 5 $M_\odot$ is shown by bold dashed lines, and by the hatched area during the central oscillations of the 7 $M_\odot$ model. Thin lines connect the off-centre T maxima to the corresponding central values. A few q values indicate the mass fraction at which the off-centre T maxima are located

Off-centre ignition!

Mup 6.6 Msol

Maeder & Meynet 1989
A&A 210 155

What does happen between Mup and Mmas (6.6 and 8 Msol)?

After the core C-burning phase, the core is degenerate.

Its mass is regulated by three competing mechanisms

1) Deepening of the outer convective zone (decreases Mcore)
2) Mass loss (decreases Mcore)
3) Activity of shell-burnings (increases Mcore)

The degenerate core never exceeds the Chandrasekhar mass
→ Evolution of the core into an ONe white-dwarf (SAGB)

The degenerate core mass becomes > Chandrasekhar mass
electron capture supernova→ type II→likely neutron star

The first and advanced phases

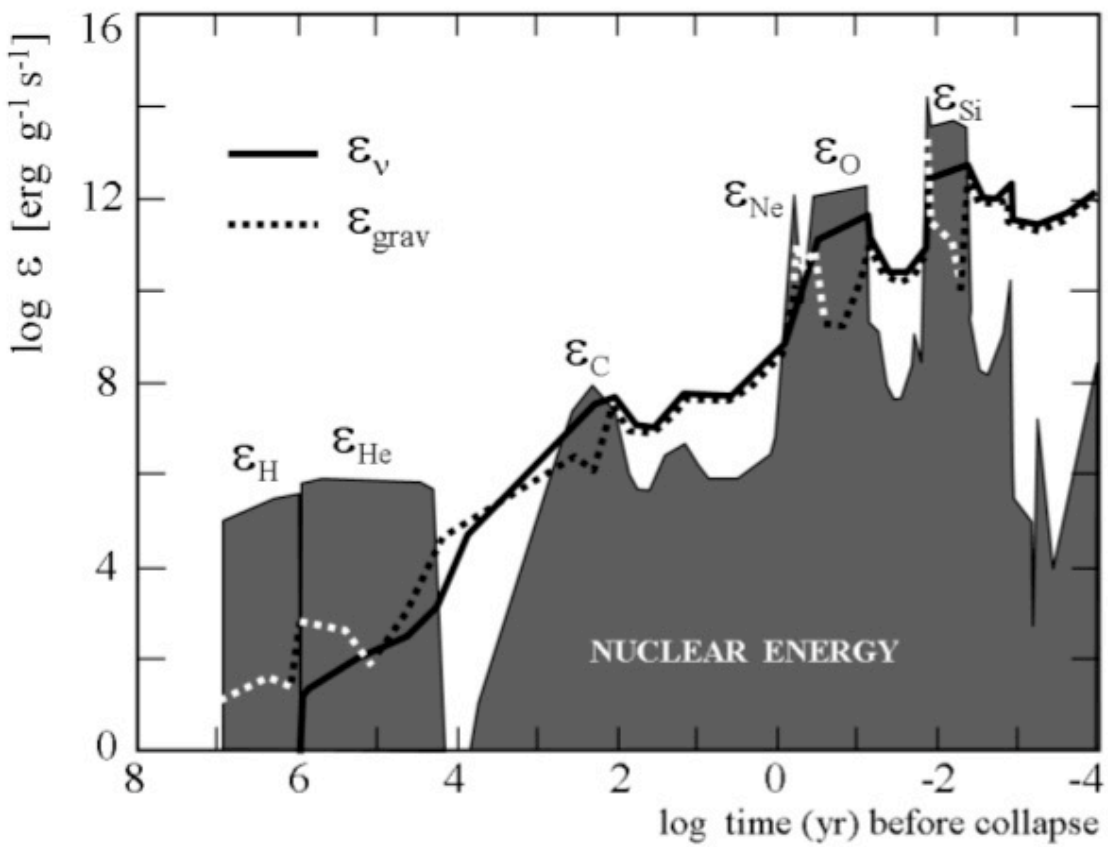
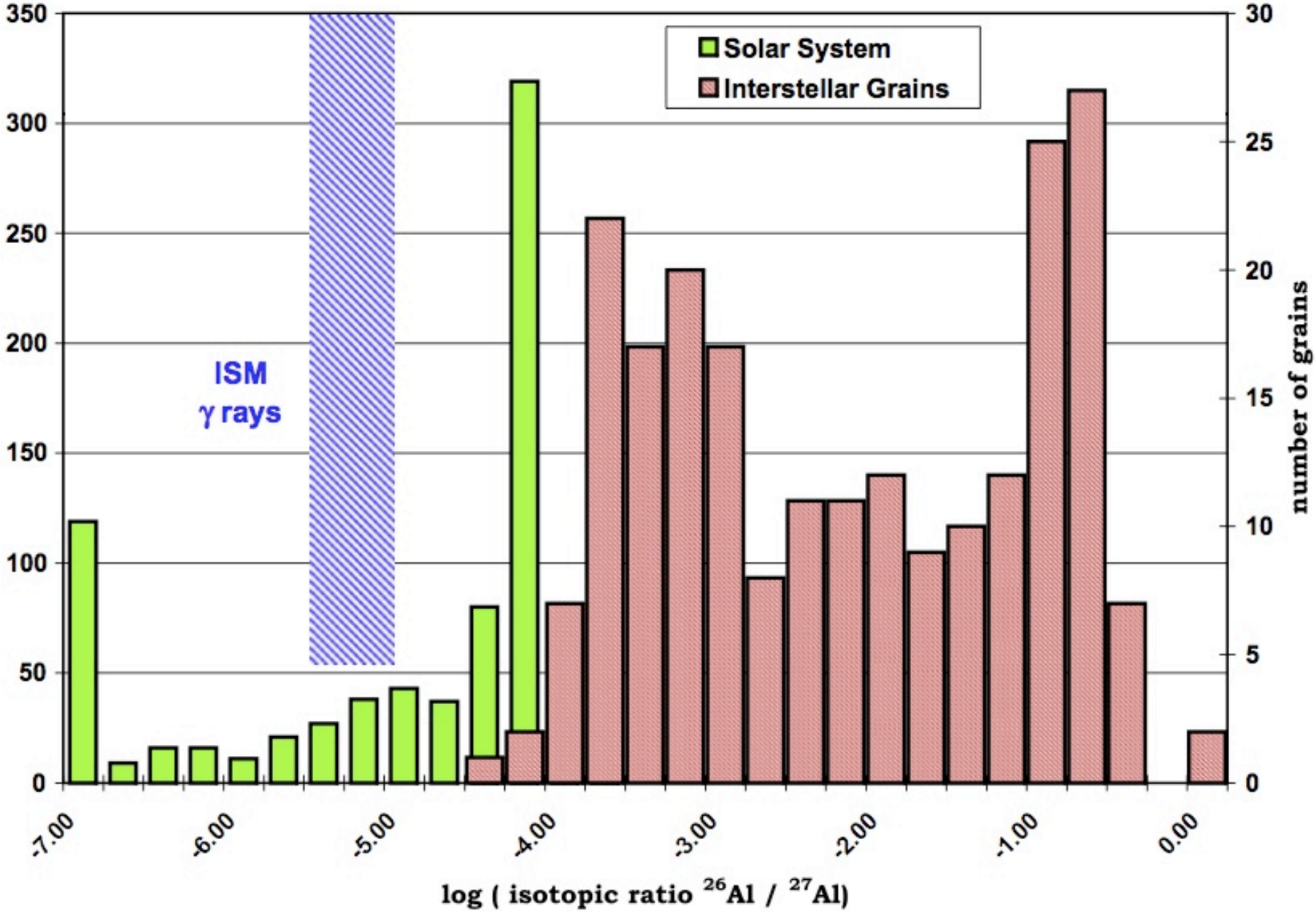


Fig. 28.6. Evolution of the rates of nuclear energy (gray), of neutrino emission (continuous line) and of gravitational energy (dotted line) for a 20 $M_\odot$ star with $Z = 0.02$. Same remark as for Fig. 28.5. Adapted from Hirschi et al. [254]



Diehl et al. 2008

Table 4 The mass fractions of H (X), He (Y) and metals (Z) for a number of widely used compilations of the solar chemical composition

Source	X	Y	Z	Z/X
Present-day photosphere:				
Anders & Grevesse (1989)[a]	0.7314	0.2485	0.0201	0.0274
Grevesse & Noels (1993)[a]	0.7336	0.2485	0.0179	0.0244
Grevesse & Sauval (1998)	0.7345	0.2485	0.0169	0.0231
Lodders (2003)	0.7491	0.2377	0.0133	0.0177
Asplund, Grevesse & Sauval (2005)	0.7392	0.2485	0.0122	0.0165
Lodders, Palme & Gail (2009)	0.7390	0.2469	0.0141	0.0191
Present work	0.7381	0.2485	0.0134	0.0181
Protosolar:				
Anders & Grevesse (1989)	0.7096	0.2691	0.0213	0.0301
Grevesse & Noels (1993)	0.7112	0.2697	0.0190	0.0268
Grevesse & Sauval (1998)	0.7120	0.2701	0.0180	0.0253
Lodders (2003)	0.7111	0.2741	0.0149	0.0210
Asplund, Grevesse & Sauval (2005)	0.7166	0.2704	0.0130	0.0181
Lodders, Palme & Gail (2009)	0.7112	0.2735	0.0153	0.0215
Present work	0.7154	0.2703	0.0142	0.0199

[a]The He abundances given in Anders & Grevesse (1989) and Grevesse & Noels (1993) have here been replaced with the current best estimate from helioseismology (Section 3.9).

Asplund et al. 2009

→ tracks, lifetimes, supernova type, surface abundances

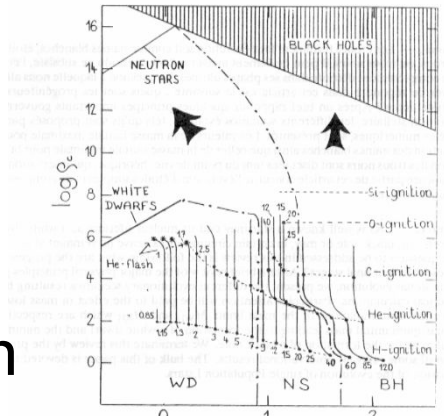
→ Population of massive stars

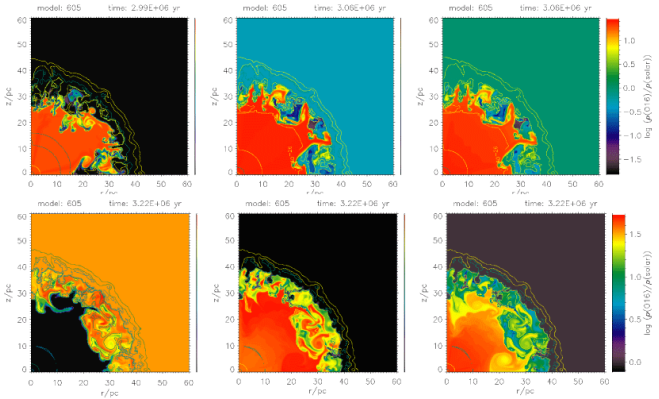
→ Evolution and nature of the remnant

→ Energy release into the interstellar medium

→ Injection of new synthesized elements

→ Hardness of the ionizing radiation field





Note that→ known since 1920 that radiation pressure is able to eject atoms from stars

Only in late 60s→ sensitive UV mass loss diagnostics of O stars

Hot stellar winds (OB MS stars)

High $V_{inf} \sim 3\ V_{esc}$ =2000-3000 km/s

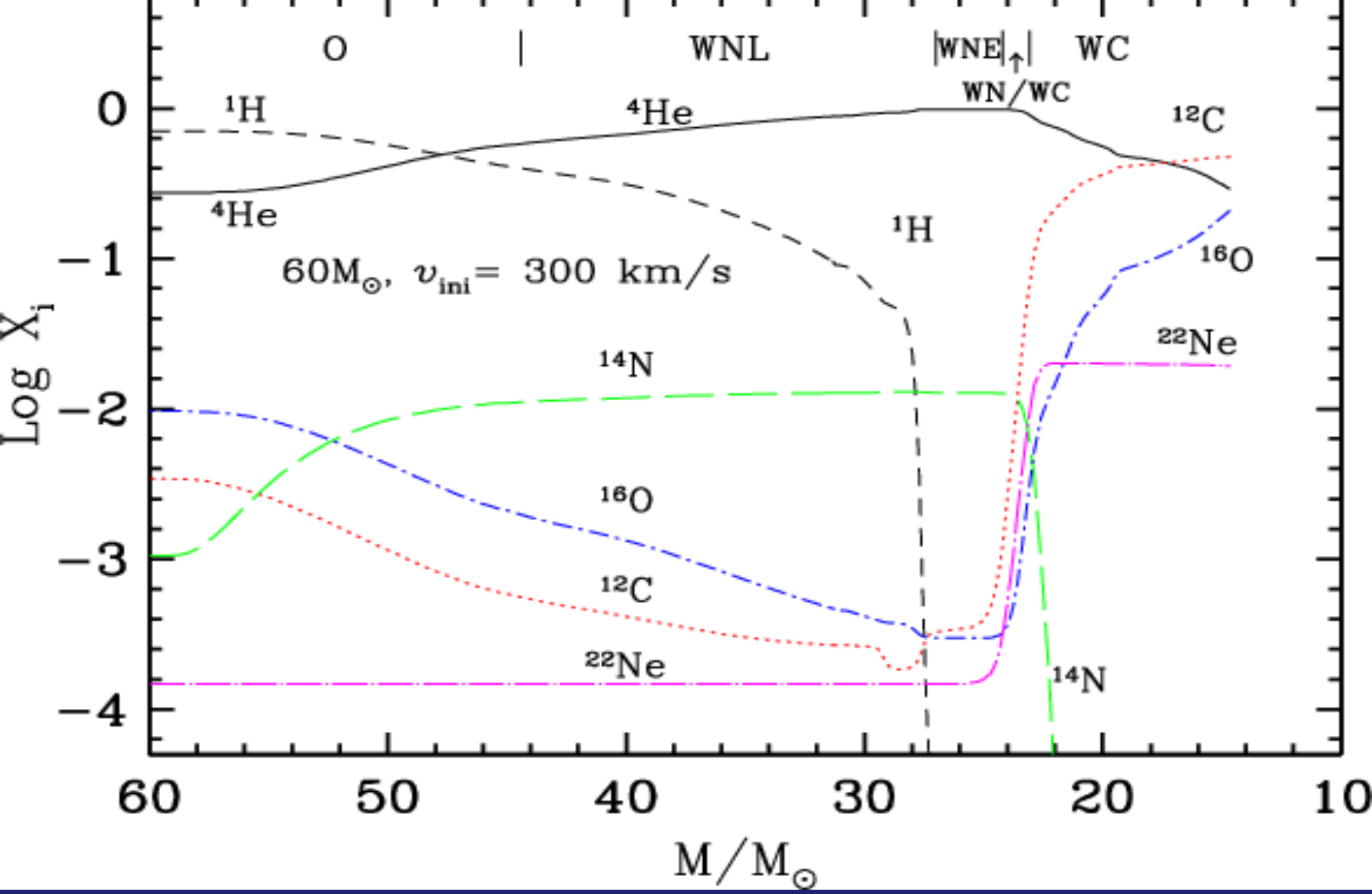
High $M_{dot} \sim 10^{-4}\ 10^{-8}\ M_{sol}$/year

LBV have superwind phases 10^{-1}-10^{0} M_{sol}/year (Eta Car)
quite phases 10^{-4}-10^{-3} M_{sol}/year

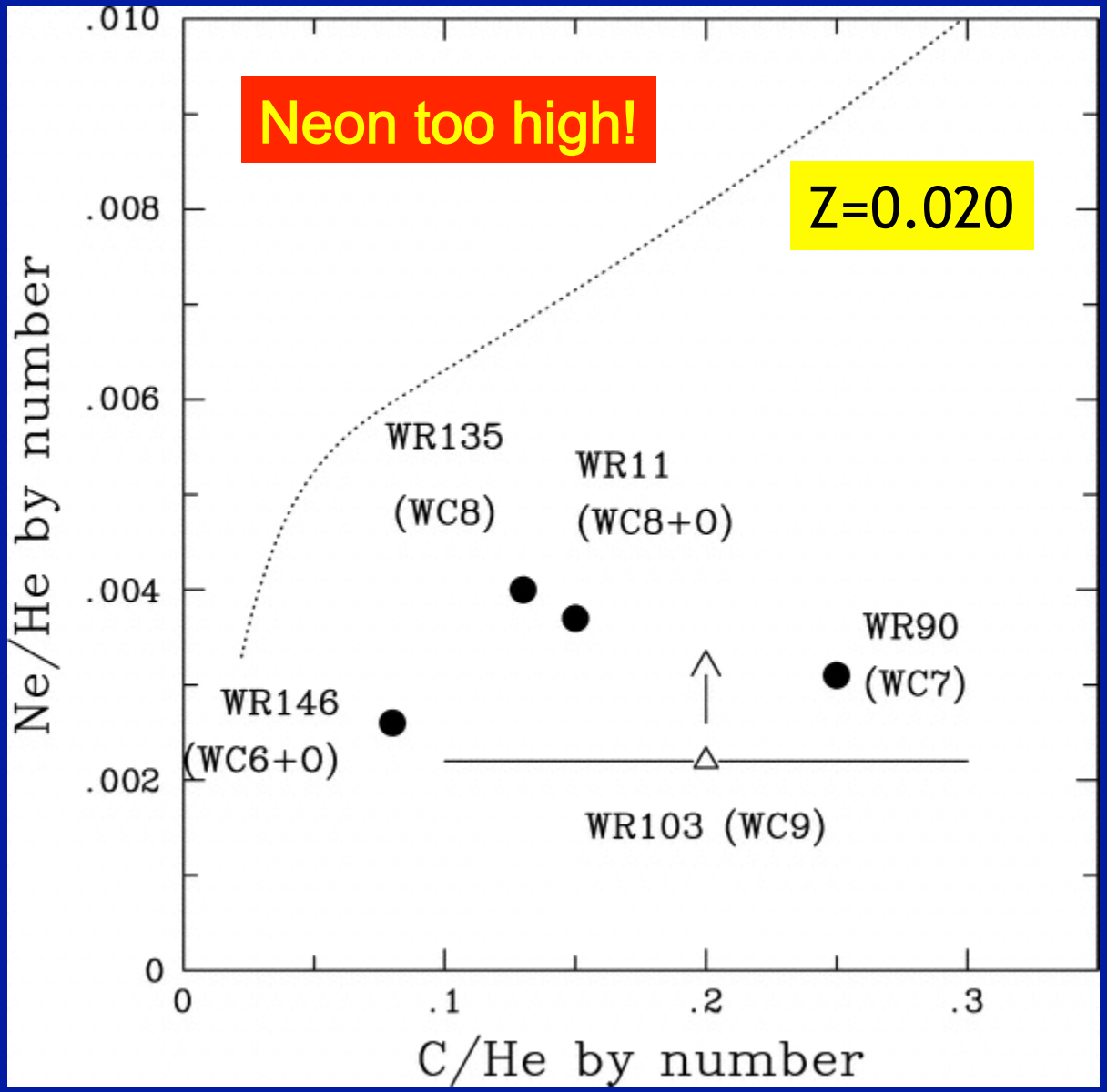
Radiation pressure gradient

Act via line opacity in hot massive MS stars

May act through continuum opacity in super Eddington LBVs



TESTS OF THE NUCLEAR REACTIONS



Crowther et al. 2006

Table 5 Comparison of the protosolar abundances with those in nearby B stars and HII regions[a]

Elem.	Sun[b]	Sun[c]	B stars[d]	HII[e]	GCE[f]
He	10.98 ± 0.01	10.98 ± 0.01	10.98 ± 0.02	10.96 ± 0.01	0.01
C	8.56 ± 0.06	8.47 ± 0.05	8.35 ± 0.03	8.66 ± 0.06	0.06
N	7.96 ± 0.06	7.87 ± 0.05	7.76 ± 0.05	7.85 ± 0.06	0.08
O	8.87 ± 0.06	8.73 ± 0.05	8.76 ± 0.03	8.80 ± 0.04	0.04
Ne	8.12 ± 0.06	7.97 ± 0.10	8.08 ± 0.03	8.00 ± 0.08	0.04
Mg	7.62 ± 0.05	7.64 ± 0.04	7.56 ± 0.05		0.04
Si	7.59 ± 0.05	7.55 ± 0.04	7.50 ± 0.02		0.08
S	7.37 ± 0.11	7.16 ± 0.03	7.21 ± 0.13	7.30 ± 0.04	0.09
Ar	6.44 ± 0.06	6.44 ± 0.13	6.66 ± 0.06	6.62 ± 0.06	
Fe	7.55 ± 0.05	7.54 ± 0.04	7.44 ± 0.04		0.14
	Z=0.02	Z=0.014	Z= 0.014		

[a]The solar values given here include the effects of diffusion (Turcotte & Wimmer-Schweingruber 2002) as discussed in Section 3.11. The HII numbers include the estimated elemental fractions tied up in dust; the dust corrections for Mg, Si, and Fe are very large and, thus, too uncertain to provide meaningful values here. Also given in the last column is the predicted Galactic chemical enrichment (GCE) over the past 4.56 Gyr.

[b]Grevesse & Sauval (1998).

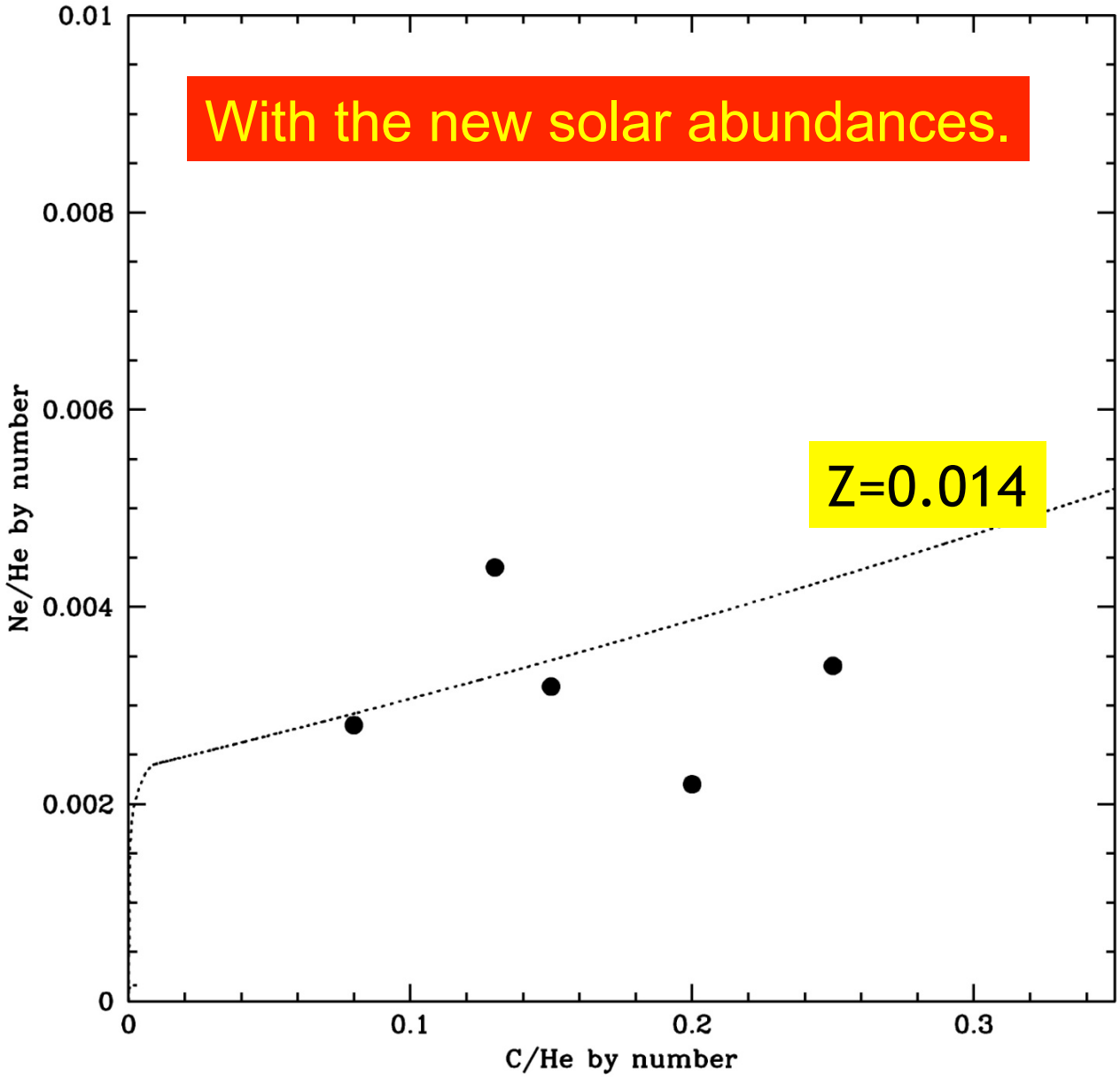
[c]Present work.

[d]Przybilla, Nieva & Butler (2008); Morel et al. (2006); Lanz et al. (2008).

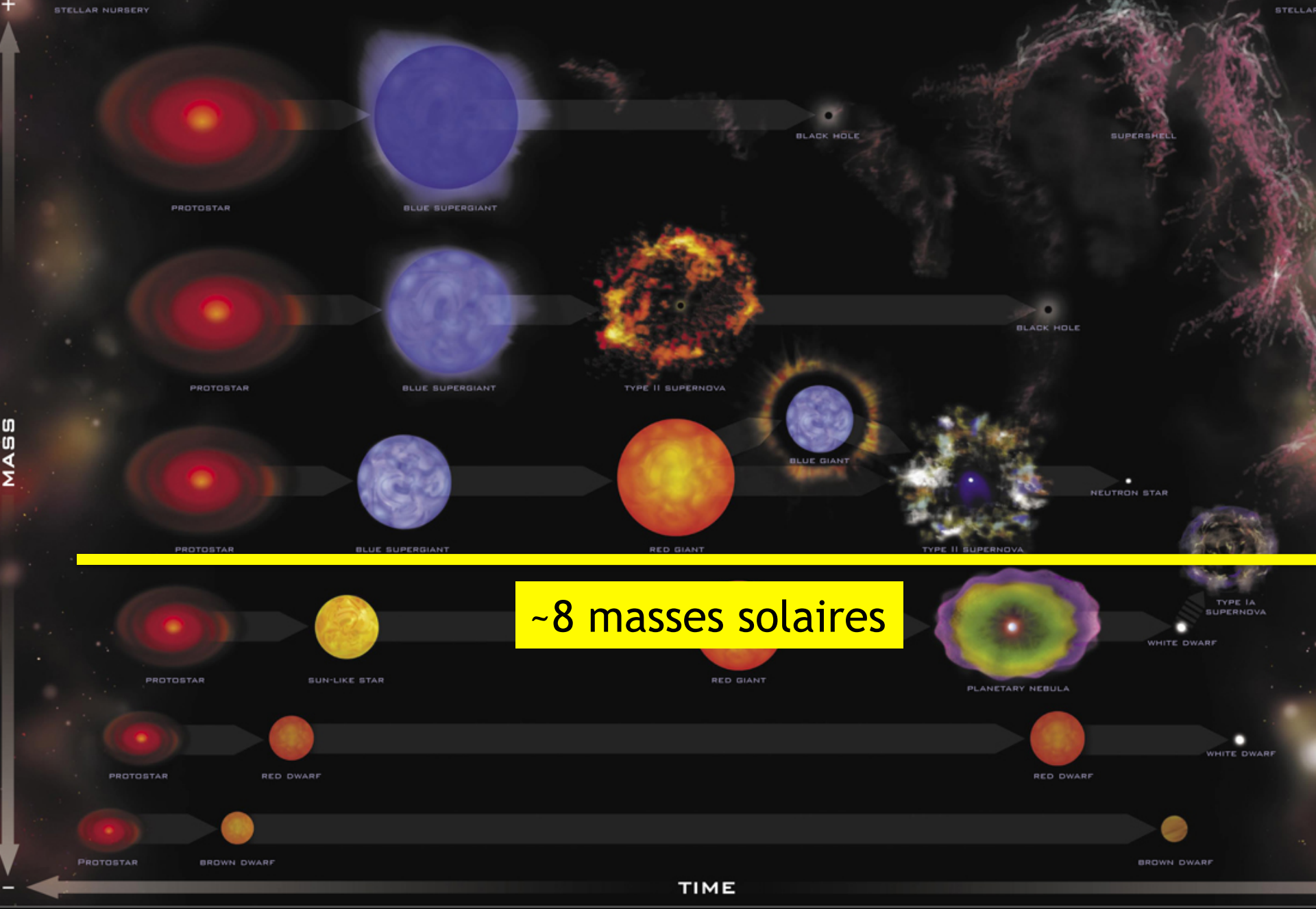
[e]Esteban et al. (2004, 2005), García-Rojas & Esteban (2007).

[f]Chiappini, Romano & Matteucci (2003).

Asplund et al. 2009


With the new solar abundances.
Z=0.014
Ne/He by number
C/He by number
0.01
0.008
0.006
0.004
0.002
0
0
0.1
0.2
0.3

What are massive stars?


STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
BLUE GIANT
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
TYPE II SUPERNOVA
NEUTRON STAR
MASS
~8 masses solaires
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
TYPE IA SUPERNOVA
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF
TIME

Mmas

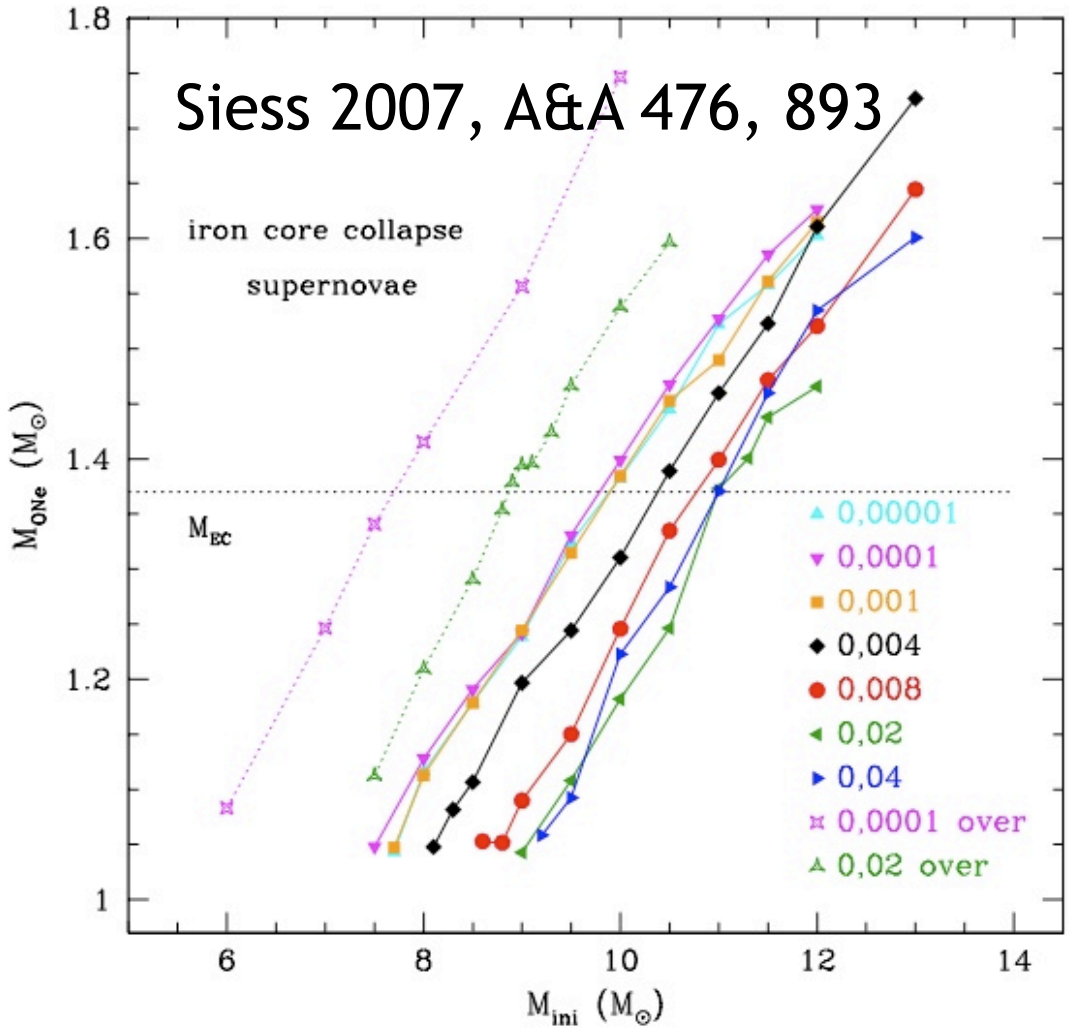


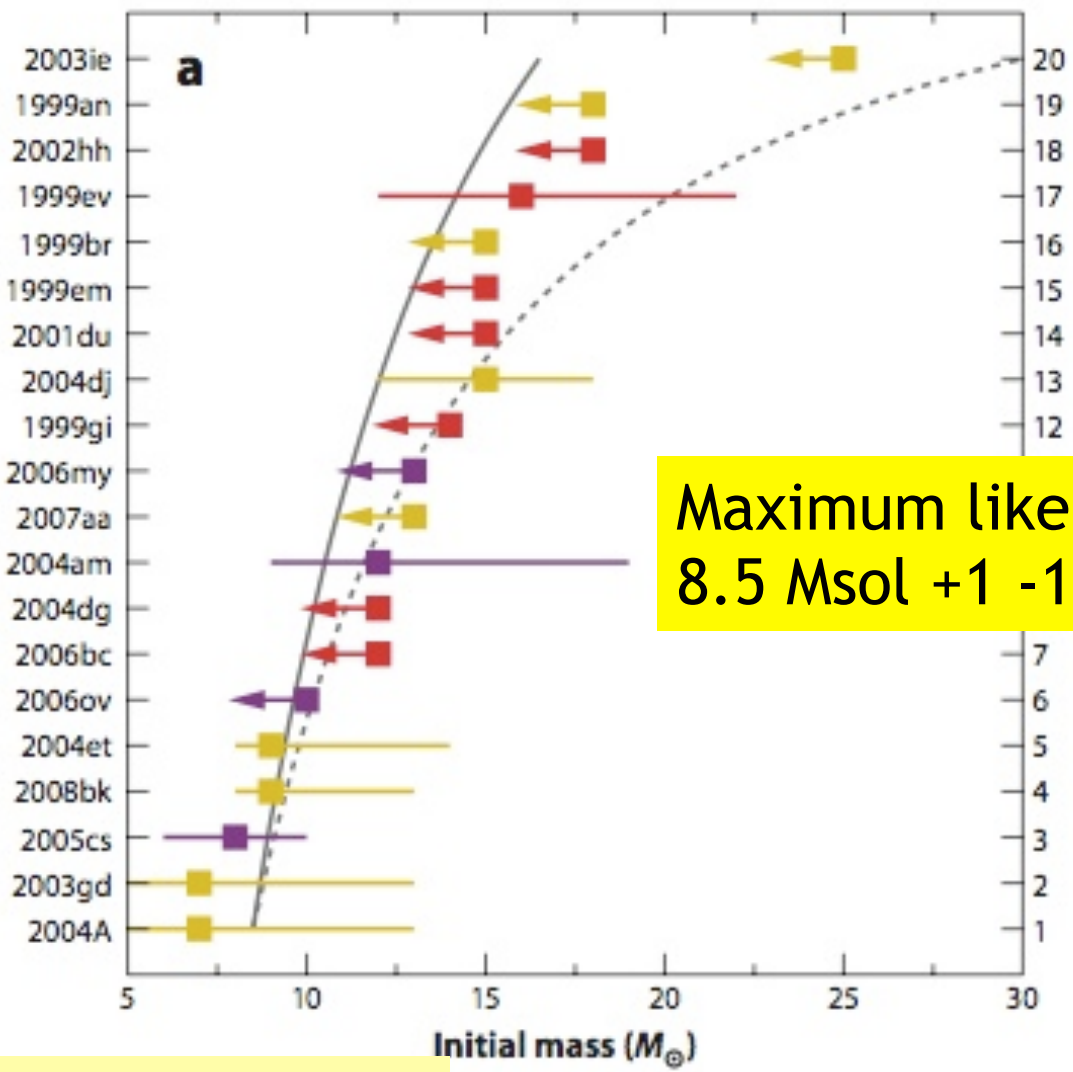
Fig. 6. Mass of the ONe core at the end of C-burning for the different initial compositions as a function of initial mass. Models with overshooting are connected by dotted lines. The horizontal line indicates the critical mass $M_{EC} = 1.37\ M_\odot$ (see Sect. 4.2).

Nomoto 1984

If the ONe core mass at the end of the C-burning phase is greater than 1.37 Msol, the star proceeds through all nuclear burning stages and evolves into an iron core collapse SN

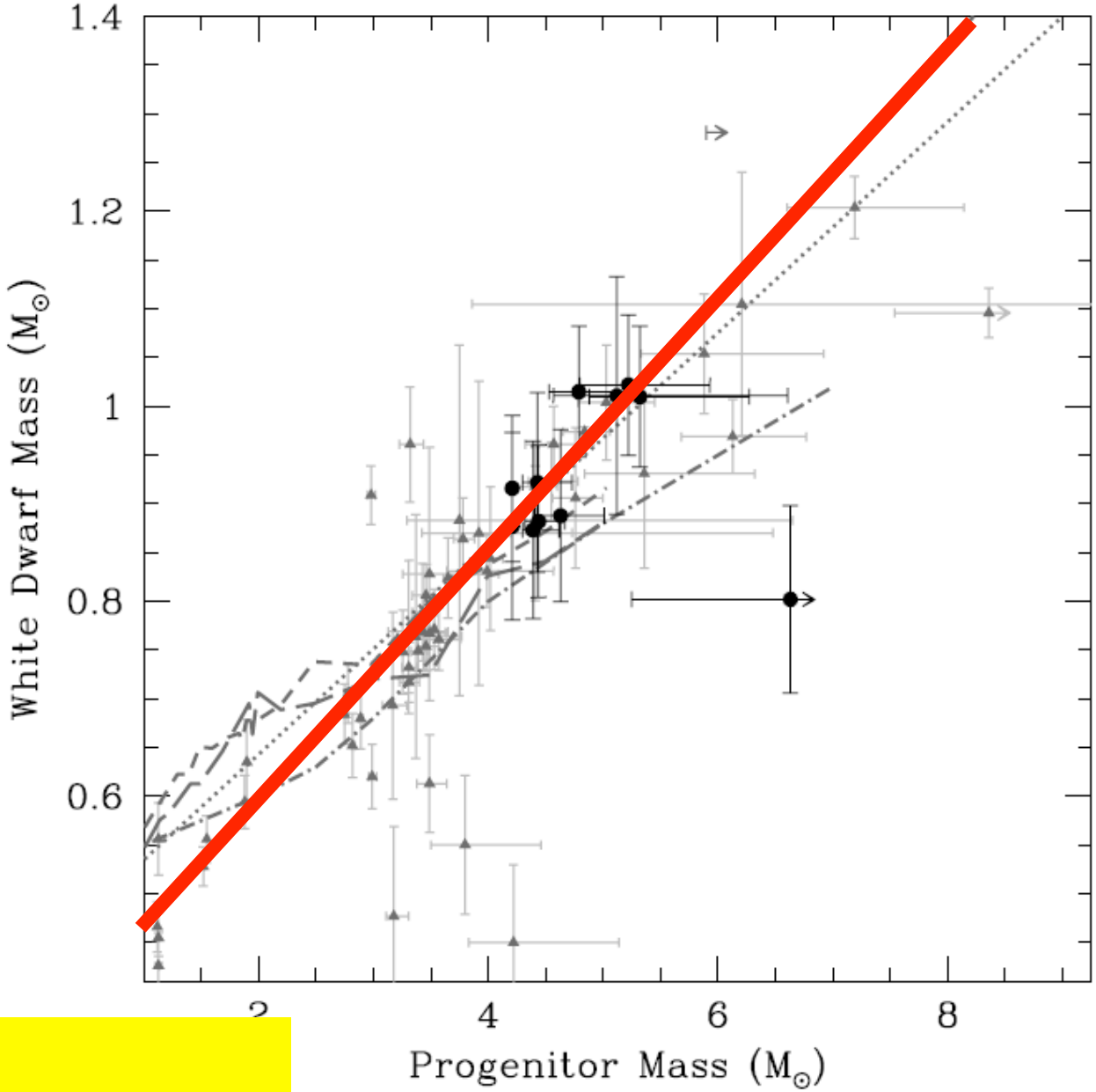
Around 8 Msol

Minimum mass for the progenitors of type II Sne (IIP)



Maximum likelihood analysis
8.5 Msol +1 -1.5Msol

Smartt, 2009, ARAA, 47, 63



See also
Koester & Reimers 1996
Weidemann 2000

Williams, et al. 2009, ApJ 693, 355

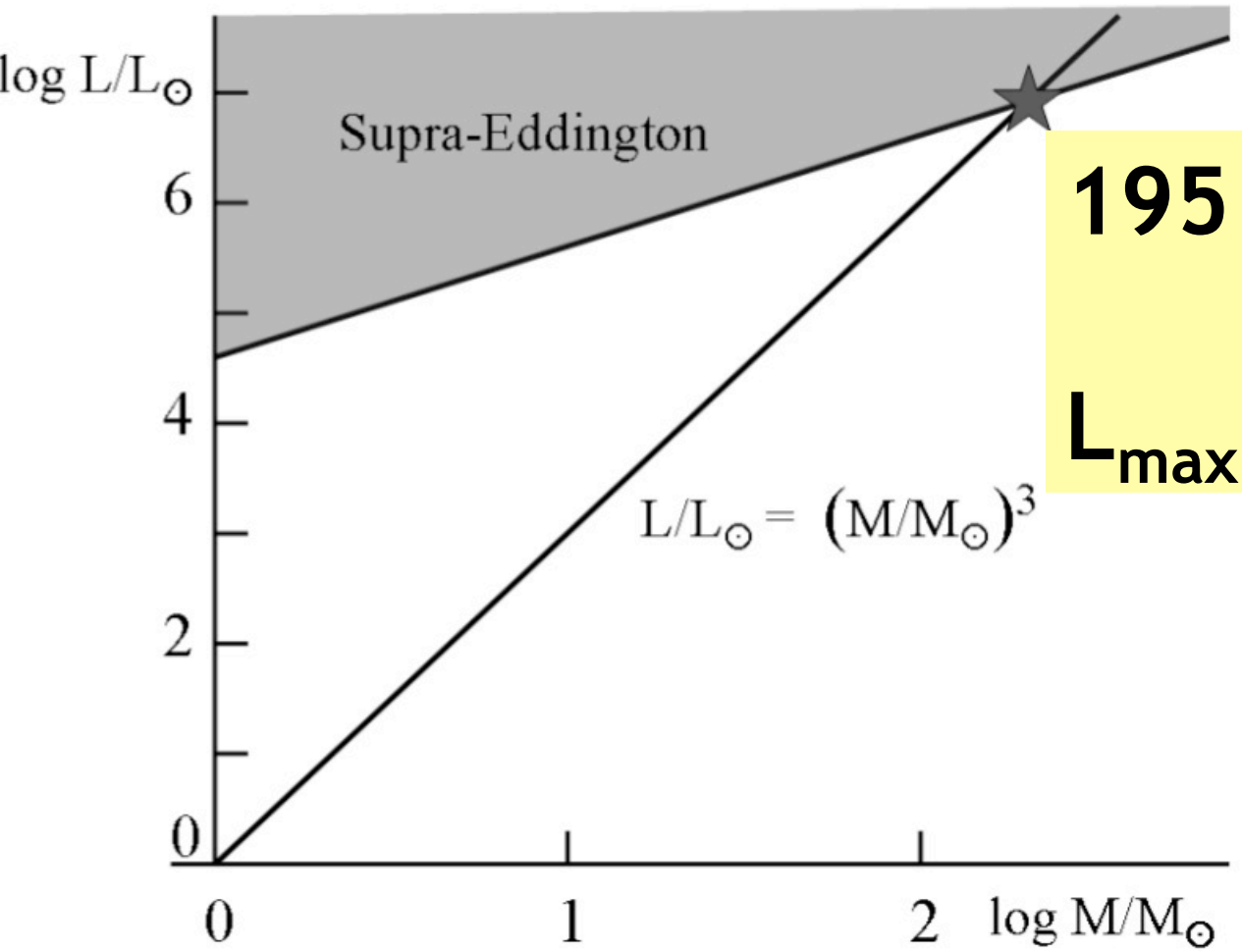
What is the upper limit?

For a given hot mass star there exist a maximum value of the luminosity called the Eddington luminosity

$$\frac{L_{\max}}{L_{sol}} = 38200 \ \frac{M}{Msol}$$

This luminosity is such that the outward acceleration given to the matter through the interactions between photons and electrons (through electron scattering) is equal to the gravity at the surface of the star

An upper bound of stellar mass

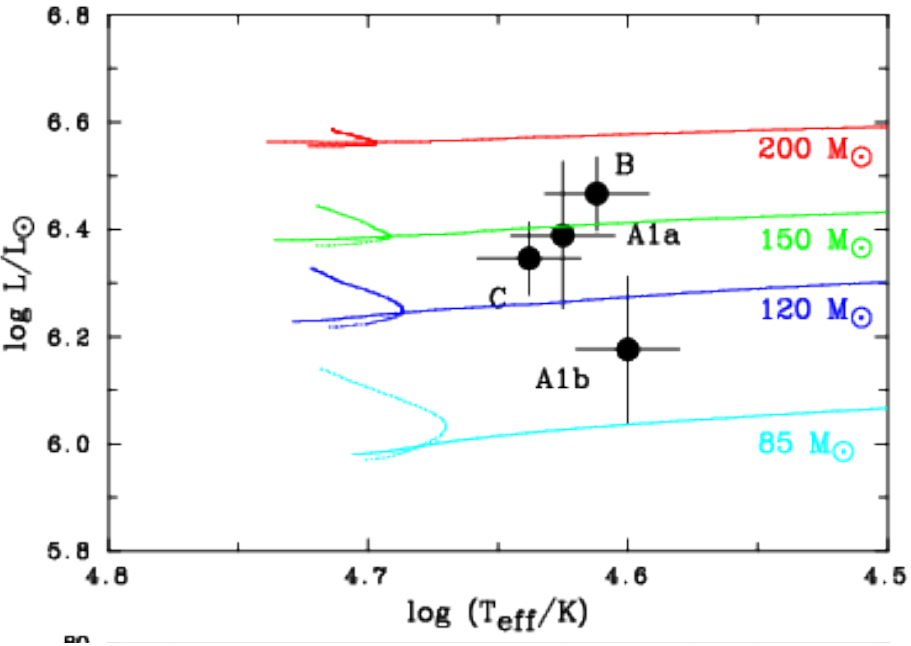


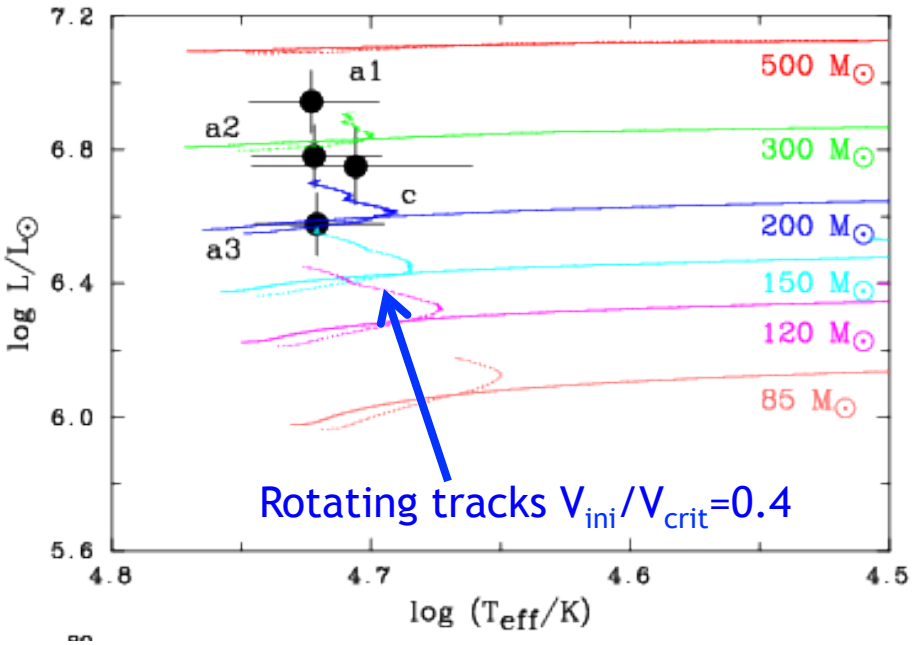
195 Msol

L_{max} 7.4 10^6 Lsol

Milky way, NGC 3603 :
10^4 $M_{sol,}$, age ~1.5 Myr
Masses→ 83 – 180 M_{sol}

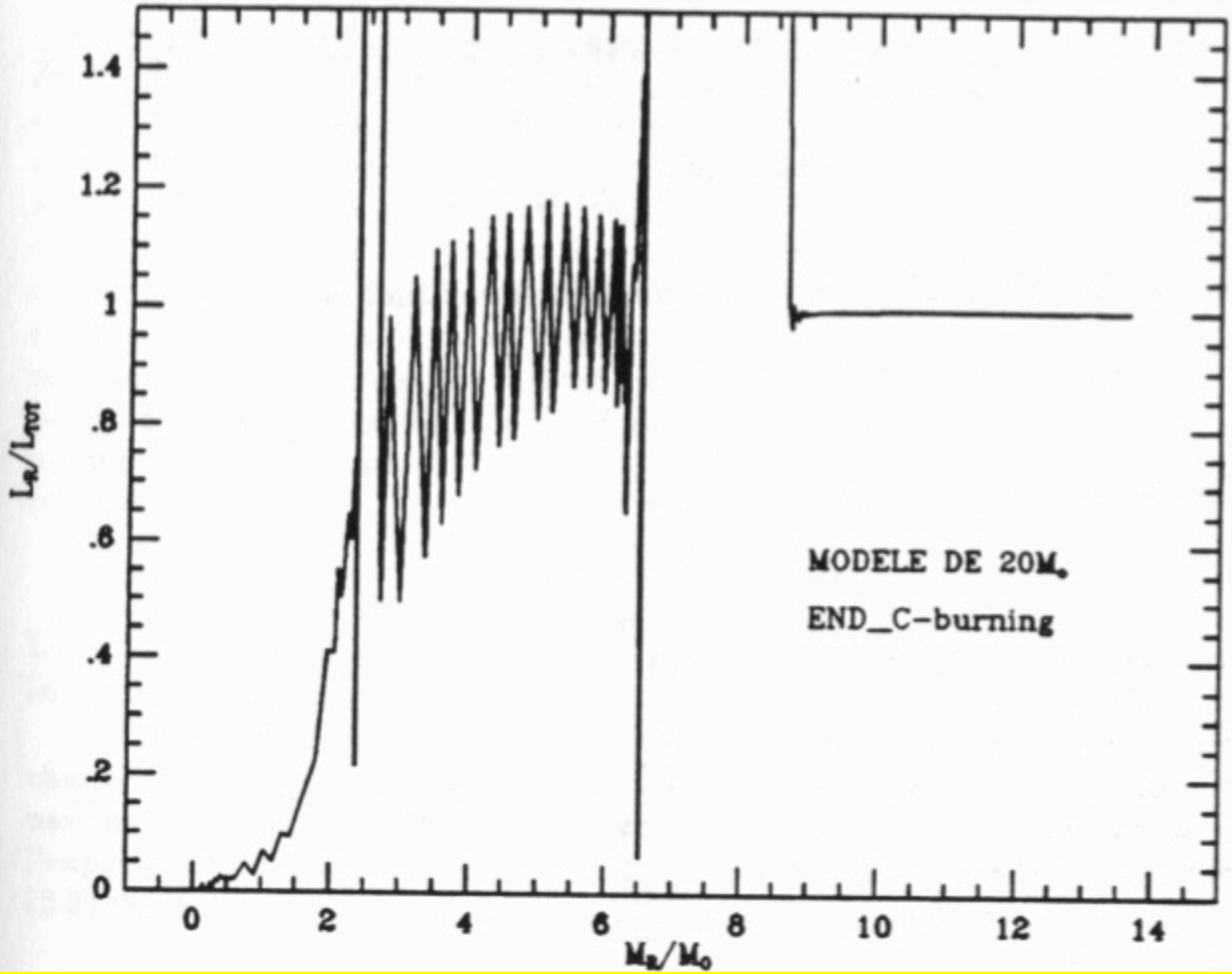
LMC, R136 :
5 10^4 $M_{sol,}$, age ~1.7 Myr
Masses→ 135- 320 M_{sol}





Crowther, Schnurr, Hirschi, Yusof, Parker, Goodwin, Abu Kassim, 2010

STARS WITH MASSES ABOVE 150 M_{sol}



Stellar structure equations are stiff: different timescale in different parts

Table 24.1. Basic Equations in Eulerian and Lagrangian Forms

1)		$\frac{dP}{dr} = -\frac{GM_r}{r^2}\varrho$	$\frac{dP}{dM_r} = -\frac{GM_r}{4\pi r^4}$
2)		$\frac{dM_r}{dr} = 4\pi r^2 \varrho$	$\frac{dr}{dM_r} = \frac{1}{4\pi\varrho r^2}$
3)		$\frac{dL_r}{dr} = 4\pi r^2 \varrho\,(\varepsilon + \varepsilon_{\rm grav} - \varepsilon_\nu)$	$\frac{dL_r}{dM_r} = (\varepsilon + \varepsilon_{\rm grav} - \varepsilon_\nu)$
4)	rad :	$\frac{dT}{dr} = -\frac{3\kappa\varrho}{4acT^3}\frac{L_r}{4\pi r^2}$	$\frac{dT}{dM_r} = -\frac{GM_rT}{4\pi r^4 P}\nabla_{\rm rad}$
	conv :	$\frac{dT}{dr} = \frac{\Gamma_2 - 1}{\Gamma_2}\frac{T}{P}\frac{dP}{dr}$	$\frac{dT}{dM_r} = -\frac{GM_rT}{4\pi r^4 P}\nabla_{\rm ad}$

One set of physical equations
but different manners of discretisizing them

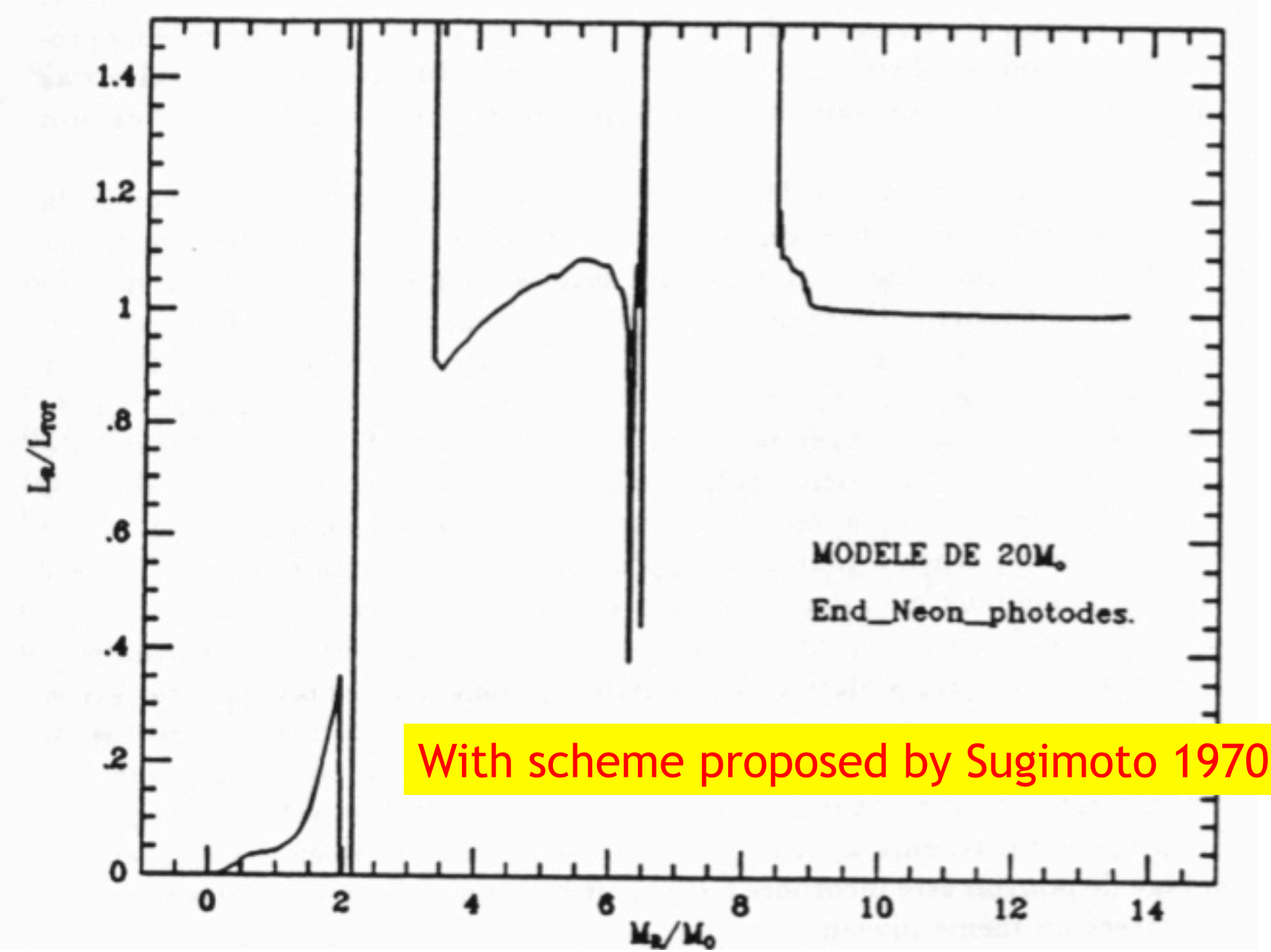
$$\frac{\partial Y_i}{\partial X} = \Phi_i(\vec{Y}, X)$$

$$\frac{Y_i(X_{k+1}) - Y_i(X_k)}{X_{k+1} - X_k} = \beta_i \Phi_i(\vec{Y}(X_{k+1}), X_{k+1}) + (1-\beta_i)\Phi_i(\vec{Y}(X_k), X_k)$$

standard case : $\beta_i = 1/2$ for the four stellar structure equations

Hybrid case : $\beta_3 = 1;\ \beta_4 = 0$

Hybrid scheme proposed by Sugimoto 1970



With scheme proposed by Sugimoto 1970

What are their impacts in the Universe?

Stars formed between 0.1 and 120 M_{sol}
Salpeter's IMF

IN A STELLAR GENERATION: 3/1000
with masses between 8 ans 120 Msol

Very low mass stars

Low and intermediate mass stars

Mass fraction in massive stars

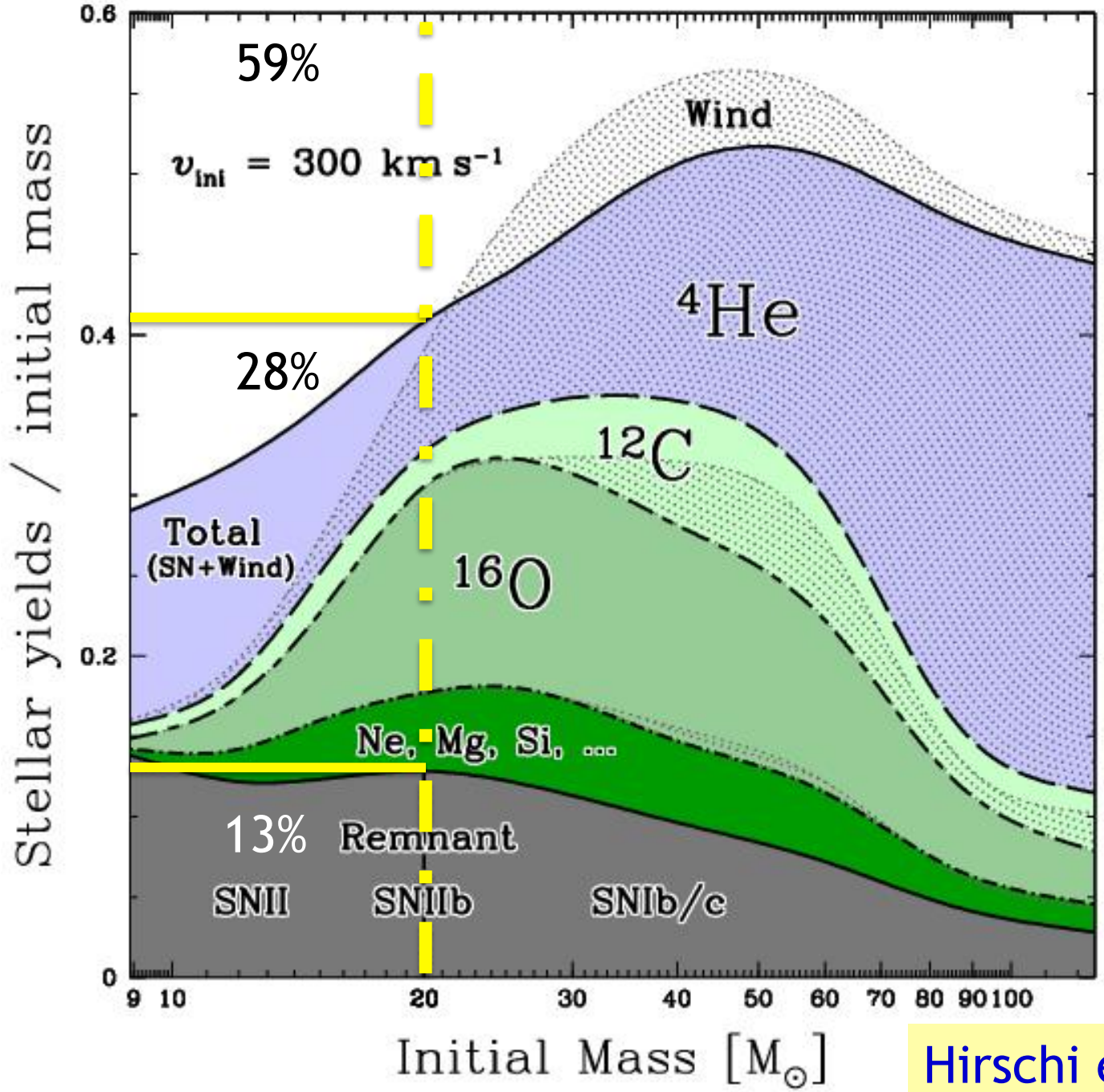
Energy released per solar mass transformed in stars (Salpeter IMF, mass range 0.01-120 solar masses)

1-8 solar masses	41 10^{61} eV
8-120 solar masses	~109 10^{61} eV

Energy released per solar mass transformed in stars (Salpeter IMF, mass range 0.01-120 solar masses)

	Nuclear energy	Gravitational Energy
1-8 solar masses	~40 10^{61} eV	~1 10^{61} eV
8-120 solar masses	~9 10^{61} eV	~100 10^{61} eV

SNe explosion



Hirschi et al. 2005

Stars formed between 0.1 and 120 M_{sol}
Salpeter's IMF

Mass fraction in massive stars

$M > 8\ M_{sol} \rightarrow$ **14%**

~1% in remnants
~13% returned

3.5 – 4.5 % new elements

Low and intermediate mass stars

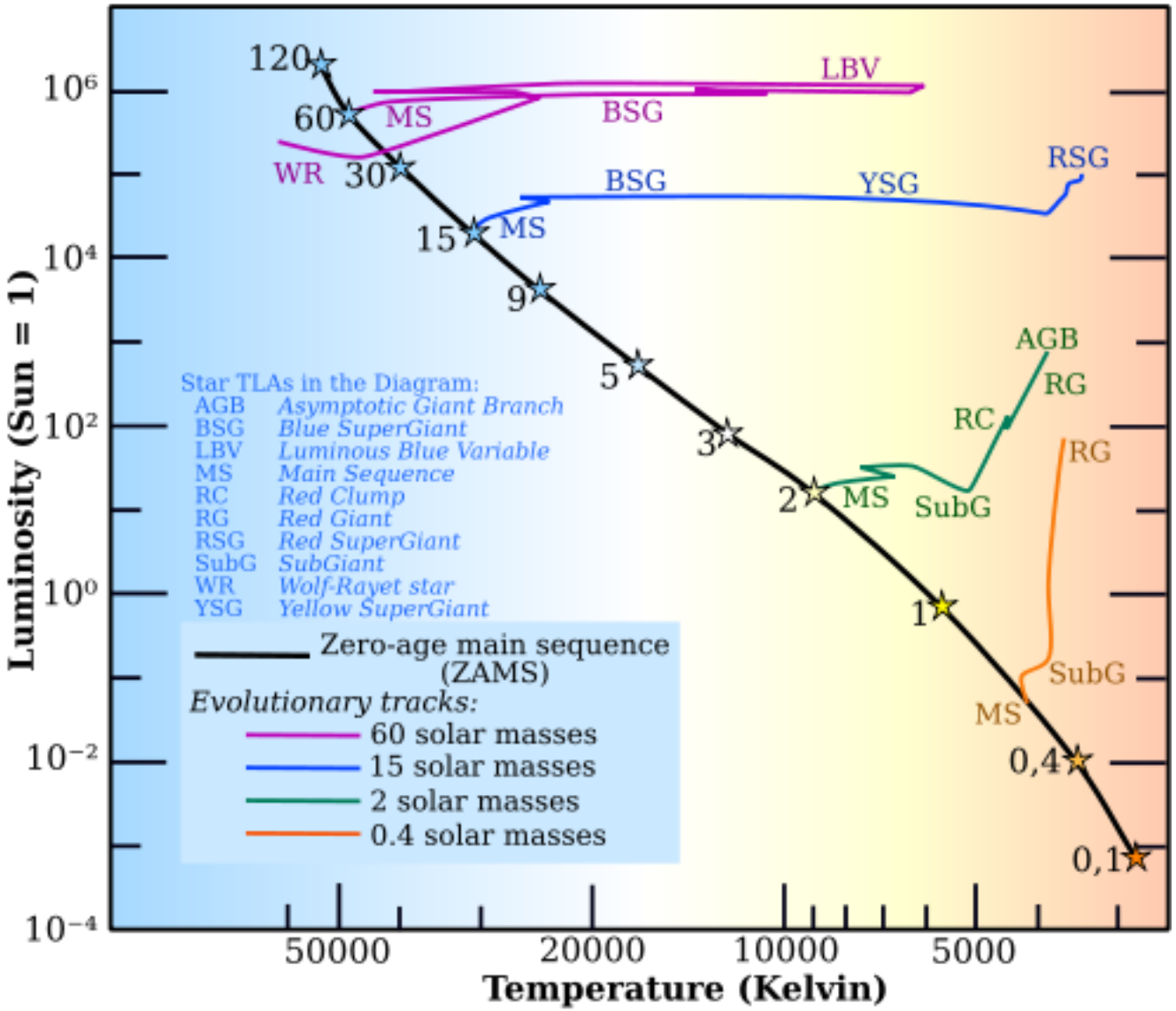
$1 < M/M_{sol} < 8 \rightarrow$ **25%**

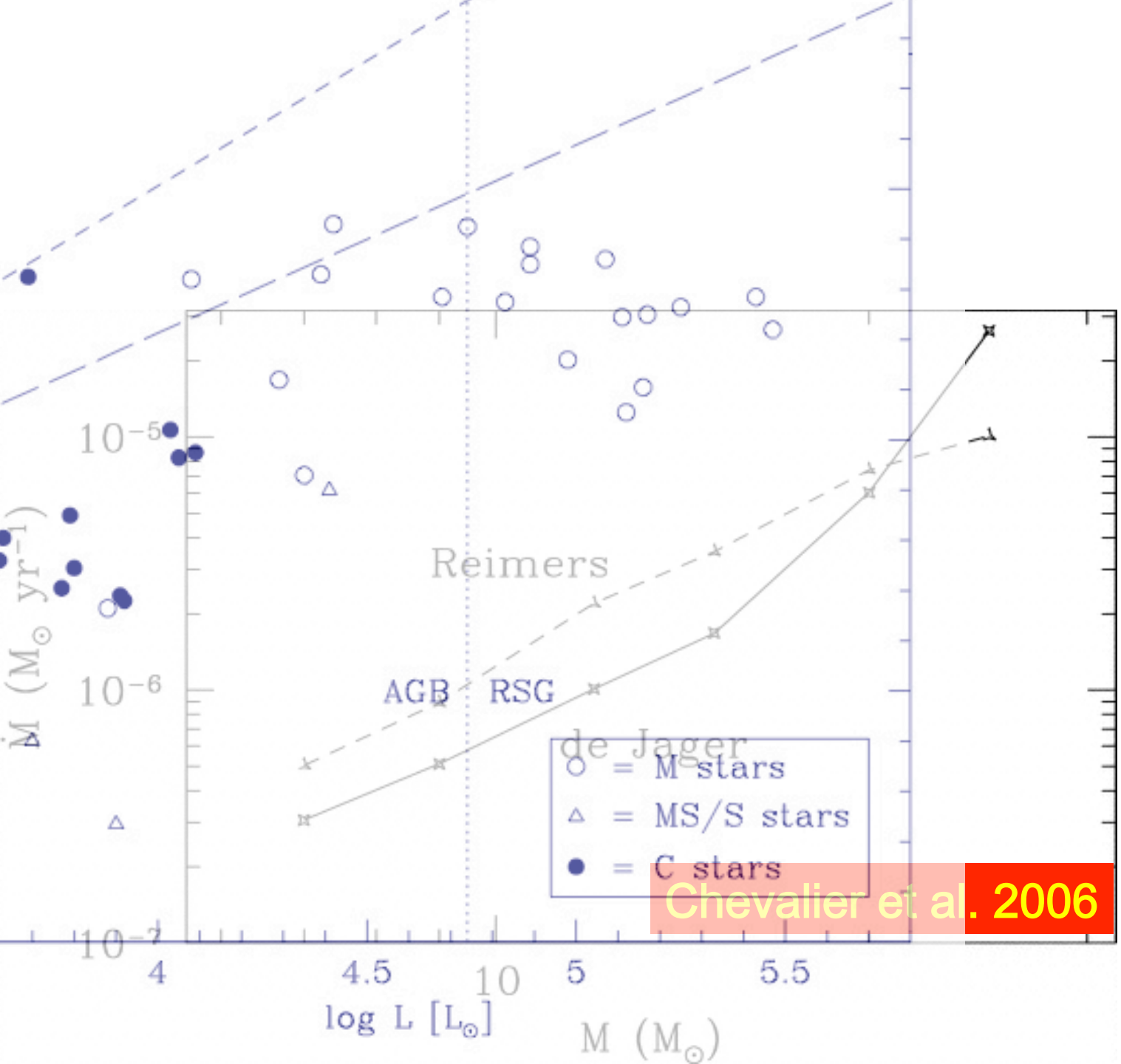
~6.5% in remnants
~18.5% returned

Very low mass stars

$0.1 < M/M_{sol} < 1 \rightarrow$ **61%**

What are the main characteristics of massive star evolution?




Reimers
AGB
RSG
de Jager
= M stars
= MS/S stars
= C stars
Chevalier et al. 2006
10^{-5}
10^{-6}
10^{-7}
$\dot{M}$ ($M_\odot$ yr^{-1})
4
4.5
5
5.5
log L [$L_\odot$]
10
M ($M_\odot$)