Massive Star Evolution

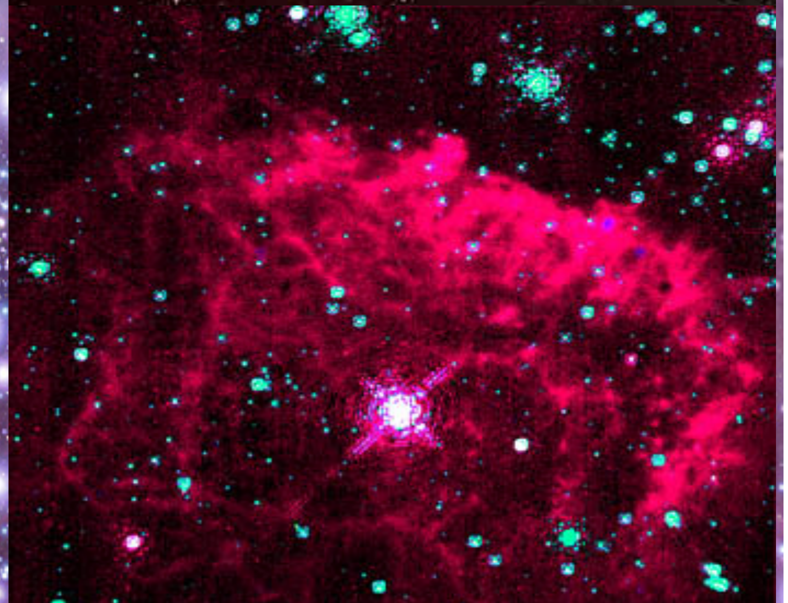
Mass Loss, Rotation and Magnetic Field

Georges Meynet
Geneva Observatory, Geneva University

Credit: Yves Grosdidier (University of Montreal and Observatoire deStrasbourg), Anthony Moffat (Universitie de Montreal), Gilles Joncas (Universite Laval), Agnes Acker (Observatoire de Strasbourg), and NASA

Credit and Copyright: P. Berlind & P. Challis (CfA), 1.2-m Telescope, Whipple Obs.

NASA, ESA and Allison Loll/Jeff Hester (Arizona State University). Acknowledgement: Davide De Martin (ESA/ Hubble)



Credit: D. F. Figer UCLA) et al., NICMOS, HST, NASA,

What are massive stars?

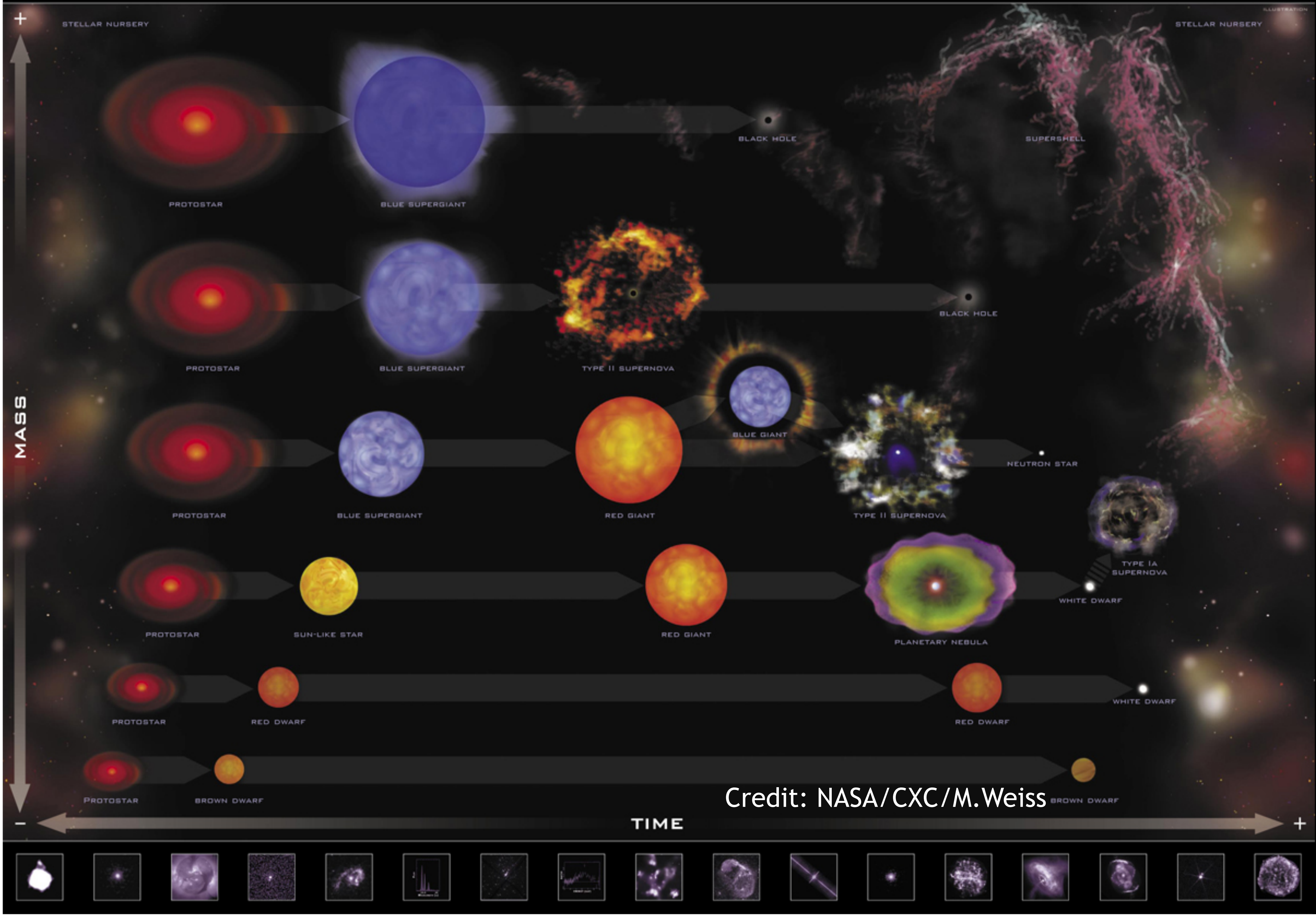
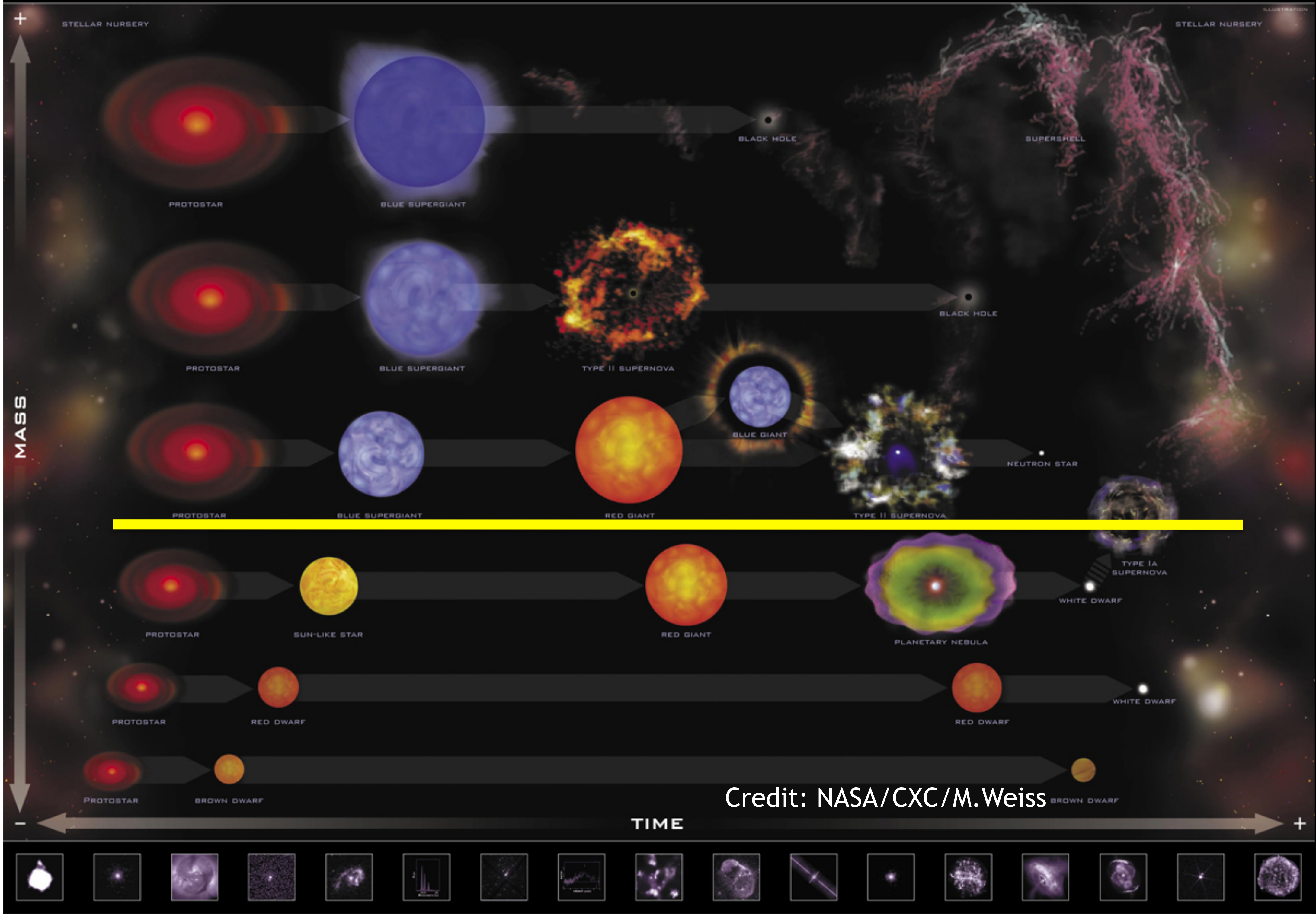


ILLUSTRATION
STELLAR NURSERY
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
BLUE GIANT
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF
MASS
TIME
Credit: NASA/CXC/M.Weiss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RED DWARF
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PROTOSTAR
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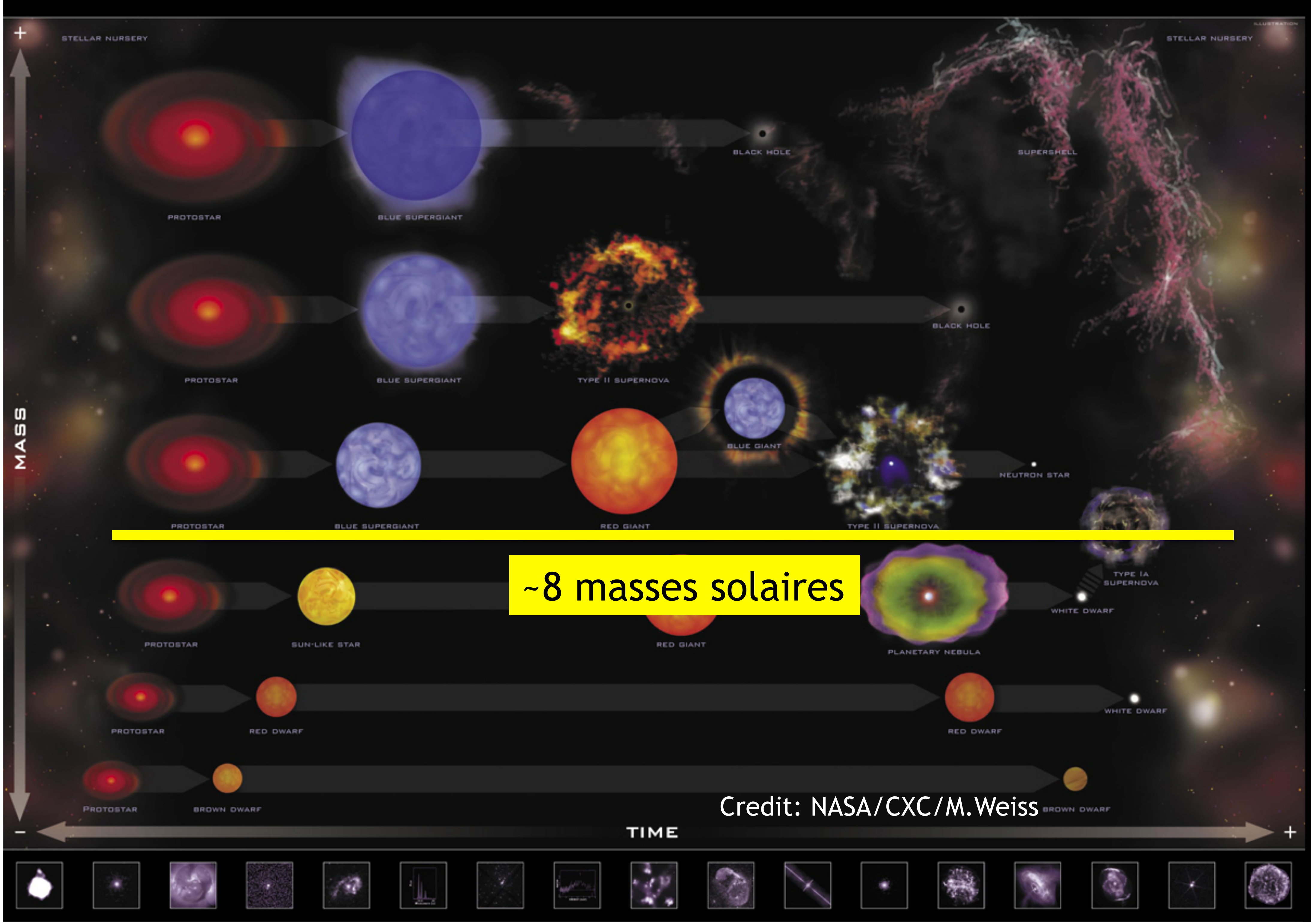
BROWN DWARF
MASS
TIME
+
−
+
Credit: NASA/CXC/M.Weiss



STELLAR NURSERY
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TYPE II SUPERNOVA
BLACK HOLE
BLUE GIANT
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
TYPE II SUPERNOVA
NEUTRON STAR
~8 masses solaires
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
Credit: NASA/CXC/M.Weiss
BROWN DWARF
MASS
TIME

Mmas

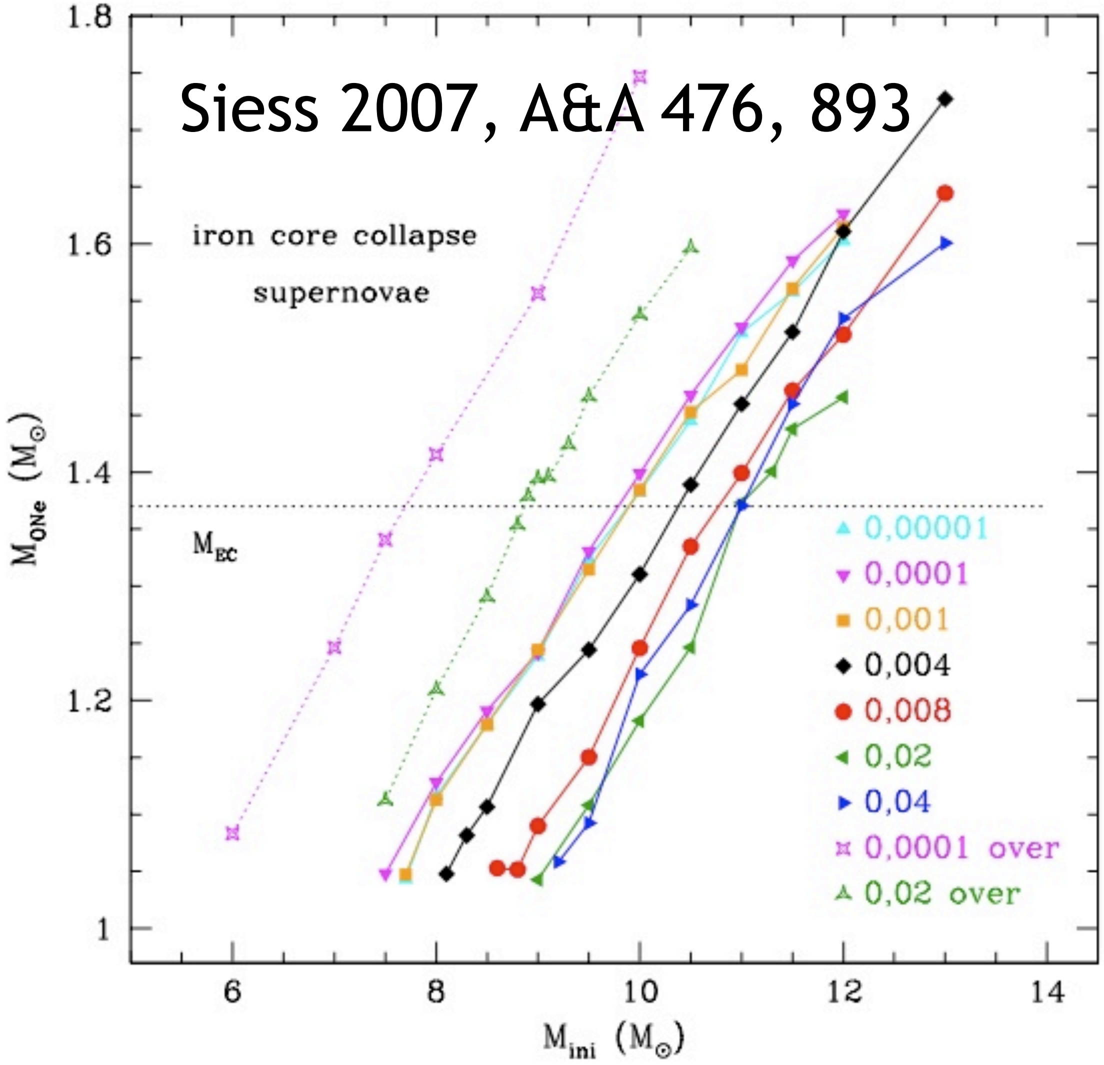


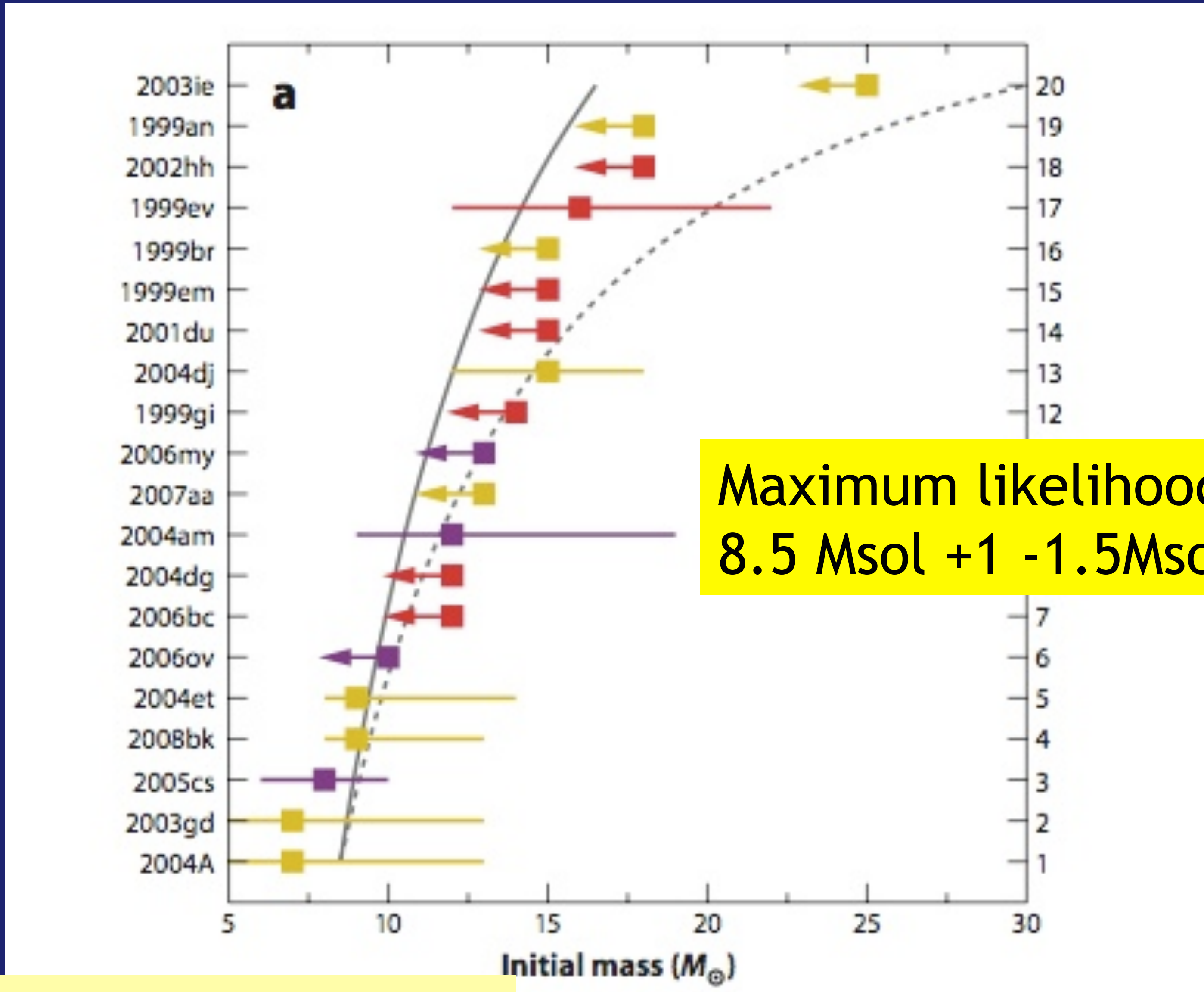
Fig. 6. Mass of the ONe core at the end of C-burning for the different initial compositions as a function of initial mass. Models with overshooting are connected by dotted lines. The horizontal line indicates the critical mass $M_{EC} = 1.37\ M_{\odot}$ (see Sect. 4.2).

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

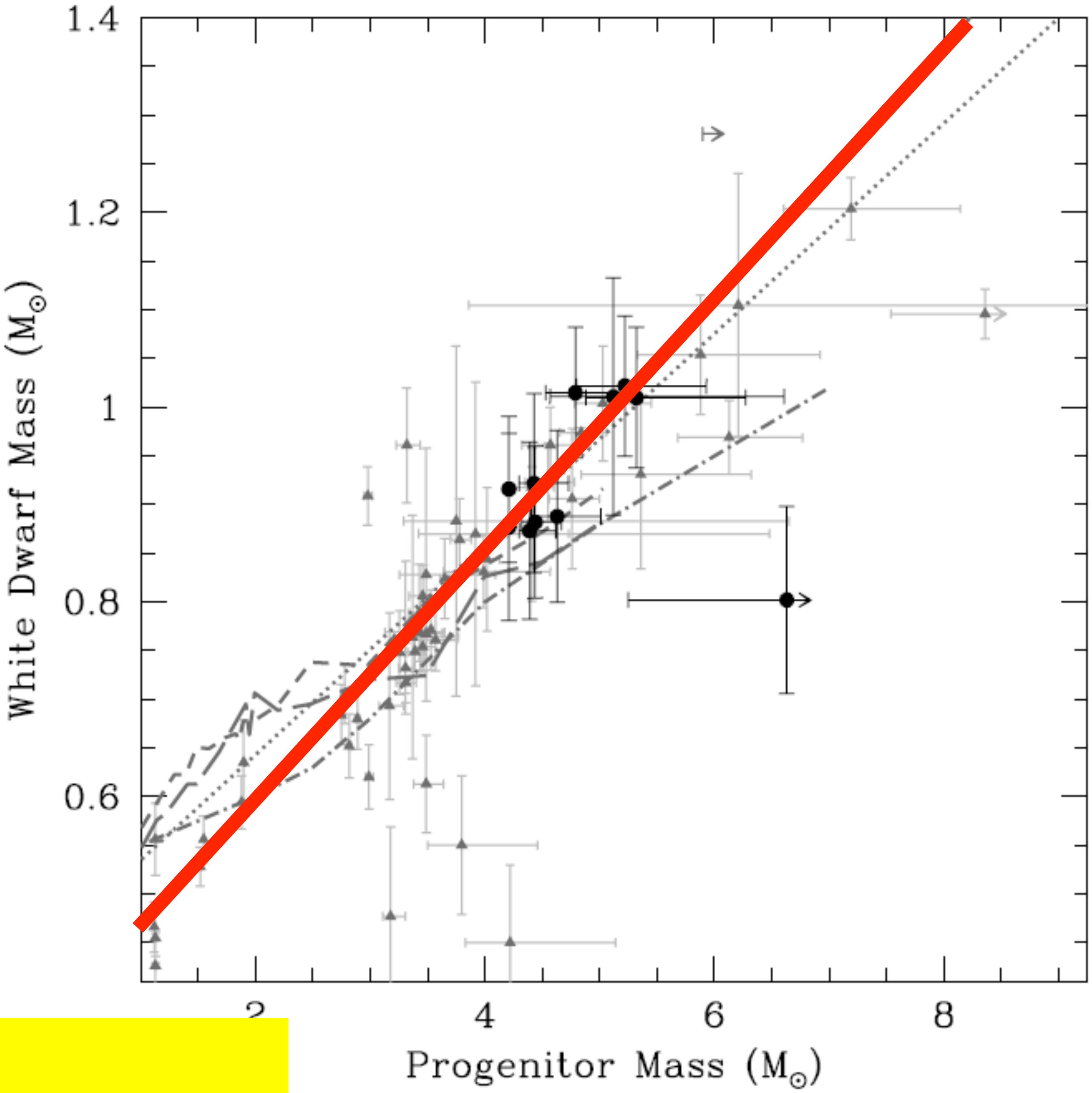
Around 8 Msol

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

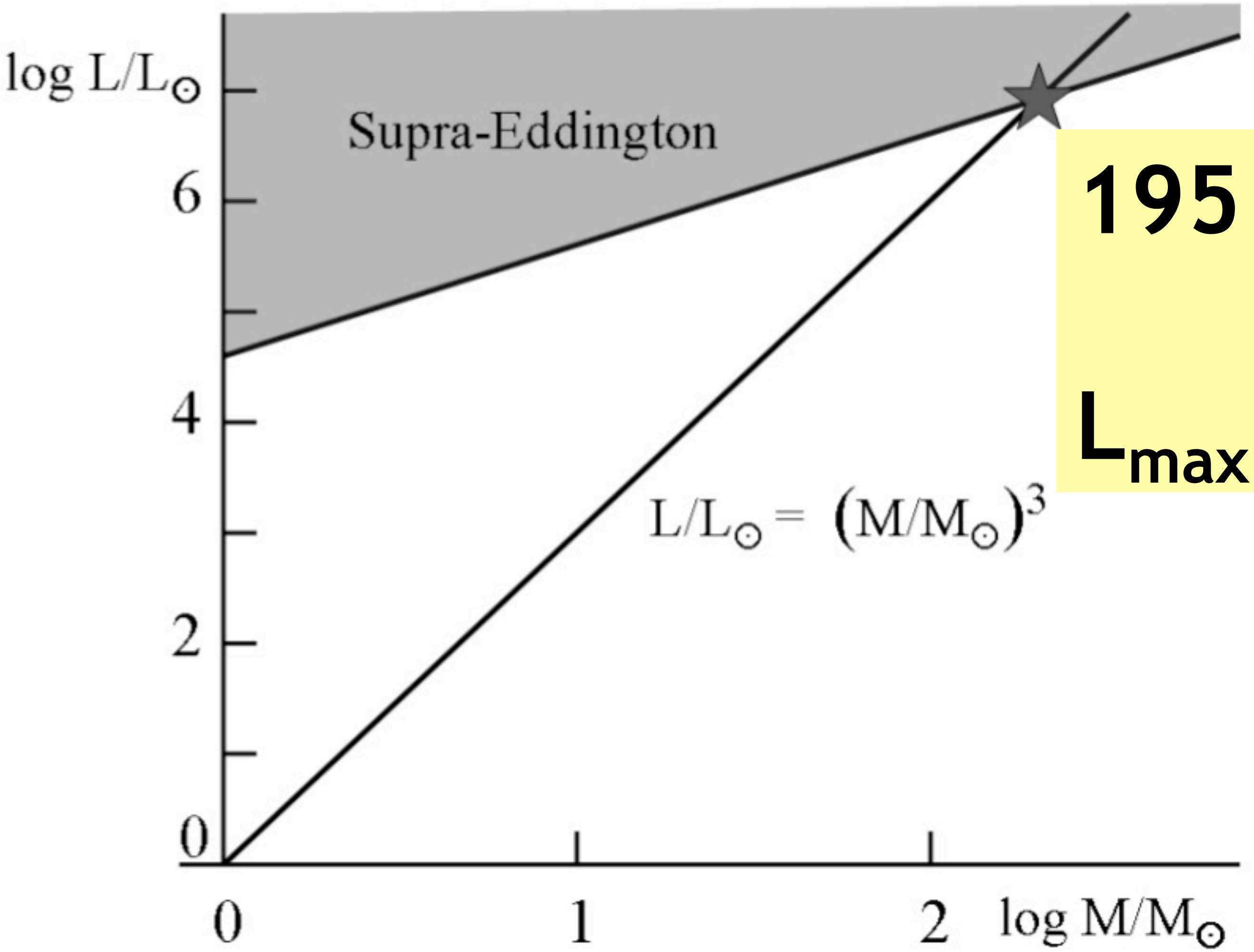
What is the upper limit?

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



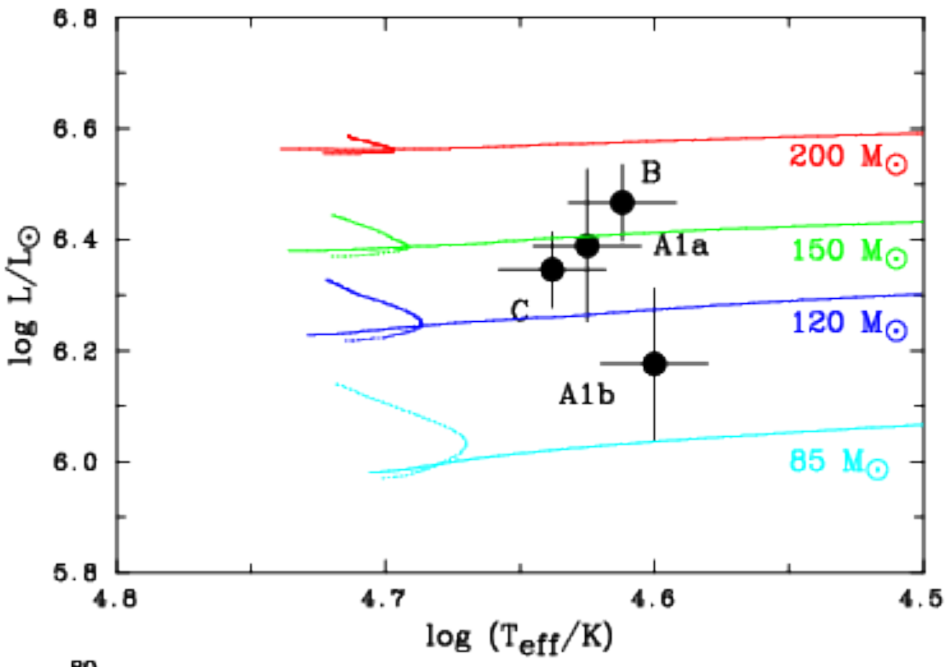
195 Msol

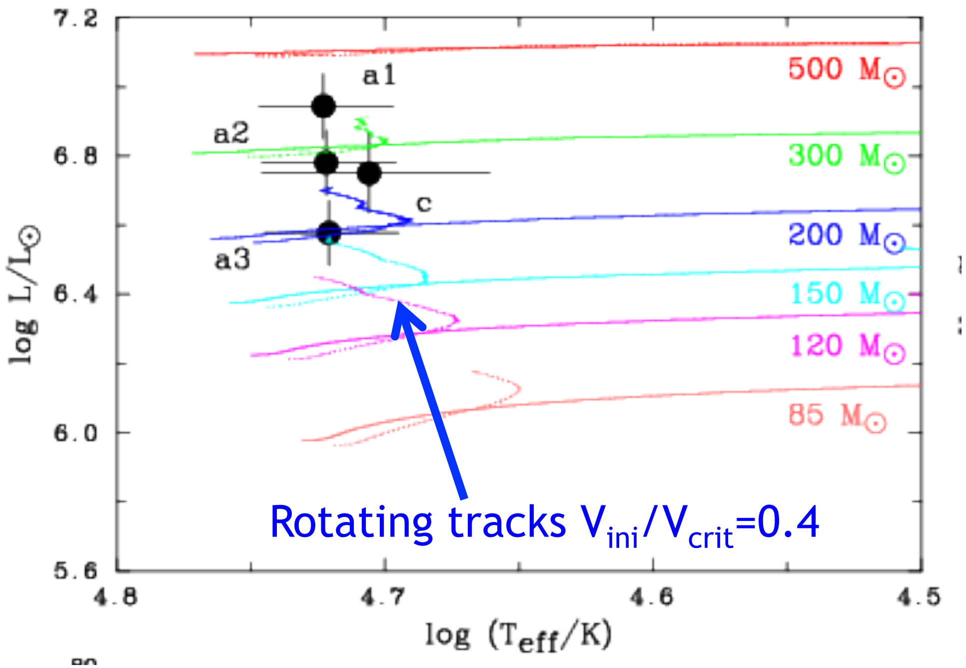
L_{max} 7.4 10^6 Lsol

Maeder (2009)

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}

What are their impacts in the Universe?

Credit: *X-ray:NASA/CXC/SAO; Infrared: NASA/JPL-Caltech; Optical: MPIA, Calar Alto, O. Krause et al.*

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

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

Low and intermediate mass stars

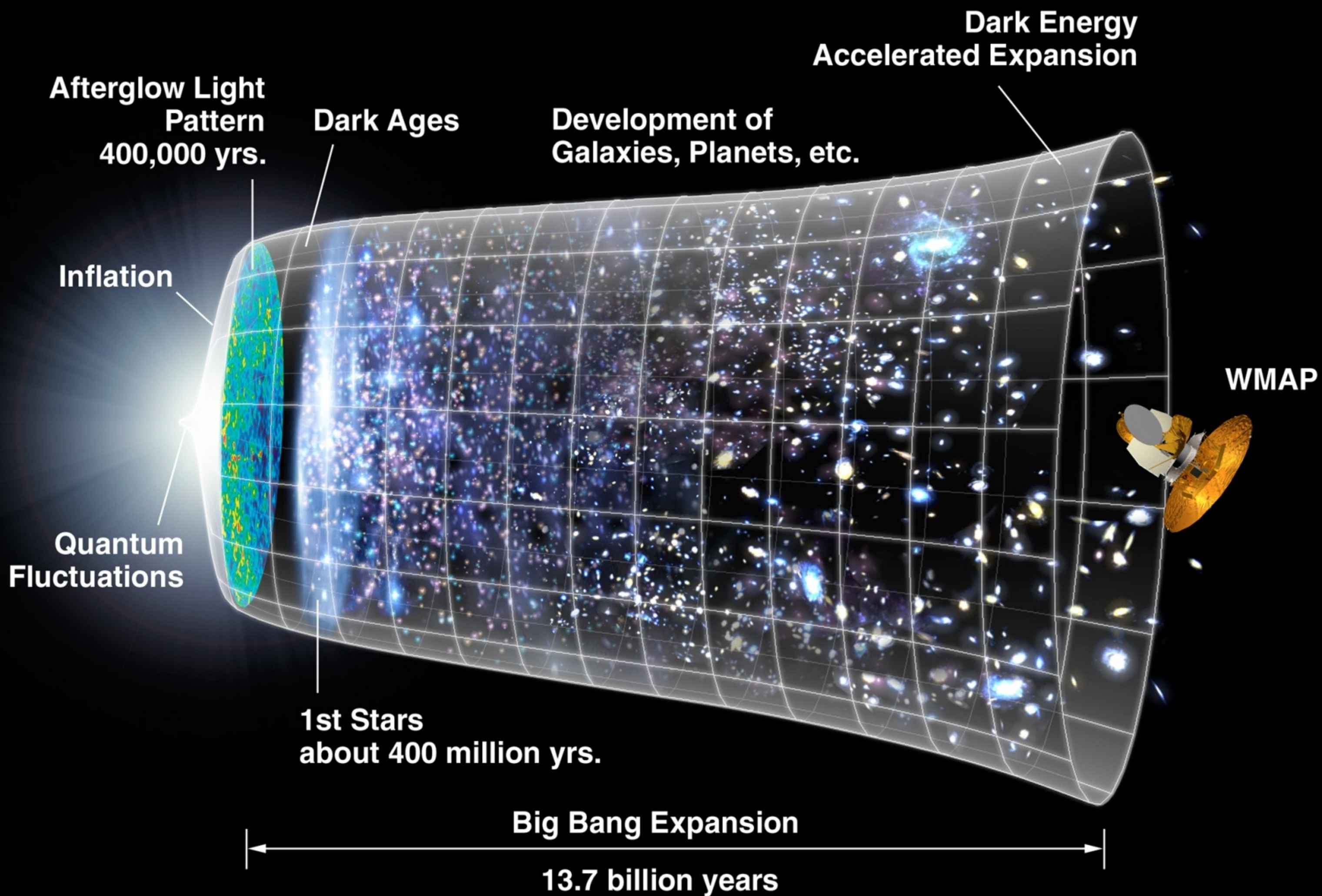
$1 < M/M_{sol} < 8 \rightarrow$ **25%**

Mass fraction in massive stars

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

PROPERTIES OF MASSIVE STARS
MASSIVE STARS AS COSMIC ENGINES

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



Credit: WMAP Science Team, NASA

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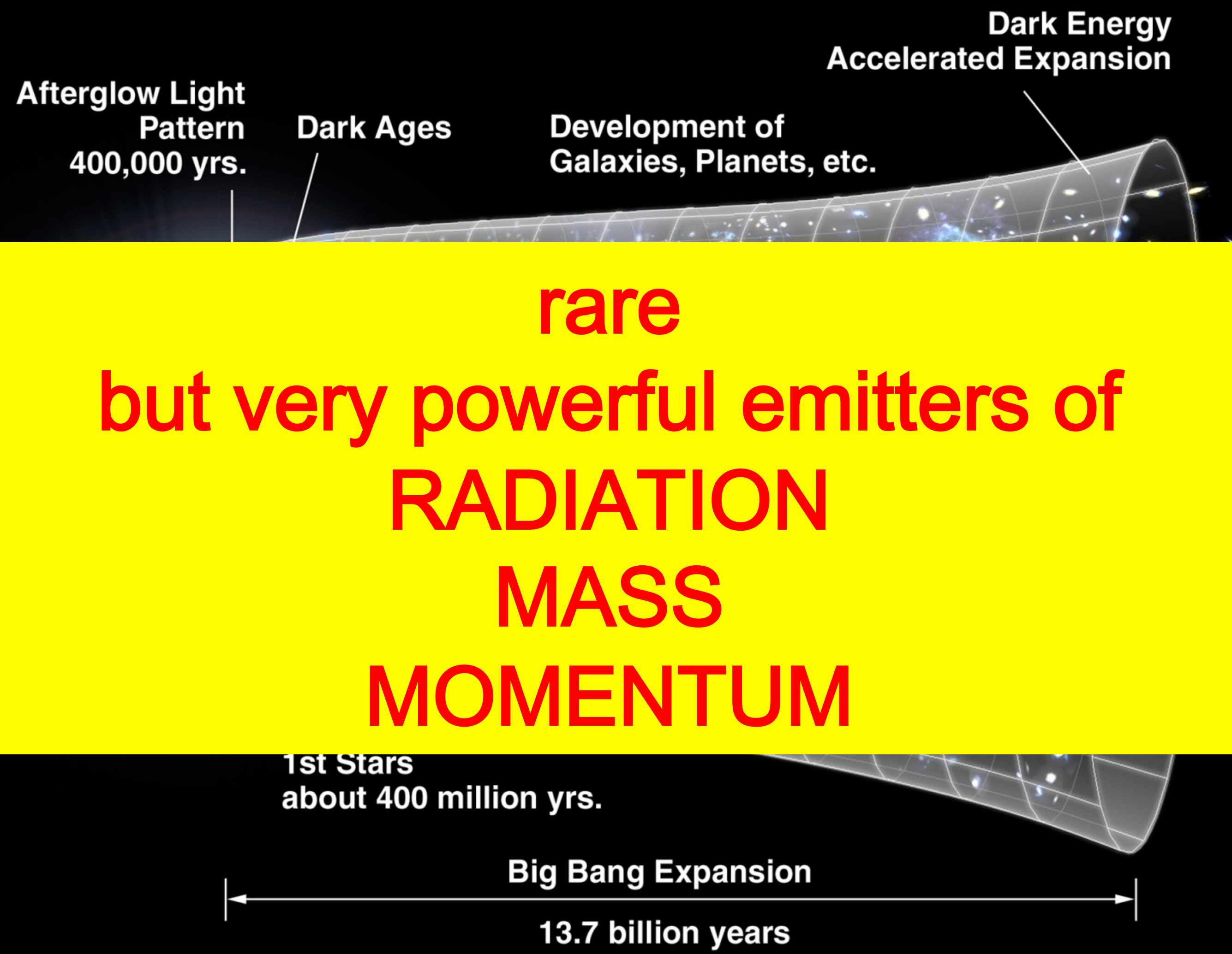


rare

but very powerful emitters of

RADIATION

MASS

MOMENTUM

Credit: WMAP Science Team, NASA

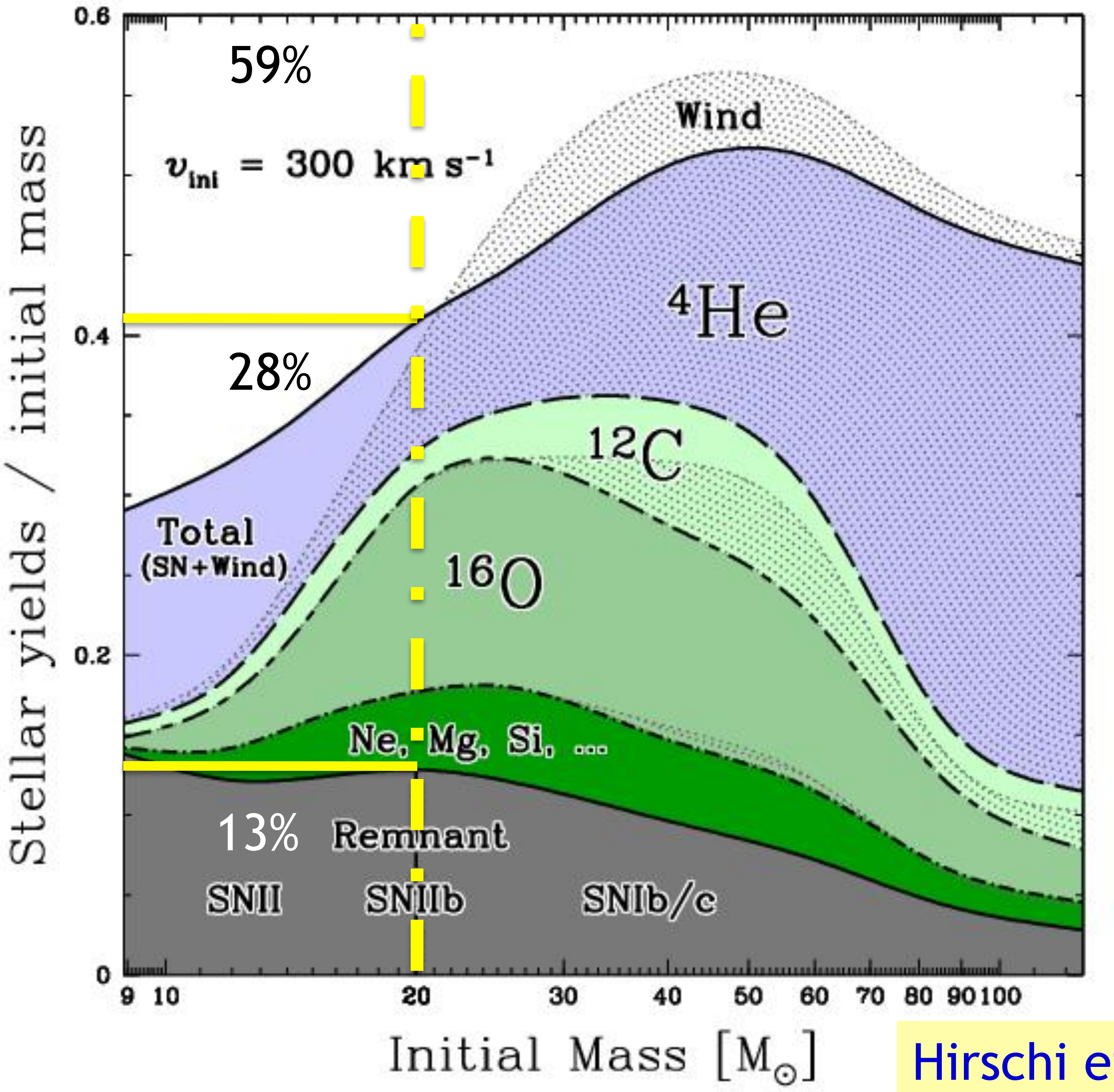
Energy released per solar mass transformed in stars (Salpeter IMF, mass range 0.01-120 solar masses)

1-8 solar masses	$41 \; 10^{61}$ eV
8-120 solar masses	$\sim 109 \; 10^{61}$ 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

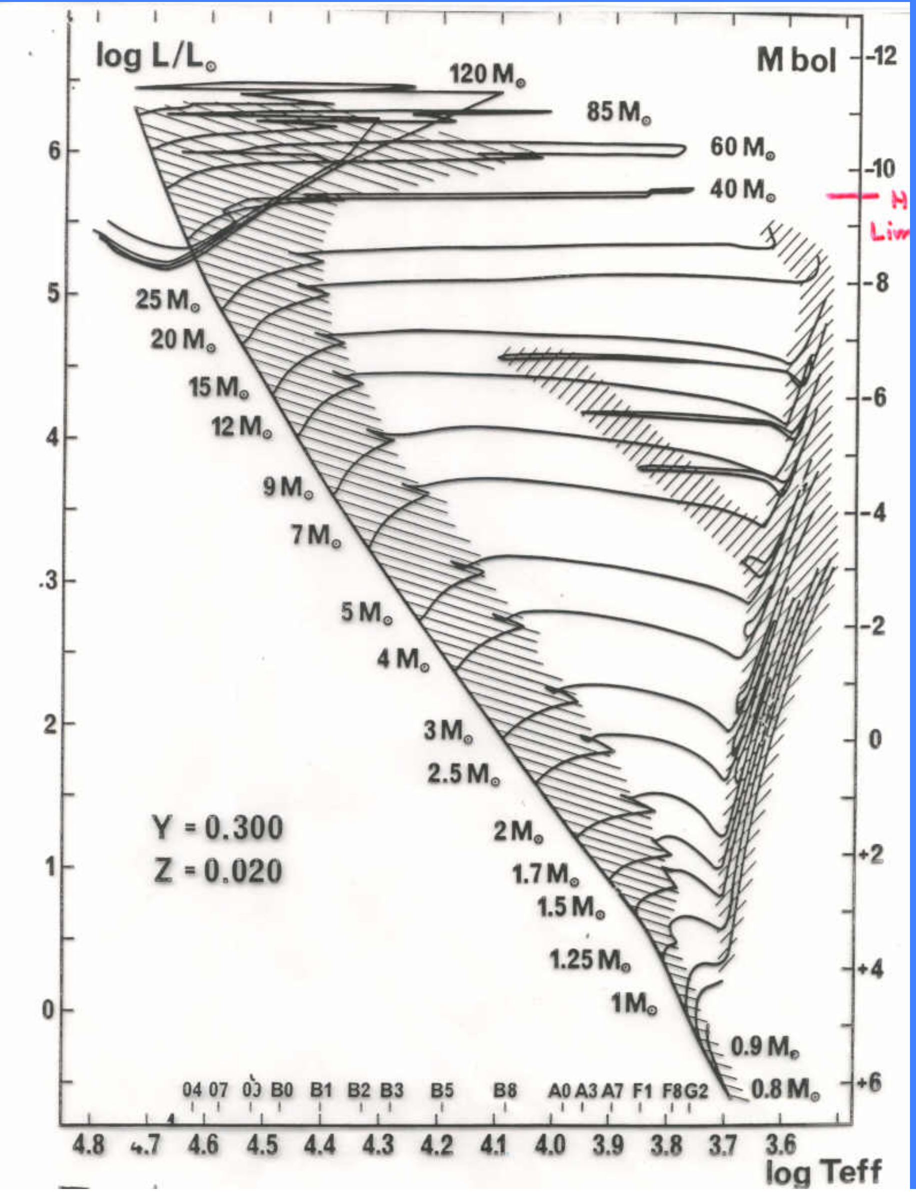
Low and intermediate mass stars

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



Maeder & Meynet 1989

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??)

LBV WR

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

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

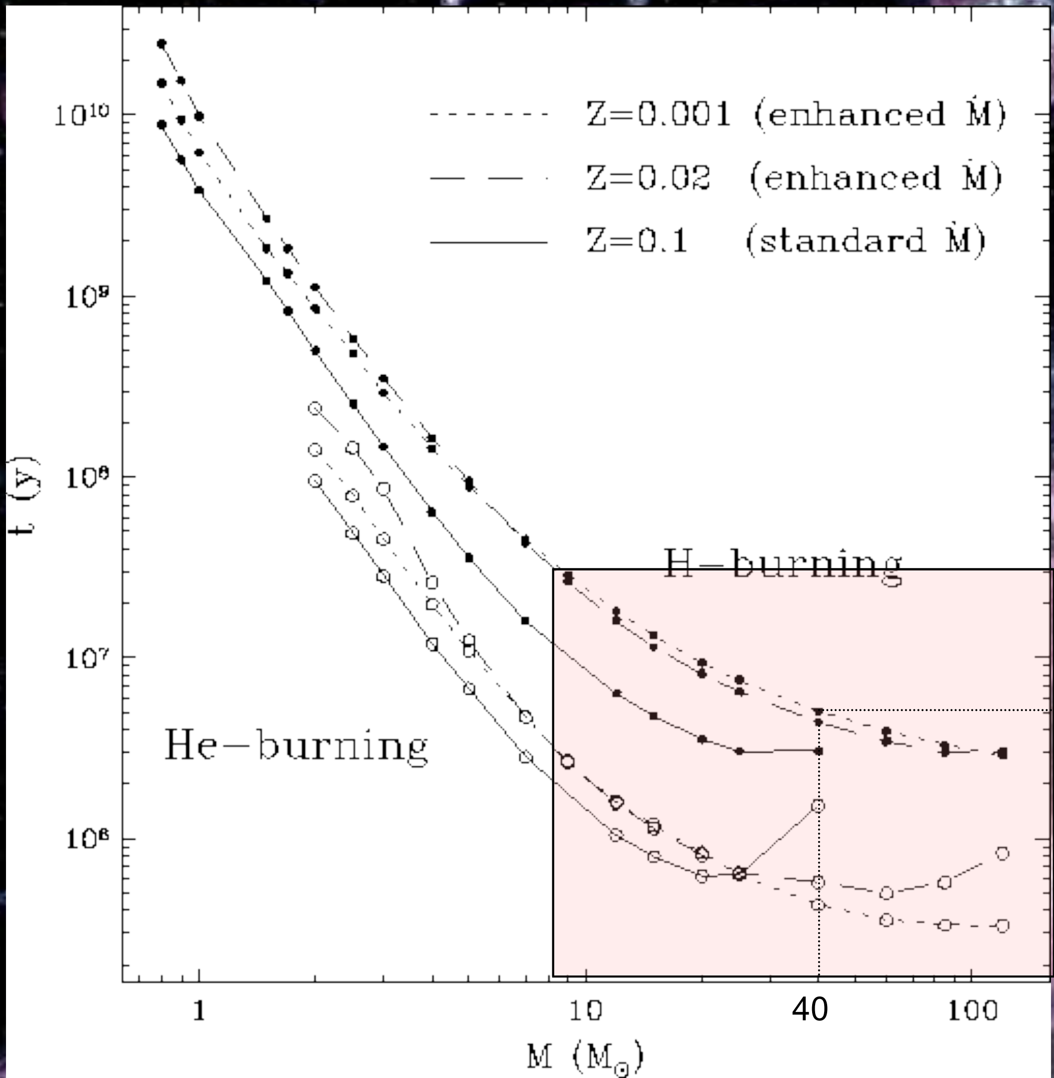
RSG

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

Mass loss
Overshooting
Rotation
Magnetic fields
Interactions in close binaries

Short lifetimes

Adolf Schaller, STScI



30 My

3 My

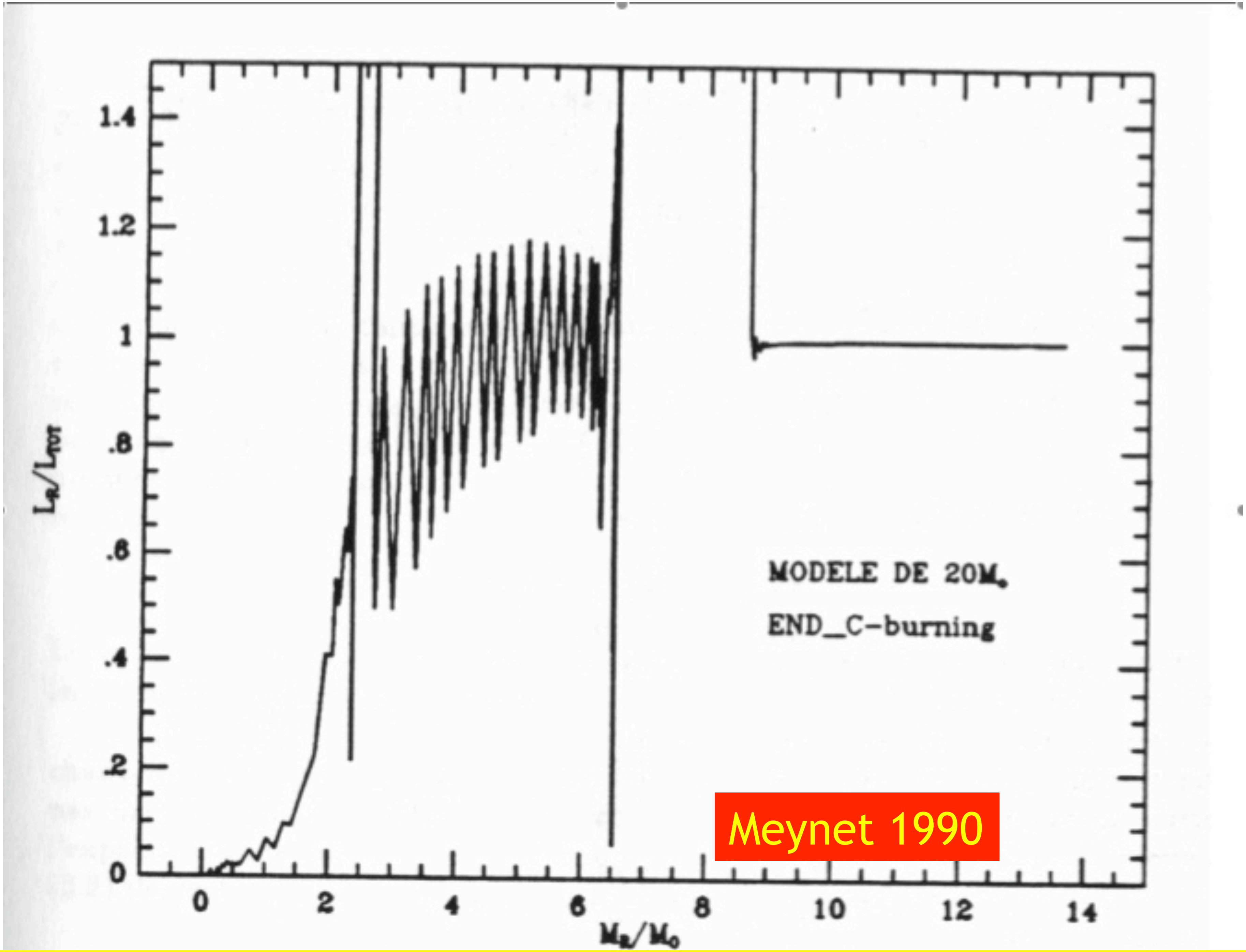
Mowlavi, Meynet , Maeder , Schaerer , Charbonnel , A&A 335, 573 (1998)

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	$> 3.6 \times 10^{11}$

Woosley, Stan & Janka, Thomas, 2005: Nature Phys., 1, 147



Stellar structure equations are stiff: different timescale in different parts

Table 24.1. Basic Equations in Eulerian and Lagrangian Forms

		Eulerian	Lagrangian
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

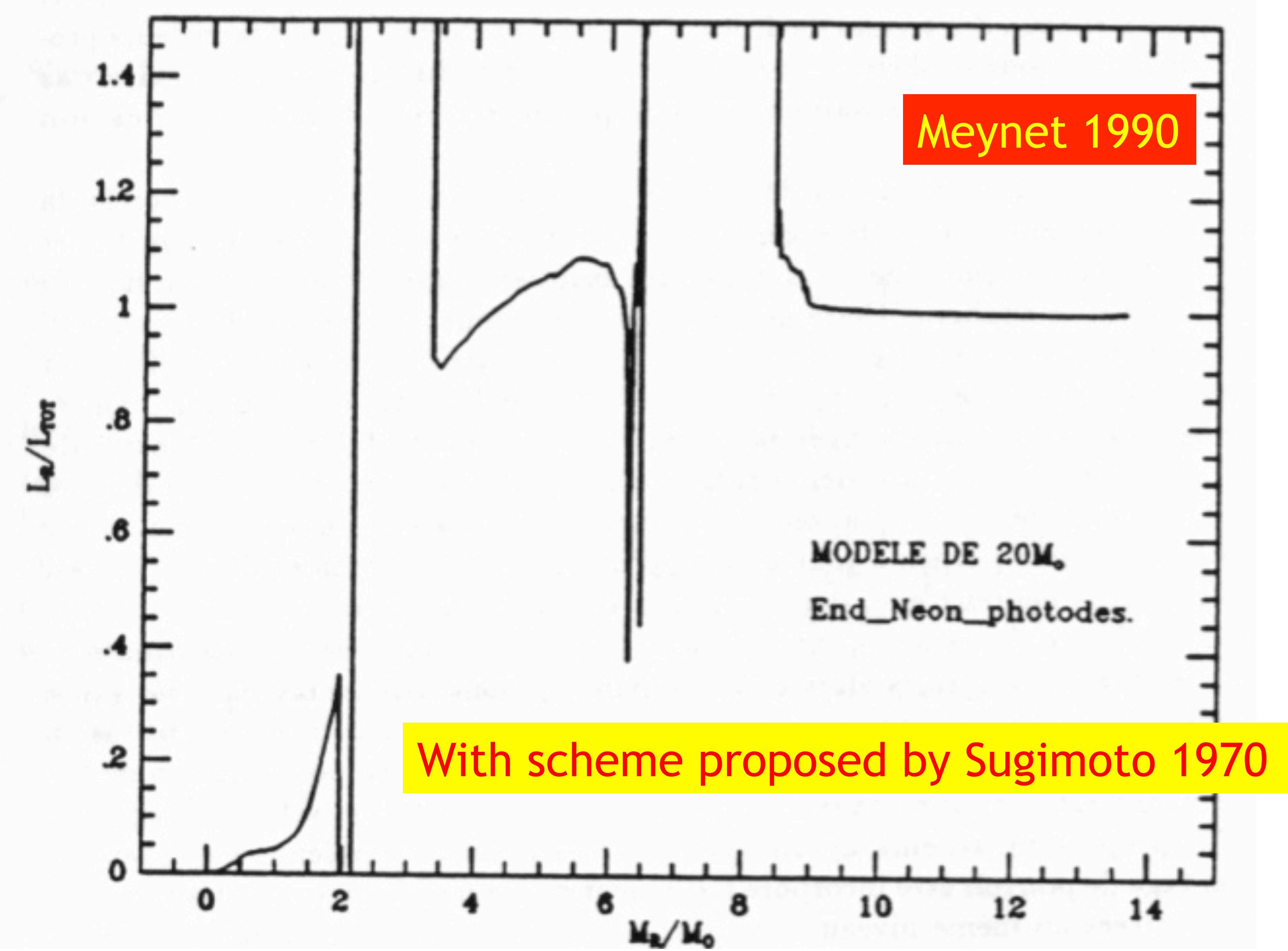
$$\frac{\partial Y_i}{\partial X} = \Phi_i(\vec{Y}, X)$$

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

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



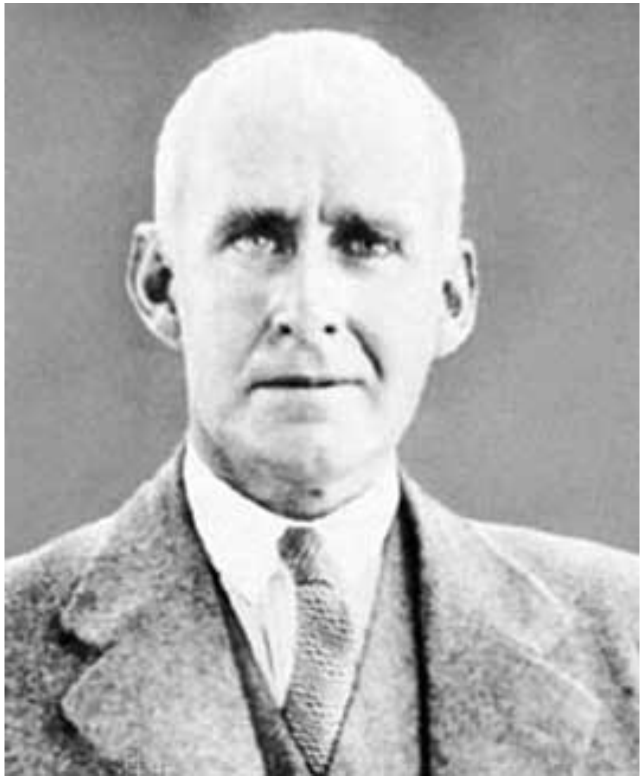
Meynet 1990
MODELE DE 20M☉
End_Neon_photodes.
With scheme proposed by Sugimoto 1970
1.4
1.2
1
.8
.6
.4
.2
0
0
2
4
6
8
10
12
14

Mass loss through radiative stellar winds

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

MASS LOSS BY STELLAR WINDS

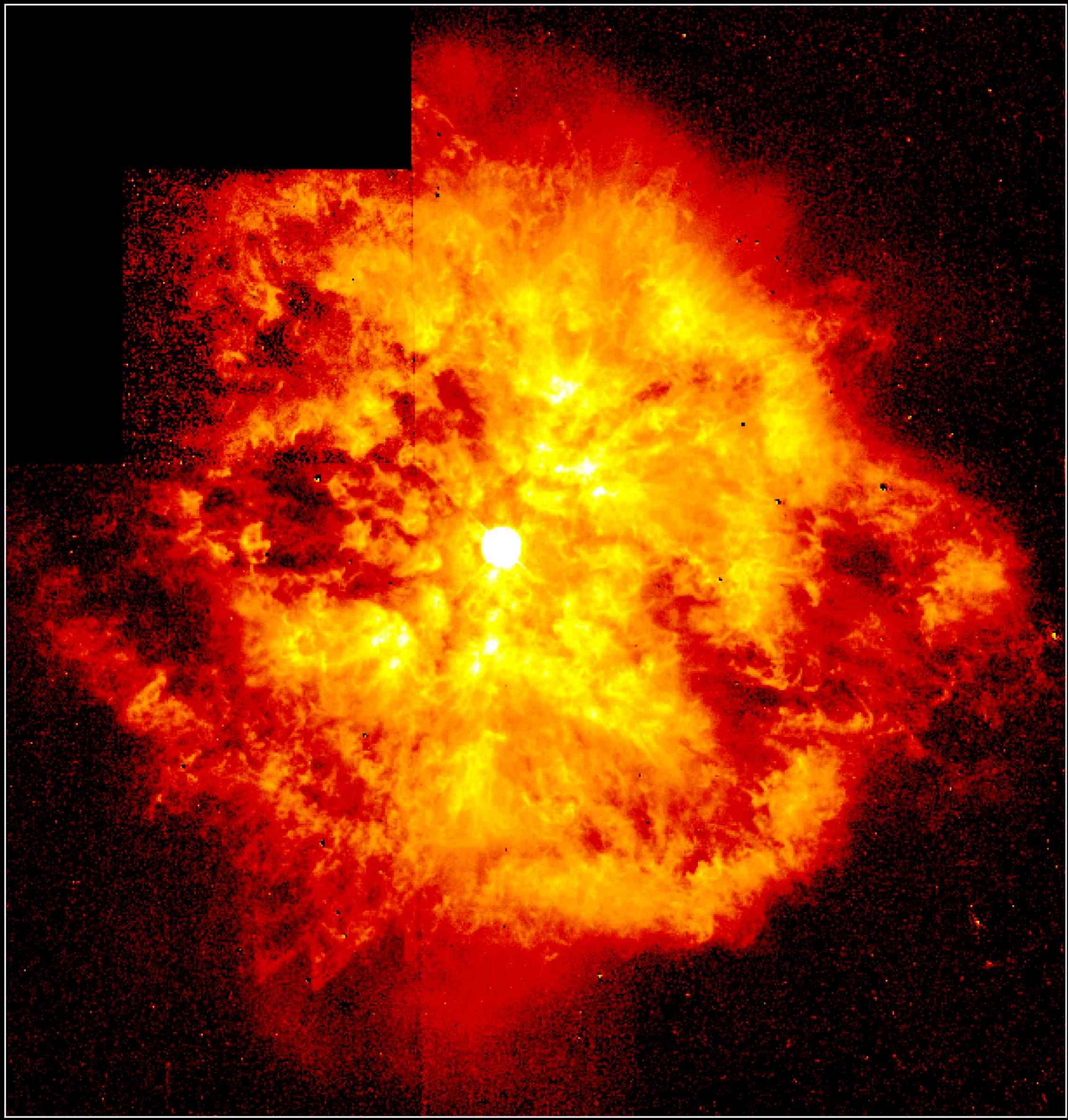
IMPORTANCE OF THE RADIATION PRESSURE



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

Eddington

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} → 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

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

Typical mass-loss rates for galactic O-type stars

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

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

$$L \propto M^2$$

$$\Rightarrow \quad \dot{M} \propto M^{3.4}$$

$$\tau_{MS} \propto M^{-0.6} \quad \Rightarrow \quad \Delta M \propto M^{2.8}$$

$$\Delta M / M \propto M^{1.8}$$

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

Mass loss rates proportional to the number of strong lines

Number of strong lines proportional to Z

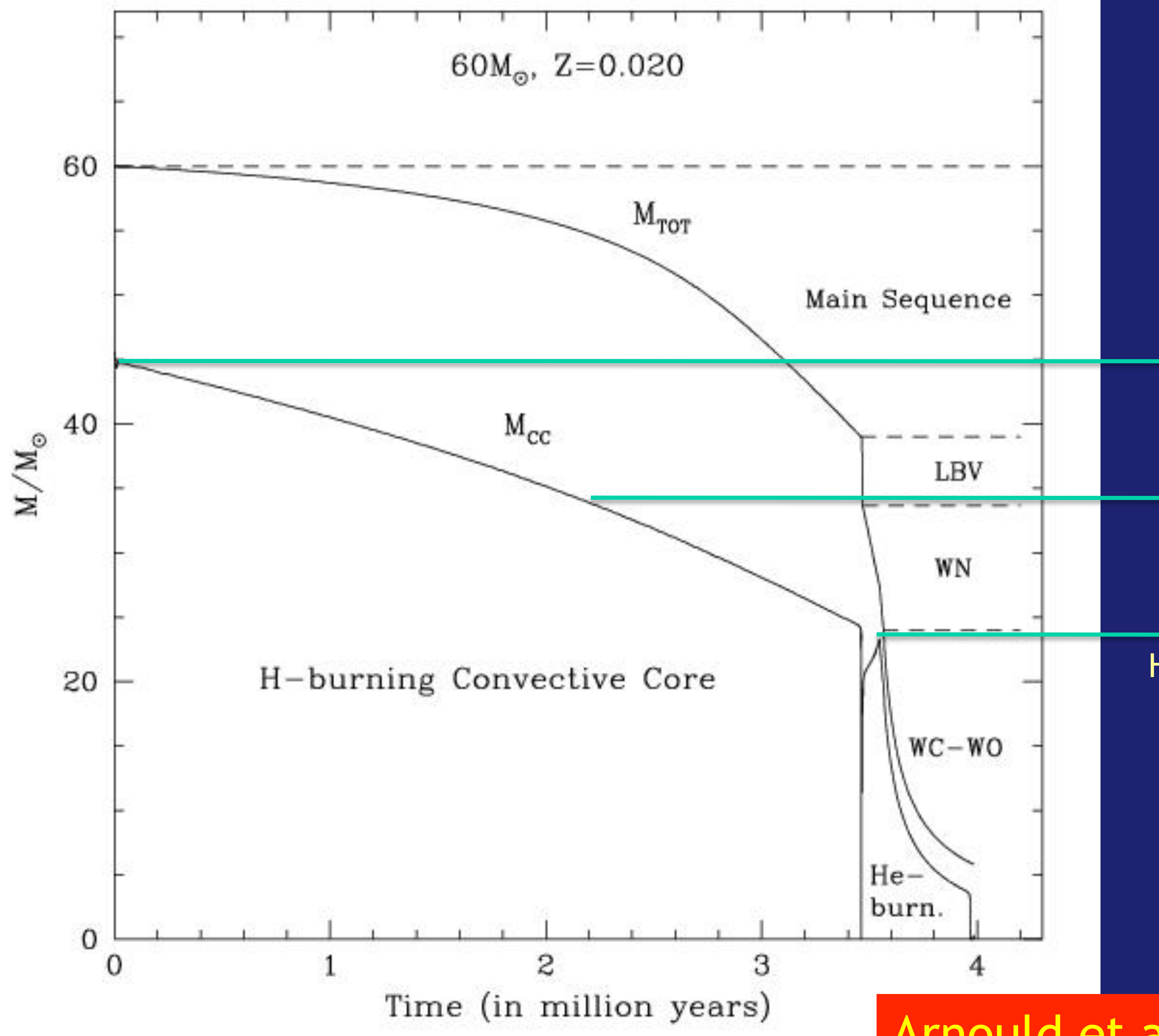
Wind models for hot stars show this effect

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



Change of surface abundances

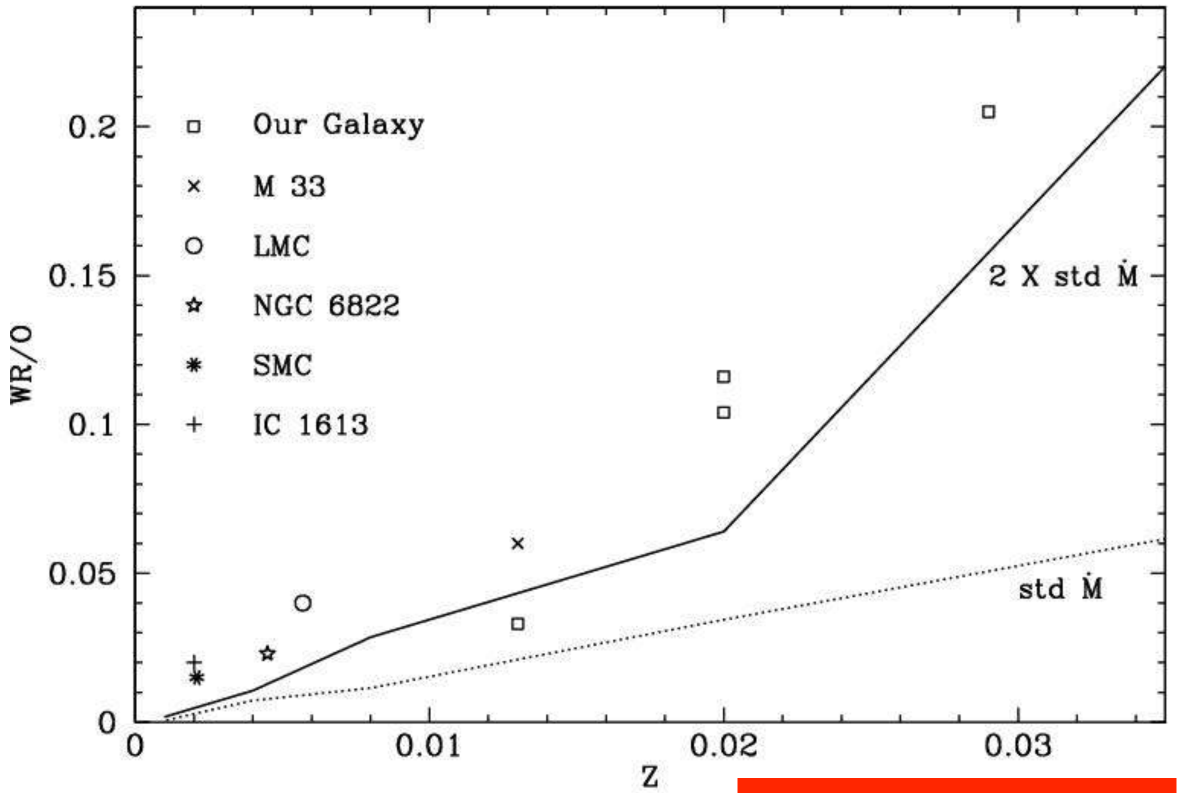
At the surface the mass fraction of H < ~0.4 (initial ~0.70)

At the surface He-burning products

Arnould et al. 1997.

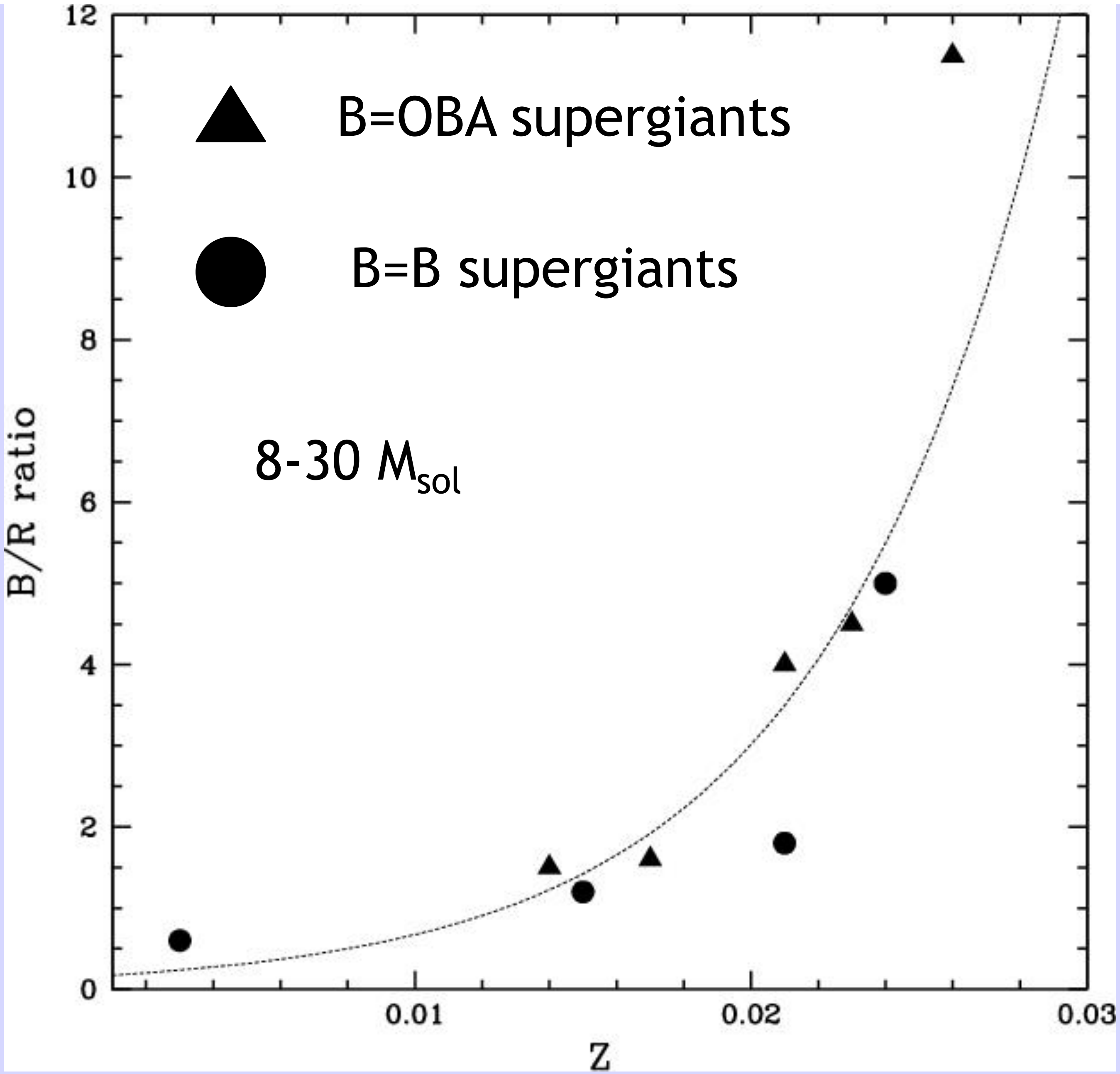
IMPORTANCE OF METALLICITY: AN ILLUSTRATION

Z-effect

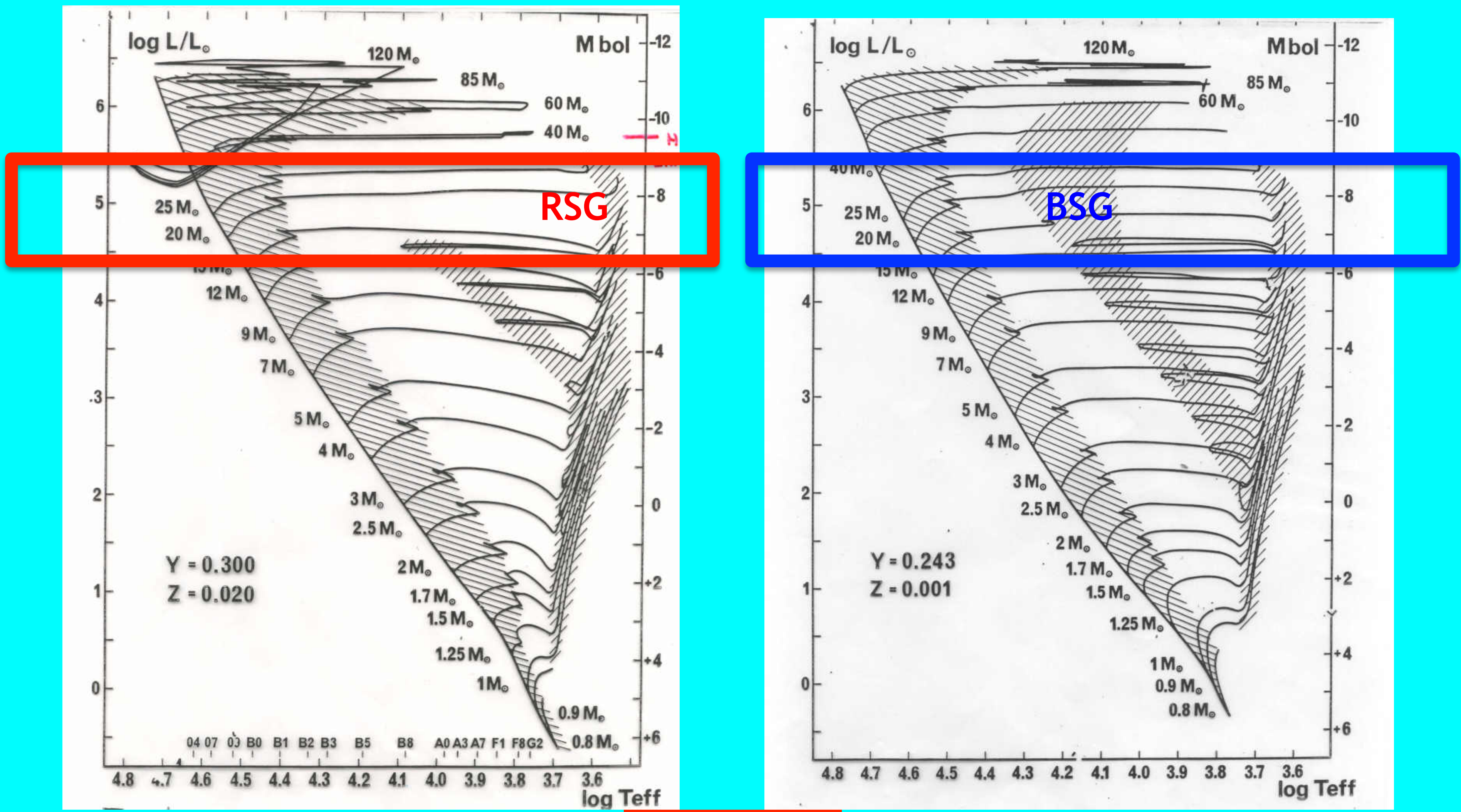


Maeder & Meynet 1994

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



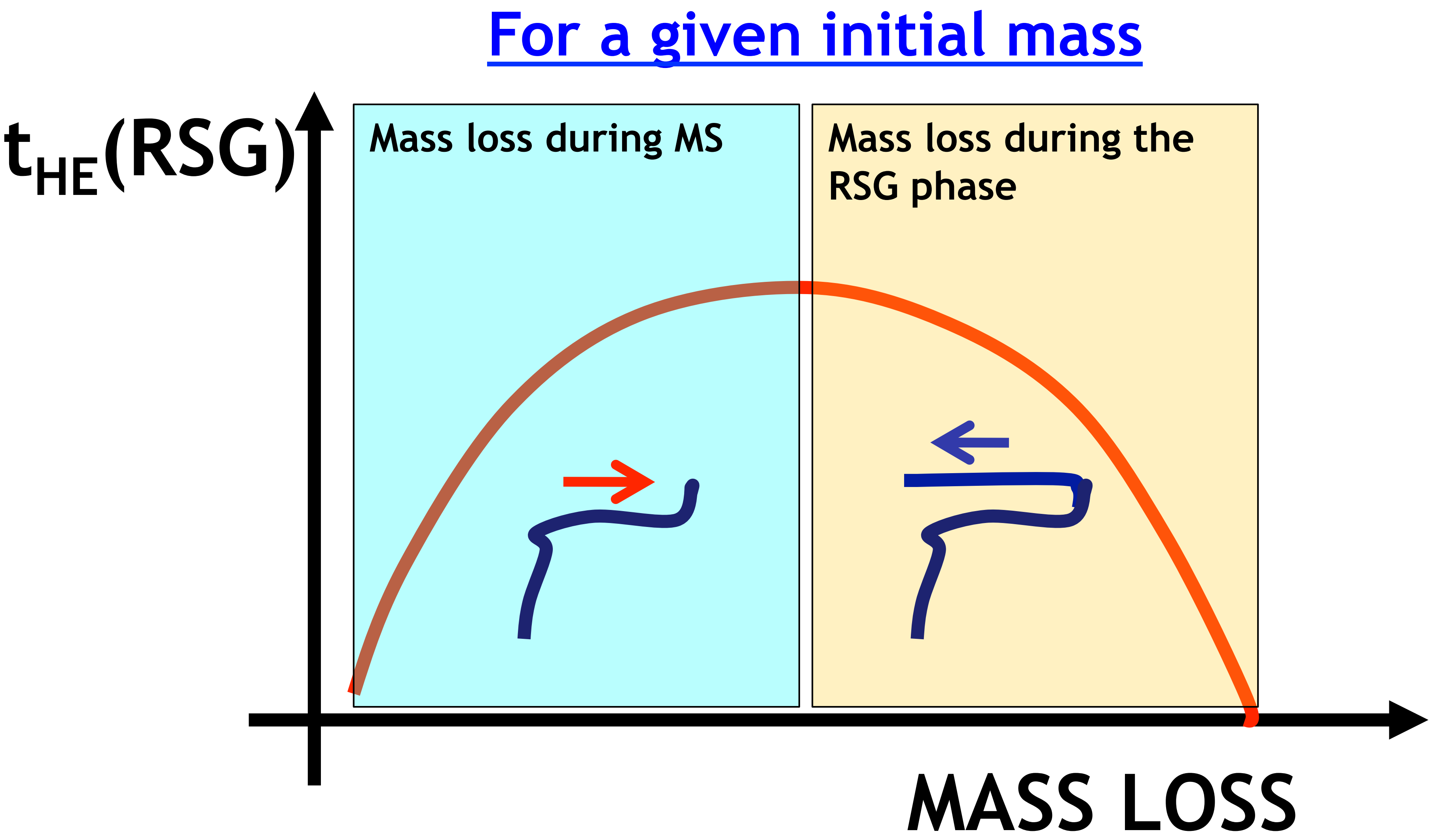
Eggenberger et al. AA, 386, 576 (2002);
Cf discussion in Langer and Maeder AA 373, 555 (1995)

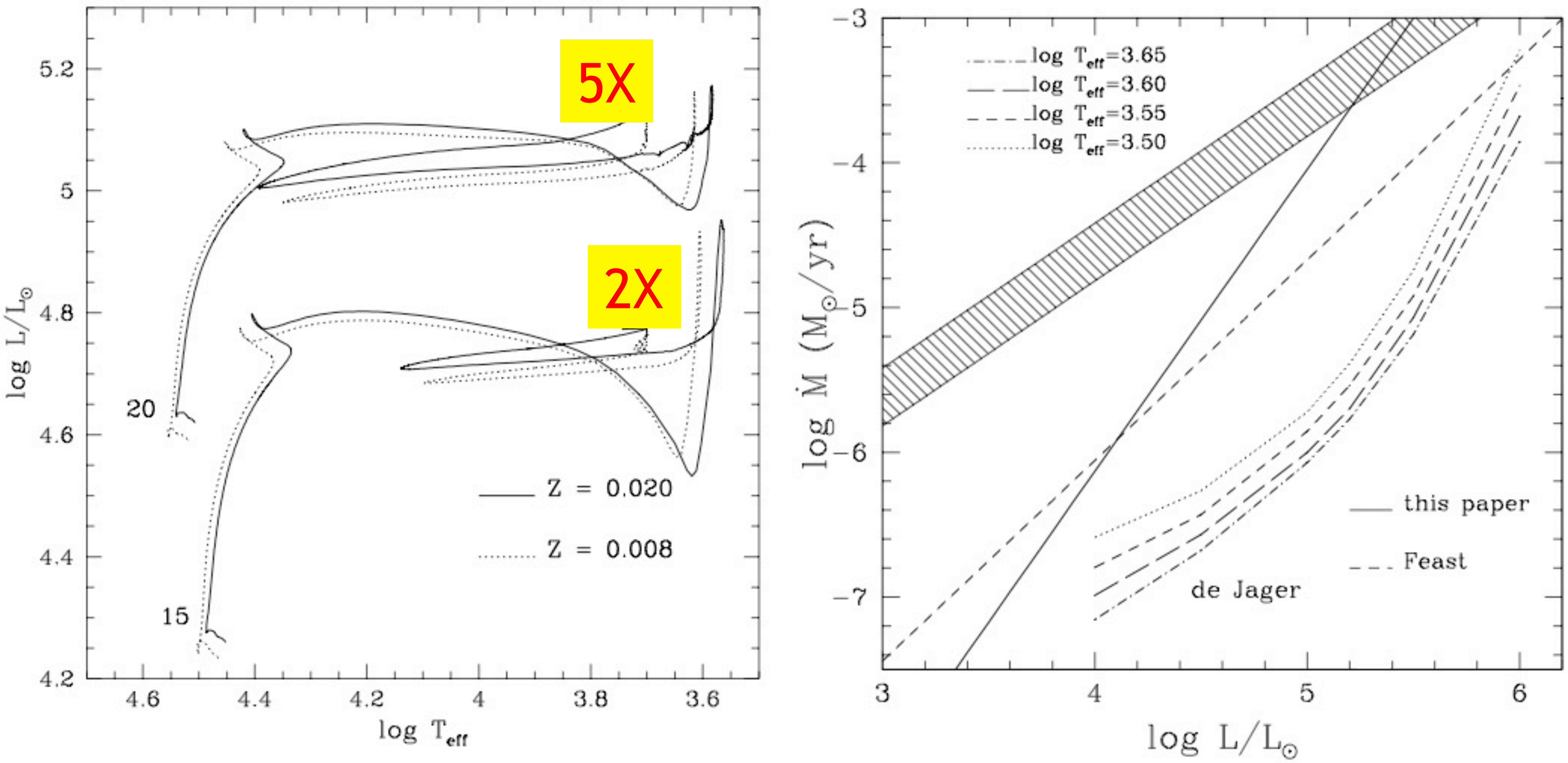


Schaller et al. 1992

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

CHANGE OF MASS LOSS





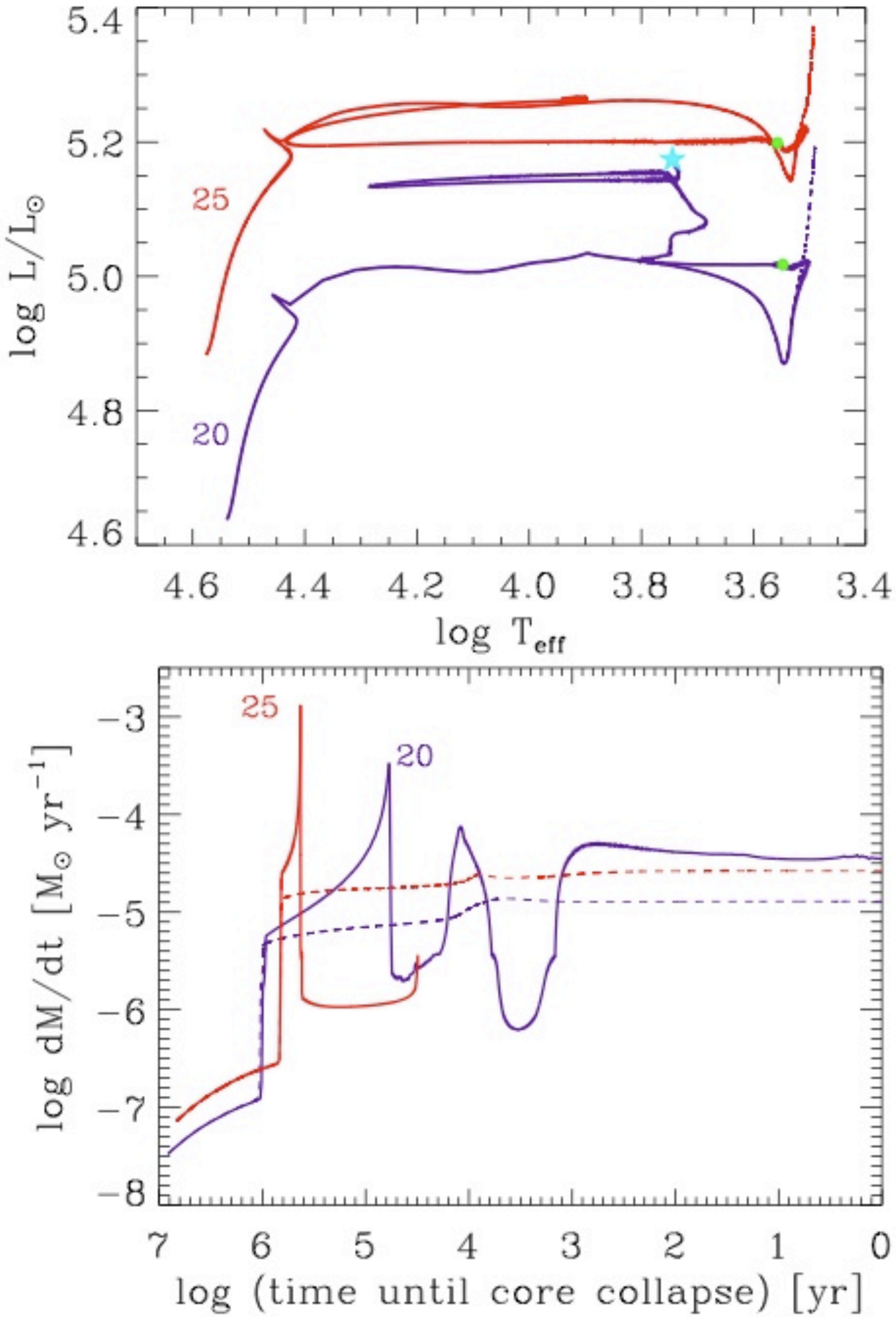
Salasnich, Bressan, Chiosi, 1999, A&A, 342, 131

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

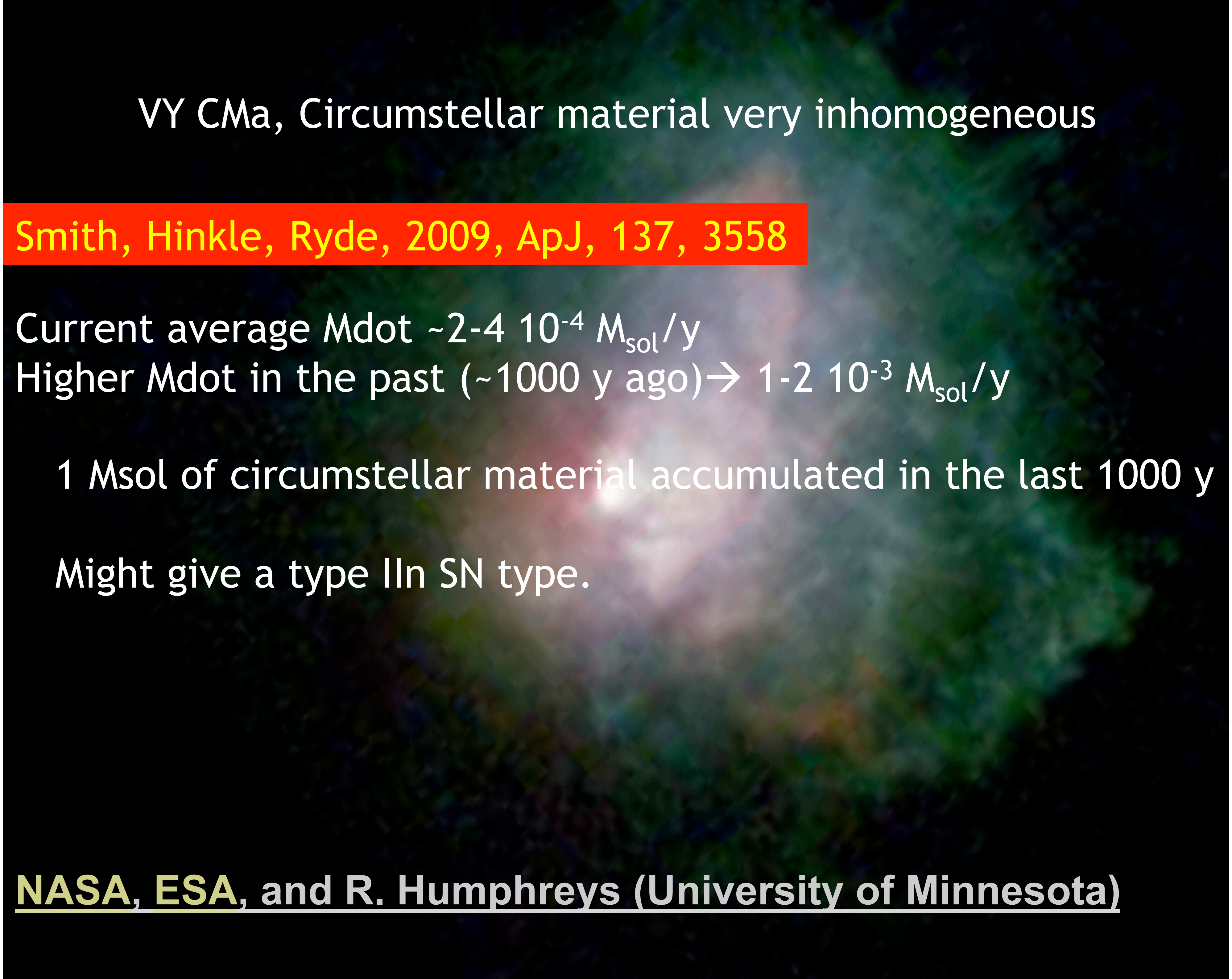
Reduction inferior mass limit for removal of outer envelope from 25 M_{sol} to ~19 M_{sol}

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



VY CMa, Circumstellar material very inhomogeneous

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

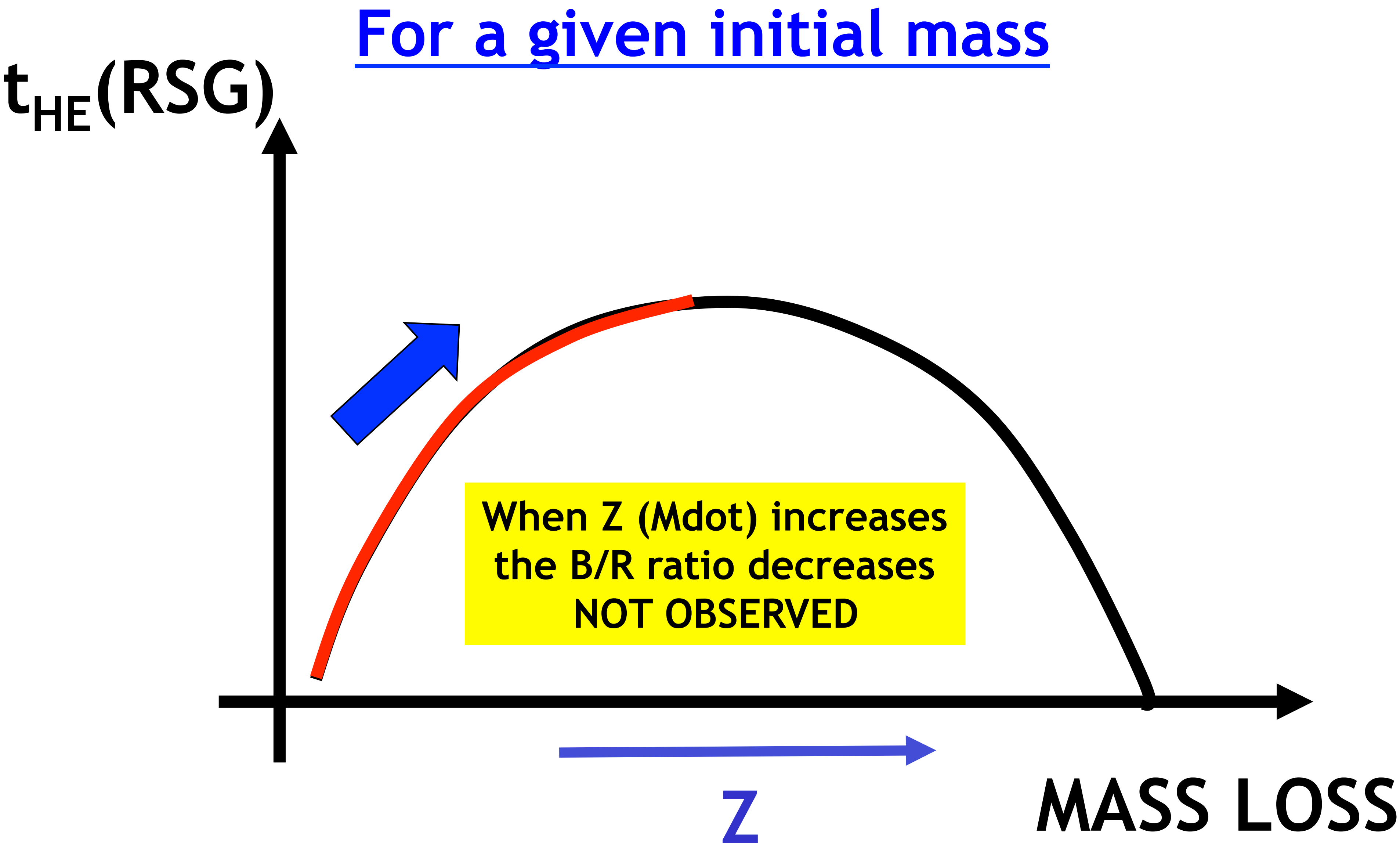
Current average Mdot ~2-4 10^{-4} M_{sol}/y
Higher Mdot in the past (~1000 y ago)→ 1-2 10^{-3} M_{sol}/y

1 Msol of circumstellar material accumulated in the last 1000 y

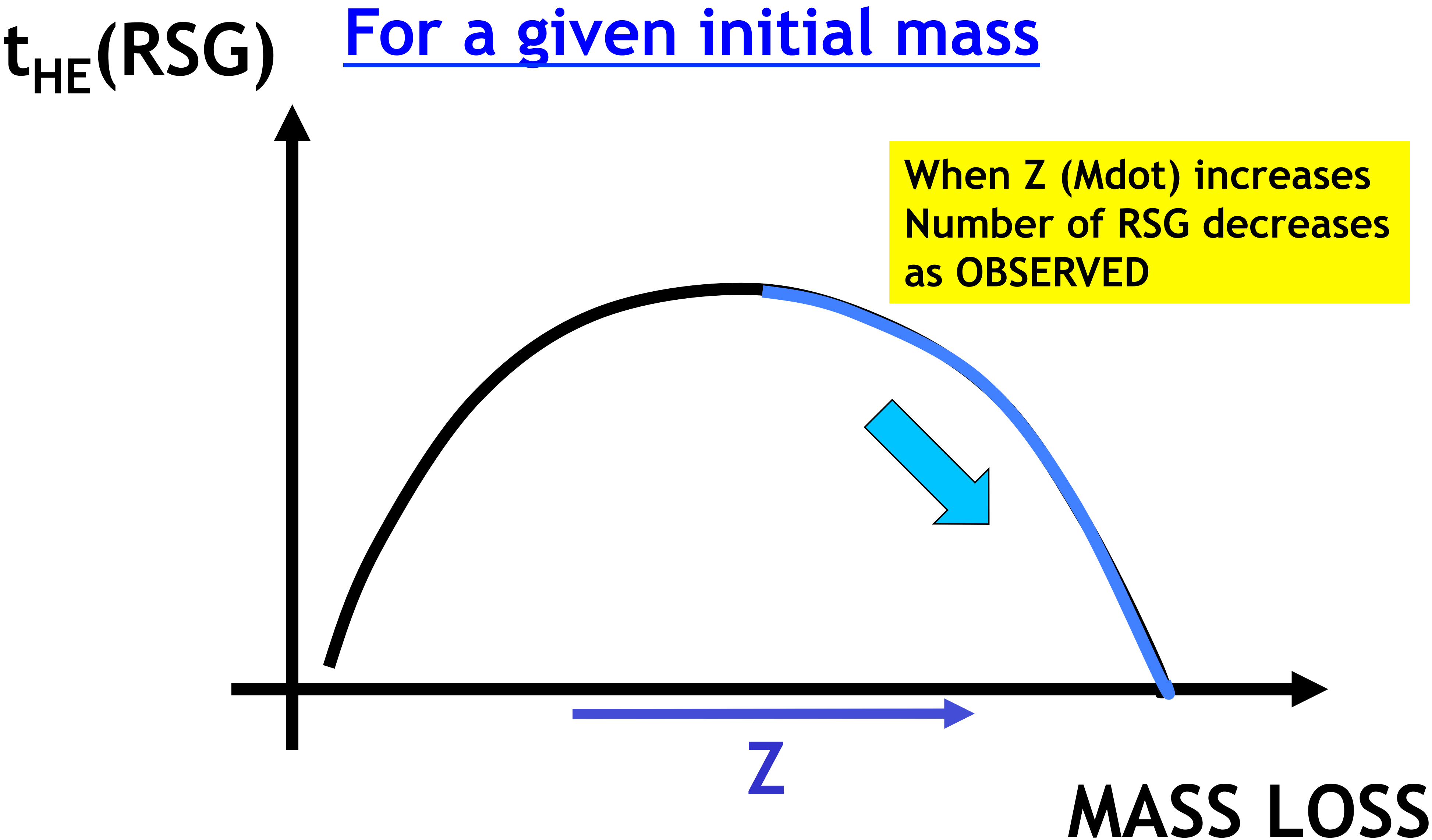
Might give a type IIn SN type.

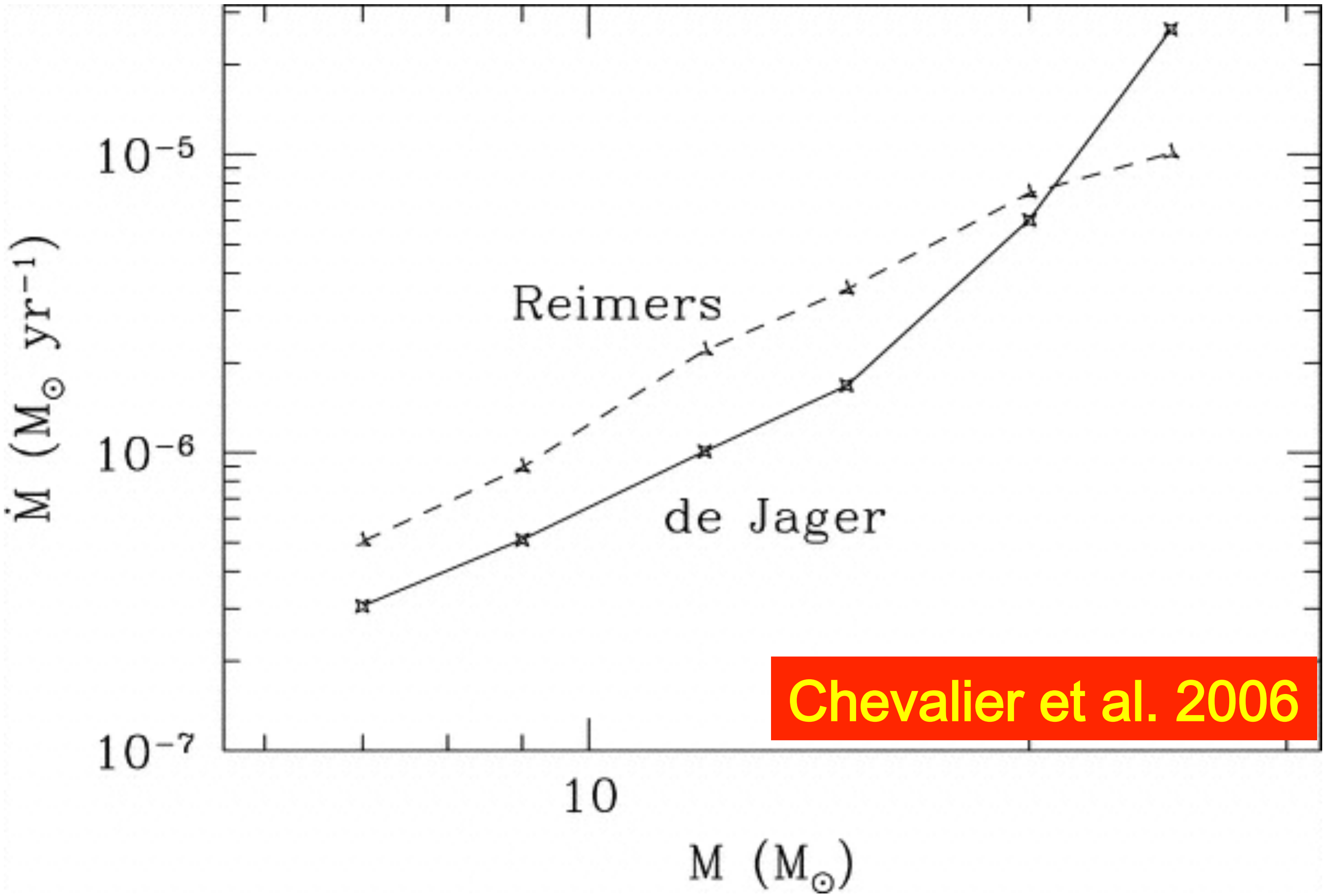
NASA, ESA, and R. Humphreys (University of Minnesota)

INCREASE OF Mdot DURING THE MS?

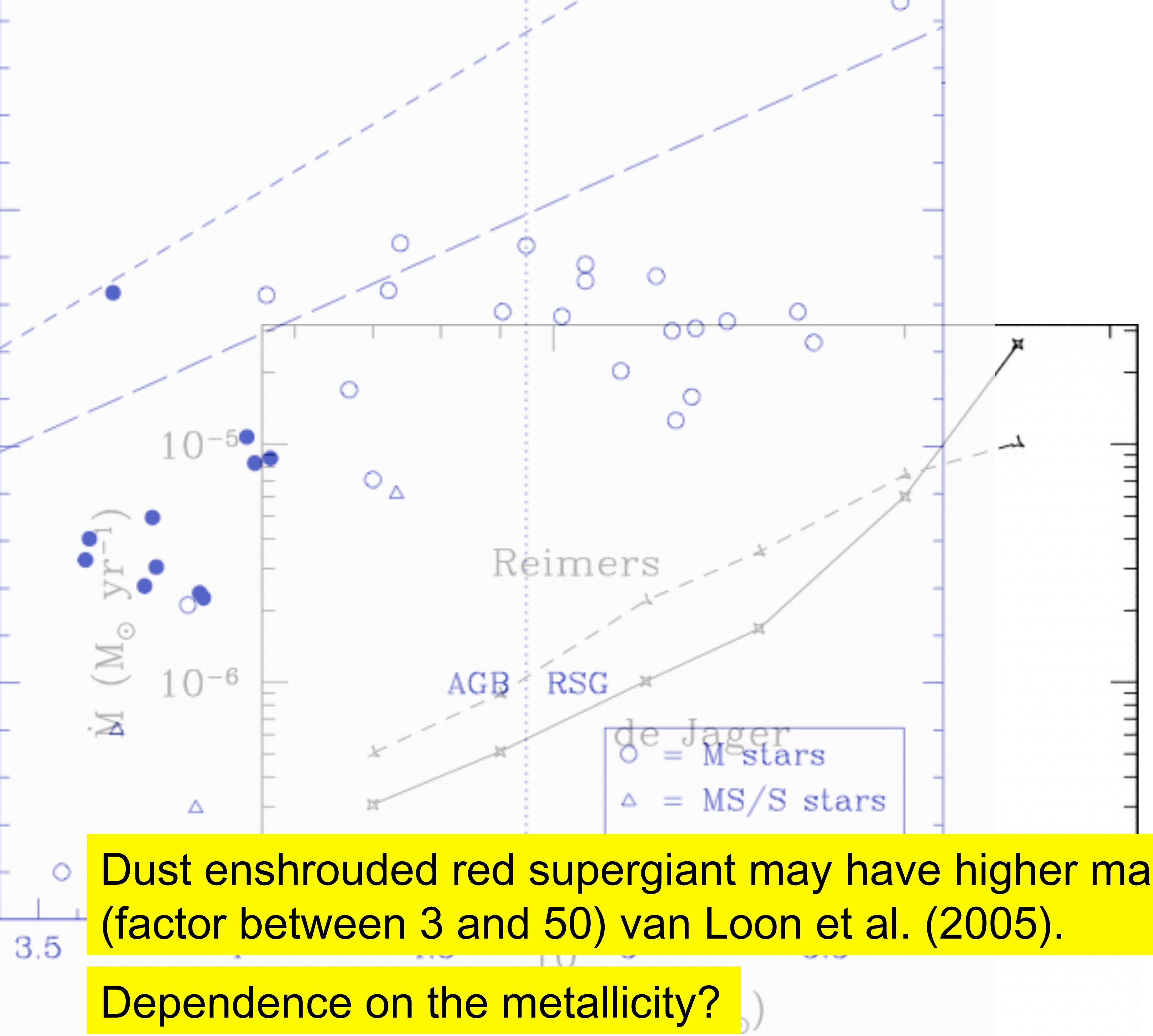


INCREASE DURING THE RSG PHASE?



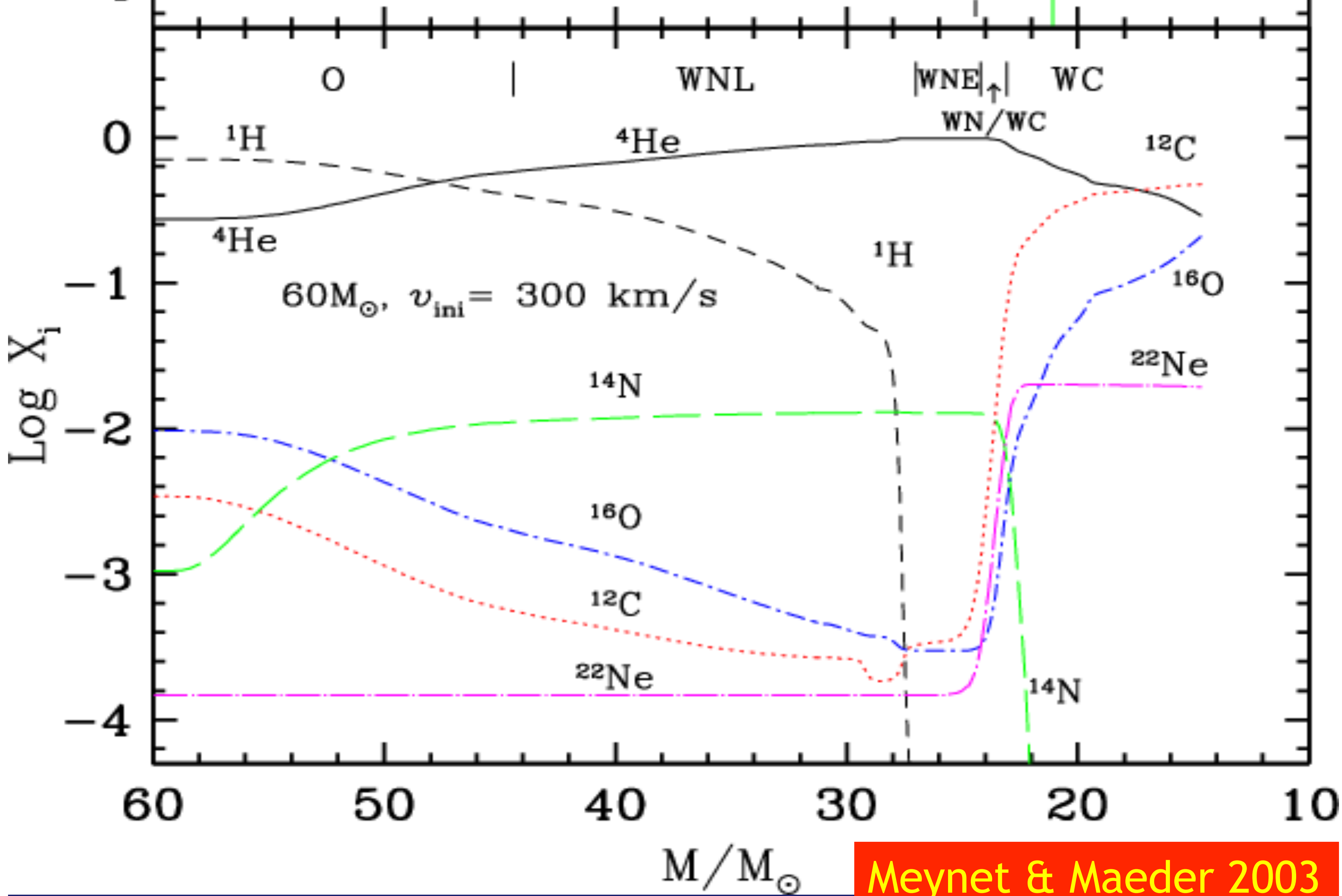


10^{-5}
10^{-6}
10^{-7}
$\dot{M}$ ($M_\odot$ yr^{-1})
Reimers
de Jager
Chevalier et al. 2006
10
M ($M_\odot$)



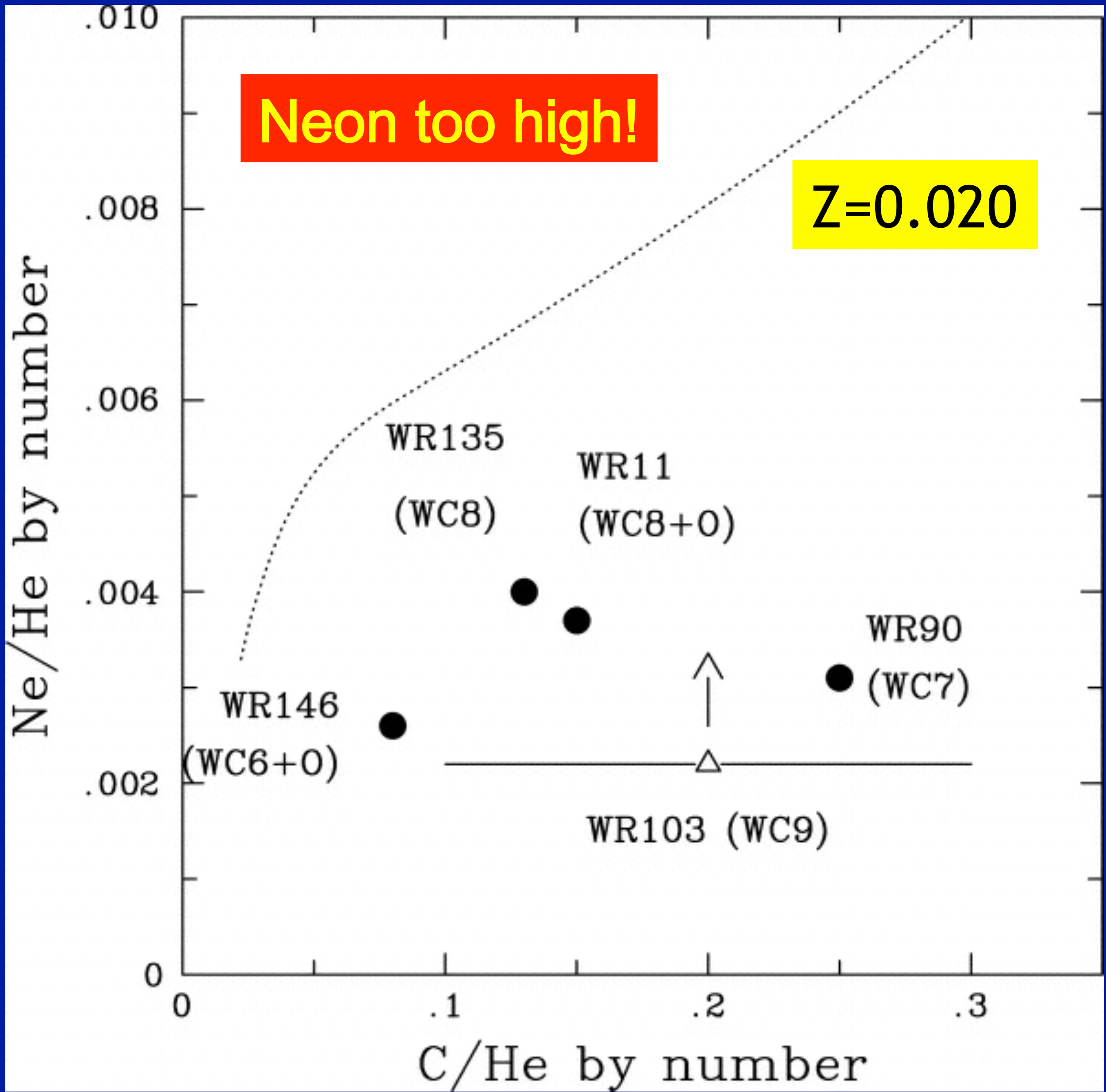
Dust enshrouded red supergiant may have higher mass loss (factor between 3 and 50) van Loon et al. (2005).

Dependence on the metallicity?



Meynet & Maeder 2003

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).

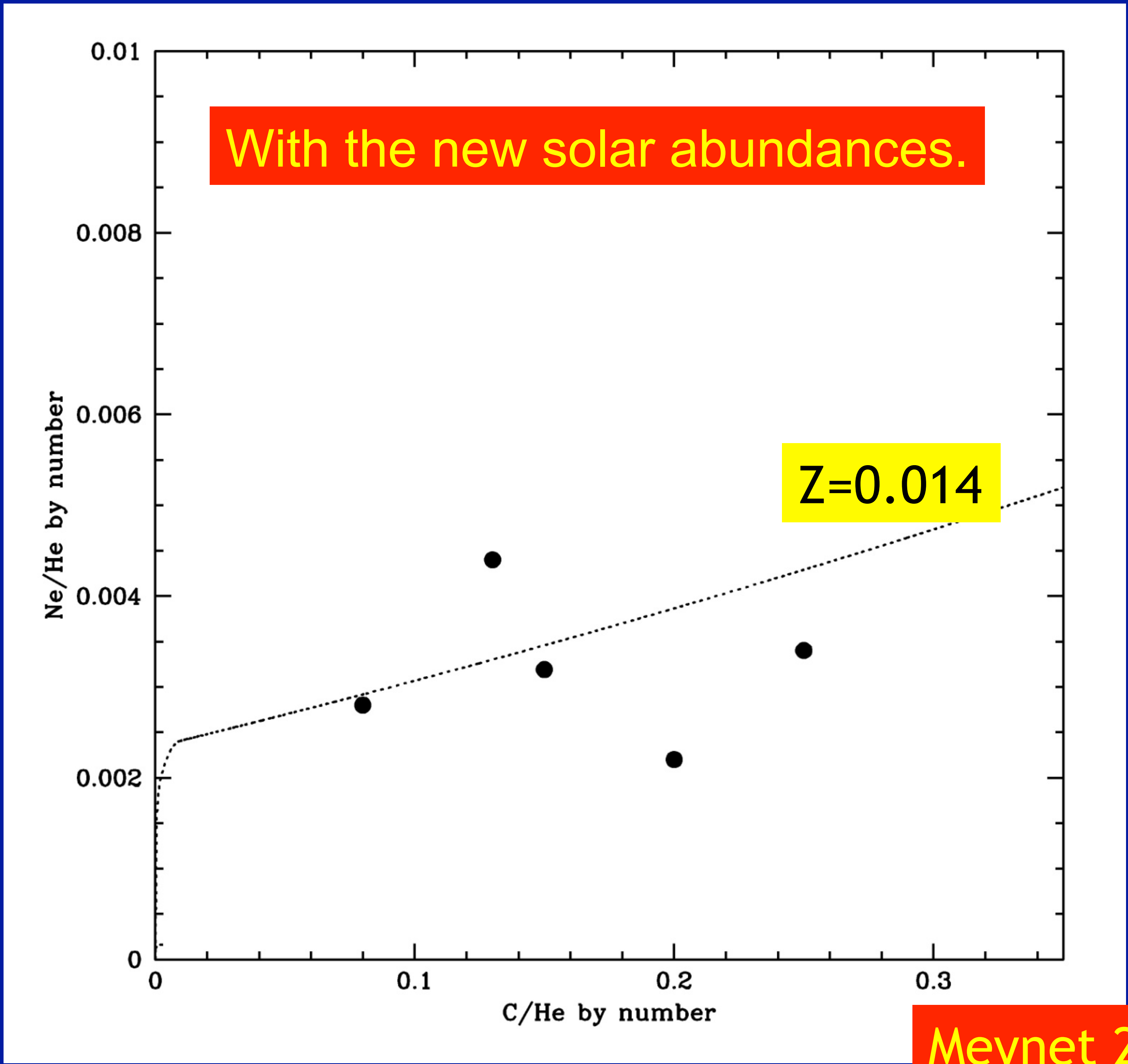
[c]Present work.

[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).

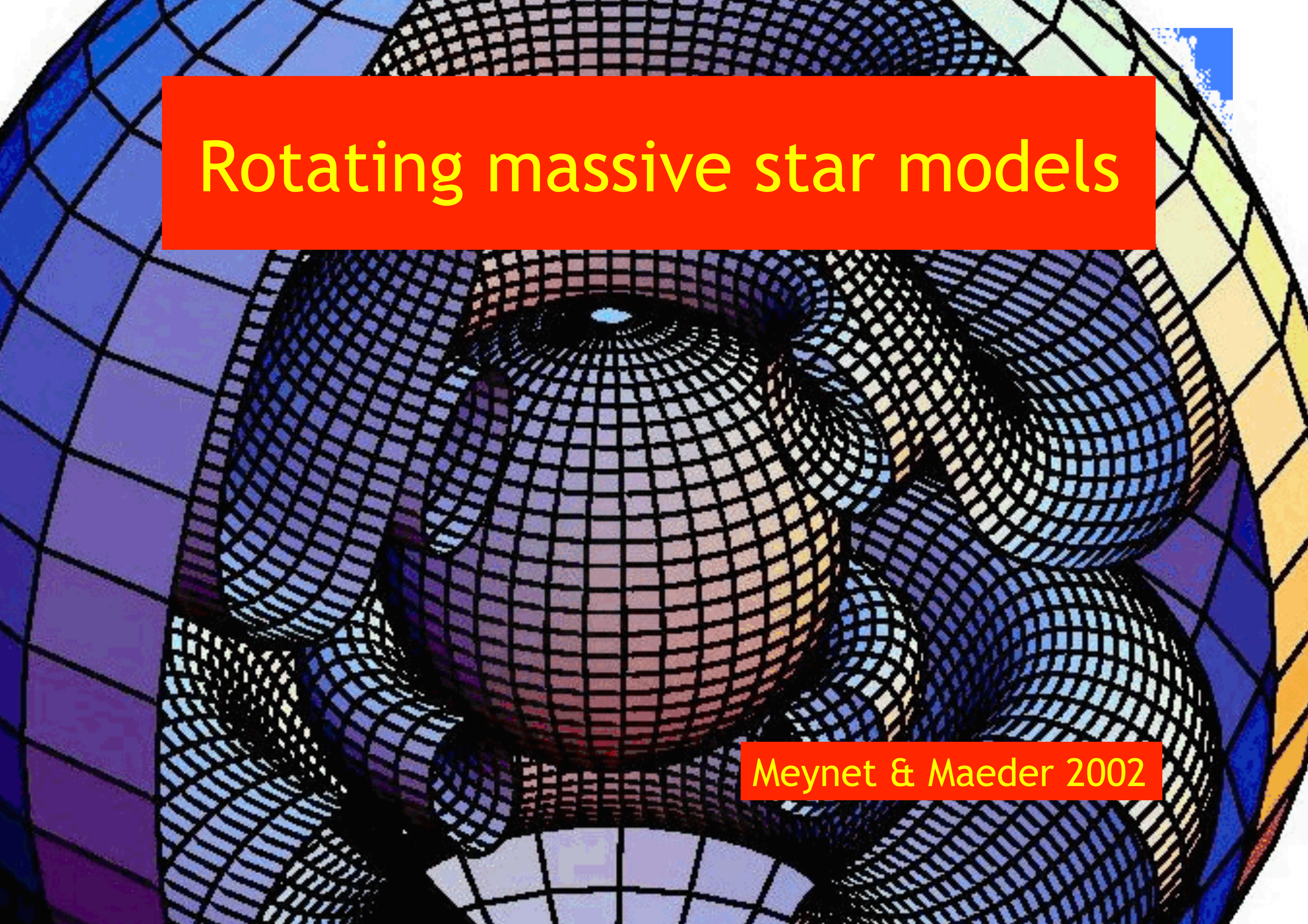
Asplund et al. 2009



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

Meynet 2008

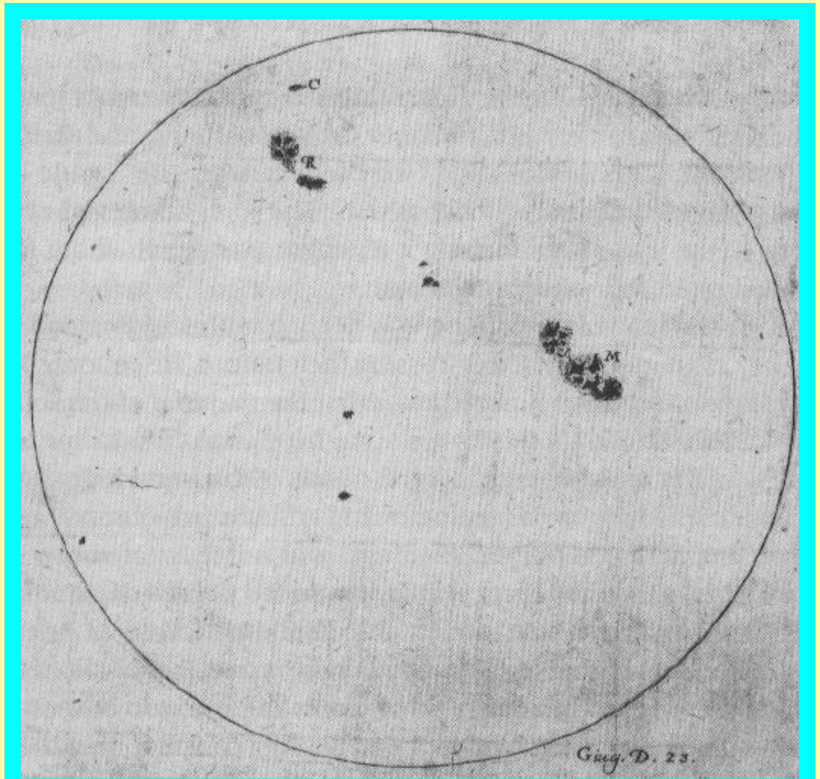
Rotating massive star models



Meynet & Maeder 2002

ROTATION…

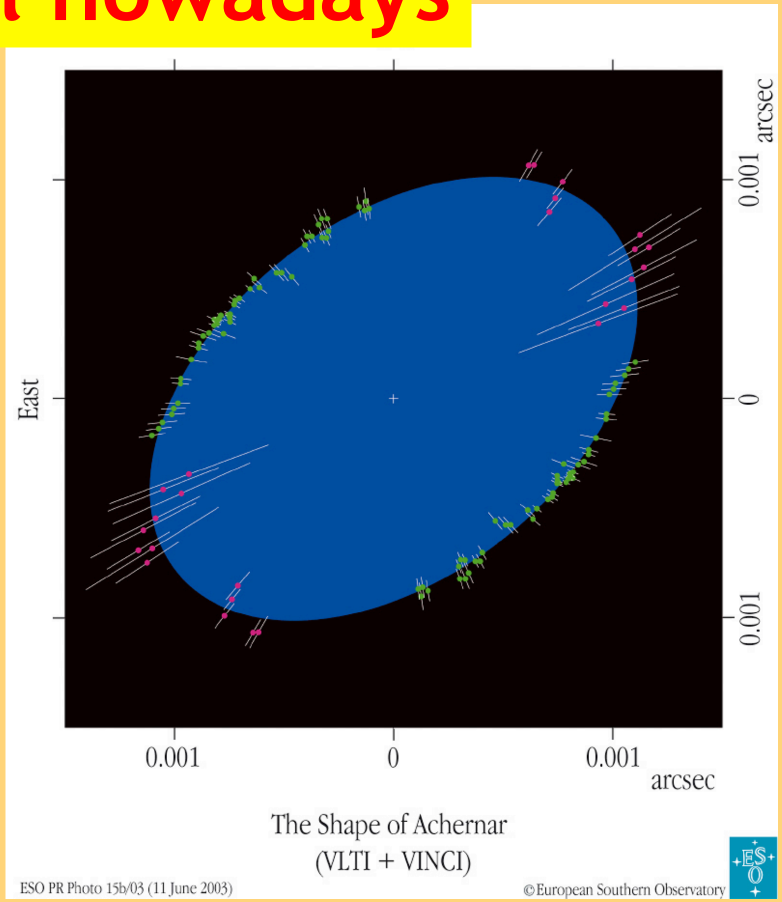
An old topic…



Von Zeipel 1924; Eddington 1925; Vogt 1925

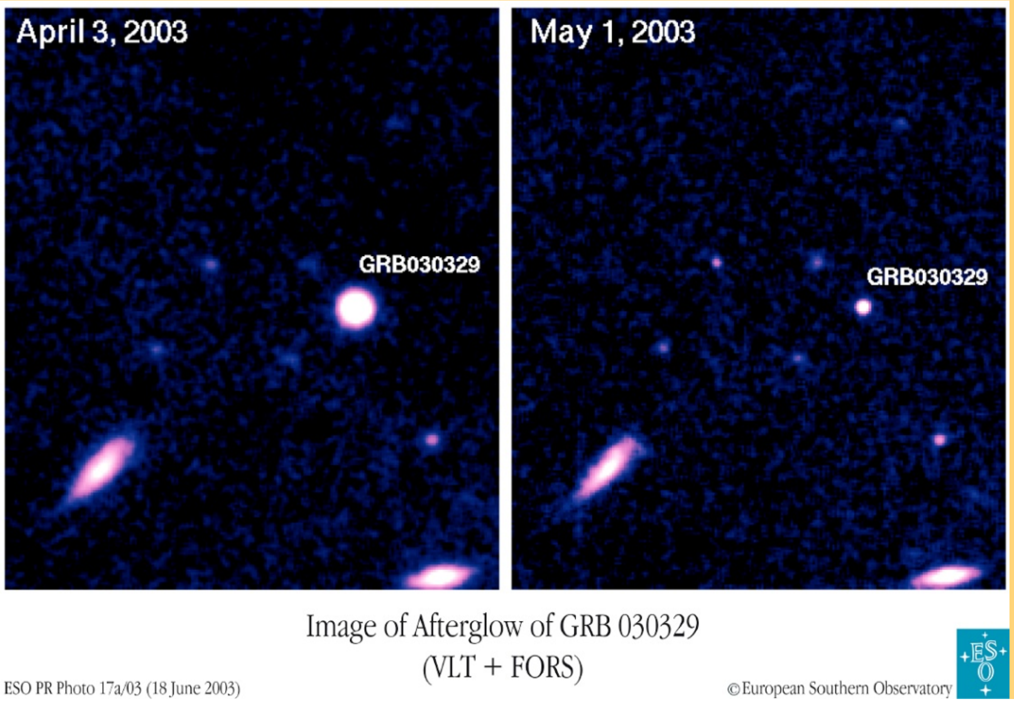
… but quite topical nowadays

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

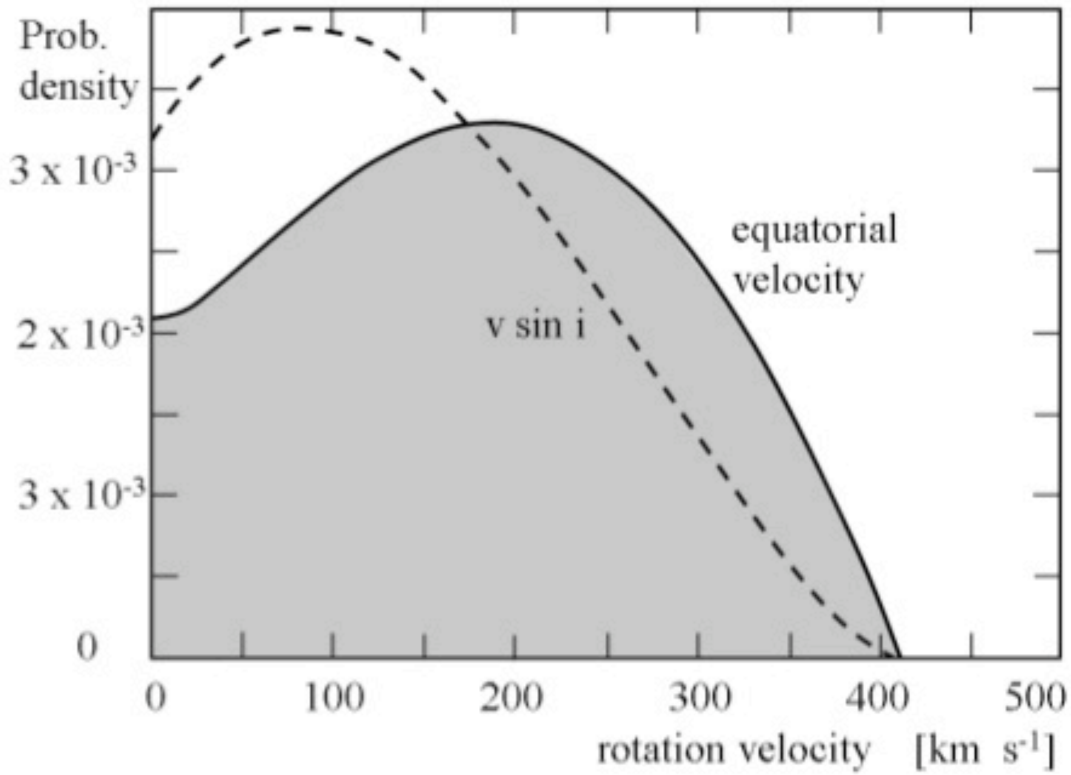
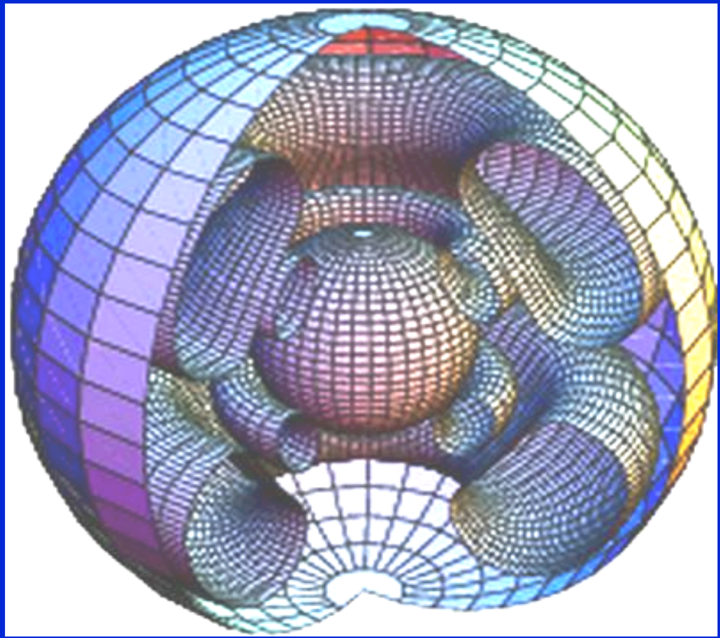
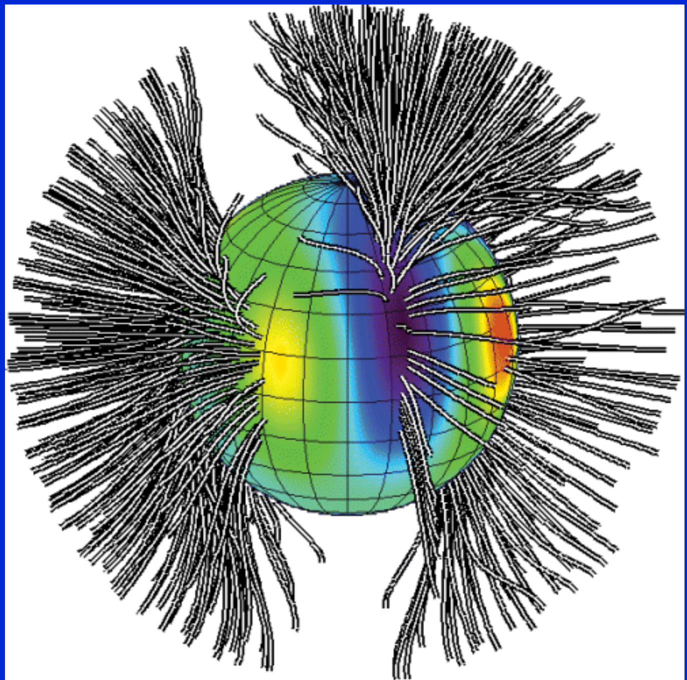


Fig. 27.1. Probability density by km s^{-1} of rotation velocities for 496 stars with types O9.5 to B8. Adapted from W. Huang and D.R.Gies [259]

Huang & Gies 2006



Meynet & Maeder 2002



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

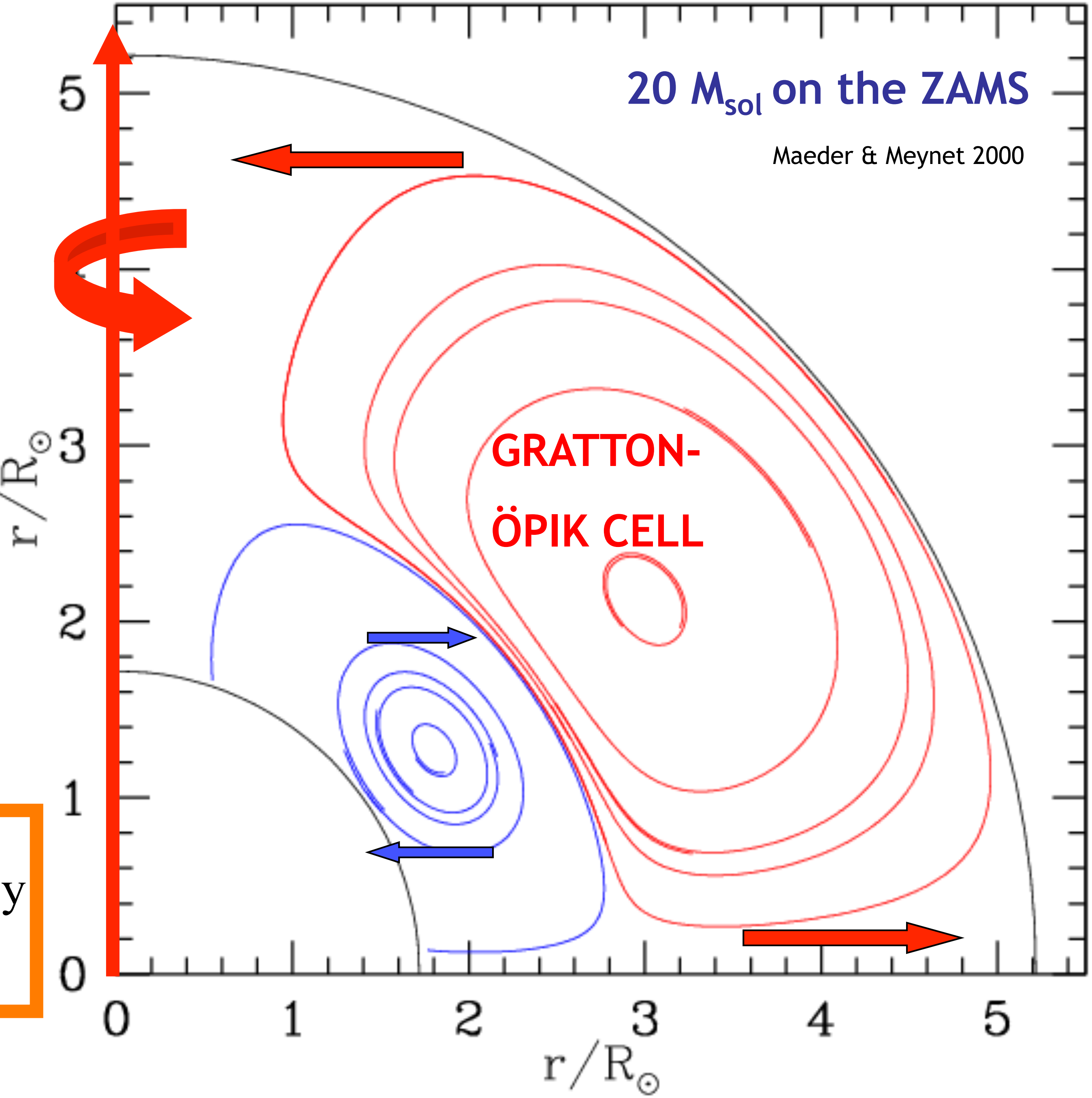
Cells of meridional circulation

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

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



THE SHEAR INSTABILITY

Where does the energy come from ?

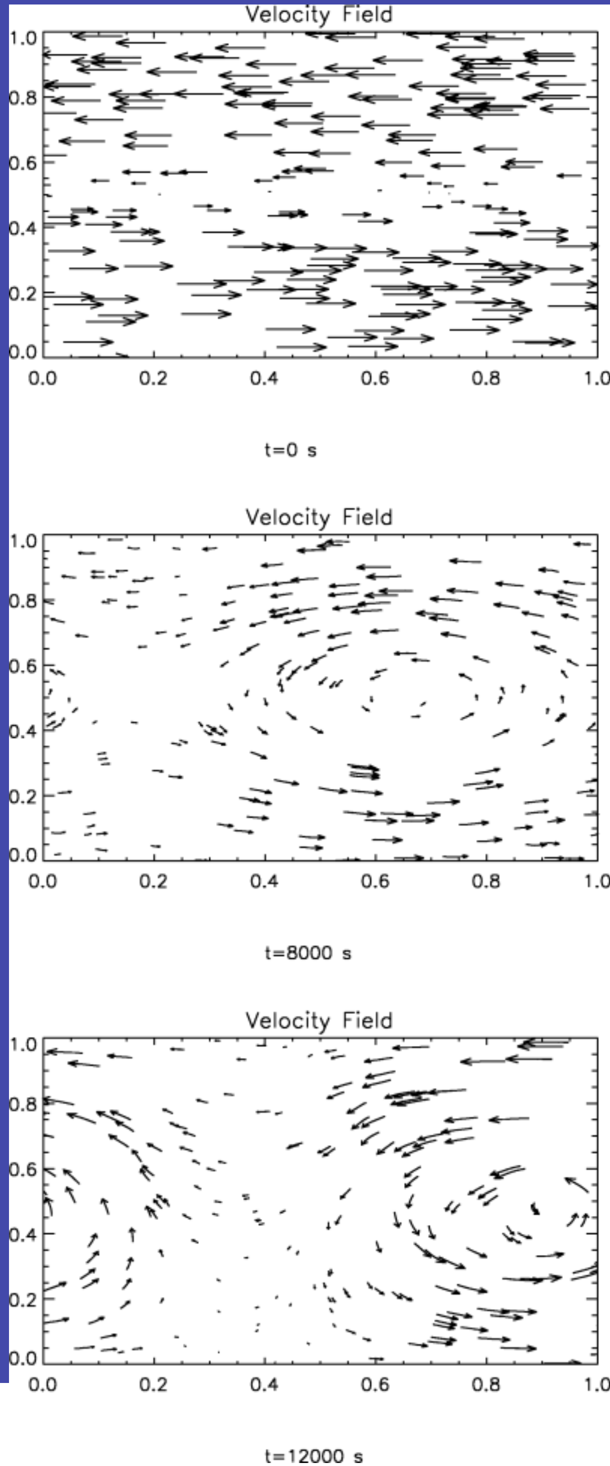
From the excess energy in the shear

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

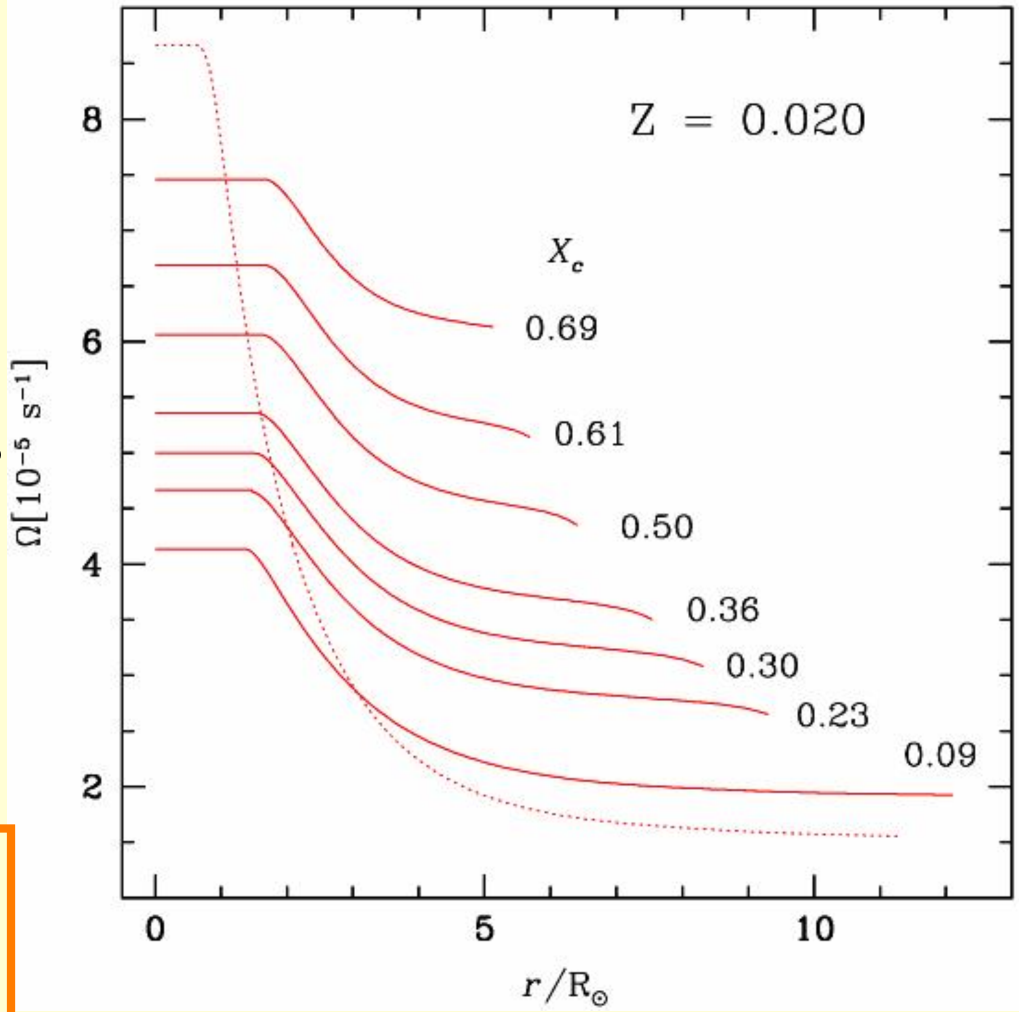
Increase of the radius

Transport of angular momentum

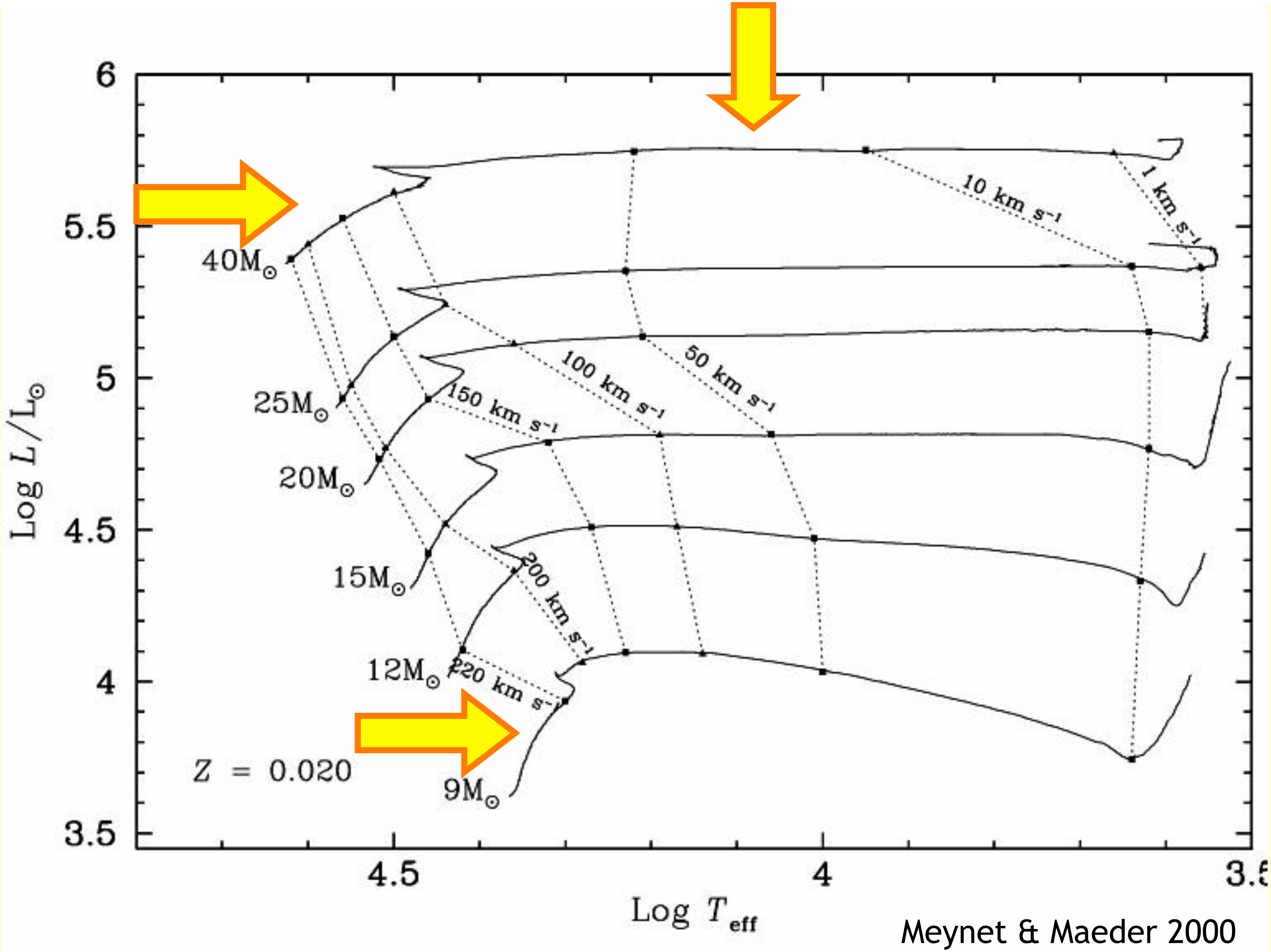
Removal of angular momentum
at the surface by the stellar winds

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

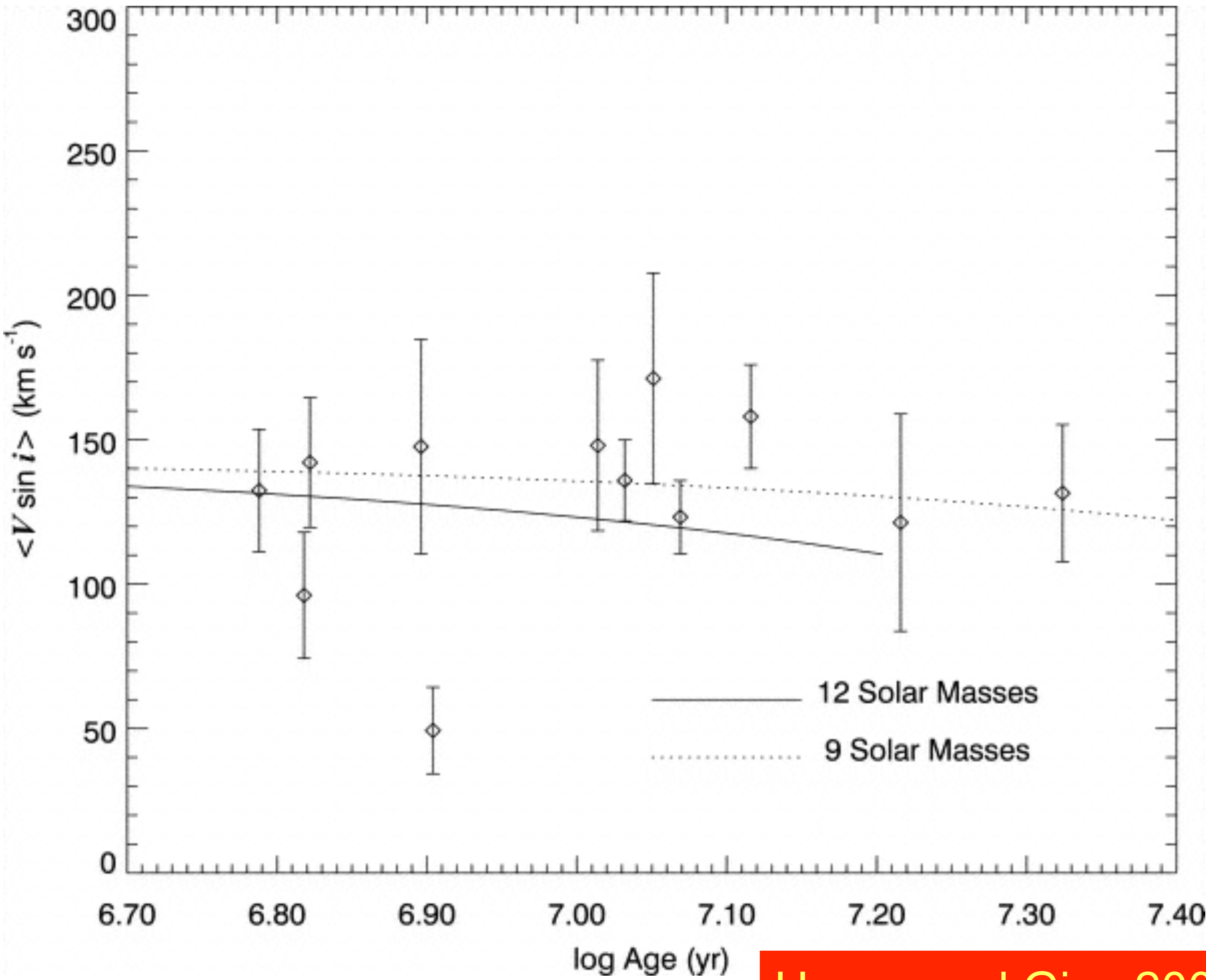


Meynet & Maeder 2000



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

<V> (MS) ~ 225 km/s

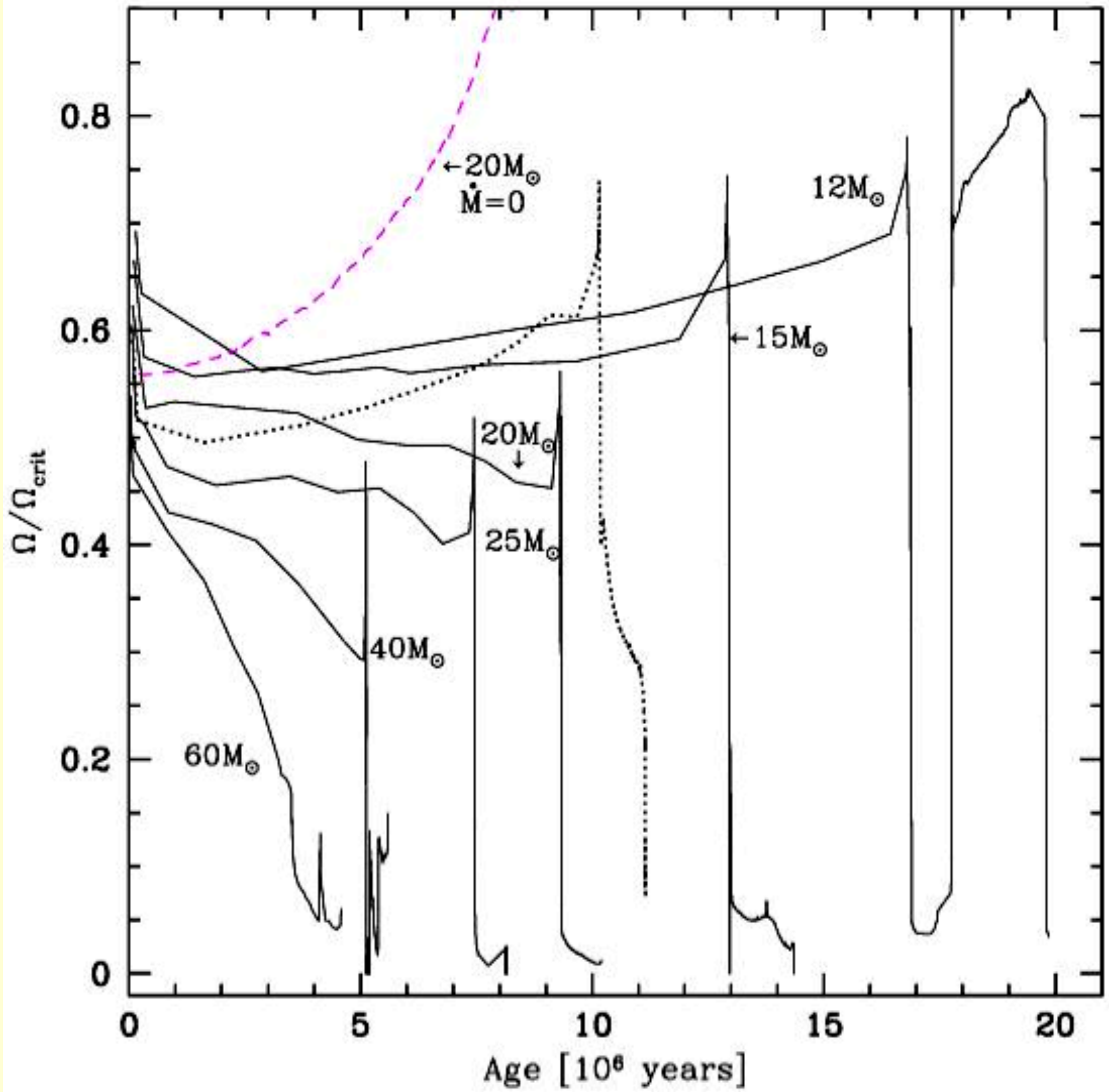


Huang and Gies 2006

Approach of the critical Velocity

Be stars

Meynet & Maeder 2000

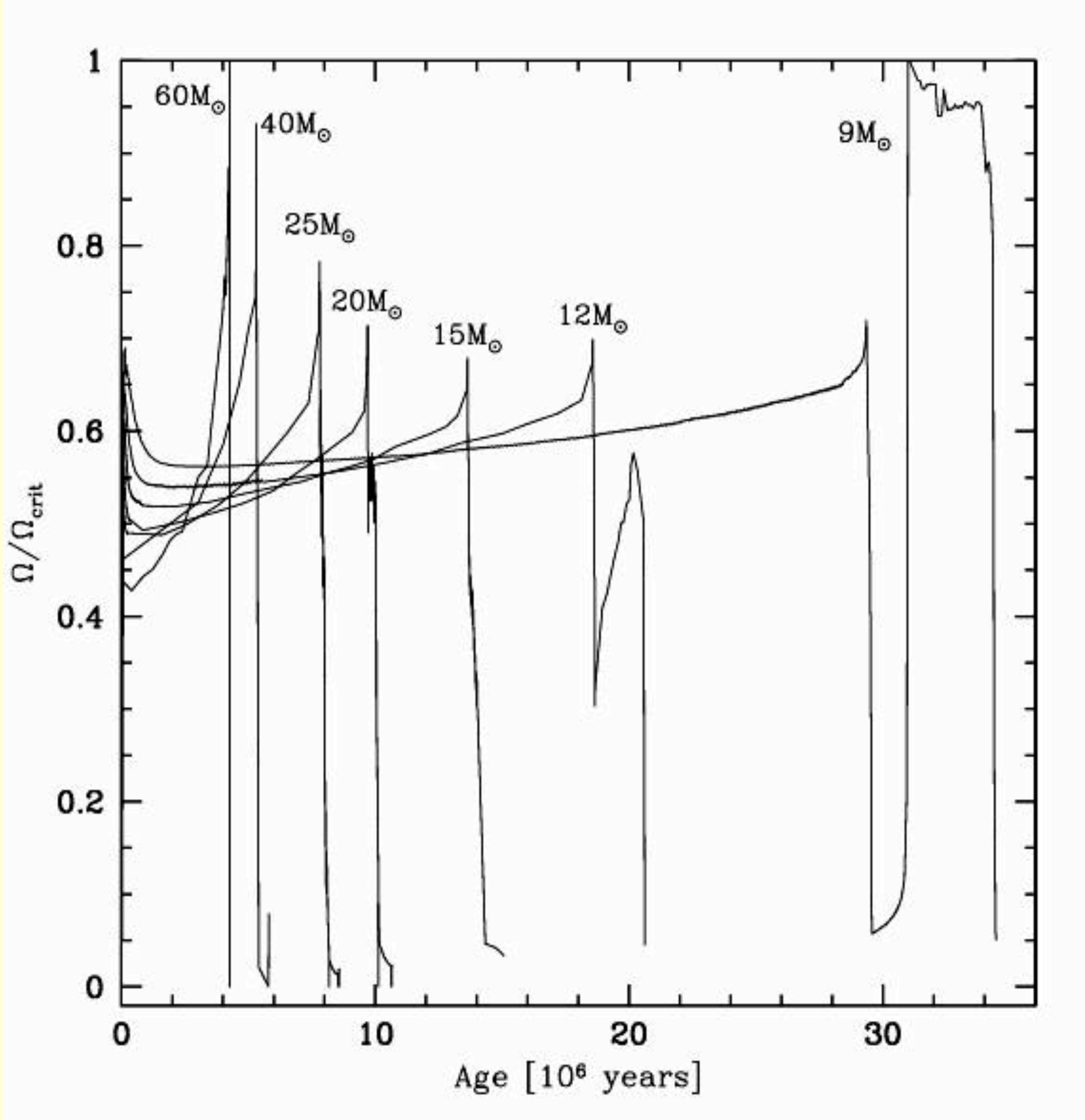


Z=0.02

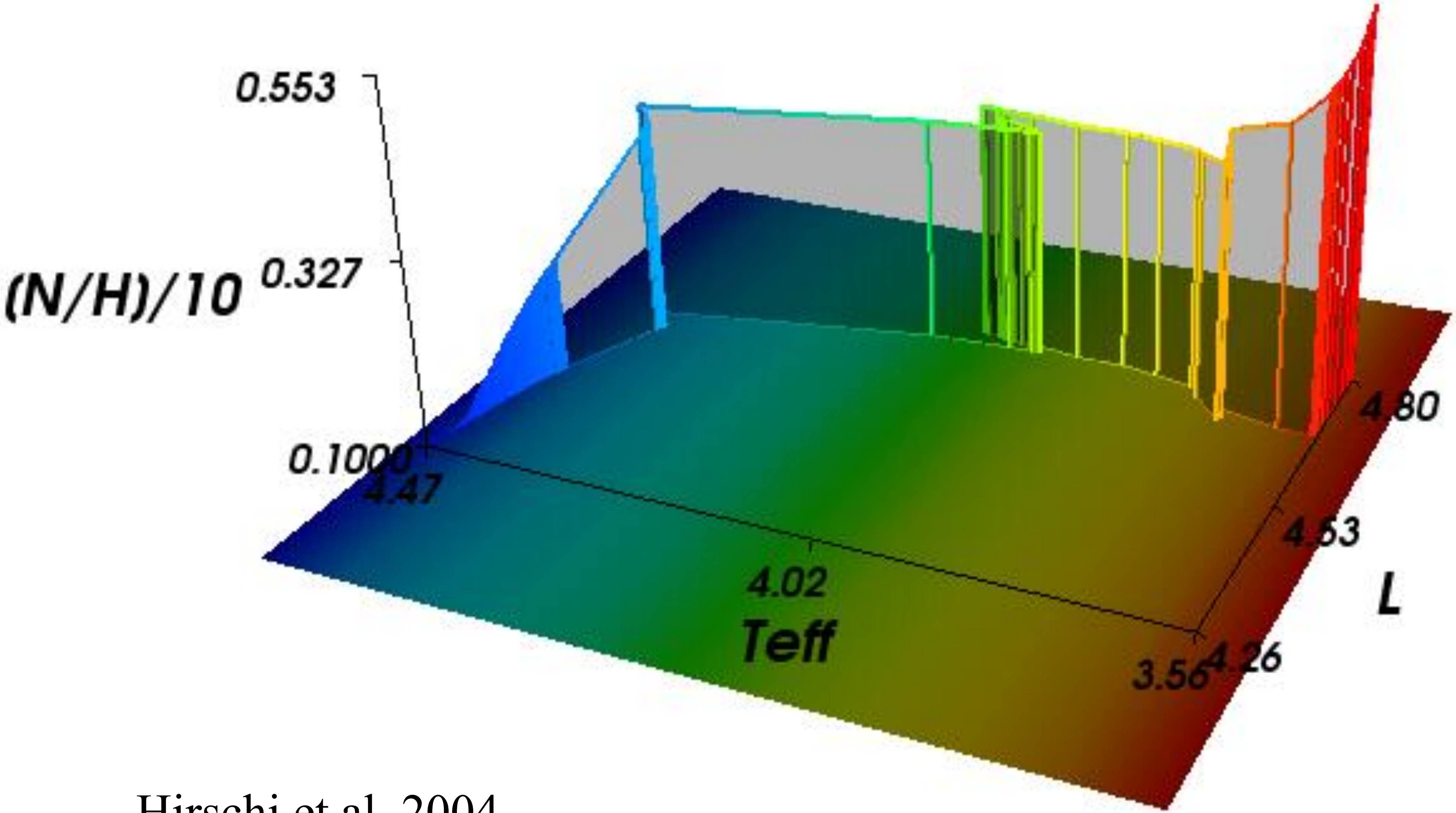
At Z=0.02, drastic decrease of velocity for high masses

Z=0.004

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



Maeder & Meynet 2001



Hirschi et al. 2004

WHY MIXING IN MASSIVE STARS ?

$$\tau \cong R^2 / D$$

$$D = \frac{4K}{(\nabla_{ad} + \frac{\varphi}{\delta}\nabla_{\mu} - \nabla)}\left[\frac{\alpha H_p}{4g\delta}\left(\Omega \frac{d\ln\Omega}{d\ln r}\right)^2 - (\nabla_{ad} - \nabla)\right]$$

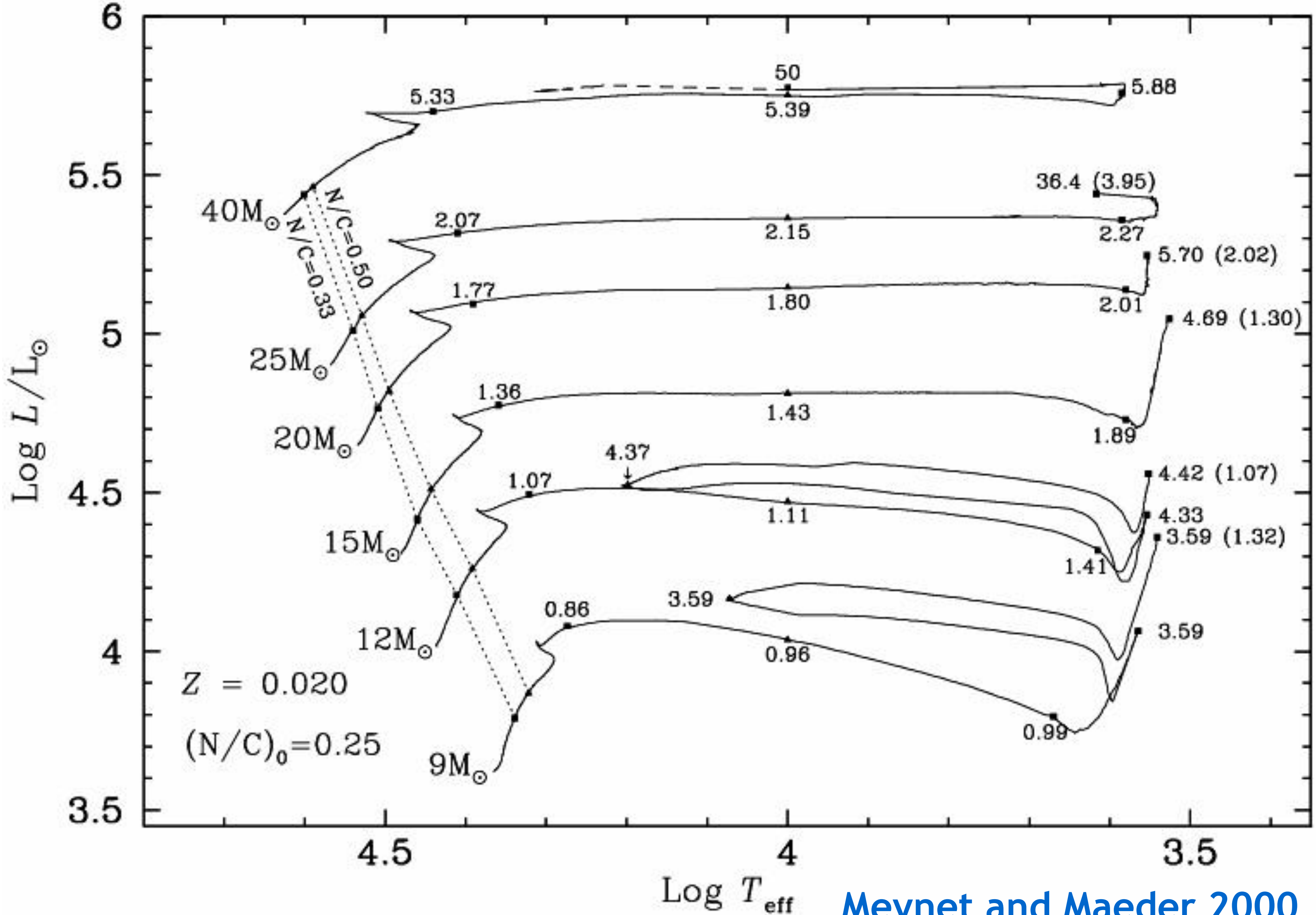
$$K = \frac{4acT^3}{3\kappa\rho^2 c_P}$$

$$\tau_{mix} \cong \cdots \frac{1}{M^{1.8}} \qquad \tau_{MS} \cong \cdots \frac{1}{M^{0.7}}$$

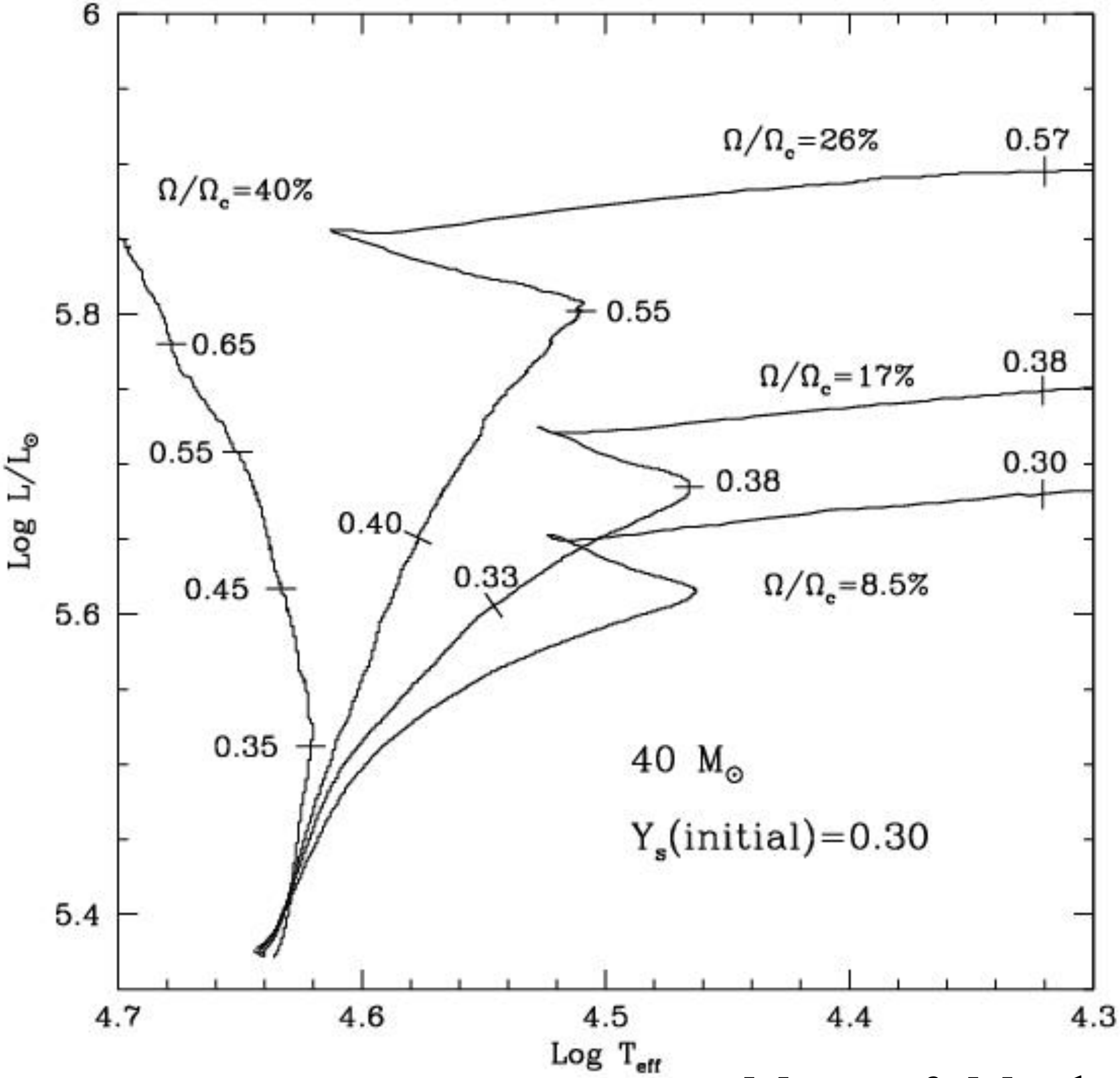
$$\frac{\tau_{mix}}{\tau_{MS}} \cong \ldots \frac{1}{M^{1.1}}$$

FOR HIGH M

MIXING TIME / MS TIMESCALE SMALL



Meynet and Maeder 2000

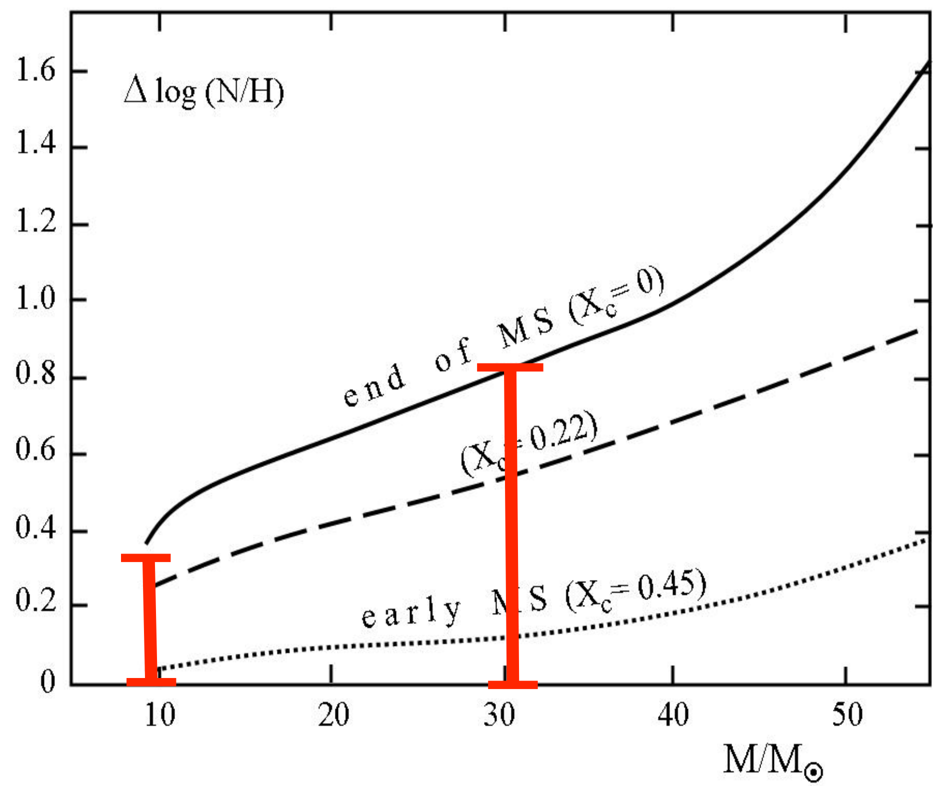


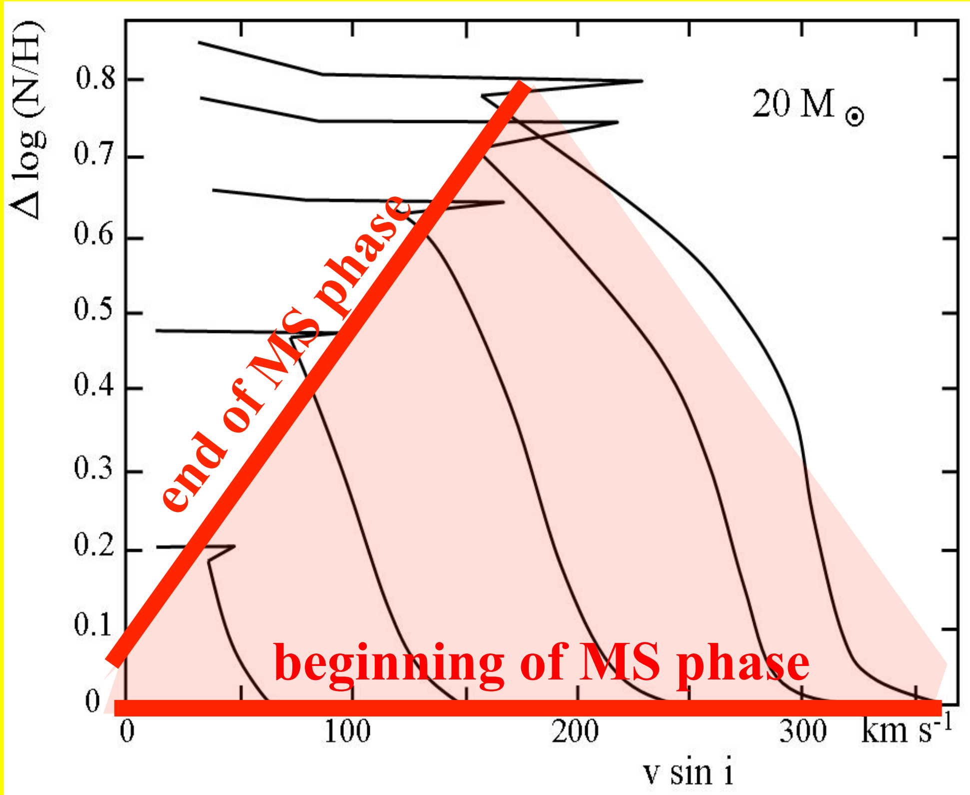
Meynet & Maeder 2000

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

Mass effect

Age effect

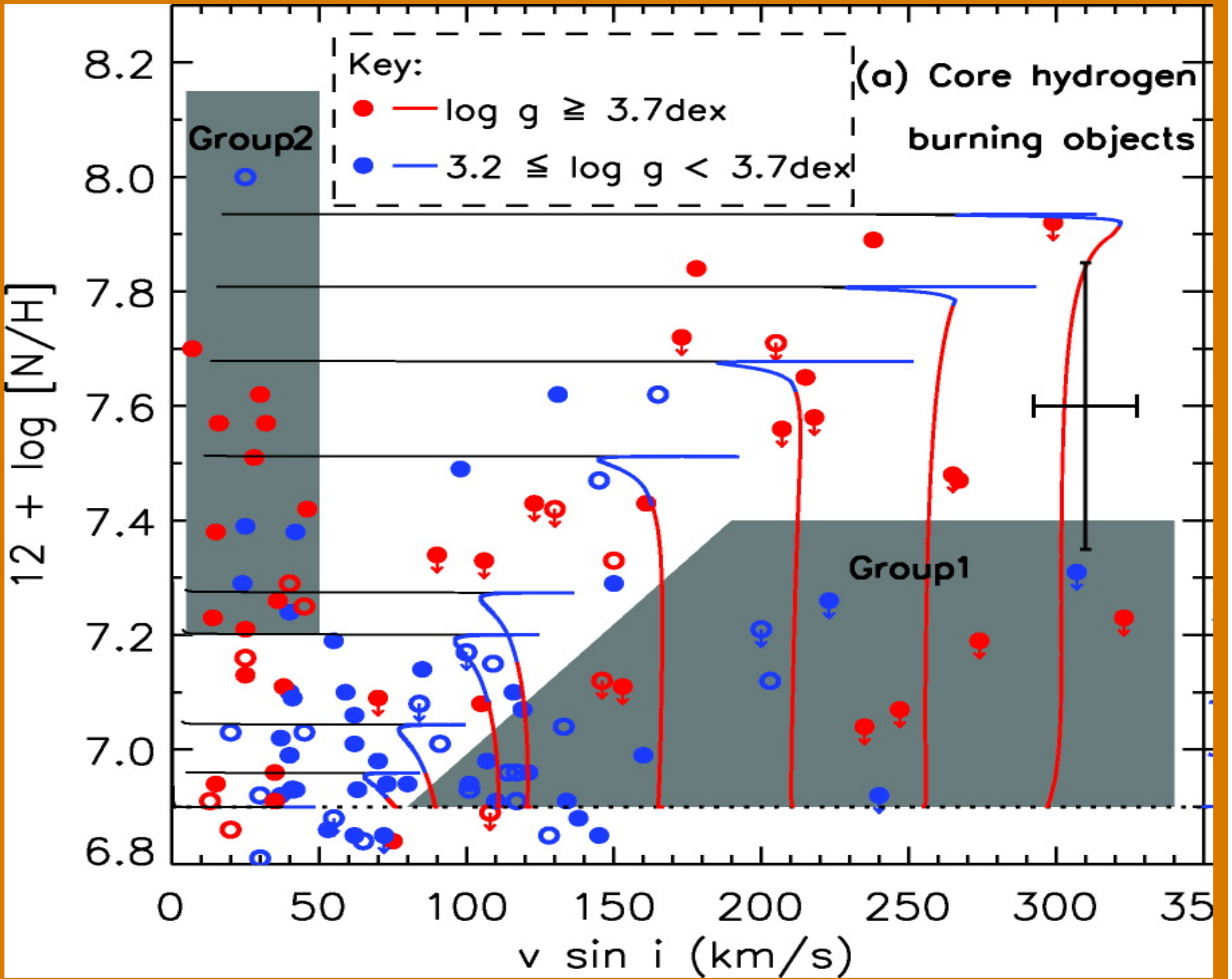




Maeder et al. 2009

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

Spread in masses and ages.



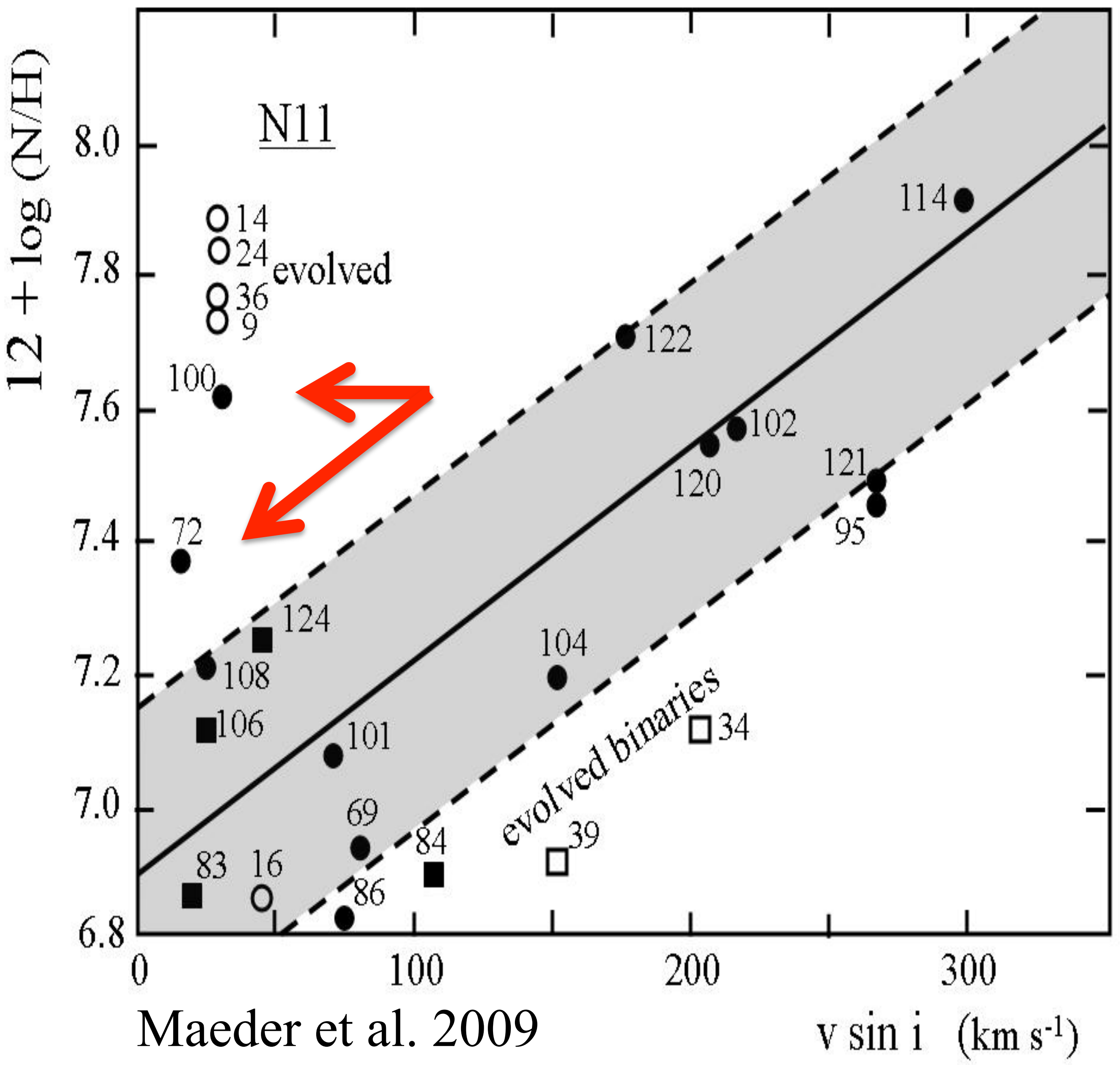
« The observation challenges the concept of rotational mixing »
Hunter et al. 2008

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

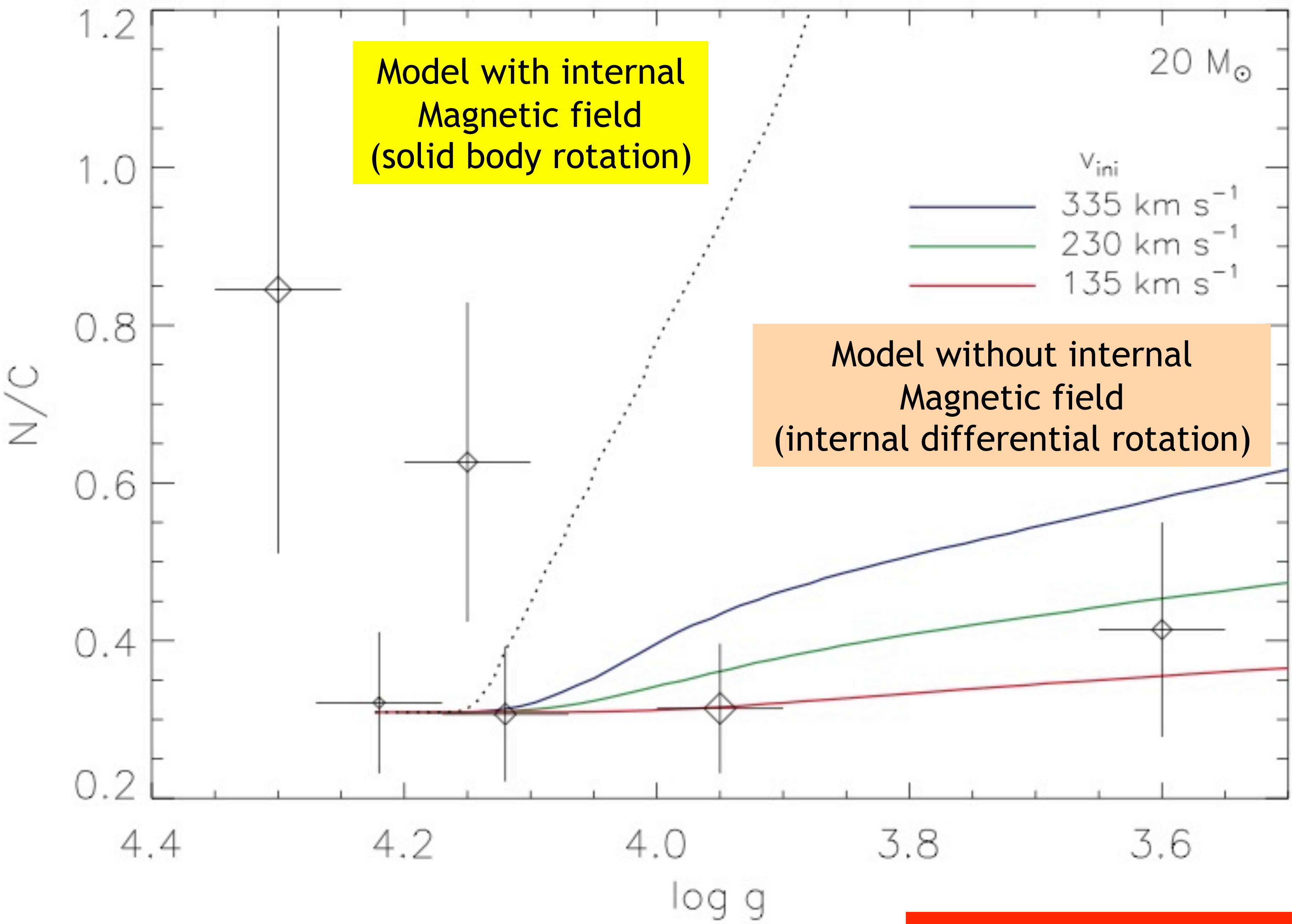
Gr 1 disappeared, except binaries

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

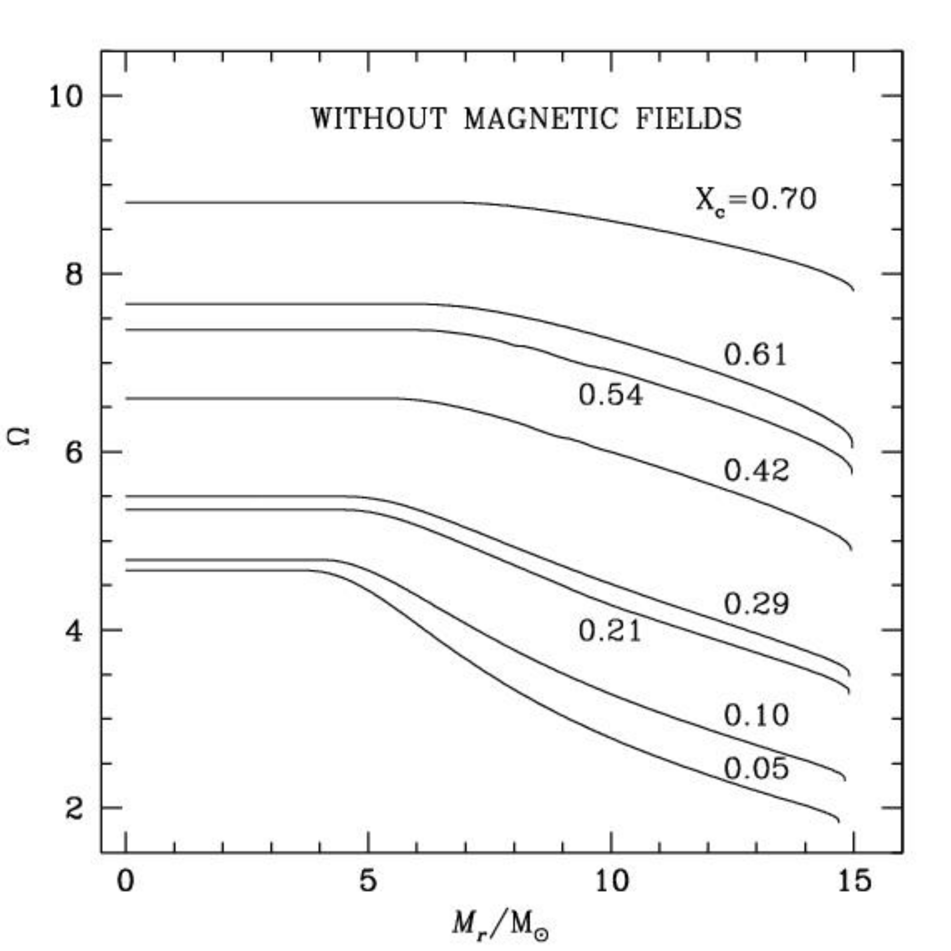


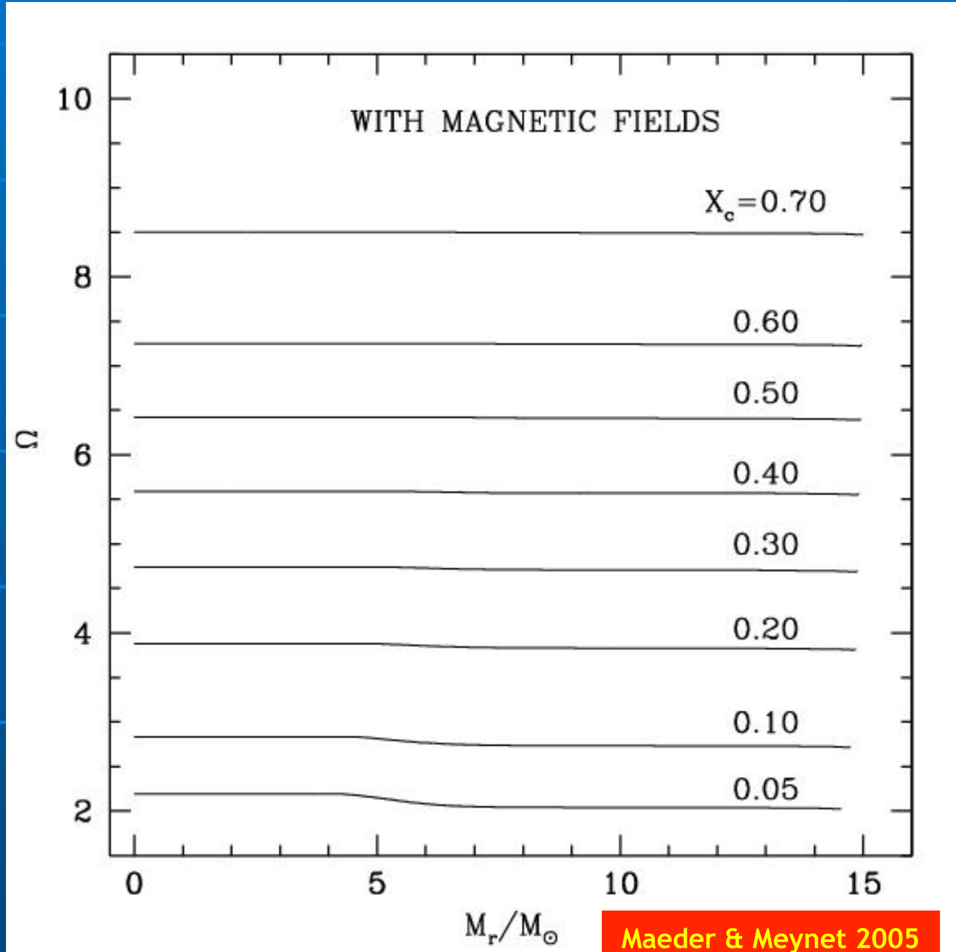
Maeder et al. 2009



Przybilla et al. 2010

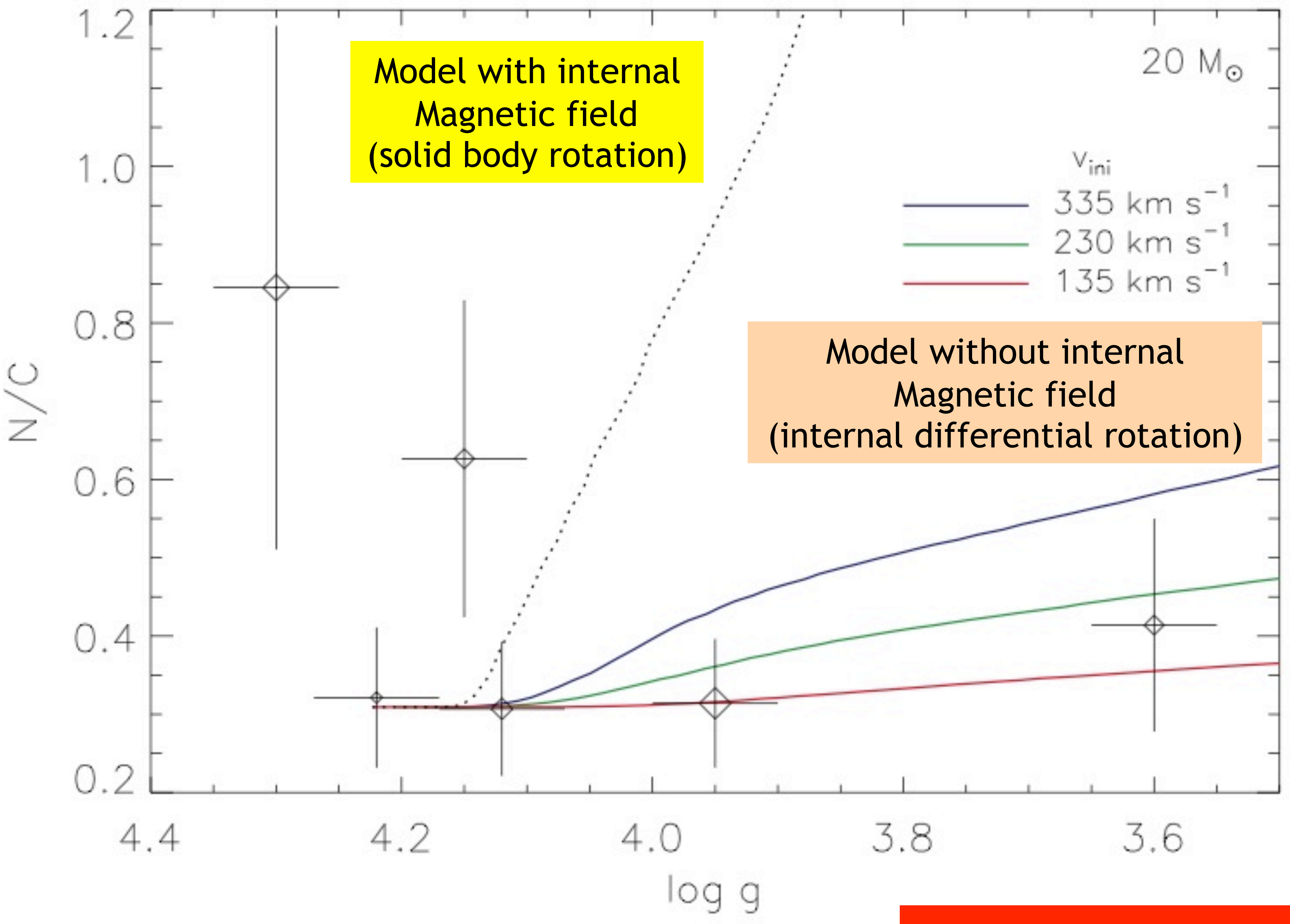
15 M_{sol}, Z=0.020, V_{ini}=300 km s^{-1}





Maeder & Meynet 2005

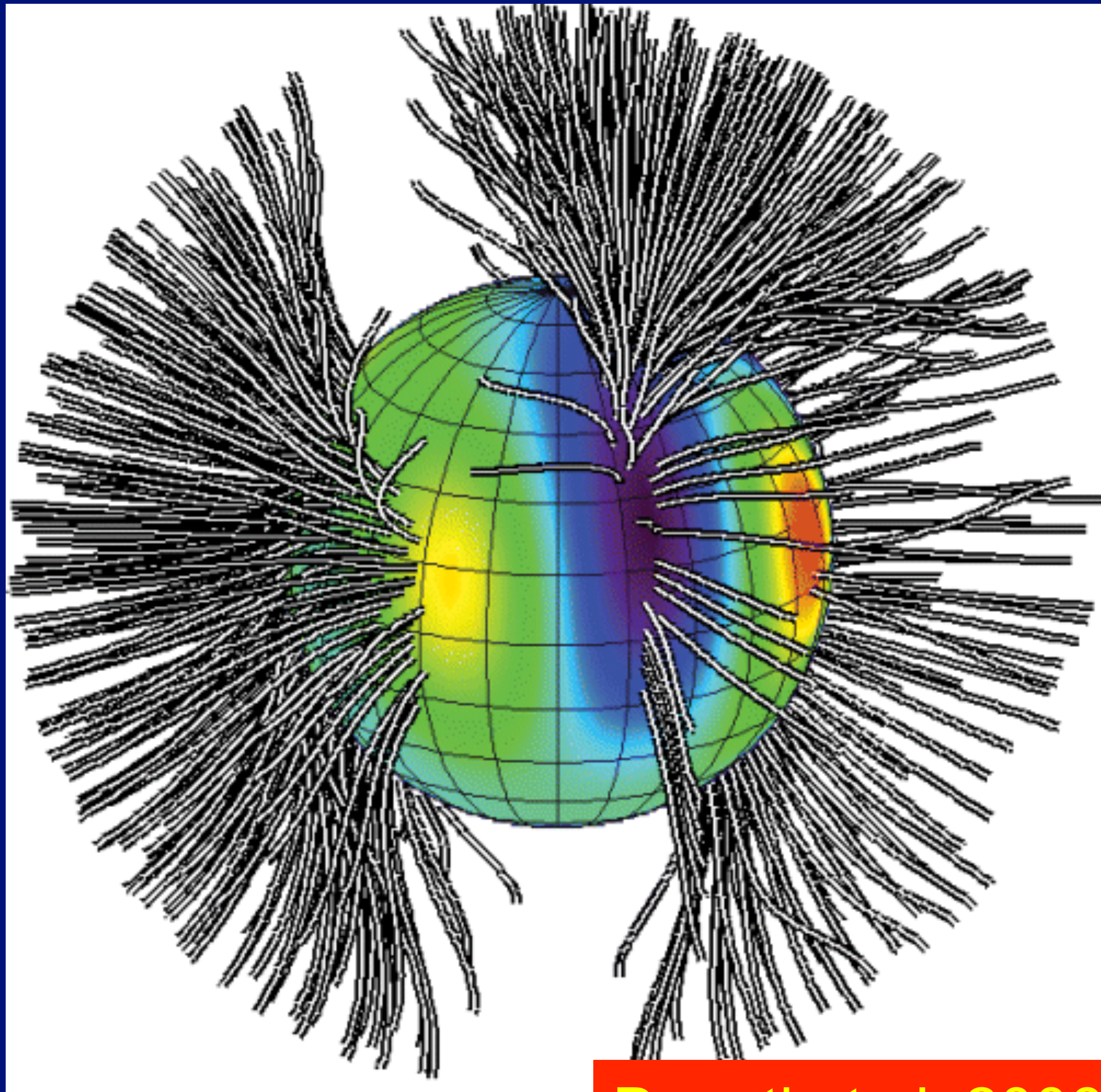
INTERNAL MAGNETIC FIELDS (10^4-10^5 G)
→ SOLID BODY ROTATION



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 $\eta > 1 \rightarrow$ wind behavior

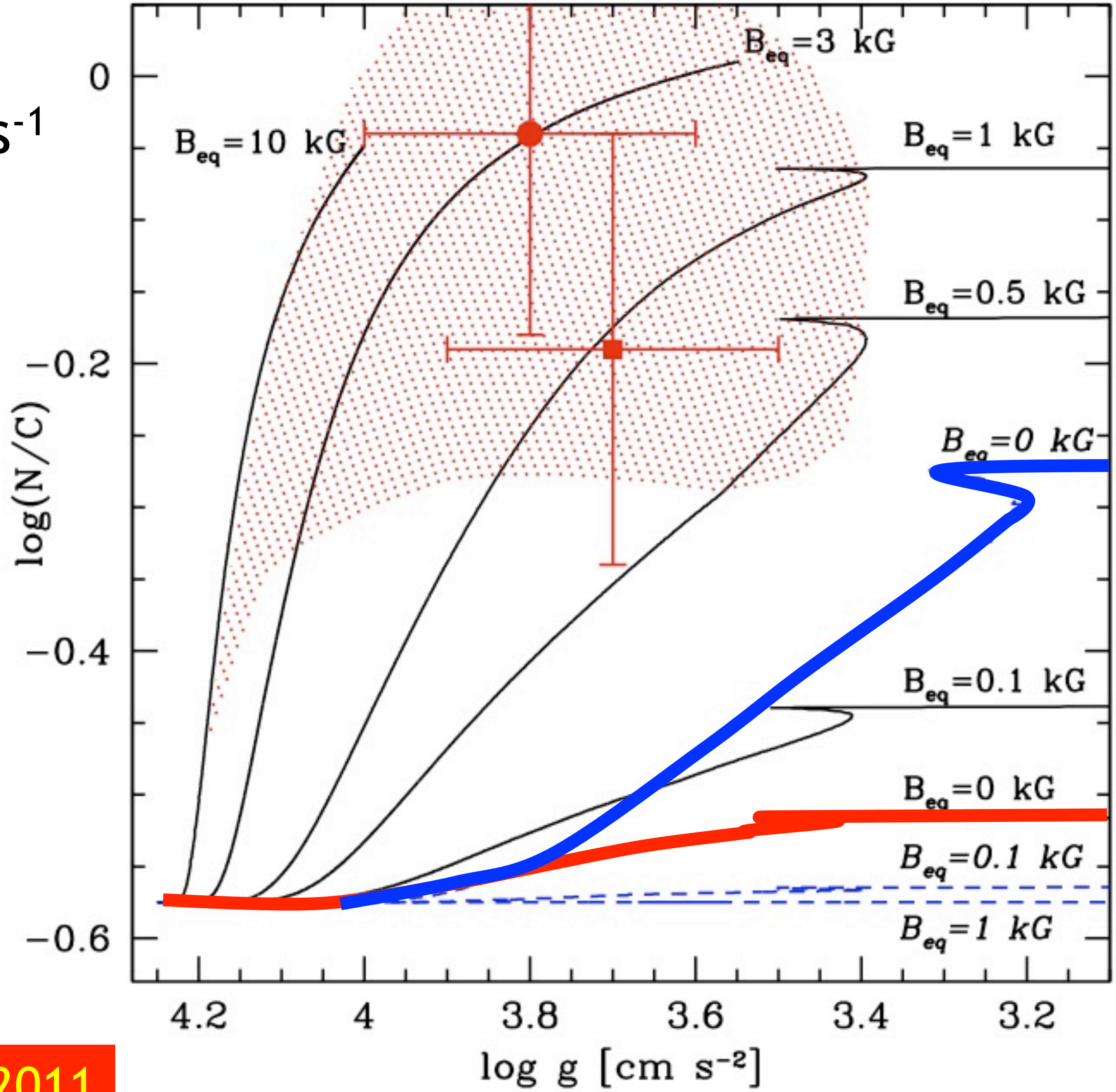
ud-Doula & Owocki (2002)

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

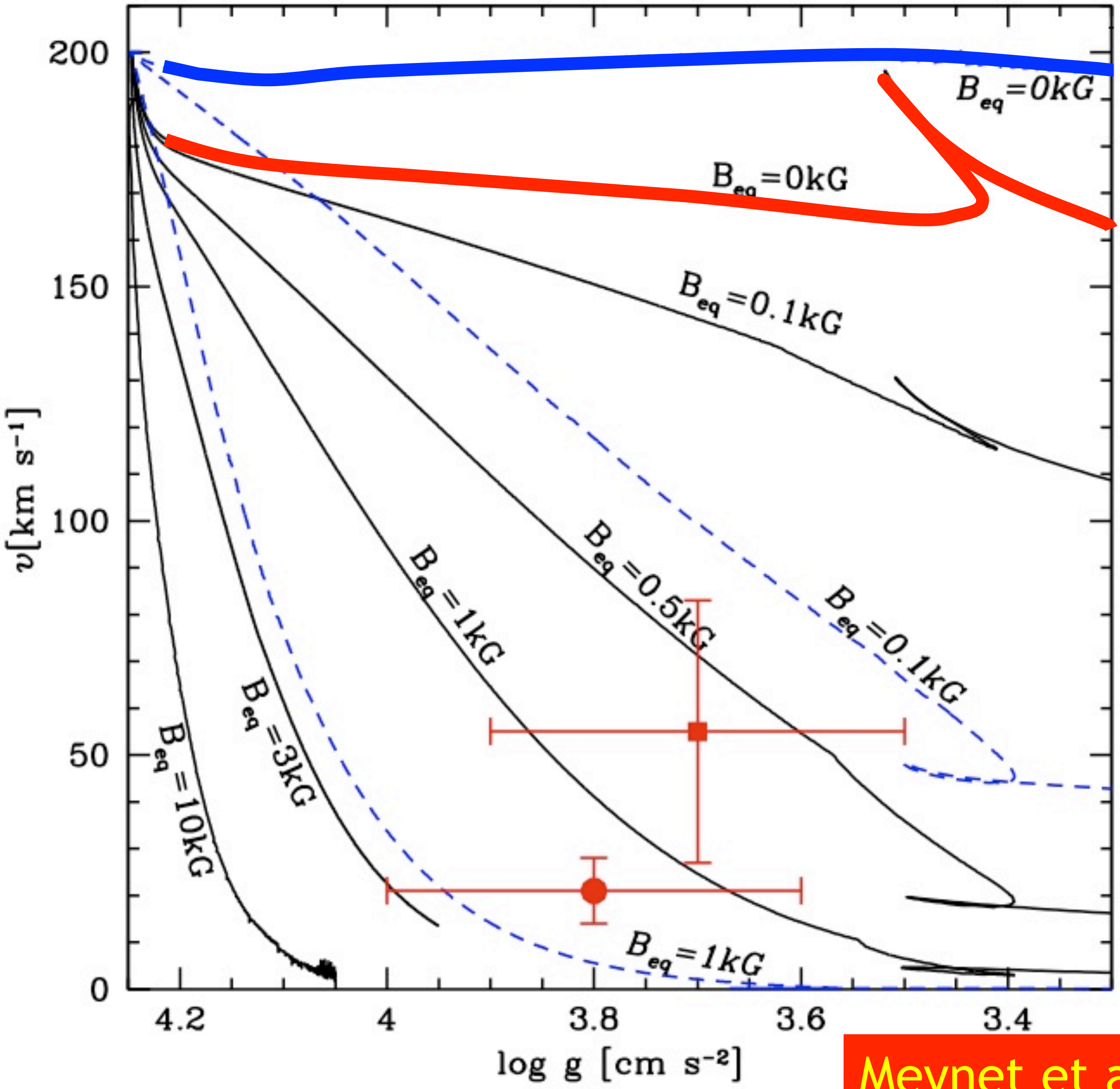
10 M_{sol}

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

Z=0.014

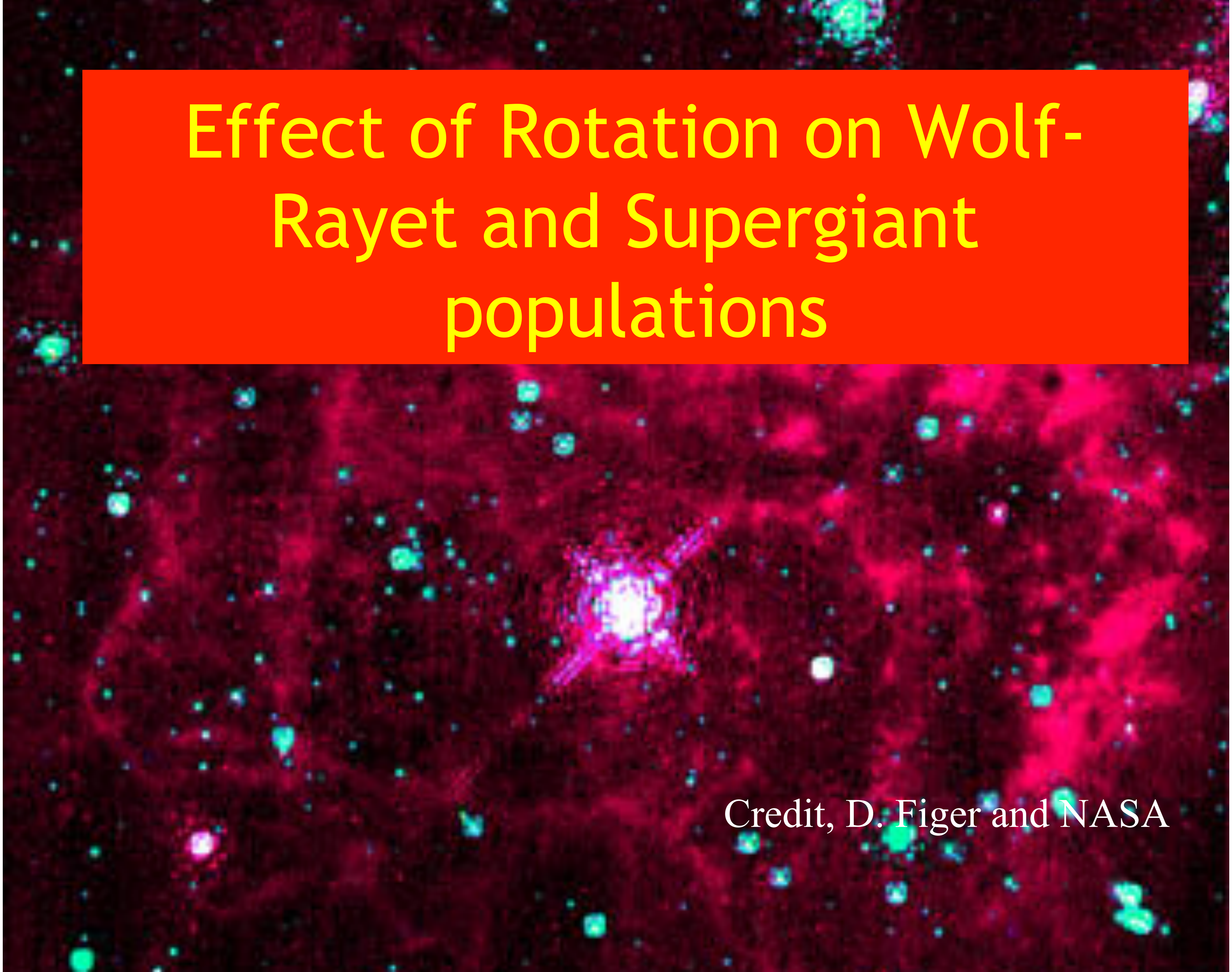


Meynet et al. 2011



Meynet et al. 2011

Effect of Rotation on Wolf-Rayet and Supergiant populations

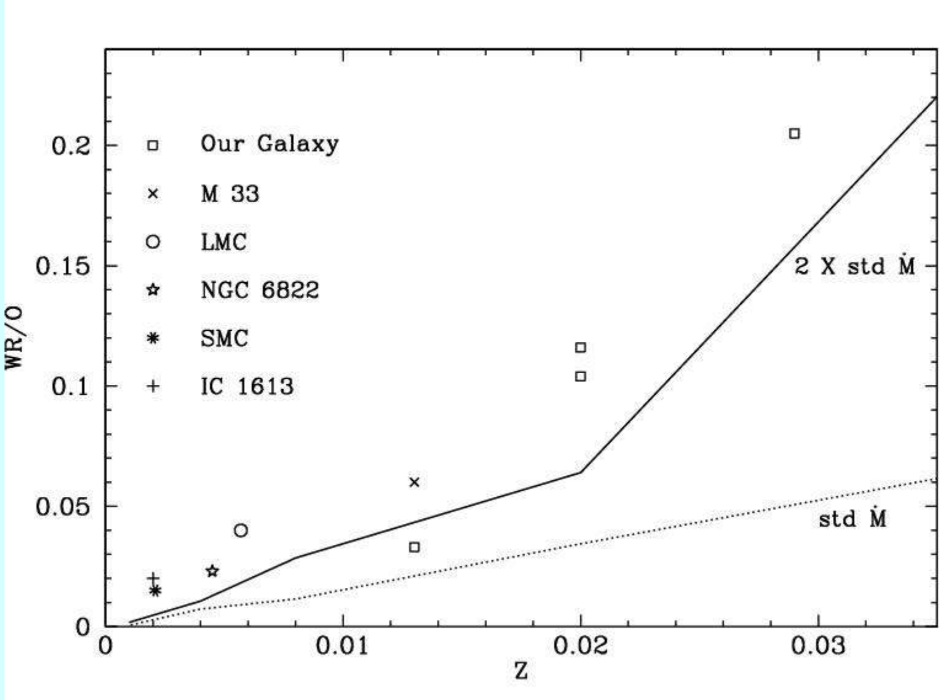


Credit, D. Figer and NASA

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

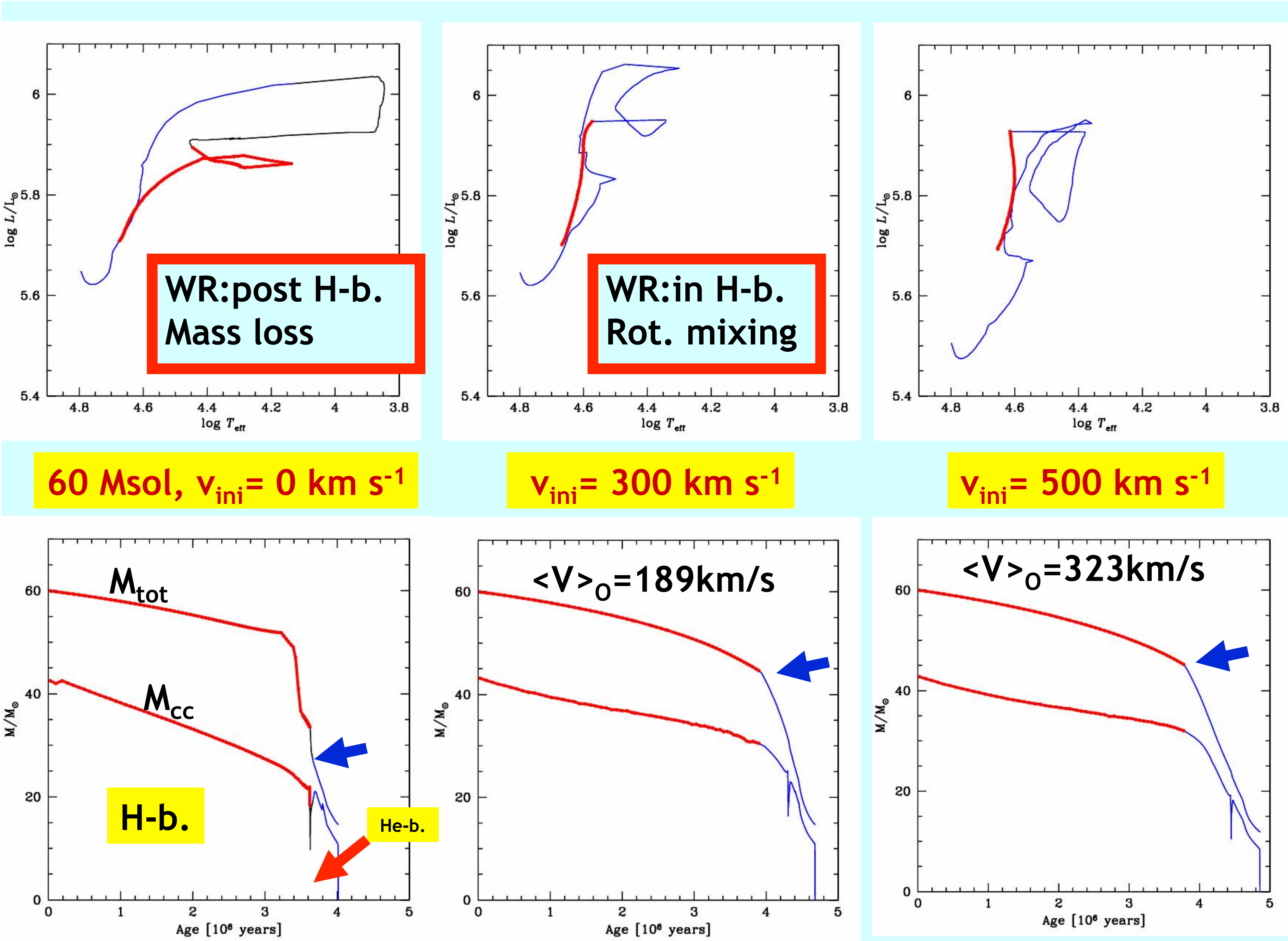


Not satisfactory ! Clumping in the winds of hot stars tends to reduce the observed mass loss rates by a factor 2 to 3

Nugis et al 98; Hamann and Koesterke 98

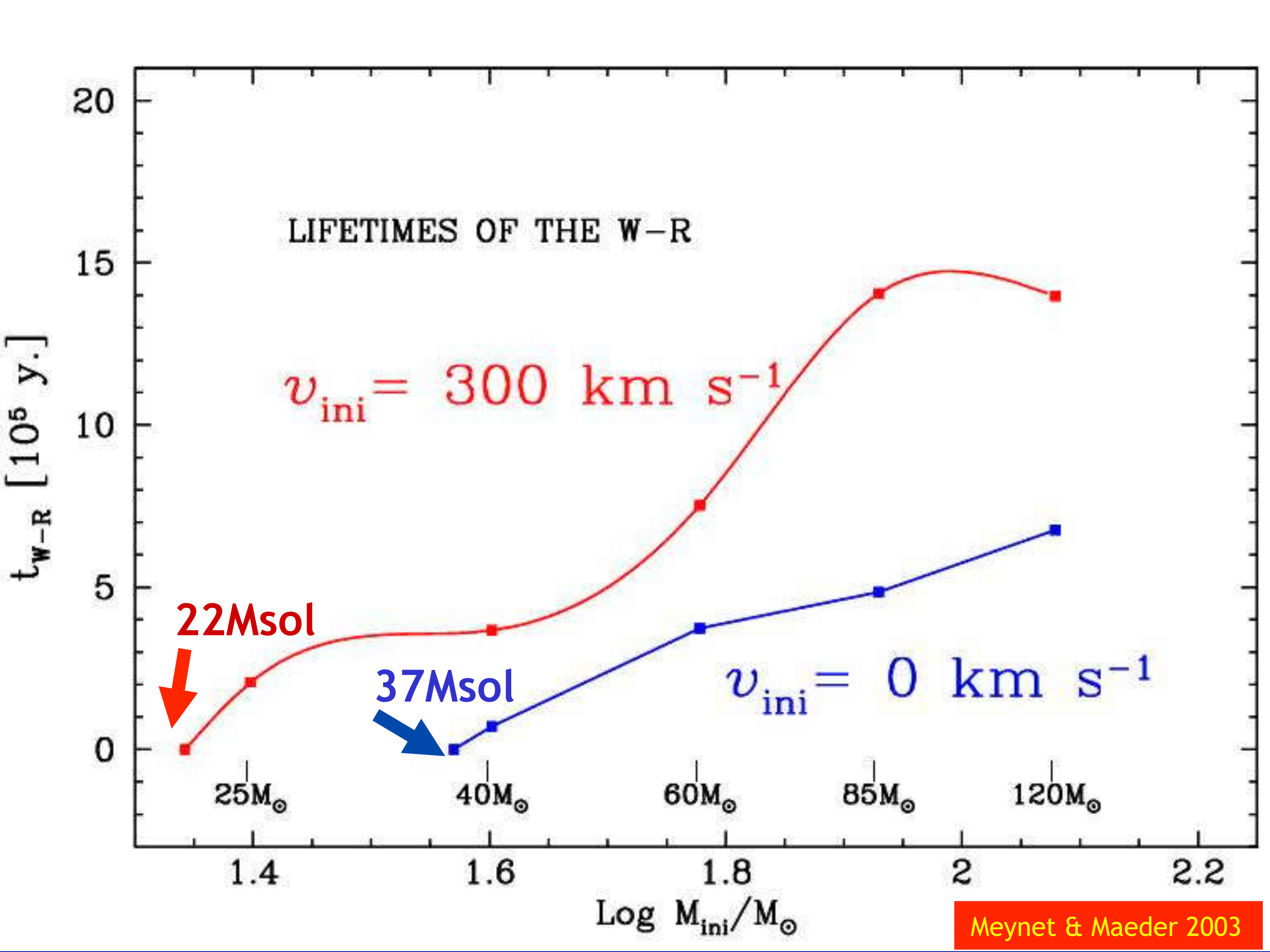
Other difficulties ⇒ Observation →smooth transition from high surface abundances to H-free atmospheres

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



Meynet & Maeder 2003

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



Meynet & Maeder 2003

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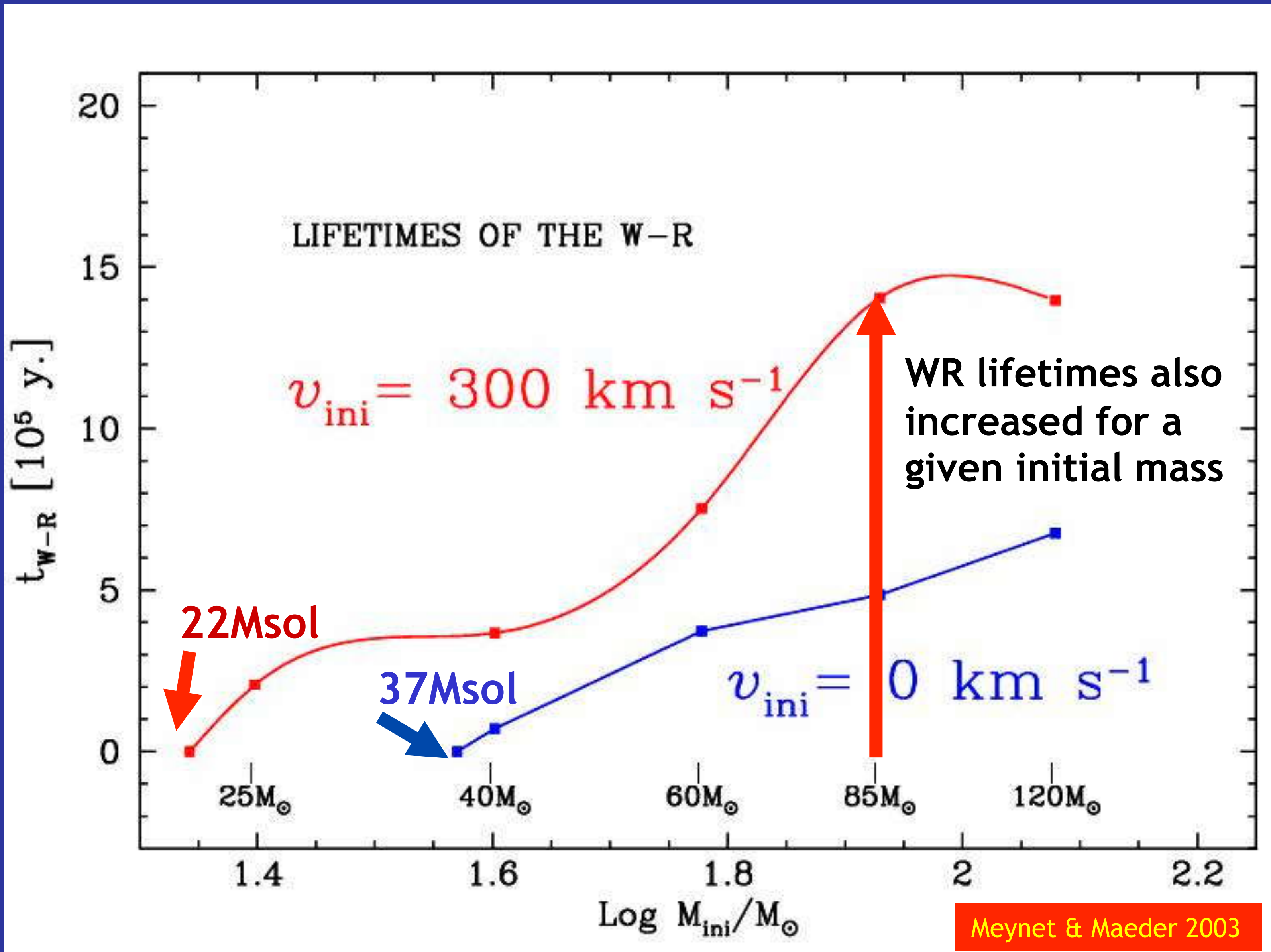
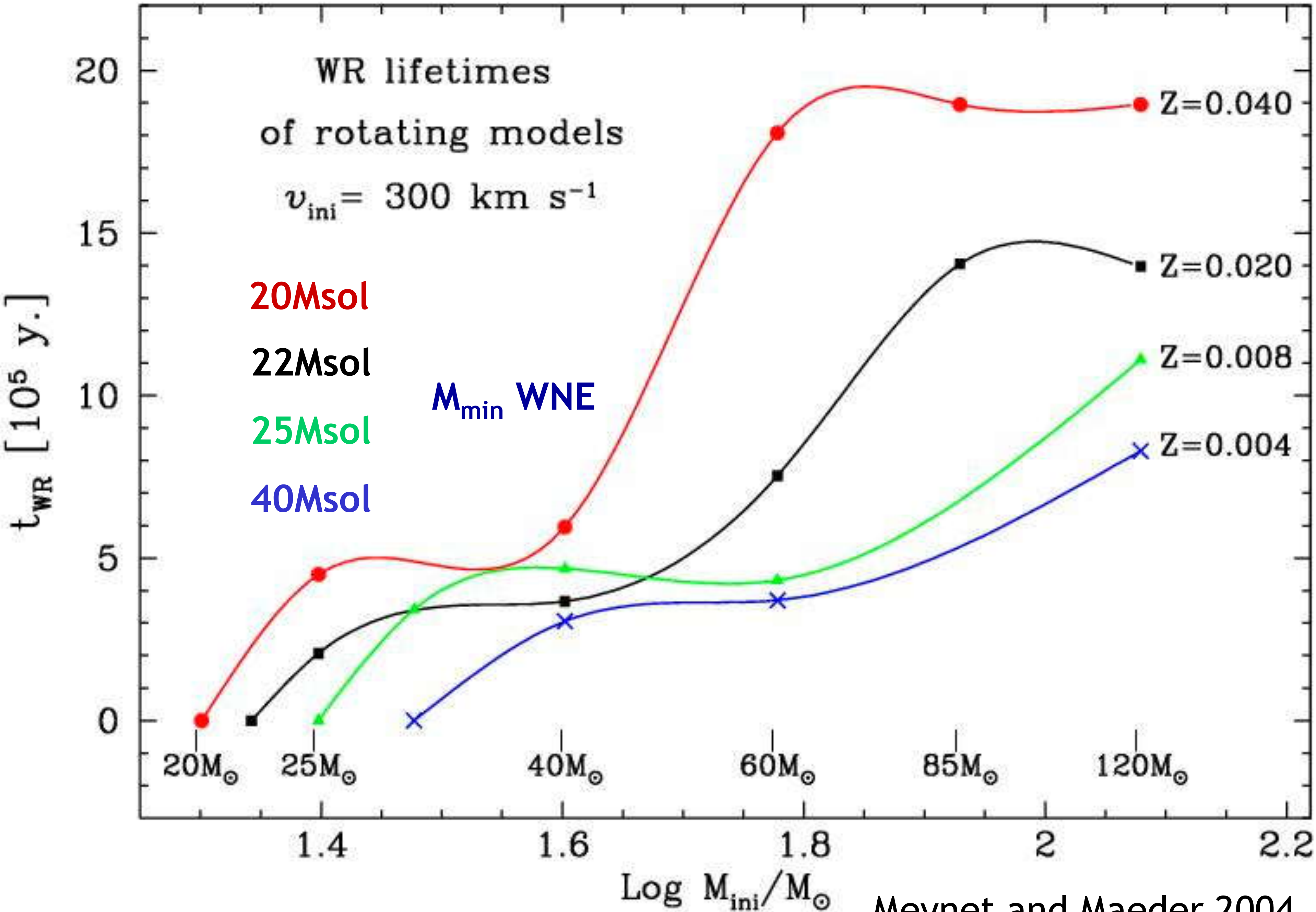
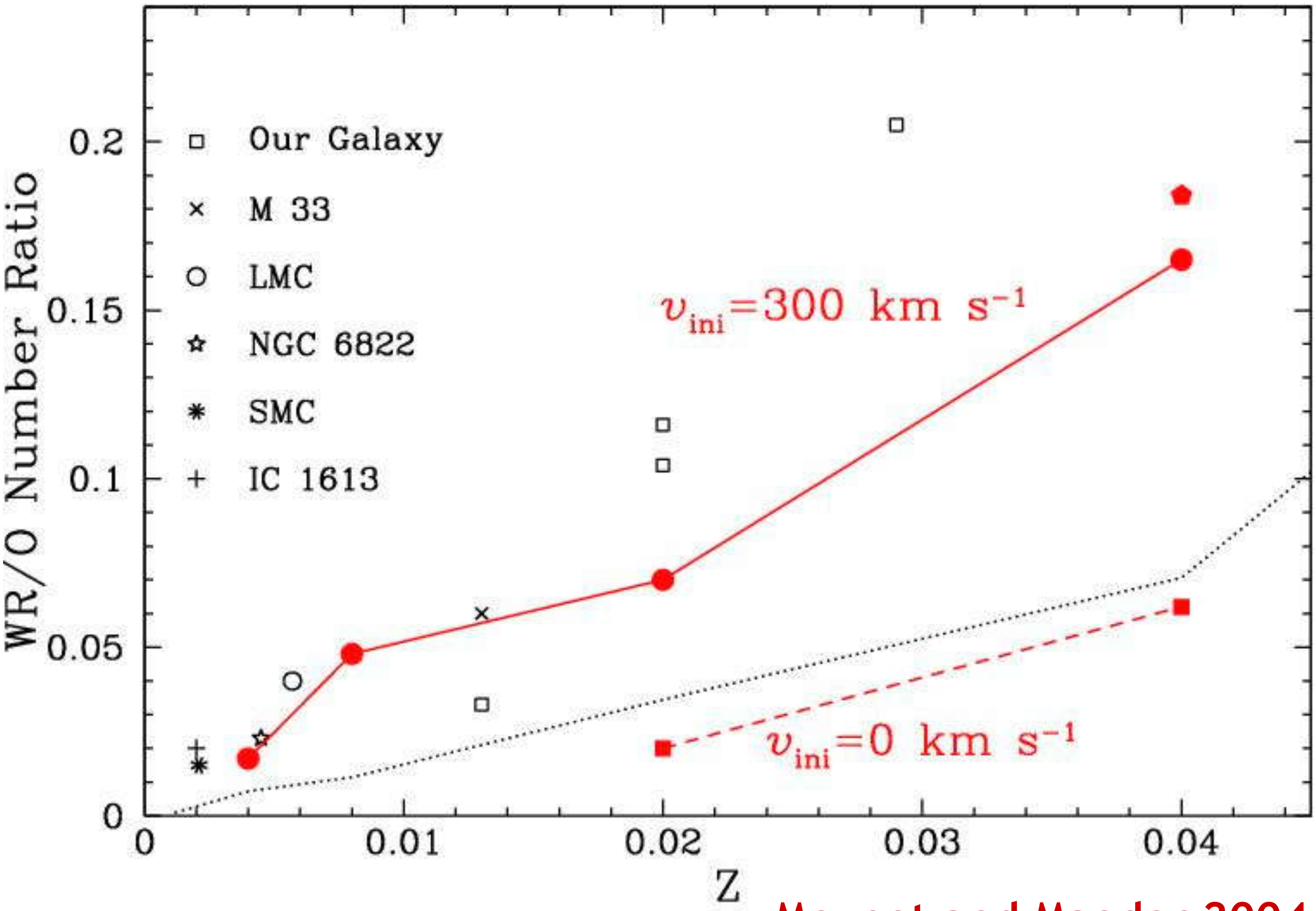
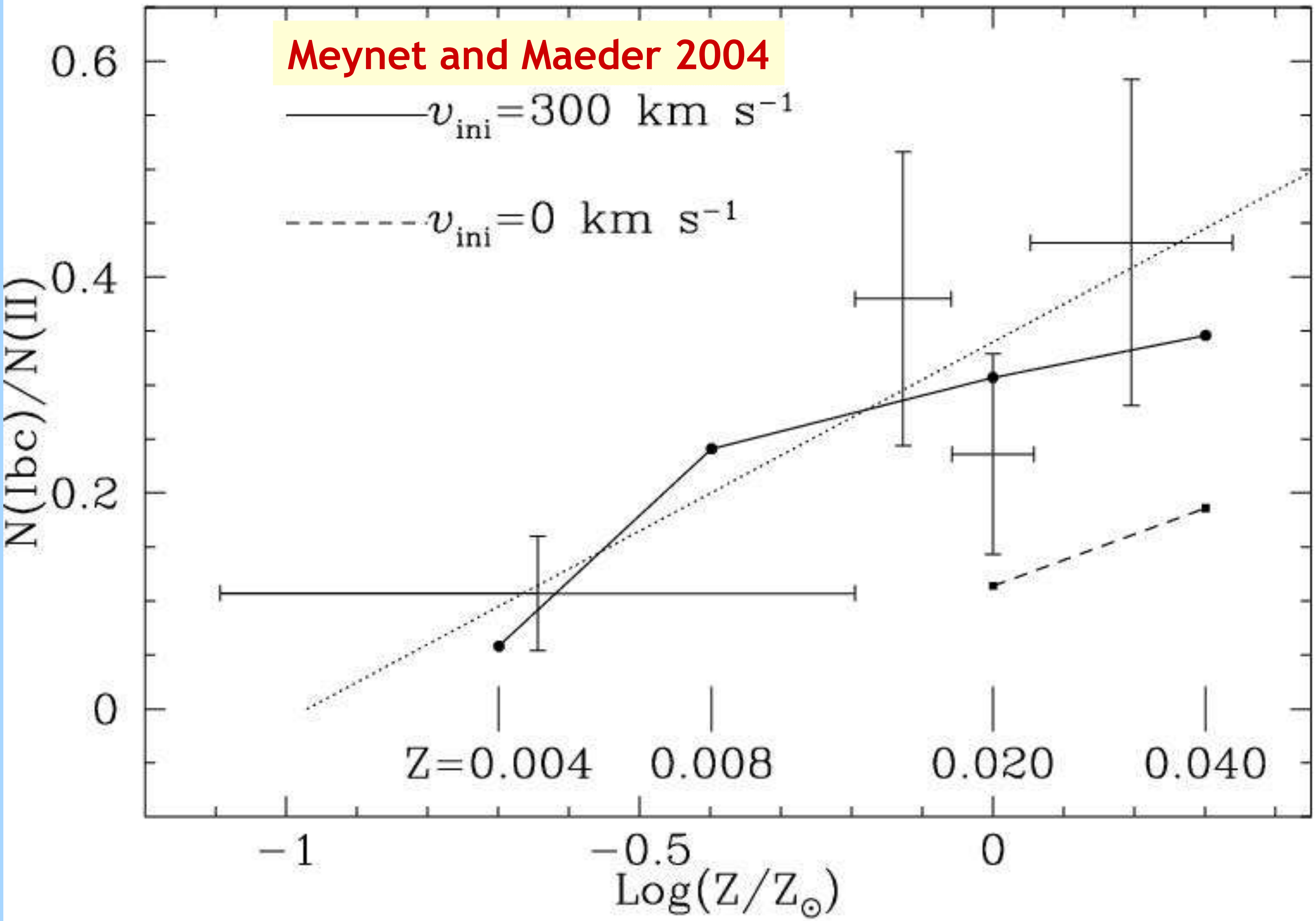




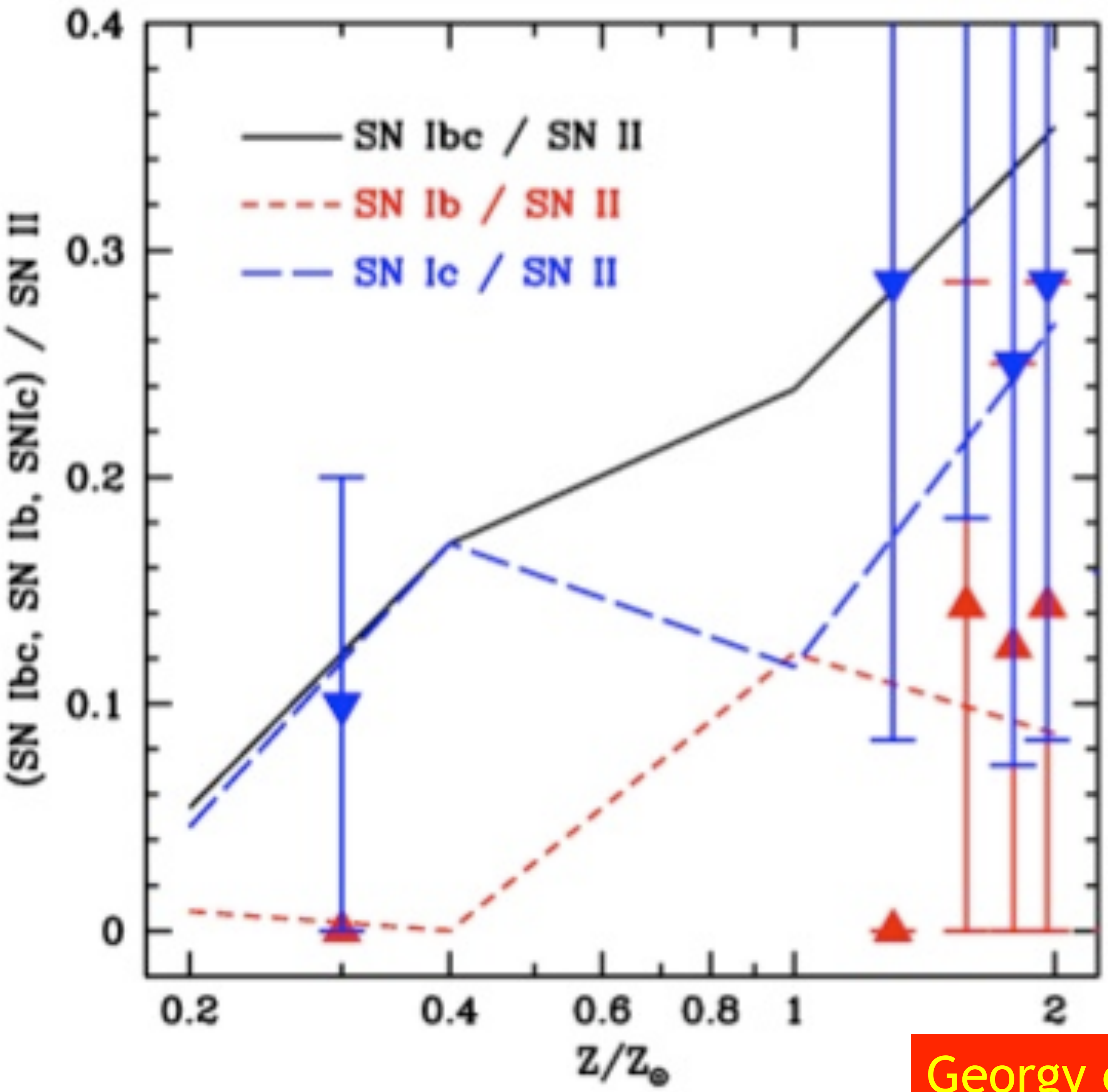
Meynet and Maeder 2004



Meynet and Maeder 2004

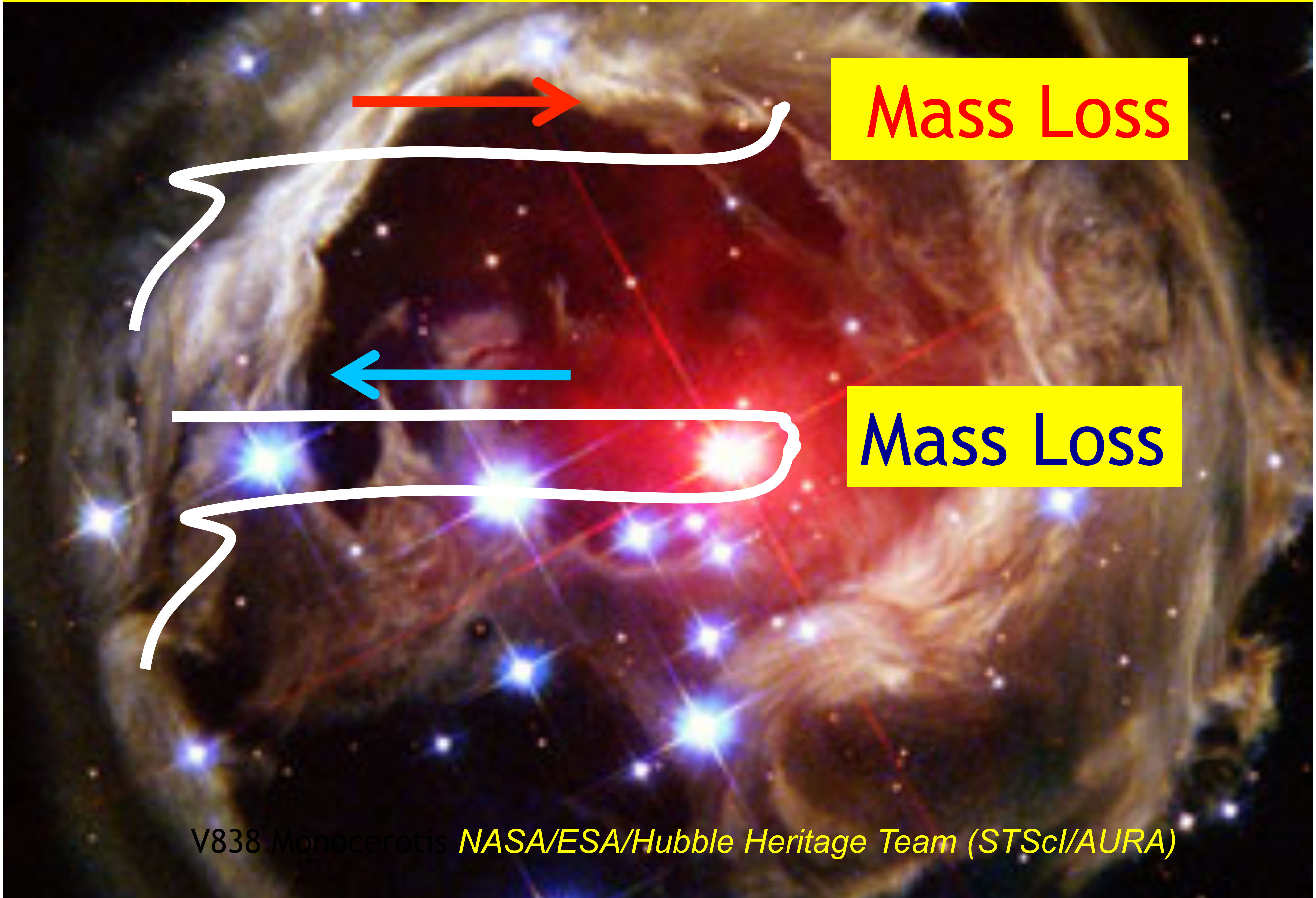


Observed points from Prantzos and Boissier (2003)



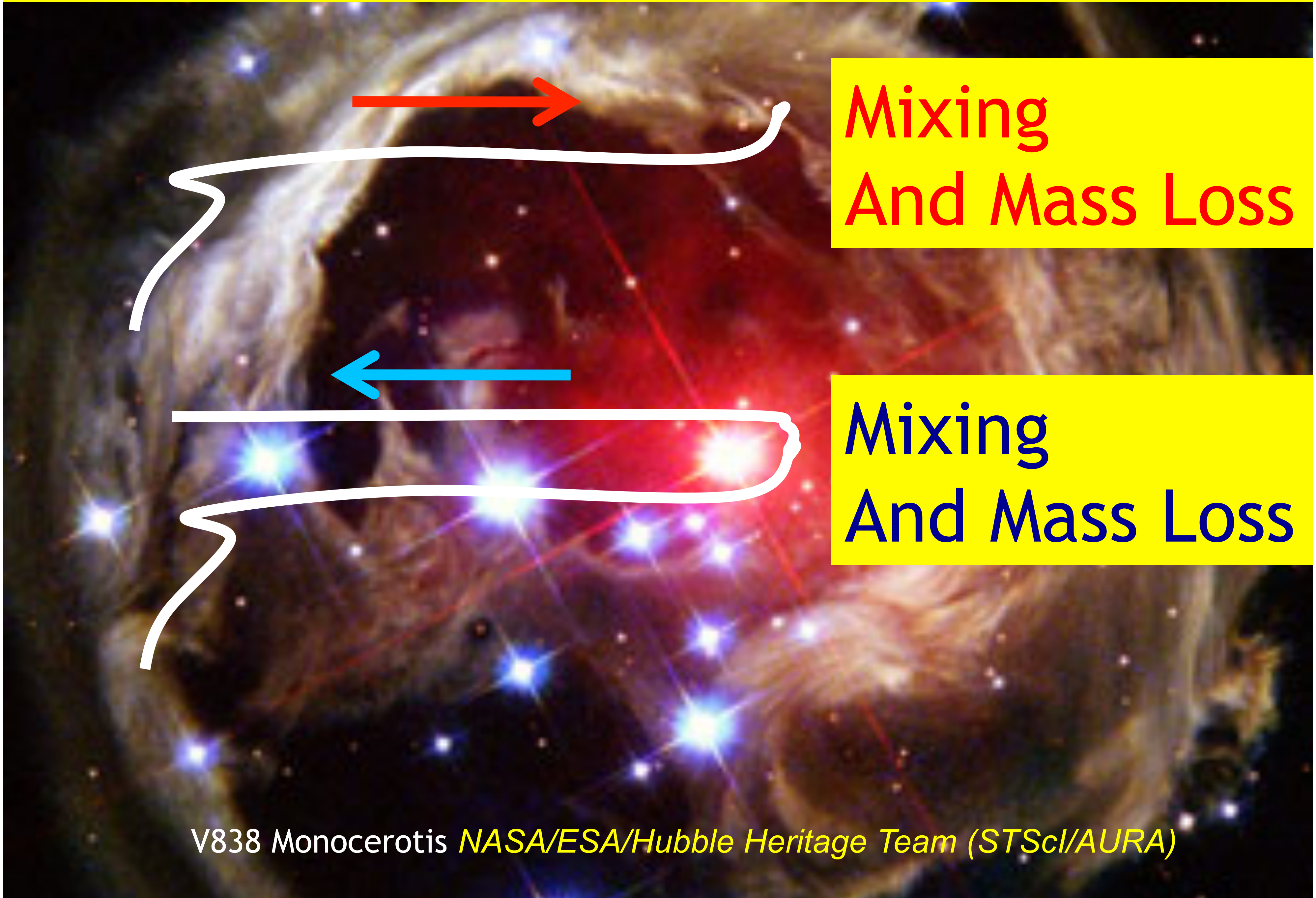
Georgy et al. 2009

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



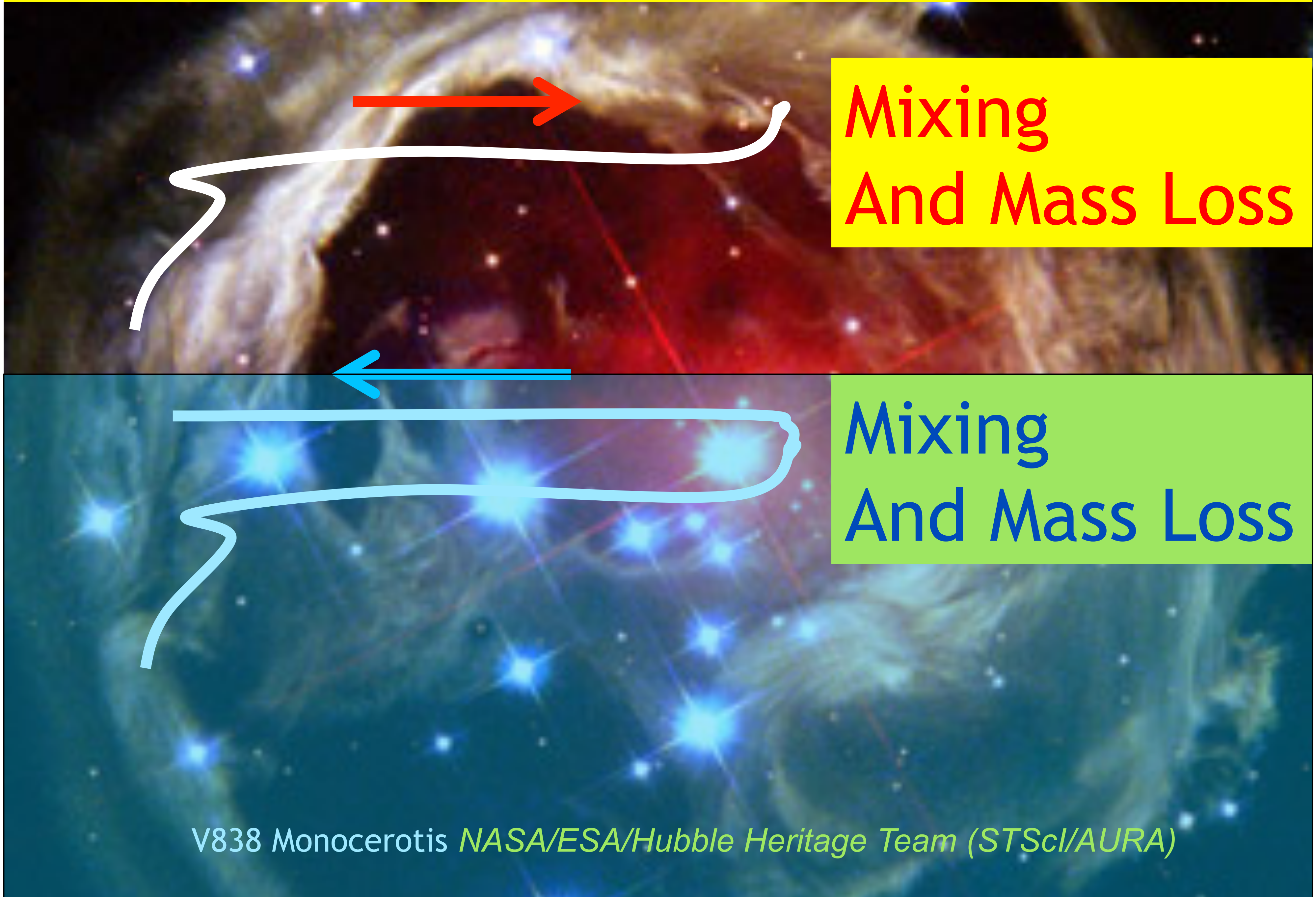
V838 Monocerotis *NASA/ESA/Hubble Heritage Team (STScI/AURA)*

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

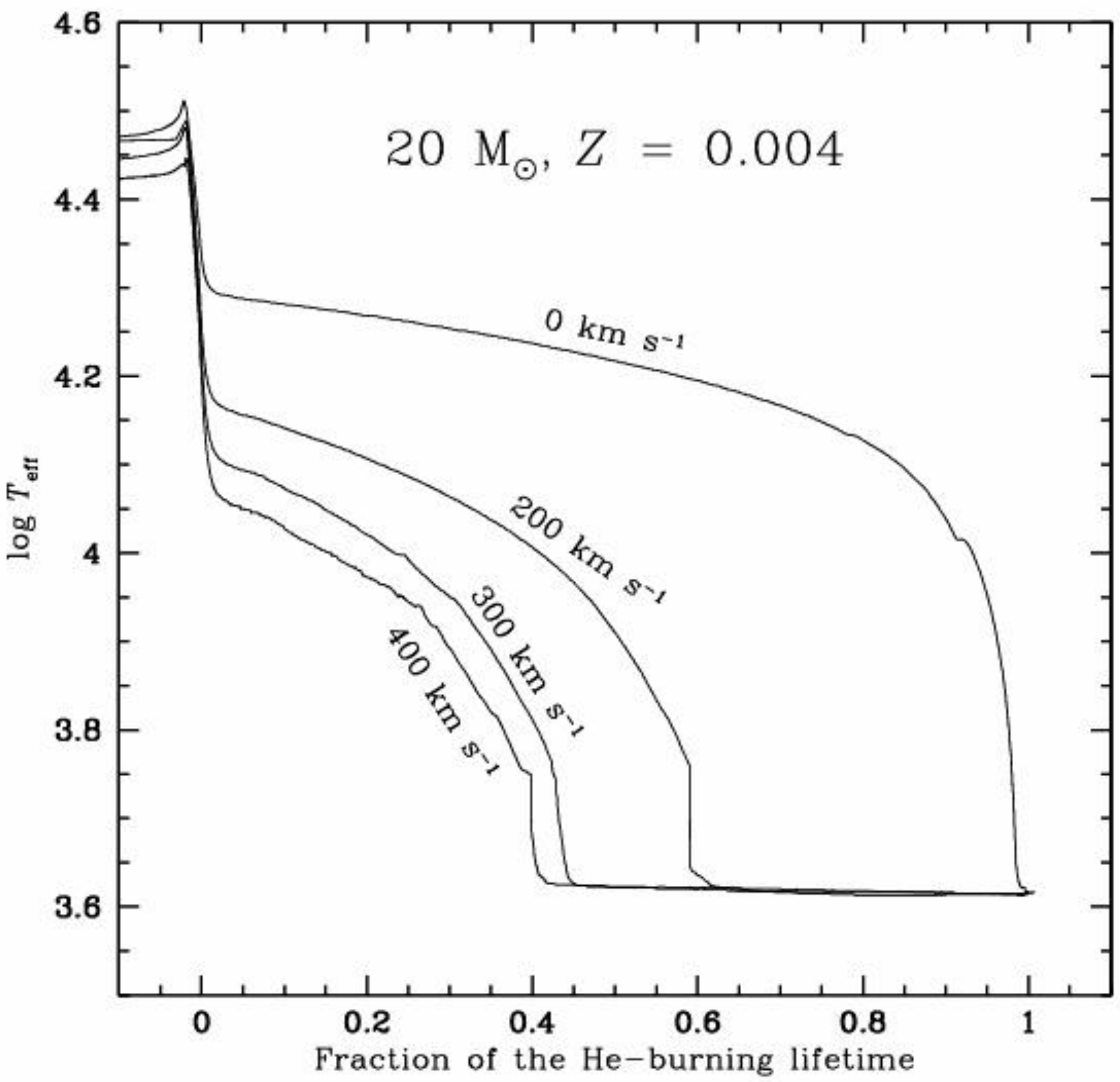


V838 Monocerotis *NASA/ESA/Hubble Heritage Team (STScI/AURA)*

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)*

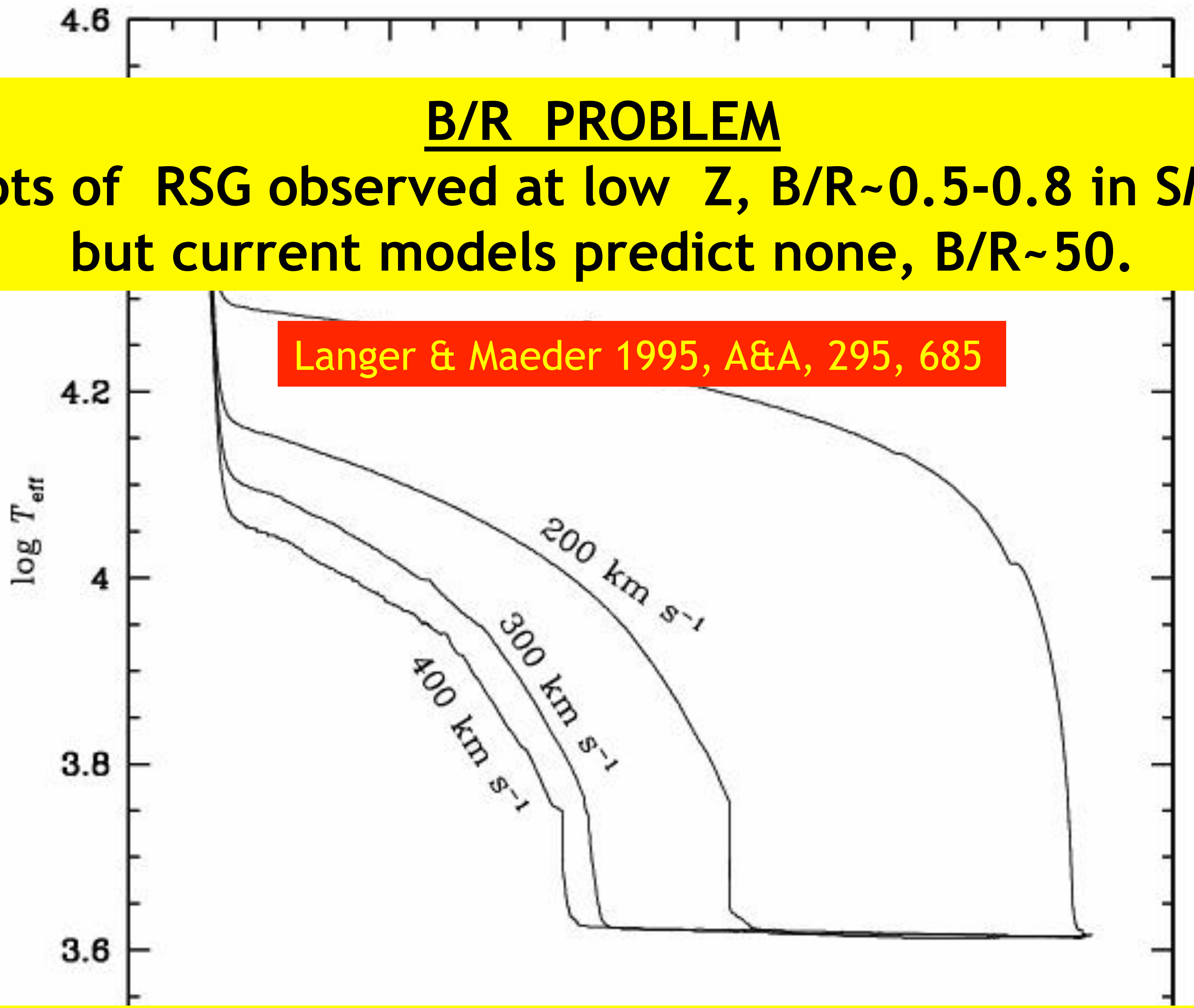


20 $M_\odot$, Z = 0.004
0 km s-1
200 km s-1
300 km s-1
400 km s-1
log T_{eff}
Fraction of the He-burning lifetime
4.6
4.4
4.2
4
3.8
3.6
0
0.2
0.4
0.6
0.8
1

B/R PROBLEM

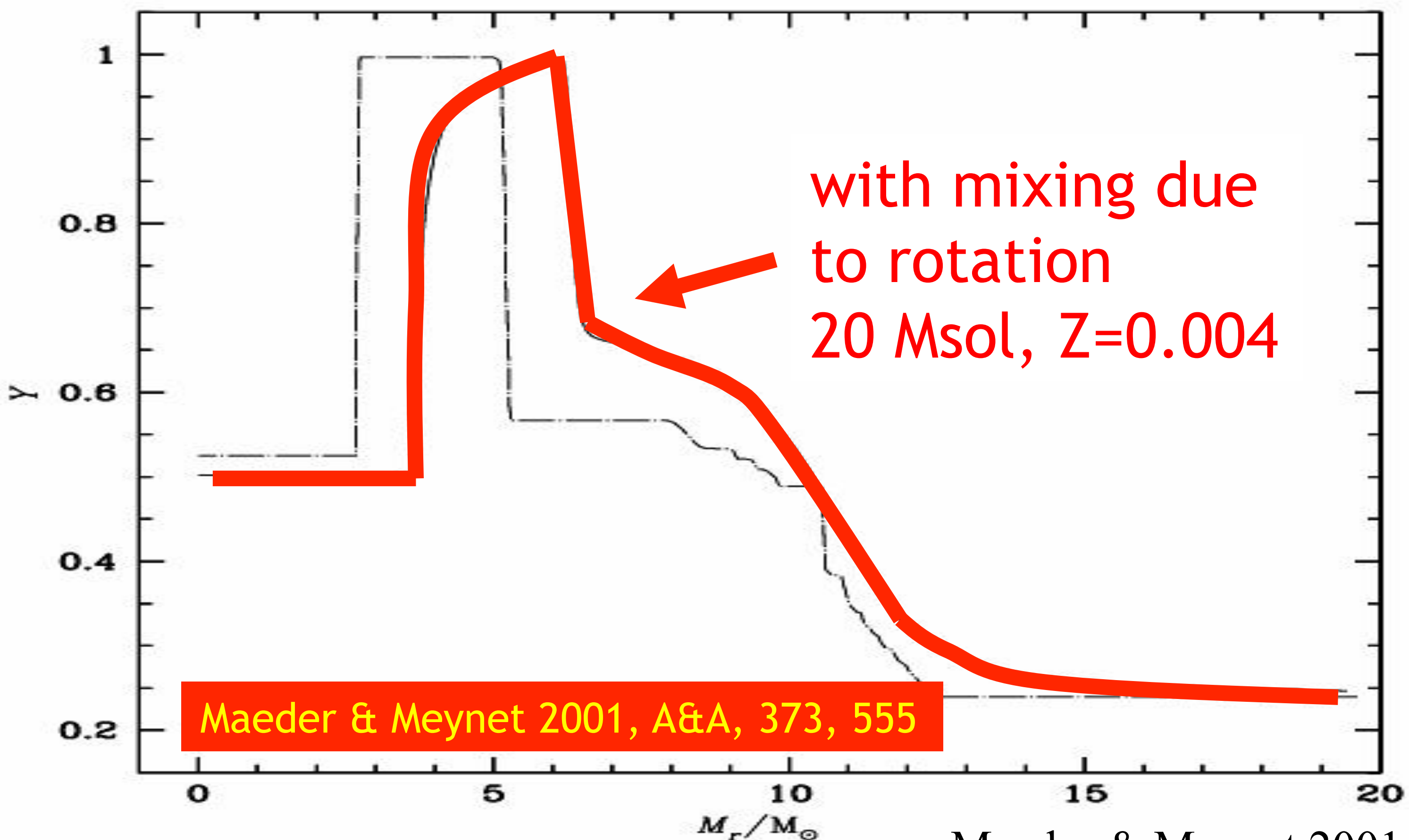
Lots of RSG observed at low Z, B/R~0.5-0.8 in SMC
but current models predict none, B/R~50.

Langer & Maeder 1995, A&A, 295, 685



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

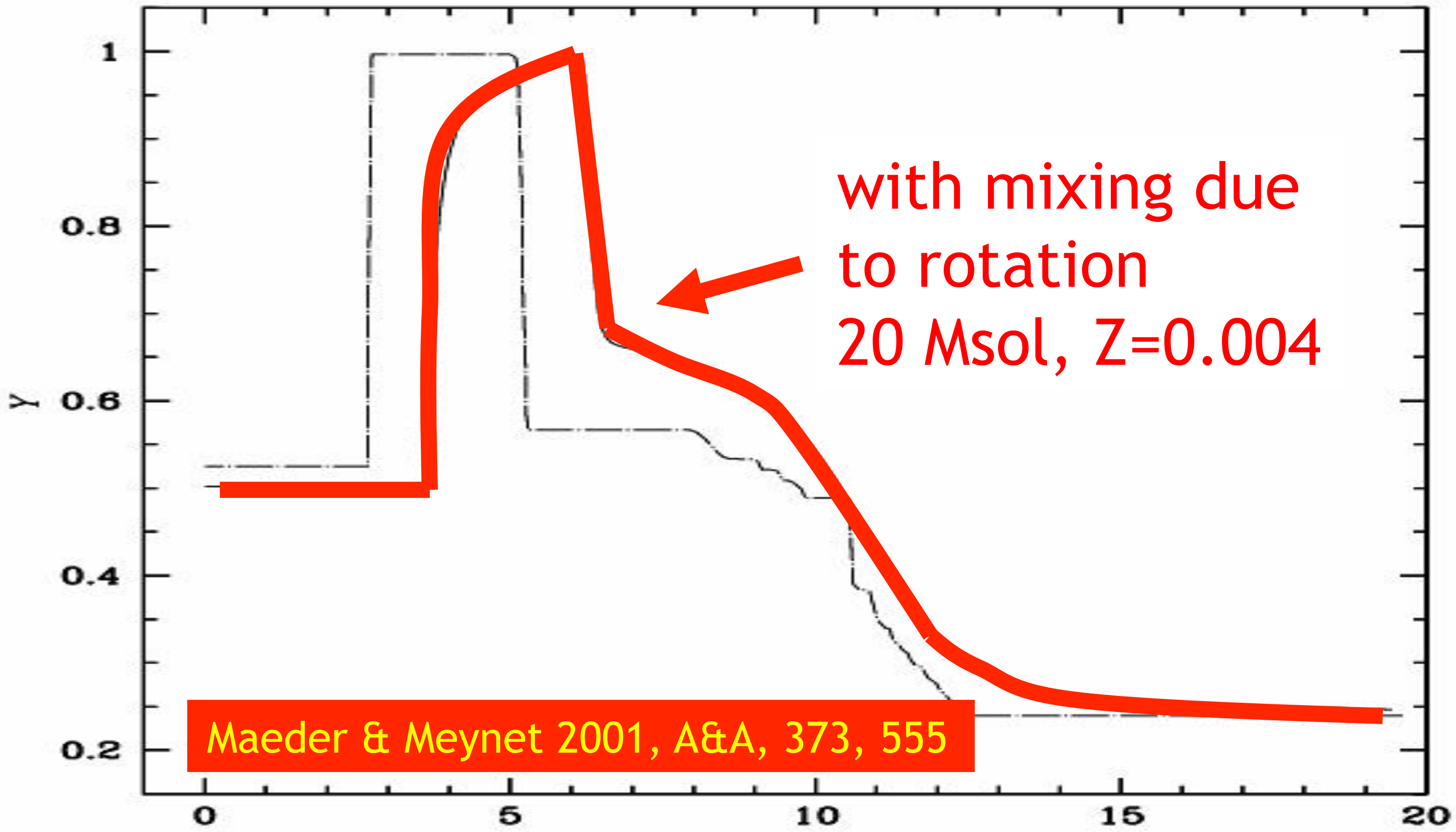
Helium mass fraction



Maeder & Meynet 2001

M_r/M_{sun}

Helium mass fraction



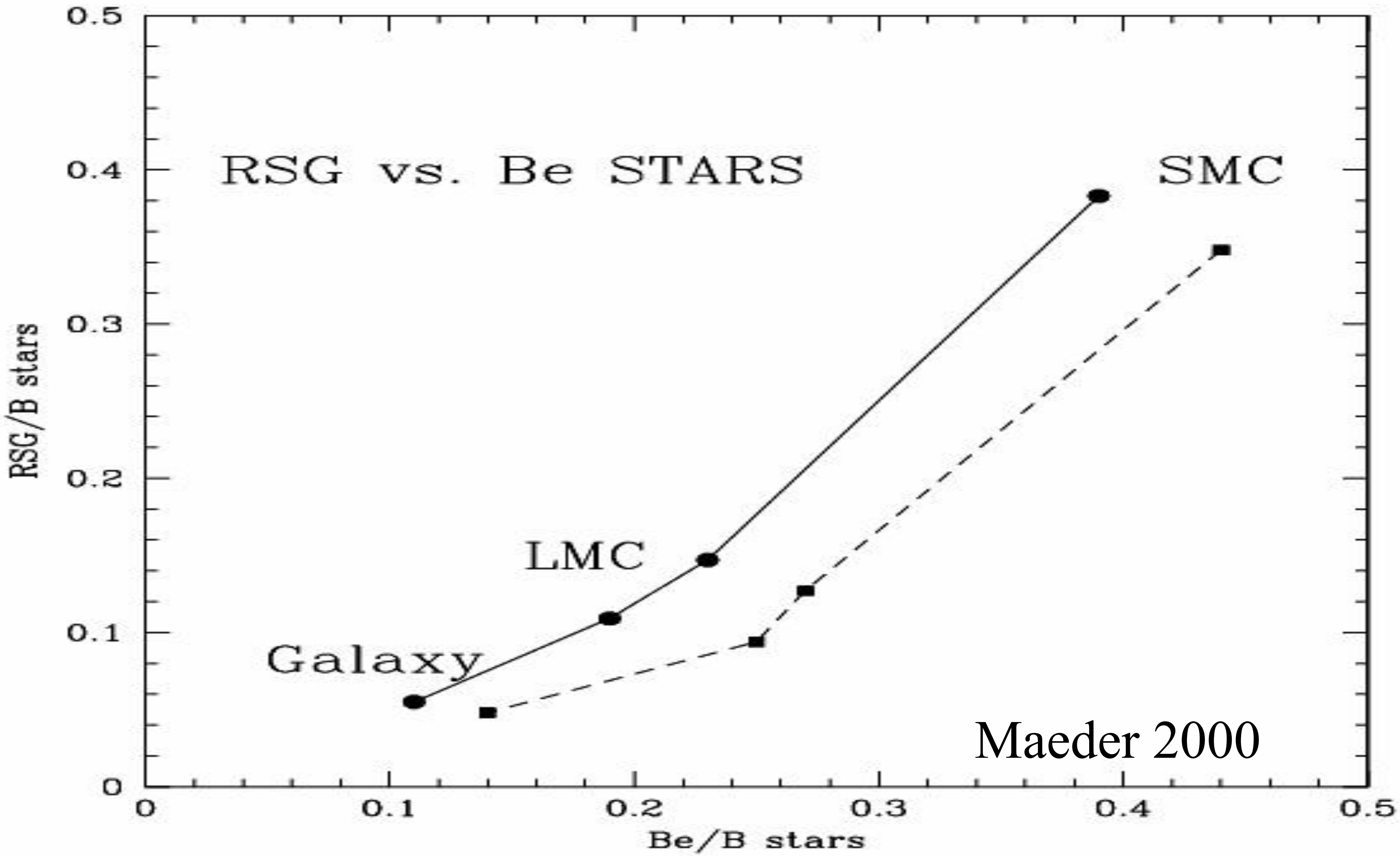
Maeder & Meynet 2001

M_r/M_{sun}

With mixing (due to rotation):

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

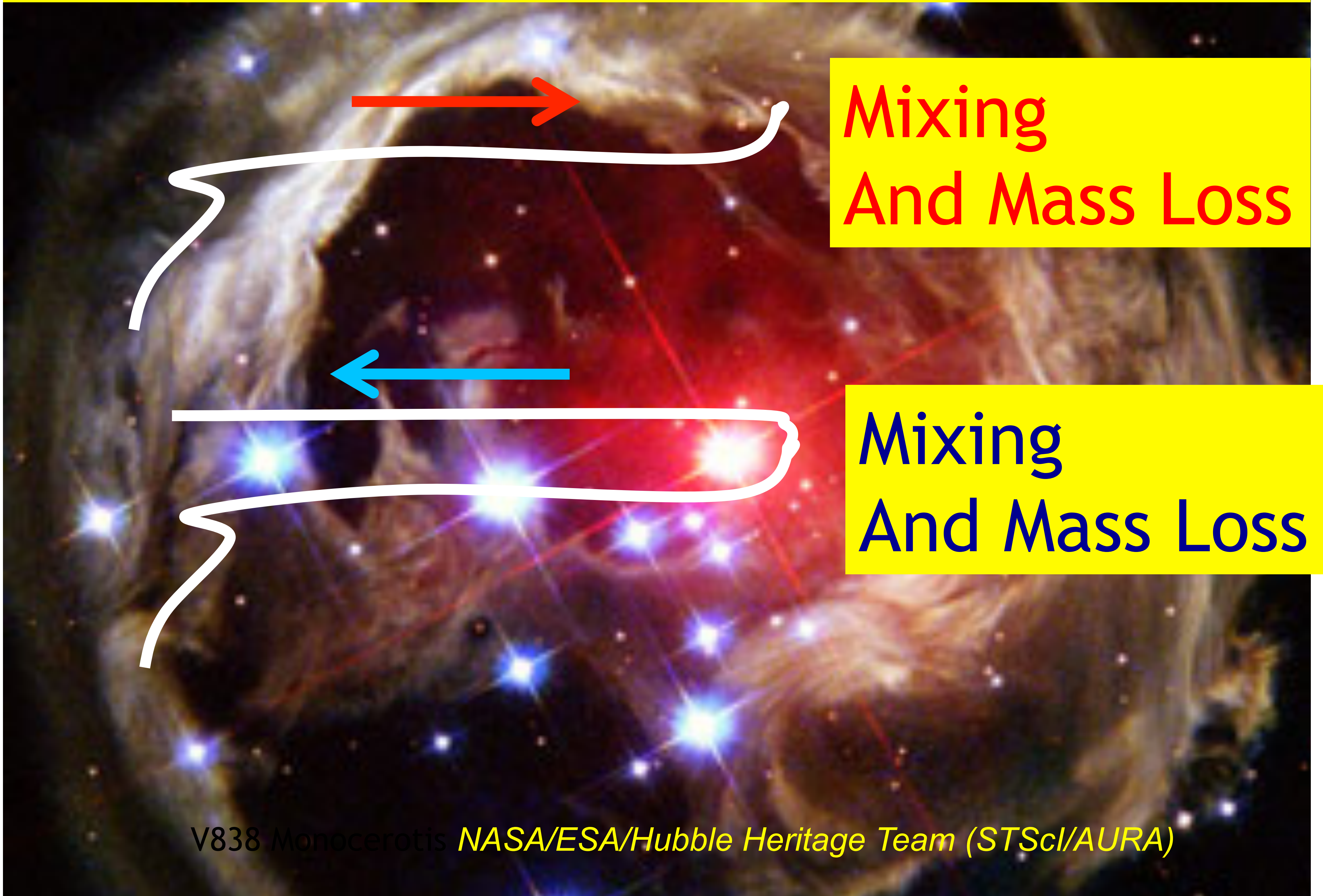
→ **RSG**



CONSISTENT WITH MODELS

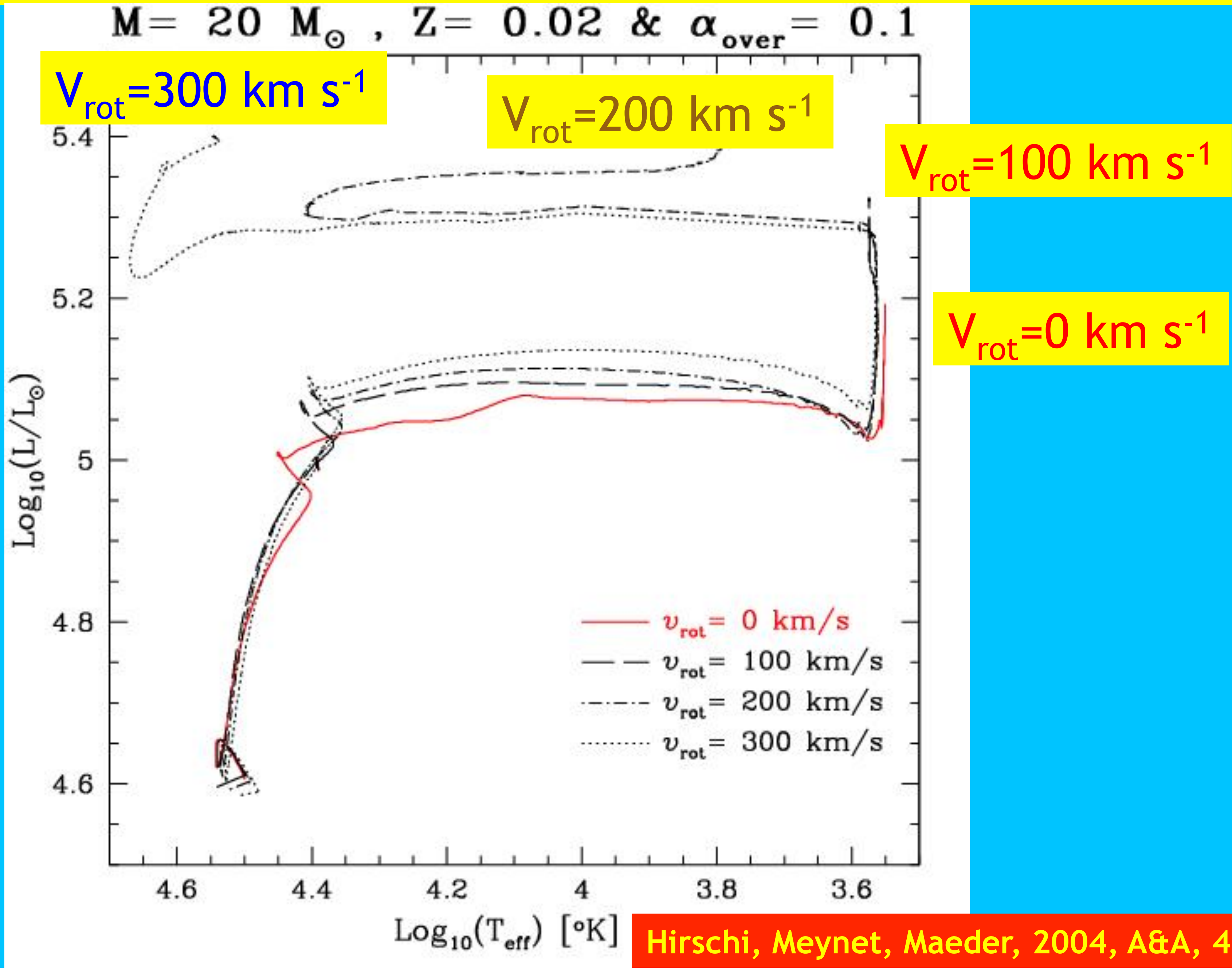
More fast Rotators → More RSG

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

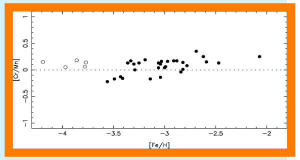


Hirschi, Meynet, Maeder, 2004, A&A, 425, 649

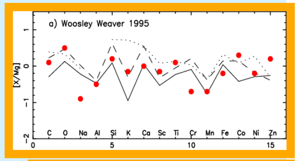
The first stellar generations

STRIKING OBSERVATIONAL FACTS

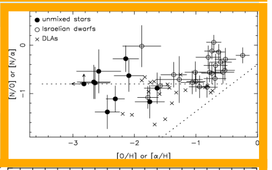
1) Different scatter for different elements



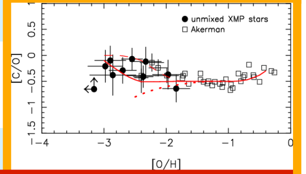
2) No sign of Pair Instability Supernovae



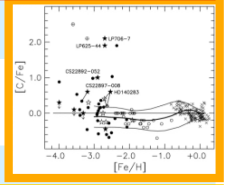
3) Important amount of primary nitrogen



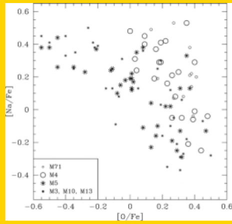
4) More carbon, less oxygen produced at low Z ?



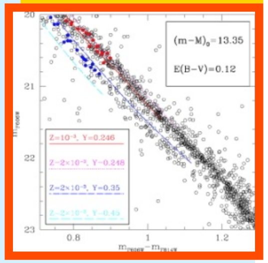
5) C-rich stars



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 ?

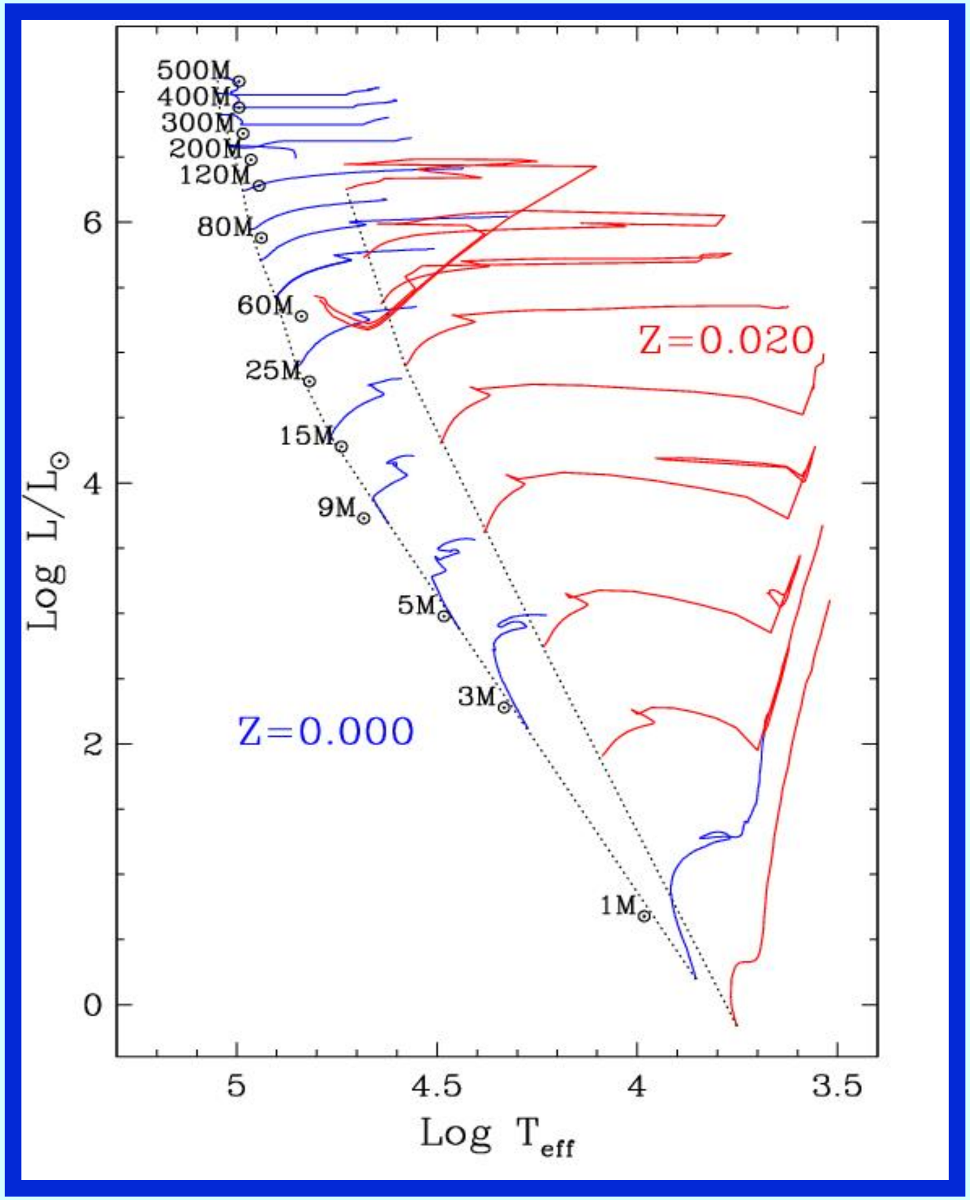
- The initial masses of the stars (?)
- The ignition of H-burning in massive stars (no CNO element catalysts at the beginning)
- The opacities are lower

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

  → Stellar winds are weaker

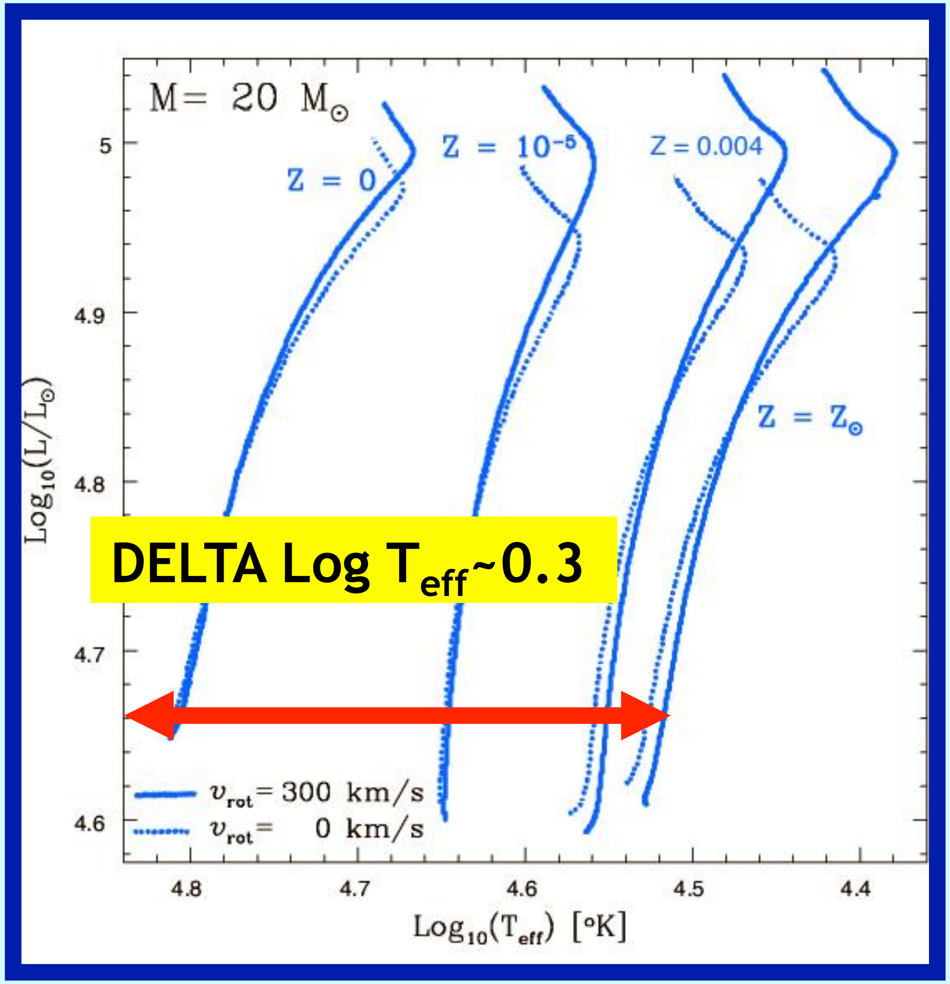
El Eid et al 1983; Ober et al 1983; Bond et al 1984; Klapp 1984; Arnett 1996; Limongi et al. 2000; Chieffi et al. 2000; Chieffi and Limongi 2002; Siess et al. 2002; Heger and Woosley 2002; Umeda and Nomoto 2003; Nomoto et al. 2003; Picardi et al. 2004; Gil-Pons et al. 2005

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

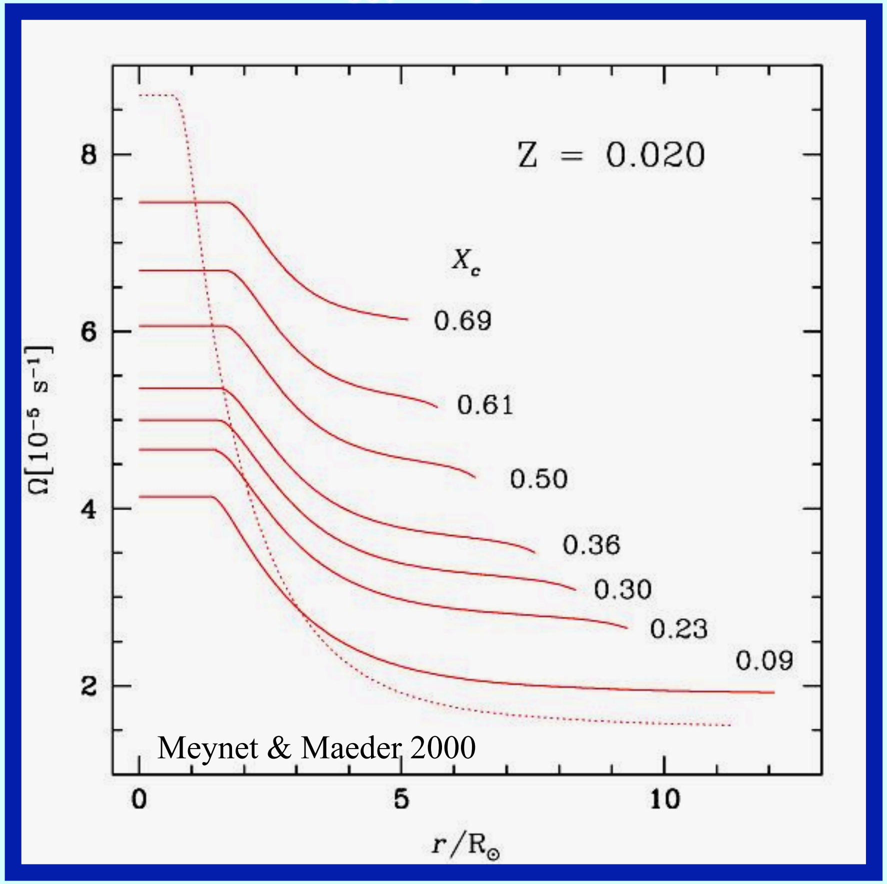
→ MORE EFFICIENT MIXING

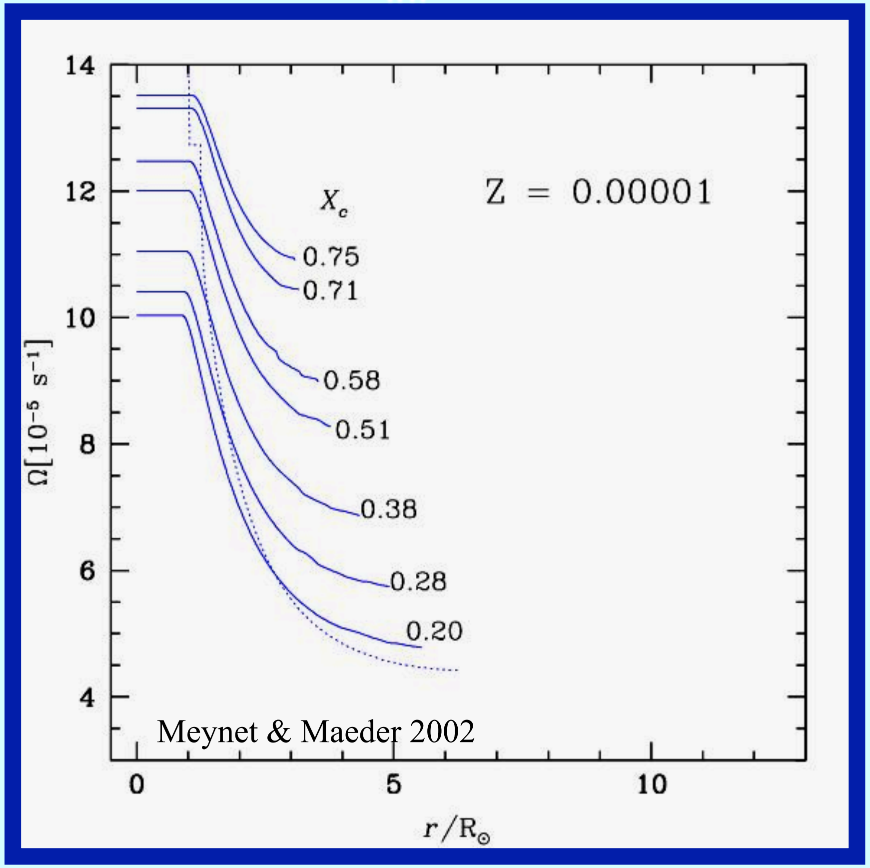
Less angular momentum removed by stellar winds

→ 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

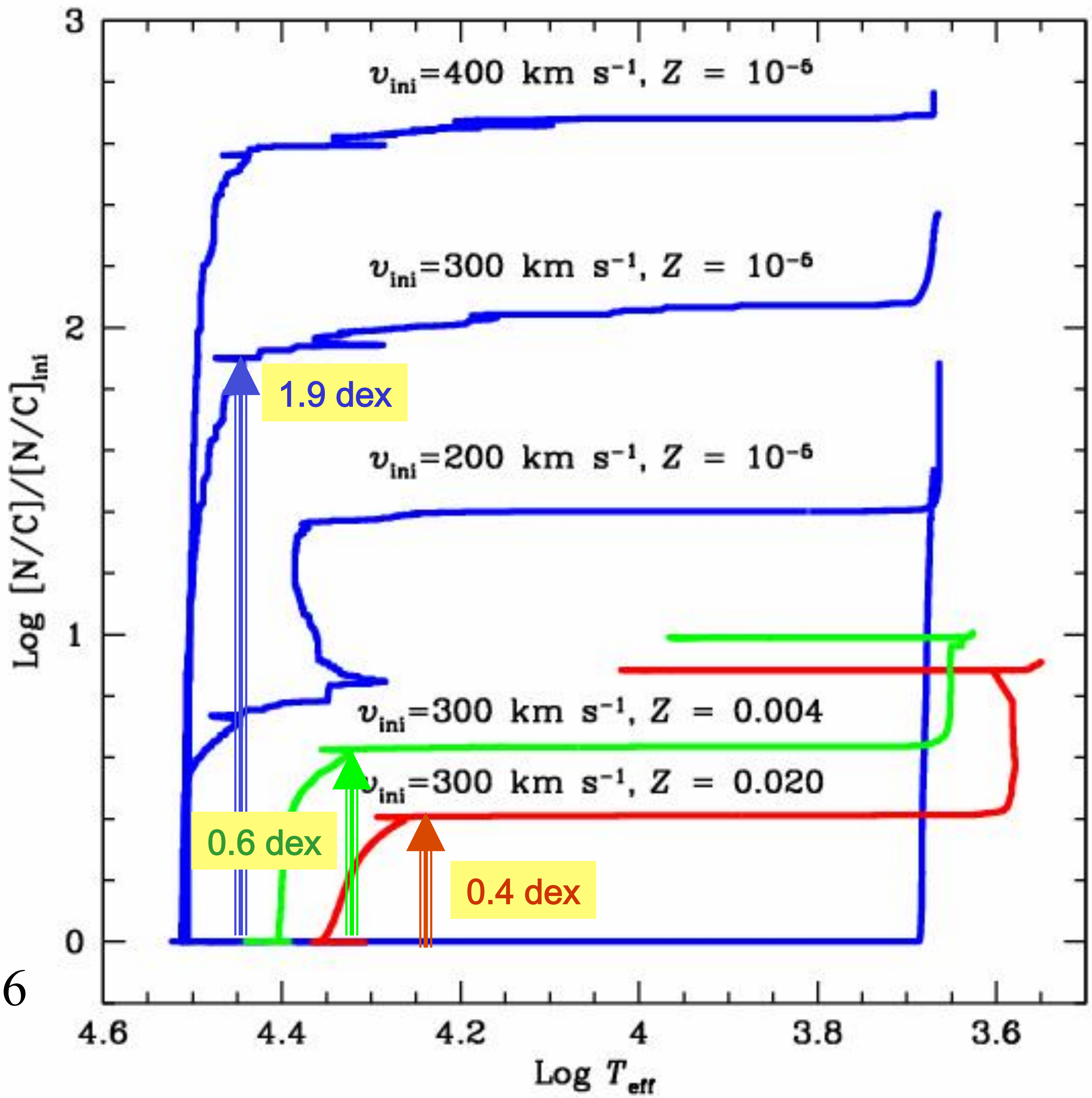
Consequences ?

More efficient mixing of the chemical elements

9 M_{sol}

When Z ↘

Surface enrichments ↗



Meynet et al. 2006

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

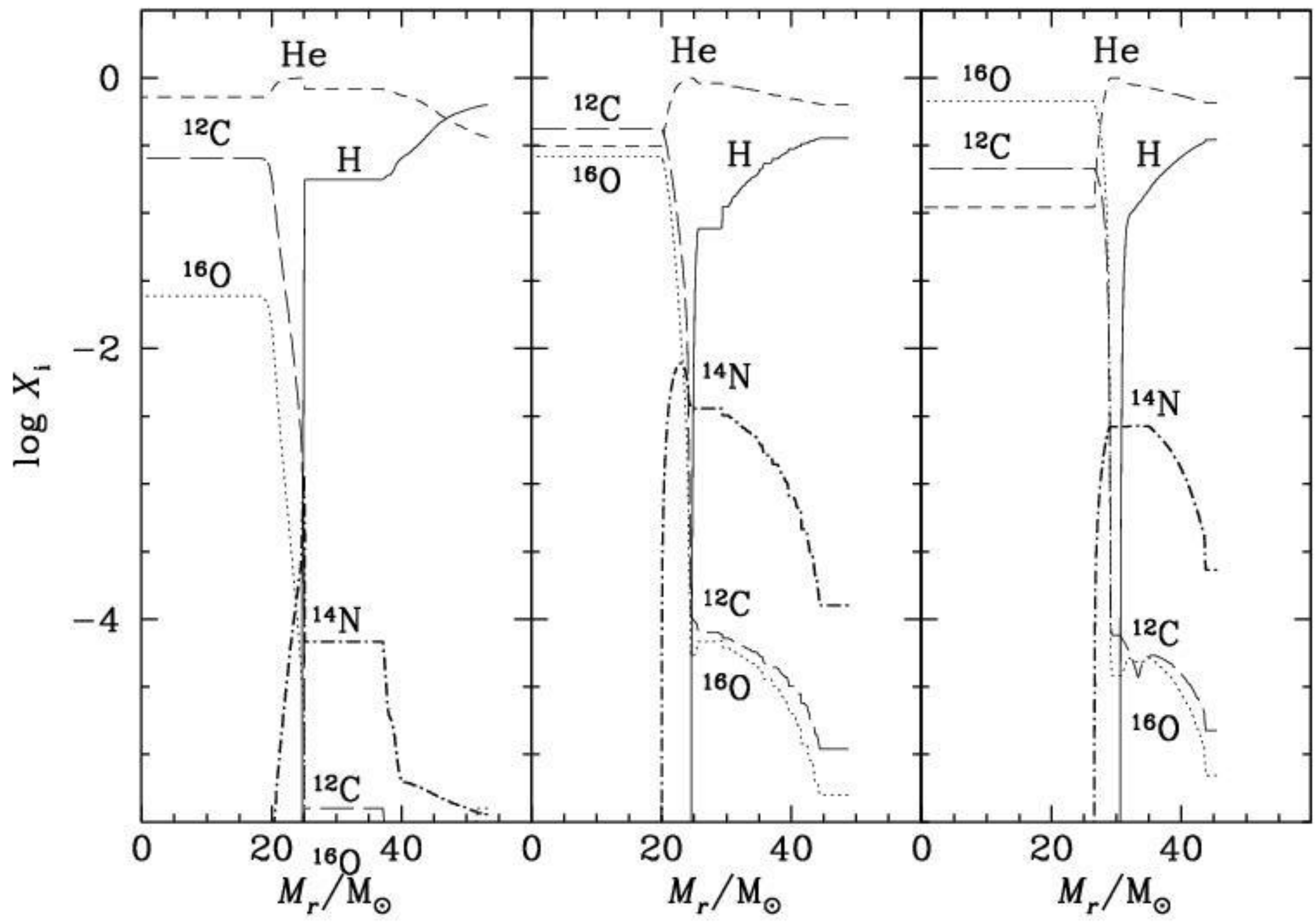
SMC: [N/H] O-stars, A-F supg. : 1.5 -1.7 dex

< 20 $M_\odot$ B – dwarfs : → 1.1 dex

B – giants, supg. : → 1.5 dex

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

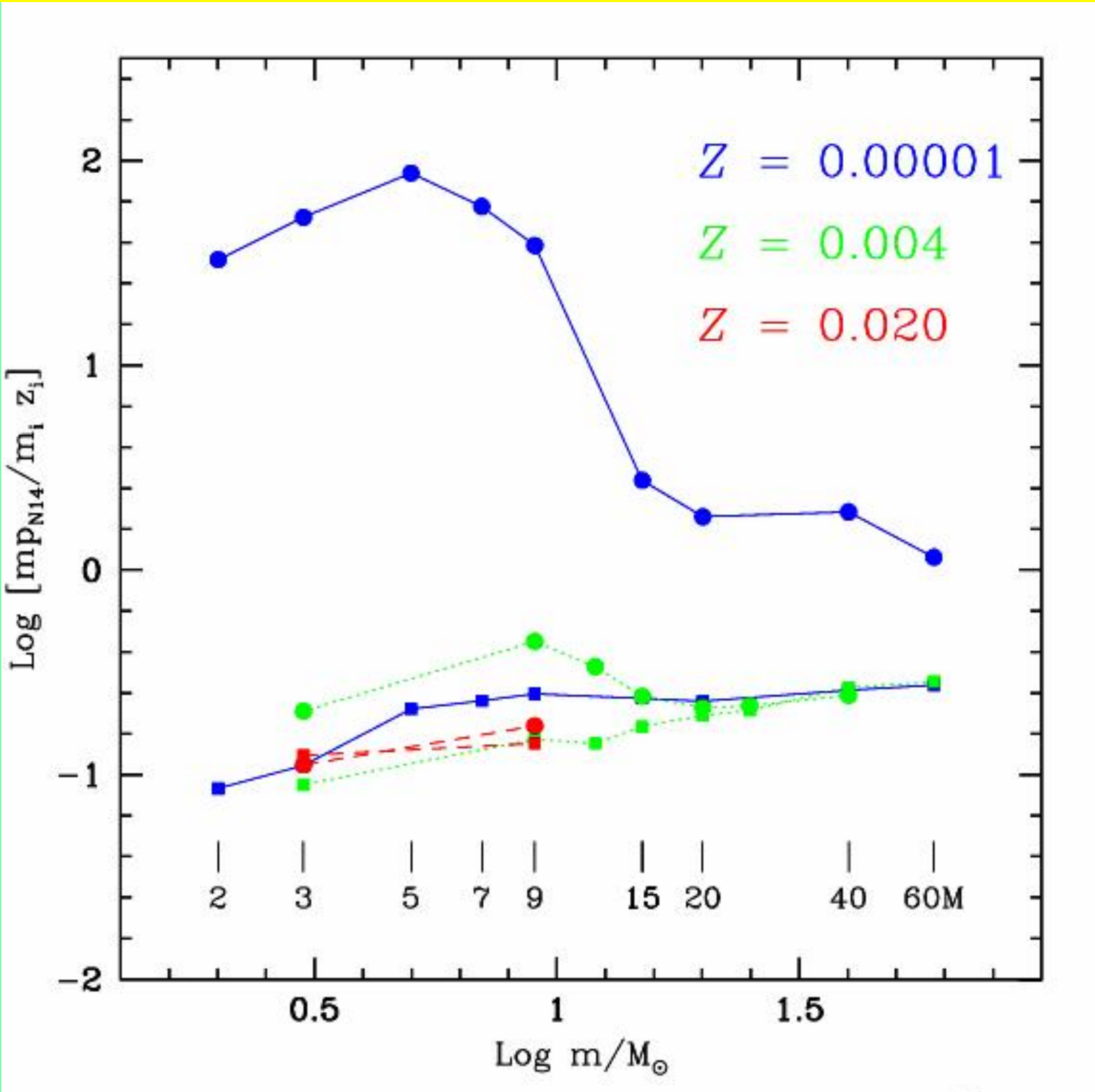
Ref: Heap & Lanz'06; Venn & Przybilla'03; Bouret et al.'03;Trundle et al.'07; Hunter et al.'07



Meynet et al. 2006

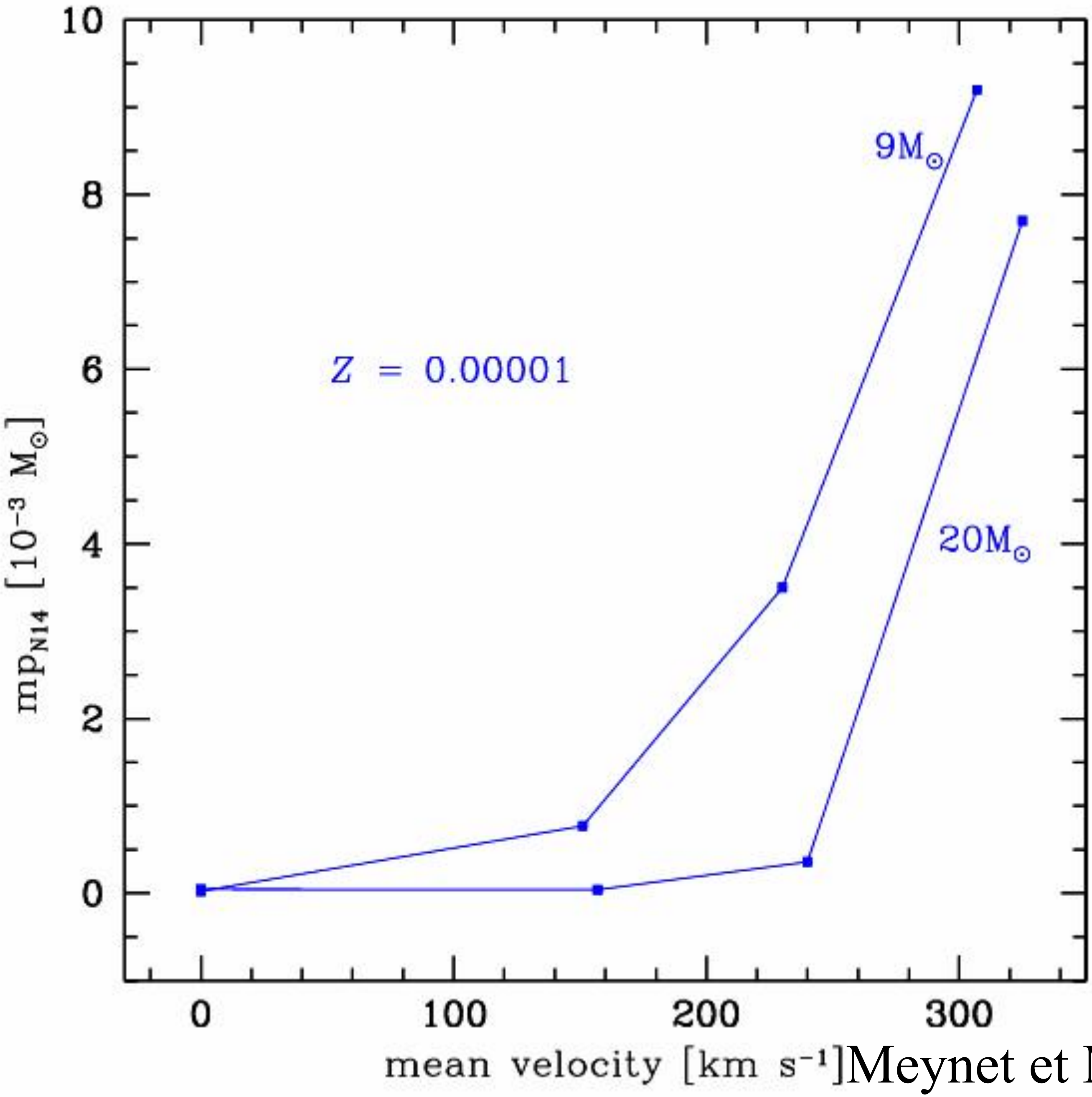
60 M_{sol}, Z=10^{-5}, Ω_{ini}/Ω = 0.85

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



Meynet & Maeder 2002

Increase of primary N production when rotation increases



Meynet et Maeder 2002

WHAT CHANGES AT LOW Z FOR ROTATING MODELS ?

Steeper gradients of the angular velocity in the interiors

⇒ MORE EFFICIENT MIXING

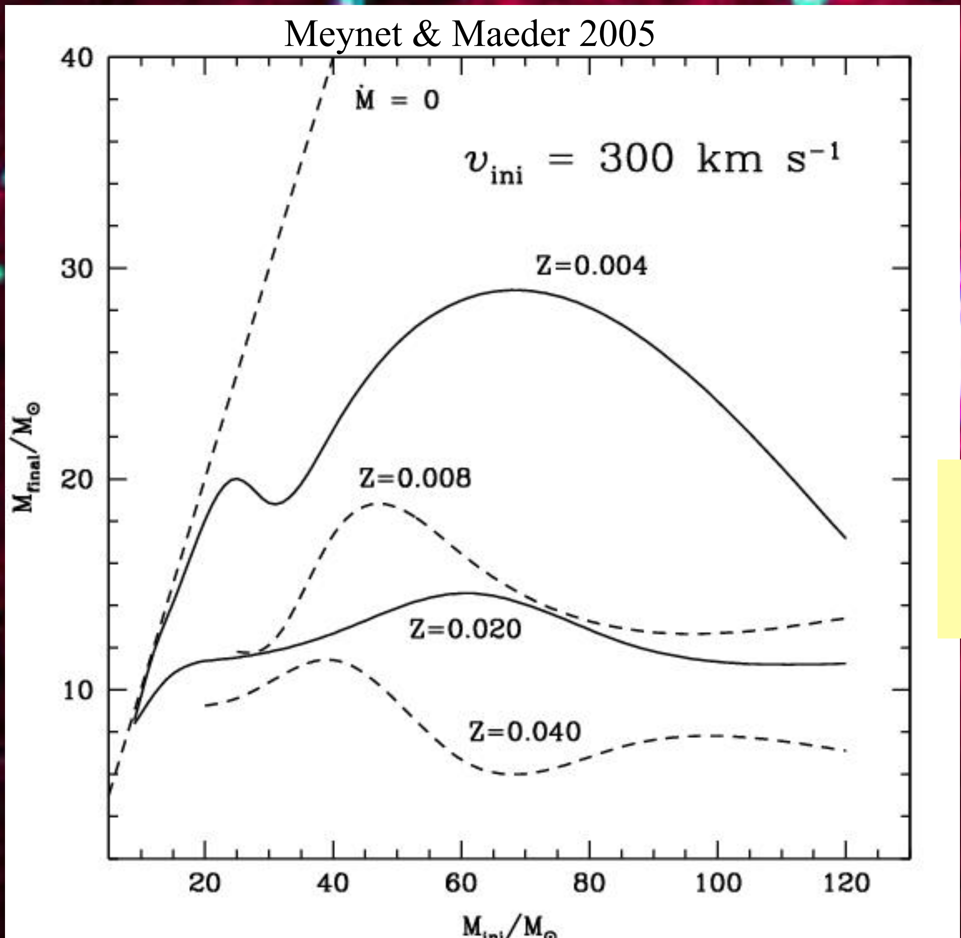
Less angular momentum removed by stellar winds

⇒ BREAK-UP LIMIT

At low metallicity, very weak radiatively driven stellar winds

Mass loss rate

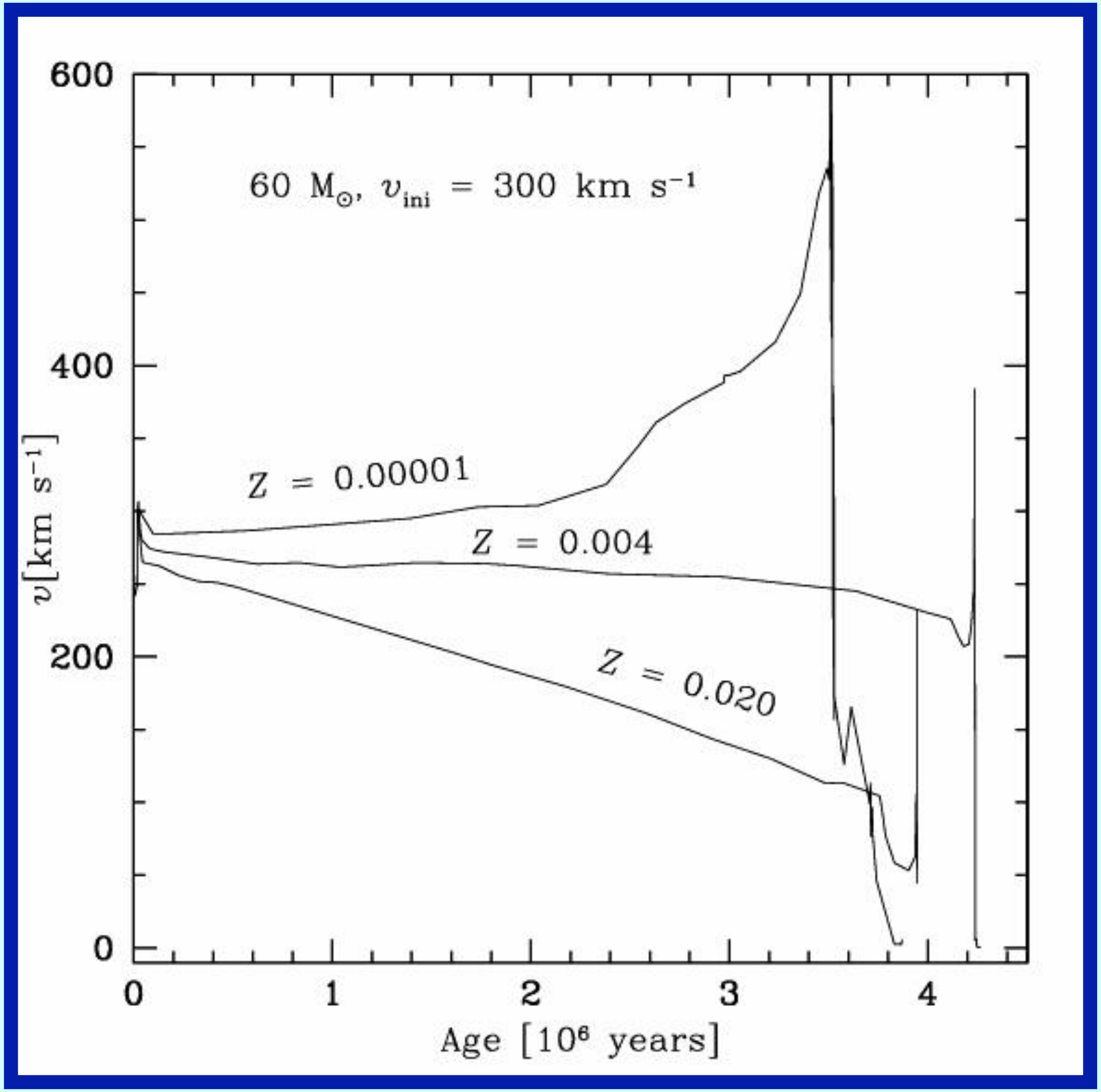
$$\dot{M}_Z = \left(\frac{Z}{Z_{sol}}\right)^{\alpha} \dot{M}_{Z_{sol}}$$



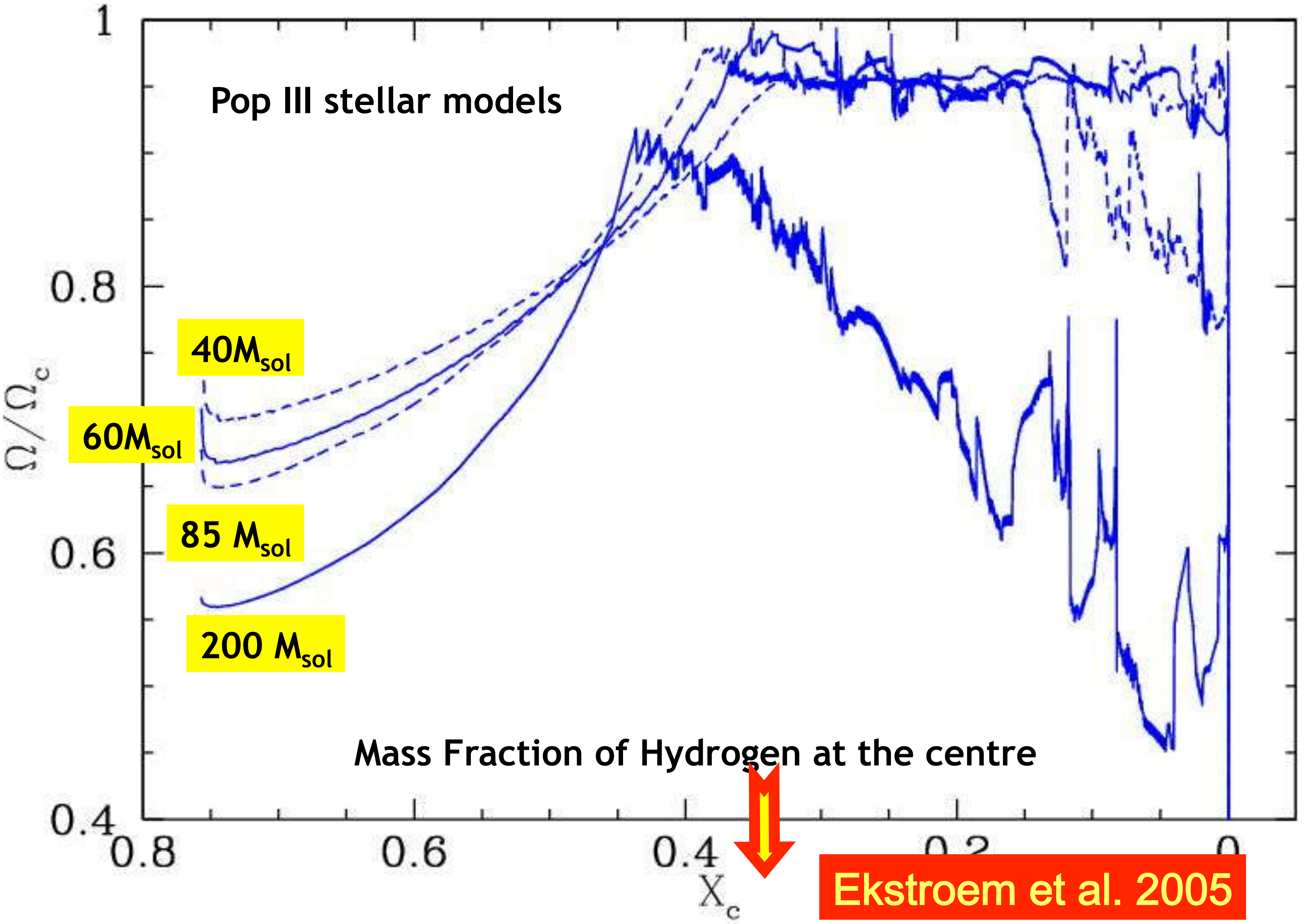
Kudritzki & Puls (2000) → α=0.5
Evans et al. (2005) → α=0.62+ - 0.15

What happens if metal poor stars are fast rotators ?

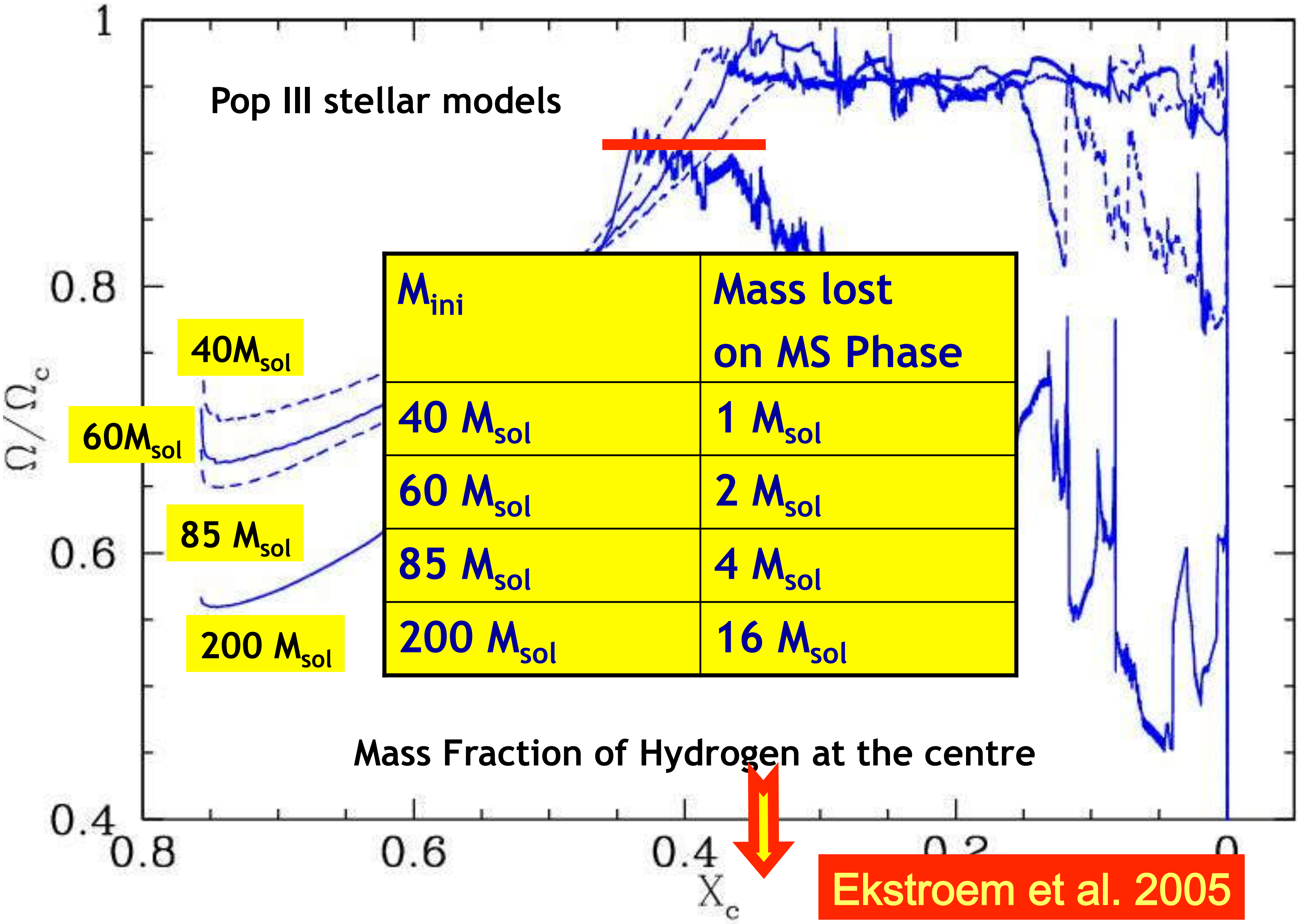
Could very low metallicity stars loose a lot of mass when reaching the break-up ?



Meynet & Maeder 2002

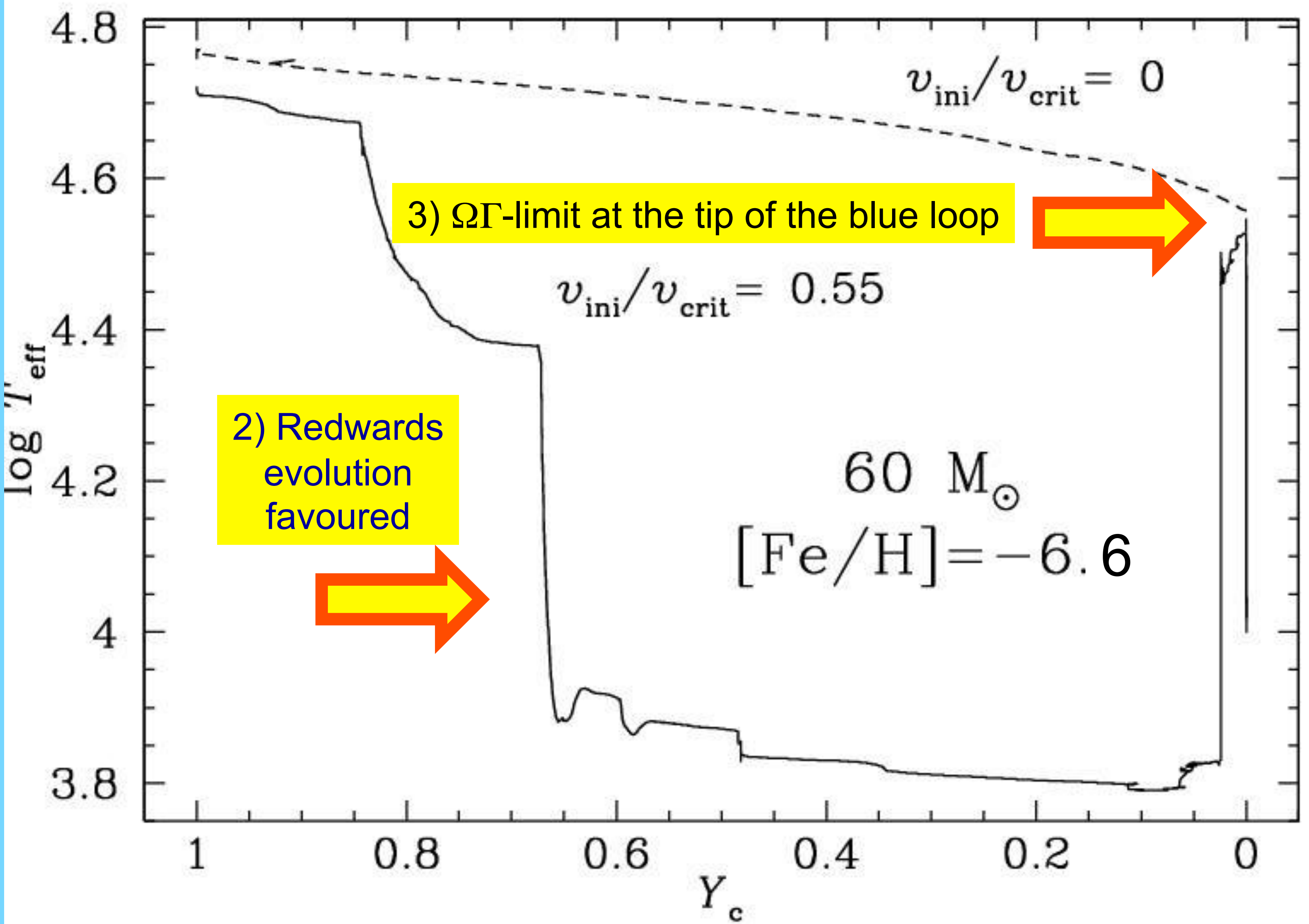


Pop III stellar models
40M sol
60M sol
85 M sol
200 M sol
Mass Fraction of Hydrogen at the centre
Ekstroem et al. 2005
Ω/Ω c
X c
1
0.8
0.6
0.4
0.8
0.6
0.4
0.2
0

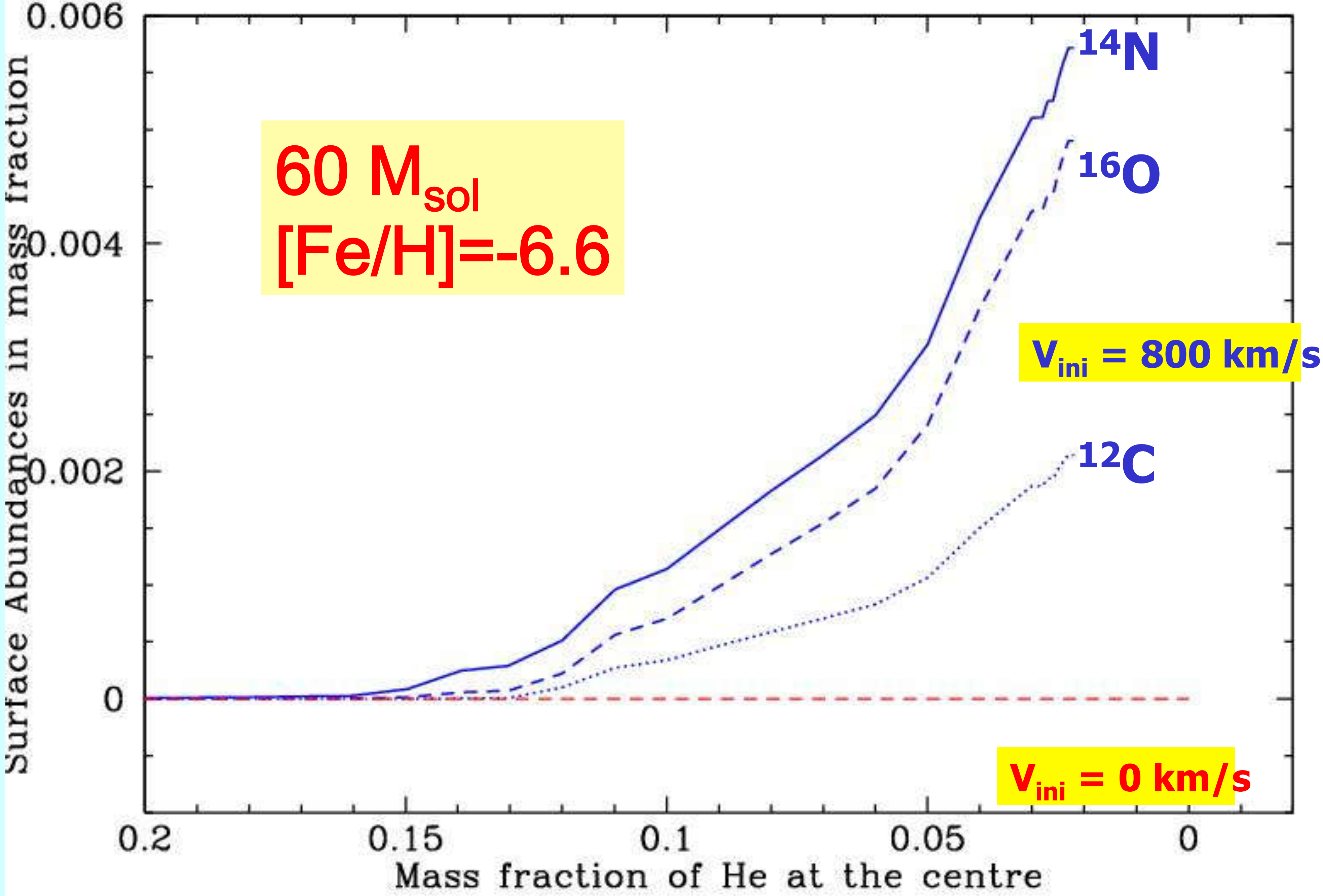


M_{ini}	Mass lost on MS Phase
$40\ M_{sol}$	$1\ M_{sol}$
$60\ M_{sol}$	$2\ M_{sol}$
$85\ M_{sol}$	$4\ M_{sol}$
$200\ M_{sol}$	$16\ M_{sol}$

Ekstroem et al. 2005

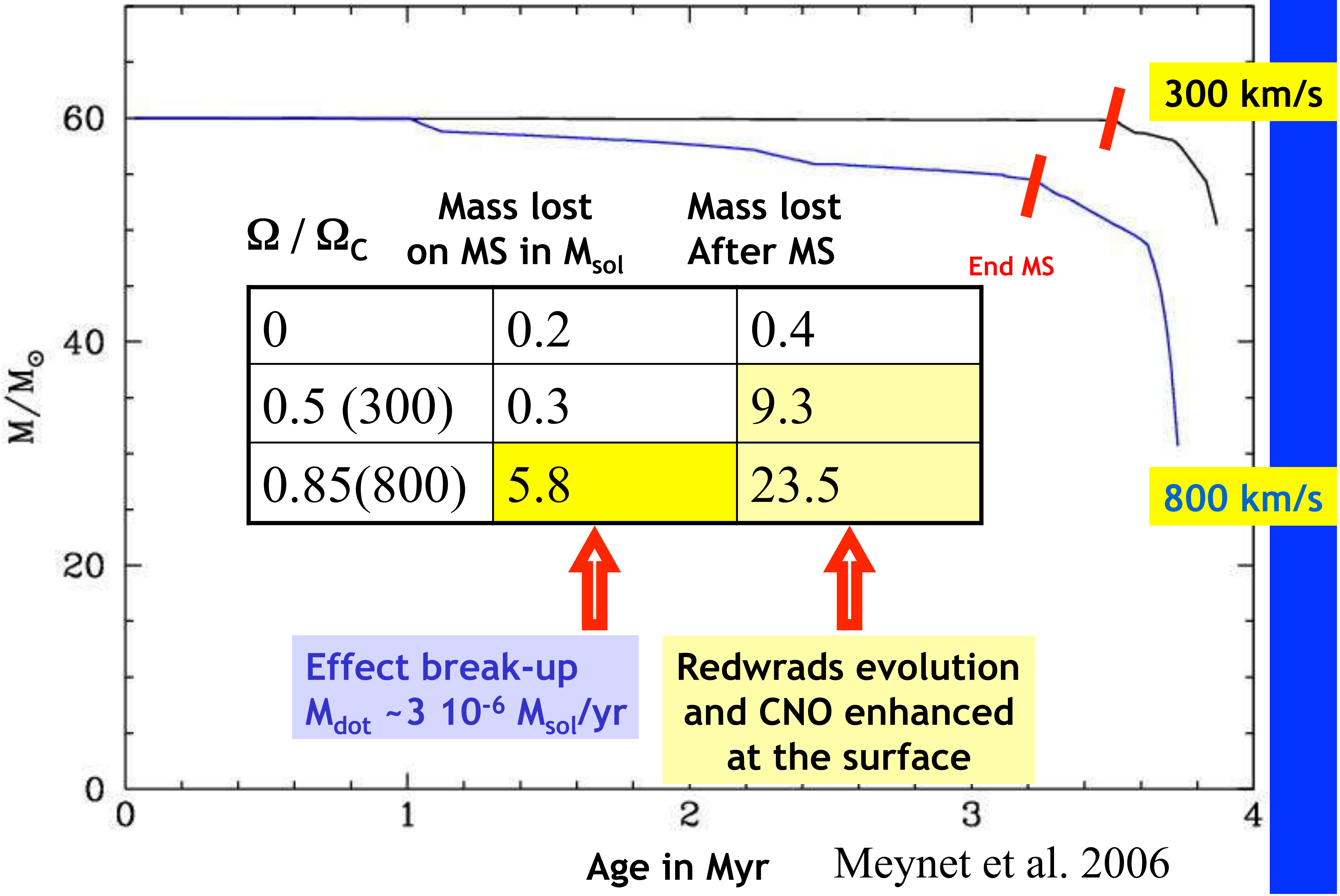


Meynet et al. 2006



Meynet et al. 2006

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

Meynet et al. 2006

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

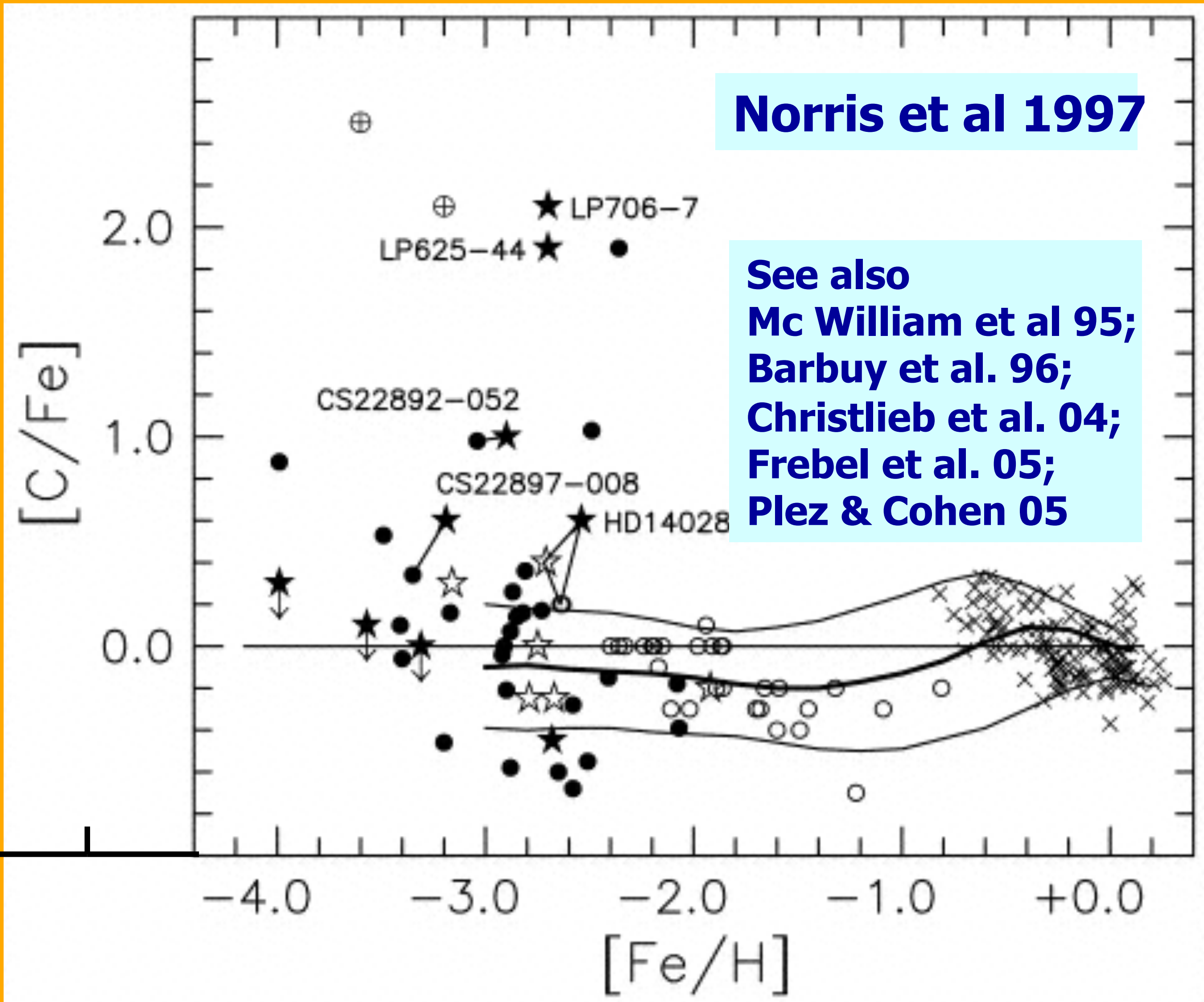
Maeder and Meynet 2006

New s-process in massive metal poor rotating stars

Pignatary et al. 2008

Carbon Rich Ultra Metal Poor Stars (CRUMPS)

Most metal poor stars



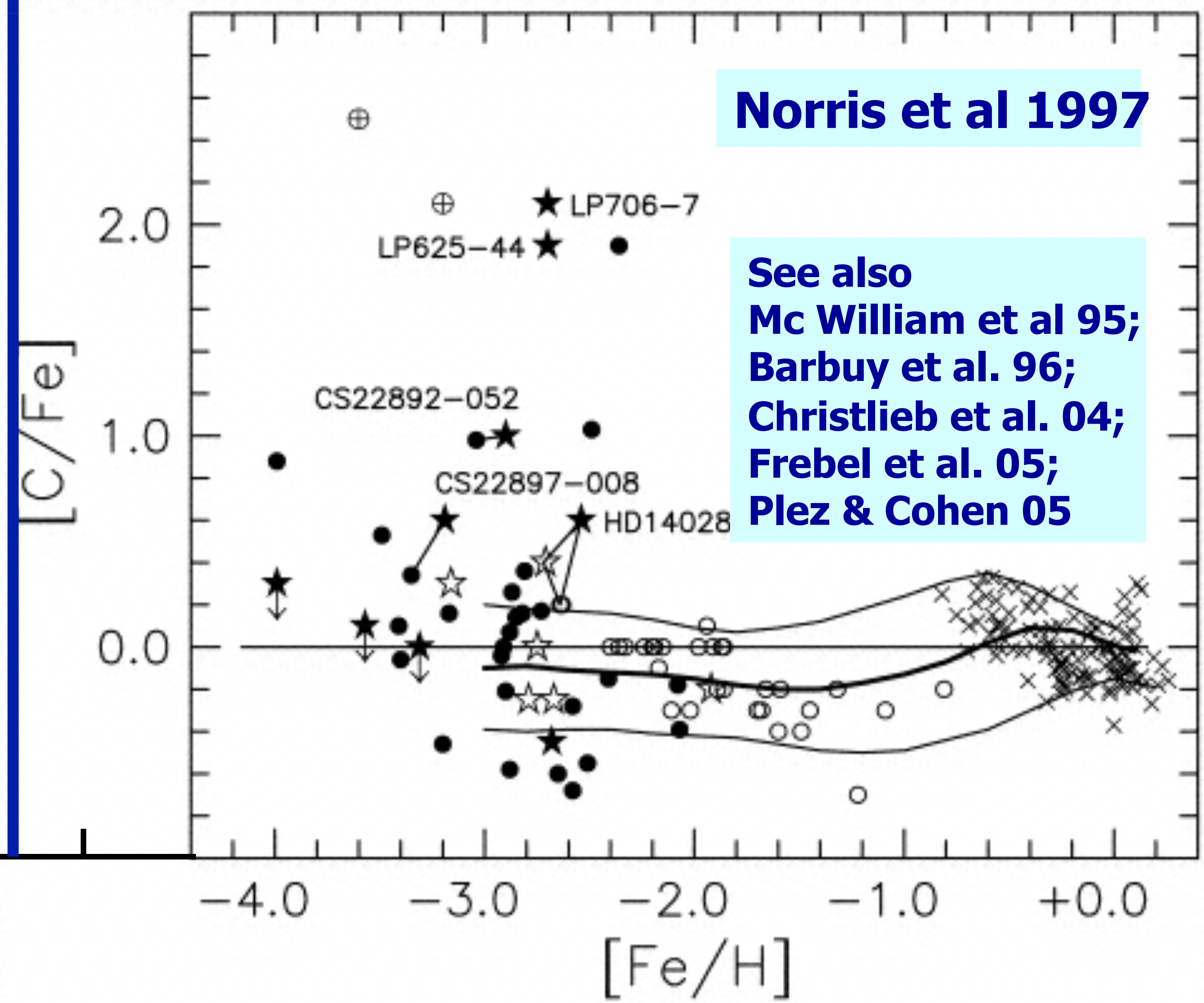
Norris et al 1997

See also
Mc William et al 95;
Barbuy et al. 96;
Christlieb et al. 04;
Frebel et al. 05;
Plez & Cohen 05

Carbon Rich Ultra Metal Poor Stars (CRUMPS)

Most metal poor stars

Christlieb et al. 2002



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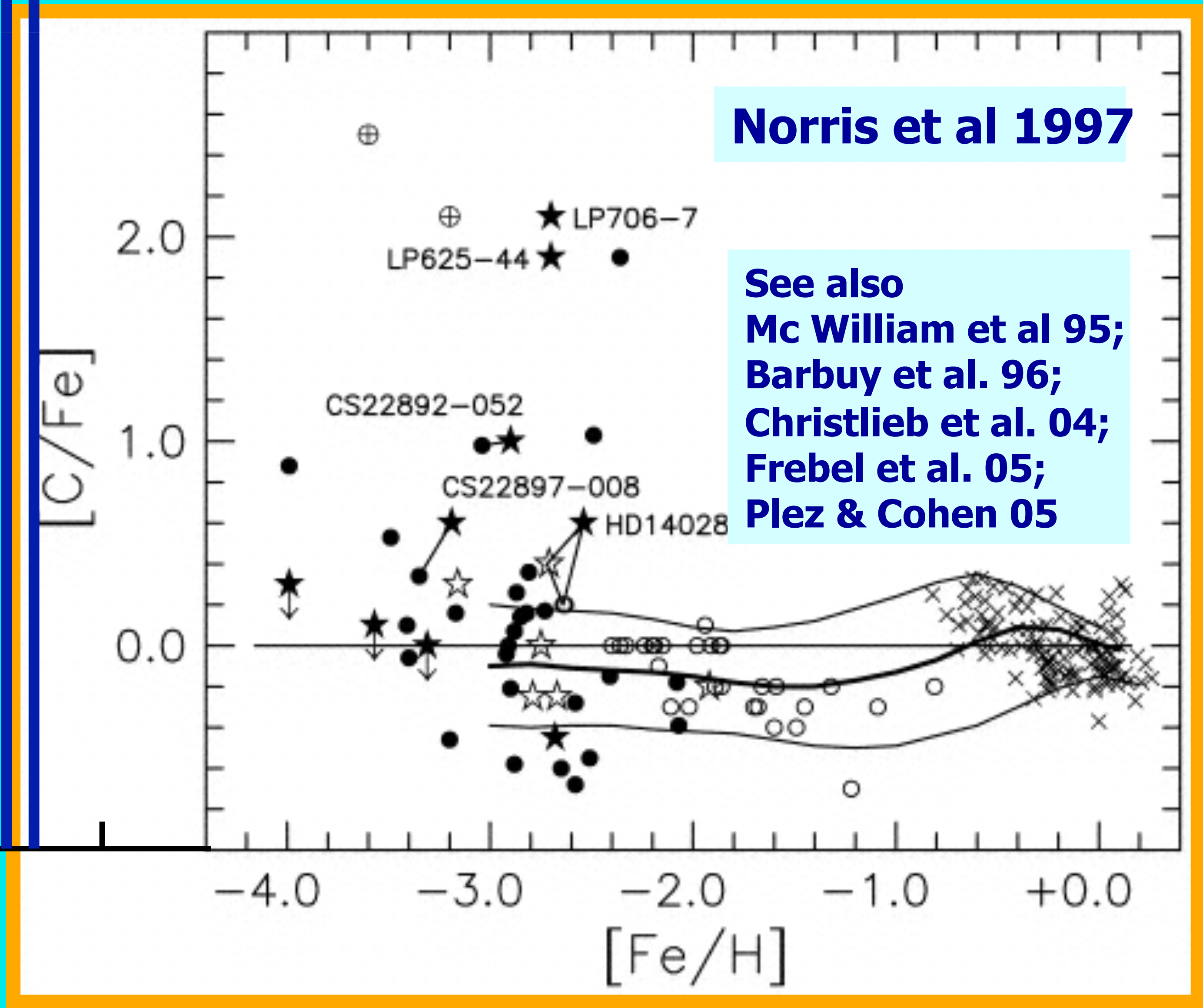

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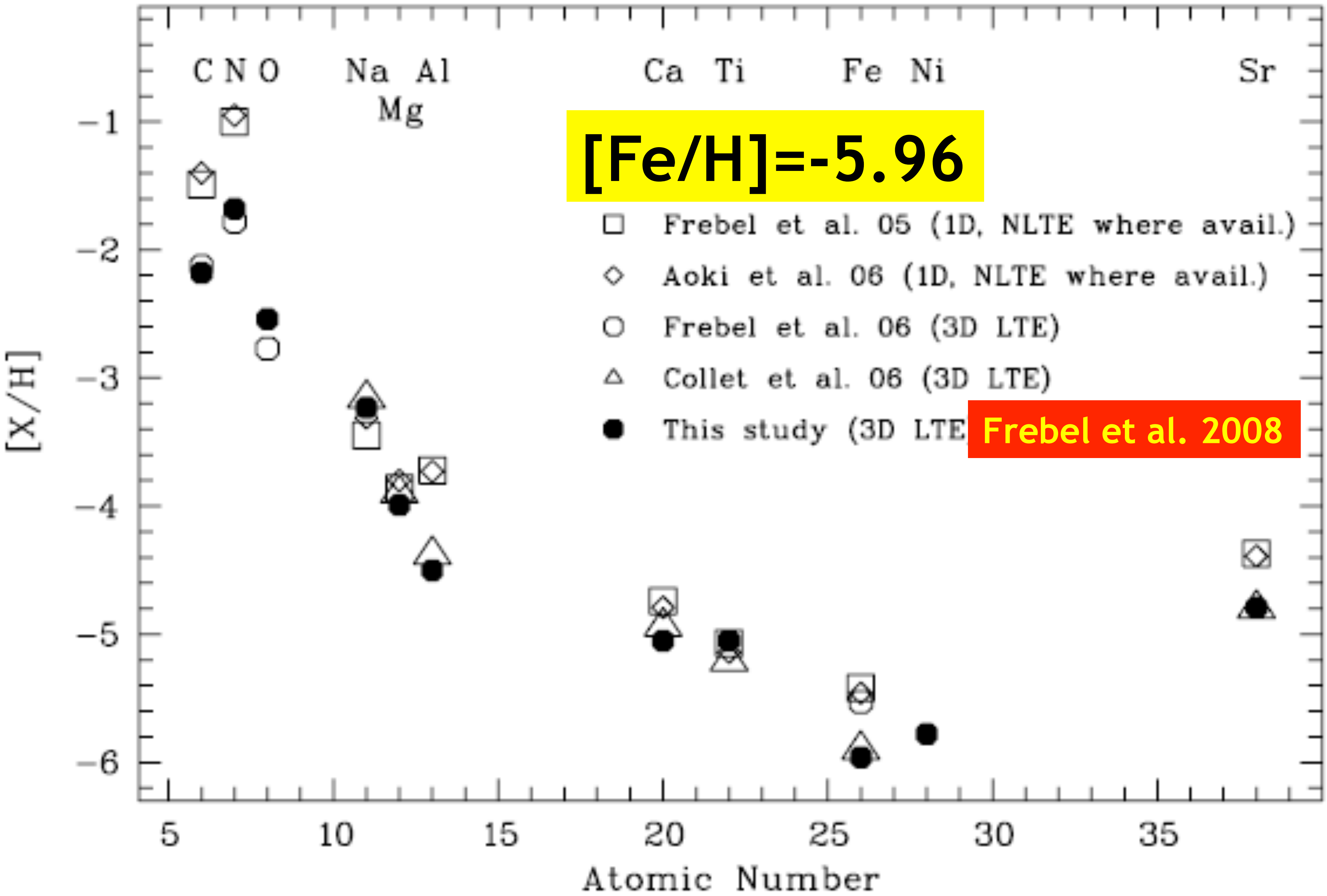
THE MOST IRON POOR STAR PRESENTLY KNOWN IN THE UNIVERSE



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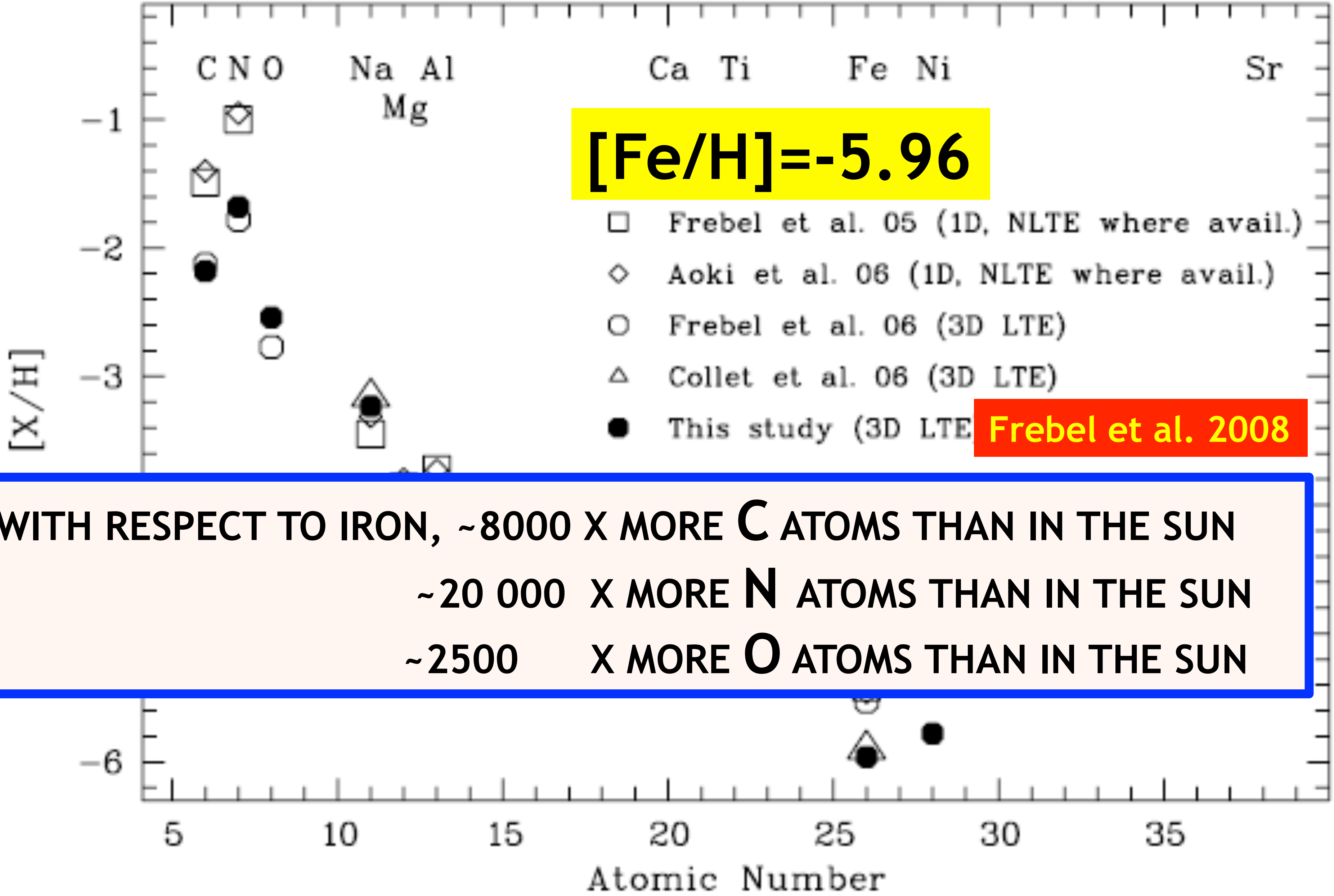
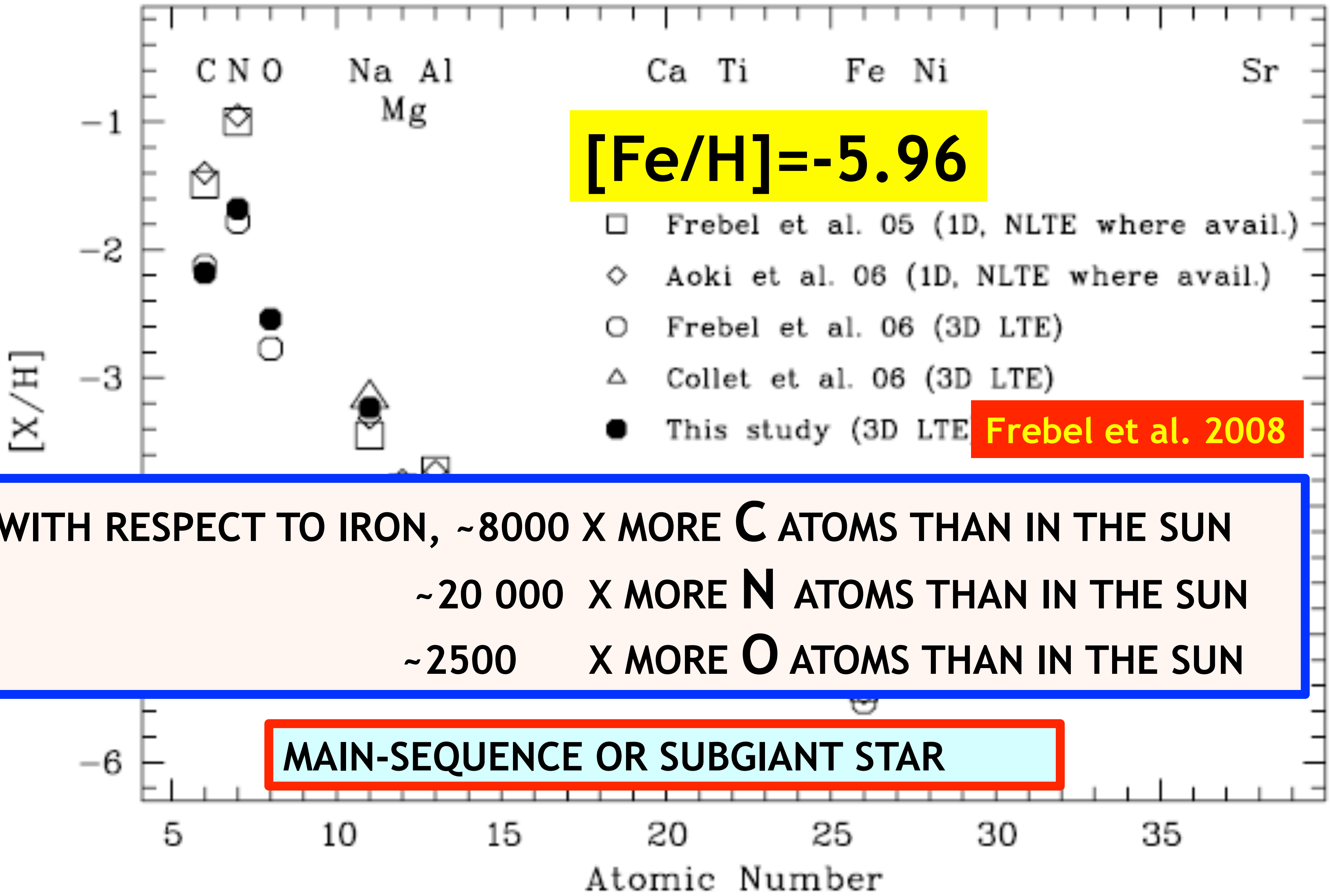


[Fe/H]=-5.96

Frebel et al. 2008

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

THE MOST IRON POOR STAR PRESENTLY KNOWN IN THE UNIVERSE



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MAIN-SEQUENCE OR SUBGIANT STAR

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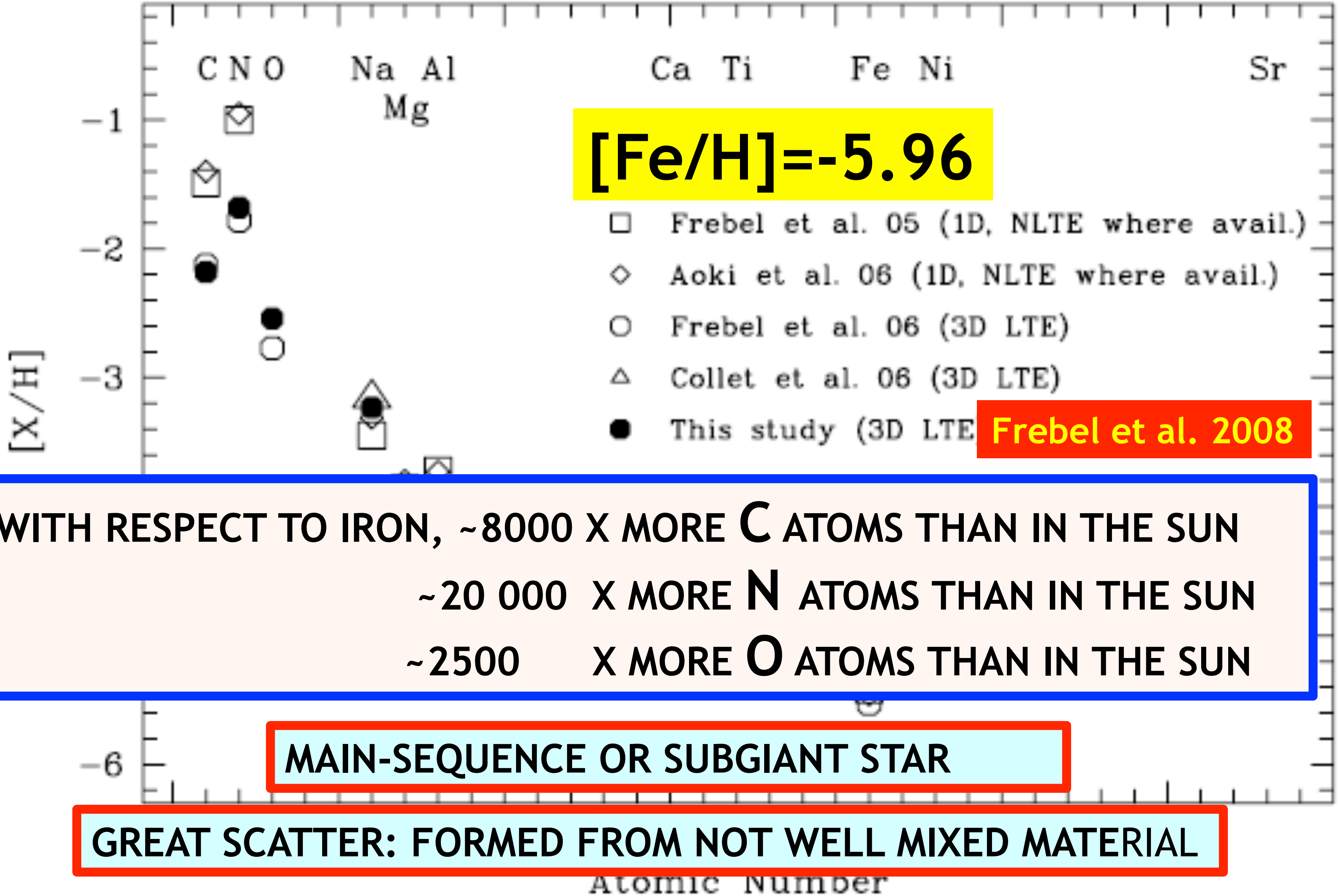

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MAIN-SEQUENCE OR SUBGIANT STAR

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!

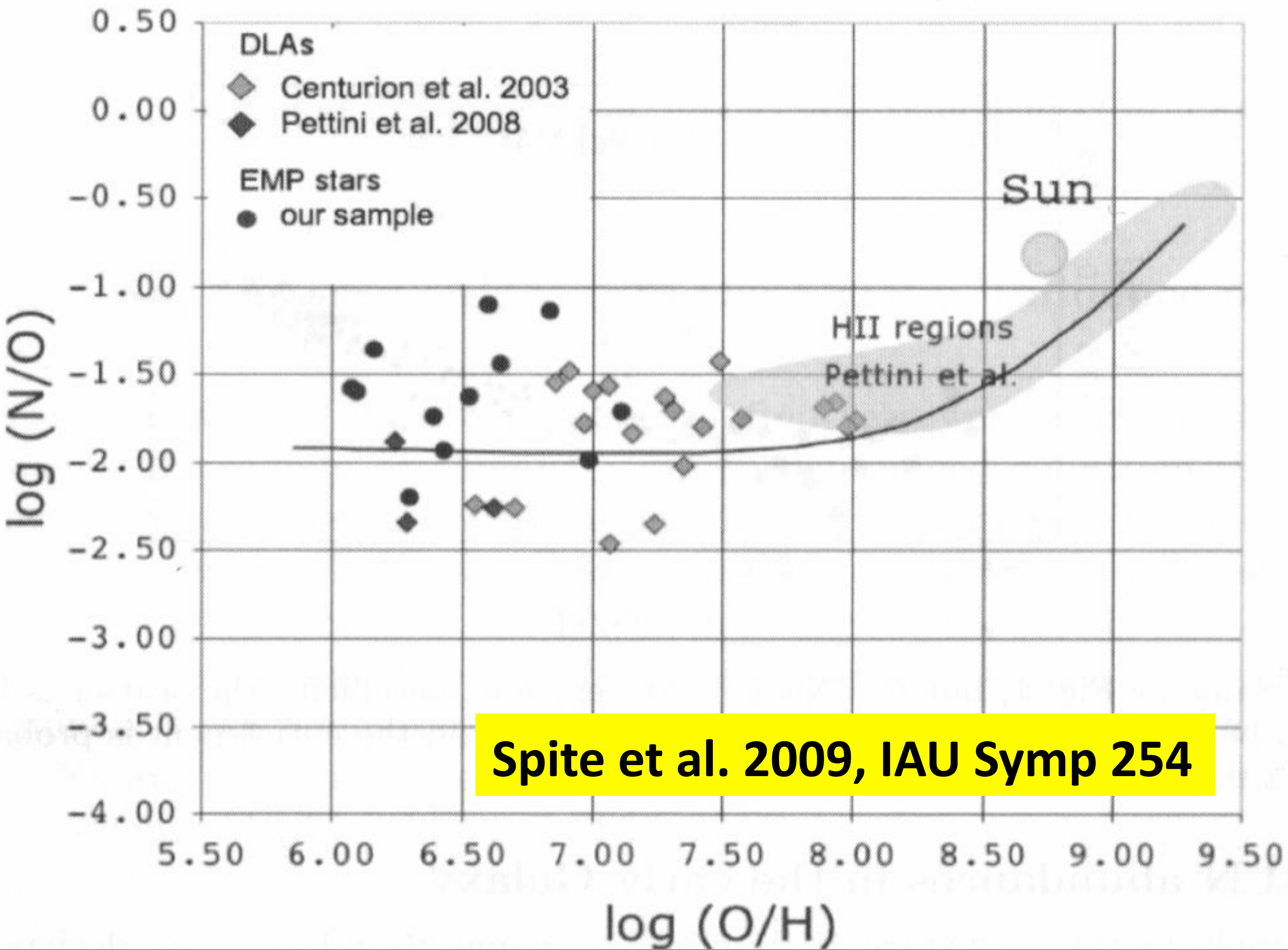
HIGH CNO NEEDS

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

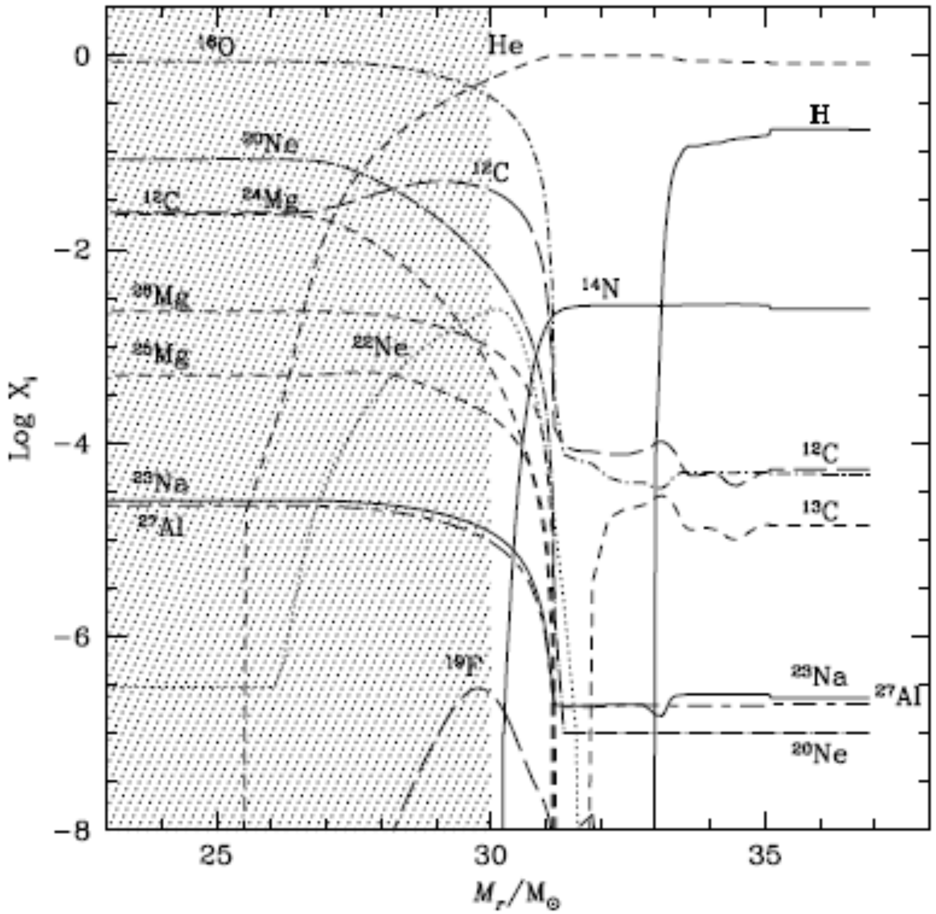
IMPORTANT PRODUCTION OF PRIMARY NITROGEN



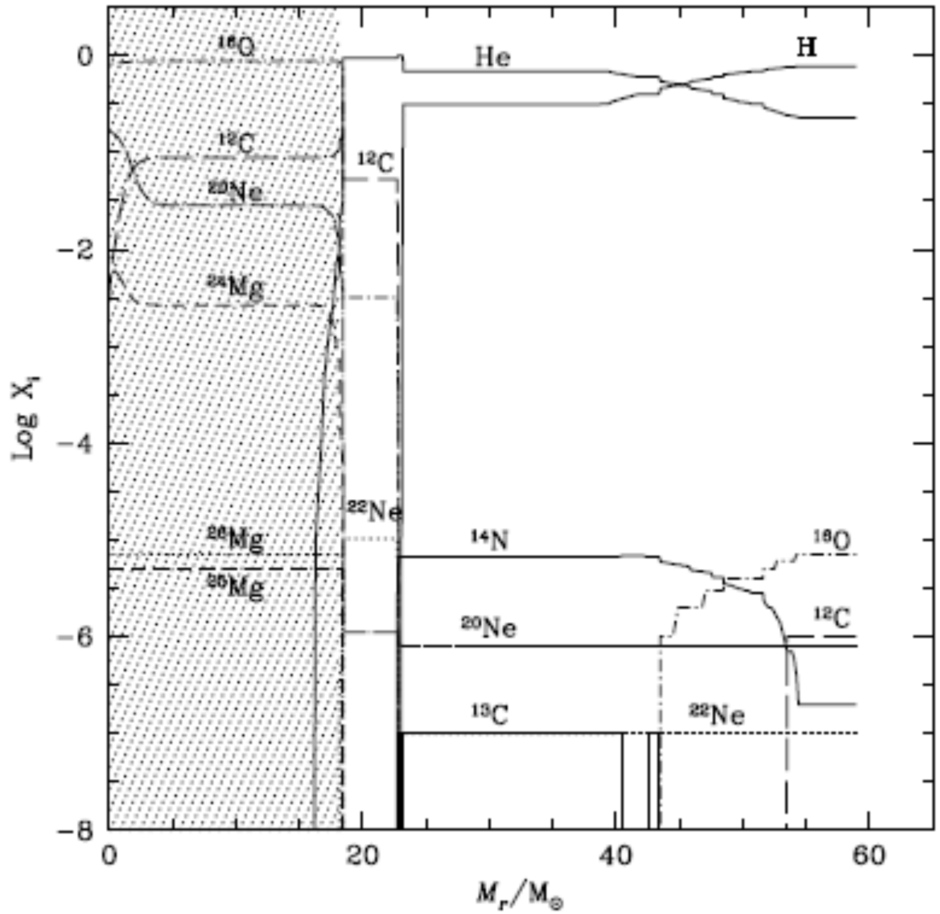
Spite et al. 2009, IAU Symp 254

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

V=800 km s^{-1}



V = 0 km s^{-1}



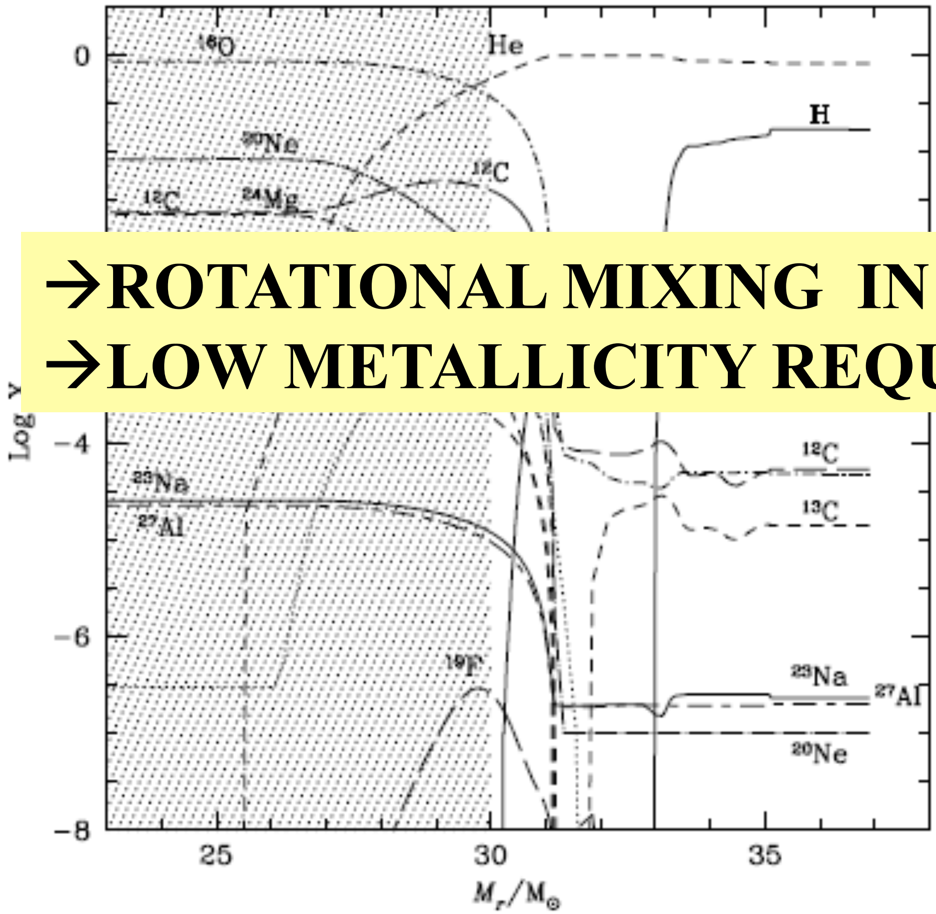
NITROGEN

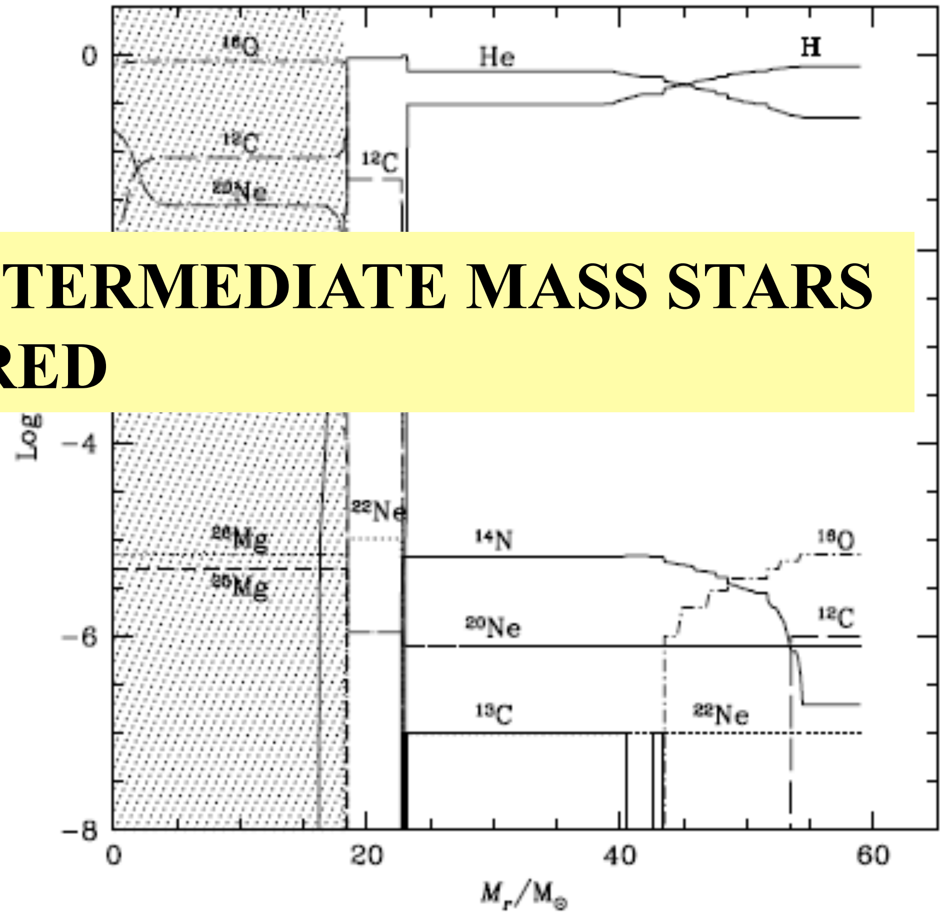
WINDS

Meynet et al. 2010

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

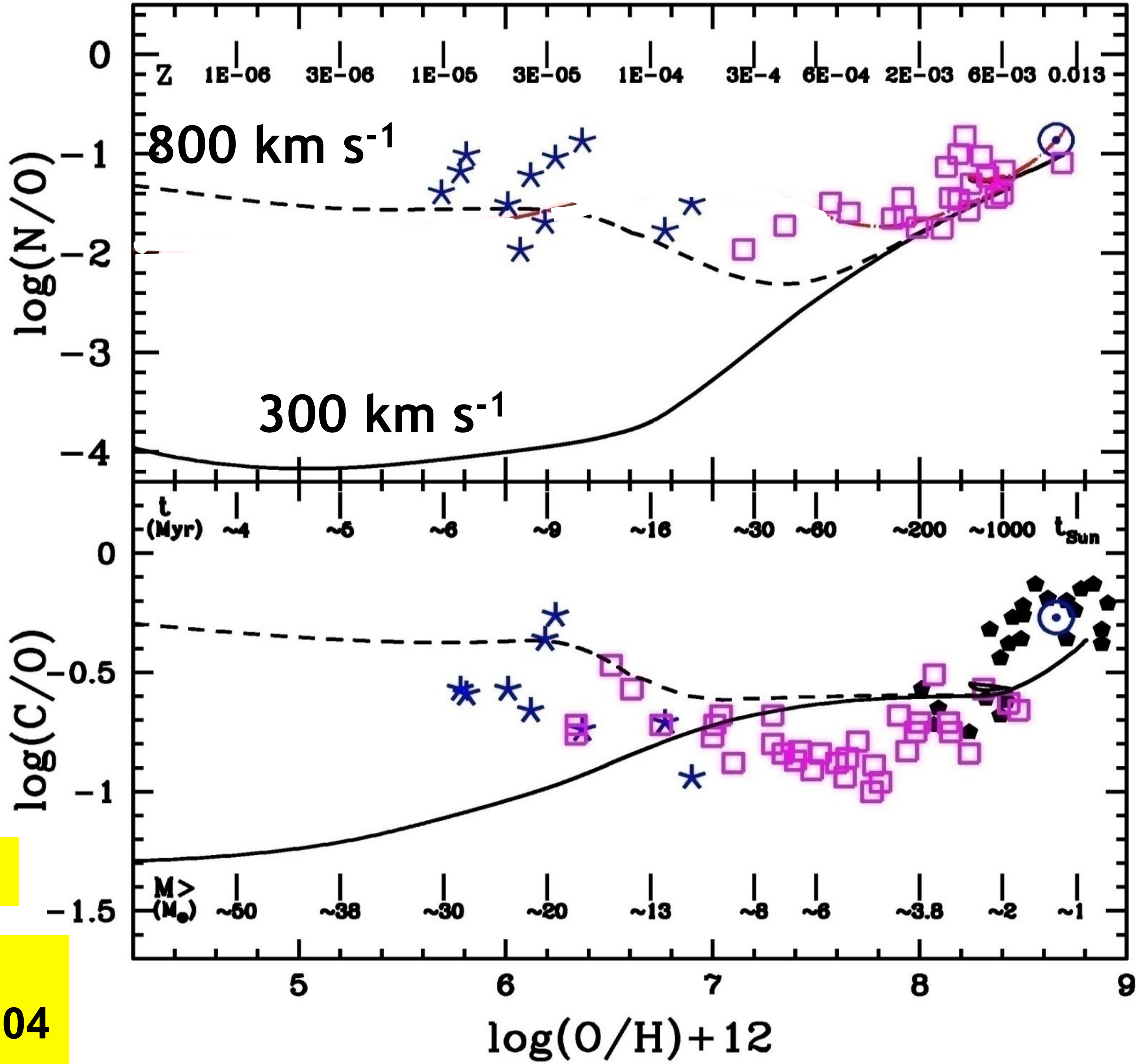
NITROGEN

WINDS

Meynet et al. 2010

N/O

C/O



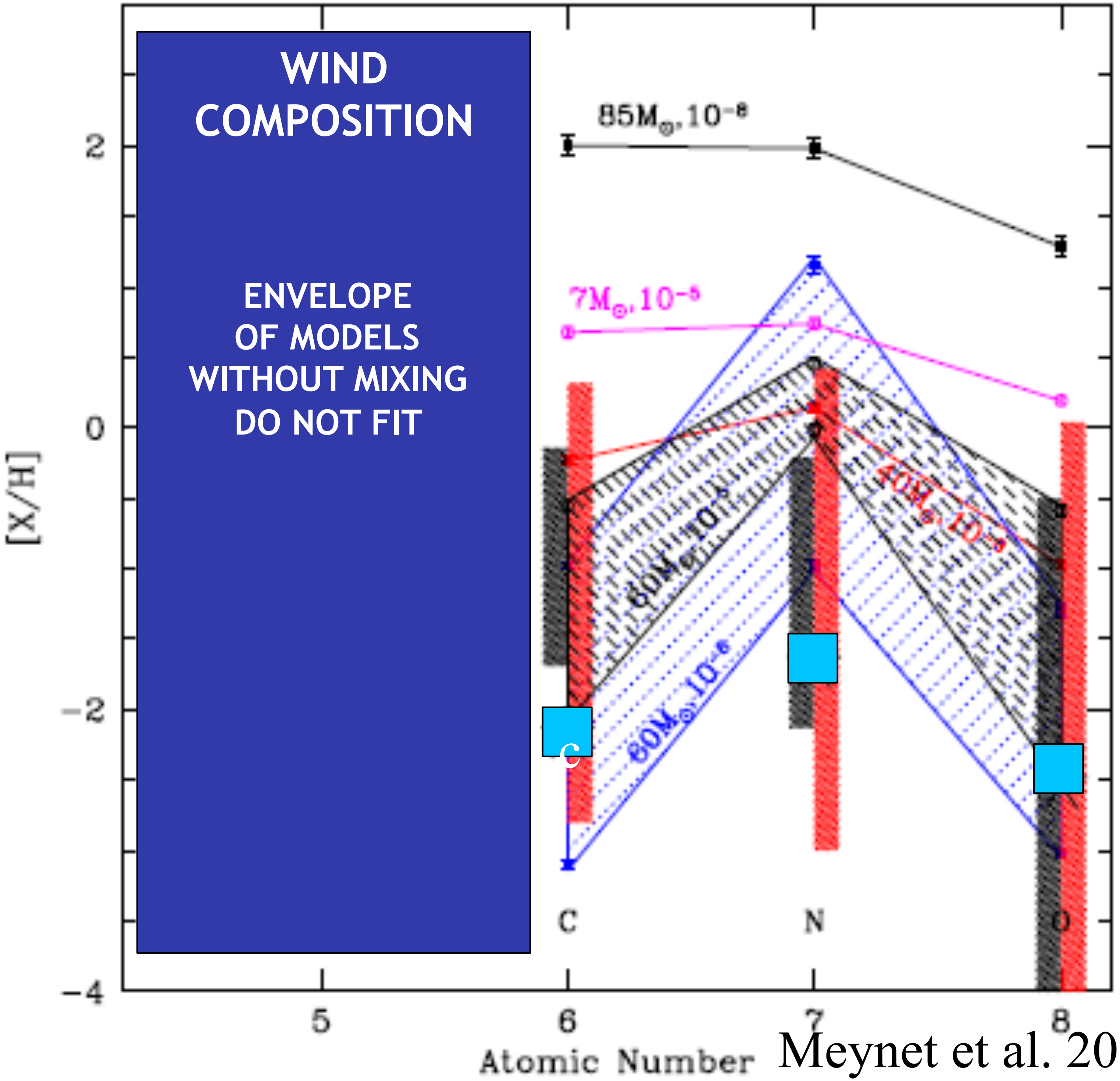
Observations from

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

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

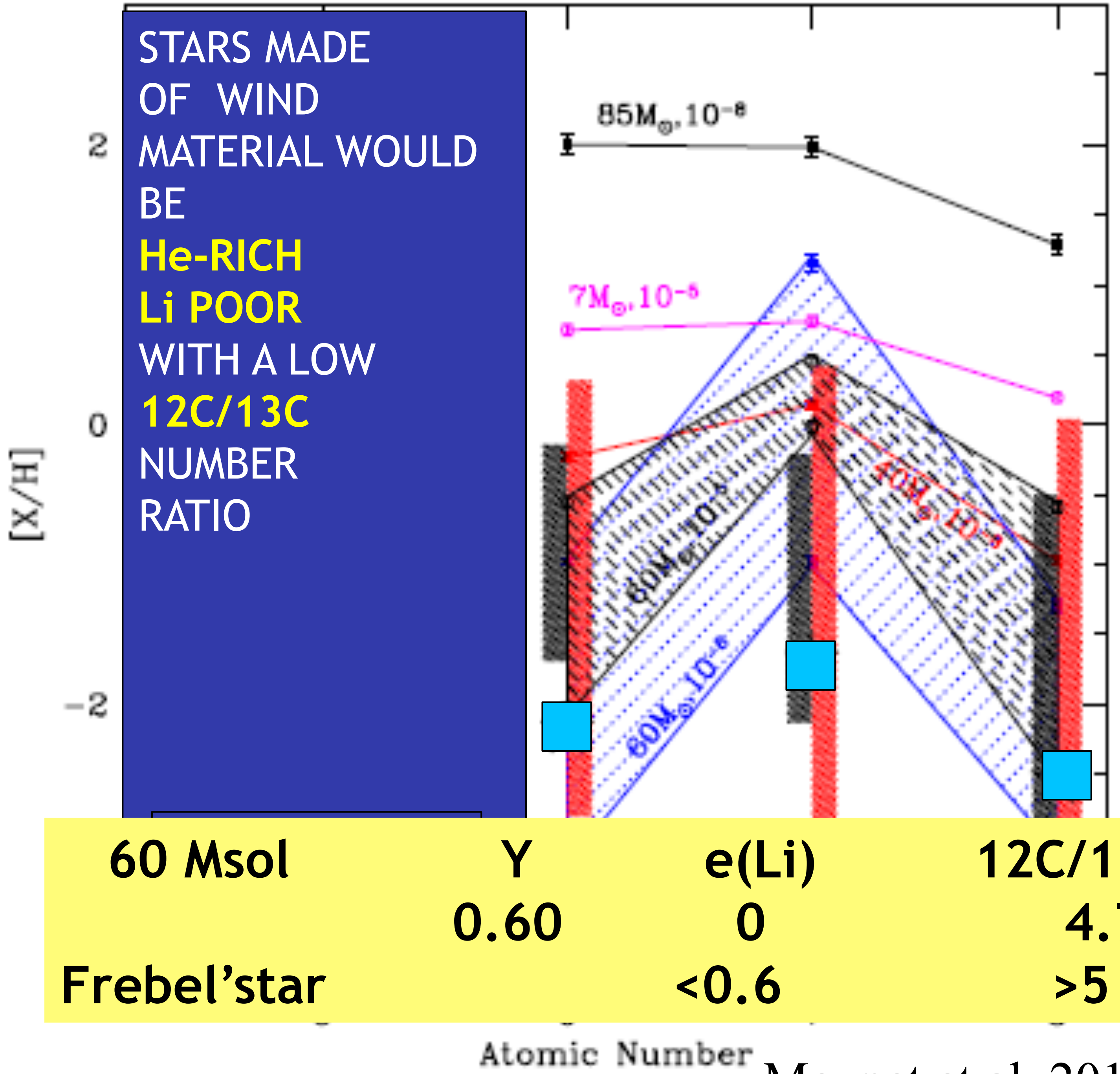
WIND COMPOSITION

ENVELOPE
OF MODELS
WITHOUT MIXING
DO NOT FIT



Meynet et al. 2010

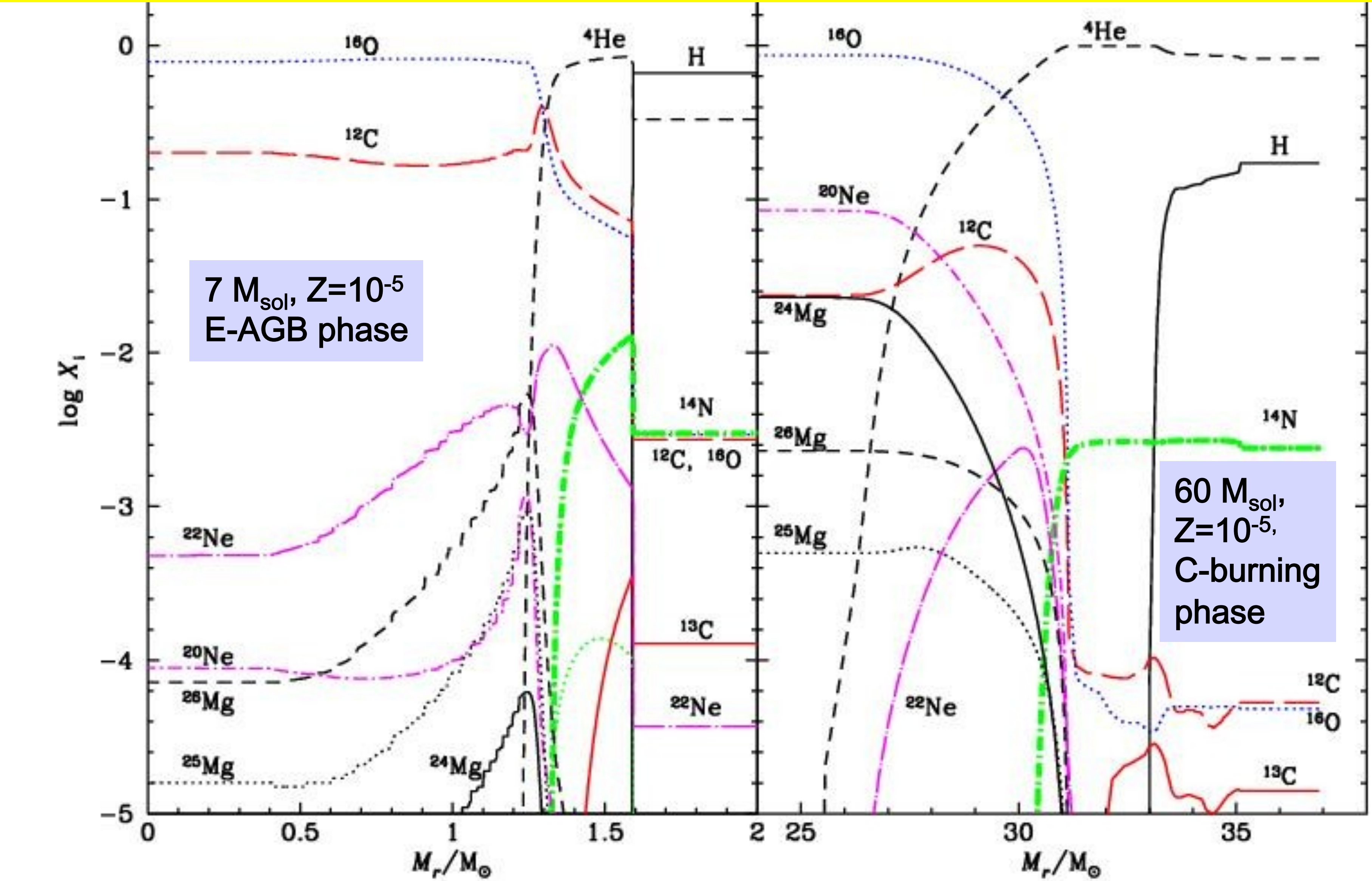
STARS MADE OF WIND MATERIAL WOULD BE
He-RICH
Li POOR
WITH A LOW **12C/13C** NUMBER RATIO



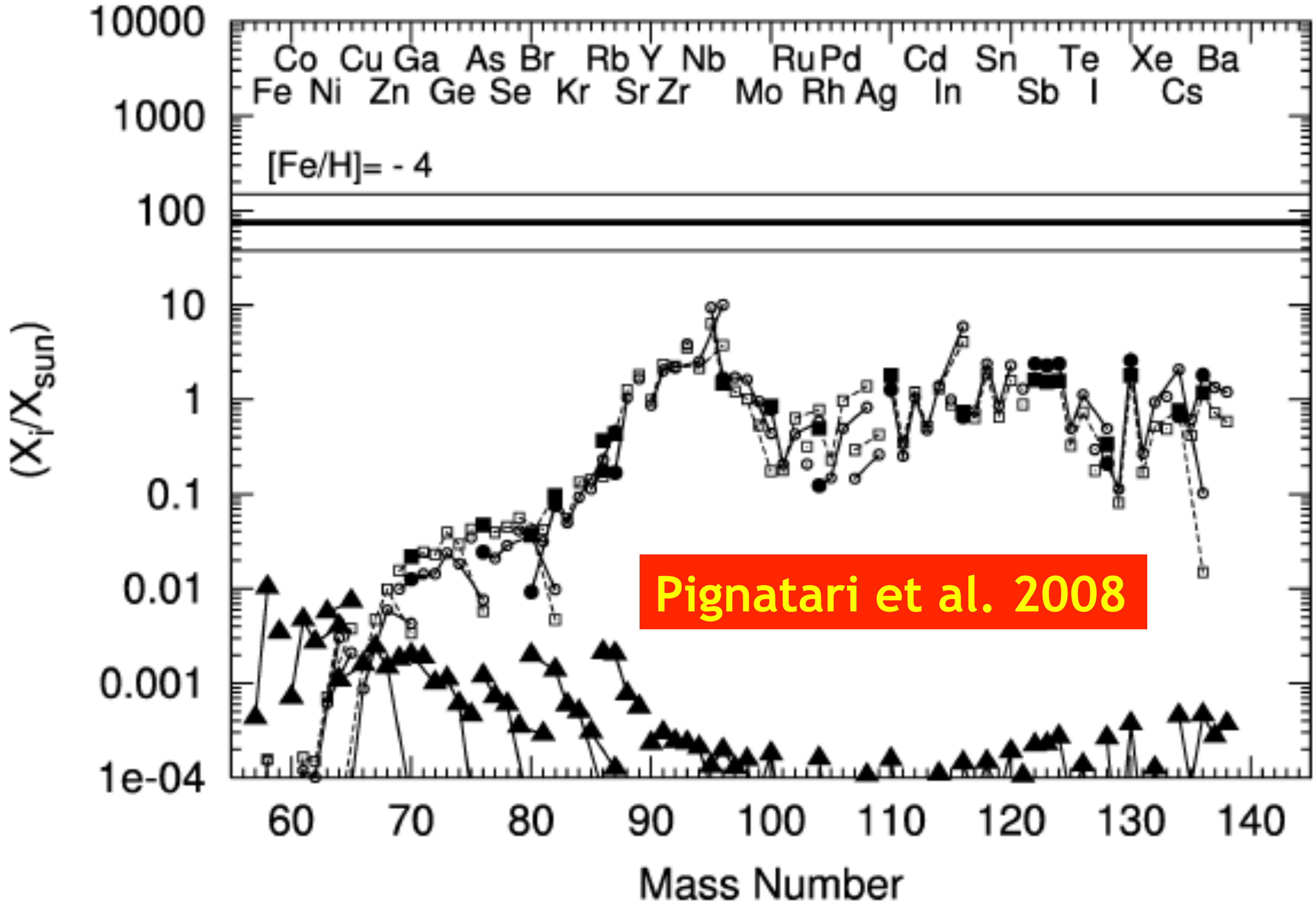
60 Msol	Y	e(Li)	12C/13C
	0.60	0	4.7
Frebel'star		<0.6	>5

Meynet et al. 2010

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



Meynet et al. 2006

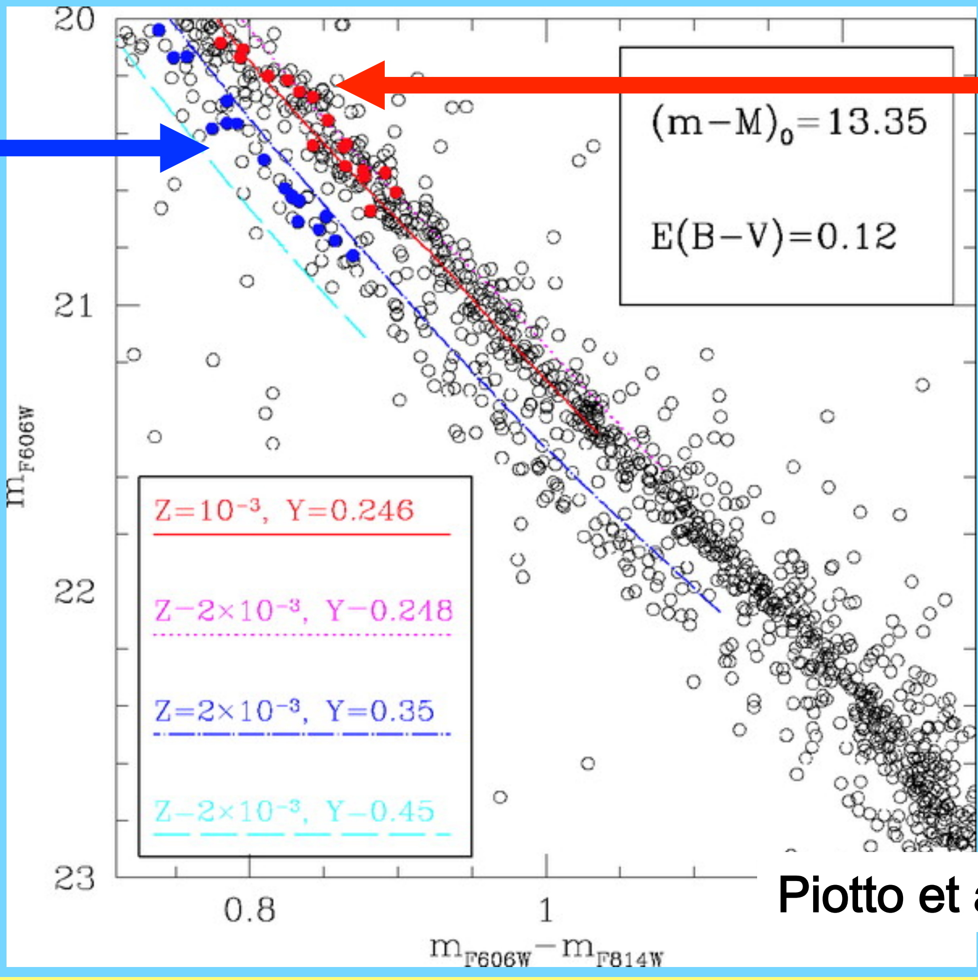


Co Cu Ga As Br Rb Y Nb Ru Pd Cd Sn Te Xe Ba
Fe Ni Zn Ge Se Kr Sr Zr Mo Rh Ag In Sb I Cs
[Fe/H]= - 4
10000
1000
100
10
1
0.1
0.01
0.001
1e-04
60
70
80
90
100
110
120
130
140
Mass Number
(X_i/X_{sun})
Pignatari et al. 2008

DOUBLE SEQUENCE.

Blue Sequence

Red Sequence



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

Blue Sequence	Red Sequence
[Fe/H]=-1.26	[Fe/H]=-1.57
[C/M]=0	[C/M]=0
[N/M]=1-1.5	[N/M] < 1.0
[Ba/M]=0.7	[Ba/M]=0.4

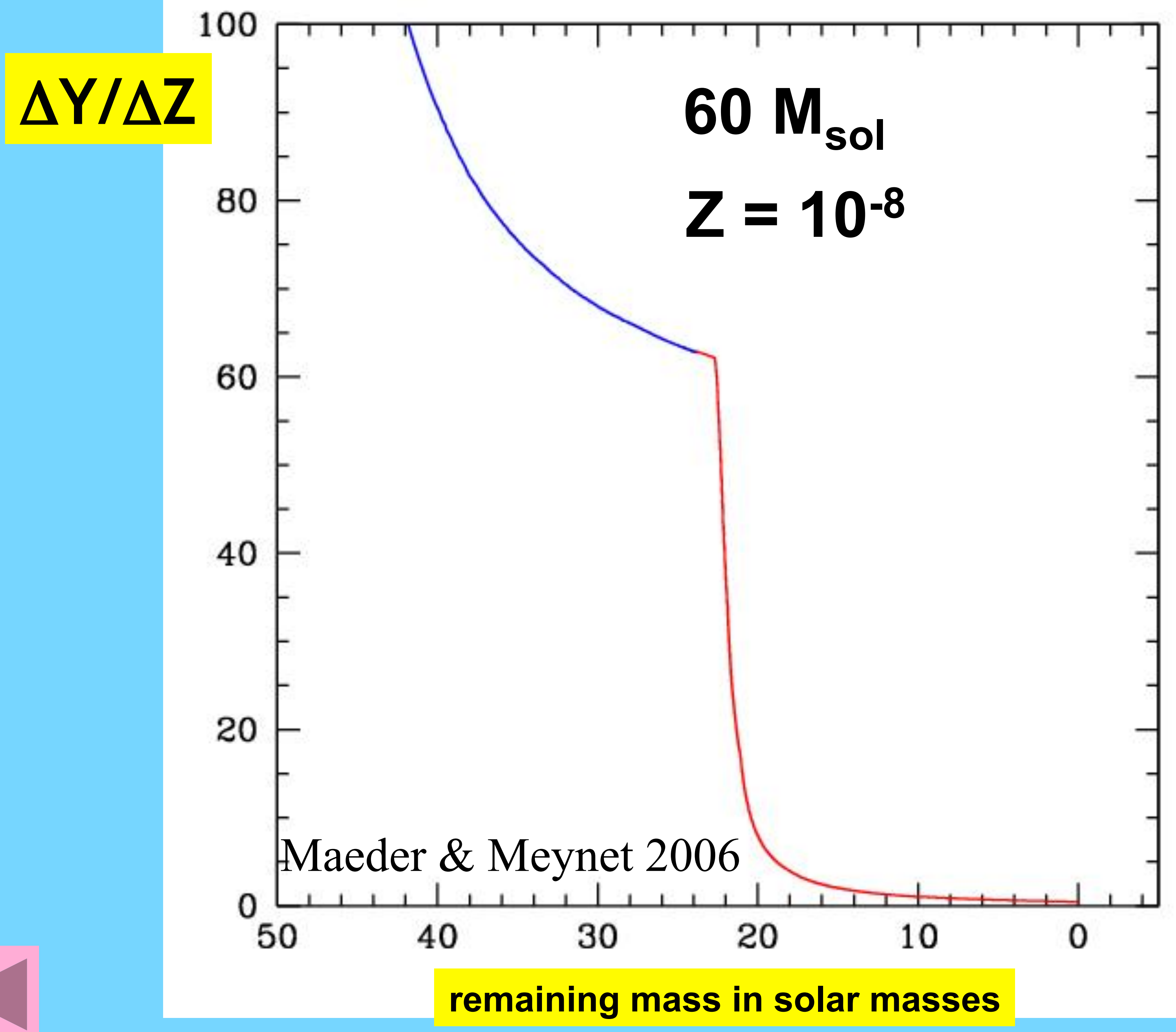
M→ Metals

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

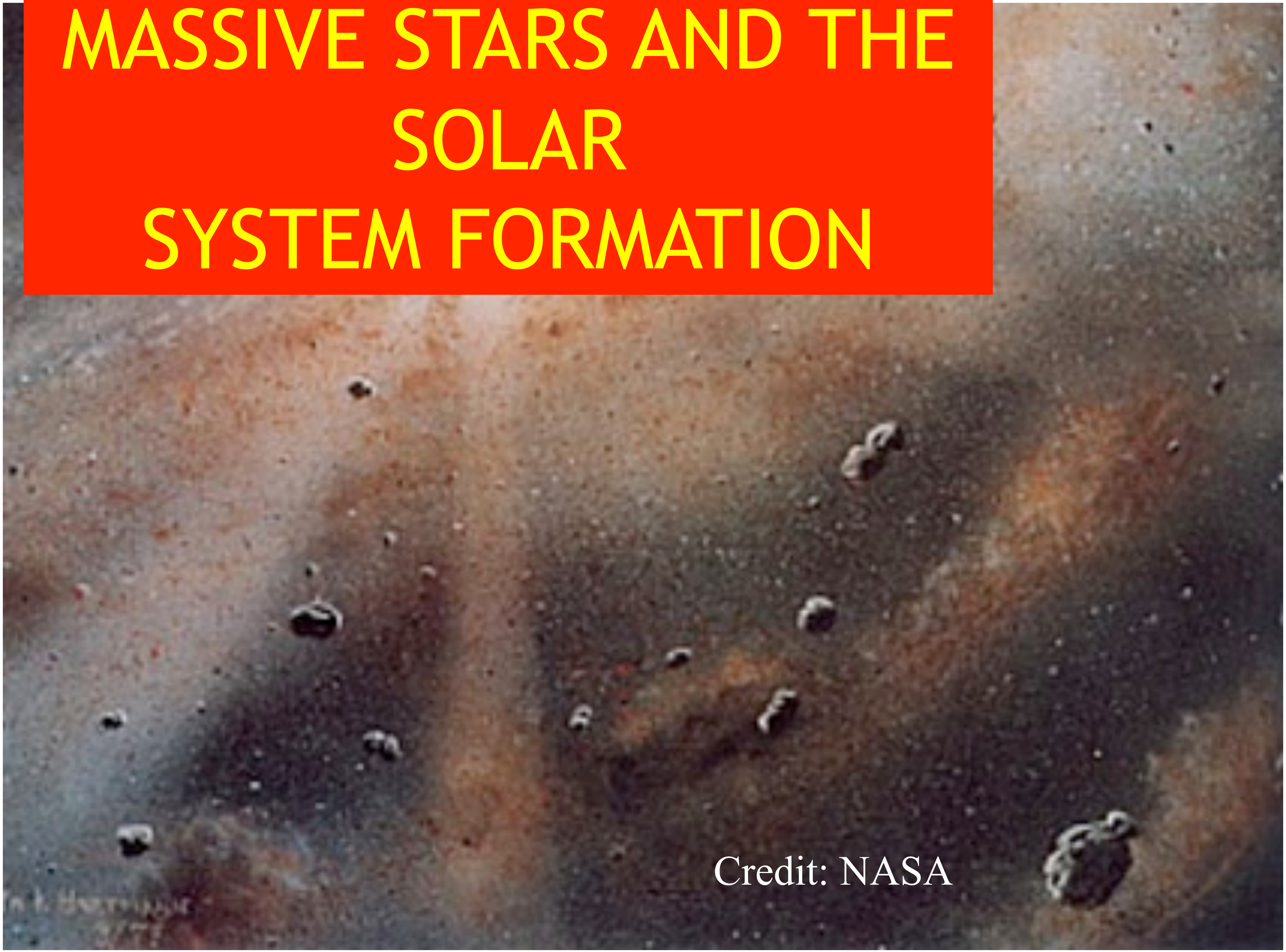
Y=0.38

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

Y=0.25


ΔY/ΔZ
100
80
60
40
20
0
50
40
30
20
10
0
60 M sol
Z = 10-8
Maeder & Meynet 2006
remaining mass in solar masses

MASSIVE STARS AND THE SOLAR SYSTEM FORMATION



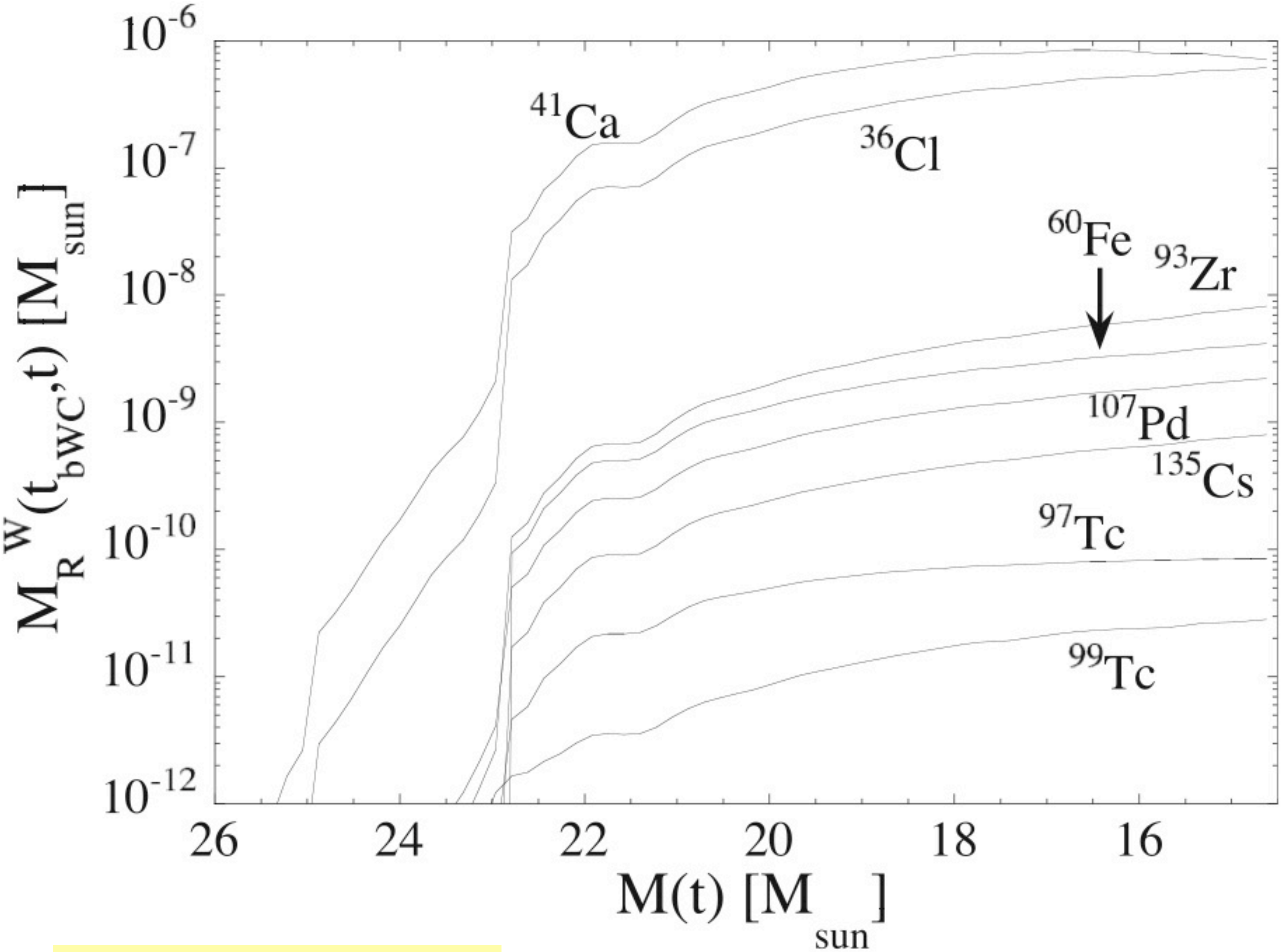
Credit: NASA

TABLE I

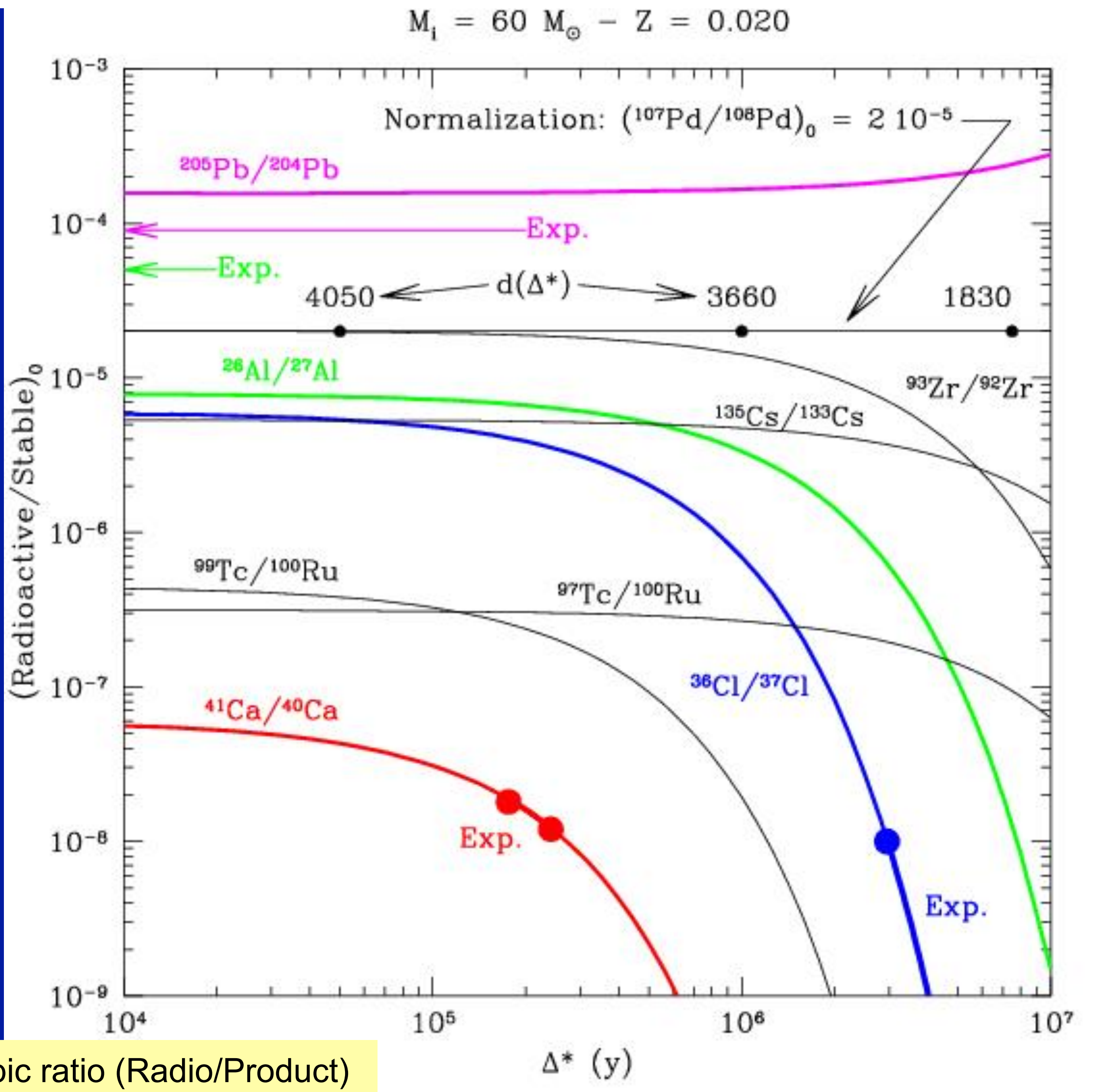
Data on short-lived radioactivities taken from Podosek and Nichols (1997)

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



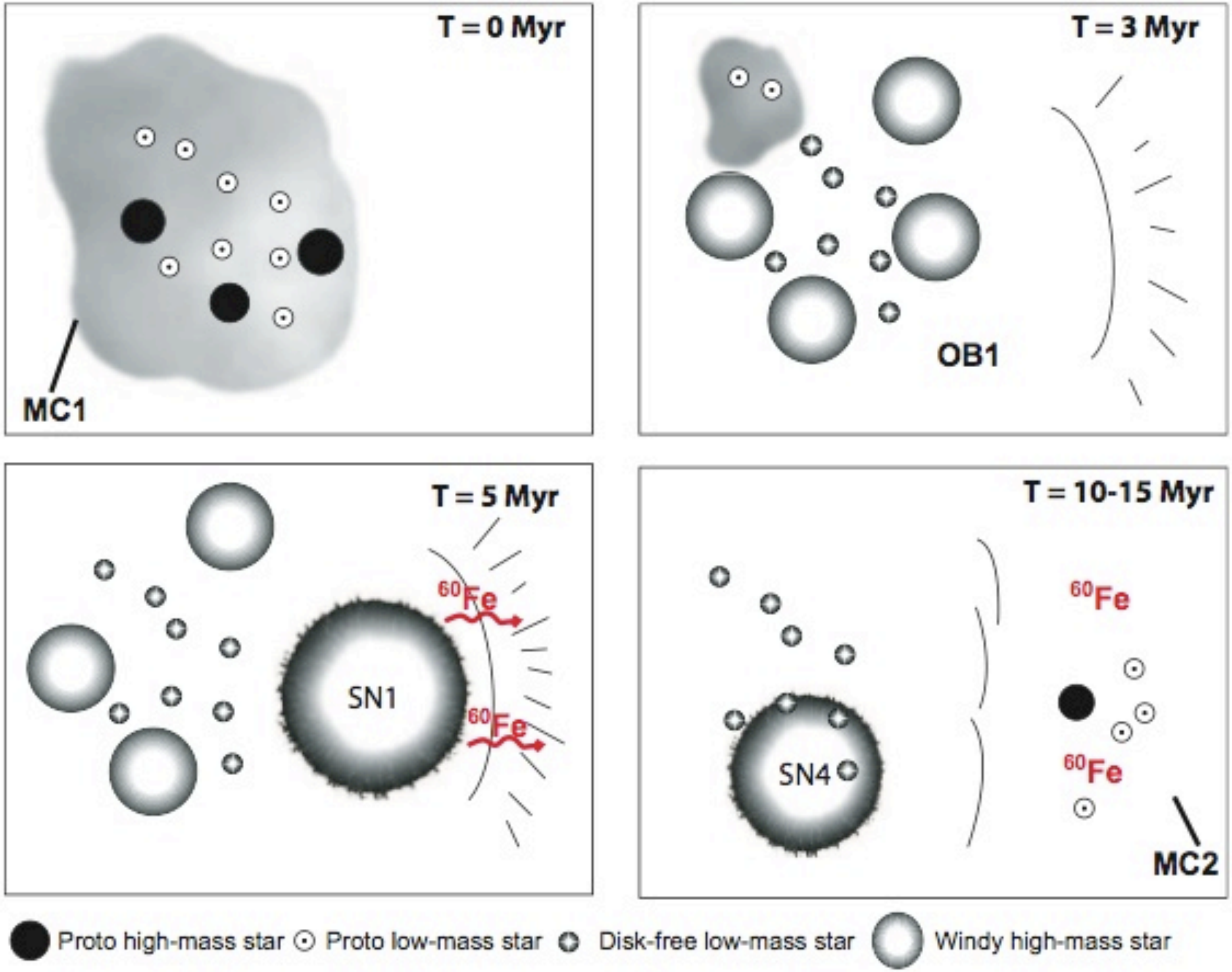
Arnould et al. 2006



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

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