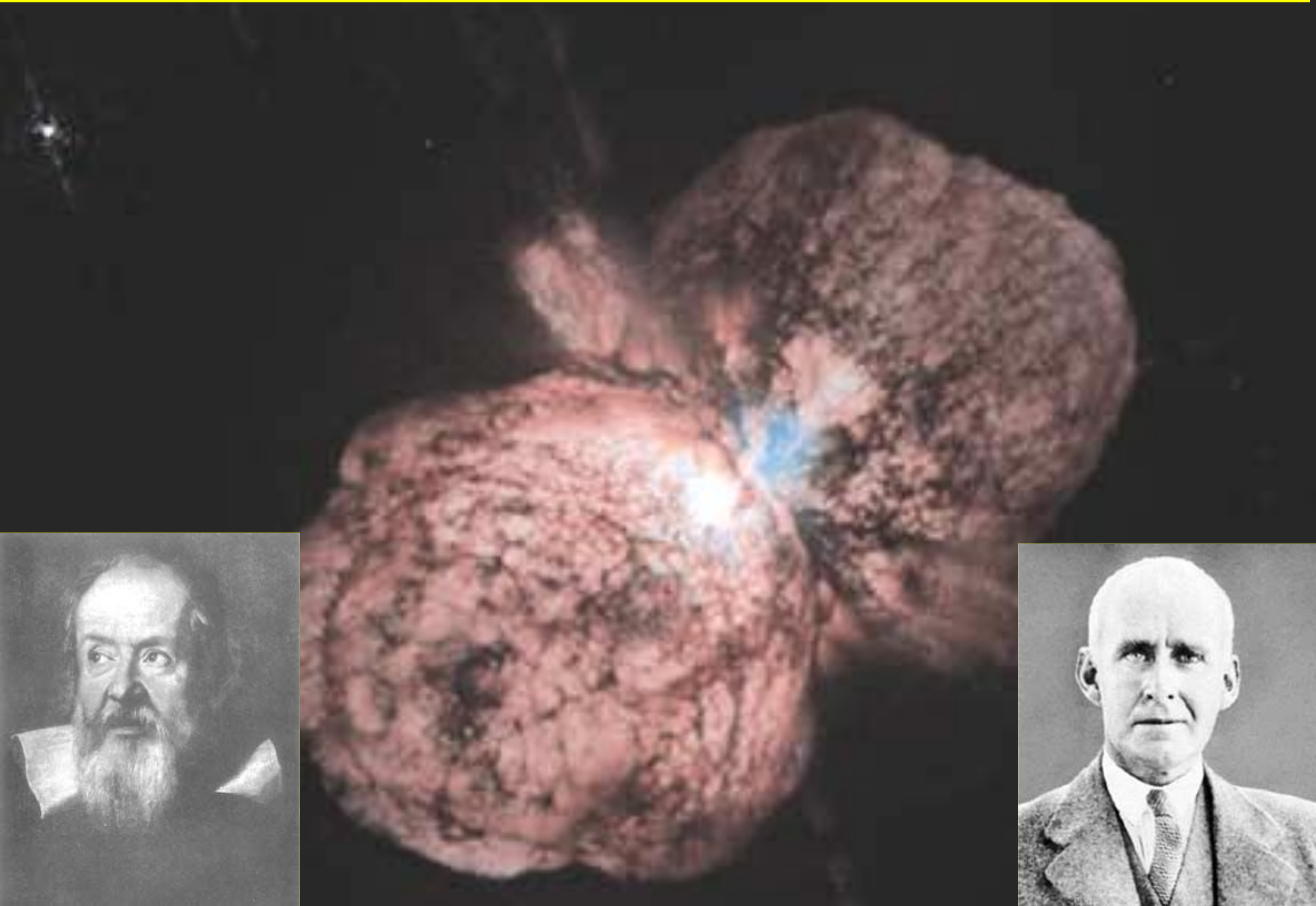
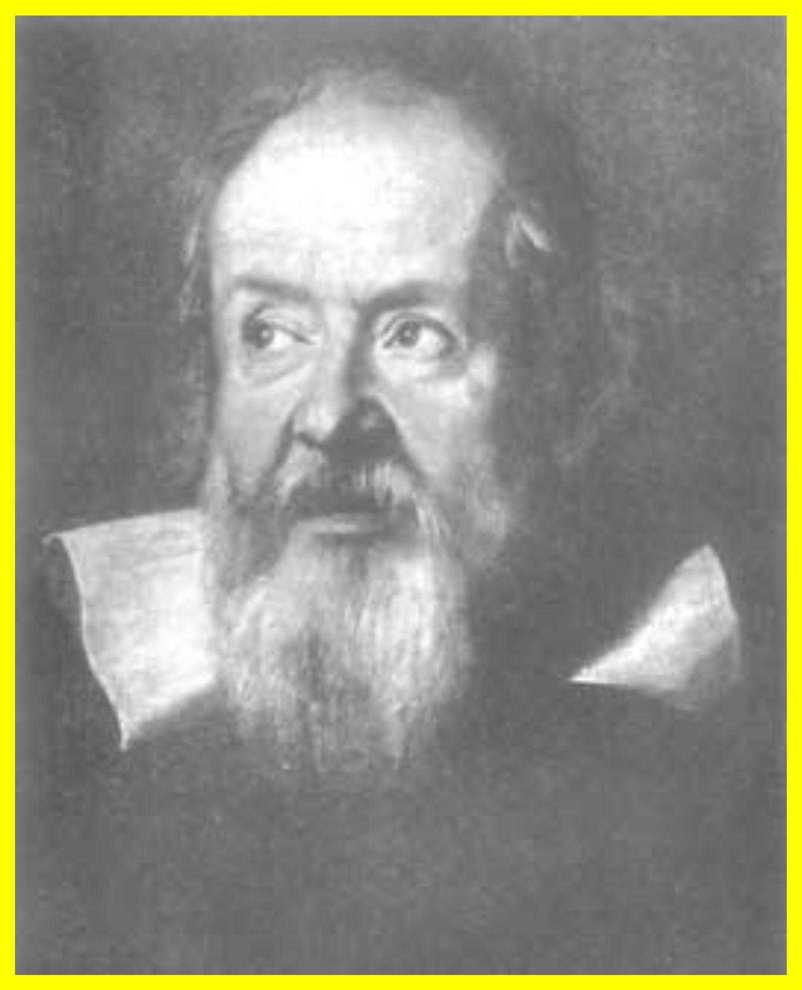
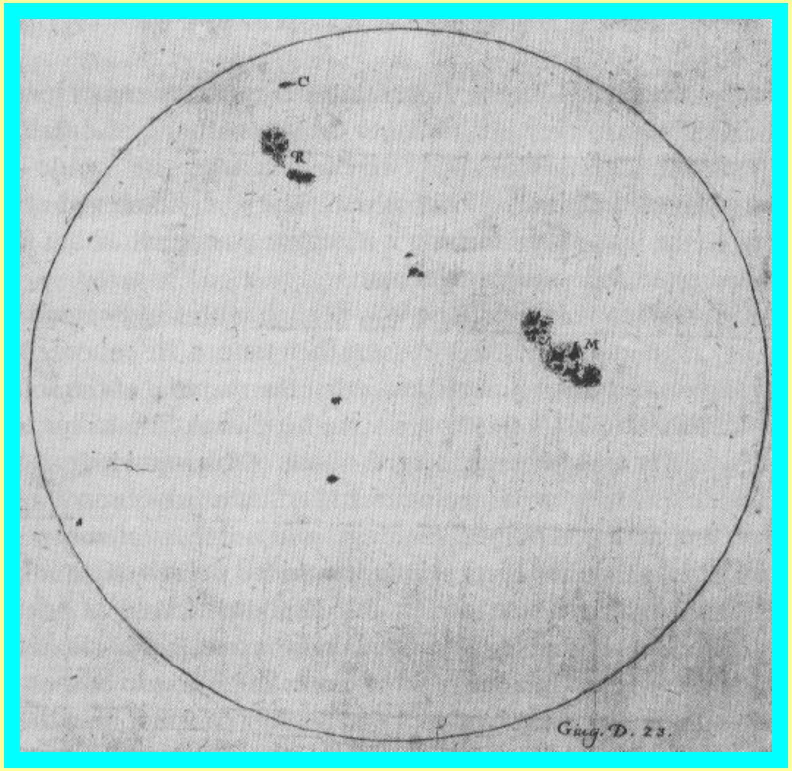
MASSIVE STAR EVOLUTION WITH ROTATION



ROTATION…

An old topic…





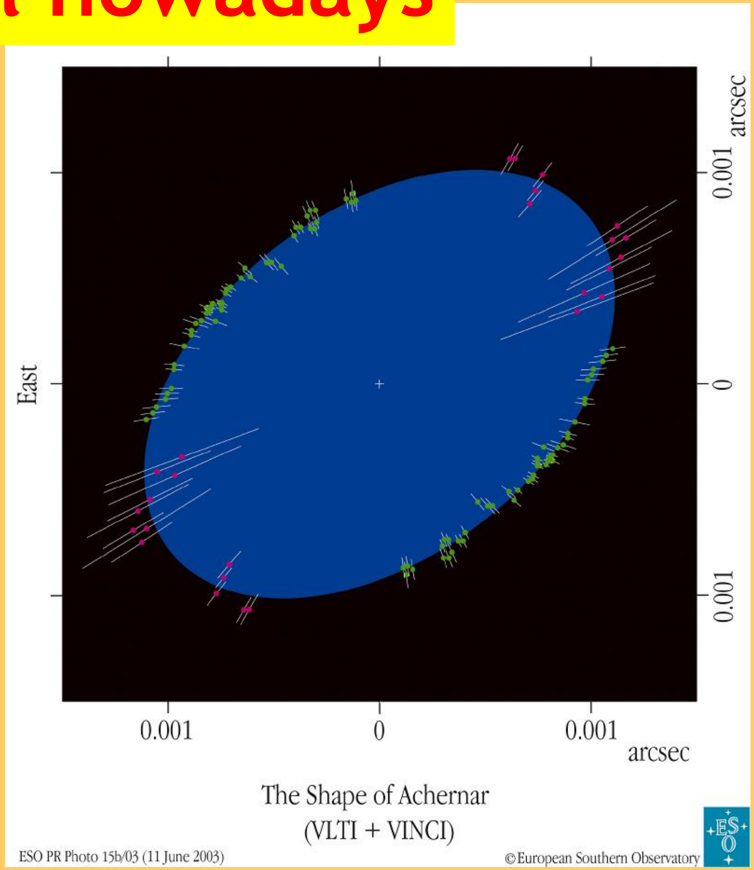
Von Zeipel 1924; Eddington 1925; Vogt 1925

… 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



The Shape of Achernar
(VLTI + VINCI)

ESO PR Photo 15b/03 (11 June 2003)

©European Southern Observatory

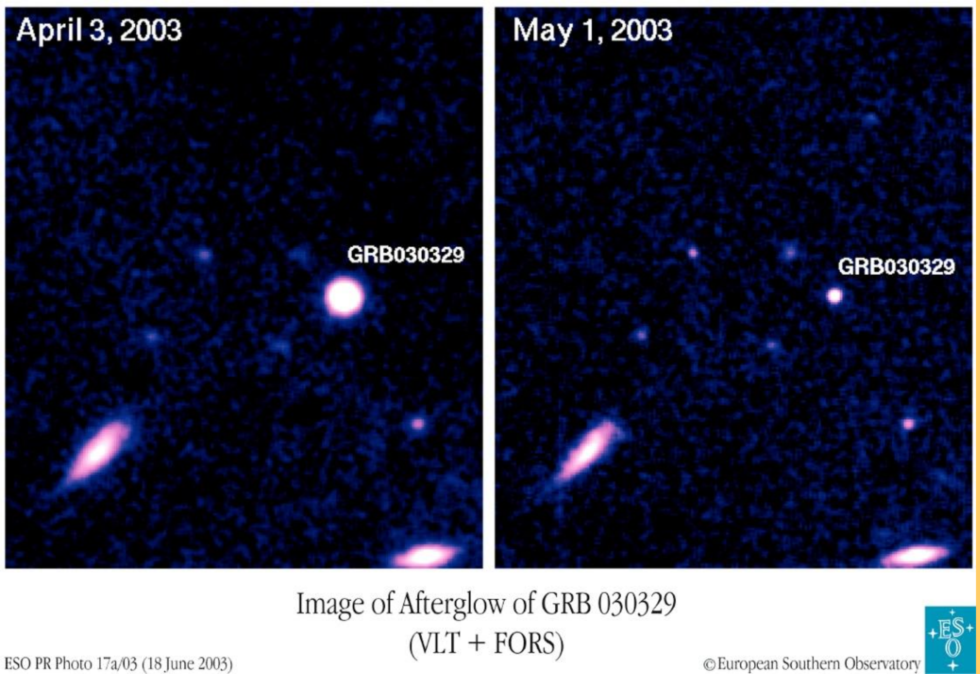


Image of Afterglow of GRB 030329
(VLT + FORS)

ESO PR Photo 17a/03 (18 June 2003)

©European Southern Observatory

Link between Long GRB and Hypernova confirmed

Hjorth et al. 2003

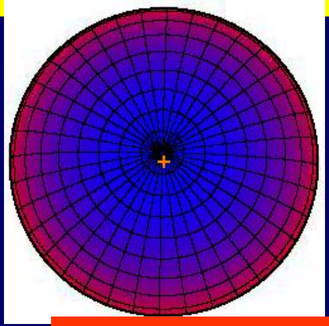
Rapid Rotators:
Interferometric observations

Achernar
$9.6M_{sol}$

Regulus
$3.4M_{sol}$

McAlister al. 2005

Vega
$2.3M_{solt}$

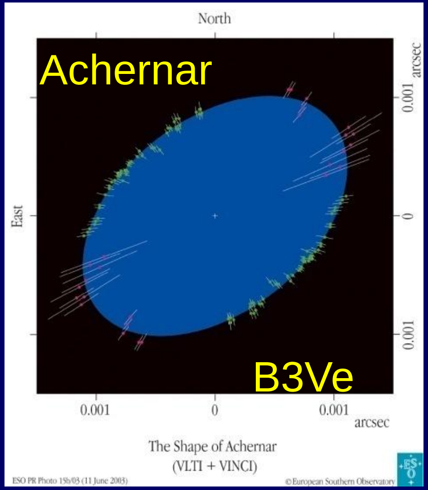


Aufdenberg et al. 2006

Achernar

B3Ve

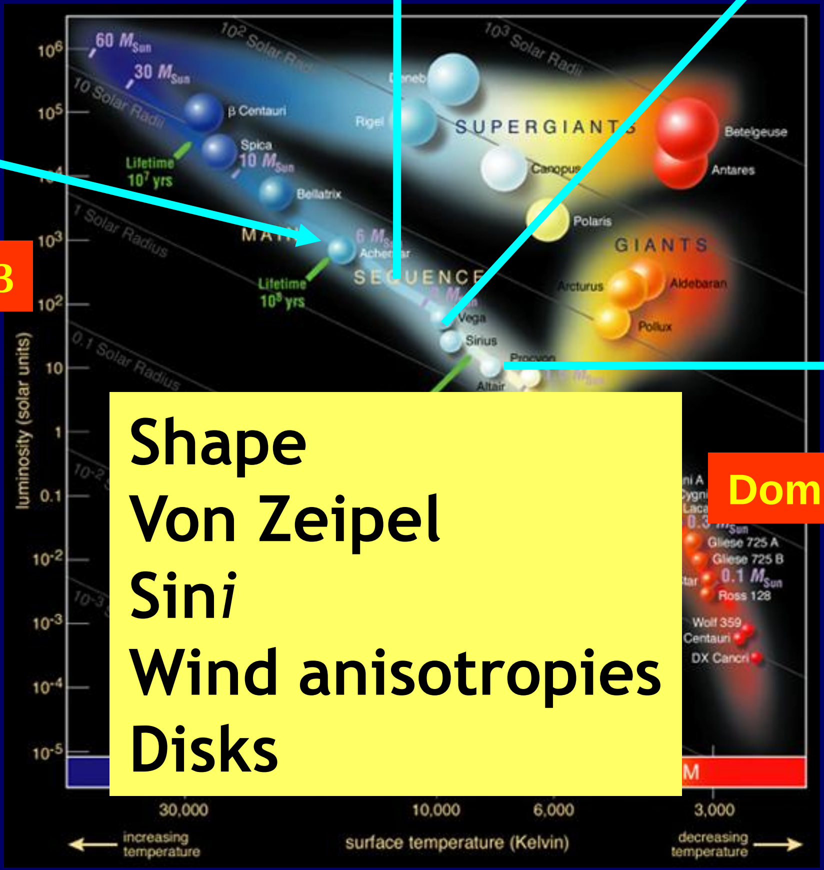
Domiciano de Souza et al. 2003



Achernar

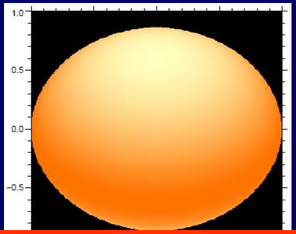
B3Ve

The Shape of Achernar
(VLTI + VINCI)

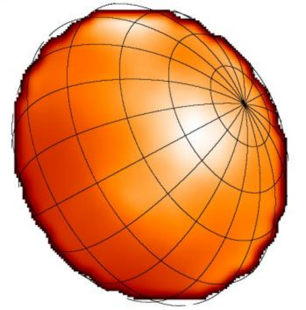


Shape
Von Zeipel
Sin*i*
Wind anisotropies
Disks

Altair
$1.8\ M_{solt}$



Domiciano de Souza et al. 2005

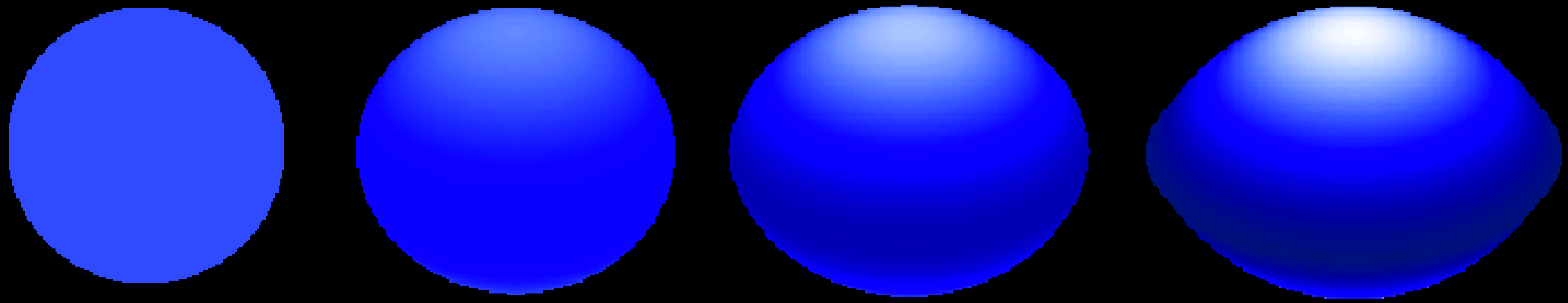


Monnier et al. 2007

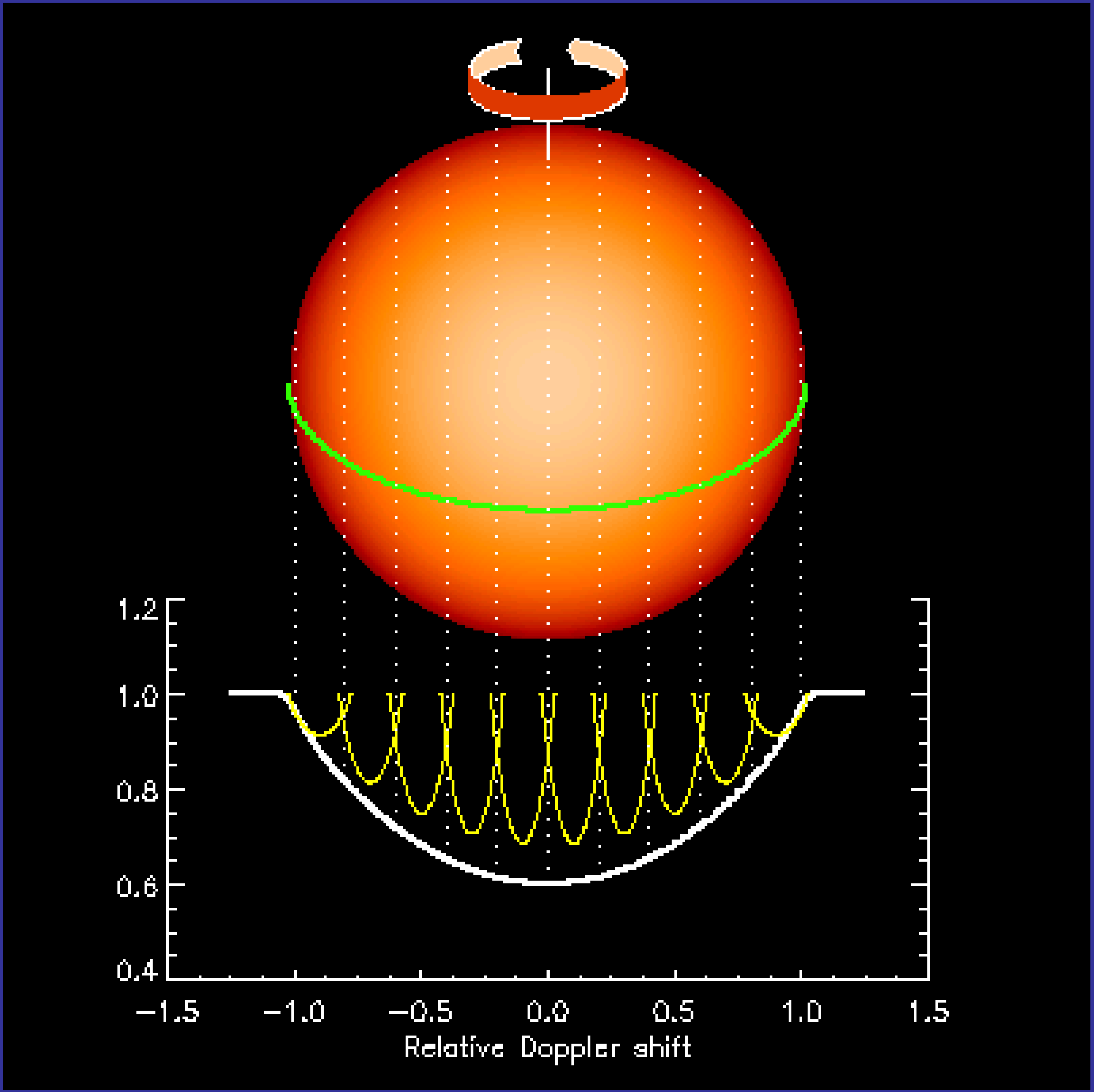
Adapted from a vewgraph of Domiciano de Souza

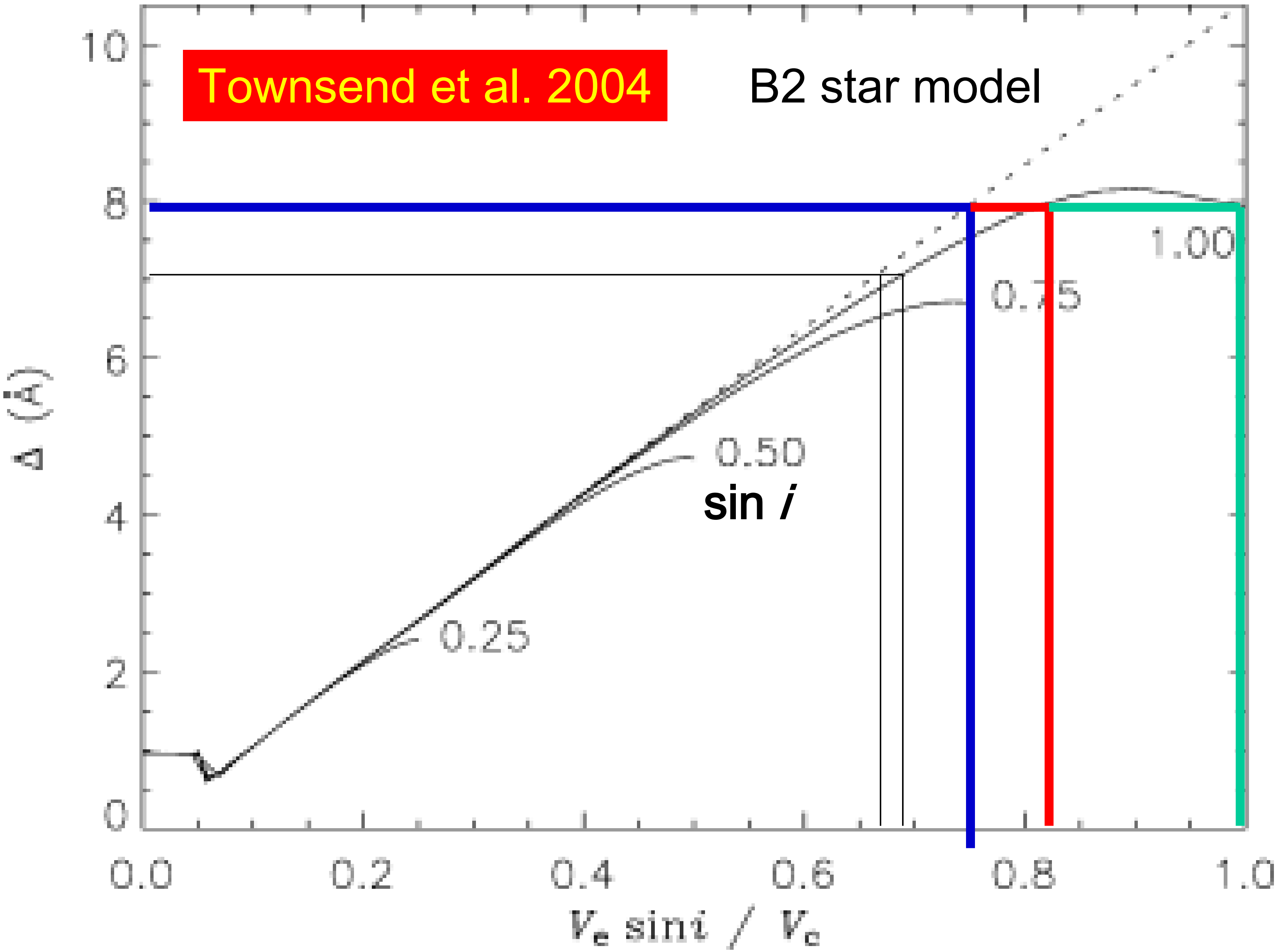
Gravity (equatorial) Darkening

increasing stellar rotation →



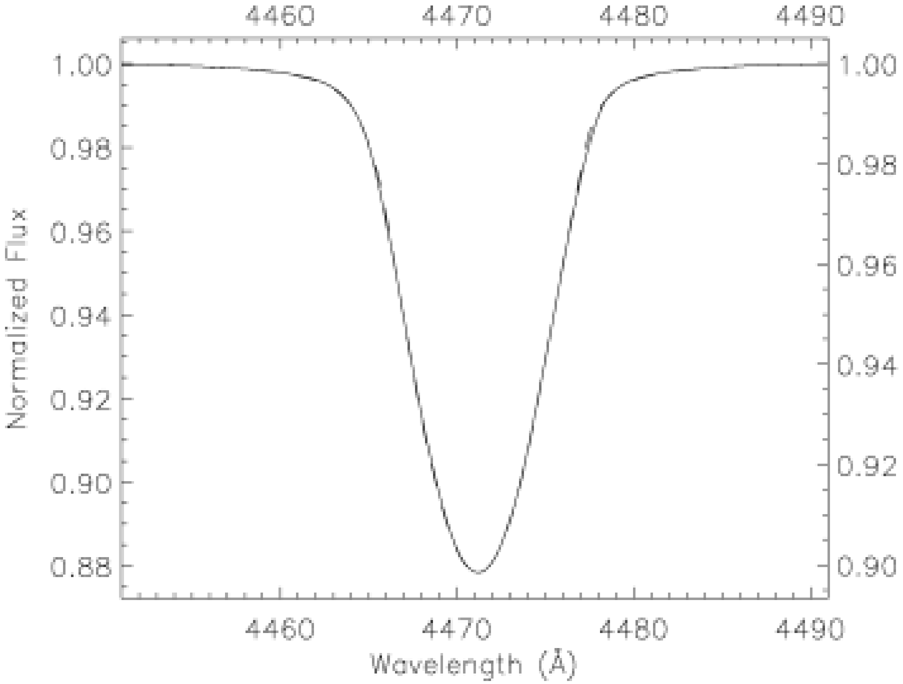
Doppler-broadened line profile



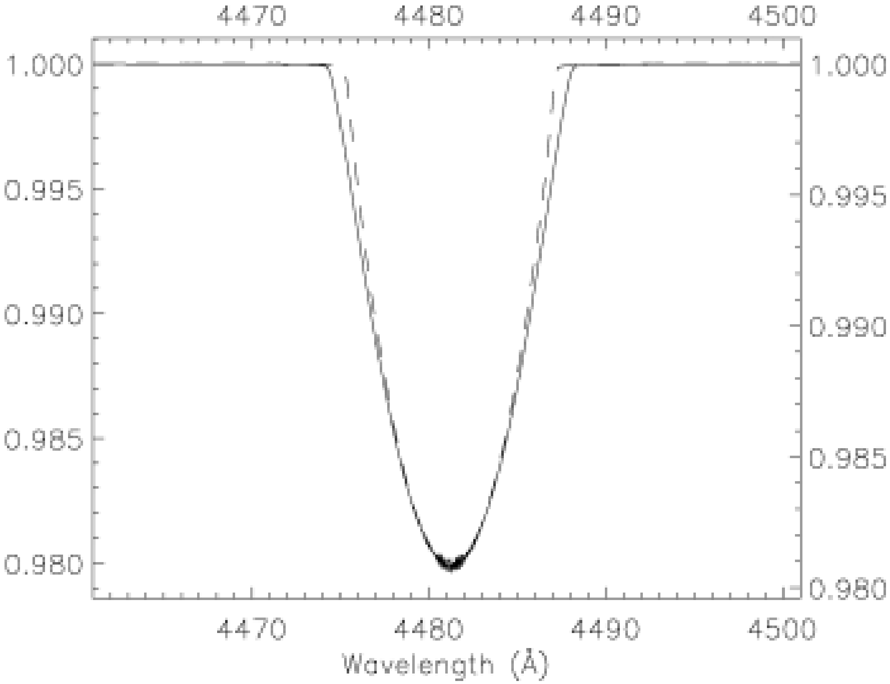

Townsend et al. 2004
B2 star model
10
8
6
4
2
0
Δ (Å)
1.00
0.75
0.50
sin i
0.25
0.0
0.2
0.4
0.6
0.8
1.0
V_e sin i / V_c

Theoretical line profile for equator on model

Townsend et al. 2004



He I 4471



Mg II 4481

B2 stellar model

Solid line 395 km/s

Dashed line 460 km/s

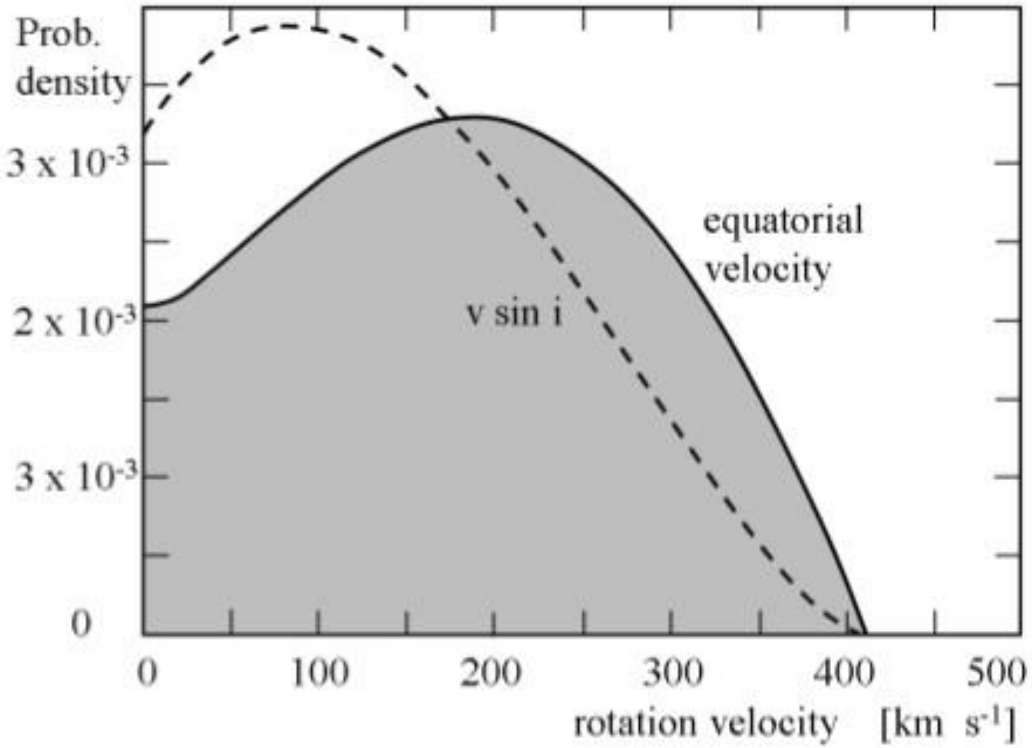
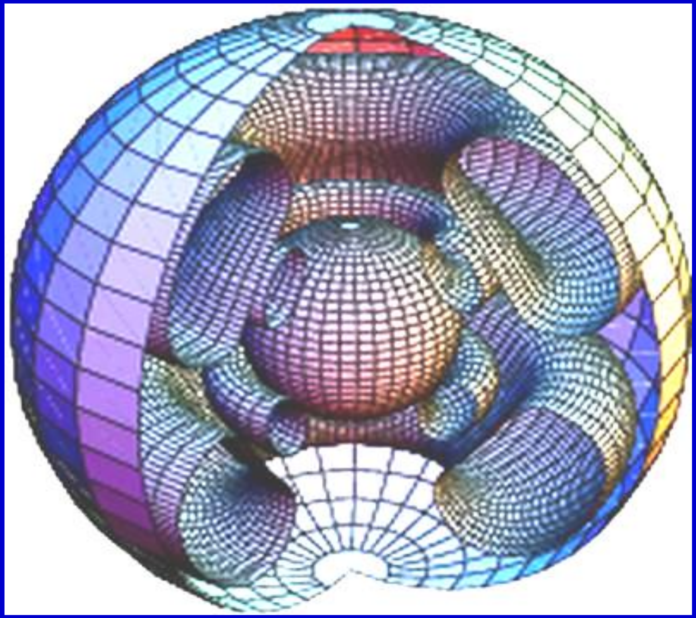
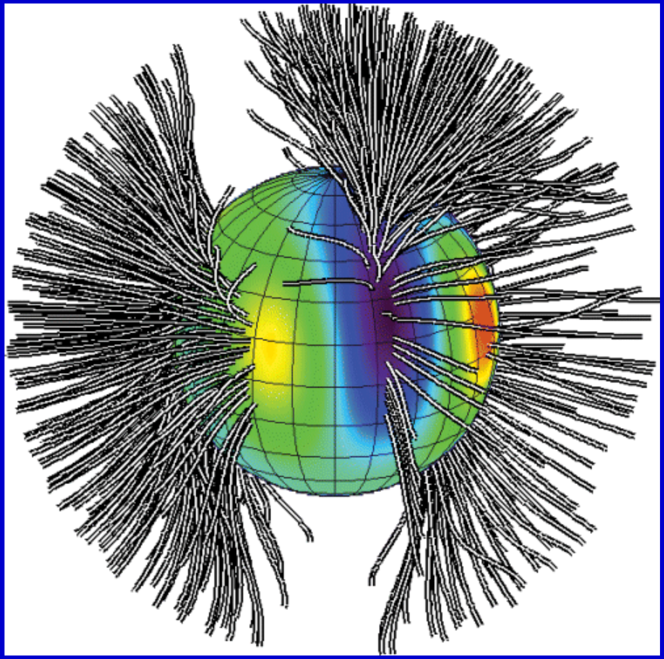


Fig. 27.1. Probability density by km s^{-1} of rotation velocities for 496 stars with types O9.5 to B8. Adapted from W. Huang and D.R.Gies [259]





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

Evolution
Meridional circulation

Shear mixing
Horizontal turbulence

↔

Gradients of Ω
4th order syst.

Zahn,'92

Transport of the chemical species

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

Transport of the angular momentum

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

Advection ! **Diffusion !**

Evolution of $\Omega(r)$ during the Main Sequence

Ω decreases inside the star

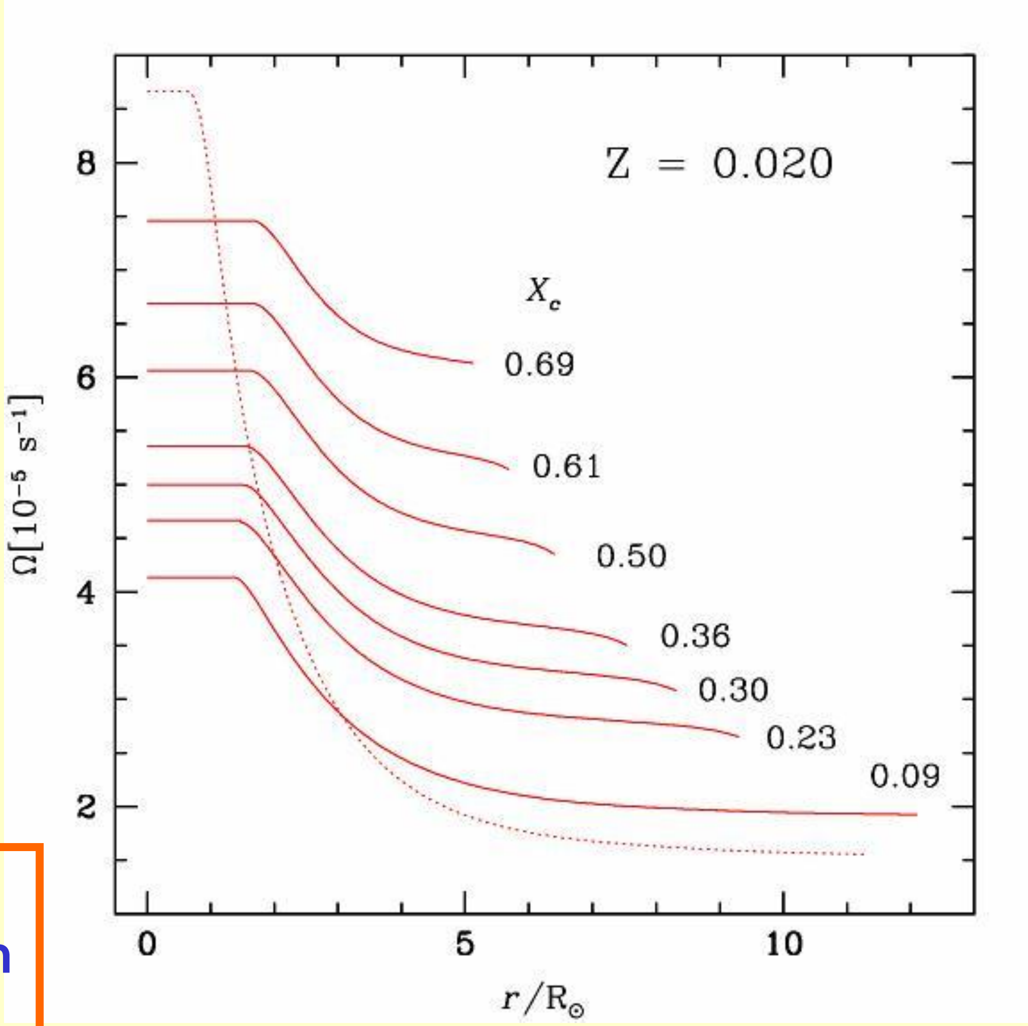
Removal of angular momentum
at the surface by the stellar winds

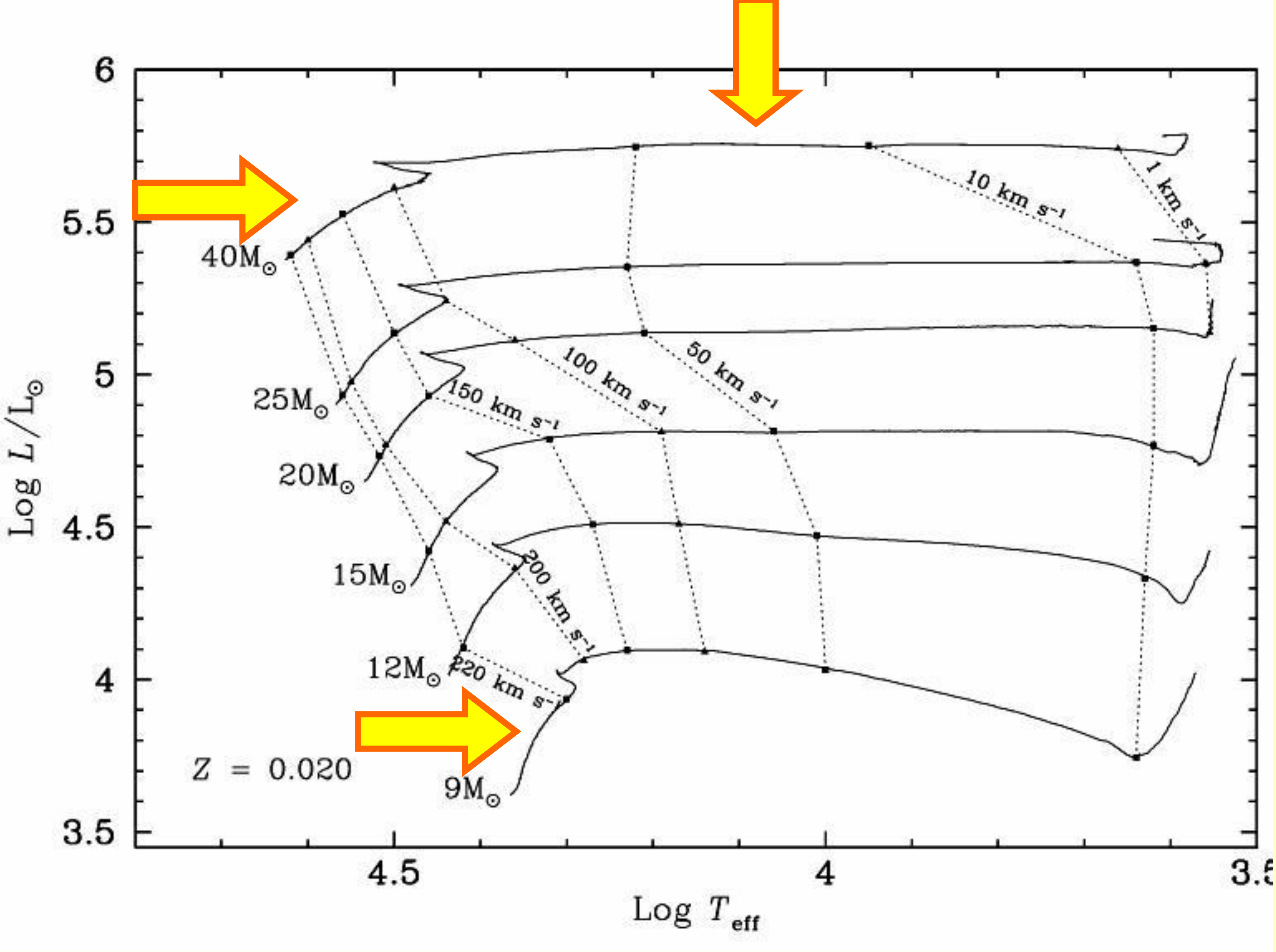
Transport of angular momentum

Increase of the radius

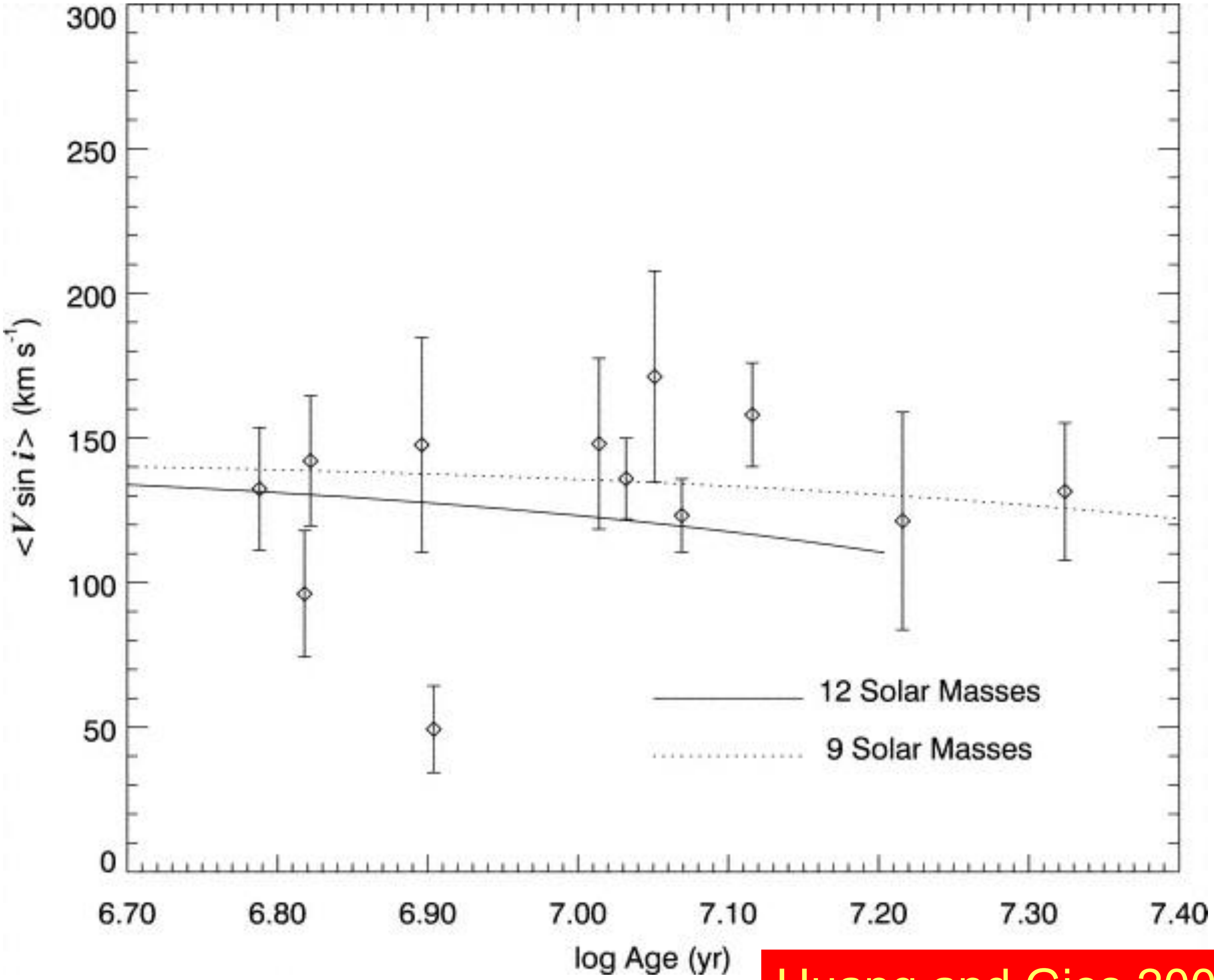
- ▫ Gradients of Ω modest but essential for chemical mixing

- ▫ 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

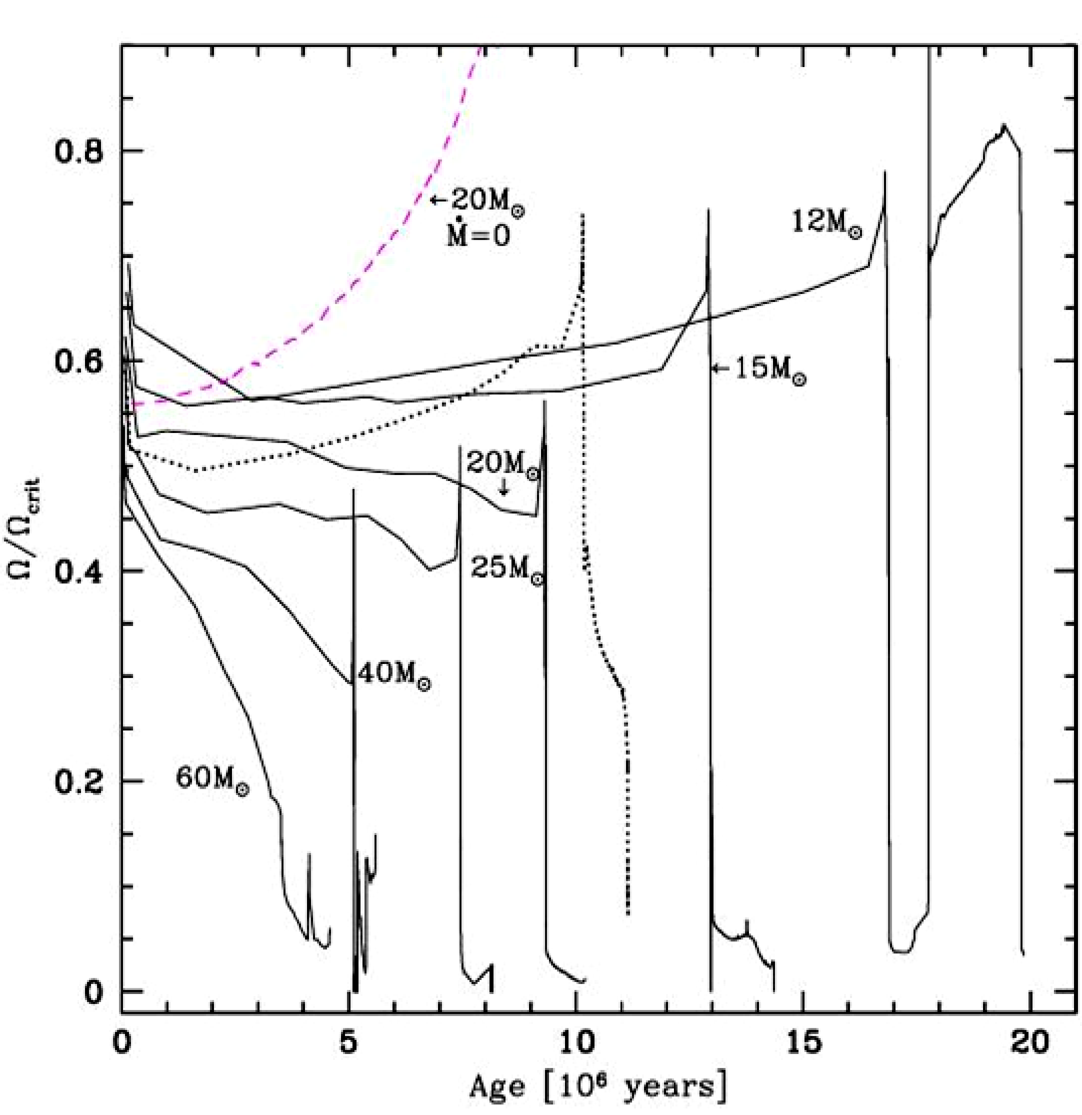
Break-up possible

LBV

Be stars

Z=0.02

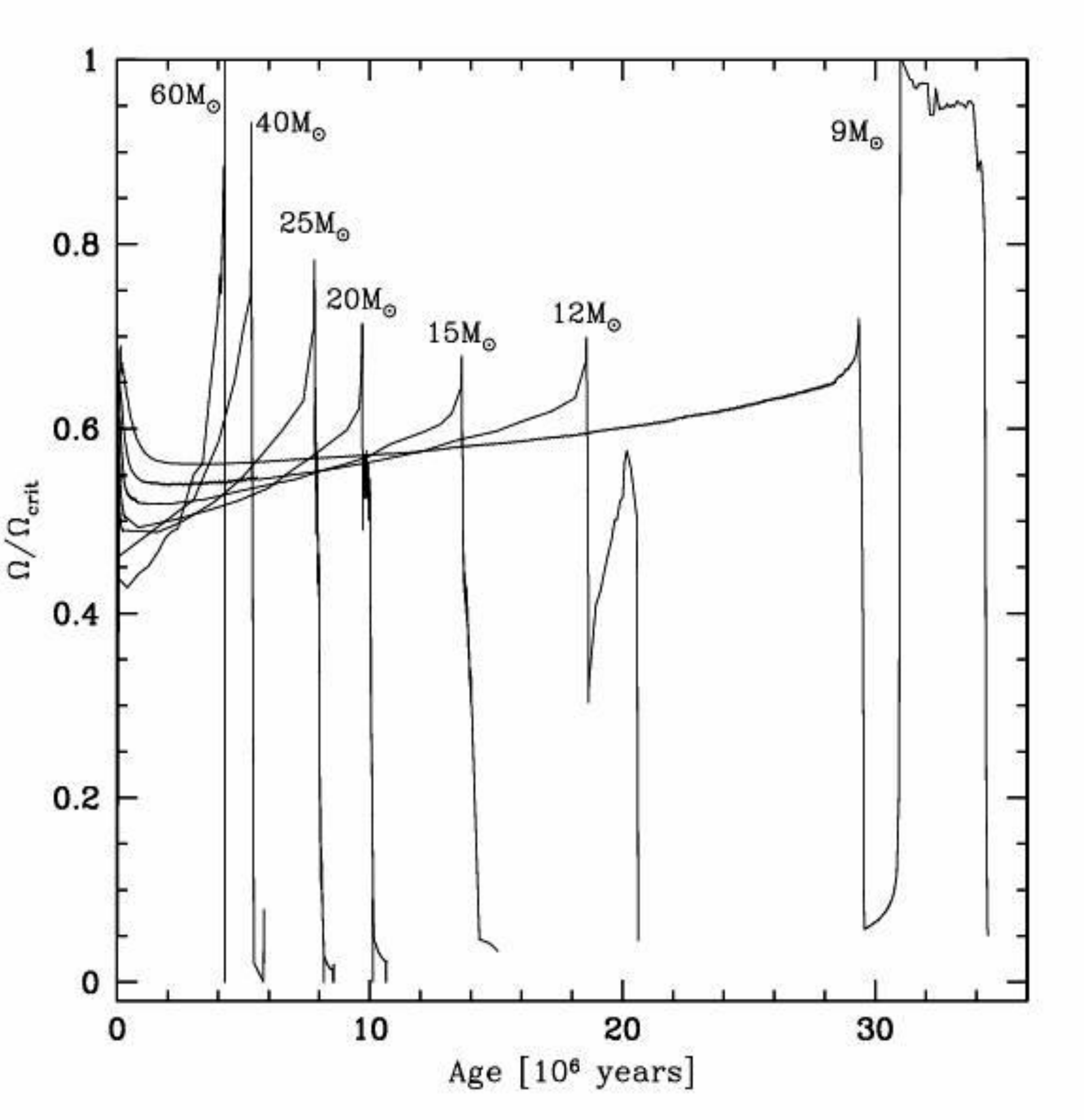
At Z=0.02, drastic decrease of for high masses

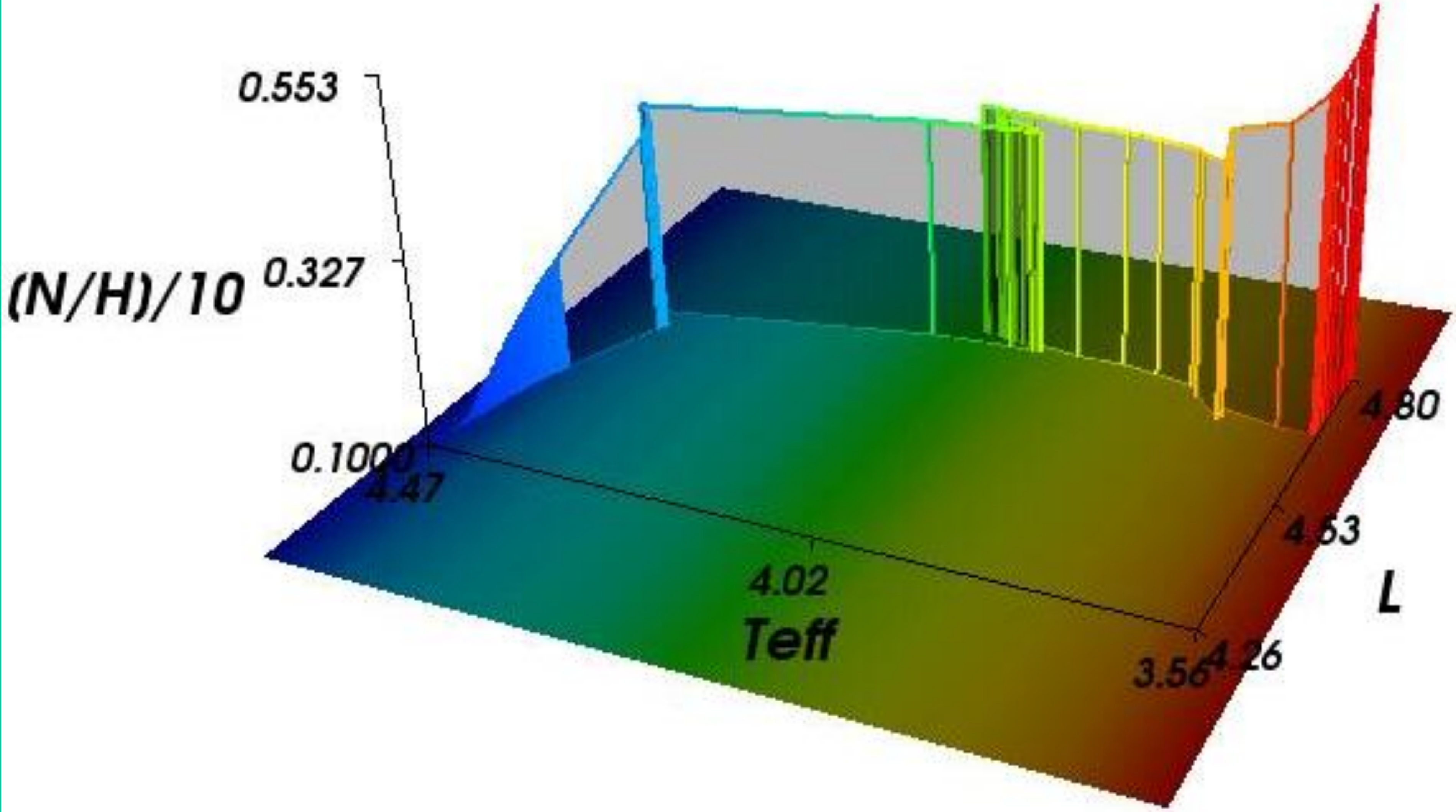


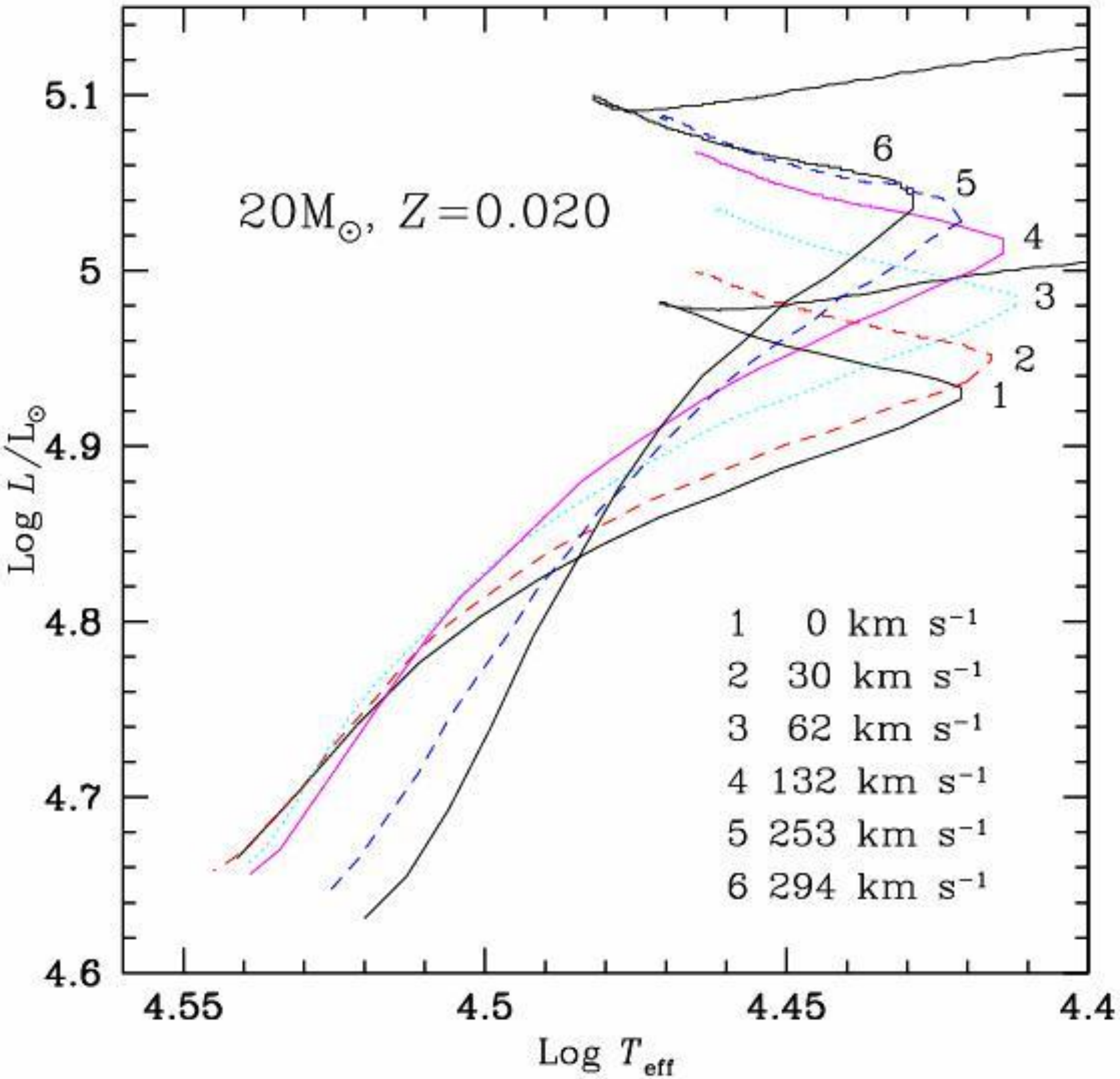
Z=0.004

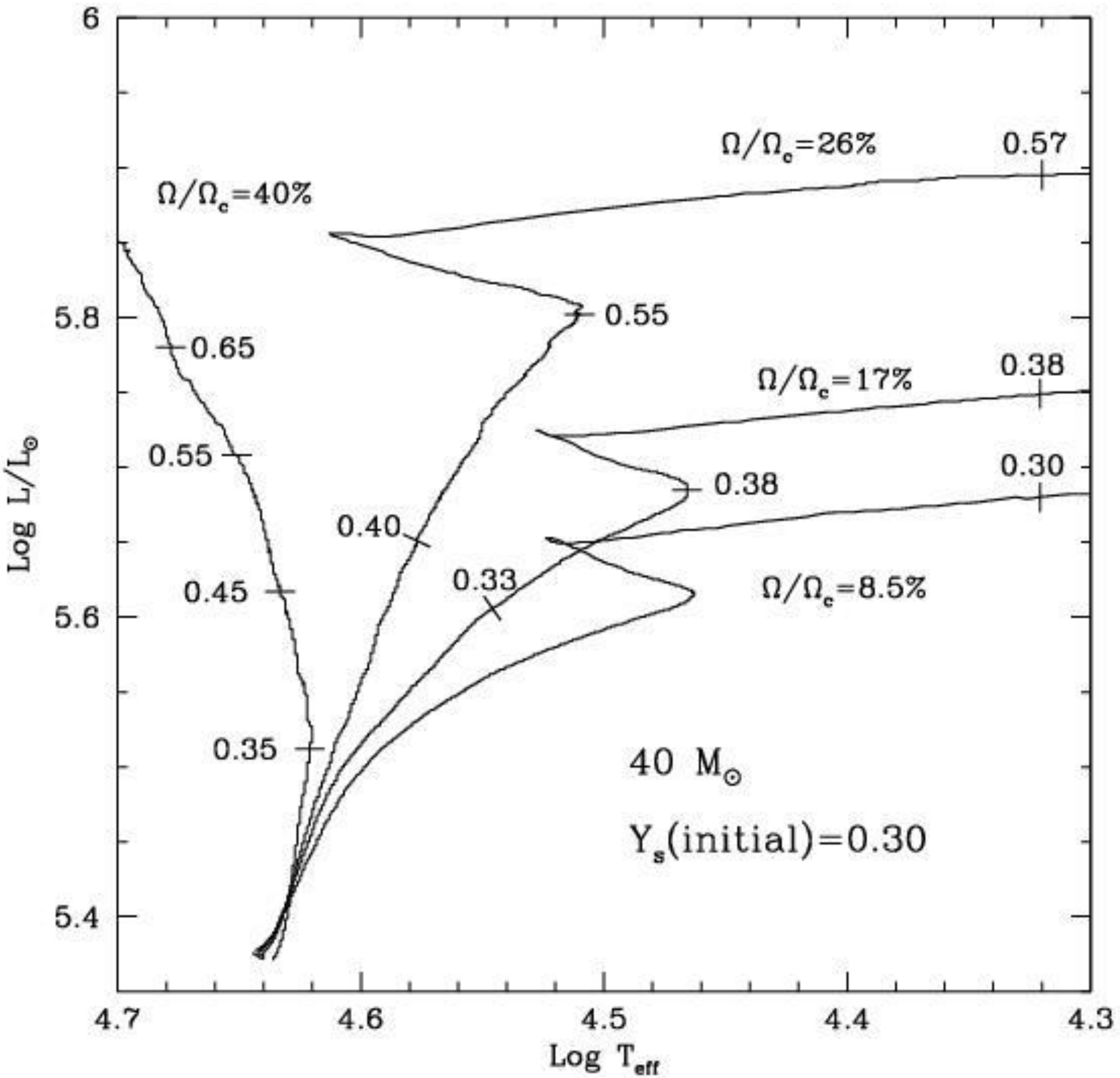
At lower Z, more stars reach break-up velocities.

PARADOXICAL !




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


20M$_\odot$, Z=0.020
Log $L/L_\odot$
Log $T_{\rm eff}$
5.1
5
4.9
4.8
4.7
4.6
4.55
4.5
4.45
4.4
1
2
3
4
5
6
1 0 km s^{-1}
2 30 km s^{-1}
3 62 km s^{-1}
4 132 km s^{-1}
5 253 km s^{-1}
6 294 km s^{-1}


6
5.8
5.6
5.4
4.7
4.6
4.5
4.4
4.3
Log L/L$_\odot$
Log T$_{eff}$
Ω/Ω$_c$=40%
Ω/Ω$_c$=26%
Ω/Ω$_c$=17%
Ω/Ω$_c$=8.5%
0.57
0.55
0.65
0.55
0.45
0.35
0.40
0.38
0.38
0.30
0.30
0.33
40 M$_\odot$
Y$_s$(initial)=0.30

WHY MIXING IN MASSIVE STARS ?

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

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

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

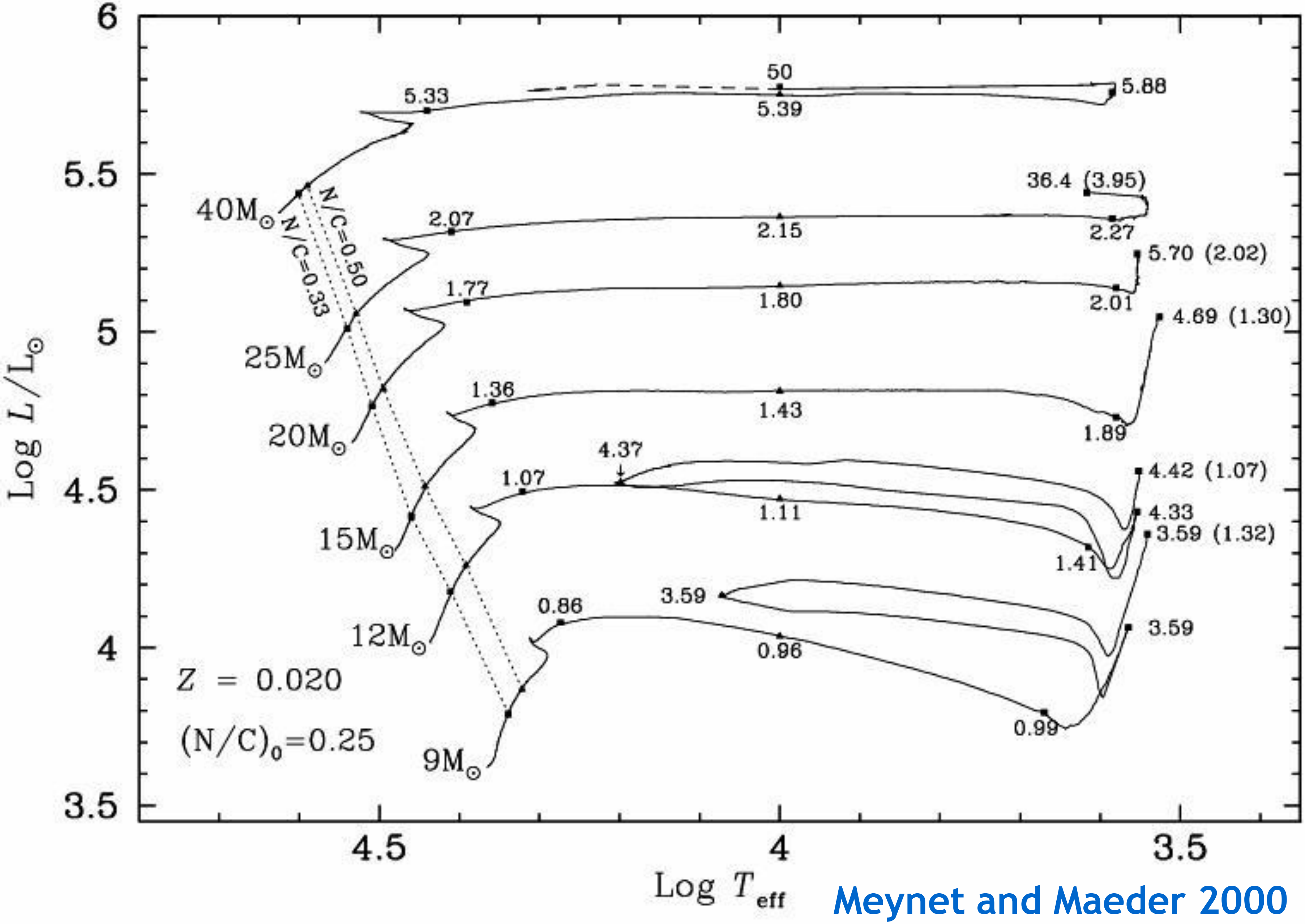
→

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

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

FOR HIGH M

MIXING TIME / MS TIMESCALE SMALL

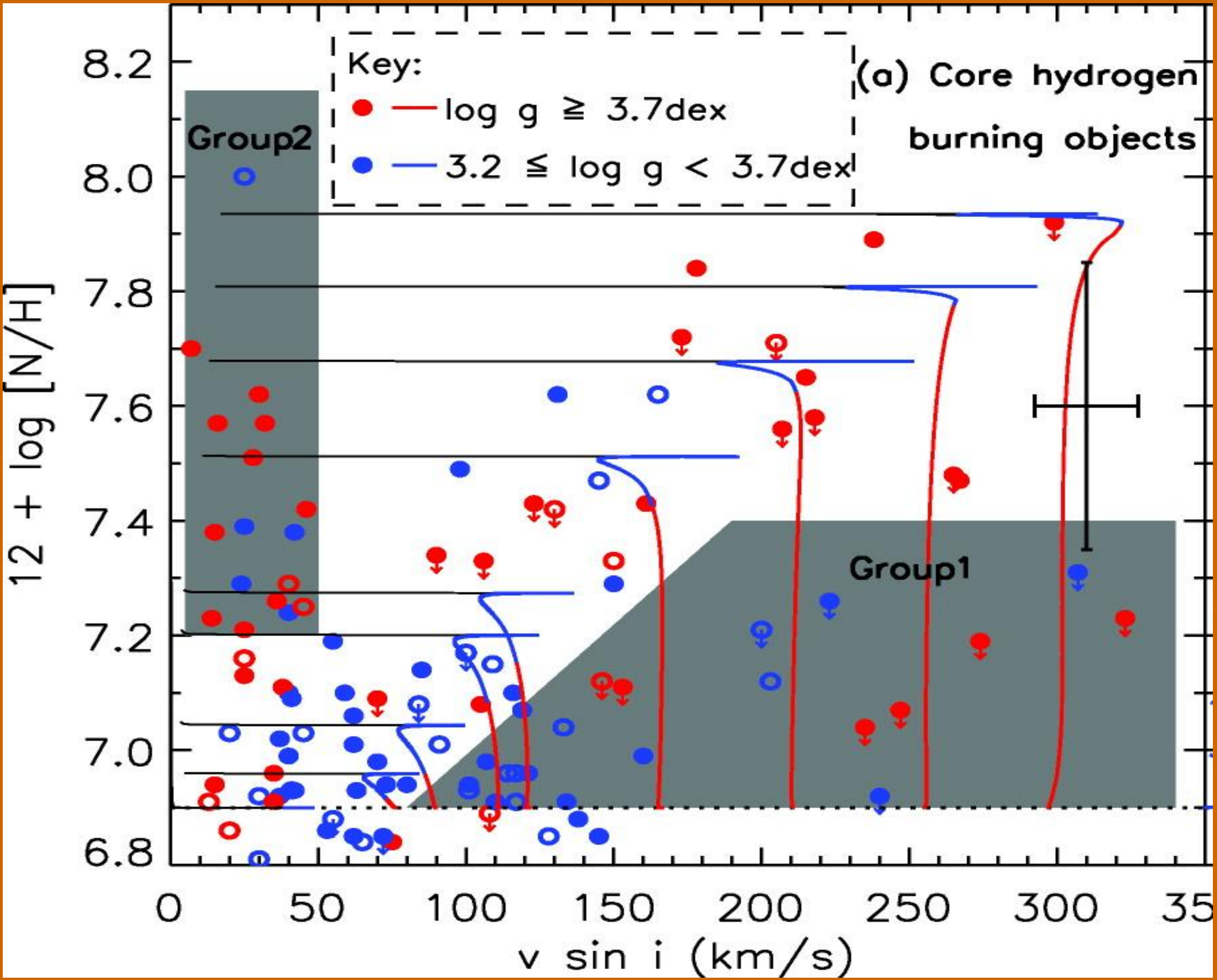


Meynet and Maeder 2000

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

Spread in masses and ages.

Sample biased toward low v sini



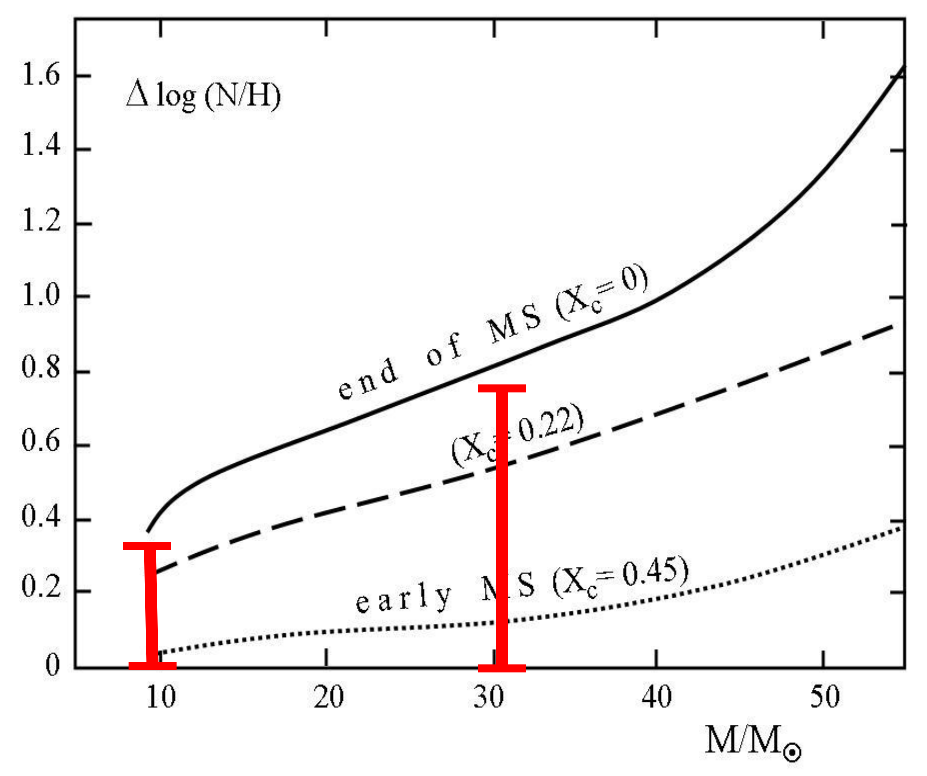
« The observation challenges the concept of rotational mixing »
Hunter et al. 2008

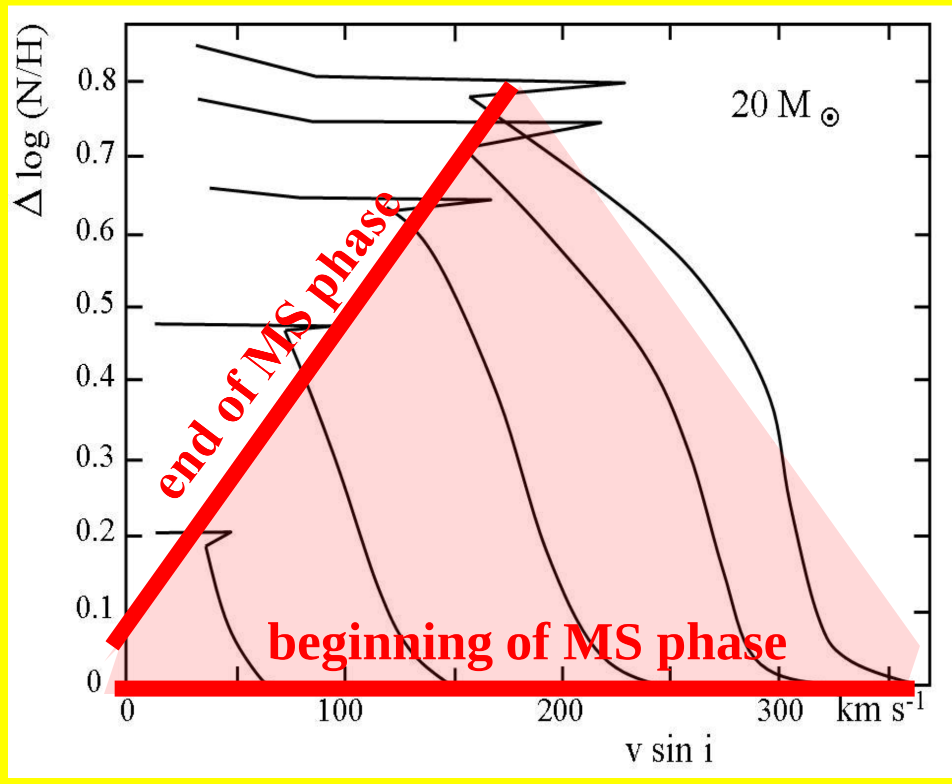
Reality: $\Delta\log(N/H) = f(v \sin i, M, \text{age}, Z, \text{binary}, \text{field} \ldots.)$

not : $\Delta\log(N/H) = f(v \sin i)$

Mass effect

Age effect



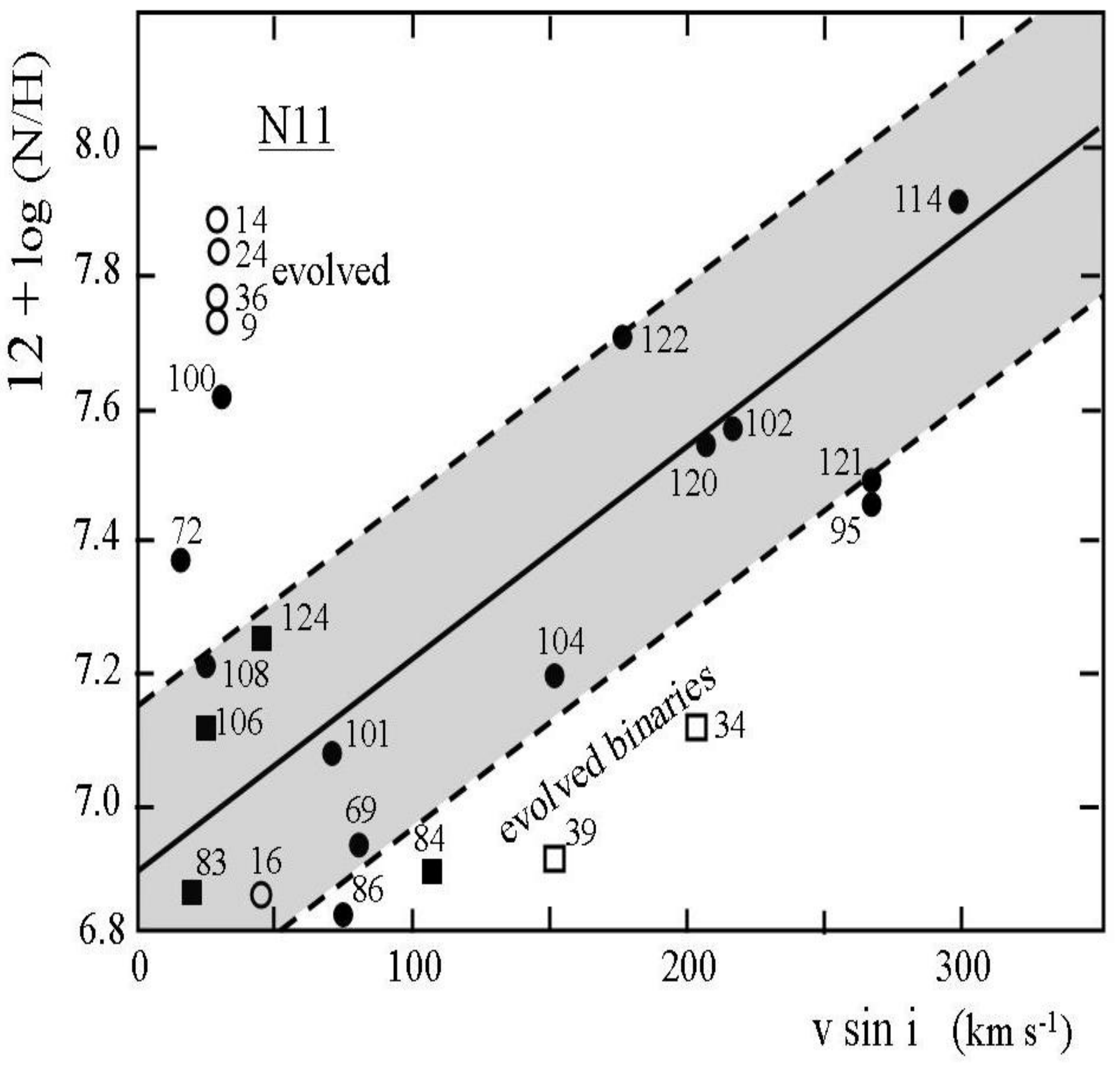


MS stars between 14 and 20 M_{sol} in the list by Hunter et al. 2008

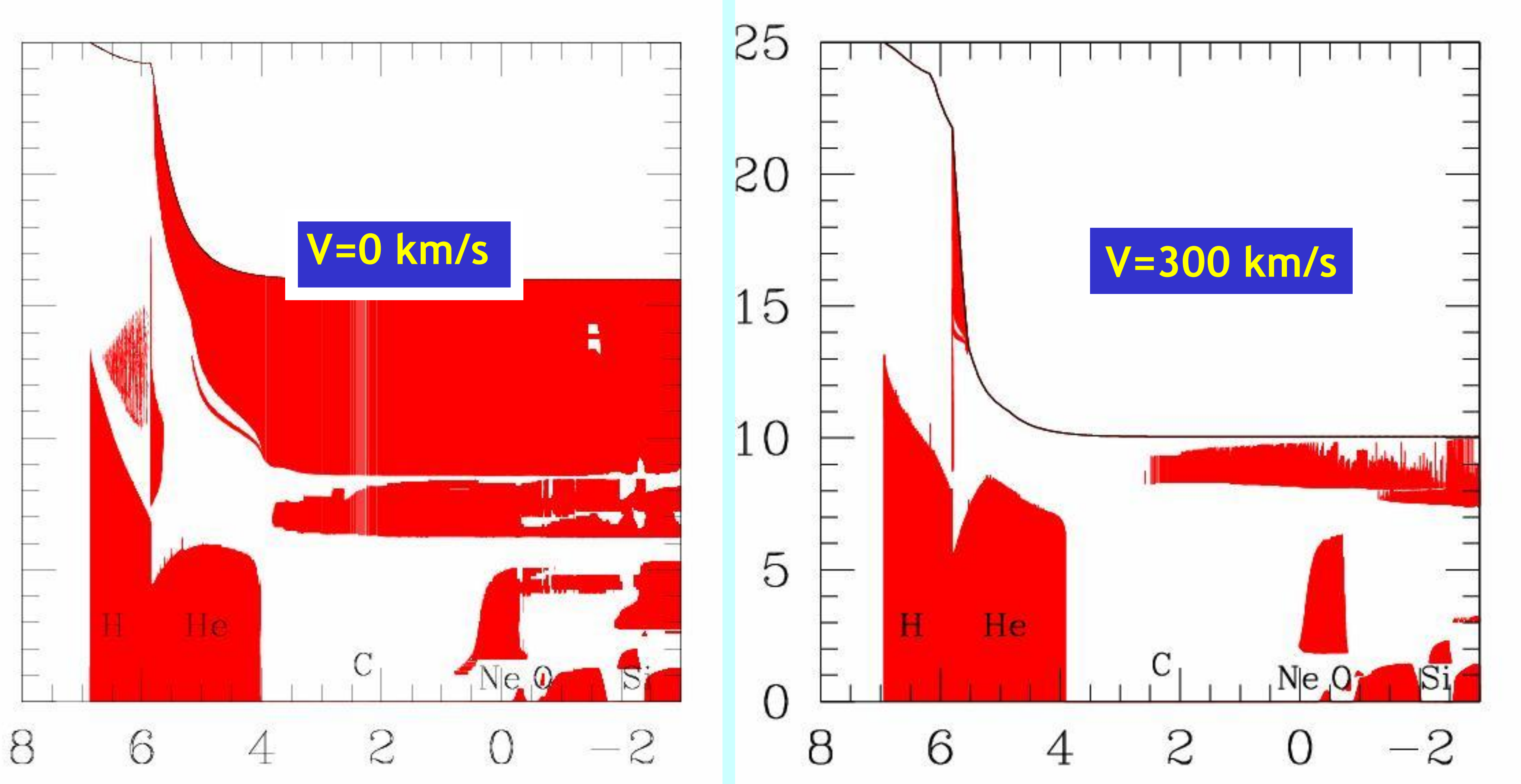
Gr 1 disappeared, except binaries

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



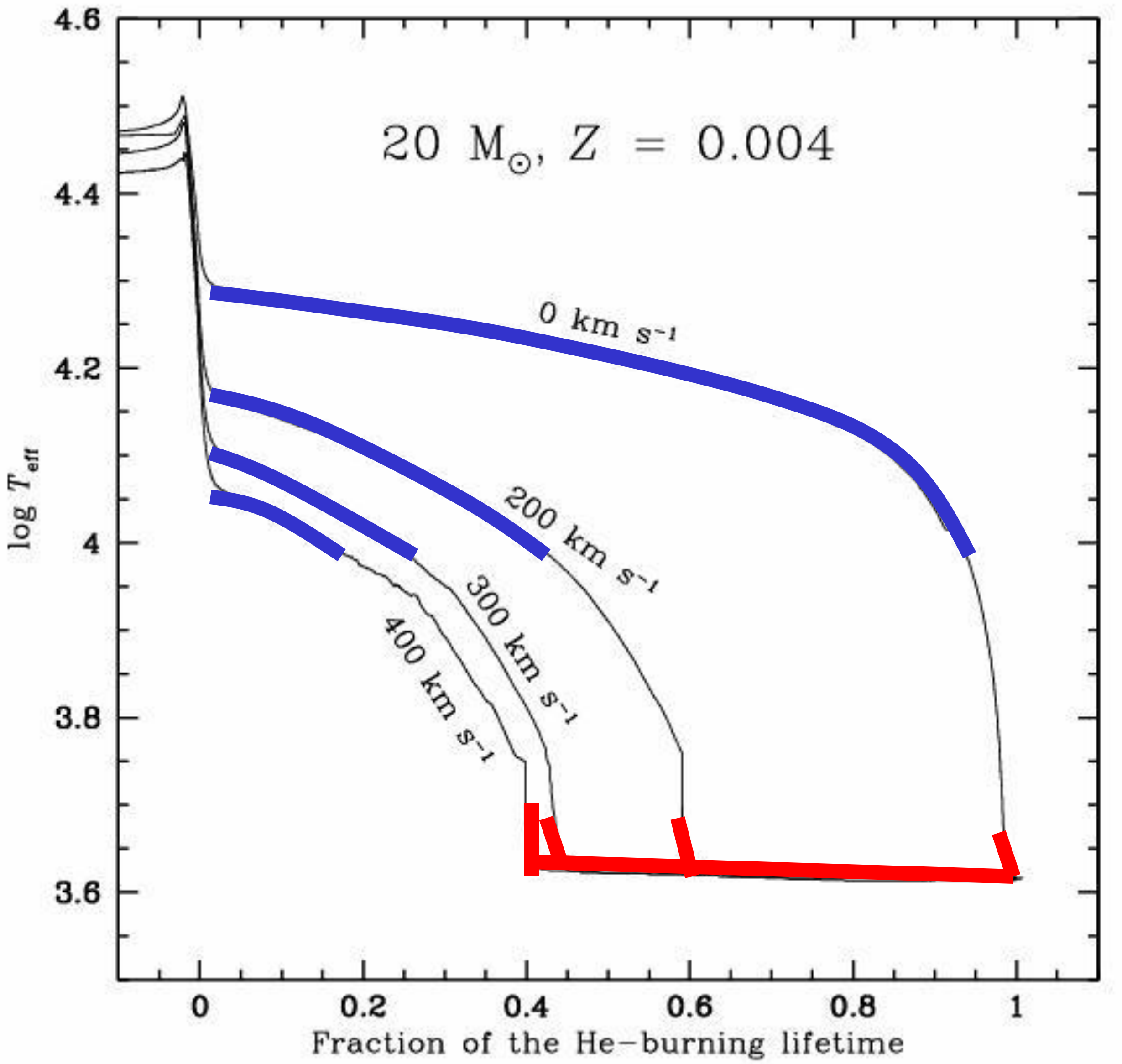
25 Msol: from core H-burning to Si-burning

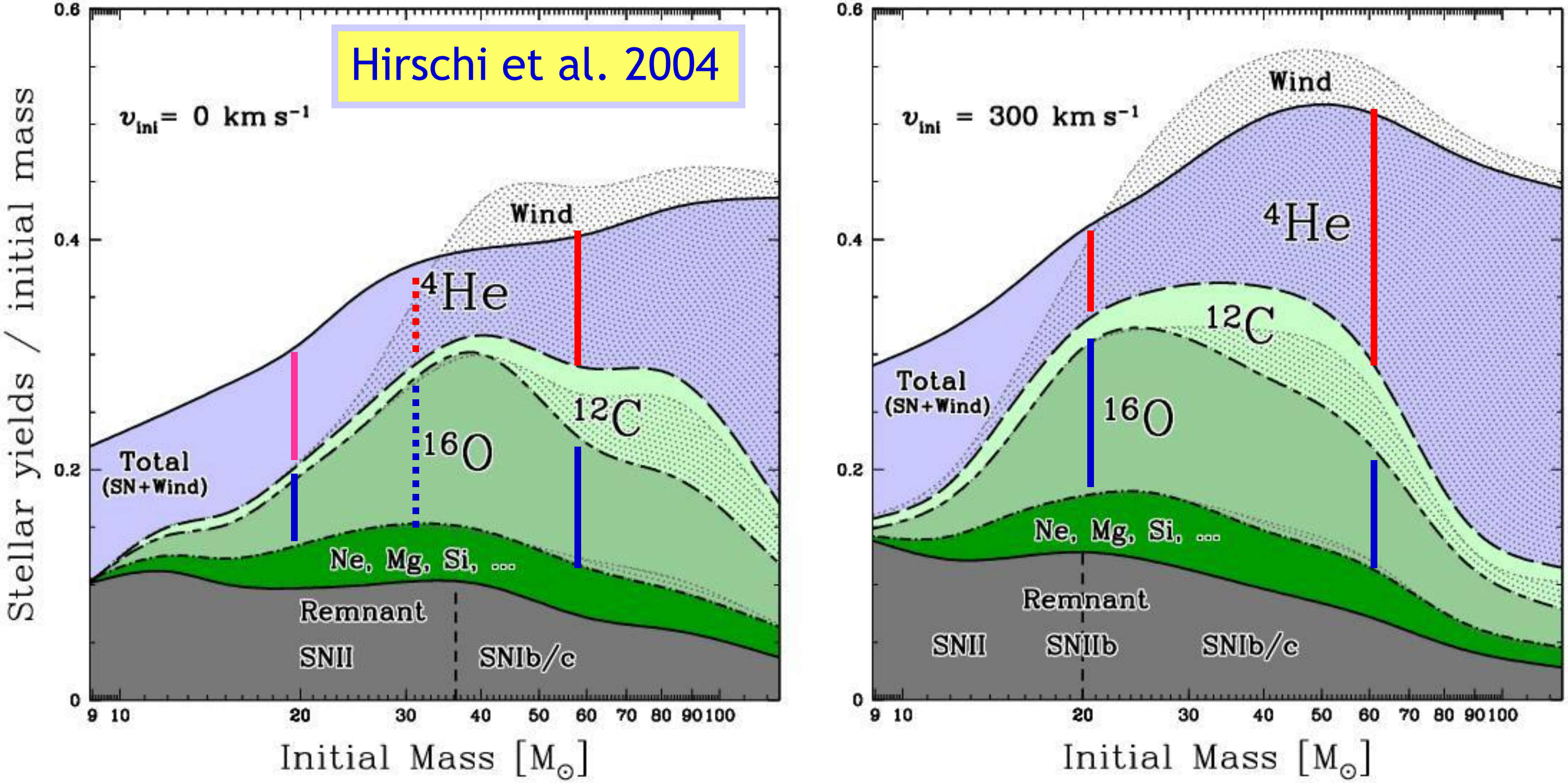


Hirschi, Meynet, Maeder, Goriely 2003

Heger, Langer, Woosley 2000

V_{ini} Km/s	ΔM_{RSG} M_{sol}
0	0.14
200	1.40
300	1.71
400	1.93



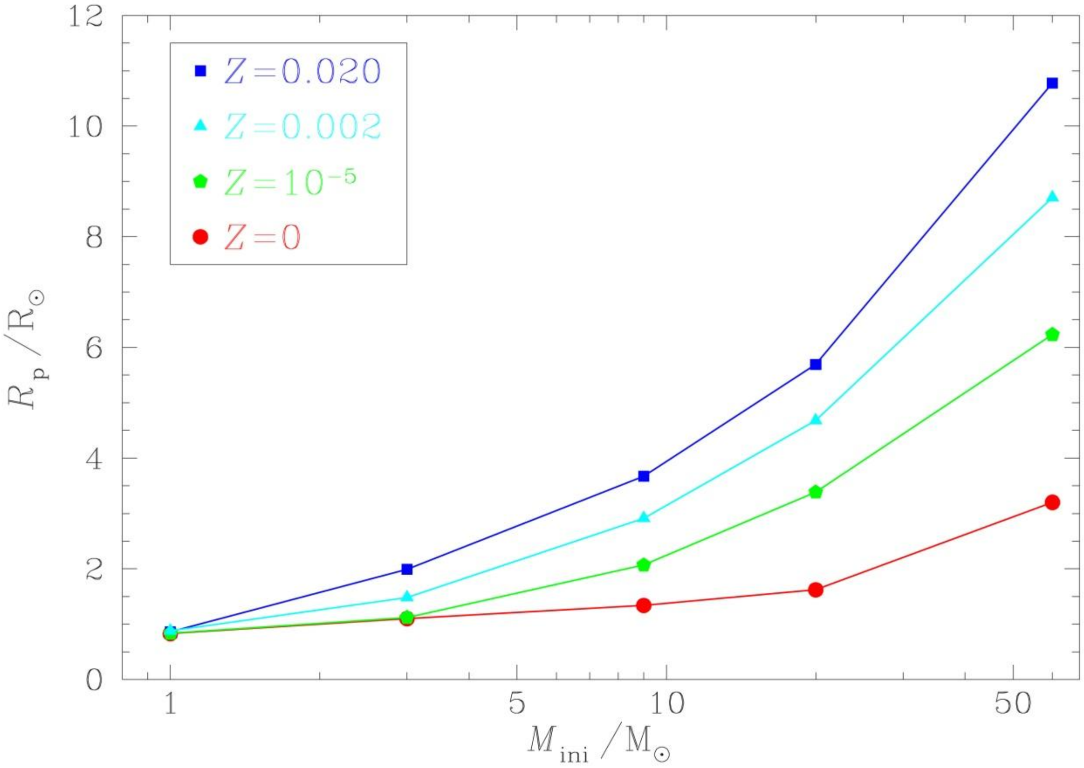


Hirschi et al. 2004

For $M_{ini} < M_{minWR}$ ROTATION → increases ^{12}C and ^{16}O by about a factor 2

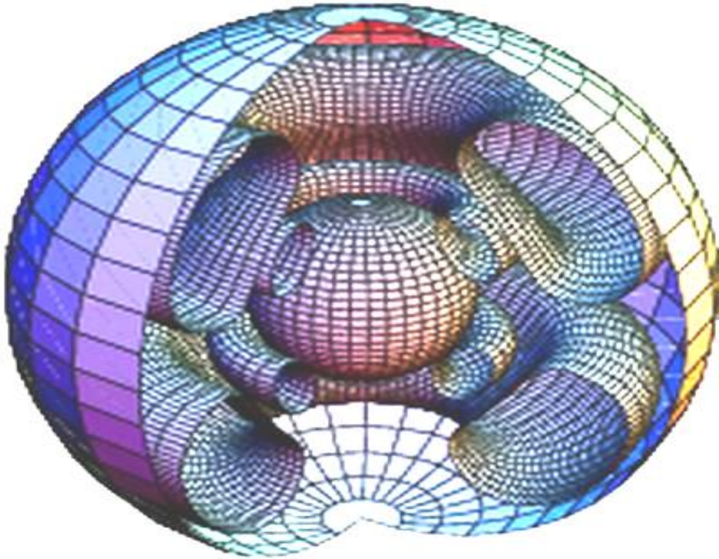
A non rotating ~30 M_{sol} as a rotating 20 M_{sol}

For $M_{ini} > M_{minWR}$ ROTATION → increases ^{4}He



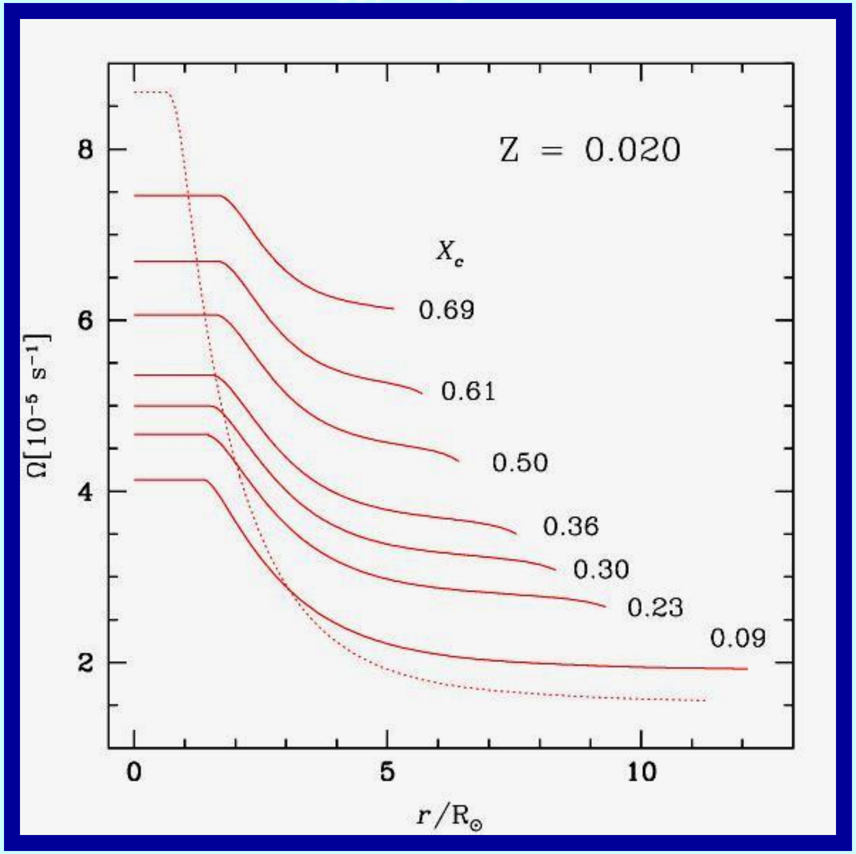
Z ↗ → R ↗

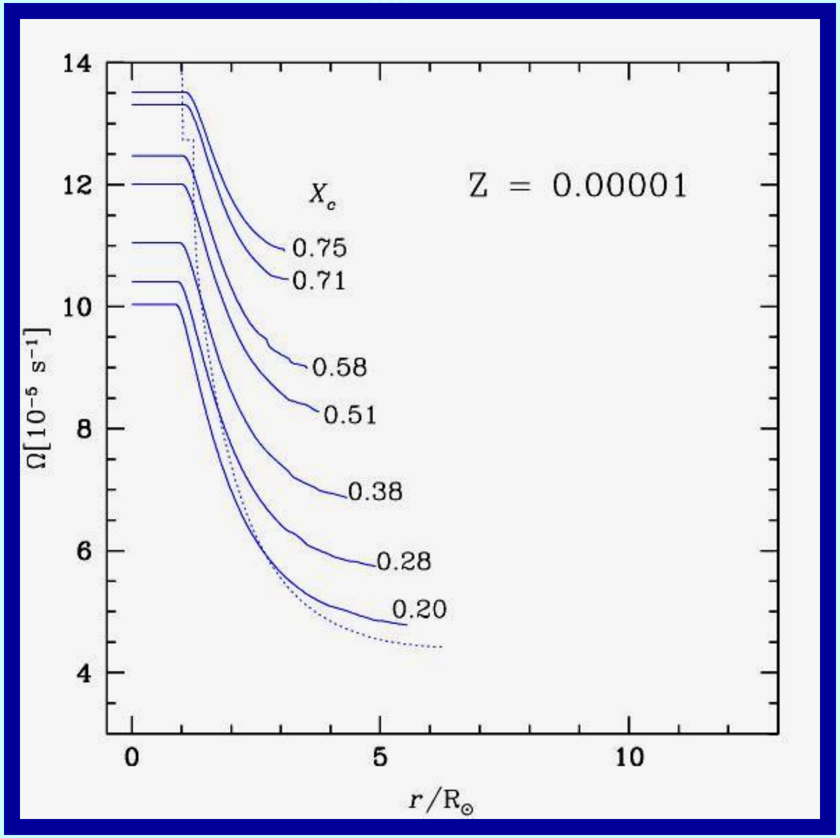
U α 1/ρ



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,
transport of angular momentum less efficient

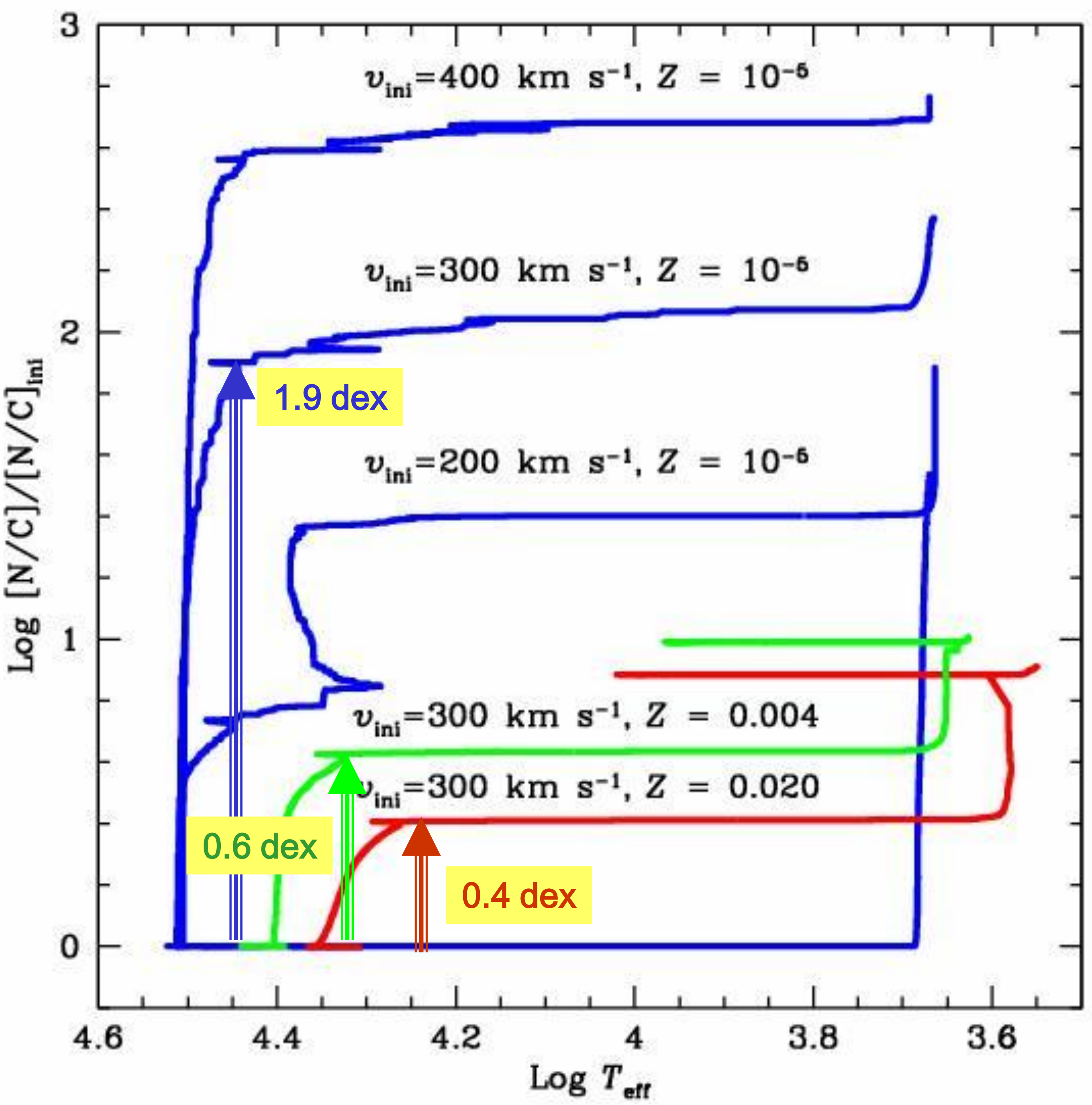
Consequences ?

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

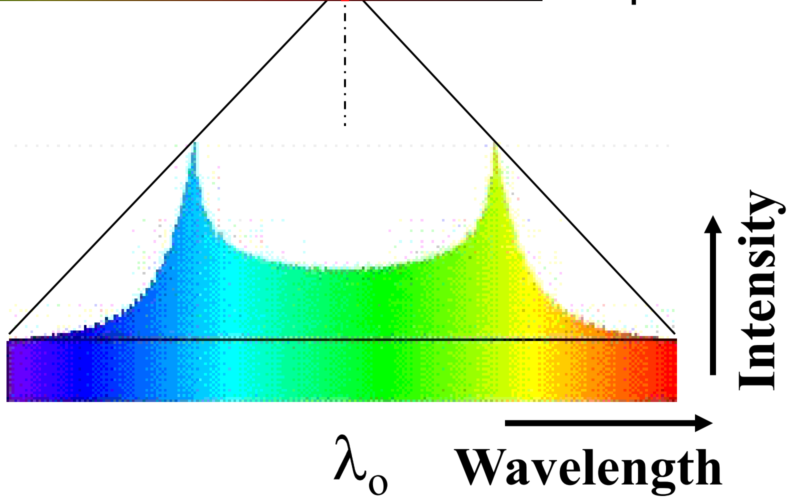
SMC: [N/H] O-stars, A-F supg. : 1.5 -1.7 dex
$< 20\ M_\odot$ B – dwarfs : → 1.1 dex
B – giants, supg. : → 1.5 dex
$> 20\ M_\odot$ B – giants , supg : → 1.9 dex
Ref: Heap & Lanz’06; Venn & Przybilla’03; Bouret et al.’03;Trundle et al.’07; Hunter et al.’07

Be stars

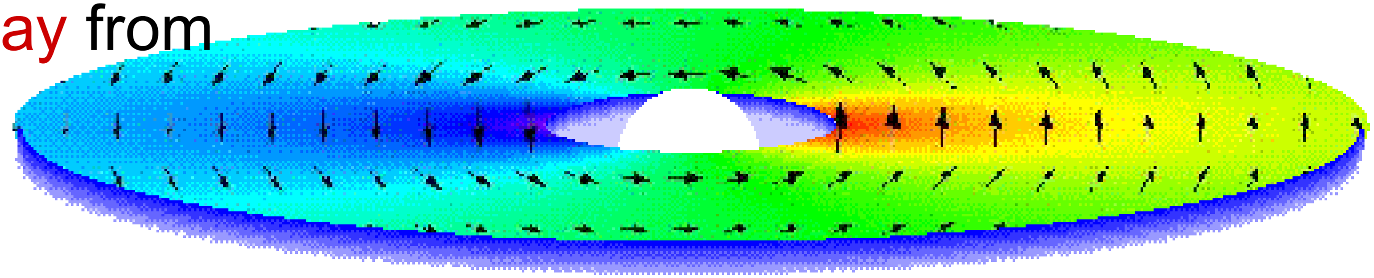
- **Hot, bright, & rapidly rotating stars.**
- **Discovered by Father Secchi in 1868**
- **The “e” stands for emission lines in the star’s spectrum**

Hydrogen spectrum

- Detailed spectra show emission intensity is split into peaks to blue and red of line-center.



- This is from Doppler shift of gas moving toward and away from the observer .



- Indicates a disk of gas orbits the star.

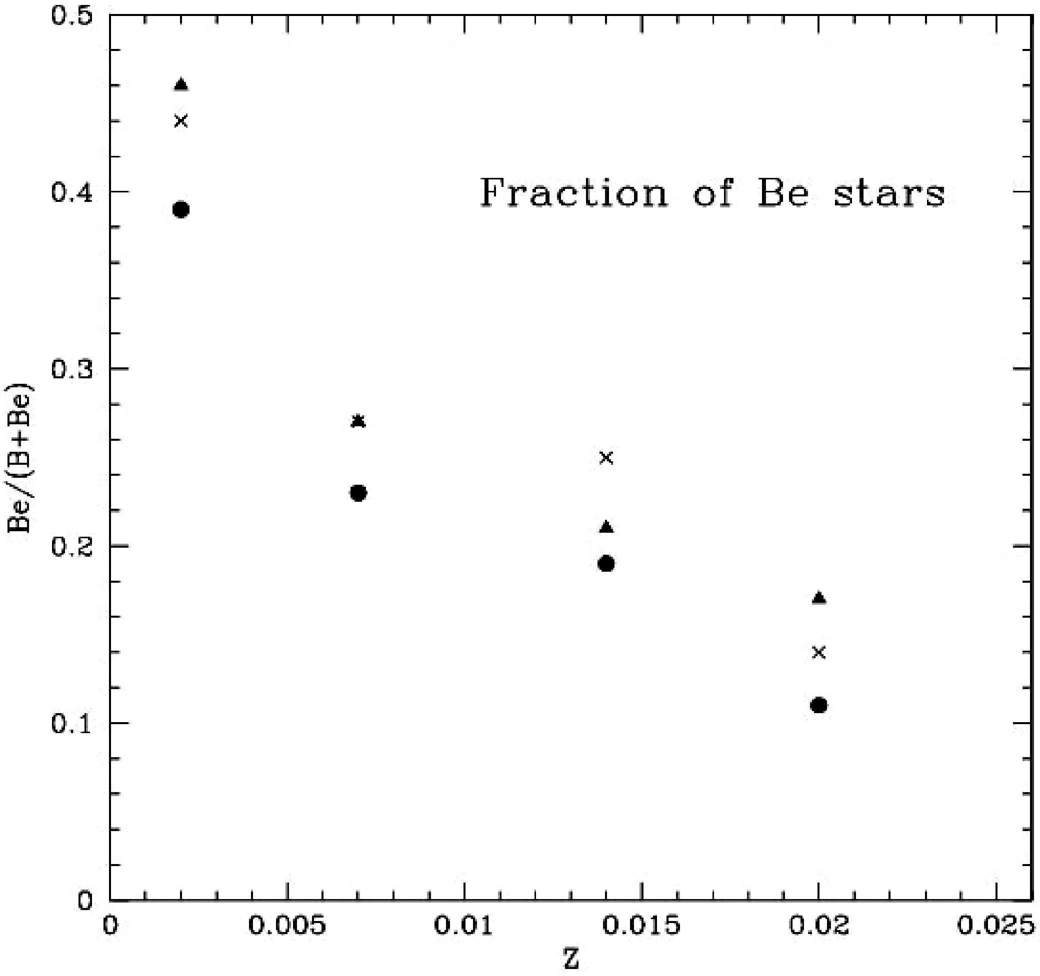
Viewgraph from Owocki

From 19 clusters in Galaxy, LMC & SMC

Rotation seems faster at lower Z

Is this a general trend ?

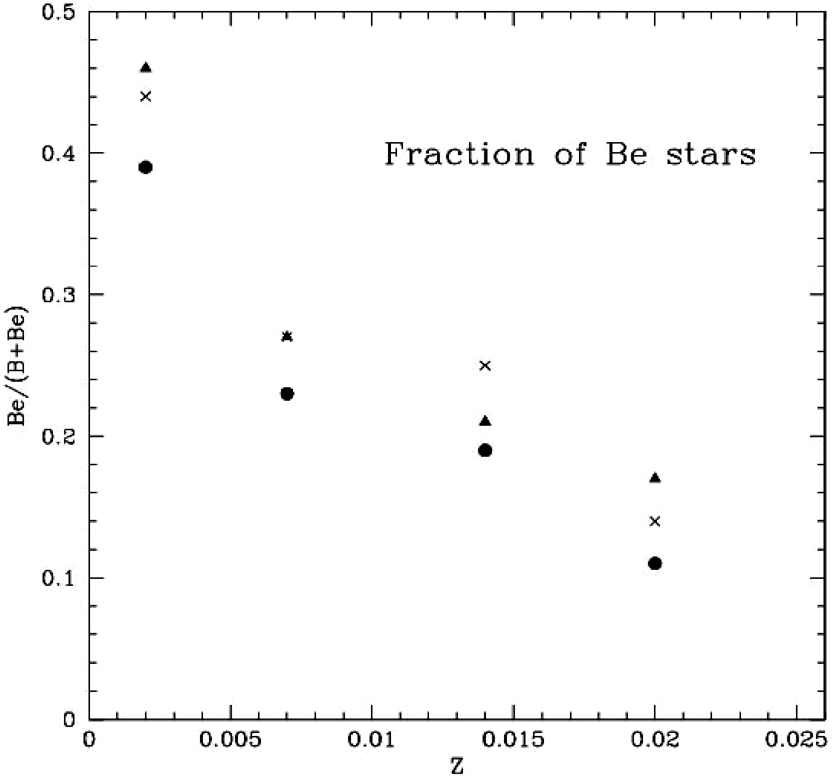
What at Z = 0 ?

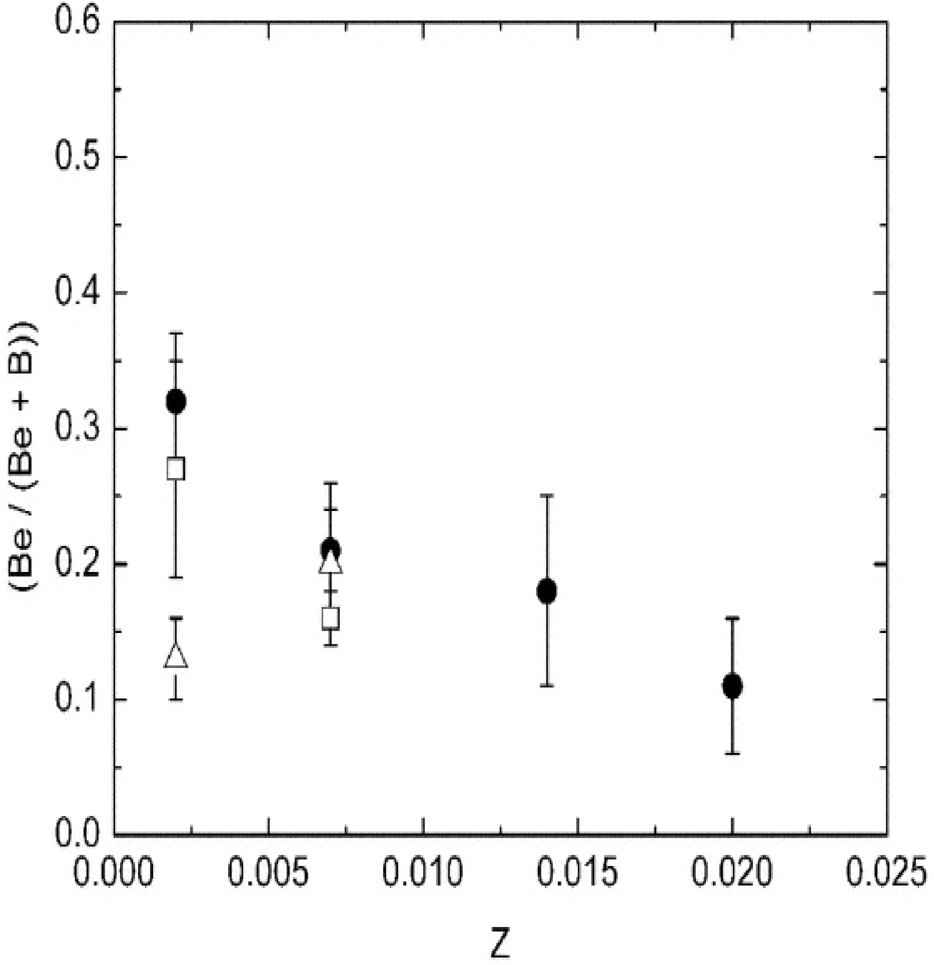


Maeder, Grebel, Mermilliod 1999

From 19 clusters in Galaxy, LMC & SMC age 10-25 Myr

Rotation seems faster at lower Z





Maeder, Grebel, Mermilliod 1999

Wisniewski and Bjorkman 2006

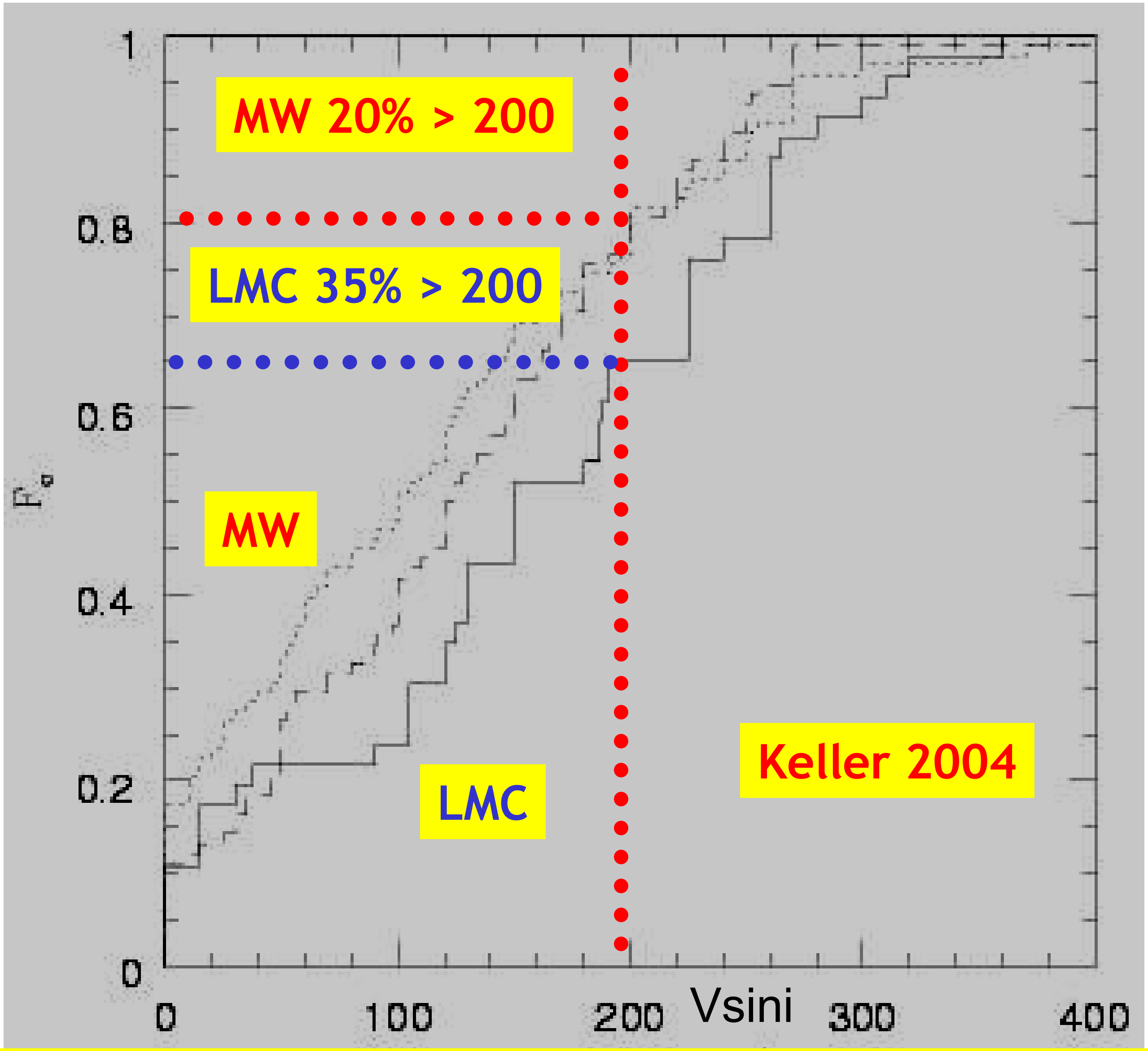
CUMULATIVE DISTRIBUTION OF V sin i

Keller 2004

100 early B-type
MS stars in LMC

Galactic young
clusters
<V>=116 km/s

LMC young
clusters
<V>=146 km/s



MW 20% > 200

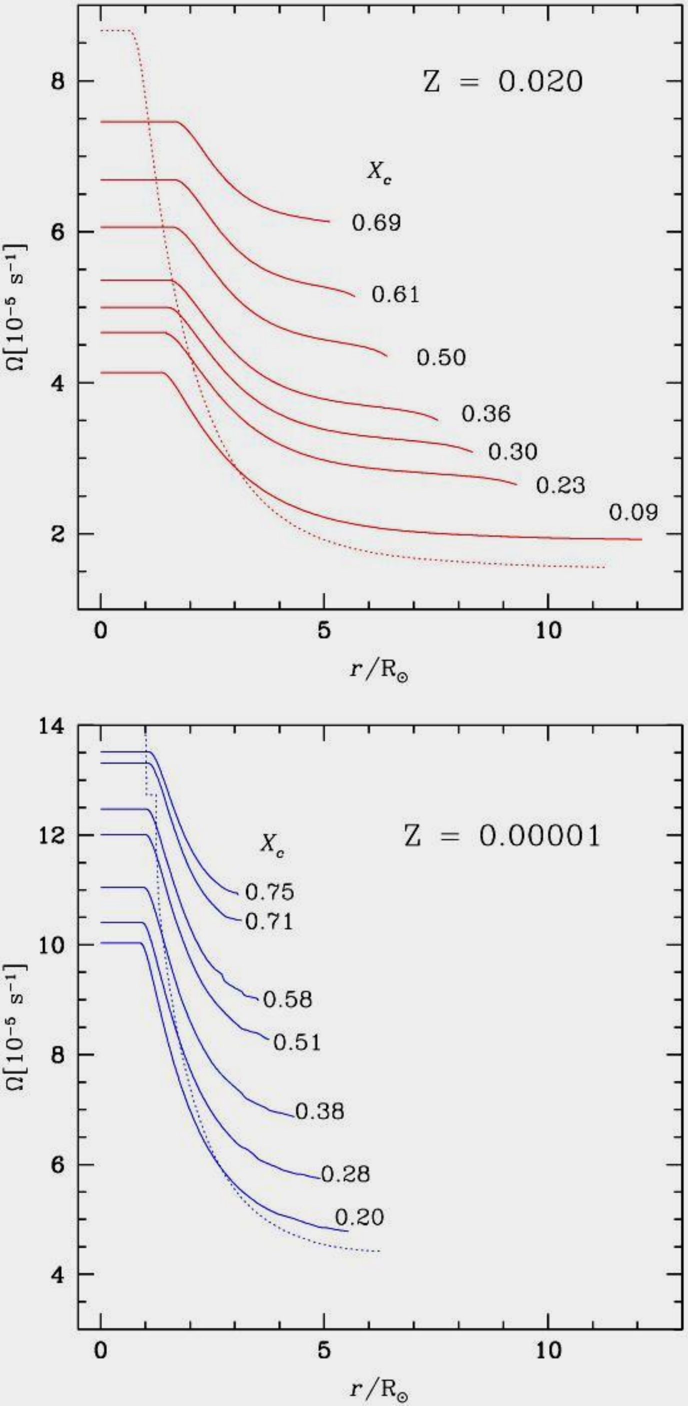
LMC 35% > 200

MW

LMC

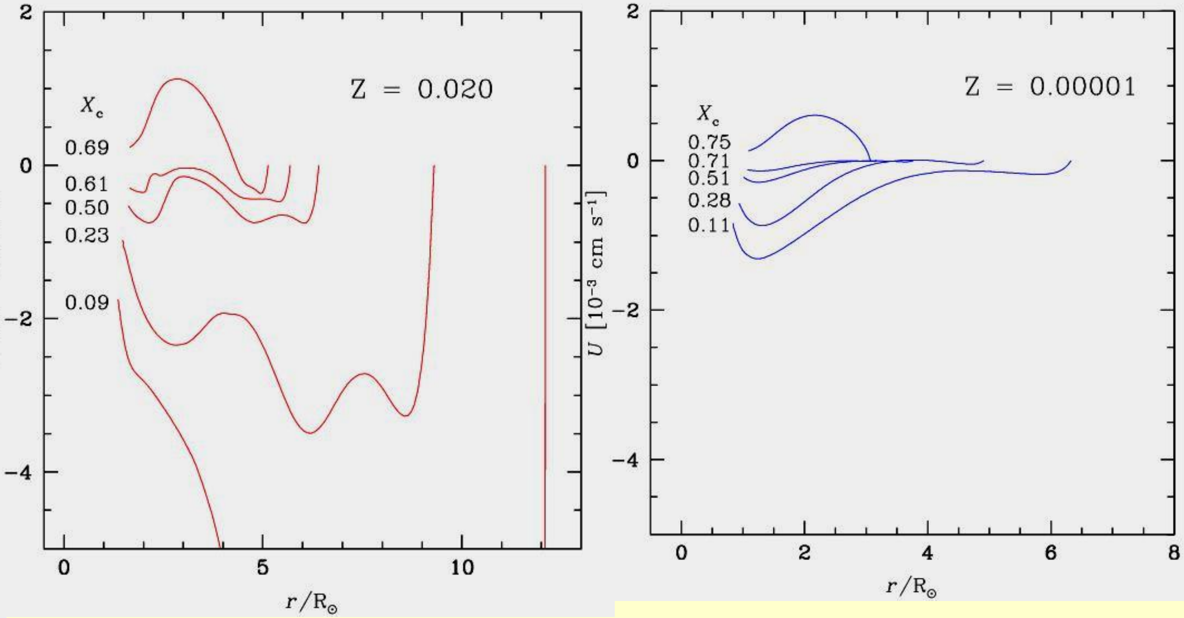
Keller 2004

But Penny et al. 2004 finds no effect for O-type stars (MW, LMC and SMC)



When Z decreases stars become more compact

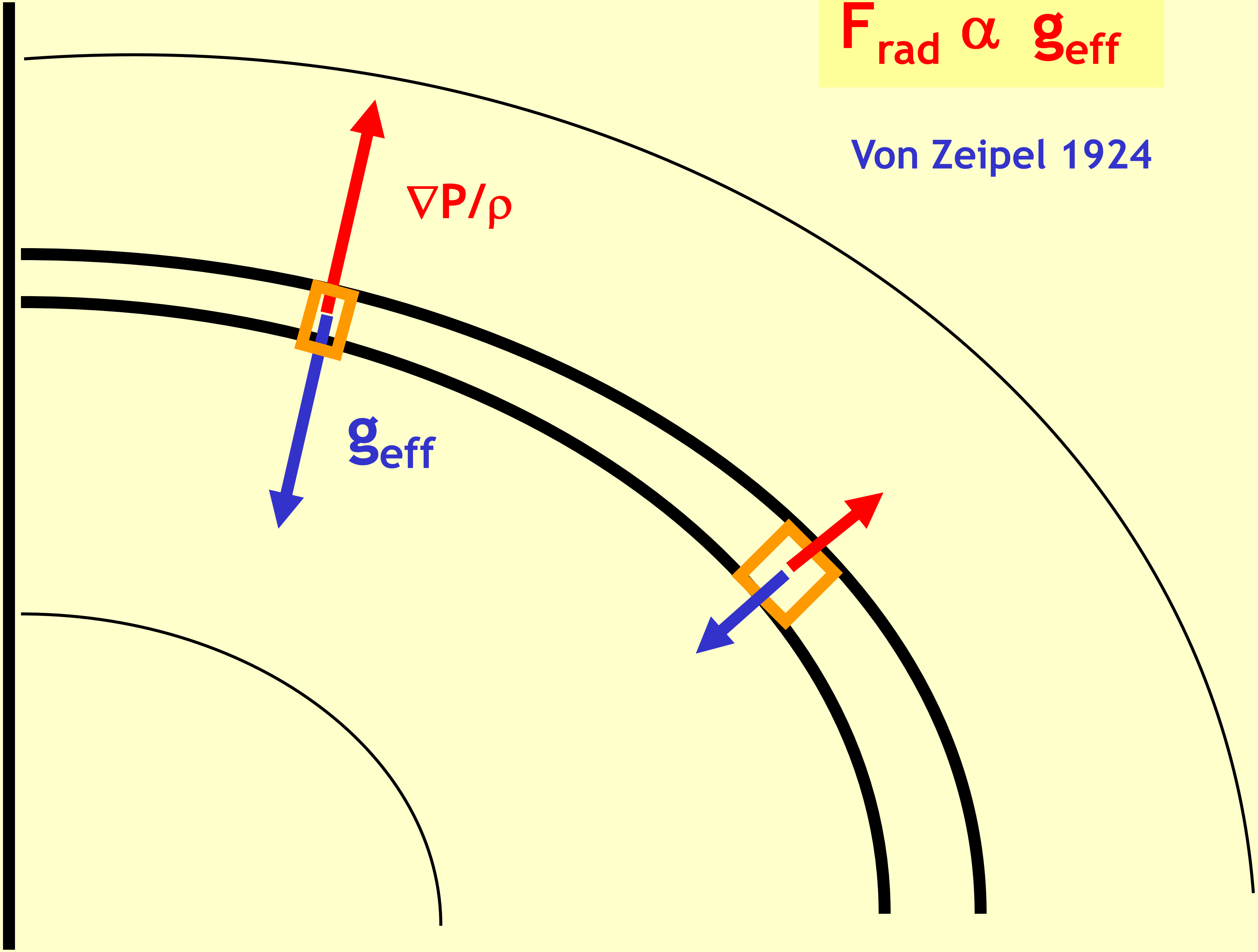
In U the Gratton Öpick scales with the Inverse of the density



Less angular momentum is removed by the stellar winds

$F_{rad}\ \alpha\ g_{eff}$

Von Zeipel 1924



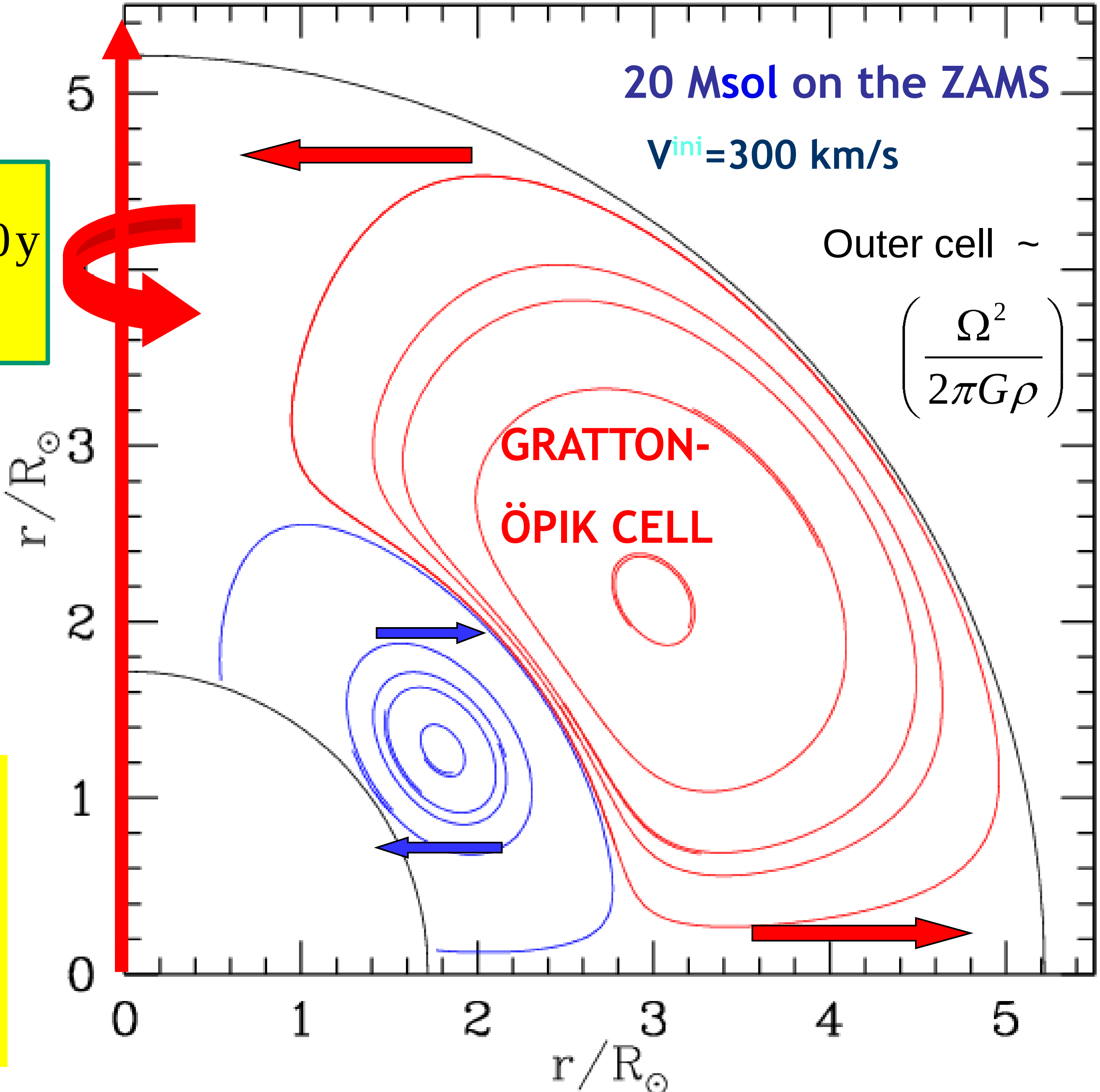
Cells of meridional circulation

Timescale→
a few times the
Kelvin-Helmholtz
timescale

$$\underbrace{\left(\frac{\Omega_{KEP}}{\Omega}\right)^{2}}_{4}\underbrace{\tau_{KH}}_{34000}\approx 140000\text{y}$$

Very important process for the transport of the angular momentum

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



THE SHEAR INSTABILITY

Where does the energy come from ?

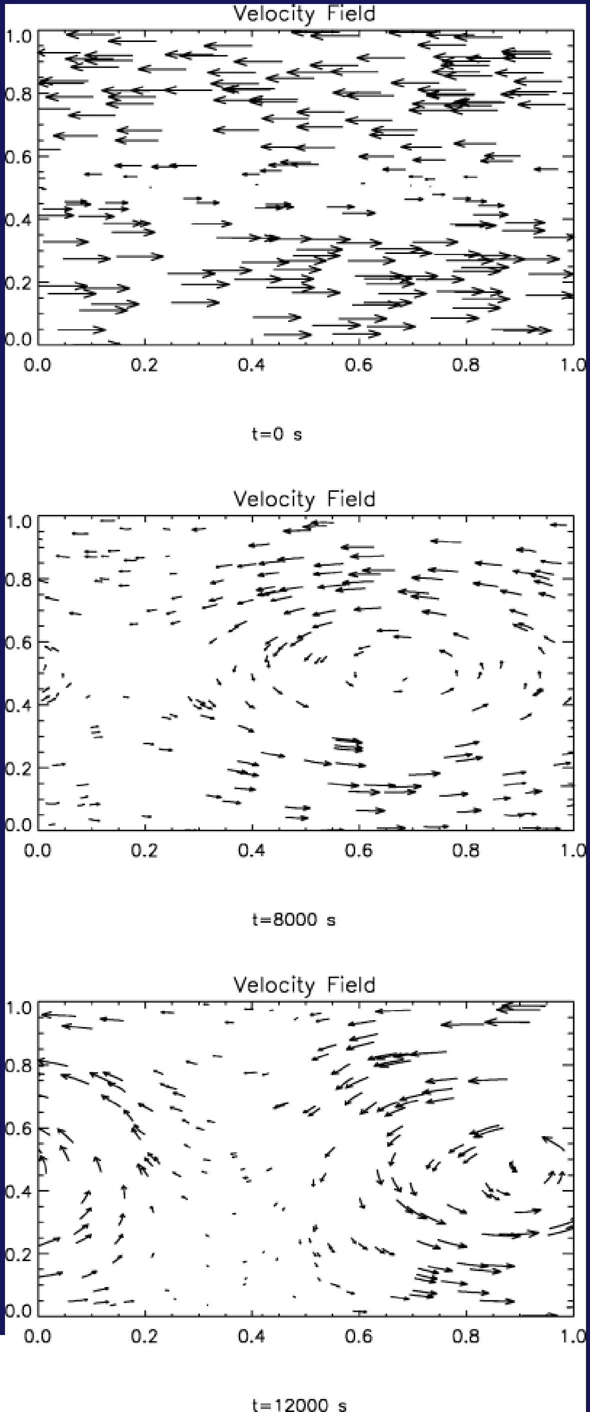
From the excess energy in the shear

When does it occur ?

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

The timescale

Secular shear → much longer than MS lifetime
Dynamical shear → dynamical timescale



Brueggen & Hillebrandt 2001

For mixing to occur

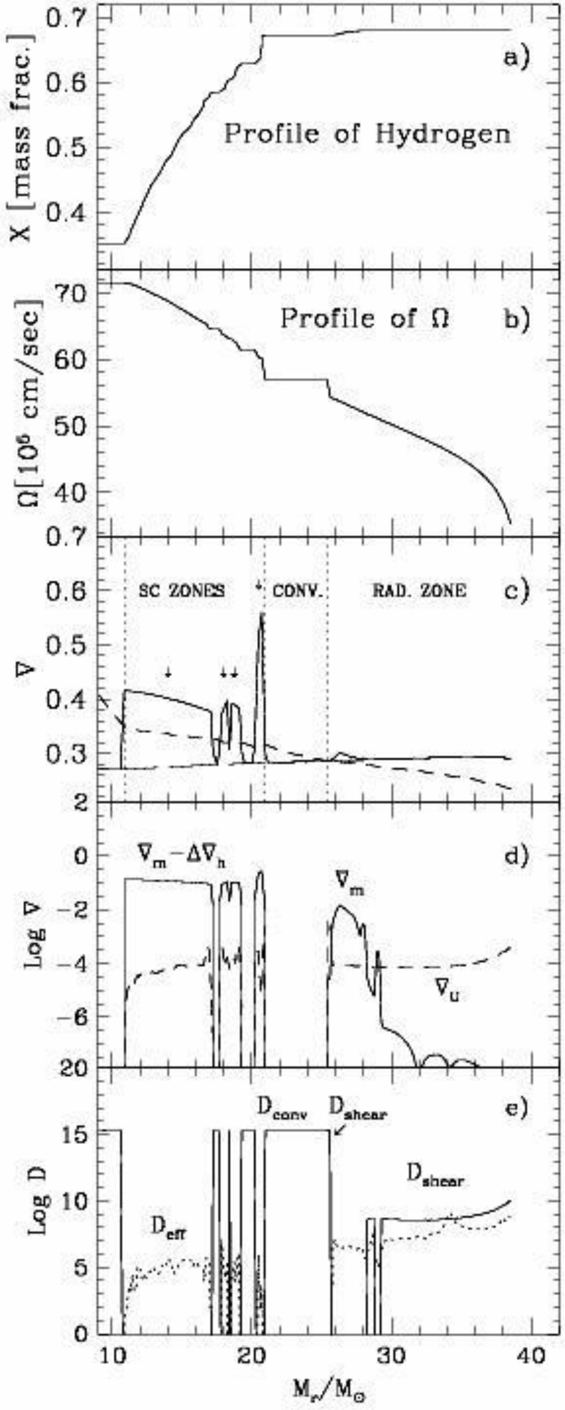
Excess of energy in the shear (Es)
>
Energy to overcome density gradient (Ed)

Richardson criterion

Instability when ¼ > Ri

$$\frac{1}{4} > \frac{\underbrace{\frac{\varphi}{\delta}\nabla\mu - \frac{1}{1+2\sqrt{6}}\left(\nabla_{rad} - \nabla_{ad}\right)}_{\nabla m - \Delta\nabla h}}{\underbrace{\frac{H_p}{g\delta}\left(\frac{dU}{dz}\right)^2}_{\nabla U}}$$

Maeder 95; Maeder & Meynet 96



Possible other solutions

Parametric approach

$$f_\mu \nabla \mu$$

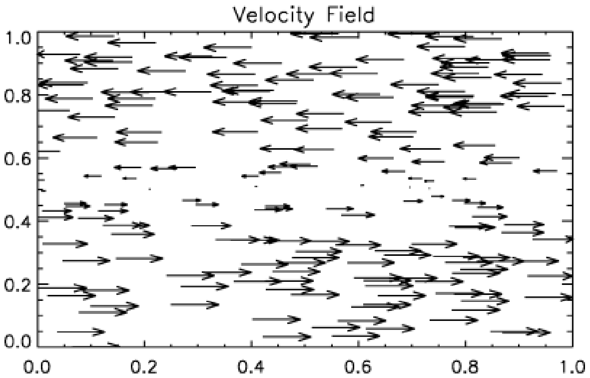
Pinsonneault 1997; Heger and Langer 2000

Multi D computations

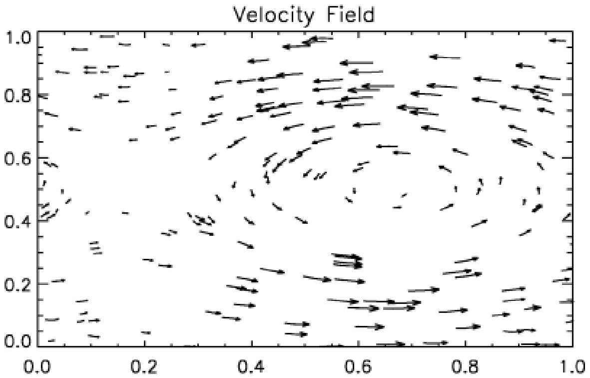
Dynamical shear

Efficient mixing occurs for Ri substantially higher than 1/4

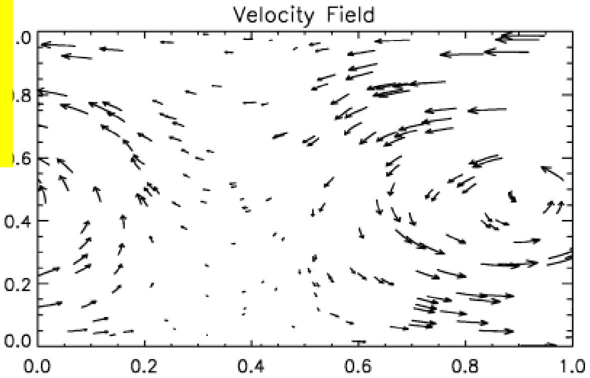
Brueggen & Hillebrandt 2001



t=0 s



t=8000 s

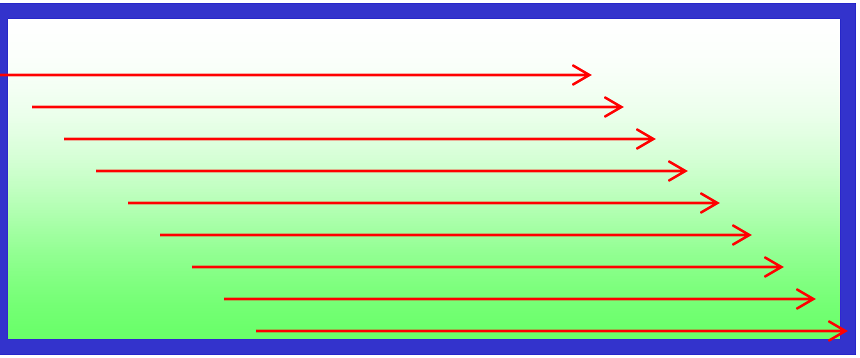


t=12000 s

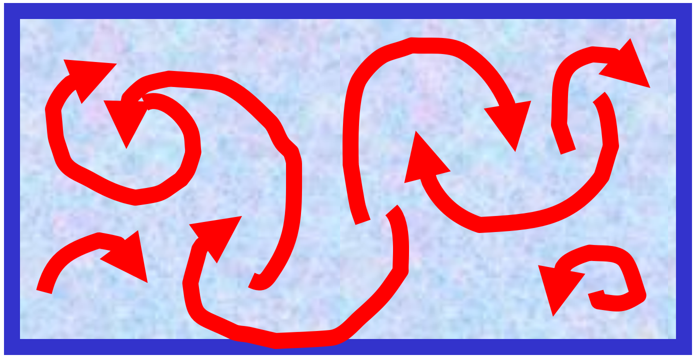
Non-linear description, based on energy considerations

medium is likely turbulent (even before any vertical shear mixing occurs)

No well stratified medium



Instead

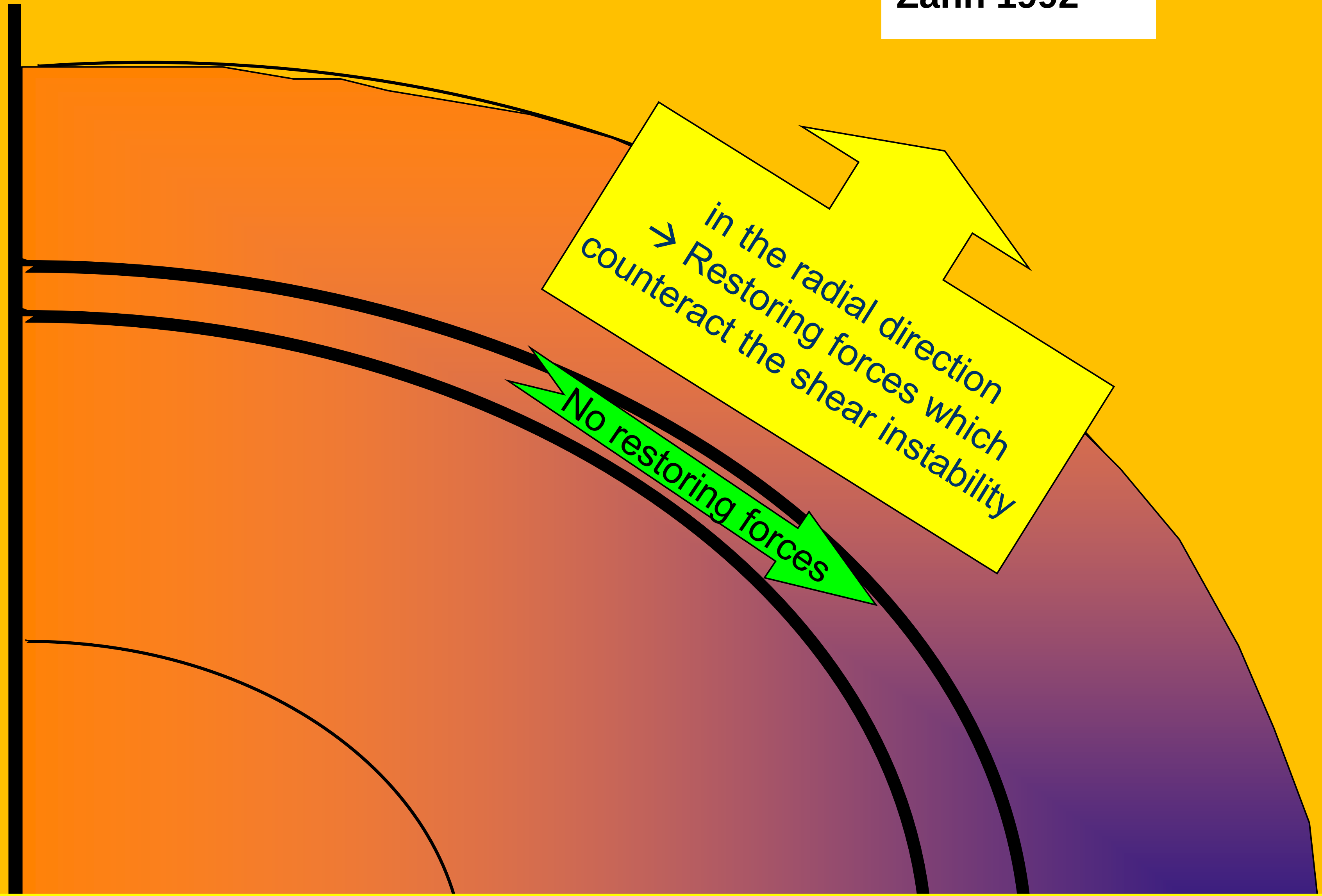


New Richardson criterion accounting for the effects of the strong horizontal turbulence which erodes the vertical molecular weight gradients and for The effects of thermal diffusion.

Maeder 97; Talon and Zahn 97

Palacios, Charbonnel, Forestini 2001; Meynet and Maeder 2000, 2003

Zahn 1992



in the radial direction
→ Restoring forces which
counteract the shear instability

No restoring forces

CONSEQUENCES

In the radial direction: gradients of Omega eroded on long timescale
In the horizontal direction: any gradient rapidly disappears→ shellular rotation law

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

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

Schear diffusion coefficient

Maeder 1997, Talon and Zahn 1997

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

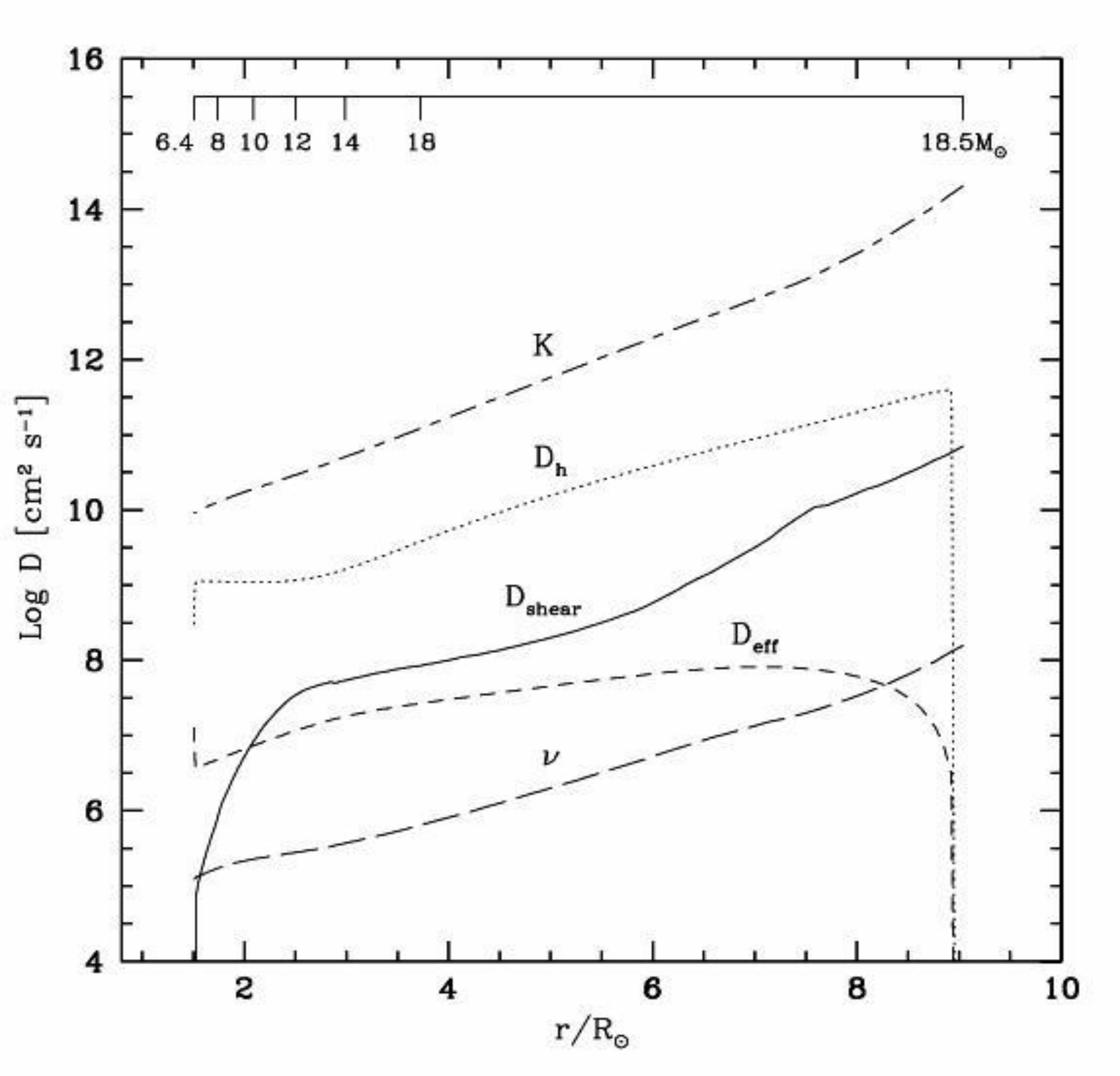
$$D_h \approx \left| rU(r) \right| \qquad D_{eff} = \frac{r^2 U^2}{30 D_h}$$

Velocity of the meridional currents

Maeder and Zahn 1998

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

DIFFUSION COEFFICIENTS



bibliography

The Rotation of Sun and Stars, Lectures notes in physics, Springer, 2009

Maeder & Meynet , 2000, Annual Rev. Of A&A, 38, 143

EXERCISES

1) Supose a star rotate like a solid body. Find the expression of the potential at the surface of a Star of mass M. Suppose that the gravity can be deduced from a spherical distribution of matter. Find the expression of the escape velocity, of the keplerian velocity and of the critical velocity. Find the ratio between the equatorial radius and the polar radius when the star is rotating at the Critical velocity.

Note that the keplerian velocity is the velocity such that, the radius remaining constant, the Centrifugal acceleration at the equator is equal to the gravity. The critical velocity is the velocity At which at the equator the centrifugal acceleration is equal to the gravity taking into account for the possible deformation of the star.

2) Using homology relations, find the ratio of the rotational mixing timescale and the MS timescale. Comment. (see viewgraph 1)

3) Imagine from the mecahnisms described in this lecture the consequences that rotation may have on the evolution of massive stars.

WHY MIXING IN MASSIVE STARS ?

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

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

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

→

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

1

$$\boxed{\frac{\tau_{mix}}{\tau_{MS}} \cong \cdots \frac{1}{M^{b}}}$$

WHY MIXING IN MASSIVE STARS ?

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

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

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

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

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

FOR HIGH M

MIXING TIME / MS TIMESCALE SMALL

ENERGY OF ROTATION

15 M_{sol}

Ω/Ω_{crit} (ini)=~0.6

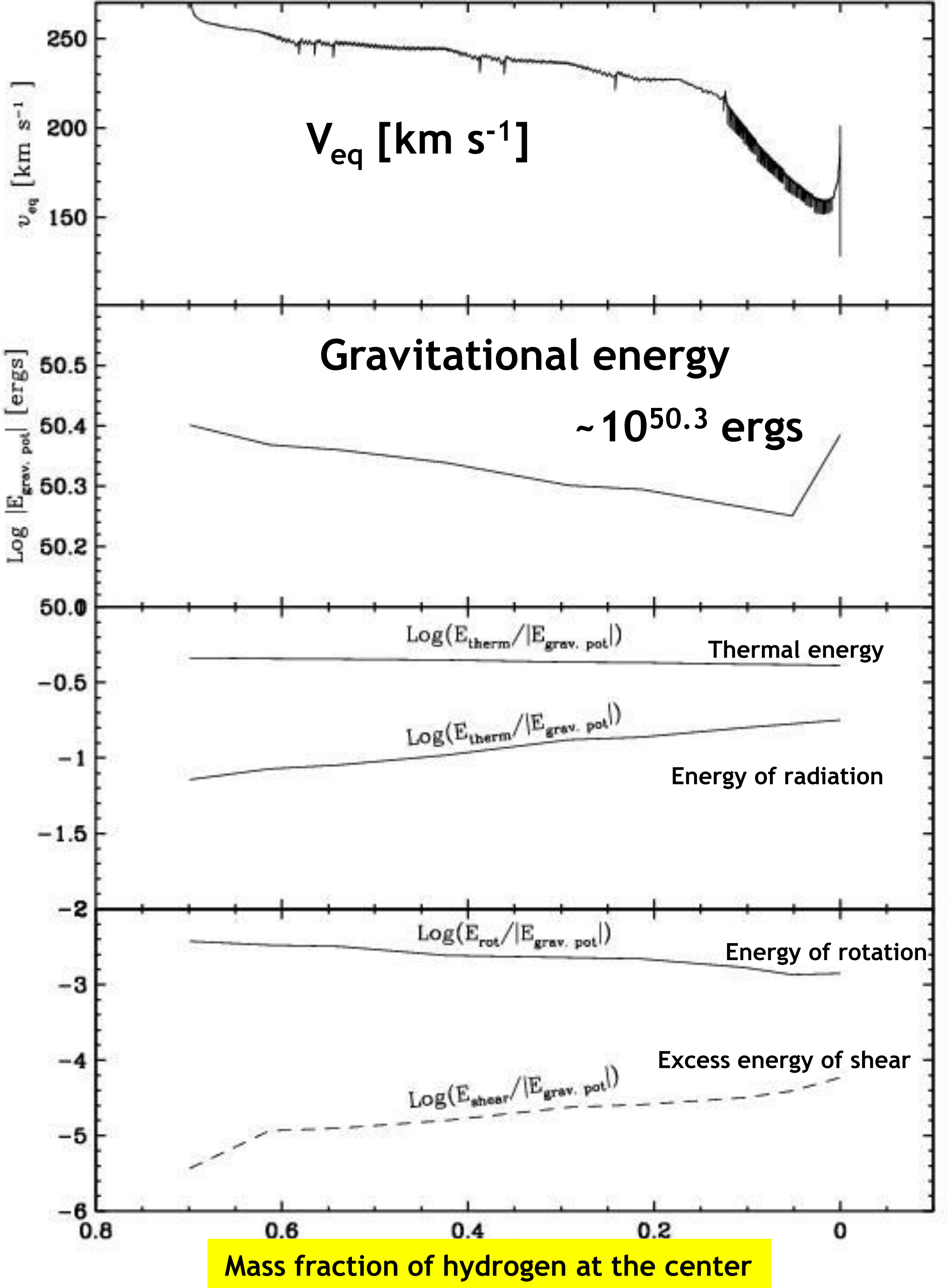
Energy of reference gravitational energy

Thermal energy ~50%

Energy of radiation ~10%

Rotational energy ~0.3%

Excess of energy in the shear ~0.003%



POSSIBLE CONSEQUENCES FOR NUCLEOSYNTHESIS

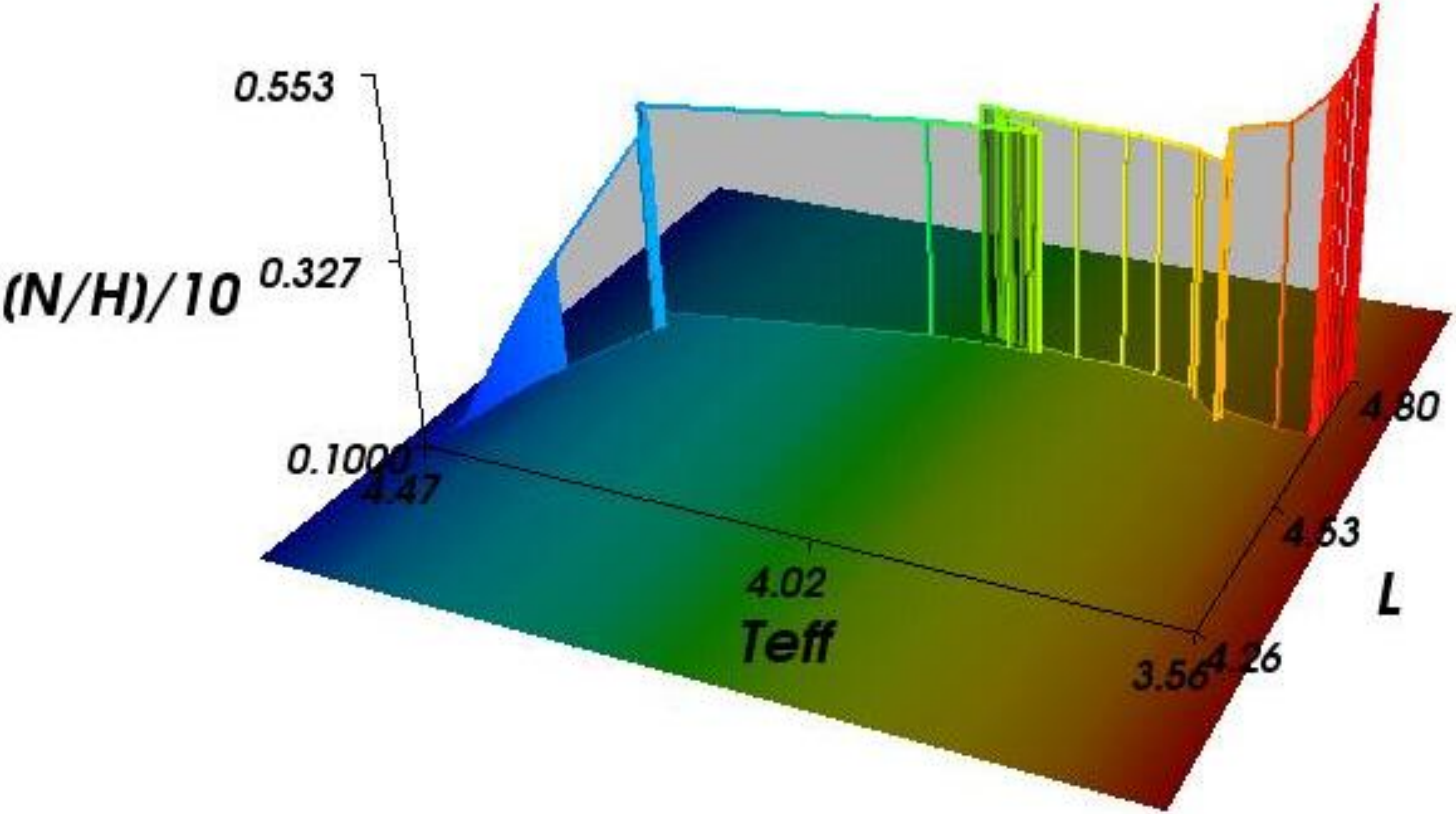
At low Z → Primary Nitrogen production greatly enhanced

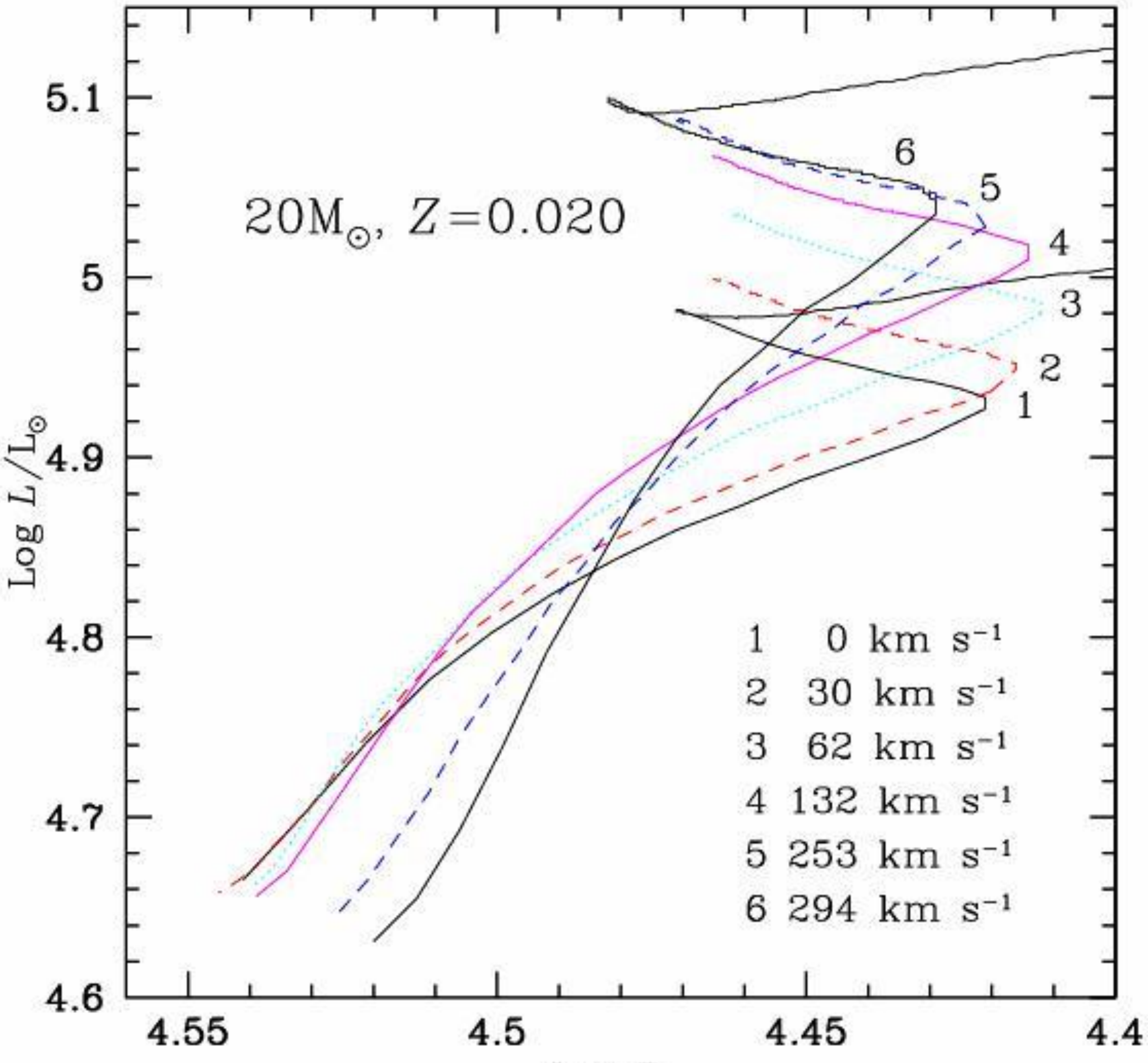
ROTATION HAS ALSO A BIG IMPACT ON MASS LOSS

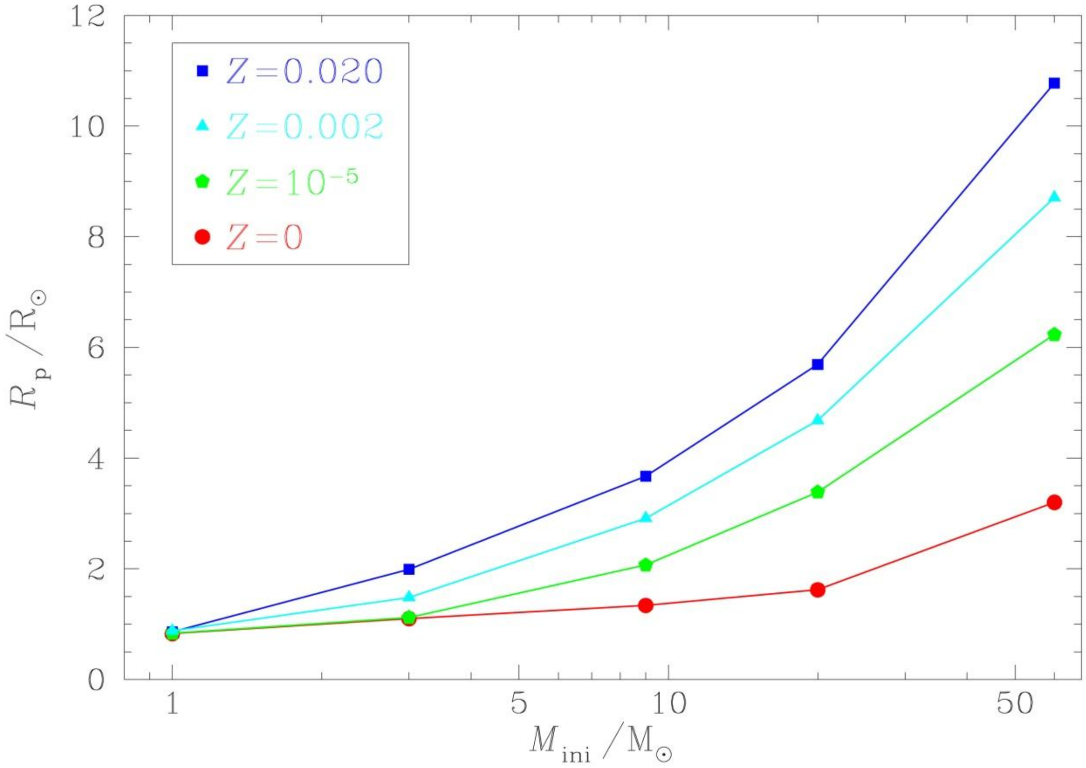
At low Z → mass loss triggered by rotation

Consequences for chemical evolution at low metallicities

CHANGE OF THE SURFACE ABUNDANCES

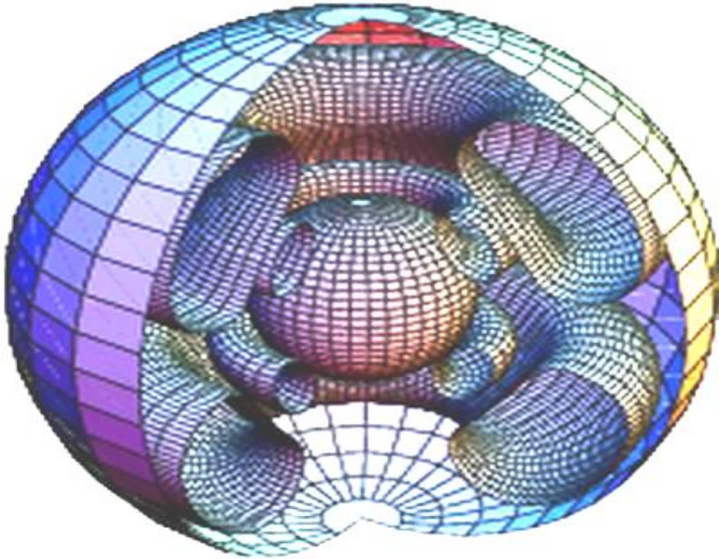

0.553
(N/H)/10
0.327
0.1000
4.47
4.02
Teff
3.56
4.26
4.53
4.80
L


$20M_\odot$, $Z=0.020$
Log $L/L_\odot$
Log $T_{\rm eff}$
5.1
5
4.9
4.8
4.7
4.6
4.55
4.5
4.45
4.4
1
2
3
4
5
6
1 0 km s^{-1}
2 30 km s^{-1}
3 62 km s^{-1}
4 132 km s^{-1}
5 253 km s^{-1}
6 294 km s^{-1}



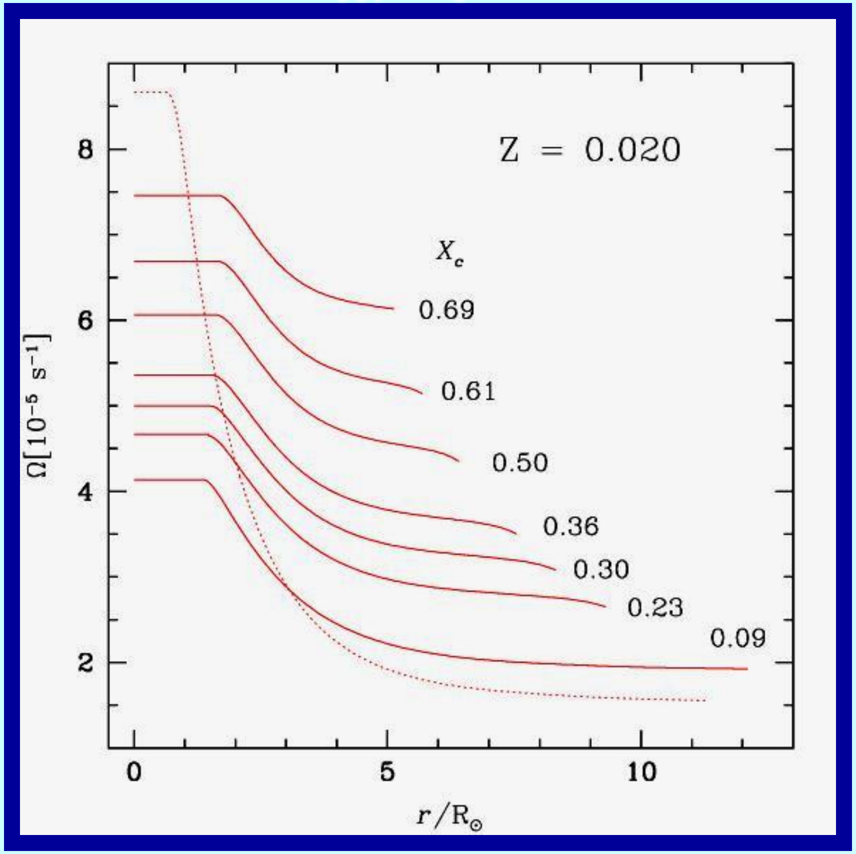
Z ↗ → R ↗

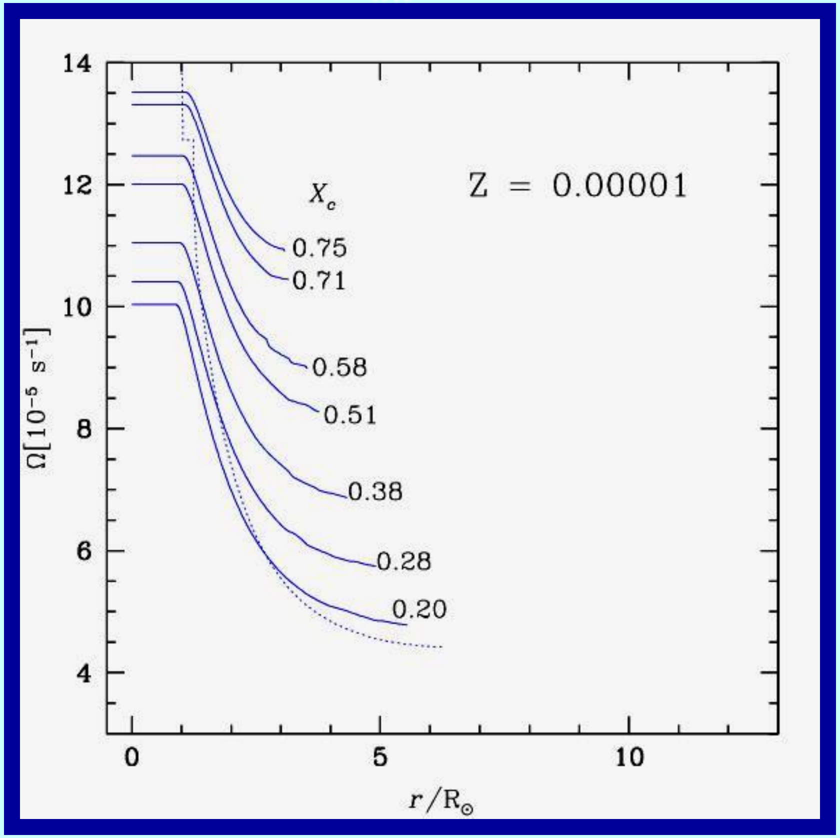
U α 1/ρ



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,
transport of angular momentum less efficient

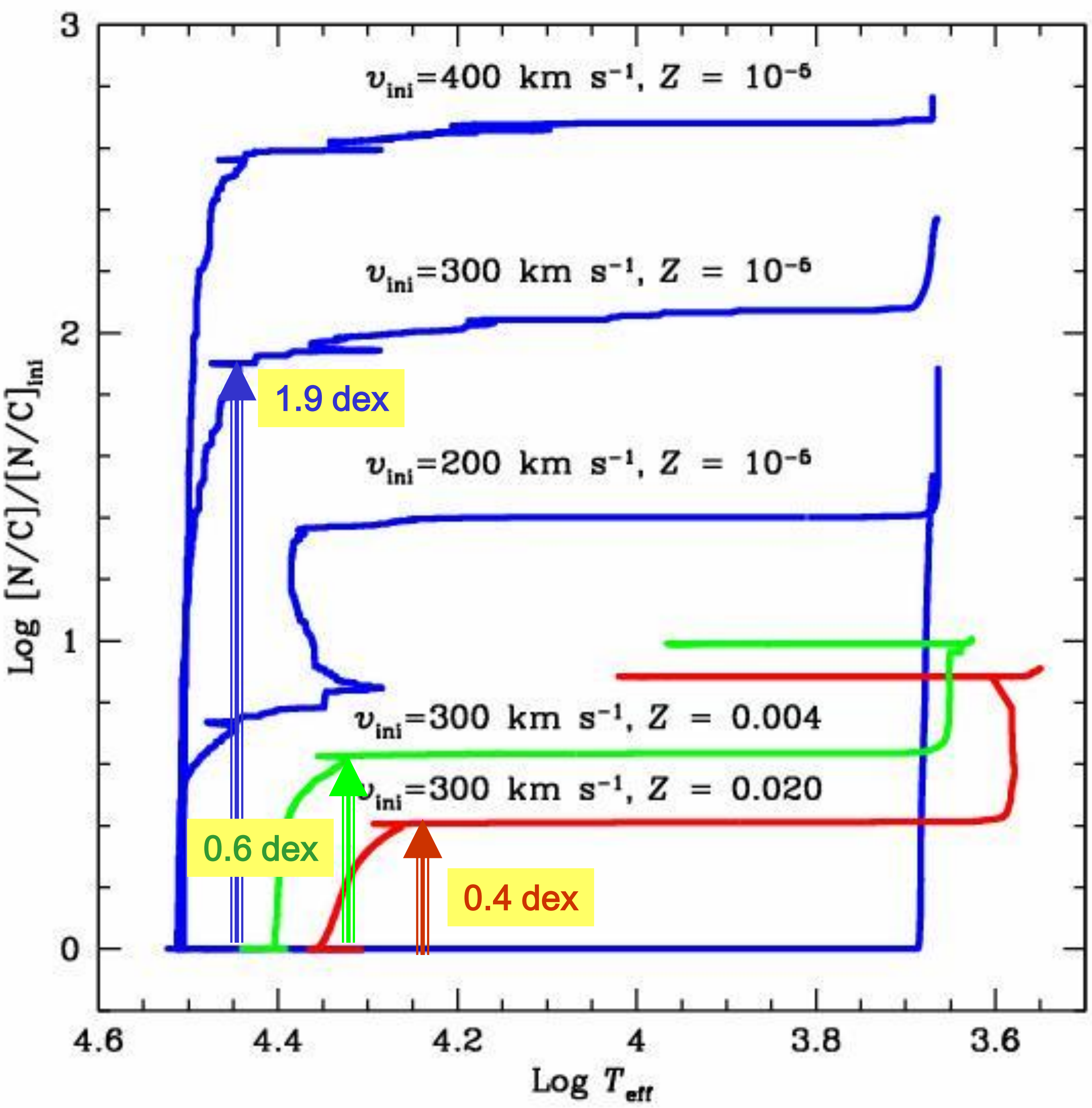
Consequences ?

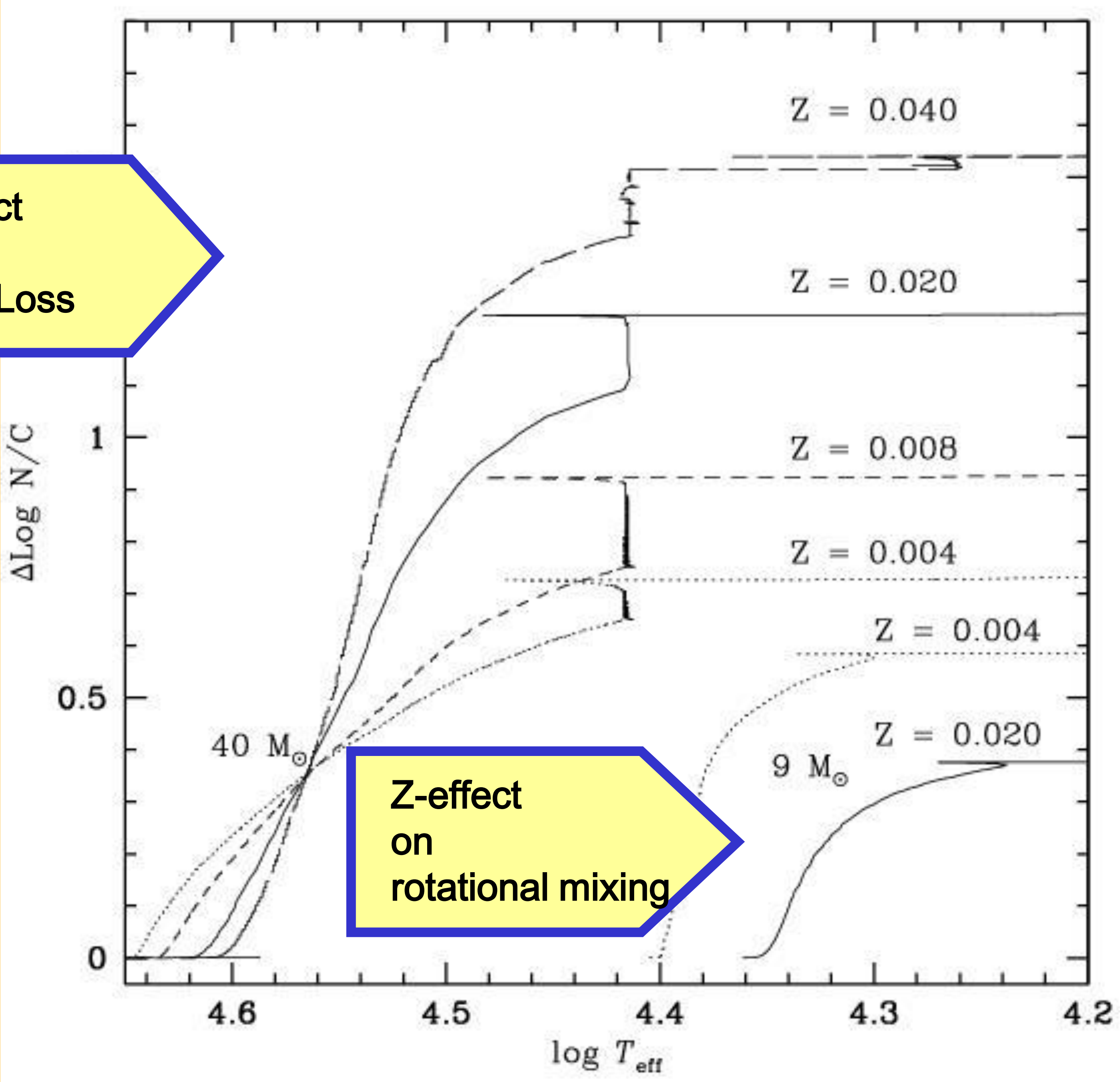
More efficient mixing of the chemical elements

9 M_{sol}

When Z ↘

Surface enrichments ↗





Z-effect
on
mass Loss

Z-effect
on
rotational mixing

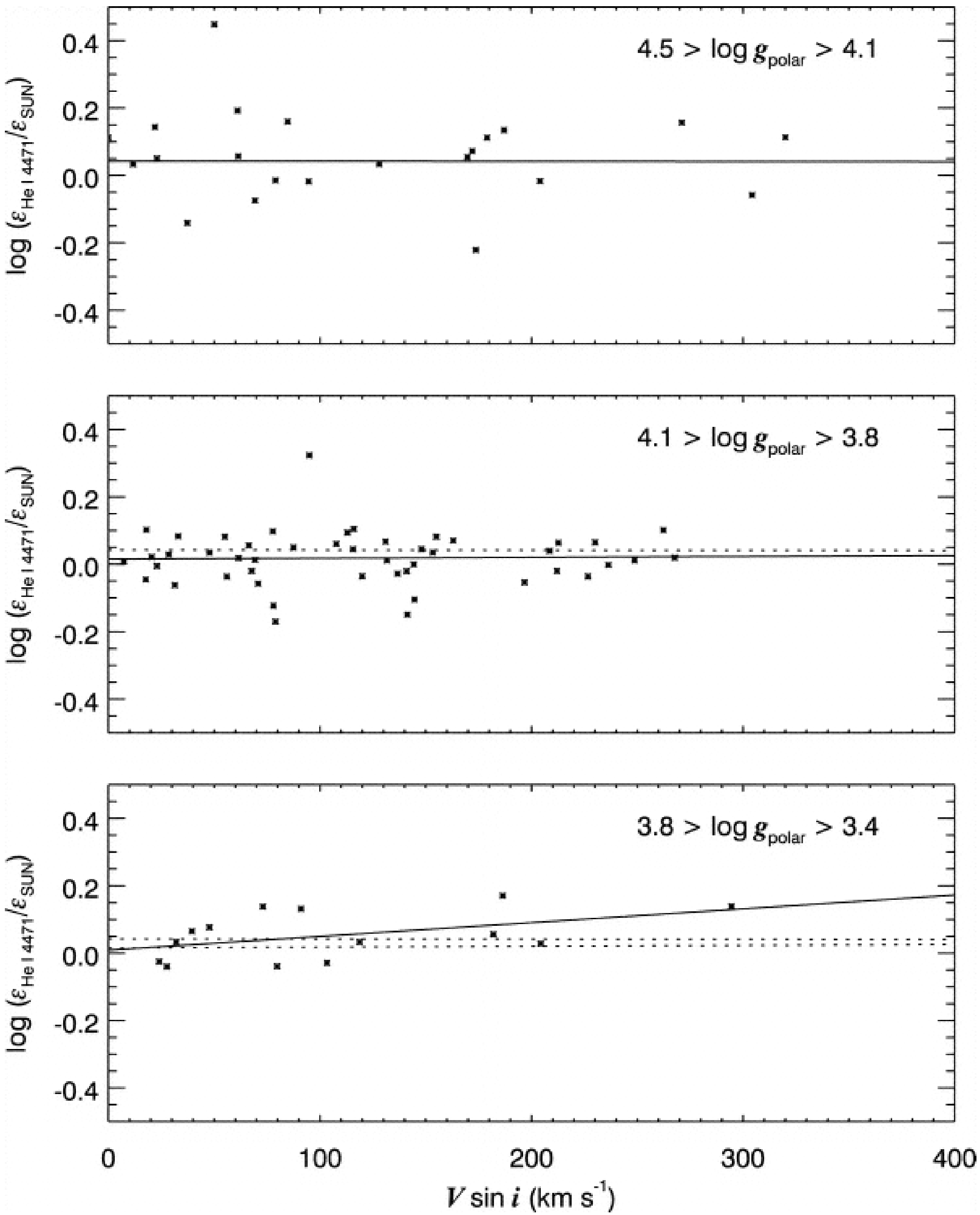
Helium abundance

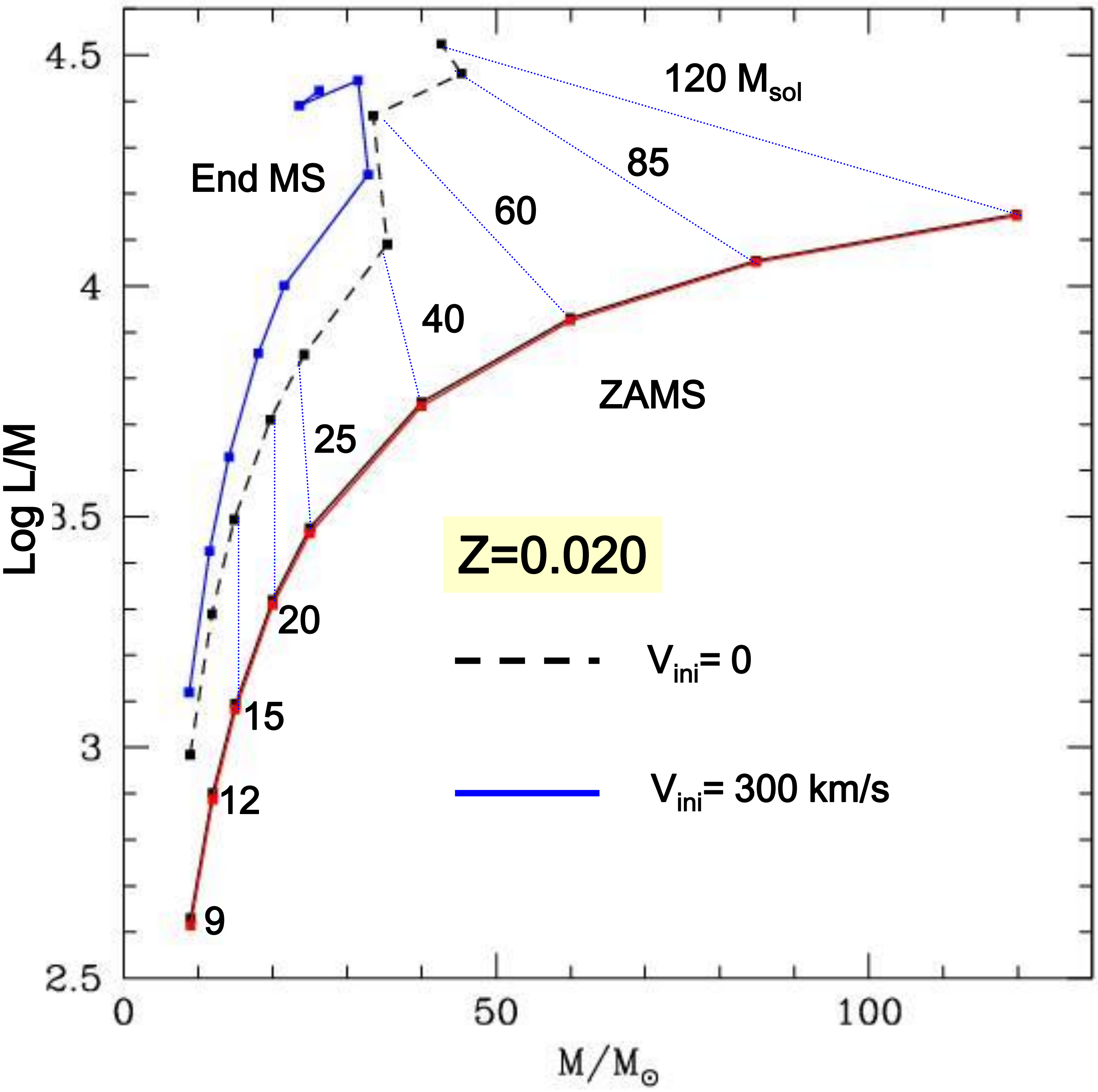
Only stars with
Teff > 23 000 K
to avoid contamination
by He peculiar stars

For high mass range
At different evolutionary
Stages (given by log g)

$8.5\ M_{sol} < M < 16\ M_{sol}$

Helium increases of
0.09 +- 0.05 dex
(or 23% +- 13%)
between ZAMS and TAMS
Cf also Lyubimkov et al. (2004)





<u>For M < 50 M_{sol}</u>

L/M ↗

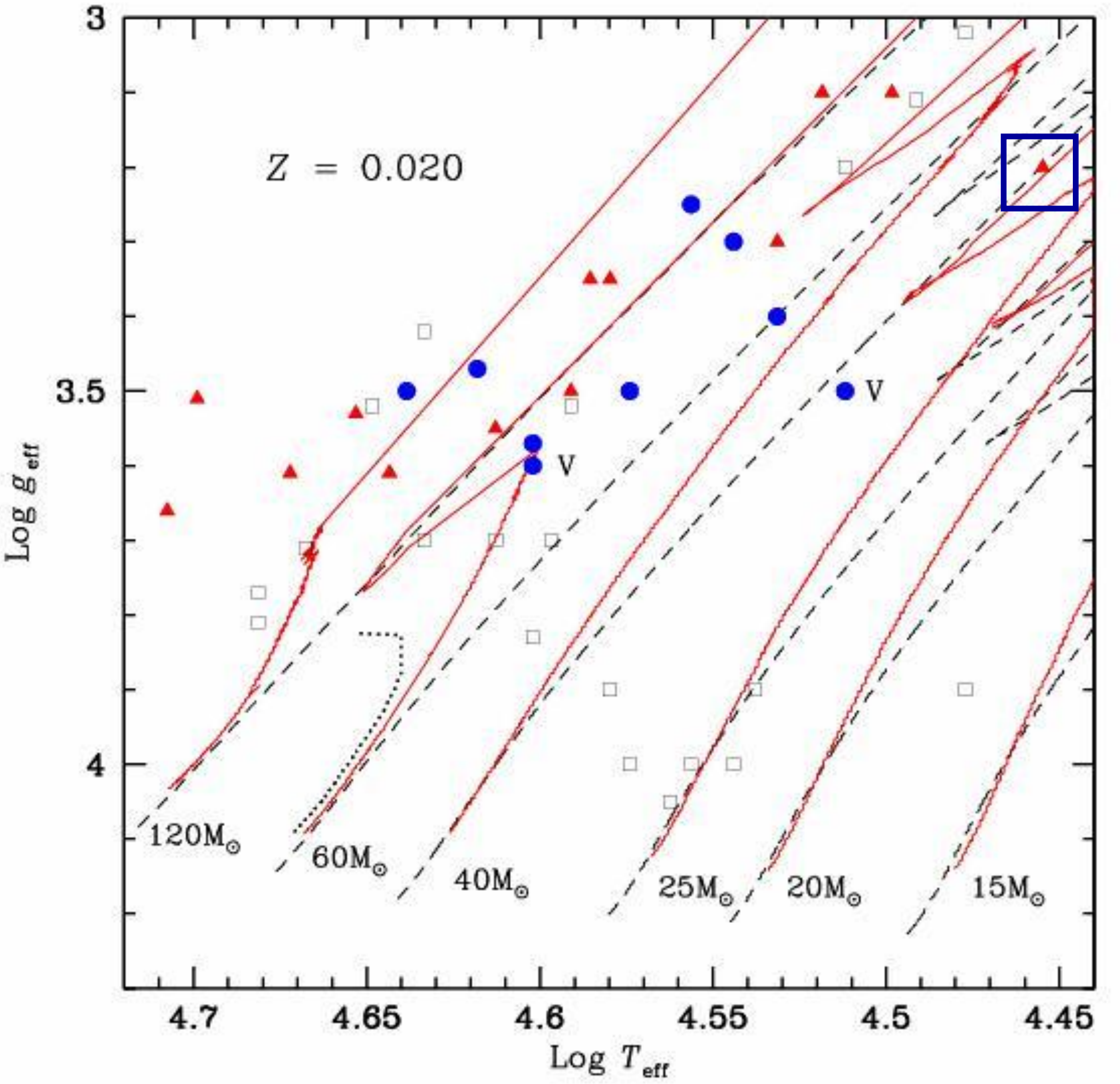
by 40-60 %

<u>For M > 50 M_{sol}</u>

→ WR

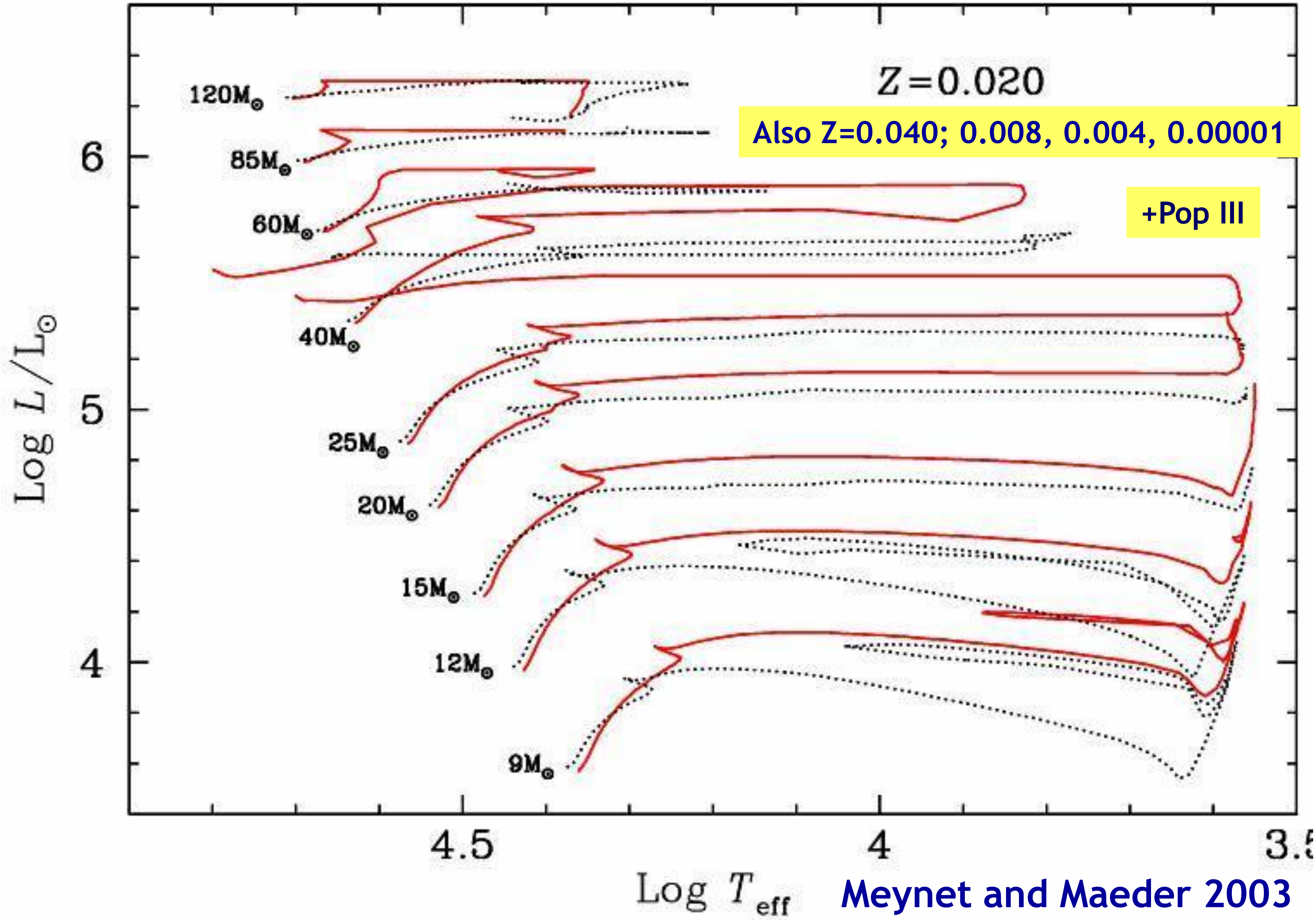
L % M

AT THE SAME LOCATION IN THE HR, WE MAY FIND STARS OF DIFFERENT MASSES (and different rotation)



Obs. by Herrero et al. ’92, ’99, ‘00

New grids of stellar models



Also Z=0.040; 0.008, 0.004, 0.00001

+Pop III

Meynet and Maeder 2003

BEFORE TO DISCUSS CONSEQUENCES FOR NUCLEOSYNTHESIS

→ CHECK OF THE MODELS

→ Surface rotational velocities

→ Surface abundances

→ Population of Wolf-Rayet Stars

→ Populations of supergiants

Effects of rotation on the quantity of mass lost by the winds

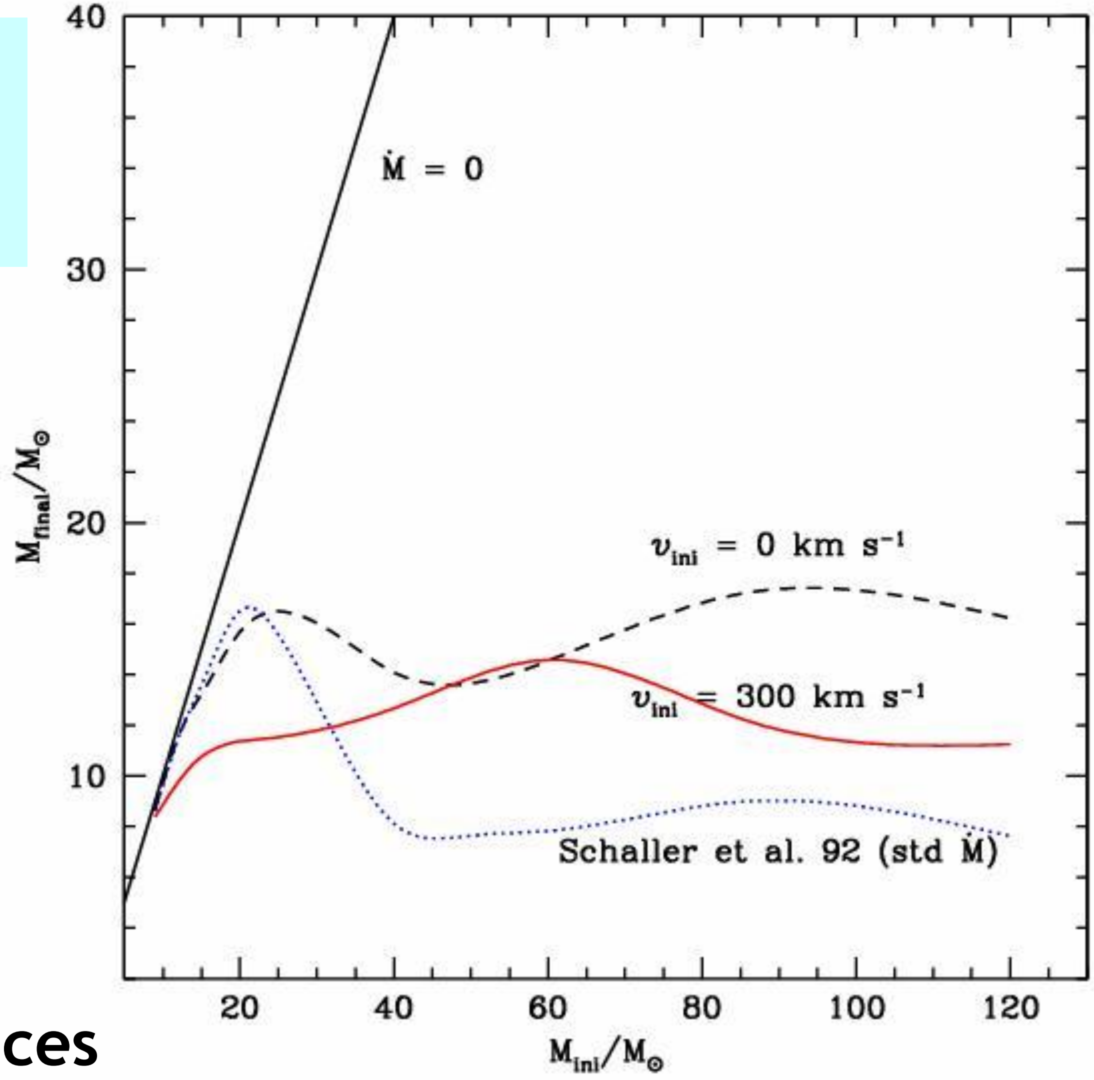
Rotation has an impact on the mass lost by stellar winds

- Direct effect
- Indirect effects

HR diagram

Lifetimes

Surface abundances



Evolution of Ω(r) during the Main Sequence

窠 Ω decreases inside the star

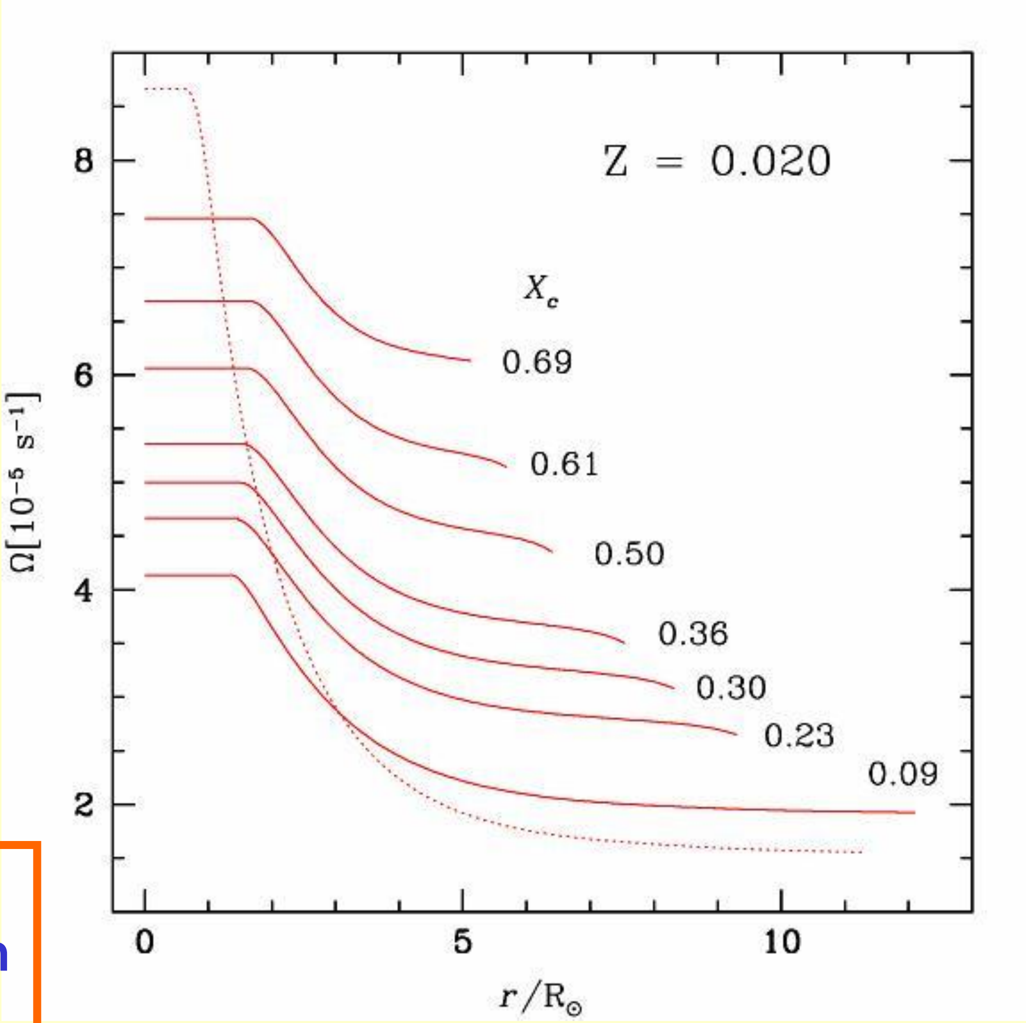
Removal of angular momentum
at the surface by the stellar winds

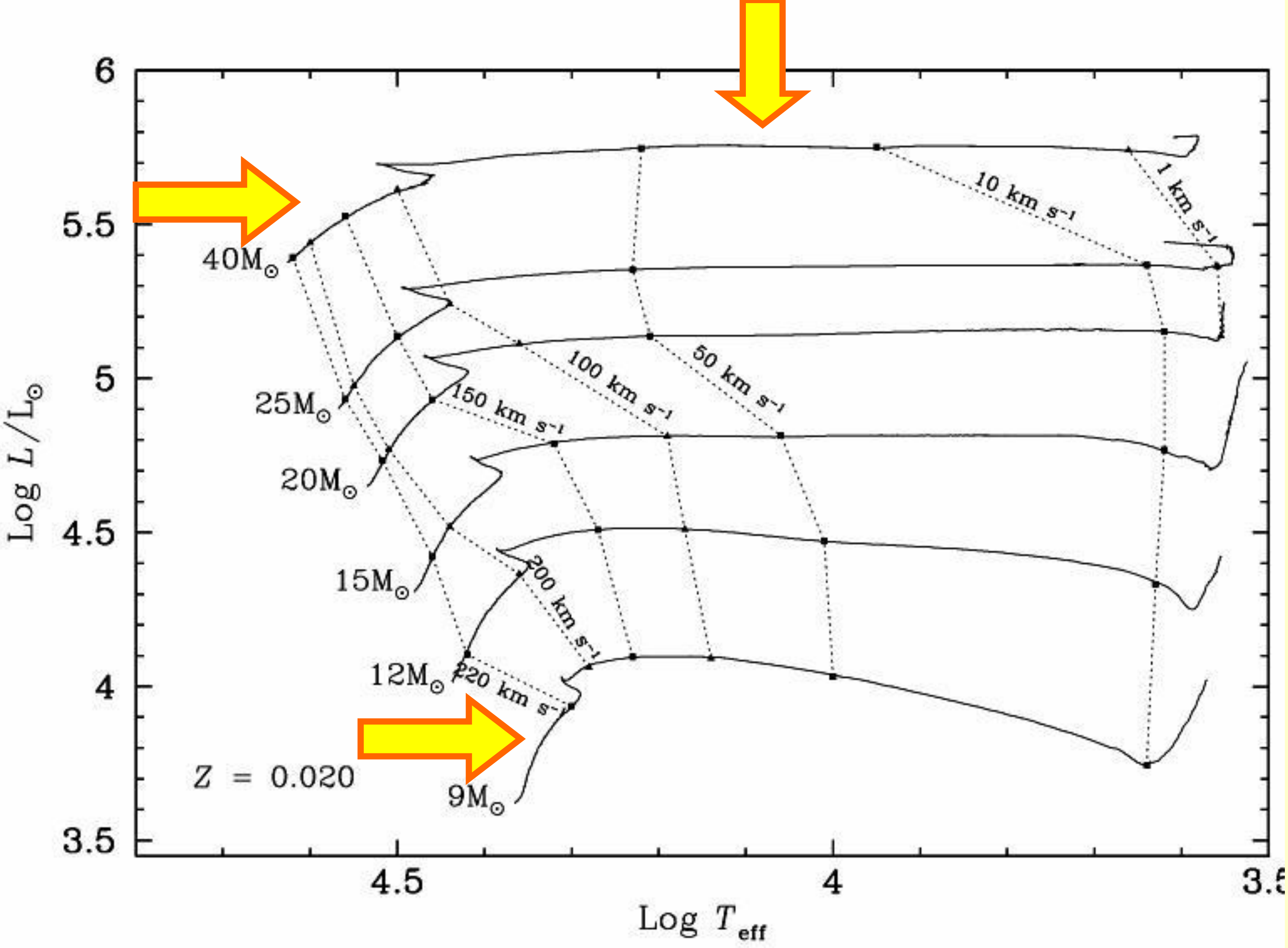
Transport of angular momentum

Increase of the radius

□ 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

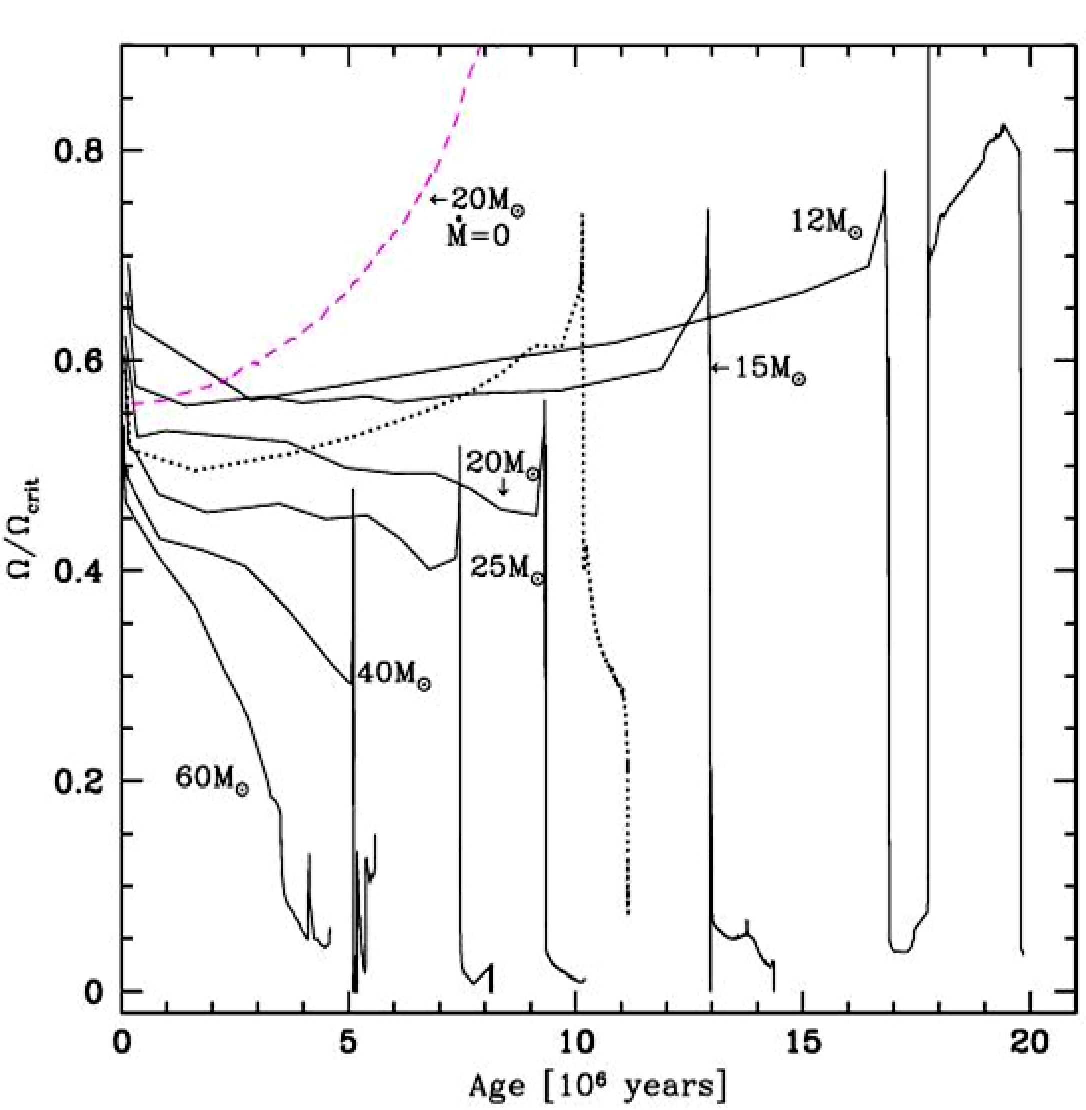
Break-up possible

LBV

Be stars

Z=0.02

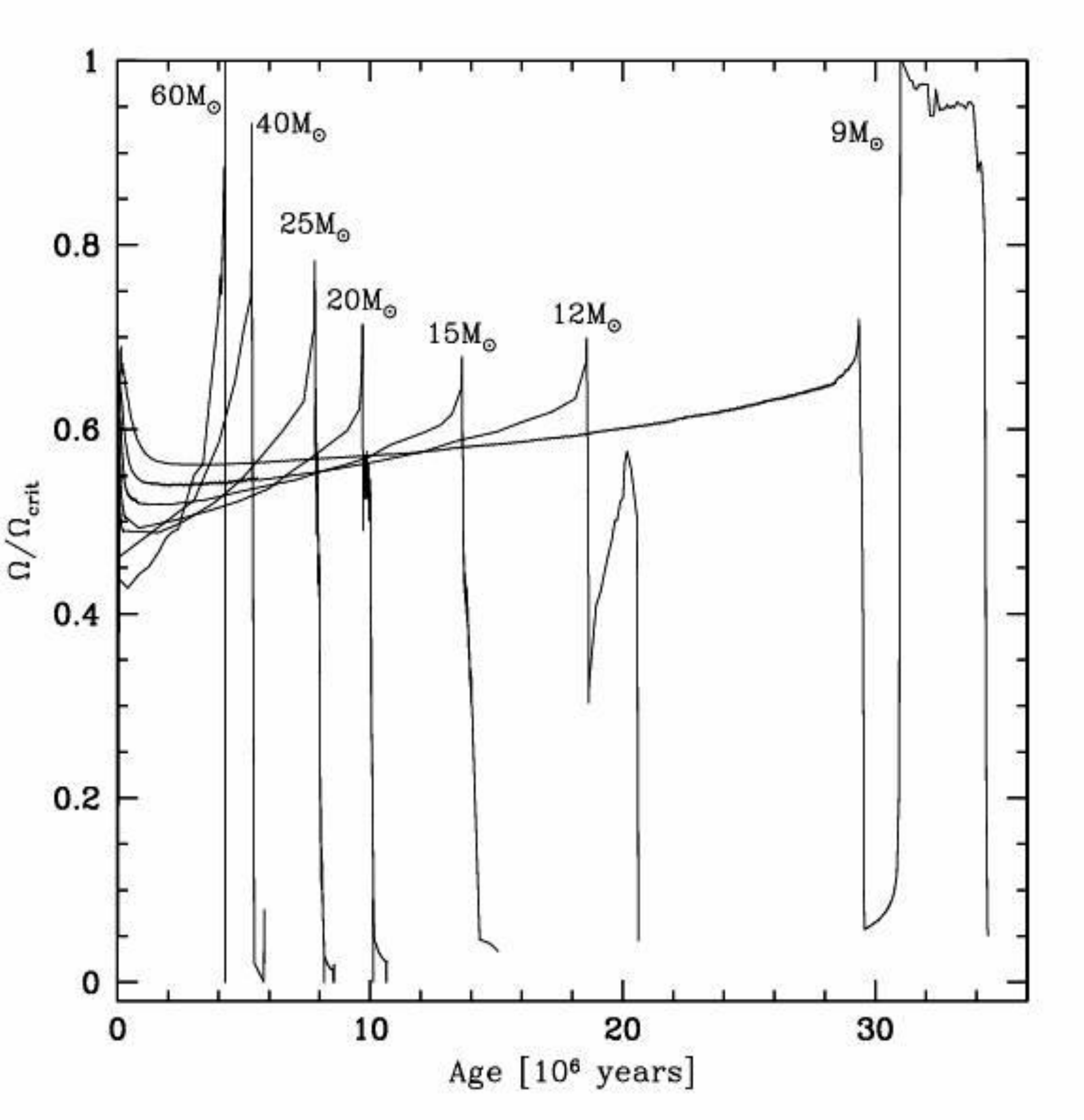
At Z=0.02, drastic decrease of for high masses



Z=0.004

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

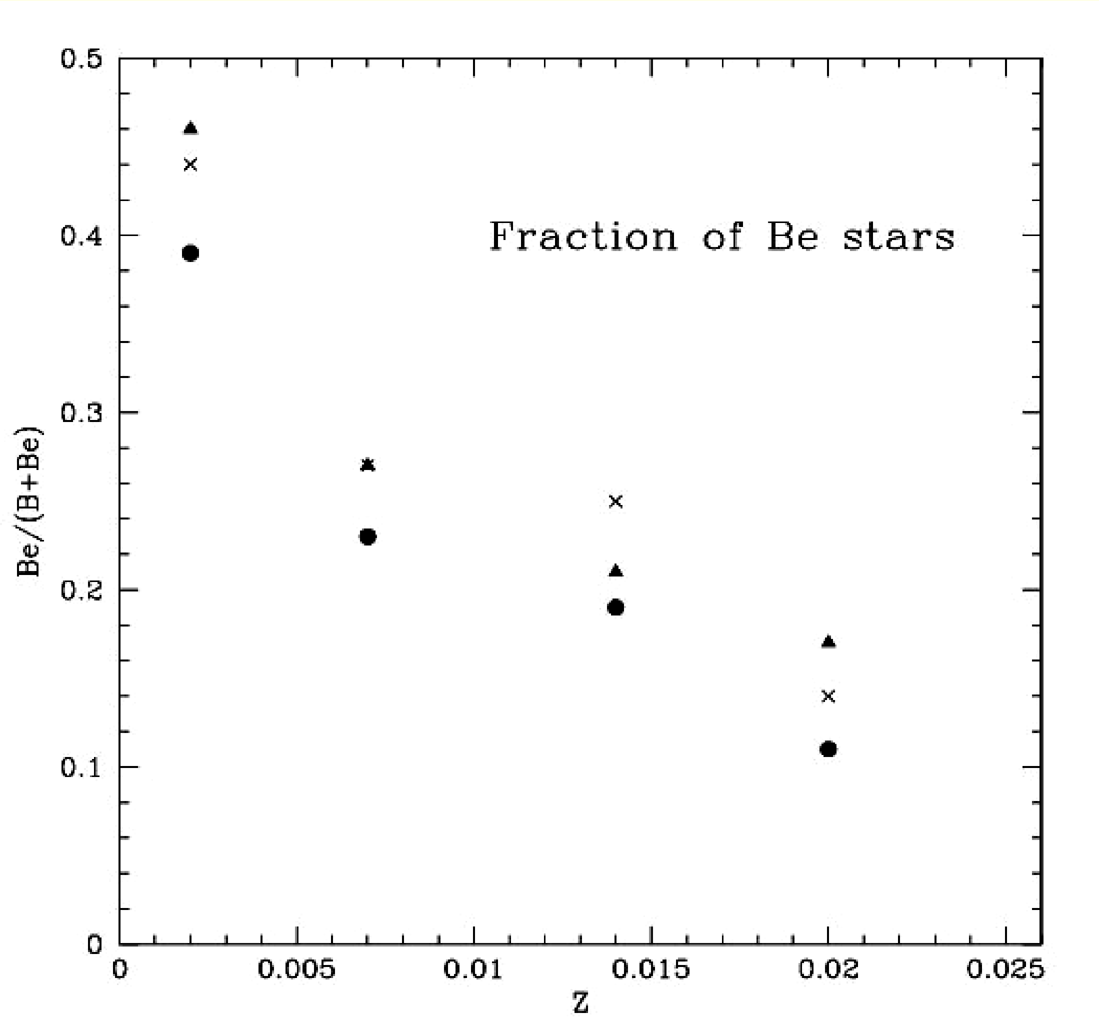
PARADOXICAL !



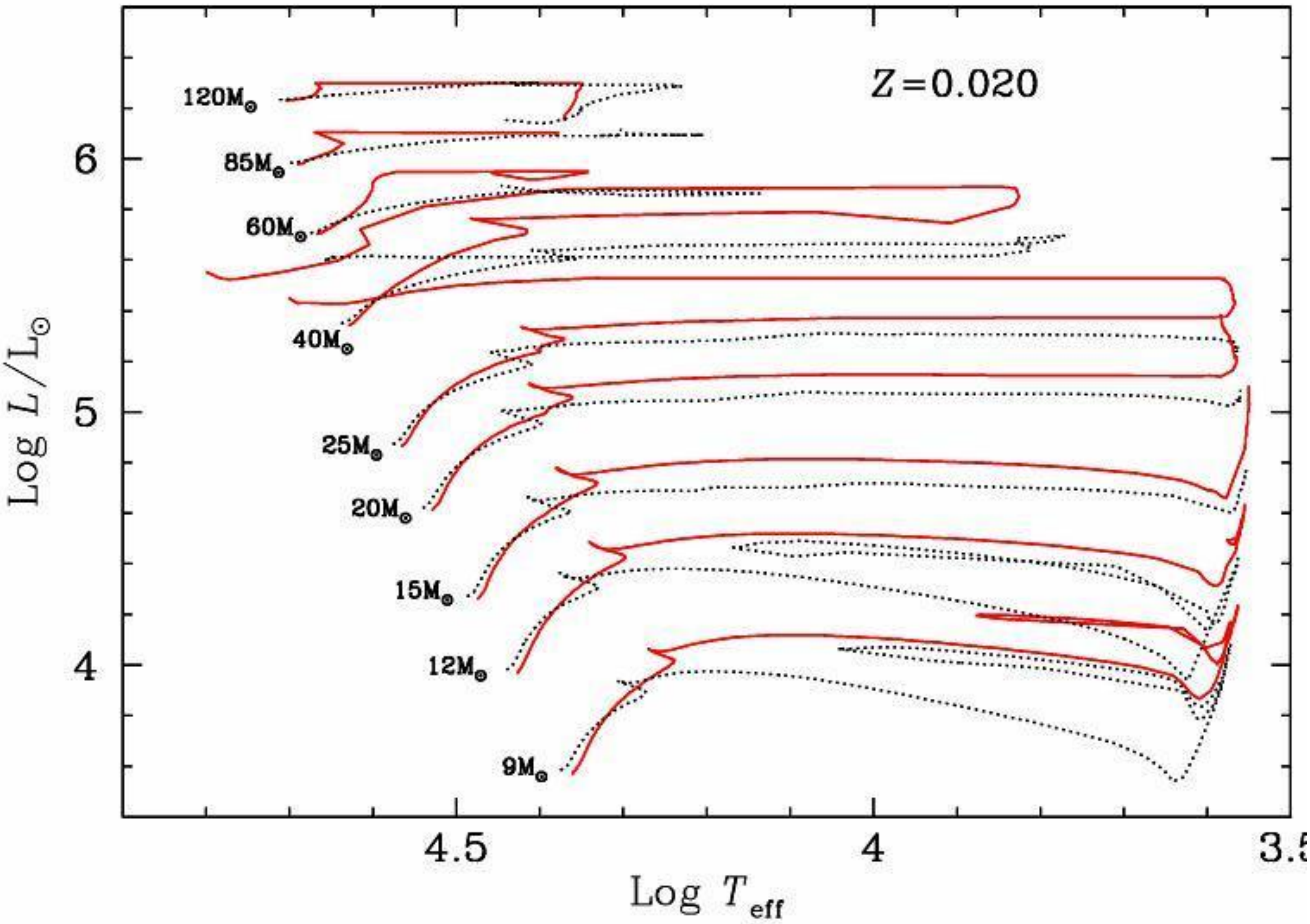
From 19 clusters in Galaxy, LMC & SMC

Rotation seems faster at lower Z

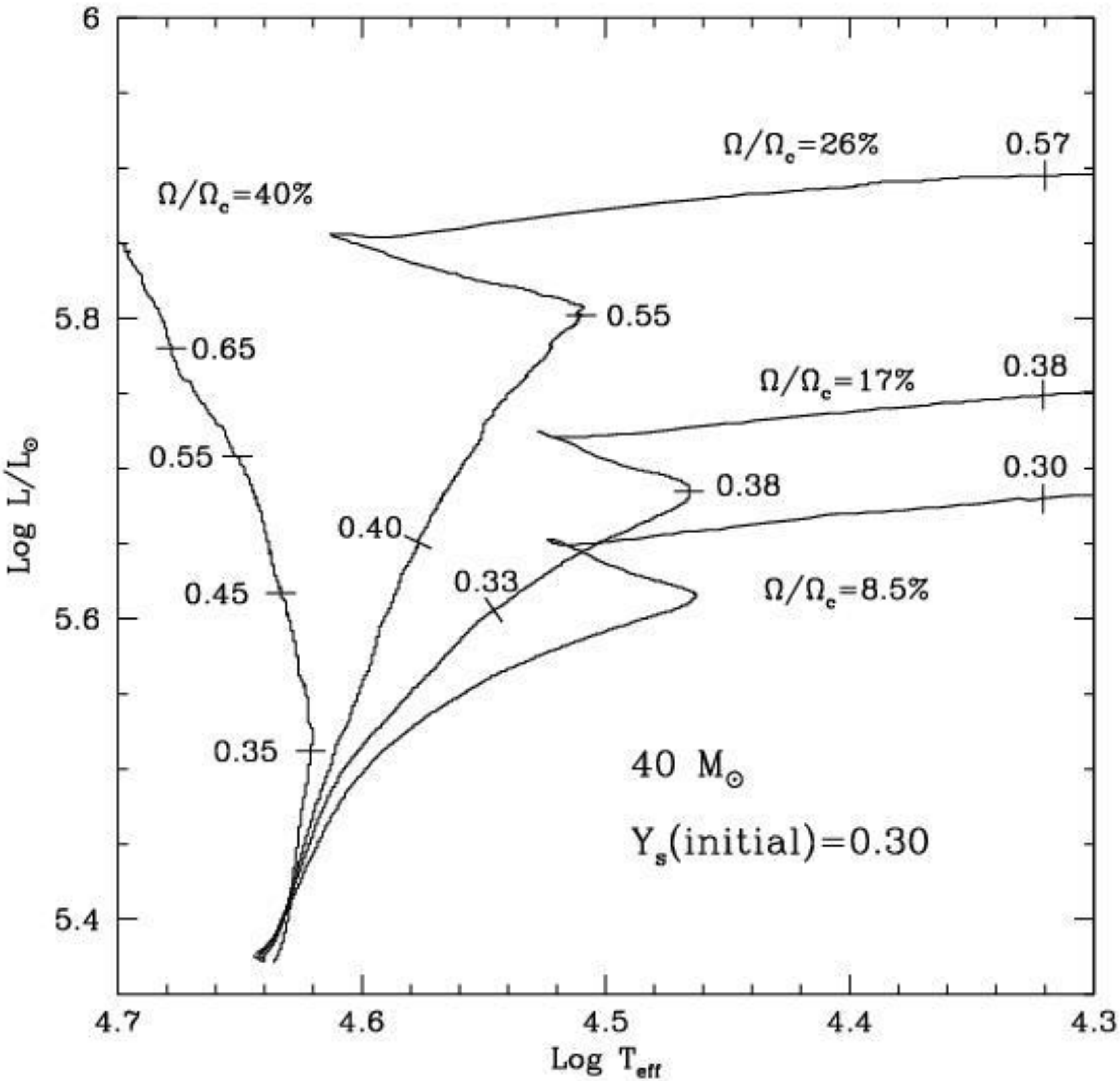
Is this a general trend ?
What at Z = 0 ?



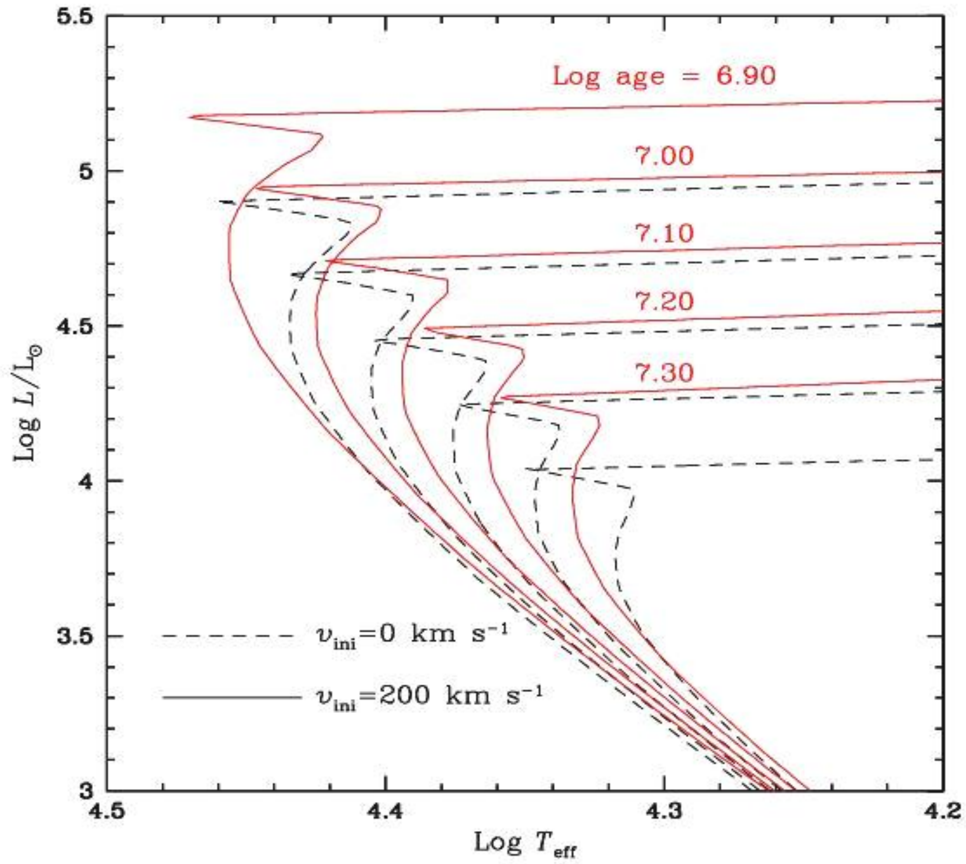
Maeder, Grebel, Mermilliod 1999



Meynet and Maeder 2003

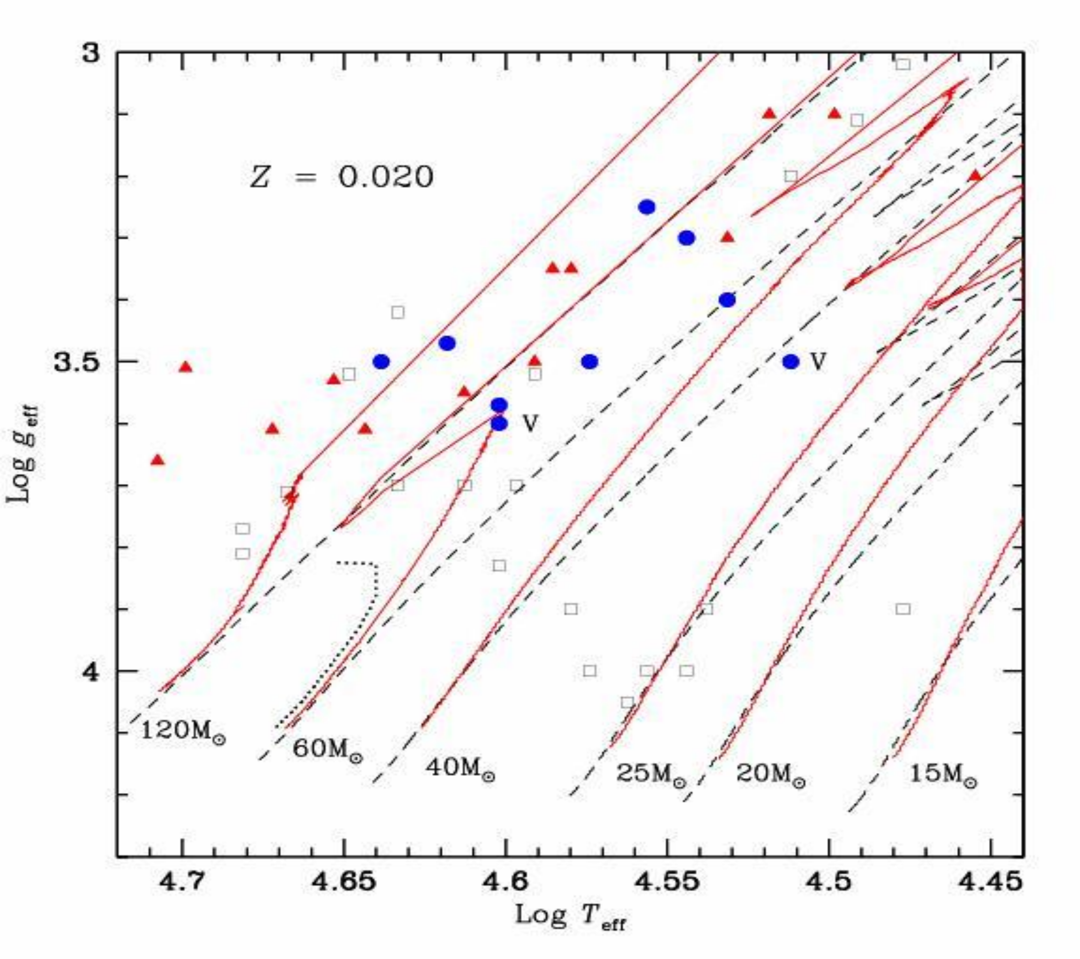


6
5.8
5.6
5.4
4.7
4.6
4.5
4.4
4.3
Log L/L$_\odot$
Log T$_{eff}$
Ω/Ω$_c$=40%
Ω/Ω$_c$=26%
Ω/Ω$_c$=17%
Ω/Ω$_c$=8.5%
0.57
0.55
0.65
0.38
0.55
0.38
0.30
0.40
0.33
0.45
0.35
40 M$_\odot$
Y$_s$(initial)=0.30



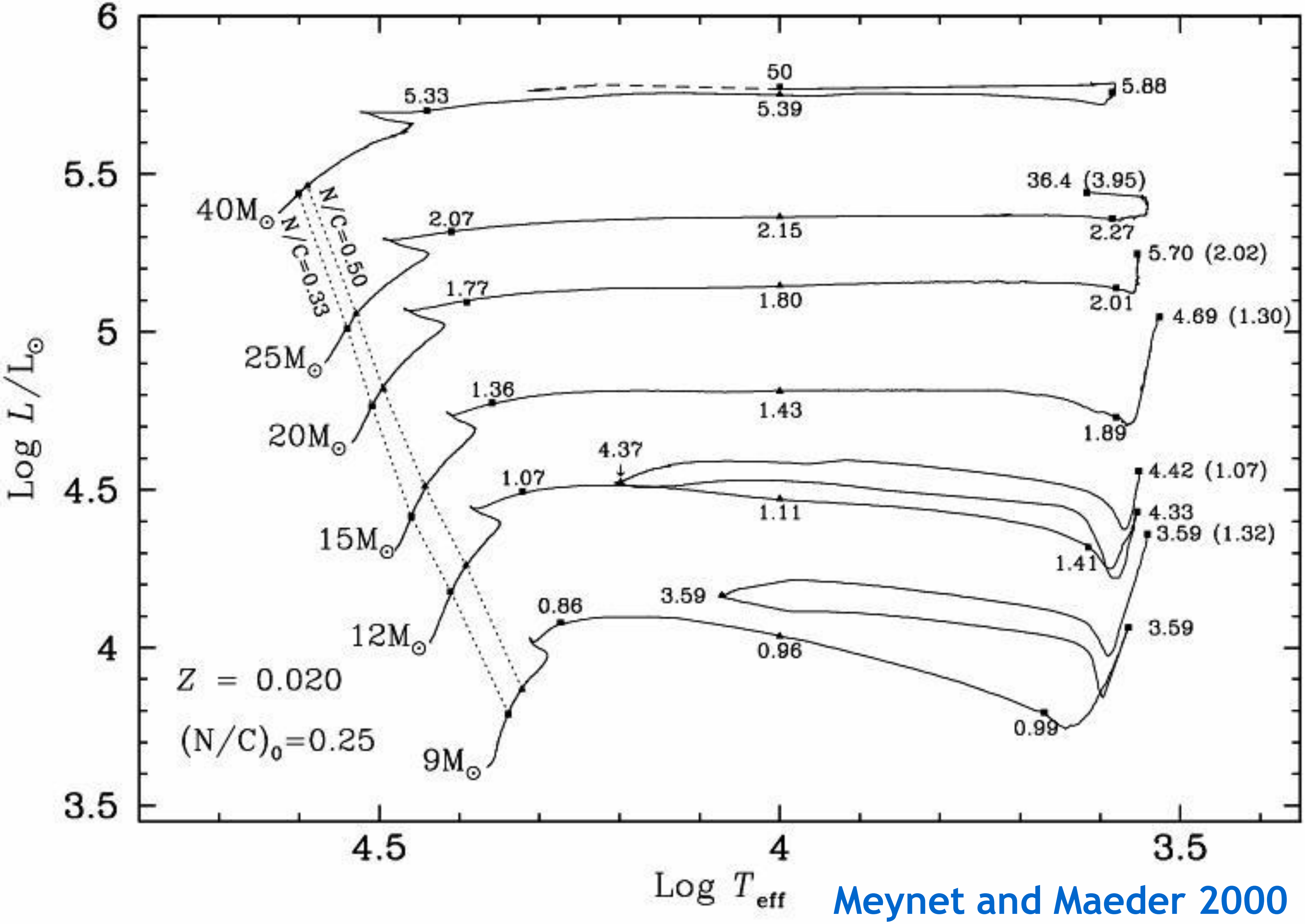
When rotation is accounted for, the ages are found 25 % larger. For Pleiades: reconcile with age from Li depletion in low M stars.

Martin et al. 1998



Obs. by Herrero et al. ’92, ’99, ‘00

AT THE SAME LOCATION IN THE HR, WE MAY FIND STARS OF DIFFERENT MASSES
(and different rotation)



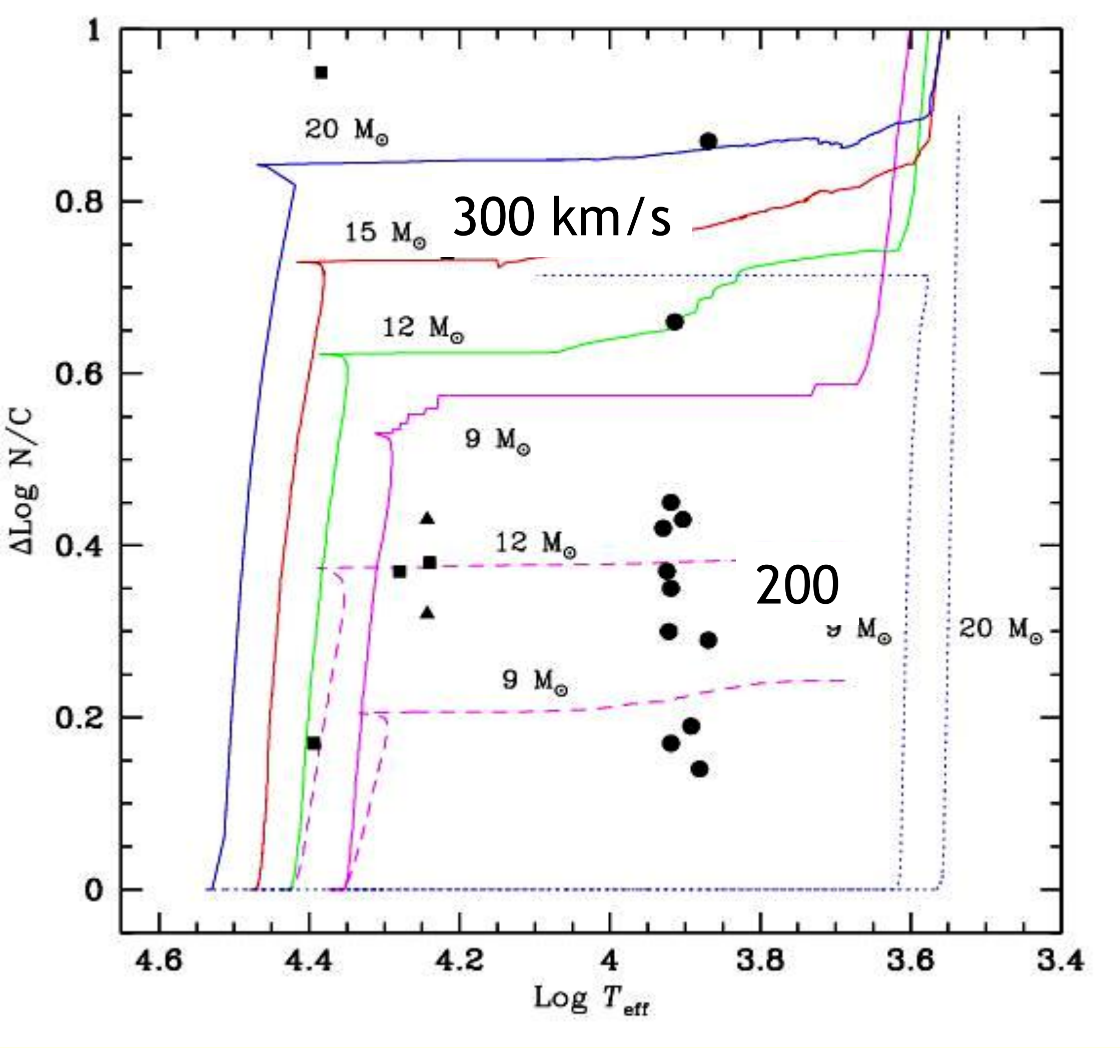
Meynet and Maeder 2000

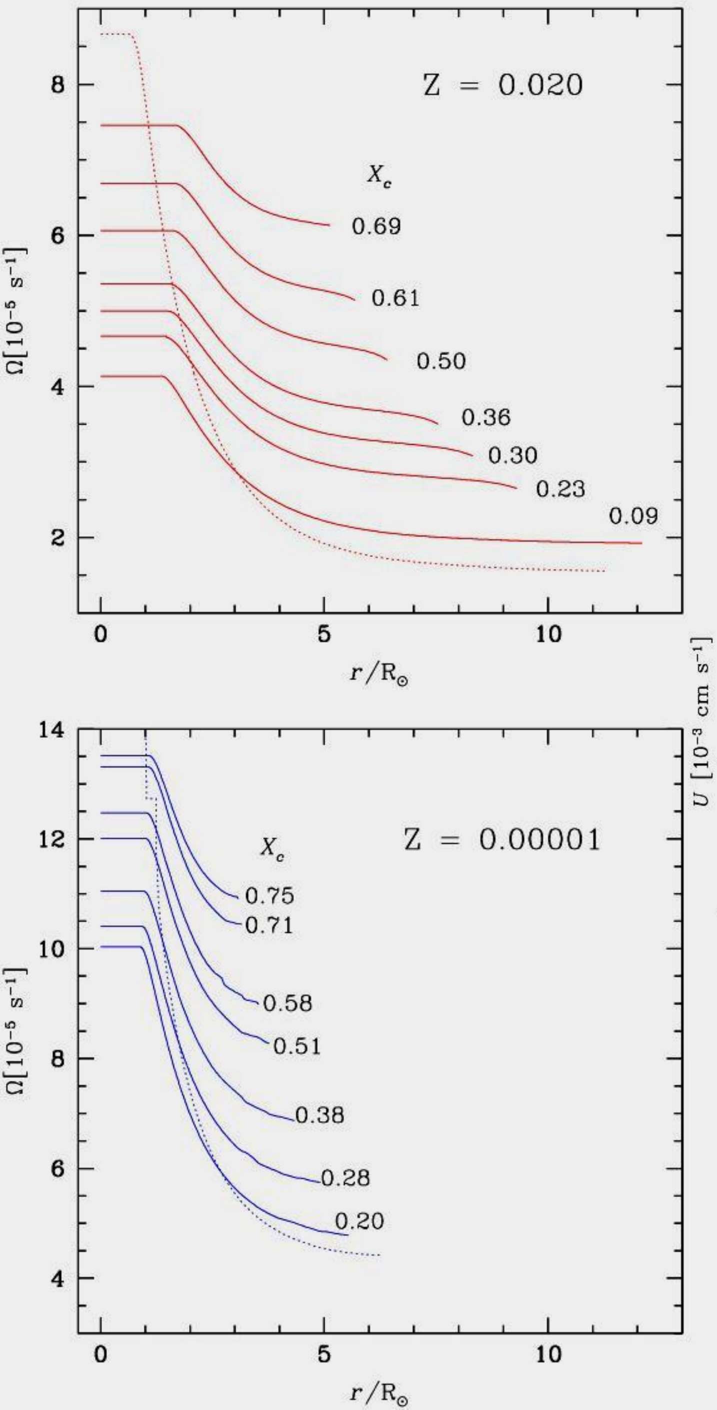
N/C grows during the MS, even for early B stars

(cf.Lyubimkov 1996)

OK with B, A supergiants

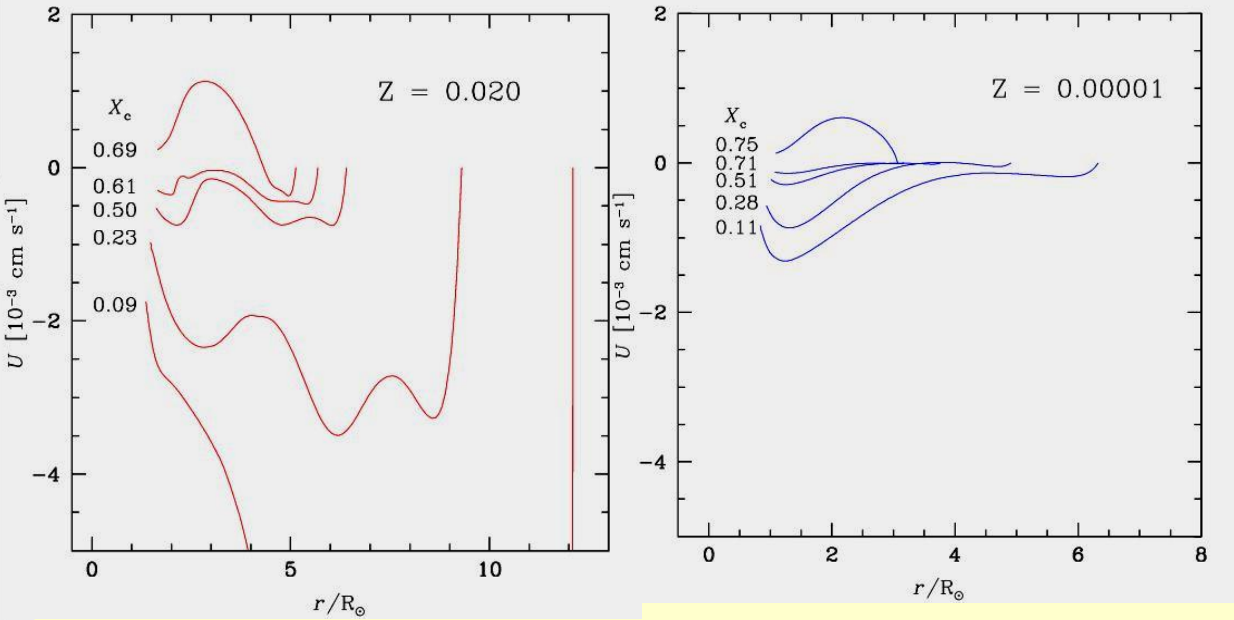
(cf. Gies & Lambert 1992; Lennon 1994; Venn 1998,…)
(cf. Maeder, 1987; Langer, 1992; ….)





When Z decreases stars become more compact

In U the Gratton Öpick scales with the Inverse of the density

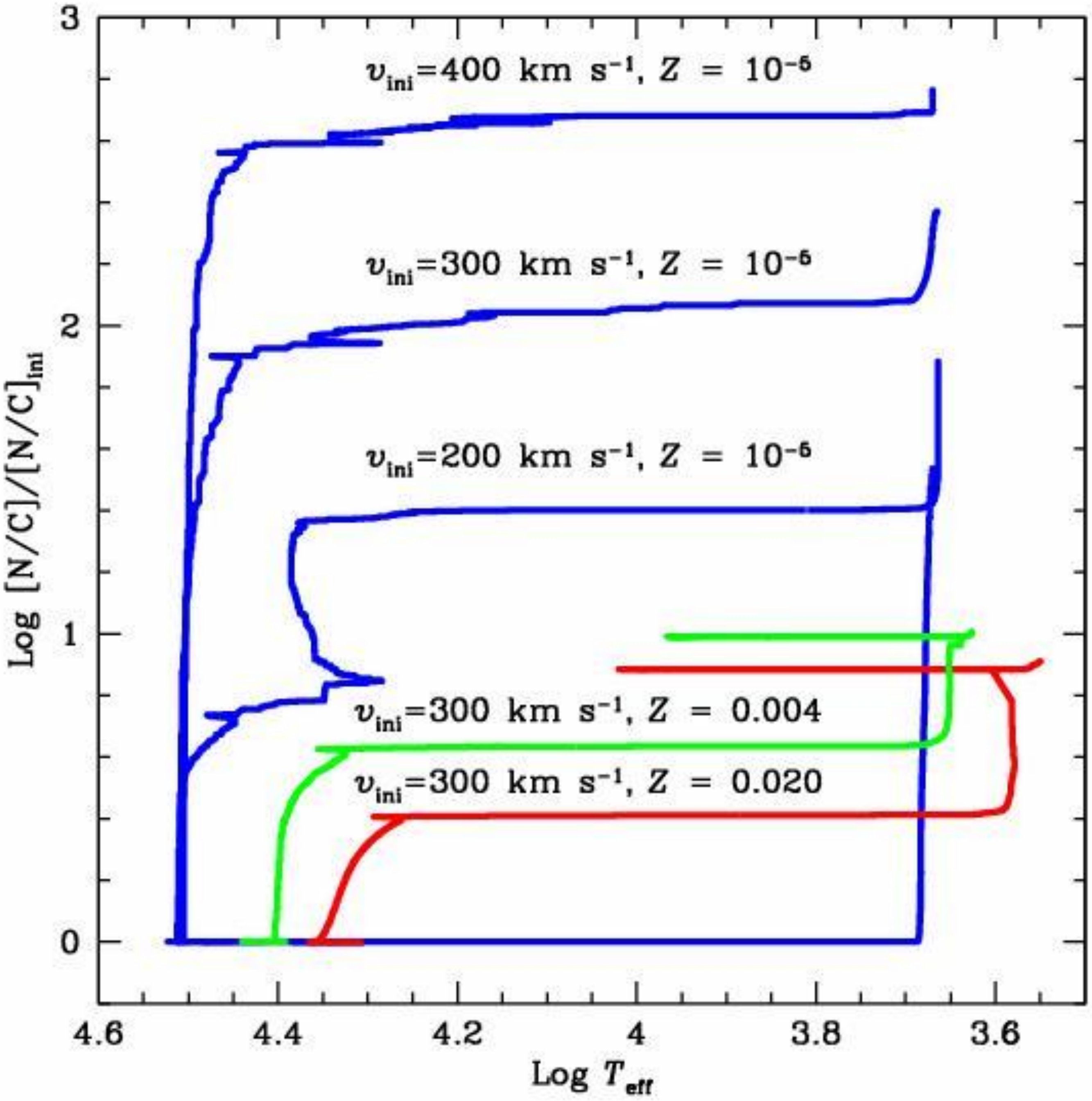


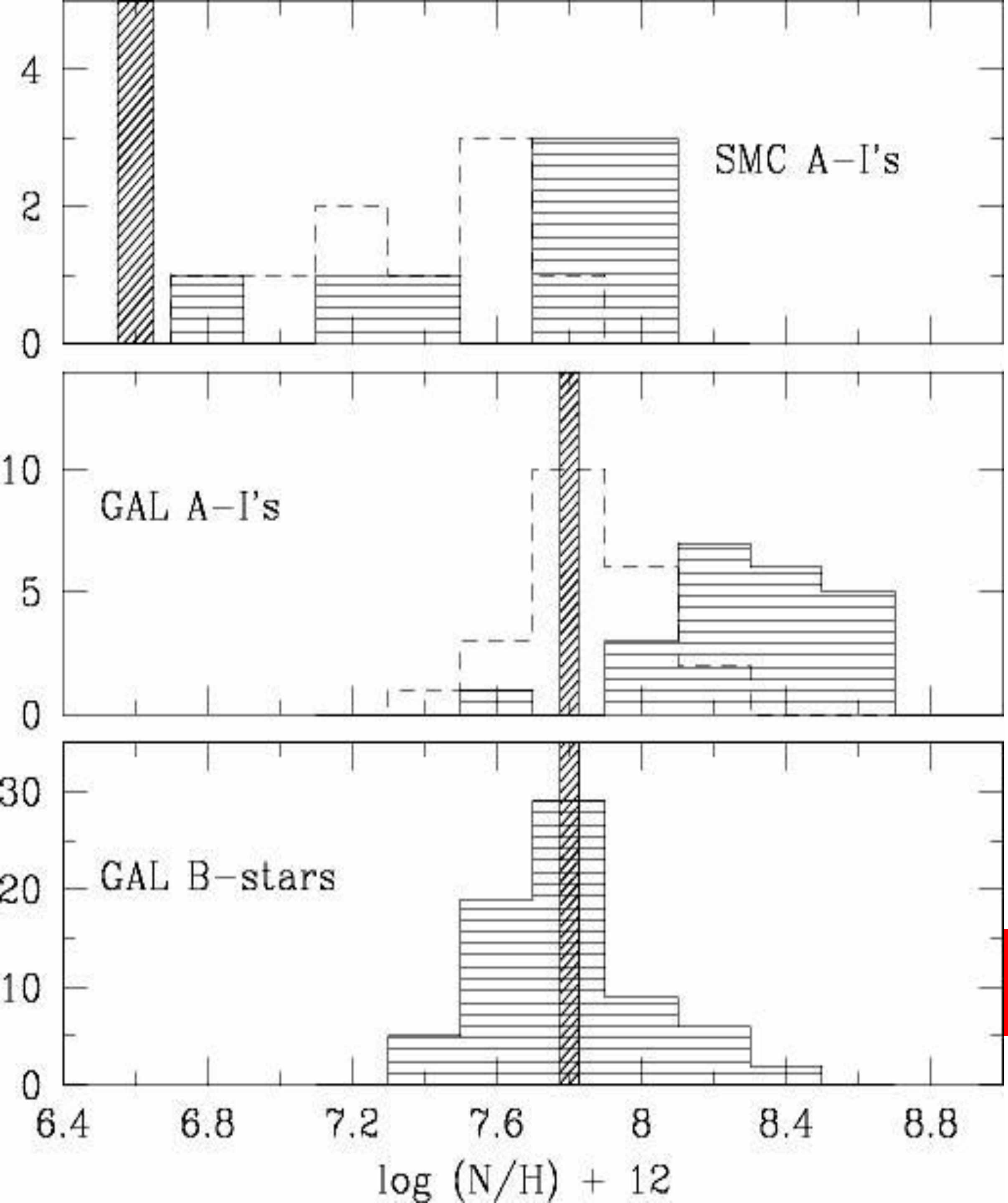
Less angular momentum is removed by the stellar winds

9 M_{sol}

When Z ↘

Surface enrichments ↗

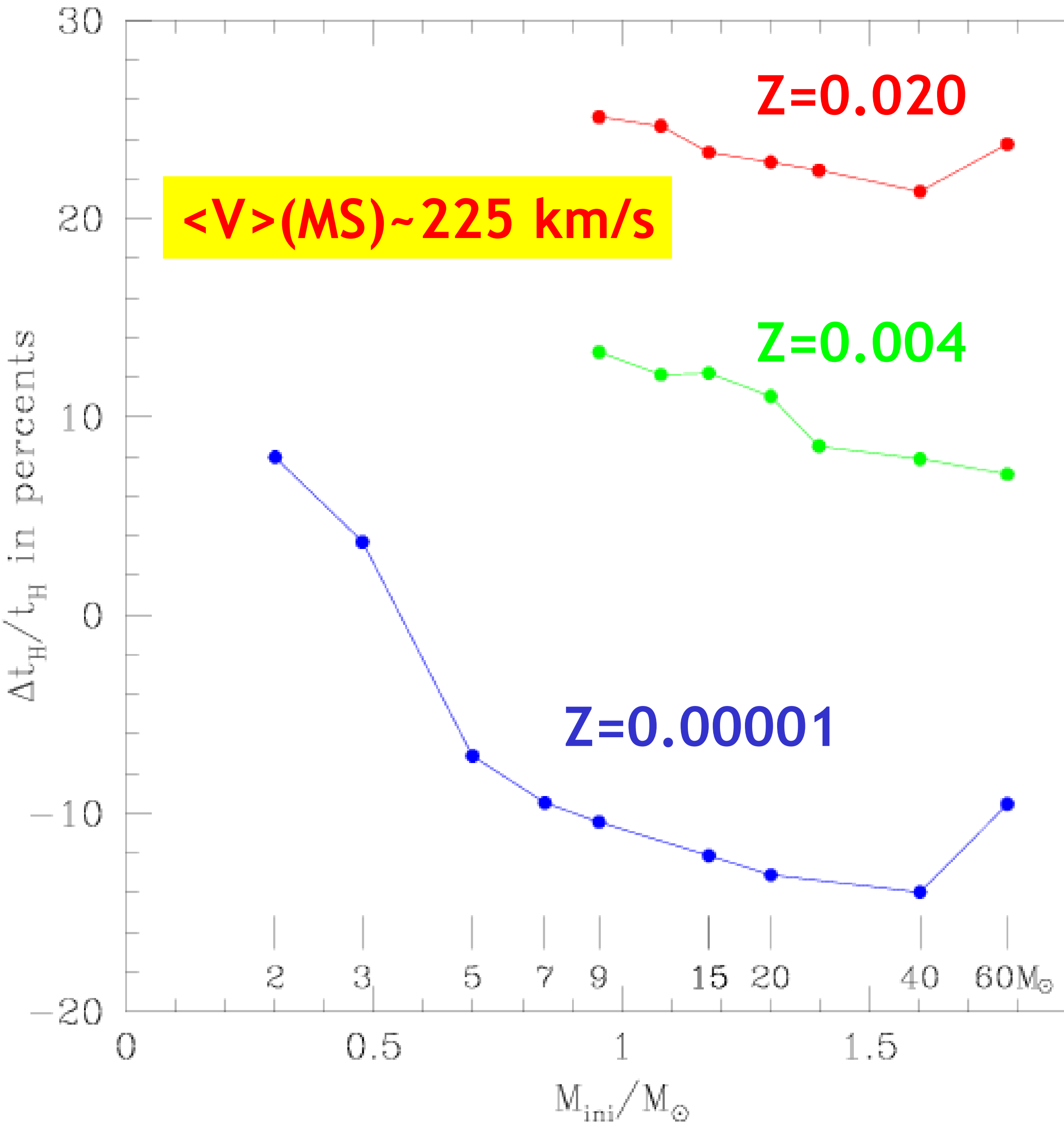




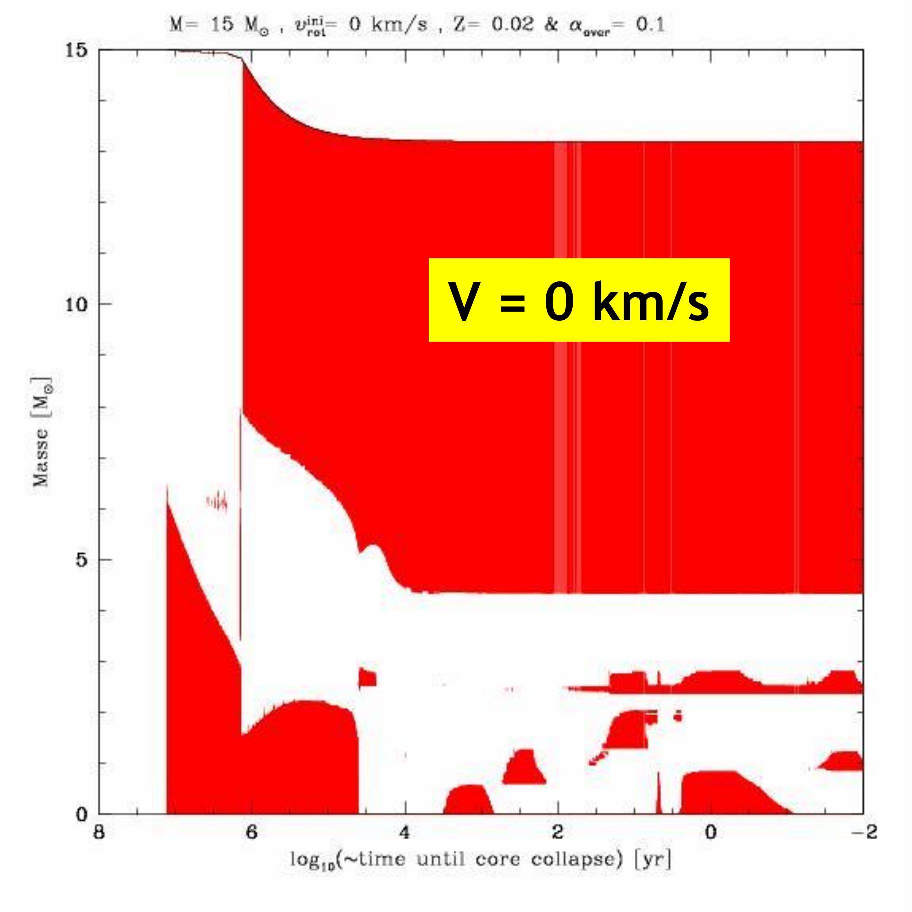
Max/ini N/H =40

Max/ini N/H =8

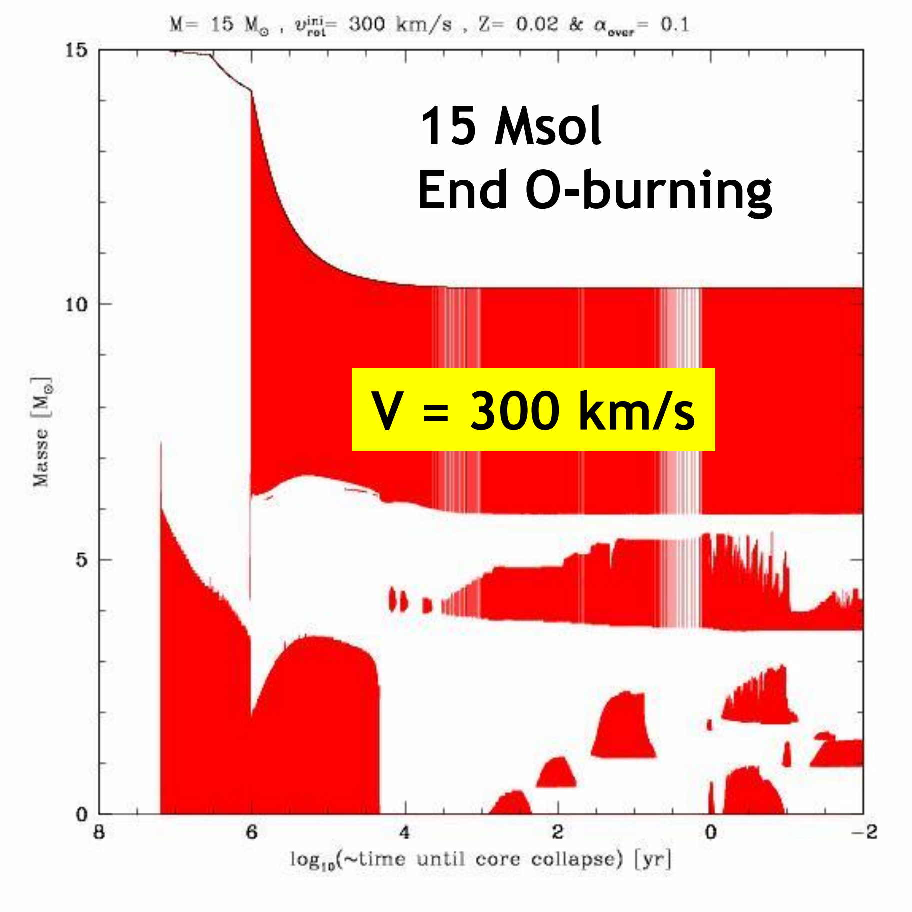
Venn & Przybilla 2003


Z=0.020
<V>(MS)~225 km/s
Z=0.004
Z=0.00001
$\Delta t_H / t_H$ in percents
30
20
10
0
−10
−20
2
3
5
7
9
15
20
40
60$M_\odot$
0
0.5
1
1.5
2
$M_{ini}/M_\odot$

Size of the convective cores
Mass removed by stellar winds



V = 0 km/s



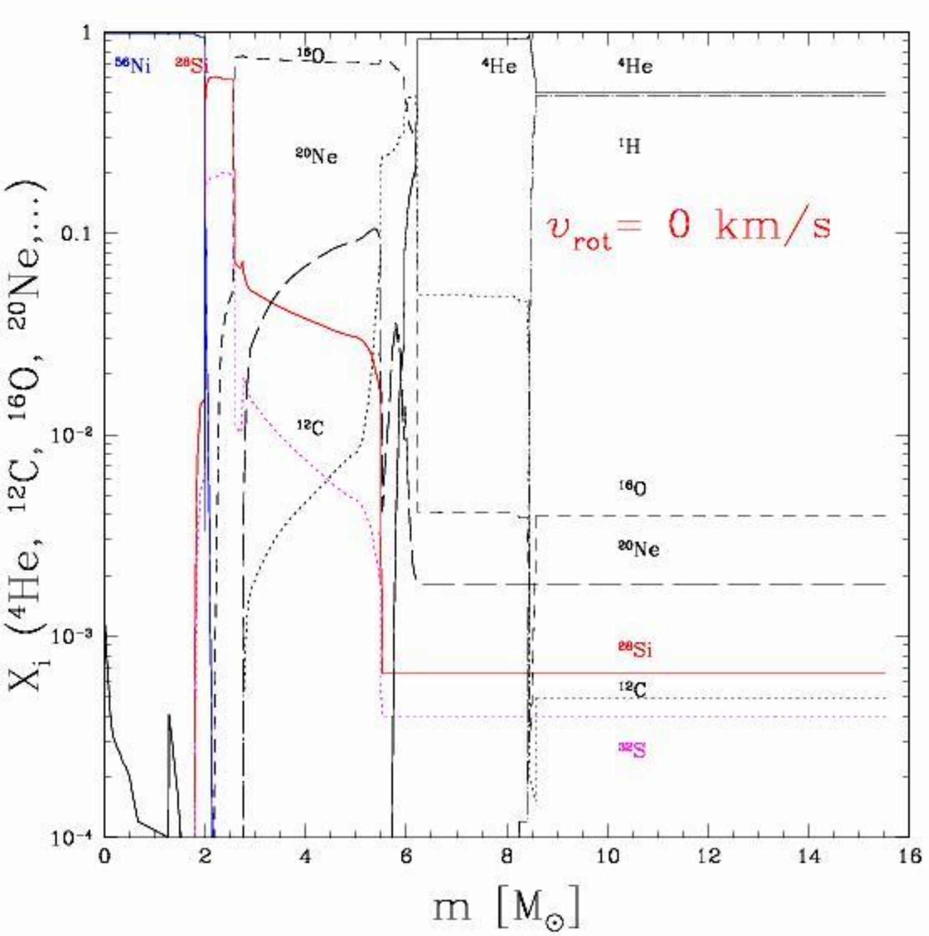
15 Msol
End O-burning

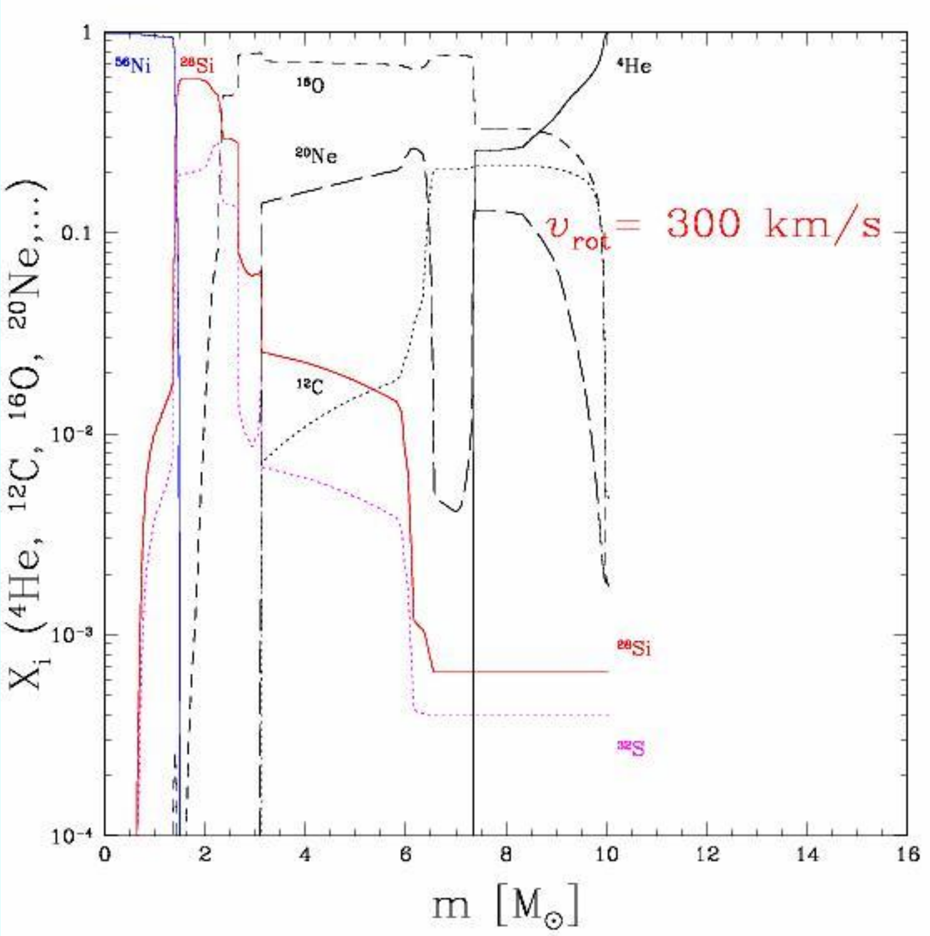
V = 300 km/s

Hirschi 2002

Cf also Heger, Langer, Woosley 2000

Yields of heavy elements increased

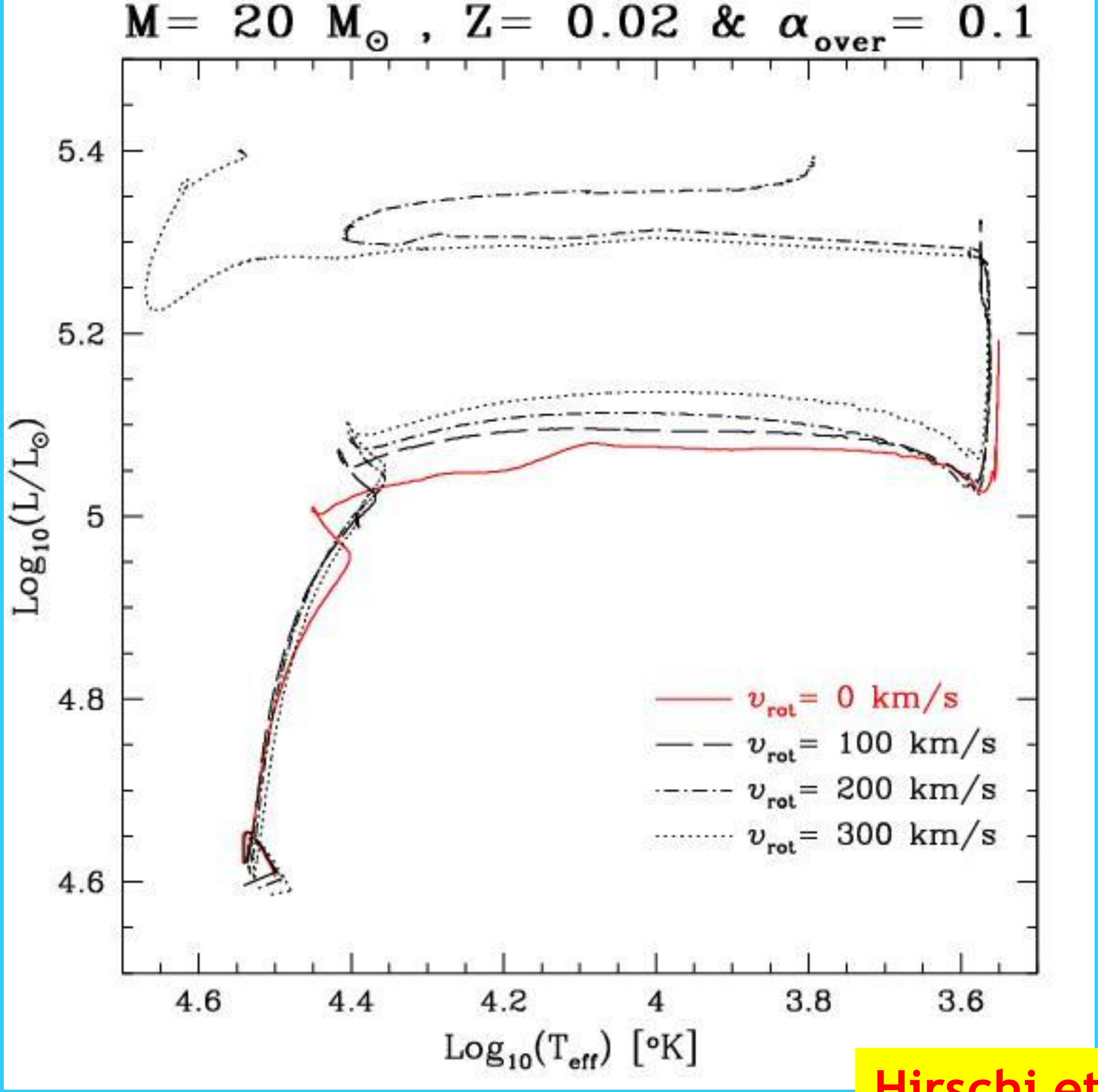




COMPARISON OF THE YIELDS FROM ROTATING AND NON-ROTATING MODELS

15 M_{sol}	^{4}He	^{12}C	^{14}N	^{16}O	Z
V_{ini}=0 km/s	1.70	0.18	0.05 3%	0.42	0.92
V_{ini}=300 km/s	1.55 19%	0.32	0.03 45%	1.08	1.97

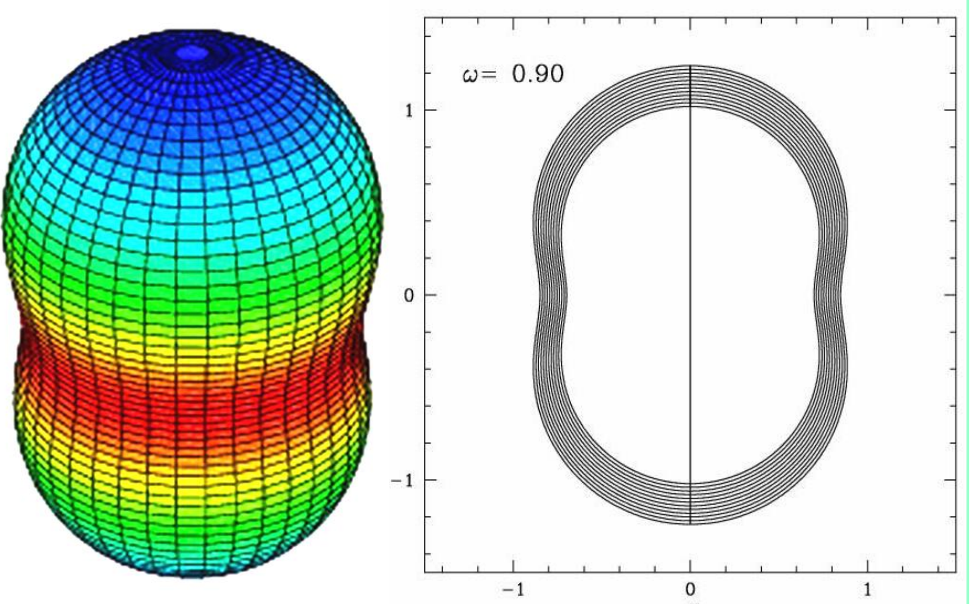
THE COLOUR OF THE PROGENITOR DEPEND ON ROTATION



Hirschi et al.2003

LA ROTATION → ANISOTROPIE DU VENT

THEORIE



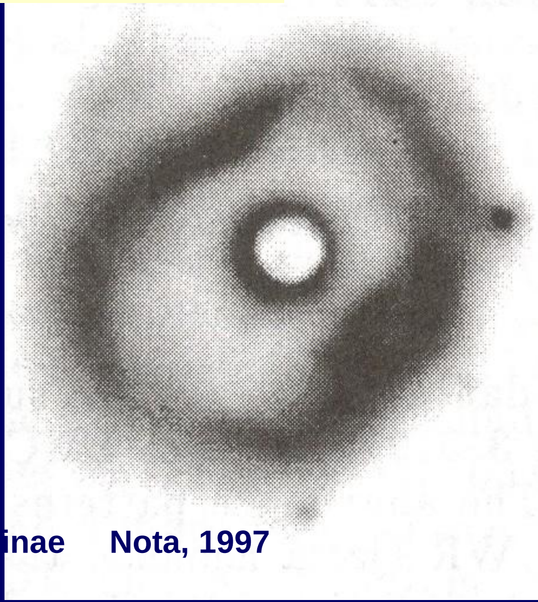
Maeder, 1999

120 M_{sol},
Log L/L_{sol} = 6.0,
T_{eff}=30 000 K,

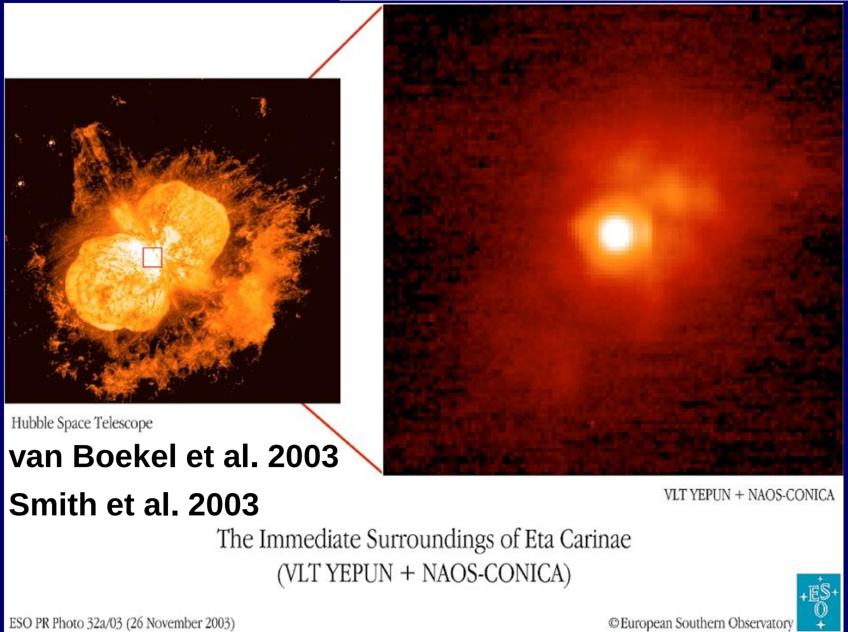
CONSEQUENCE

PEU DE MOMENT ANGULAIRE PERDU

OBSERVATIONS



inae Nota, 1997



van Boekel et al. 2003

Smith et al. 2003

The Immediate Surroundings of Eta Carinae
(VLT YEPUN + NAOS-CONICA)

ESO PR Photo 32a/03 (26 November 2003)

©European Southern Observatory

LA ROTATION → INTENSITE DES VENTS

Maeder, Meynet, A&A 361, 159 (2000)

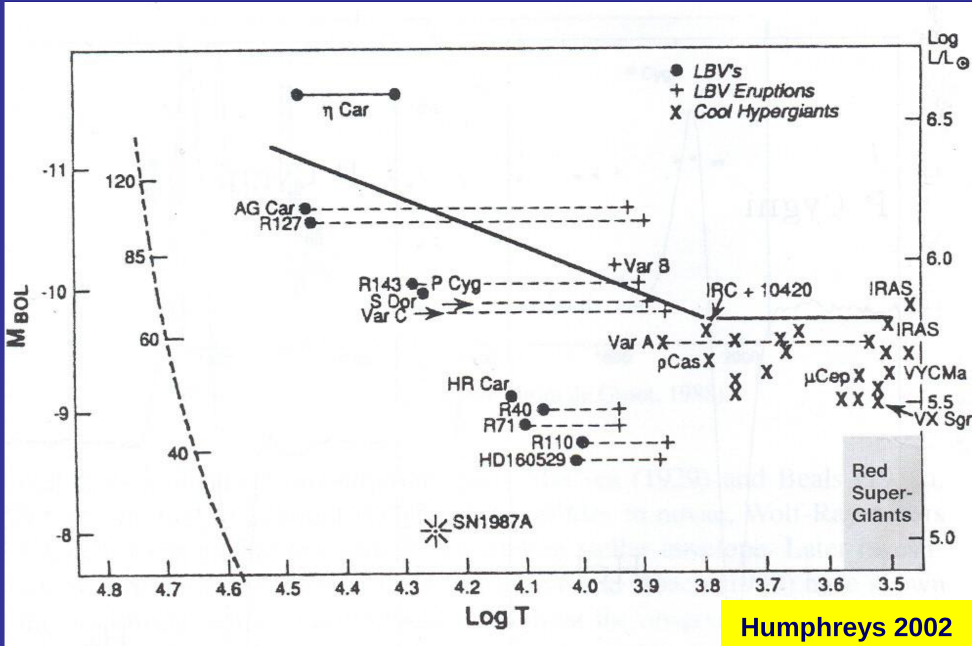
- 20 M_{sol} à la vitesse critique → perte de masse augmentée par moins d’ un facteur 2

- Pour les étoiles proches de L_{EDD}→ la rotation peut rendre l’étoile supra-Eddington

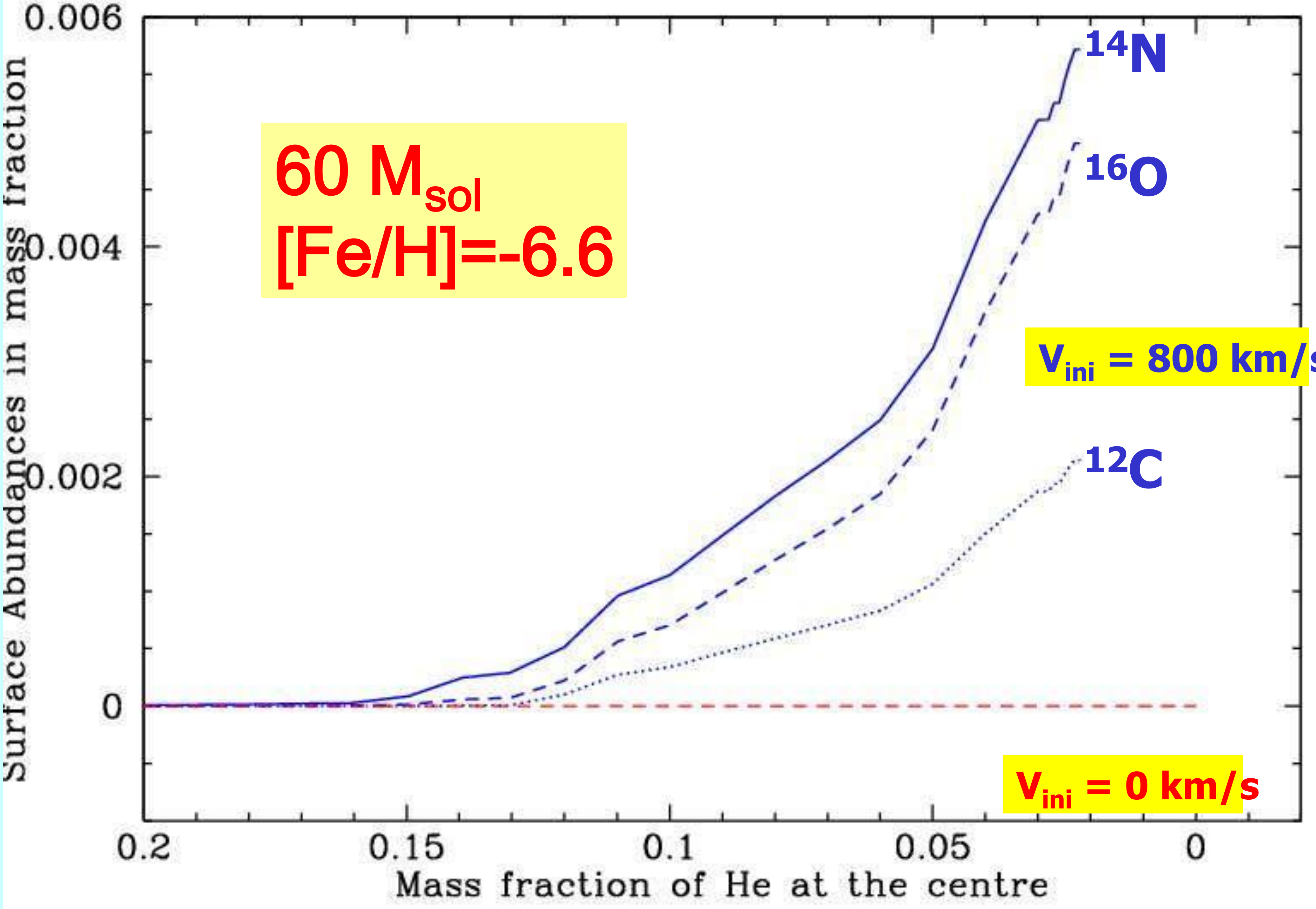
$$\Gamma_\Omega = \frac{L}{\underbrace{\frac{4\pi c G M}{\kappa}\left(1-\frac{\Omega^2}{2\pi G \rho_m}\right)}_{L_{\max}}}$$

Très forte augmentation de la perte de masse

Lien avec les ``Luminous Blue Variables”



Humphreys 2002

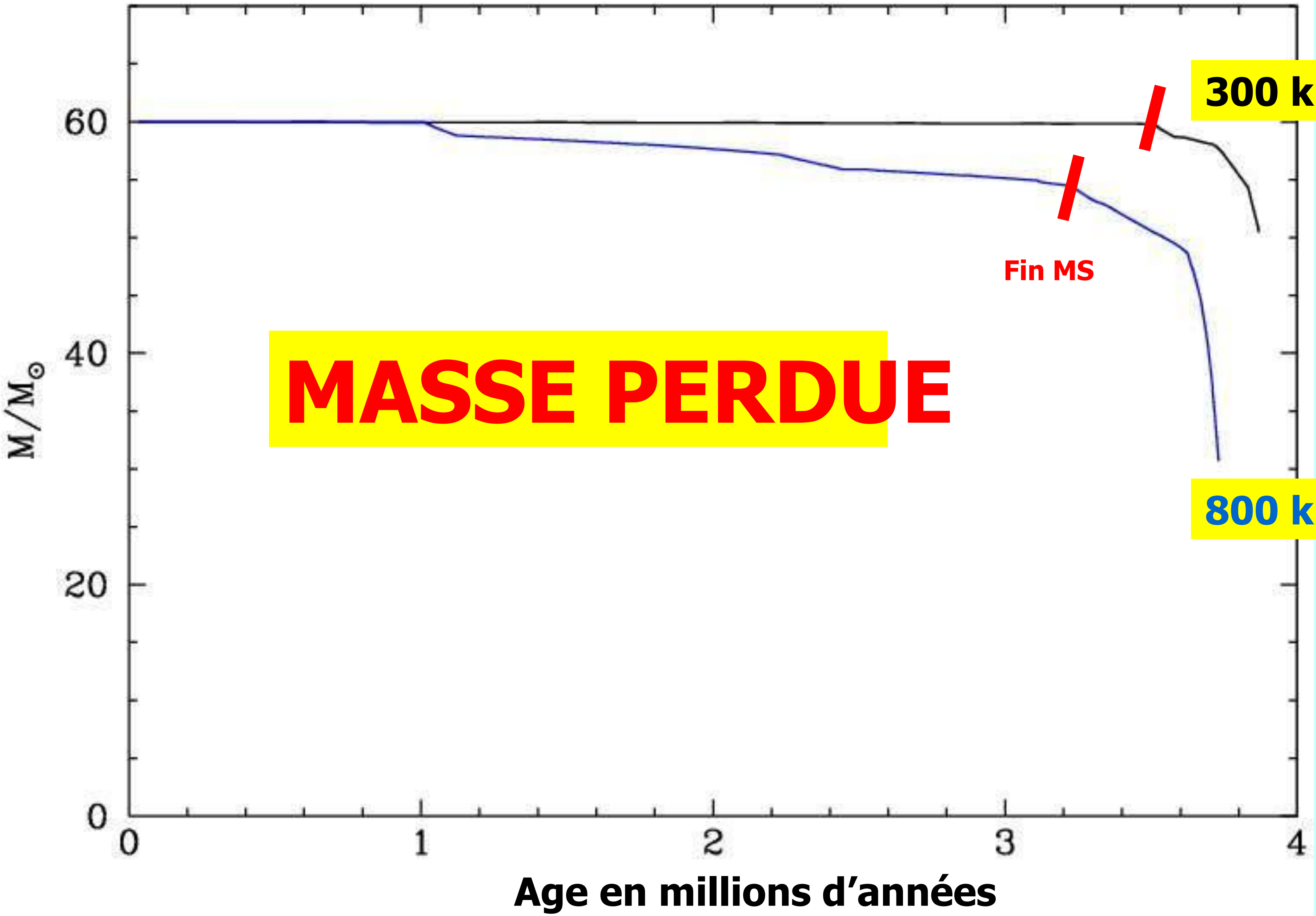


60 M_{sol}
[Fe/H]=-6.6

V_{ini} = 800 km/s

V_{ini} = 0 km/s

[Fe/H]=-6.6



300 km/s

Fin MS

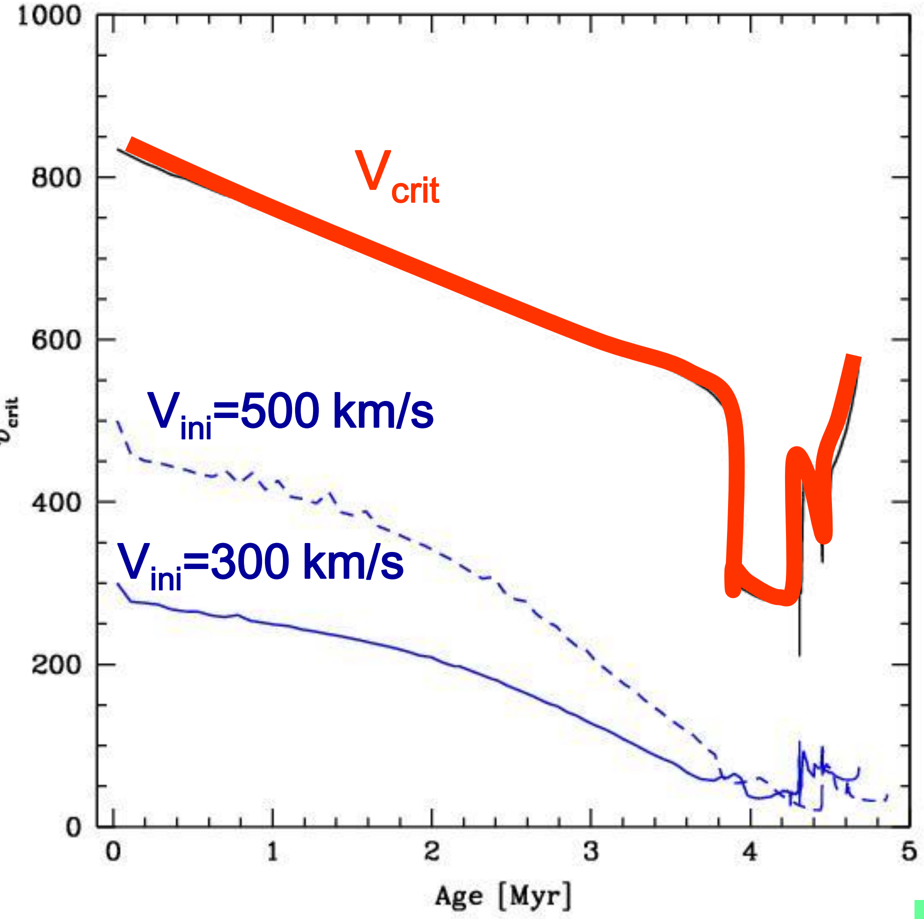
MASSE PERDUE

800 km/s

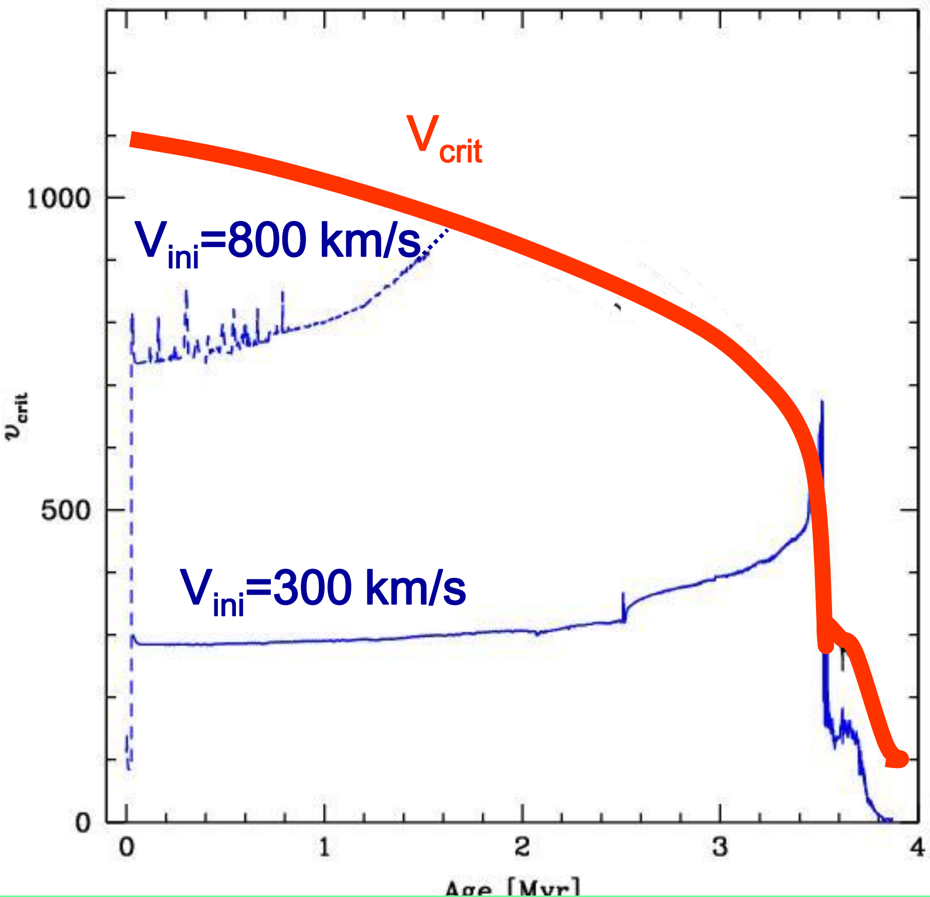
LA ROTATION FAVORISE LA PERTE DE MASSE

1) Les étoiles atteignent plus facilement la rupture

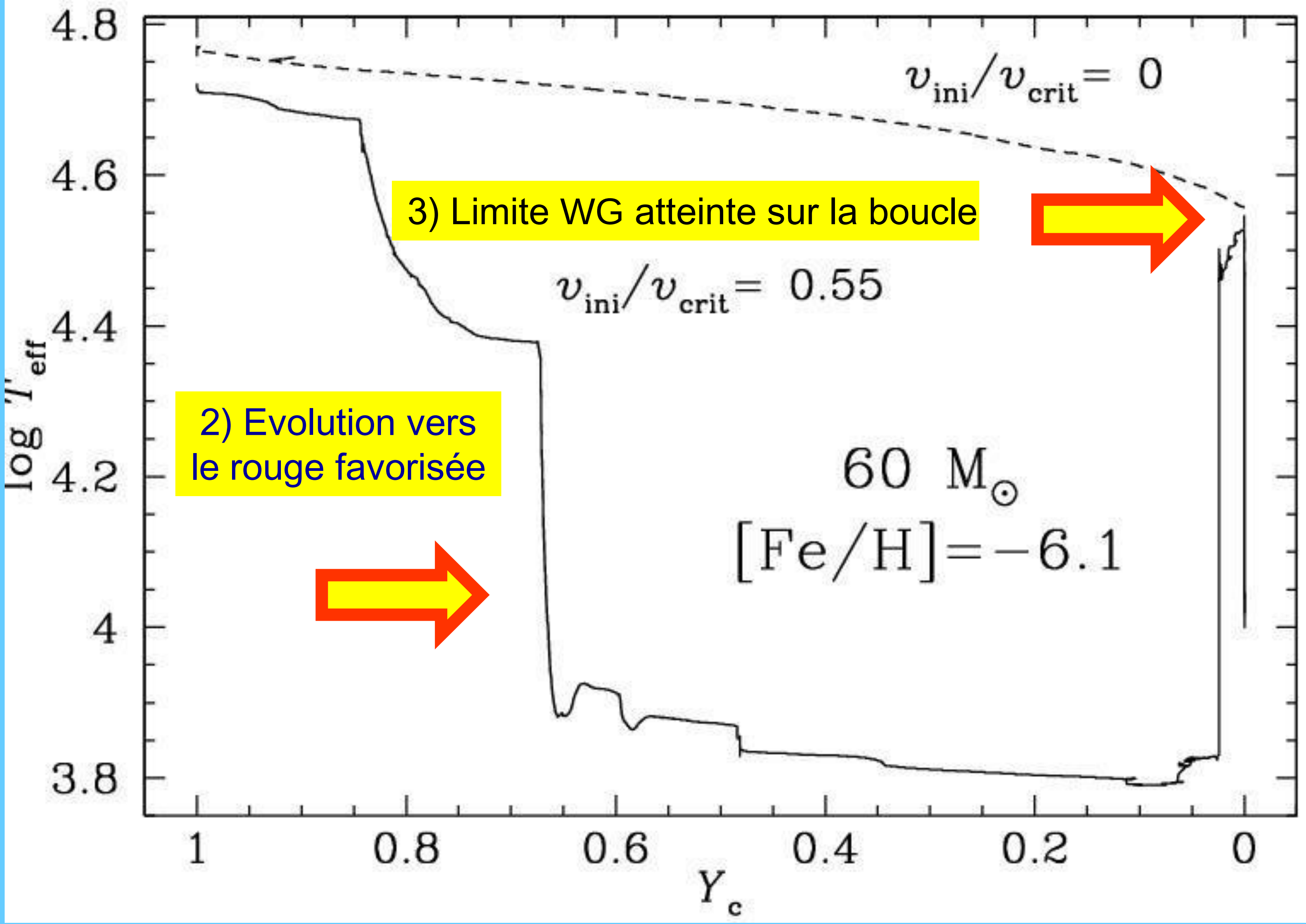
60 M_{sol}, Z = 0.020



60 M_{sol}, Z = 0.00001



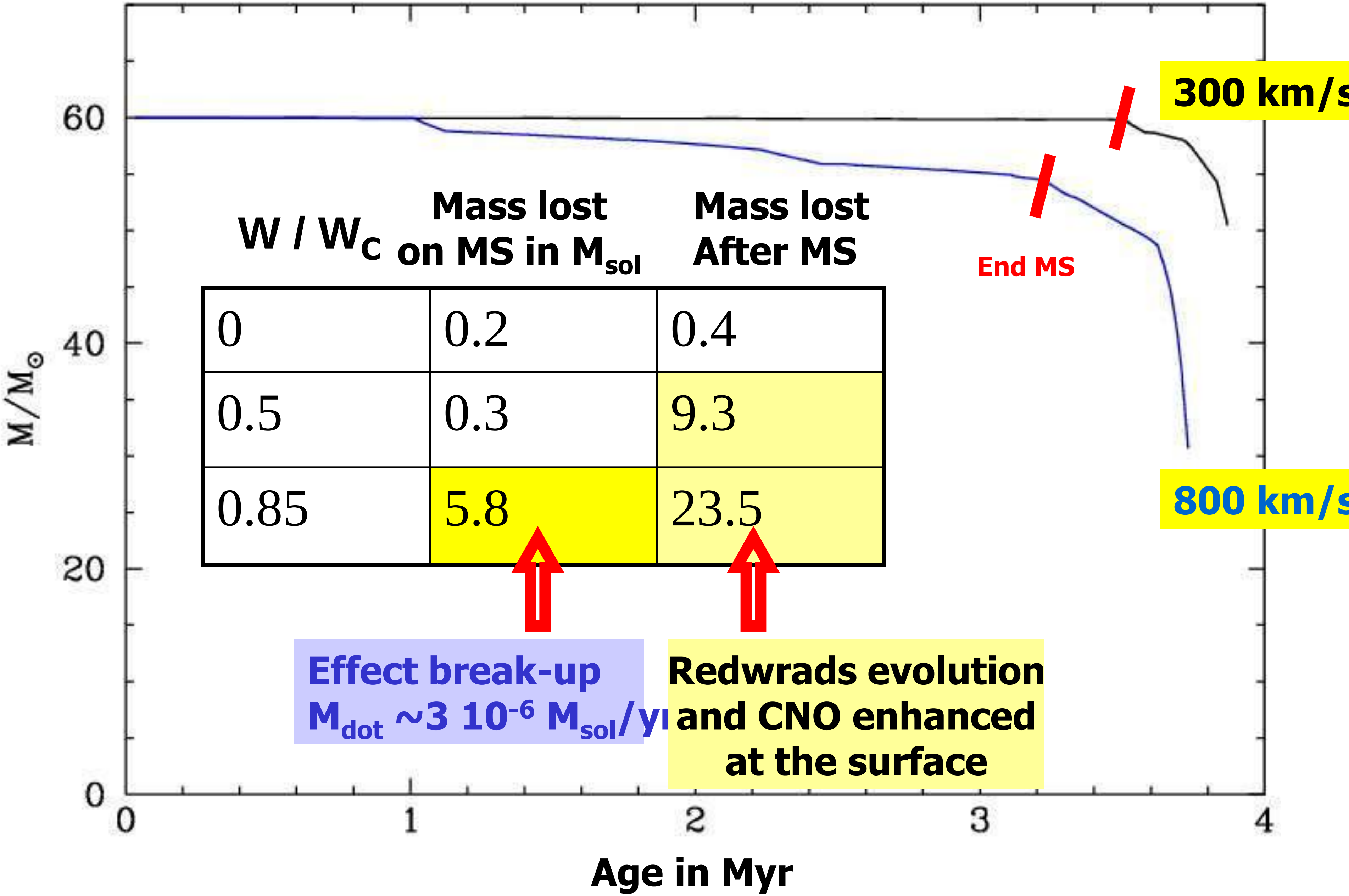
Cf also Sackman & Anand 1979; Langer 1998



2) Evolution vers
le rouge favorisée

3) Limite WG atteinte sur la boucle

MASSE PERDUE

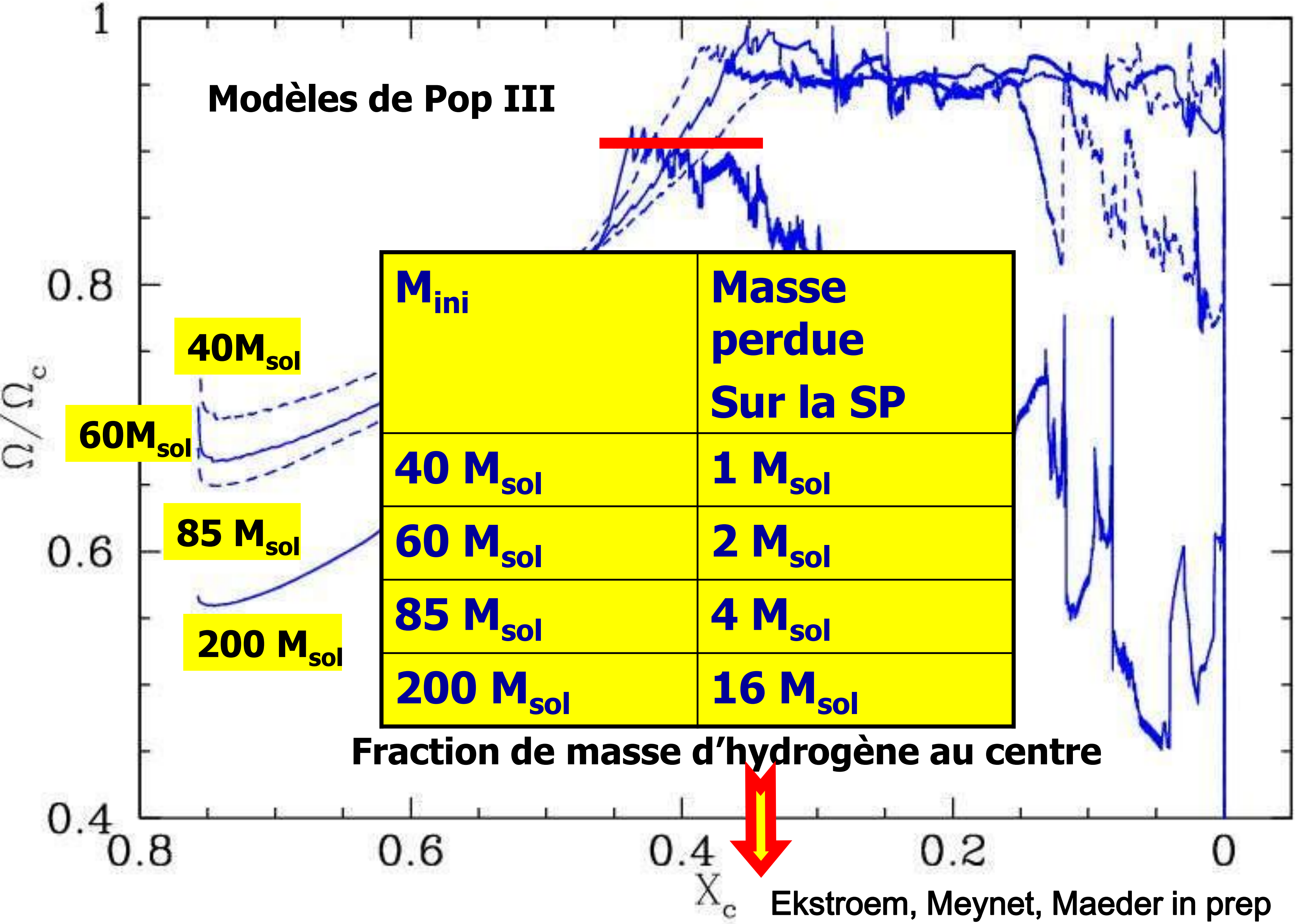


W / W$_C$	Mass lost on MS in M$_{sol}$	Mass lost After MS
0	0.2	0.4
0.5	0.3	9.3
0.85	5.8	23.5

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

Redwrads evolution
and CNO enhanced
at the surface

Modèles de Pop III



$40M_{sol}$

$60M_{sol}$

$85\ M_{sol}$

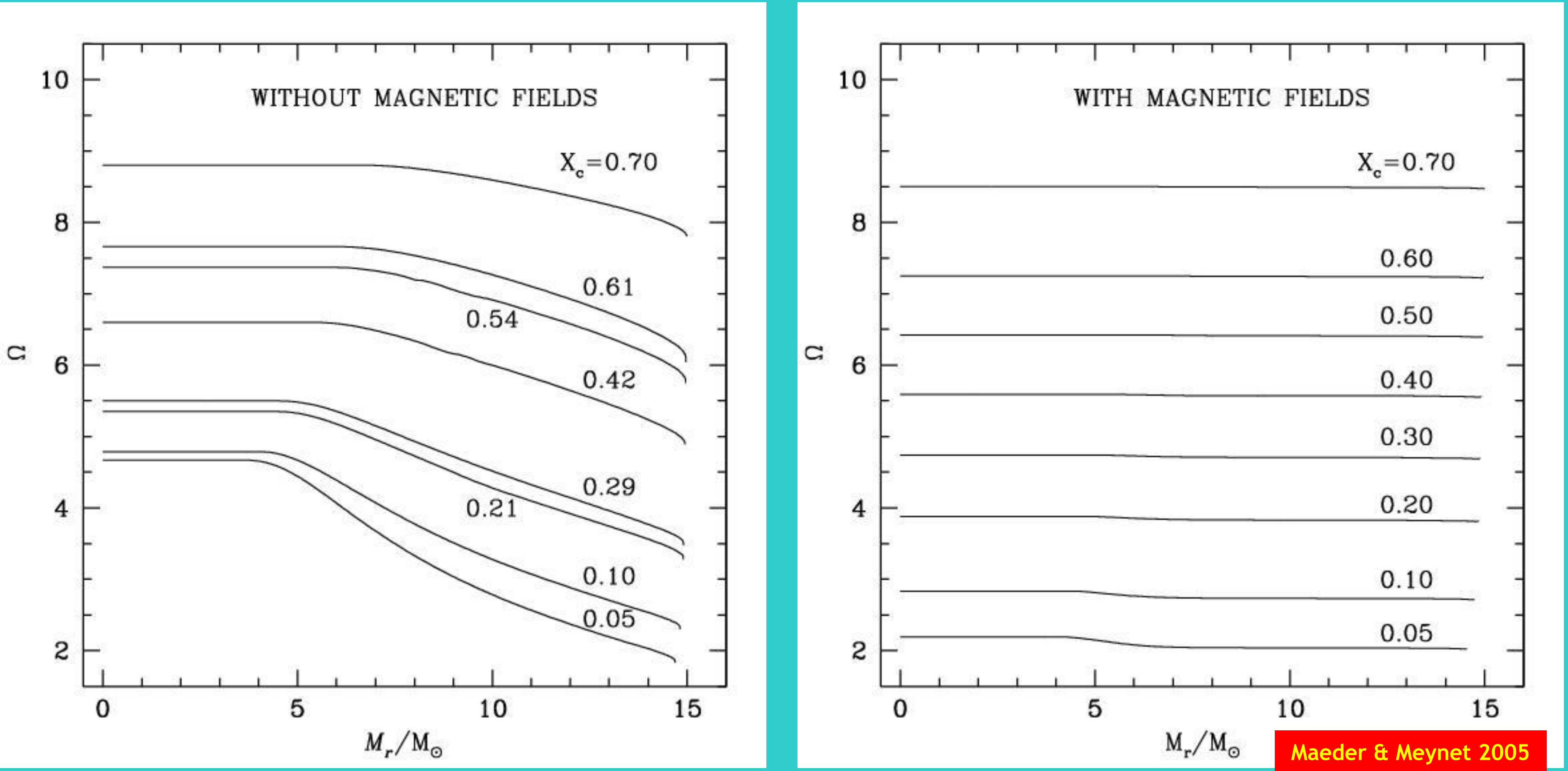
$200\ M_{sol}$

M_{ini}	Masse perdue Sur la SP
$40\ M_{sol}$	$1\ M_{sol}$
$60\ M_{sol}$	$2\ M_{sol}$
$85\ M_{sol}$	$4\ M_{sol}$
$200\ M_{sol}$	$16\ M_{sol}$

Fraction de masse d’hydrogène au centre

Ekstroem, Meynet, Maeder in prep

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

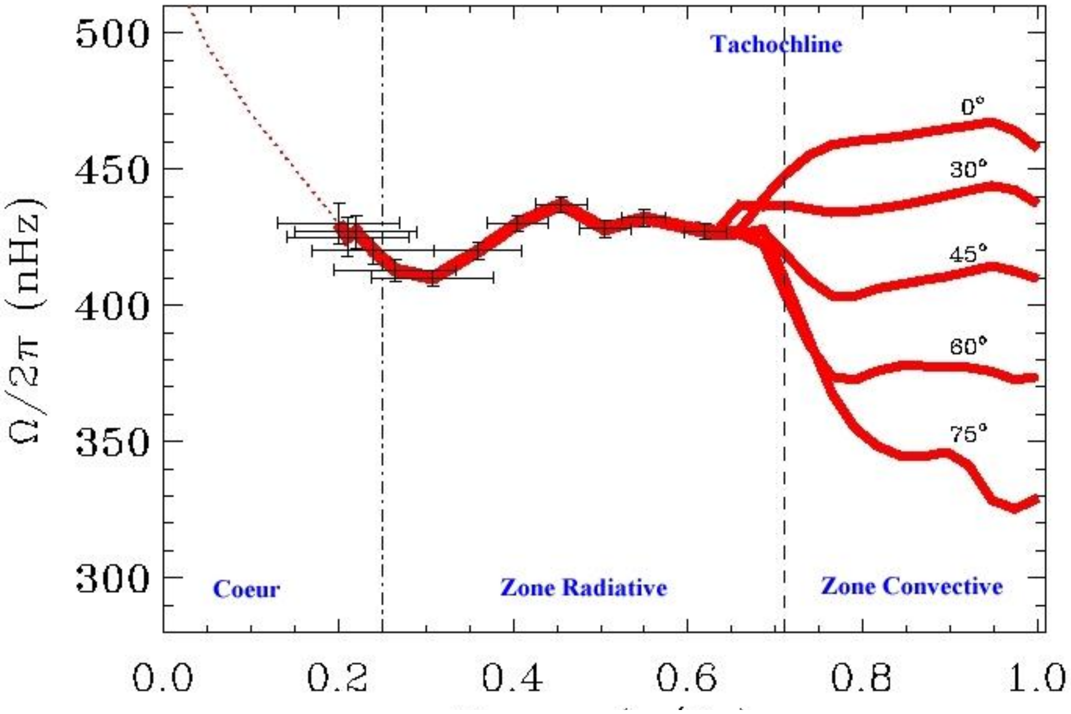


Maeder & Meynet 2005

CHAMPS MAGNETIQUES → ROTATION SOLIDE

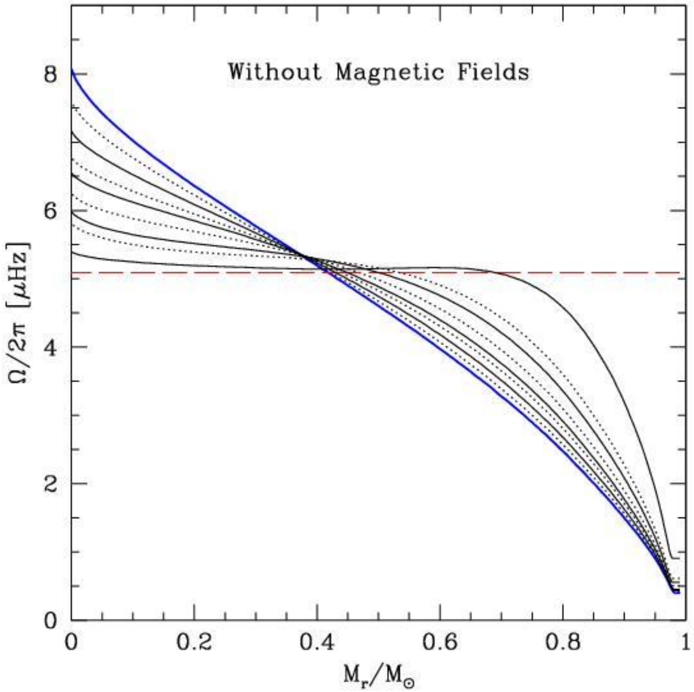
ROTATION INTERIEURE DU SOLEIL

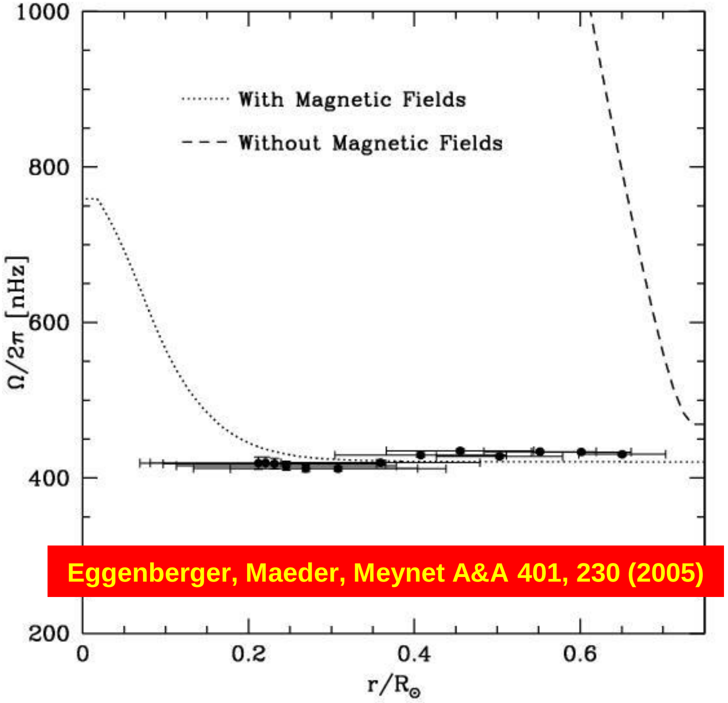
Données héliosismiques



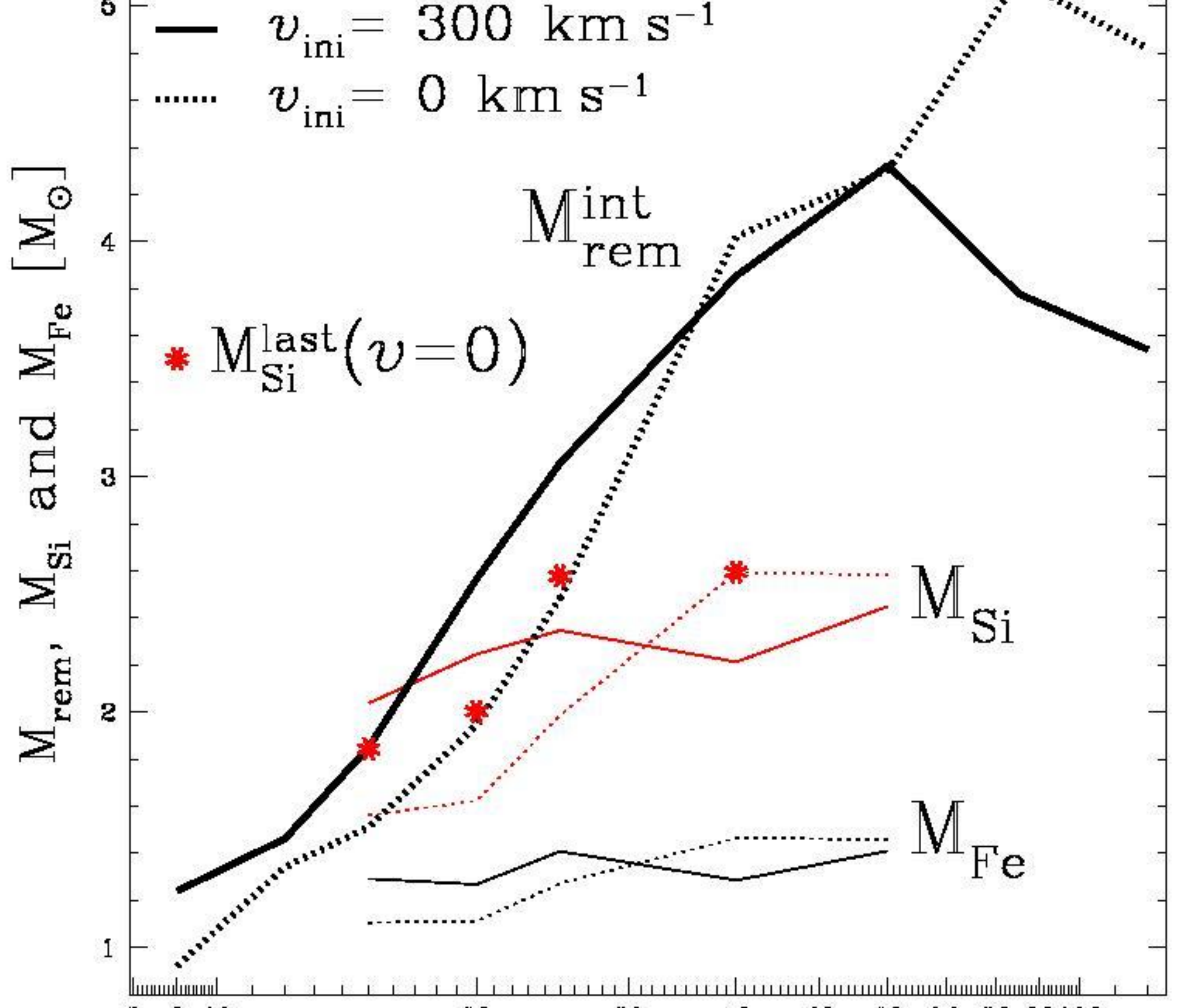
r/R_{sol}

Profil plat entre 0.2 – 0.7 R_{sol}



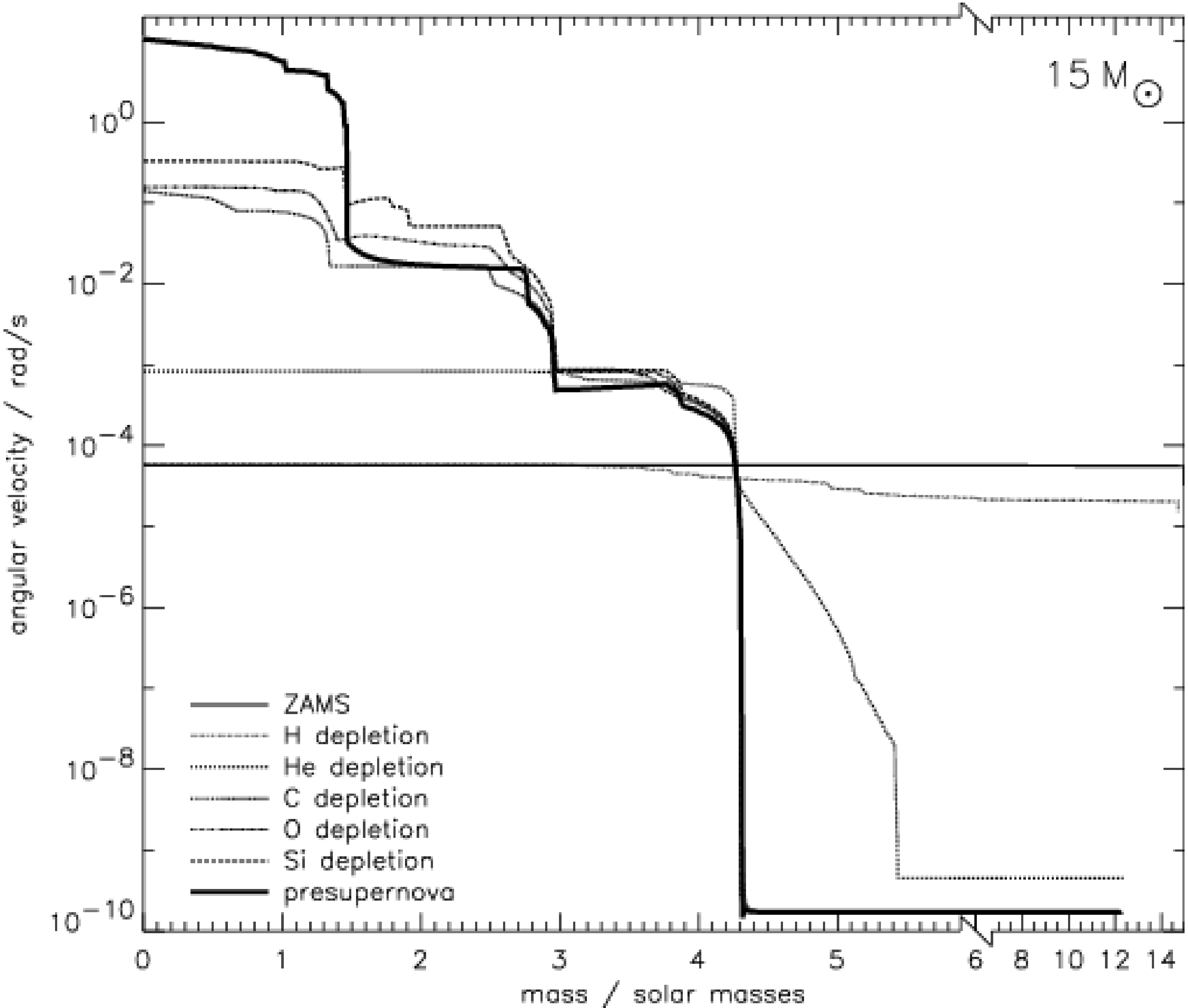


Eggenberger, Maeder, Meynet A&A 401, 230 (2005)

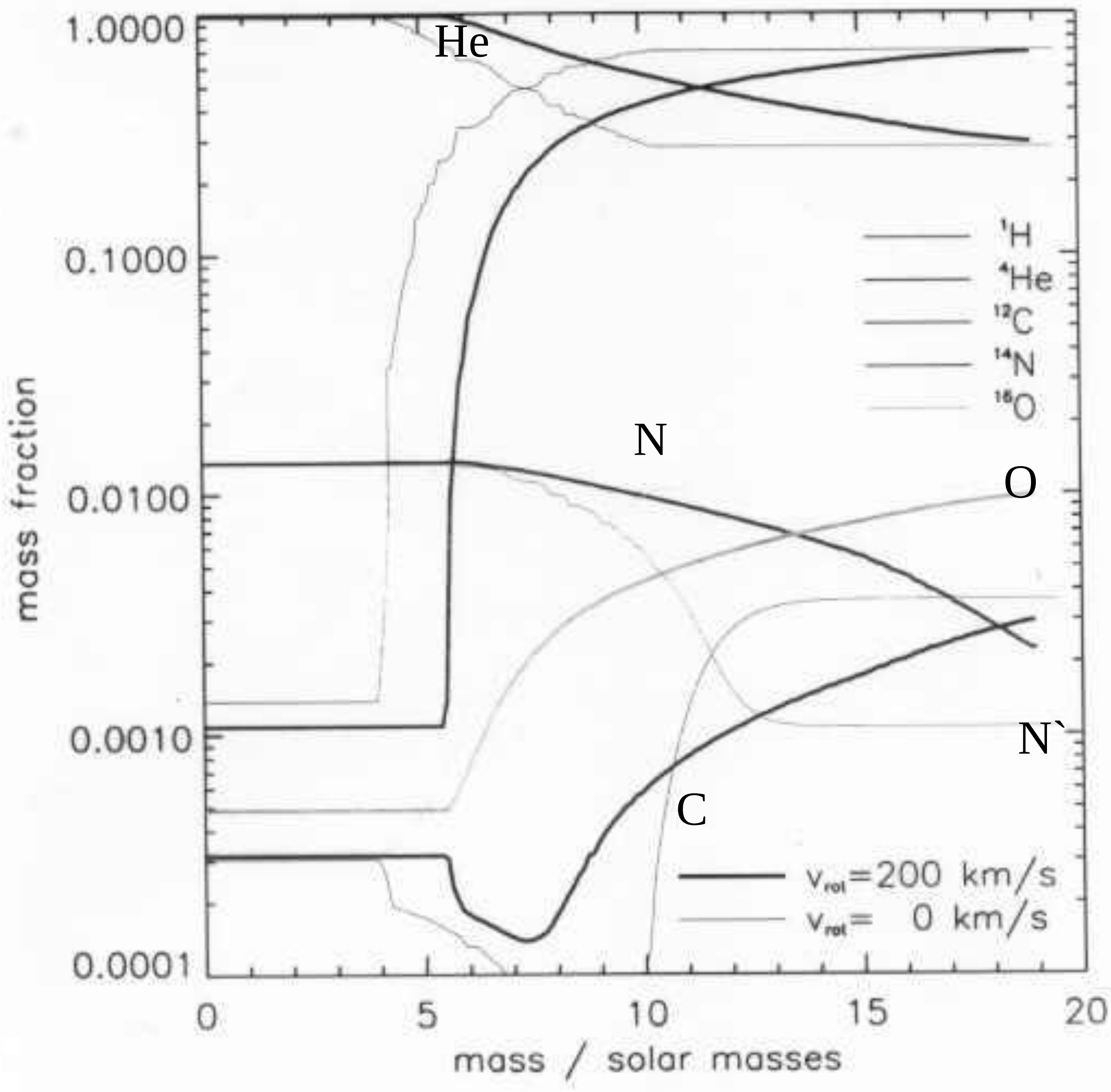

$v_{\rm ini}$= 300 km s^{-1}
$v_{\rm ini}$= 0 km s^{-1}
$M^{\rm int}_{\rm rem}$
$M^{\rm last}_{\rm Si}(v=0)$
$M_{\rm Si}$
$M_{\rm Fe}$
$M_{\rm rem}$, $M_{\rm Si}$ and $M_{\rm Fe}$ [$M_\odot$]
5
4
3
2
1

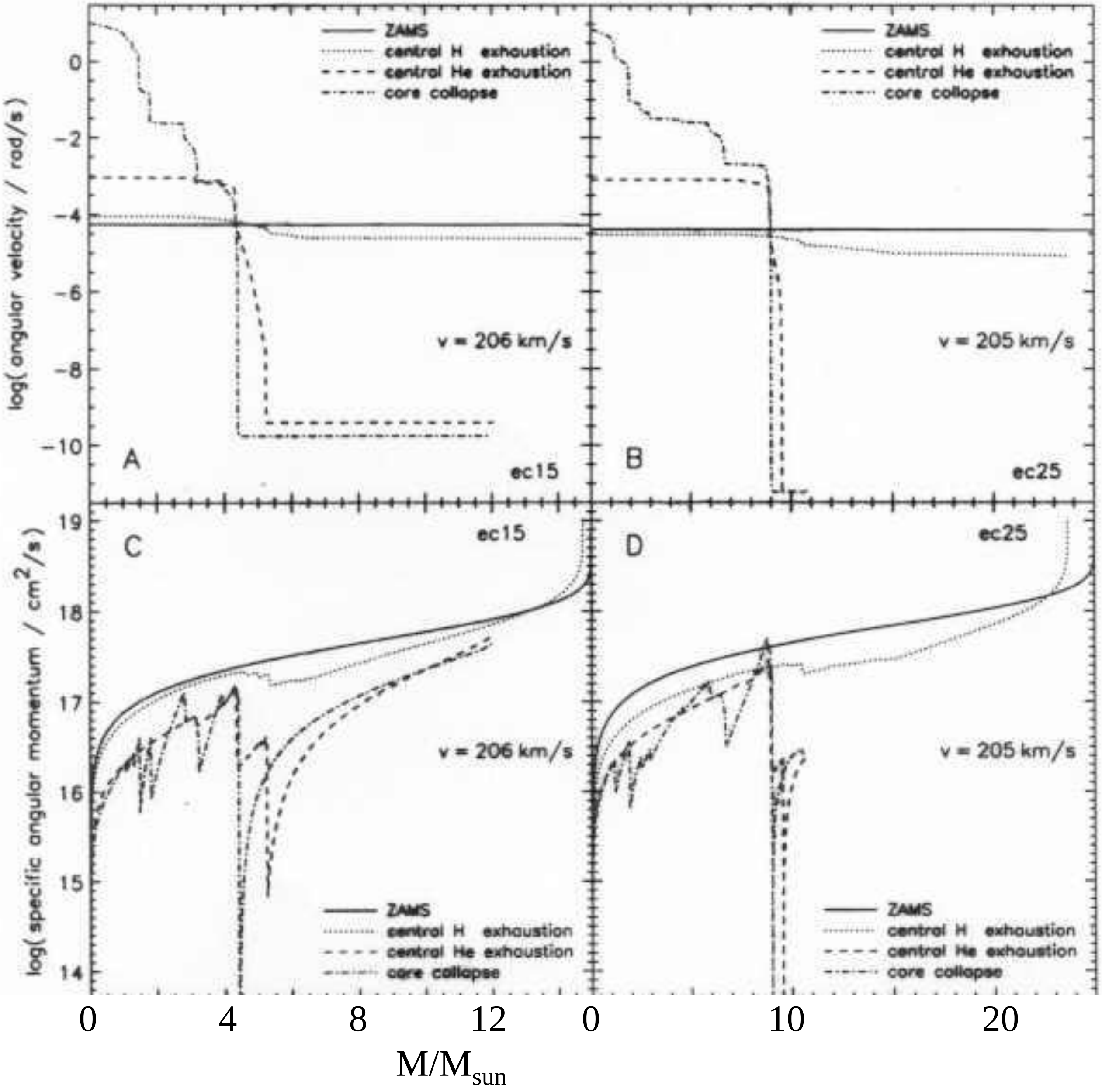
Evolution Including Rotation

Heger, Langer, and Woosley (2000), *ApJ*, **528**, 368



20 $M_\odot$ with and without rotation




log(angular velocity / rad/s)
0
−2
−4
−6
−8
−10
ZAMS
central H exhaustion
central He exhaustion
core collapse
v = 206 km/s
v = 205 km/s
A
ec15
B
ec25
log(specific angular momentum / cm^2/s)
19
18
17
16
15
14
C
ec15
D
ec25
v = 206 km/s
v = 205 km/s
ZAMS
central H exhaustion
central He exhaustion
core collapse
0
4
8
12
0
10
20
M/M$_{sun}$

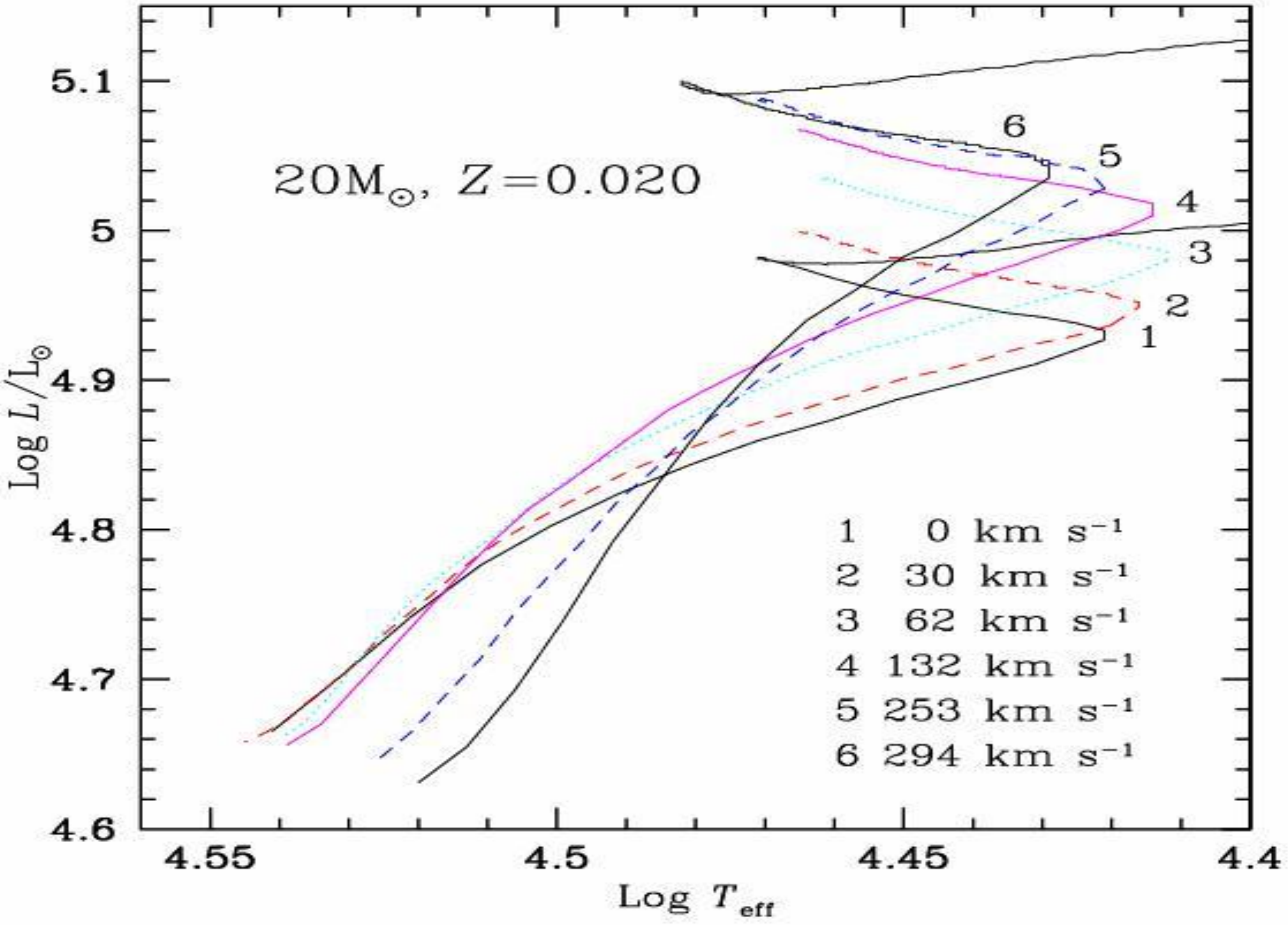
Results:

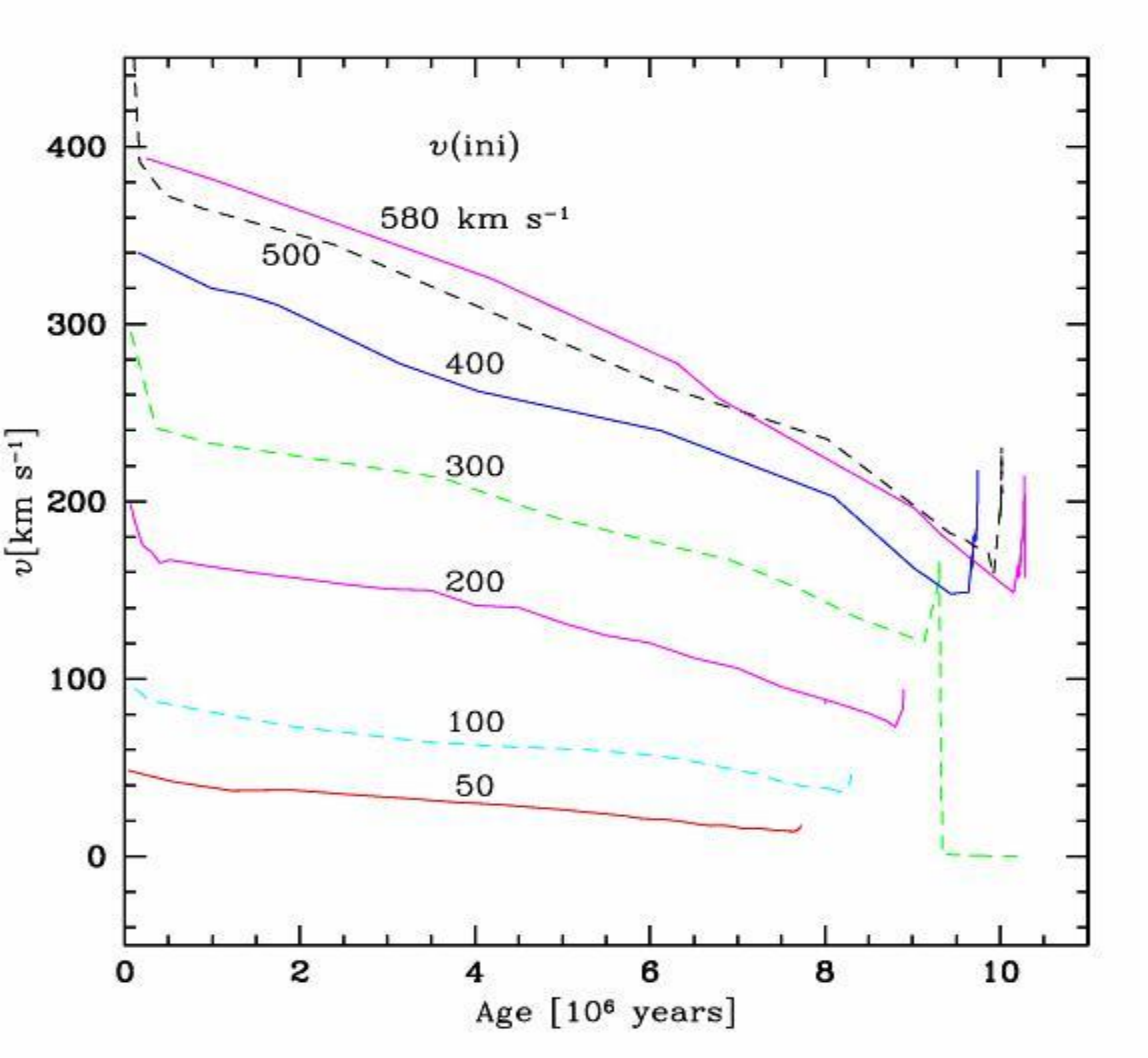
- Fragile elements like Li, Be, B destroyed to a greater extent when rotational mixing is included. More rotation, more destruction.
- Higer mass loss
- Initially luminosities are lower (because g is lower) in rotating models. later luminosity is higher because He-core is larger
- Broadening of the main sequence; longer main sequence lifetime
- More evidence of CN processing in rotating models. He, ^{13}C, ^{14}N, ^{17}O, ^{23}Na, and ^{26}Al are enhanced in rapidly rotating stars while ^{12}C, ^{15}N, ^{16,18}O, and ^{19}F are depleted.
- Decrease in minimum mass for WR star formation.

These predictions are in good accord with what is observed.

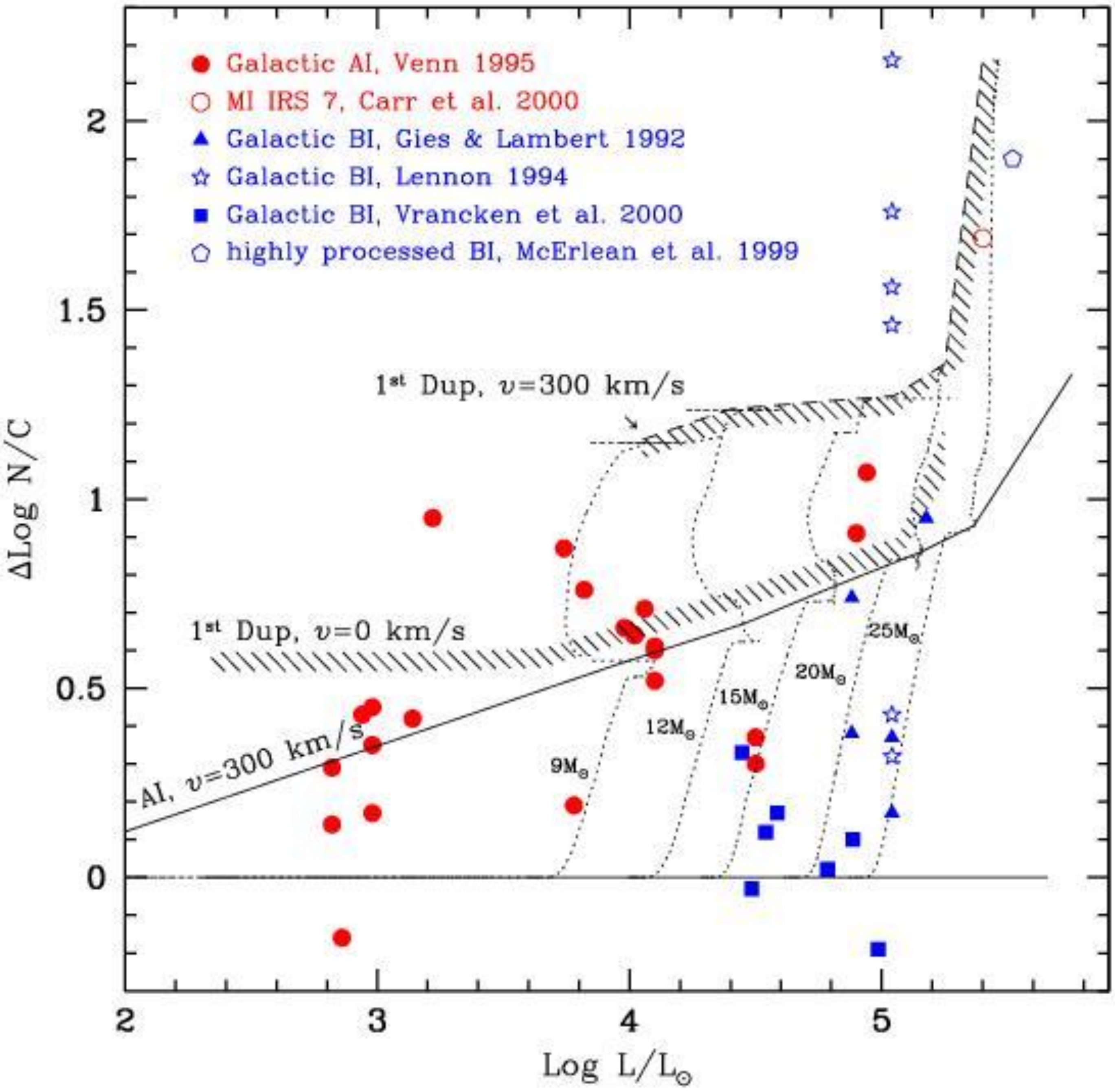
Final angular momentum distribution is important to:

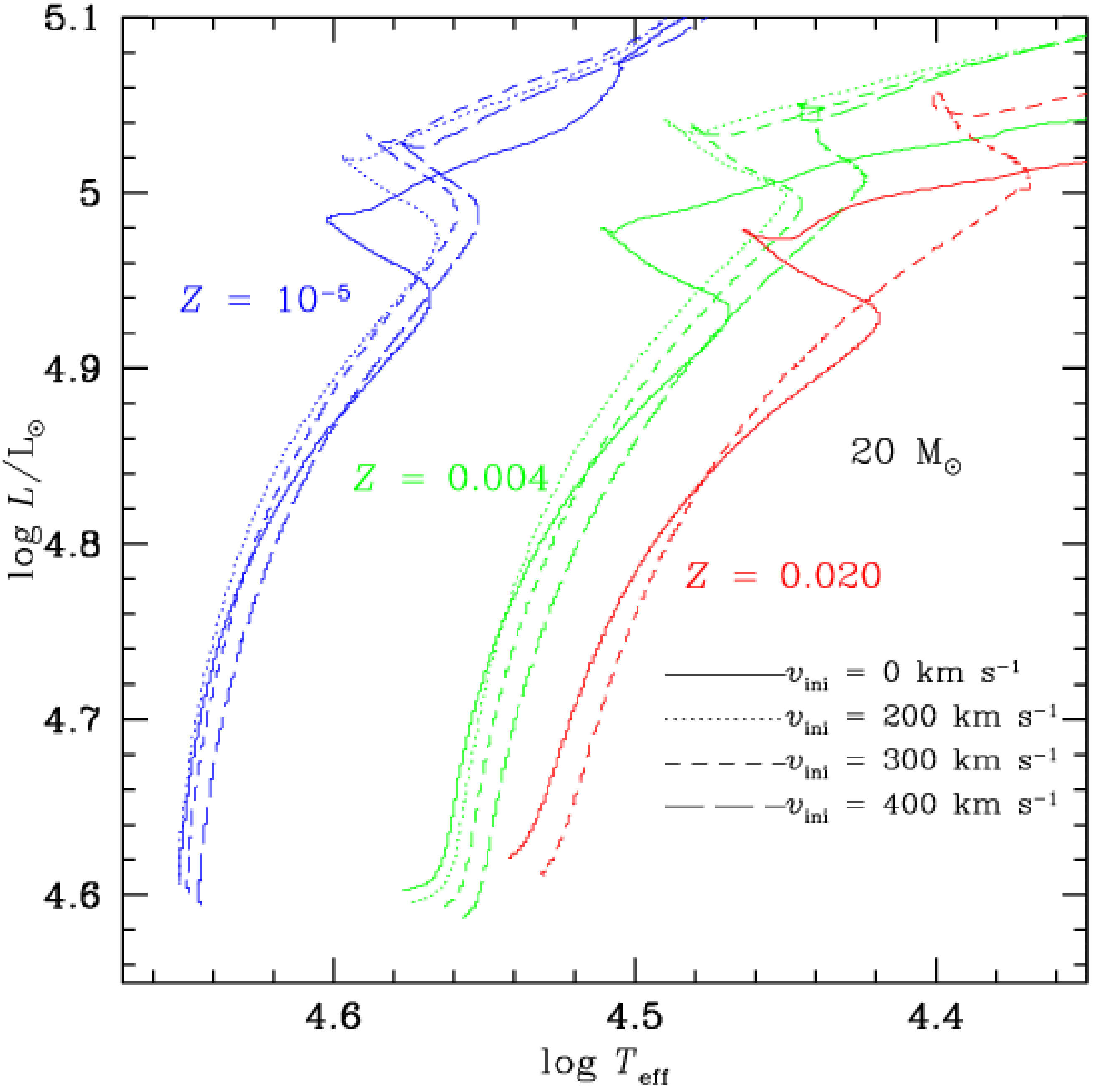
- Determine the physics of core collapse and explosion
- Determine the rotation rate and magnetic field strength of pulsars
- Determine the viability of the collapsar model for gamma-ray bursts.


20M$_\odot$, Z=0.020
Log $L/L_\odot$
Log $T_{\rm eff}$
5.1
5
4.9
4.8
4.7
4.6
4.55
4.5
4.45
4.4
6
5
4
3
2
1
1 0 km s^{-1}
2 30 km s^{-1}
3 62 km s^{-1}
4 132 km s^{-1}
5 253 km s^{-1}
6 294 km s^{-1}

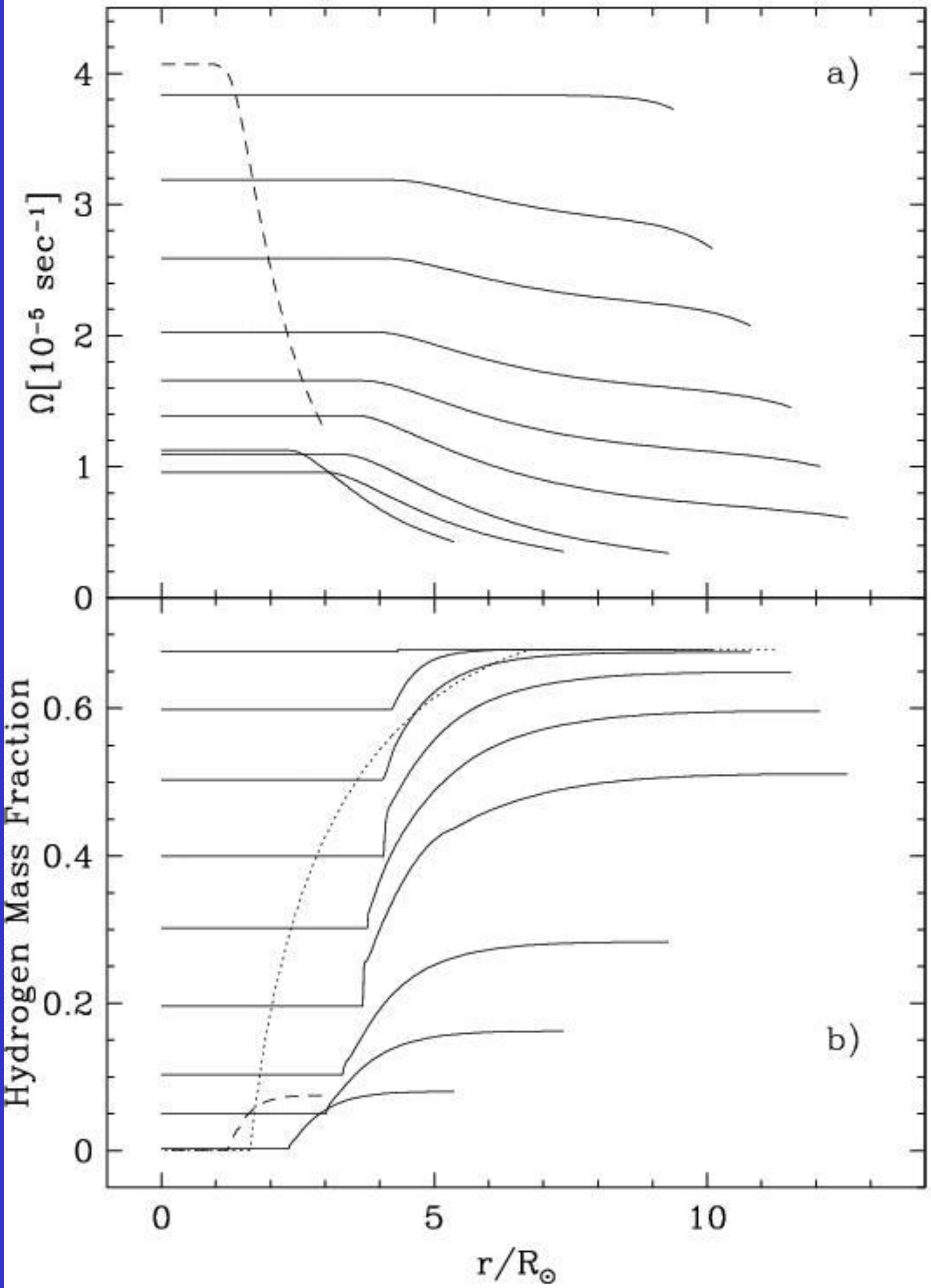


cf. Langer 1997, 1998

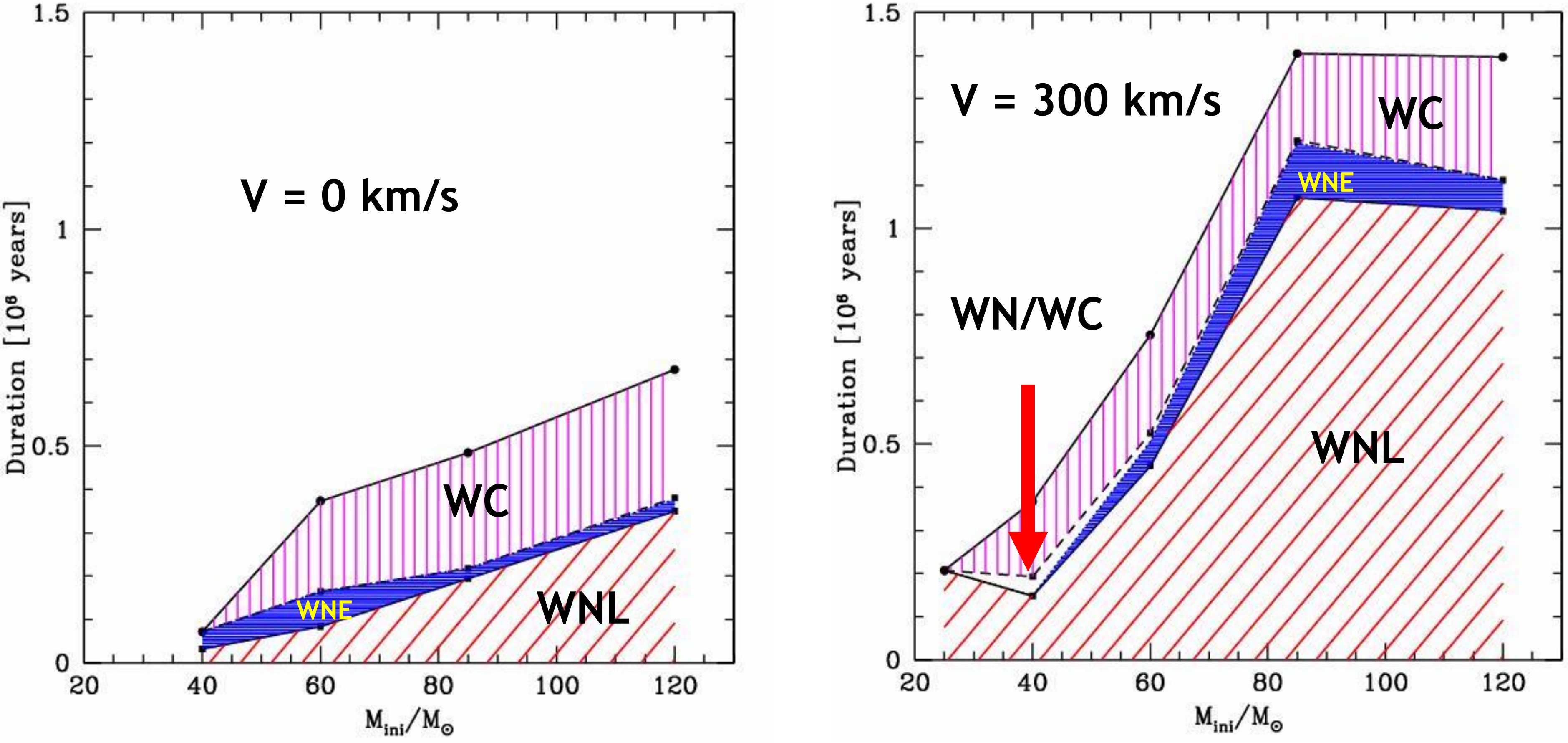

● Galactic AI, Venn 1995
○ MI IRS 7, Carr et al. 2000
▲ Galactic BI, Gies & Lambert 1992
☆ Galactic BI, Lennon 1994
■ Galactic BI, Vrancken et al. 2000
⬠ highly processed BI, McErlean et al. 1999
1st Dup, v=300 km/s
1st Dup, v=0 km/s
AI, v=300 km/s
9M☉
12M☉
15M☉
20M☉
25M☉
ΔLog N/C
Log L/L☉
0
0.5
1
1.5
2
2
3
4
5



5.1
5
4.9
4.8
4.7
4.6
log $L/L_\odot$
4.6
4.5
4.4
log T_{eff}
$Z = 10^{-5}$
$Z = 0.004$
$Z = 0.020$
20 $M_\odot$
v_{ini} = 0 km s^{-1}
v_{ini} = 200 km s^{-1}
v_{ini} = 300 km s^{-1}
v_{ini} = 400 km s^{-1}


a)
Ω[10^{-5} sec^{-1}]
0
1
2
3
4
b)
Hydrogen Mass Fraction
0
0.2
0.4
0.6
0
5
10
r/R$_\odot$

Effects of rotation for different initial masses



IN ROTATING MODELS Minimum mass for WR lowered (from ~37 to 22M)

WNL phase becomes more important

WN/WC for masses between ~30 and 50 Msol (4%)

For M_{ini} < ~50 M_{sol}

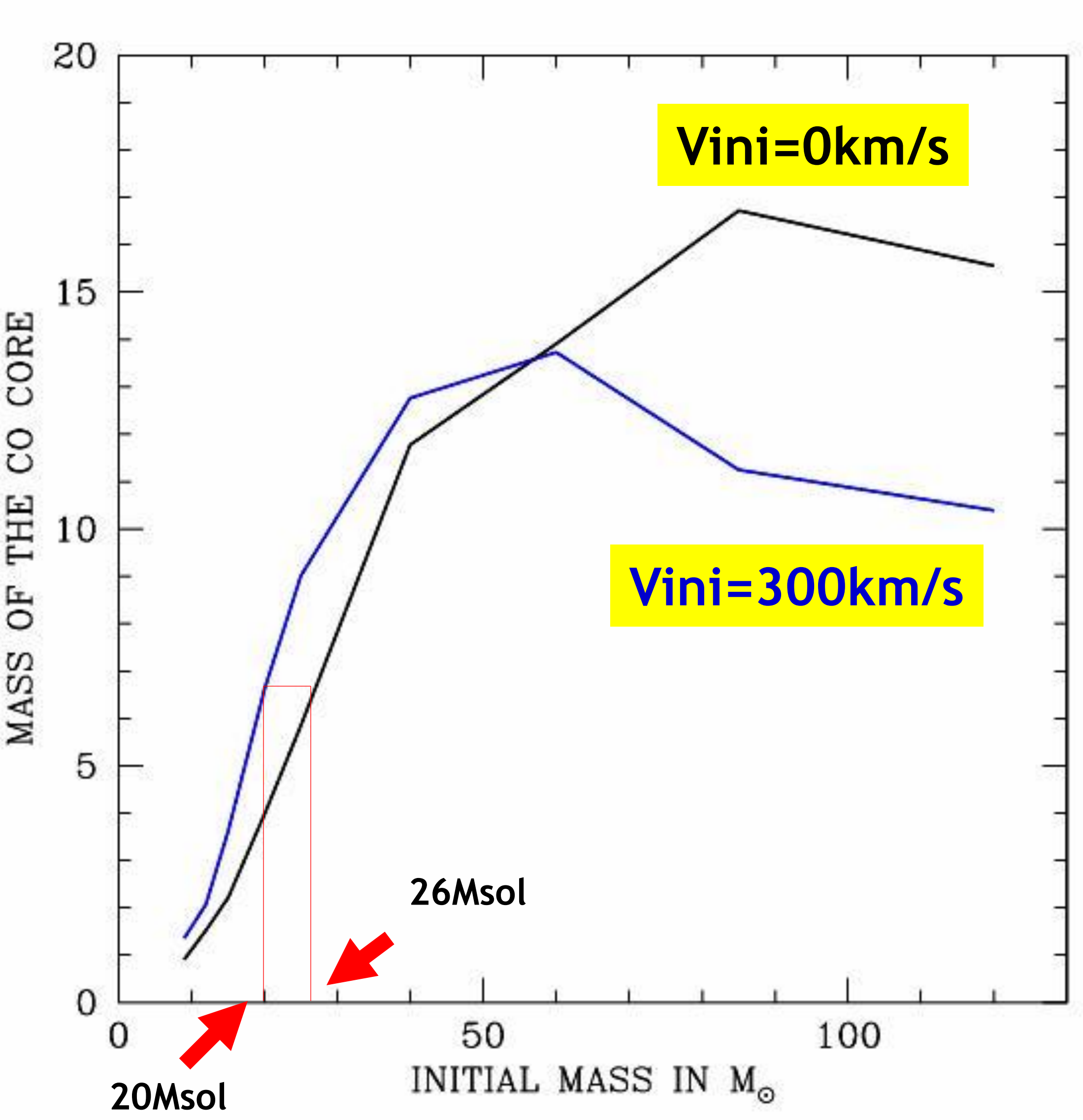
M_{CO} increased by rotation

By ~50% for 9-25 M_{sol}

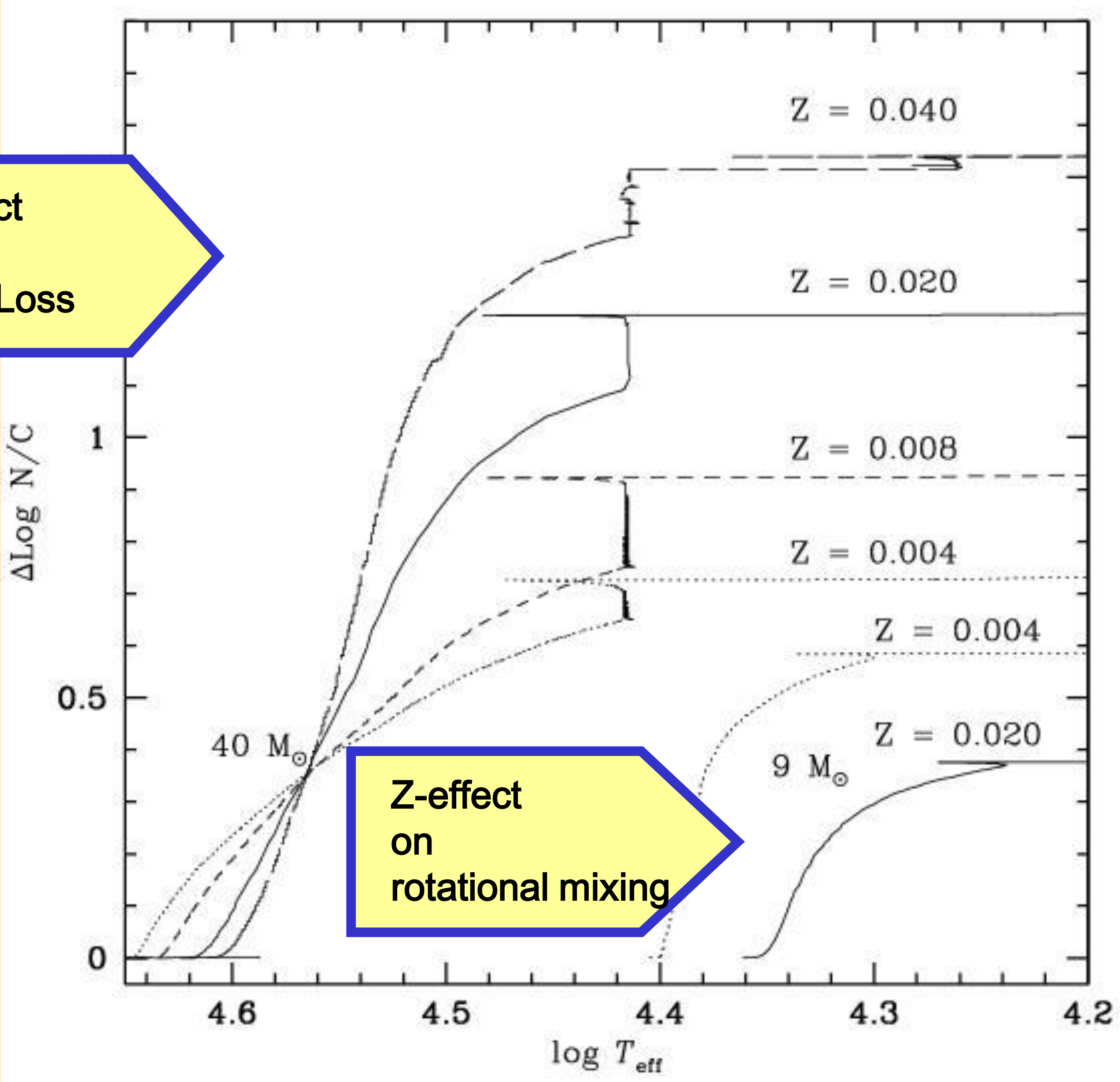
Mixing effects dominant

For Mini > ~50 Msol

Mass loss effects are dominant

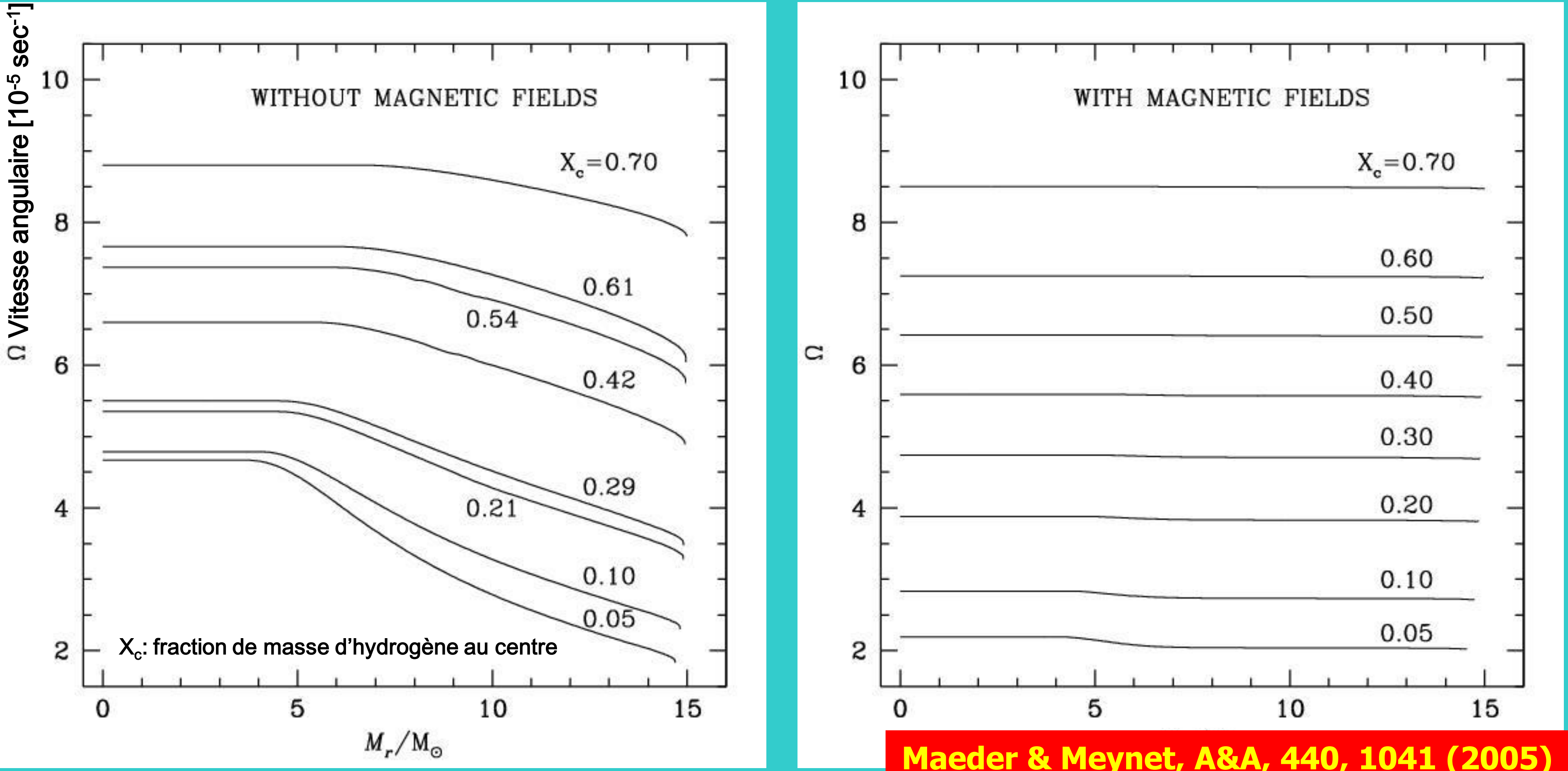


Z-effect
on
mass Loss



Z-effect
on
rotational mixing

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

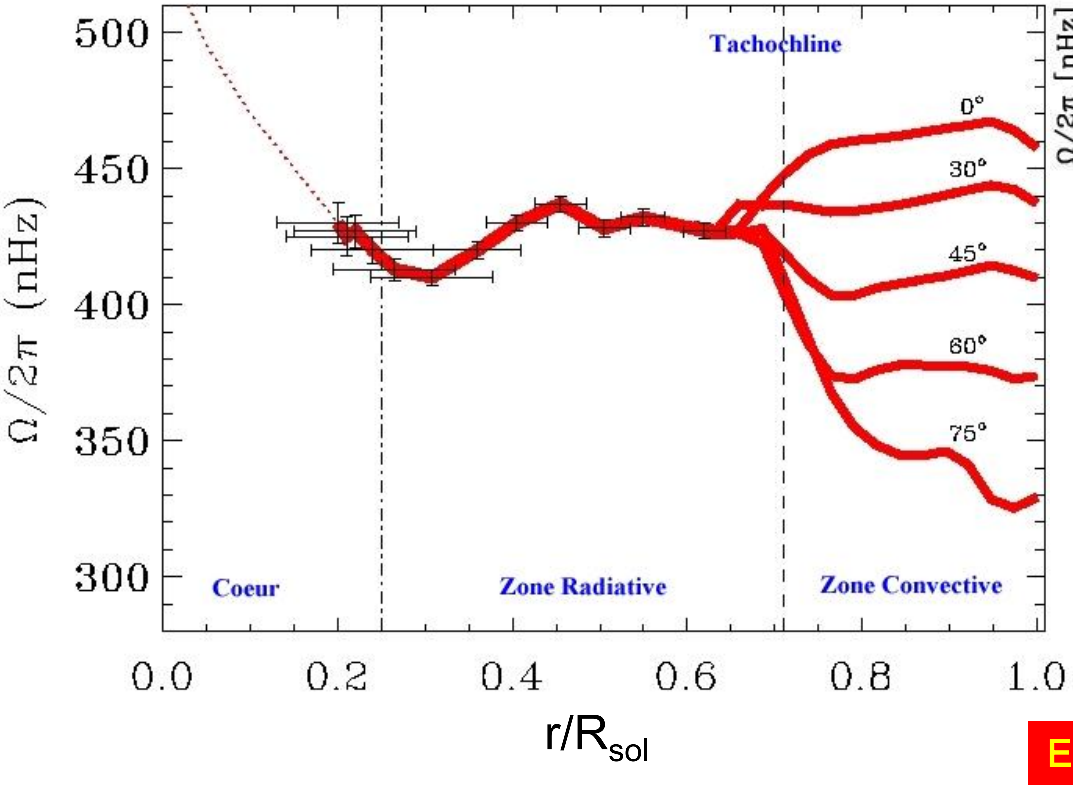


Maeder & Meynet, A&A, 440, 1041 (2005)

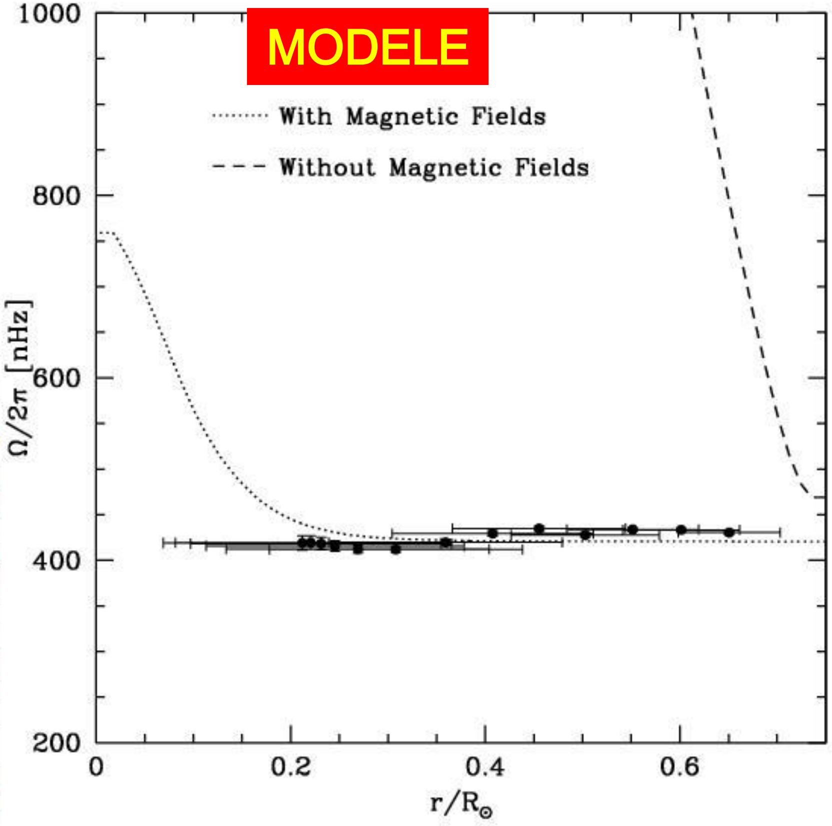
CHAMPS MAGNETIQUES → ROTATION SOLIDE

ROTATION INTERIEURE DU SOLEIL

OBSERVATION



MODELE

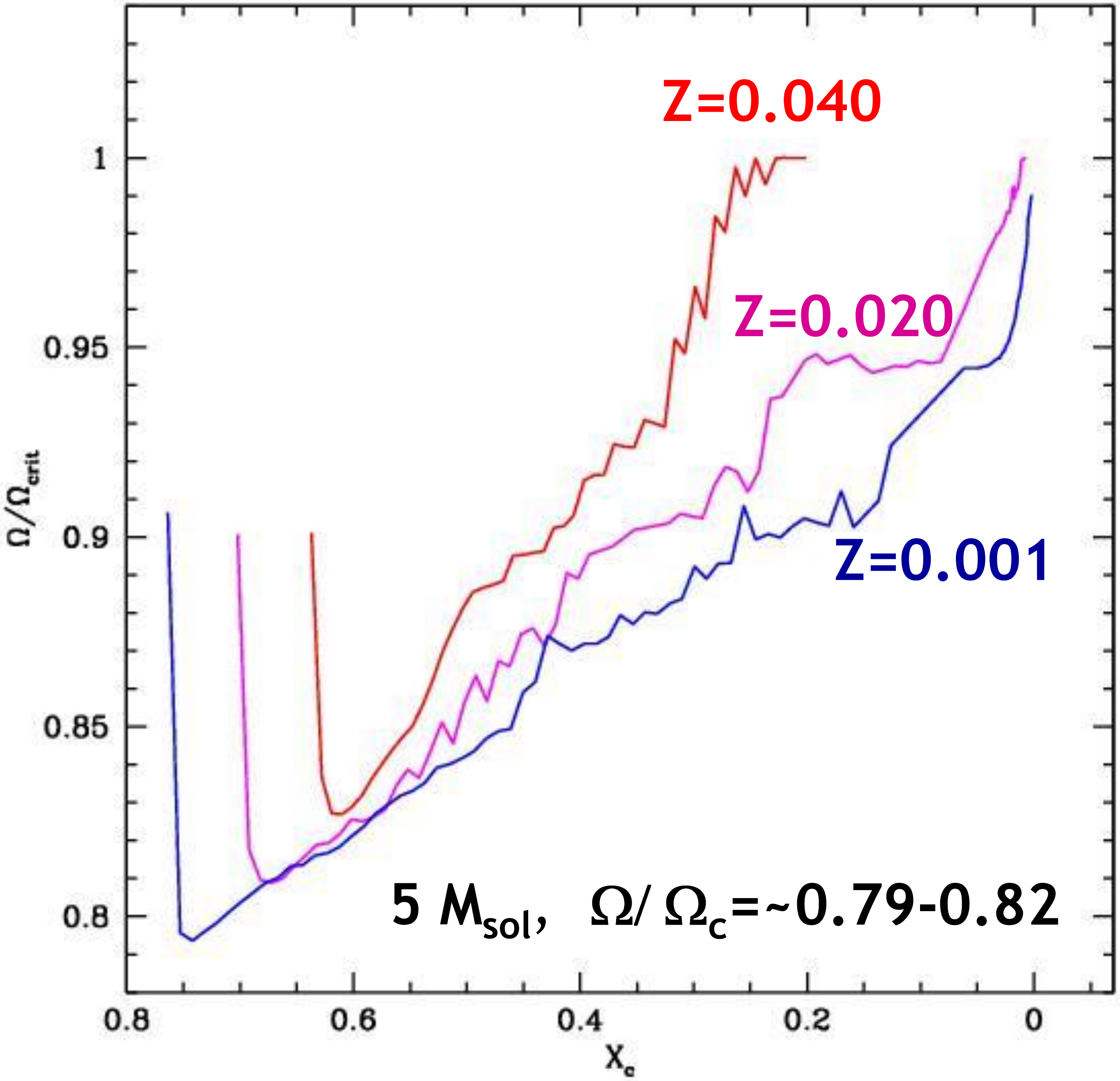


Eggenberger, Maeder, Meynet A&A 401, 230 (2005)

Profil plat entre 0.2 – 0.7 R_{sol}

CHAMP MAGNETIQUE

WHEN Z INCREASES STARS LESS COMPACT→ MORE EFFICIENT TRANSPORT OF ANGULAR MOMENTUM

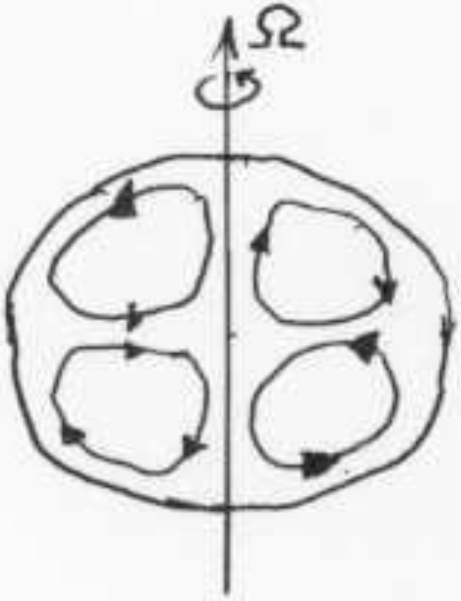


Z	V_{ini}
0.001	435 km/s
0.020	362 km/s
0.040	344 km/s

Eppure si muove

Rotation: an old topical subject

EDDINGTON SWEET CIRCULATION

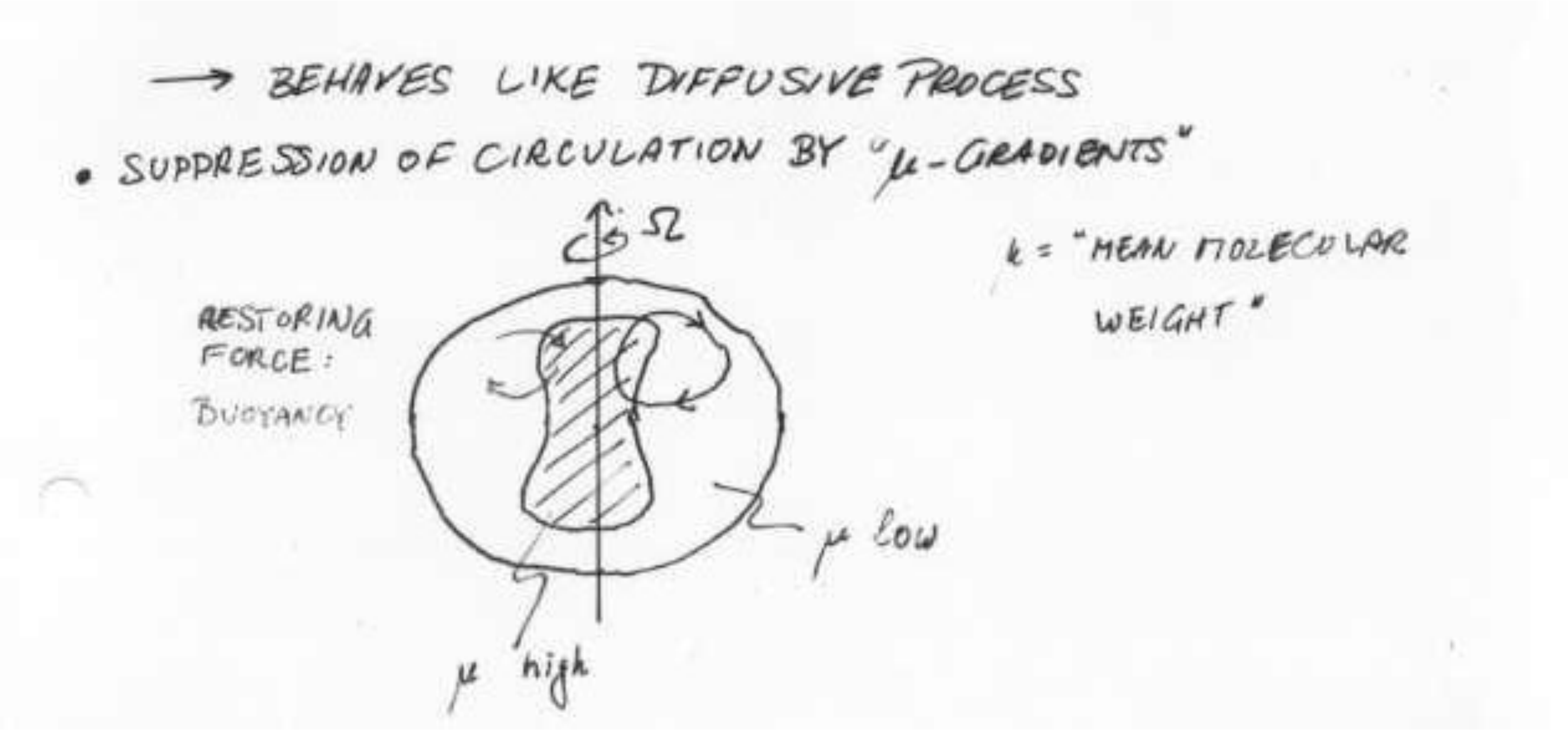


- RIGID ROTATION :
  RISING AT POLE

- DIFFERENTIAL ROTATION
  → OPPOSITE CIRCULATION
  DIRECTION POSSIBLE

$\tau_{MIX} \sim \left(\frac{\Omega_{KEP}}{\Omega}\right)^2 * \tau_{KH}$

If the composition of the star were constant then massive stars would mix on a time scale of order their Kelvin-Helmholtz time scale. Observationally this is known not to happen. Theoretically the reason why is the stabilizing influence of composition gradients.



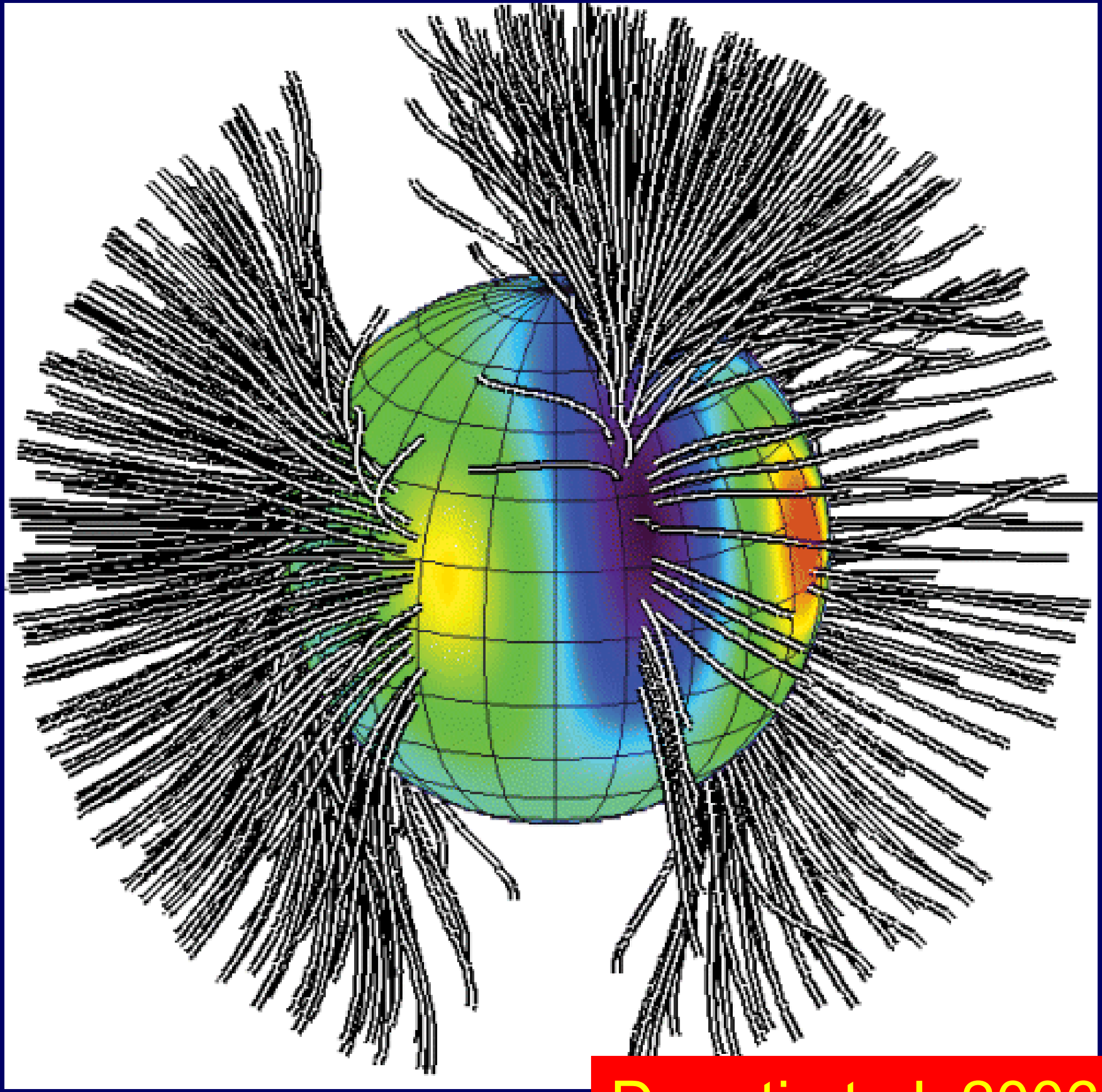
→ BEHAVES LIKE DIFFUSIVE PROCESS

- SUPPRESSION OF CIRCULATION BY "μ-GRADIENTS"

μ = "MEAN MOLECULAR WEIGHT"

SURFACE MAGNETIC FIELDS

τ Sco



Donati et al. 2006

MAGNETIC FIELDS IN MASSIVE STARS

A few dozen He-peculiar stars

Only 7 OB stars have been found to be magnetic

	Ref	Sp. T.	Vsini Km/s	Prot days	M Msol	Incl. Deg.	β Deg.	Bpol G
HD191612	(6)			538			45	~1500
Θ Ori C	(1)	O4-6V	20	15.4	45	45	42+-6	1100+-100
βCep	(2)	B1IVe	27	12.00	12	60+-10	85+-10	360+-40
τ Sco	(7)	B0.2V		41				~500
V2052 Oph	(3)	B1V	63	3.64	10	71+-10	35+-17	250+-190
ζCas	(4)	B2IV	17	5.37	9	18+-4	80+-4	340+-90
ωOri	(5)	B2IVe	172	1.29	8	42+-7	50+-25	530+-200
He-peculiar		B1-B8p		0.9-22	<10			1000-10000

Only 2 magnetic
O star known

(1) Donati et al. 2003 (2) Henrichs et al. 2000 (3,4,5) Neiner et al. 2003abc, (6,7) Donati et al. 2006ab

β Angle between the magnetic axis and the rotation axis

Question: are these values compatible with magnetic fields observed in pulsars?

Pulsars→ 10^{12} G

$$Br^2 = const.$$

$(10\text{ km}/5\ R_{sol})^2 \times 10^{12}$ G ~ 10 G.

$$B_+ / B_- = (r_- / r_+)^2$$

Answer: observed magnetic are one-two orders of magnitude higher→More compatible with progenitors of magnetars 10^{15} G

Question: may the observed values have an impact on the wind?

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

if η > 1 → wind behavior

ud-Doula & Owocki (2002)

Answer: YES. For early-type stars, η >1 for B~ 50-100 G

All magnetic B stars appeared to have some abundance anomaly

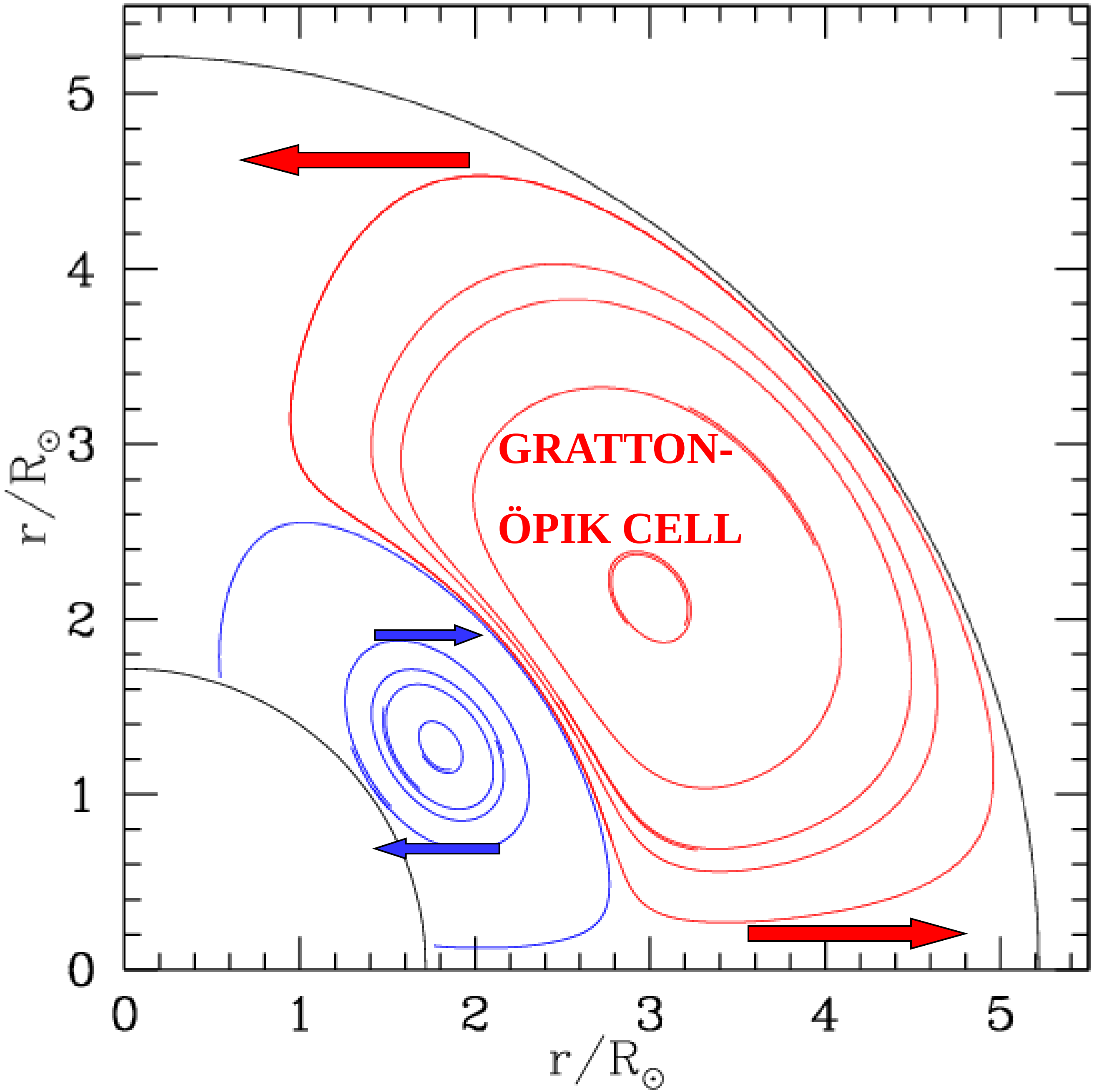
Log [number nuclei N in star/number nuclei N in the Sun]
Grevesse & Sauval 1998

	Ref	Sp. T.	He I	C II	N II	O II
bCep	(2)	B1IVe			0.09 (1.2) +-0.06	
V2052 Oph	(3)	B1V	0.32 (2.1) +-0.05	-0.13 (0.7) +-0.04	0.10 (1.3) +-0.06 N/C=1.9	-0.31 (0.5) +-0.11
zCas	(4)	B2IV	0.11 (1.3) +-0.06	-0.05 (0.9) +-0.09	0.41 (2.6) +-0.10 N/C=2.9	-0.09 (0.8) +-0.14
wOri	(5)	B2IVe	0.00 (1.0) +-0.01	0.00 (1.0) +-0.07	0.26 (1.8) +-0.10 N/C=1.8	-0.09 (0.8) +-0.06

Cells of meridional circulation

Very important process for the transport of the angular momentum

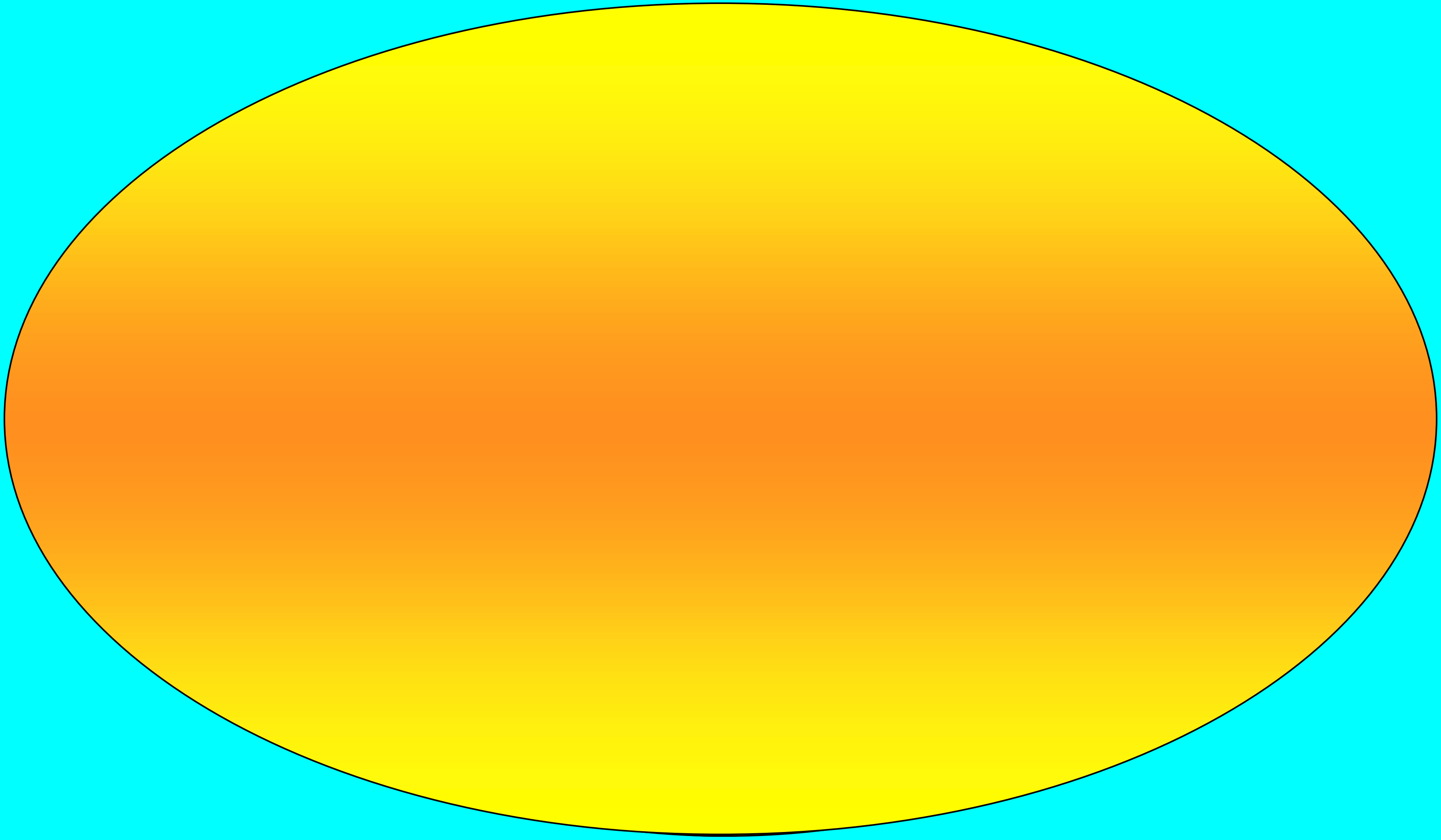
Outwards and inwards transport of angular momentum



Velocity of the meridional currents

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

Maeder and Zahn 1998



SHORT EJECTION

Peanut shaped nebulae