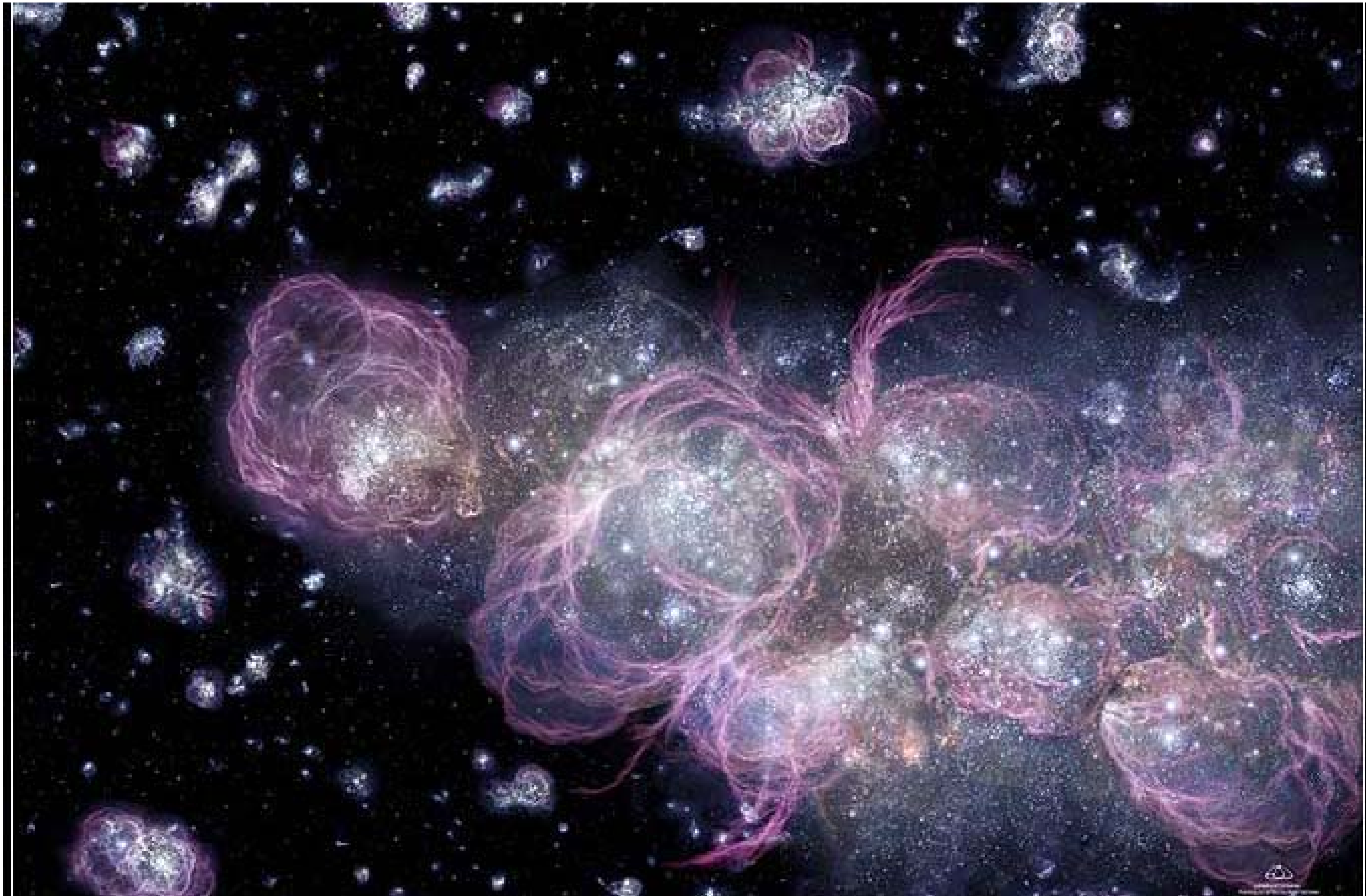


Artist's View of Star Formation in the Early Universe

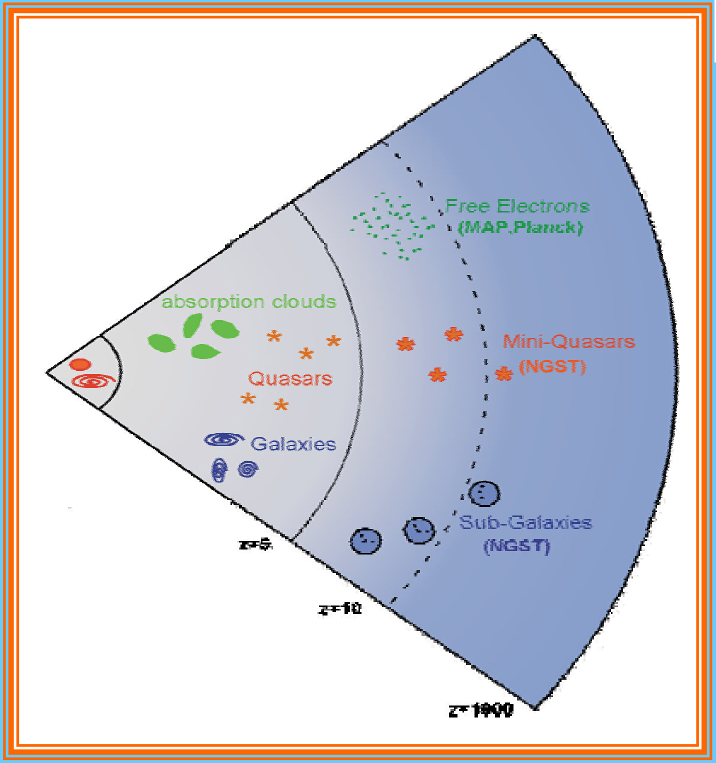
Painting by Adolf Schaller • STScI-PRC02-02

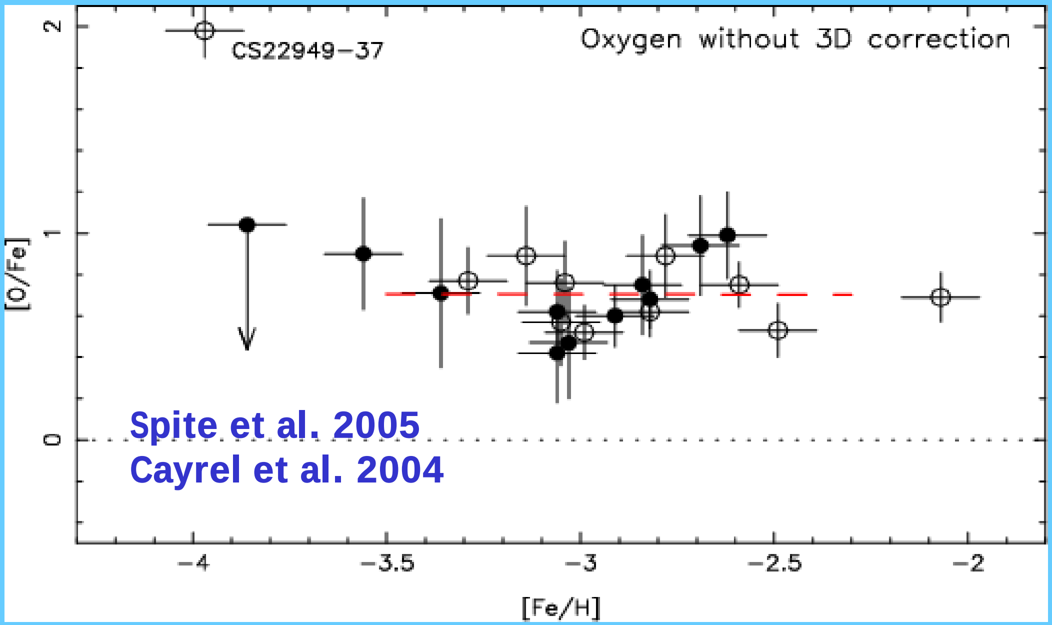
Nucleosynthesis from the first generations of stars in the Universe

Georges Meynet, André Maeder, Sylvia Ekström

Geneva Observatory

and Raphael Hirschi
Basel University





Reionization at high redshift

Early chemical evolution of galaxies

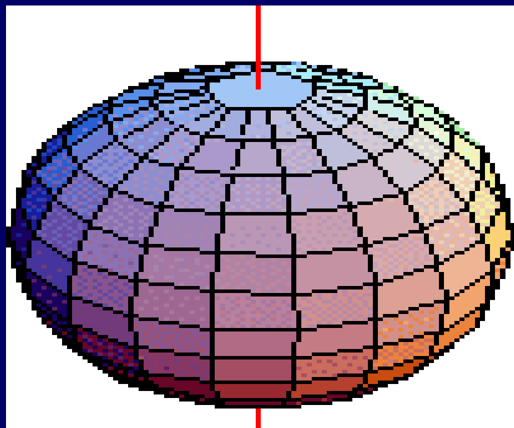
What is different at very low Z ?

- **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**

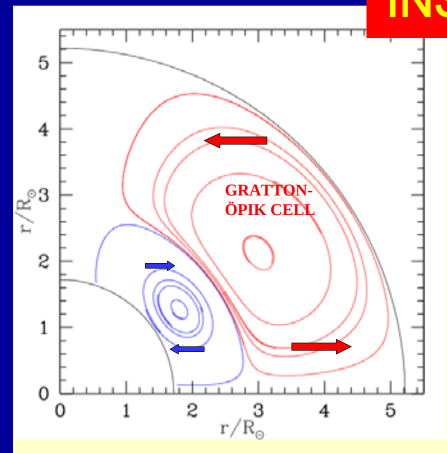
  → Stars more compact: R(popIII) = R(Z_{sol})/4

  → 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



INSTABILITIES



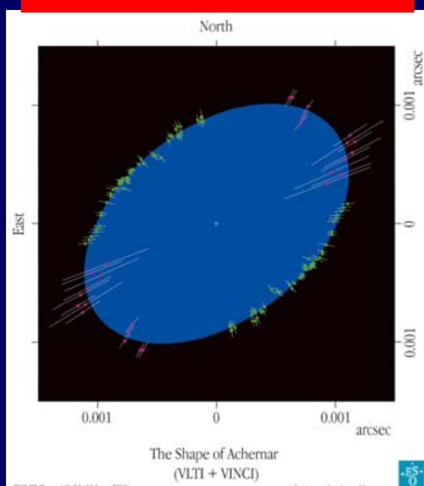
Meridional currents

Shear instabilities

Zahn 1992

Maeder & Zahn 1998

DEFORMATION

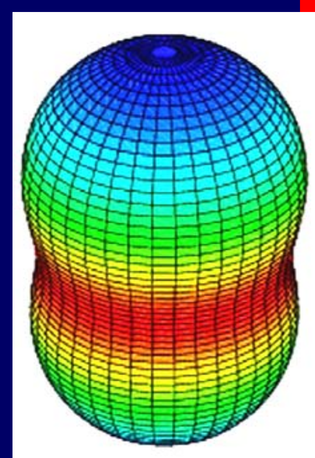


Dominiciano de Souza et al. 2003

Kippenhahn & Thomas 1970

Meynet & Maeder, A&A 321, 465 (1997)

Stellar winds



Anisotropies

Ejected mass

Owocki et al. 1996; Maeder 1999

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

STELLAR MODELS

Surface enrichments (N, He)

Standard models

Rotating models

Heger and Langer 2000; Meynet and Maeder, A&A, 361, 101 (2000)

Number ratios of blue to red supergiants

Standard models

Rotating models

Maeder and Meynet, A&A, 373, 555 (2001)

Populations of Wolf-Rayet Stars

Standard models

Rotating models

Meynet and Maeder, A&A, 404, 975 (2003)

Variations with metallicity of N(SNIbc)/N(SNII)

Standard models

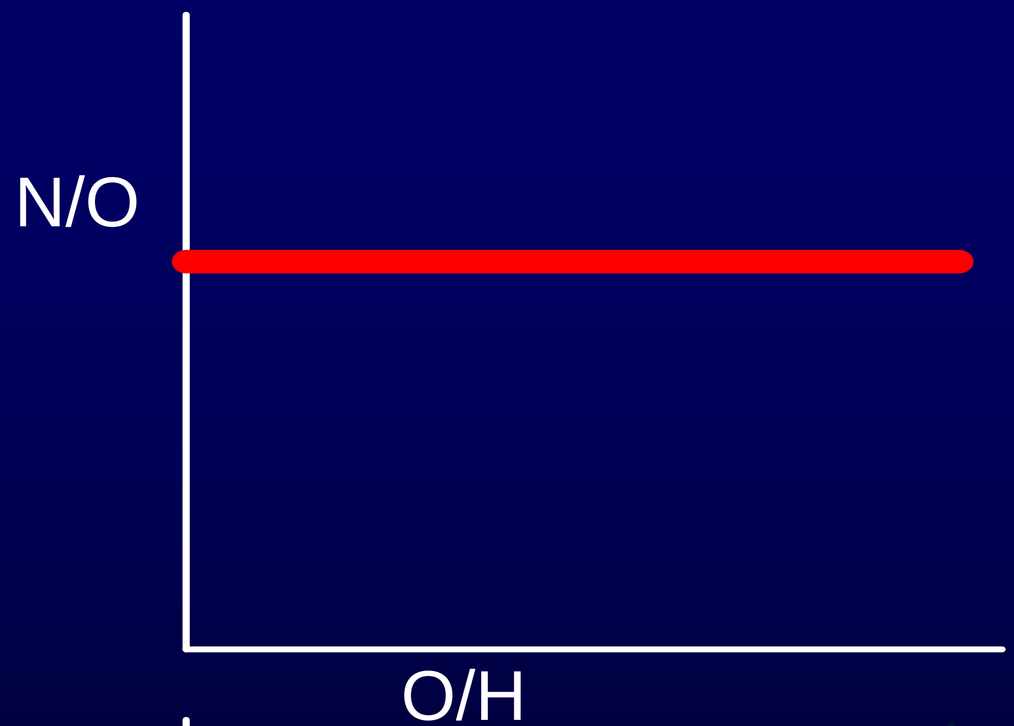
Rotating models

Meynet and Maeder, A&A, 429, 581 (2005)

CNO → N

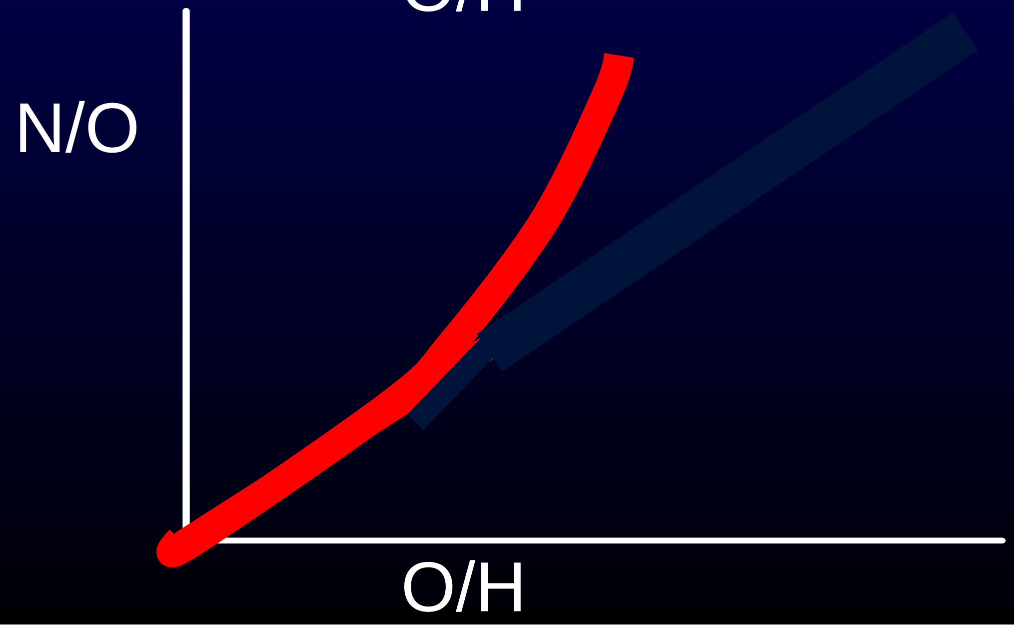
PRIMARY

C et O synthesized by the star



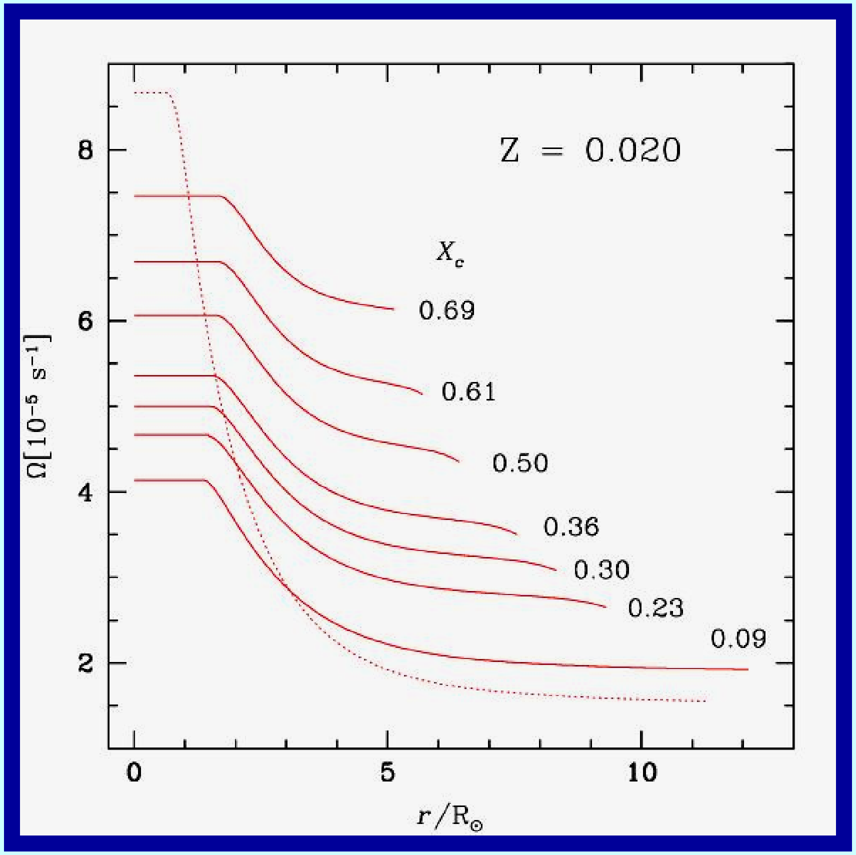
SECONDARY

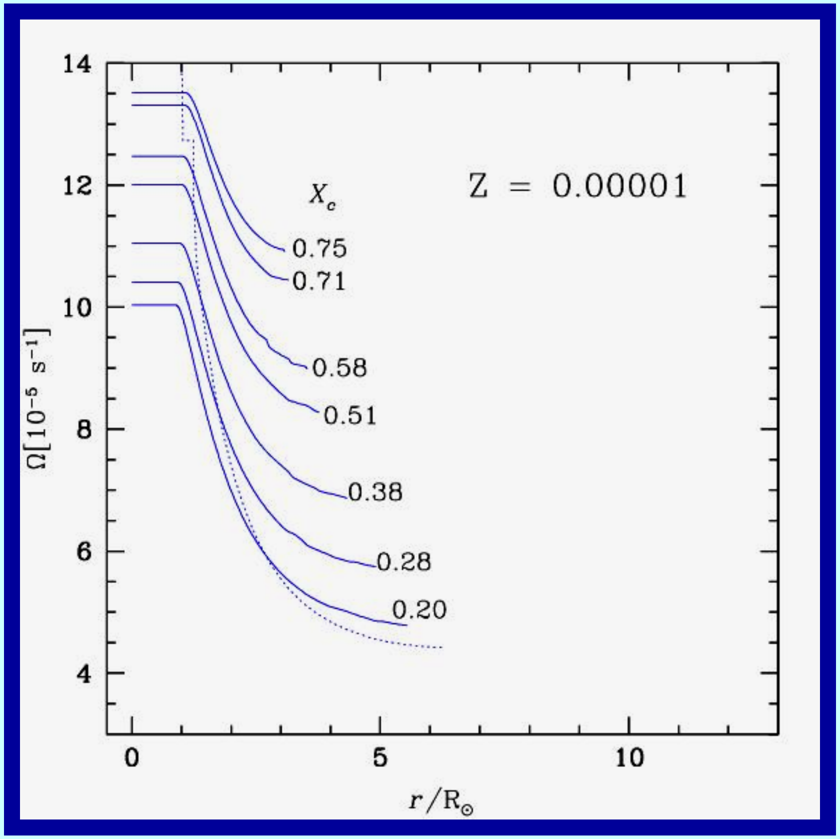
C et O initialy present in the star



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

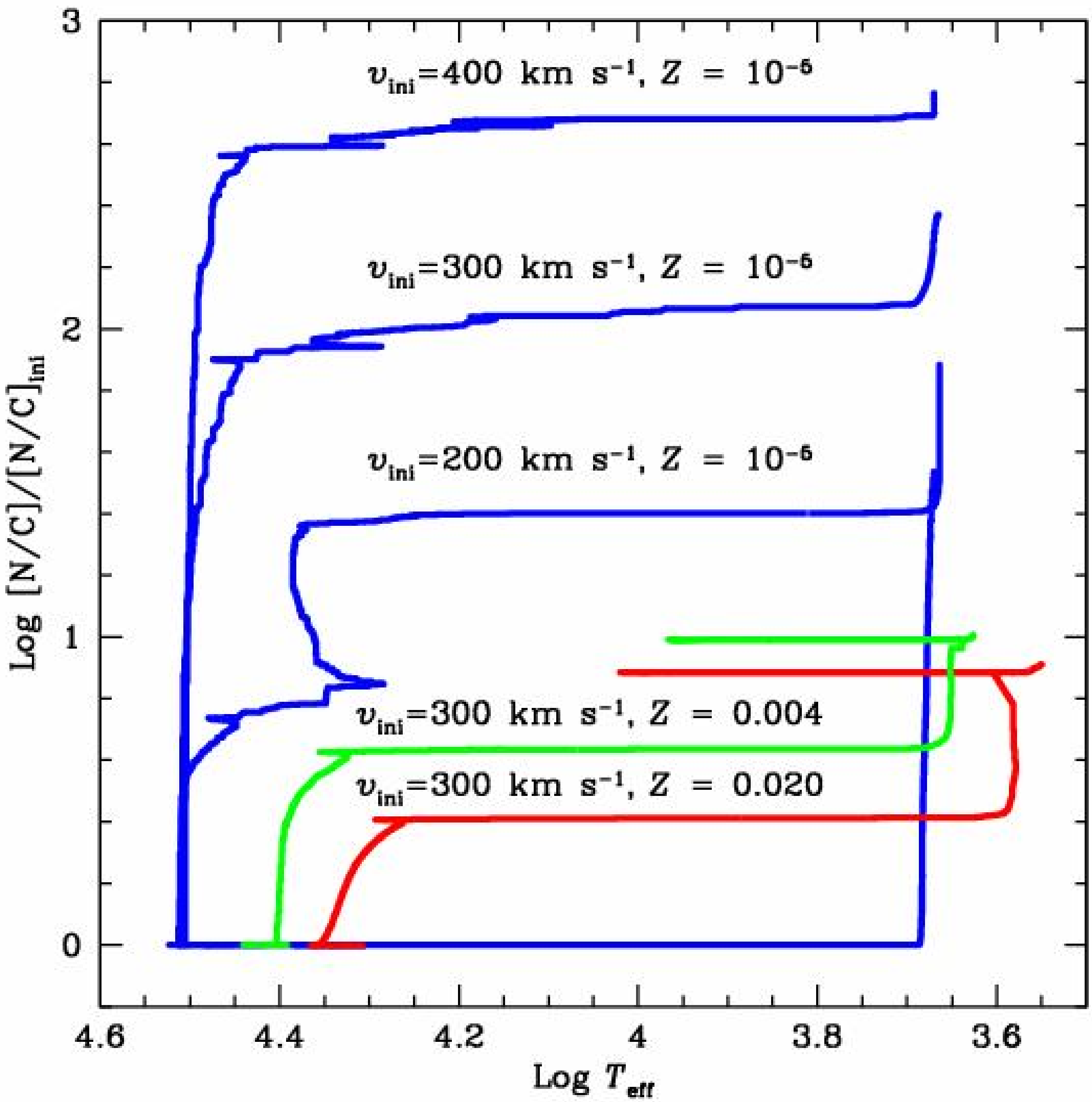
Consequences ?

More efficient mixing of the chemical elements

9 M_{sol}

When Z ↘

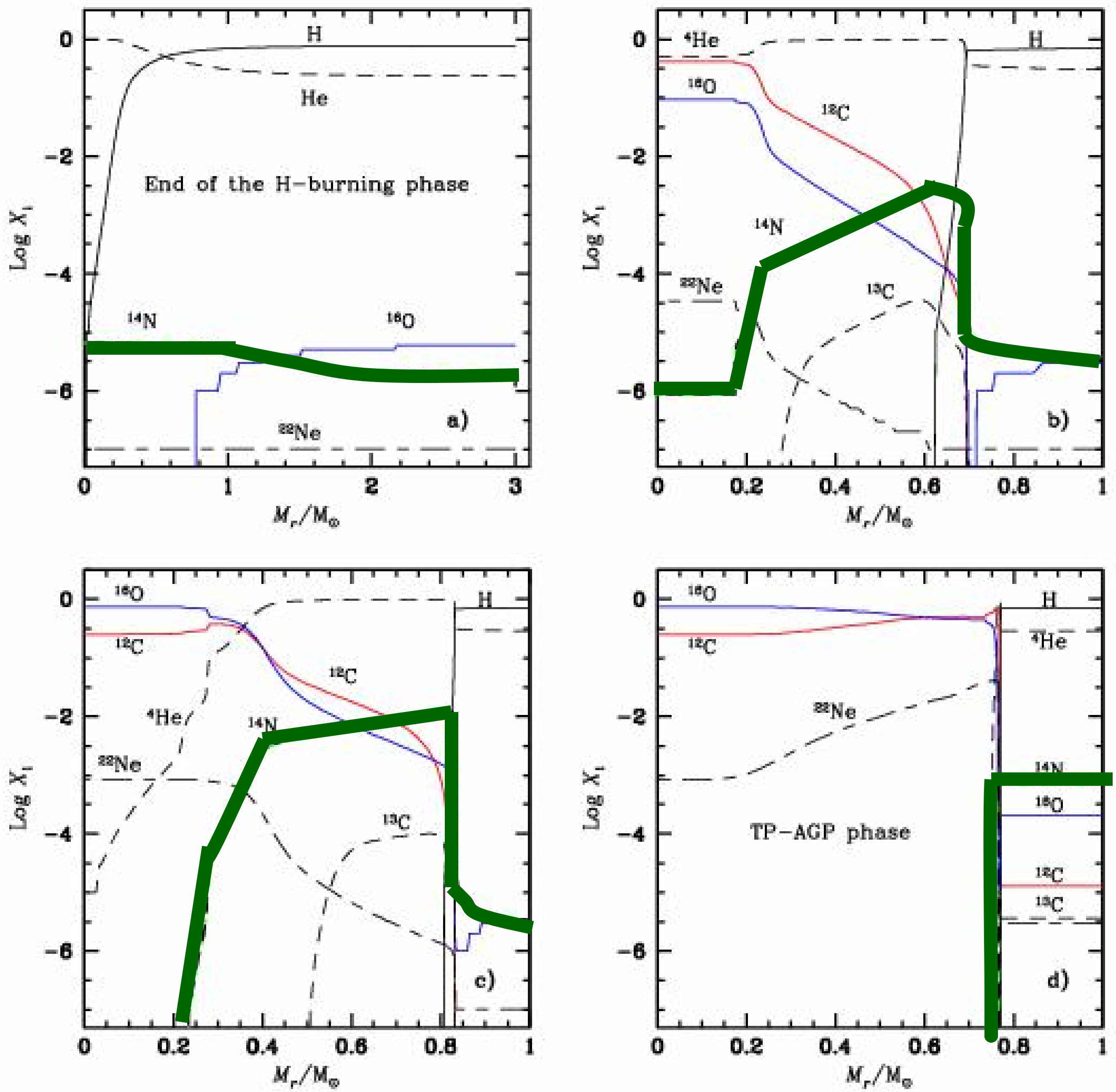
Surface enrichments ↗



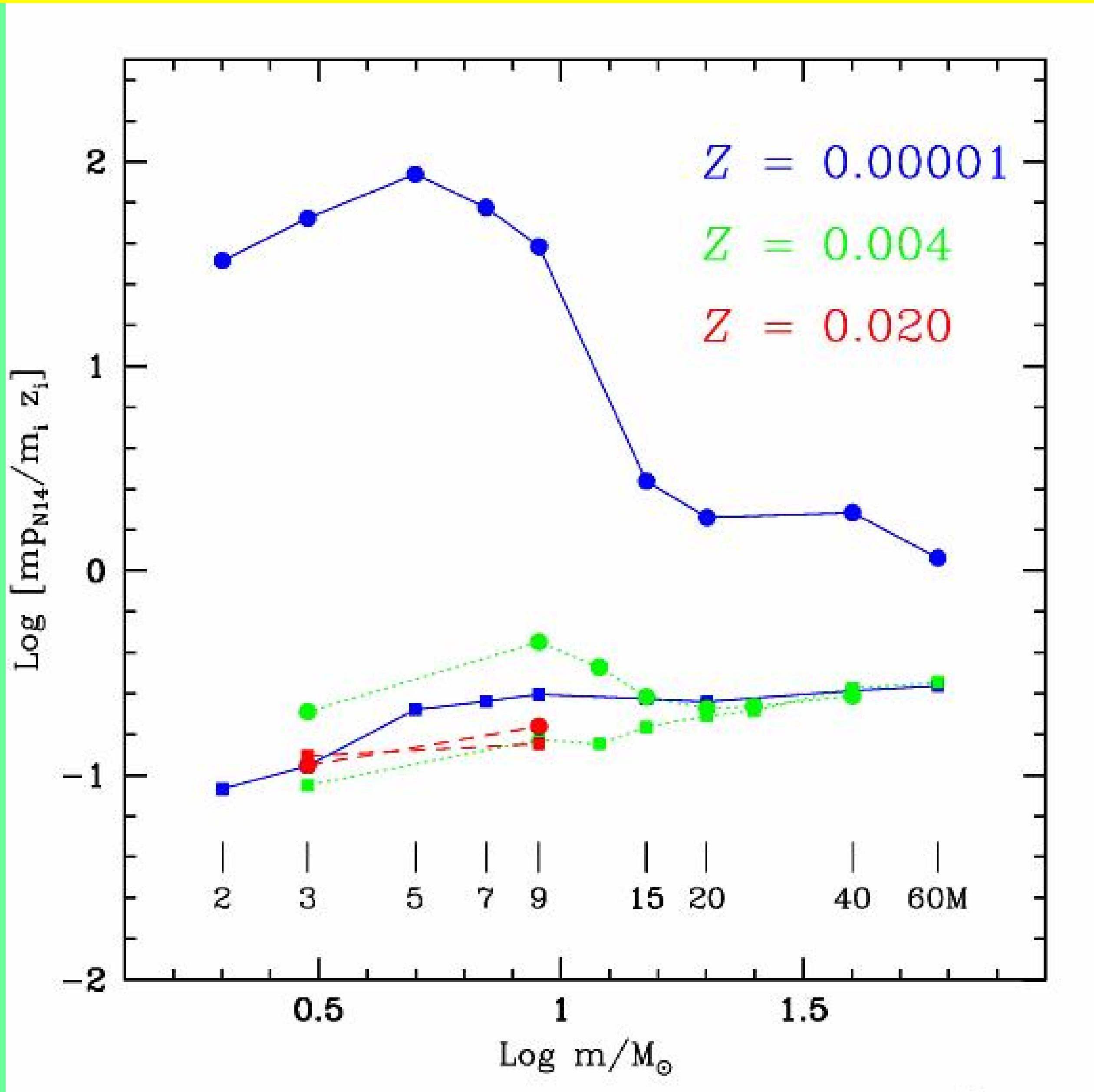
A new mechanism induced by rotation

Meynet and Maeder 2002

S-process ?

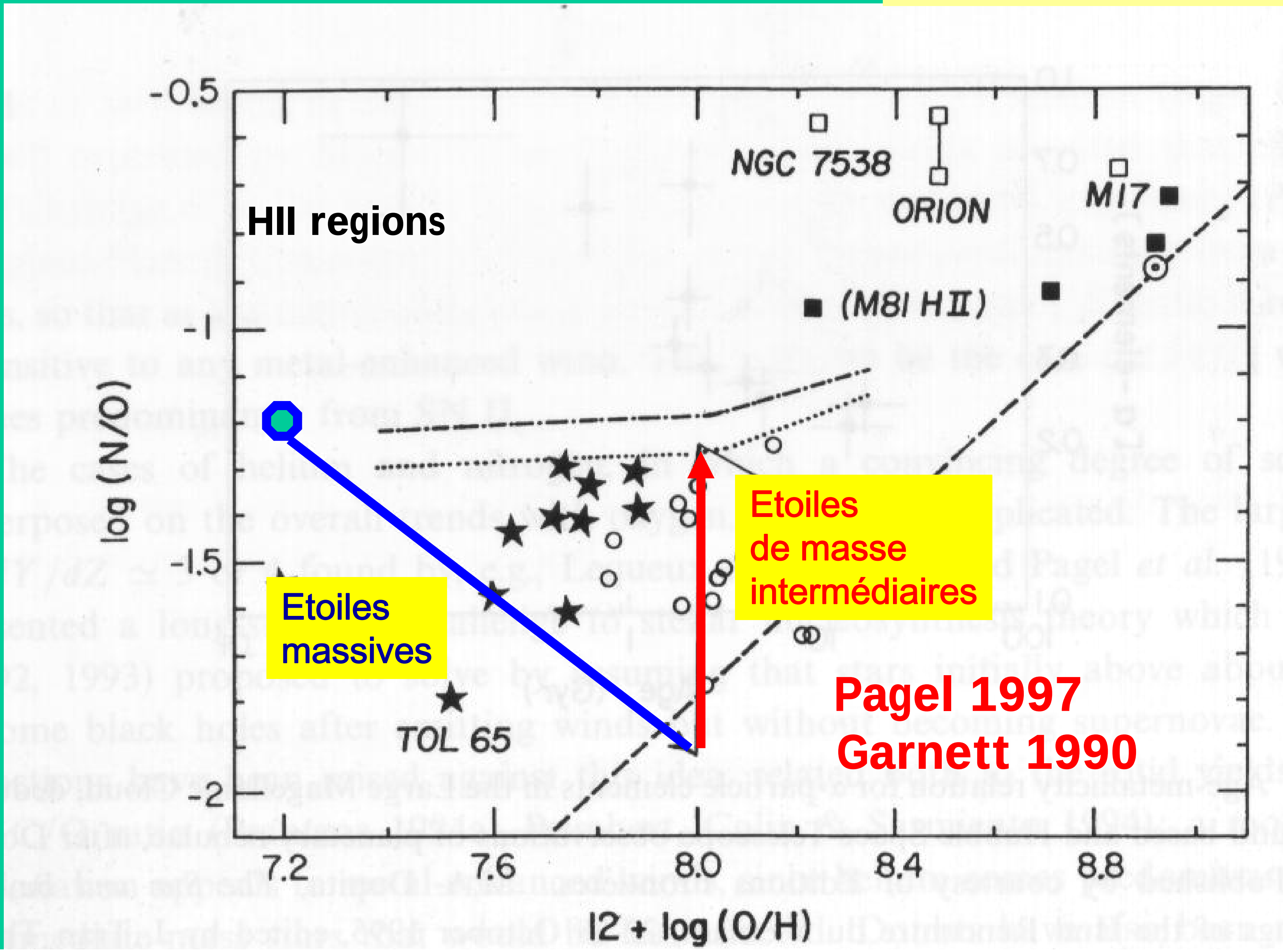


For Z=0.004 and Z=0.020 , nearly no primary N production

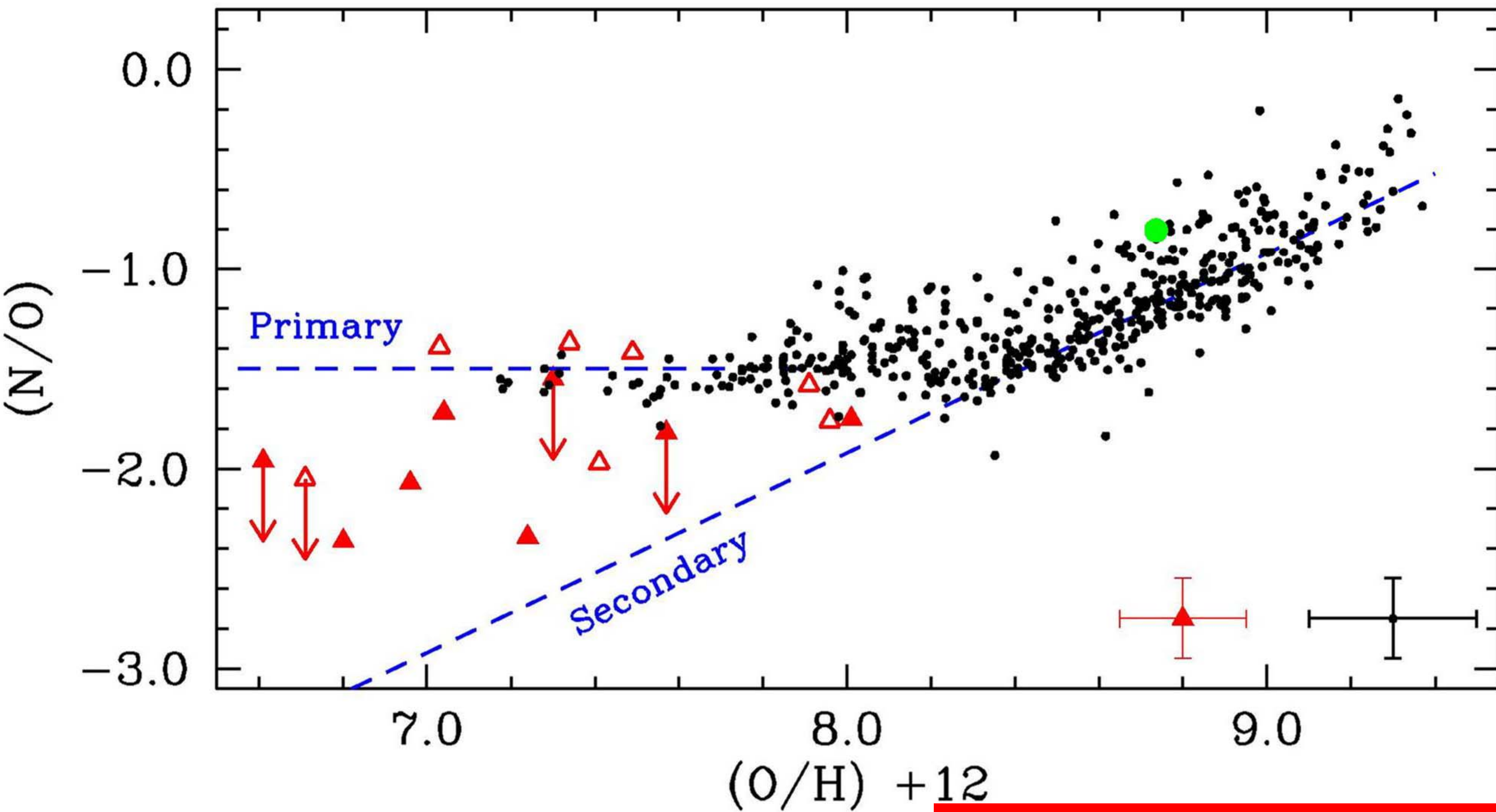


L'AZOTE COMME HORLOGE GALACTIQUE

Edmunds and Pagel 1978



UNE APPLICATION: LES ``DAMPED LYMAN ALPHA SYSTEMS''



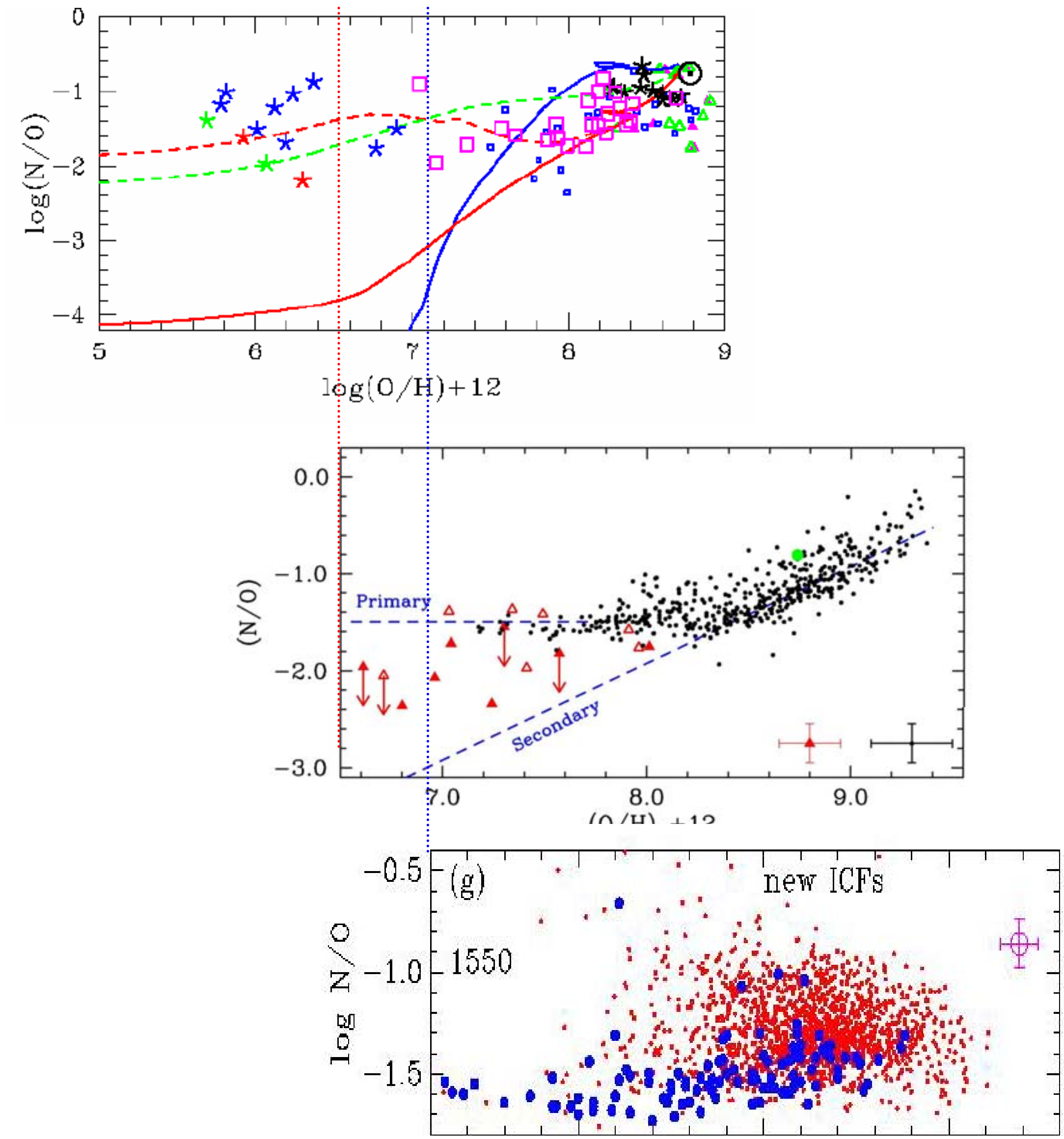
Meynet and Pettini, IAU Symp. 215, (2003)

Chiappini, Matteucci, Meynet, A&A, 410, 257

→ Quantités produites

→ Durée de la période intermédiaire → 700 Millions d'années.

HALO STARS



HALO STARS

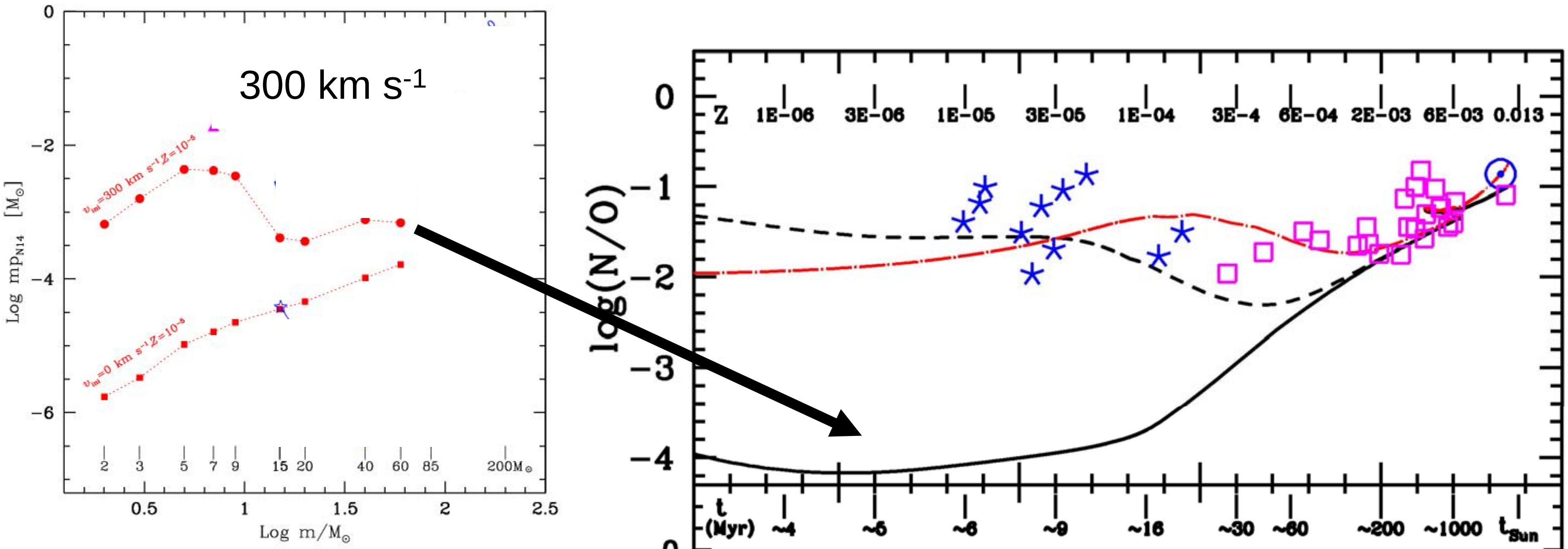
Spite et al. (2004)
Israelian et al. (2004)

DAMPED LYMAN ALPHA SYSTEMS

Pettini et al. (2002)
Dessauge et al. (2005)

EMISSION LINE GALAXIES AND BLUE COMPACT DWARF GALAXIES

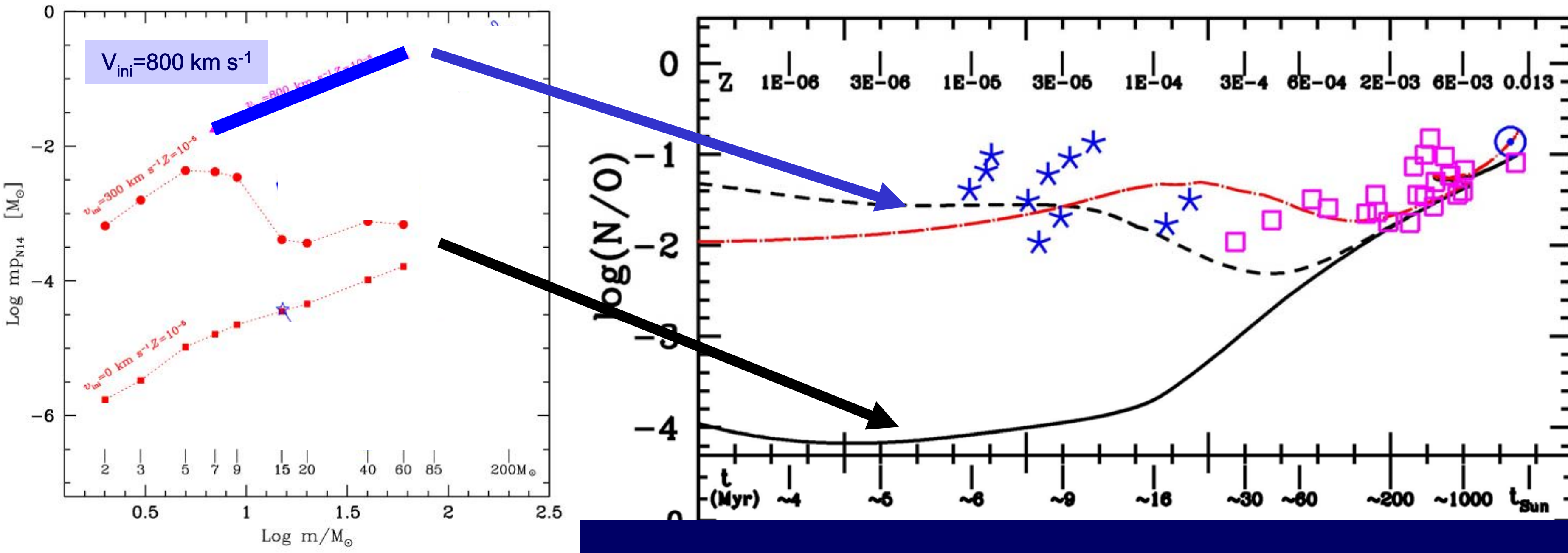
Izotov, Stasinska, Meynet, Guseva, Thuan
A&A, in press, (2006)



Meynet, Maeder, A&A, A&A letter, 381, 25 (2002)

Chiappini, Hirschi, Meynet, Ekström, Maeder, Matteucci, in press

FASTER ROTATION ?

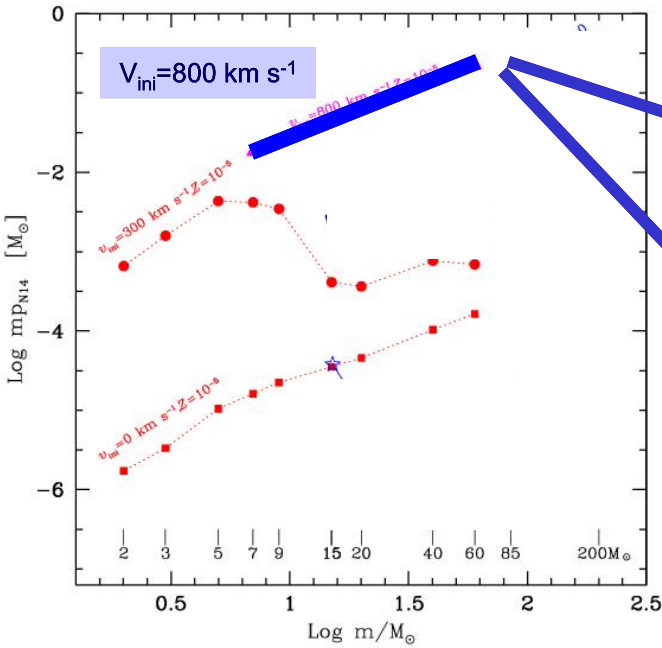


Meynet, Ekström, Maeder, IAU Symp. 228, in press, 2006

Chiappini, Hirschi, Meynet, Ekström, Maeder, Matteucci, in press

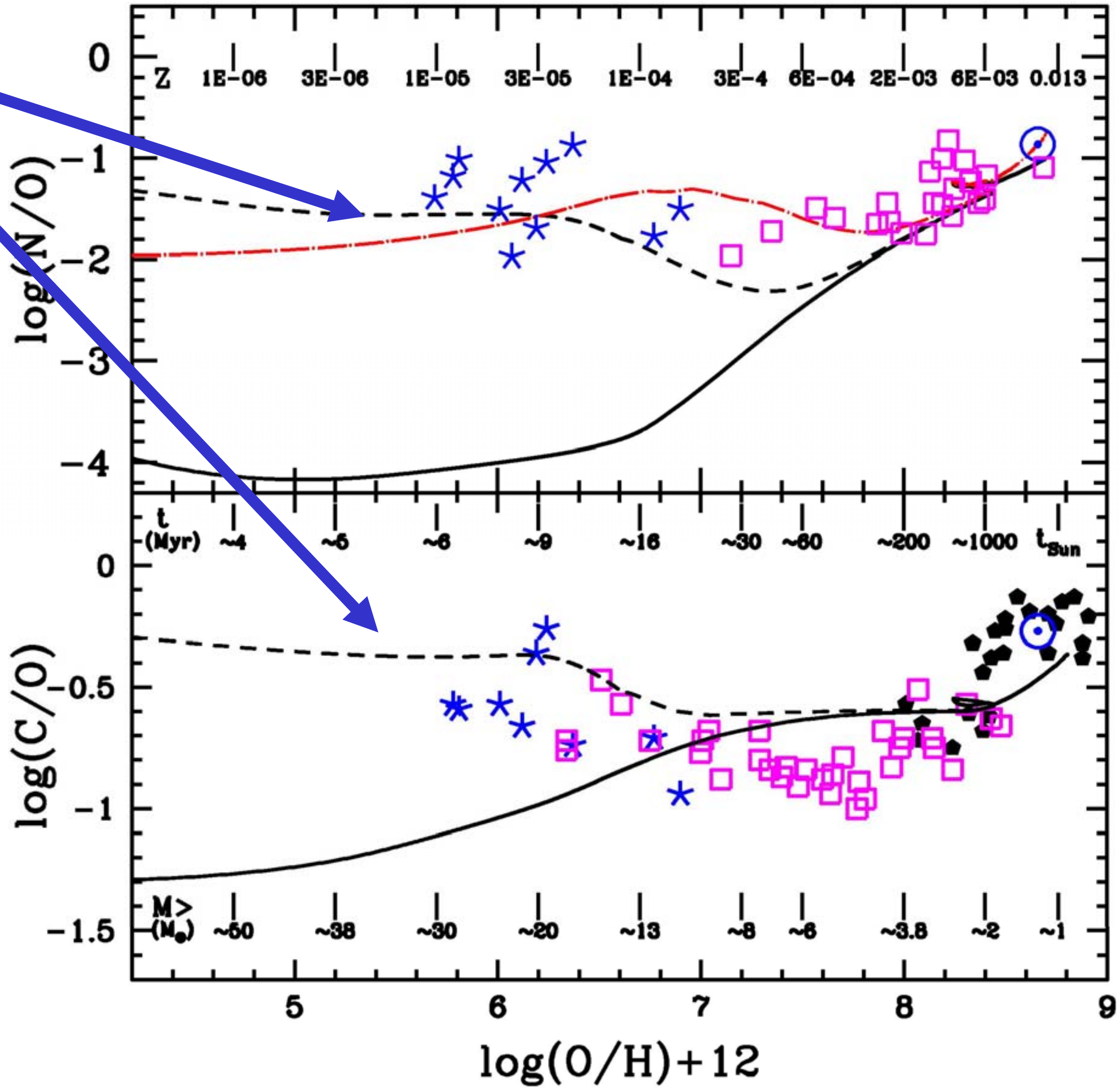
FASTER ROTATION→

NOT NECESSARILY MUCH HIGHER ANGULAR MOMENTUM CONTENT



Meynet, Ekström, Maeder, IAU Symp. 228, 2005

C/O

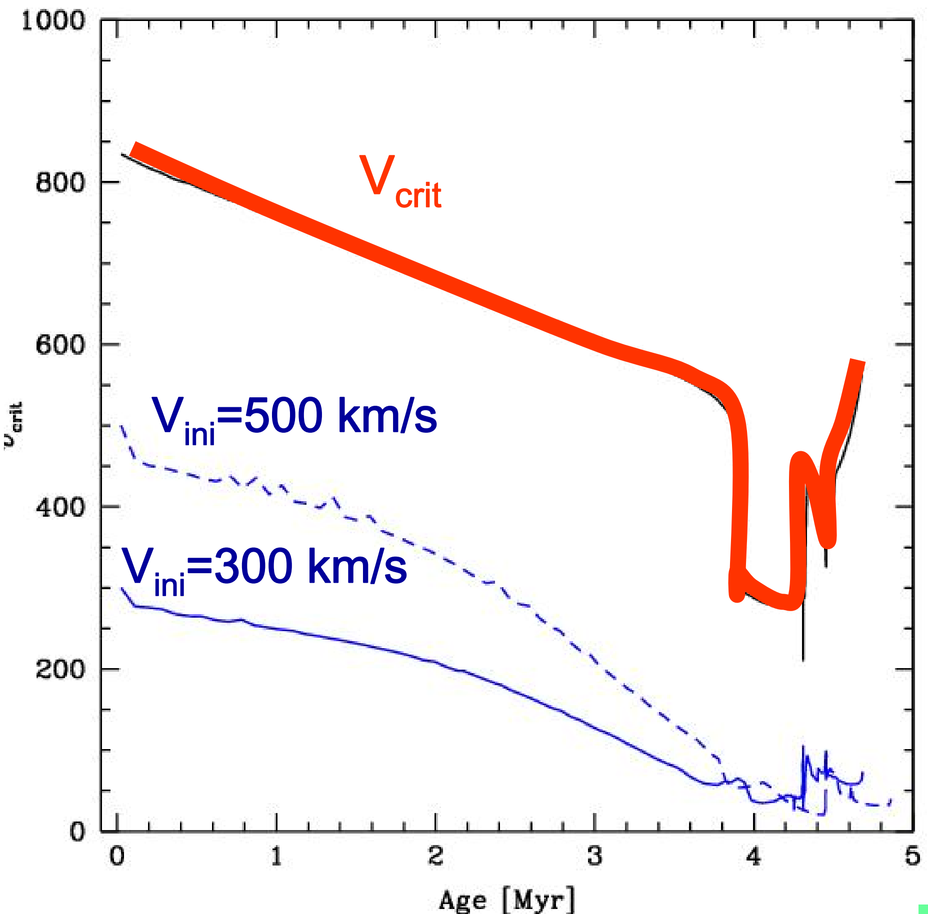


Chiappini, Hirschi, Meynet, Ekström, Maeder, Matteucci, in press

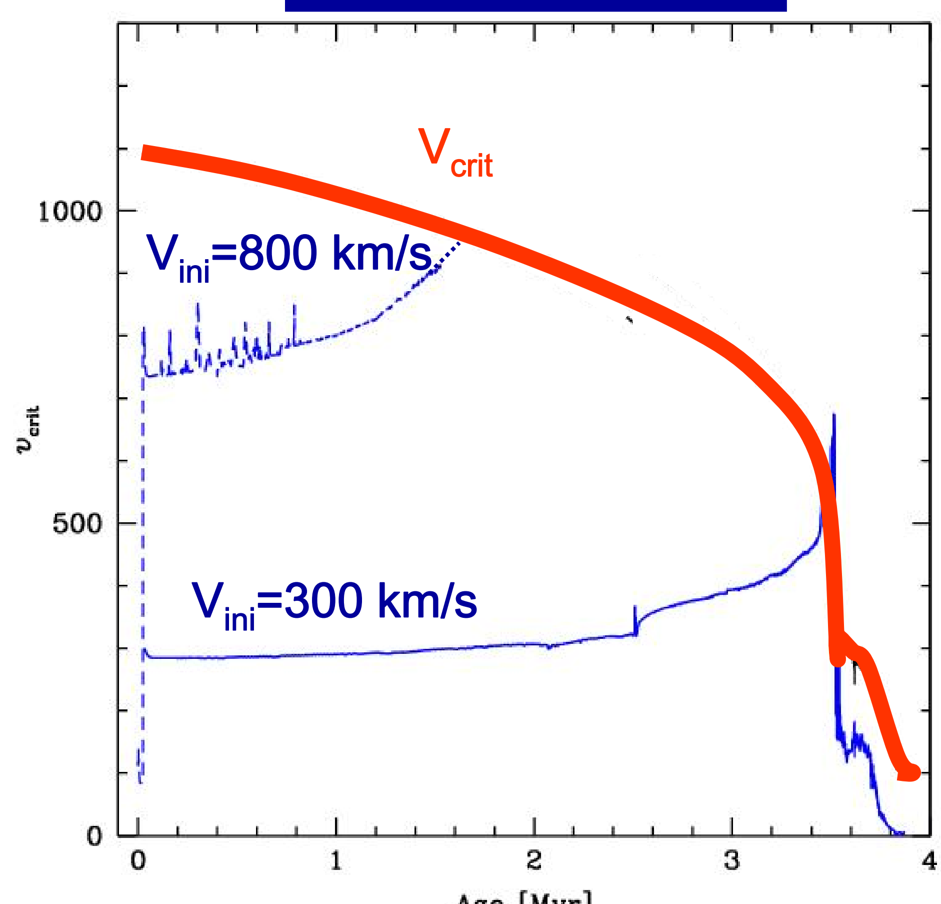
ROTATION FAVOURS MASS LOSS AT LOW METALLICITY

1) STARS CAN REACH THE CRITICAL VELOCITY

60 M_{sol}, Z = 0.020

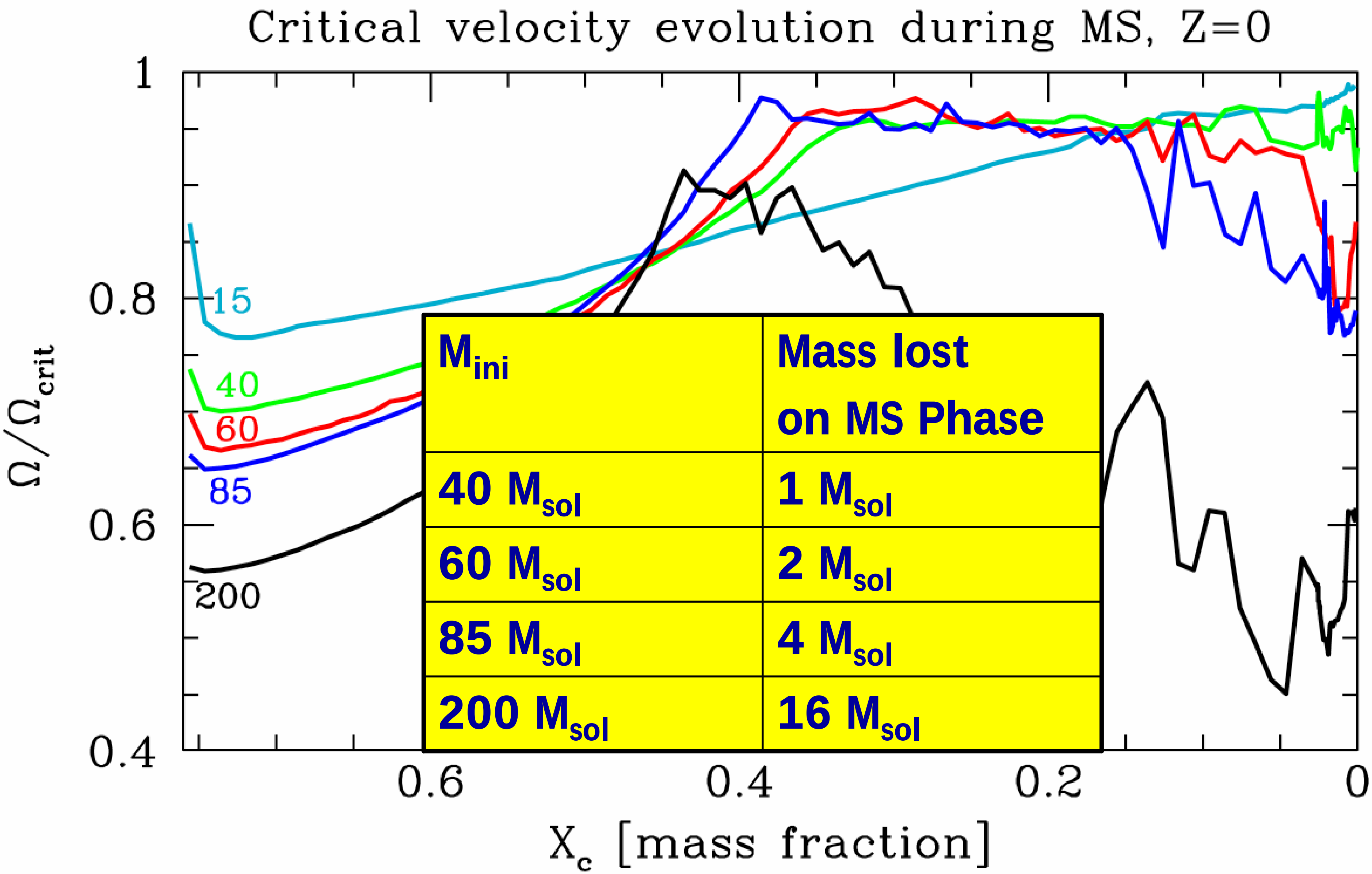


60 M_{sol}, Z = 0.00001



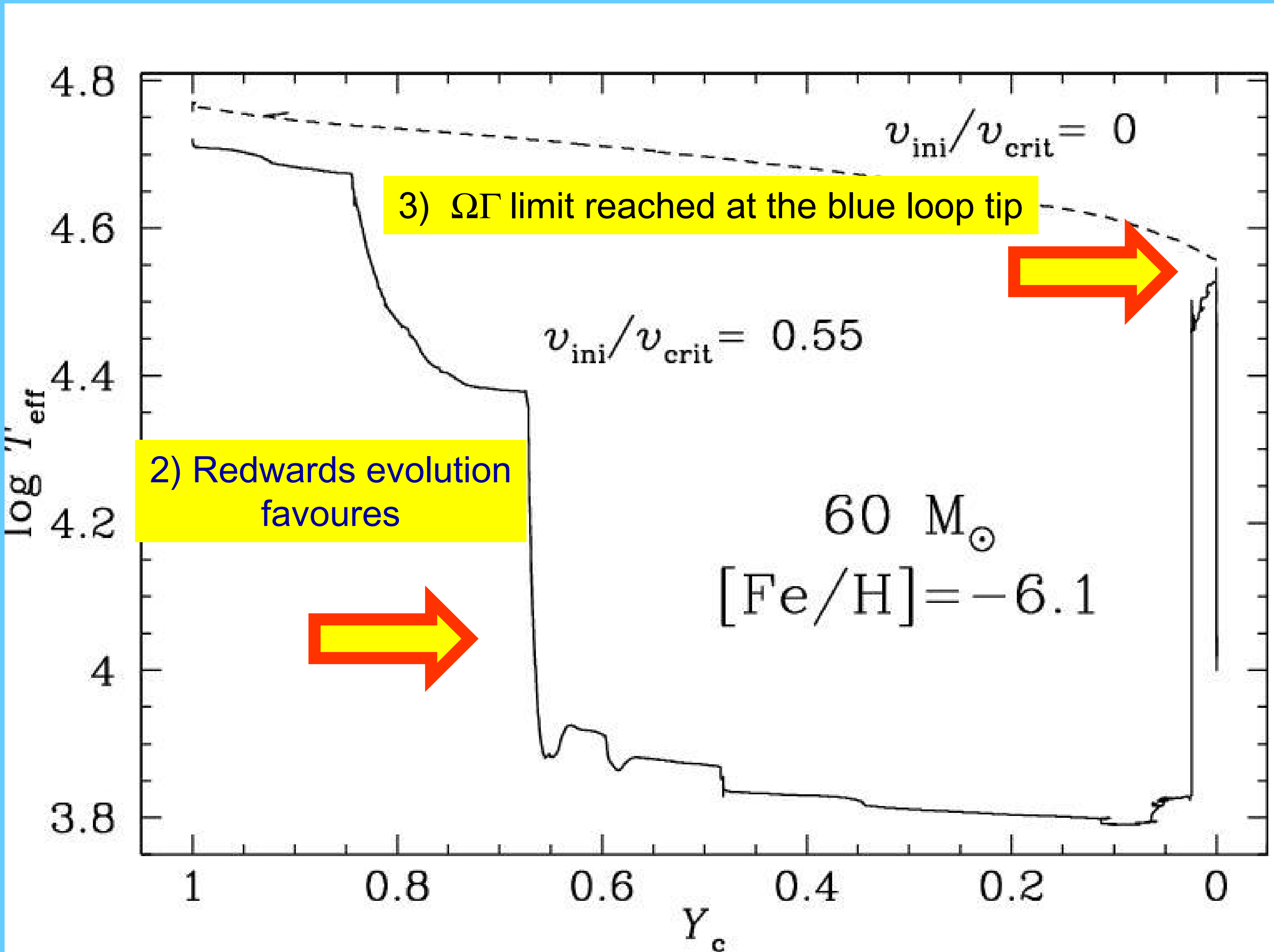
Cf also Sackman & Anand 1979; Langer 1998

CONSEQUENCES

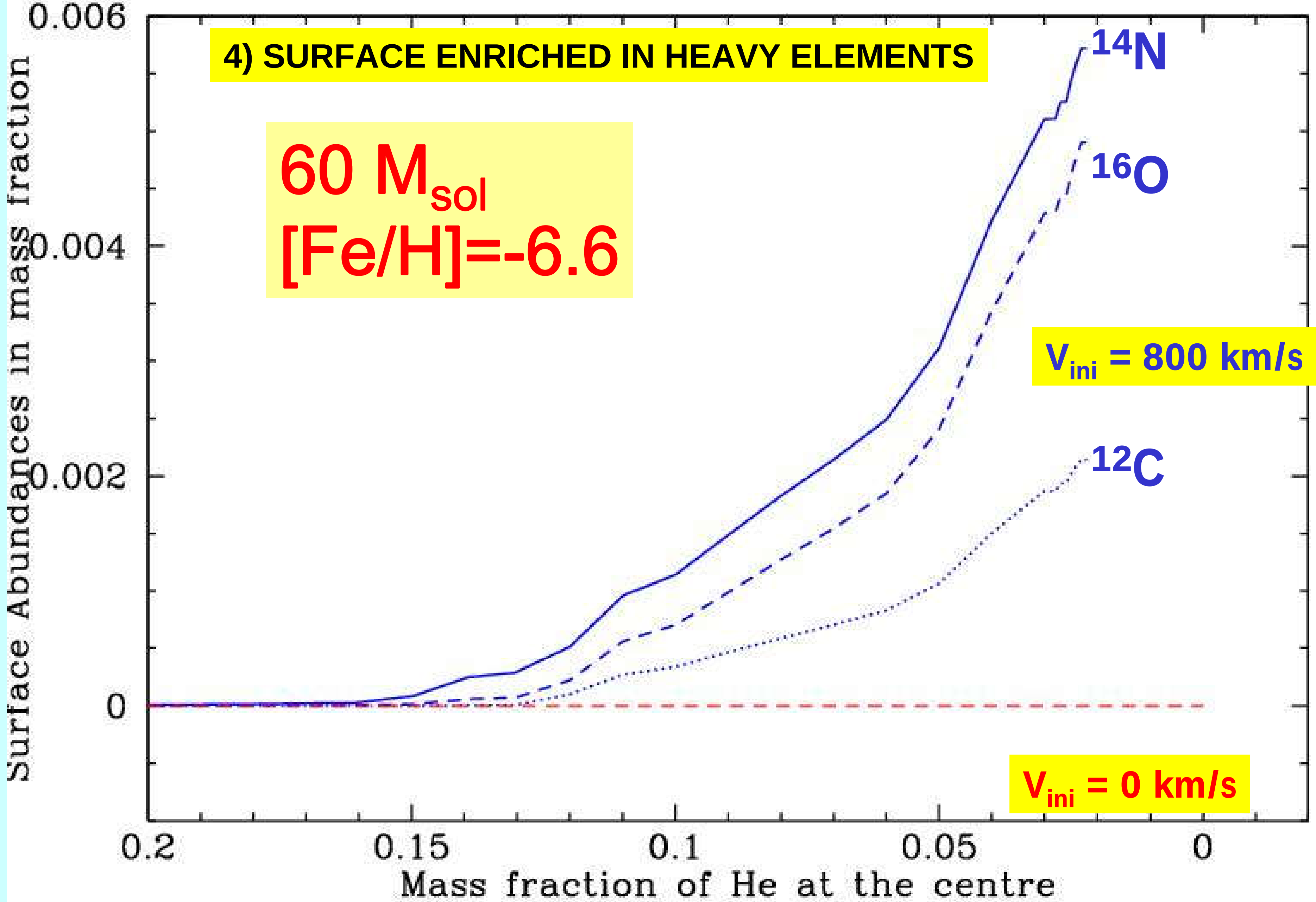


M_{ini}	Mass lost on MS Phase
40 M_{sol}	1 M_{sol}
60 M_{sol}	2 M_{sol}
85 M_{sol}	4 M_{sol}
200 M_{sol}	16 M_{sol}

Ekstroem, Meynet, Maeder 2005

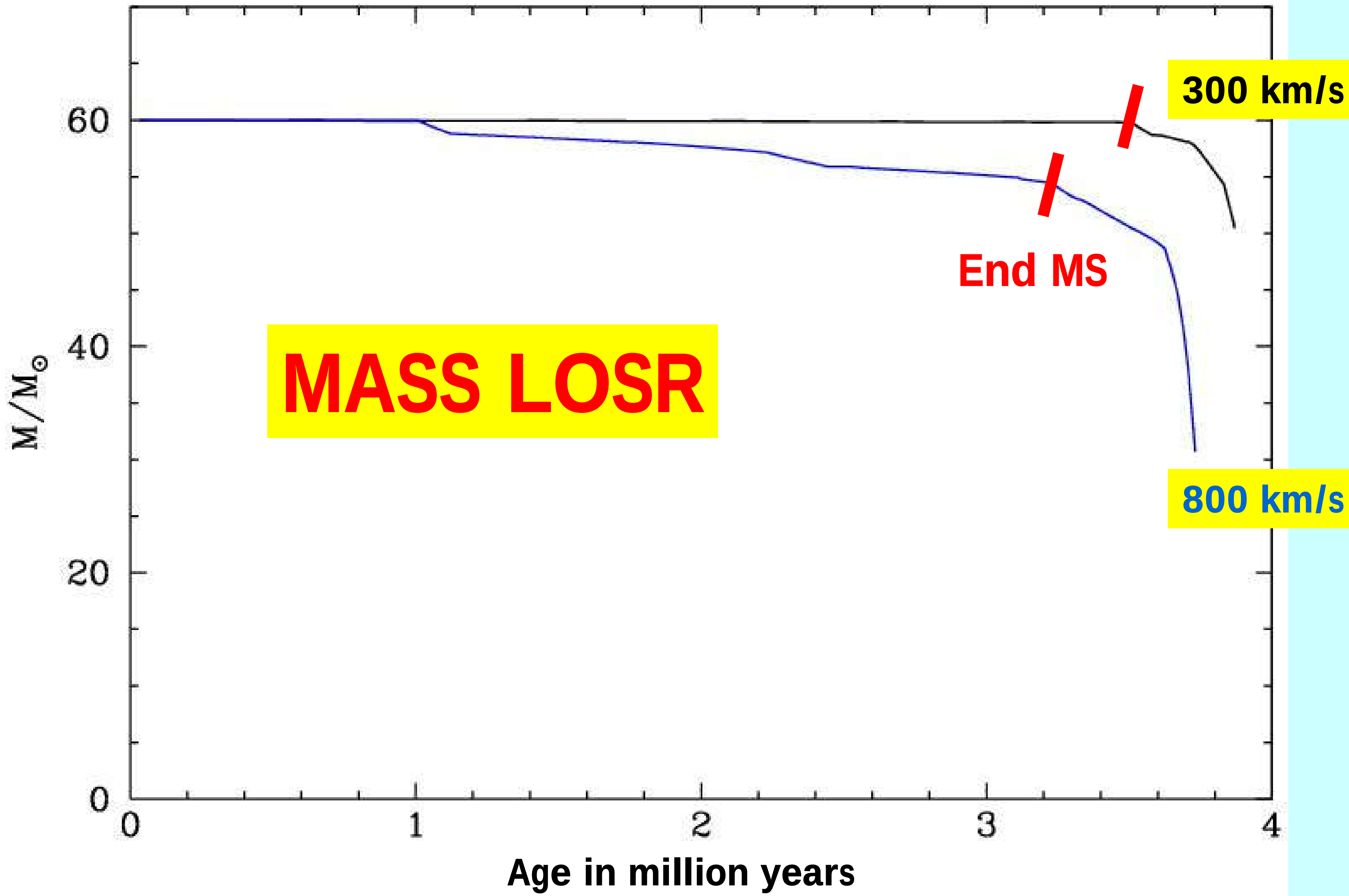


3) ΩΓ limit reached at the blue loop tip
2) Redwards evolution favoures
$v_{ini}/v_{crit} = 0$
$v_{ini}/v_{crit} = 0.55$
60 $M_\odot$
[Fe/H]=−6.1
log T_{eff}
Y_c
4.8
4.6
4.4
4.2
4
3.8
1
0.8
0.6
0.4
0.2
0



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

[Fe/H]=-6.6



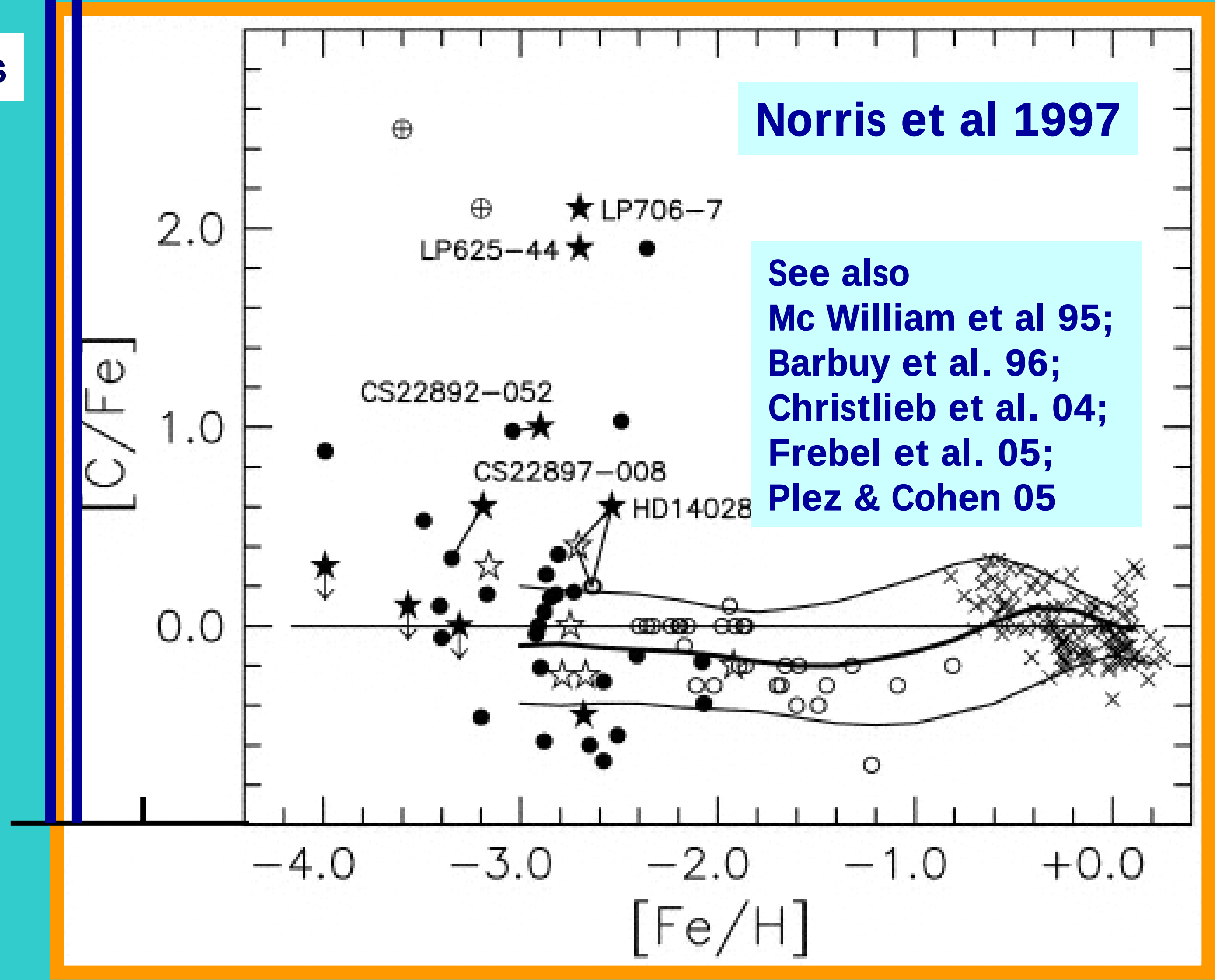
300 km/s
800 km/s
End MS
MASS LOSR
M/M⊙
60
40
20
0
0
1
2
3
4
Age in million years

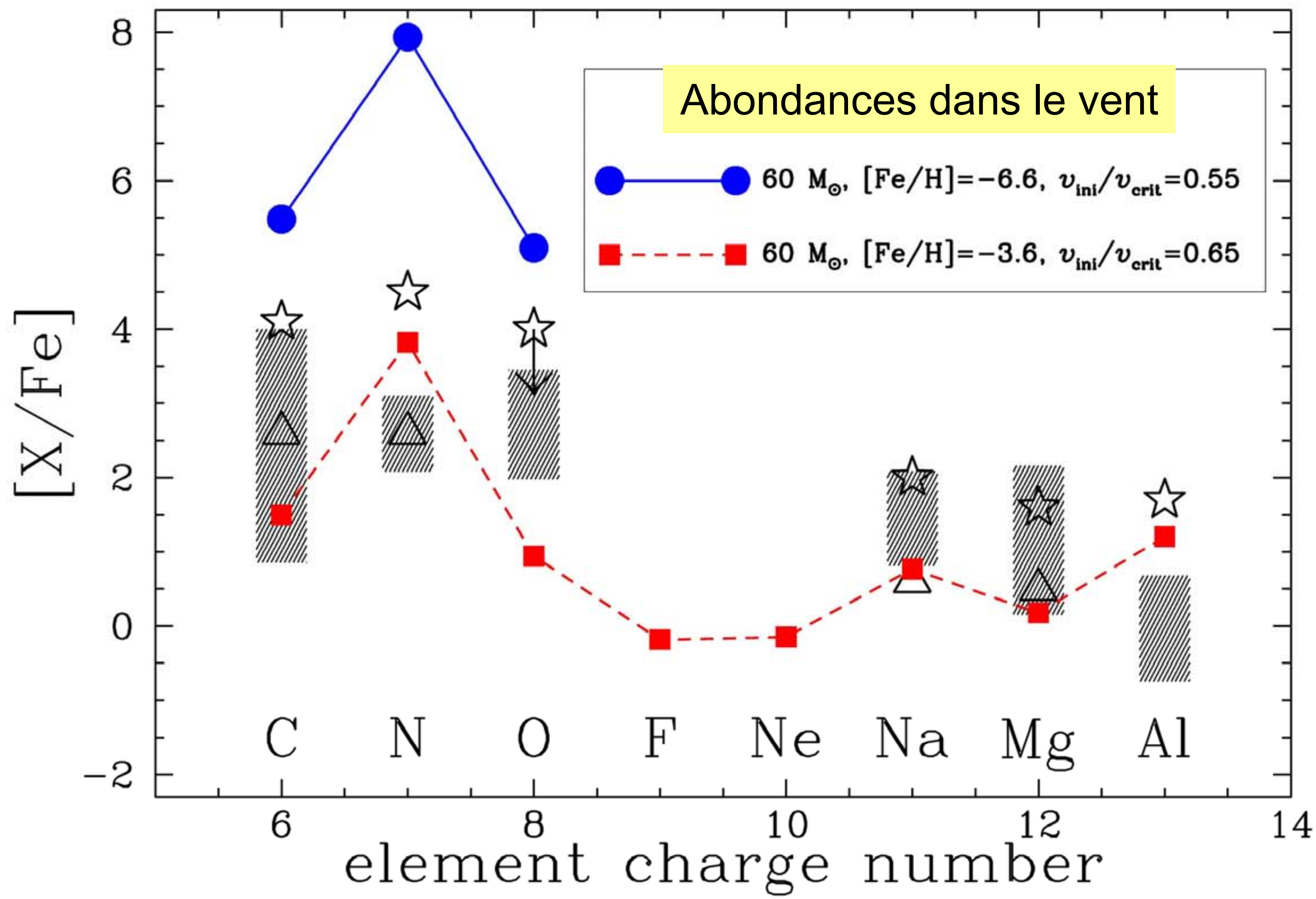
Carbon Rich Ultra Metal Poor Stars (CRUMPS)

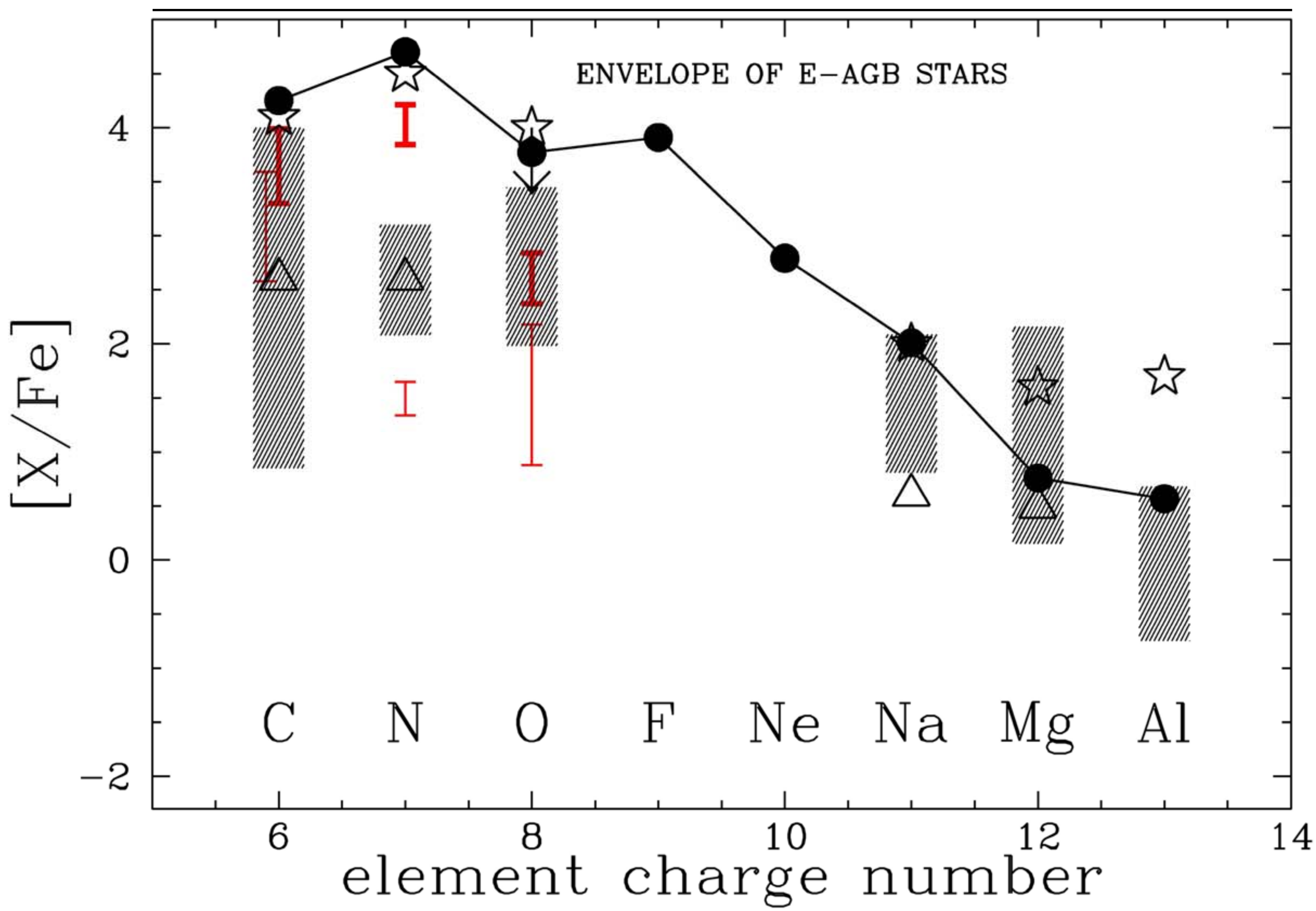
Most metal poor stars

Christlieb et al. 2002

Frebel et al. 2005




Abondances dans le vent
60 $M_\odot$, [Fe/H]=−6.6, v_{ini}/v_{crit}=0.55
60 $M_\odot$, [Fe/H]=−3.6, v_{ini}/v_{crit}=0.65
[X/Fe]
C N O F Ne Na Mg Al
element charge number
Meynet, Ekström, Maeder, A&A, in press (2006)



Meynet, Ekström, Maeder, A&A, in press (2006)

CONCLUSION

EFFECTS OF ROTATION AT VERY LOW METALLICITY

MIXING→ IMPACT ON THE YIELDS

C, N, O ENHANCED (He)

STARS MAY LOOSE GREAT AMOUNT OF MASS

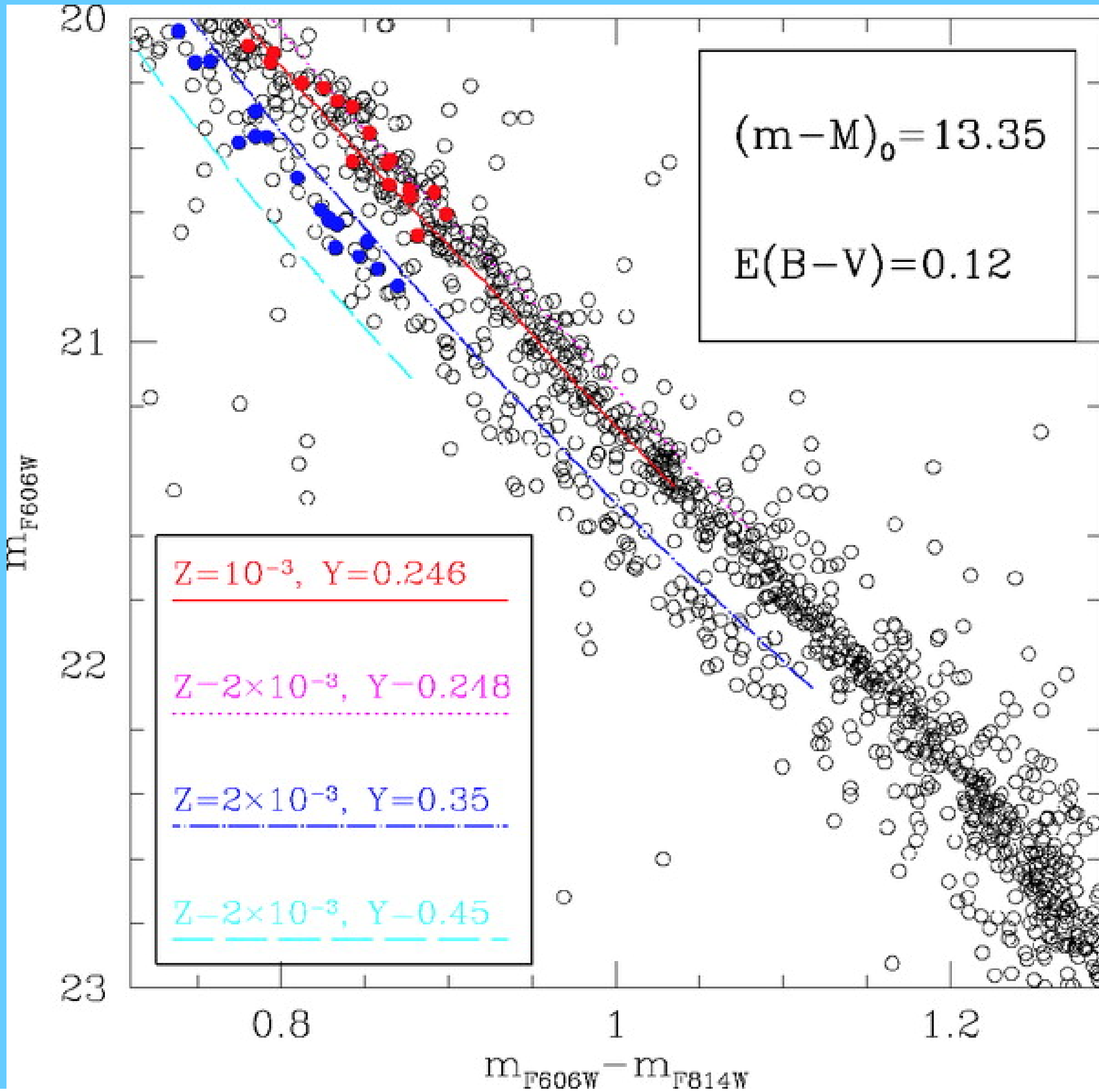
⇒ BREAK-UP LIMIT REACHED

⇒ REDWARDS EVOLUTION & SURFACE METALLICITY ENHANCED

NUCLEOSYNTHESIS AND FINAL FATE

A STRIKING OBSERVATIONAL FACTS

→ **Very Helium-rich stars in ω Centuri ?**



EFFECTS OF ROTATION AT VERY LOW METALLICITY

ROTATIONAL MIXING

^{13}C and ^{14}N produced in great quantities

ROTATIONAL MASS LOSS

May loose half of their initial mass through stellar winds

→ NUCLEOSYNTHESIS

→ Pair instability supernovae avoided ?

CONCLUSION

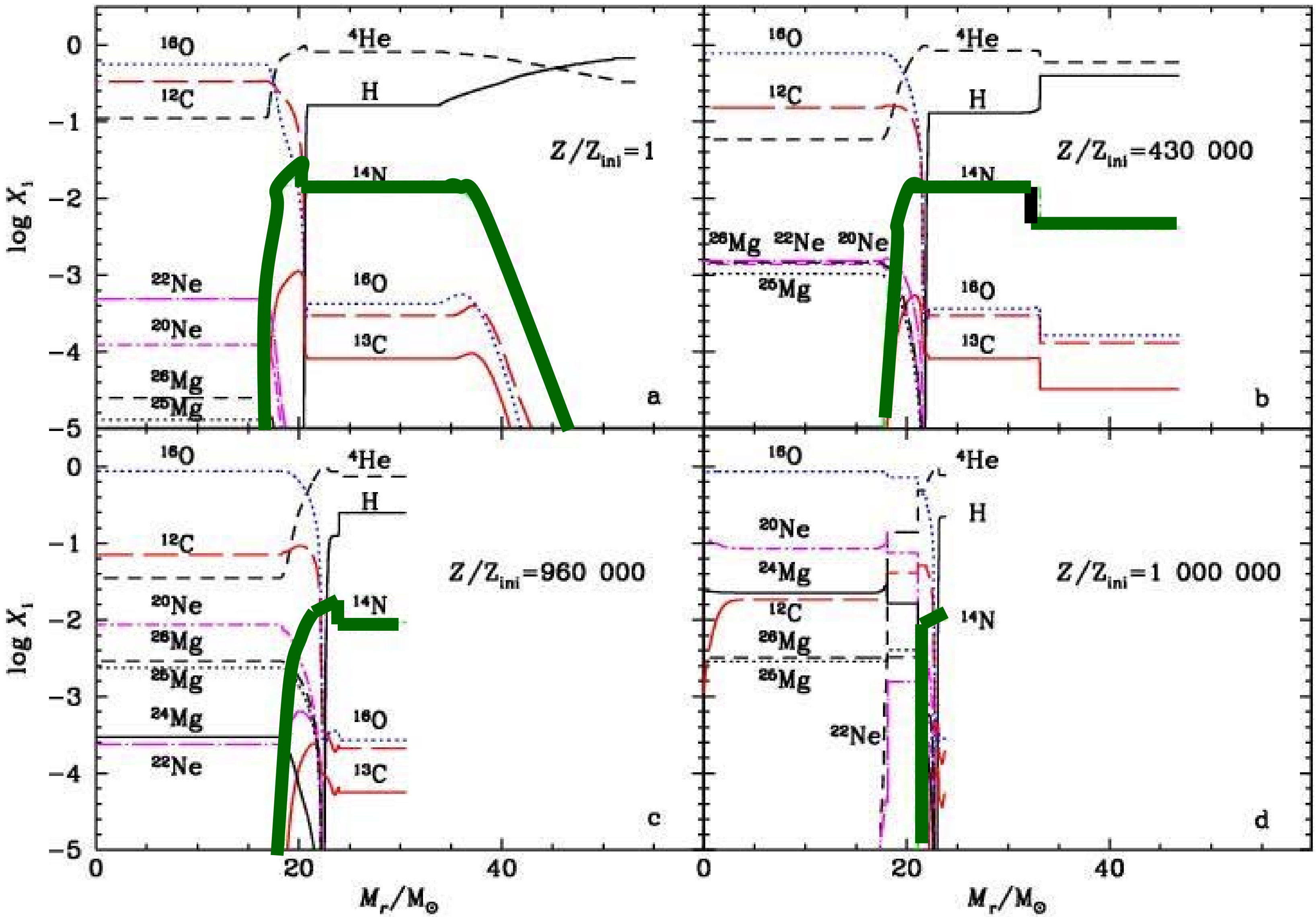
The effects of rotation are amplified at low metallicity
→ mixing enhanced
→ induce mass loss

NUMEROUS INTERESTING CONSEQUENCES

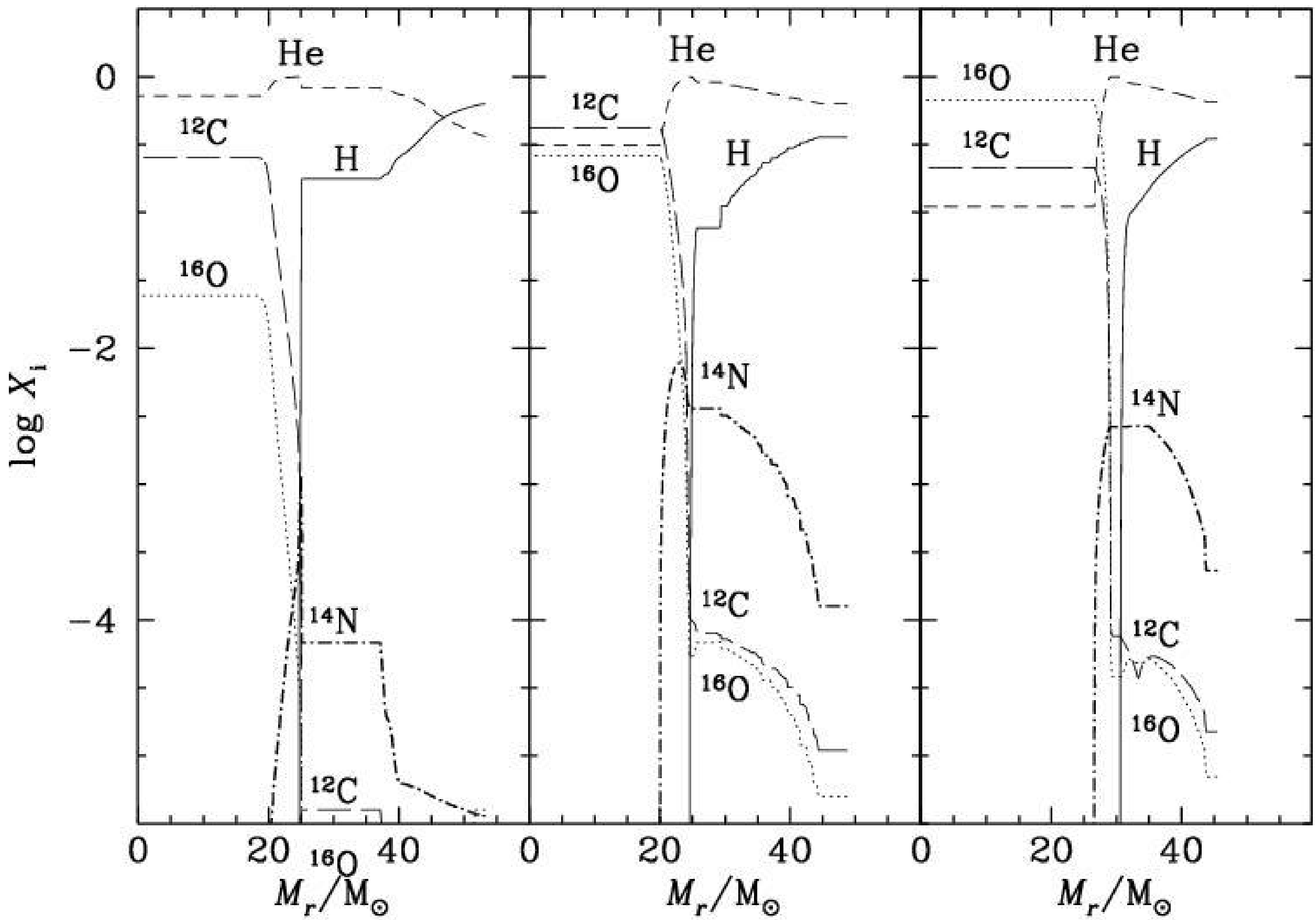
• Higher surface enrichments at low Z	Maeder &Meynet 2001; Venn & Przybilla 2003
• Change with Z of populations of Be stars	Maeder et al. 1999
of blue to red supergiant ratio	Langer & Maeder 1995; Maeder &Meynet 2001
of LBV and WR stars	Fliegner & Langer 1995; Meynet & Maeder 2005
of type Ibc to II SN ratio	Prantzos & Boissier 2003; Meynet & Maeder 2005
of collapsar progenitors	MacFadyen & Woosley 1999; Hirschi et al 2005
• Change with Z of the stellar yields	Meynet & Maeder 2002; Ekström et al. in prep.

→ A LOT OF INTERESTING PROBLEMS TO STUDY…

Les abondances CNO augmentent en surface



Meynet, Ekstroem, Maeder 2005



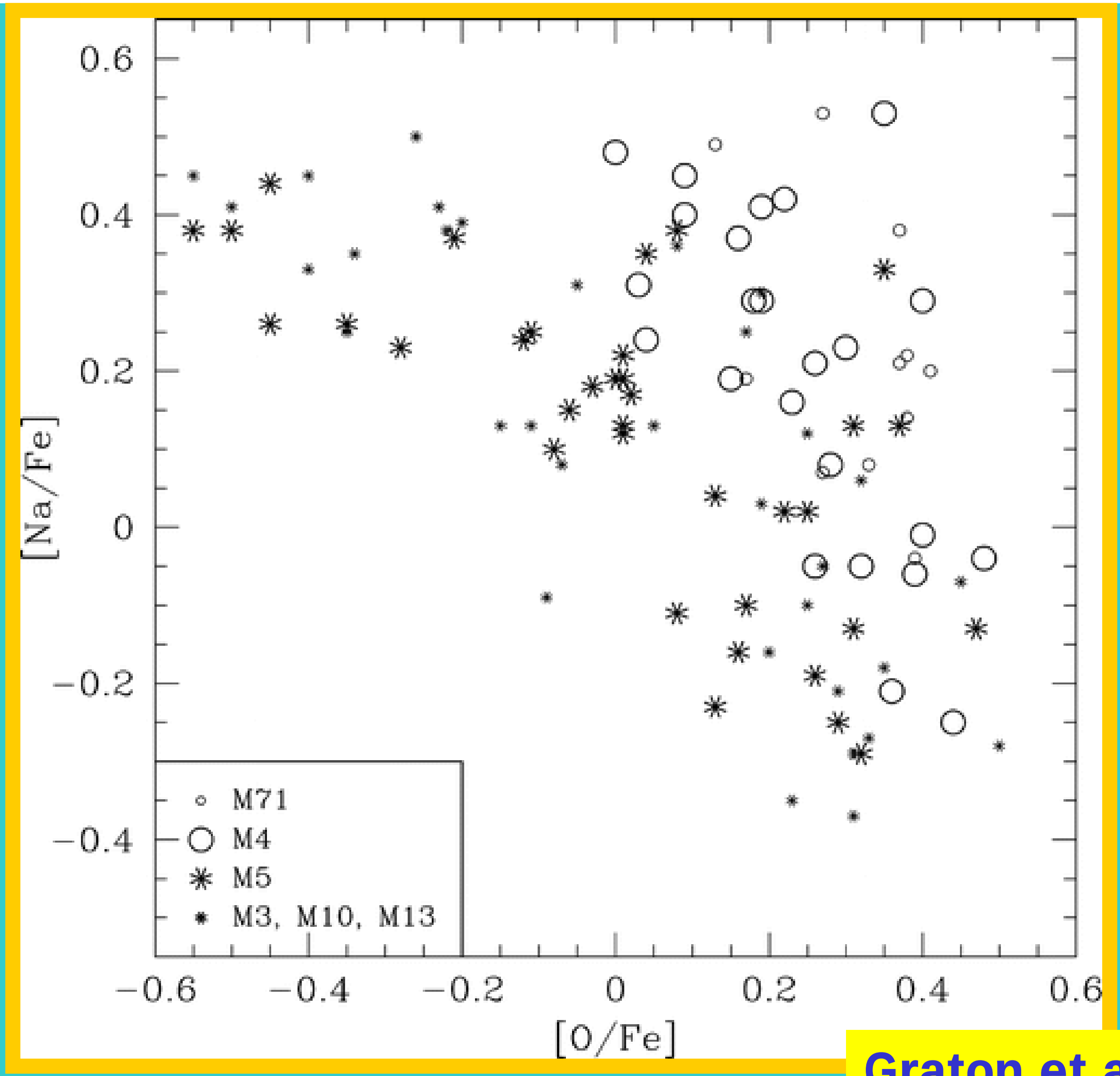
60 M_{sol}, $Z=10^{-5}$, $\Omega_{ini}/\Omega_{crit}$ = 0.85

QUELLE ÉTAIT LA NATURE, L' EVOLUTION DES PREMIERES ETOILES?

Artist's View of Star Formation in the Early Universe

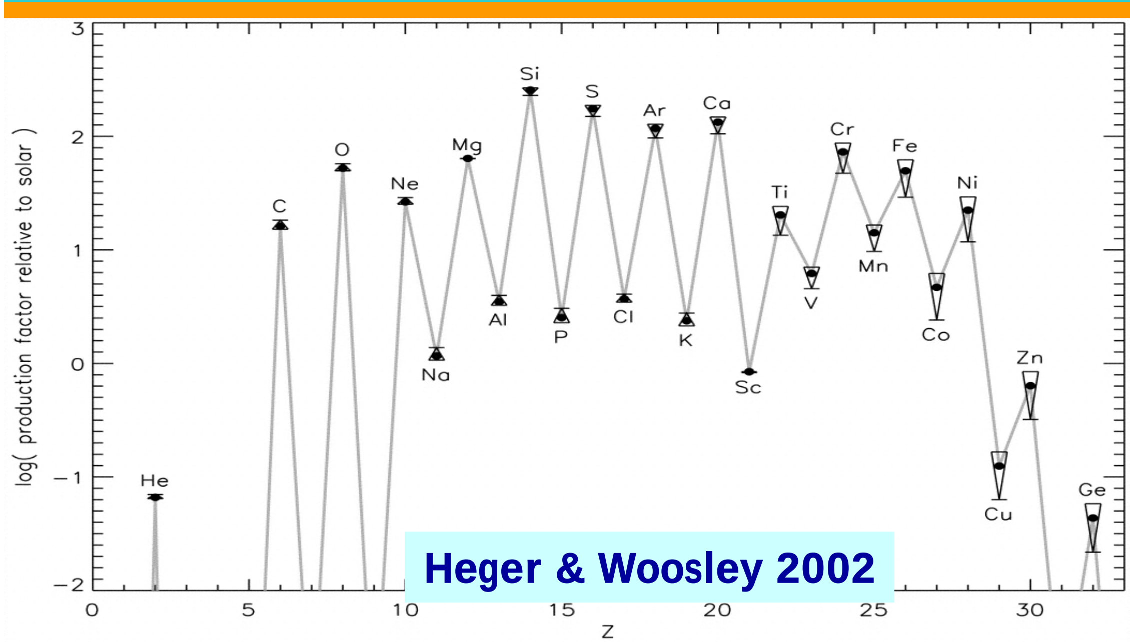
Painting by Adolf Schaller • STScI-PRC02-02

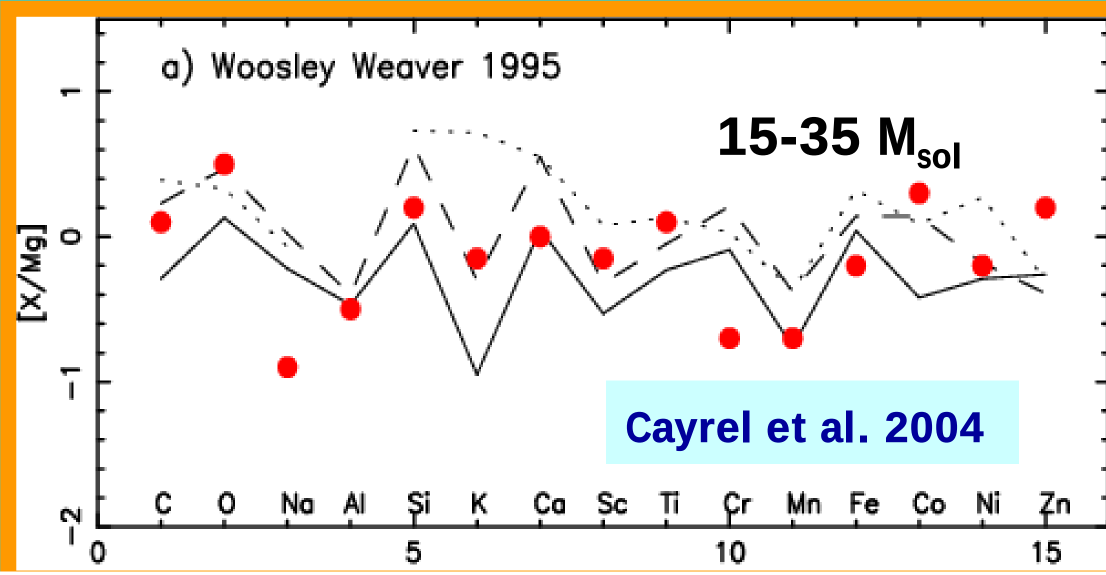
→5) Des abondances portant la signature de la fusion de l'H à haute température à la surface d'étoile de très petites masses non évoluées, dans les amas globulaires.



Graton et al 2004

→2) Aucune trace des supenovae par instabilité de paires

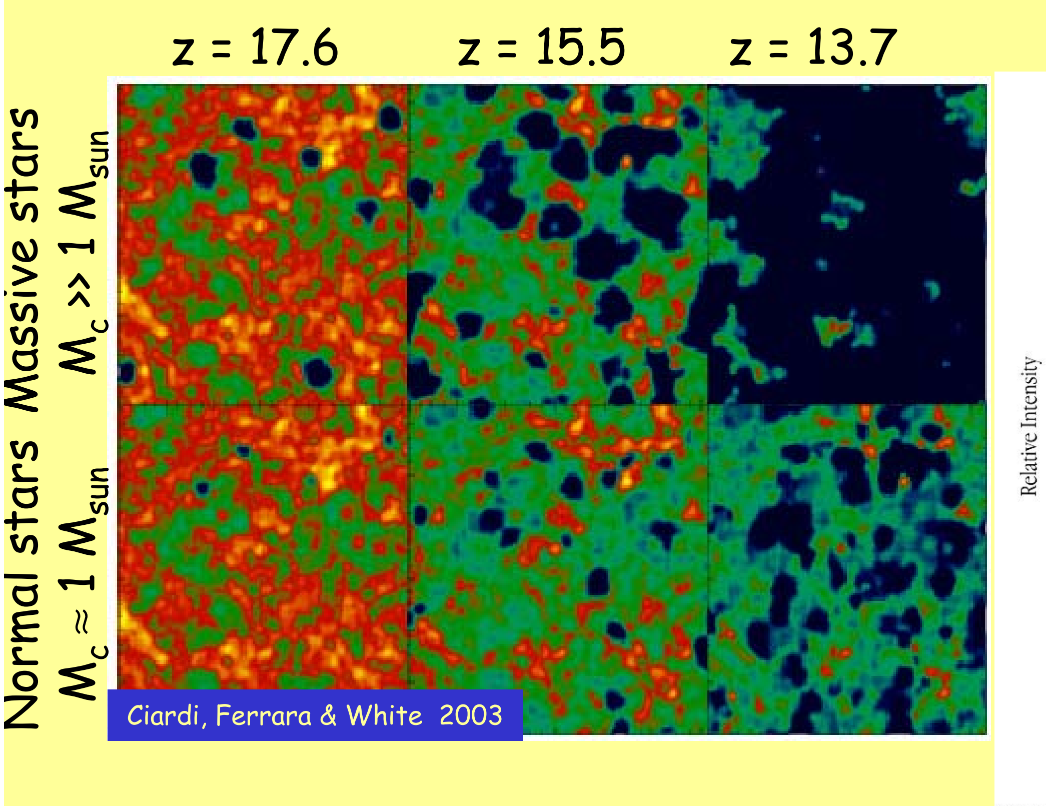





Le sel du ciel
Comme un parfum…
…Si peu de masse pour tant d'émotions
André Brahic parlant des anneaux des planètes

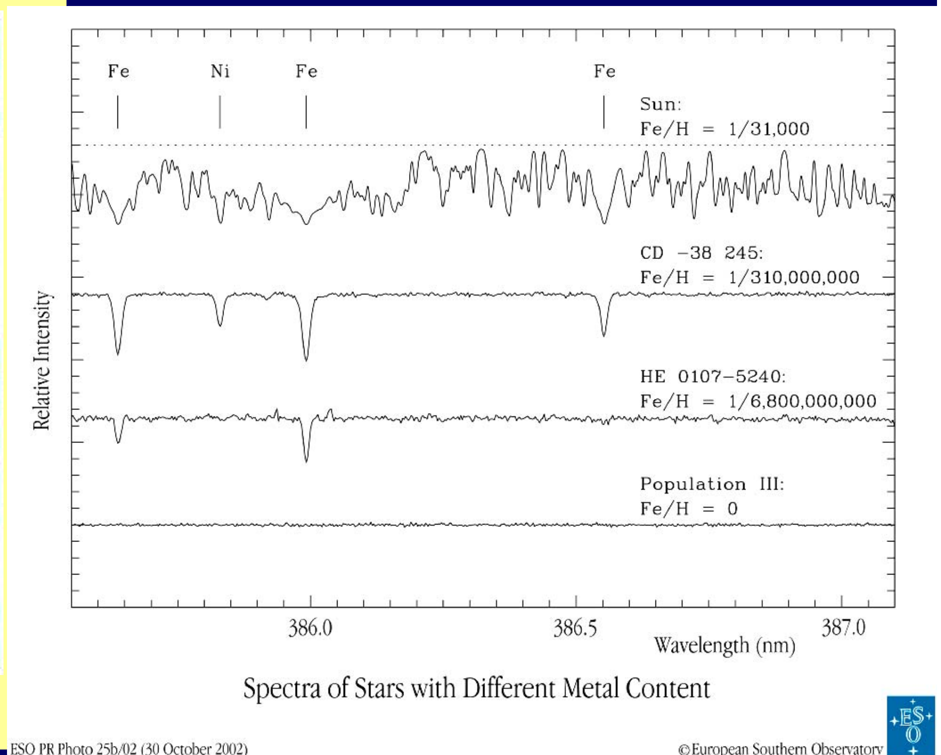
ETUDE DE L'UNIVERS PRECOCE

A haut redshift



Reionization à haut redshift

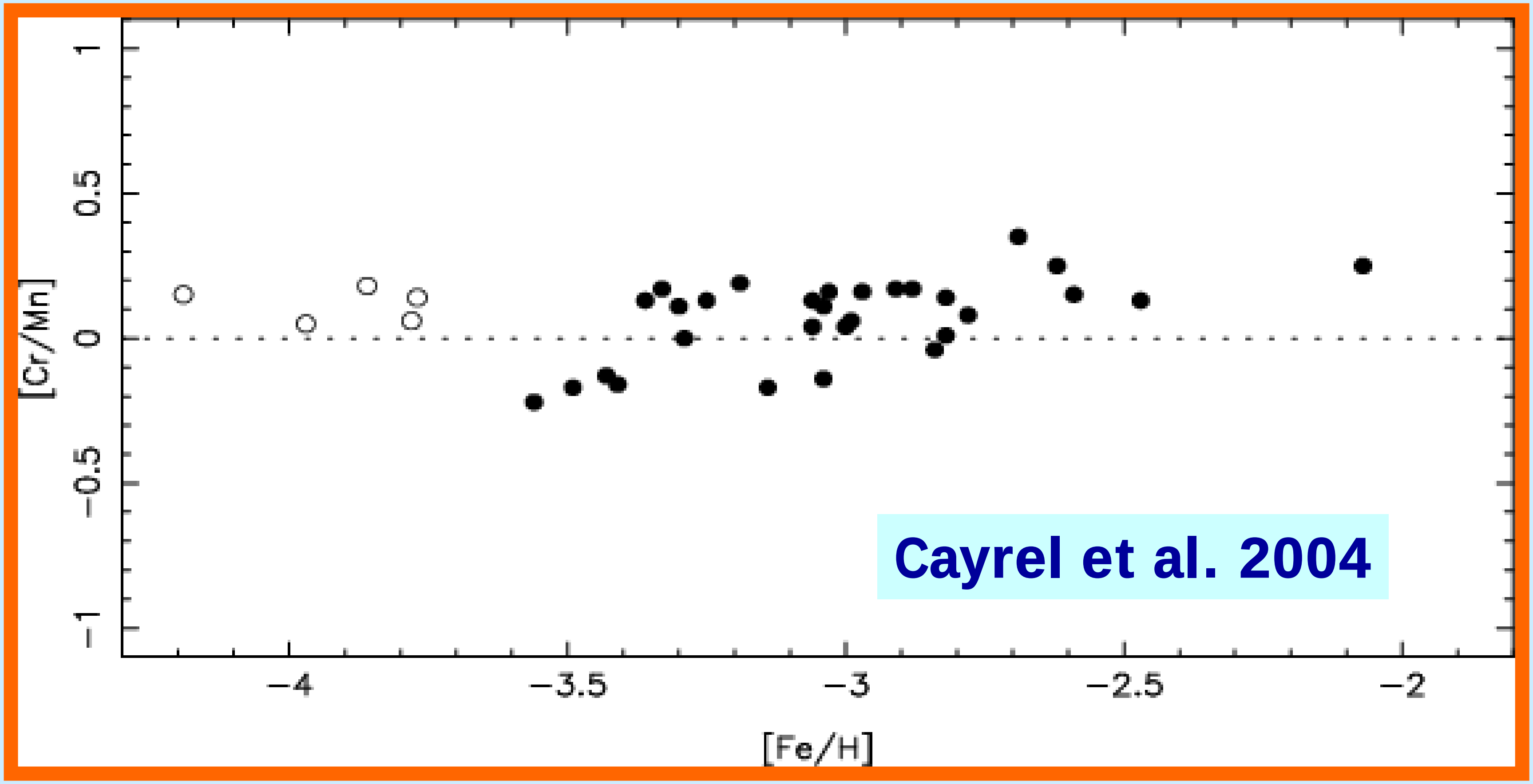
Dans l'Univers local



Abondances à la surface des étoiles du halo les plus déficientes en métaux

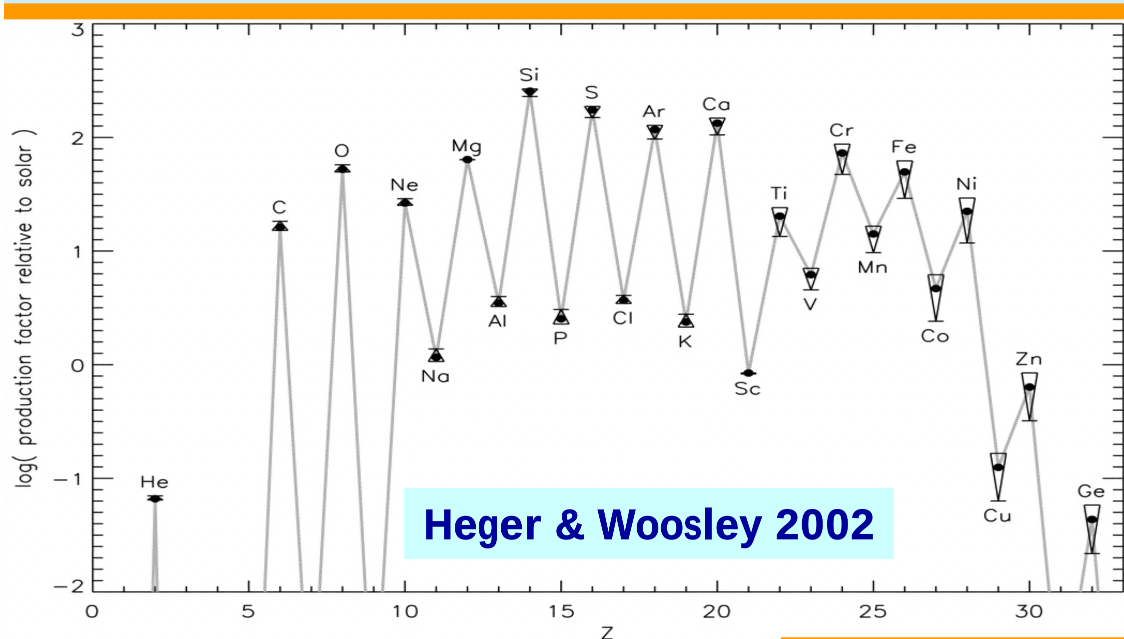
STRIKING OBSERVATIONAL FACTS

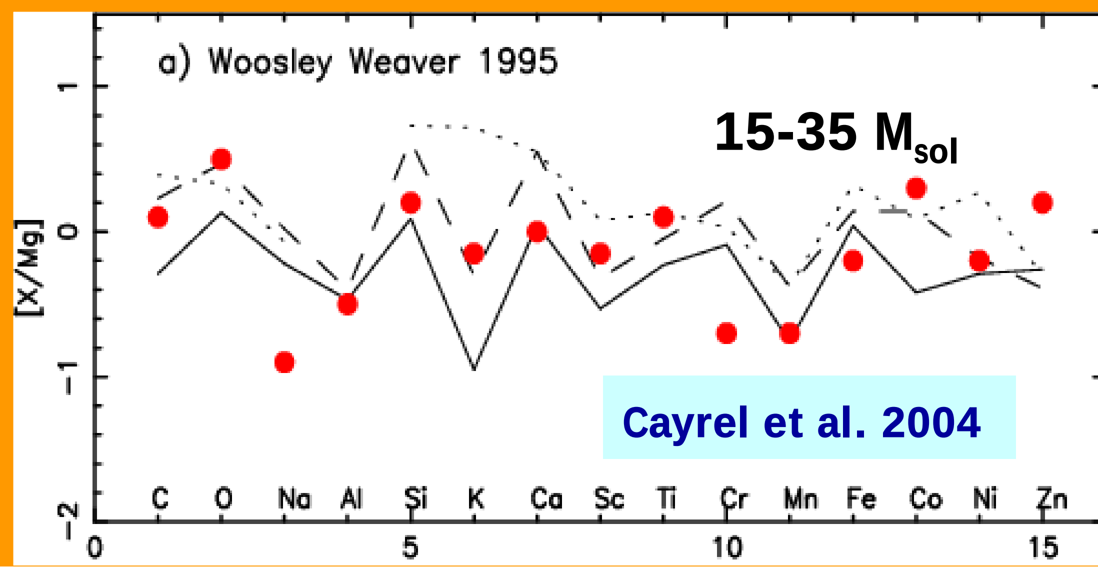
→ 1) **Very small scatter**



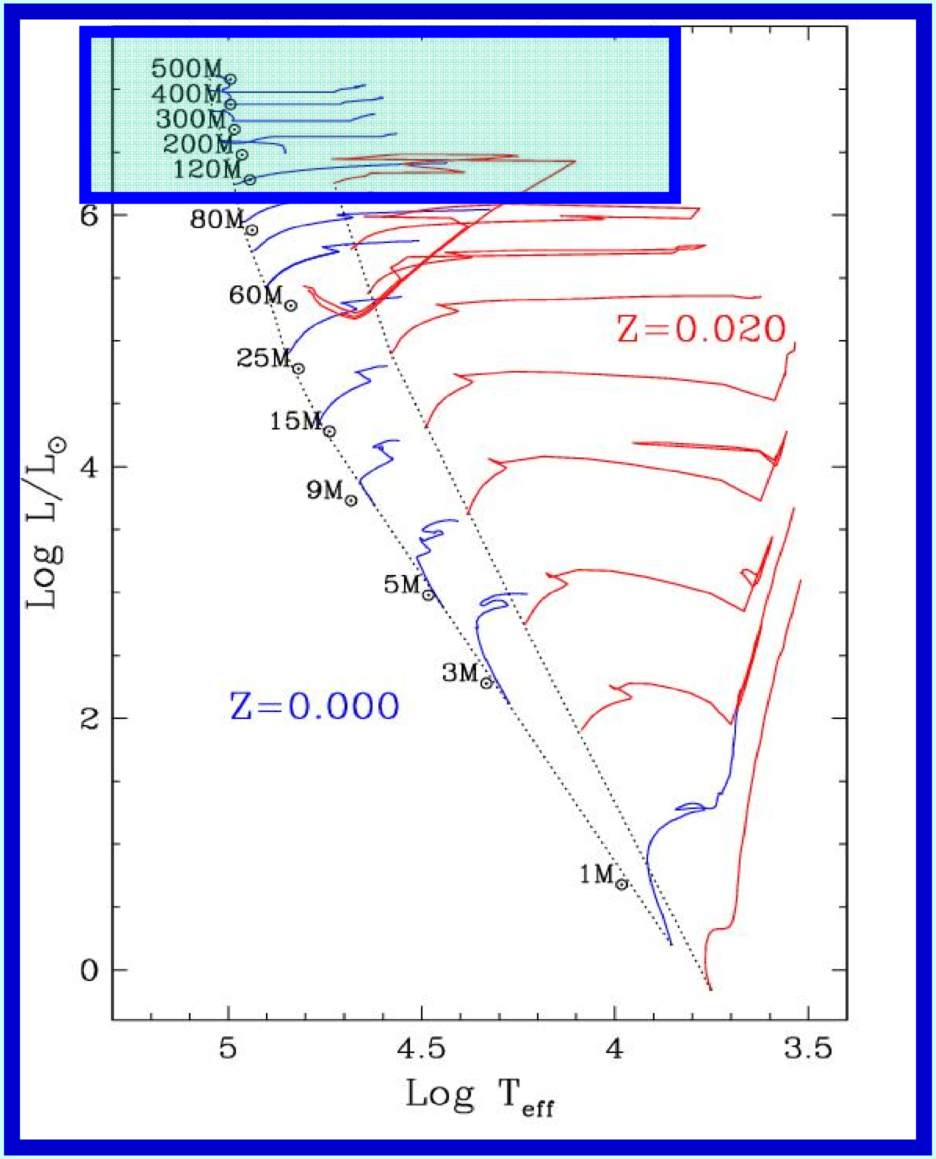
STRIKING OBSERVATIONAL FACTS

→2) No sign of Pair Instability Supernovae



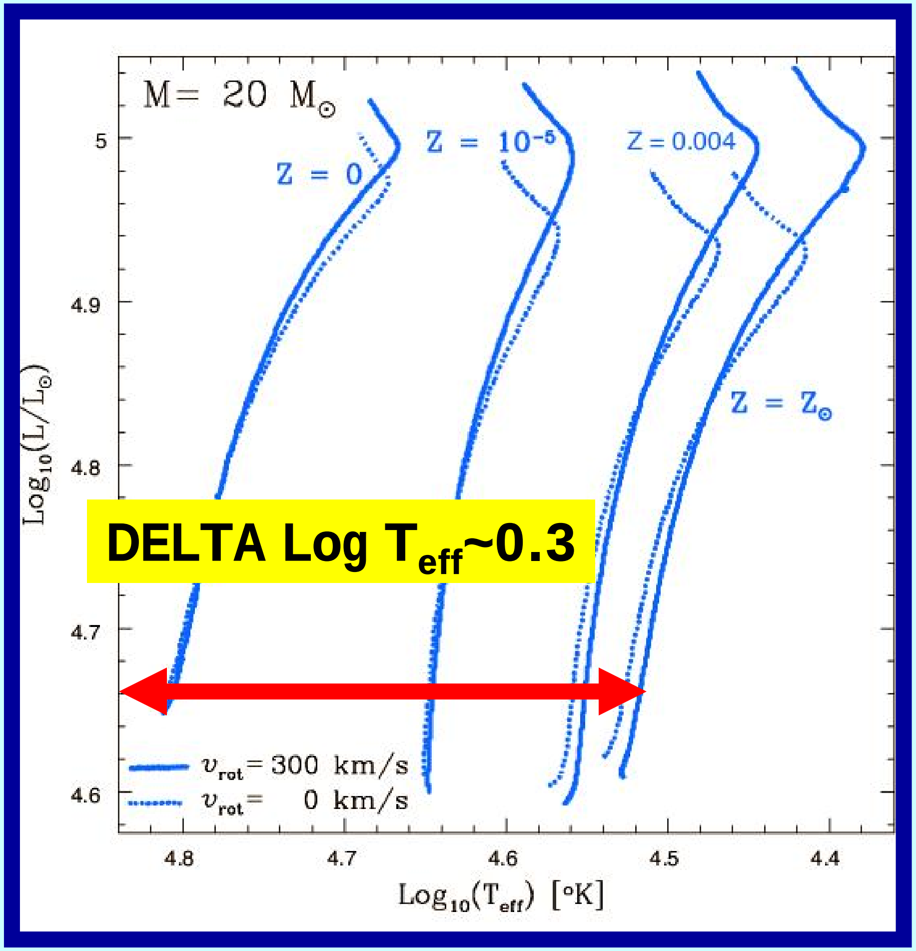


Z= 0



Feijoo 1999 diploma work

PopIII → Rayon/4



Ekström 2004 diploma work

QU'EST-CE QUI CHANGE A TRES FAIBLE Z POUR LES MODELES ENROTATION ?

Vitesses de circulation méridienne plus faibles

⇒ **MOMENT ANGULAIRE PLUS IMPORTANT DANS LE COEUR**

Gradient de Ω plus forts

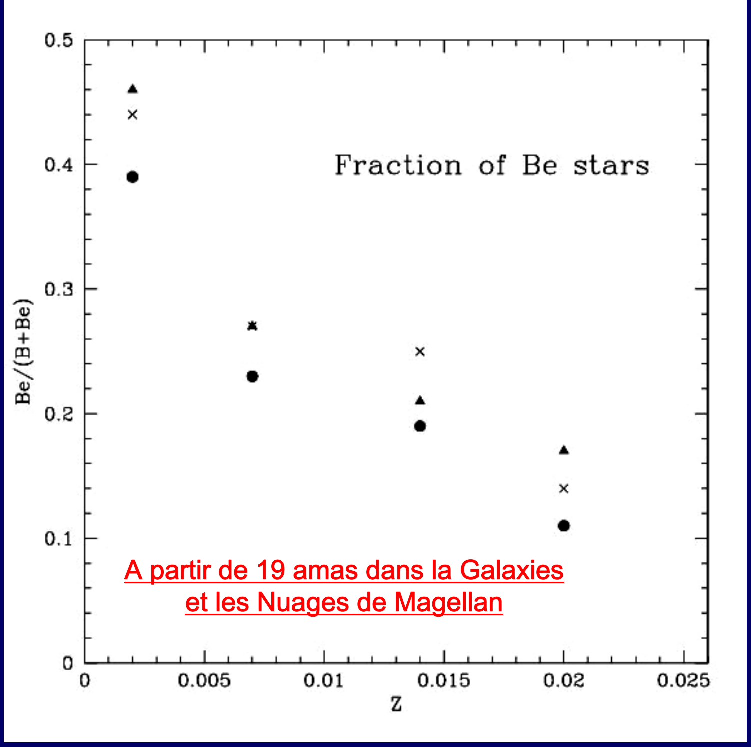
⇒ **MELANGE DES ELEMENTS CHIMIQUES PLUS EFFICACE**

Moins de moment angulaire enlevé en surface

⇒ **LIMITE DE LA RUPTURE ATTEINTE PLUS FACILEMENT**

LES VITESSES DE ROTATION INITIALES PLUS ELEVEES ?

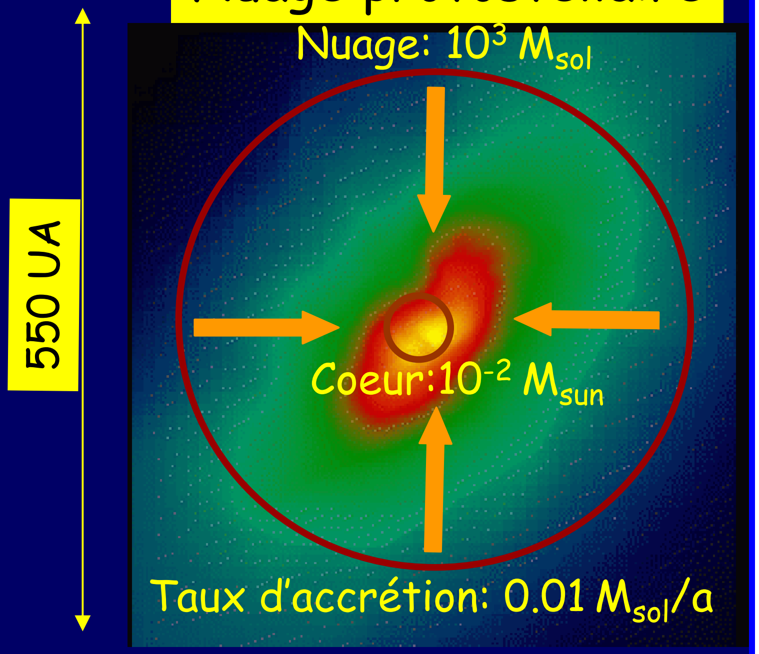
La proportion de rotateurs rapides semble croître



Maeder, Grebel, Mermilliod 1999

Evacuation du moment angulaire moins efficace à faible Z

Nuage protostellaire



Pour une 60 M_{sol}

A Z=0.020, Ω/Ω_{crit}=0.7 correspond à 400 km/s

A Z=0.0, Ω/Ω_{crit}=0.7 correspond à 800 km/s