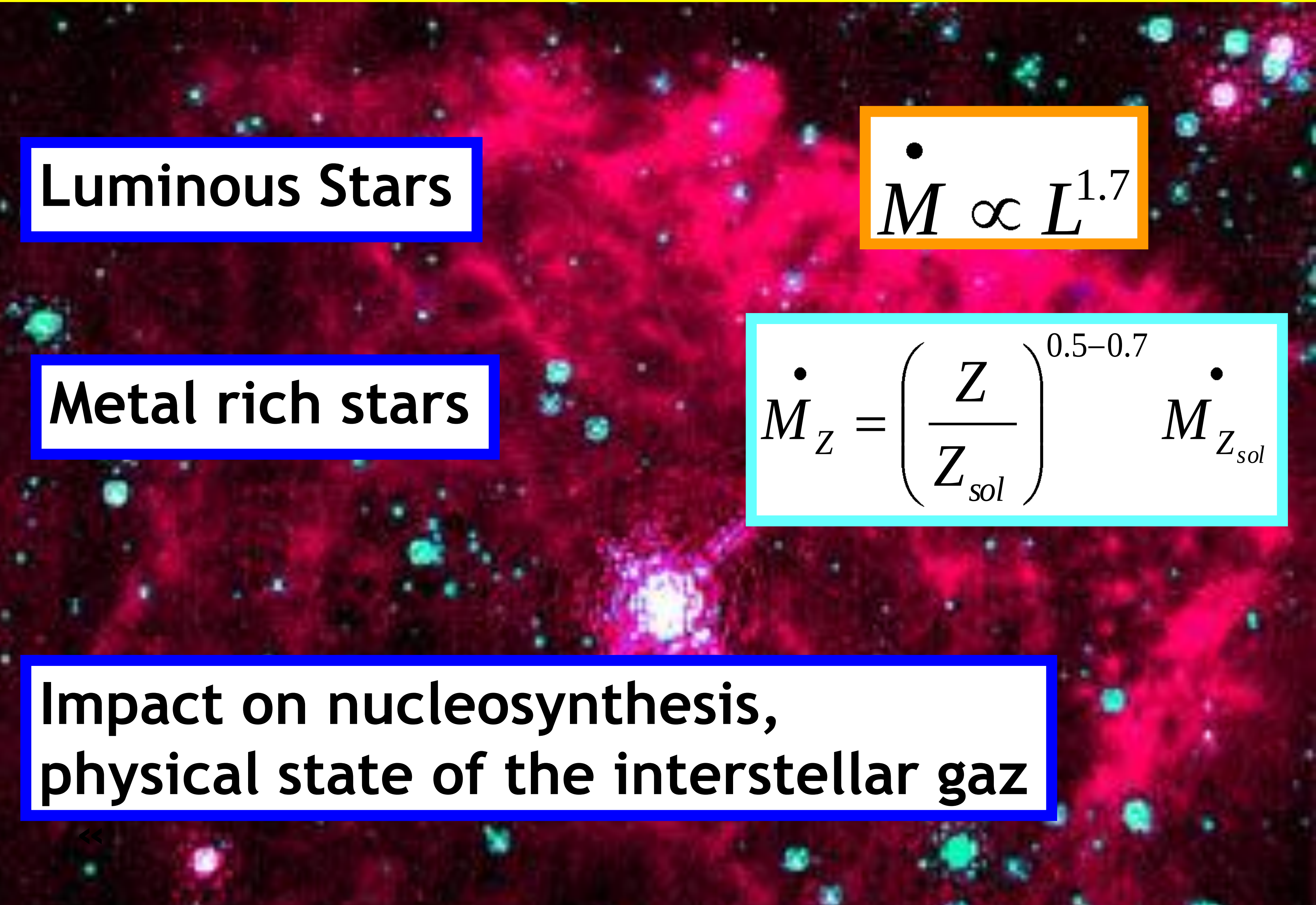
The metabolism of galaxies

From stars to the chemical evolution of galaxies

MASS LOSS BY LINE DRIVEN WINDS



Luminous Stars

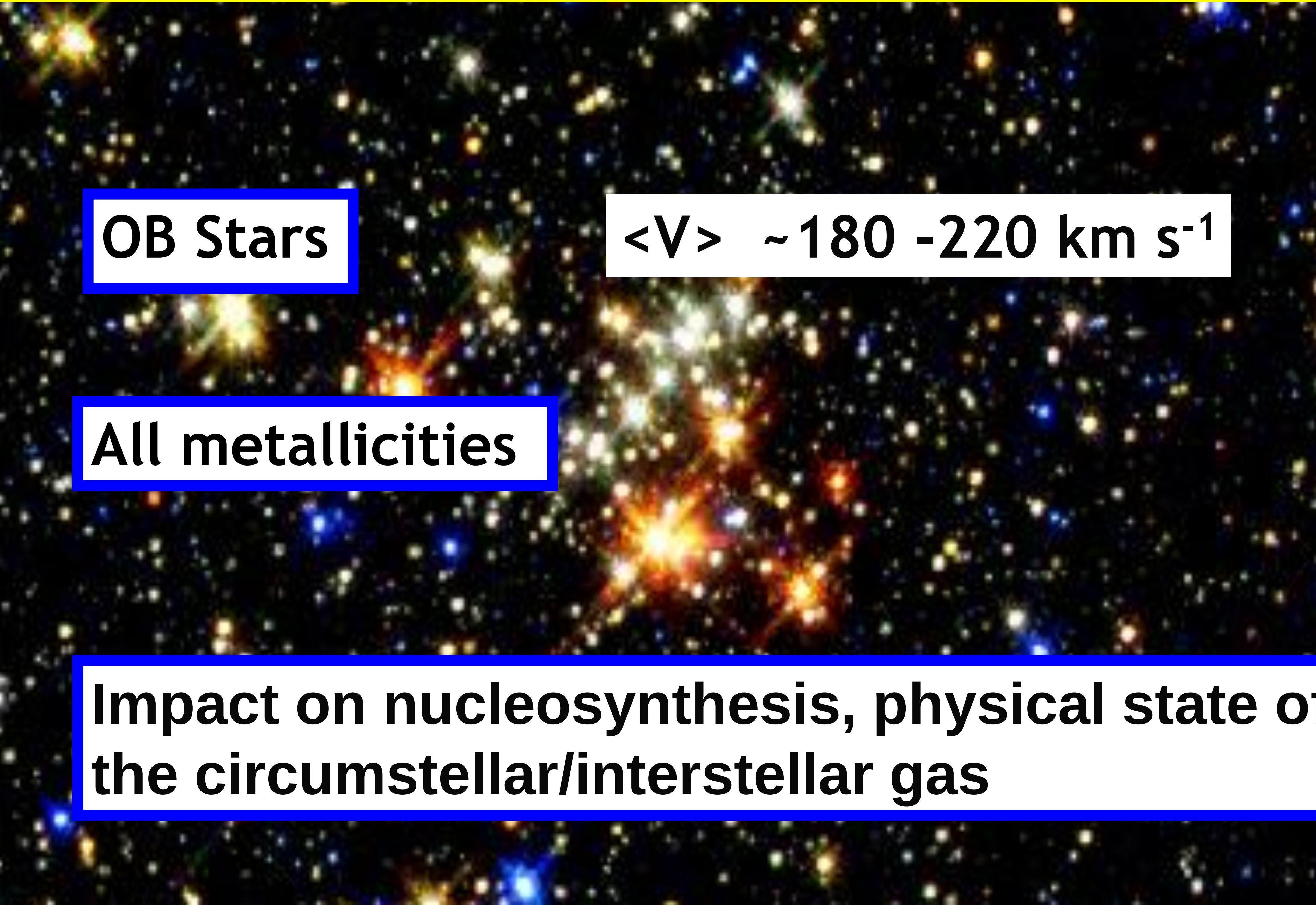
$$\dot{M} \propto L^{1.7}$$

Metal rich stars

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

Impact on nucleosynthesis,
physical state of the interstellar gaz

ROTATION



OB Stars

$\langle V \rangle$ ~180 -220 km s^{-1}

All metallicities

Impact on nucleosynthesis, physical state o the circumstellar/interstellar gas

METALLICITY AND CHEMICAL ENRICHMENTS BY MASSIVE STARS

METALLICITY CAN BE INVOLVED AT DIFFERENT LEVELS

INITIAL CONDITIONS

- Range of masses formed
- Distribution of masses (IMF)
- Initial rotation, fraction of binaries, magnetic fields…

Z-EFFECT ON EVOLUTION

- Mass loss
- Rotation

Consequences for nucleosynthesis

- Effects of Mass Loss

→ At solar and higher than solar metallicities

MASSIVE STAR EVOLUTION IS DIFFERENT AT HIGH METALLICITY

MAINLY BECAUSE THE METALLICITY DEPENDENCE OF MASS LOSS

→ Massive stars populations

Wolf-Rayet stars

The ratio of blue to red supergiant

Be stars (fast rotating stars near break-up limit)

Supernovae types

Long GRB progenitors

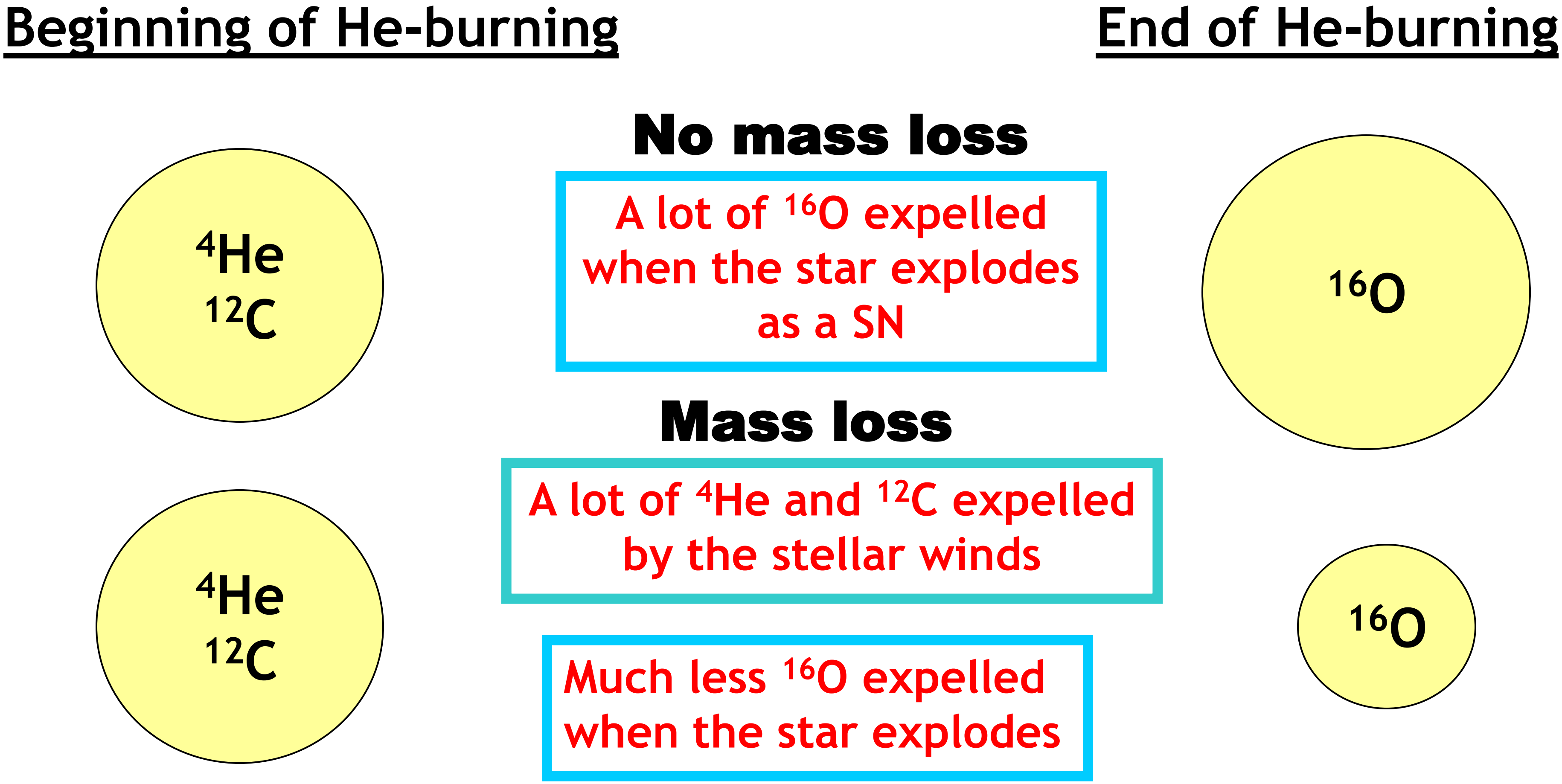
Nature of the remnant

→ Chemical enrichment ^{4}He, ^{12}C, (^{16}O) , ^{19}F,^{22}Ne, ^{26}Al, weak s-process

Other effects→ Initial rotation, fraction of binaries, magnetic fields…

Mass loss, by removing matter at an early stage of the evolution of the star, may save from further destruction some elements

One example



Beginning of He-burning

End of He-burning

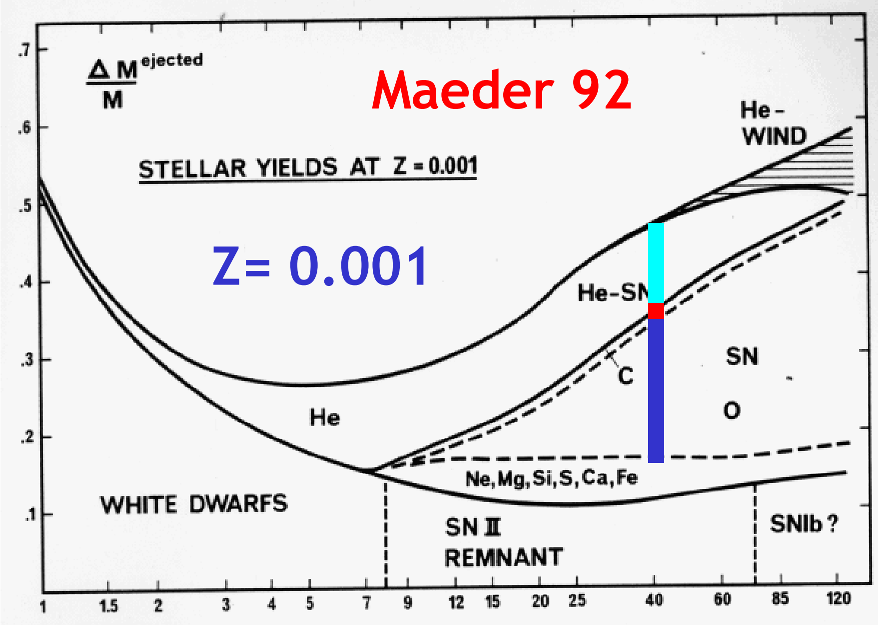
No mass loss

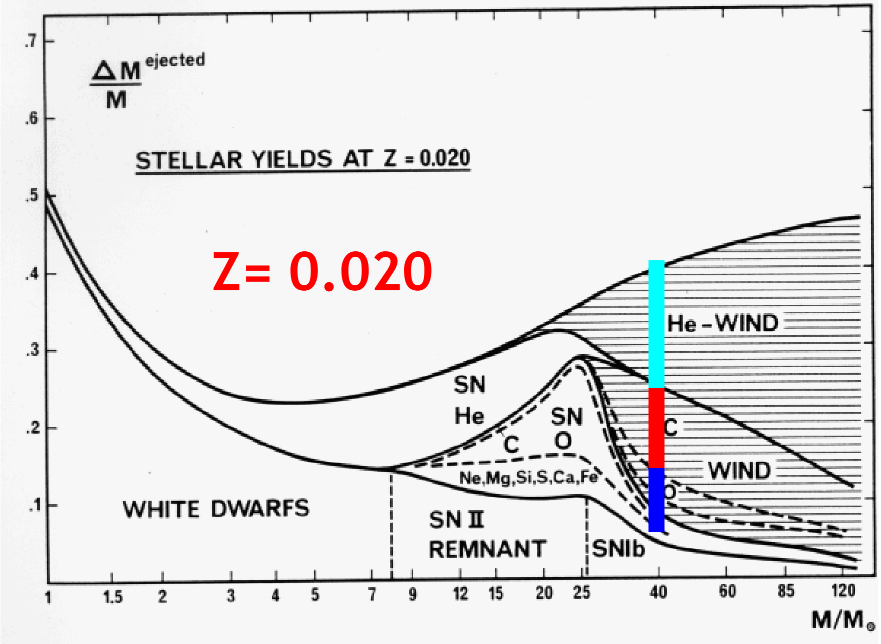
A lot of ^{16}O expelled when the star explodes as a SN

Mass loss

A lot of ^{4}He and ^{12}C expelled by the stellar winds

Much less ^{16}O expelled when the star explodes





Weak winds (low Z)

Ejecta rich in ^{16}O

40Msol, Z=0.001

^{4}He	^{12}C	^{16}O	Z
4.24	**0.55**	**6.80**	9.71

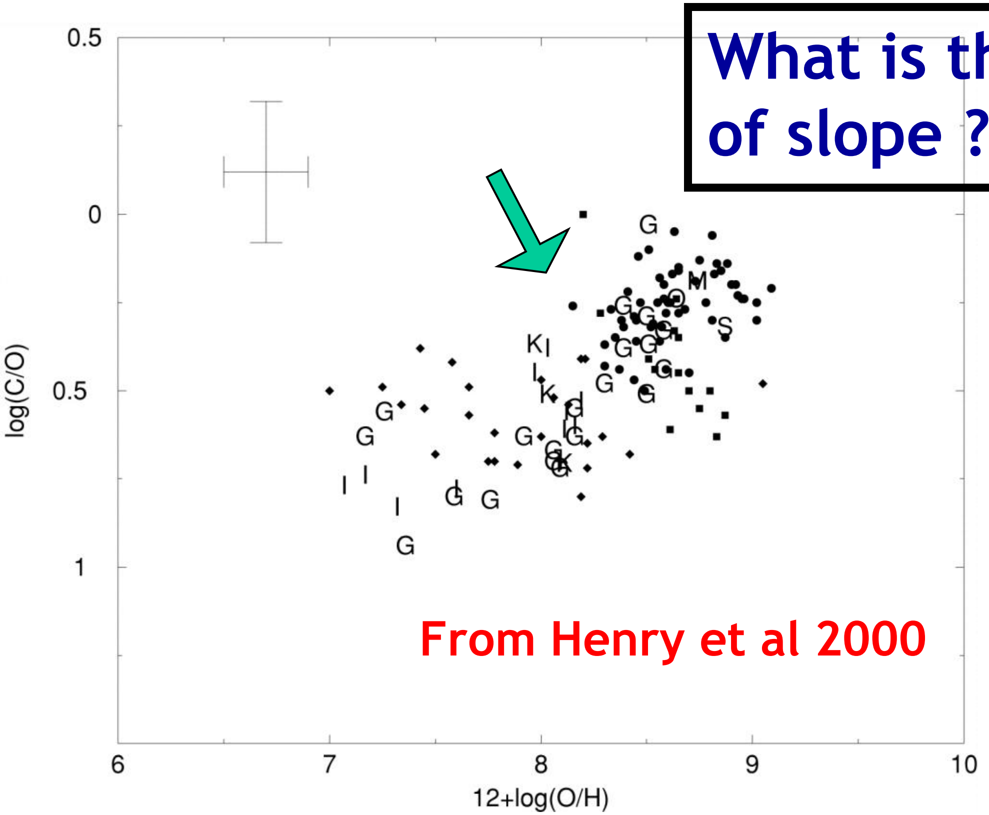
Strong winds (high Z)

Ejecta rich in ^{4}He and ^{12}C

40Msol, Z=0.020

^{4}He	^{12}C	^{16}O	Z
6.10	**4.88**	**2.08**	8.01

Log (C/O) vs 12+Log(O/H) for extragalactic HII regions and stars



From Henry et al 2000

What is the cause of the change of slope ?

- **Intermediate mass stars**
- **High metallicity Massive stars**

HII regions from Garnett et al. 95, 97, 99
Izotov and Thuan 99
Kobulnicky and Skillman 88
Stellar data from Gustafsson et al 99
Gummersbach et al. 98
Tomkin et al 92

EMPRICAL YIELDS

OBSERVED FEATURES

Number of WC stars → 44 (R < 3 kpc) van der Hucht (01)

Mass loss rate of WC stars → $10^{-4.8}$ M_{sol}/y Hamann & Gräfener (06) Crowther et al (02)

Mass fraction of ^{12}C in wind → 0.35 Crowther et al. (95; 02) Herald et al. (01)

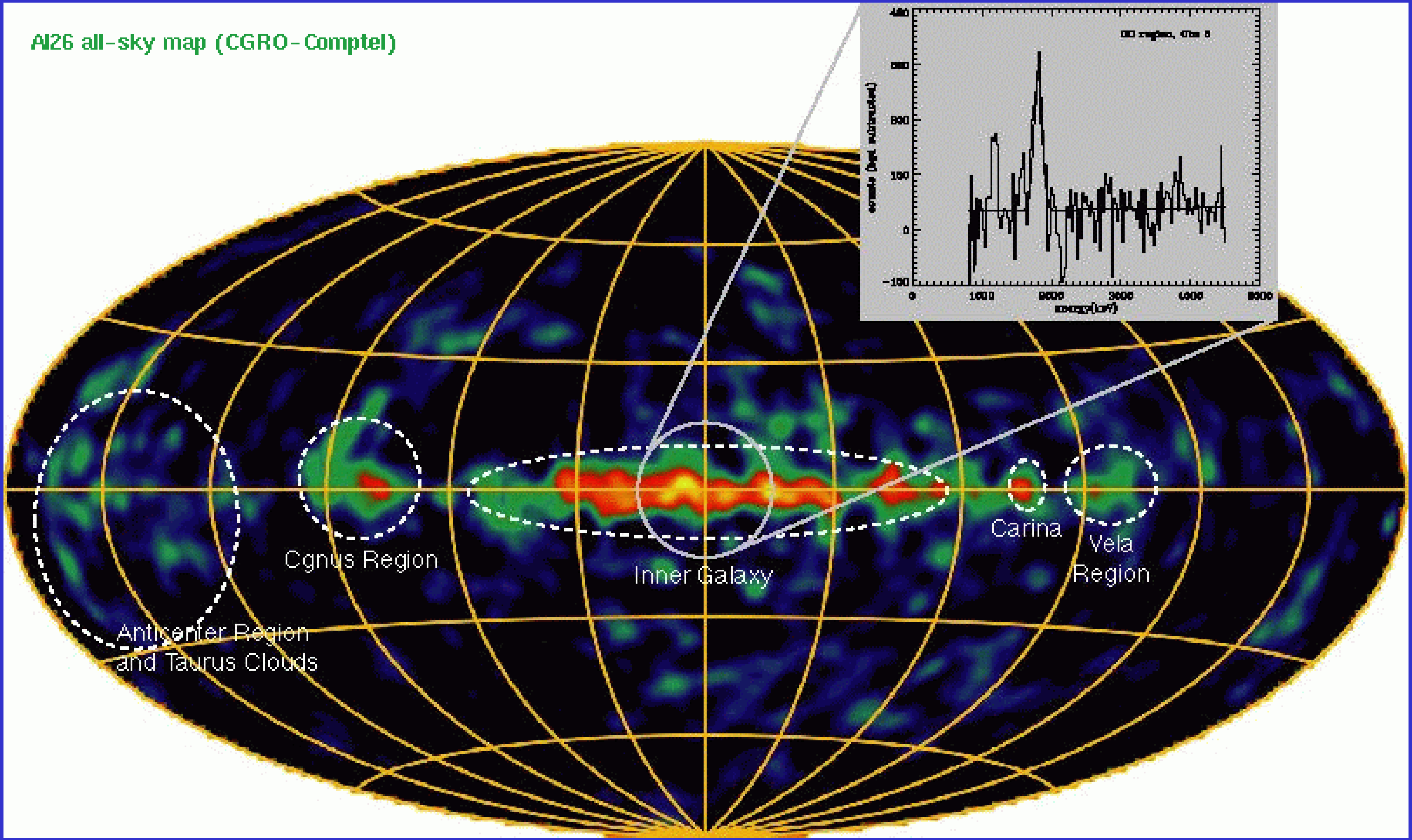
Star Formation rate → 2-4 $M_{sol}/(pc^2$ Gy)

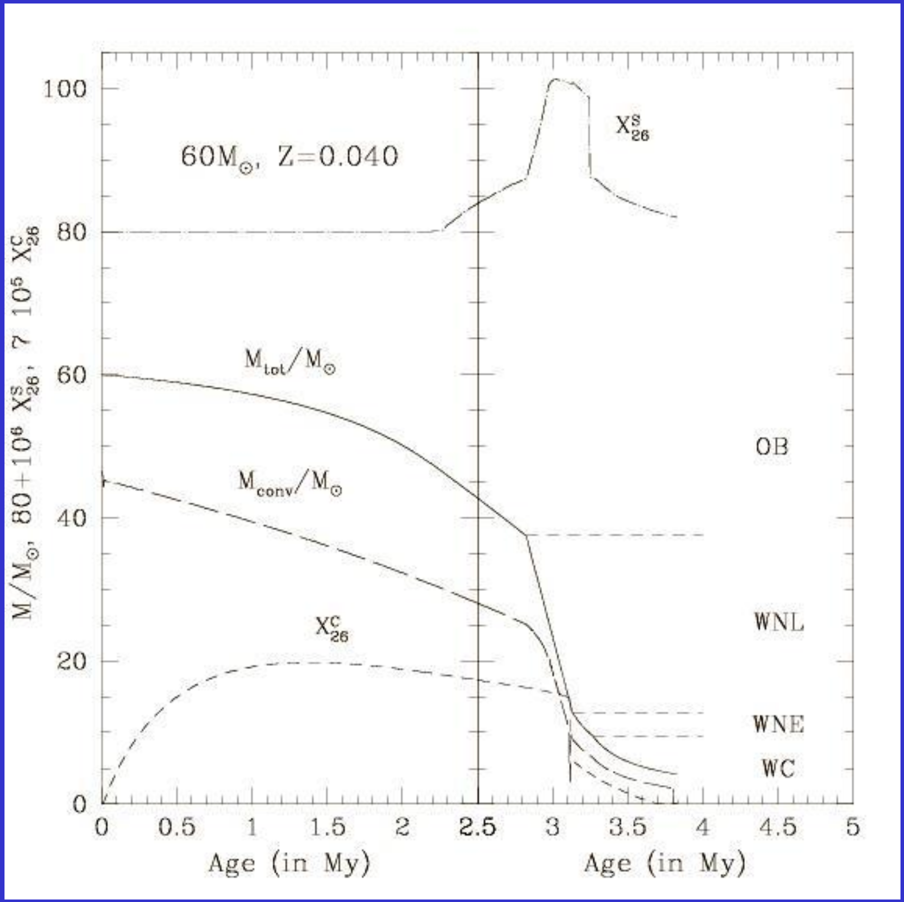
(Mass of ^{12}C ejected by WC winds)/(Mass of stars) ~0.25-0.5 %

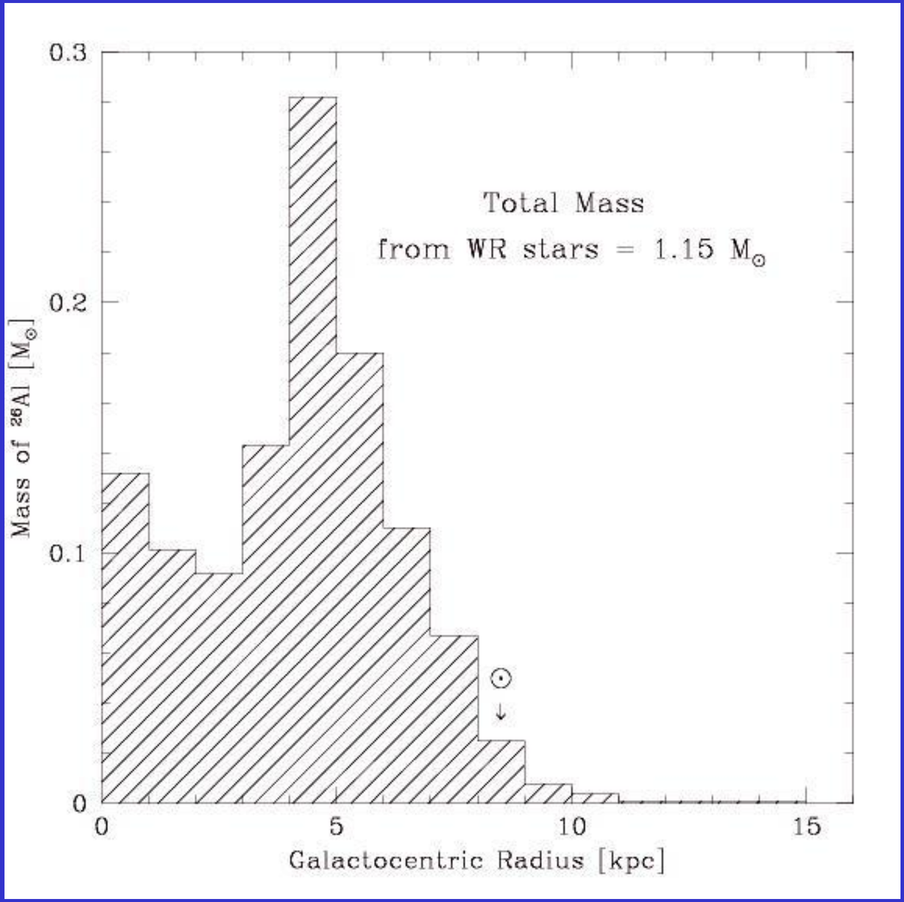
MODELS → ~0.2% - 0.6%

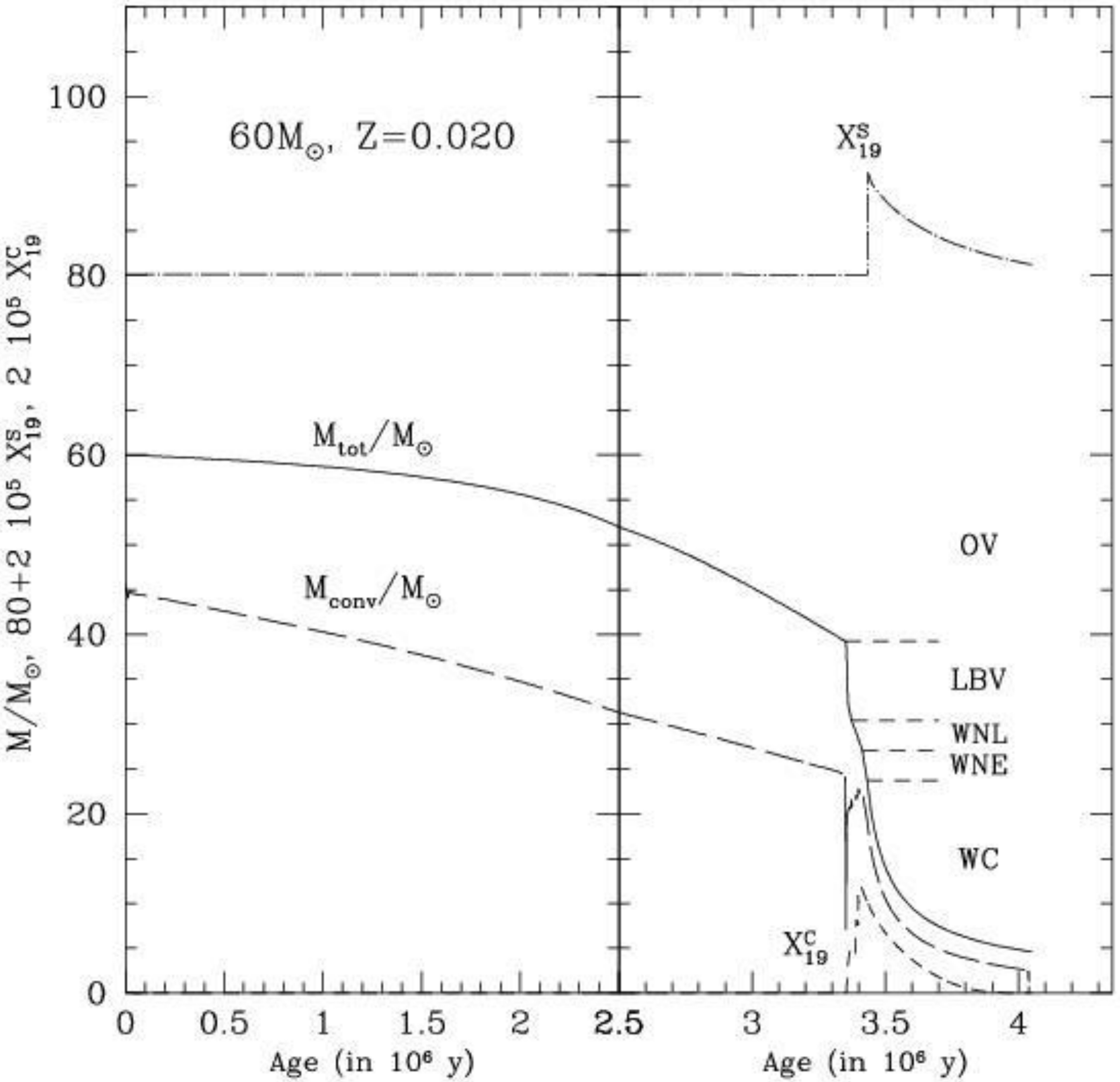
Hirschi et al. (2005)
Maeder (1992)

WIND MASSIVE STAR CONTRIBUTIONS CANNOT BE NEGLECTED


Al26 all-sky map (CGRO-Comptel)


60M⊙, Z=0.040
X^S_26
M_tot/M⊙
M_conv/M⊙
X^C_26
OB
WNL
WNE
WC
M/M⊙, 80+10^6 X^S_26, 7 10^5 X^C_26
0
20
40
60
80
100
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Age (in My)
Age (in My)


Total Mass
from WR stars = 1.15 M⊙
Mass of 26Al [M⊙]
Galactocentric Radius [kpc]
0
0.1
0.2
0.3
0
5
10
15
⊙
↓



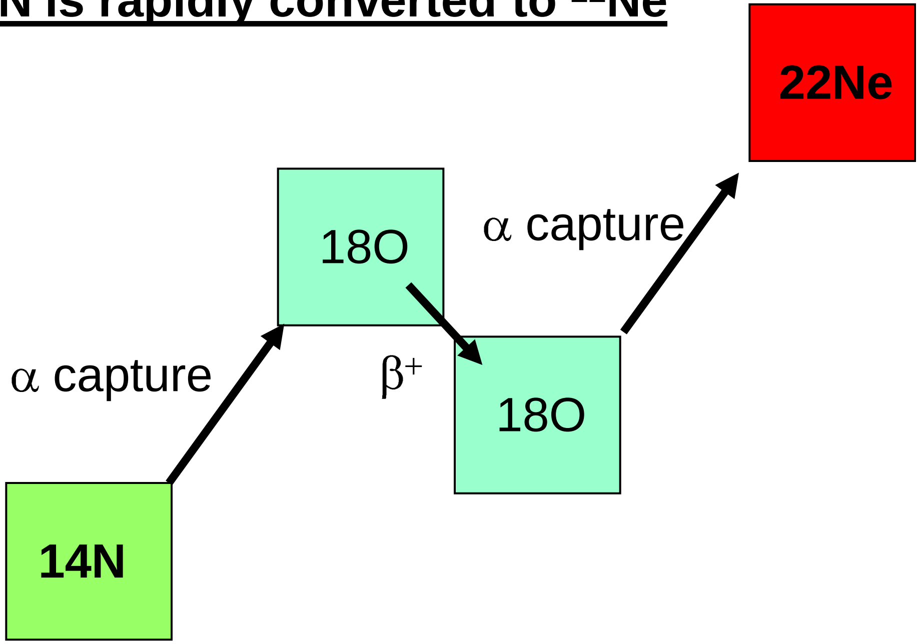
60M$_\odot$, Z=0.020
X_{19}^{S}
$M_{tot}/M_\odot$
$M_{conv}/M_\odot$
OV
LBV
WNL
WNE
WC
X_{19}^{C}
$M/M_\odot$, 80+2 10^5 X_{19}^{S}, 2 10^5 X_{19}^{C}
0
20
40
60
80
100
0
0.5
1
1.5
2
2.5
3
3.5
4
Age (in 10^6 y)
Age (in 10^6 y)

The weak s-process

Site: Core He burning (and shell C-burning) in massive stars (e.g. 25 solar masses)

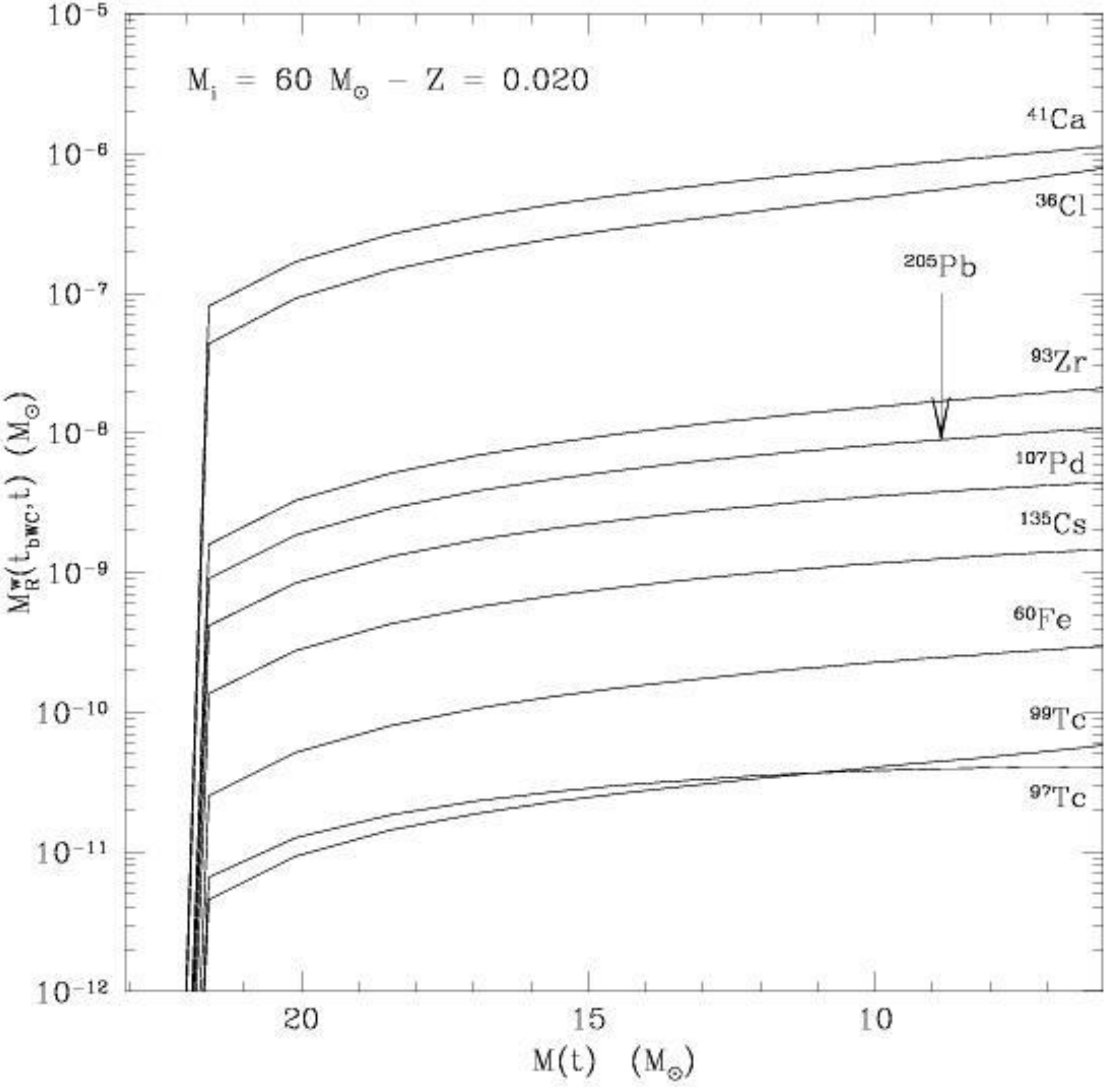
He burning core contains initially ^{14}N

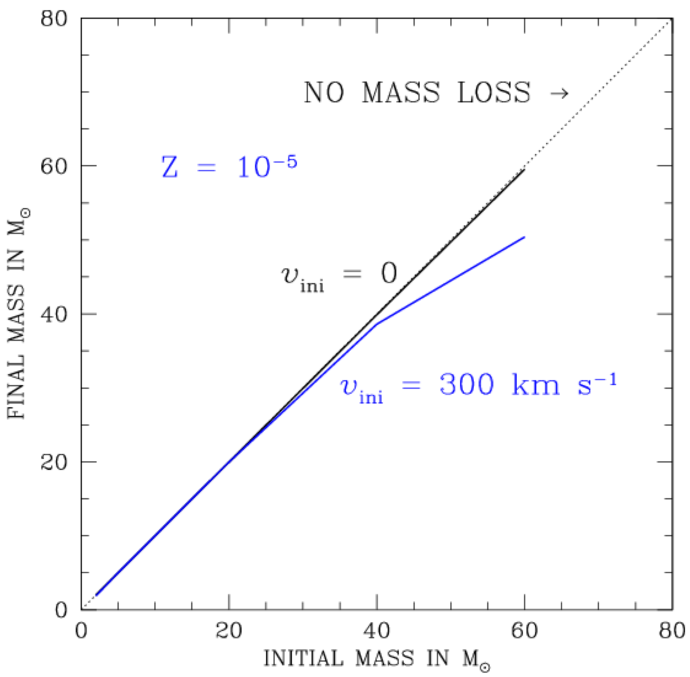
^{14}N is rapidly converted to ^{22}Ne

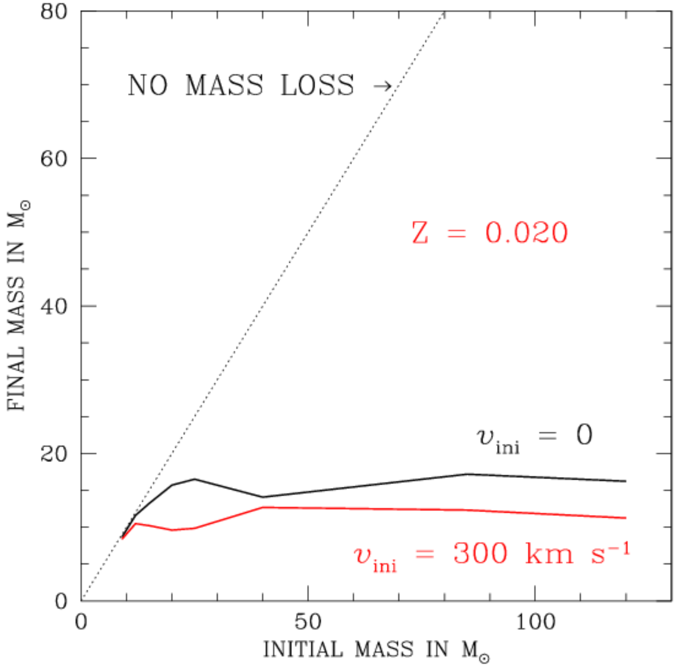


Towards the end of He burning T~3e8 K: **$^{22}Ne(\alpha,n)$** provides a neutron source

→ preexisting Fe (and other nuclei) serve as seed for a (secondary) s-process


$M_i = 60\ M_\odot - Z = 0.020$
^{41}Ca
^{36}Cl
^{205}Pb
^{93}Zr
^{107}Pd
^{135}Cs
^{60}Fe
^{99}Tc
^{97}Tc
$M_R^w(t_{bWC},t)$ $(M_\odot)$
$M(t)$ $(M_\odot)$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
20
15
10



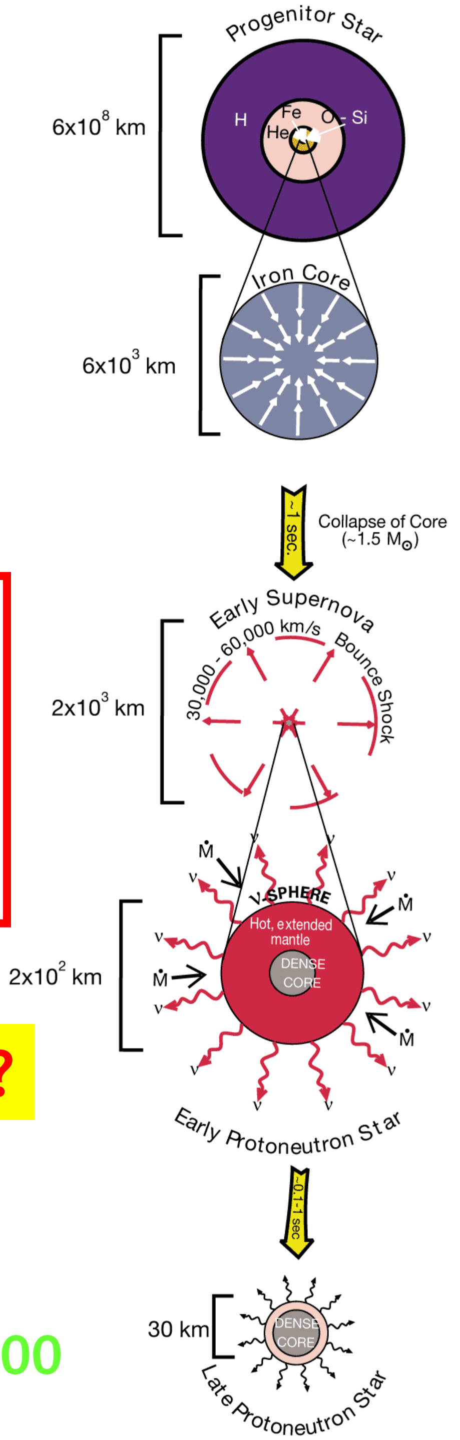


Black Hole formation favoured at low Z

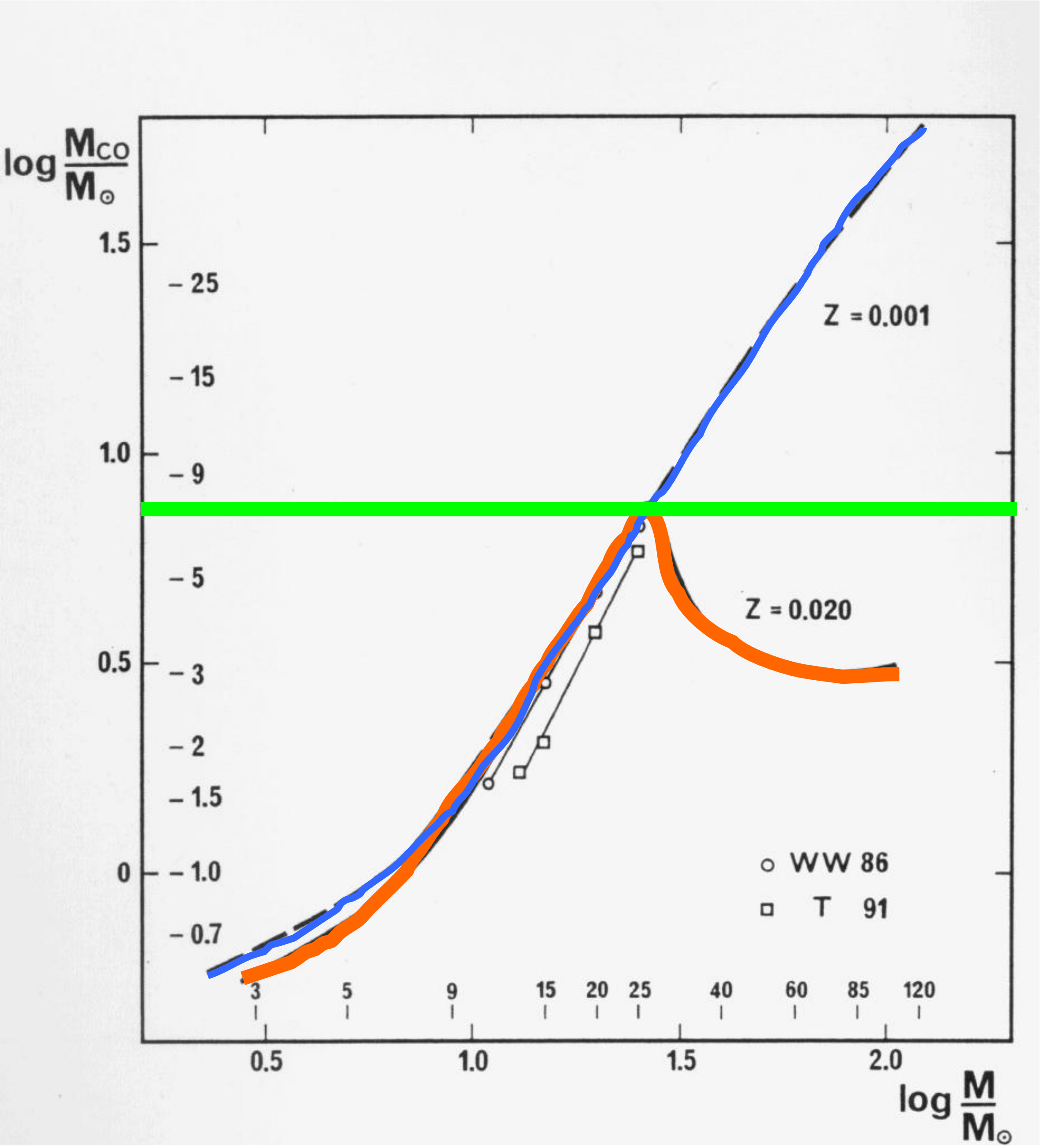
Less Type Ib/Ic SNe

When a BH forms
Is the whole progenitor
Envelope swallowed by
The BH ?
Cf Burrows 92

What happens if yes ?



Burrows 2000



All stars with M_{co} > 8 M_{sol}
Become BH

Z = 0.001
M_{BH} ~27.5 M_{sol}

Z = 0.020
No BH
No change

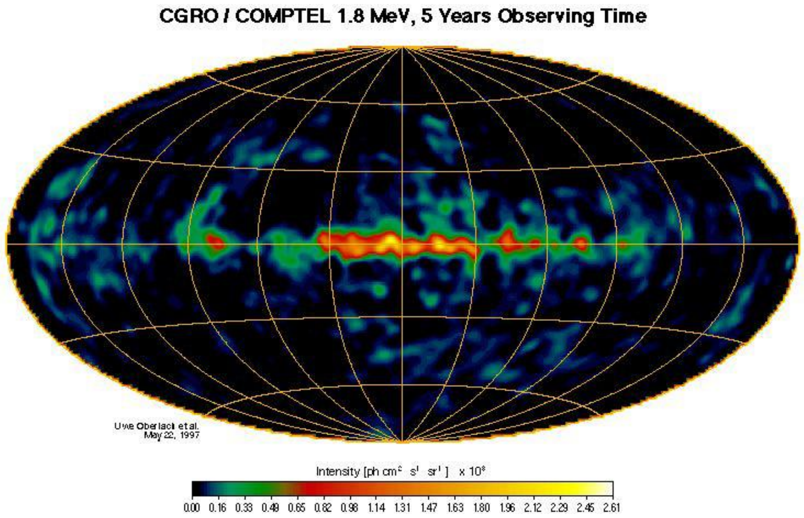
Net yields of an element Xi: ratio of the mass that a generation of stars ejects as a newly formed element Xi with respect to the mass of the same generation that remains locked into stellar remants, long-lived stars, objects that do not become stars.

	He	C	O	Z	$\Delta Y / \Delta Z$
Z=0.001 $M_{BH}=27.5M_{sol}$	0.044	0.001 $\Delta Y / \Delta Z$	0.004	0.010	4.4
Z=0.020 $M_{BH}=120M_{sol}$	0.053	0.002	0.019	0.030	1.8

A great part of the heavy elements remains locked in the BH if $M_{BH}=27.5\ M_{sol}$

Strong impact on $\Delta Y / \Delta Z$

ELEMENTS WITH WIND CONTRIBUTION



Uwe Oberlack et al.
May 22, 1997

H-burning products → ^{26}Al

Palacios et al. (2005)
Chieffi & Limongi (2005)

He-burning products → ^{4}He, ^{12}C

Maeder (1992)

→ ^{19}F

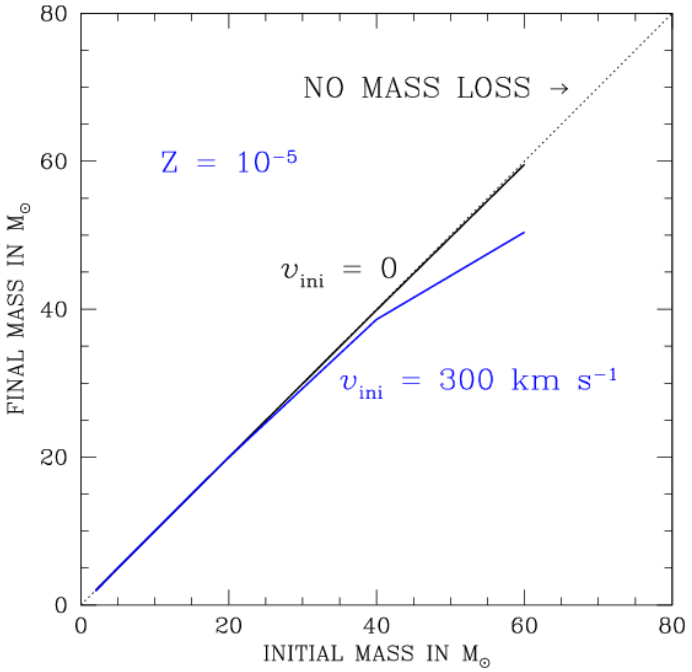
Meynet & Arnould (1999),
Palacios et al. (2005),

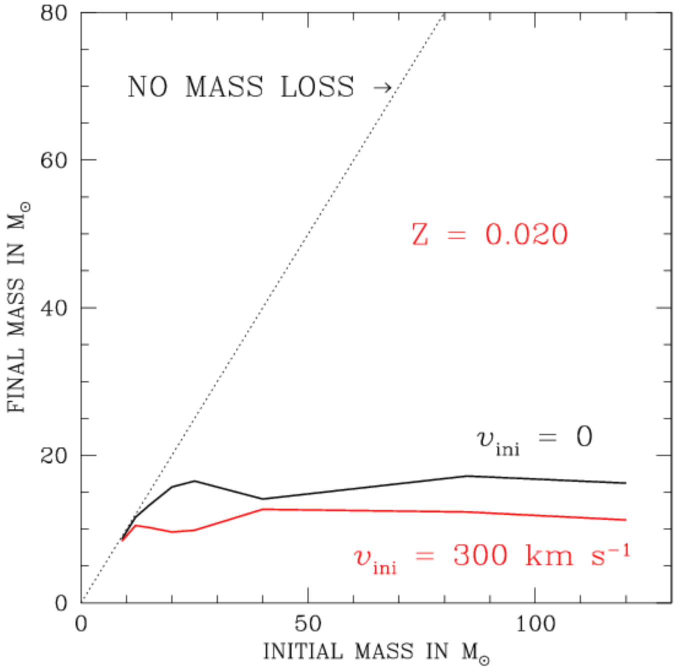
→^{22}Ne

Cassé & Paul (1981)
Binns et al. (2005)

→Weak s-process components (A < 100)

Arnould et al (1997; 2005)





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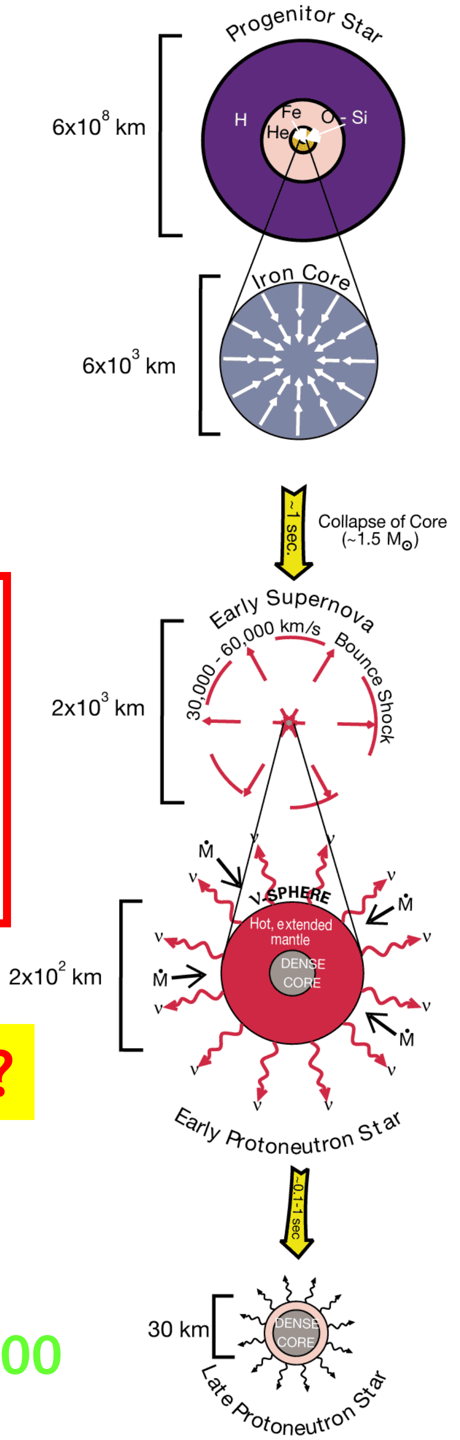
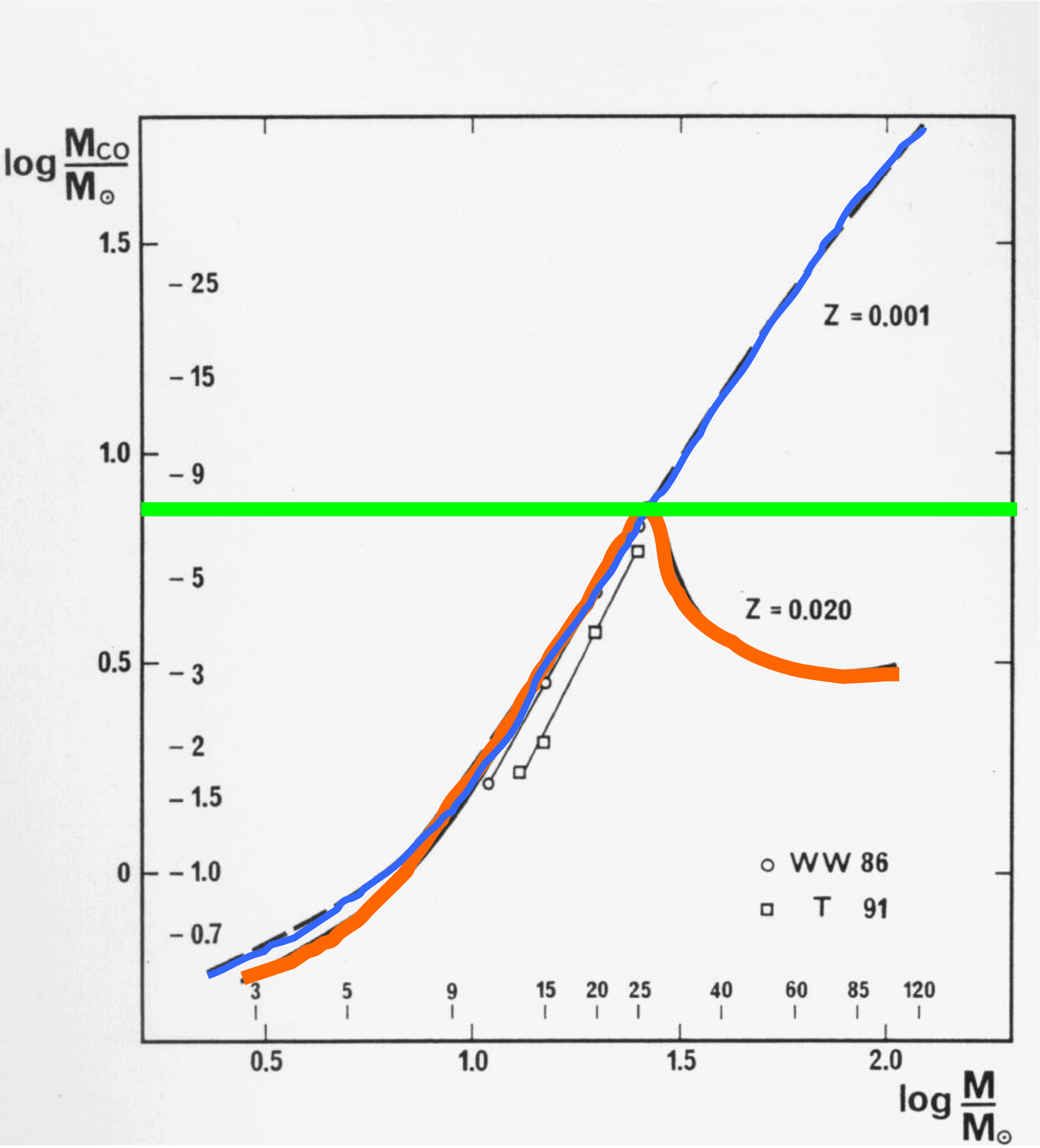


Burrows 2000



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$M_{BH} \sim 27.5\ M_{sol}$

$Z = 0.020$

No BH

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Strong impact on $\Delta Y / \Delta Z$

Consequences for nucleosynthesis

- Rotation

→ Very metal poor stars

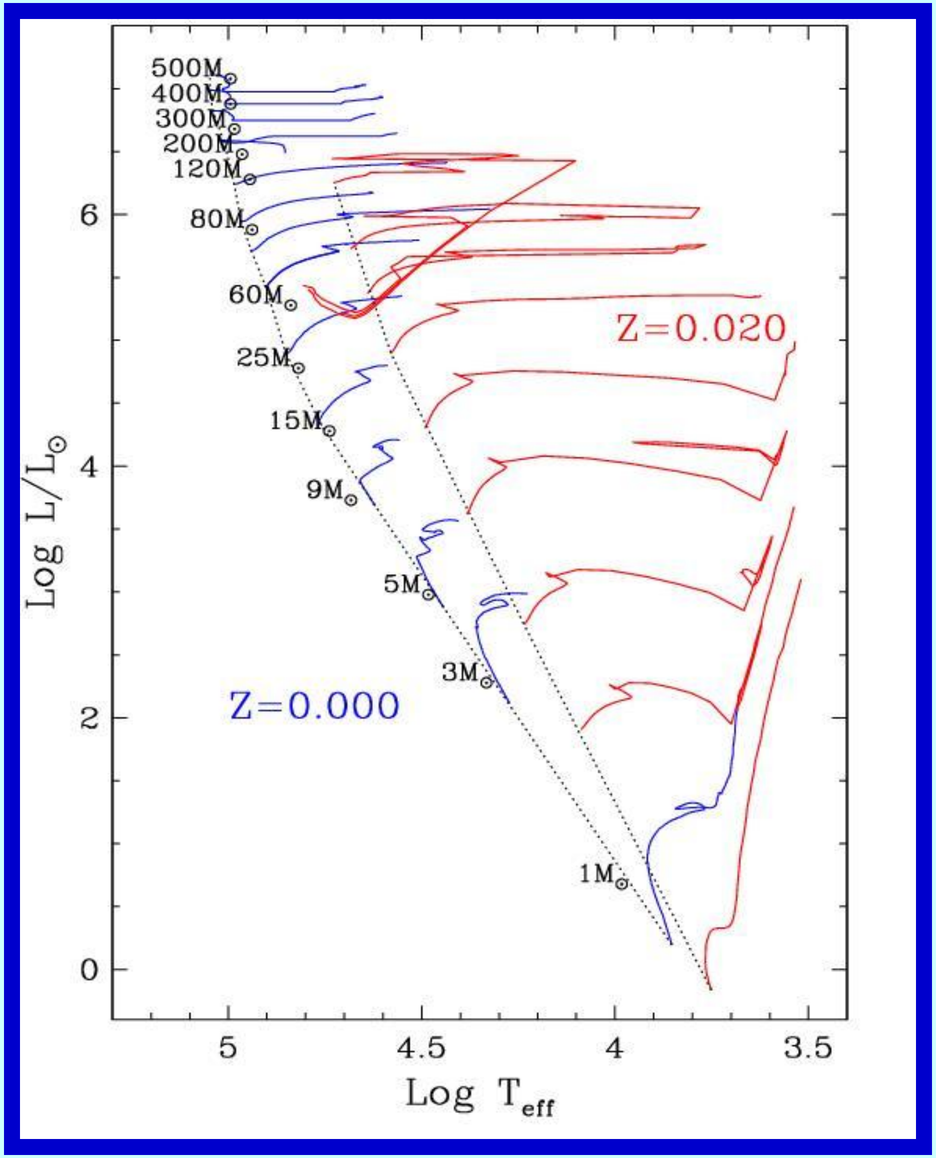
WHAT CHANGES AT VERY LOW Z FOR ROTATING MODELS ?

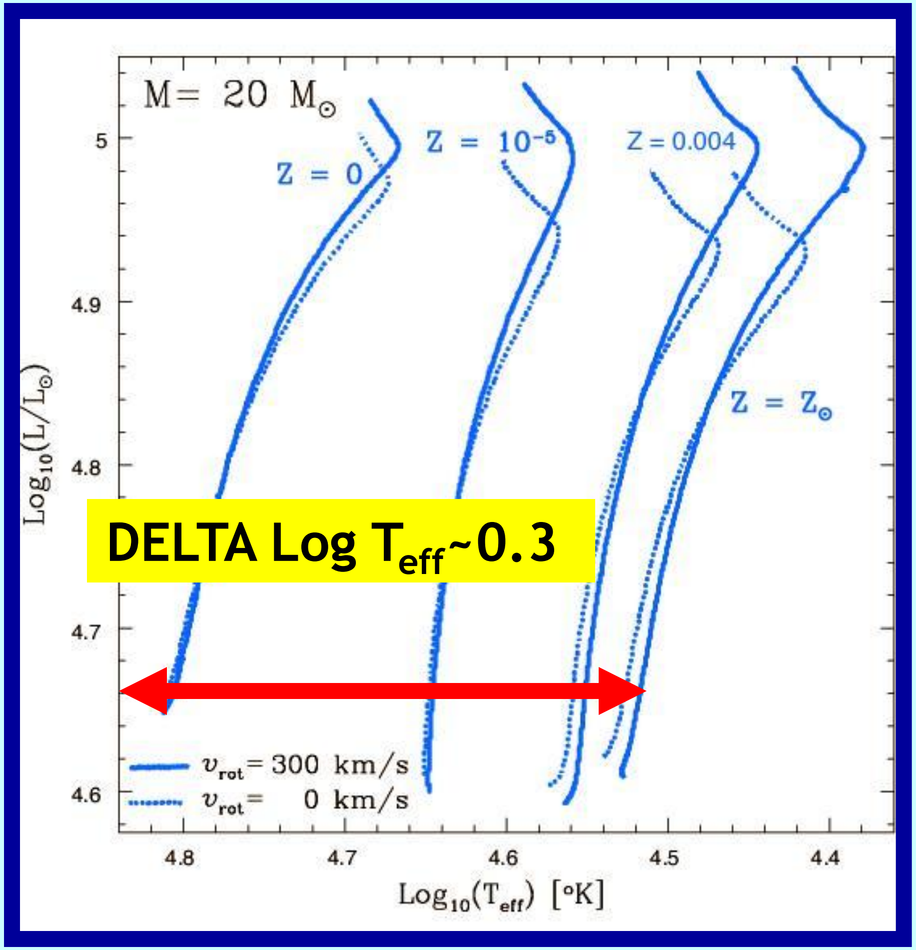
Meridional velocities smaller

→ MORE ANGULAR MOMENTUM IN THE CORE

At Z= 0, stars are more compact

PopIII star: radii decreased by a factor 4





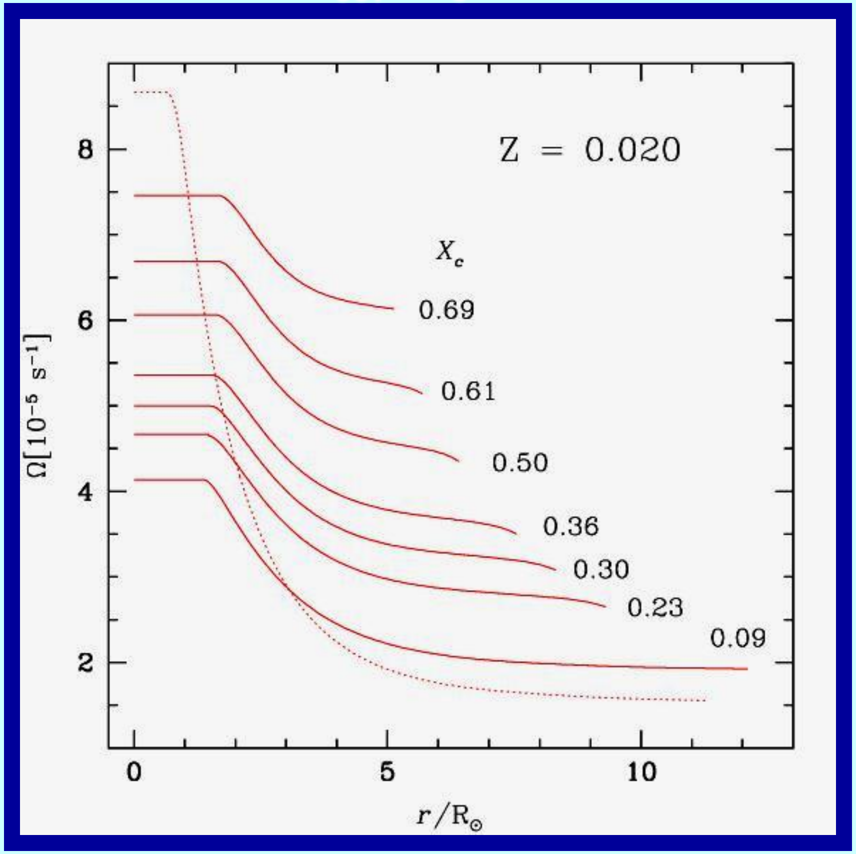
DELTA Log T_{eff}~0.3

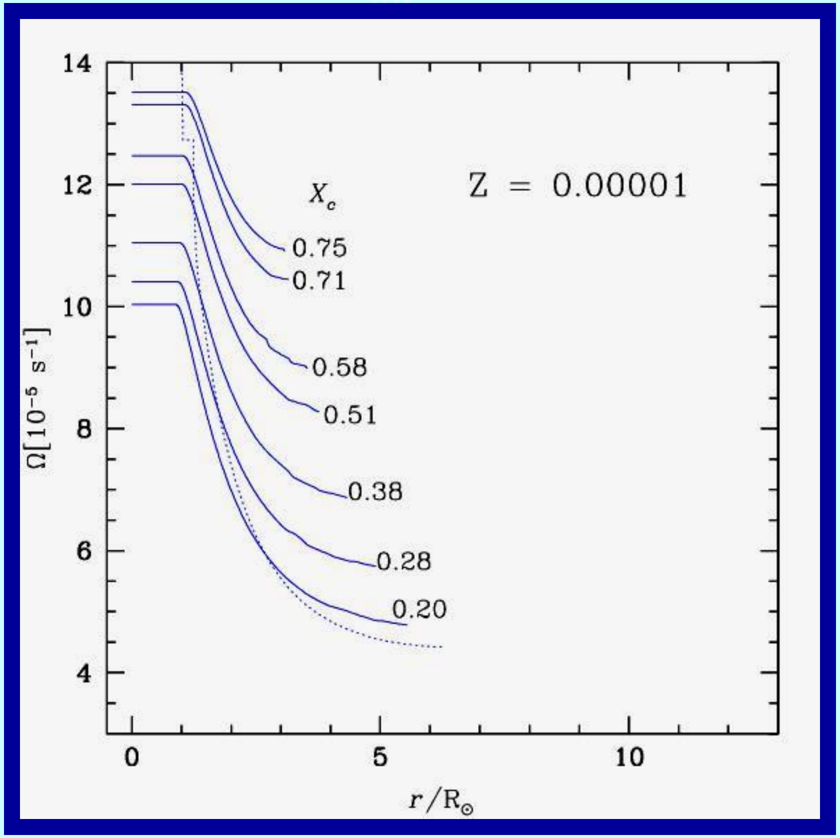
Feijoo 1999 diploma work

Ekström 2004 diploma work

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

WHAT CHANGES AT VERY LOW Z FOR ROTATING MODELS ?

Meridional velocities smaller

→ MORE ANGULAR MOMENTUM IN THE CORE

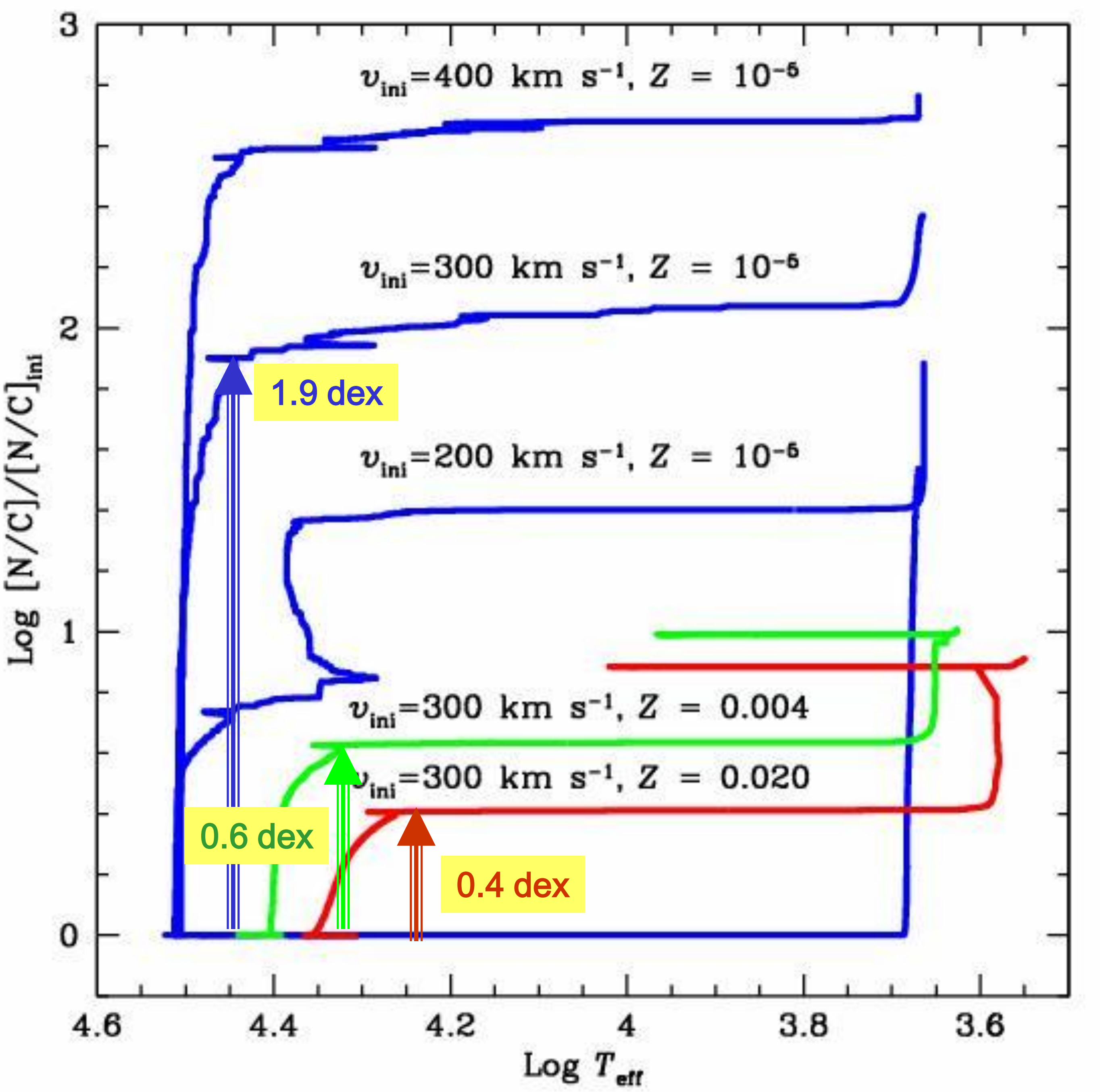
Steeper gradients of the angular velocity in the interiors

→ MORE EFFICIENT MIXING

9 M_{sol}

When Z ↘

Surface enrichments ↗



ABUNDANCES:

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

$< 20\ M_\odot$ B – dwarfs : ~ 0.5 dex

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

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

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

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

B – giants, supg. : → 1.1 -1.2 dex

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

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

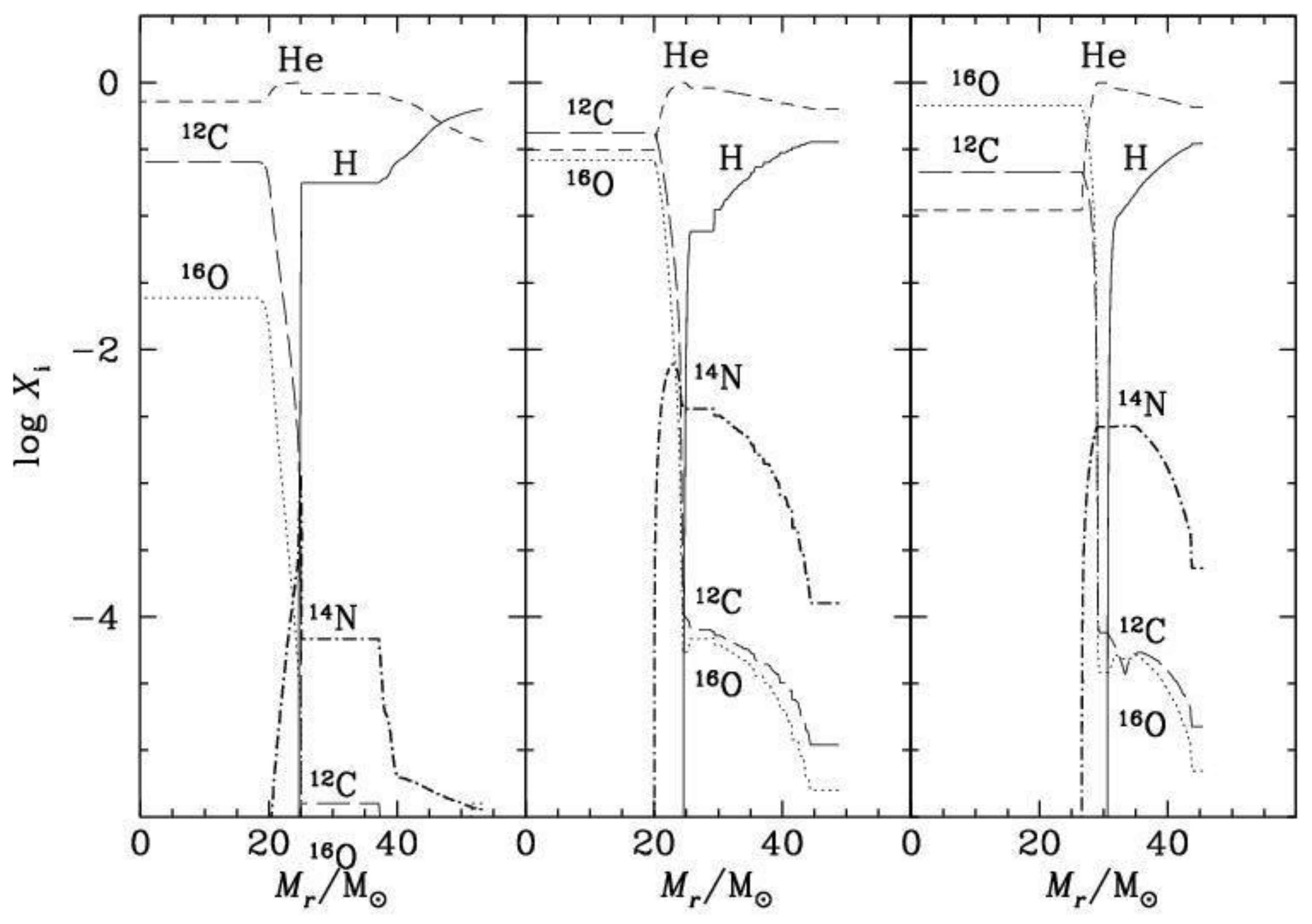
SMC: [N/H] O-stars, A-F supg. : 1.5 -1.7 dex

$< 20\ M_\odot$ B – dwarfs : → 1.1 dex

B – giants, supg. : → 1.5 dex

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

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



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

WHAT CHANGES AT VERY LOW Z FOR ROTATING MODELS ?

Meridional velocities smaller

⇒ MORE ANGULAR MOMENTUM IN THE CORE

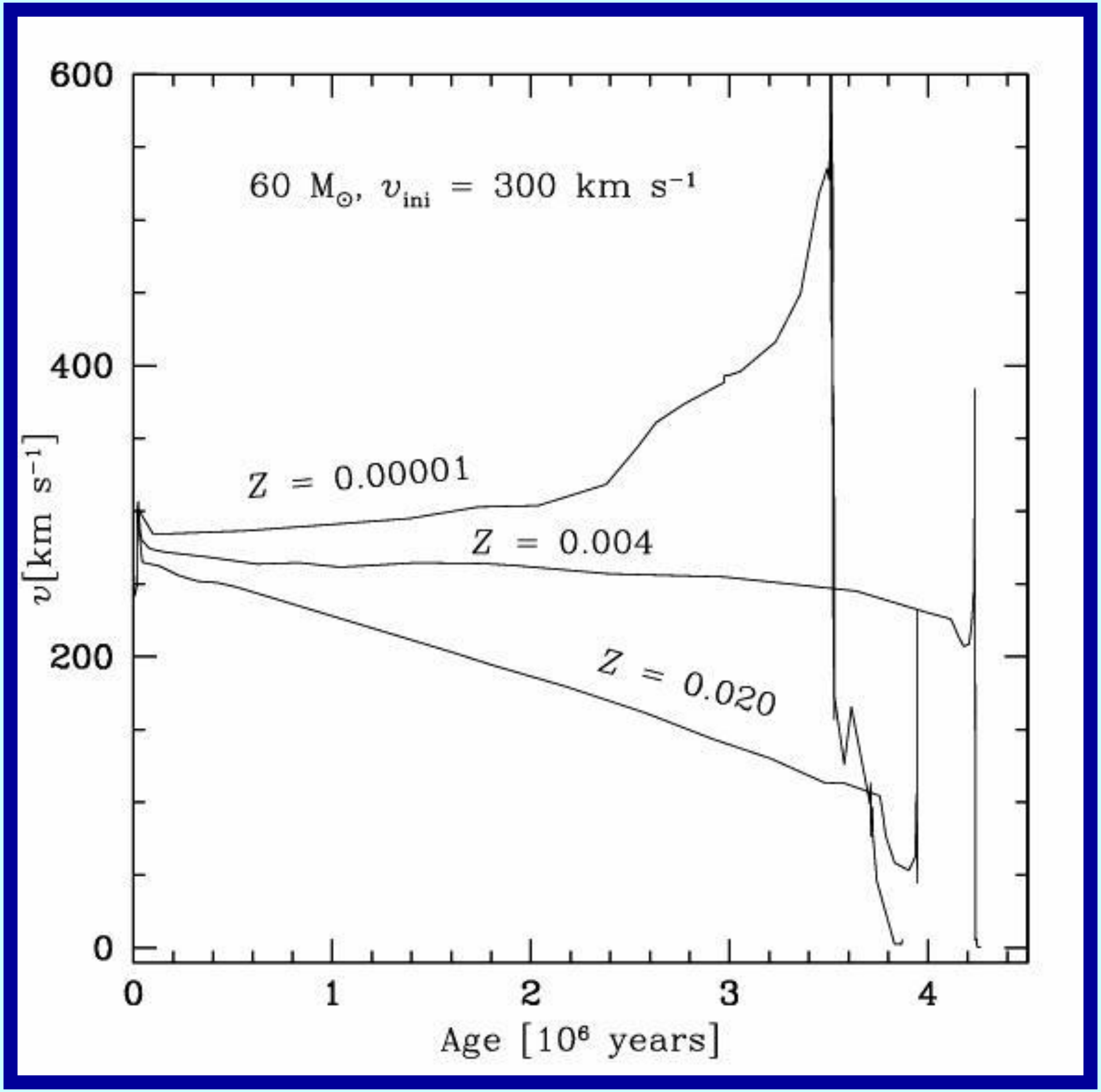
Steeper gradients of the angular velocity in the interiors

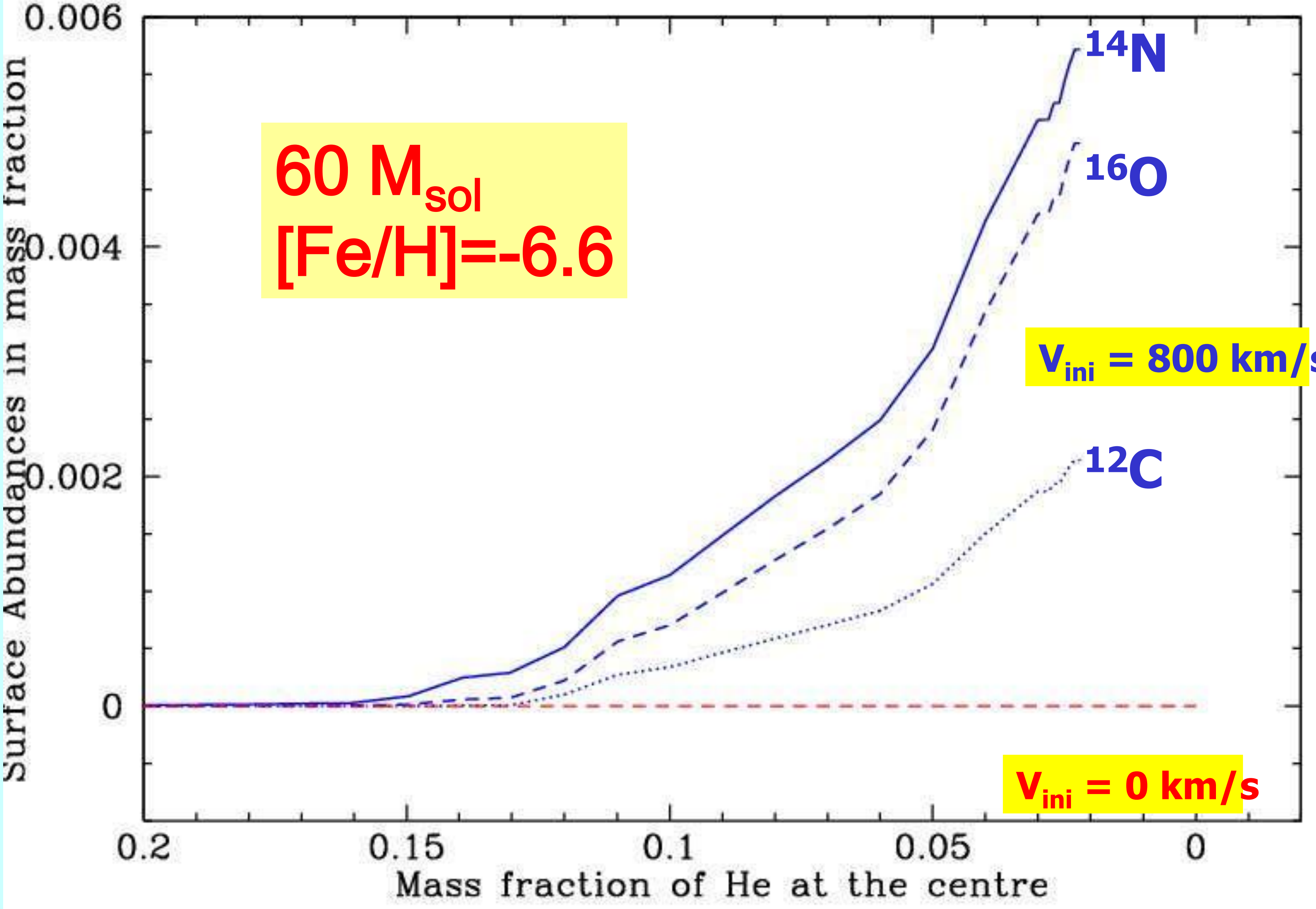
⇒ MORE EFFICIENT MIXING

Less angular momentum removed by stellar winds
More metals at the surface

⇒ more mass loss

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



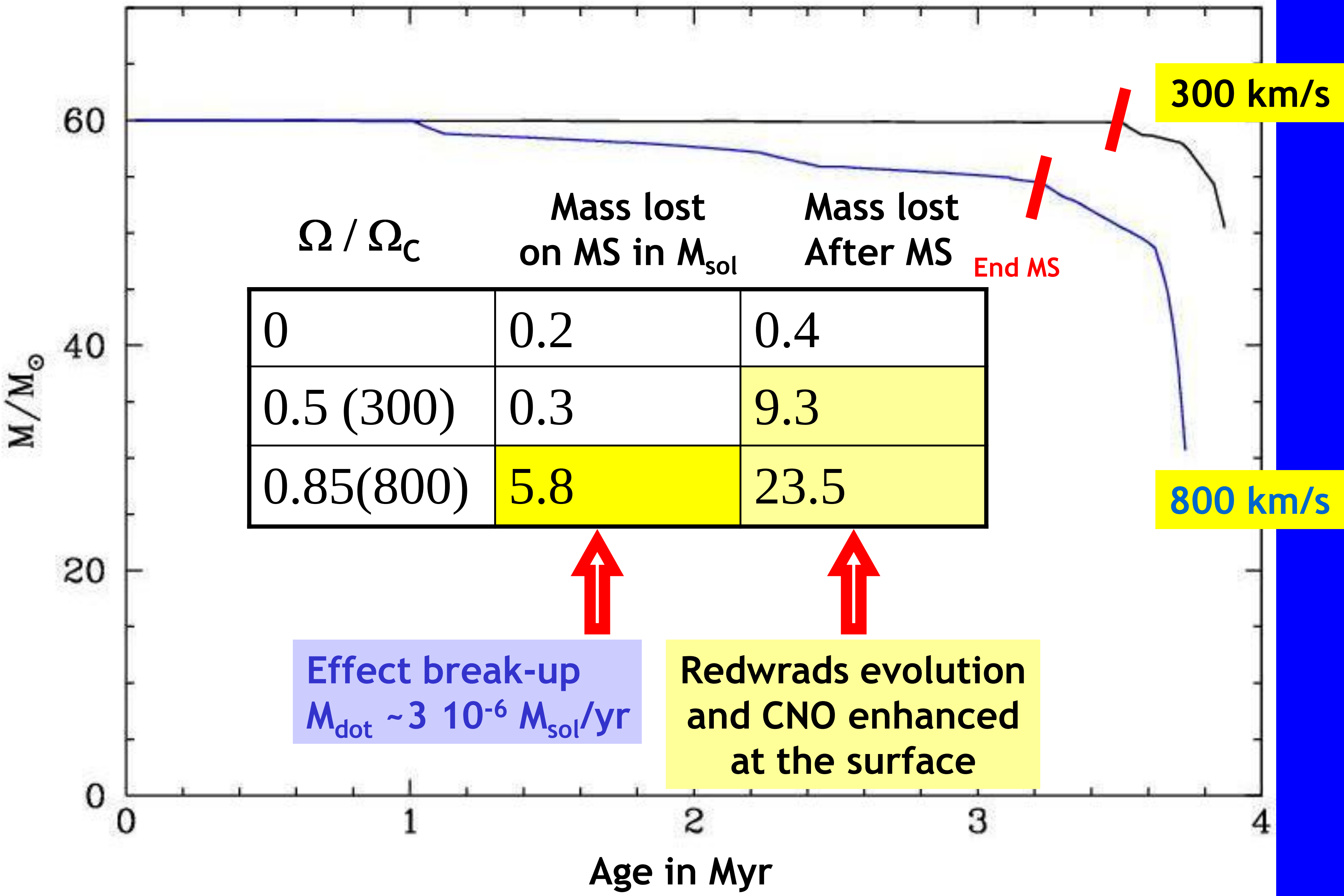


60 M_{sol}
[Fe/H]=-6.6

V_{ini} = 800 km/s

V_{ini} = 0 km/s

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

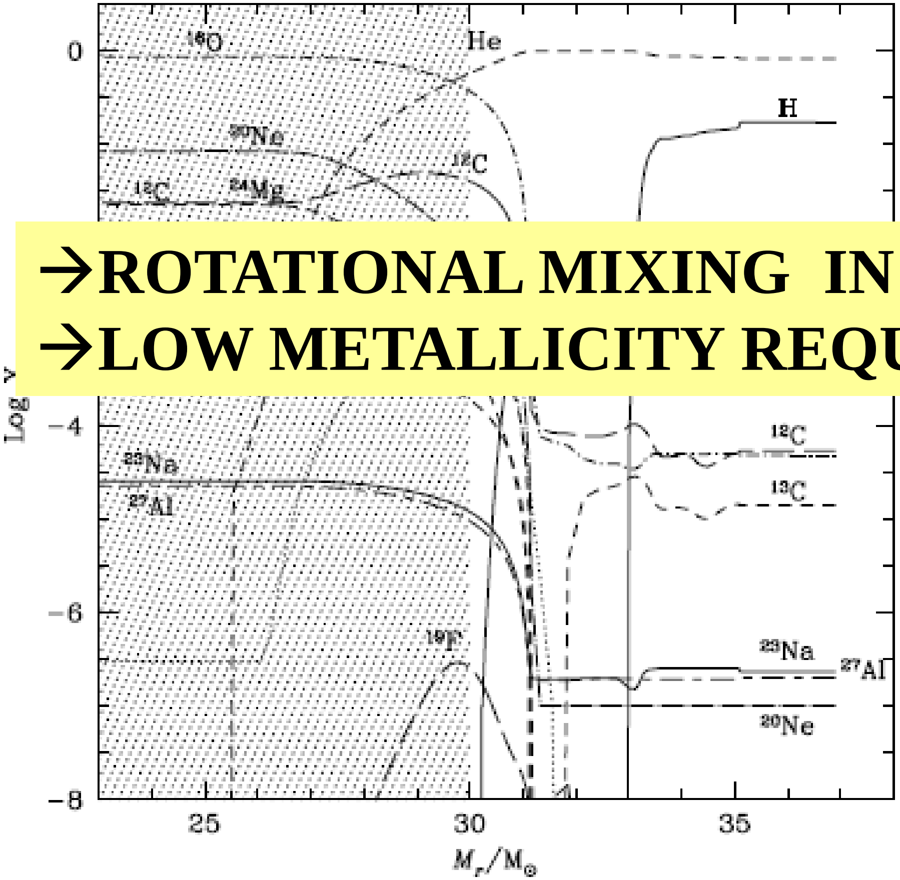
Effect break-up
M_{dot} ~3 10^{-6} M_{sol}/yr

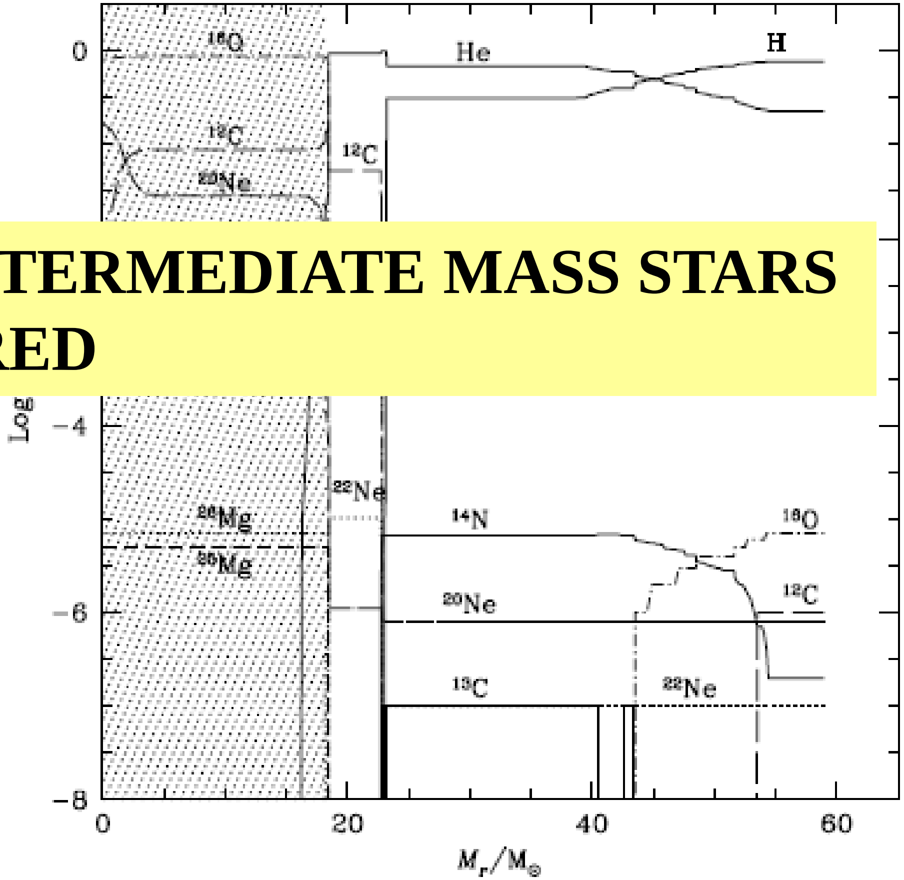
Redwrads evolution
and CNO enhanced
at the surface

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

V=800 km s^{-1}

V = 0 km s^{-1}





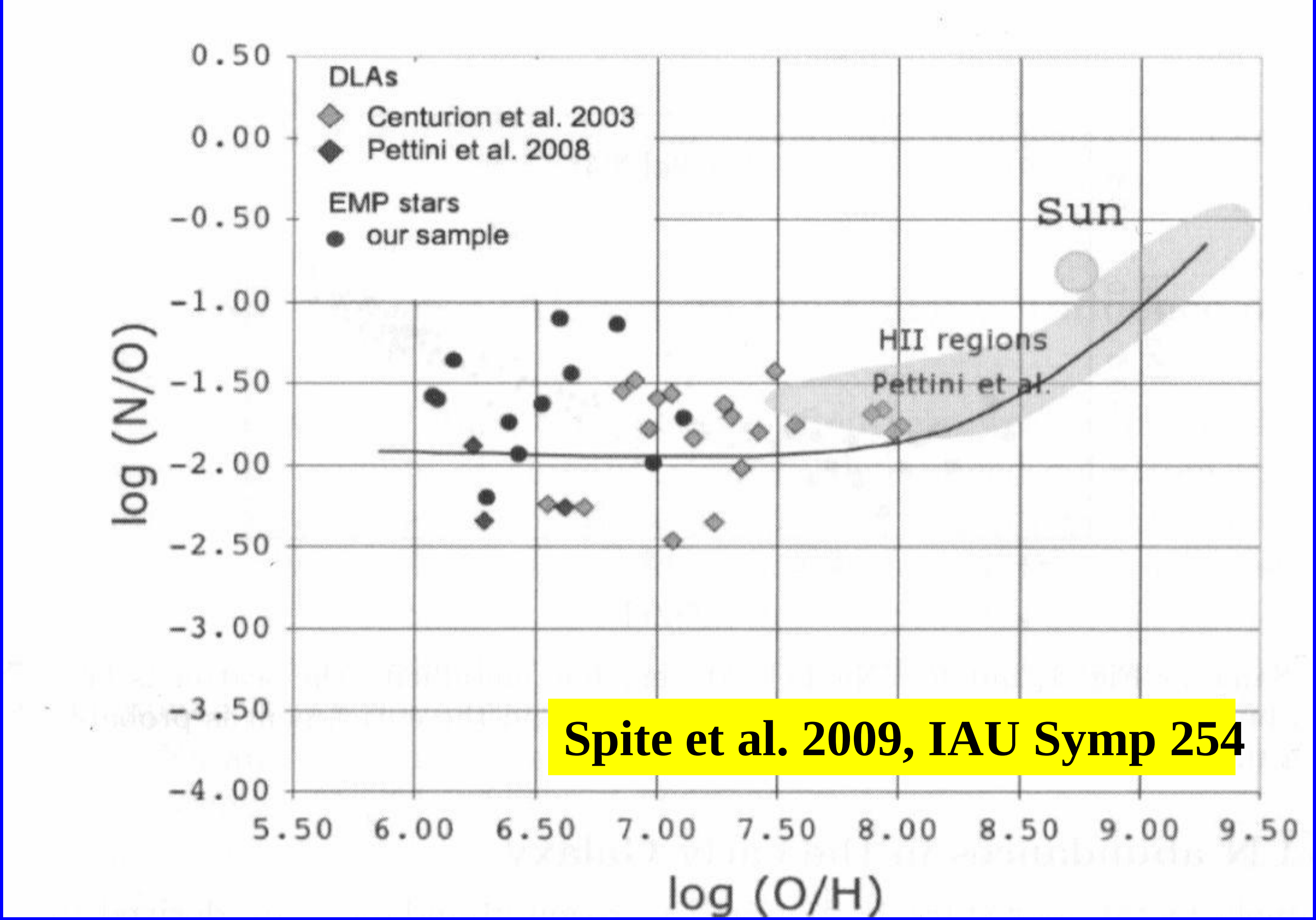
→ROTATIONAL MIXING IN INTERMEDIATE MASS STARS

→LOW METALLICITY REQUIRED

NITROGEN

WINDS

IMPORTANT PRODUCTION OF PRIMARY NIT



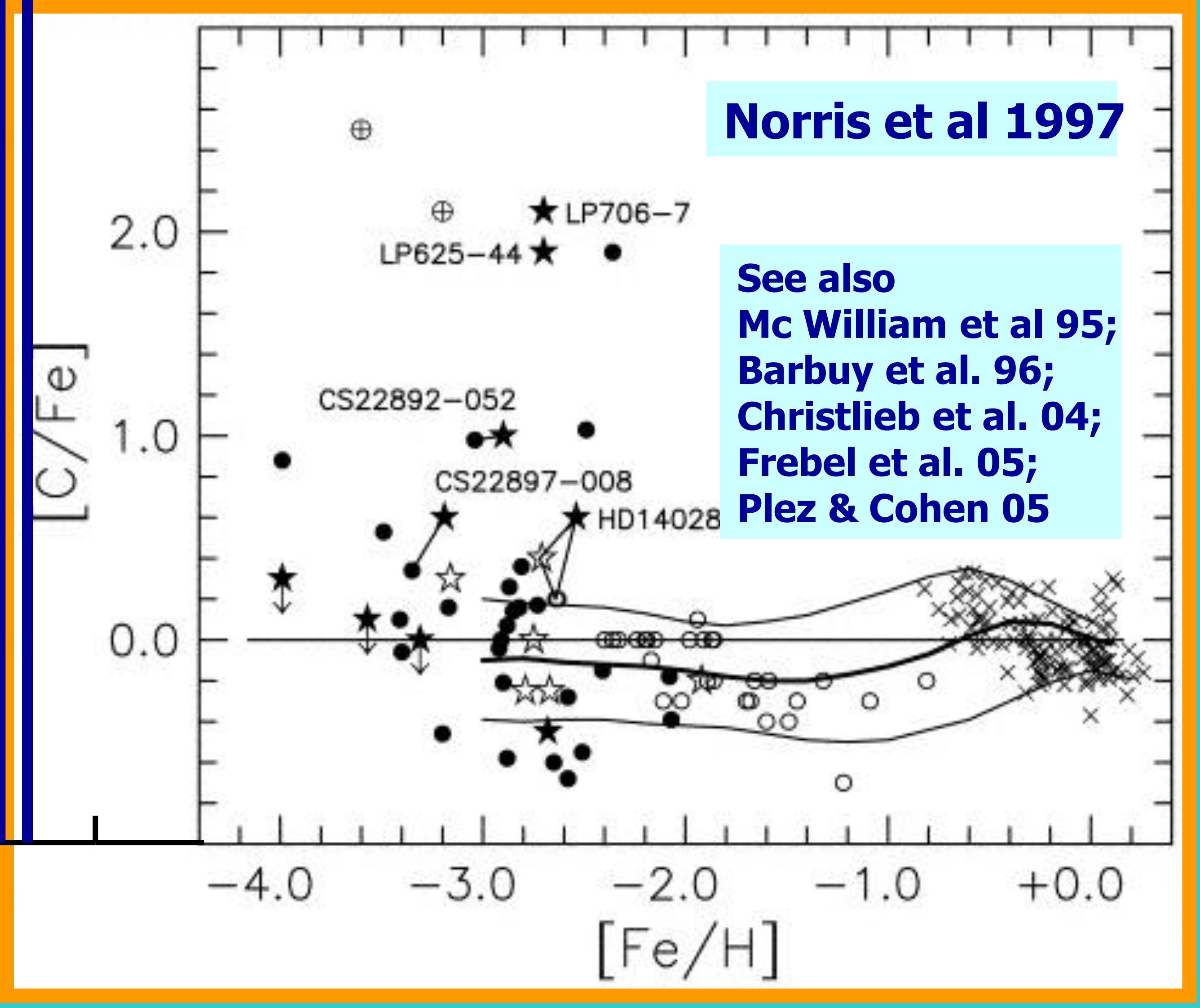
Spite et al. 2009, IAU Symp 254

Carbon Rich Ultra Metal Poor Stars (CRUMPS)

Most metal poor stars

Christlieb et al. 2002

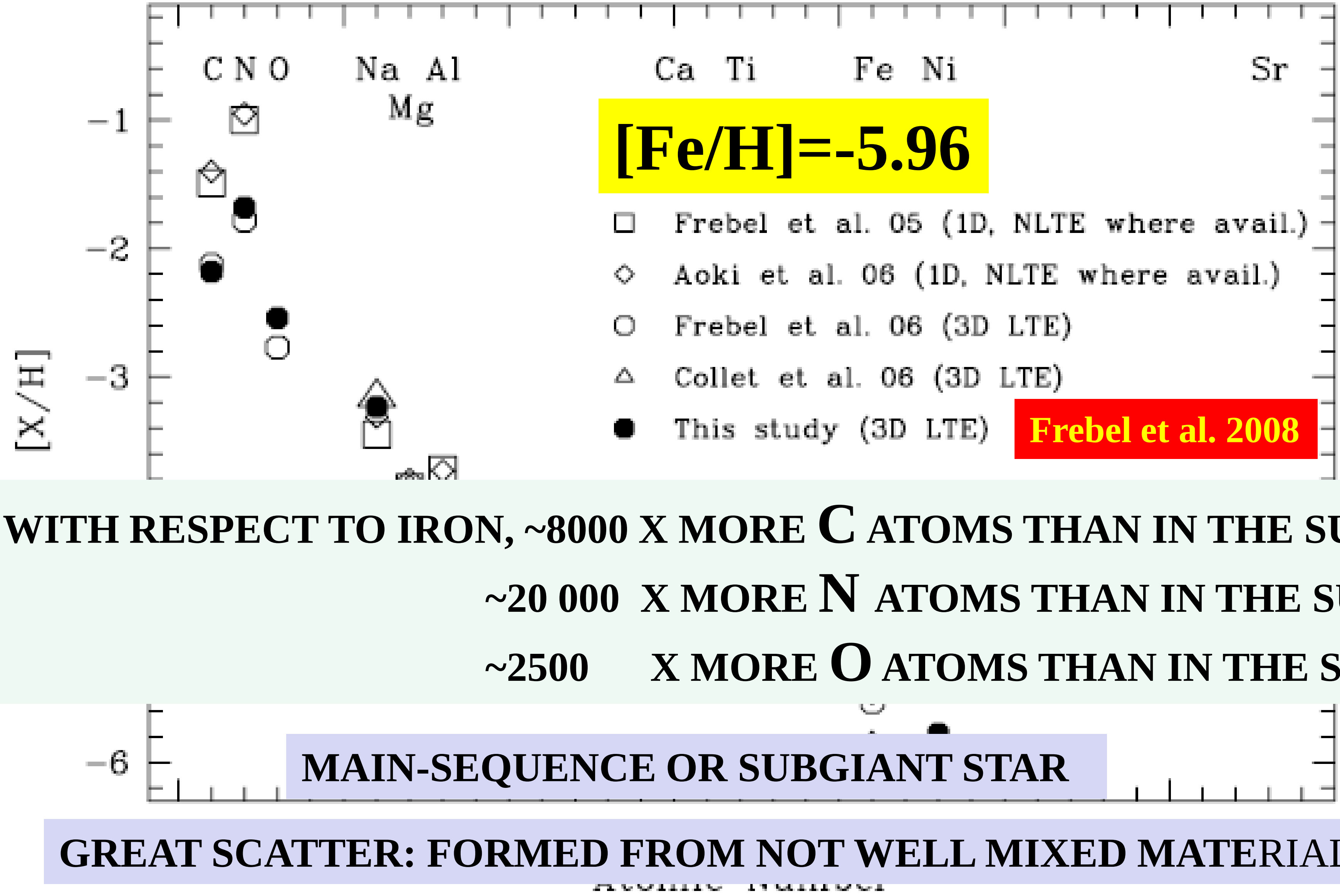
Frebel et al. 2005



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

THE MOST IRON POOR STAR PRESENTLY KNOWN IN THE UNIVERSE



[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

MAIN-SEQUENCE OR SUBGIANT STAR

GREAT SCATTER: FORMED FROM NOT WELL MIXED MATERIAL

WHAT CAN WE LEARN FROM THE HIGH CNO CONTENT?

NITROGEN: H-BURNING, FROM CO

CARBON: He-BURNING, FROM He

OXYGEN: He-BURNING, FROM He

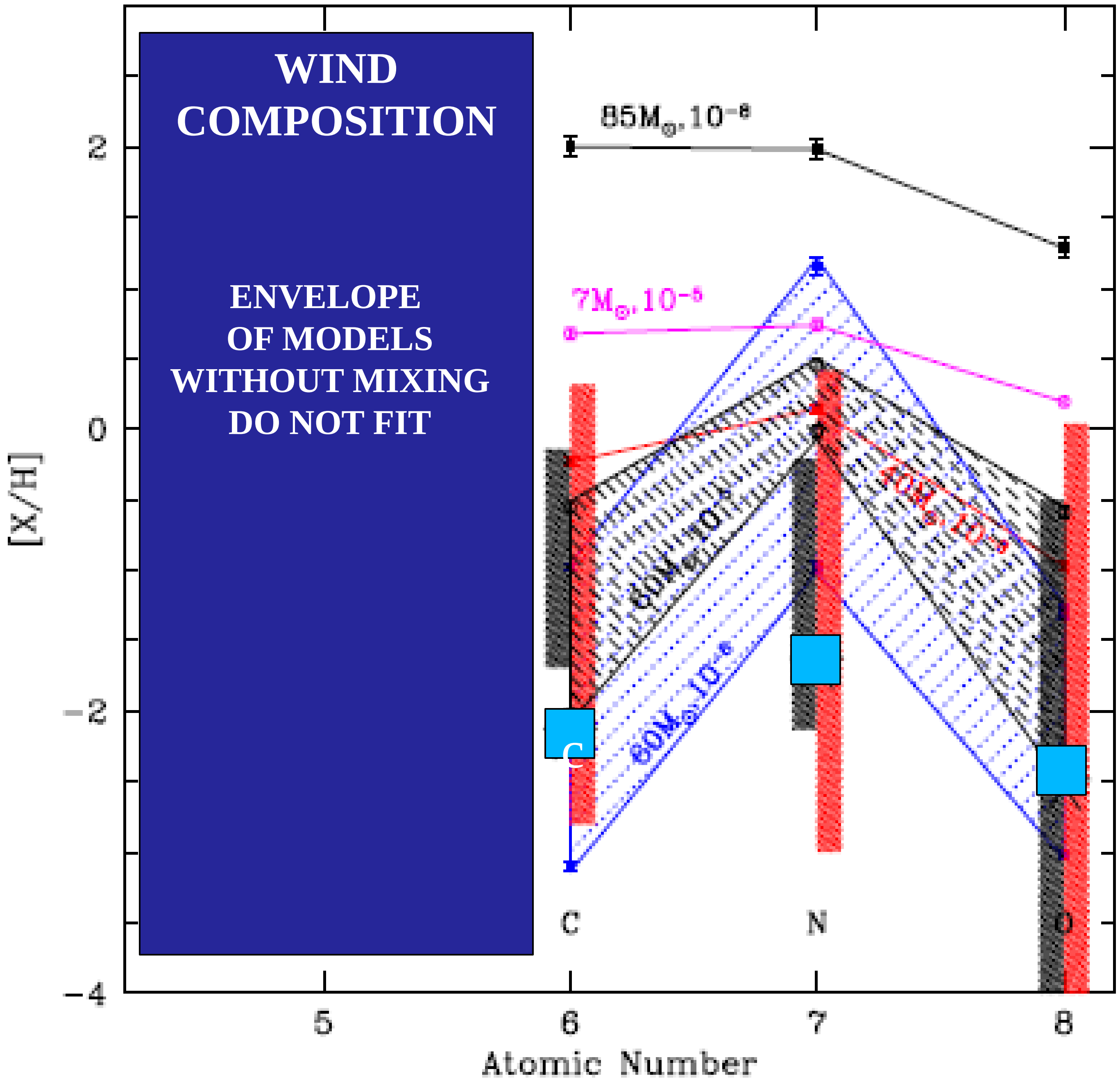
HIGH CNO NEEDS

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

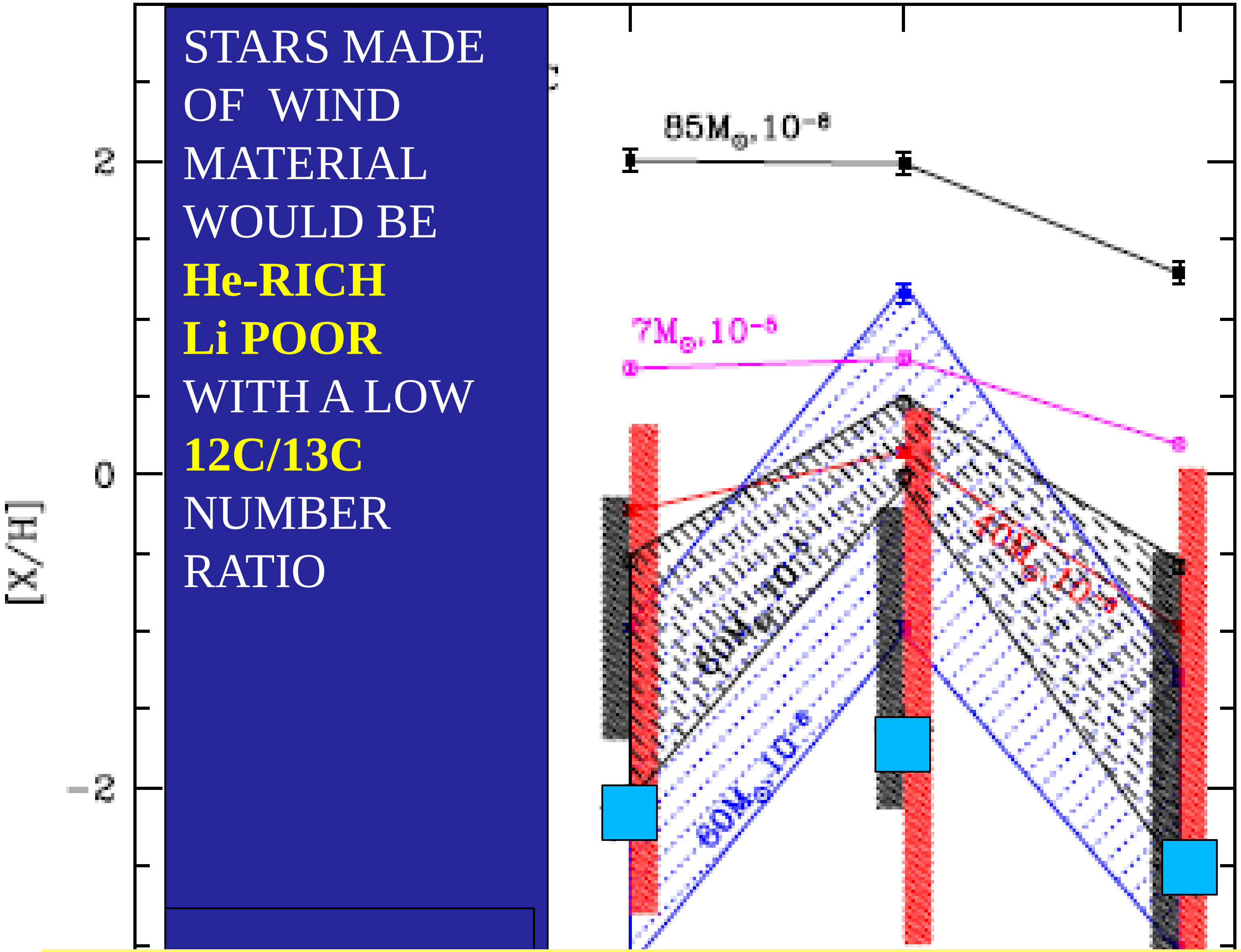
2) DIFFUSION BETWEEN THE He-CORE AND THE H-BURNING SHELL

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

WIND COMPOSITION



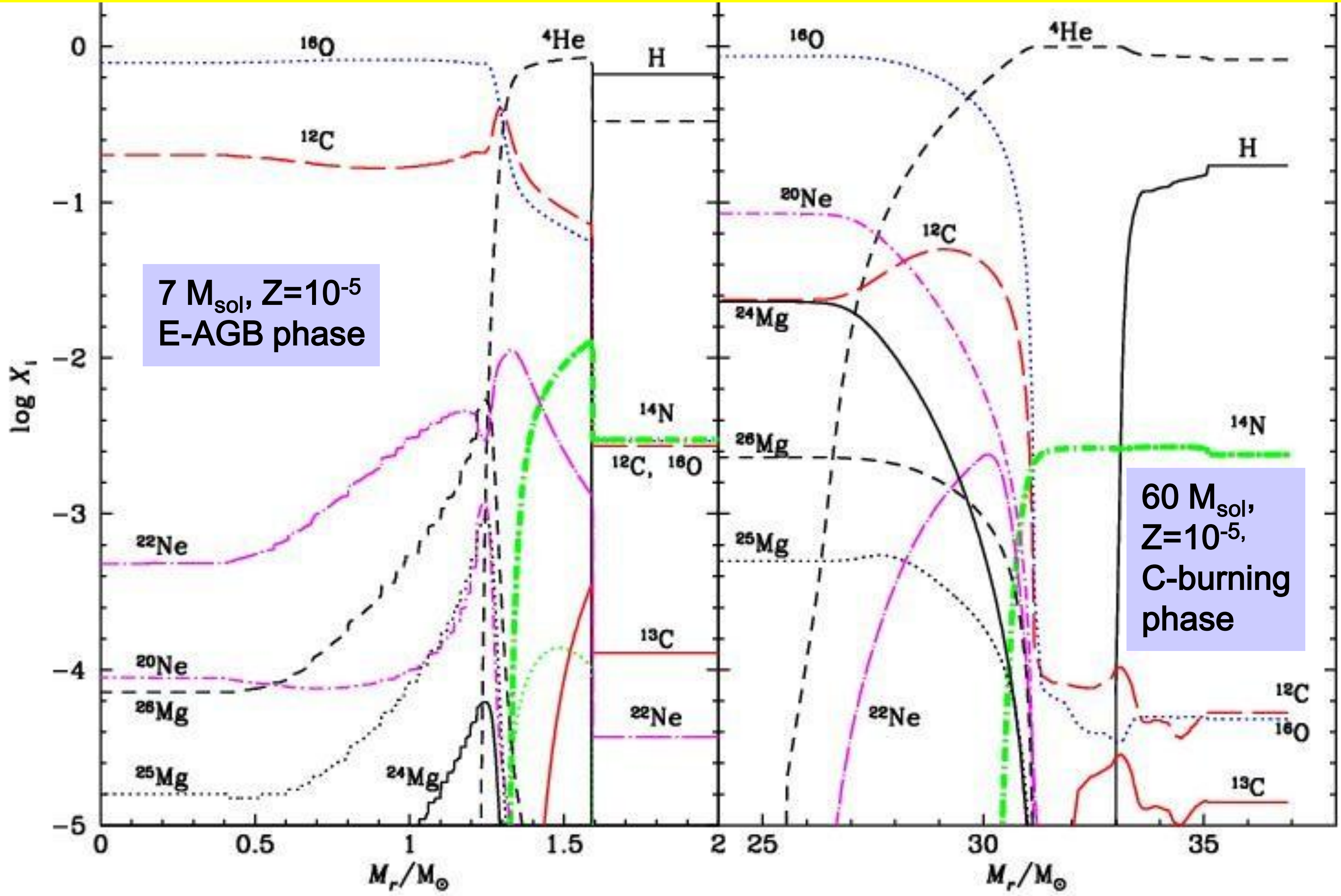
ENVELOPE
OF MODELS
WITHOUT MIXING
DO NOT FIT



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

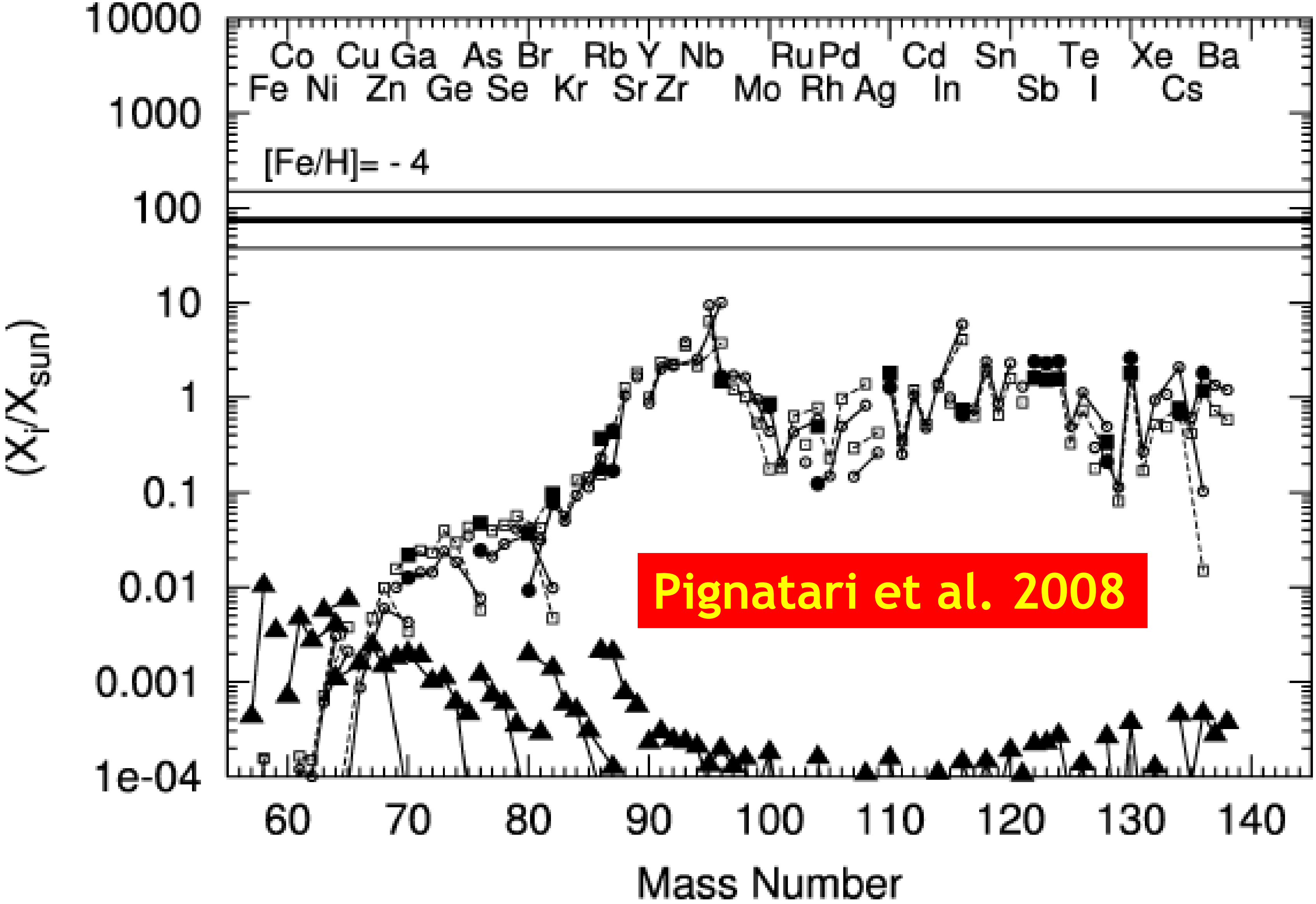
	Y	e(Li)	12C/13C
	0.60	0	4.7
Frebel'star		<0.6	>5

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



7 M_{sol}, Z=10^{-5}
E-AGB phase

60 M_{sol},
Z=10^{-5},
C-burning
phase

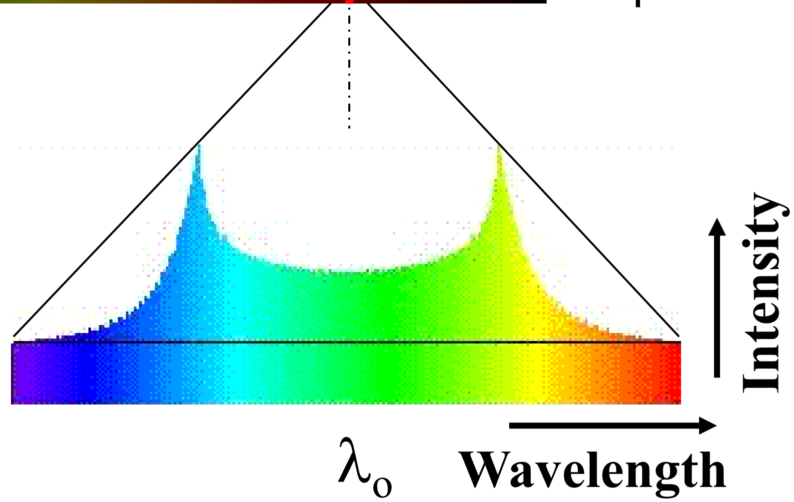


Pignatari et al. 2008

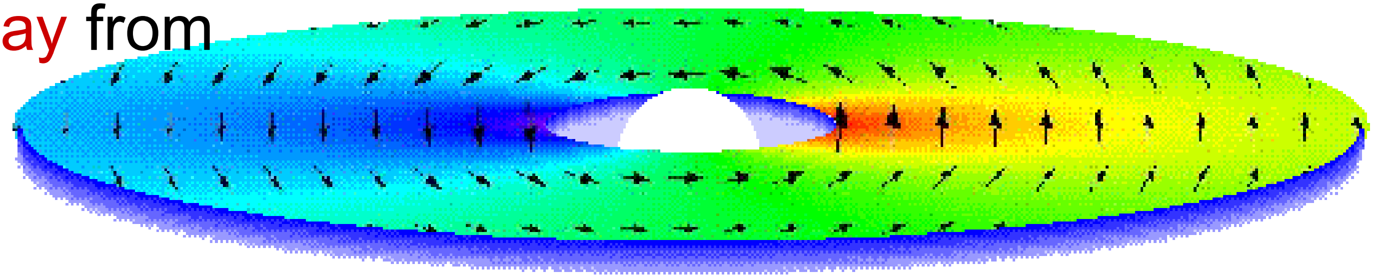
Be stars

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



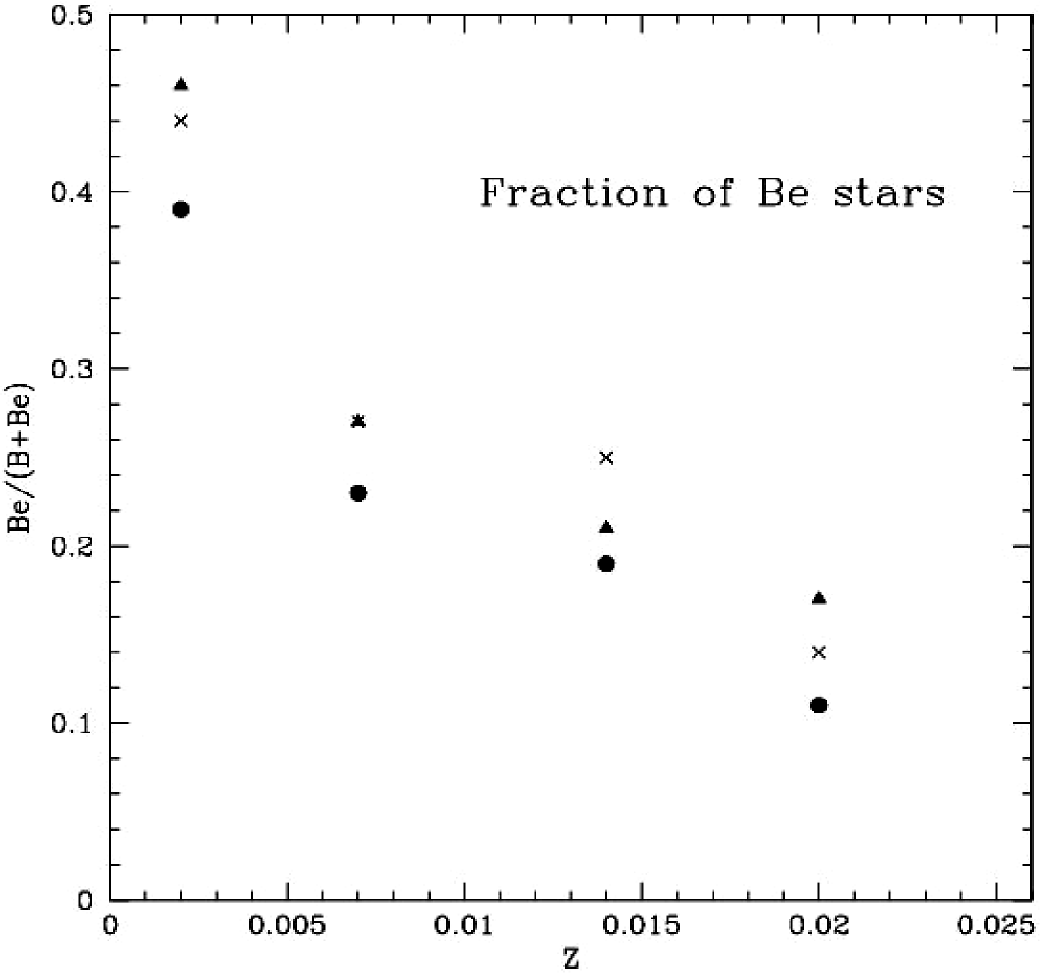
- Indicates a disk of gas orbits the star.

Viewgraph from Owocki

From 19 clusters in Galaxy, LMC & SMC

Rotation seems faster at lower Z

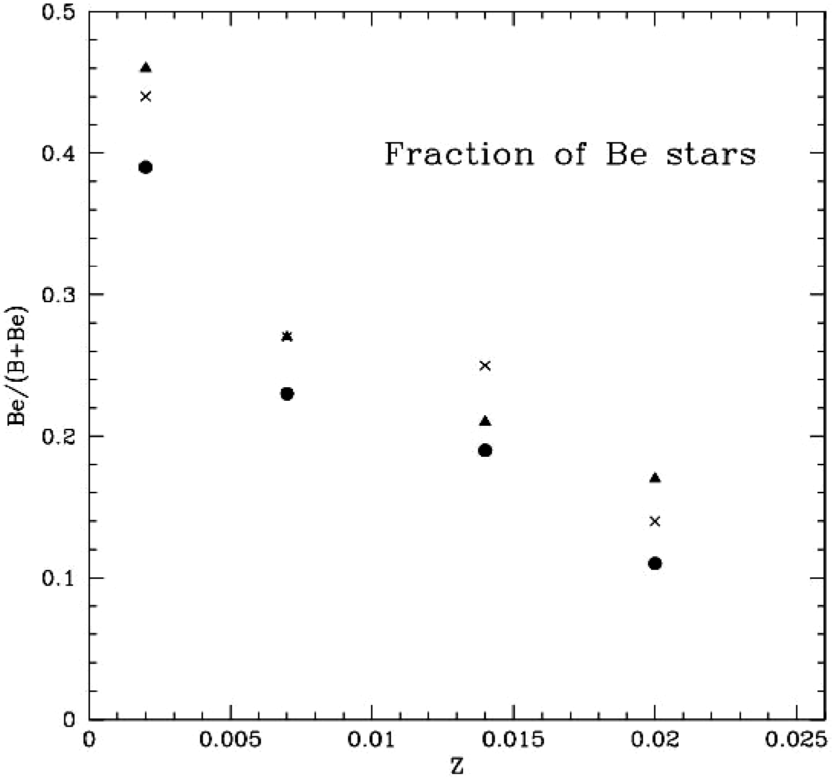
Is this a general trend ?
What at Z = 0 ?

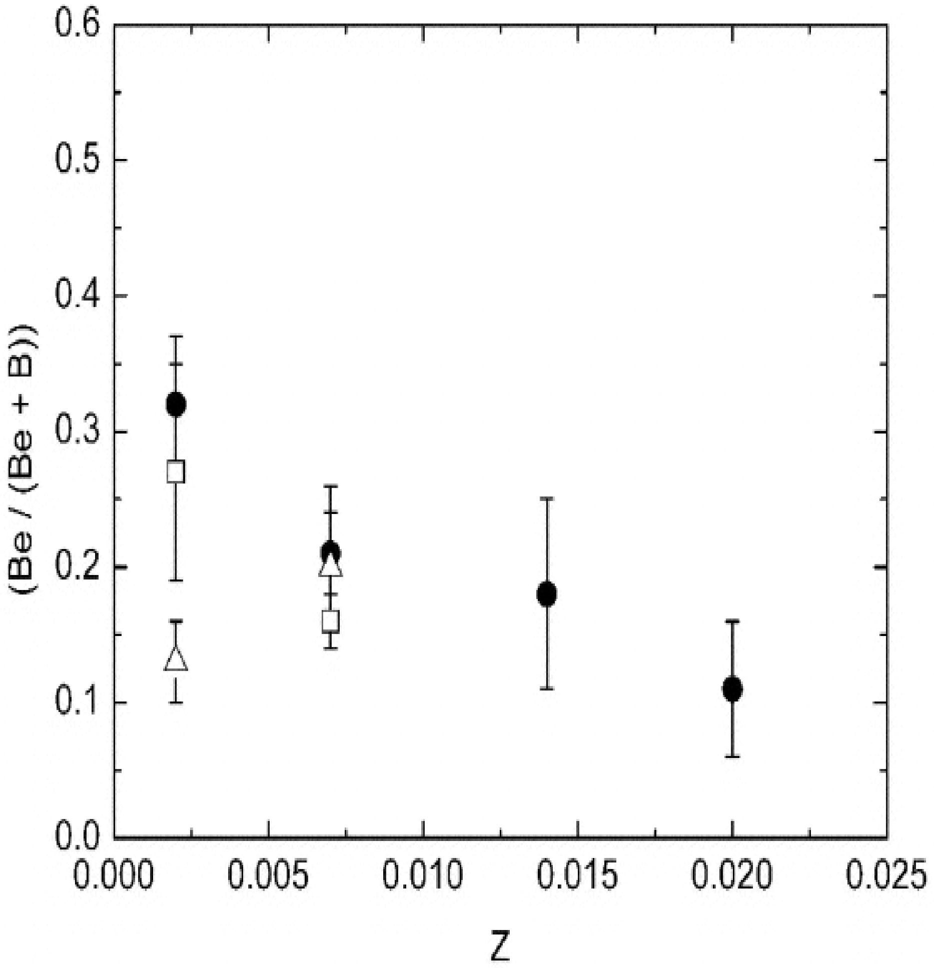


Maeder, Grebel, Mermilliod 1999

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

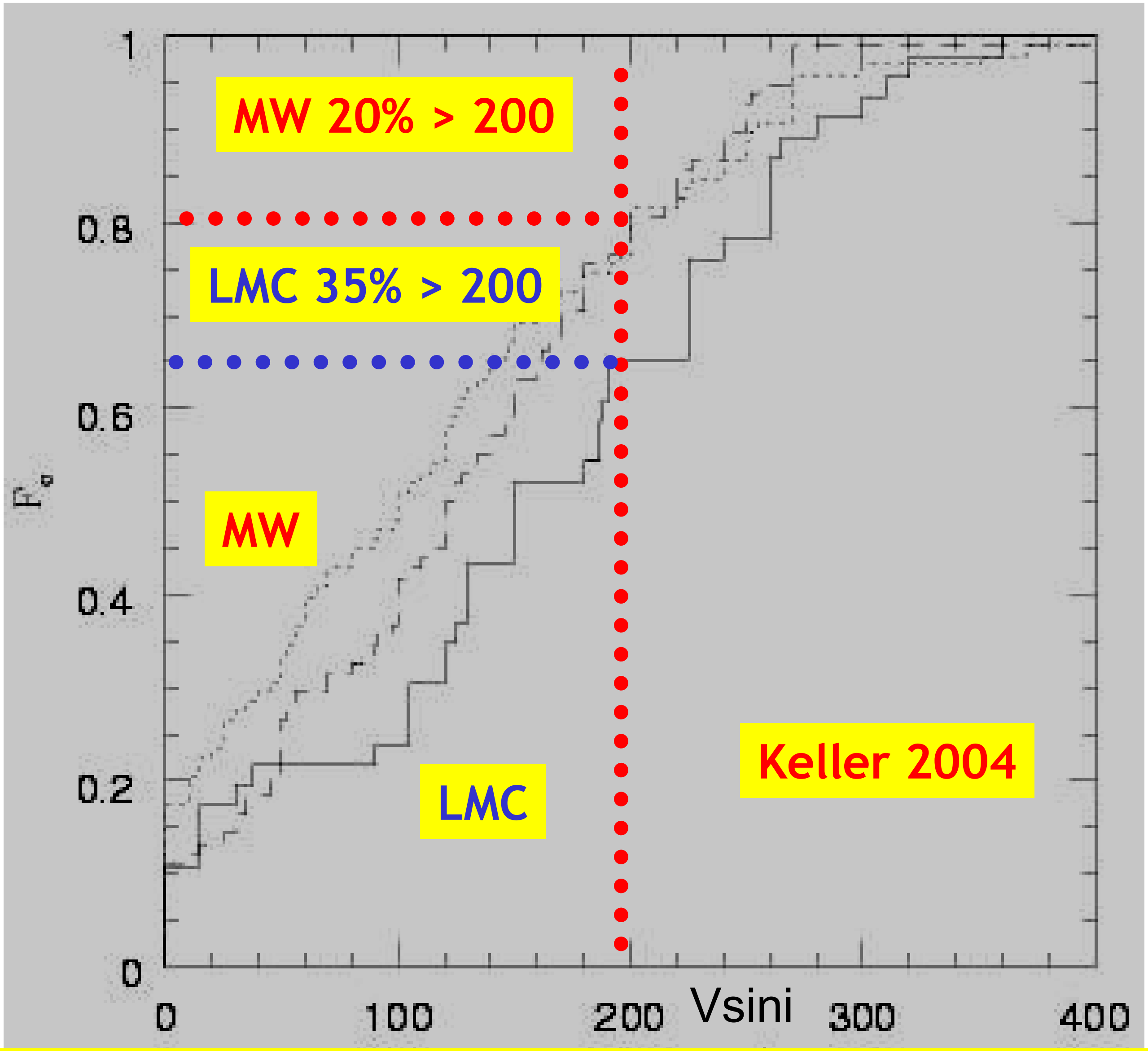
Keller 2004

CUMULATIVE DISTRIBUTION OF V sin i

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

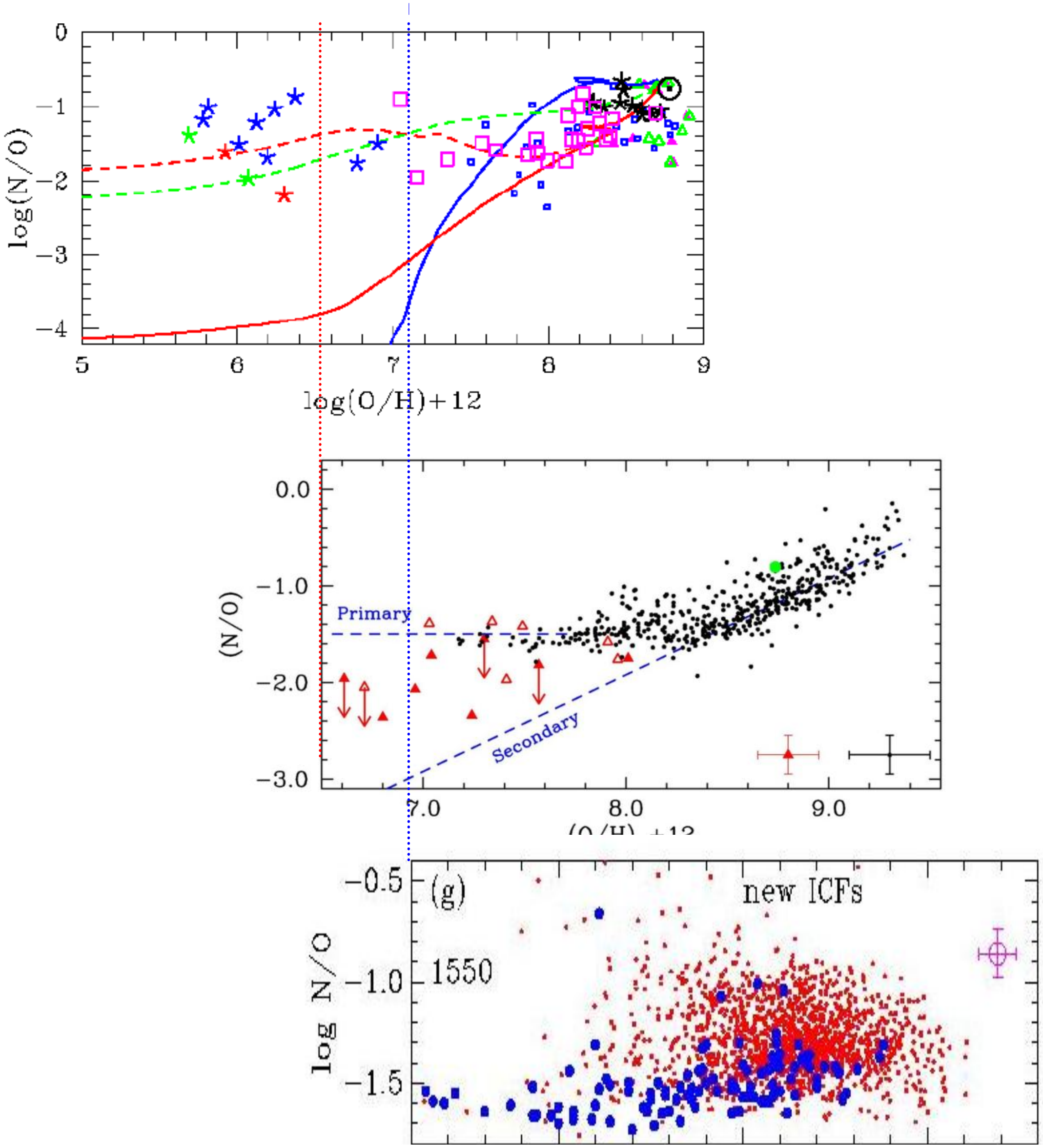
MW

LMC

Keller 2004

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

LES ETOILES DU HALO



ETOILES DU HALO

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

DAMPED LYMAN ALPHA SYSTEMS

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

GALAXIES A RAIES D'EMISSION ET BLEUES COMPACTES

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

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

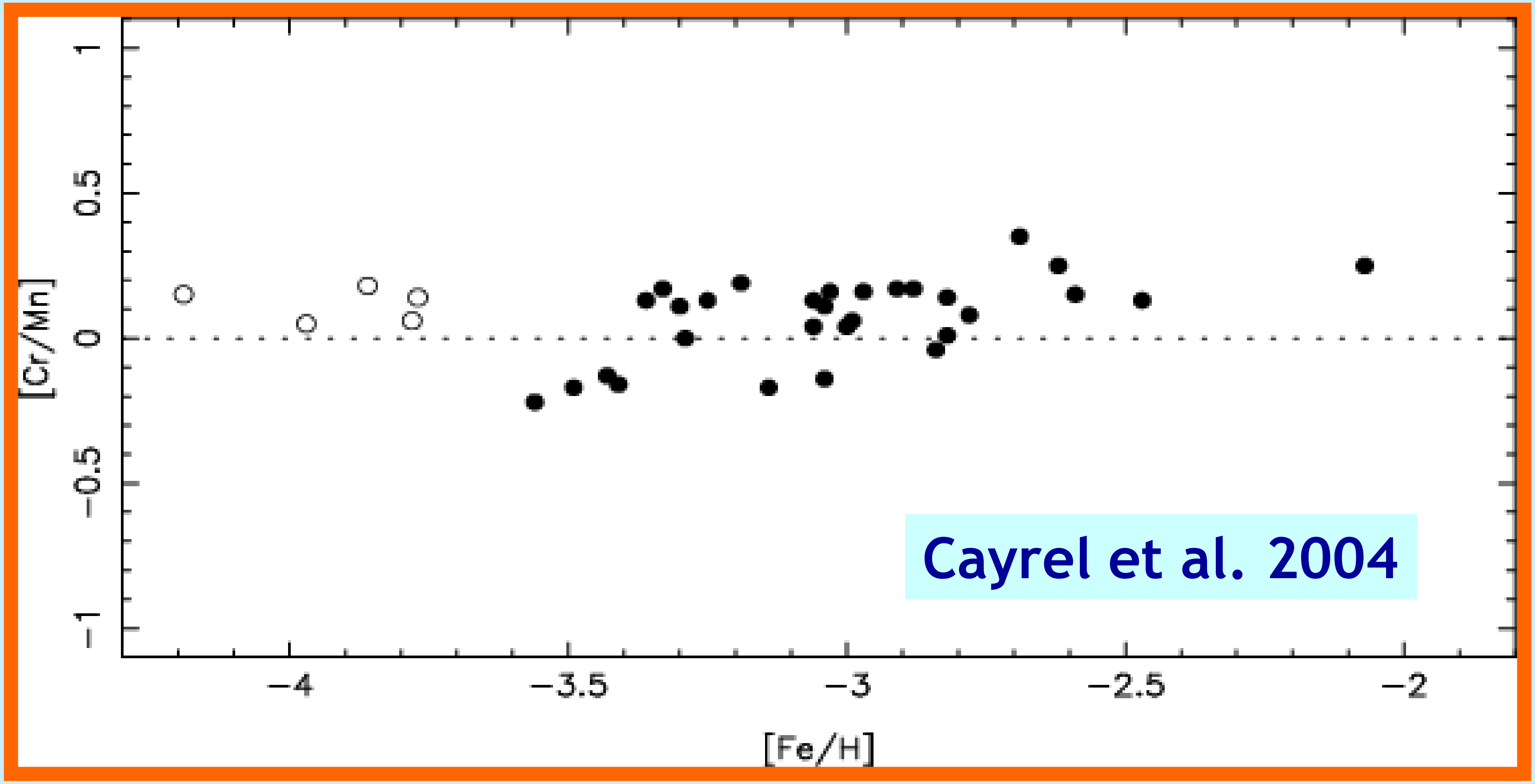
→ Stars more compact: R(popIII) = R(Z_{sol})/4

→ 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

STRIKING OBSERVATIONAL FACTS

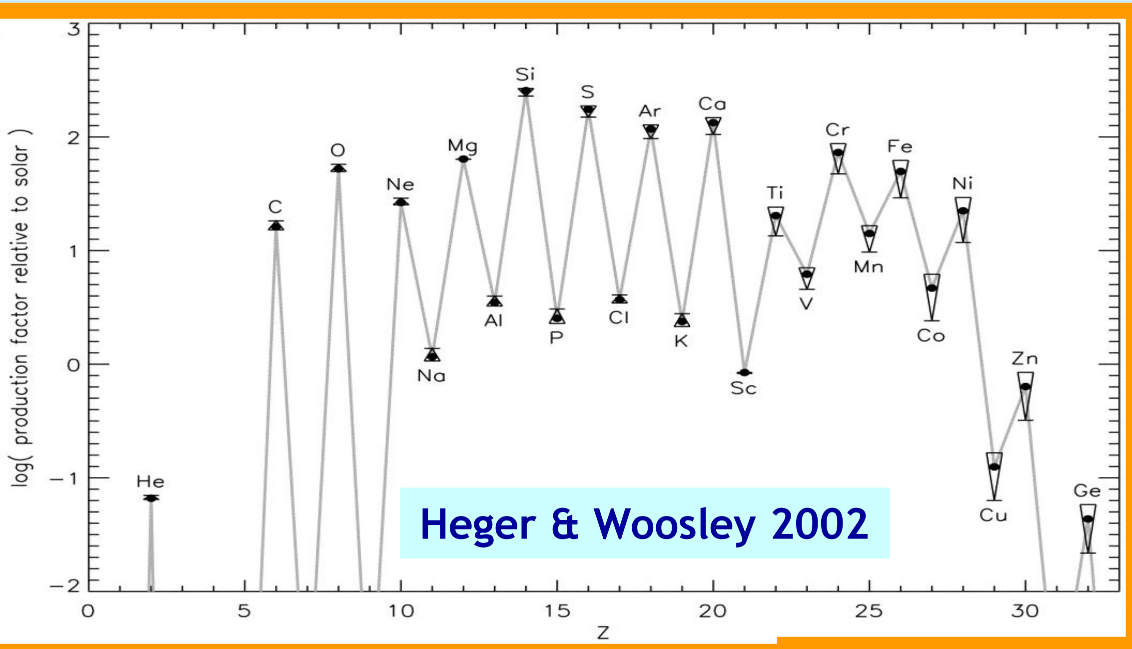
→ 1) Very small scatter



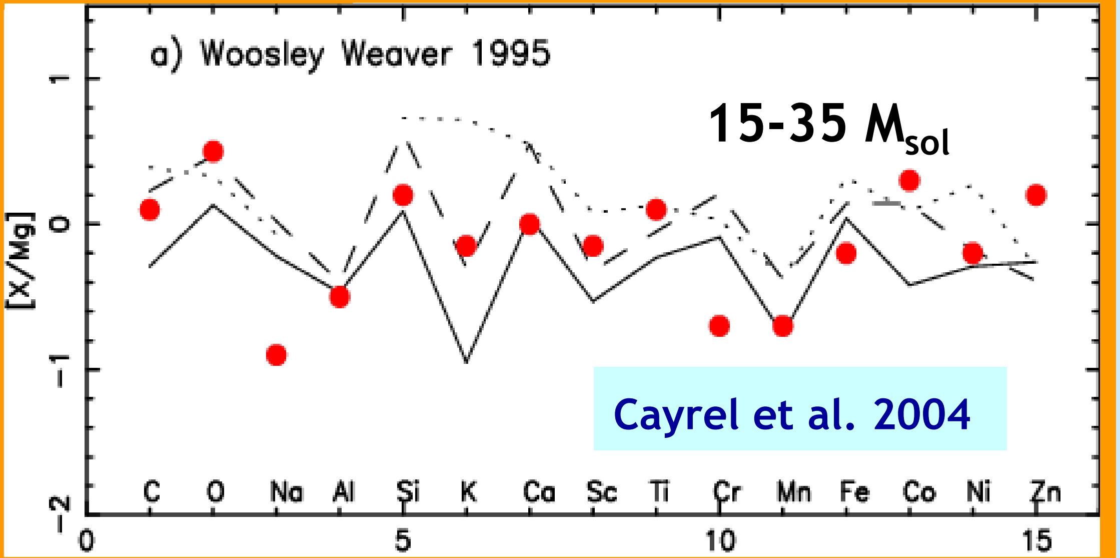
Cayrel et al. 2004

STRIKING OBSERVATIONAL FACTS

→2) No sign of Pair Instability Supernovae



Heger & Woosley 2002

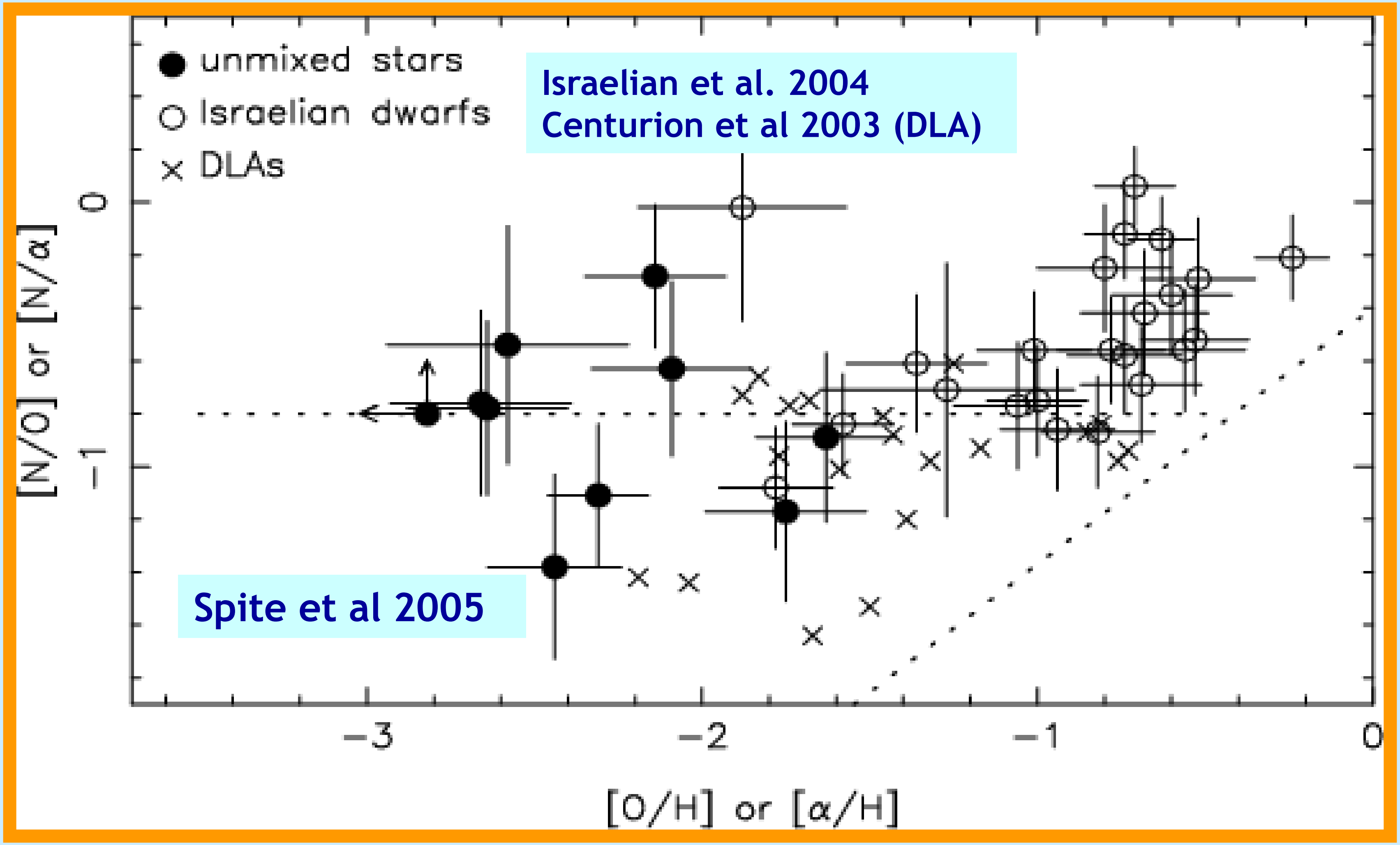


15-35 M_{sol}

Cayrel et al. 2004

STRIKING OBSERVATIONAL FACTS

→3) Important amount of primary nitrogen

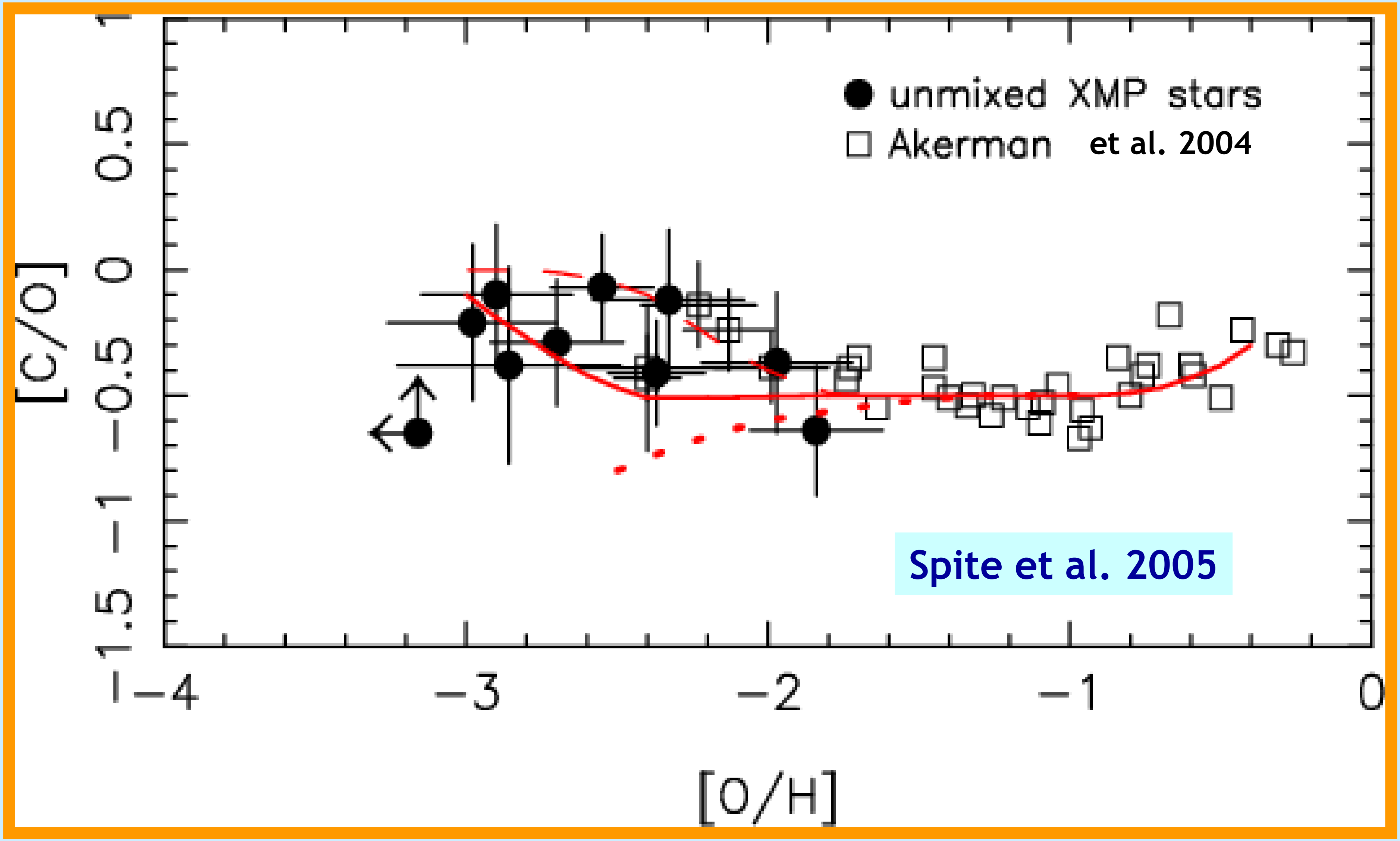


Israelian et al. 2004
Centurion et al 2003 (DLA)

Spite et al 2005

STRIKING OBSERVATIONAL FACTS

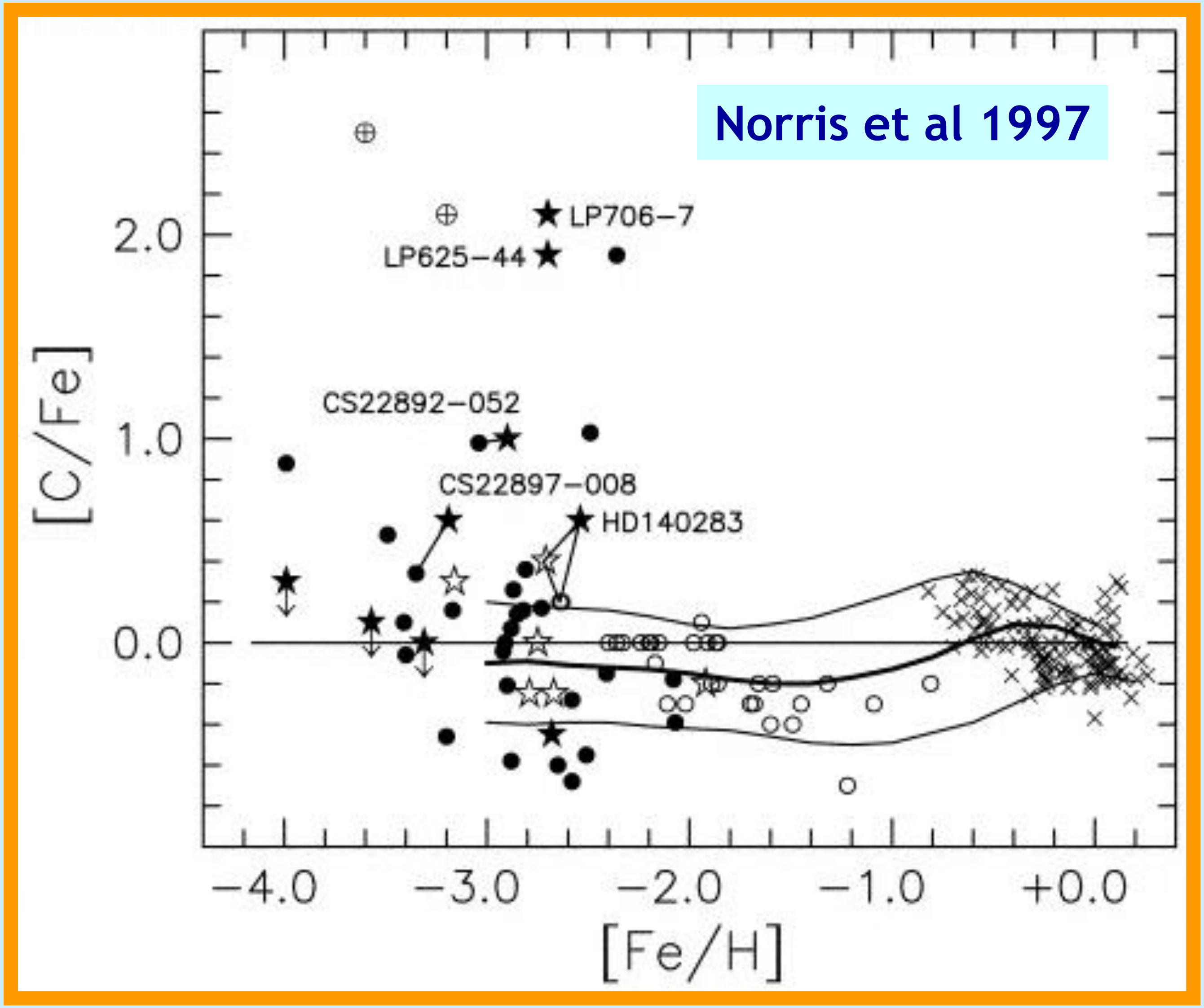
→4) More carbon, less oxygen produced at low Z ?



Spite et al. 2005

STRIKING OBSERVATIONAL FACTS

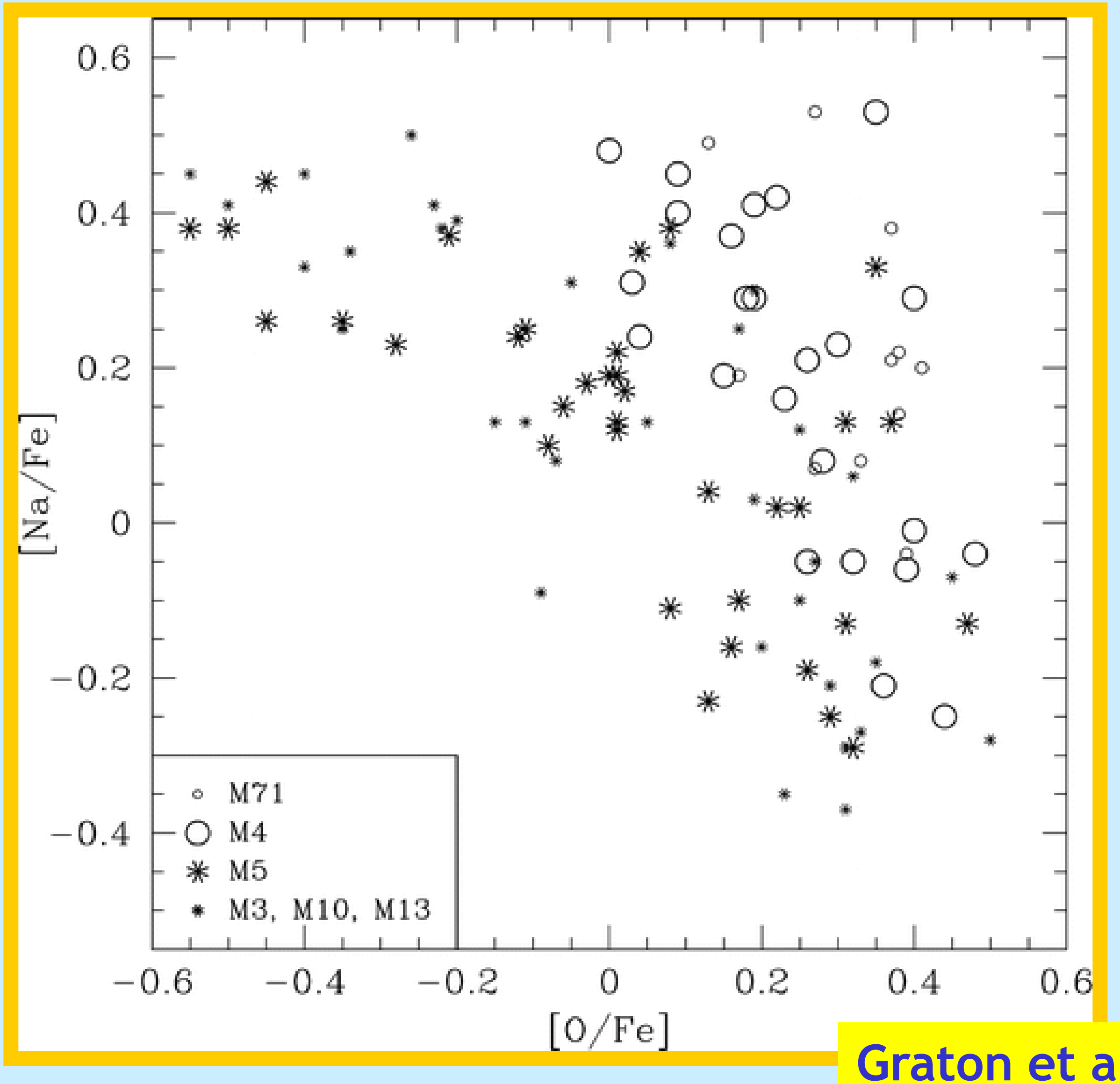
→5) C-rich stars



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

STRIKING OBSERVATIONAL FACTS

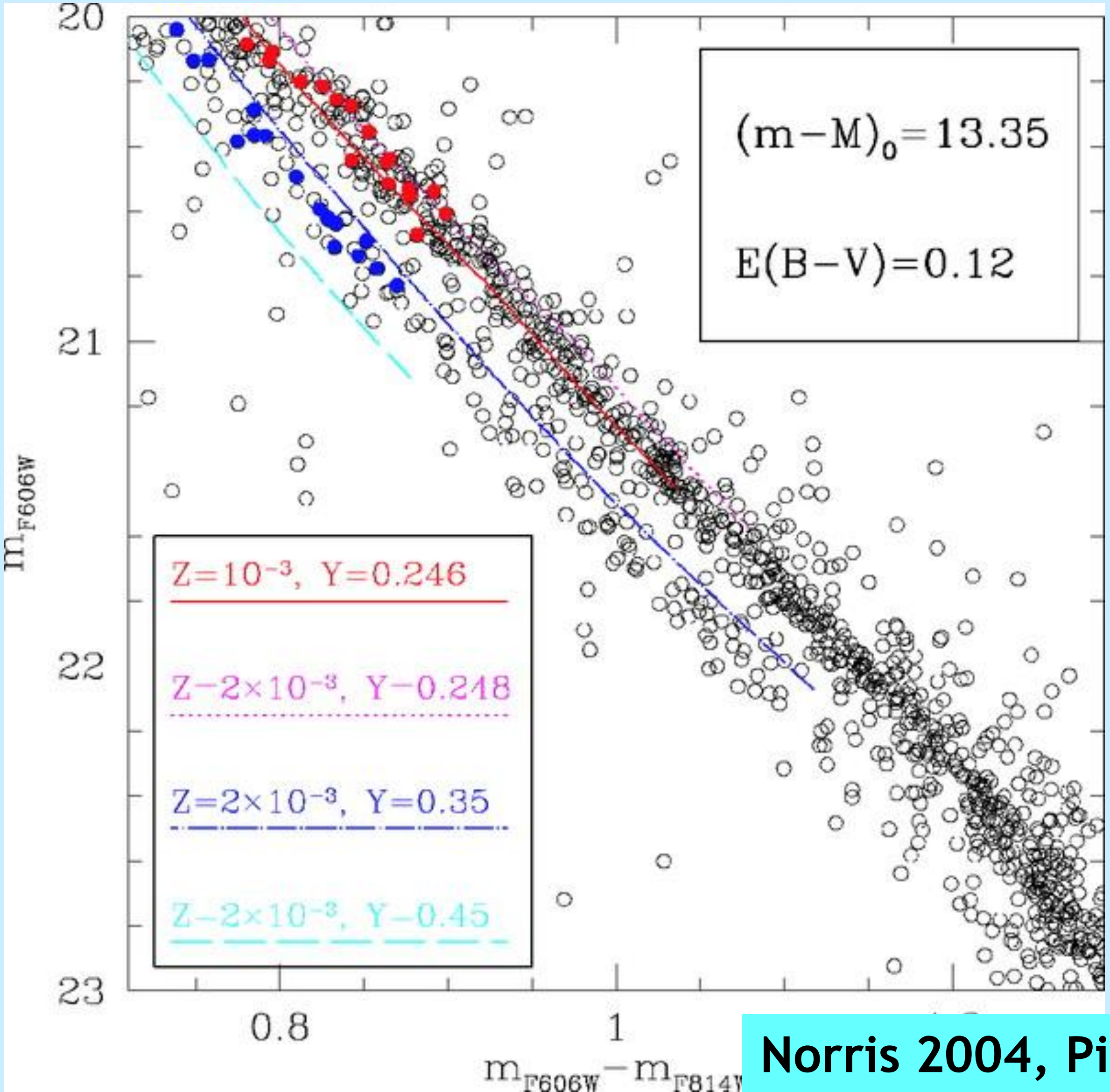
→6) The O-Na, Mg-Al anticorrelation in globular cluster stars



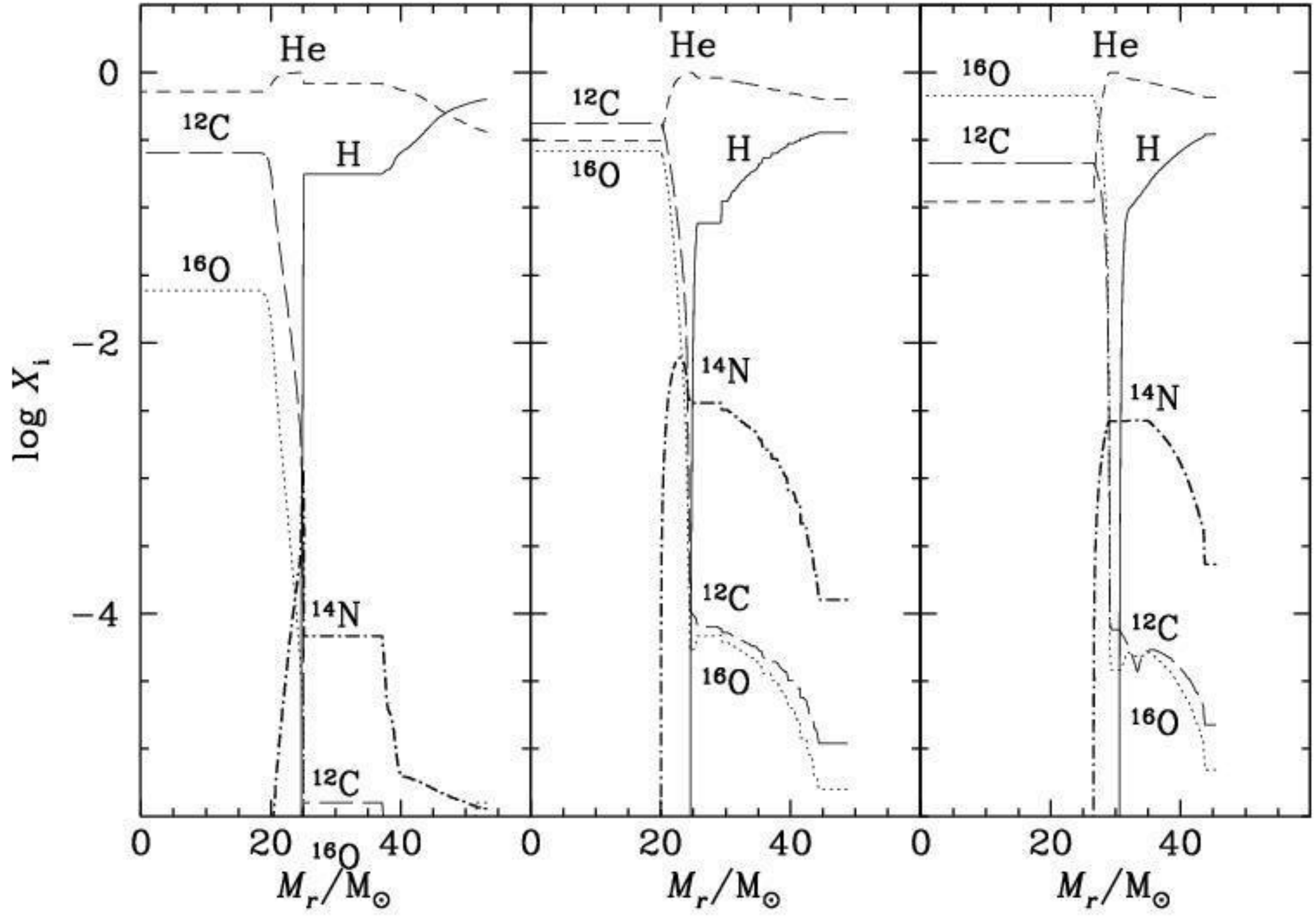
Graton et al 2004

STRIKING OBSERVATIONAL FACTS

→7) **Very Helium-rich stars in ω Centuri ?**

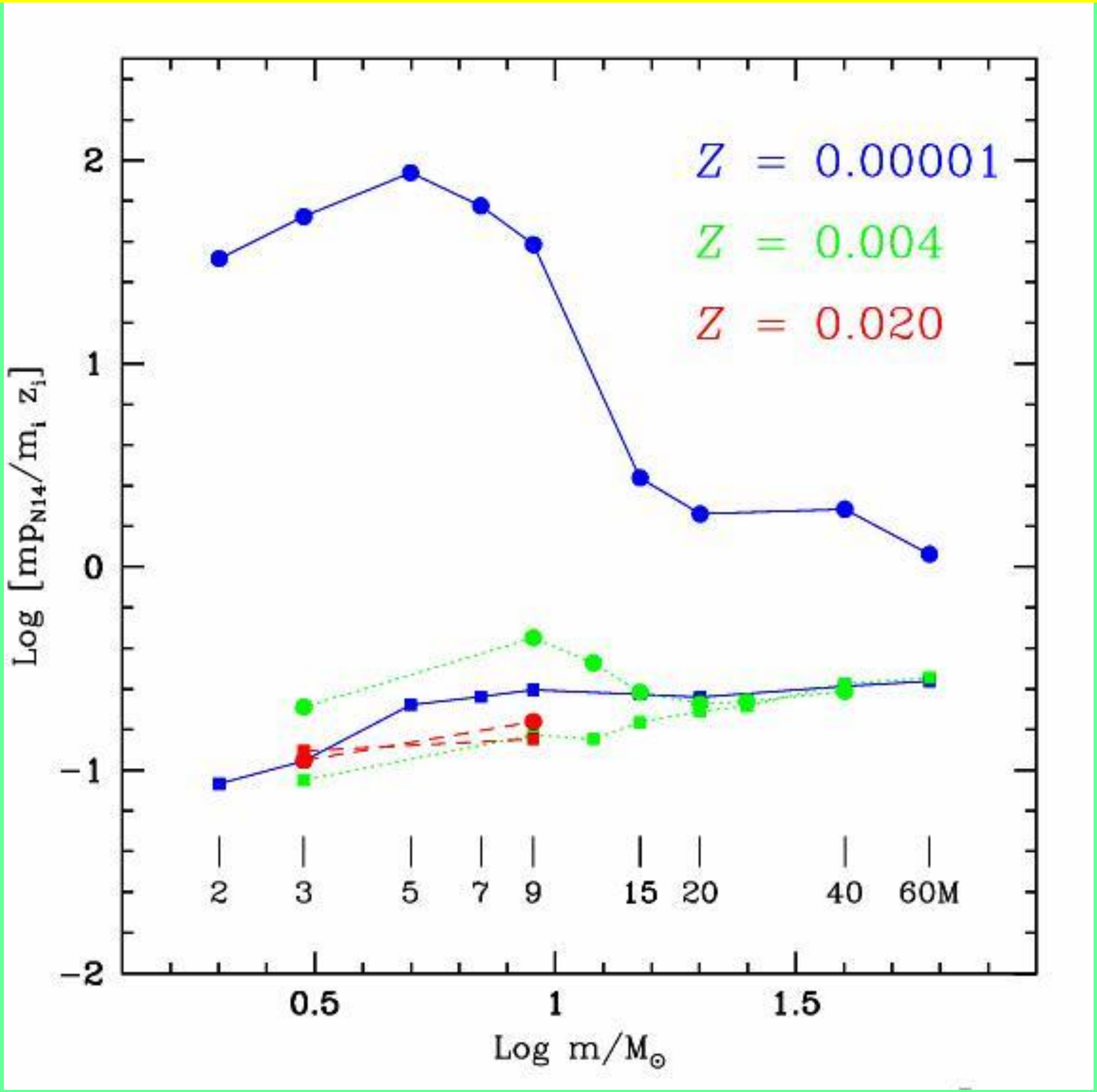


Norris 2004, Piotto et al. 2005

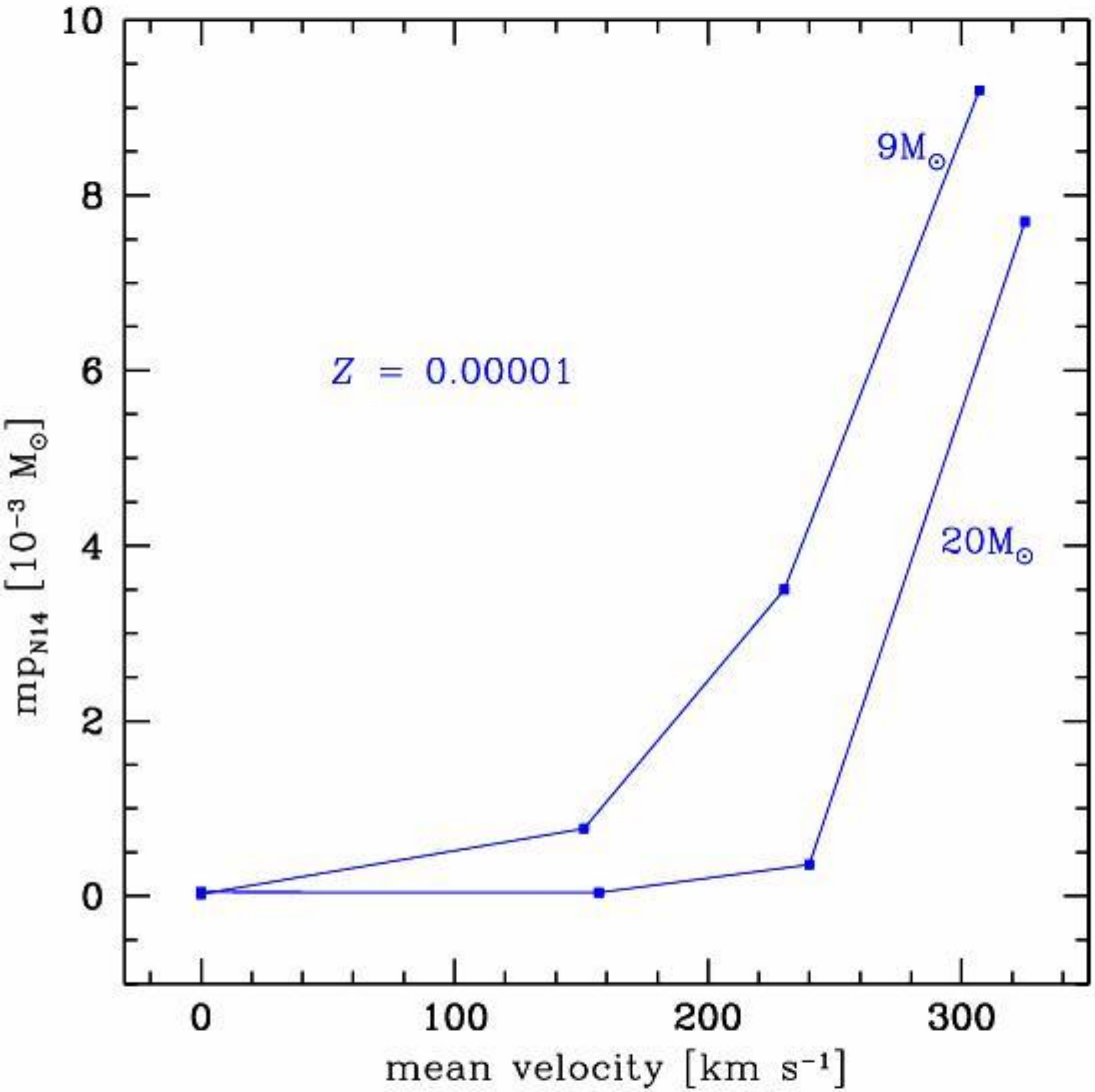


60 M_{sol}, $Z=10^{-5}$, $\Omega_{ini}/\Omega = 0.85$

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



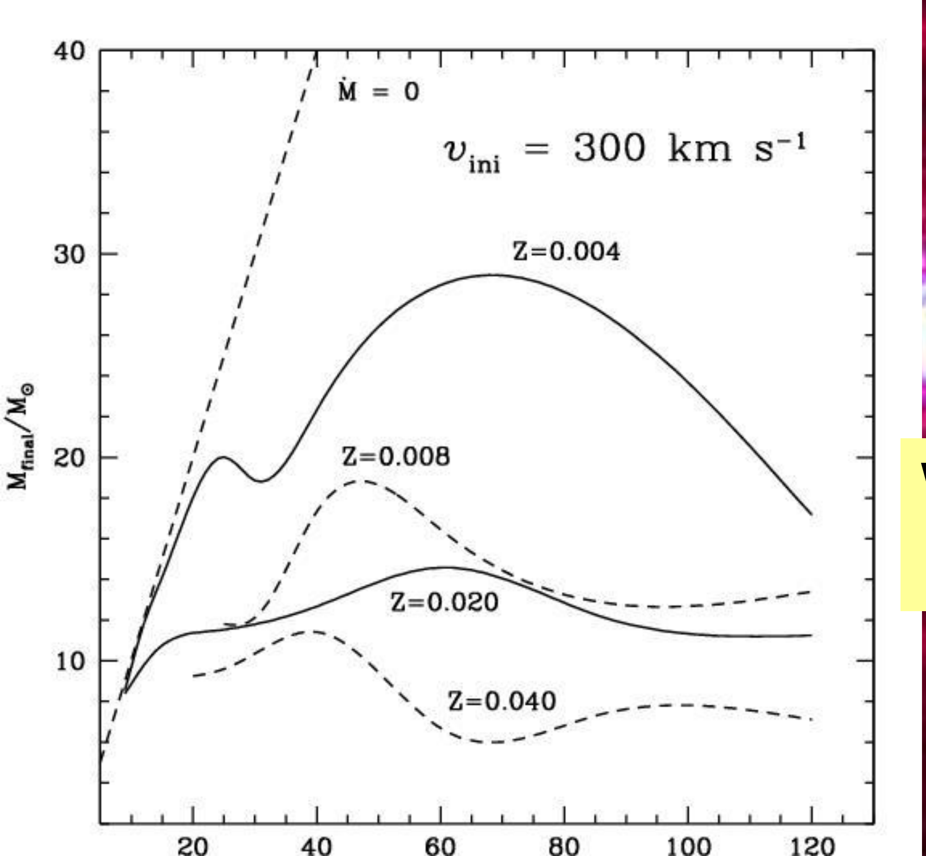
Increase of primary N production when rotation increases



At low metallicity, very weak radiatively driven stellar winds

Mass loss rate

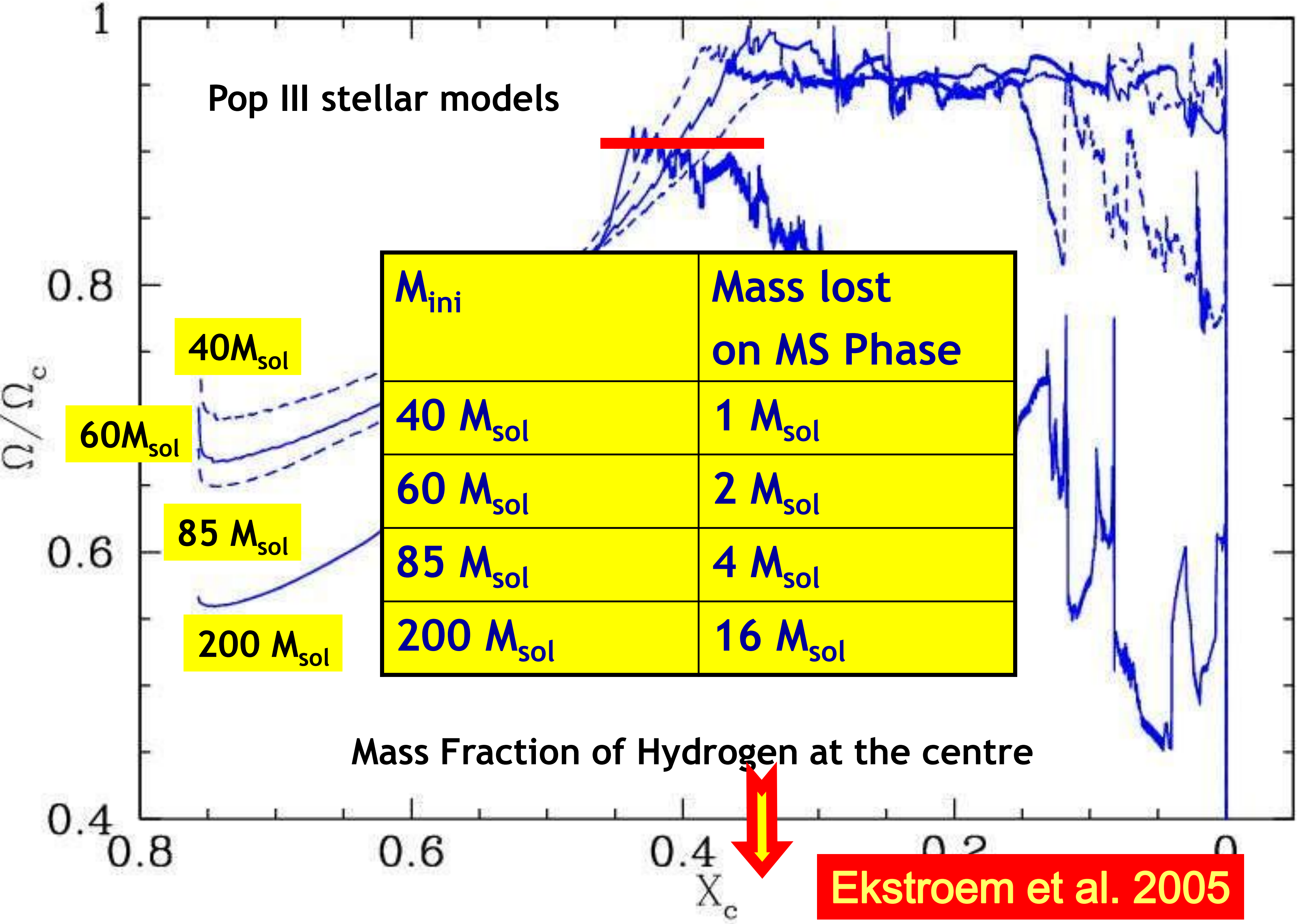
$$\dot{M}_Z = \left(\frac{Z}{Z_{sol}}\right)^{\alpha} \dot{M}_{Z_{sol}}$$



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

What happens if metal poor stars are fast rotators ?

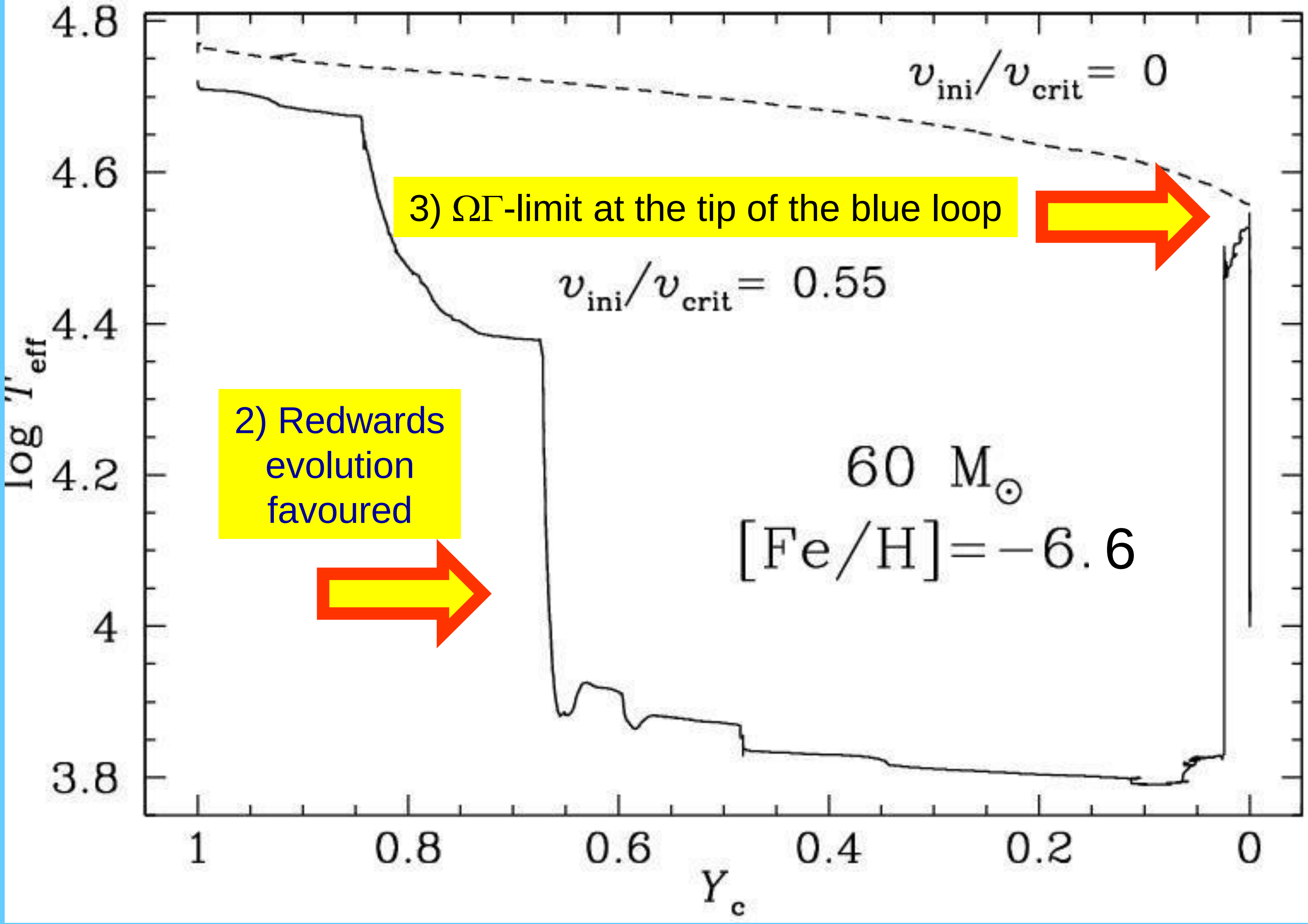
Pop III stellar models



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

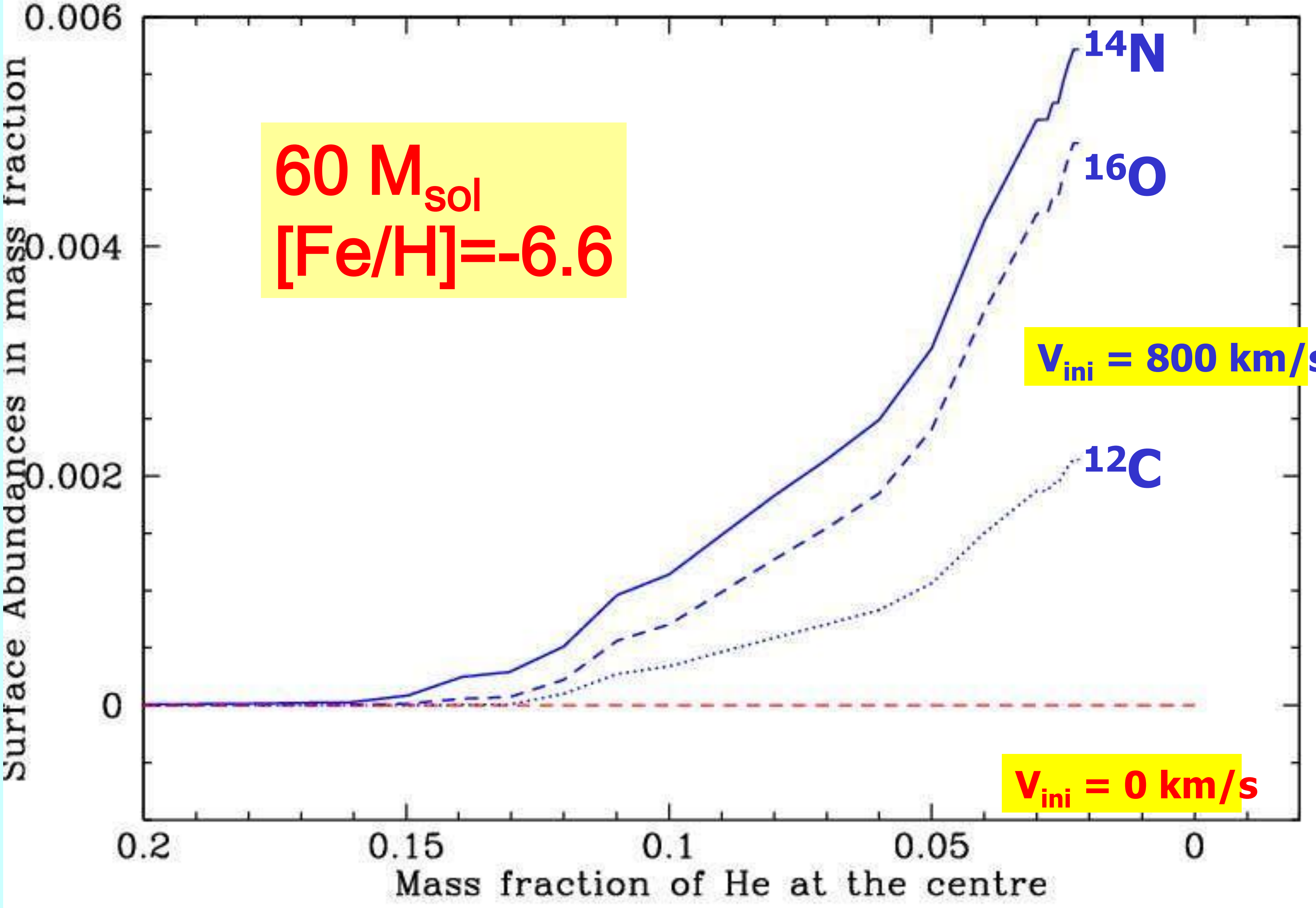
Mass Fraction of Hydrogen at the centre

Ekstroem et al. 2005

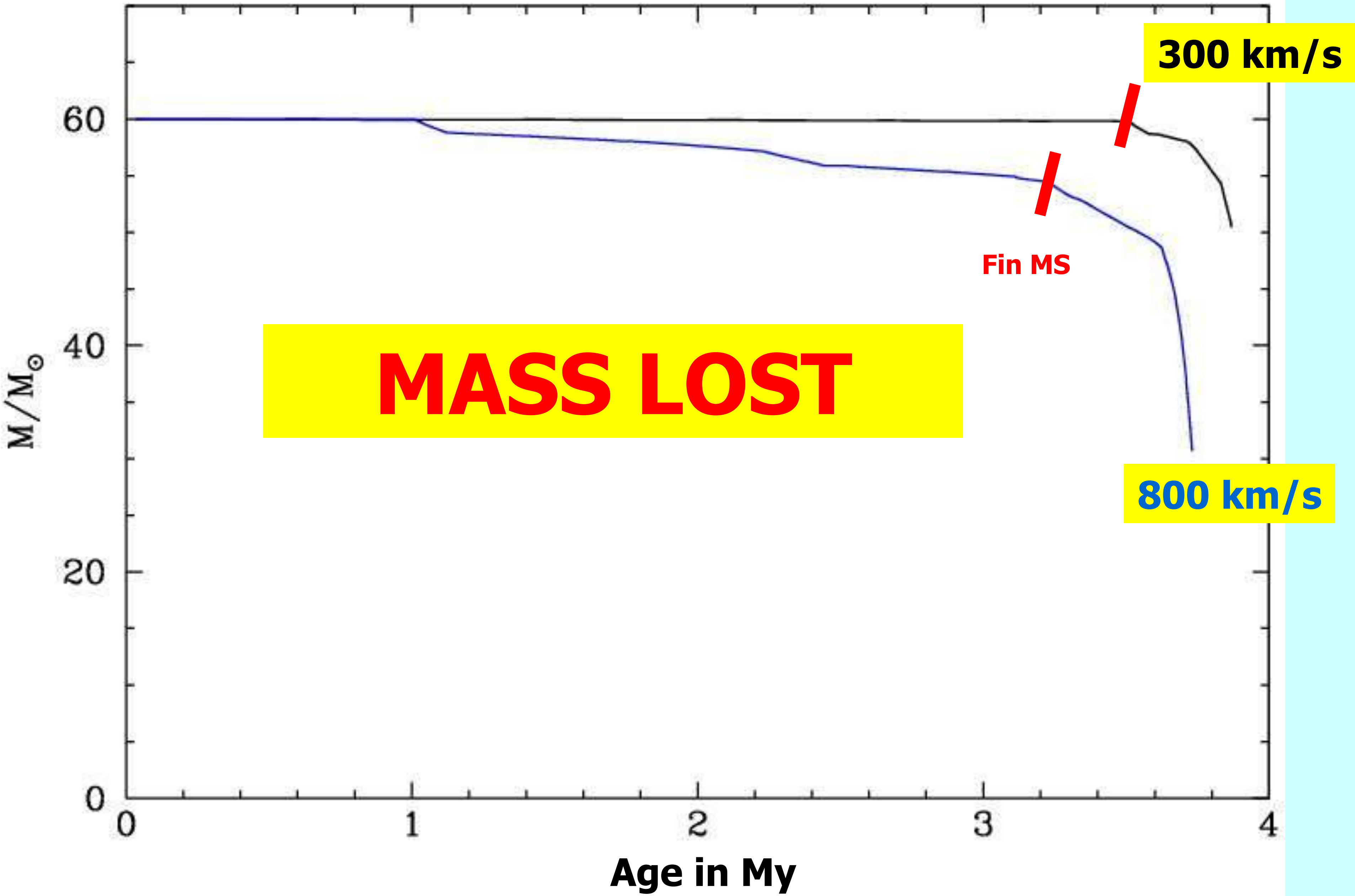


3) ΩΓ-limit at the tip of the blue loop

2) Redwards evolution favoured


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

[Fe/H]=-6.6



MASS LOST

300 km/s

800 km/s

Fin MS

IMPACTS OF ROTATION INDUCED MASS LOSS IN METAL POOR ENVIRONMENTS

- → C-rich extremely metal poor stars

Meynet, Ekström, Maeder (2006), Hirschi (2006)

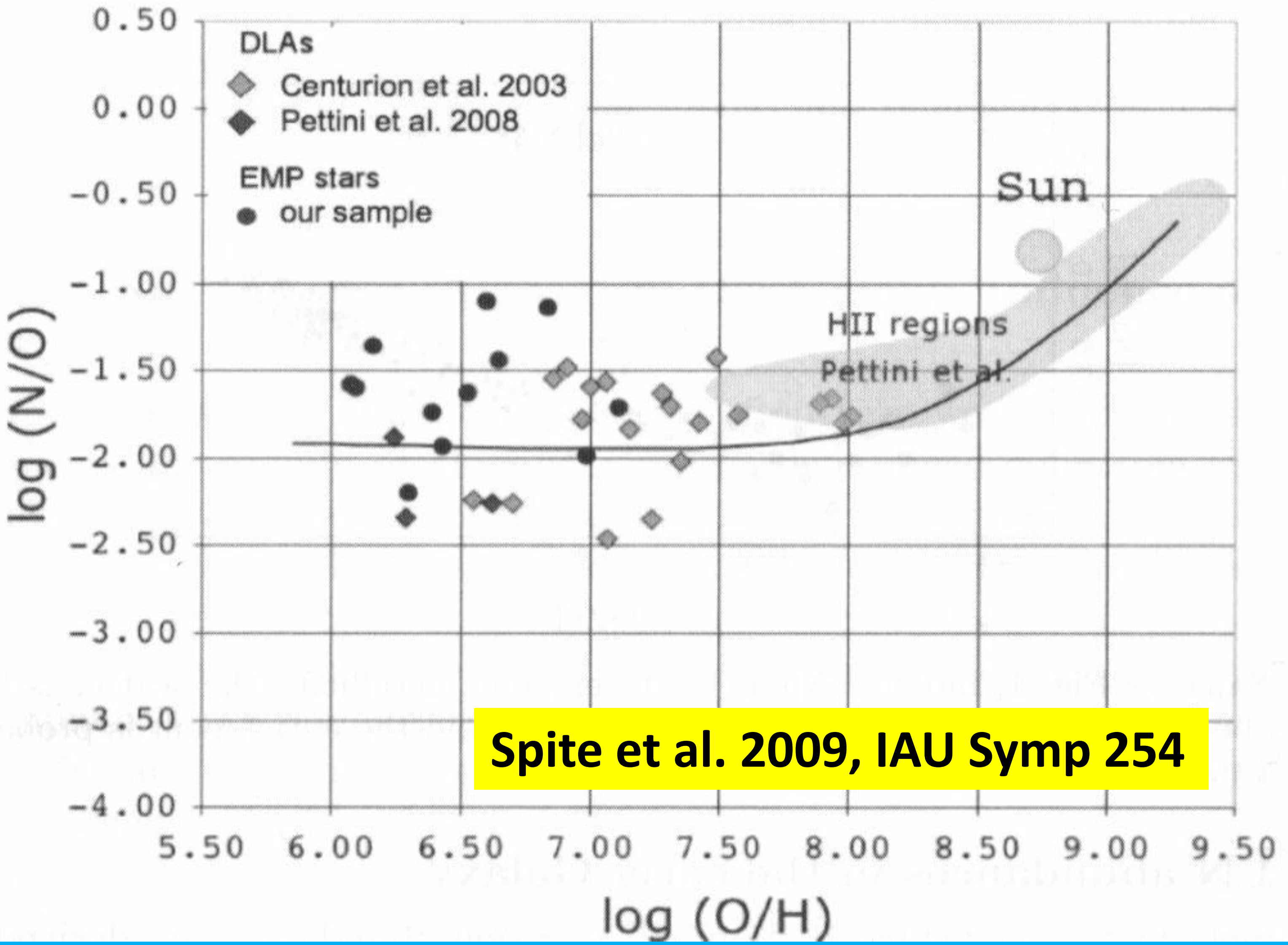
- → He-rich stars in ω Cen

Maeder & Meynet (2006)

- → Abundance inhomogeneities in globular clusters

Decressin, Meynet, Charbonnel, Prantzos, Ekström, submitted

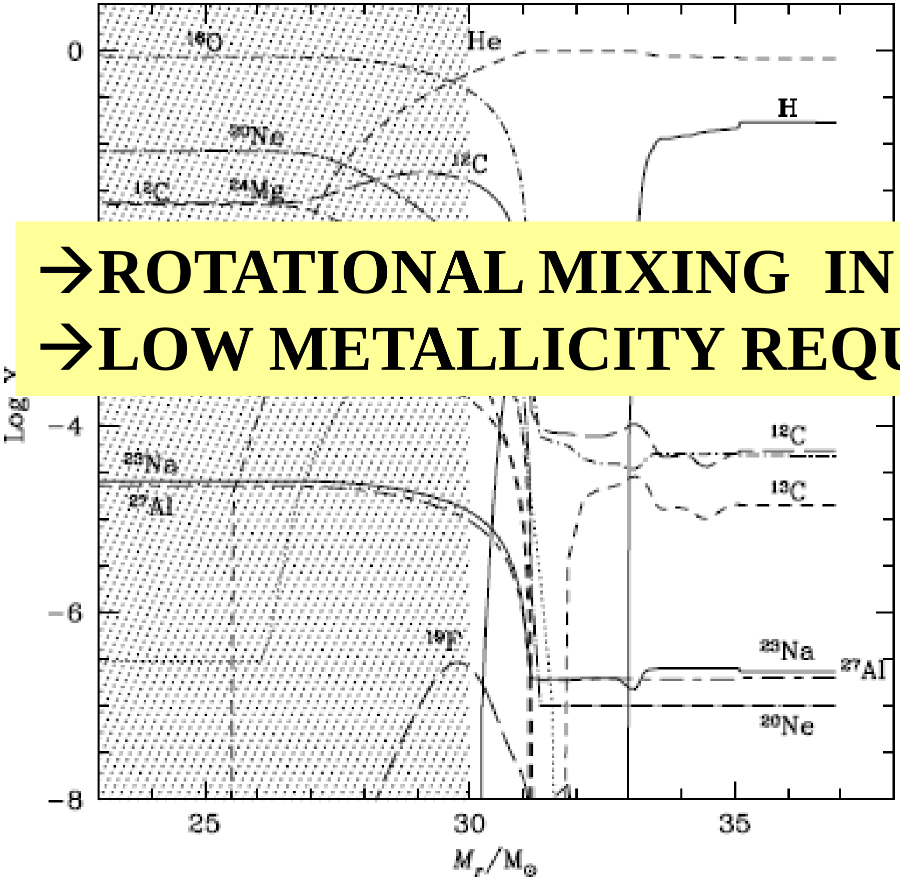
IMPORTANT PRODUCTION OF PRIMARY NITROGEN



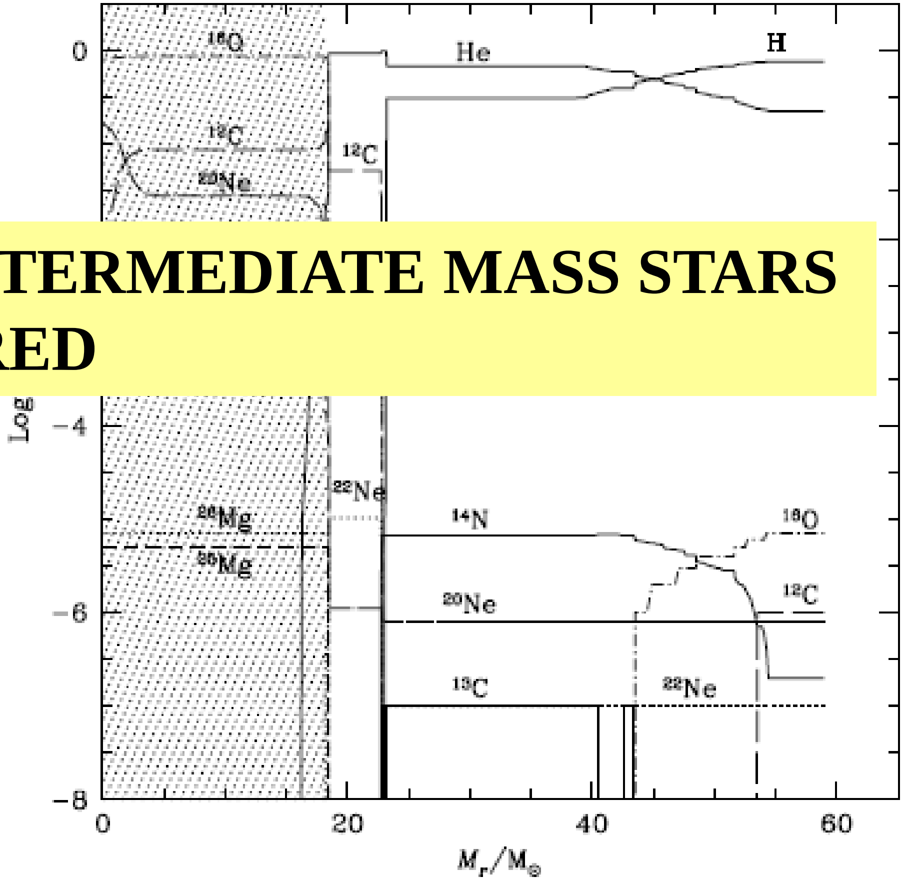
Spite et al. 2009, IAU Symp 254

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

$V=800\ km\ s^{-1}$



$V = 0\ km\ s^{-1}$



→ROTATIONAL MIXING IN INTERMEDIATE MASS STARS

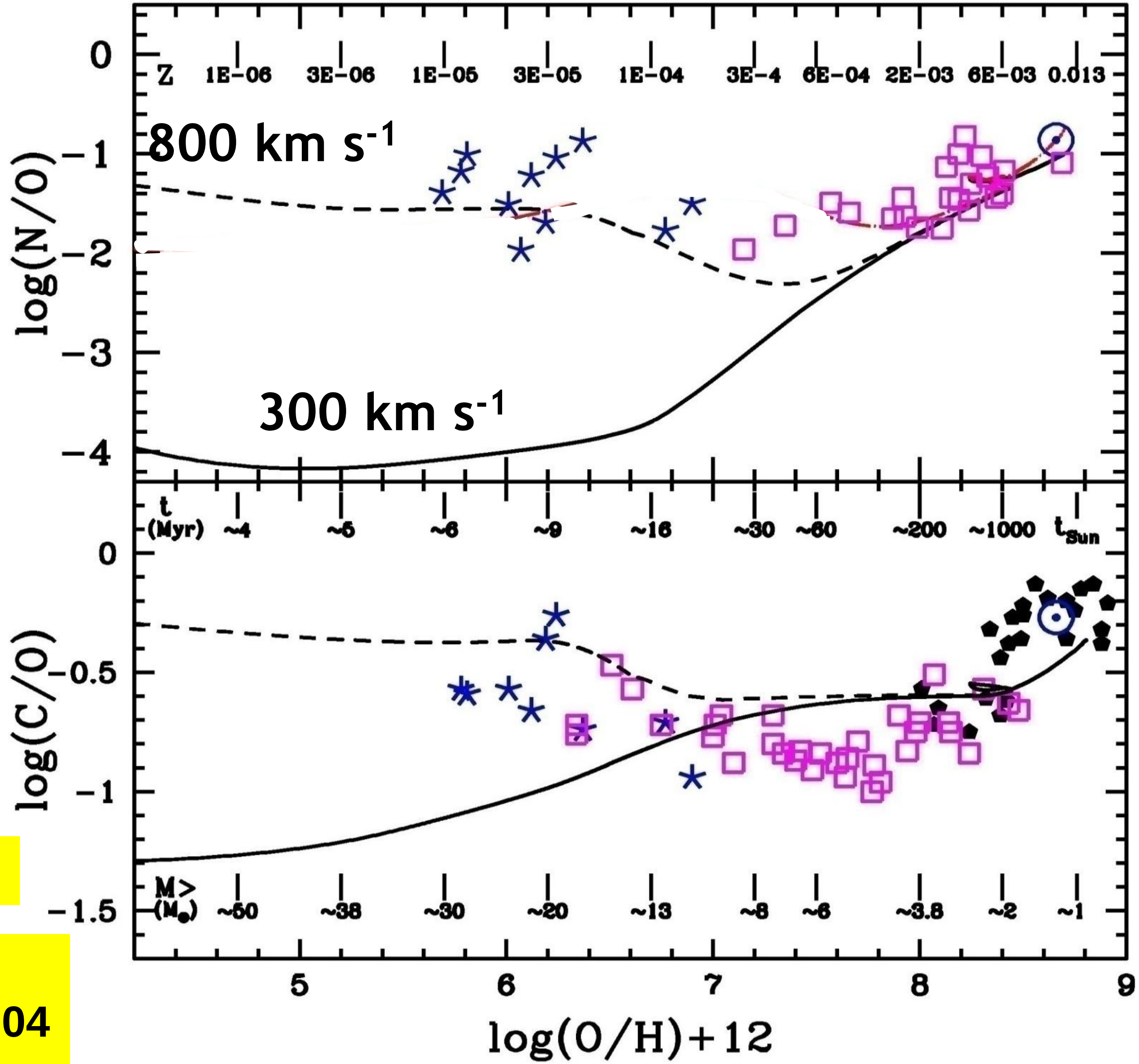
→LOW METALLICITY REQUIRED

NITROGEN

WINDS

N/O

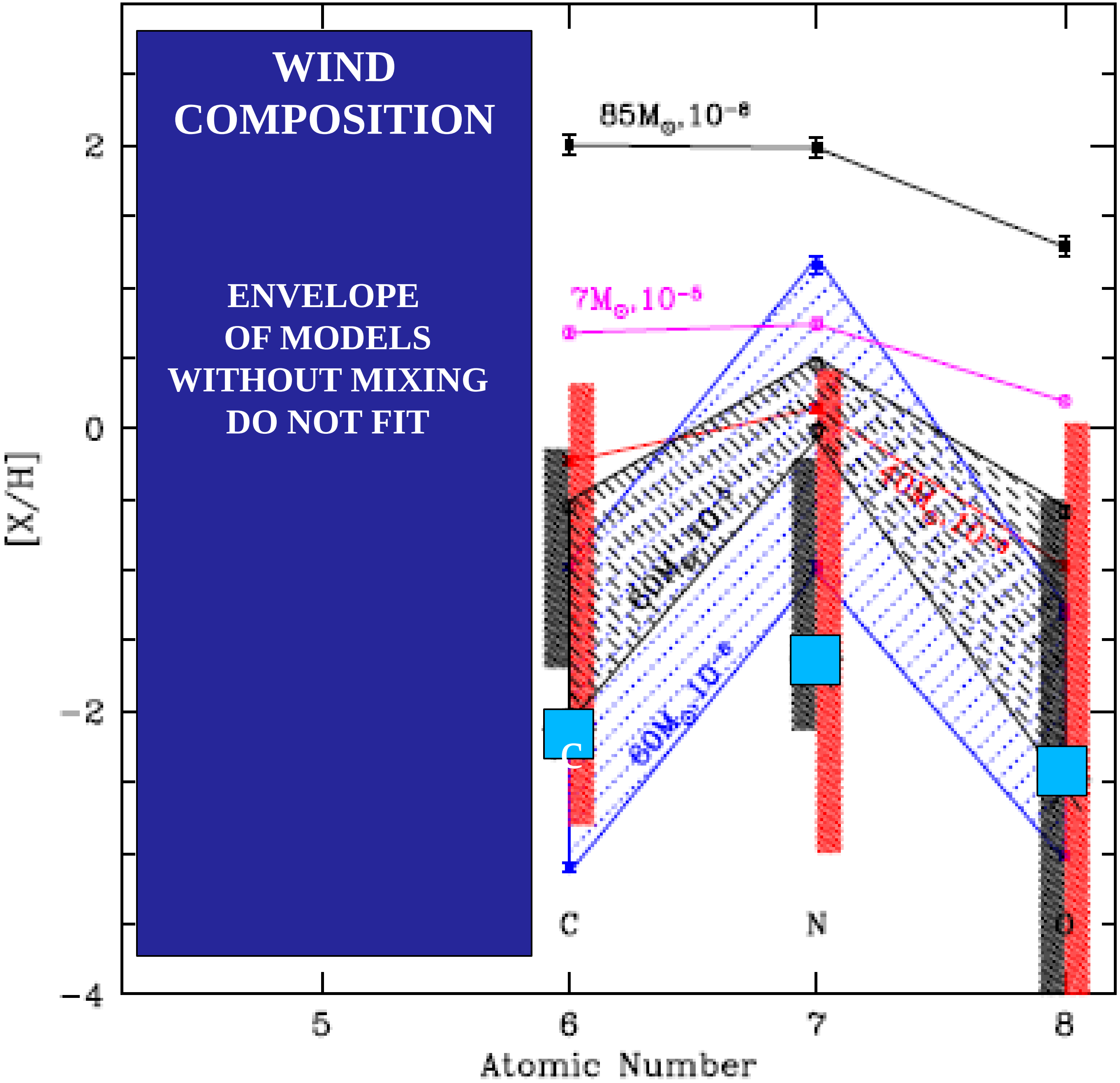
C/O



Observations from

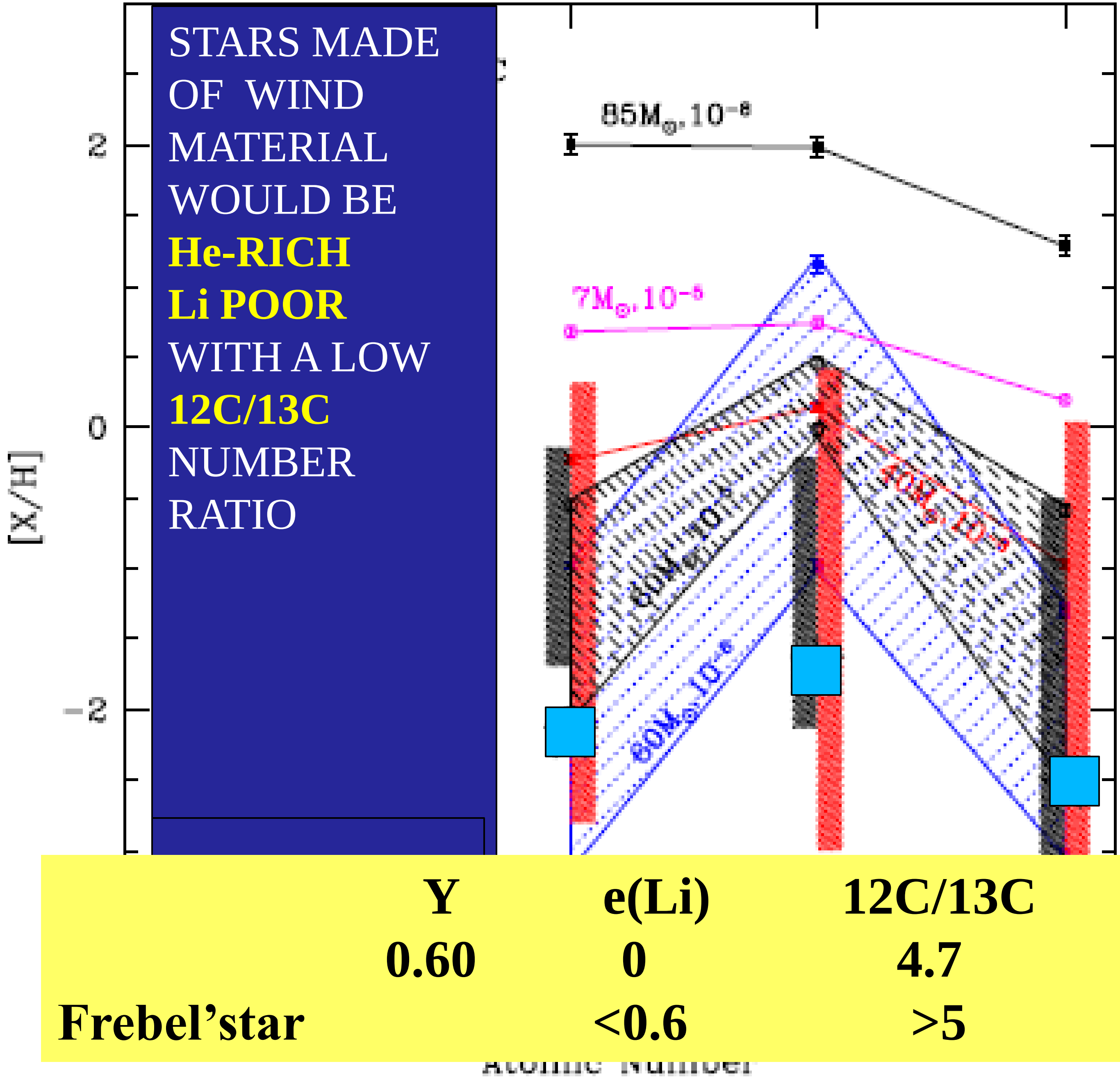
Spite et al. 2005
Akerman et al. 2004
Nissen 2004

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



WIND COMPOSITION

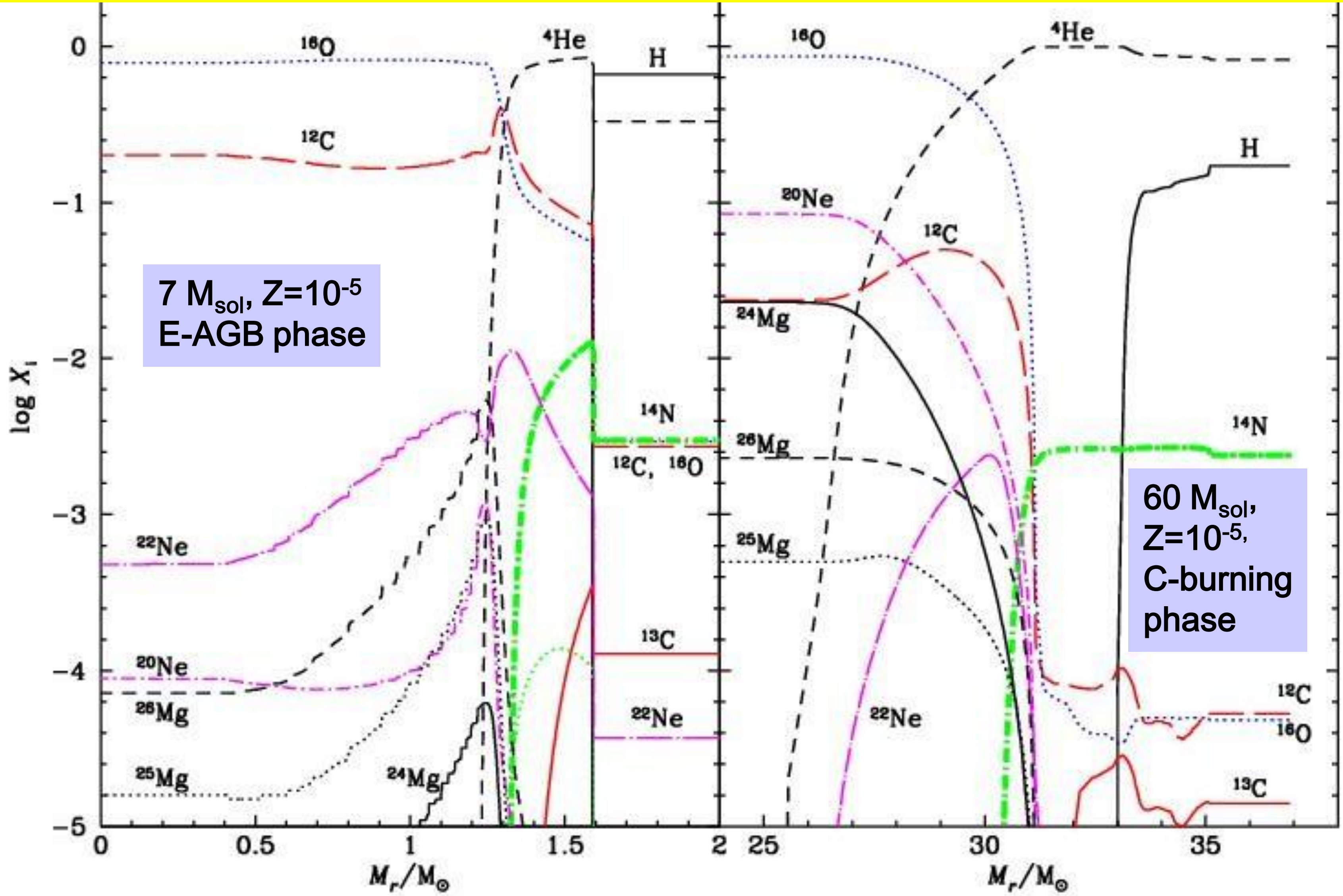
ENVELOPE
OF MODELS
WITHOUT MIXING
DO NOT FIT



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

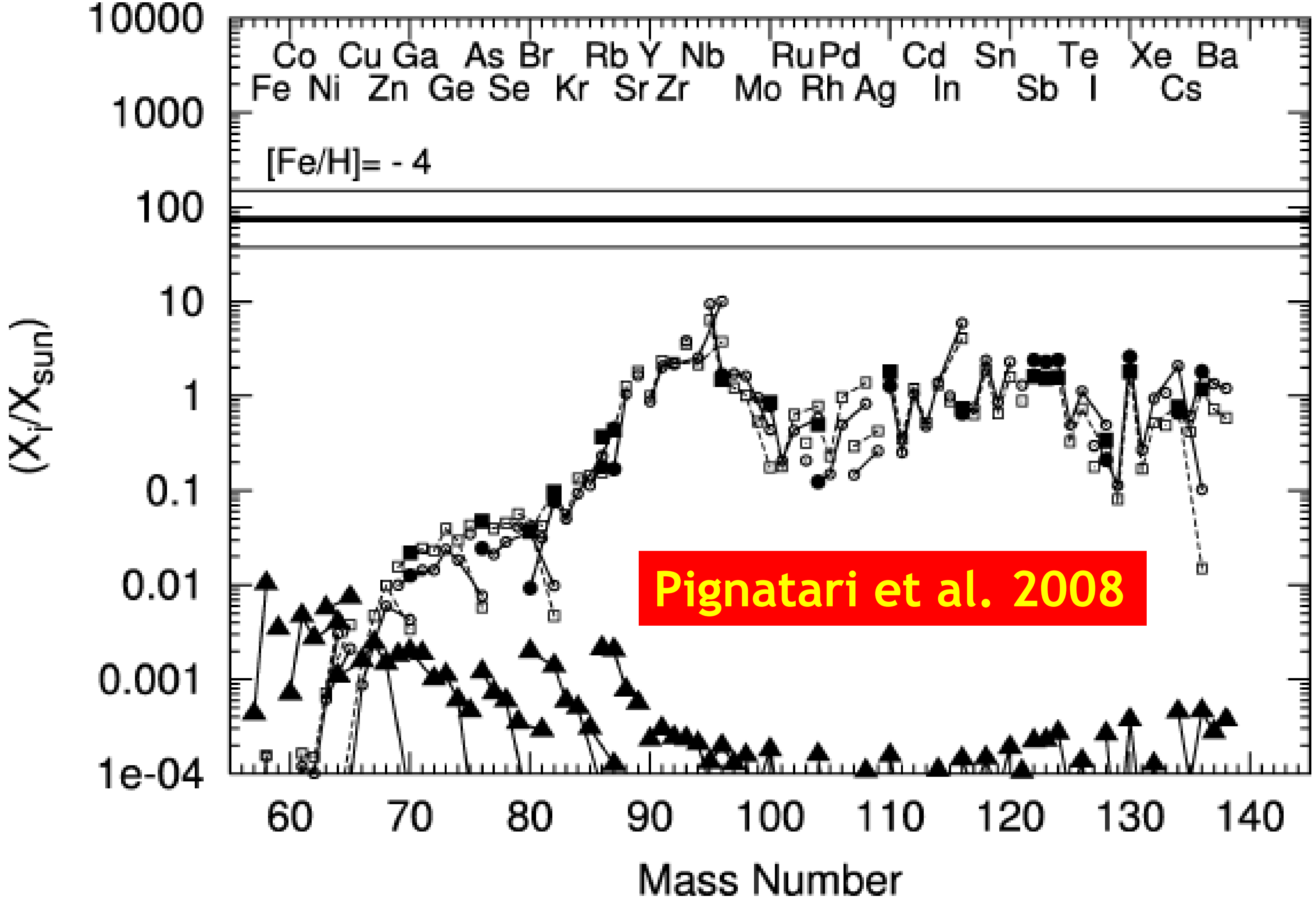
	Y	**e(Li)**	**12C/13C**
	0.60	**0**	**4.7**
Frebel'star		**<0.6**	**>5**

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



7 M_{sol}, Z=10^{-5}
E-AGB phase

60 M_{sol},
Z=10^{-5},
C-burning
phase



Pignatari et al. 2008

DOUBLE SEQUENCE.

Blue Sequence

[Fe/H]=-1.26

[C/M]=0

M→ Metals

[N/M]=1-1.5

[Ba/M]=0.7

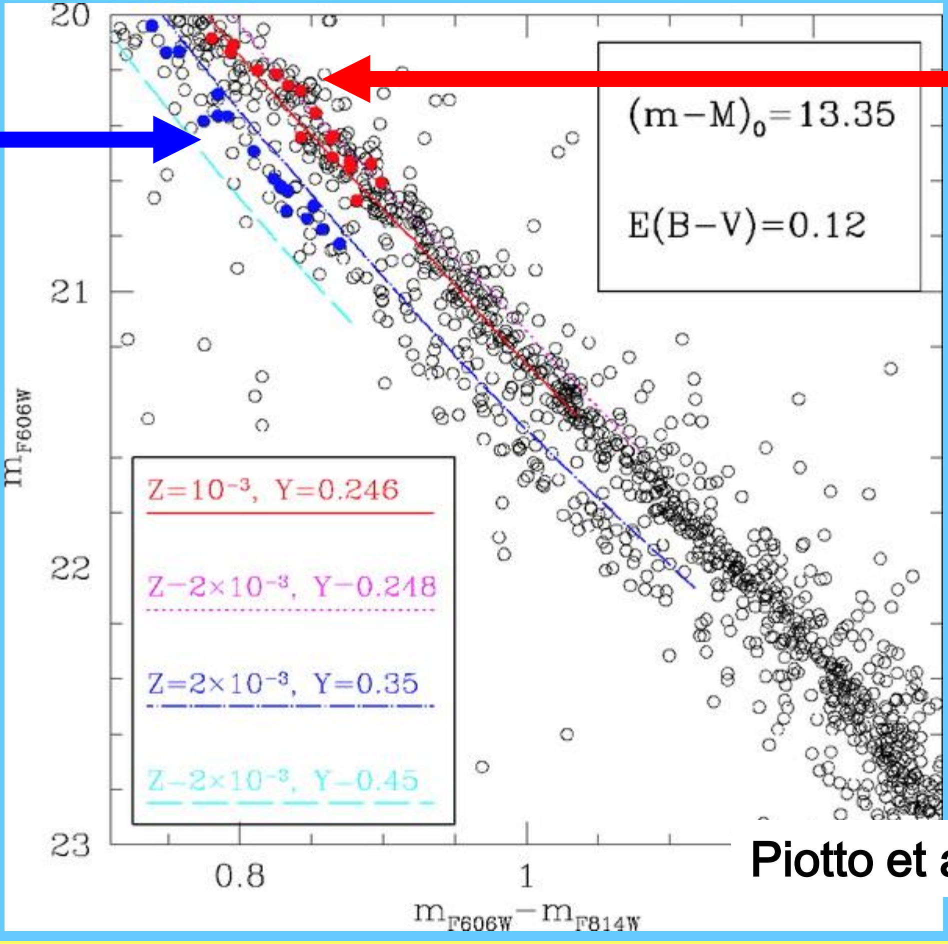
Red Sequence

[Fe/H]=-1.57

[C/M]=0

[N/M] < 1.0

[Ba/M]=0.4



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

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

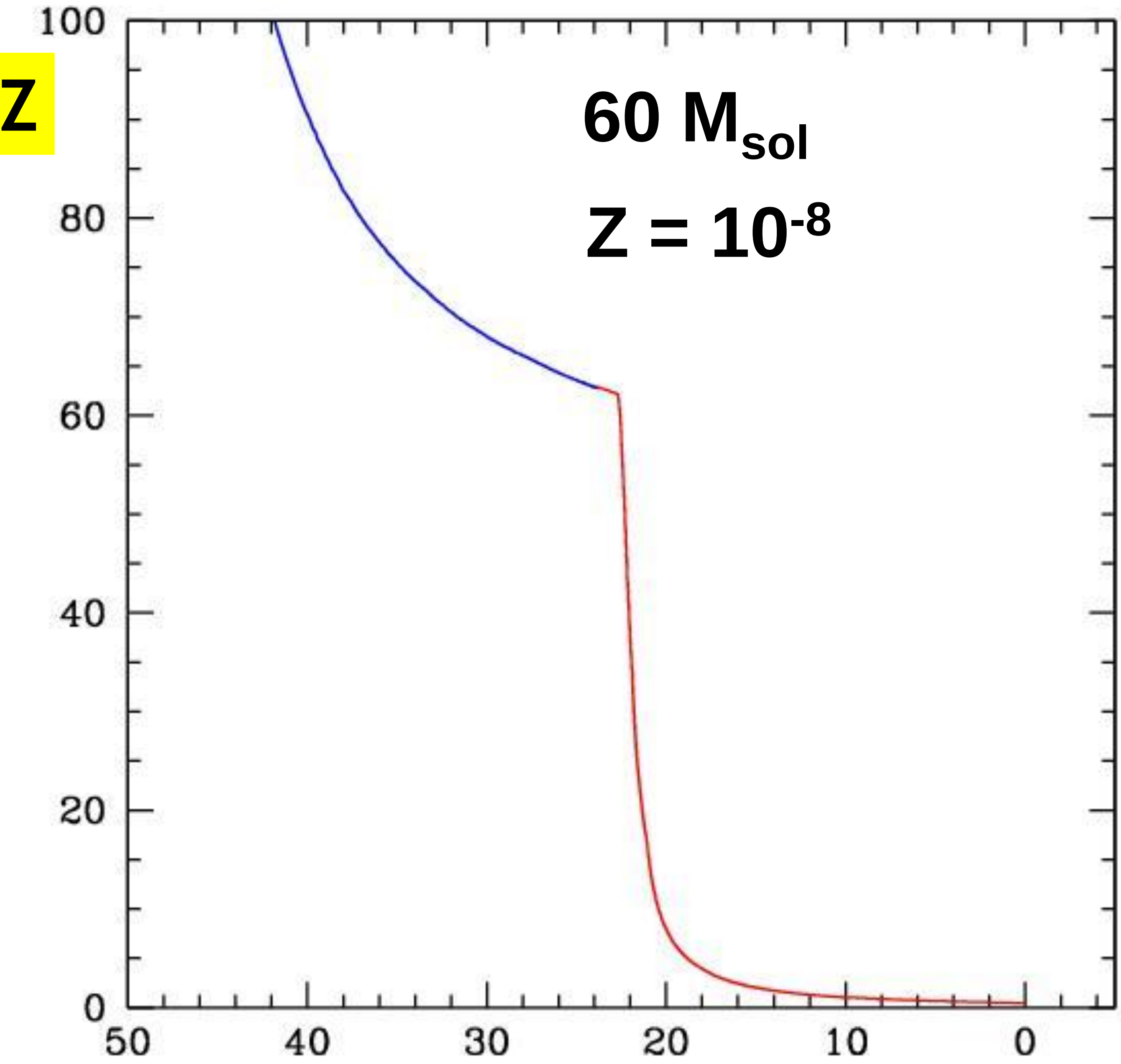
2

Y=0.38

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

Y=0.25

$\Delta Y/\Delta Z$

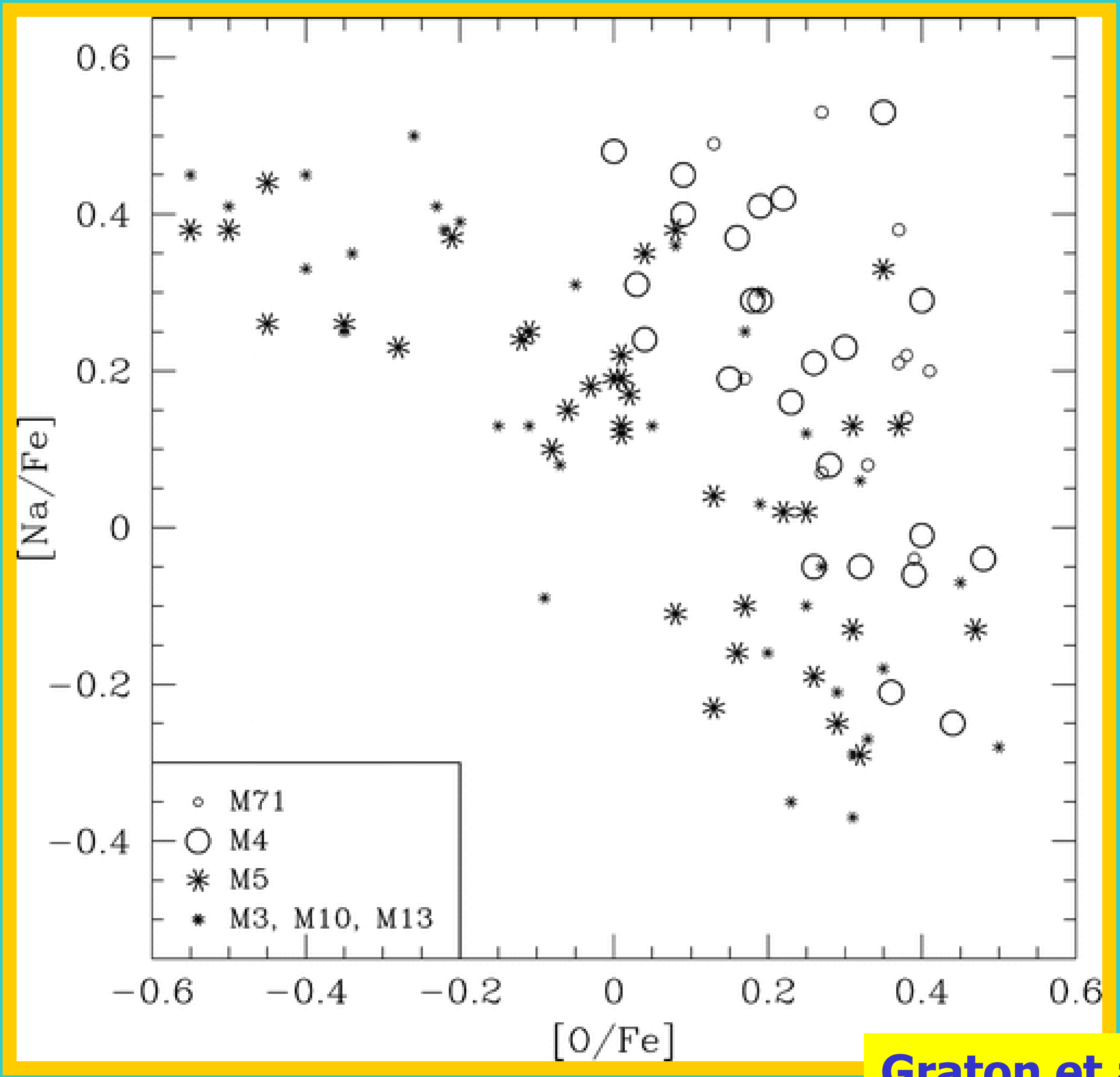


60 M_{sol}

$Z = 10^{-8}$

remaining mass in solar masses

GLOBULAR CLUSTERS: O-poor and Na-rich stars



Graton et al 2004

60 M_{sol}

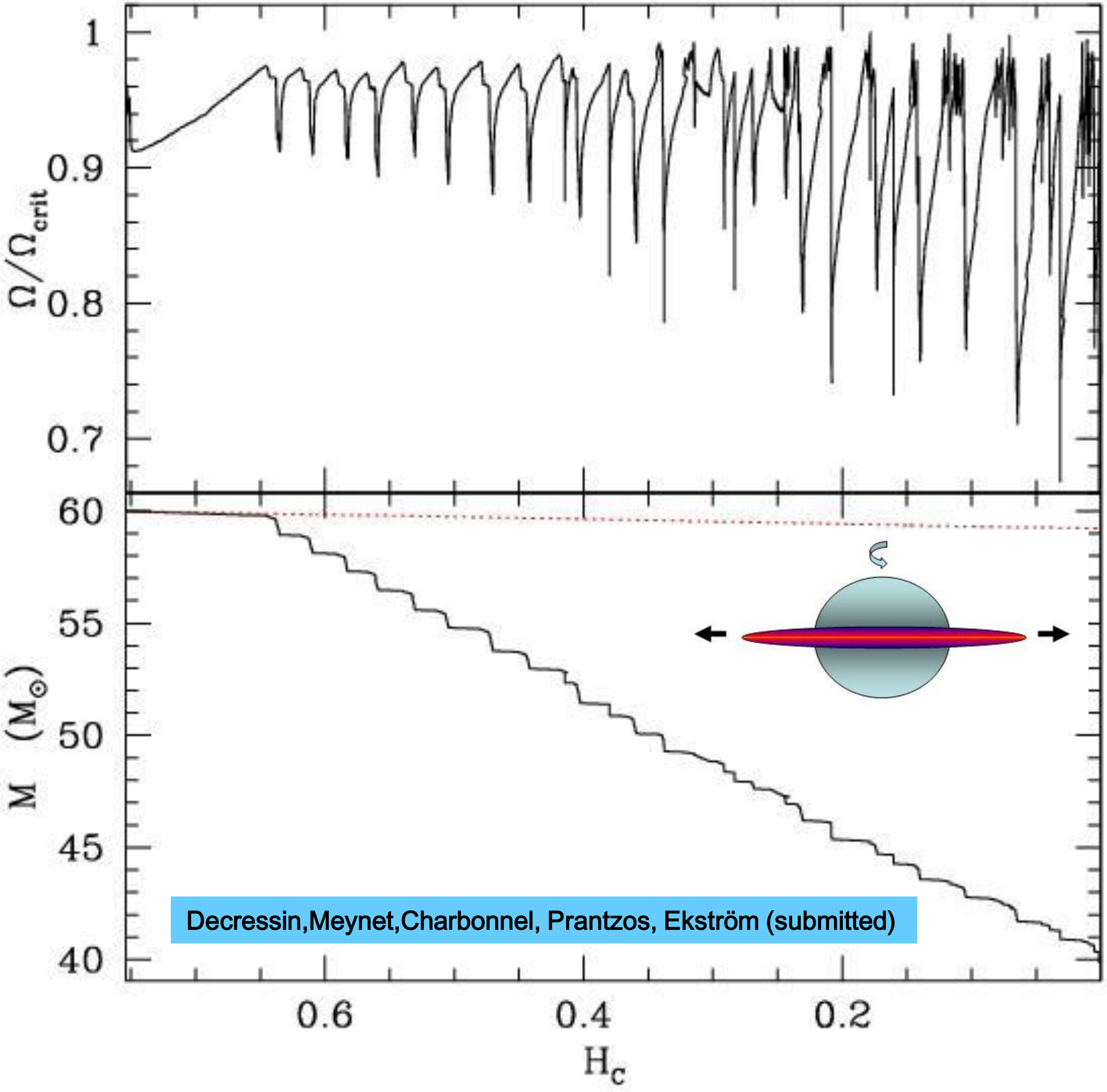
$Z=0.0006$

On Main-Sequence

20 M_{sol} lost

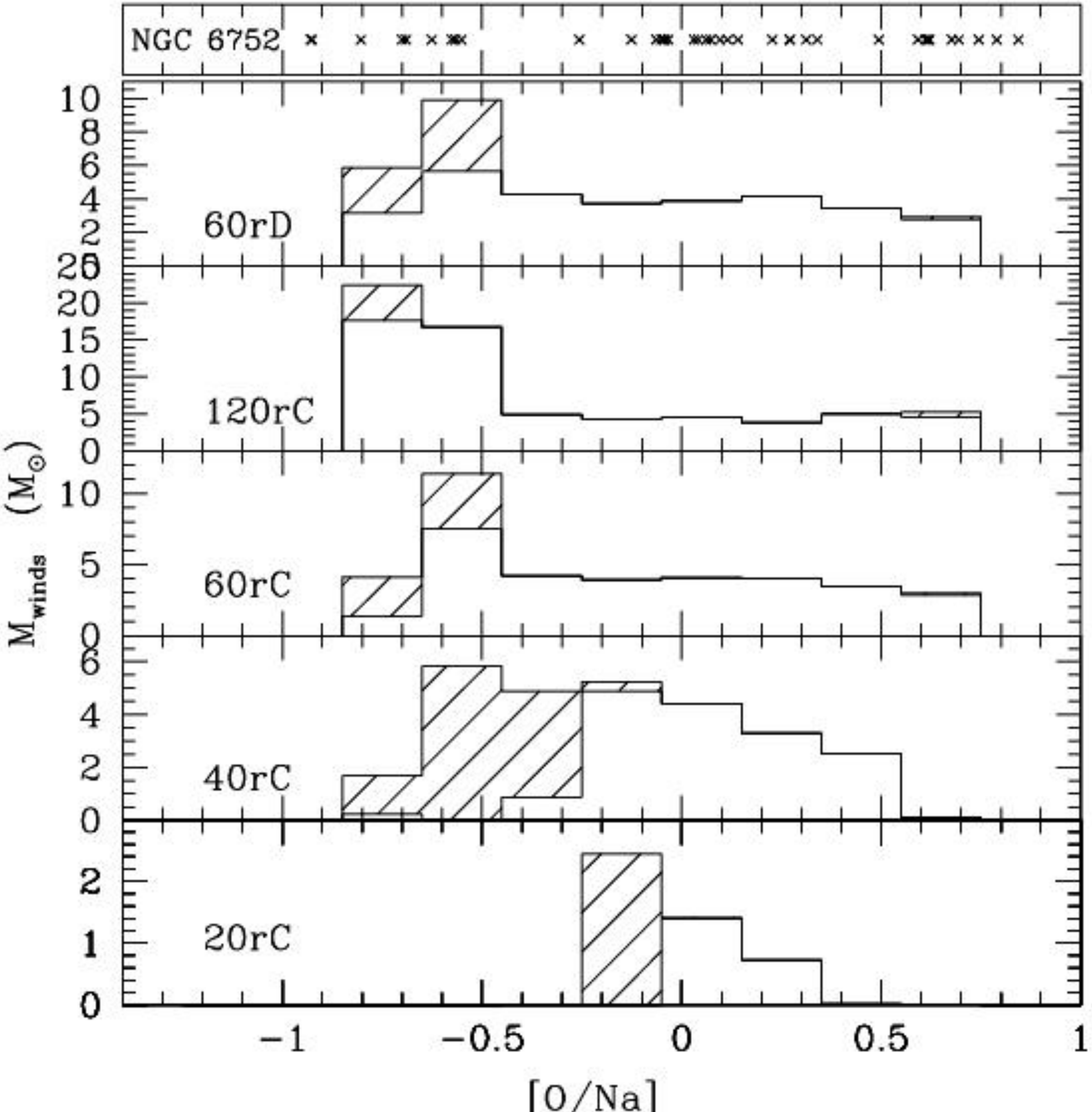
Non rotating model

0.8 M_{sol} lost



Decressin,Meynet,Charbonnel, Prantzos, Ekström (submitted)

[O/Na]


NGC 6752
60rD
120rC
60rC
40rC
20rC
M_{winds} $(M_\odot)$
10
8
6
4
2
0
20
15
10
5
0
10
5
0
6
4
2
0
2
1
0
−1
−0.5
0
0.5
1
[O/Na]

EFFECTS OF ROTATION AT VERY LOW METALLICITY

CHEMICAL MIXING ENHANCED

STARS MAY LOOSE GREAT AMOUNT OF MASS

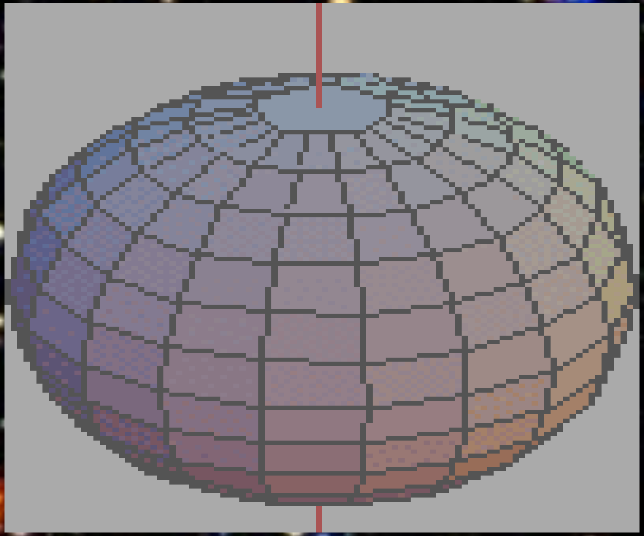
→ LUMINOSITY, IONIZING POWER

→ YIELDS

→ IMPACT ON FINAL FATE

Evolution = f (M, Z, Ω, …)

- Lifetimes, tracks
- Evolution properties Be, B[e], LBV, WR stars in galaxies
- Nebulae
- Evolution of rotational velocities
- Cepheid properties
- Abundances in massive stars and red giants
- Primary N
- Pre - supernova stages
- Chemical yields and nucleosynthesis
- Rotation periods of pulsars
- Final masses
- Collapsars, γ- bursts, ….



ROTATION AND MASS LOSS

Radiatively driven stellar winds

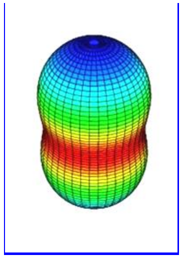
$$\frac{\dot{M}(\Omega)}{\dot{M}(0)} \approx \frac{(1-\Gamma)^{\frac{1}{\alpha}-1}}{\left(1-\frac{4}{9}\frac{v^2}{v^2_{crit,1}}-\Gamma\right)^{\frac{1}{\alpha}-1}}$$

Increase of mass loss

Maeder & Meynet 2000

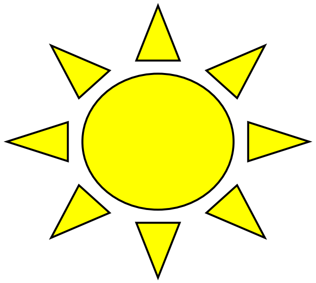
Anisotropies (fast rotation)

Owocki, 1996; Maeder, 1999



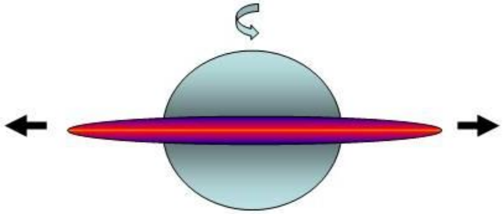
Surface enrichments

Meynet et al. 2006
Hirschi 2007



``Mechanical mass loss”

Reaching of the critical or break-up limit Ω_{limit}



CONCLUSION

HIGH CNO, LOW 12C/13C → MIXING BETWEEN He- AND H-burning zone
→ ONLY OUTER LAYERS EJECTED

IF He-RICH: LOW DILUTION WITH ISM, NEARLY PURE EJECTA,

IF NORMAL-He : SIGNIFICANT DILUTION WITH ISM
→ IF LI-POOR
NECESSARILY IN SITU DEPLETION OF Li

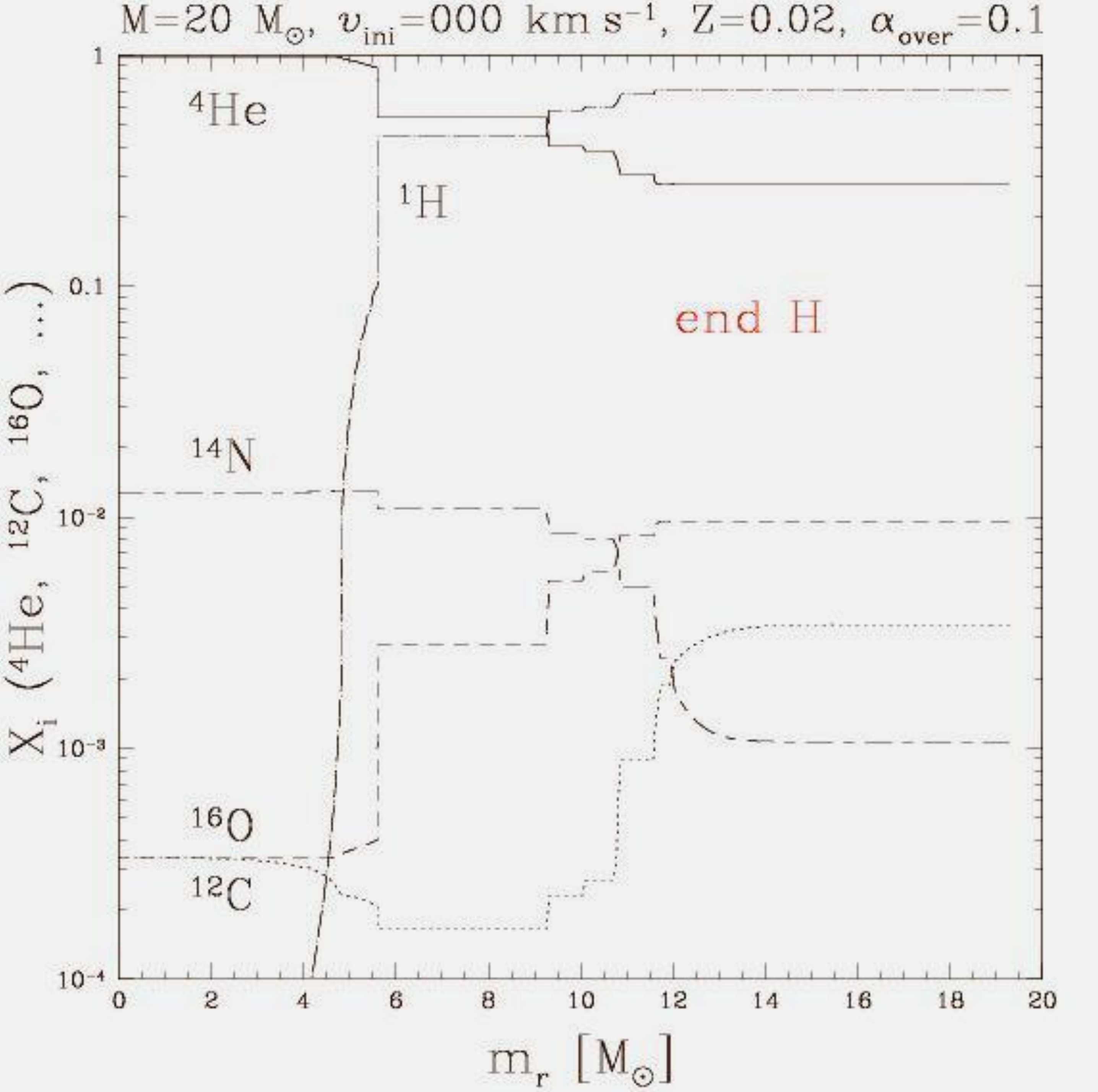
OTHER CONSTRAINTS

Ne-Na, Mg-Al

s-process elements

r-process elements

ROTATION?


$M=20\ M_\odot,\ \upsilon_{ini}=000\ km\ s^{-1},\ Z=0.02,\ \alpha_{over}=0.1$
^4He
^1H
end H
^{14}N
^{16}O
^{12}C
$X_i\ (^4He,\ ^{12}C,\ ^{16}O,\ \ldots)$
1
0.1
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10
12
14
16
18
20
$m_r\ [M_\odot]$

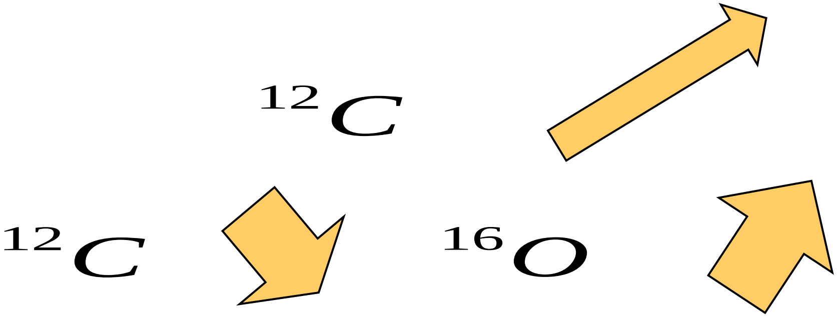
3α Salpeter 52, Hoyle et al. 53

$$^{4}He(\alpha,\gamma)^{8}Be(\alpha,\gamma)^{12}C$$

$$\tau_{Be} \approx 10^{-16}\ \mathrm{sec}$$

$$^{12}C(\alpha,\gamma)^{16}O(\alpha,\gamma)^{20}Ne$$

- Beginning of He-burning
- End of He-burning



^{12}C

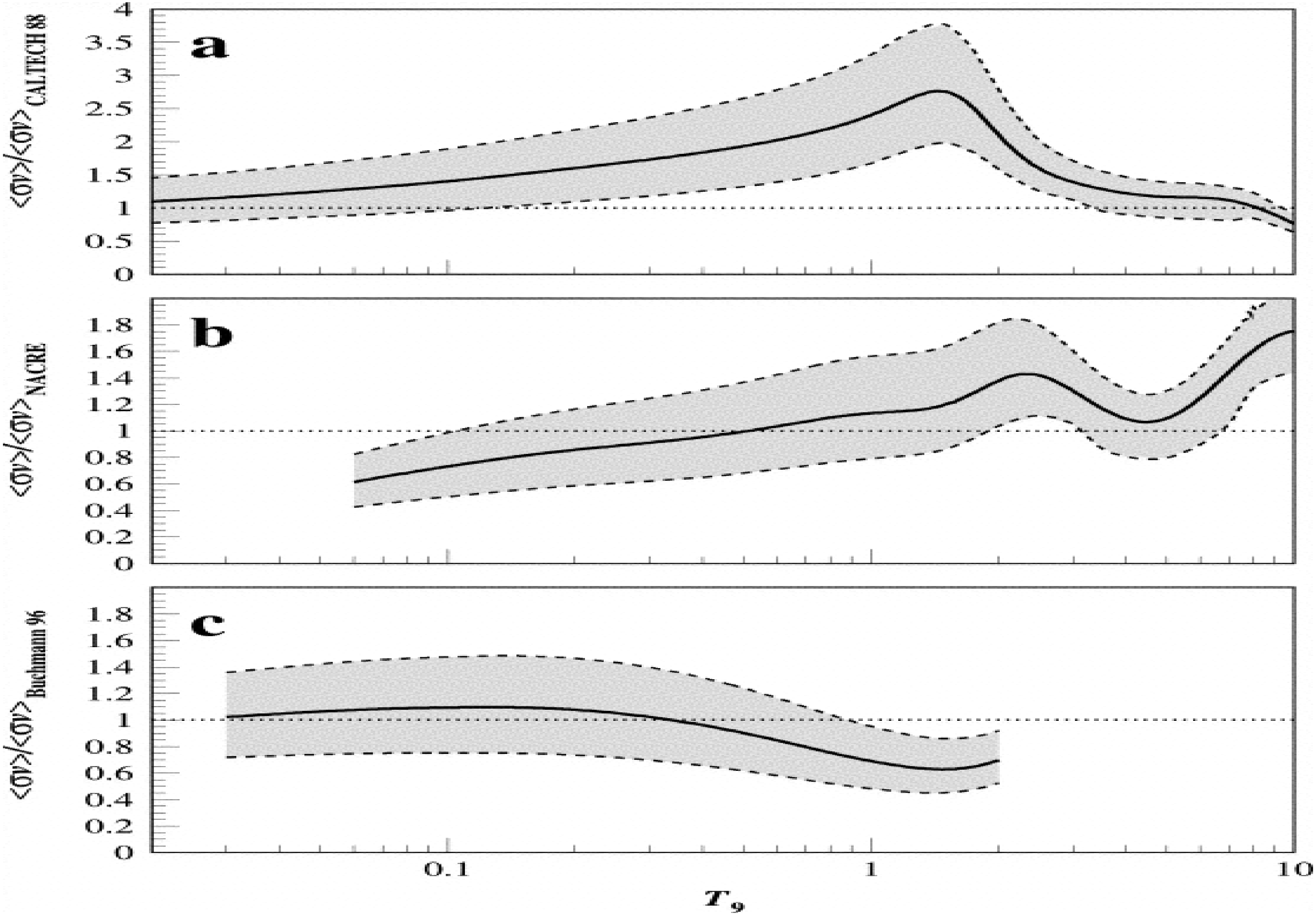
^{12}C

^{16}O

Determine chemical composition of the core at the end of the He-burning phase

Affects the next evolutionary phases

Kunz et al. 2002



Rate of $^{12}C(\alpha,\gamma)^{16}O$ uncertain

Higher is the rate

⇒ **More oxygen synthesized.**

⇒ **Shorter C-burning phase**

⇓

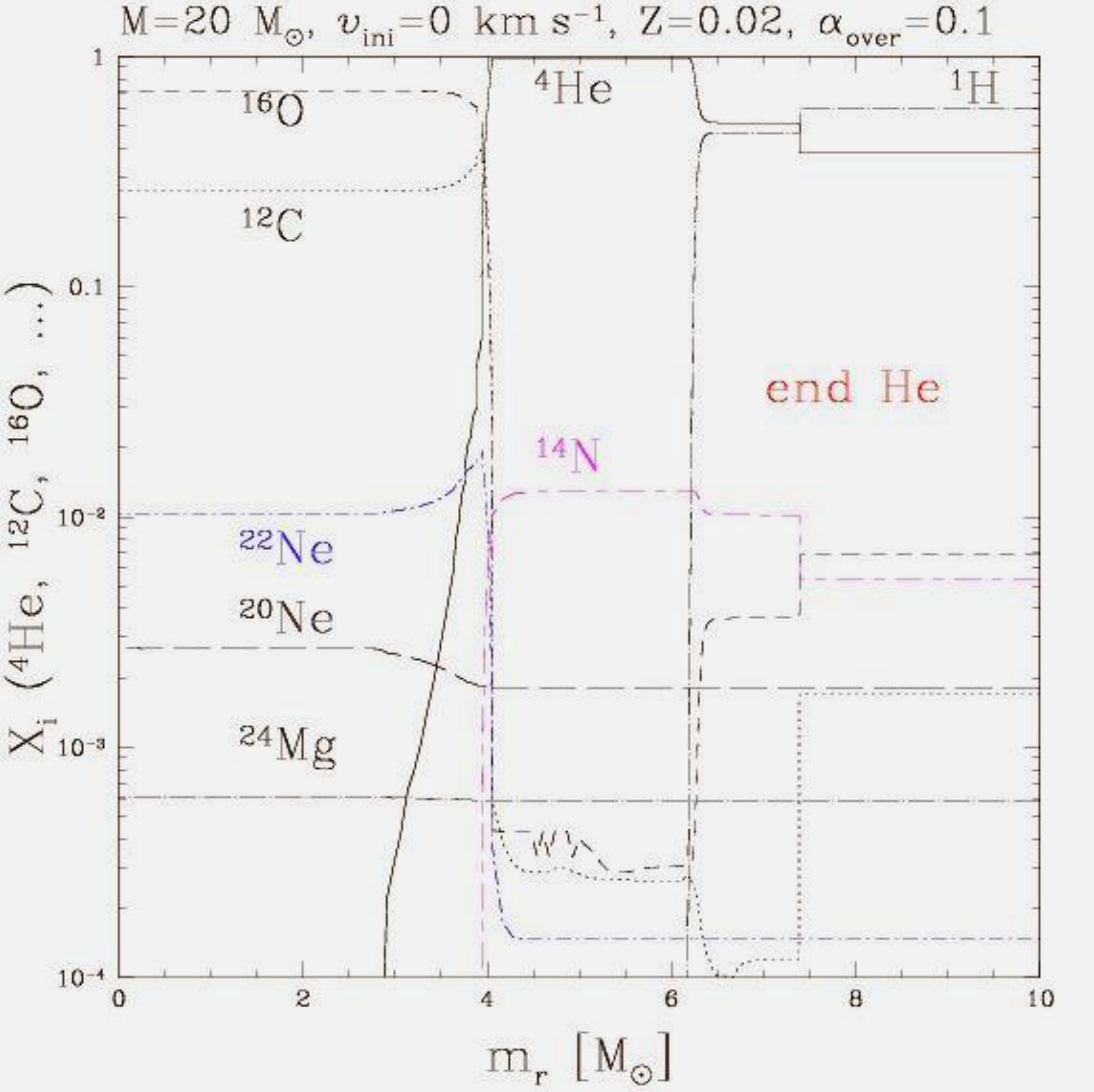
Less time for the entropy to be evacuated from the central regions

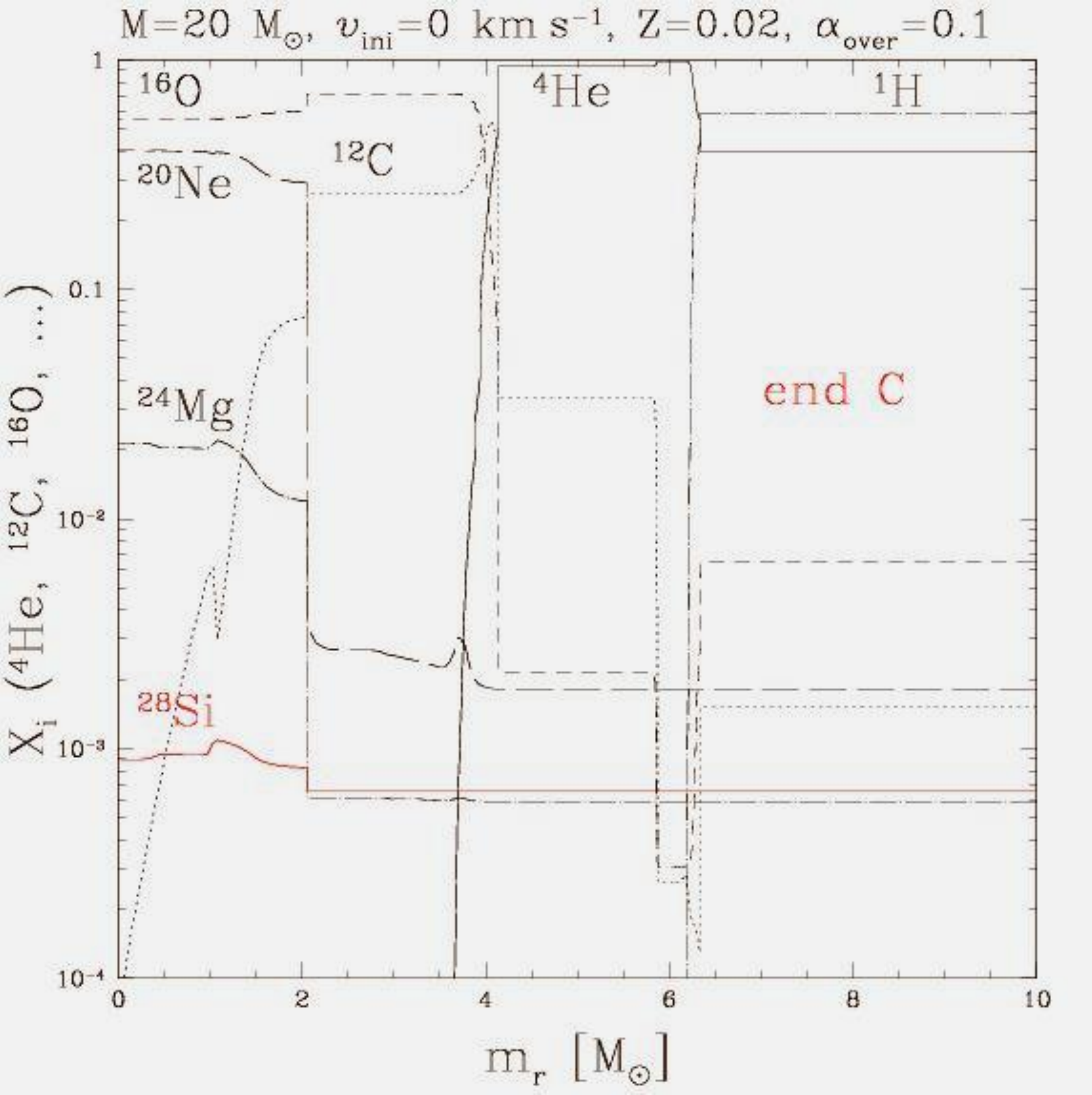
⇓

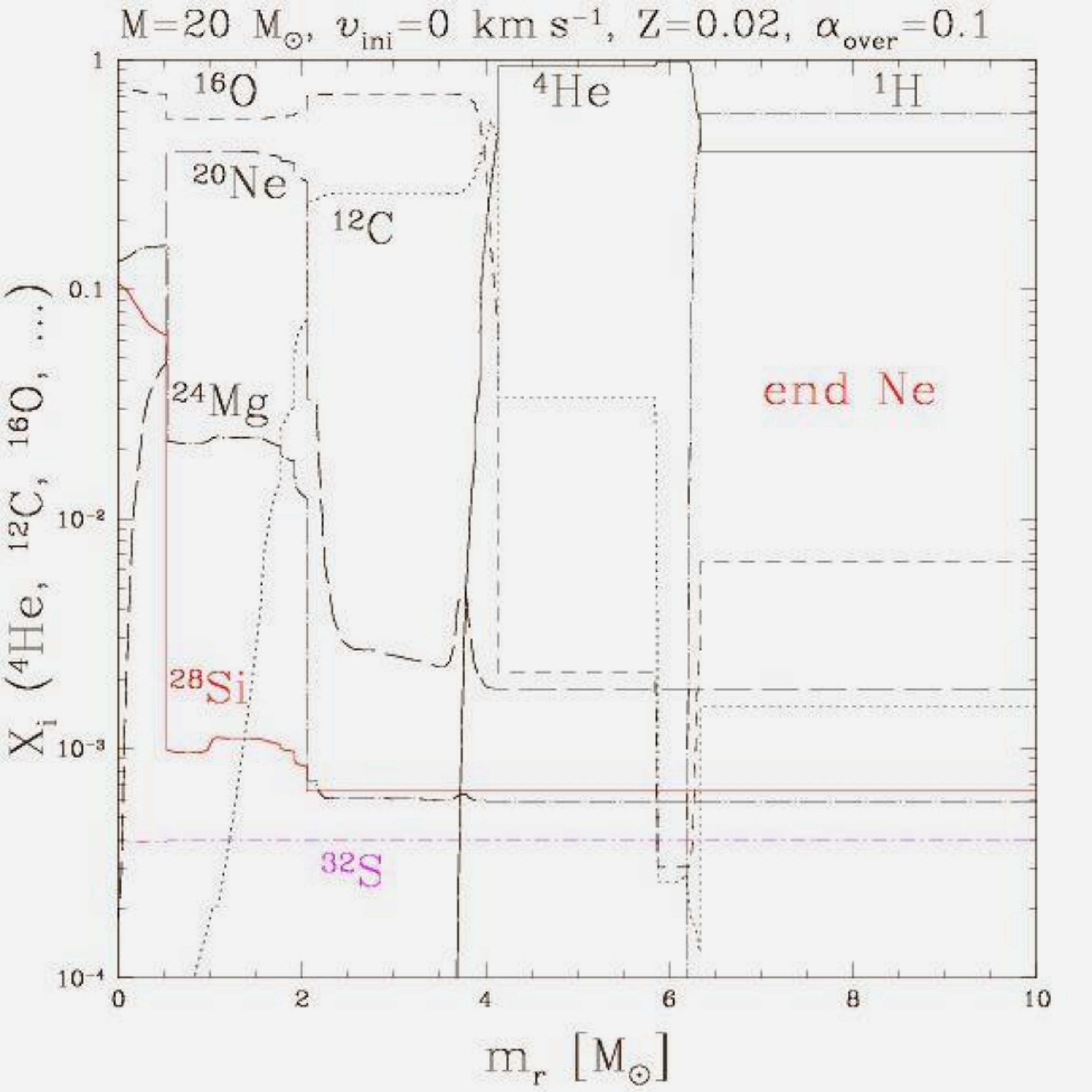
Smaller sensitivity to degeneracy effects

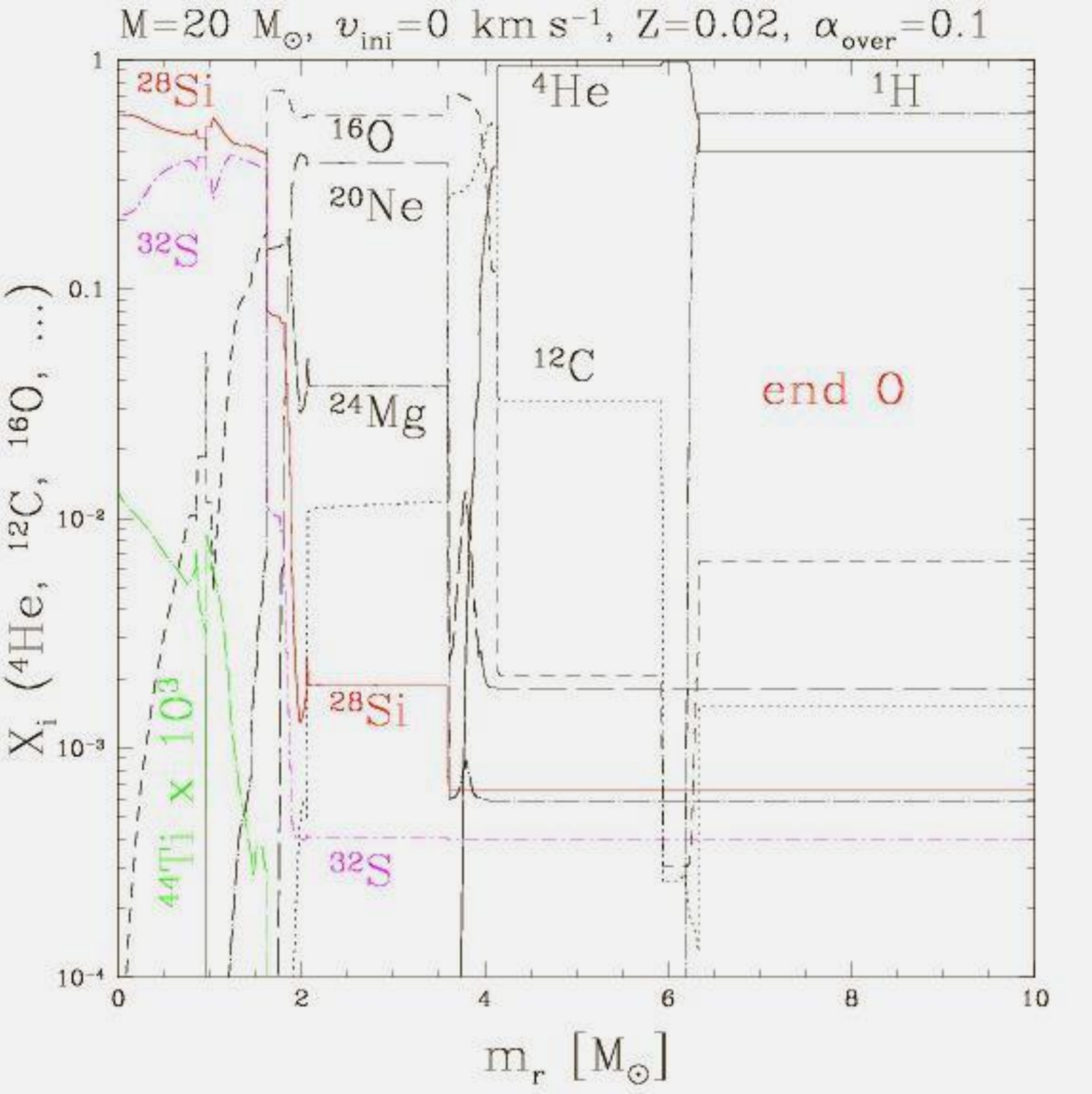
⇓

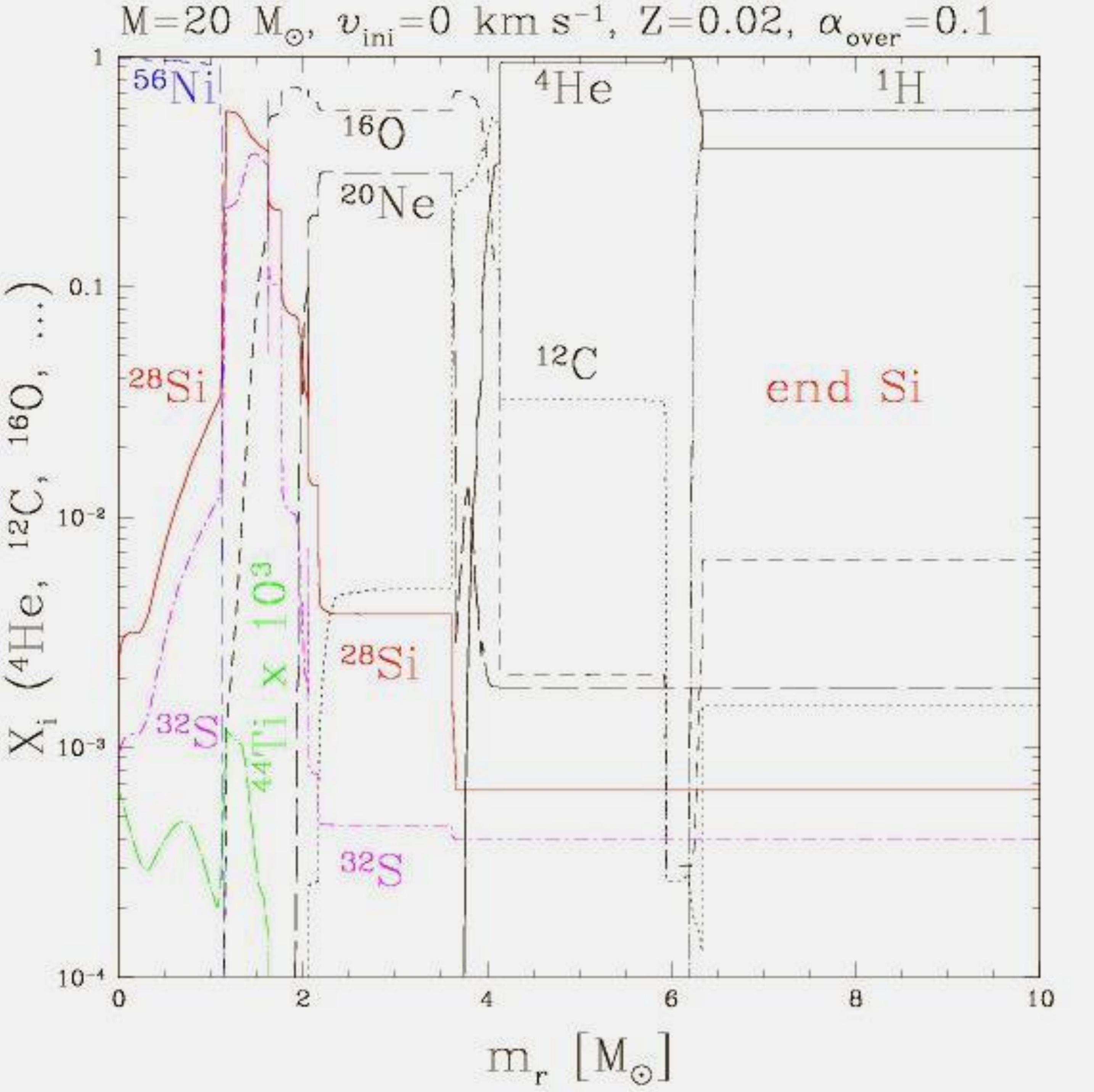
Formation of bigger cores, favours Black Holes formation (cf Woosley 1986).


M=20 M$_\odot$, υ_{ini}=0 km s^{-1}, Z=0.02, α_{over}=0.1
^{16}O
^{12}C
^{4}He
^{1}H
end He
^{14}N
^{22}Ne
^{20}Ne
^{24}Mg
X$_i$ (^{4}He, ^{12}C, ^{16}O, ...)
1
0.1
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10
m$_r$ [M$_\odot$]


M=20 M$_\odot$, $\upsilon_{\rm ini}$=0 km s^{-1}, Z=0.02, $\alpha_{\rm over}$=0.1
^{16}O
^{12}C
^{20}Ne
^{4}He
^{1}H
^{24}Mg
^{28}Si
end C
X$_i$ (^{4}He, ^{12}C, ^{16}O, ...)
m$_r$ [M$_\odot$]
1
0.1
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10



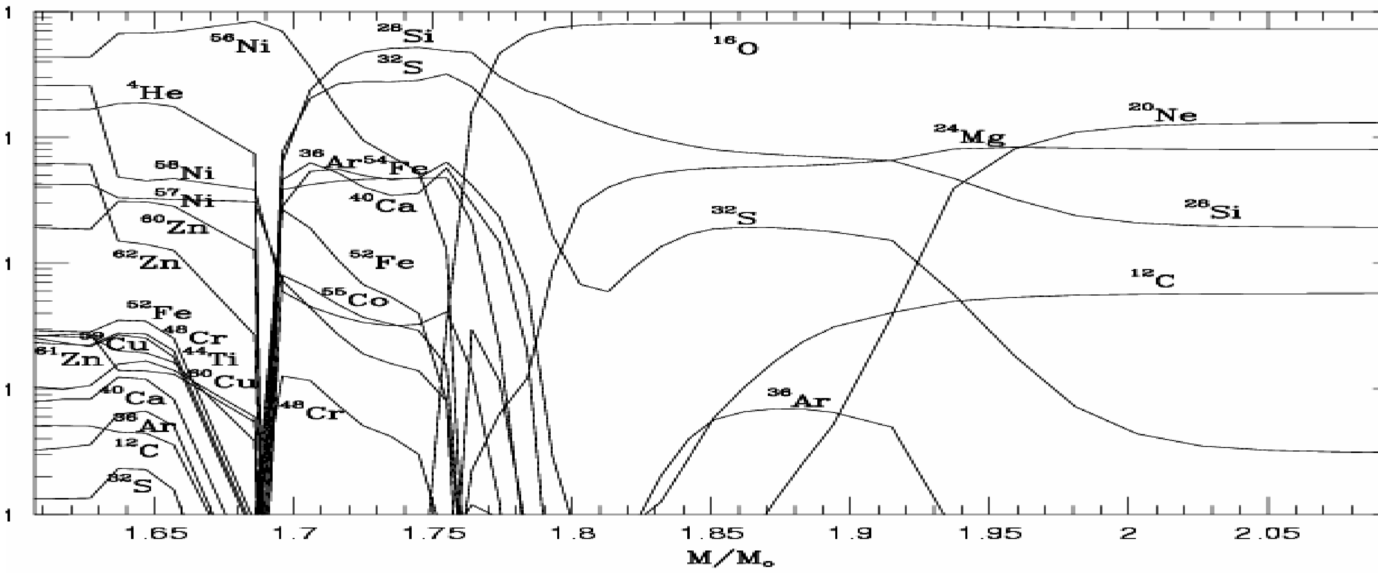

M=20 M$_\odot$, $\upsilon_{\rm ini}$=0 km s^{-1}, Z=0.02, $\alpha_{\rm over}$=0.1
^{28}Si
^{32}S
^{16}O
^{20}Ne
^{24}Mg
^{4}He
^{1}H
^{12}C
end O
^{28}Si
^{32}S
^{44}Ti x 10^{3}
X$_i$ (^{4}He, ^{12}C, ^{16}O, ...)
m$_r$ [M$_\odot$]
1
0.1
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10


M=20 M⊙, v_{ini}=0 km s⁻¹, Z=0.02, α_{over}=0.1
^{56}Ni
^{16}O
^{20}Ne
^{4}He
^{1}H
^{12}C
^{28}Si
^{28}Si
end Si
^{32}S
^{32}S
^{44}Ti x 10^3
X_i (^{4}He, ^{12}C, ^{16}O, ...)
m_r [M⊙]
1
0.1
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10

20 Msol,type II

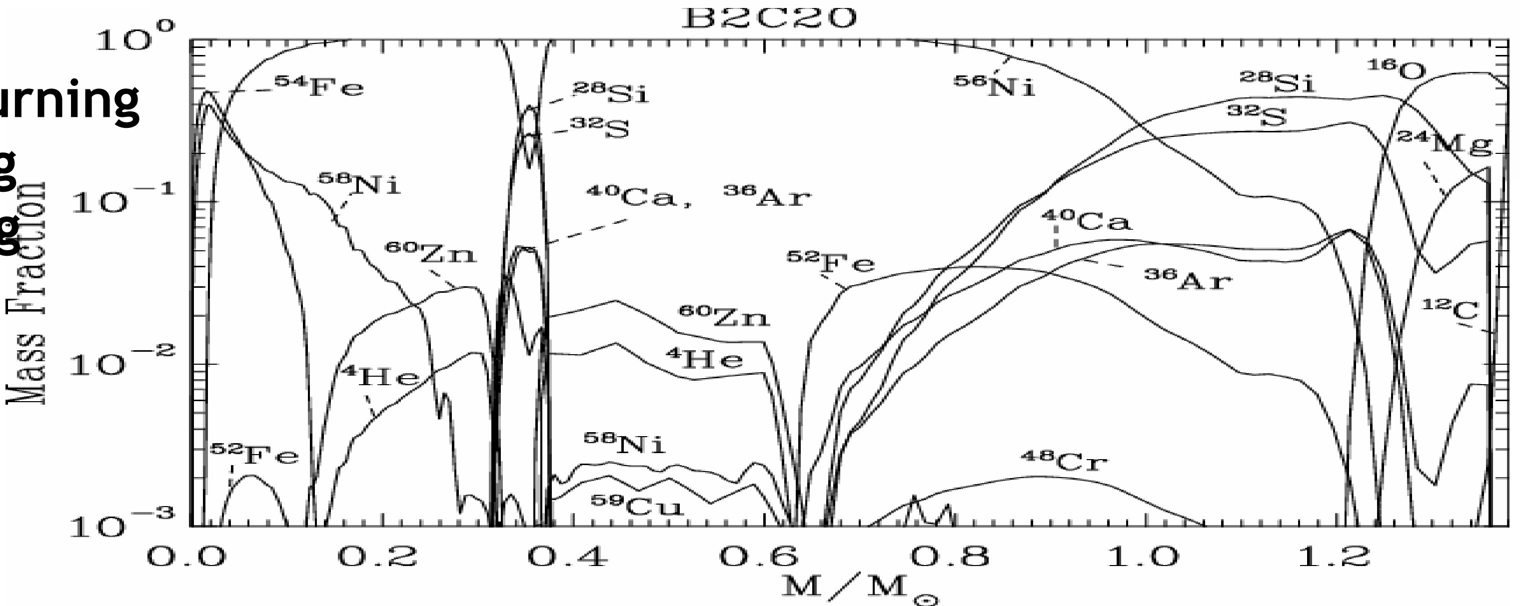
Thielemann et al. 1996, 2001

Abundances of O, Ne, Mg, Si, S, Ar and Ca dominate strongly over Fe if mass cut adjusted to 0.07 Msol of ^{56}Ni (SN87A)

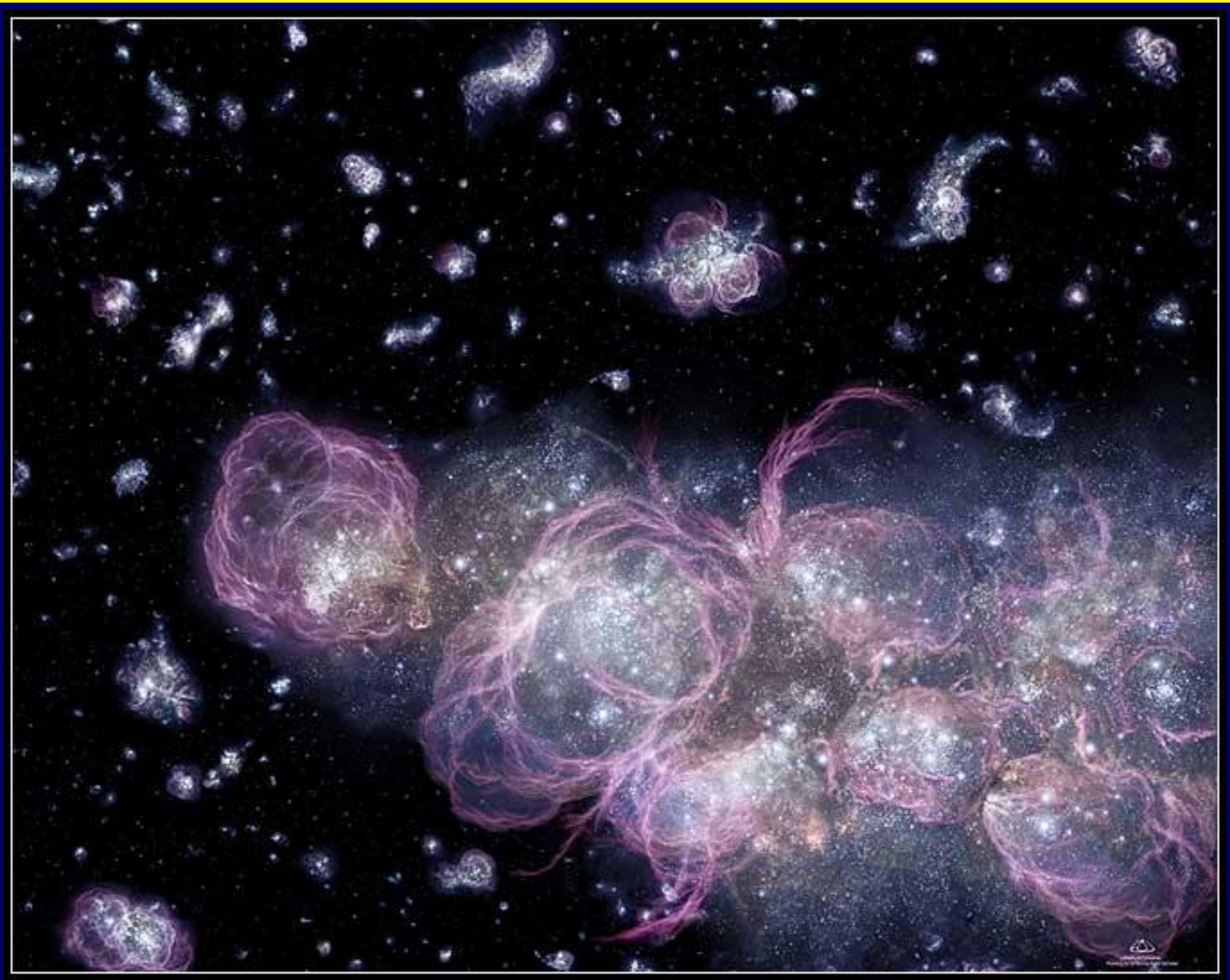


Type Ia

Products of explosive Si-burning (^{56}Ni) O-burning (^{28}Si)Ne-burning (^{16}O,^{24}Mg) Minor amounts Of C-burning (^{20}Ne)

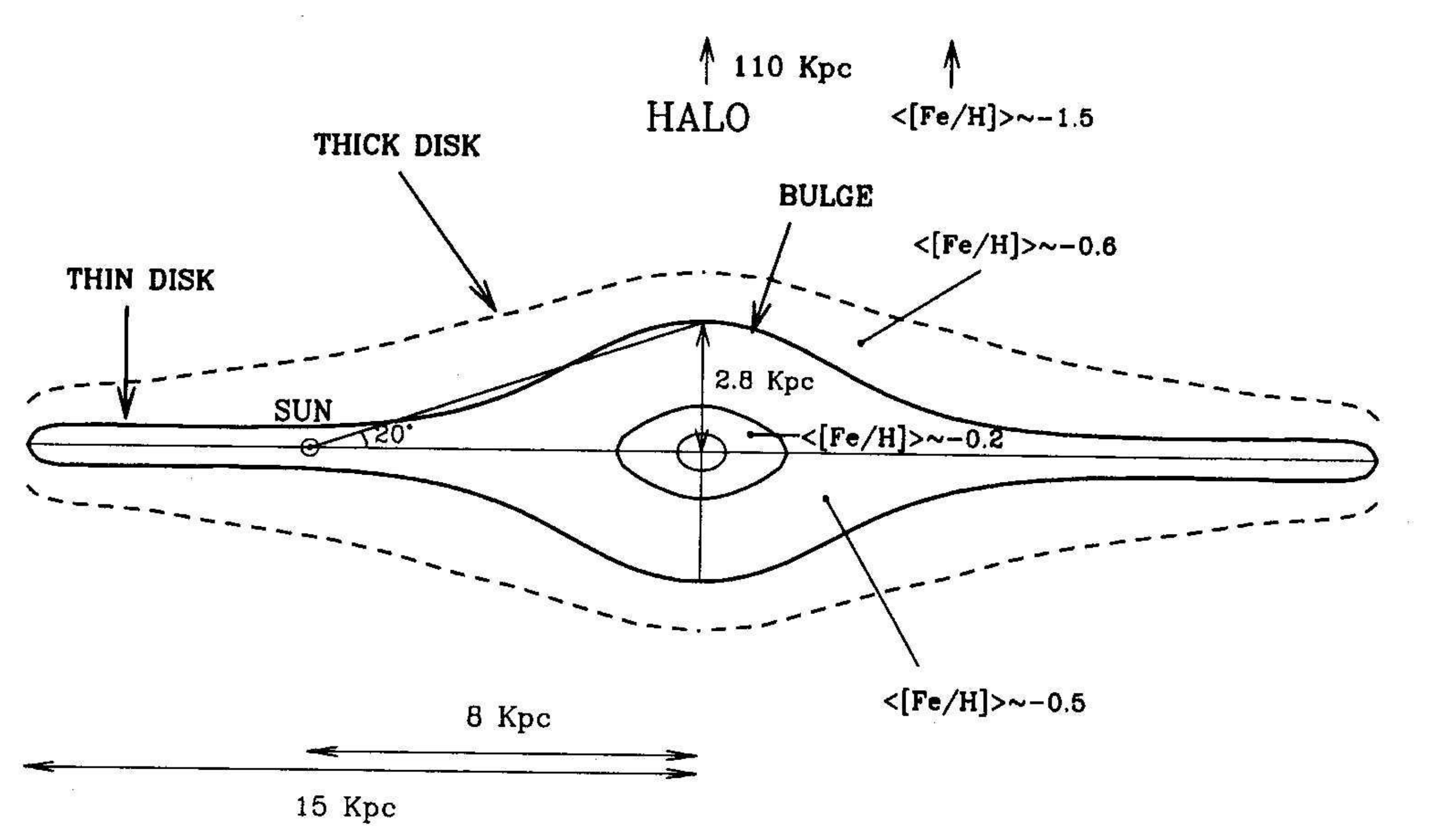


The early phases of the chemical evolution of the Milky Way ?



Artist's View of Star Formation in the Early Universe

Painting by Adolf Schaller • STScI-PRC02-02

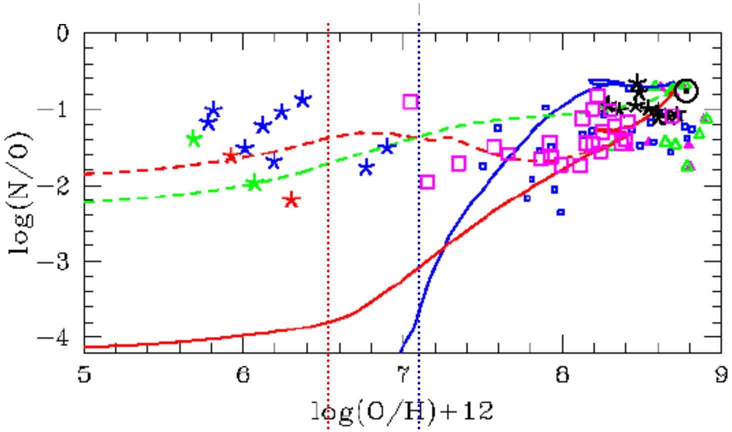


Structure of MW with mean metallicities of each component (from Matteucci 1991)

LES ETOILES DU HALO

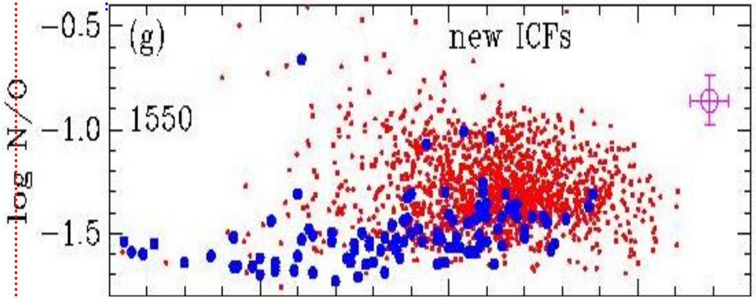
ETOILES DU HALO

Spite et al. 2004
Israelian et al. 2004



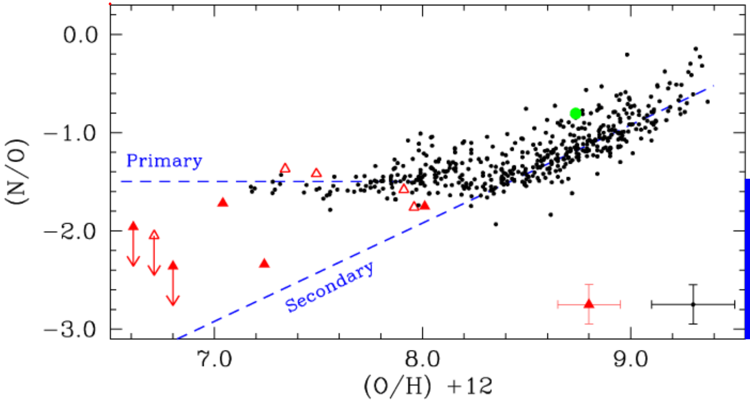
GALAXIES A RAIES D’EMISSION ET BLEUES COMPACTES

Izotov, Stasinska, Meynet, Guseva, Thuan A&A, in press

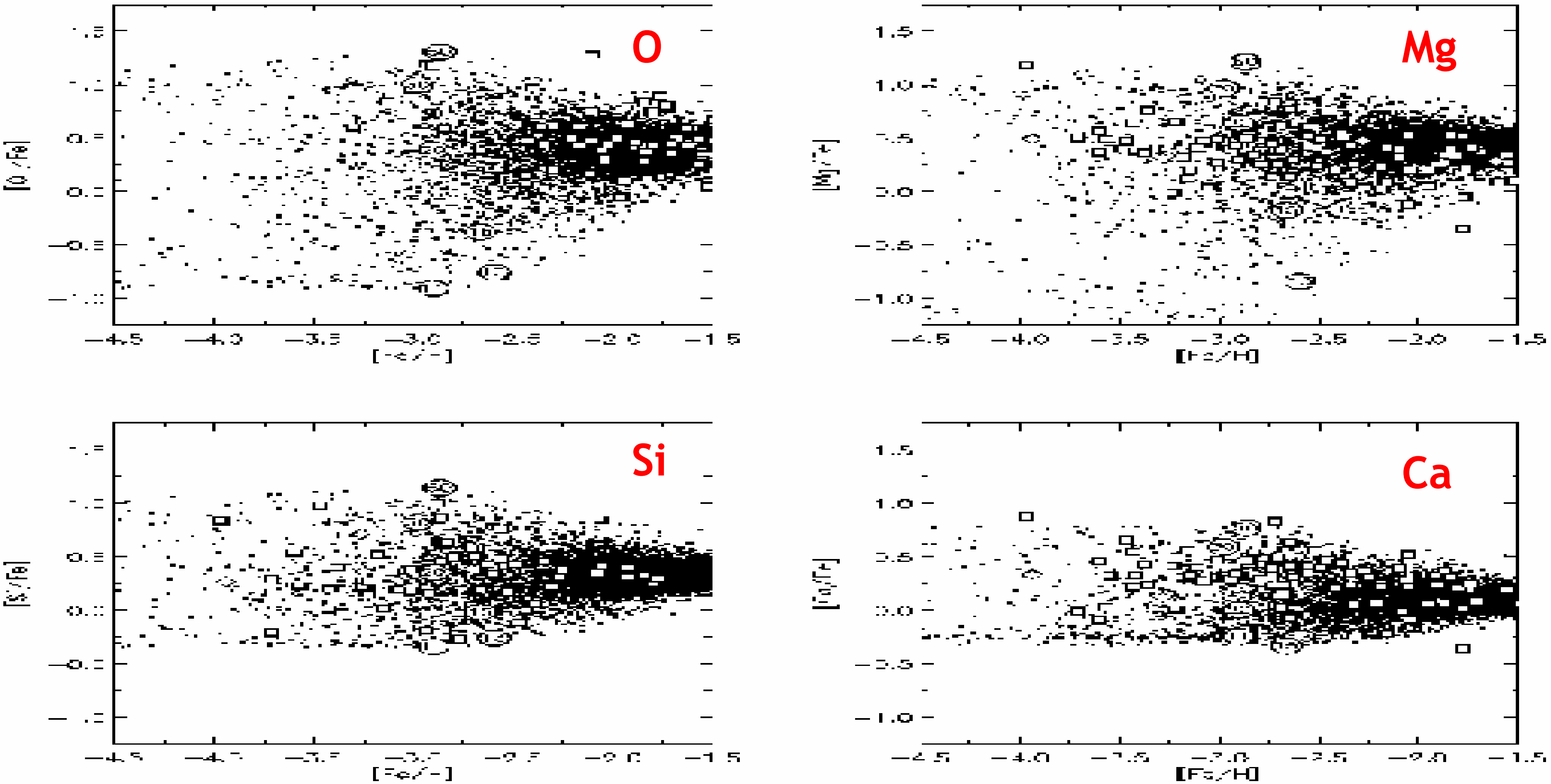


DAMPED LYMAN ALPHA SYSTEMS

Pettini et al. 2002



Domaines de métallicité différents
Histoire de la formation stellaire différente



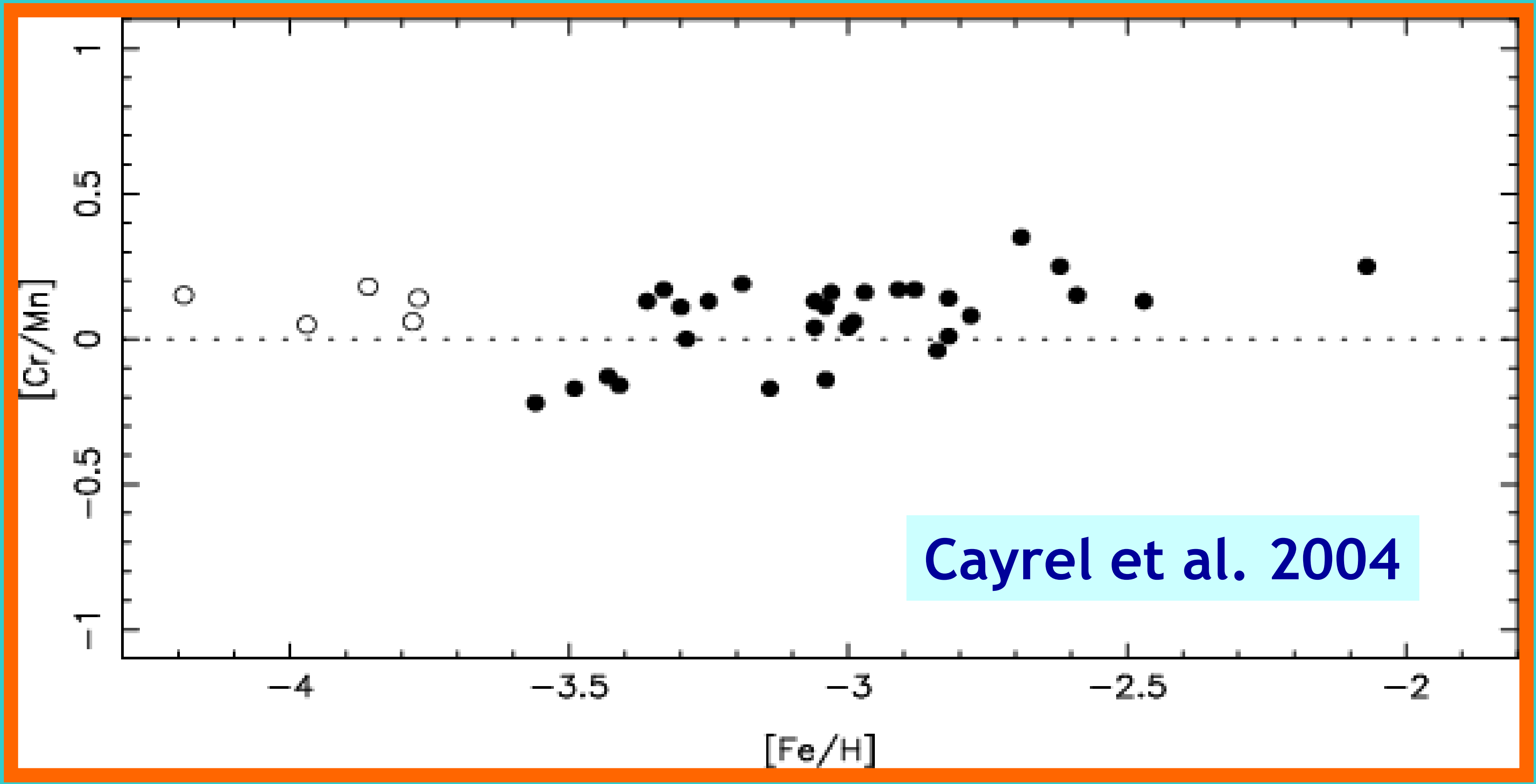
Comparison of low metallicity observations with SNII Yields, Argast et al. 2000, 2001

Squares=observation

Open circles=x/Fe and Fe/H in a volume of 104 Msol polluted by a single SN

Dots=galactic evolution model stars

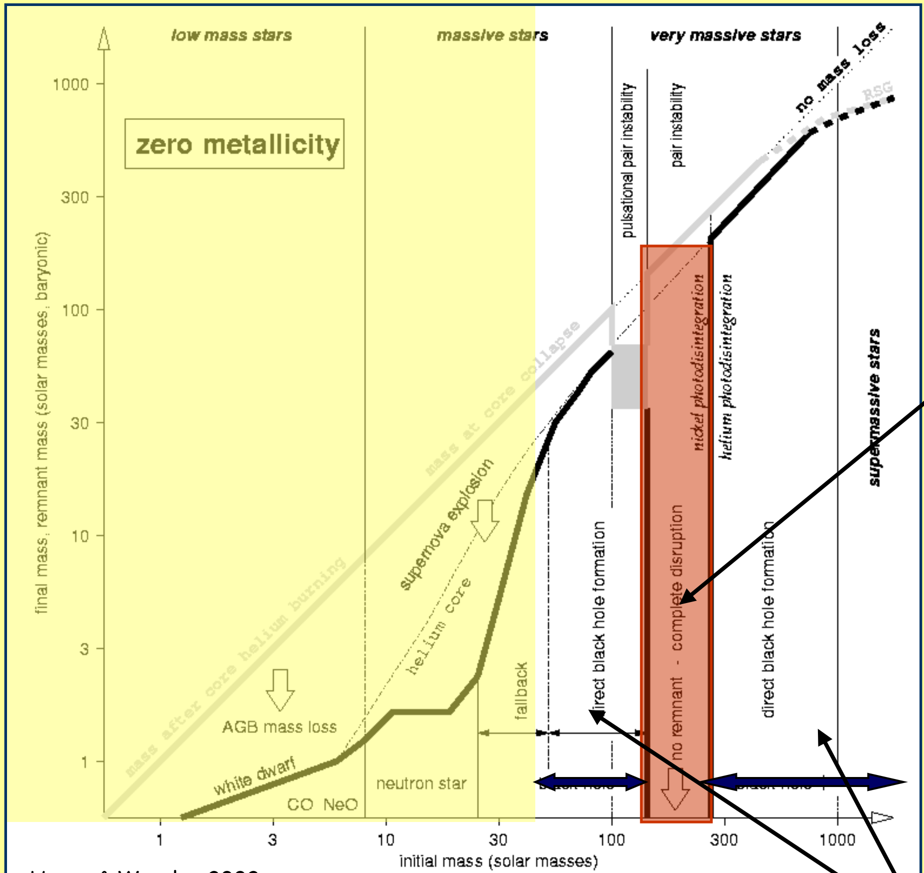
MANY PUZZLING FACTS



Cayrel et al. 2004

→ 1) Very small dispersion

Final fate of the first stars



Heger & Woosley 2002

140 Msun < M < 260 Msun

PISN pair-instability supernovae

ejection of all metals

no remnants

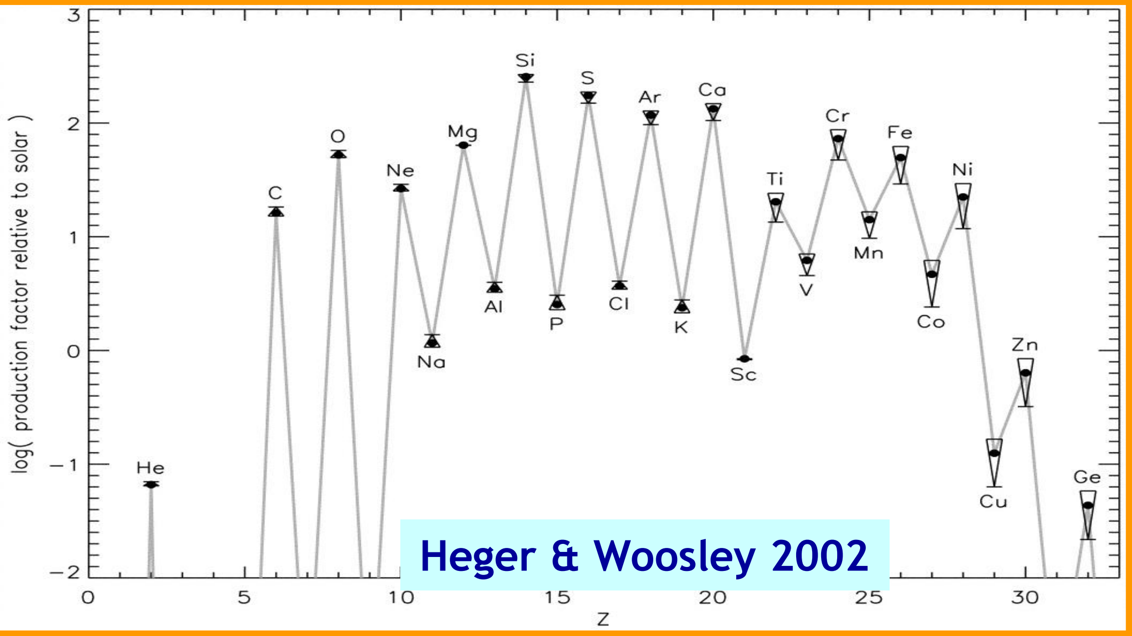
BH black hole collapse

no metal/mass ejected

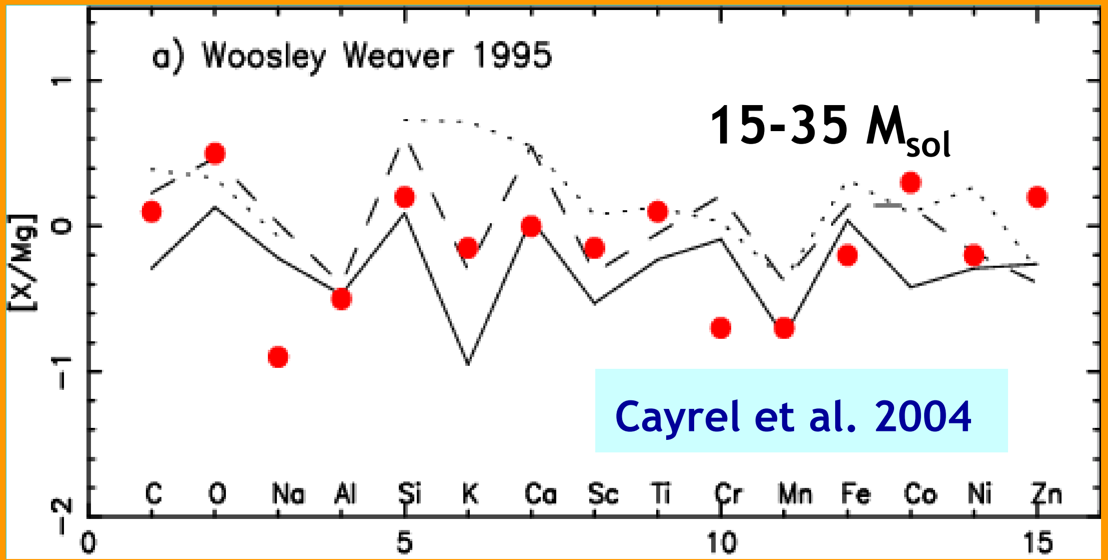
very massive BH remnants

50 Msun < M <140 Msun   M > 260 Msun

→2) No sign of pair instability supernovae



Heger & Woosley 2002



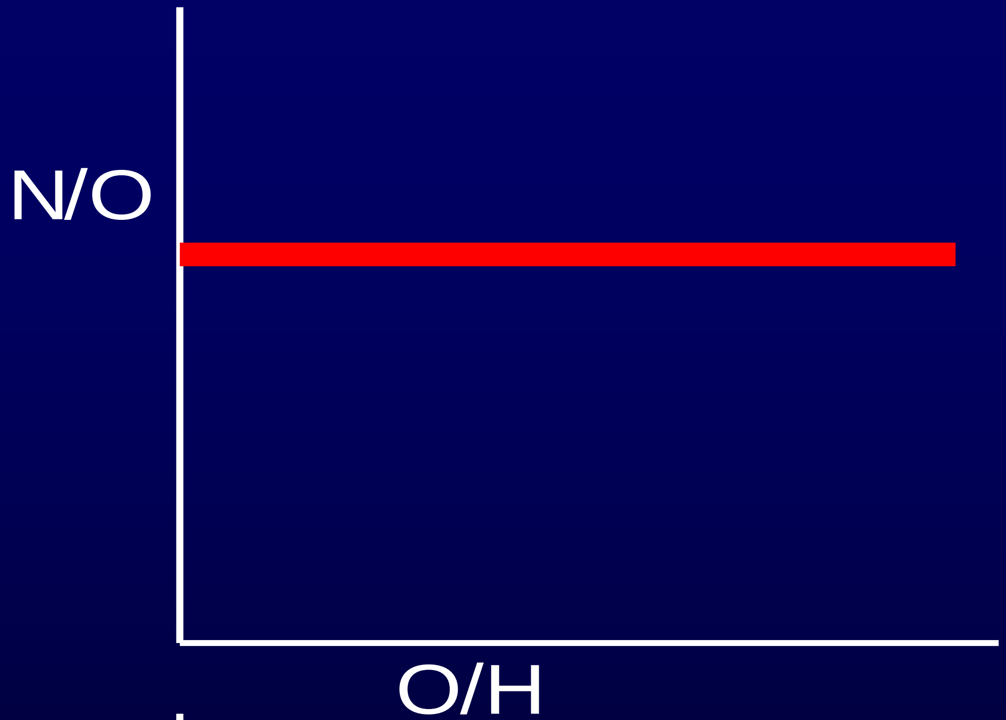
15-35 M_{sol}

Cayrel et al. 2004

CNO → N

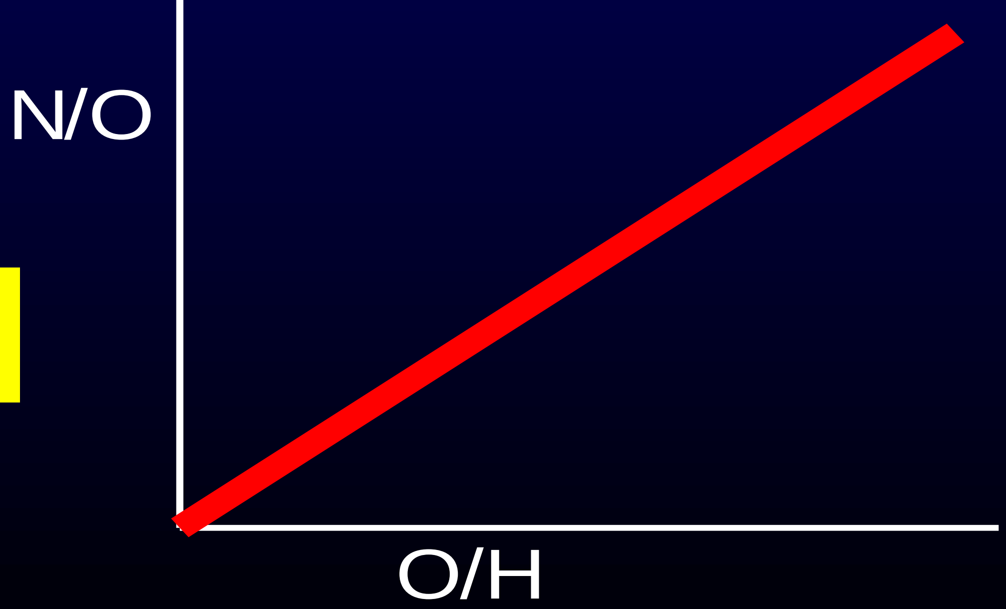
PRIMAIRE

C et O synthétisés par l’étoile

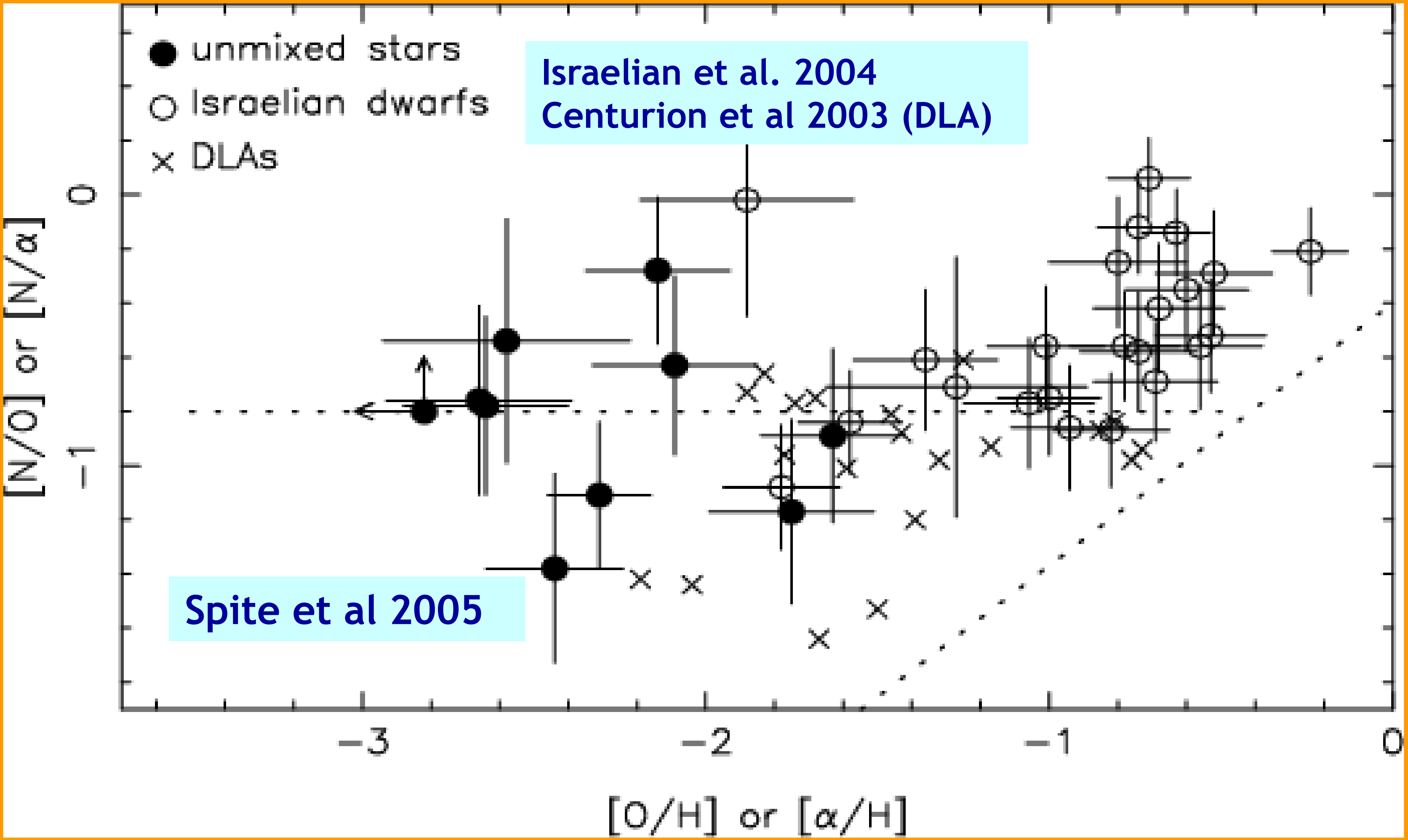


SECONDAIRE

C et O initialement présents dans l’étoile



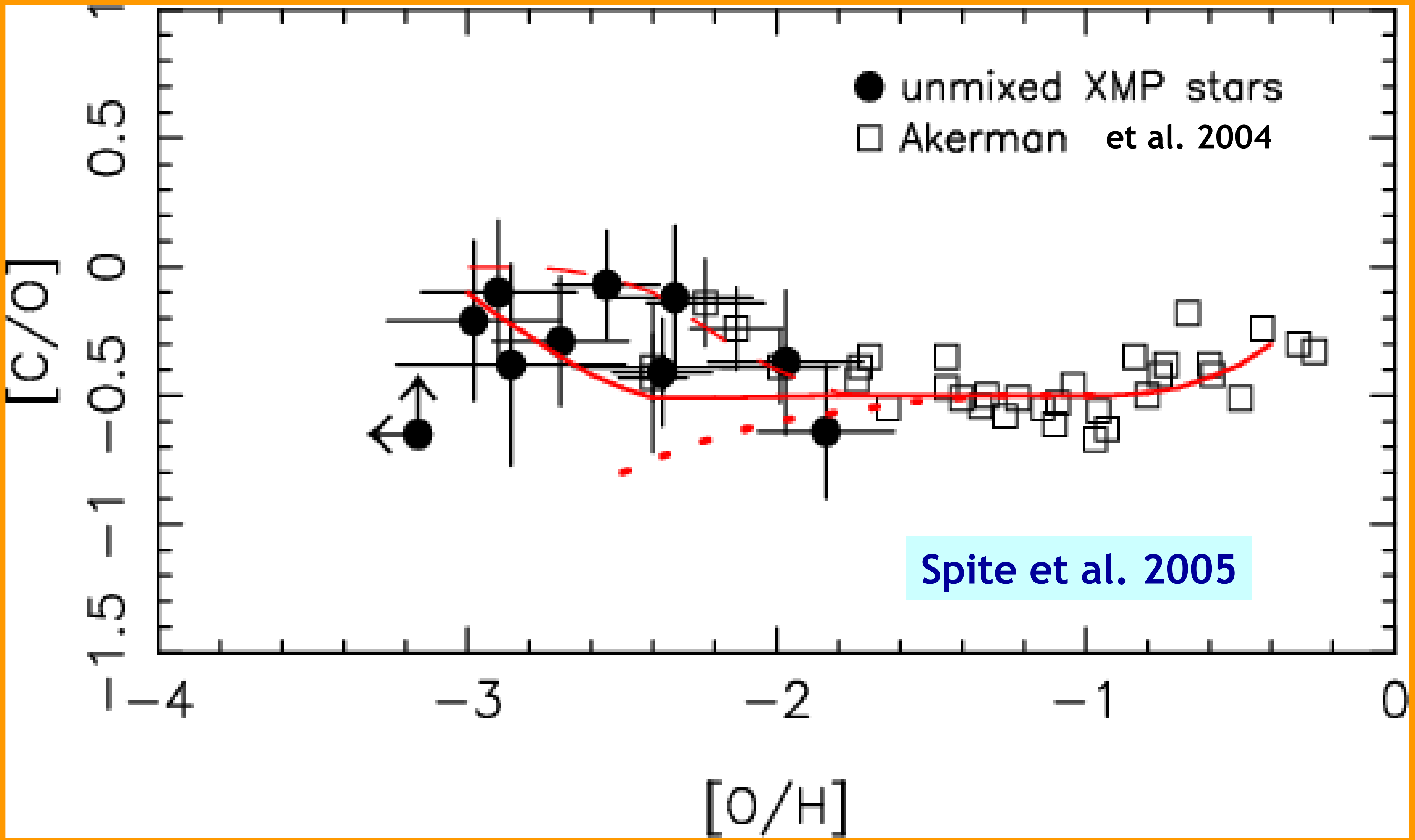
→3) High N/O ratios



Israelian et al. 2004
Centurion et al 2003 (DLA)

Spite et al 2005

→4) The C/O upturn



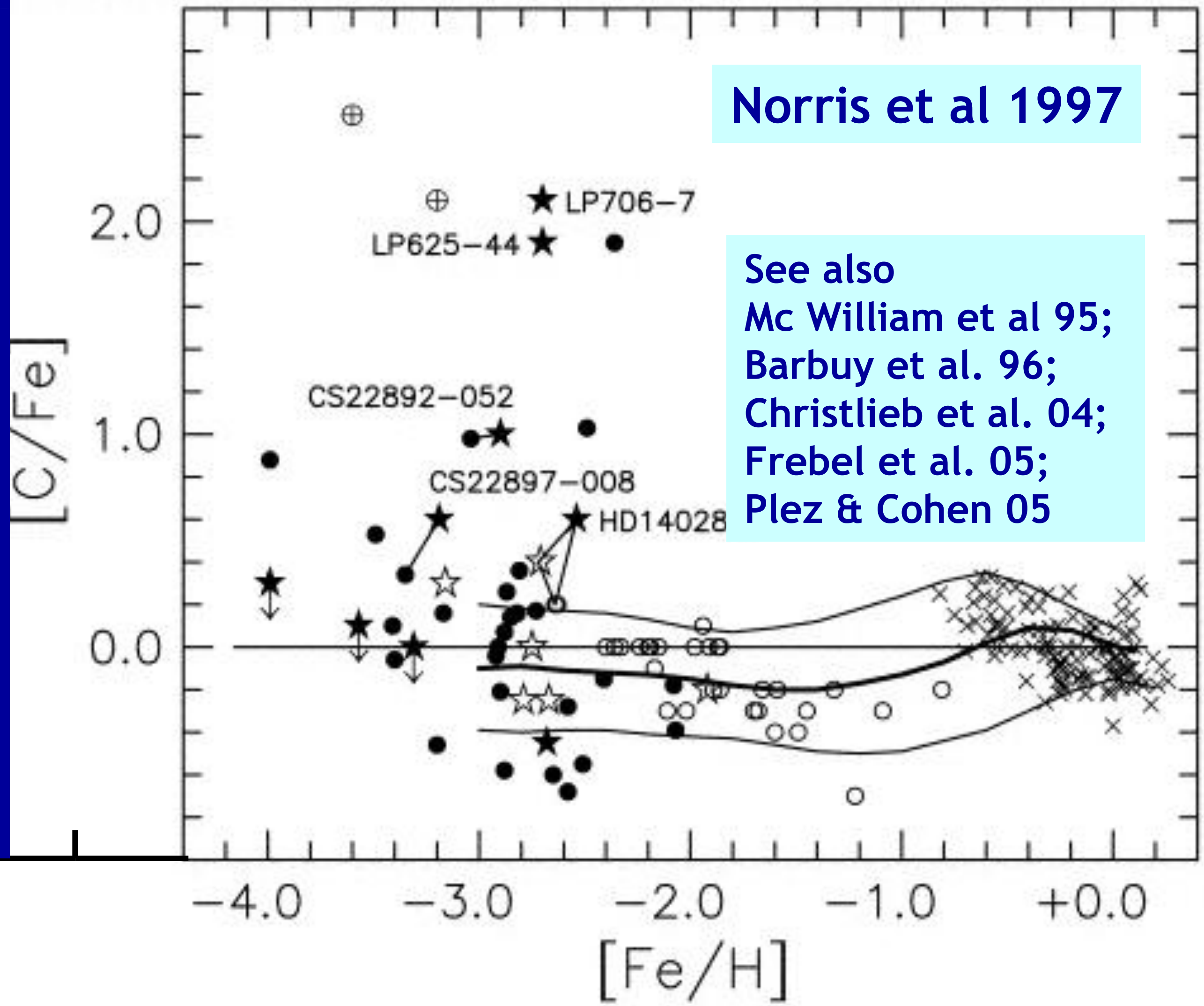
Spite et al. 2005

→5) C-rich stars

Les étoiles les plus pauvres en métaux

Christlieb et al. 2002

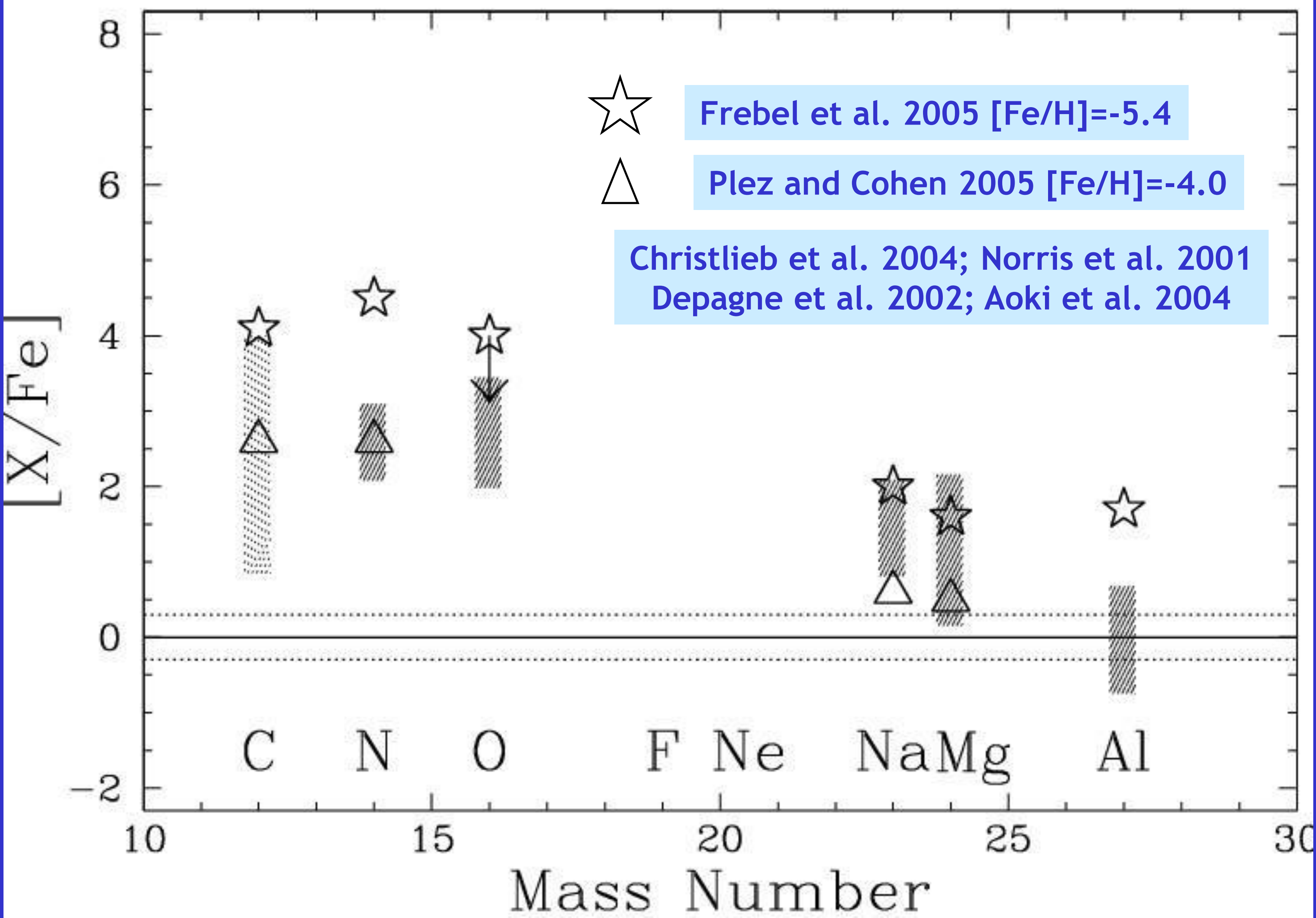
Frebel et al. 2005



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

LES DEUX ETOILES LES PLUS PAUVRES EN FER SONT RICHES EN CARBONE

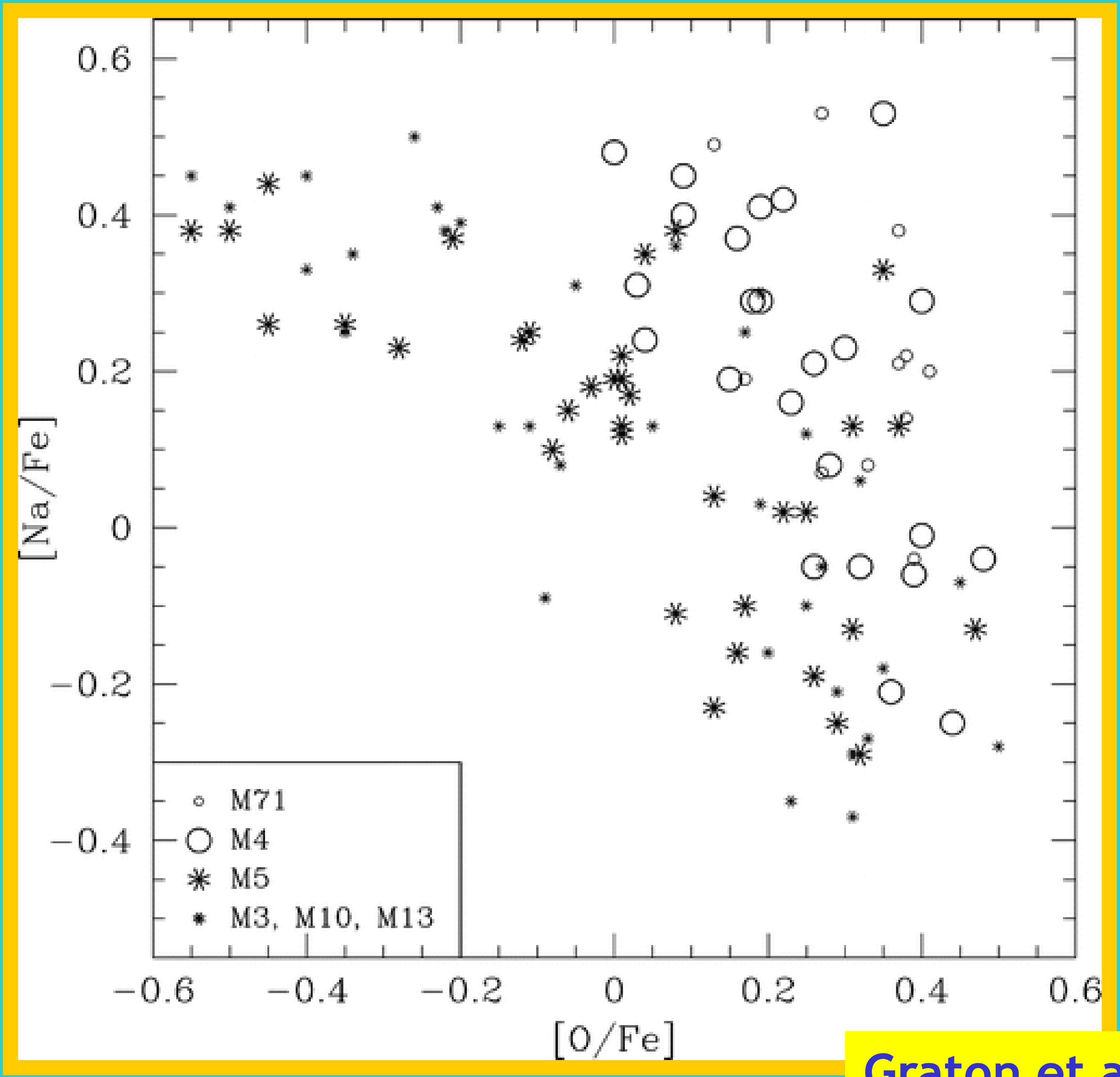


☆ Frebel et al. 2005 [Fe/H]=-5.4

△ Plez and Cohen 2005 [Fe/H]=-4.0

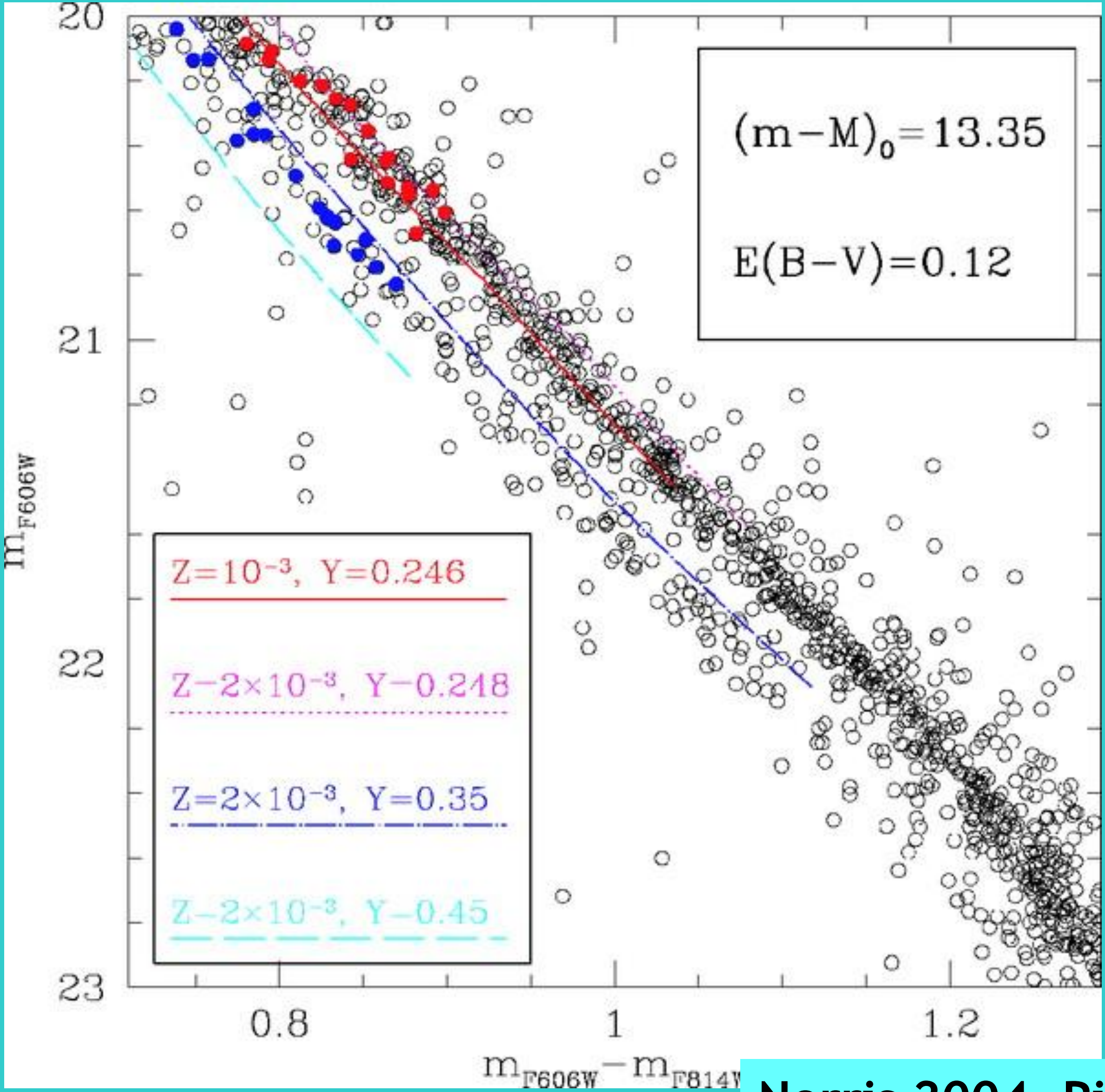
Christlieb et al. 2004; Norris et al. 2001
Depagne et al. 2002; Aoki et al. 2004

→6) anticorrelations in Globular Clusters



Graton et al 2004

→7) He-rich stars in ω Cen



Norris 2004, Piotto et al. 2005

Metal-poor dwarfs of the Solar neighborhood

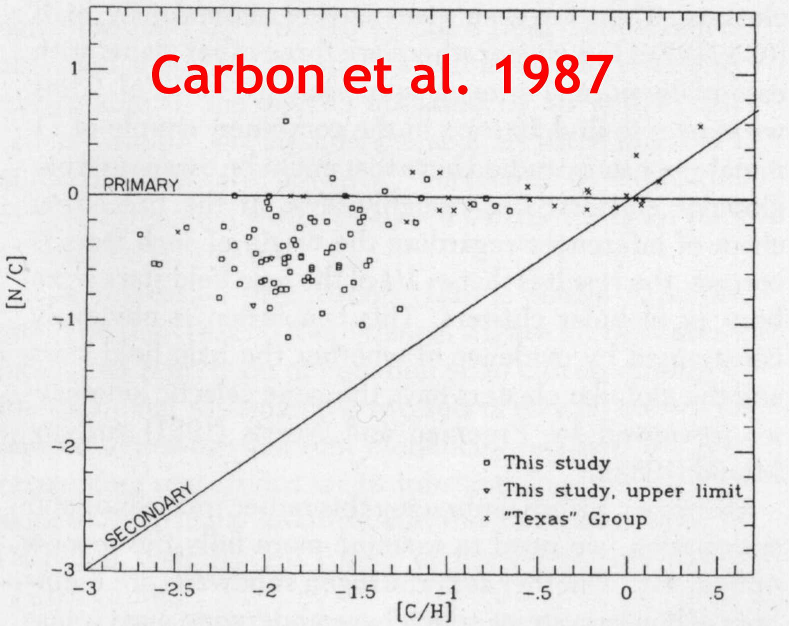
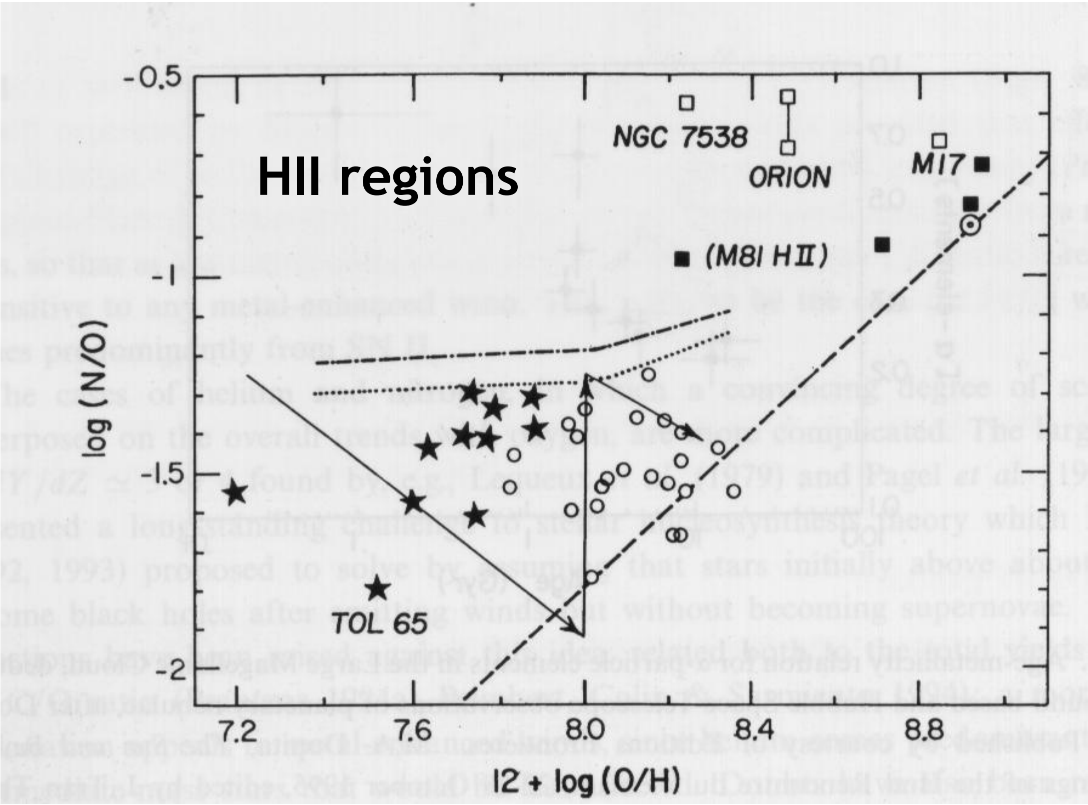
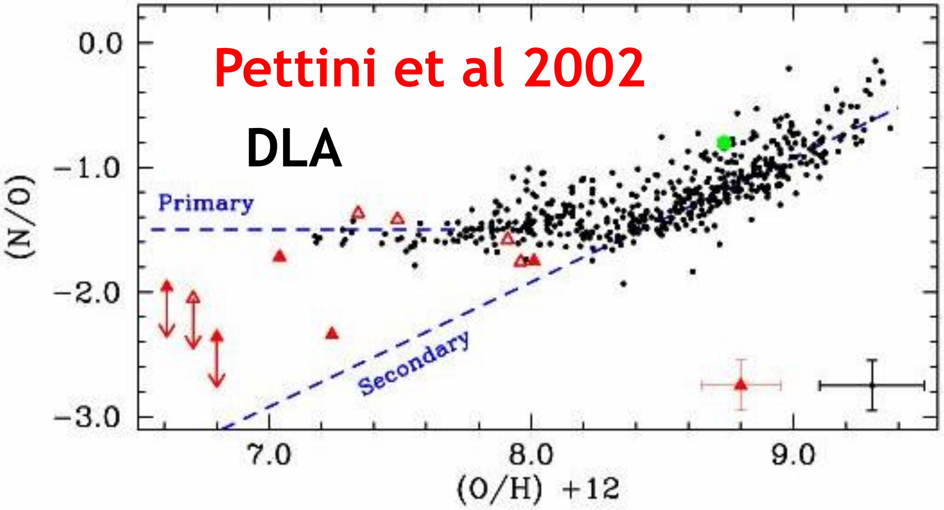

Carbon et al. 1987

FIG. 19–[N/C] vs. [C/H]. The data combine the present results with those of the "Texas Group."


HII regions

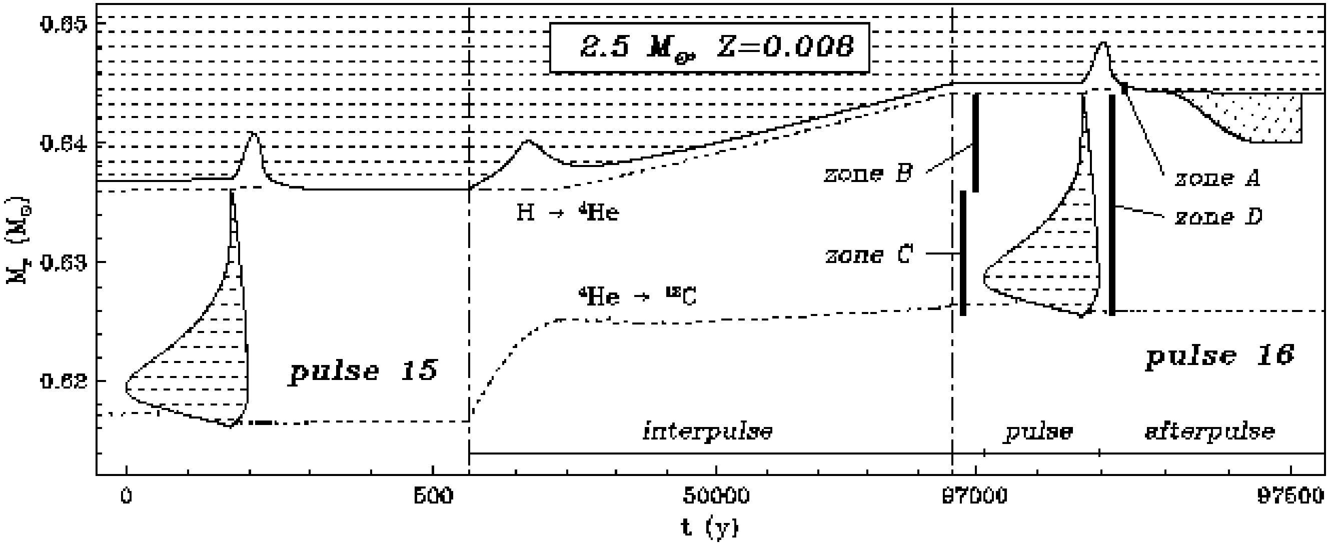

Pettini et al 2002

DLA

Adapted by Pagel 1997 from Garnett 1990

See also Matteucci and Tosi 85
Matteucci 86

THEORY

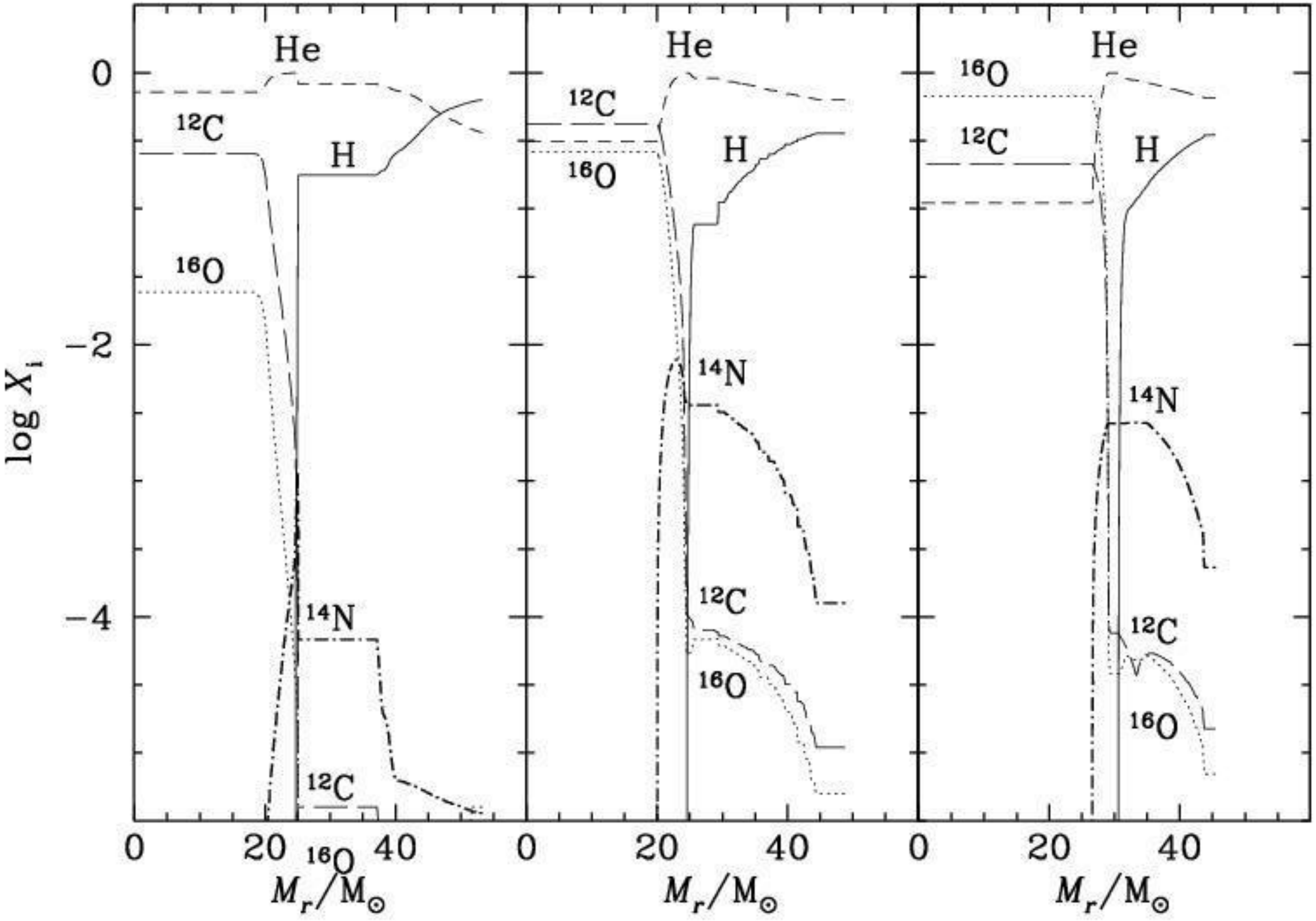


Intermediate mass stars : Yields at low Z

Marigo 1998; 2001
Van den Hoek, Groenewegen 1997

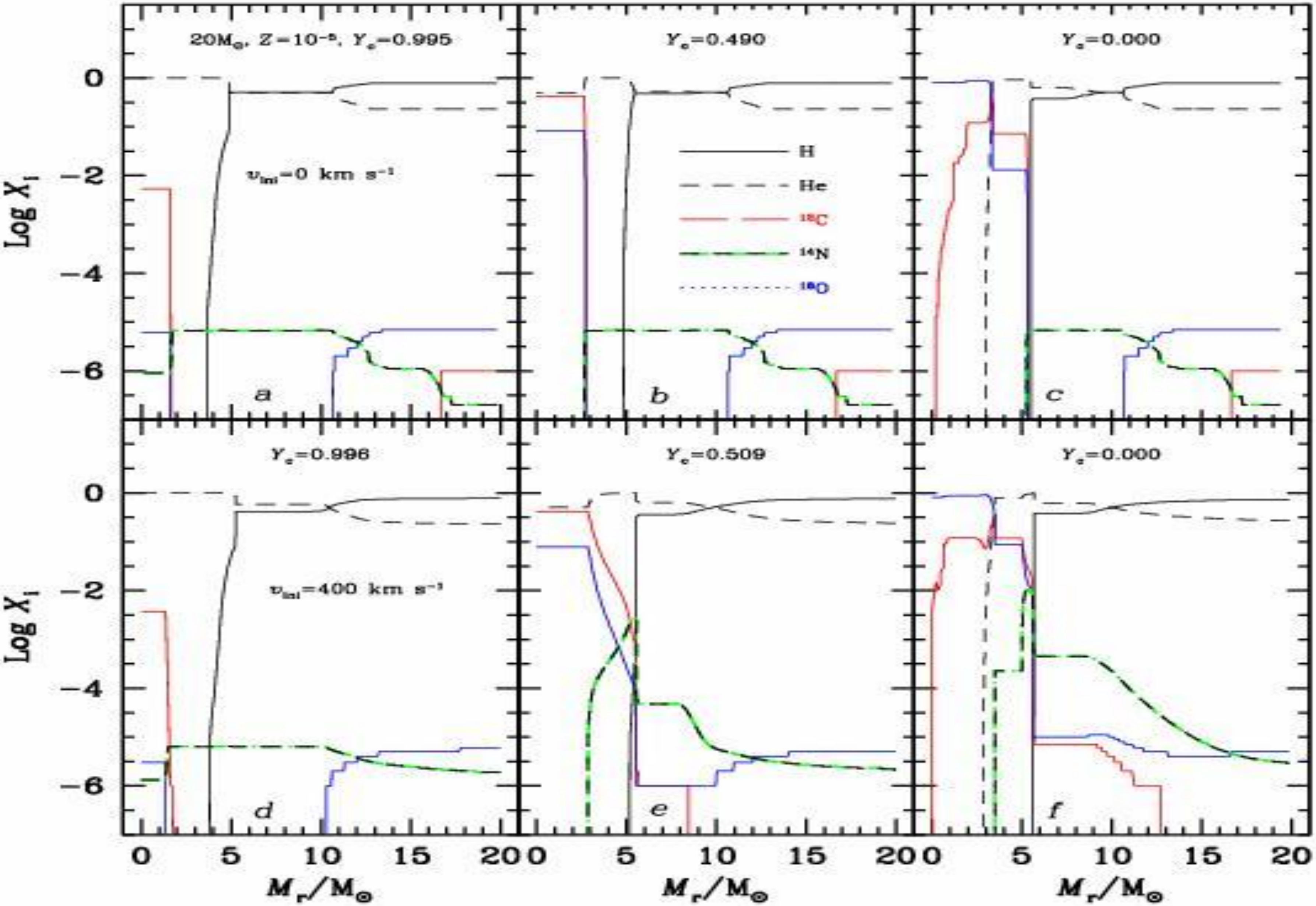
Massive stars

Woosley and Weaver 1995; Umeda et al. 2000;
Heger, Woosley, Waters 2000



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

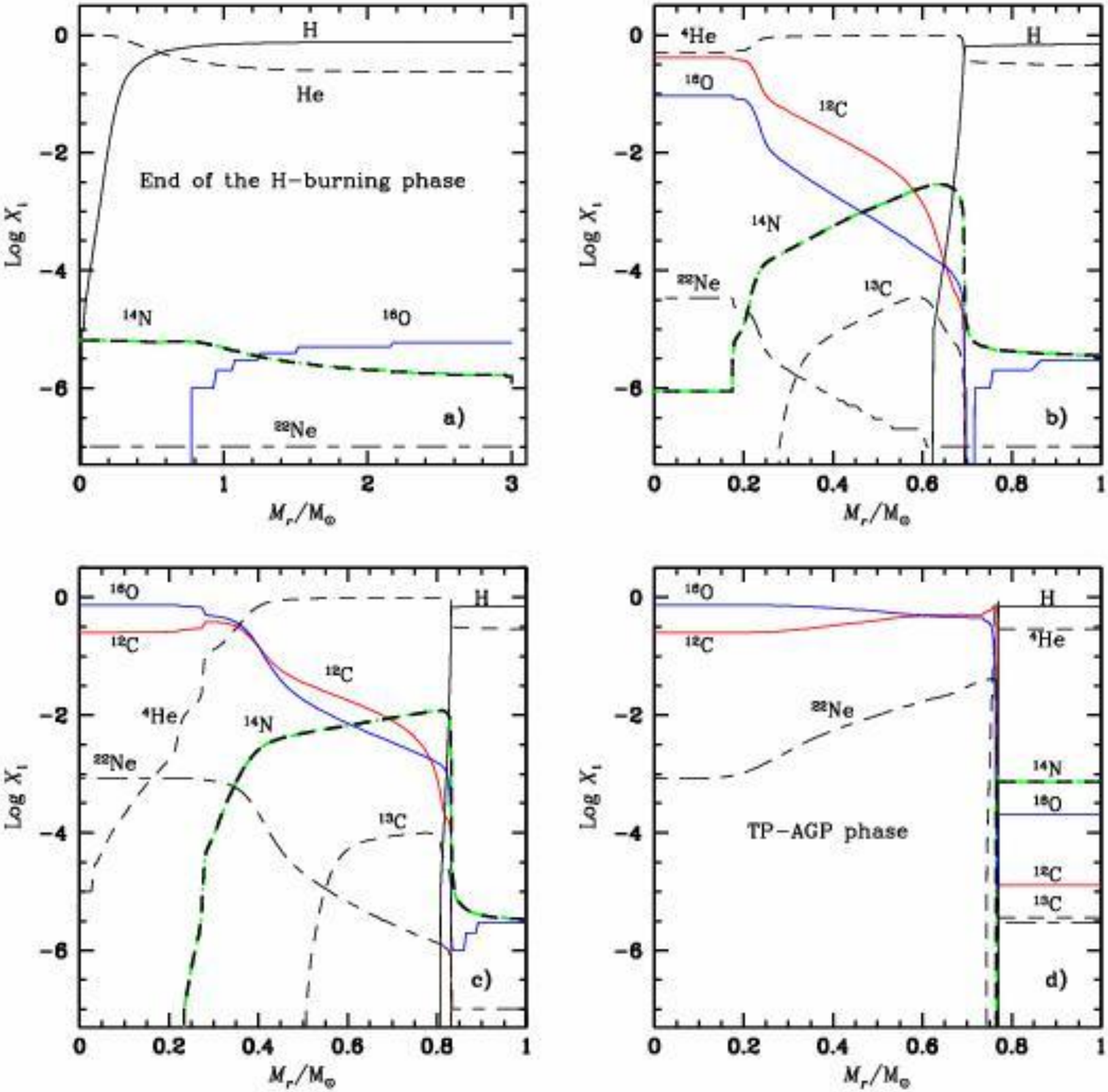
A new mechanism for primary N synthesis

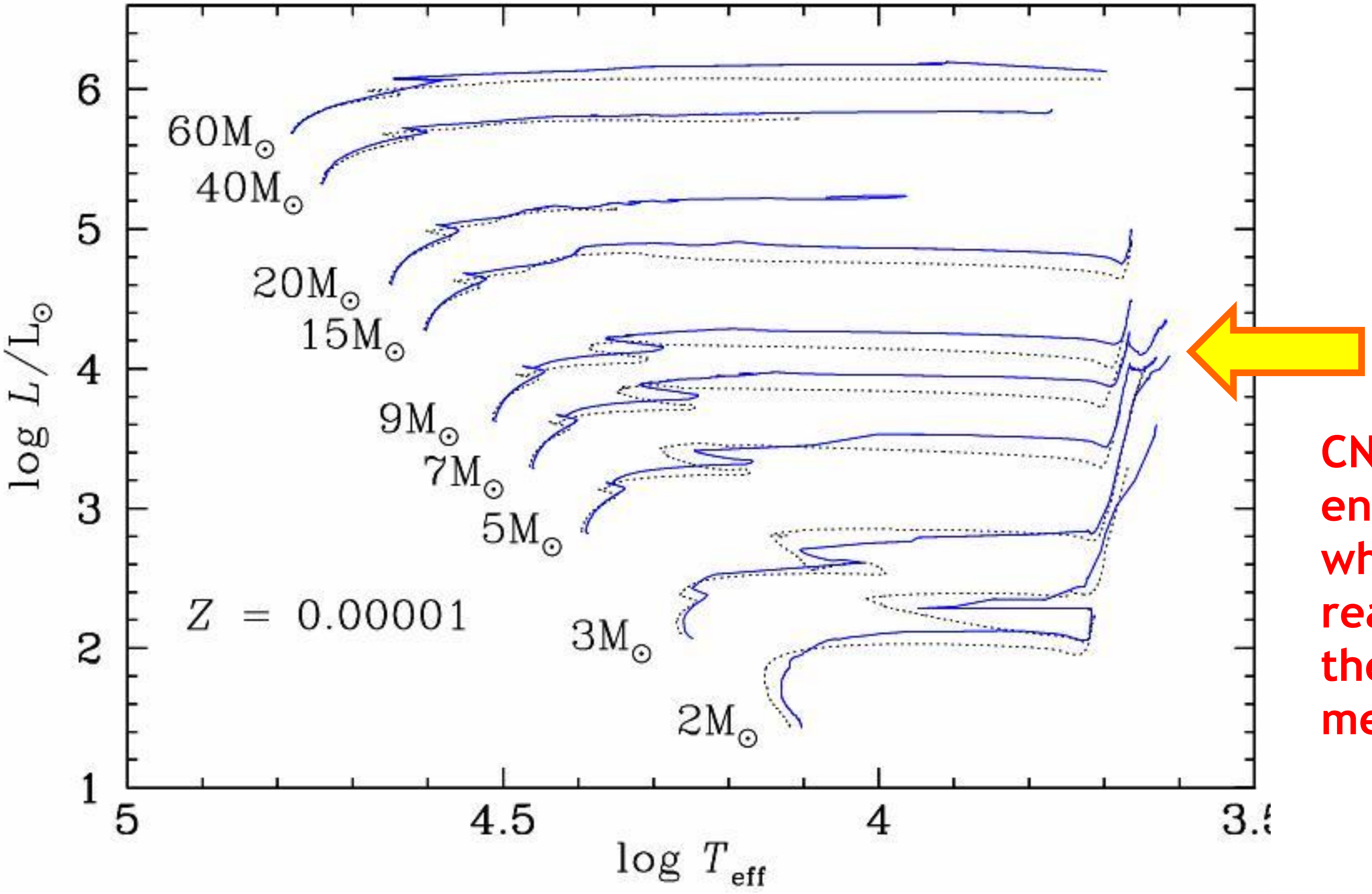


The same mechanism also works in intermediate mass stars

S-process

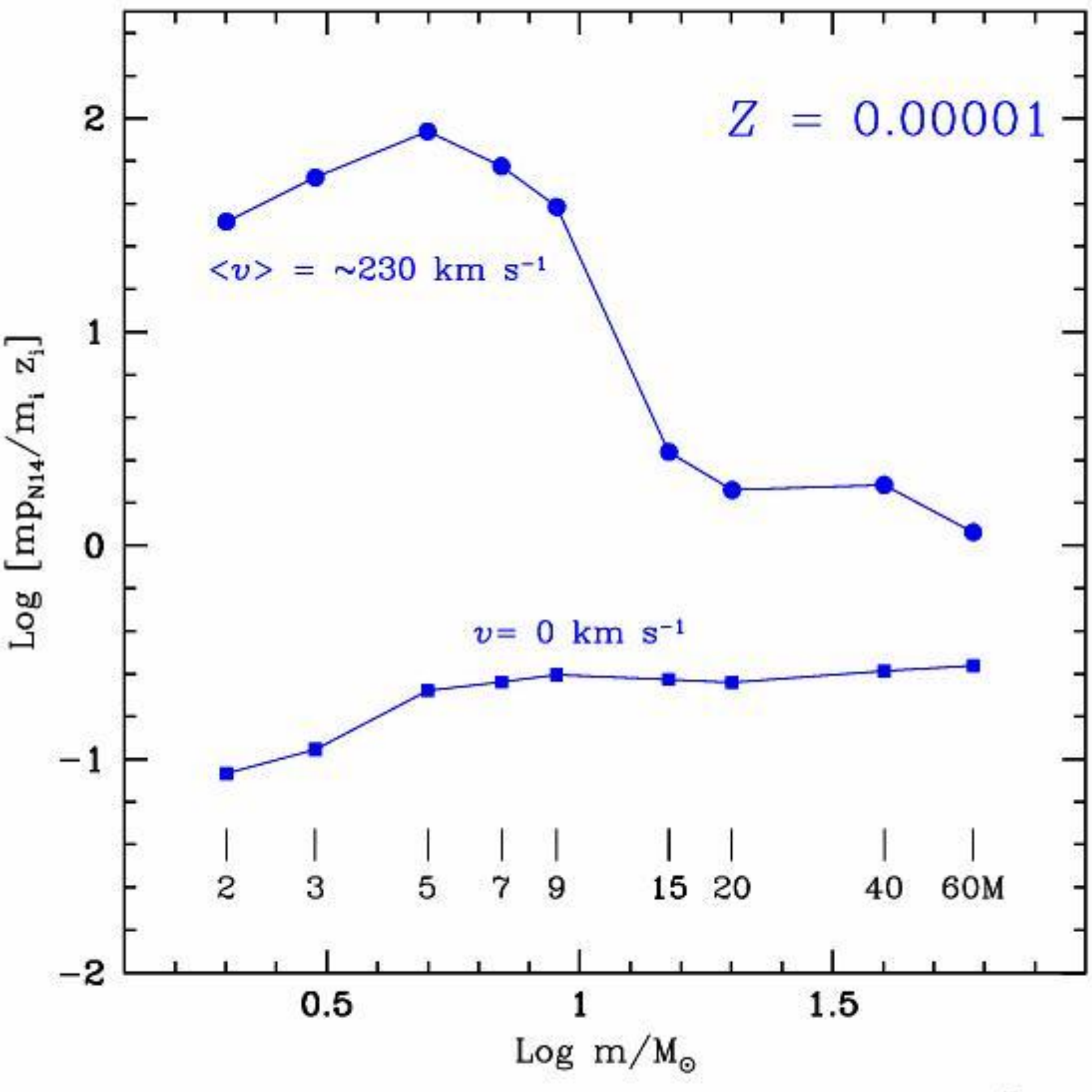
Cf. Langer, Heger, Wellstein, Herwig, 1999

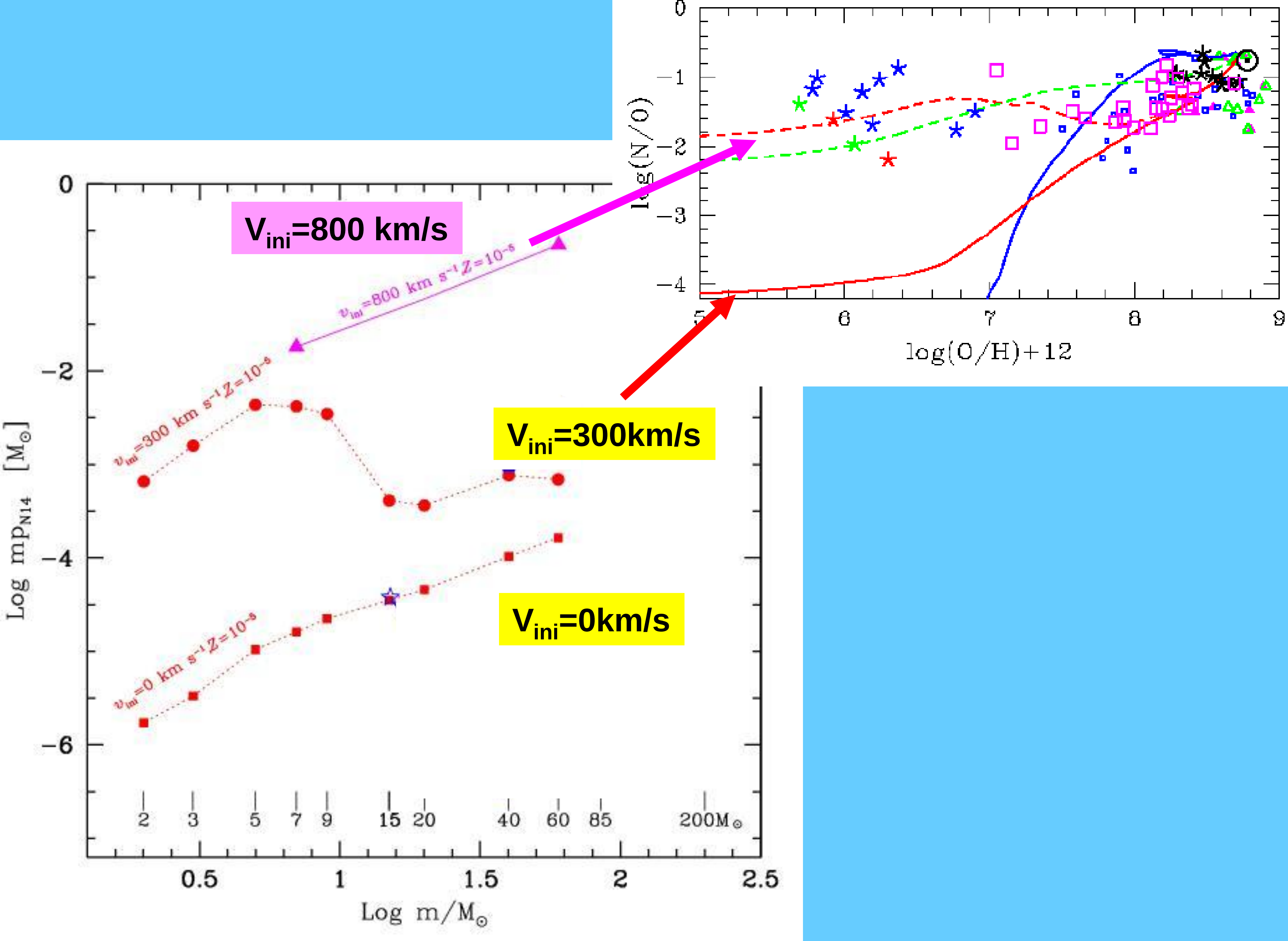




CNO surface enrichment which may reach 100 X the initial metallicity

The quantity of new primary N synthesized may reach 100 X the initial quantity of metals



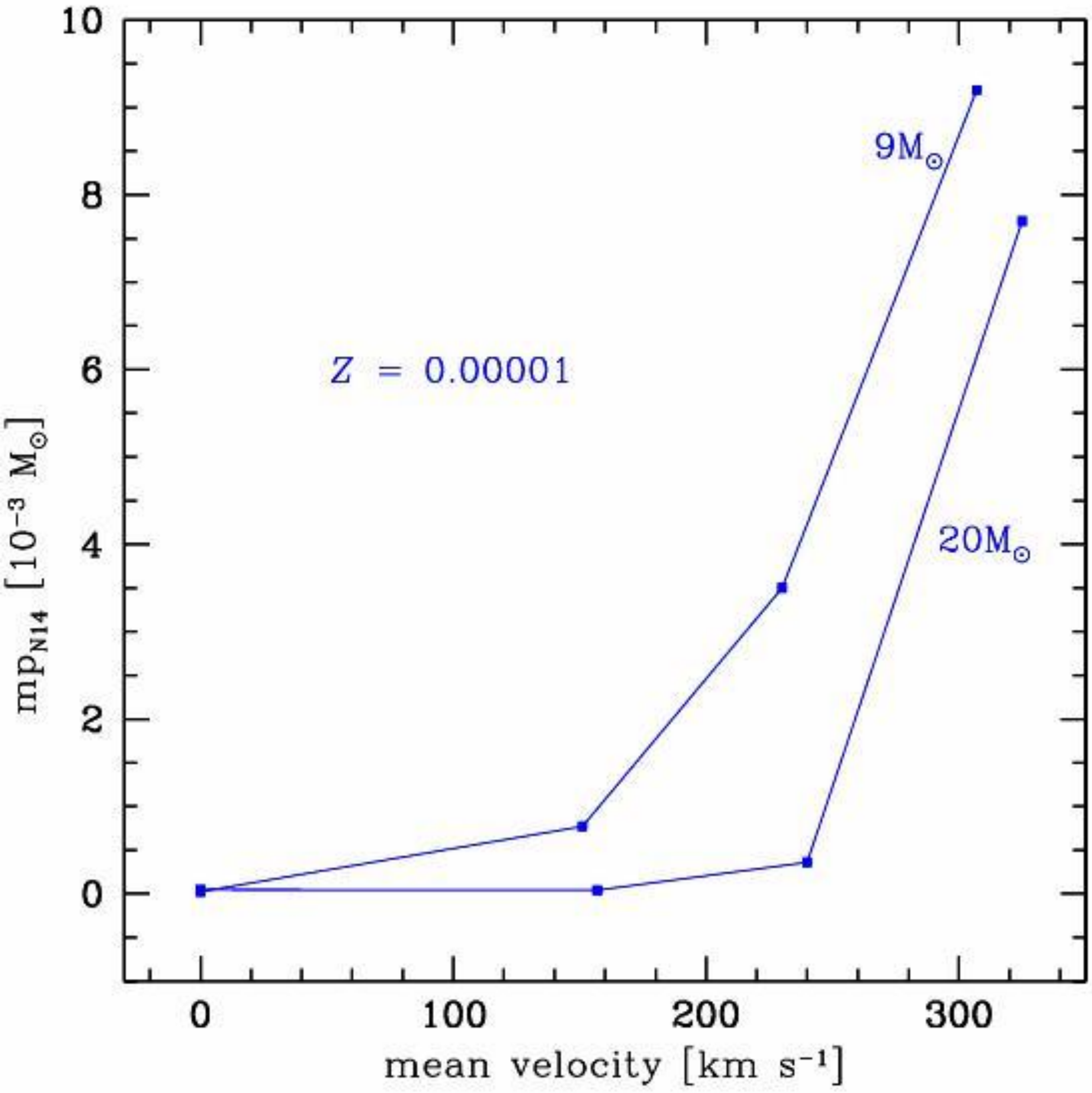


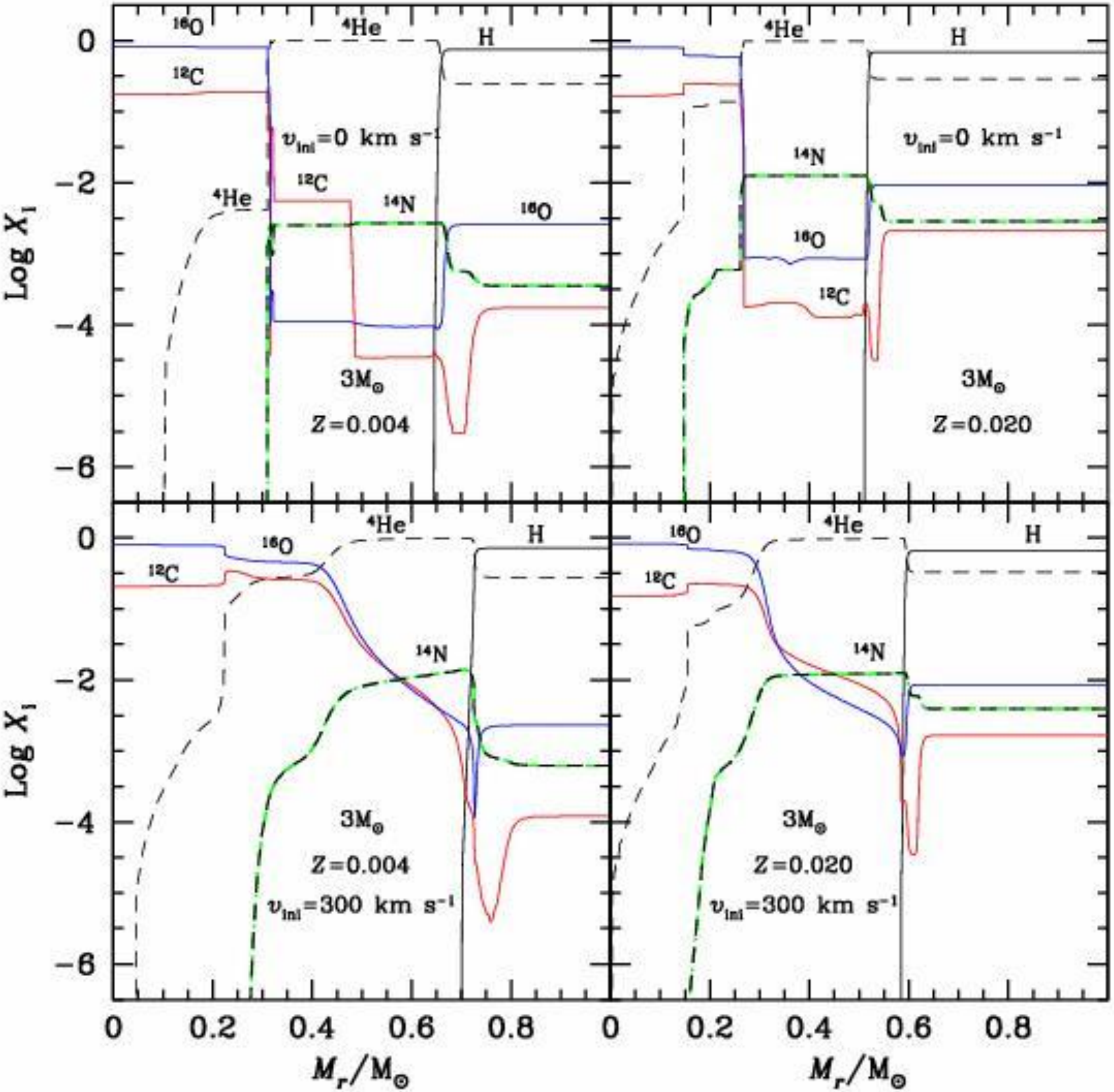
V_{ini}=800 km/s

V_{ini}=300km/s

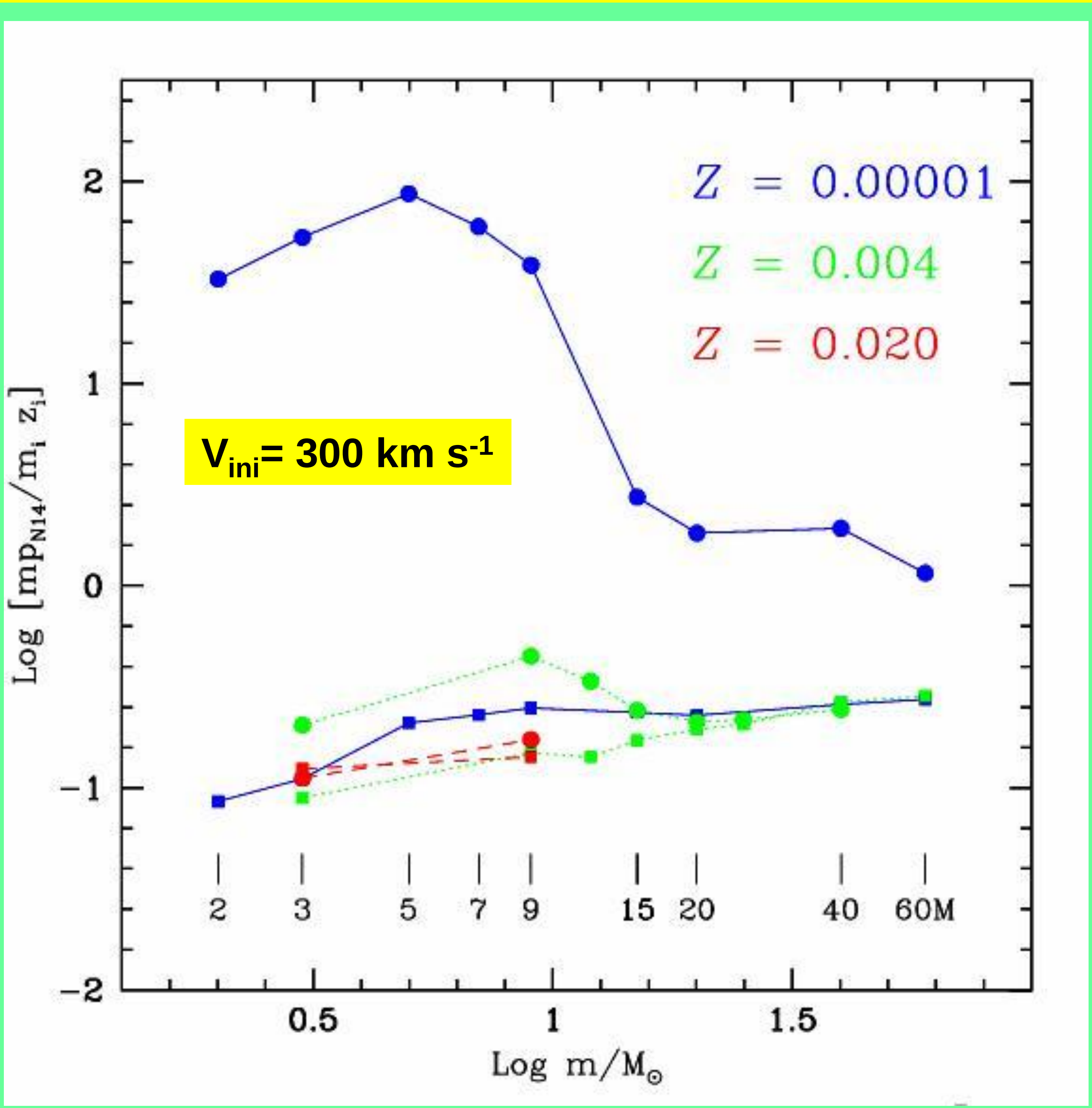
V_{ini}=0km/s

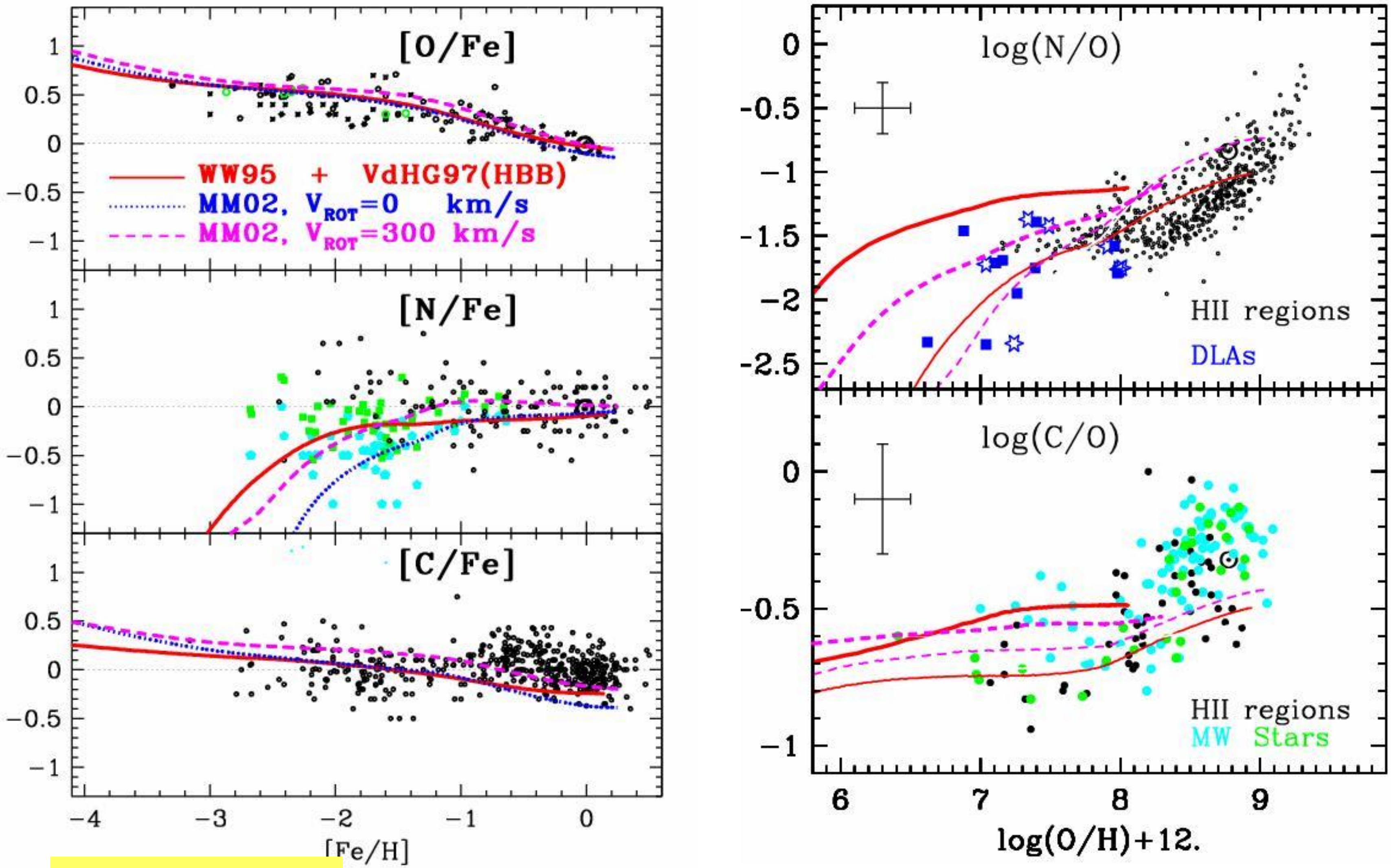
Increase of primary N production when rotation increases




^{16}O
^{4}He
H
^{12}C
$\upsilon_{\rm ini}$=0 km s^{-1}
^{12}C
^{4}He
^{14}N
^{16}O
3M$_\odot$
Z=0.004
^{4}He
H
$\upsilon_{\rm ini}$=0 km s^{-1}
^{14}N
^{16}O
^{12}C
3M$_\odot$
Z=0.020
^{16}O
^{4}He
H
^{12}C
^{14}N
3M$_\odot$
Z=0.004
$\upsilon_{\rm ini}$=300 km s^{-1}
^{16}O
^{4}He
H
^{12}C
^{14}N
3M$_\odot$
Z=0.020
$\upsilon_{\rm ini}$=300 km s^{-1}
Log $X_{\rm i}$
0
−2
−4
−6
0
0.2
0.4
0.6
0.8
M_r/M$_\odot$

L’AZOTE PRIMAIRE N’EST PRODUIT QU’A FAIBLE Z.



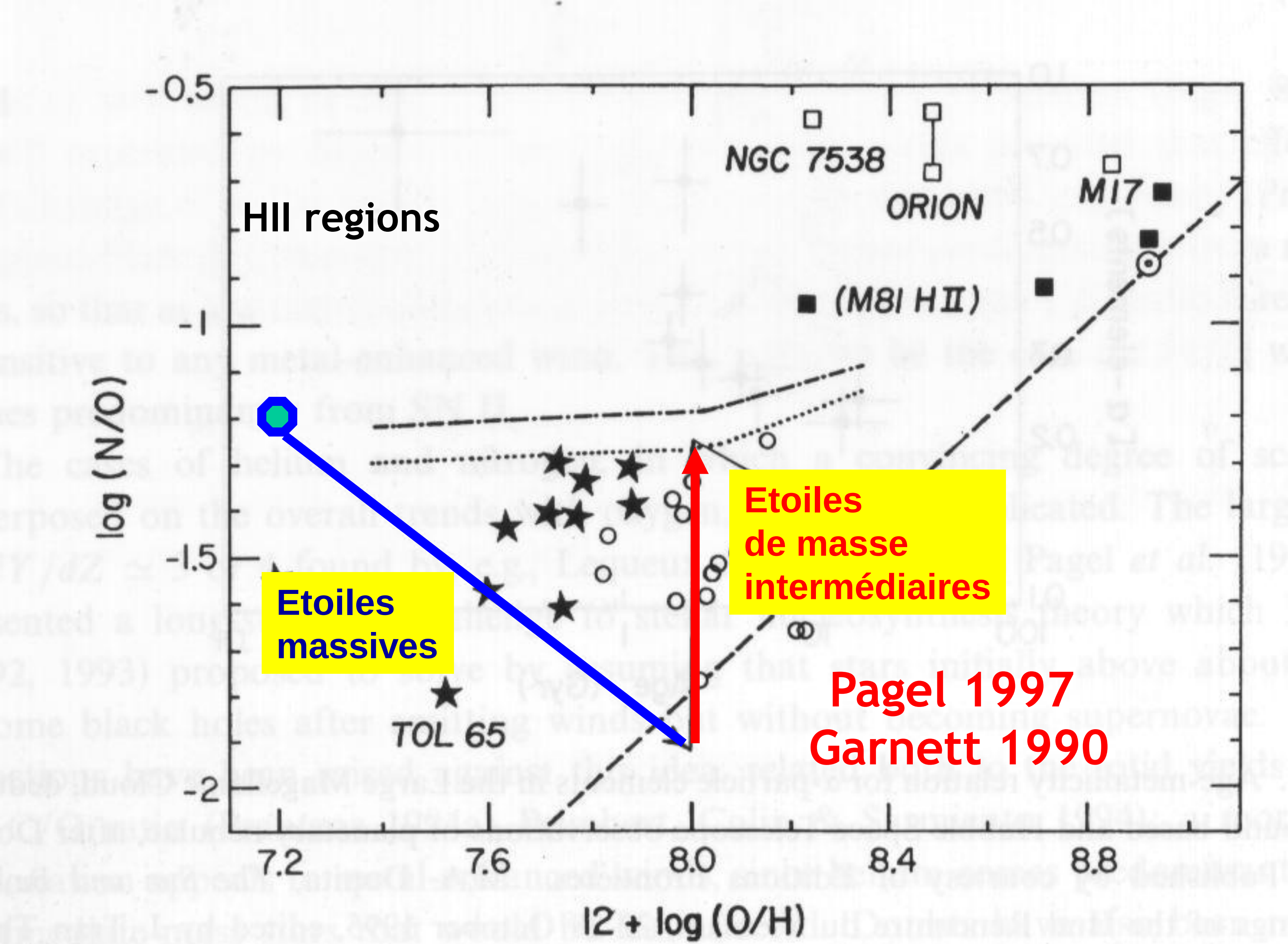


Prantzos 2003

See also Carigi 2003; Chiappini et al. 2003

Contribution from rotation of the same order of magnitude as contribution from classical models of thermal pulse AGB stars.

LE PRINCIPE DE L’HORLOGE A L’AZOTE



HII regions

Etoiles massives

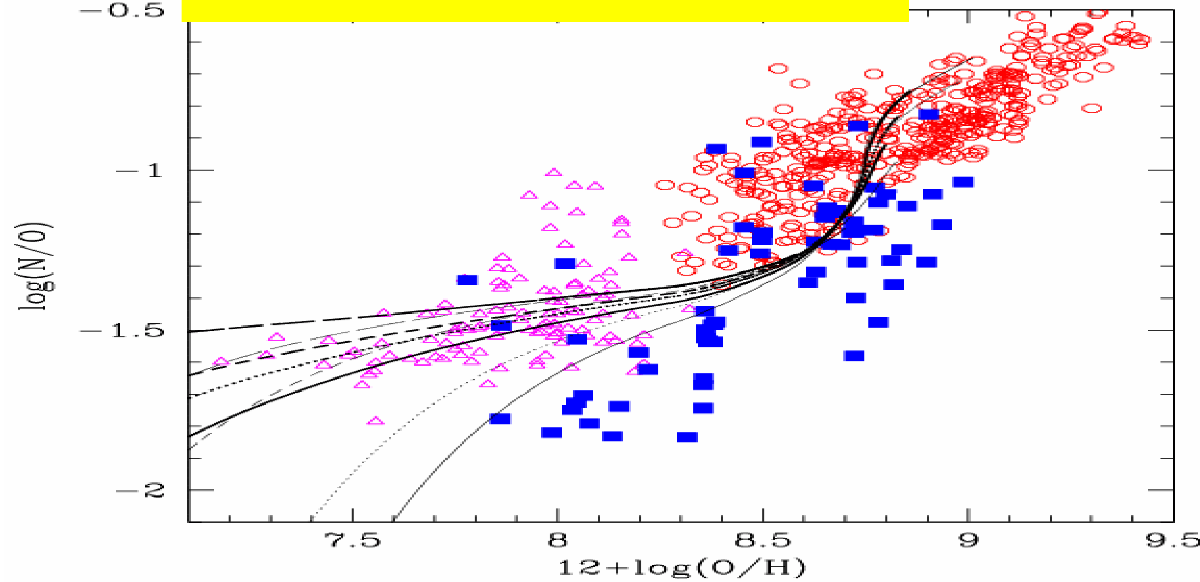
Etoiles de masse intermédiaires

Pagel 1997
Garnett 1990

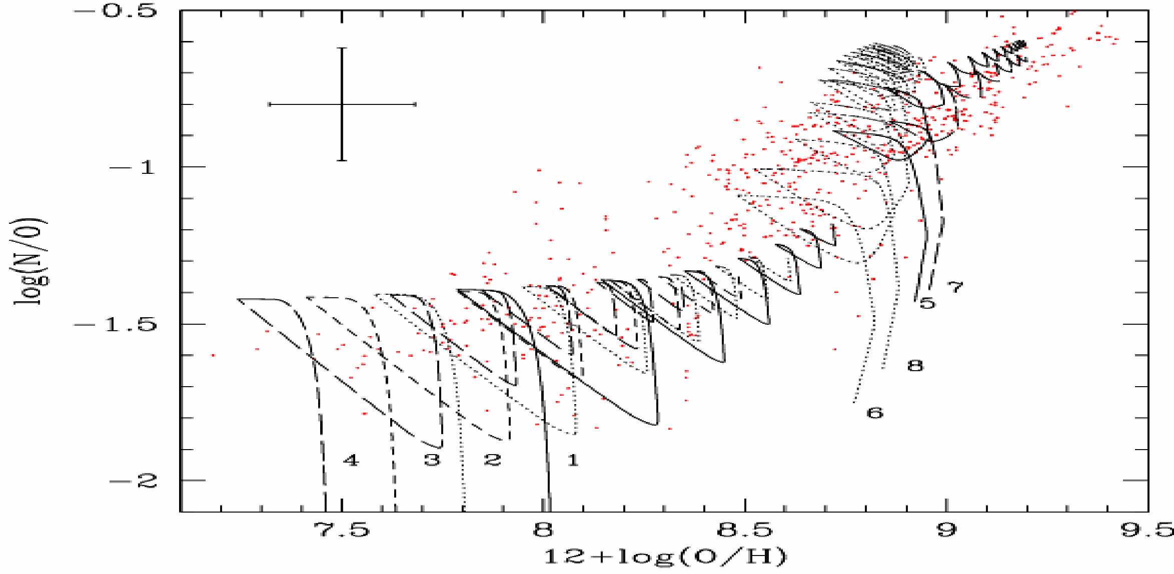
Scatter might be due to different Star Formation History

Mouhcine and Contini 2002

Continuous star formation rate



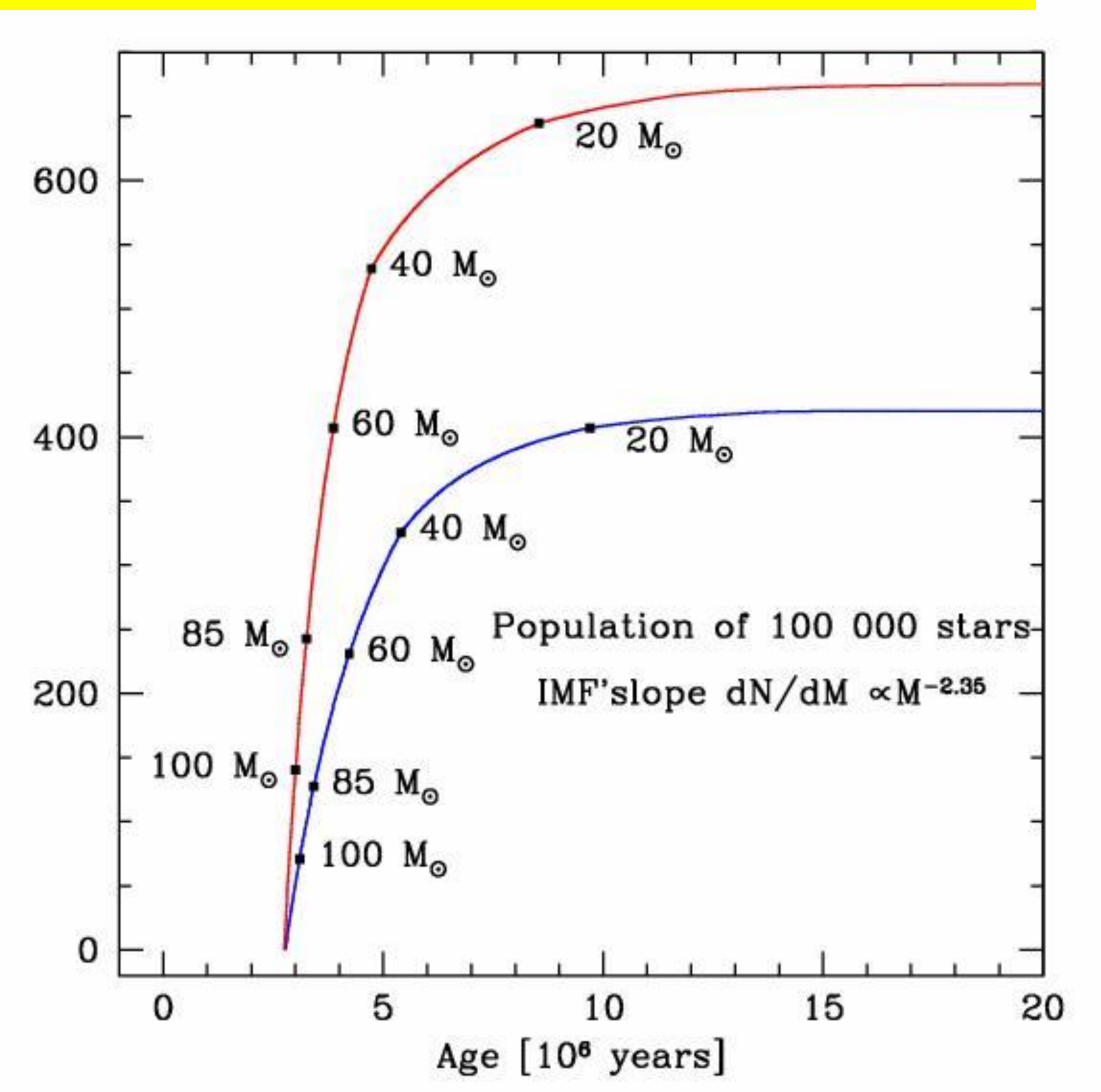
Succession of starburst epsiodes



Masse d'^{16}O nouvellement synthétisé, en masses solaires, éjectée par une population de 100 000 étoile en fonction du temps

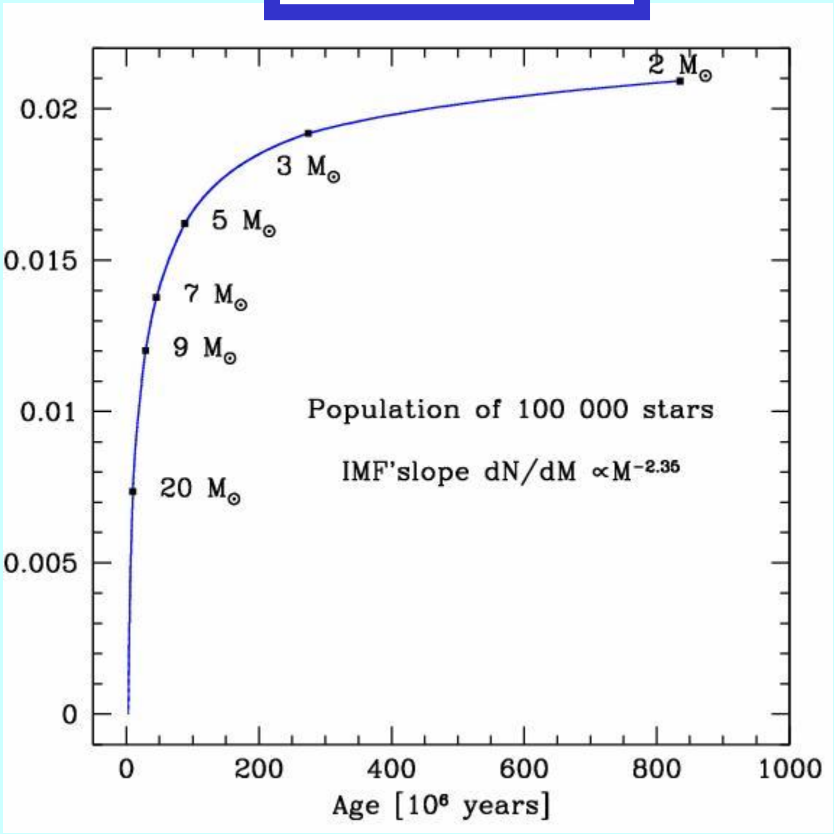
La rotation augmente
la quantité totale
par un facteur ~1.6

Dans les deux cas,
plus de
95% de la quantité
totale éjectée
est ejectée
avant 10^7 ans

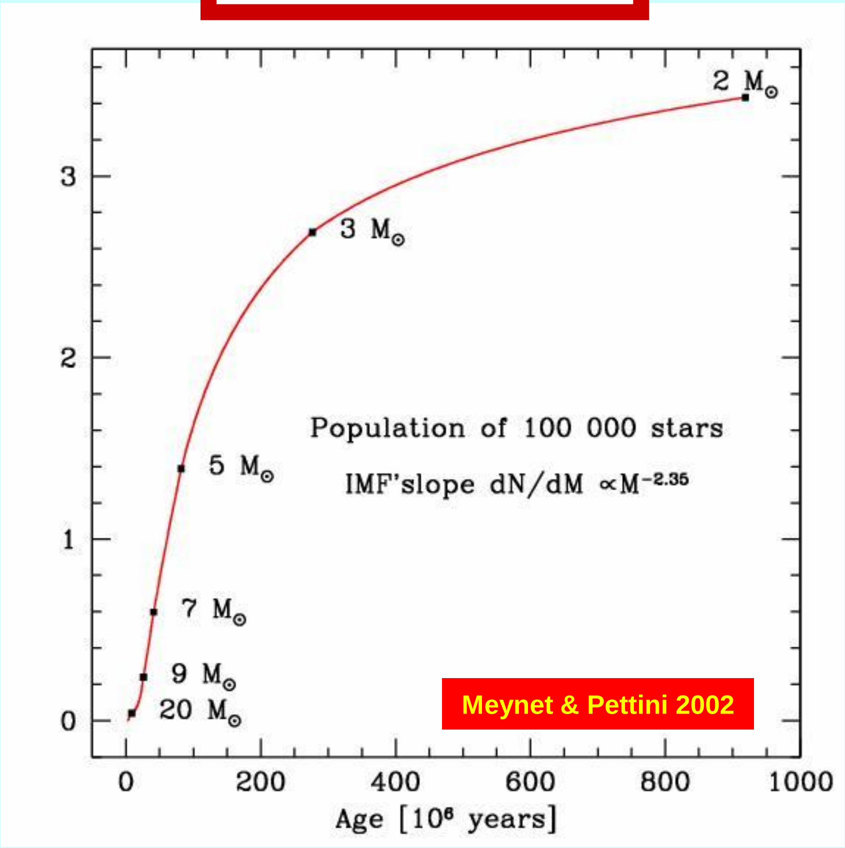


Masse d'^{14}N nouvellement synthétisé

V_{ini}= 0 km s^{-1}



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



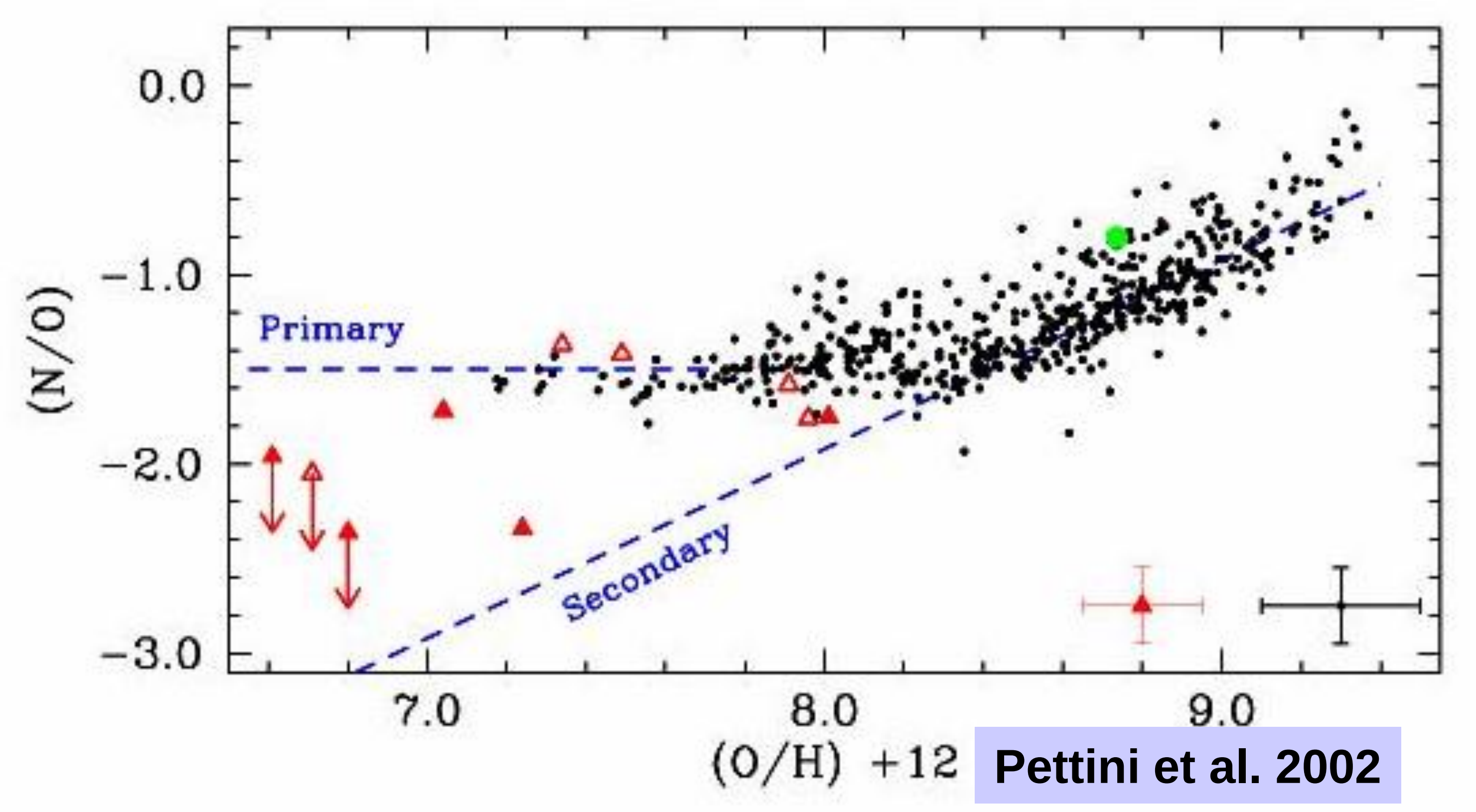
95% de la quantité totale éjectée après

425 10^6 années

668 10^6 années

La rotation augmente le délais temporel entre l'éjection de l'oxygène et de l'azote. DLA → 700 10^6 années

UNE APPLICATION: LES ``DAMPED LYMAN ALPHA SYSTEMS”



Pettini et al. 2002

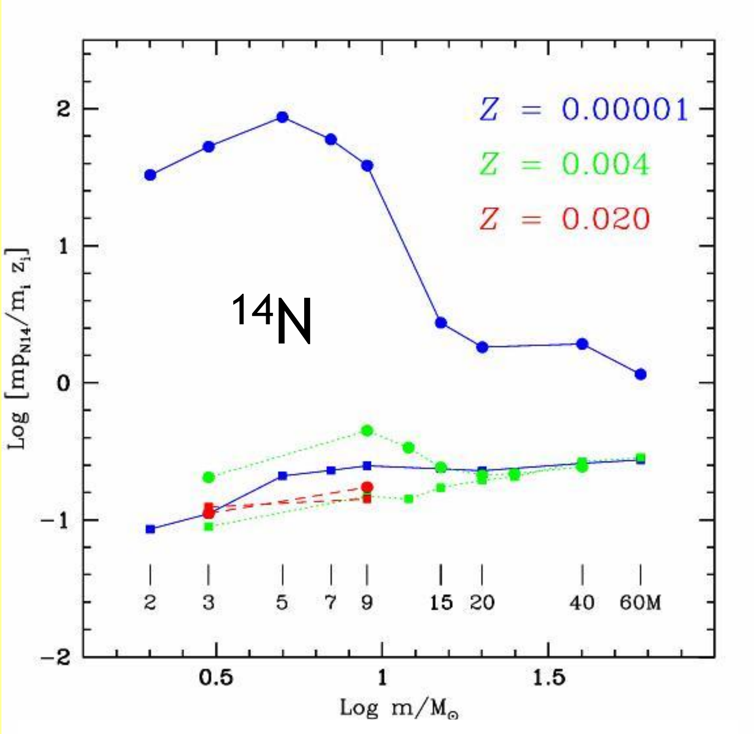
Pettini et al. 2002 → 10 DLAs, au moins 4 dans la période intermédiaire

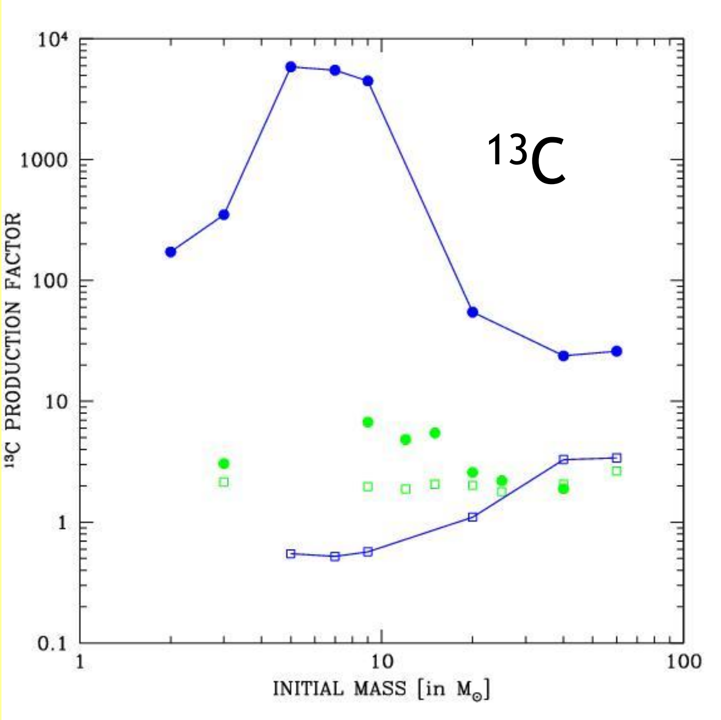
(Durée de la période intermédiaire)/(Age des plus vieux DLA) ~ 0.4
si DLA formé continuellement

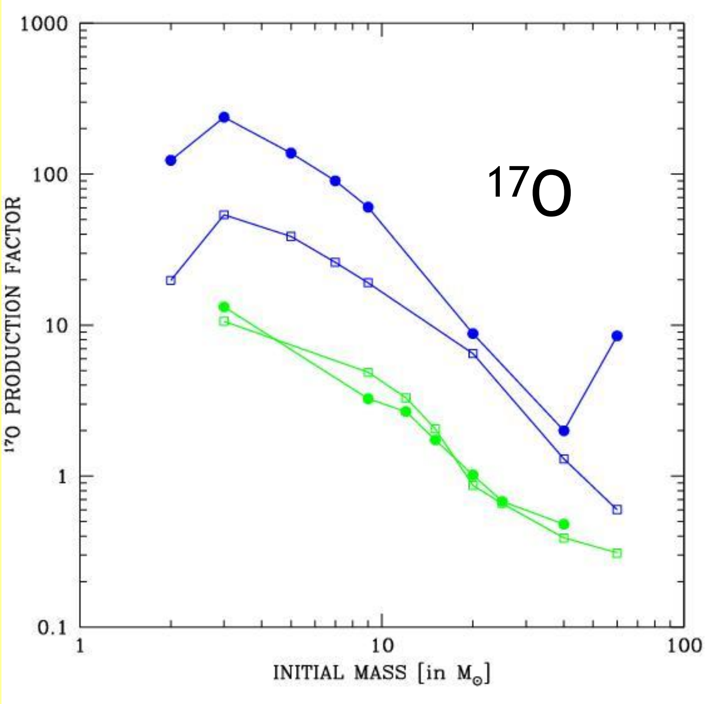
Age des DLA les plus vieux (formés à z~6) observé à <z> ~ 2.5 = ~1.8 Ga

→ Durée de la période intermédiaire ~ 0.4 X 1.8 Ga ~0.7 Ga.

A très faible métallicité, Les effets de la rotation sur les ``yields’’ de certains isotopes peuvent être très importants



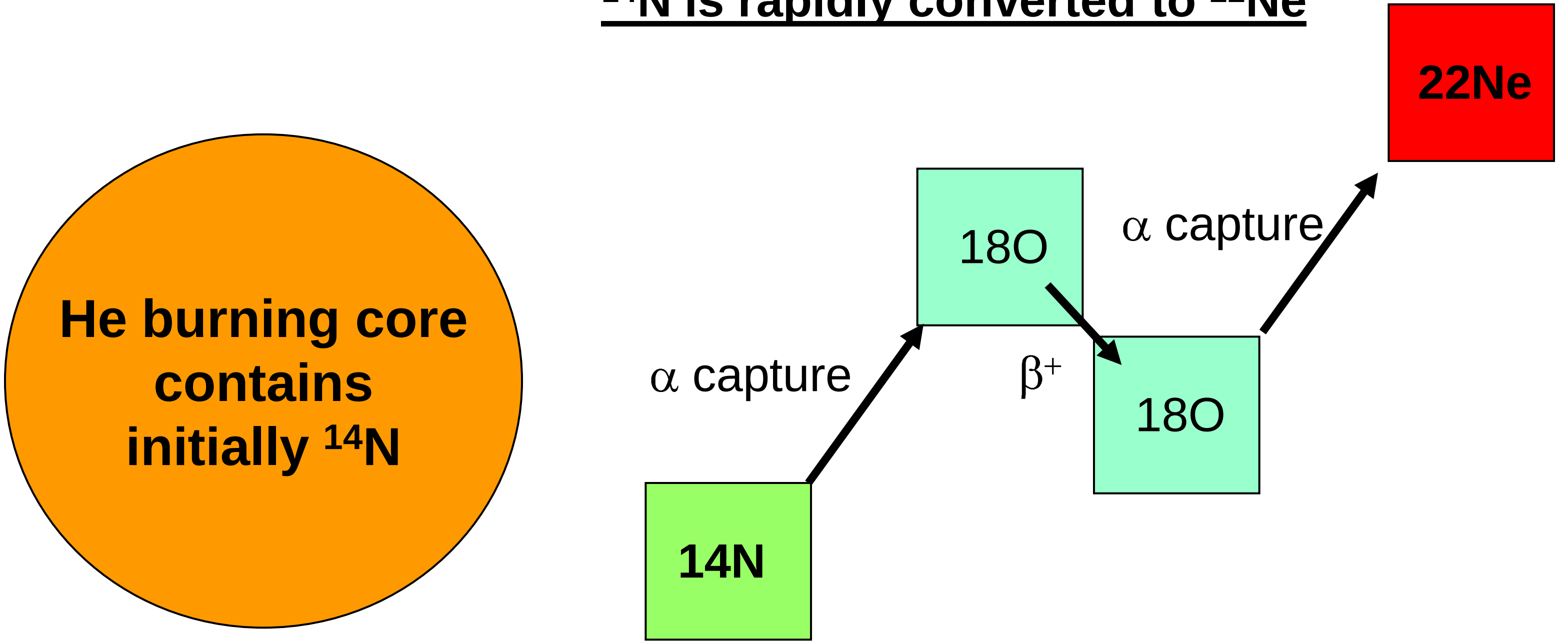




The weak s-process

Site: Core He burning (and shell C-burning) in massive stars (e.g. 25 solar masses)

^{14}N is rapidly converted to ^{22}Ne



He burning core contains initially ^{14}N

14N

α capture

18O

β+

18O

α capture

22Ne

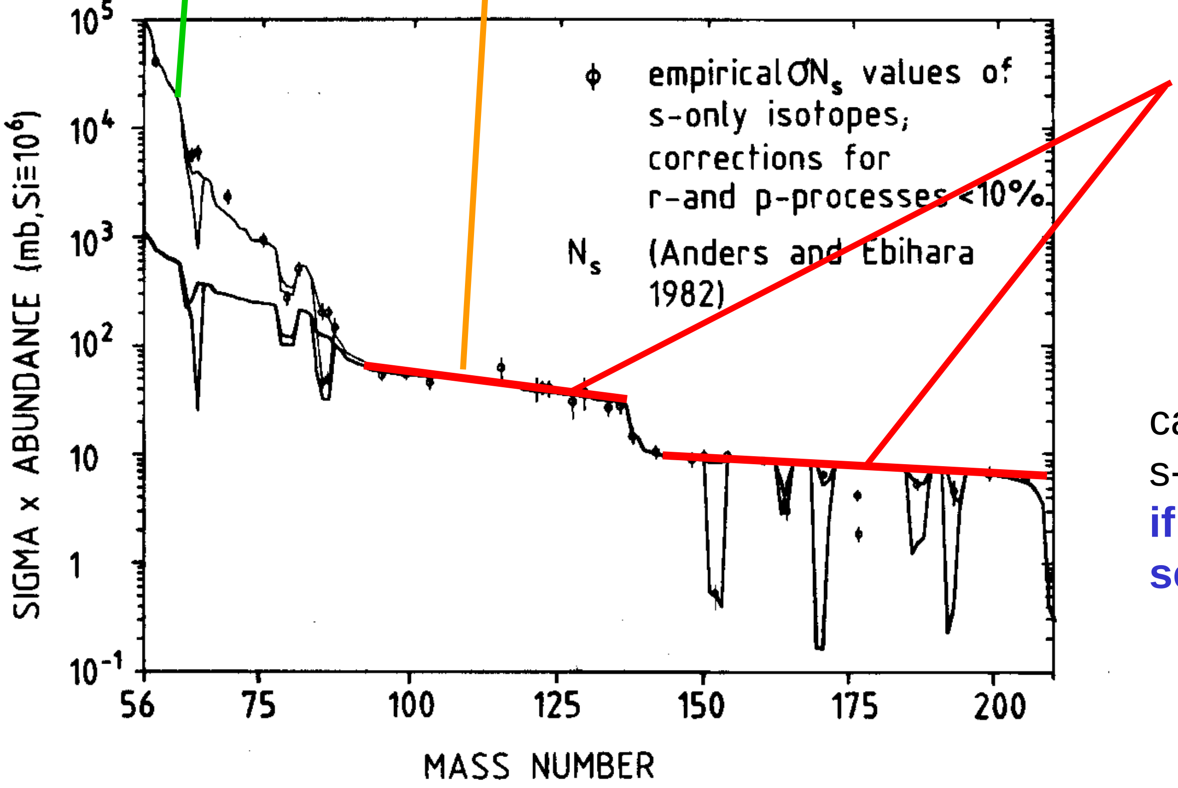
Towards the end of He burning T~3e8 K: **^{22}Ne(α,n)** provides a neutron source

→ preexisting Fe (and other nuclei) serve as seed for a (secondary) s-process

The sites of the s-process

weak s-process: **core He/ shell C burning in massive stars**

main s-process: **He shell flashes in low mass TP-AGB stars**

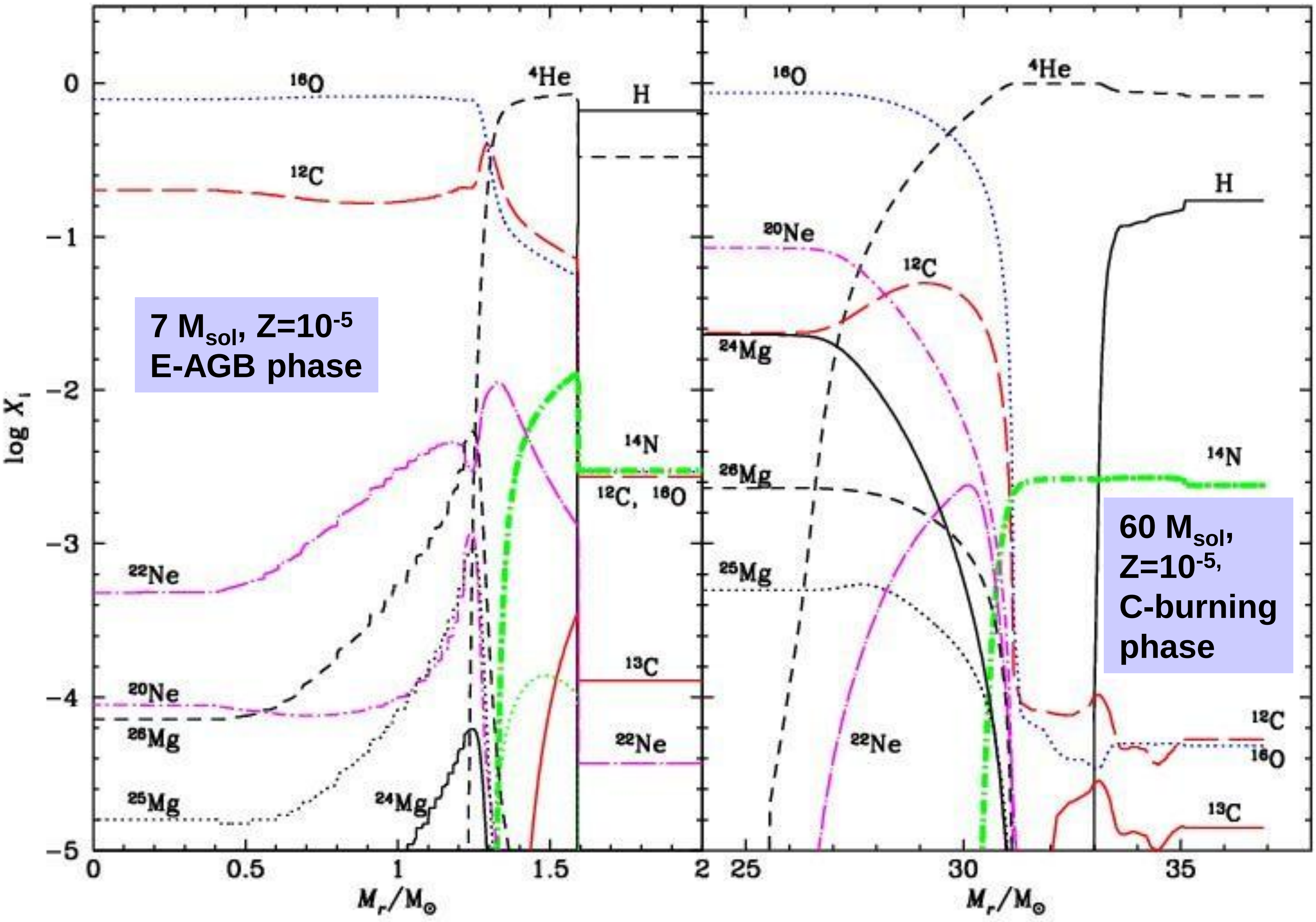


approx. steady flow

$$Y\lambda \propto Y\sigma_{(n,\gamma)} \approx \text{const}$$

↓

can easily interpolate
s-contribution for s+r-nuclei
if neutron capture cross sections are known



7 M_{sol}, Z=10^{-5}
E-AGB phase

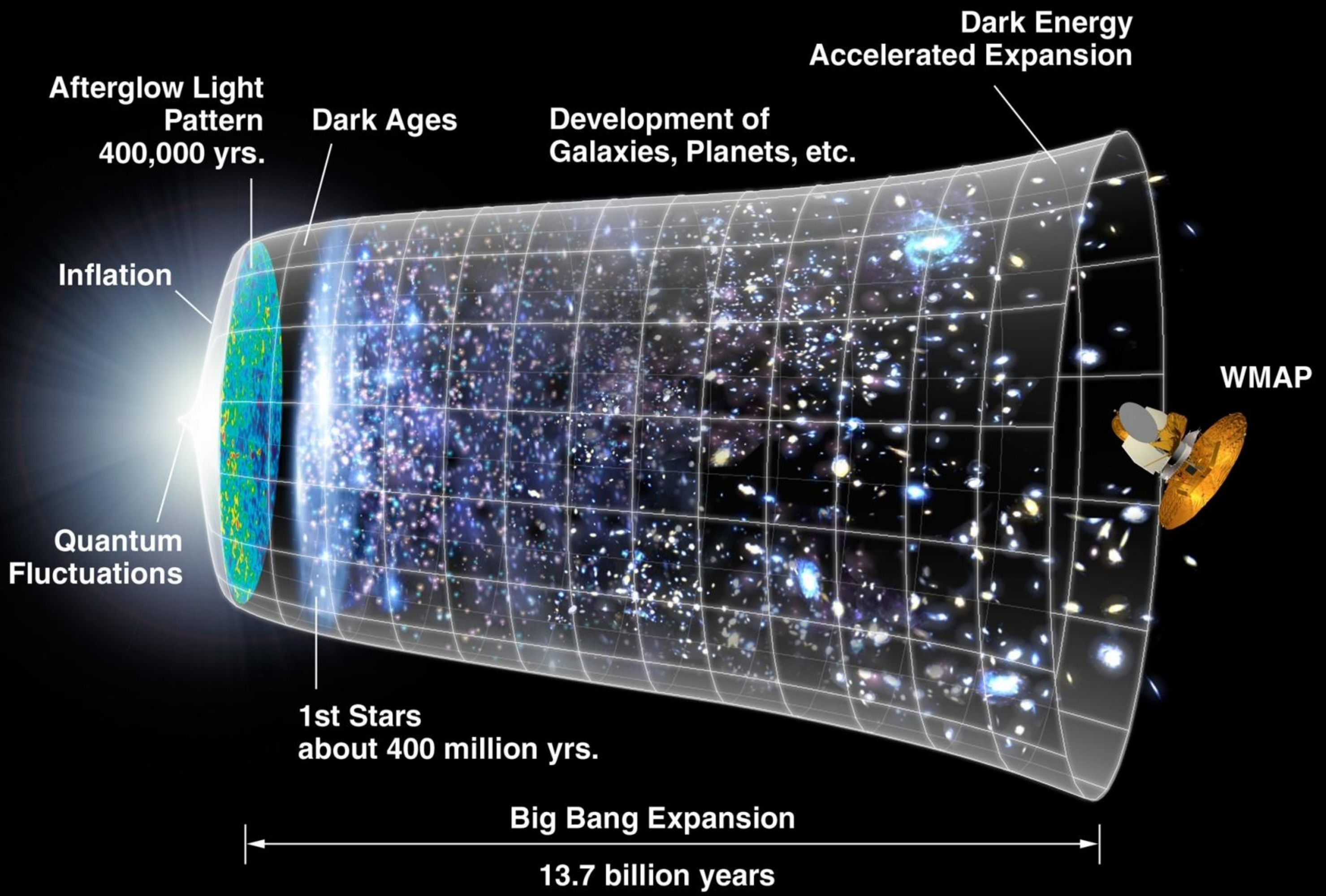
60 M_{sol},
Z=$10^{-5,}$
C-burning
phase

MASS	2-4 Msol	4-8 Msol	10-40 Msol	>40 Msol
^{12}C 3α----->^{12}C HeB	Shell HeB P $3D_{up}$ + PN f ~2-5	Shell HeB P $3D_{up}$ + PN f~1 HBB f~8 no HBB	Core HeB P SN f~3-4	Core Heb P WR + SN f~40, Z_{sol} f~4, Z=0.1 Z_{sol}
^{14}N C,O---->^{14}N CNO cycle	Core HB S $1D_{up}$ + RG f~2	Core HB S $1D_{up}$ + RG f~3 no HBB or HBB P $3D_{up}$ + PN f~30	Core HB S SN f~3	Core HB S WR(RSG) + SN f~40, Z_{sol} f~3, Z=0.1 Z_{sol}
^{16}O 12C(α,γ)16O HeB			Core HeB P SN f~10	Core HeB P WR, SN F~4, Z=Z_{sol} F~20,Z=0.1Z_{sol}

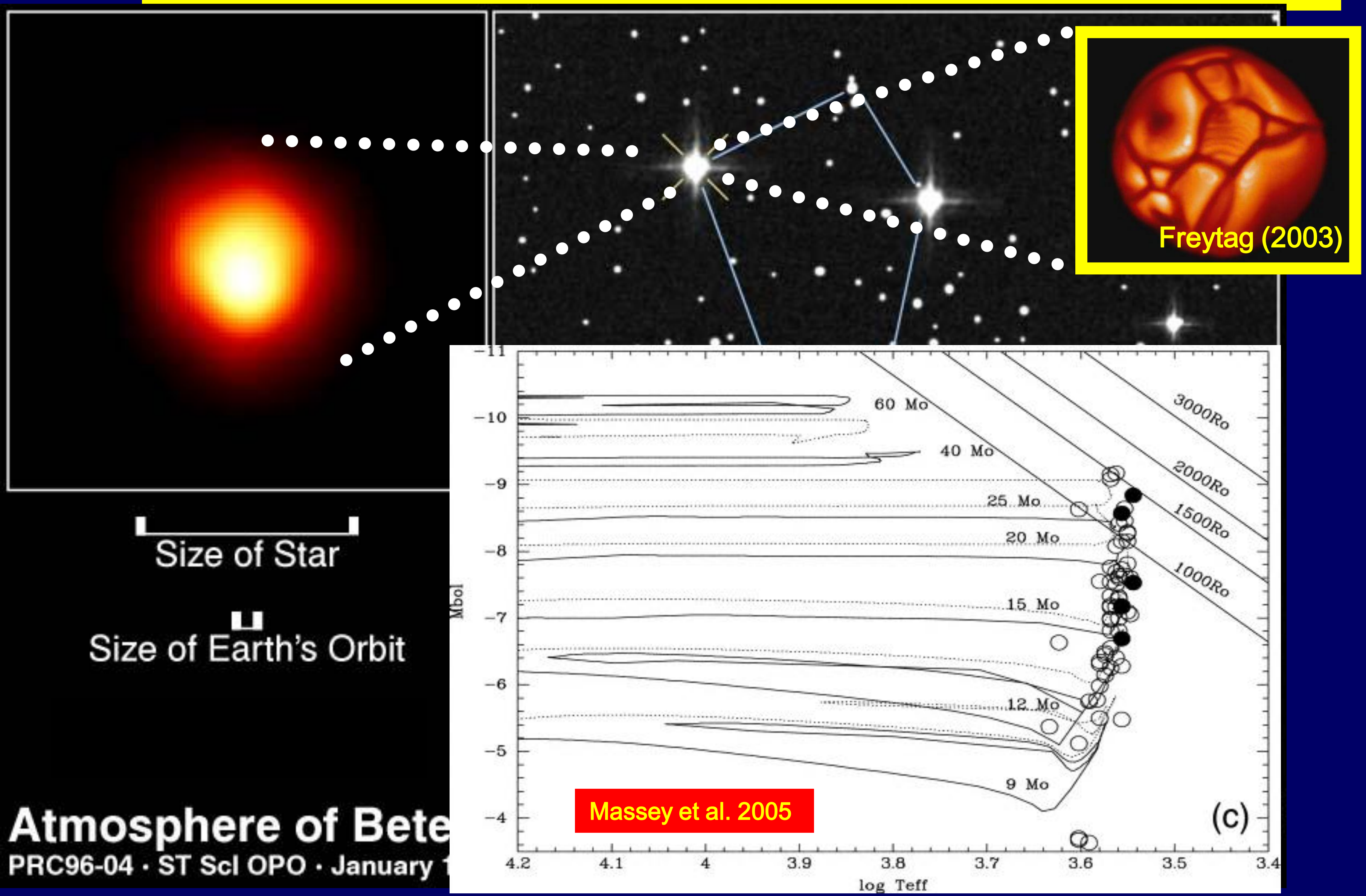
Adapted from Prantzos et al. 1996

MASSIVE STARS AS COSMIC ENGINES

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



IN A STELLAR GENERATION: 3/1000 !



Freytag (2003)

Massey et al. 2005

Diamètre de HD 206936, 1500 R_{sol}

SN Ic
GRB → MASSIVE STARS
Record redshift 6.29!

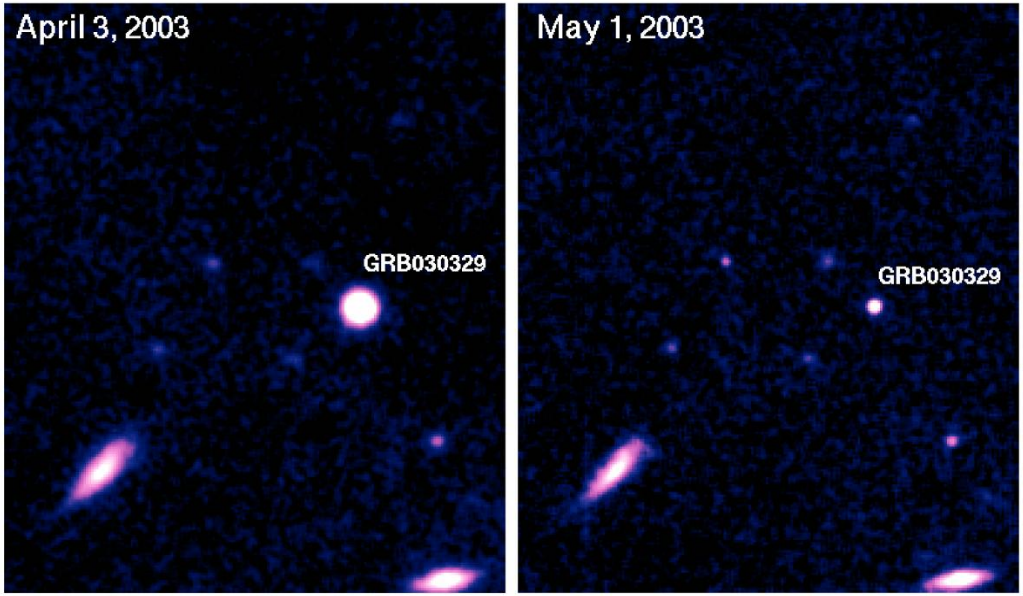
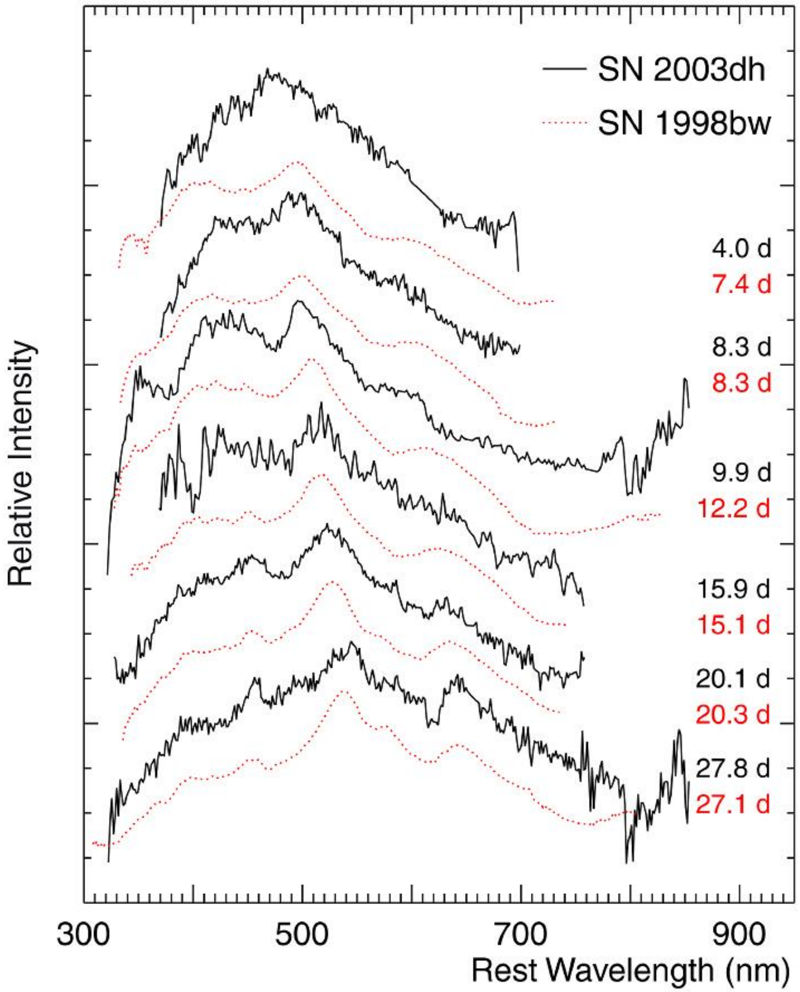


Image of Afterglow of GRB 030329
(VLT + FORS)

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

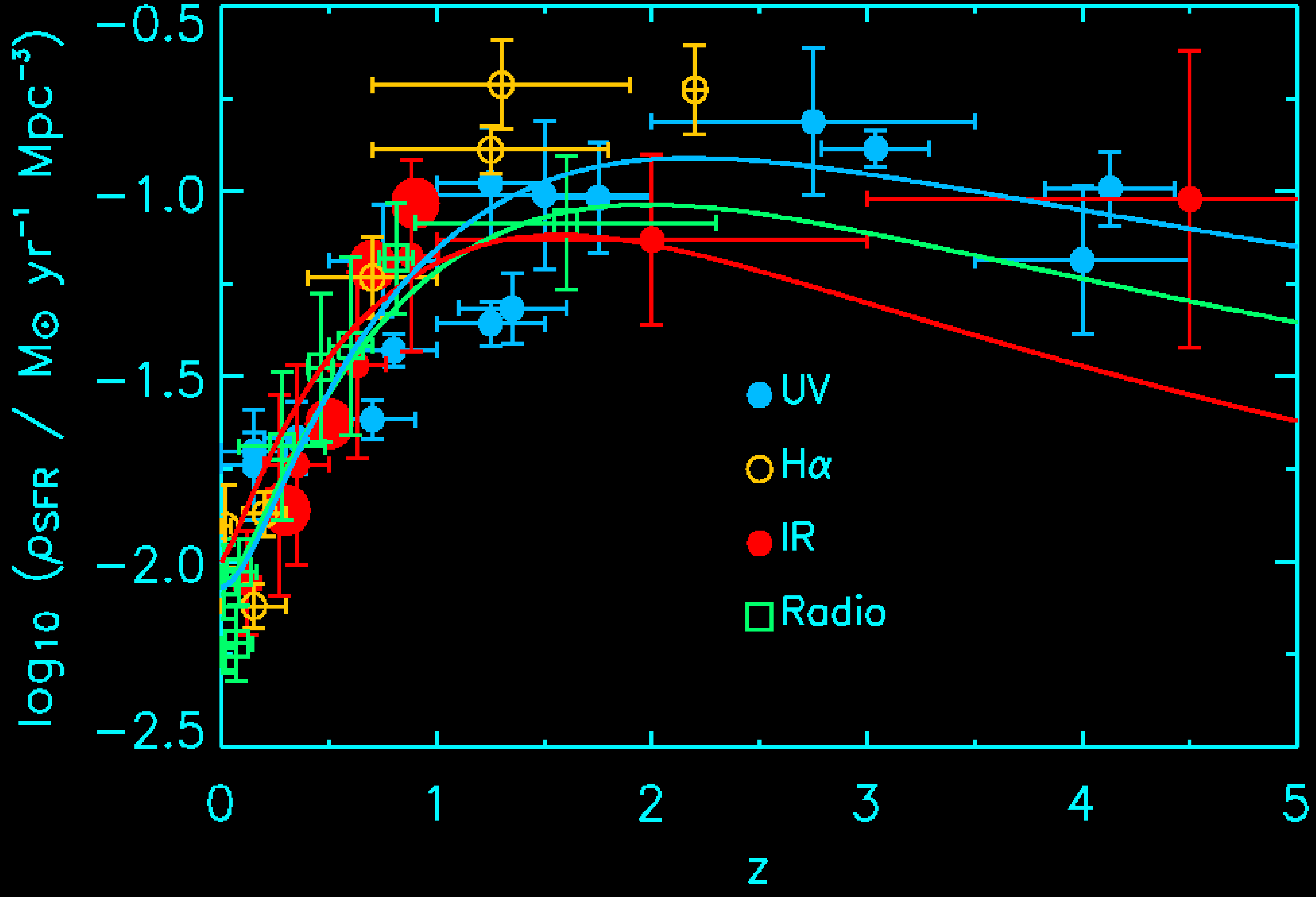
E_{kin}=4 x 10^{52} ergs
0.35 M_{sol} of ^{56}Ni
Ejecta ~8 M_{sol}
Mass 25-30 M_{sol}



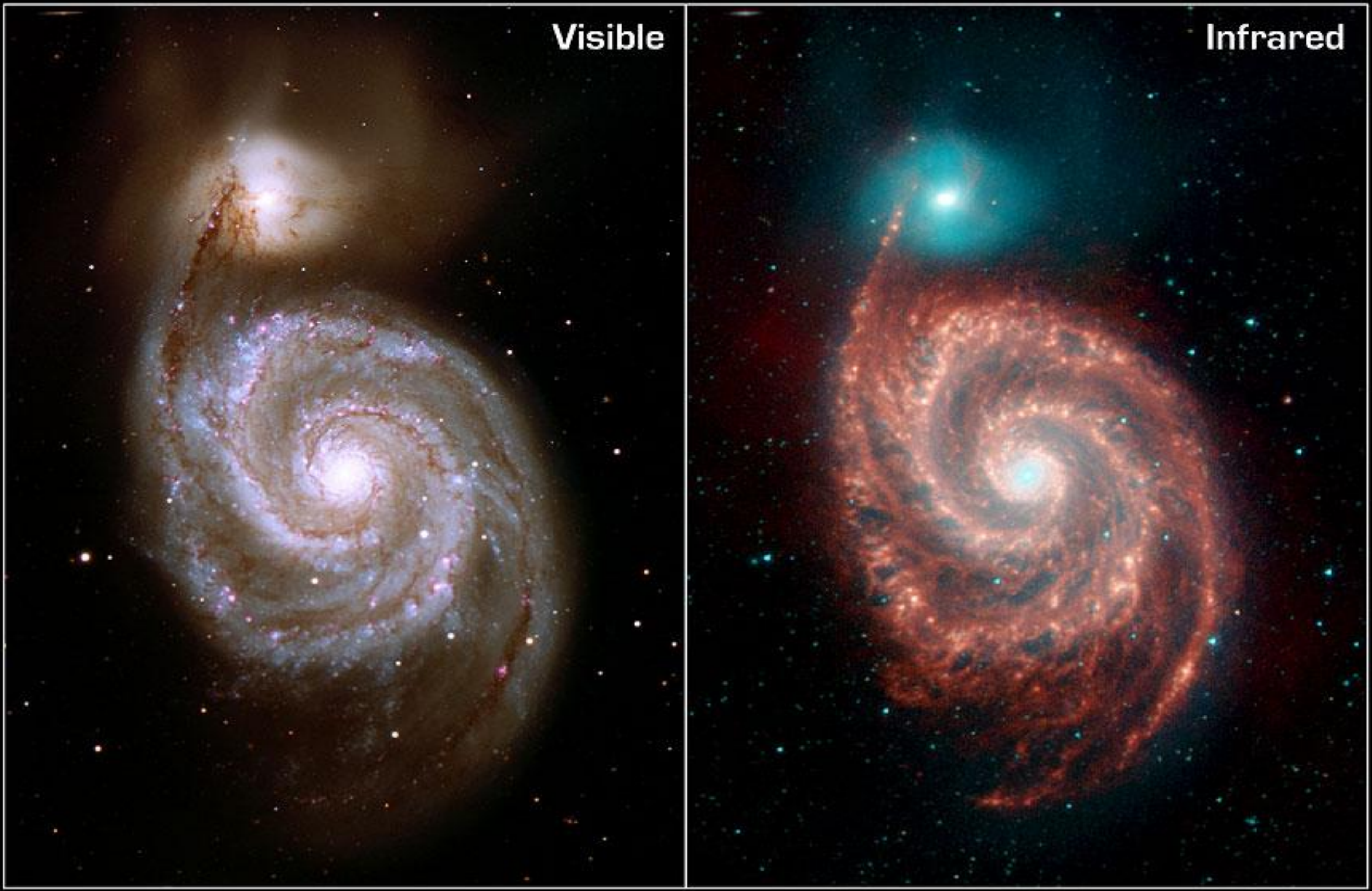
Visual Spectra of Hypernova in GRB 030329
(VLT + FORS)

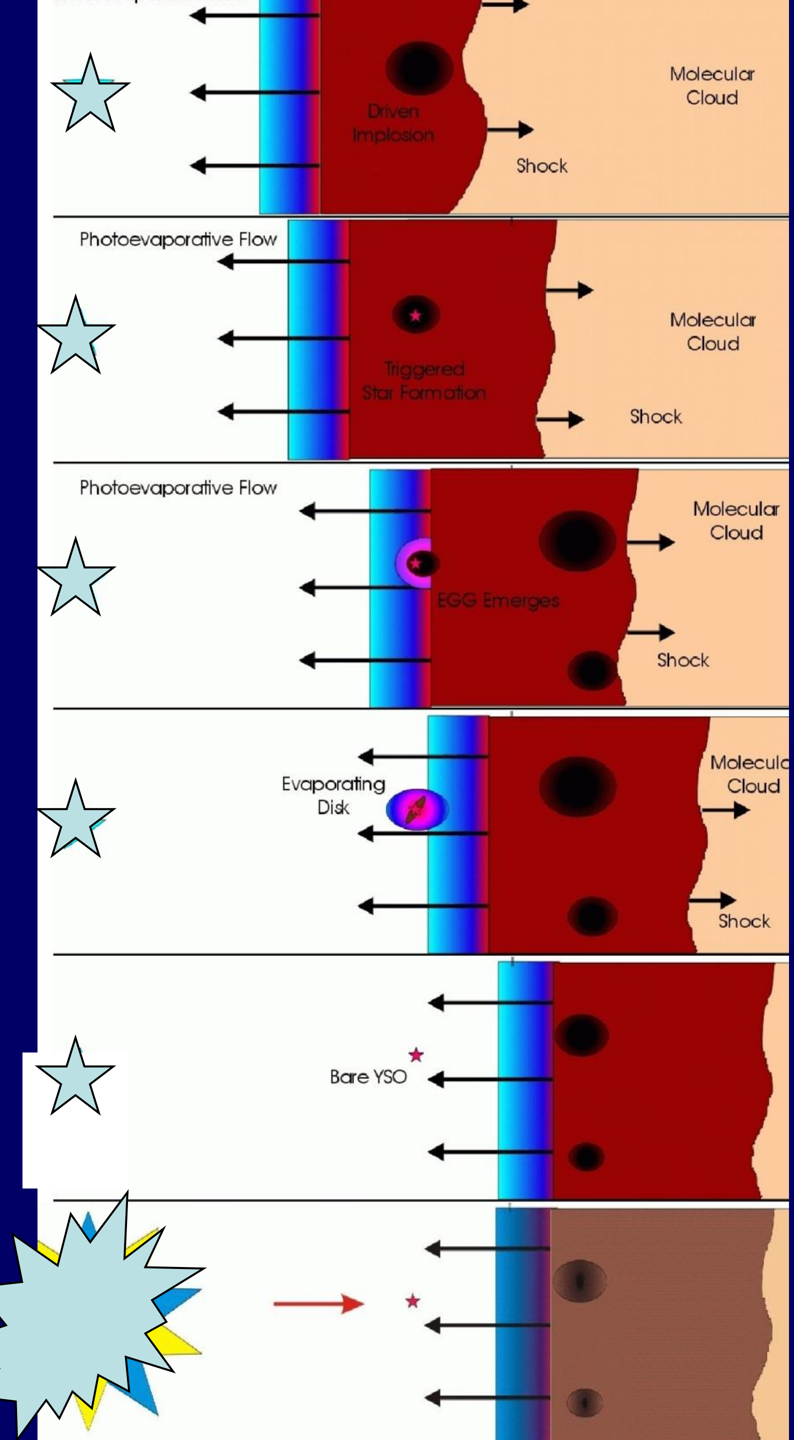
ESO PR Photo 17b/03 (18 June 2003)

Hjorth et al. 2003, Nature, 423, 847
Stanek et al. 2003, ApJ, 591, L17



log10 (ρ_{SFR} / M⊙ yr^{-1} Mpc^{-3})
−0.5
−1.0
−1.5
−2.0
−2.5
0
1
2
3
4
5
z
● UV
○ Hα
● IR
□ Radio

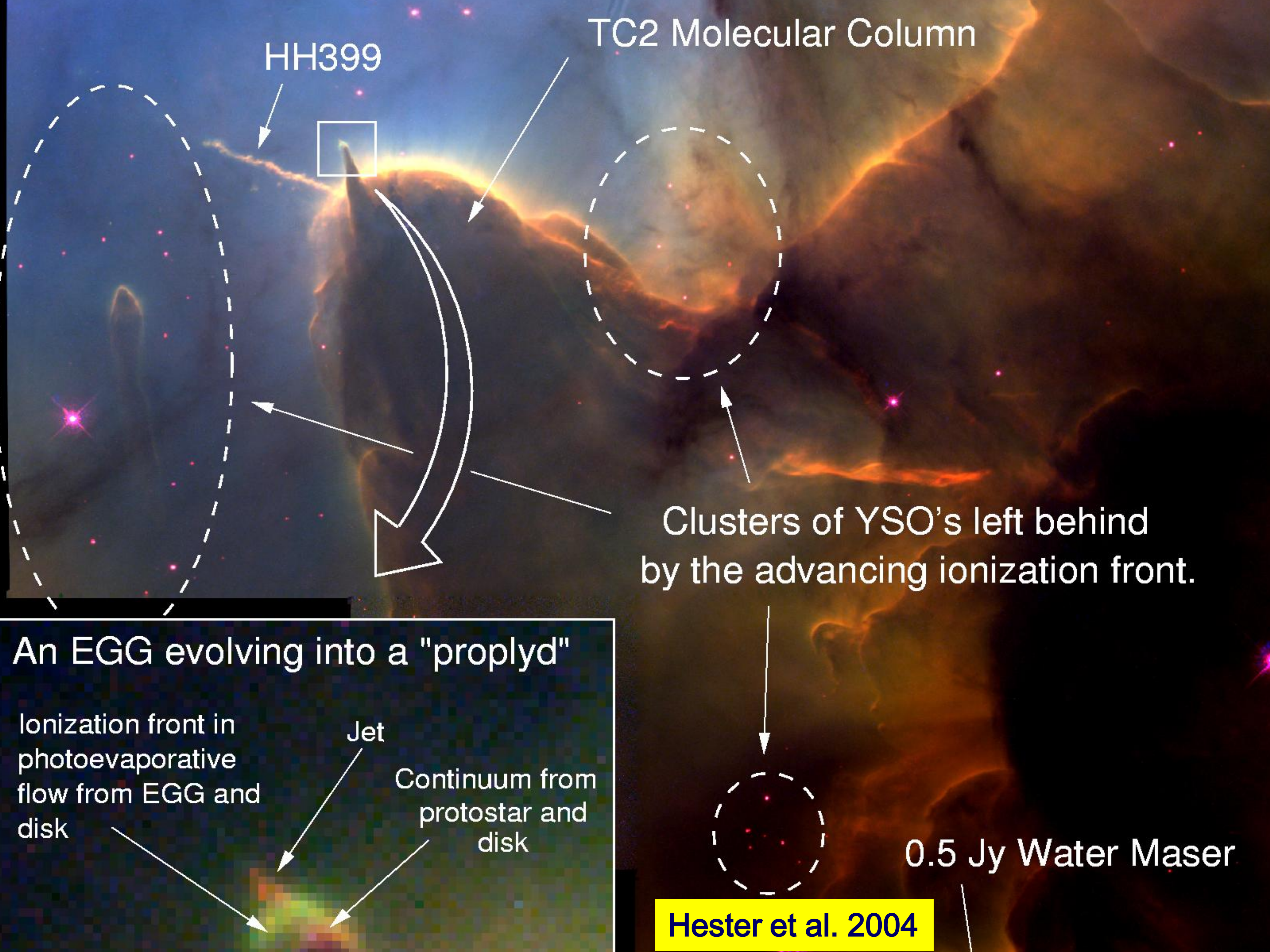

Visible
Infrared



Protoplanetary Disks
Orion Nebula

HST • WFPC2

PRC95-45b • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA



HH399

TC2 Molecular Column

Clusters of YSO's left behind by the advancing ionization front.

0.5 Jy Water Maser

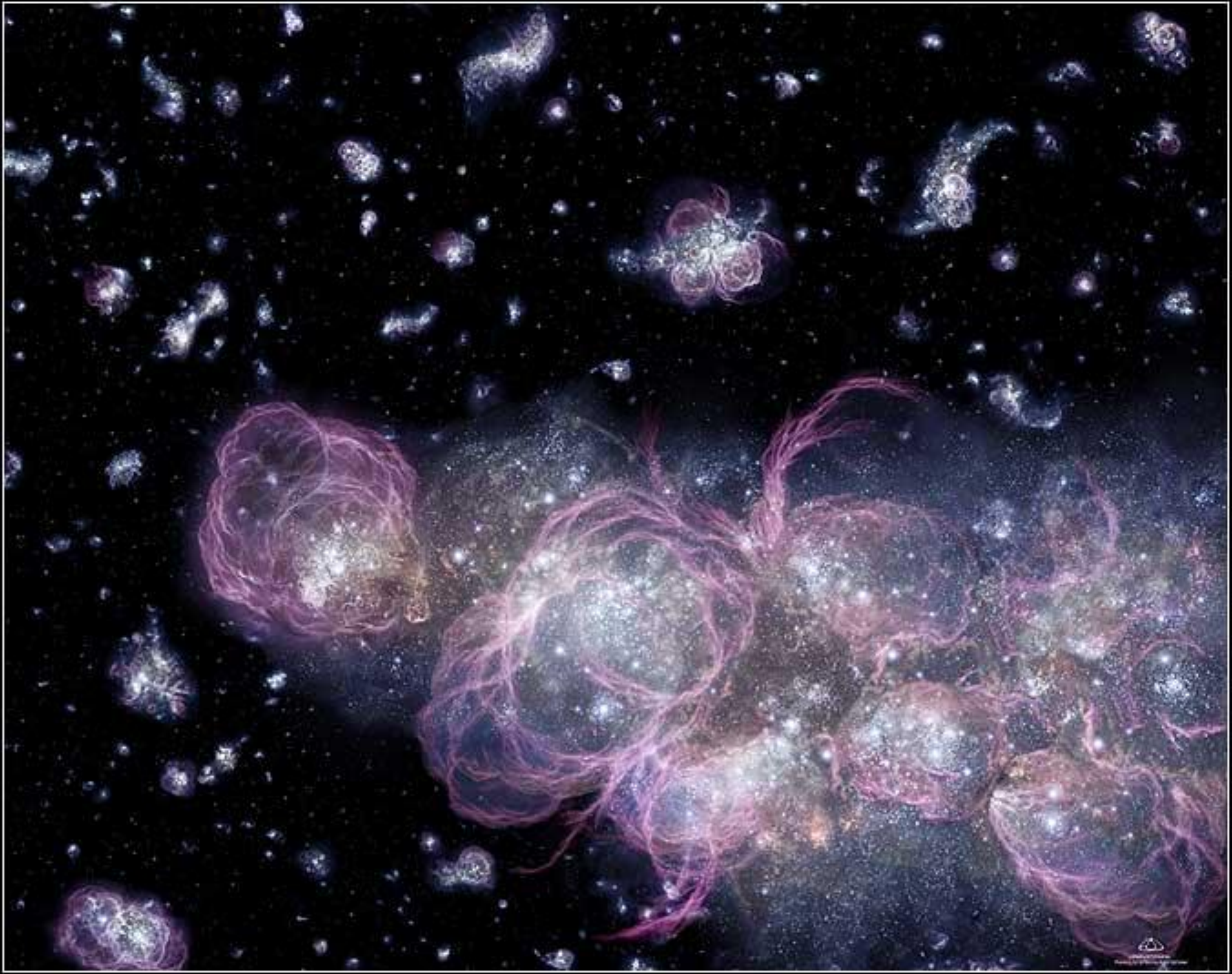
An EGG evolving into a "proplyd"

Ionization front in photoevaporative flow from EGG and disk

Jet

Continuum from protostar and disk

Hester et al. 2004



Artist's View of Star Formation in the Early Universe

Painting by Adolf Schaller • STScI-PRC02-02

Aventure intellectuelle extraordinaire…

Destin de

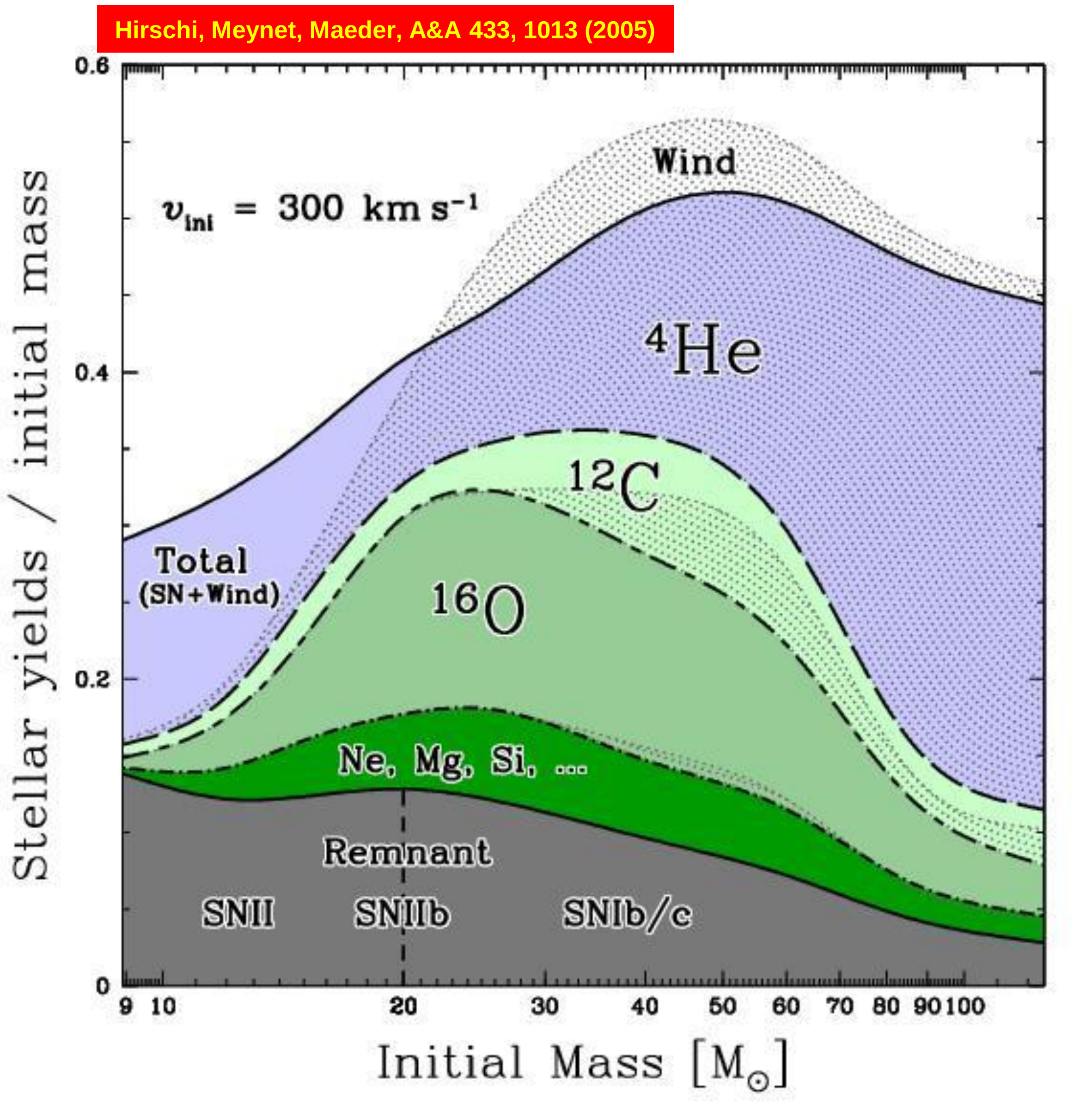
15 747 724 136 275 002 577 605 653 961 181 555 468 044 717 914 527 116 709 366 231 425 076 185 631 031 296

$$1.6\ 10^{79}$$

Protons et d’autant d’électrons dans l’Univers

Arthur Stanley Eddington (1939)

MOTEURS DE L'EVOLUTION CHIMIQUE DES GALAXIES



Hirschi, Meynet, Maeder, A&A 433, 1013 (2005)

L’ABONDANCE D’AZOTE: UNE HORLOGE GALACTIQUE ?

LES MODELES

Enrichissements de surface

🚫 Modèles standards

Modèles avec rotation ☺

Rapport des supergéantes bleues/rouges

🚫 Modèles standards

Modèles avec rotation ☺

Variation avec Z des populations de Wolf-Rayet

🚫 Modèles standards

Modèles avec rotation ☺

Variation avec Z des rapport SNe Ibc/II

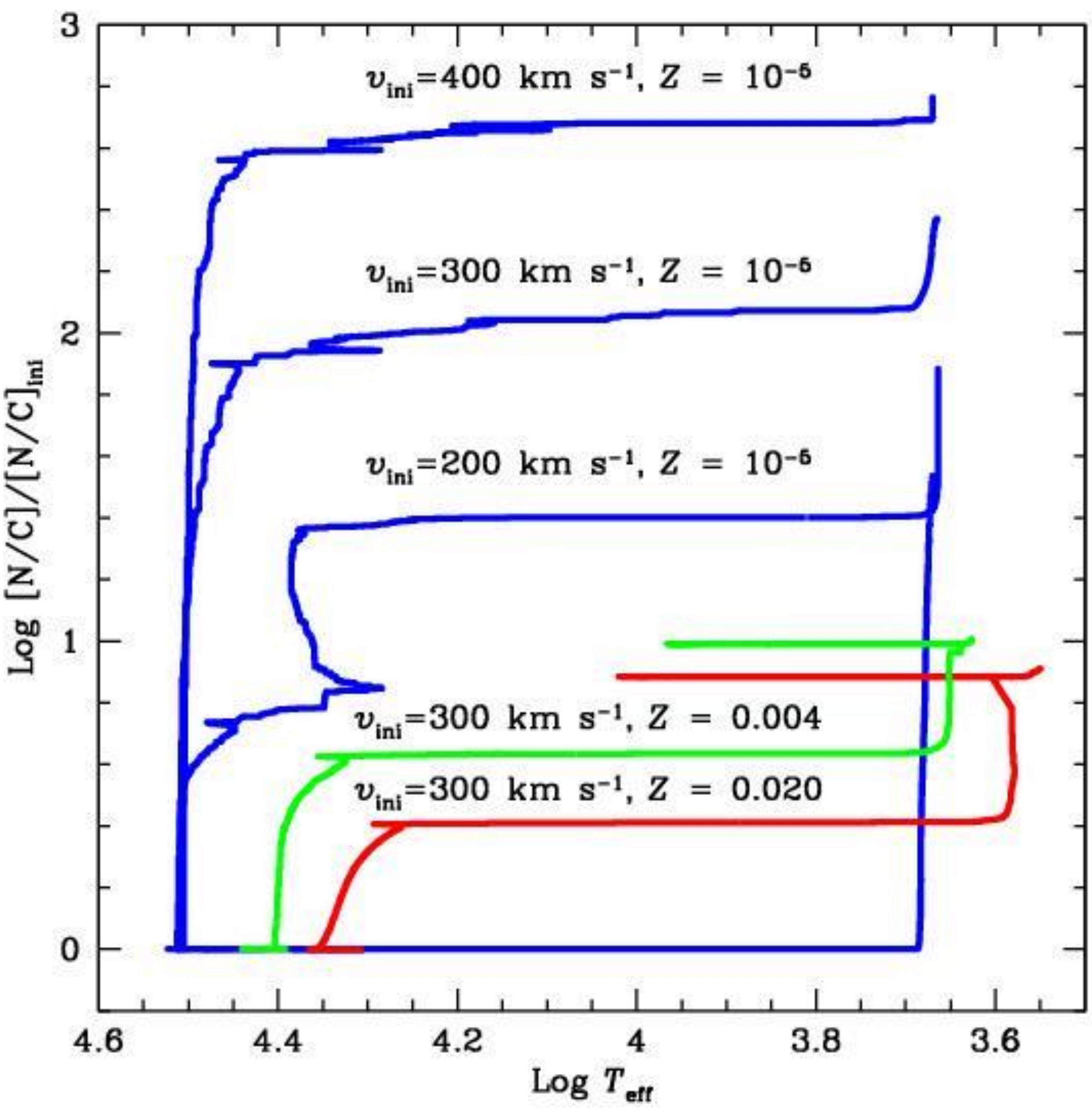
🚫 Modèles standards

Modèles avec rotation ☺

9 M_{sol}

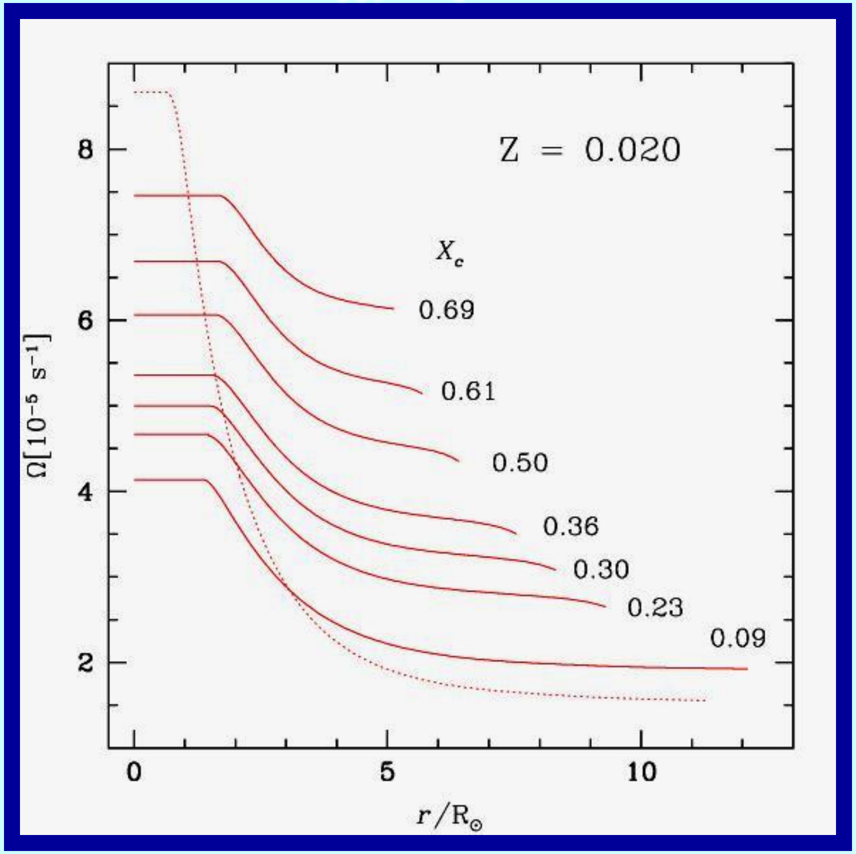
Lorsque Z ↘

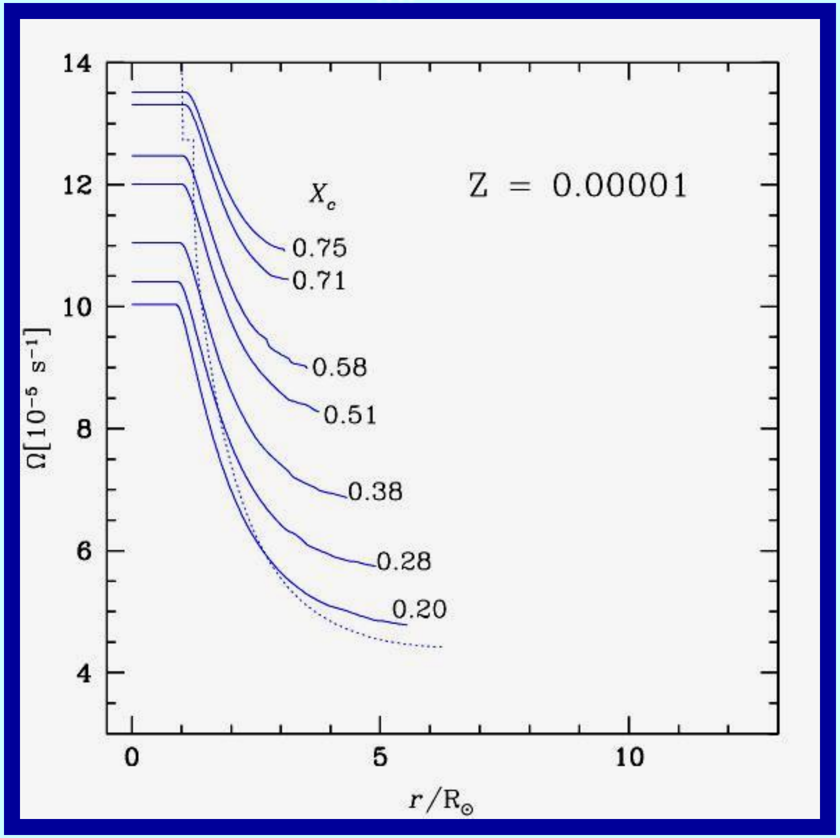
Les enrichissements de surface ↗



Les gradients de Ω sont plus raides à faible Z

20 M_{sol}, X_c fraction de masse d'H au centre, V_{ini}= 300 km/s





Pourquoi ?

Les étoiles sont plus compactes,
Le transport du moment angulaire par la circulation méridienne est moins efficace

Consequences ?

Mélange plus efficace des éléments

Qu’est-ce qui est différent à petits Z ?

- La masse initiale des étoiles (?)
- Début de la fusion de l’hydrogène (pas d’éléments CNO)
- Les opacités sont plus faibles

  → les étoiles sont plus compactes: R(popIII) = $R(Z_{sol})/4$

  → Les vents stellaires sont plus faibles

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

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

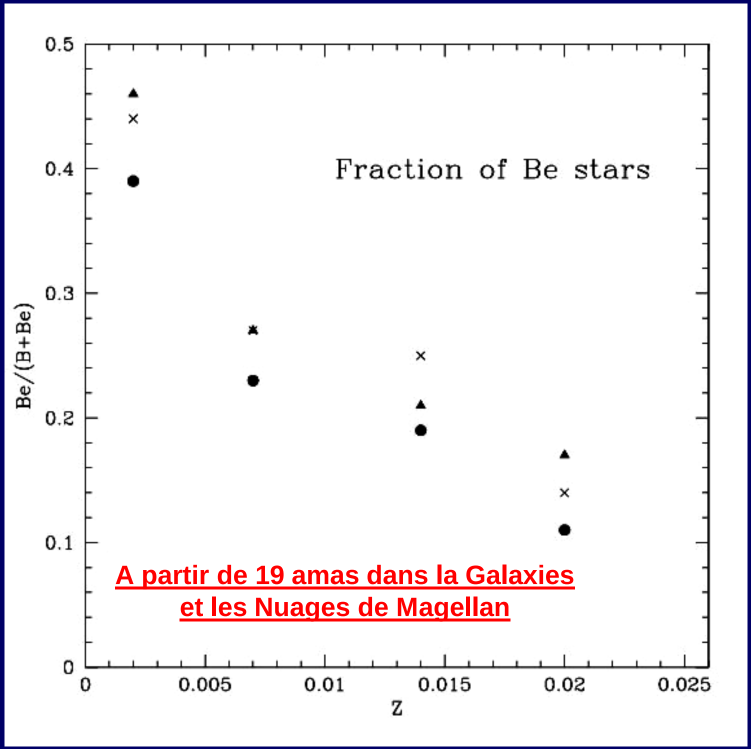
MELANGE DES ELEMENTS CHIMIQUES PLUS EFFICACE

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

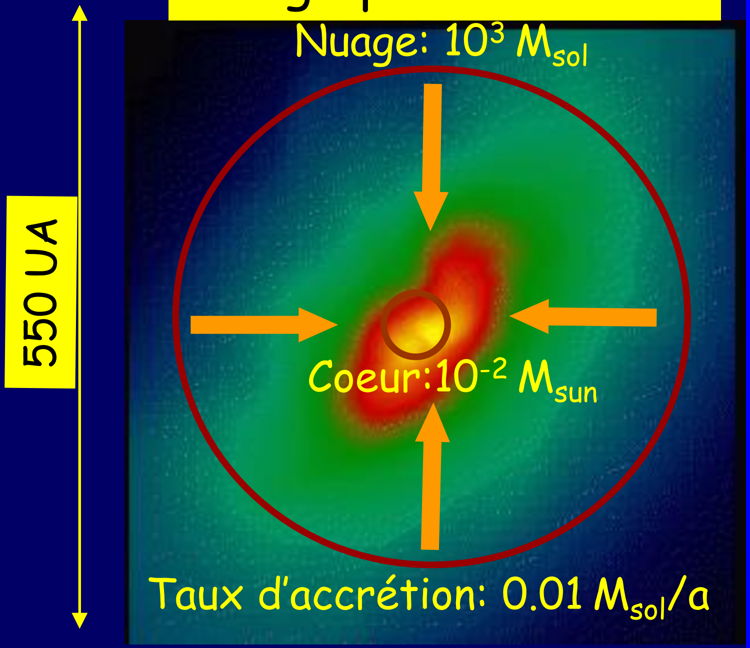


A partir de 19 amas dans la Galaxies et les Nuages de Magellan

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

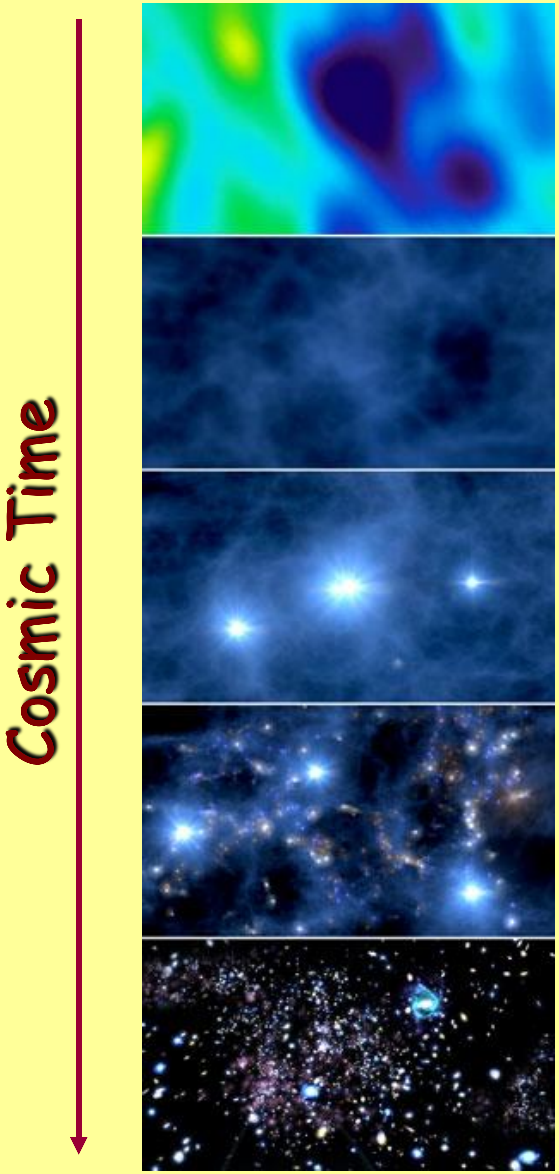
A Z=0.0, Ω/Ω_{crit}=0.7 correspond à 800 km/s

FIRST STARS

Finding Pop III (VMOs, SMOs)

- Look for their supernovae in IR (important in JWST’s survey strategy)
- Look for deep-IR-only GRB afterglows
- Early ionization input seen by WMAP??
- Understand chemical prehistory of stars
- Look for their remnant black holes
- Read Stephen Baxter’s *Vacuum Diagrams*…

Looking back in time

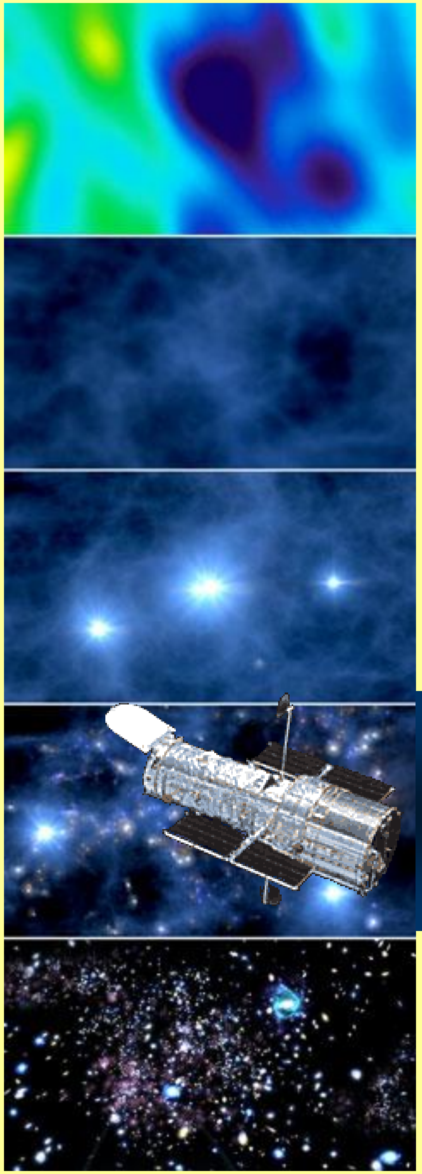


380,000 yr
CMBR Temperature fluctuations
$z \approx 1089$

13,7 Gyr
The present-day Universe
$z = 0$

Looking back in time

Cosmic Time



380,000 yr
CMBR Temperature fluctuations
$z \approx 1089$

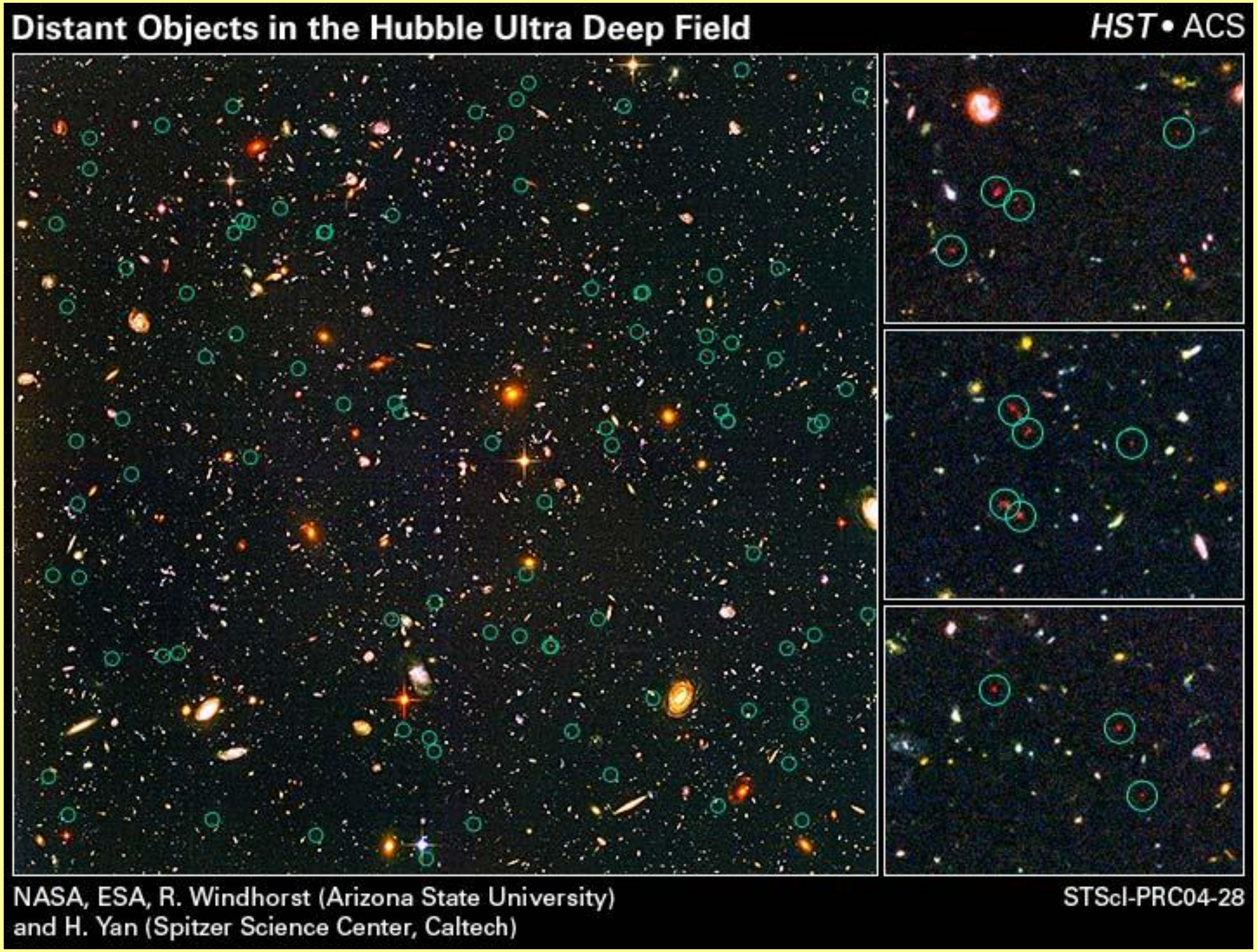
Hubble Space Telescope

f structures

13,7 Gyr
The present-day Universe
$z = 0$

The oldest observed galaxies

The Ultra Deep Field of the Hubble Space Telescope

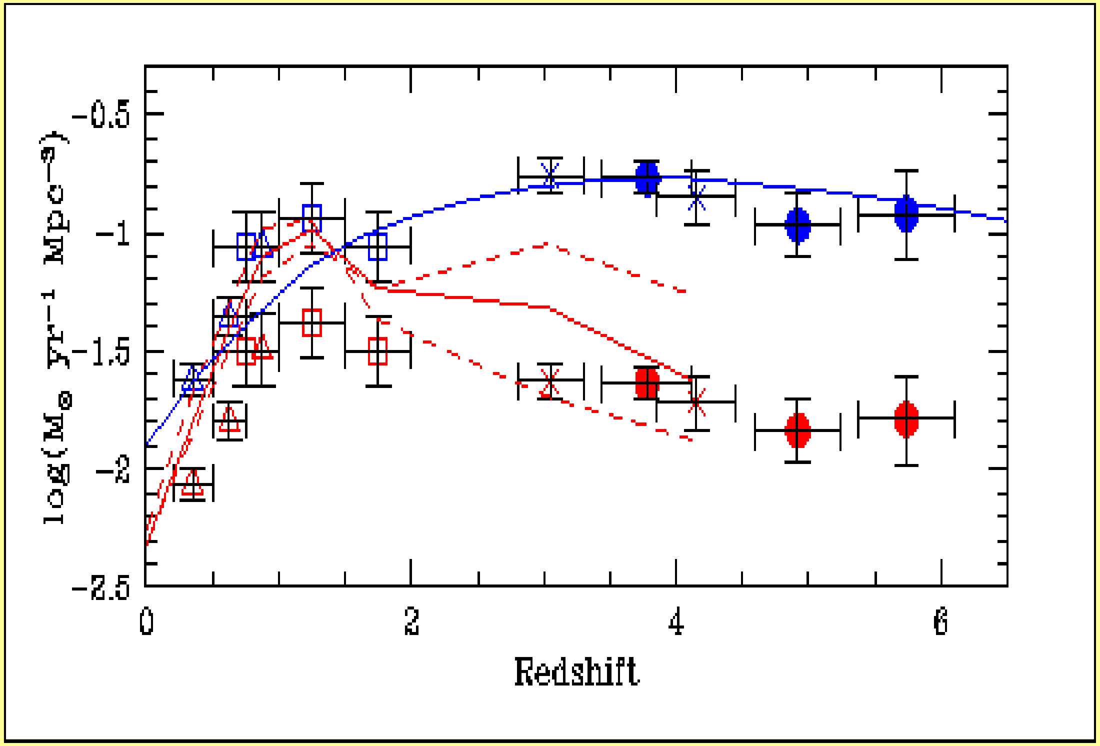


NASA, ESA, R. Windhorst (Arizona State University) and H. Yan (Spitzer Science Center, Caltech)

STScI-PRC04-28

600 – 900 Myr
after the
Big Bang

Observed Star Formation History

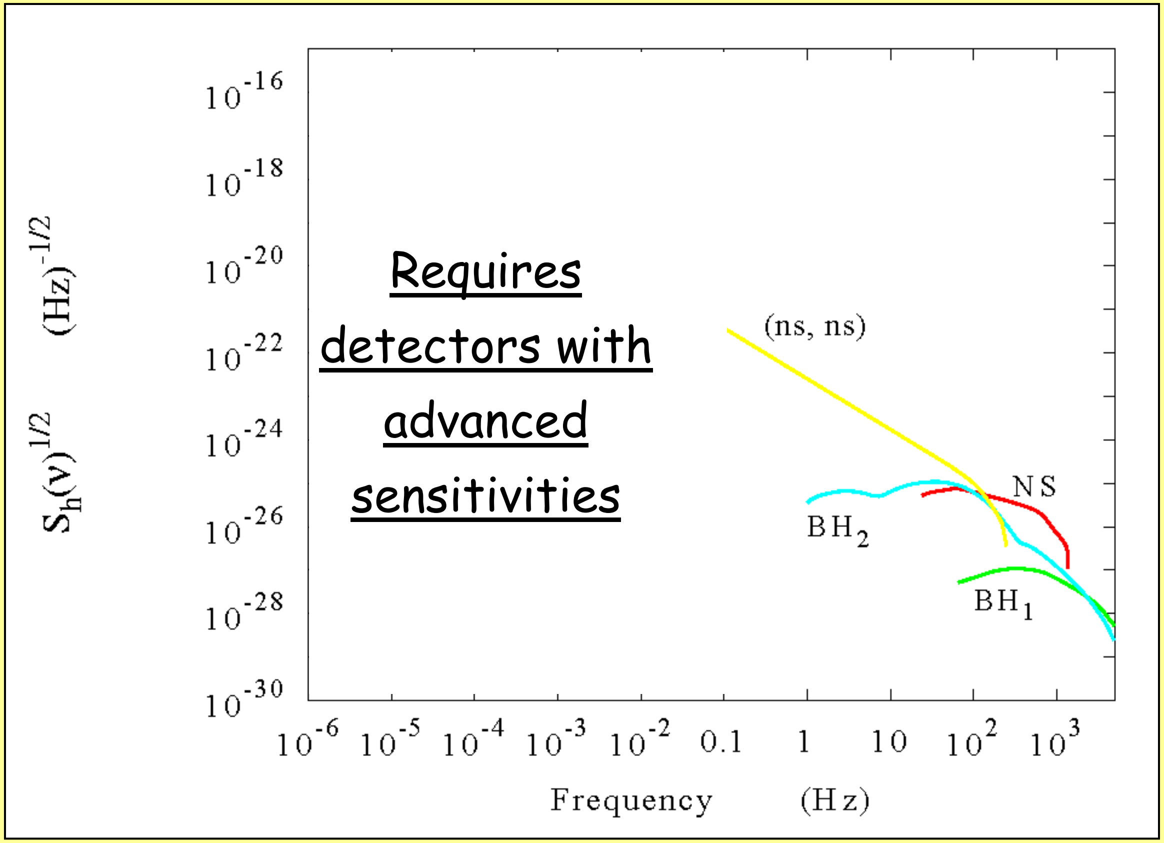


Giavalisco et al 2004 from the GOODS survey

GW emission waveform

- Stellar collapse to black hole: $20\ M_{sun} < M_{star} < 100\ M_{sun}$
  axysimmetric rotating collapse (Stark & Piran 1985)
  model BH_1 → only 10% of the initial progenitor stars collapse
  model BH_2 → for $M_{star} > 40\ M_{sun}$ all the progenitor stars collapse
- R-mode instabilities in young, hot rapidly rotating neutron stars
- Inspiral of compact binaries: binary population synthesis code

Extragalactic Backgrounds

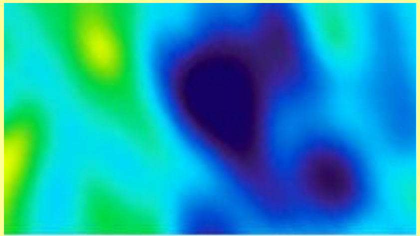


Requires detectors with advanced sensitivities

Ferrari, Matarrese & Schneider, 1999, MNRAS, 303, 247
Ferrari, Matarrese & Schneider, 1999, MNRAS, 303, 258
Schneider, Ferrari, Matarrese & Portegies Zwart, 2001, MNRAS

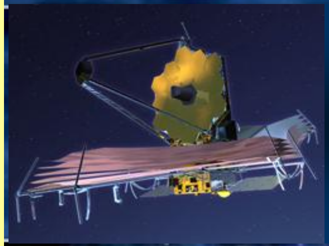
Looking back in time

Cosmic Time



380,000 yr
CMBR Temperature fluctuations
$z \approx 1089$

Matter condensing in high density peaks



James Webb Space Telescope

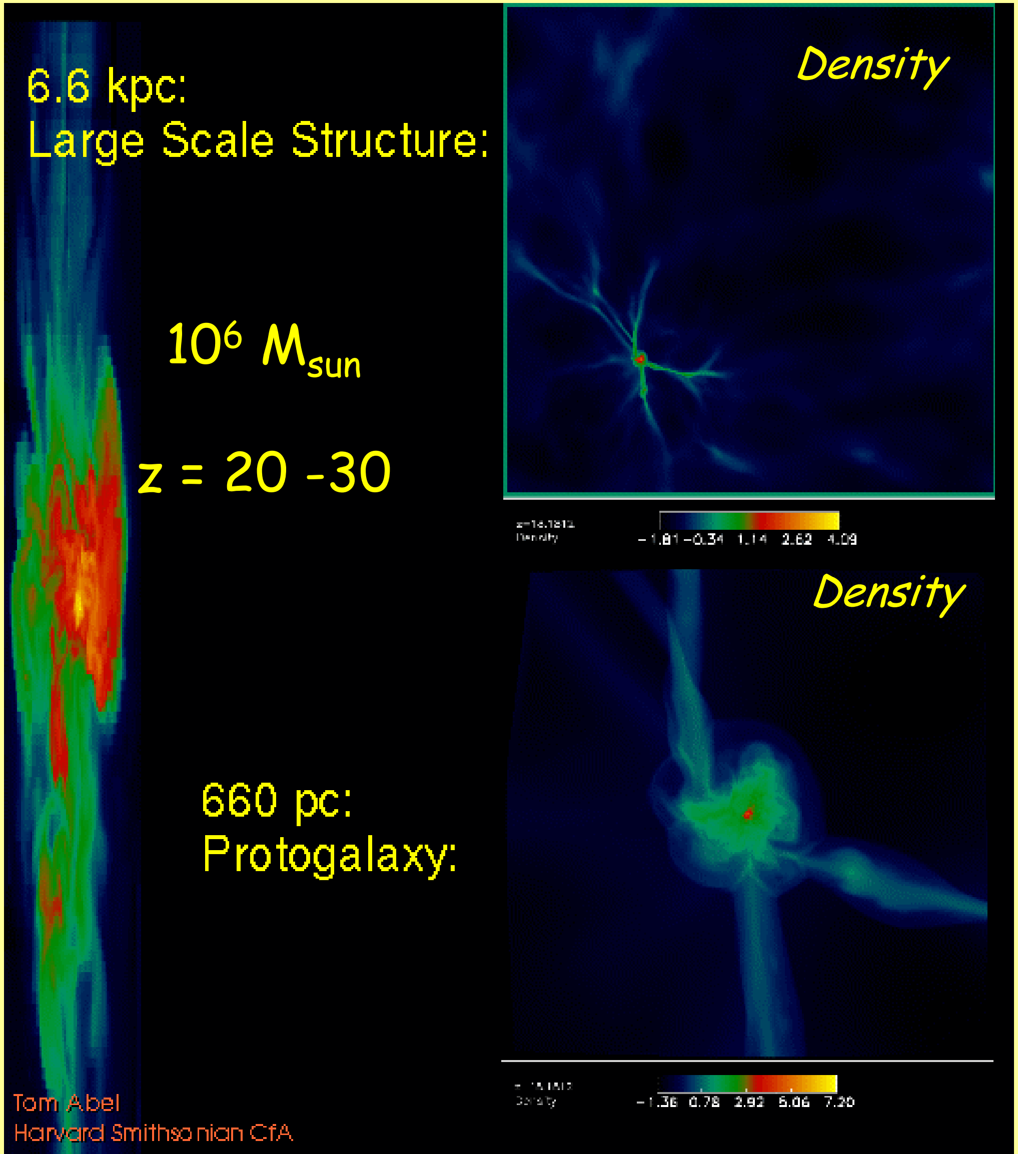
ces

600 - 900 Myr
Galaxy forms along filaments: a web of structures
$z \approx 6$

13,7 Gyr
The present-day Universe
$z = 0$

Simulating the Cosmic Dawn

From the Large Scale Structure to the protostars in 3D



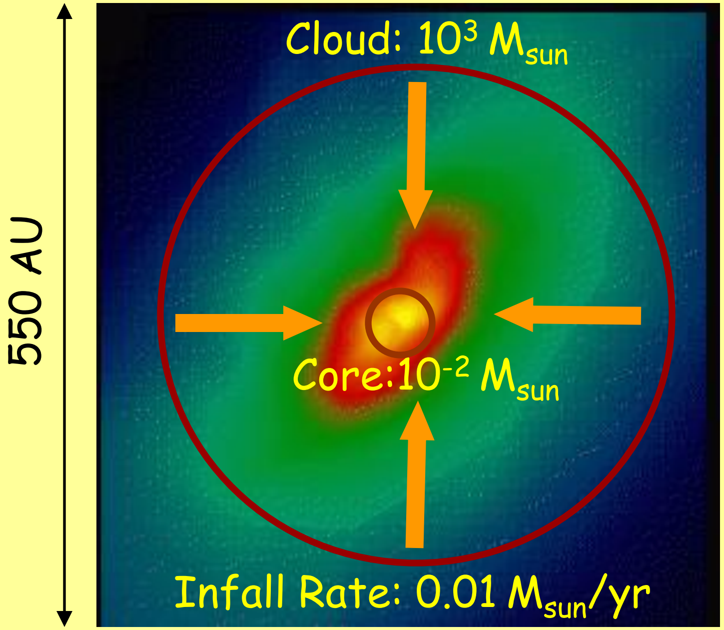
6.6 kpc:
Large Scale Structure:

10^6 M_{sun}

$z = 20 - 30$

660 pc:
Protogalaxy:

Protostellar cloud



550 AU

Cloud: 10^3 M_{sun}

Core: 10^{-2} M_{sun}

Infall Rate: 0.01 M_{sun}/yr

Abel, Bryan & Norman (2000-2002)

What is the final stellar mass?

Very peculiar environment:

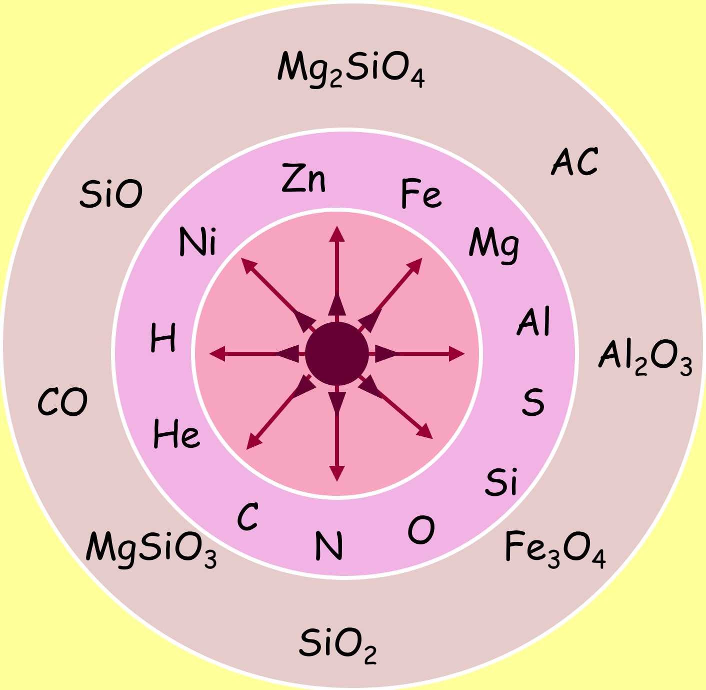
- Gas of primordial composition: H, He, Li
- No heavier elements (metals) are present in the gas
- No metals are locked into solid dust grains

Inhibit strong fragmentation
Favour gas accretion

Very massive stars
100 M_{sun} - 600 M_{sun}

Omukai & Nishi '98, Nakamura & Umemura '02,
Omukai & Inutsuka '02, Ripamonti et al 02,
Schneider et al '02, Omukai & Palla '03

First Cosmic Polluters



Supernova explosions pollute the surrounding gas with metals AND dust

(Todini & Ferrara 2001; Kozasa et al 2003; Schneider et al 2004)

metals and dust
change star formation process:
the mass of 2nd stellar generations

(Bromm et al 2001;Schneider et al 2002, 2003)

metal and dust properties
are linked to the progenitor star
clear footprint of the first stars

(Schneider et al 2003; Maiolino et al 2004)

Massive Black Hole Population

gravitational waves
VIRGO
(Fryer et al 2001, Schneider et al 2001)

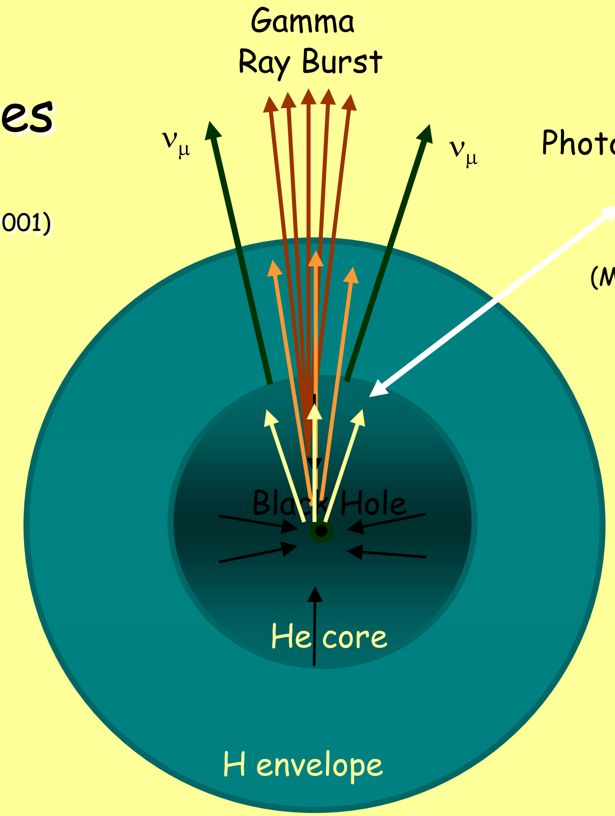


Photo-meson interaction
$p + \gamma \rightarrow \pi^+ + n$
$\pi^+ \rightarrow \mu^+ + \nu_\mu$

(Meszaros & Waxman 2001)

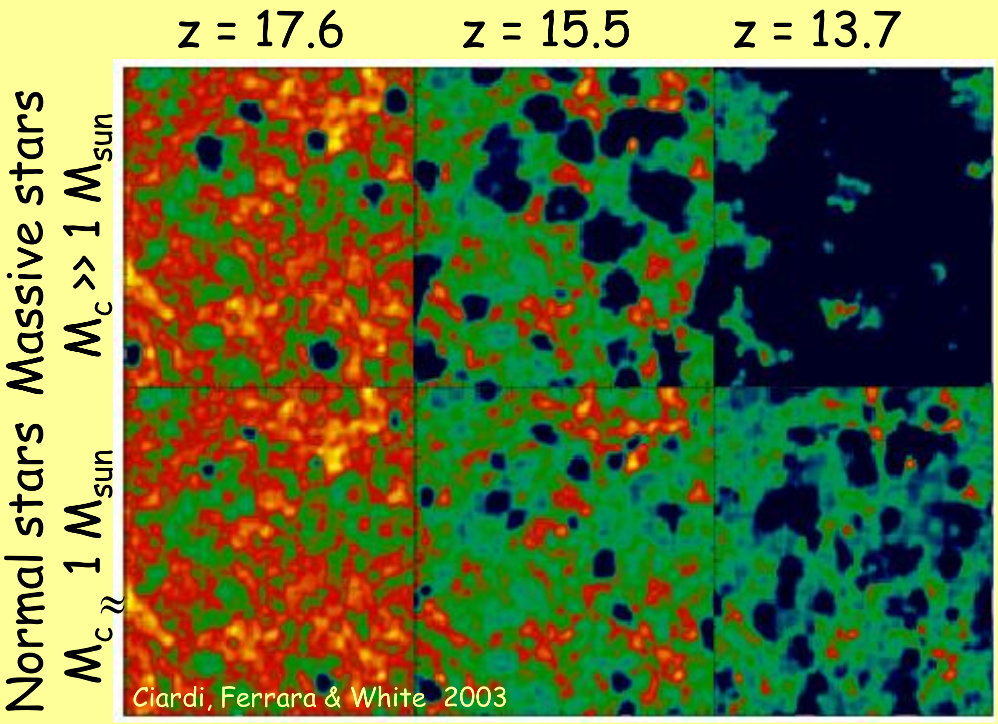
high energy neutrinos
ANTARES
(Schneider et al 2001)

BH seeds for
Super-massive BHs
in present-day galaxies

High redshift
Gamma Ray Bursts
Longer Duration
Peak energy in X-rays
No optical afterglow
No Iron lines

Light from the first stars

Metal free very massive stars → powerful sources of ionizing photons



Ciardi, Ferrara & White 2003

Important Role in Cosmic Reionization

WMAP data:

$\tau_e = 0.16 \pm 0.04$

$z_{rei} > 12$

Early Reionization by the first massive stars

Constraining the first star formation rate

- Important role in cosmic reionization

WMAP data:

$\tau_e = 0.16 \pm 0.04$

$z_{rei} > 12$

Early Reionization by the first massive stars

- Can explain the Near IR background residuals and fluctuations

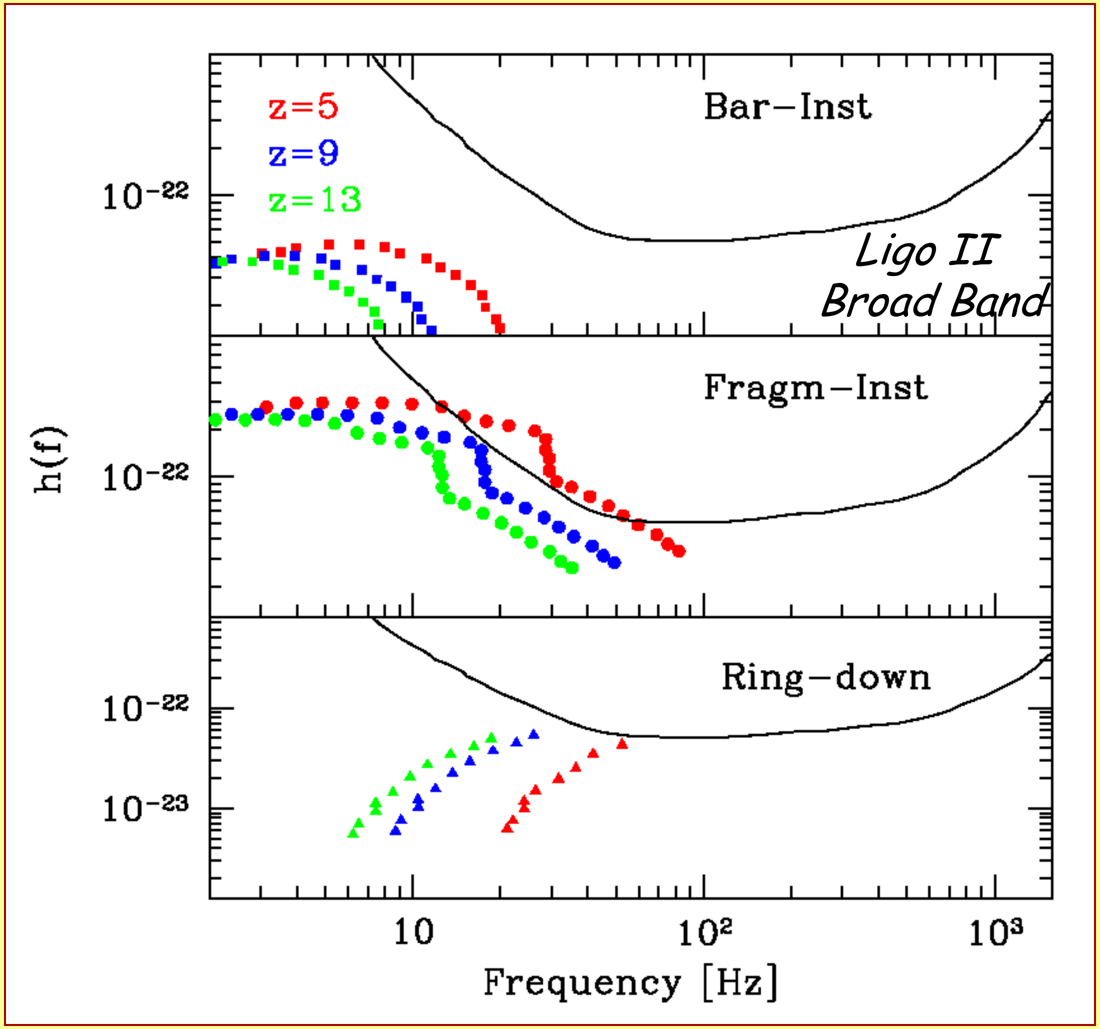
Massive stars dominate at z > 9 and predominantly collapse to BH

VMBHs as sources for VIRGO/LIGO

T/W is large enough for the onset of bar instabilities

Fryer et al 2001

Single source emission in different configurations

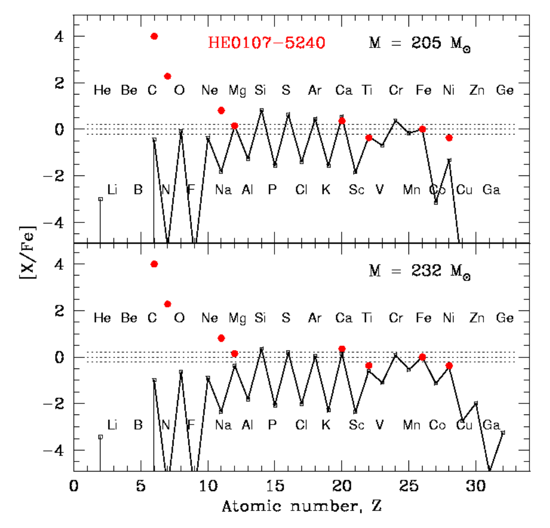


Advanced VIRGO will have better performance at low frequency:

Better chance of detecting GWs from first stars!

VESF
VIRGO EGO SCIENTIFIC FORUM

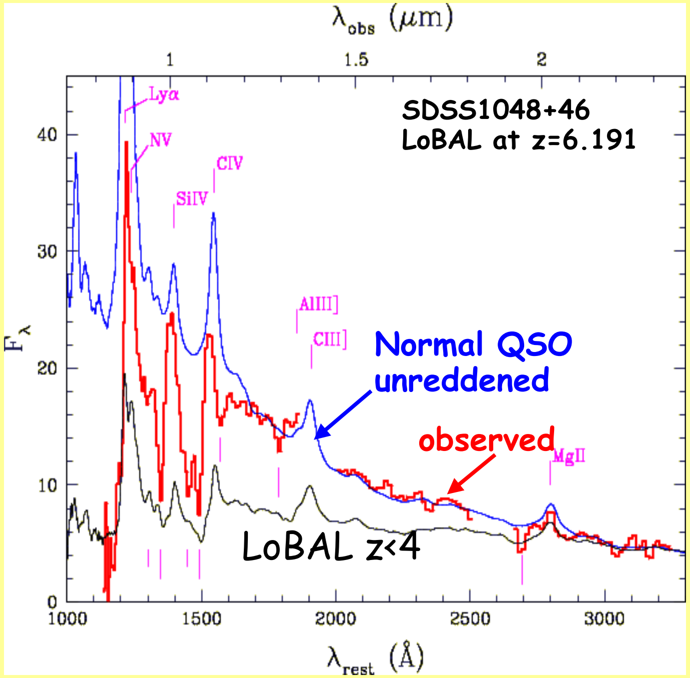
Looking for the ashes of the first stellar explosions



Christlieb et al (2002)

Stellar Archeology in the local universe

Interpreting the observed properties
of the oldest stars in the halo of our Galaxy
(Schneider et al Nature 2003; Umeda & Nomoto Nature 2003)



At the frontiers of the observable universe

Using the light of the most distant QSOs
to illuminate the properties of their host
galaxies (Maiolino, Schneider, Oliva et al Nature 2004)

Conclusions

- Extragalactic backgrounds can be generated by a variety of sources at cosmological distances
- Their detection requires advanced interferometers
- Improved GWs waveforms are required!
- Deep surveys can constrain source formation rate z < 6
- First stars are predicted to be very massive: > 100 Msun → BH collapse
- The first stages of star formation in the universe might be very interesting for gravitational wave astronomy!

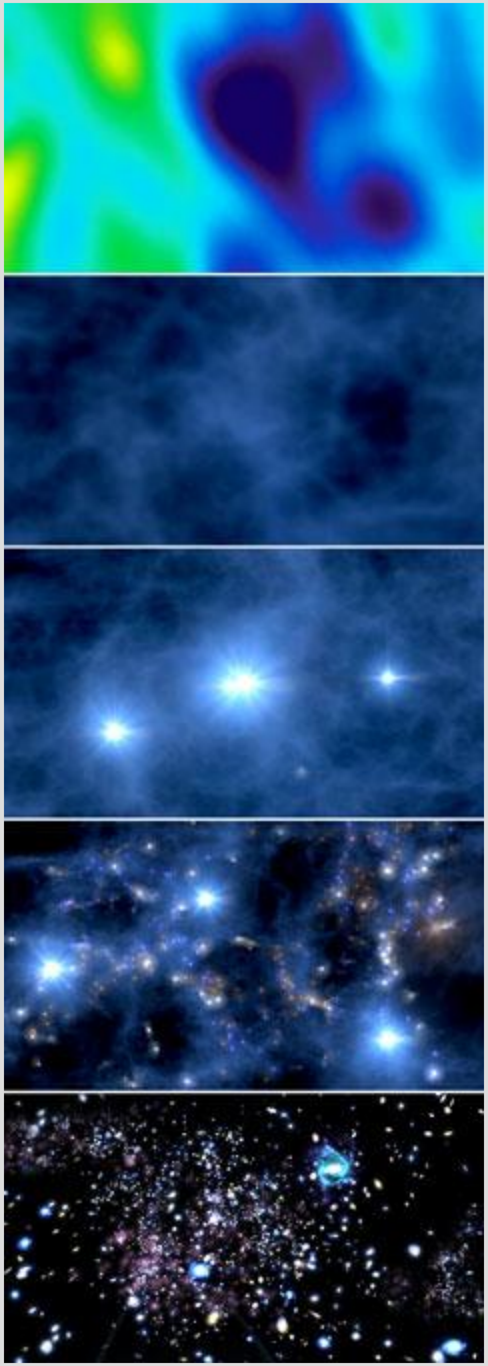
The First Stars

The birth, life and death of Population III stars

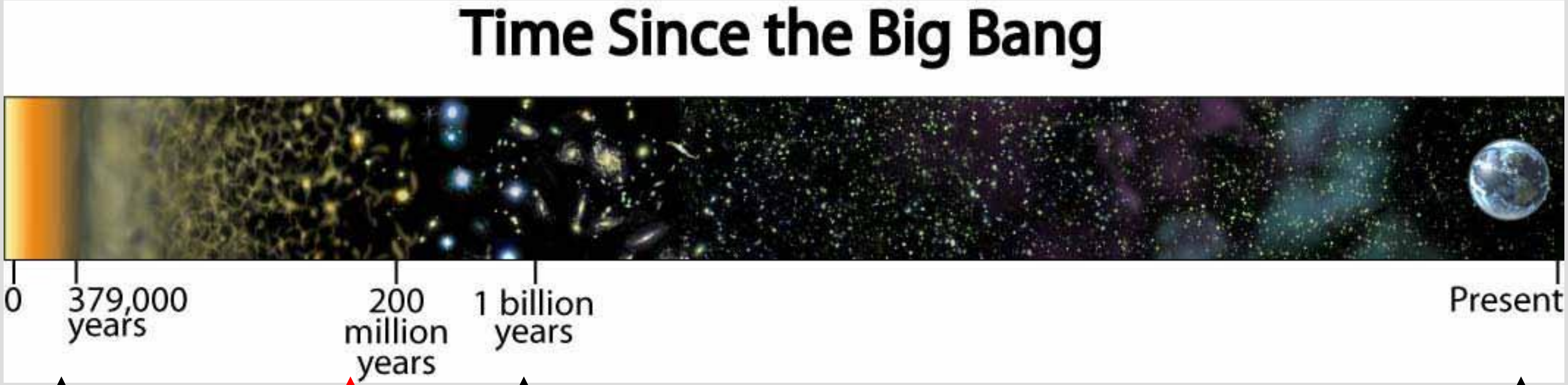
Michael Koppelman

Eric Stewart

Mike Rannow



Where in Time is Population III?



Population III Stars: Most estimates place the era of Population III stars between 100 million and 1 billion years after the Big Bang.

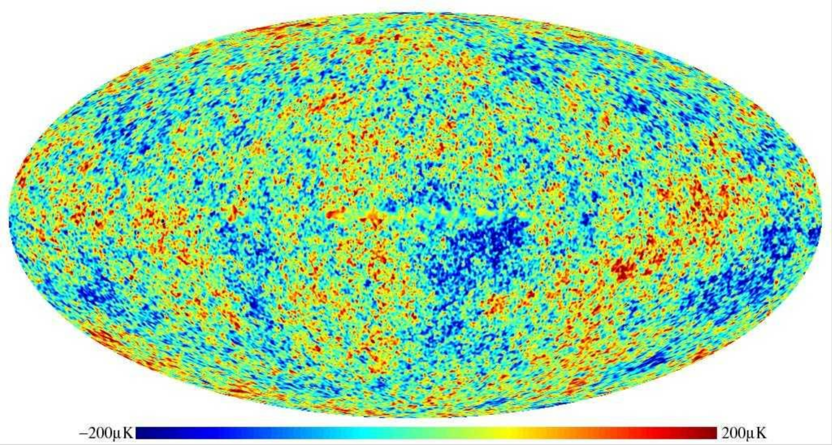
You are here

Hubble has directly observed early quasars back to about 1 billion years after the Big Bang

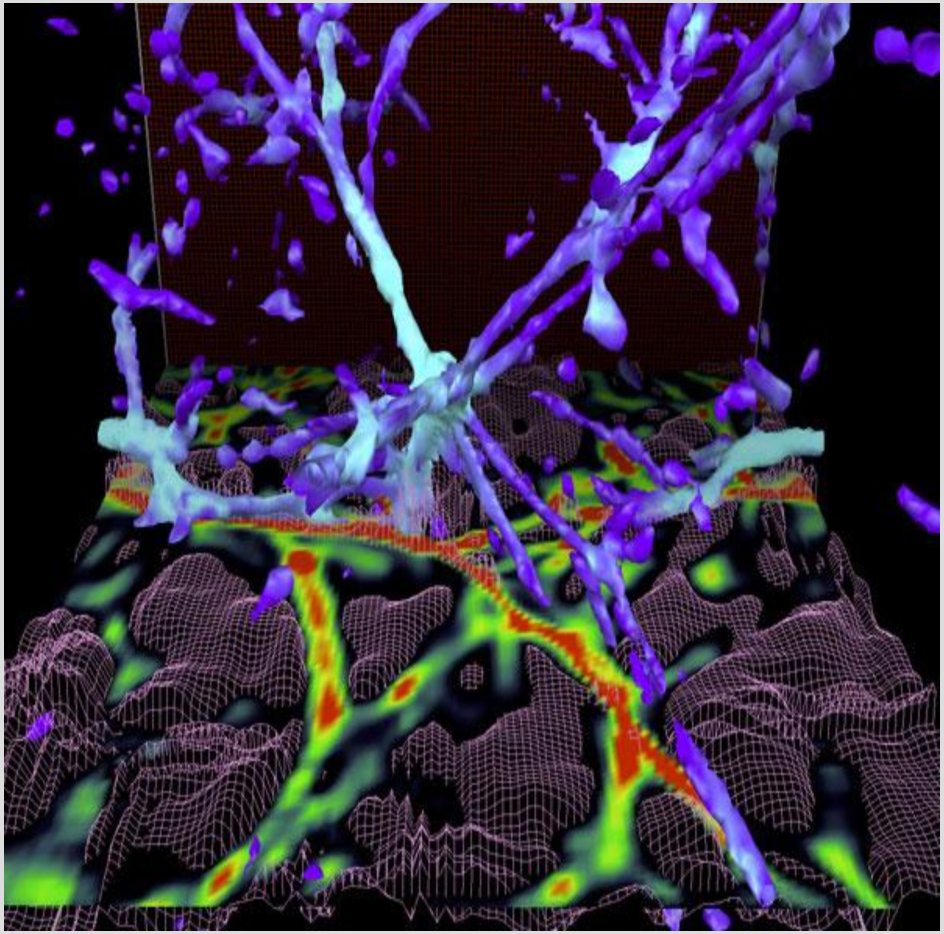
Matter-Radiation decoupling, the CMB is emitted

Chunky or Smooth?

- Small density perturbations must have existed in order for the first stars to form
- Variations of up to .01% existed at the time of the CMB emission
- Dark matter needed to produce large enough variations

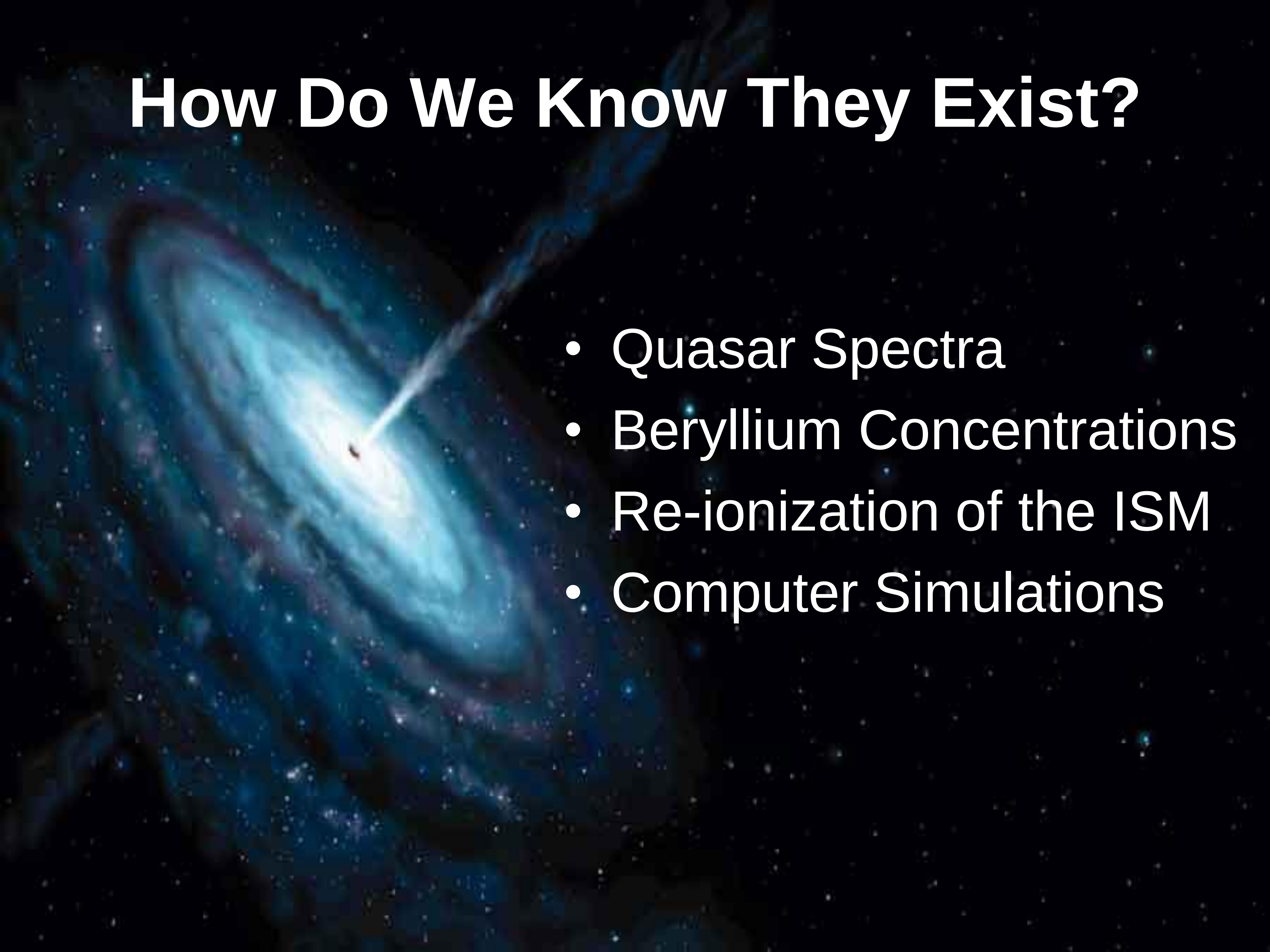


Structure Formation



- Filamentary network formed
- Highest density at the nodes
- Stars form in Dark Matter Halos
- Computer simulations are used to predict structure formation

How Do We Know They Exist?



- Quasar Spectra
- Beryllium Concentrations
- Re-ionization of the ISM
- Computer Simulations

The Eddington Limit

$$L_{\max} = \left[\frac{4\pi G m_p c}{\sigma_T} \right] M = 32{,}000 \frac{L_O}{M_O} M$$

$$\frac{(dyne)(cm^2)(g)(m)}{(g^2)(cm^2)(s)} = \frac{(dyne)(cm)}{(g)(s)} = \frac{erg/s}{g} = \frac{L}{M}$$

Mass Limit?

$$L = \left(\frac{M}{M_O}\right)^{\alpha} L_O$$

Mass-Luminosity Function

$1 < \alpha < 3$ for high mass stars

$$M_{\max}(\alpha) = (32000)^{\frac{1}{\alpha-1}} M_O$$

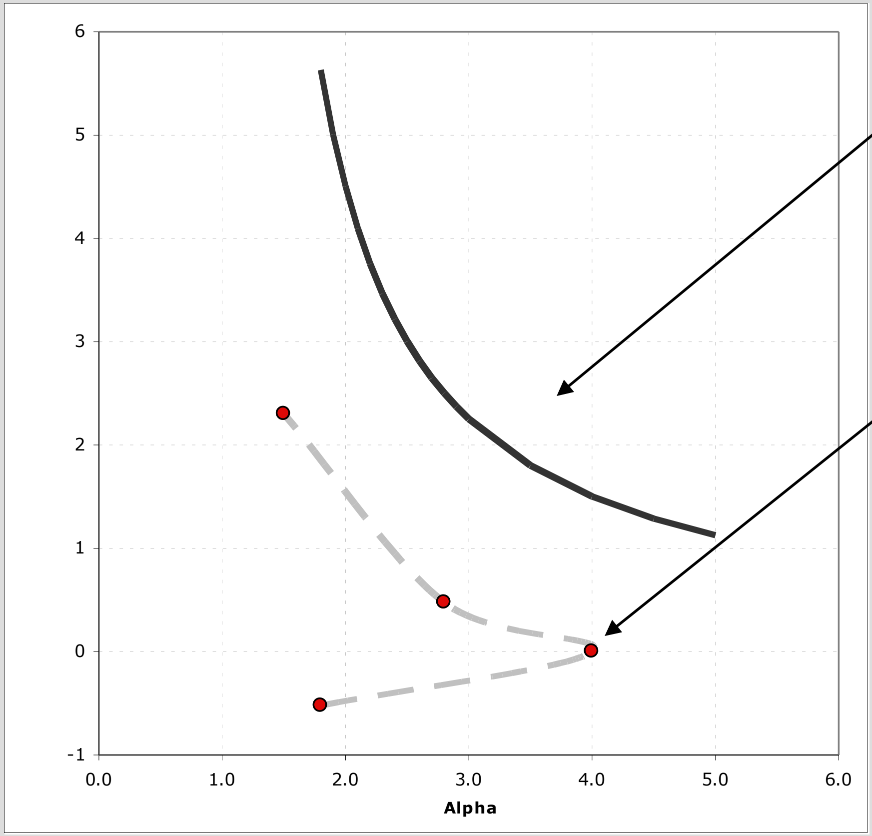
α is a function of *M*

$M_{max}(4)=32M_O$

$M_{max}(2.8)=300M_O$

$M_{max}(2)=32{,}000M_O$

Radiation – Probably not the constraint



$$M_{\max}(\alpha) = (32000)^{\frac{1}{\alpha-1}} M_O$$

Empirical M-L Relationship

$$L \propto \frac{T^3}{\kappa} \Rightarrow$$

high T and/or low opacity for Eddington Limit to be a constraint

Age Estimate

- Age estimates based on Beryllium concentration is second generation stars.
  - Second generation stars in nearby globular cluster 13.4 billion years old have been shown to have small amounts of Beryllium.
  - With this an estimate can be made as to the age of the first stars. It appears **they formed less than 200 million years after the big bang**.

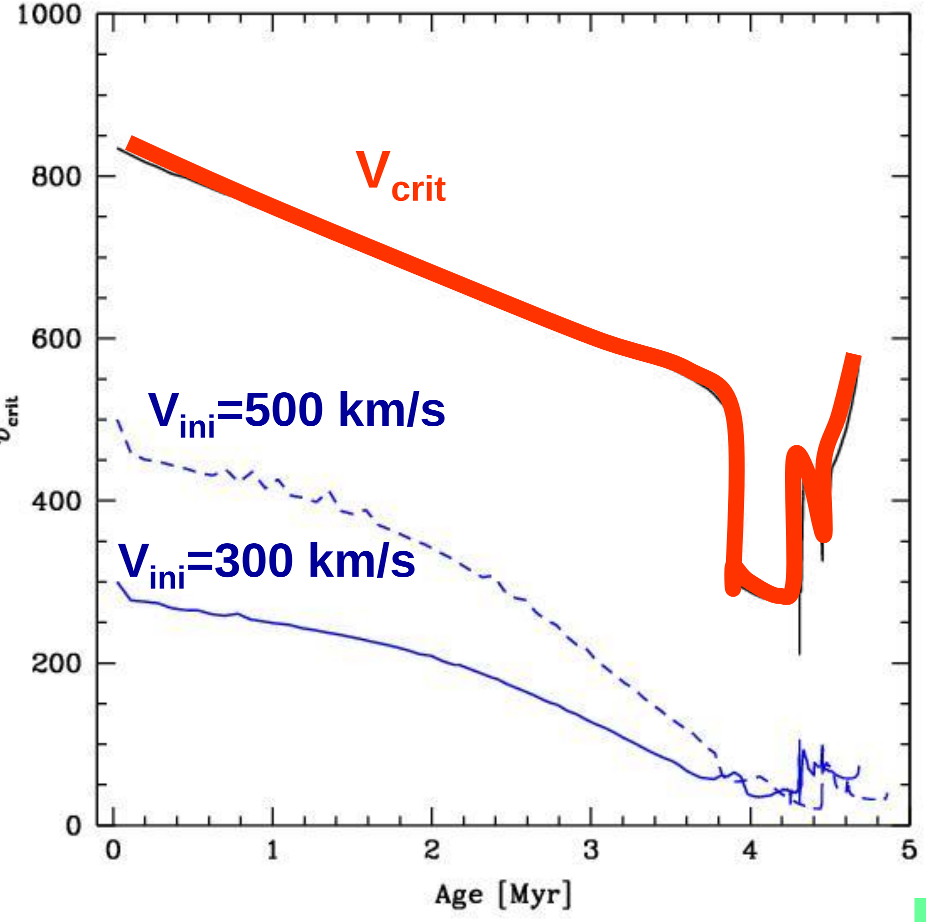
Other Effects of Massive First Stars

- Ionization of the interstellar medium
- Potentially the nucleation of galaxies around the buildup of first generation massive black holes
- Creation of super massive black holes in the center of galaxies

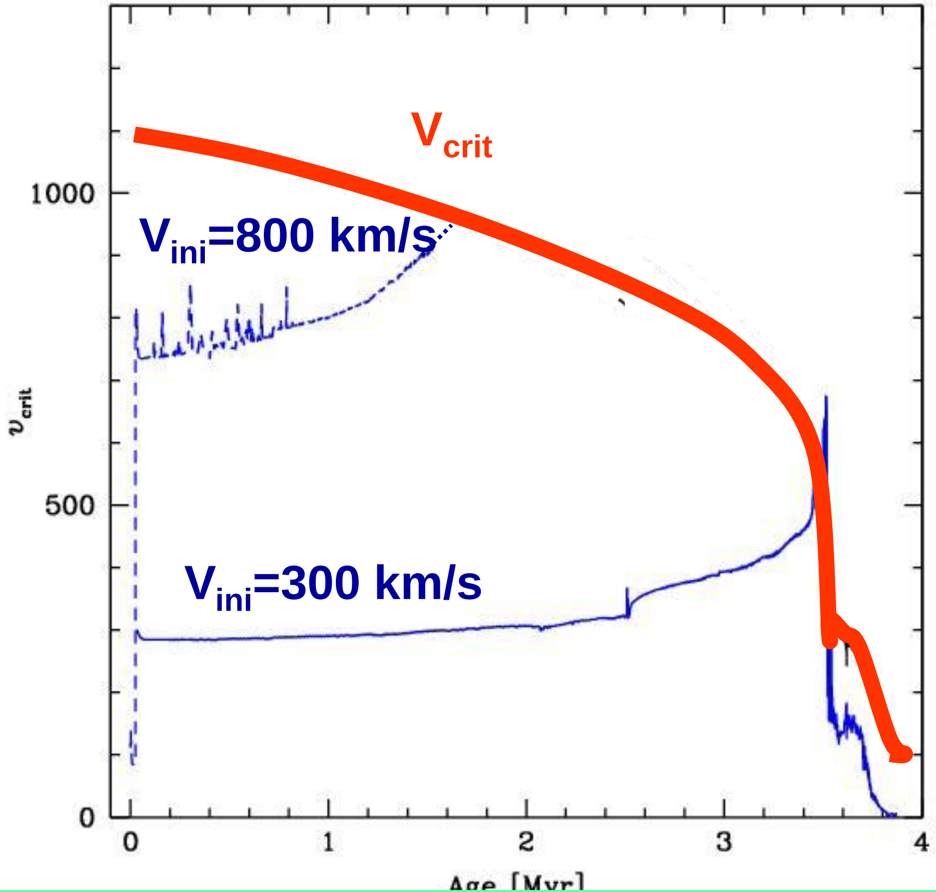
LA ROTATION FAVORISE LA PERTE DE MASSE

1) Les étoiles atteignent plus facilement la rupture

60 M_{sol}, Z = 0.020

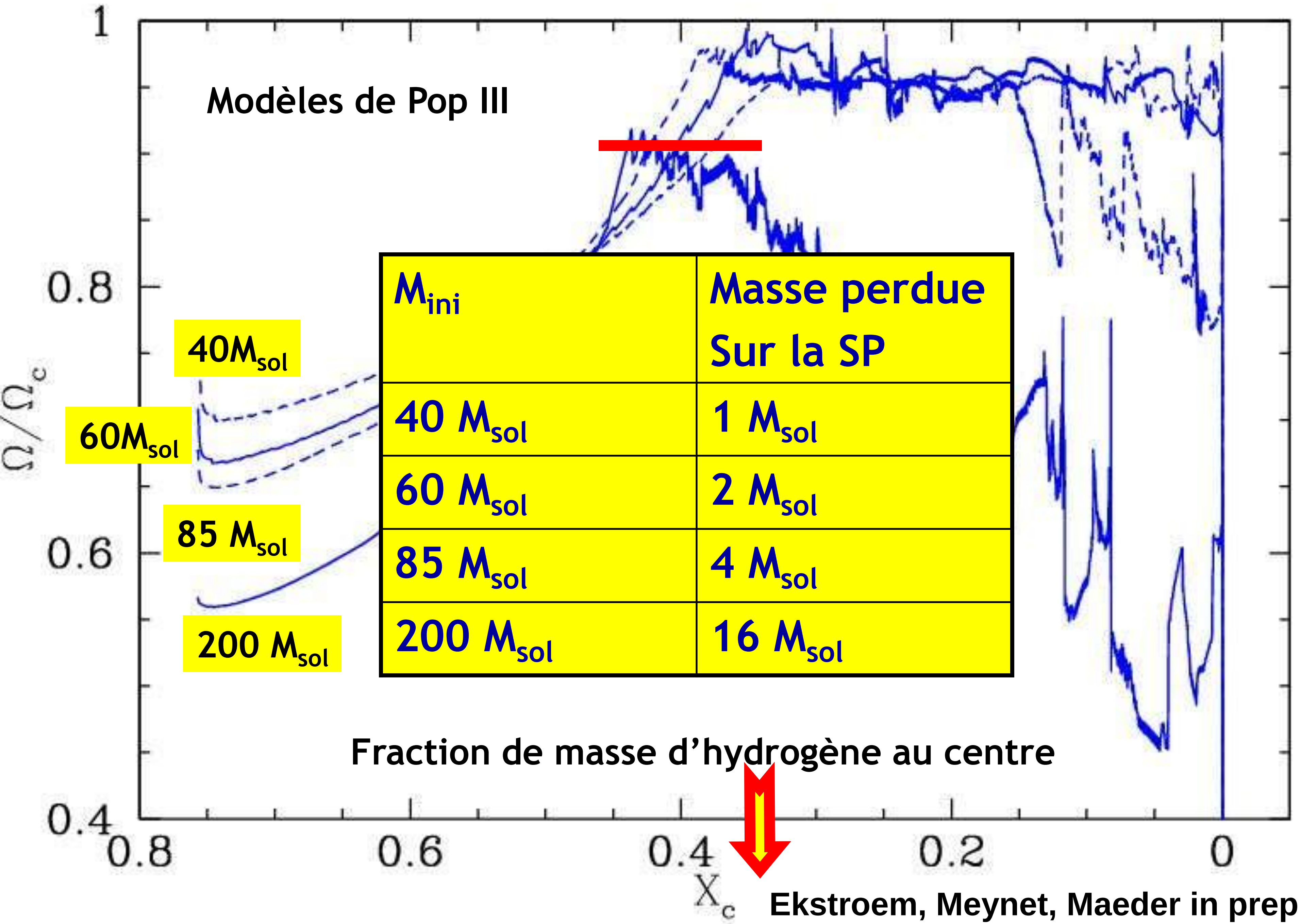


60 M_{sol}, Z = 0.00001



Cf also Sackman & Anand 1979; Langer 199

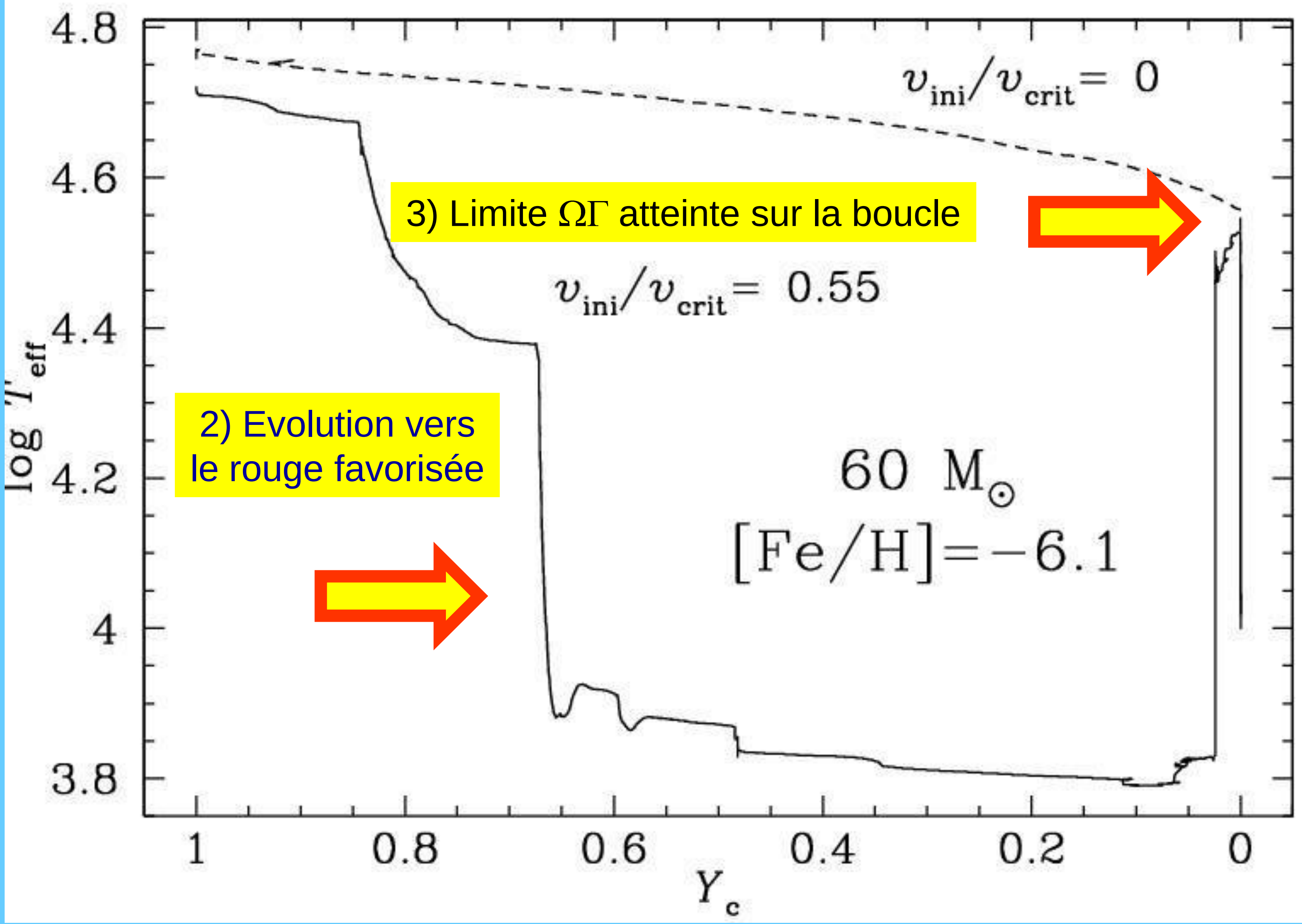
Modèles de Pop III



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

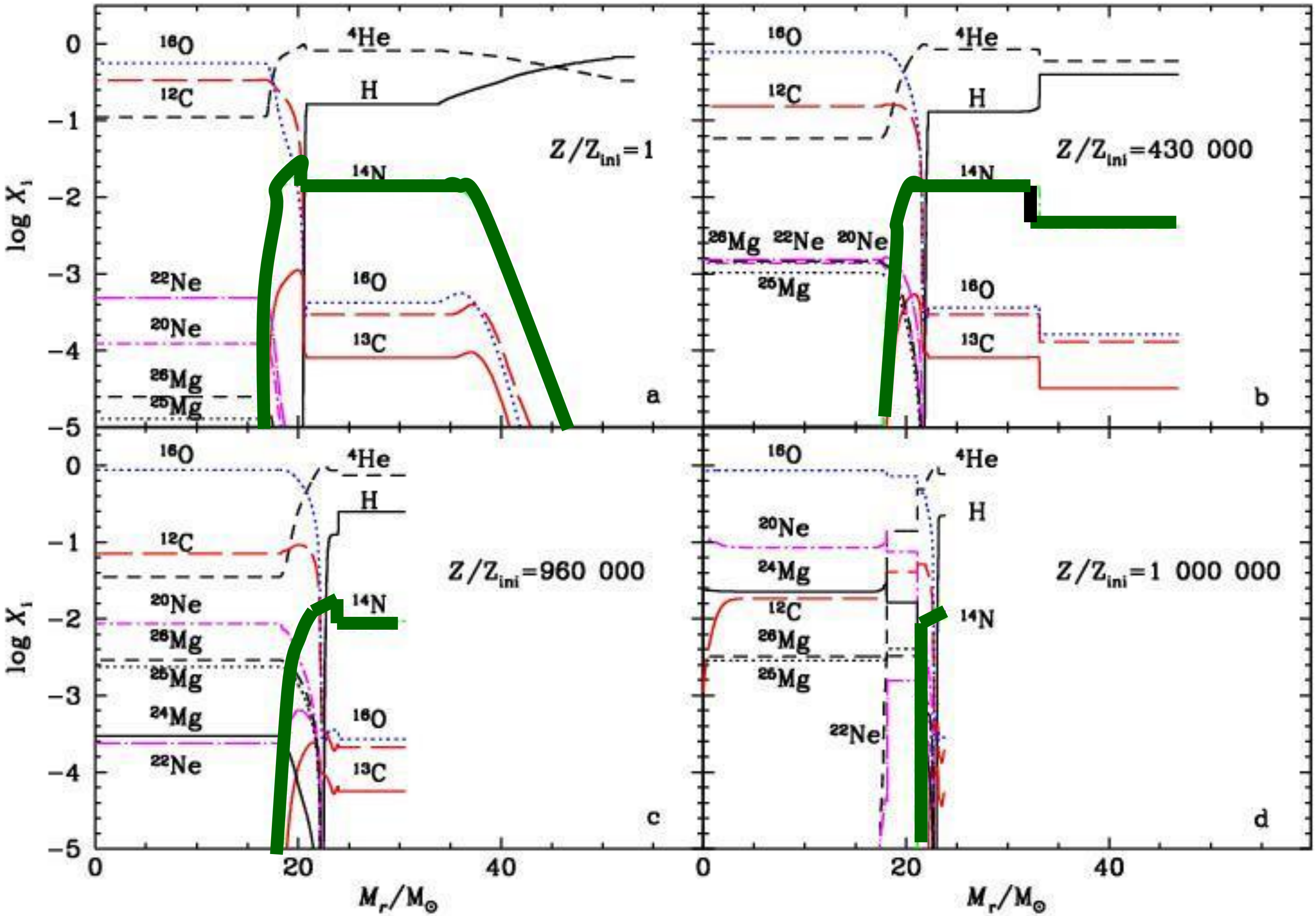
Ekstroem, Meynet, Maeder in prep



3) Limite ΩΓ atteinte sur la boucle

2) Evolution vers le rouge favorisée

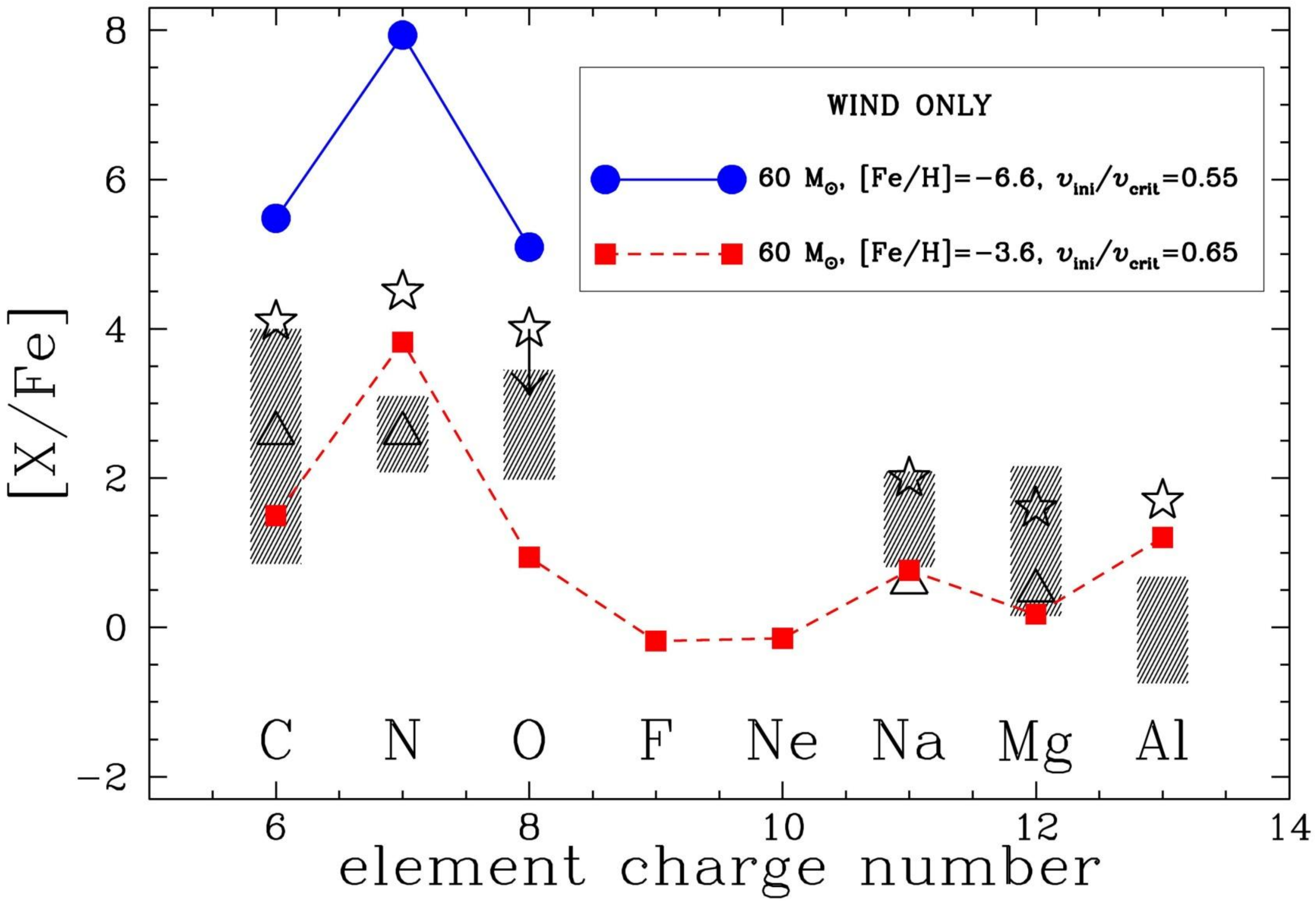
Les abondances CNO augmentent en surface



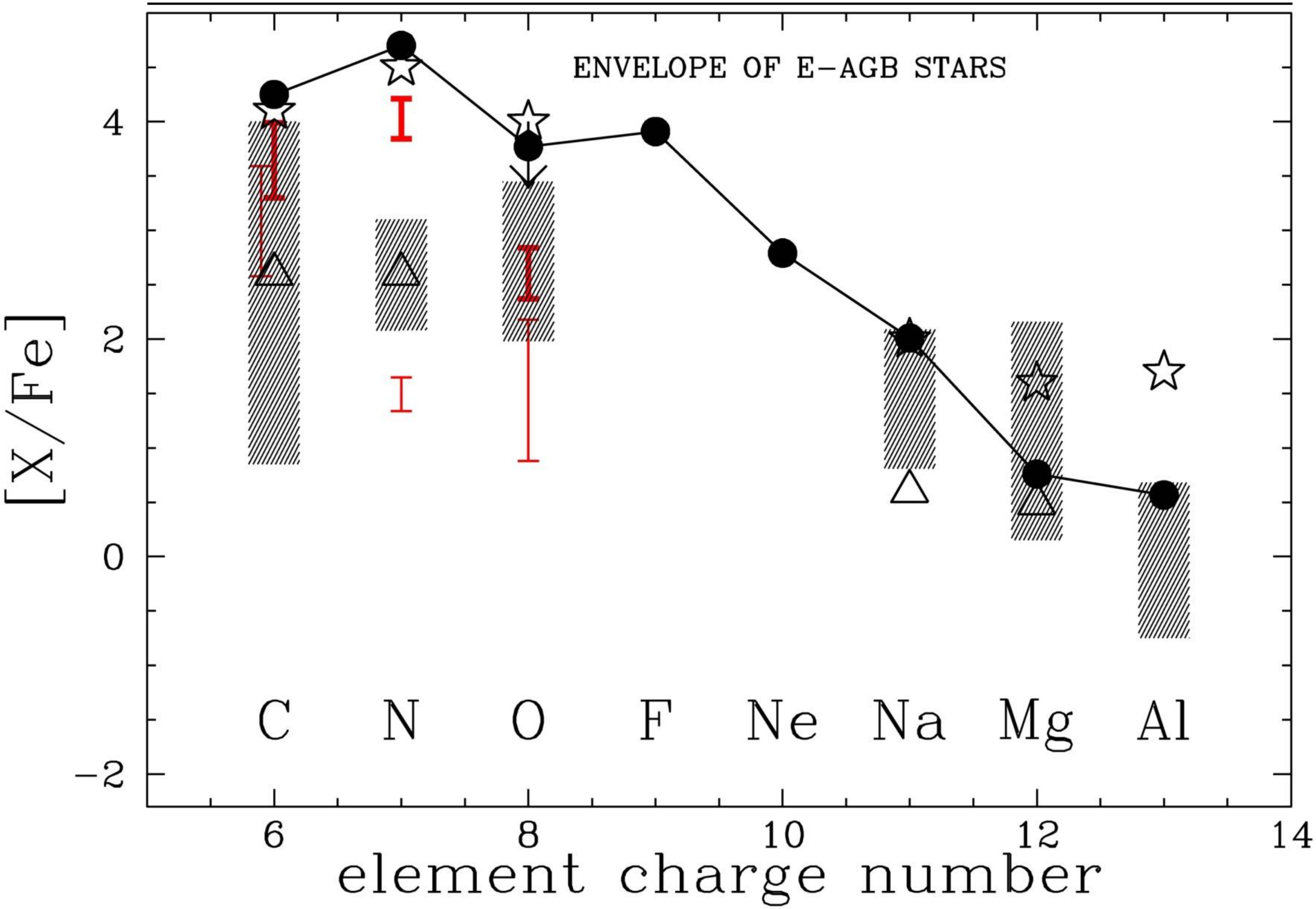
Meynet, Ekstroem, Maeder 2005

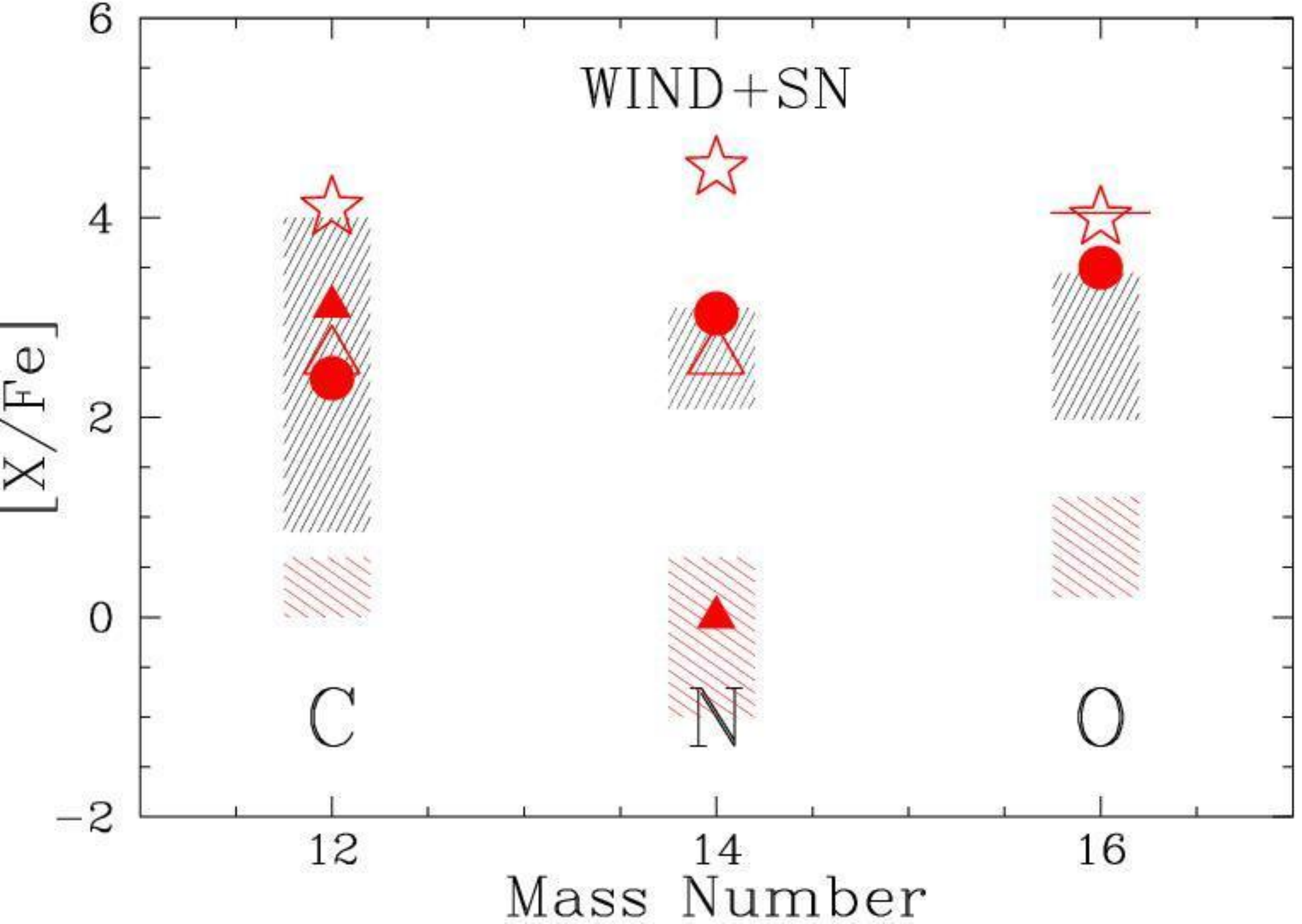
CONSEQUENCES

- Les Supernovae par instabilité de paires
- Nature des restes stellaires
- Des GRB à très faible Z ?
- Les anti-corrélations dans les amas globulaires
- Les enrichissements en Helium
- Les ``C-rich'' Ultra-Metal Poor Stars (CRUMPS)

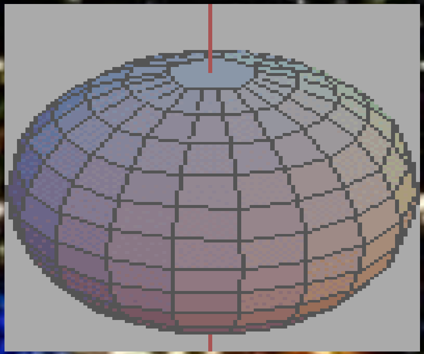


WIND ONLY
60 $M_\odot$, [Fe/H]=−6.6, v_{ini}/v_{crit}=0.55
60 $M_\odot$, [Fe/H]=−3.6, v_{ini}/v_{crit}=0.65
[X/Fe]
8
6
4
2
0
−2
C
N
O
F
Ne
Na
Mg
Al
6
8
10
12
14
element charge number


ENVELOPE OF E-AGB STARS
[X/Fe]
element charge number
C
N
O
F
Ne
Na
Mg
Al
4
2
0
−2
6
8
10
12
14


WIND+SN
[X/Fe]
6
4
2
0
−2
C
N
O
12
14
16
Mass Number

Evolution = f (M, Z, Ω, …)



Le sel du ciel

Comme un parfum…

Integrated Abundances of Spiral Galaxies

Courtesy NASA, ESA, S. Beckwith, & the Hubble Heritage Team

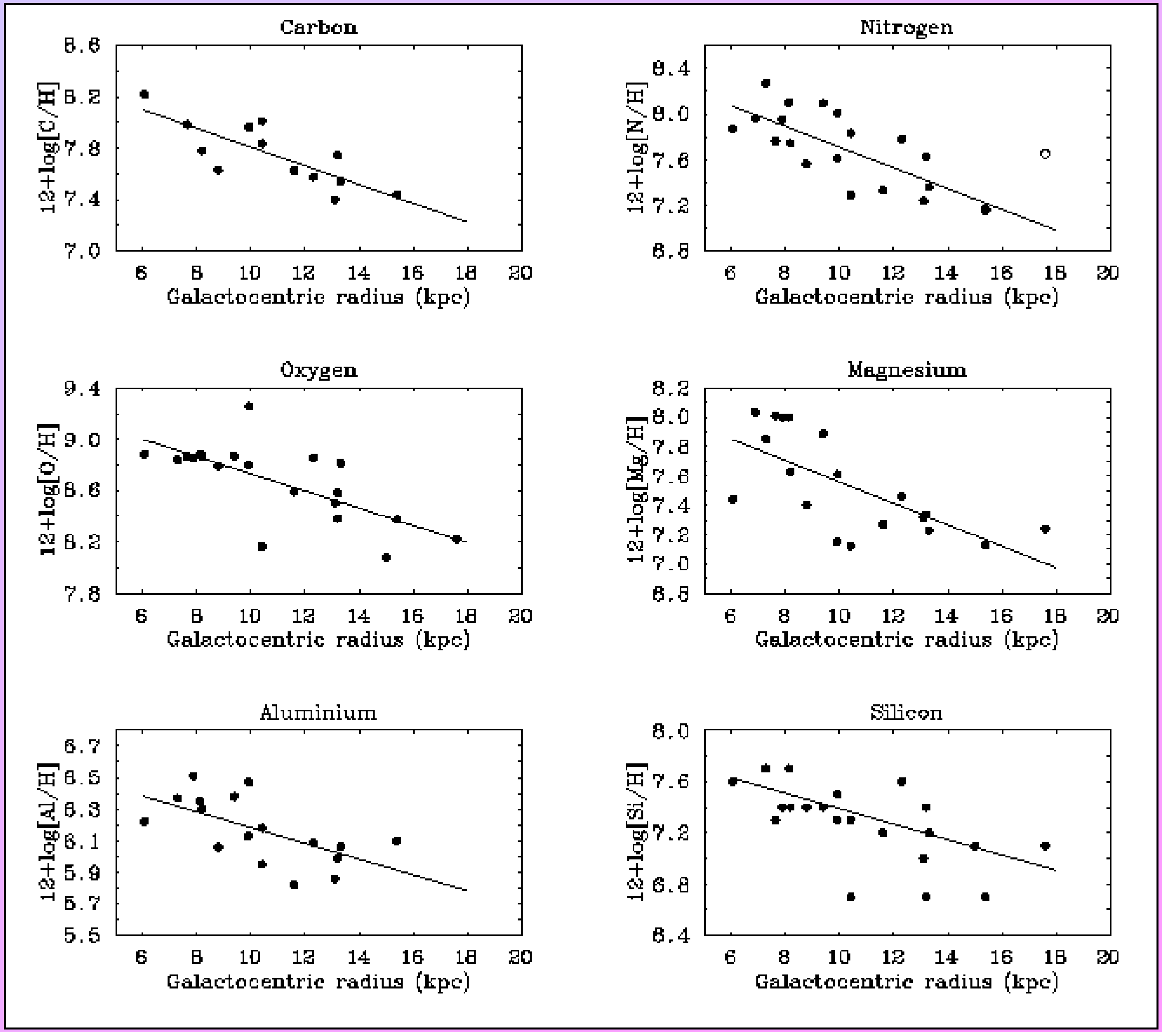
Spiral galaxies exhibit abundance gradients that decrease from the center outward by a factor of ~1.6 per disk scale-length.

Some specific questions:

- **What characteristic radius does a galaxy's integrated abundance correspond to?**
- **How important are differential extinction effects on integrated abundances?**
- **Does diffuse ionized gas emission bias integrated abundance measurements?**

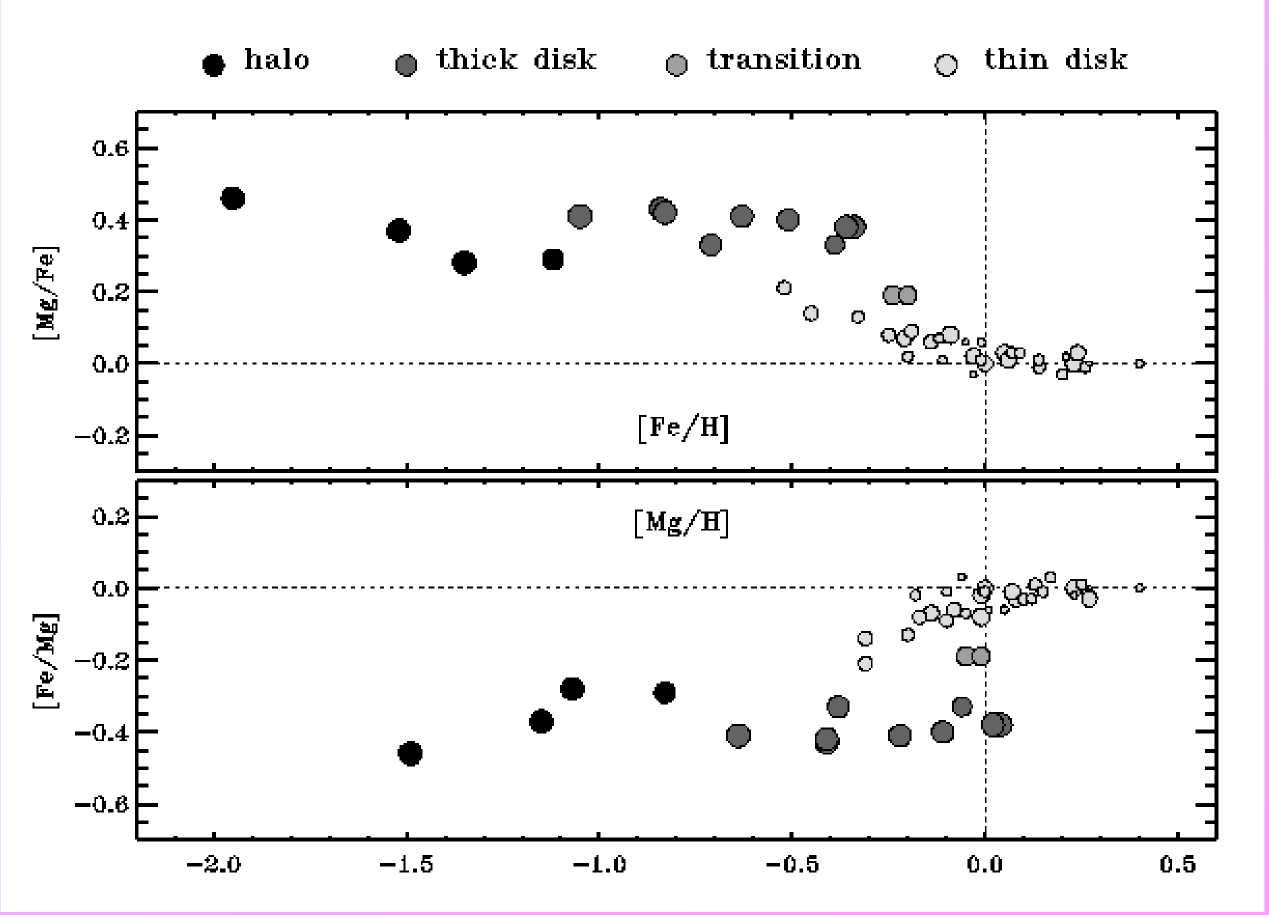
GCE: Observational clues

- Galactic Gradients in Chemical Composition (e.g., Rolleston *et al.* 2000)



GCE: Observational clues

- "alpha" elements (Mg, Si, etc) overabundant relative to iron in very low-Z stars (e.g., Fuhrmann 1998)



Conclusions:

Evolution = f (M, Z, Ω)

- Evolution of rotational velocities
- Lifetimes, tracks
- Evolution properties Be, B[e], LBV, WR stars in galaxies
- Nebulae
- Cepheid properties
- Surface abundances in massive stars and red giants
- Primary N
- Pre – supernova stages
- Chemical yields and nucleosynthesis
- Rotation periods of pulsars
- Final masses
- Collapsars, γ- bursts, ….

PERSPECTIVES

OTHER TRANSPORT PROCESSES: GRAVITY WAVES, MAGNETIC FIELDS (EFFECTS ON MASS LOSS).

PRE MAIN SEQUENCE EVOLUTION OF MASSIVE STARS.

BINARY STELLAR EVOLUTION

OTHER TECHNICS, MULTI-DIMENSIONAL APPROACHES.

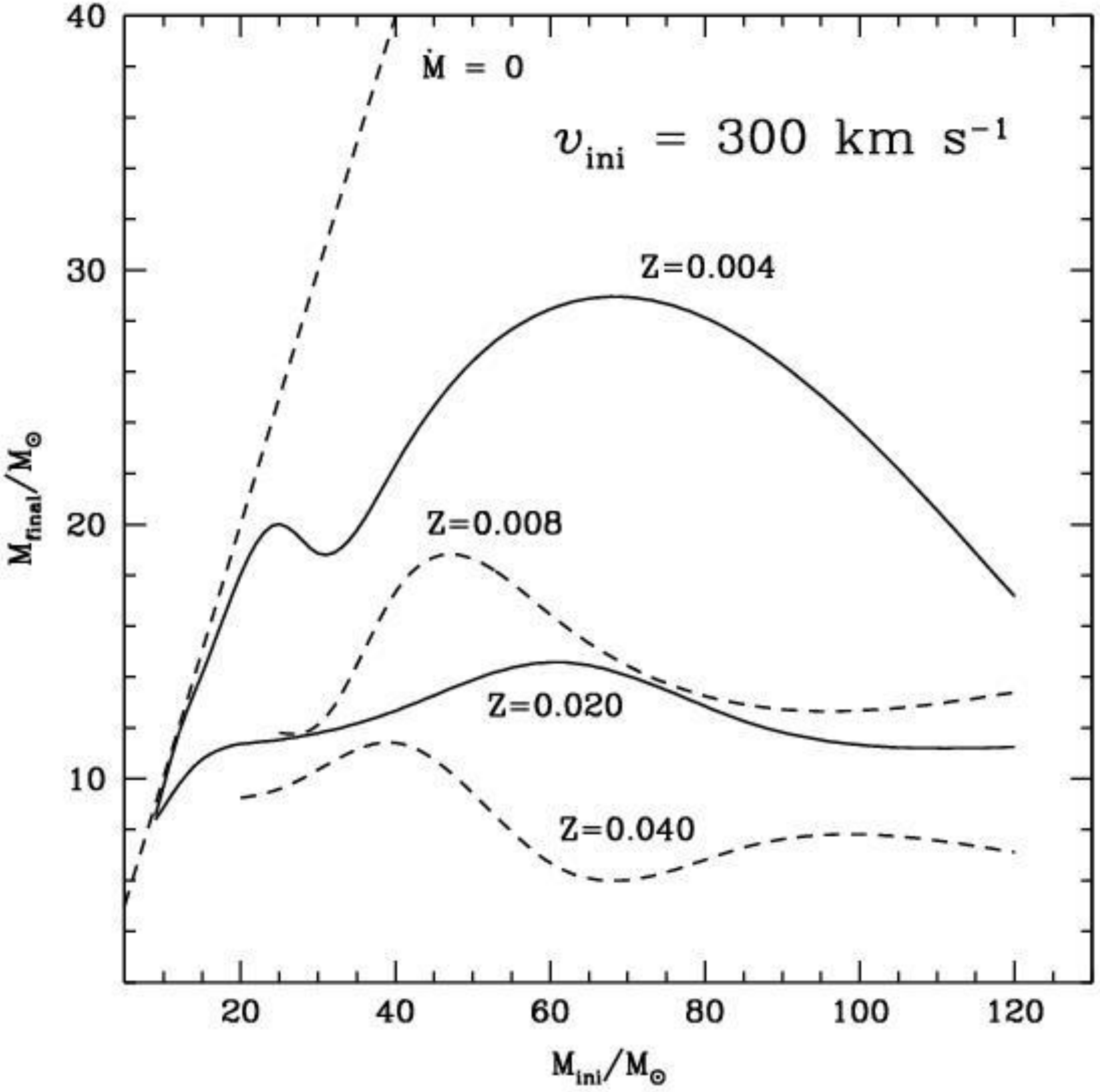
OBSERVATIONAL CONSTRAINTS: SURFACE ABUNDANCES, SURFACE VELOCITIES, ASTEROSISMOLOGY, EFFECTS OF METALLICITY.

Stellar yields depend at least on two main physical processes

- Mass loss by stellar winds
- Interior mixing processes

Rotation affects both mass loss and mixing processes

Effect at solar metallicity	Langer, Braun, Fliegner 1995 Heger 1998 Heger, Langer, Woosley 2000 Meynet, Maeder 2002

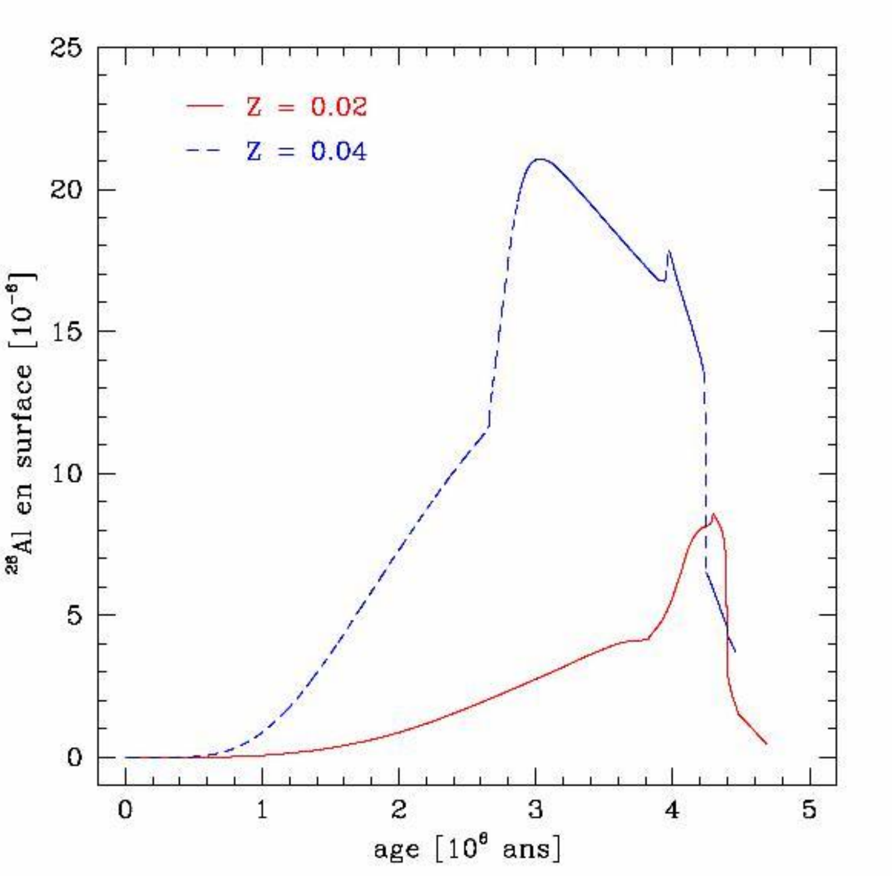


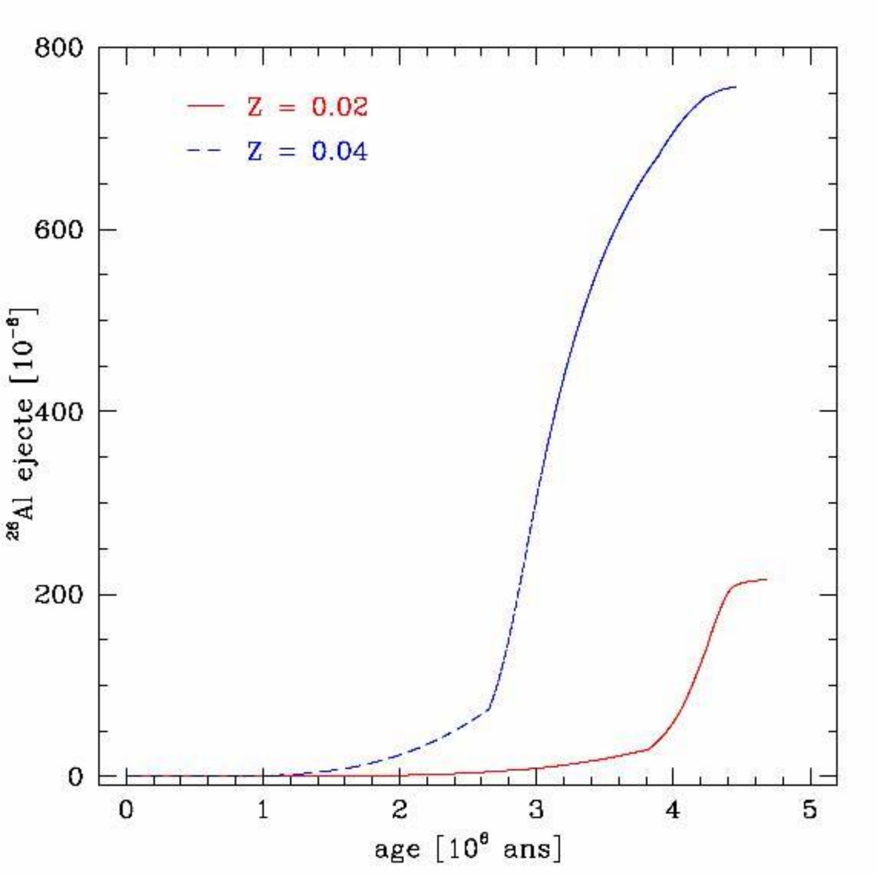
$\dot{M}$ = 0
υ_{ini} = 300 km s^{-1}
Z=0.004
Z=0.008
Z=0.020
Z=0.040
$M_{final}/M_{\odot}$
$M_{ini}/M_{\odot}$
10
20
30
40
20
40
60
80
100
120

WHEN THE METALLICITY INCREASES

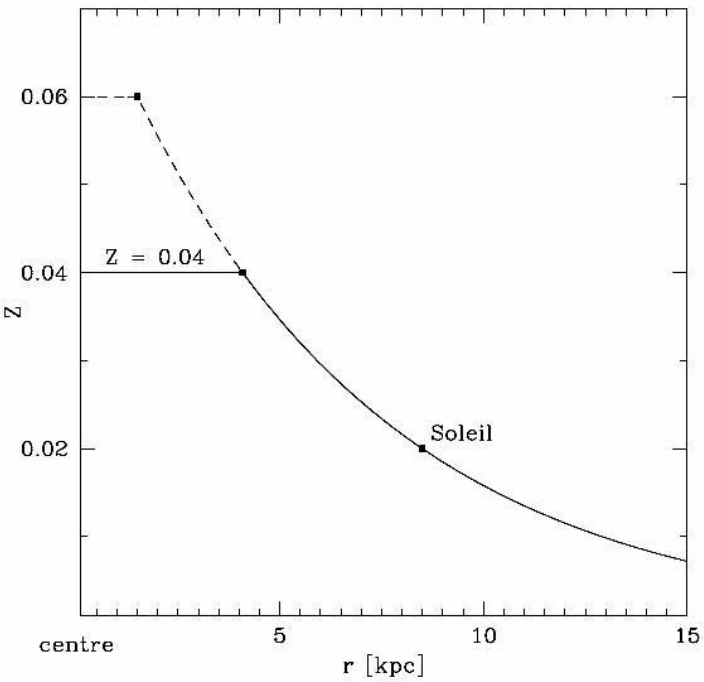
60 Msol

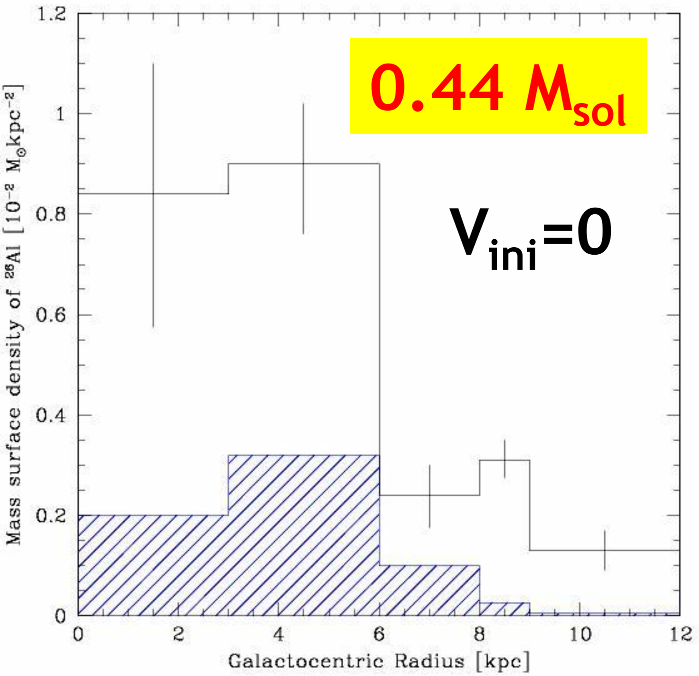
	Z=0.02	Z=0.04
0 km sec-1	$1.3\ 10^{-4}$	$3.0\ 10^{-4}$
300 km sec-1	$2.2\ 10^{-4}$ (1.7)	$7.6\ 10^{-4}$ (2.5)





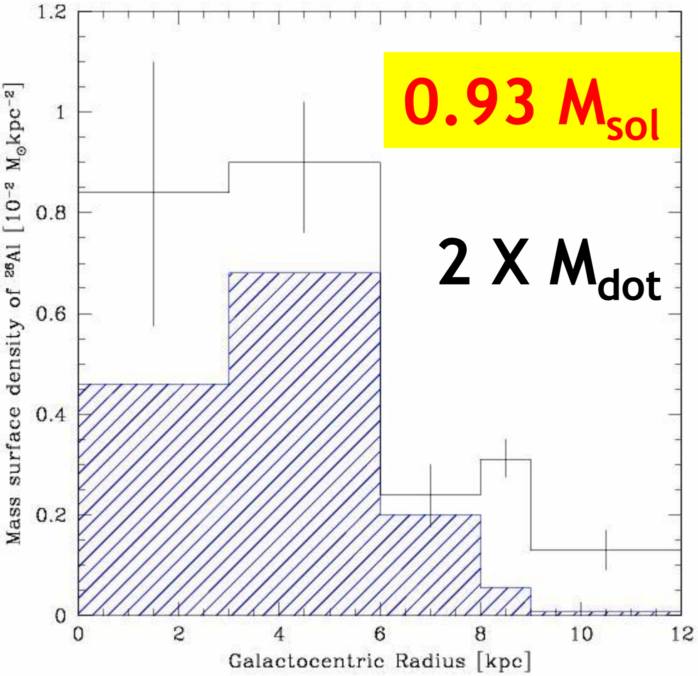
IMF: 1.70





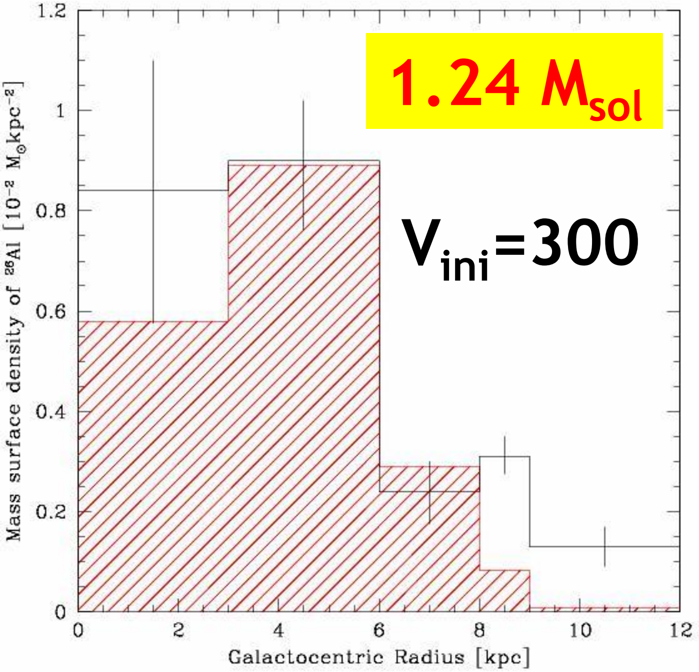
$0.44\ M_{sol}$

$V_{ini}=0$



$0.93\ M_{sol}$

$2\ X\ M_{dot}$

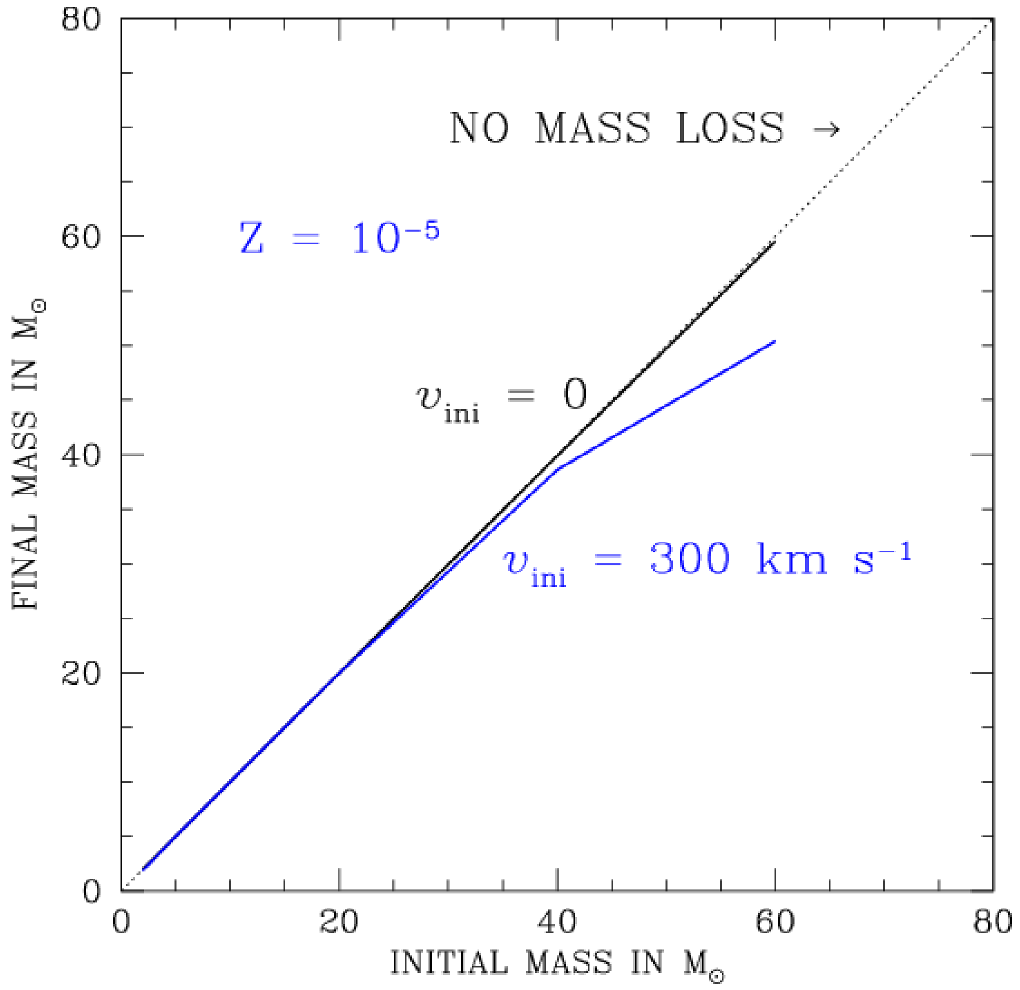


$1.24\ M_{sol}$

$V_{ini}=300$

What is different at very low Z ?

mass removed by stellar winds decreased



Yields of carbon and oxygen enhanced

Deduced from models by Maeder and Meynet 2001
Meynet and Maeder 2002

Net yields

Z	V	C	O
10^{-5}	0	5.3	42
10^{-5}	300	6.2	74
0.004	0	4.6	49
0.004	300	6.2	74

MASS	2-4 Msol	4-8 Msol	10-40 Msol	>40 Msol
^{12}C 3α----->^{12}C HeB	Shell HeB P $3D_{up}$ + PN f ~2-5	Shell HeB P $3D_{up}$ + PN f~1 HBB f~8 no HBB	Core HeB P SN f~3-4	Core Heb P WR + SN f~40, Z_{sol} f~4, Z=0.1 Z_{sol}
^{14}N C,O---->^{14}N CNO cycle	Core HB S $1D_{up}$ + RG f~2	Core HB S $1D_{up}$ + RG f~3 no HBB or HBB P $3D_{up}$ + PN f~30	Core HB S SN f~3	Core HB S WR(RSG) + SN f~40, Z_{sol} f~3, Z=0.1 Z_{sol}
^{16}O 12C(α,γ)16O HeB			Core HeB P SN f~10	Core HeB P WR, SN F~4, $Z=Z_{sol}$ F~20, $Z=0.1Z_{sol}$

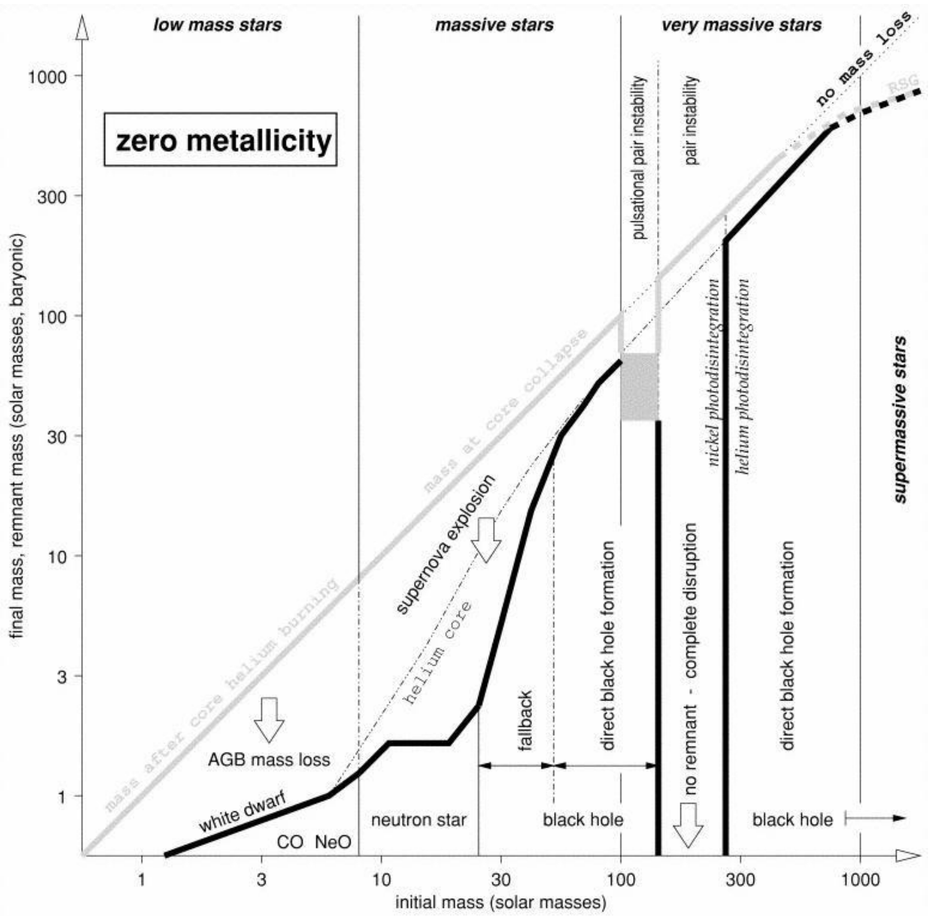
Adapted from Prantzos et al. 1996

PRODUCTION FACTORS (SOLAR)

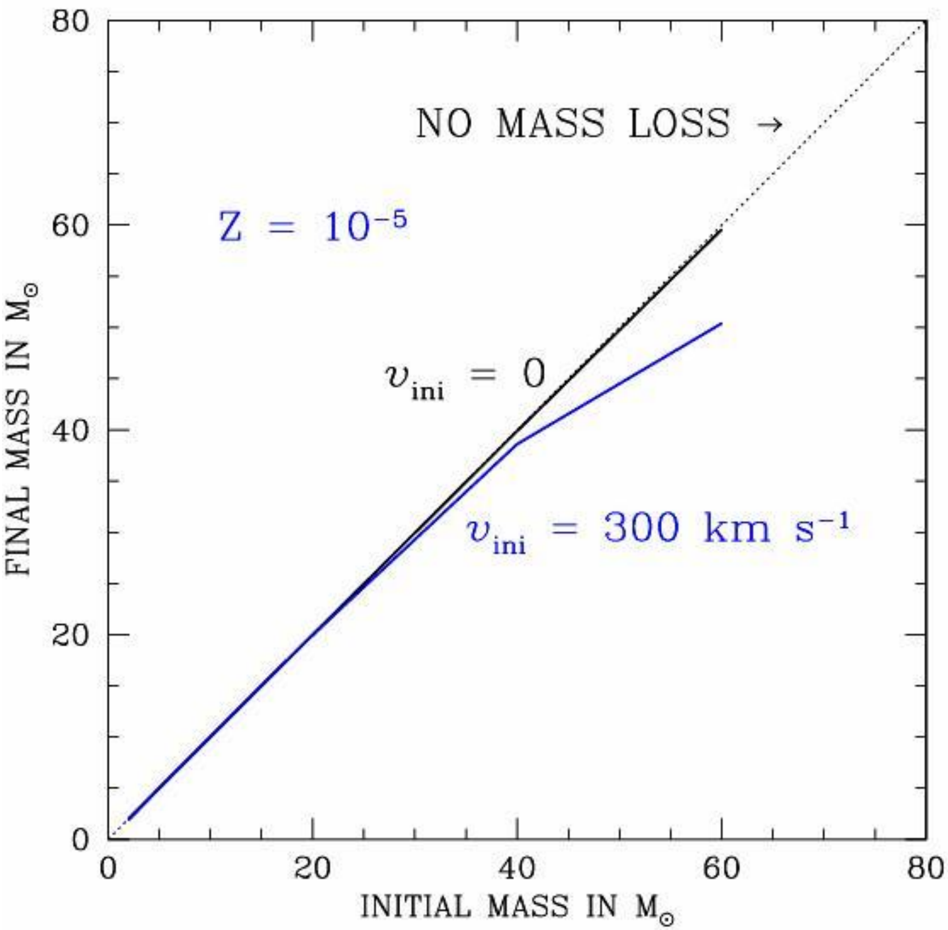
Model	^{4}He	^{12}C	^{14}N	^{16}O	^{20}Ne	^{24}Mg
V=0 km/s	1.46	5.00	4.46	4.27	10.86	2.87
V=300 km/s	1.43	8.00	3.14	9.49	19.51	6.33
Heger et al. 2000 dc15 V=0km/s	1.32	4.17	3.60	6.76	12.0	6.31
Heger et al. 2000 ec15, V=200km/s	1.32	3.66	4.32	8.00	10.70	6.00
Heger 98 KE15B V=200km/s	1.46	3.95	4.47	4.13	4.33	4.68

Change of the nucleosynthesis of the most massive primordial star

Cf Marigo et al. IAU Symp. 212

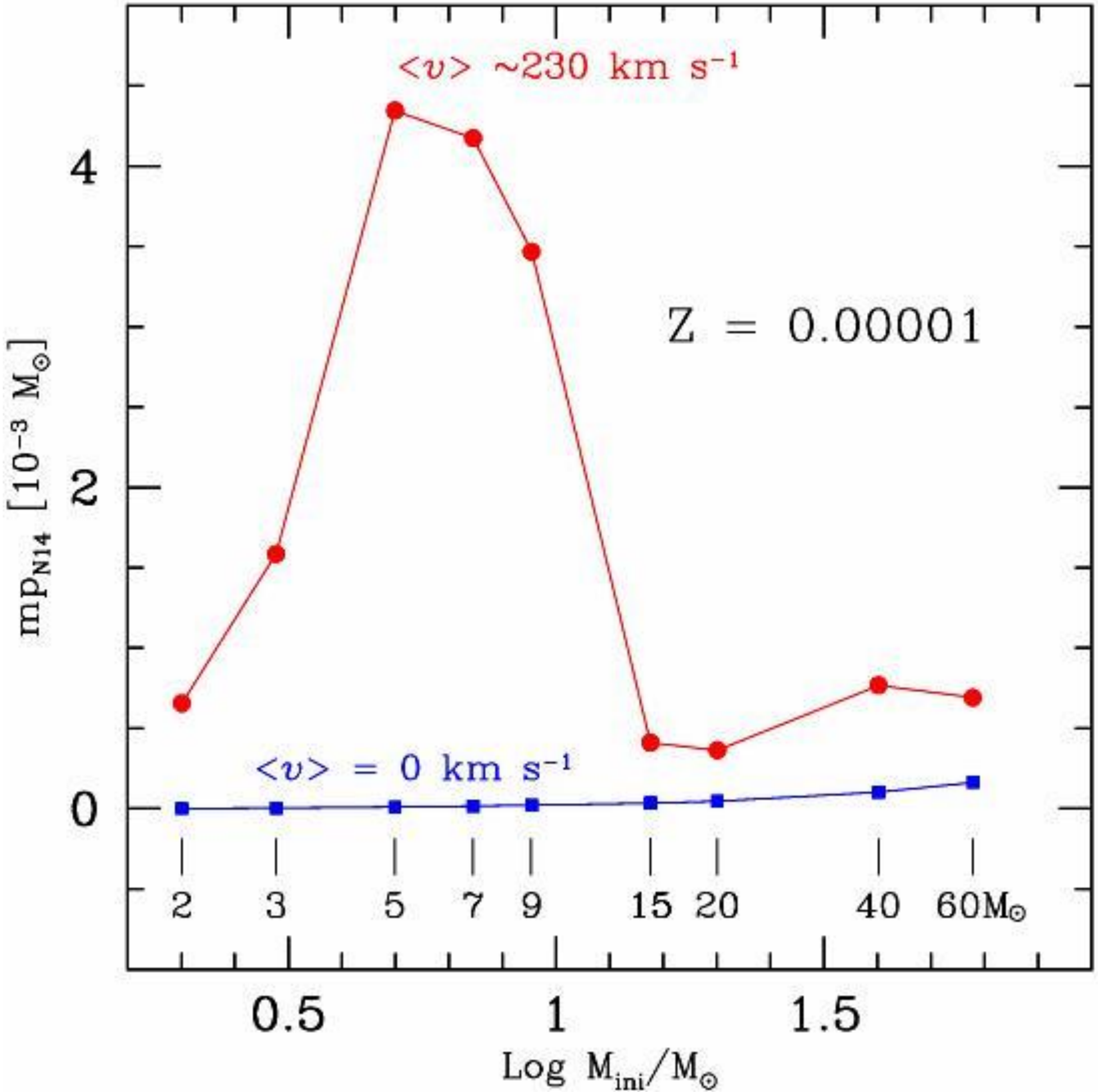


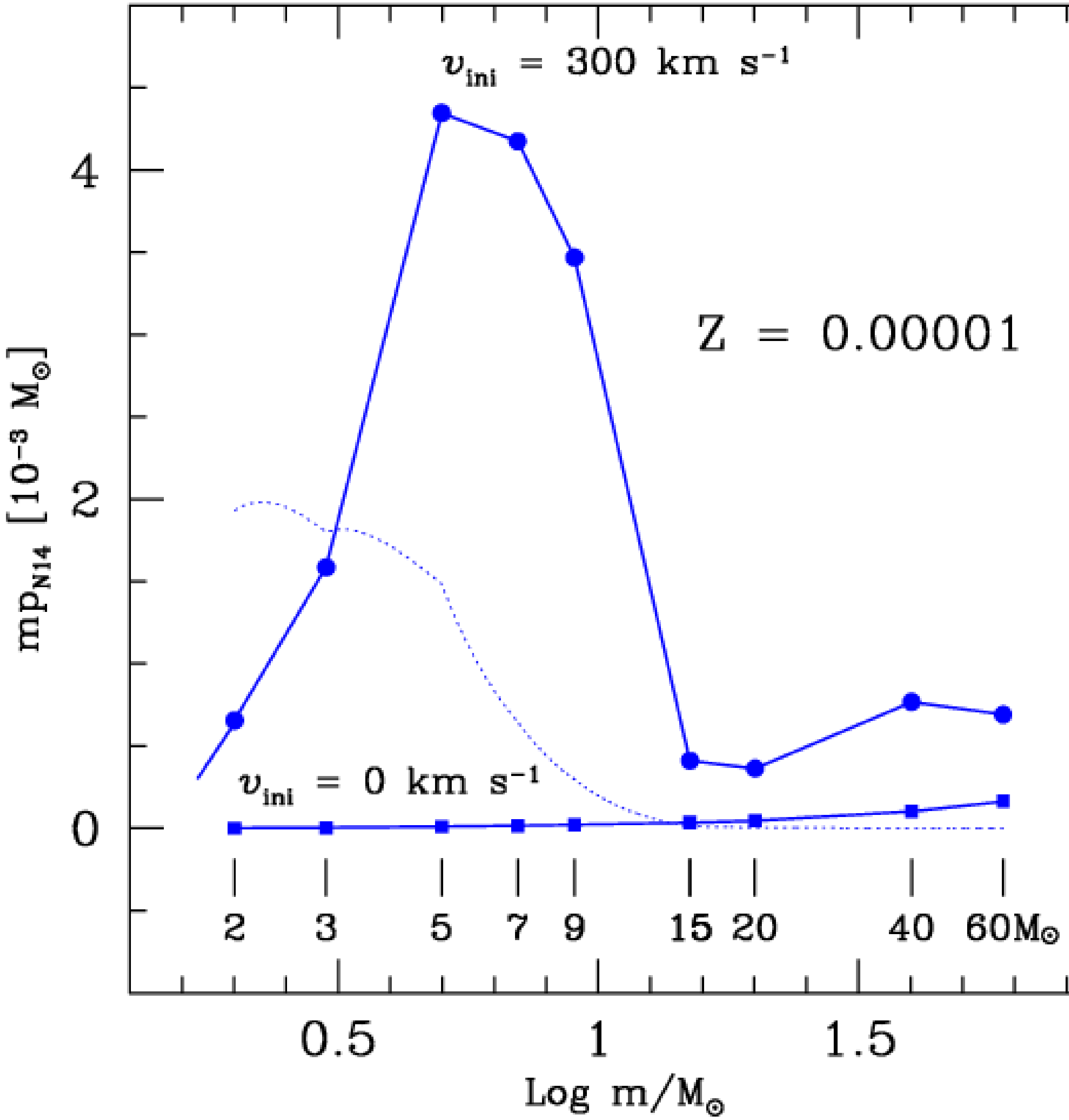
Heger and Woosley 2002



MM 2002

The most important contributors are stars with masses between 2 - 5 M_{sol}

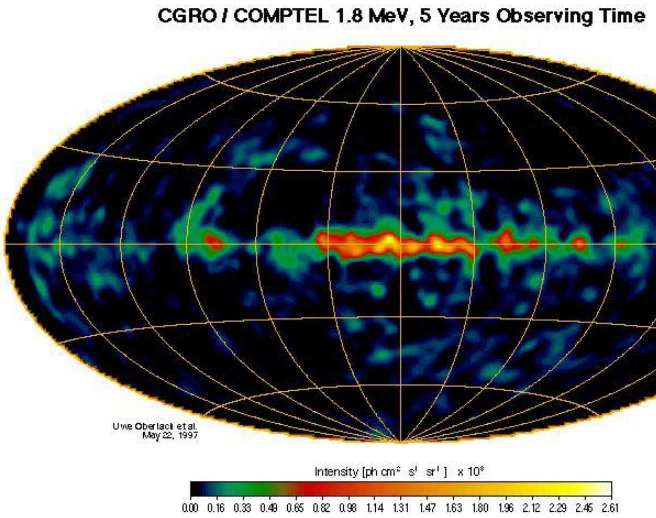



v_{ini} = 300 km s^{-1}
Z = 0.00001
v_{ini} = 0 km s^{-1}
mp_{N14} [10^{-3} $M_\odot$]
0
2
4
2
3
5
7
9
15
20
40
60$M_\odot$
0.5
1
1.5
Log m/$M_\odot$

ELEMENTS WITH WIND CONTRIBUTION

H-burning products → ^{26}Al

Palacios et al. (2005)
Chieffi & Limongi (2005)



He-burning products → ^{4}He, ^{12}C — Maeder (1992)

→ ^{19}F — Meynet & Arnould (1999),
Palacios et al. (2005),

→^{22}Ne — Cassé & Paul (1981)
Binns et al. (2005)

→Weak s-process components (A < 100)
Arnould et al (1997; 2005)

Pettini et al 2002 ------> 10 DLAs, 4, at least, in the interim period. (Duration interim period)/(Age of the oldest DLA) ~ 0.4 if DLA formed continuously.

Age of oldest DLA (formed z~6), observed with a <z> ~2.5= ~ 1.8 Gyr.

This would imply Duration interim period~Time delay~0.4 X 1.8 Gyr ~0.7 Not far from our 0.67 Gyr !