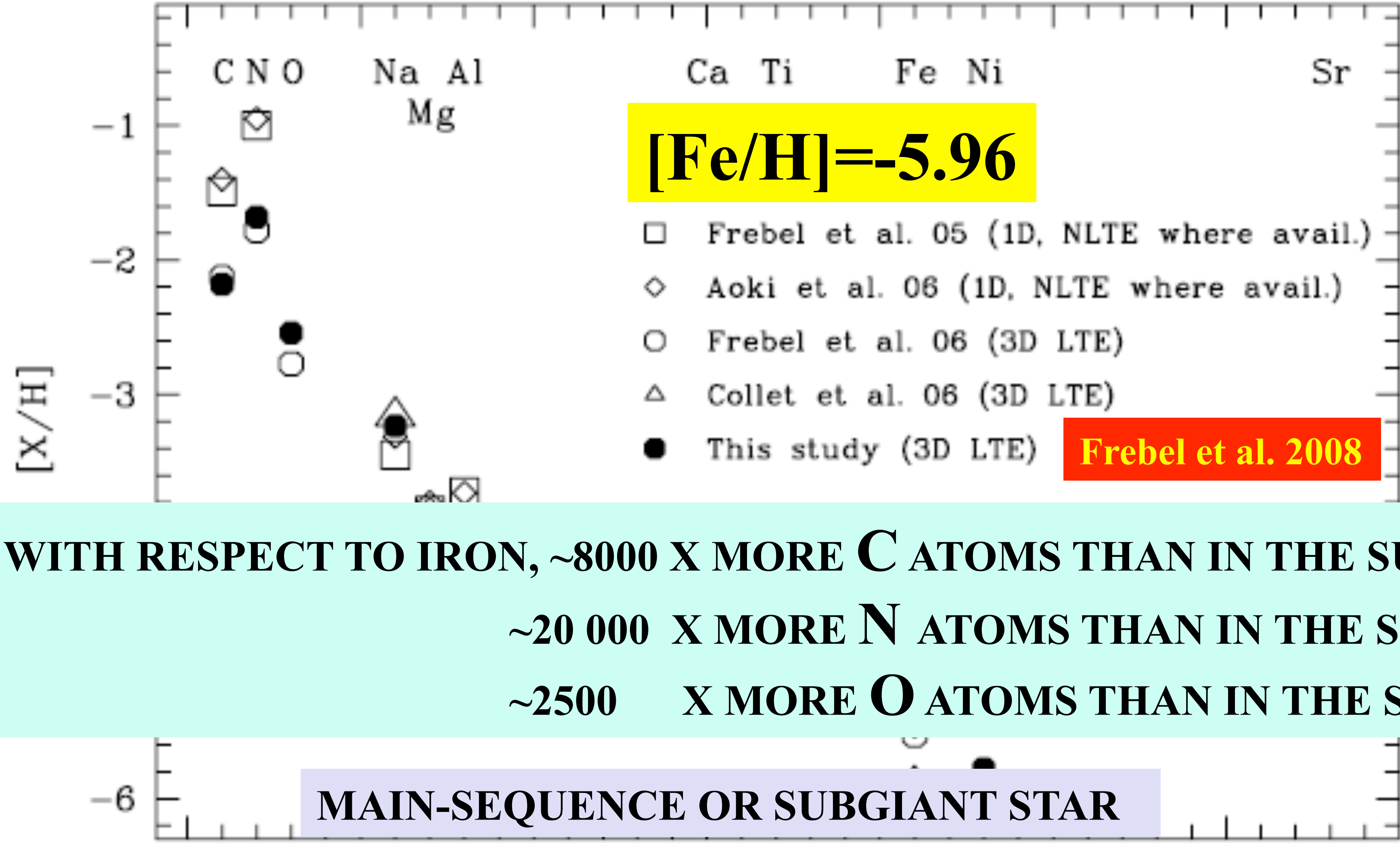
ARE THE MOST IRON POOR STARS IN THE HALO He-RICH?

Georges Meynet
Geneva Observatory, University of Geneva

In collaboration with

Raphael Hirschi, Keele, UK
Sylvia Ekstöm, Geneva
Cyril Georgy, Geneva
André Maeder, Geneva
Patrick Eggenberger, Geneva
Cristina Chiappini, Geneva-Trieste
Corinne Charbonnel, Geneva
Thibaud Decressin, Bonn

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

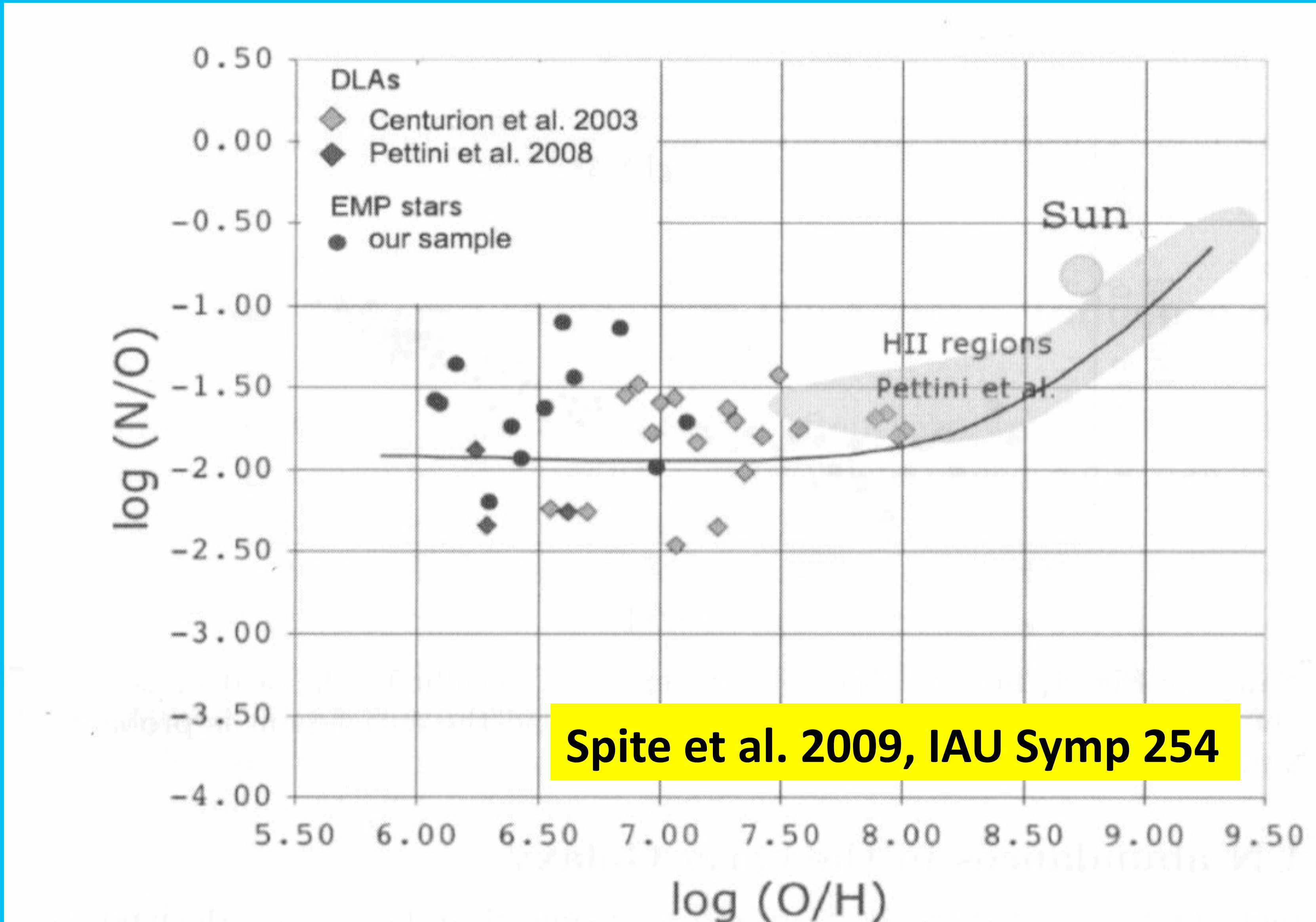
CARBON: He-BURNING, FROM He

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**

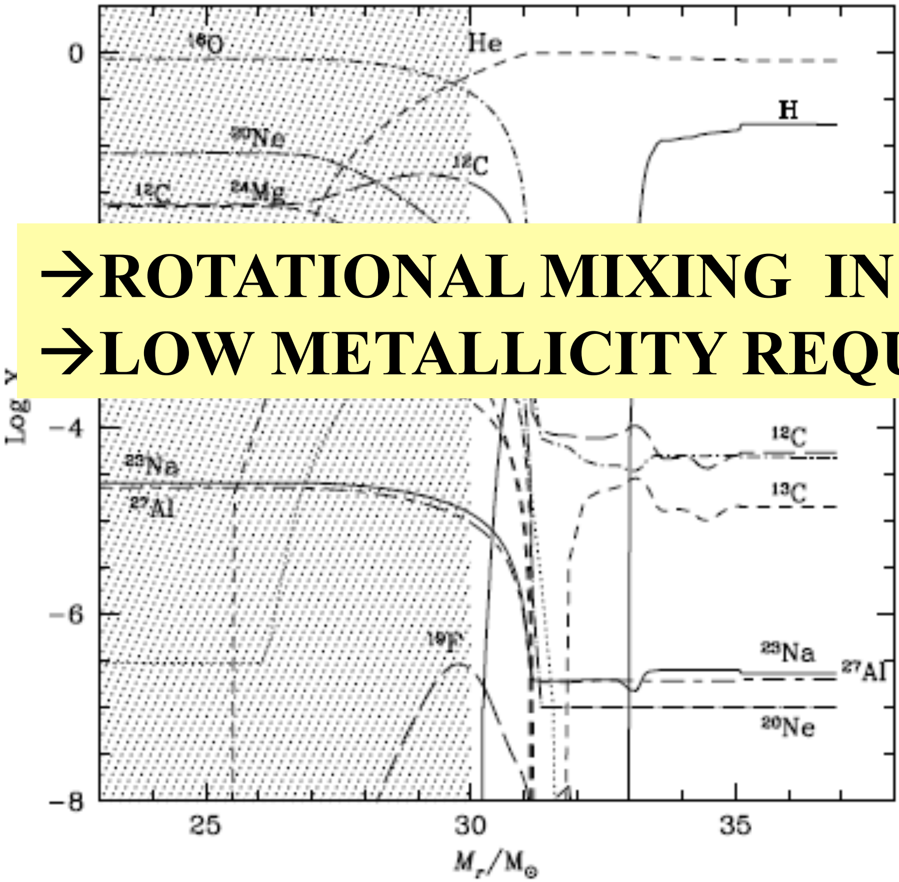
IMPORTANT PRODUCTION OF PRIMARY NITROGEN



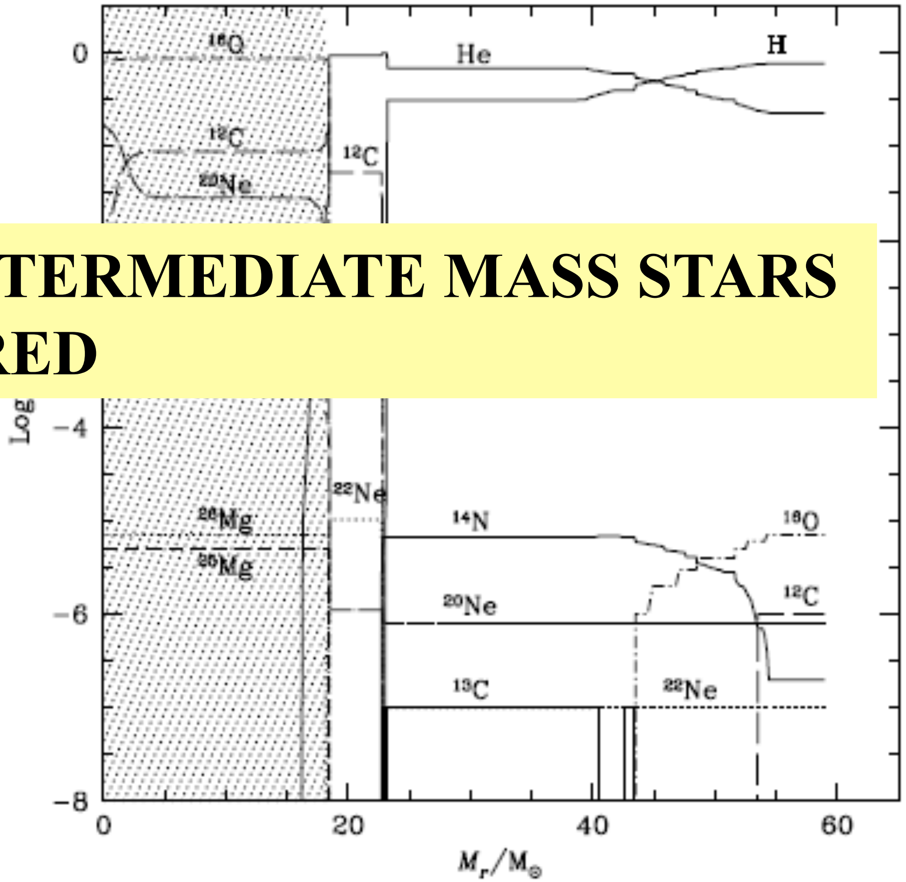
Spite et al. 2009, IAU Symp 254

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

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



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



→ROTATIONAL MIXING IN INTERMEDIATE MASS STARS

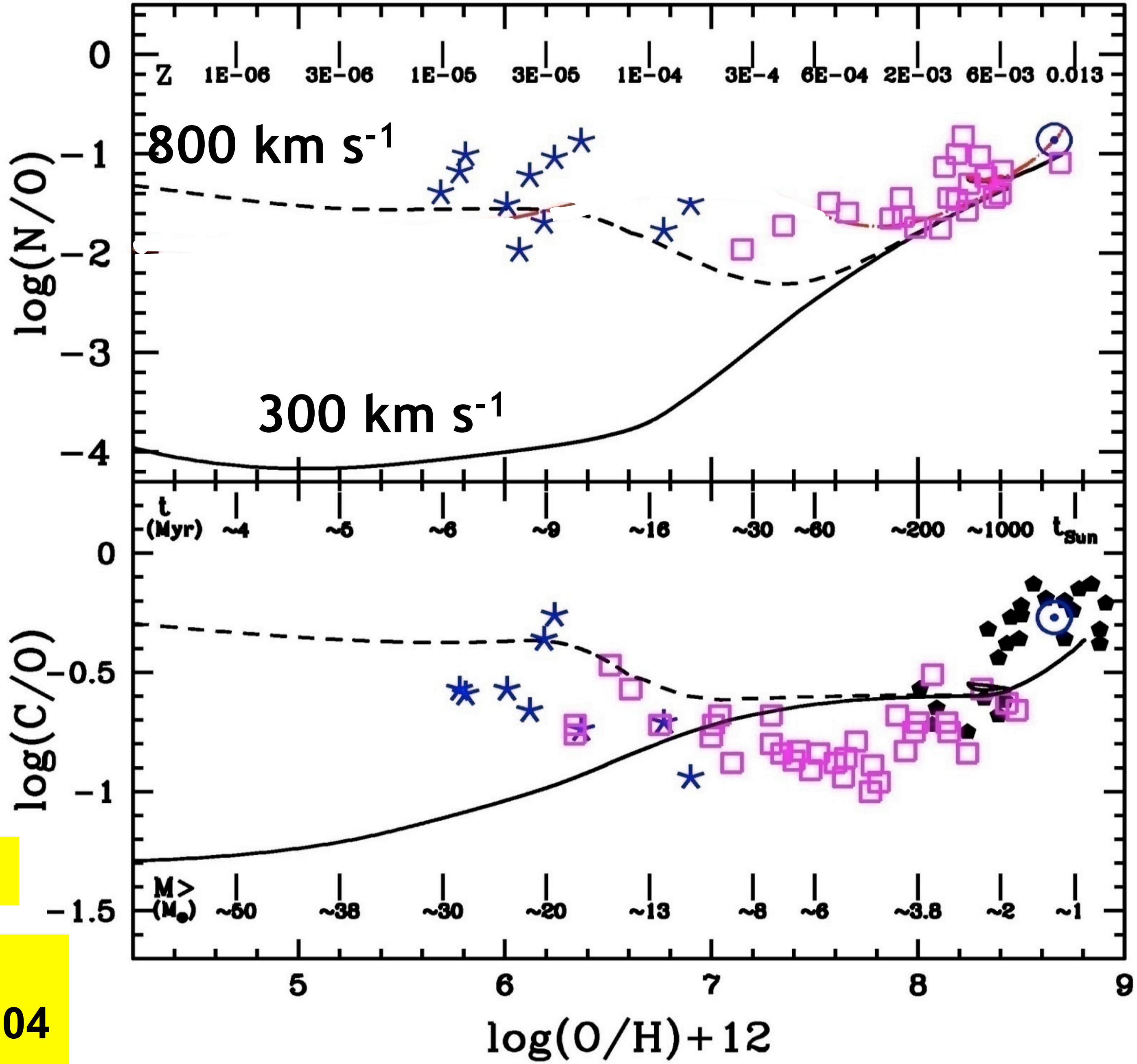
→LOW METALLICITY REQUIRED

NITROGEN

WINDS

N/O

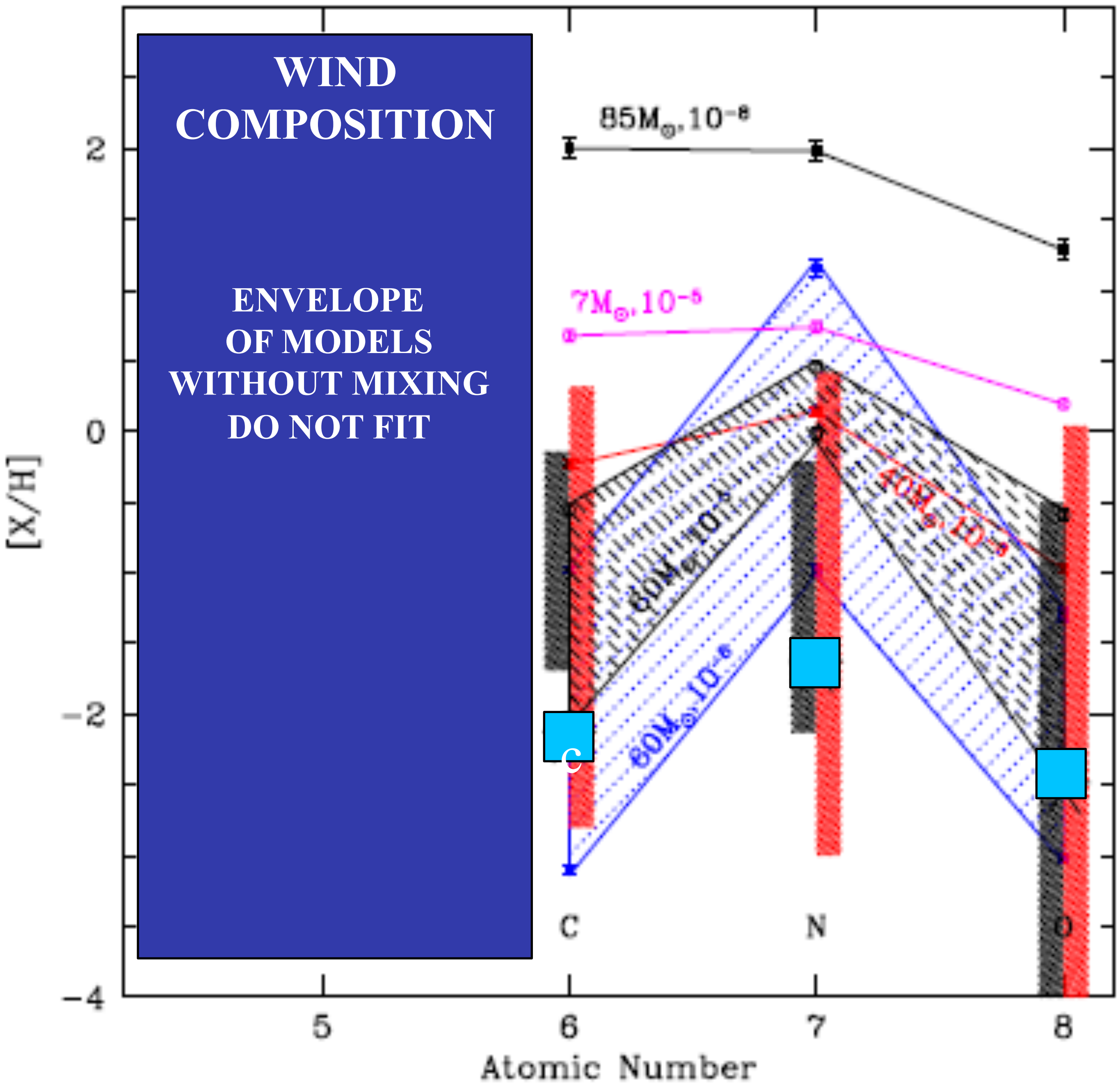
C/O



Observations from

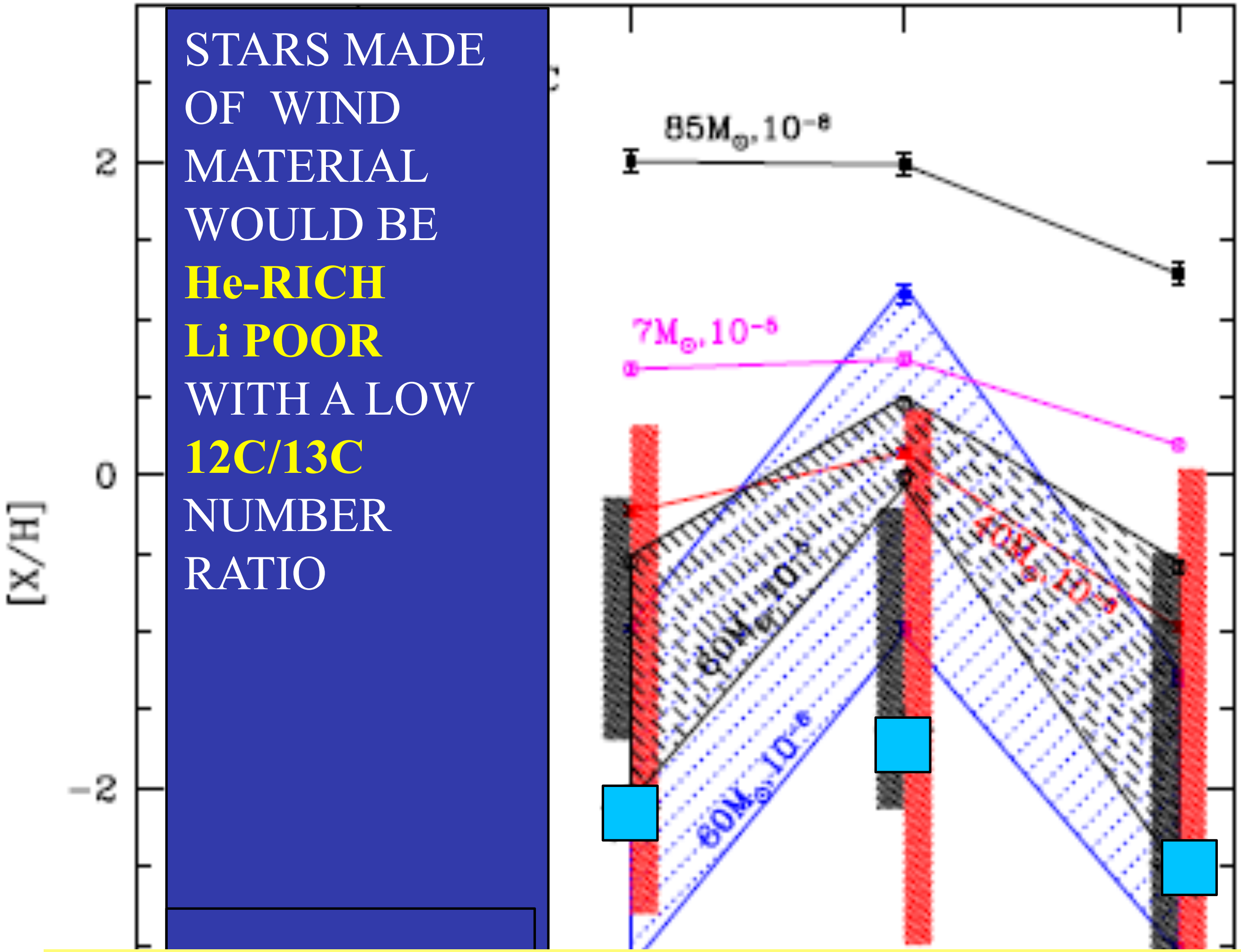
Spite et al. 2005
Akerman et al. 2004
Nissen 2004

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



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

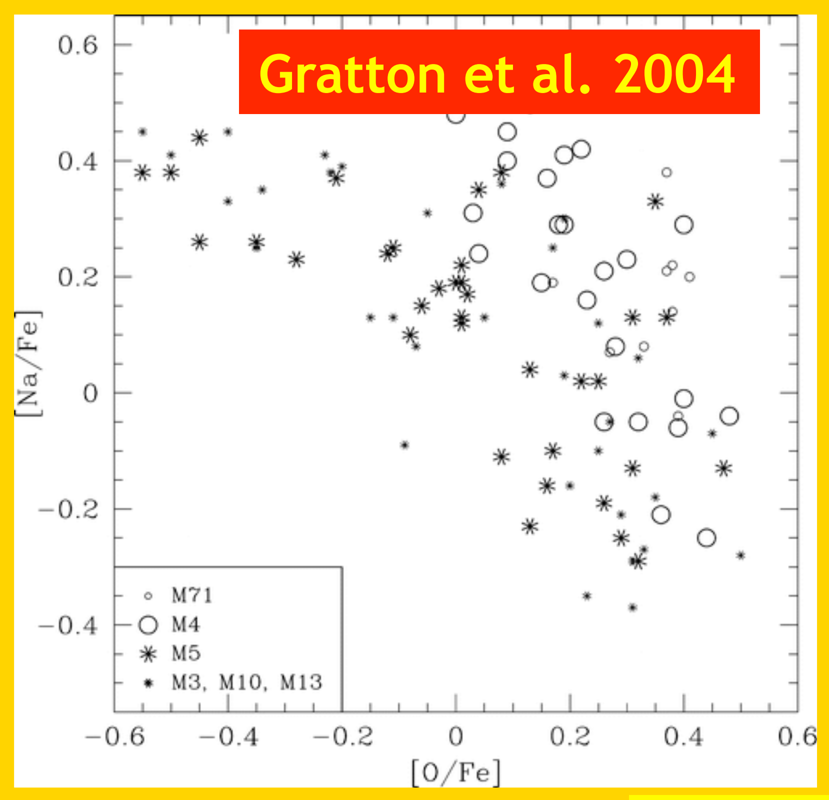
STARS MADE
OF WIND
MATERIAL
WOULD BE
He-RICH
Li POOR
WITH A LOW
12C/13C
NUMBER
RATIO



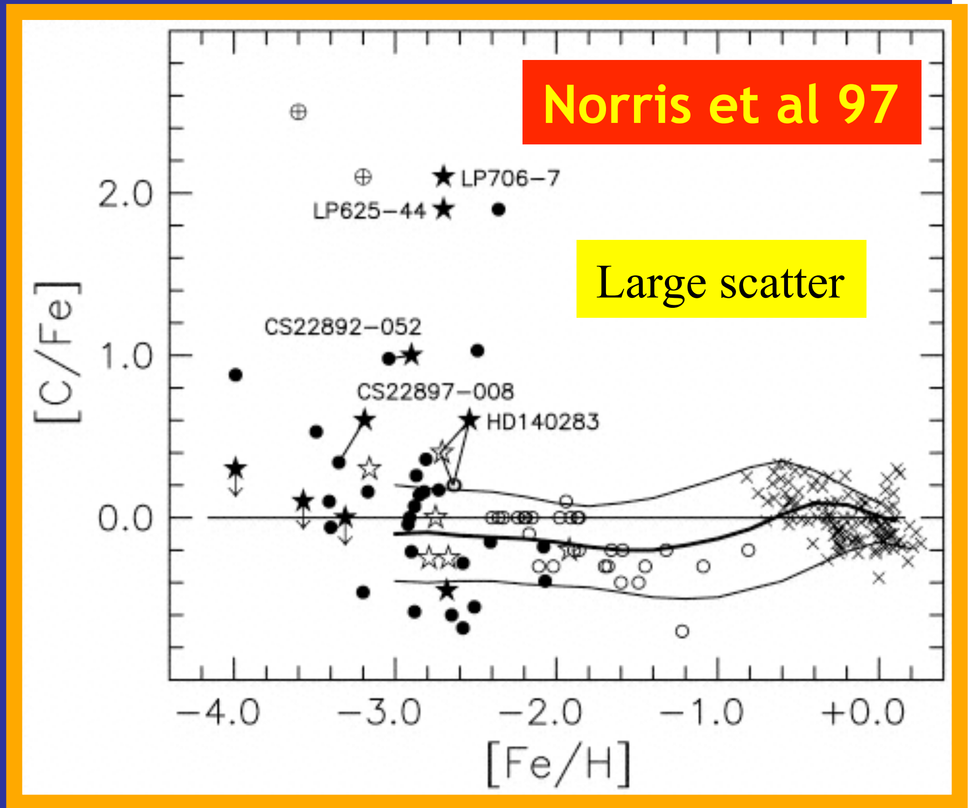
	Y	e(Li)	12C/13C
	0.60	0	4.7
Frebel'star		<0.6	>5

IN THE HALO TWO KINDS OF CHEMICALLY PECULIAR STARS

IN GLOBULAR CLUSTERS



IN THE FIELD



STARS MADE OF

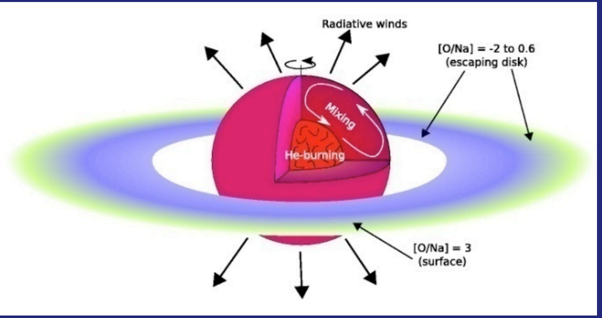
H-burning products

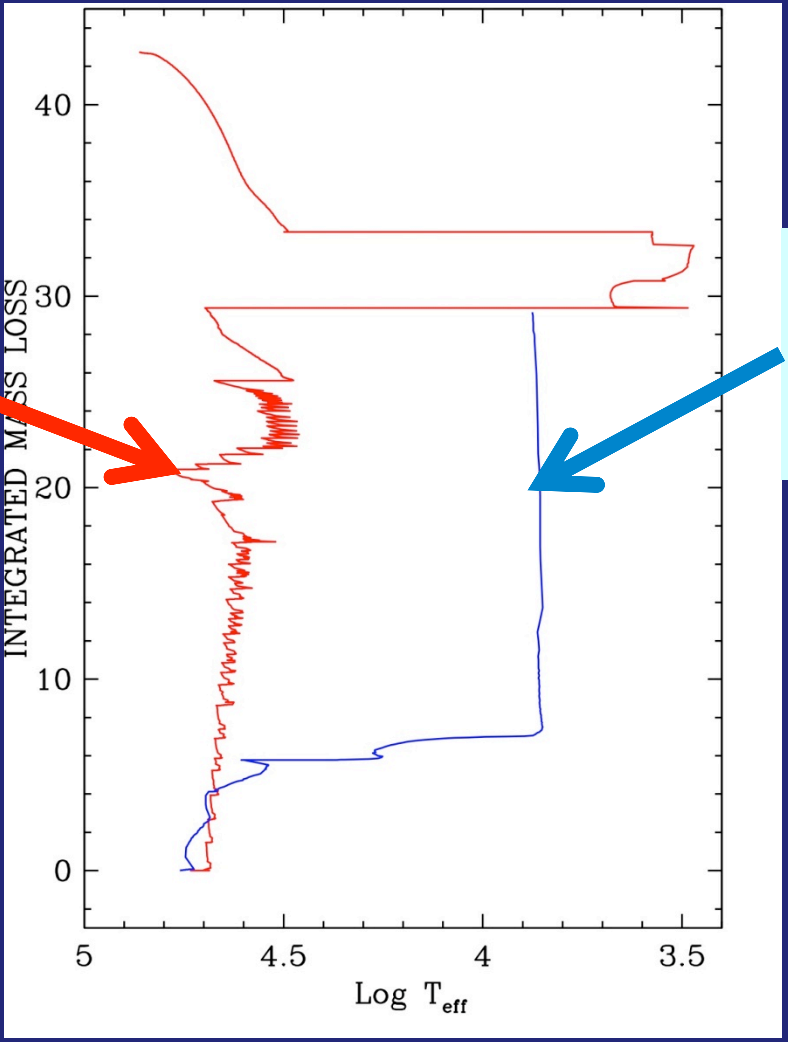
H- and He-burning products

SAME MASS: 60 M_{sol}, SAME V_{ini}=800 km s^{-1}

Z=0.00050

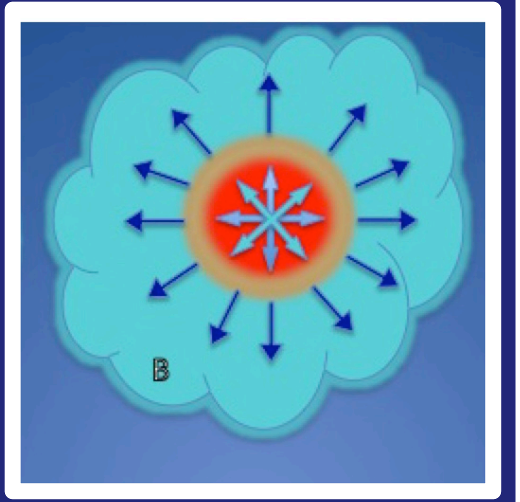
Slow wind: MS
Only enriched in
H-burning
products





Z=0.00001

Slow wind: YSG
enriched in
H- and He-burning
products



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

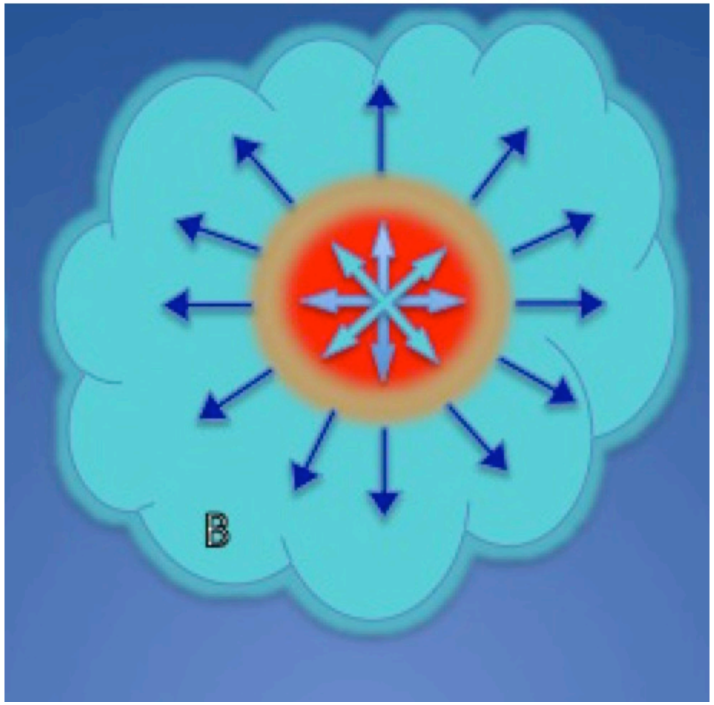
s-process elements

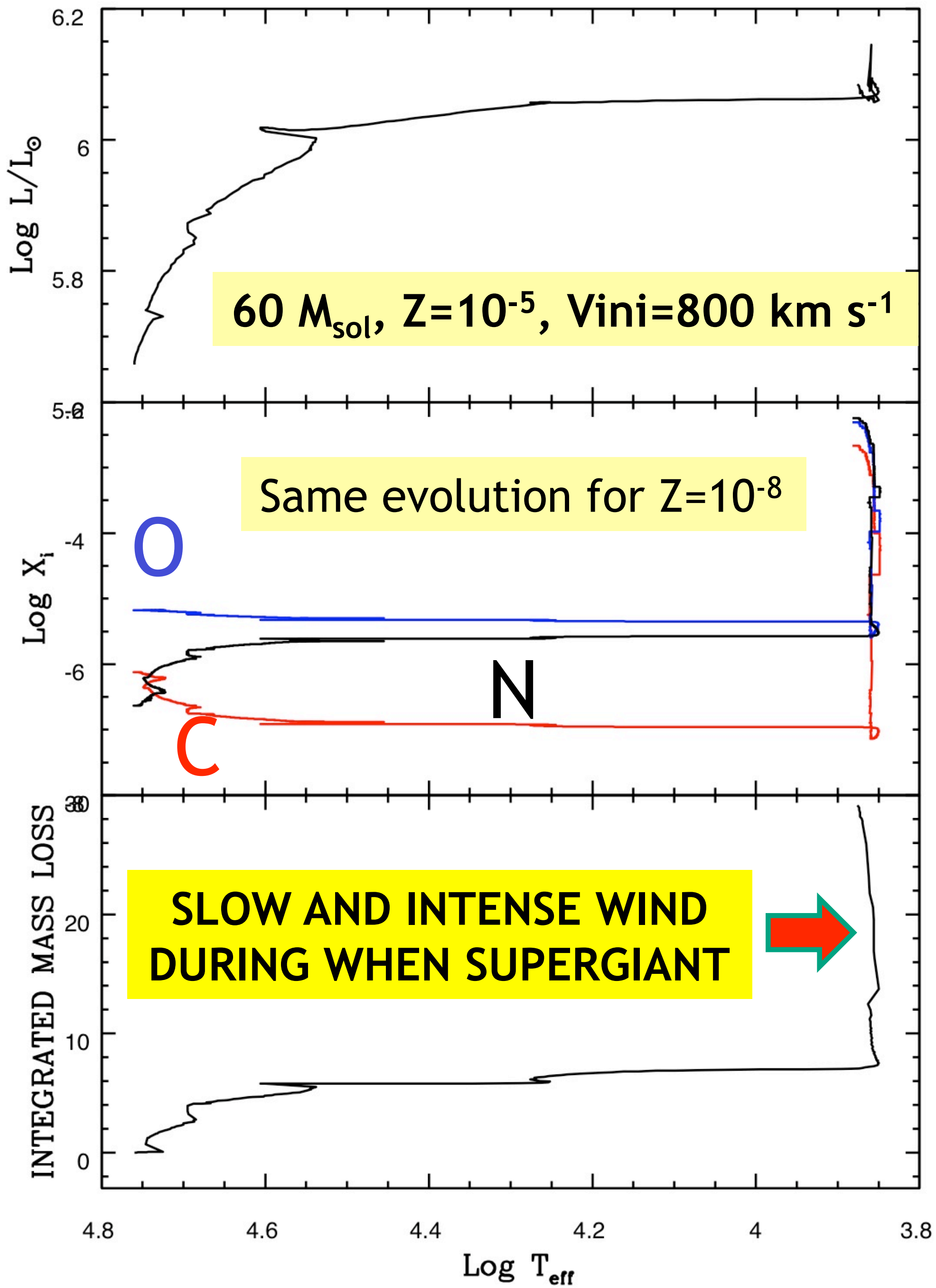
r-process elements

ROTATION?

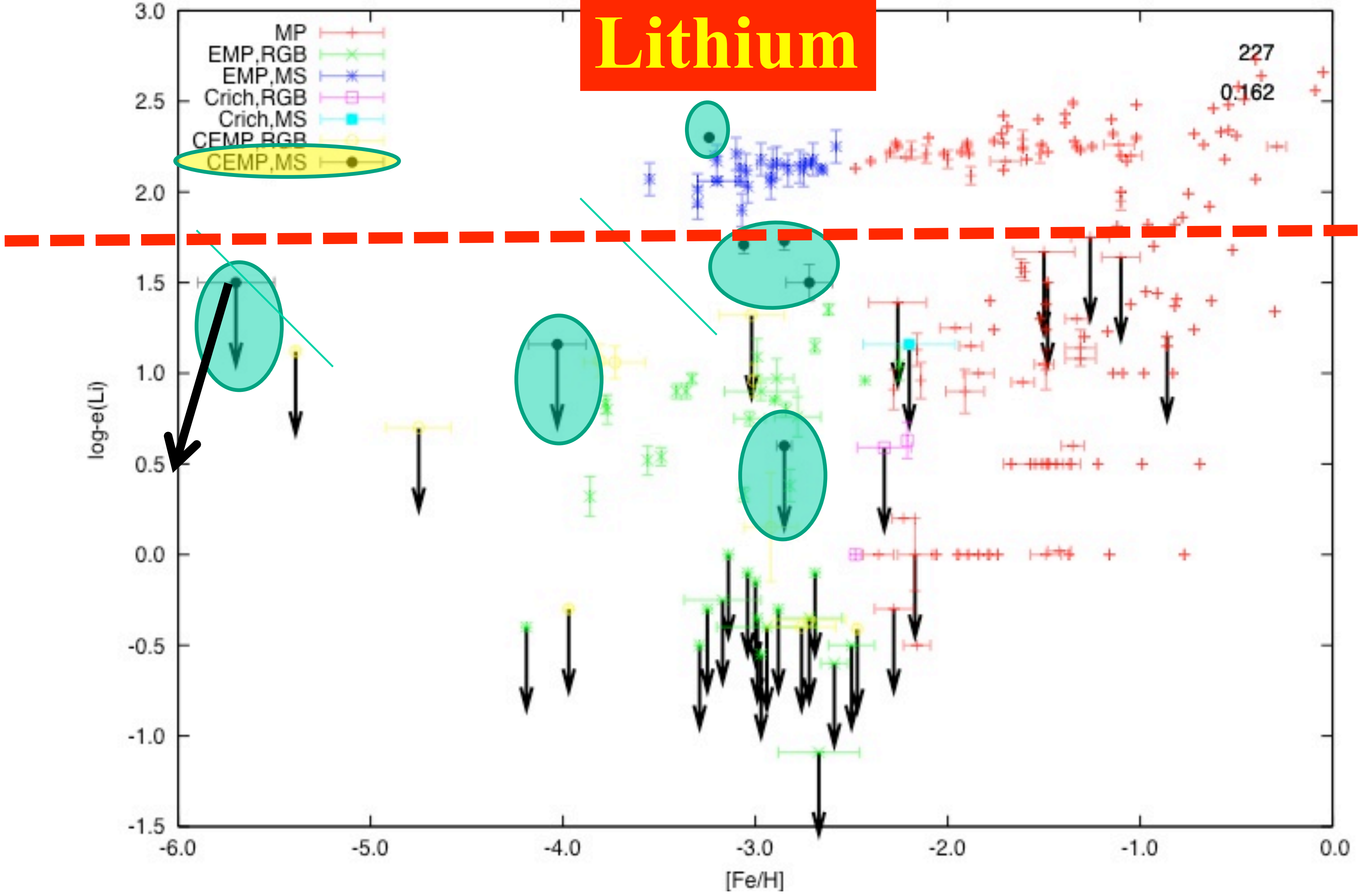
Due to rotational mixing

Star → evolve to red
→ outer convective zone
→ surface enrichment
→ strong mass loss

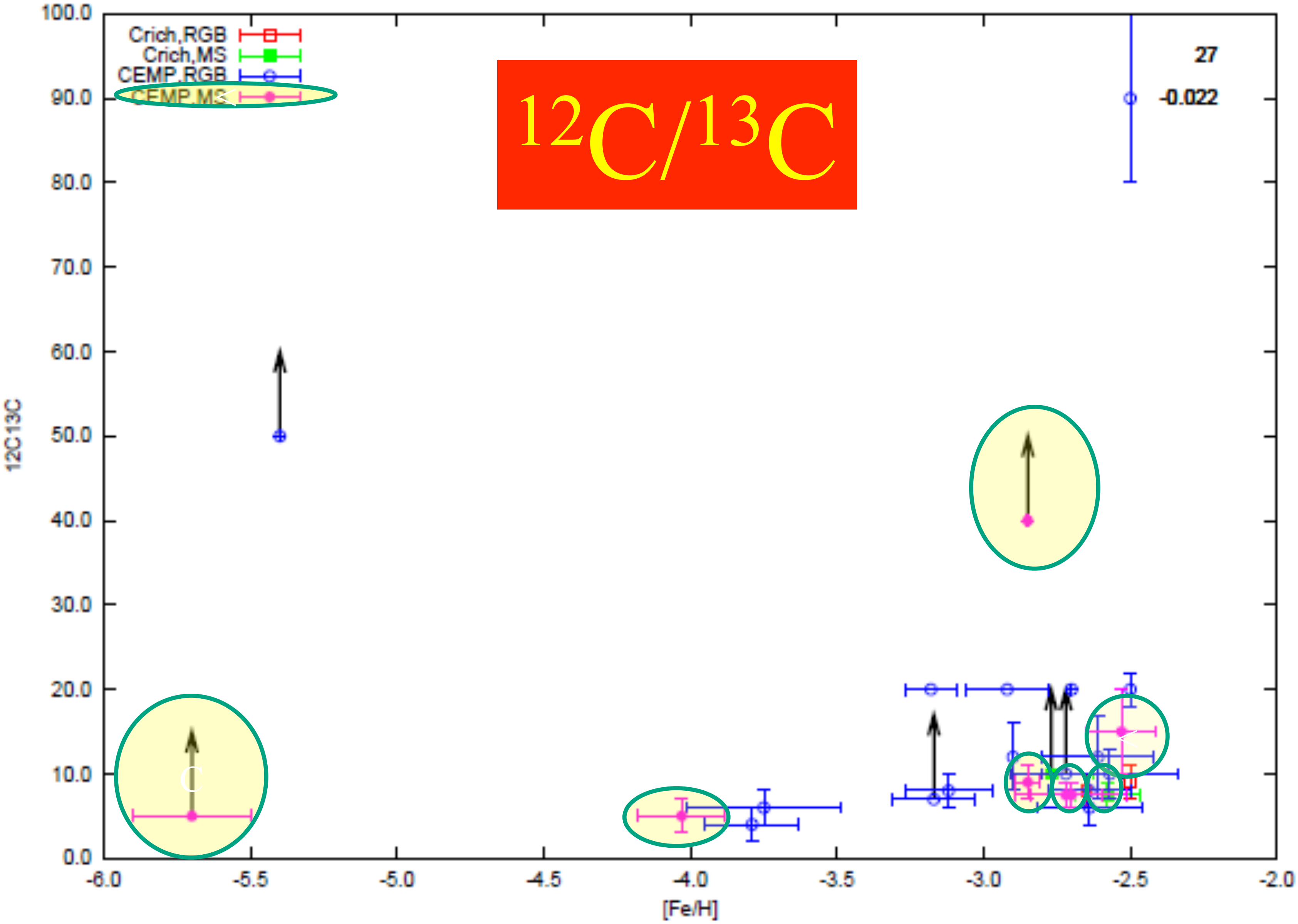




Lithium



SAGA DATABASE Suda et al. 2008

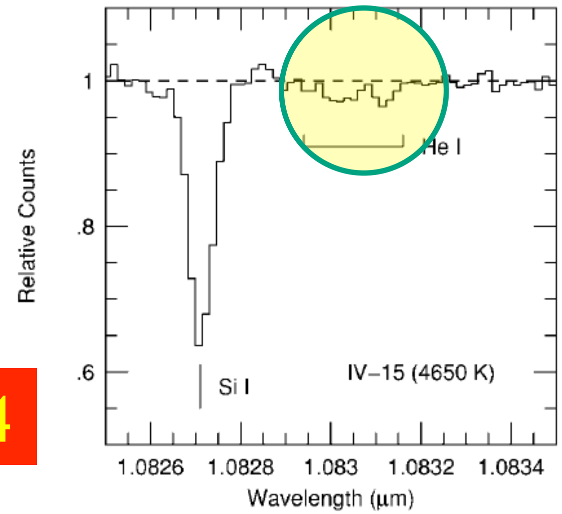


SAGA DATABASE Suda et al. 2008

TESTING HELIUM?

NIR chromospheric
Helium line in red giants

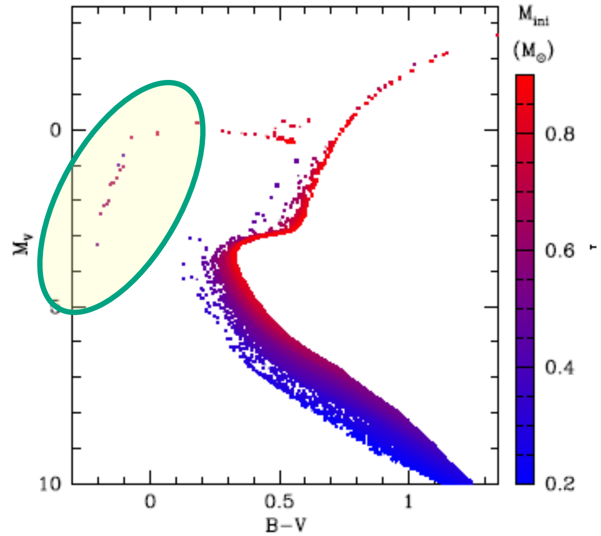
Smith et al. 2004

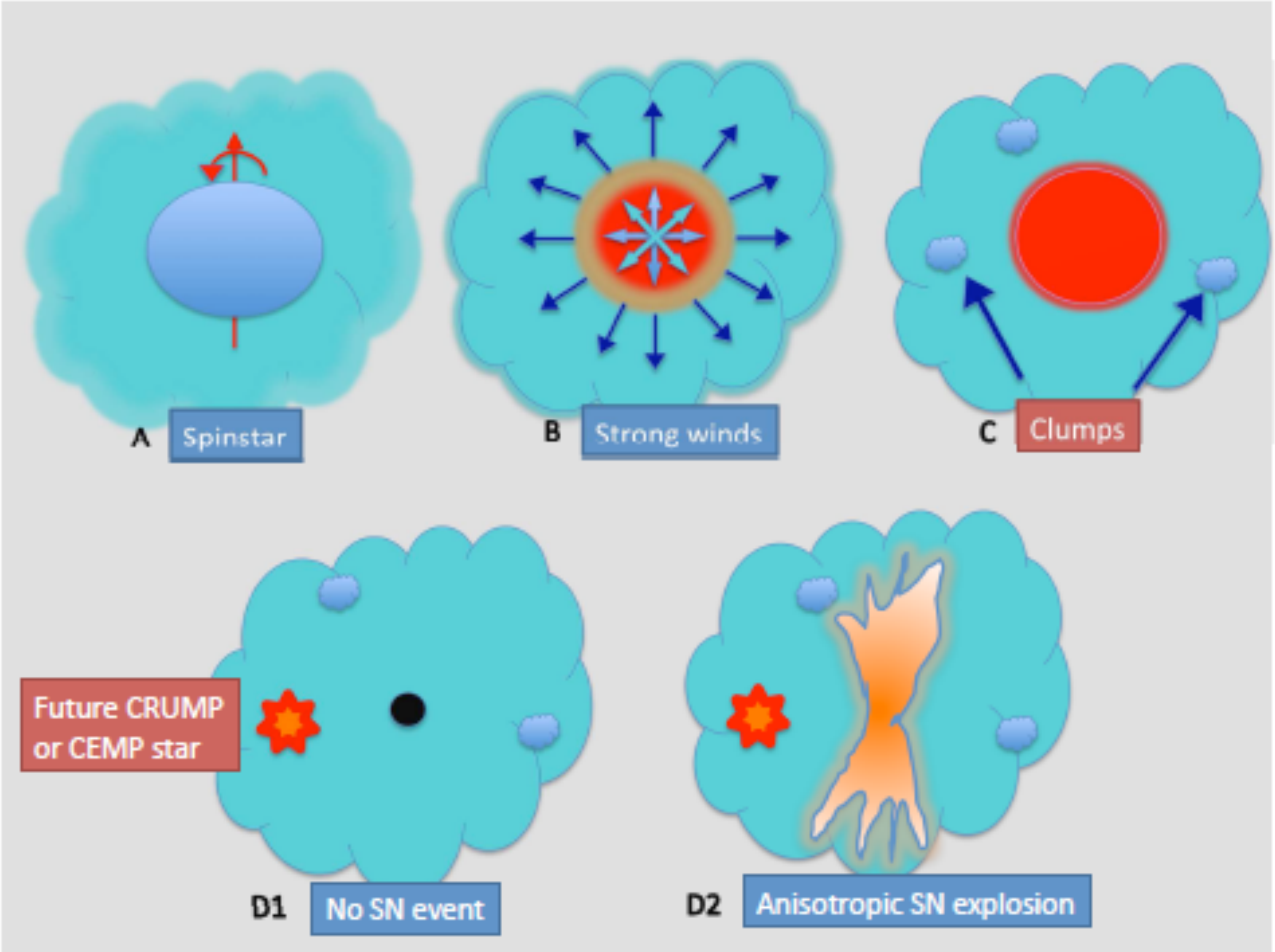


Mass + position in HR diagram for eclipsing binaries

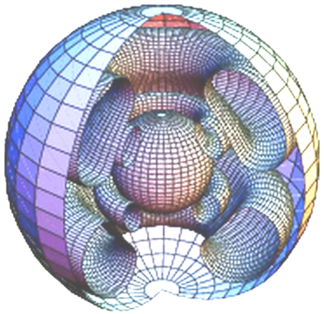
Asteroseismology ?

blue horizontal branch

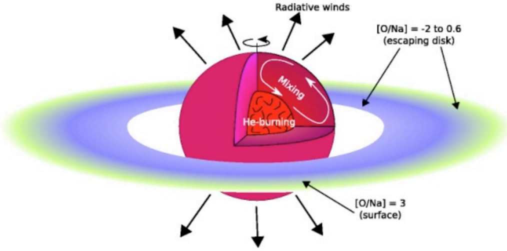



A
Spinstar
B
Strong winds
C
Clumps
Future CRUMP
or CEMP star
D1
No SN event
D2
Anisotropic SN explosion

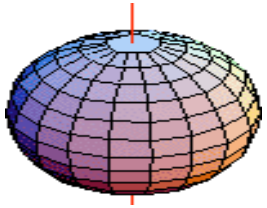
- Mixing



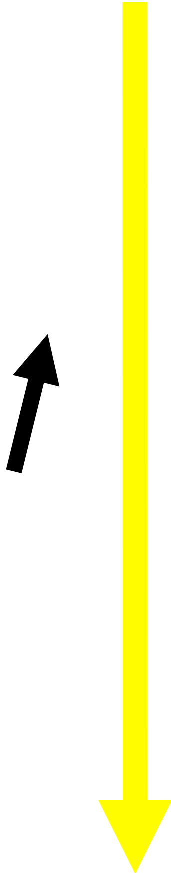
- Rotational mass loss → equatorial disks



→ through opacity



- Homogeneous evolution



Increasing angular momentum content

All these effects of rotation vary with Z

STRONGER AT LOW Z

CONSEQUENCES

Evolutionary tracks MS width, blue loops, surface abundances

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

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

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

Supernova types II, Ib, Ic, collapsars

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

Binary evolution

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

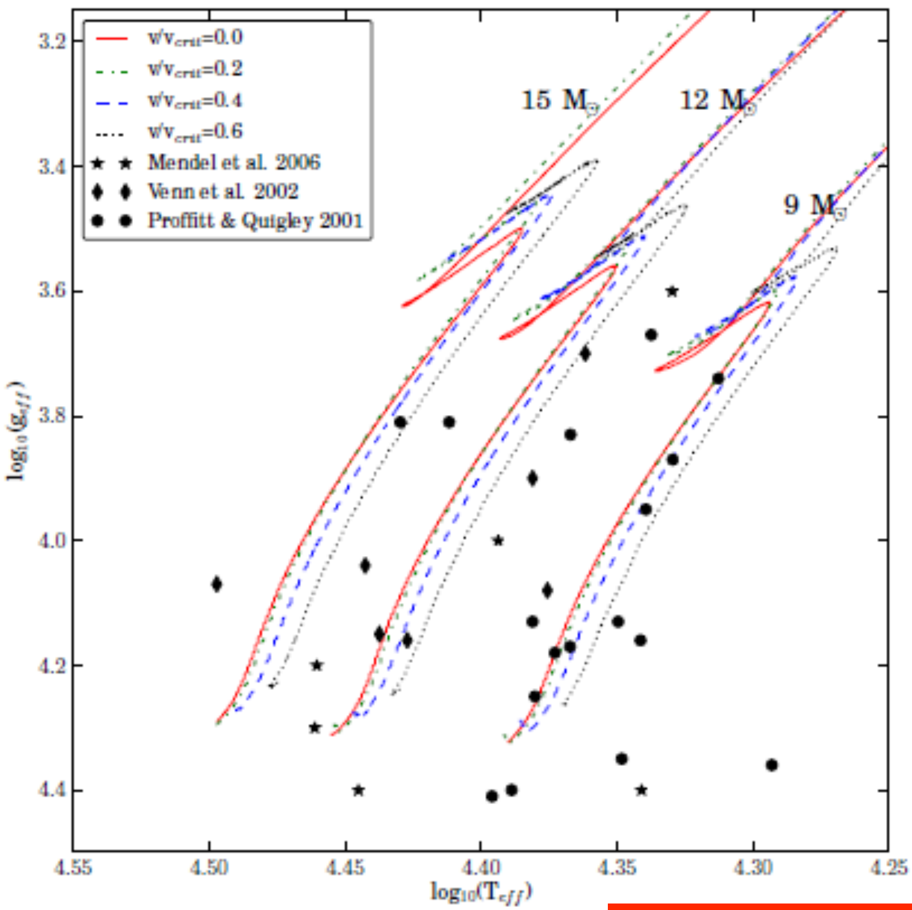
Chemical evolution of globular clusters and of galaxies

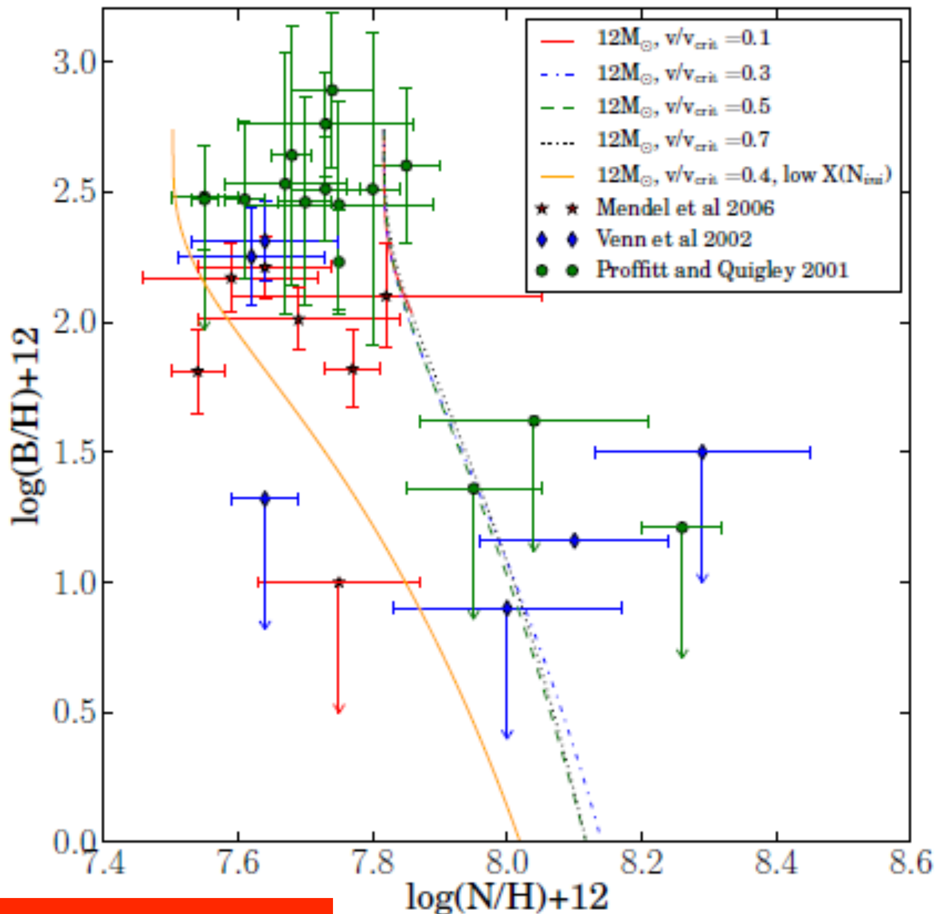
He, CNO, Ne, Al, s-process...

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

BORON DEPLETION AT THE SURFACE OF B-TYPE STARS ON THE MS

See Venn et al. 2002, Mendel et al. 2006, and poster by Urs Frischknect



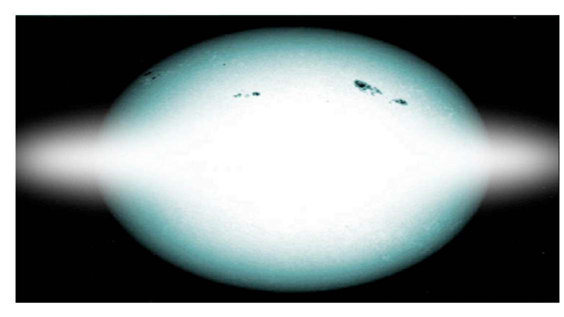


Frischknect et al. In preparation

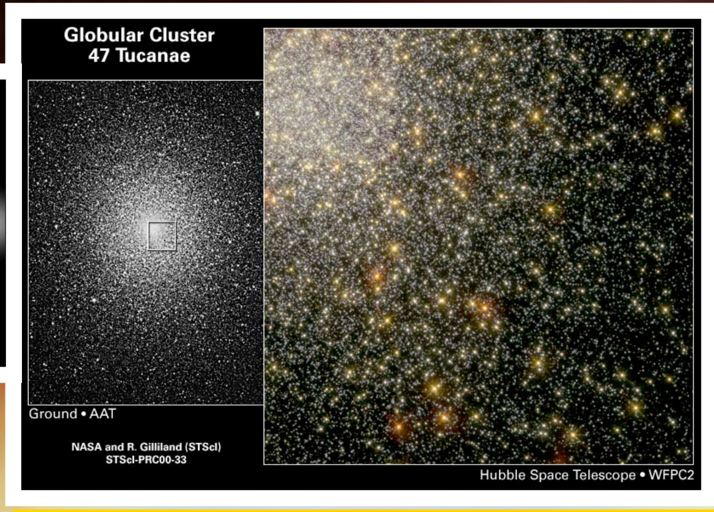
ROTATIONAL MIXING CAN WELL REPRODUCE MOST OF THE OBSERVATIONS

``Spinstars" at low metallicities?

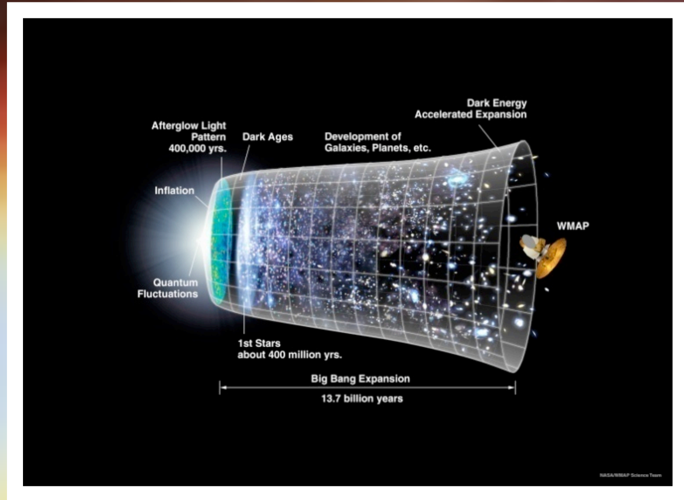
Stars at the critical limit



Composition of stars in globular clusters



Early chemical evolution of galaxies



Observation→
more Be
stars at low Z
Theory→
more rapid
Rotators at low Z

Maeder et al. 1999
Ekstroem et al. 2007

Abundance anomalies
In globular clusters
(Li,C,N,O,F, Na,Mg,Al)

Decressin et al 2007

Helium-rich stars in
Globular clusters

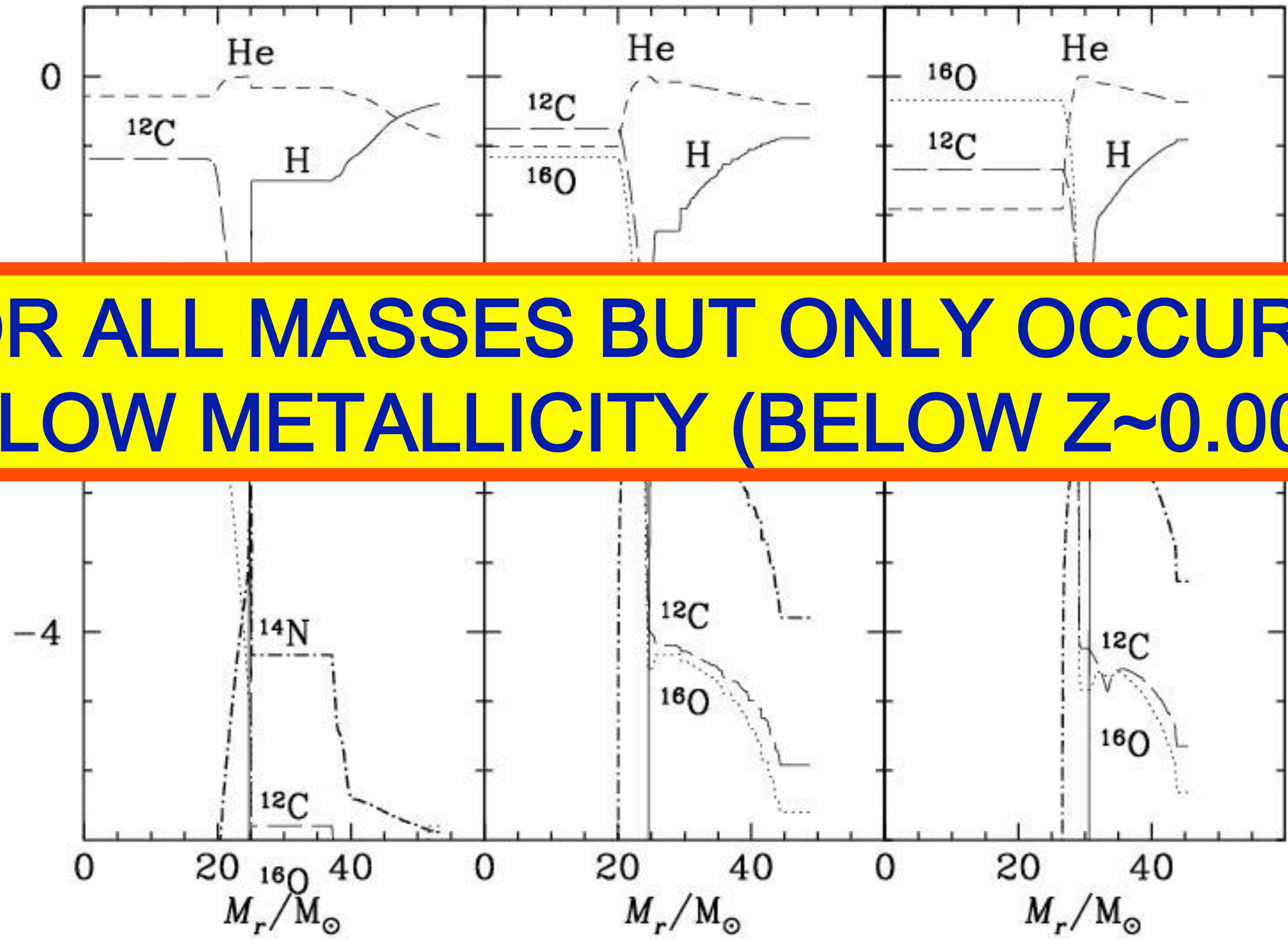
Maeder & Meynet 2007

High N/O in very metal
poor halo stars requires
rapid rotators

Chiappini et al. 2005, 2006ab

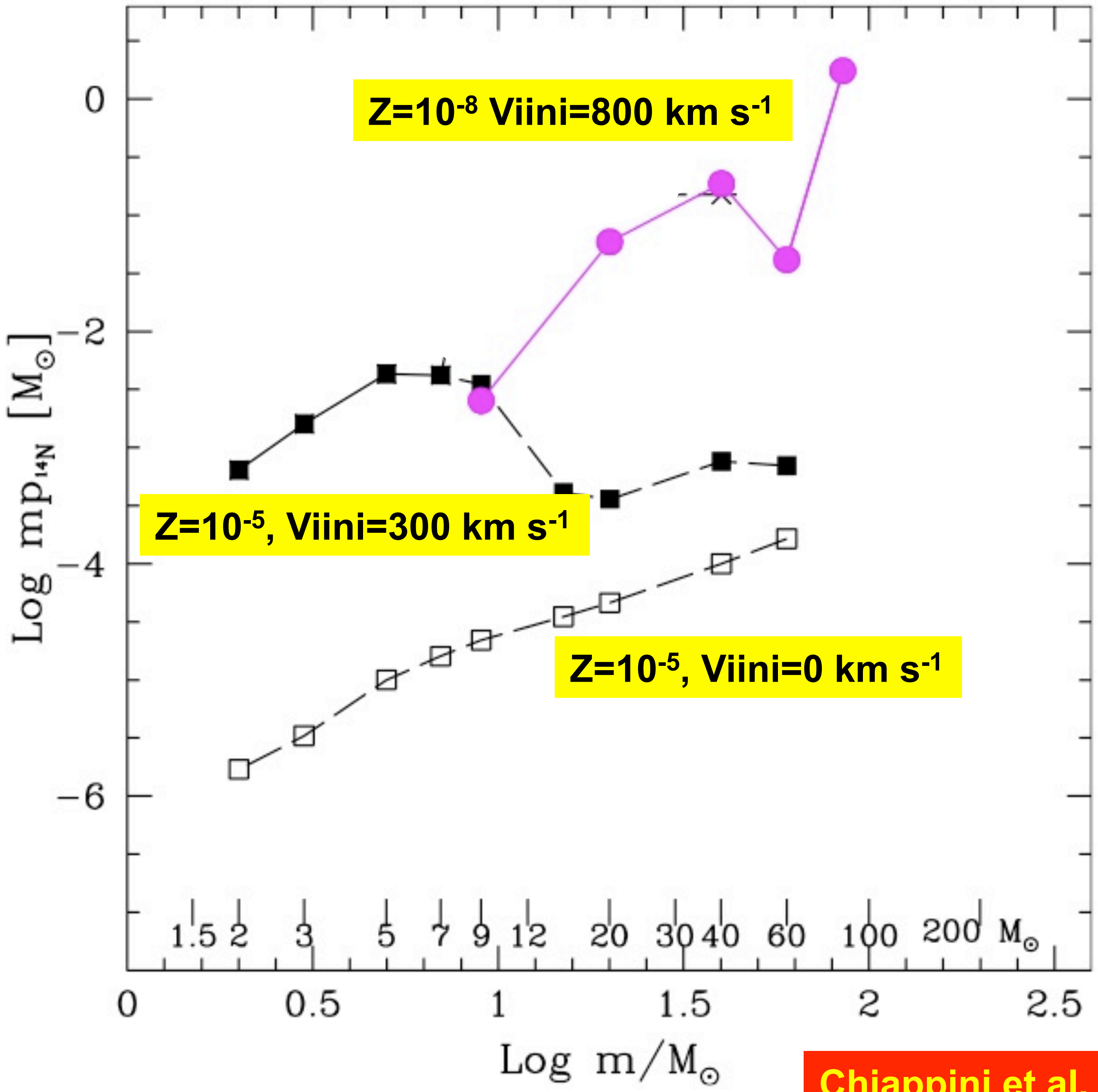
C-rich ultra-metal poor stars
might be explained if formed
from envelope of rapid
rotating stars

Meynet et al. 2006;Hirschi 2006

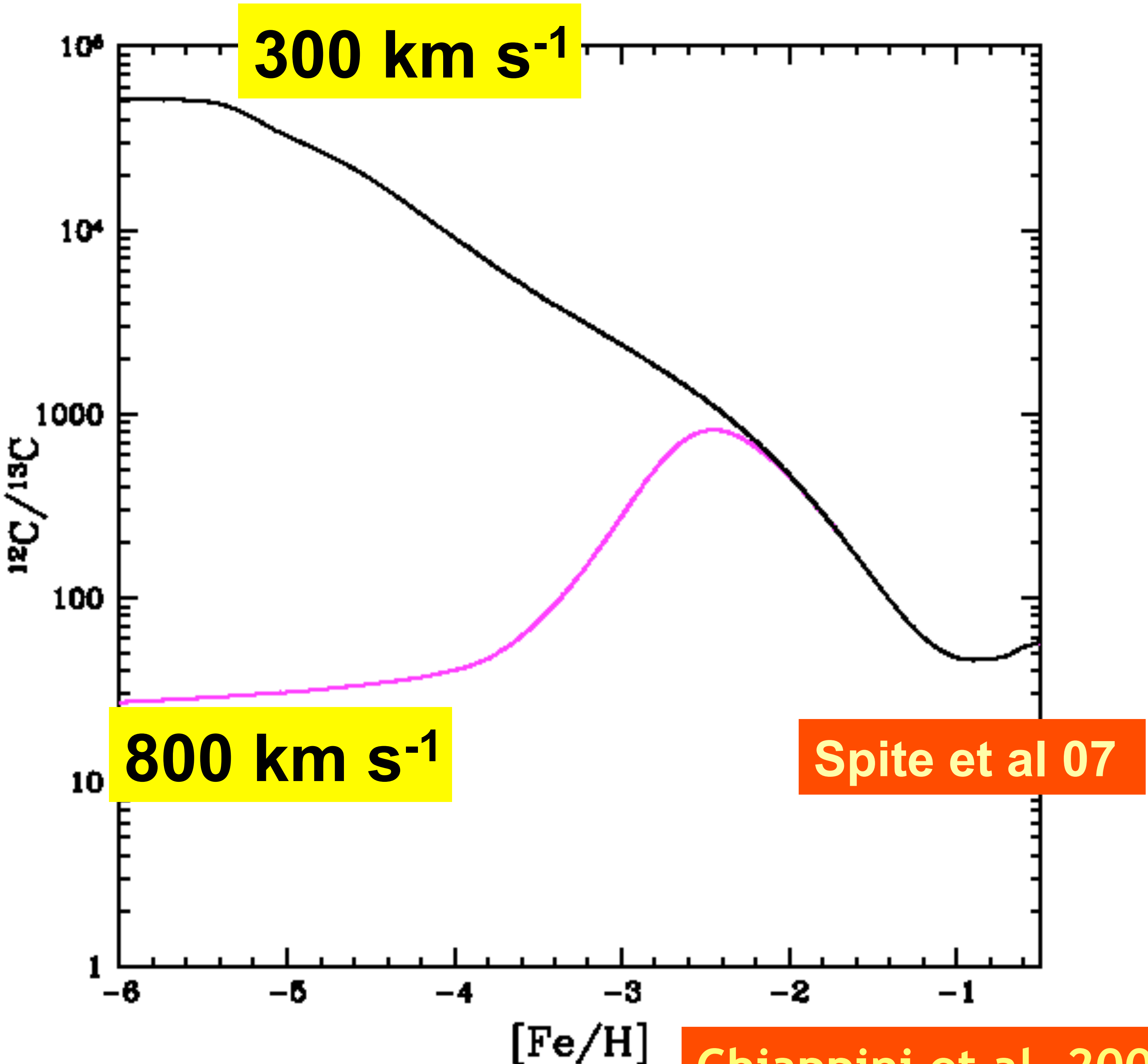


FOR ALL MASSES BUT ONLY OCCURS AT LOW METALLICITY (BELOW Z~0.001)

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

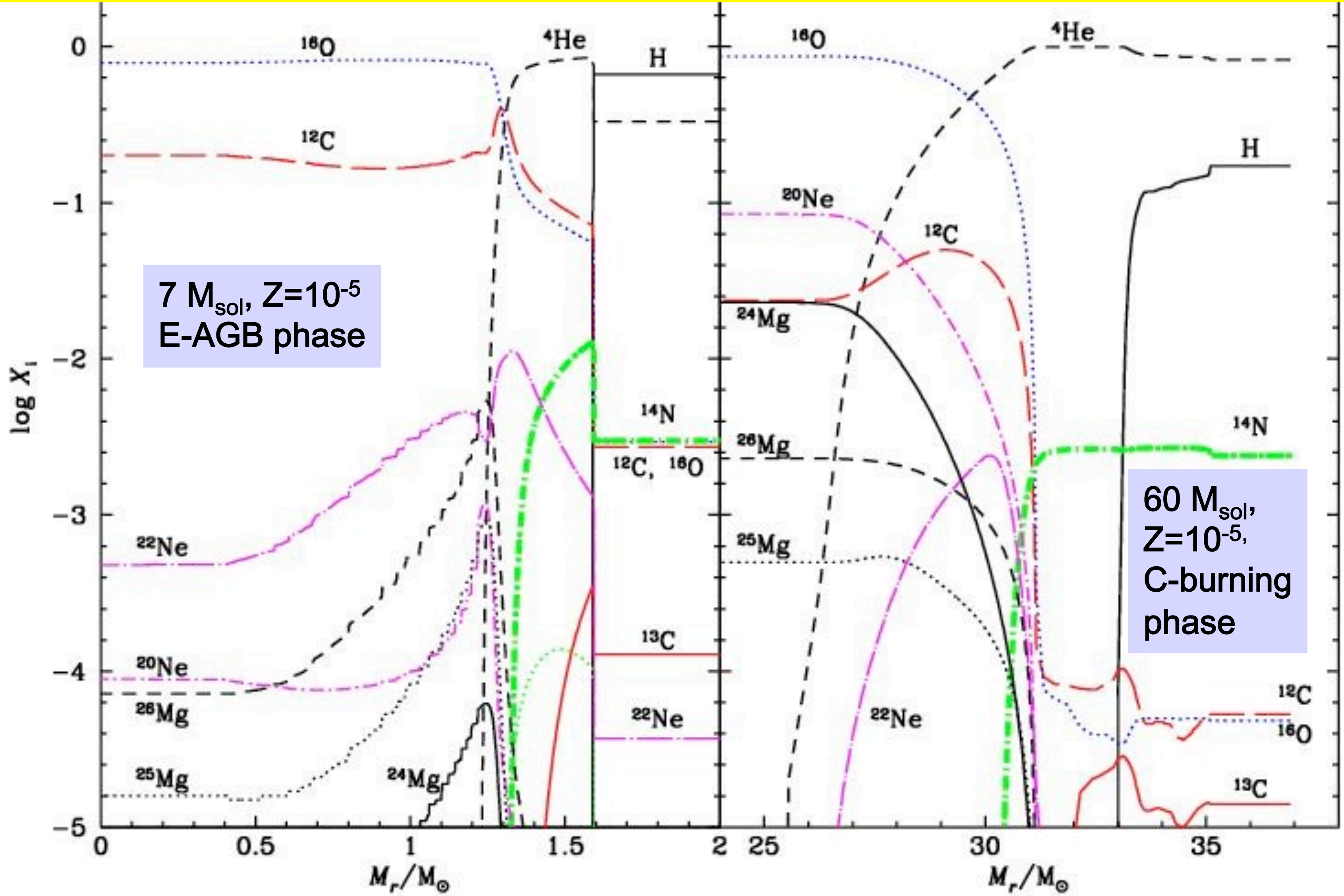


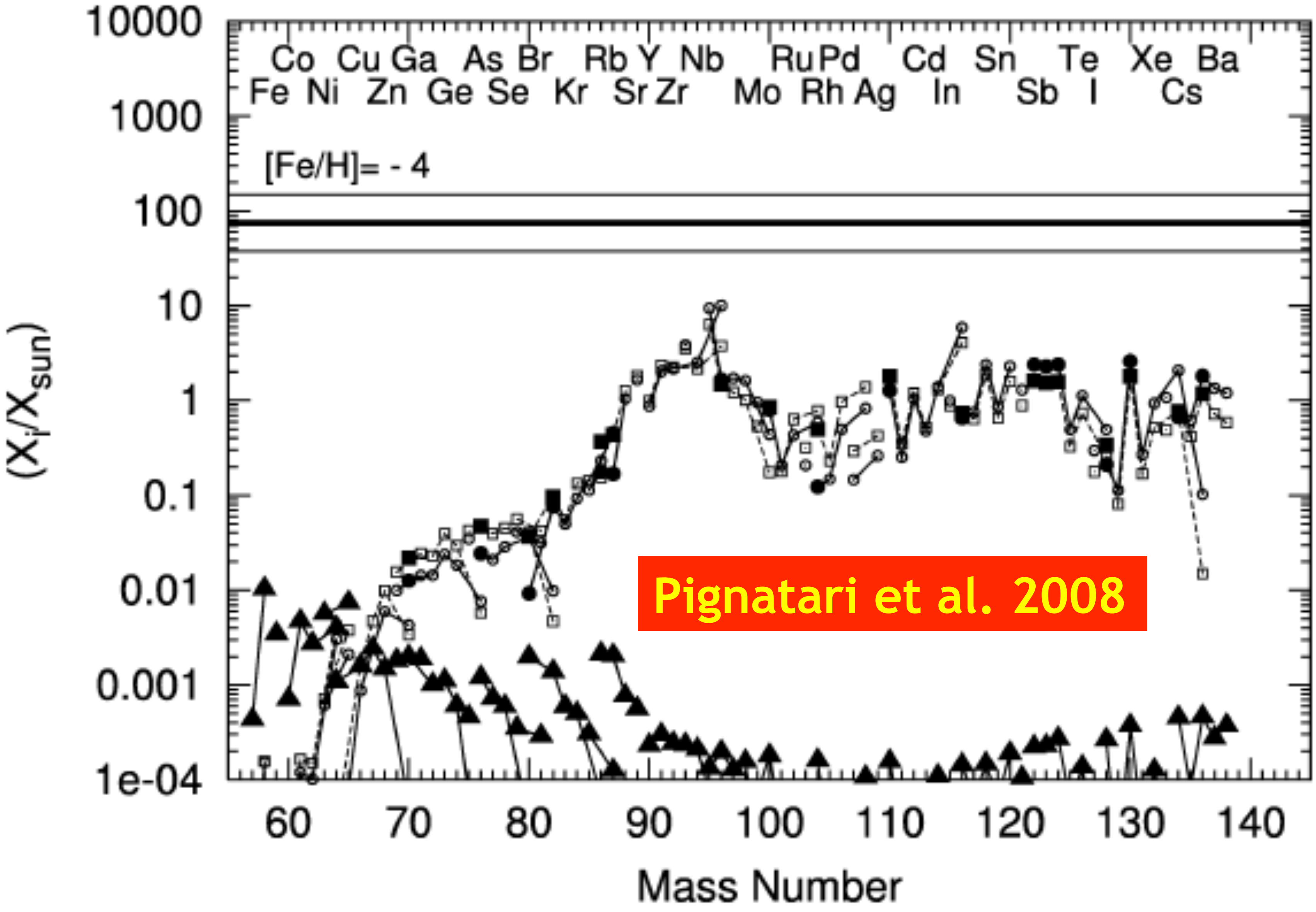
Chiappini et al. 2006



Chiappini et al. 2008

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



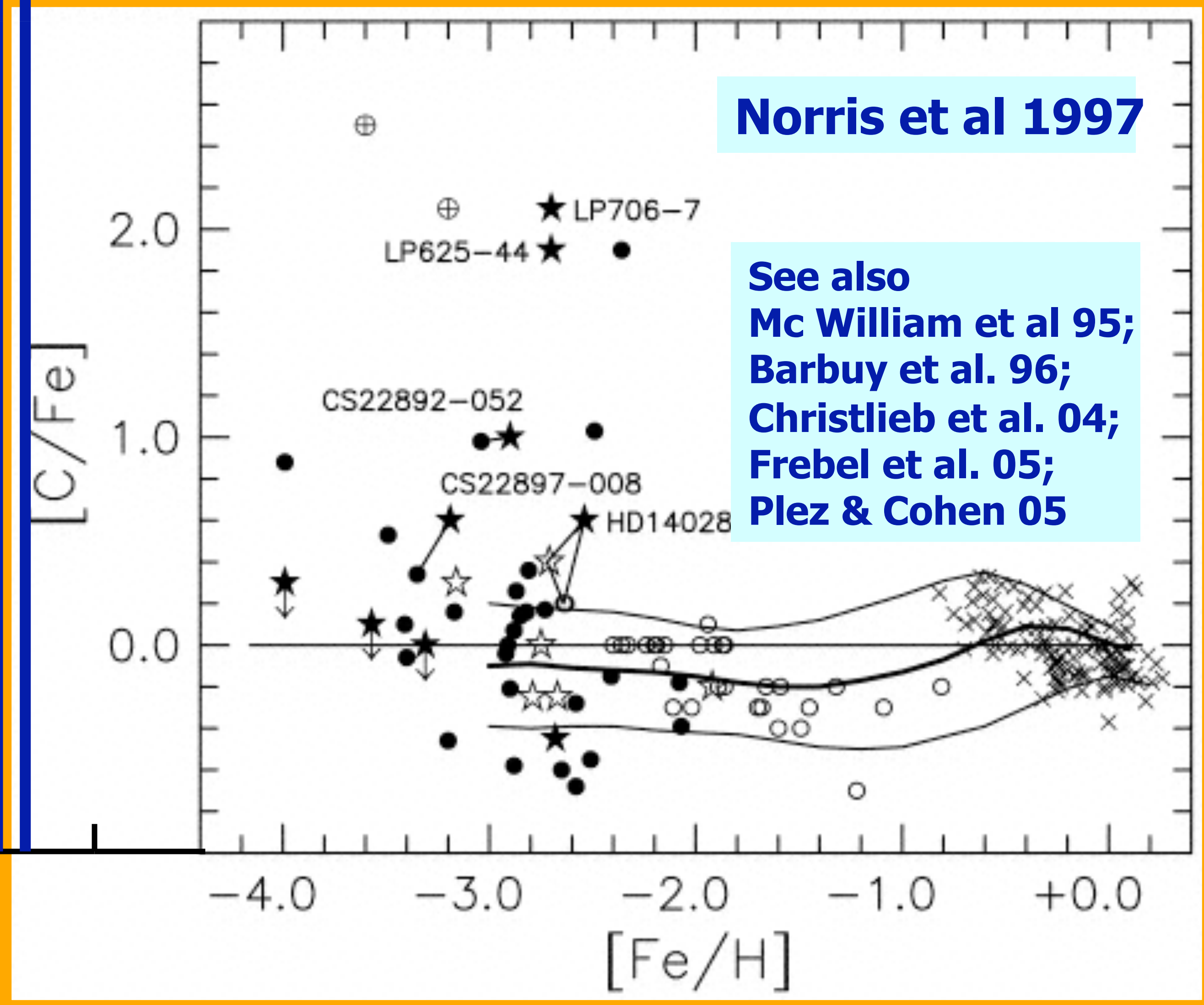

Co Cu Ga As Br Rb Y Nb Ru Pd Cd Sn Te Xe Ba
Fe Ni Zn Ge Se Kr Sr Zr Mo Rh Ag In Sb I Cs
[Fe/H]= - 4
Pignatari et al. 2008
10000
1000
100
10
1
0.1
0.01
0.001
1e-04
60
70
80
90
100
110
120
130
140
Mass Number
(X_i/X_{sun})

Carbon Rich Ultra Metal Poor Stars (CRUMPS)

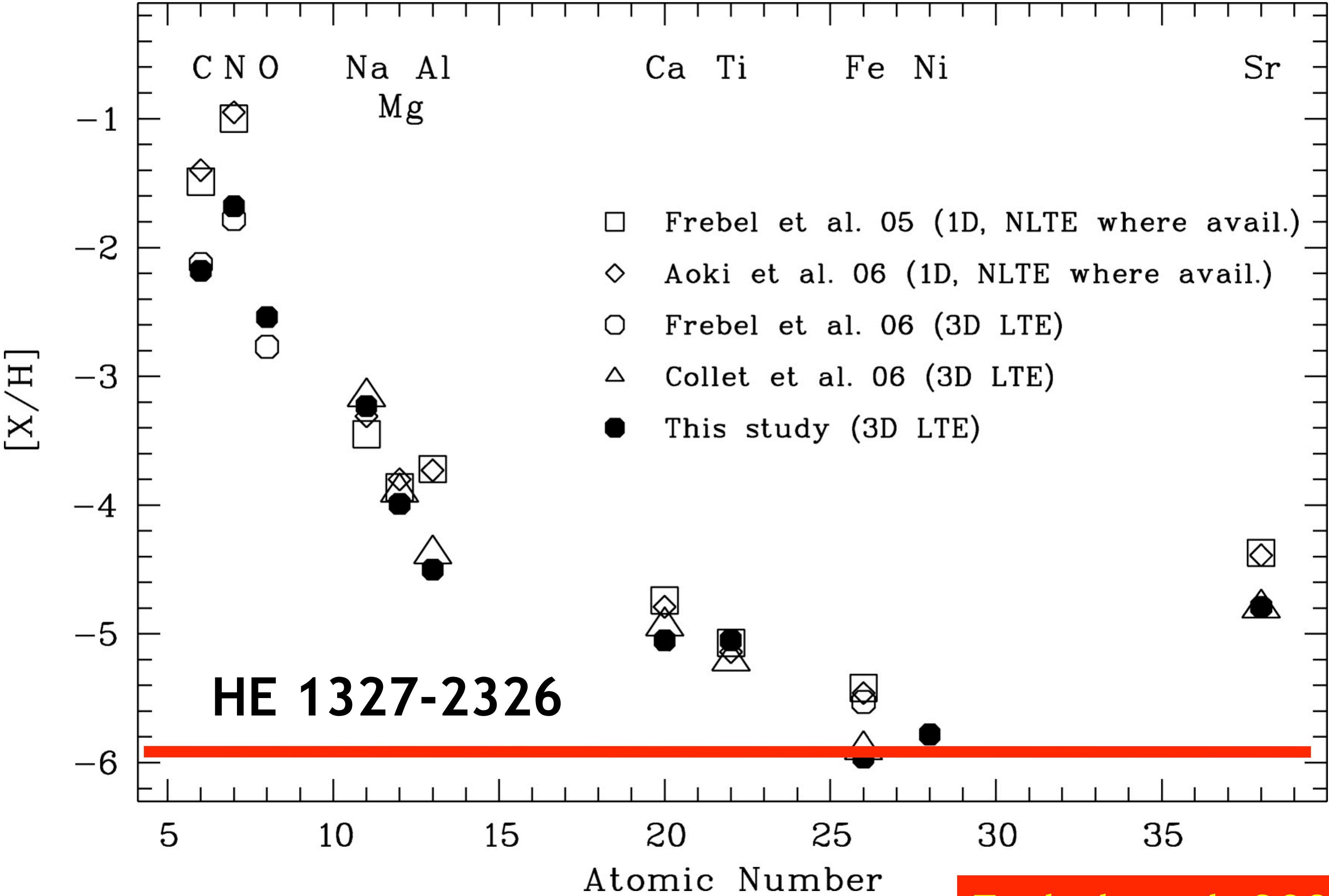
Most metal poor stars

Christlieb et al. 2002

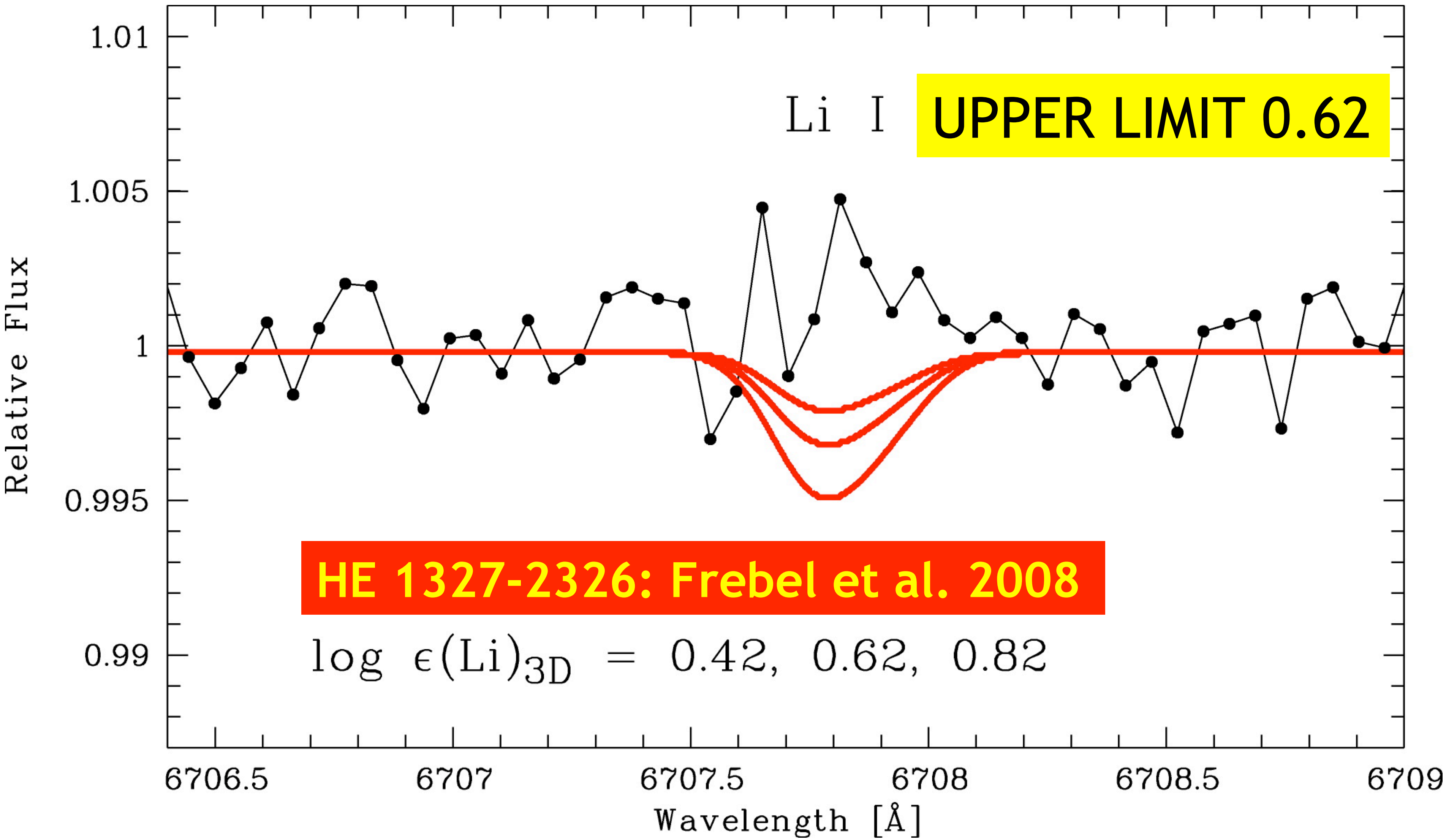
Frebel et al. 2005



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



Frebel et al. 2008

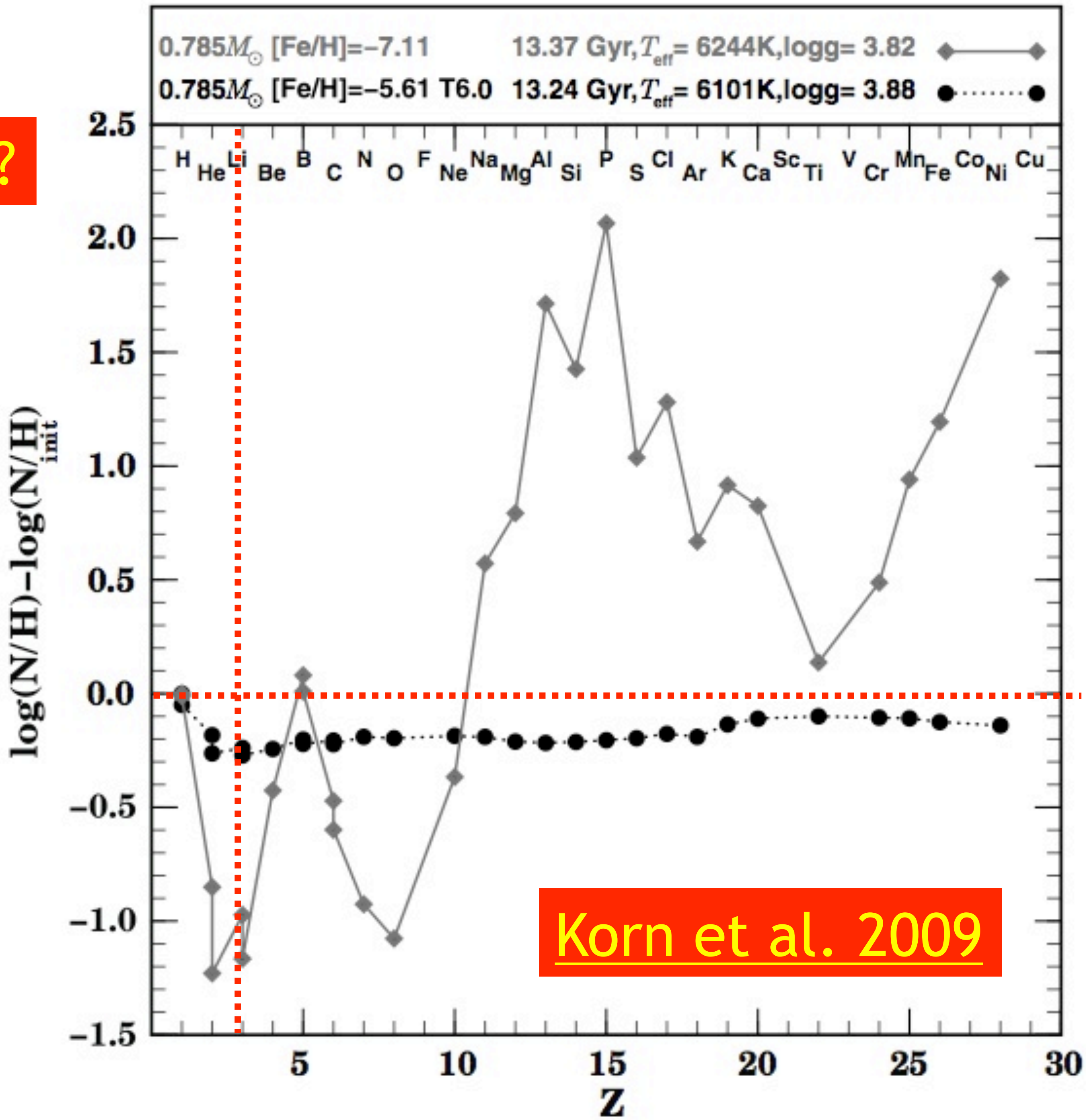


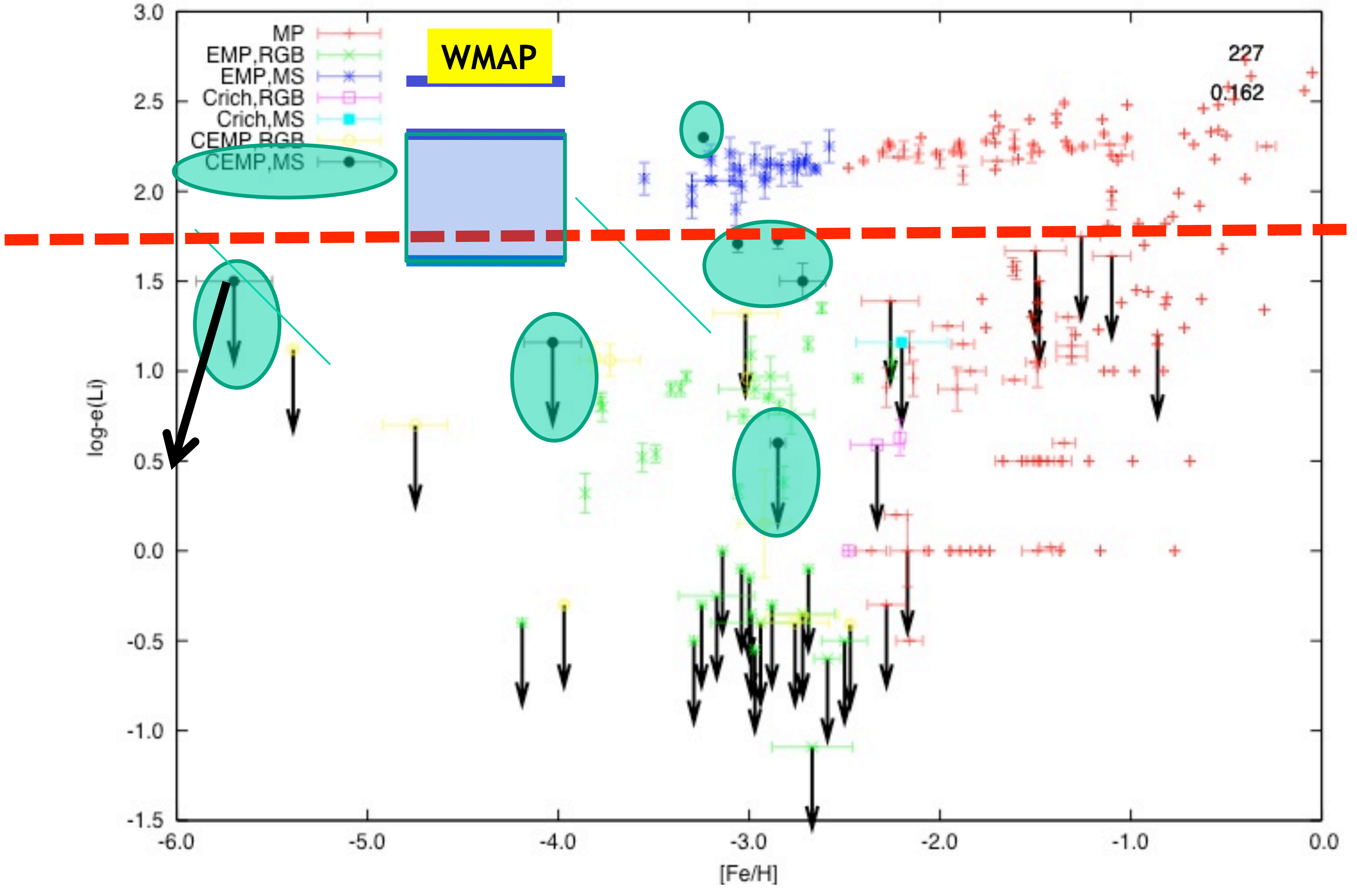
WMAP 2.6

Spite PLATEAU 2.3

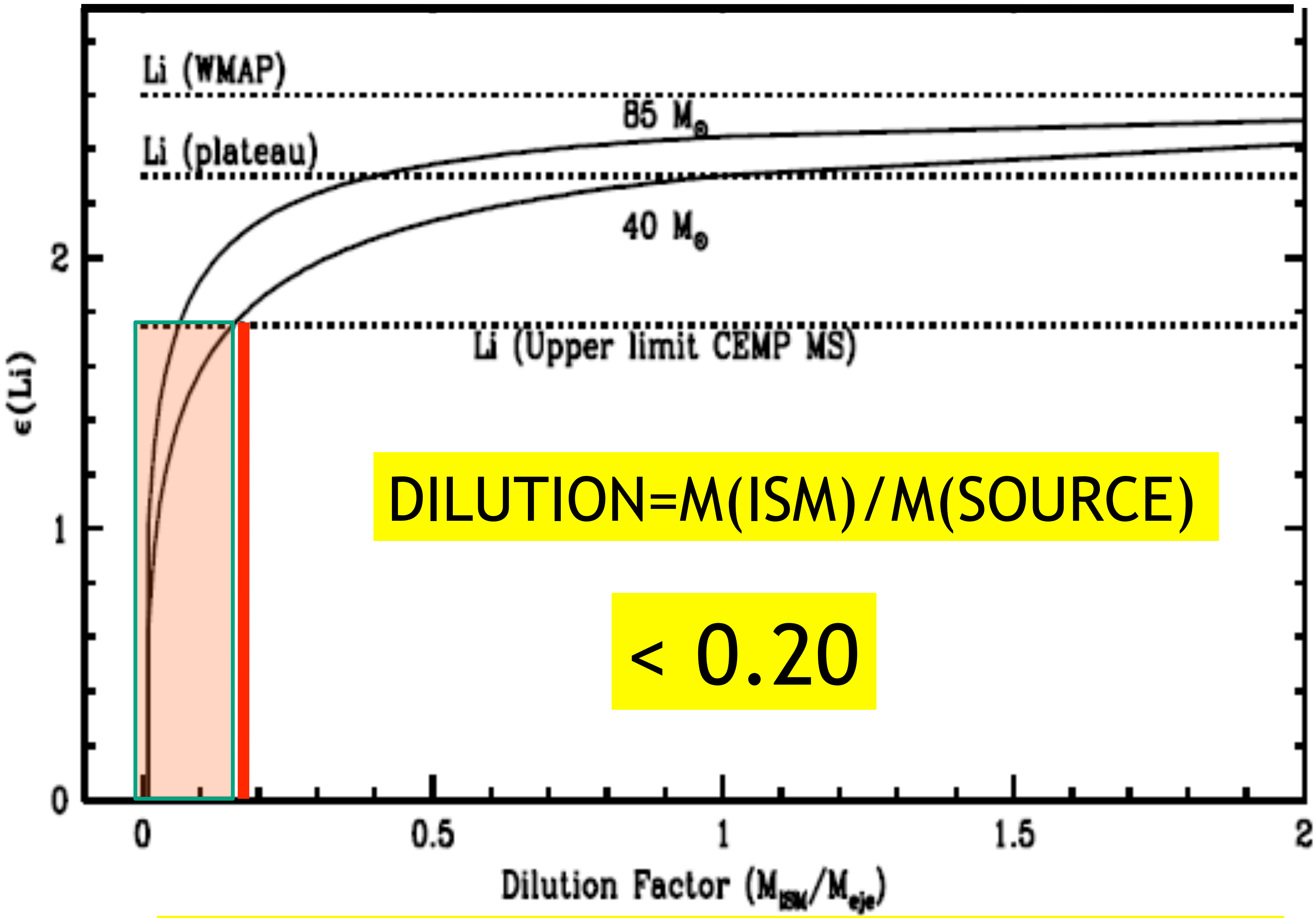
Atomic diffusion?

-0.2 dex
- 1 dex





SAGA DATABASE Suda et al. 2008



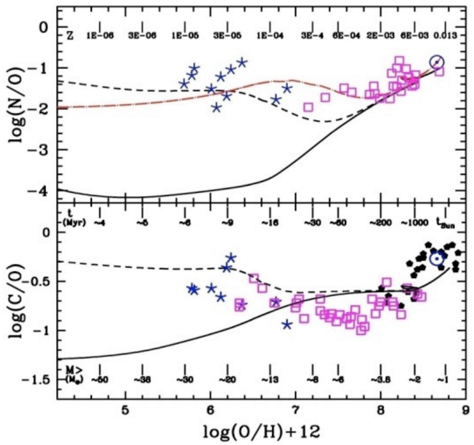
Same argument for $^{12}C/^{13}C$ if very low

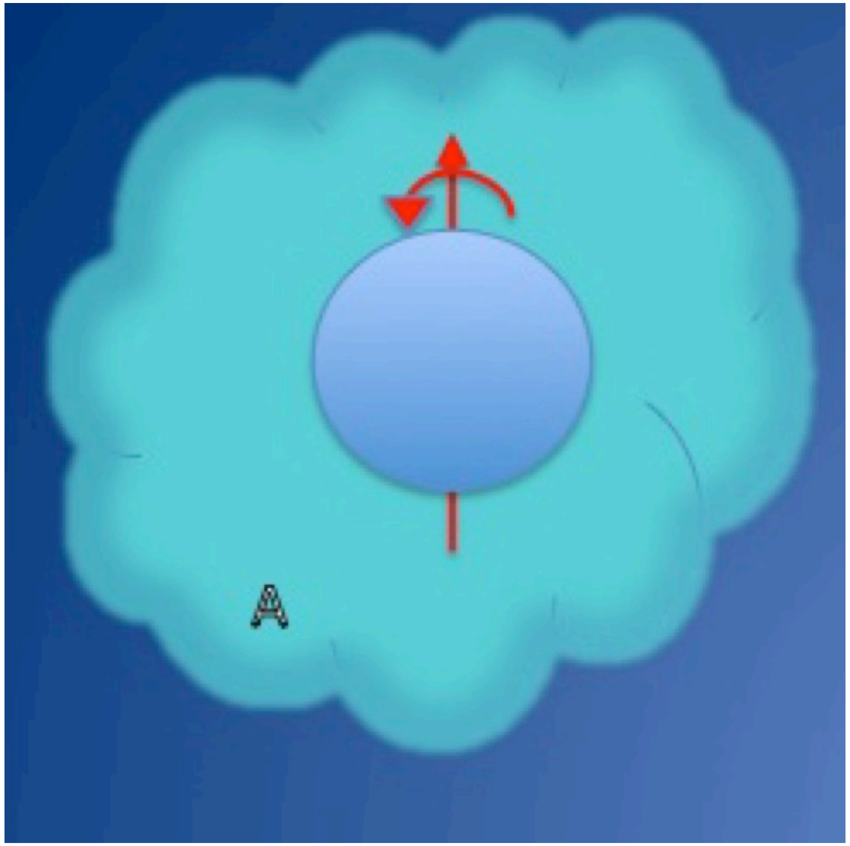
THE ``SPINSTAR'' MODEL

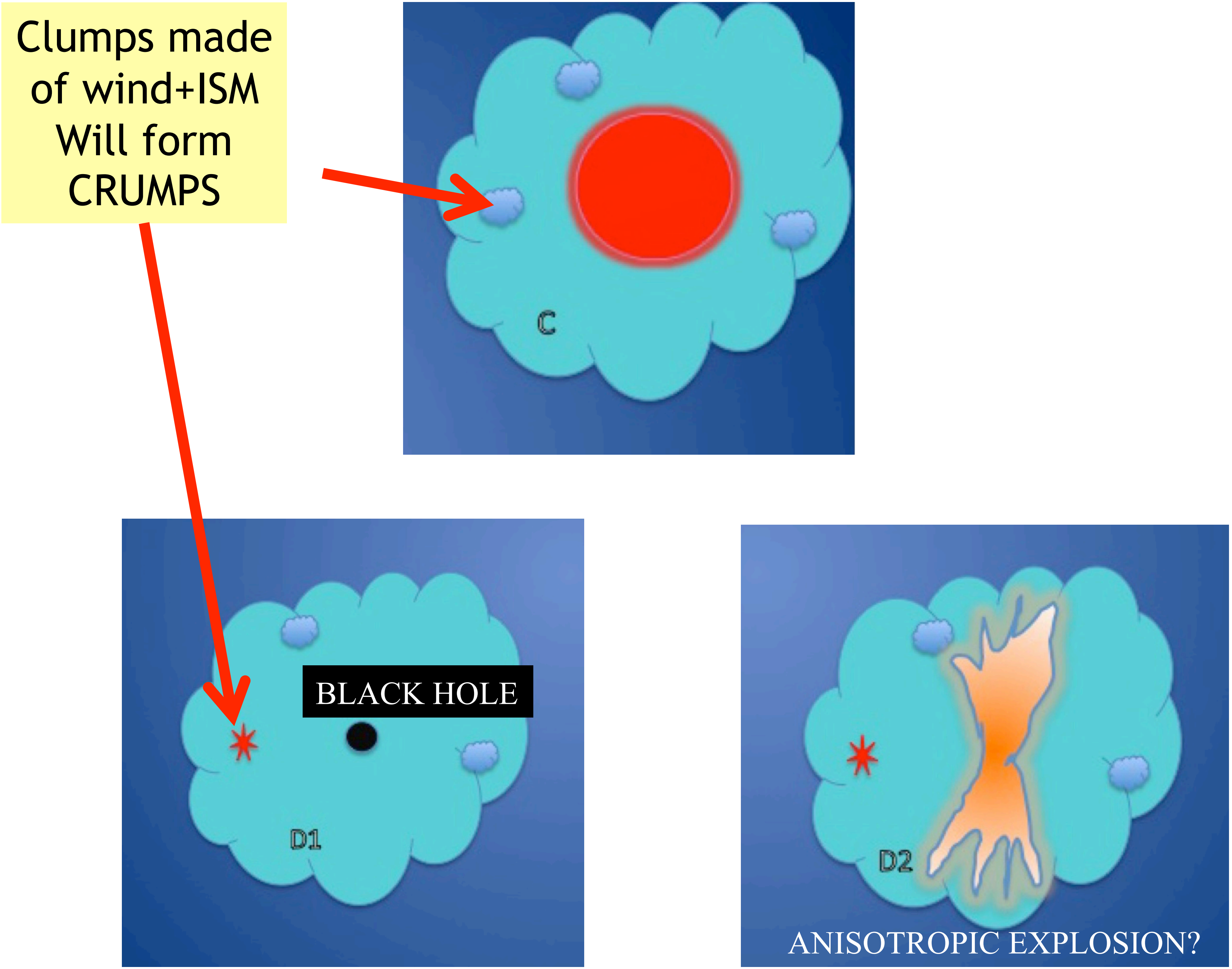
AT THE BEGINNING A MASSIVE ROTATING STAR AT VERY LOW METALLICITY

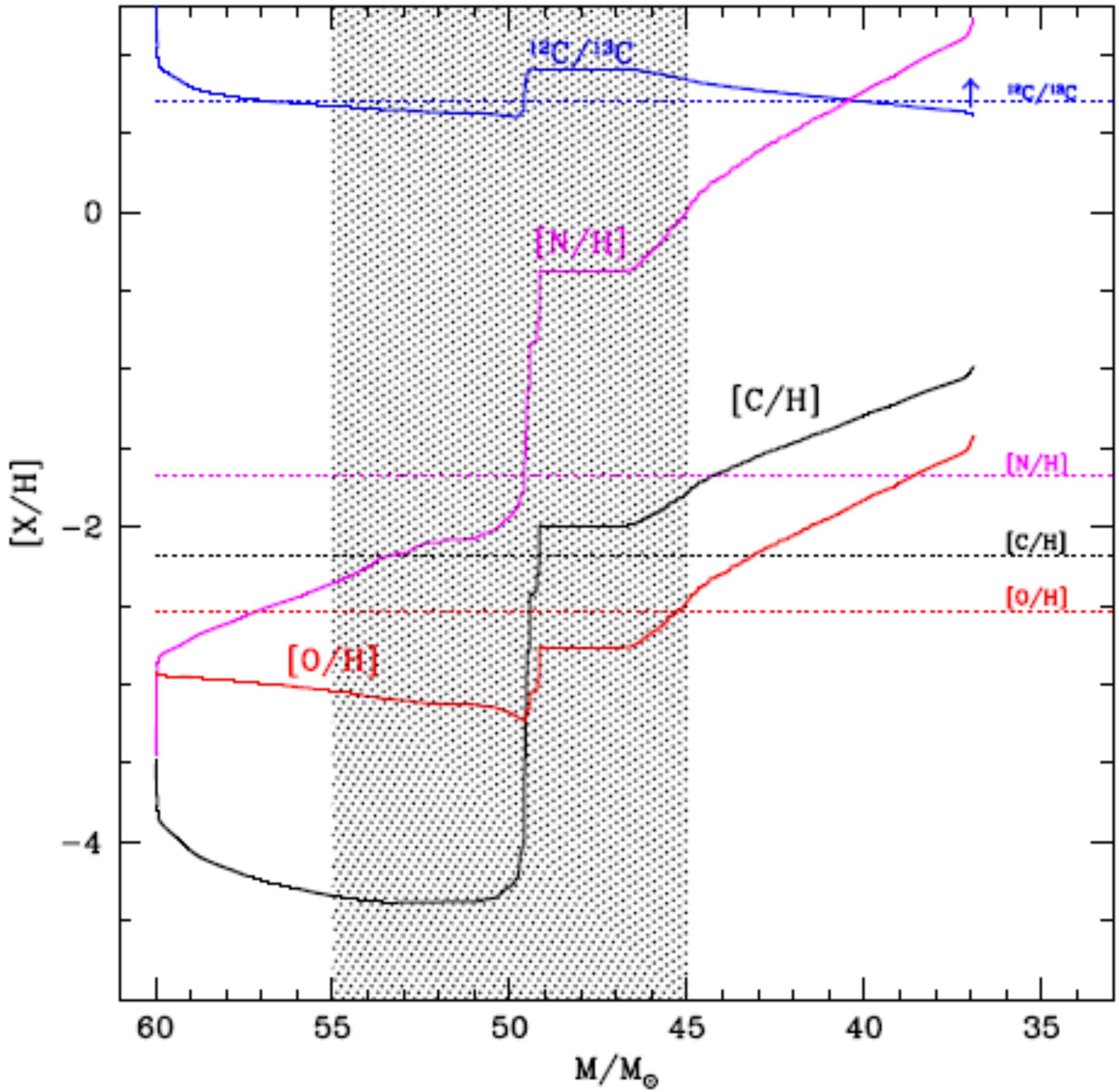
About 1.4 X Angular momentum
Content of a normal star
at solar metallicity.
Z < 0.0001

Same characteristics as for N/O

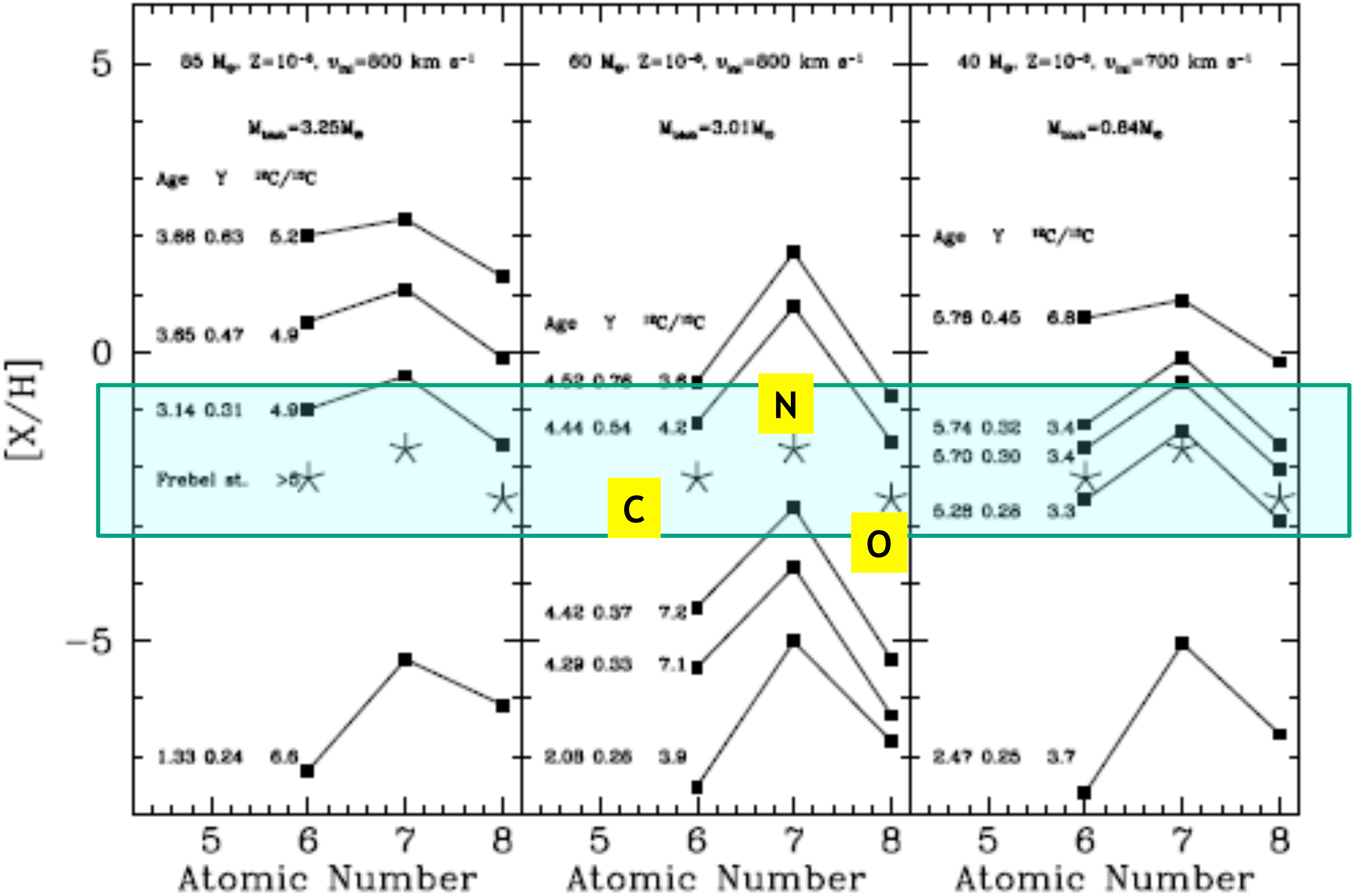





Clumps made of wind+ISM Will form CRUMPS
C
BLACK HOLE
D1
D2
ANISOTROPIC EXPLOSION?



$^{12}C/^{13}C$
$^{12}C/^{13}C$
[N/H]
[C/H]
[N/H]
[C/H]
[O/H]
[O/H]
0
−2
−4
[X/H]
60
55
50
45
40
35
$M/M_\odot$



CONSEQUENCE→ CRUMPS WOULD He-RICH

``Spinstars” at low metallicities?

BELOW Z 0.0001, ROTATION → PRIMARY ^{13}C, ^{14}N, ^{22}Ne,…
WIND MADE UP OF H- AND He-BURNING PRODUCTS

N/O, C/O in NORMAL
NON-C-RICH” HALO STARS
(well mixed reservoir)

TEST

^{12}C/^{13}C

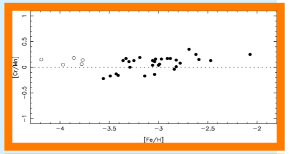
Li, ^{12}C/^{13}C, CNO
in CRUMPS

TEST

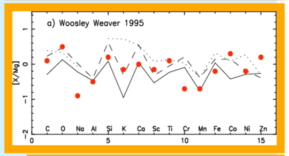
He-rich

STRIKING OBSERVATIONAL FACTS

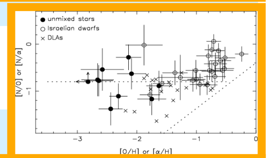
1) Very small scatter/big scatter depending on elements



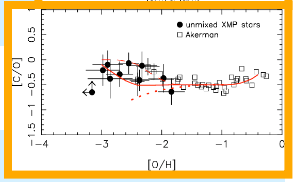
2) No sign of Pair Instability Supernovae



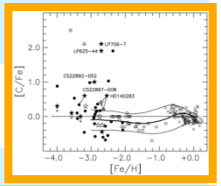
3) Important amount of primary nitrogen



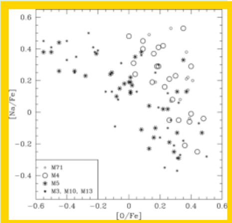
4) More carbon, less oxygen produced at low Z ?



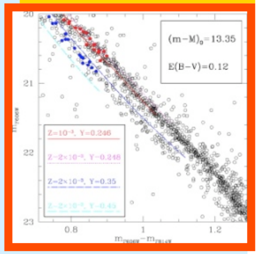
5) C-rich stars



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

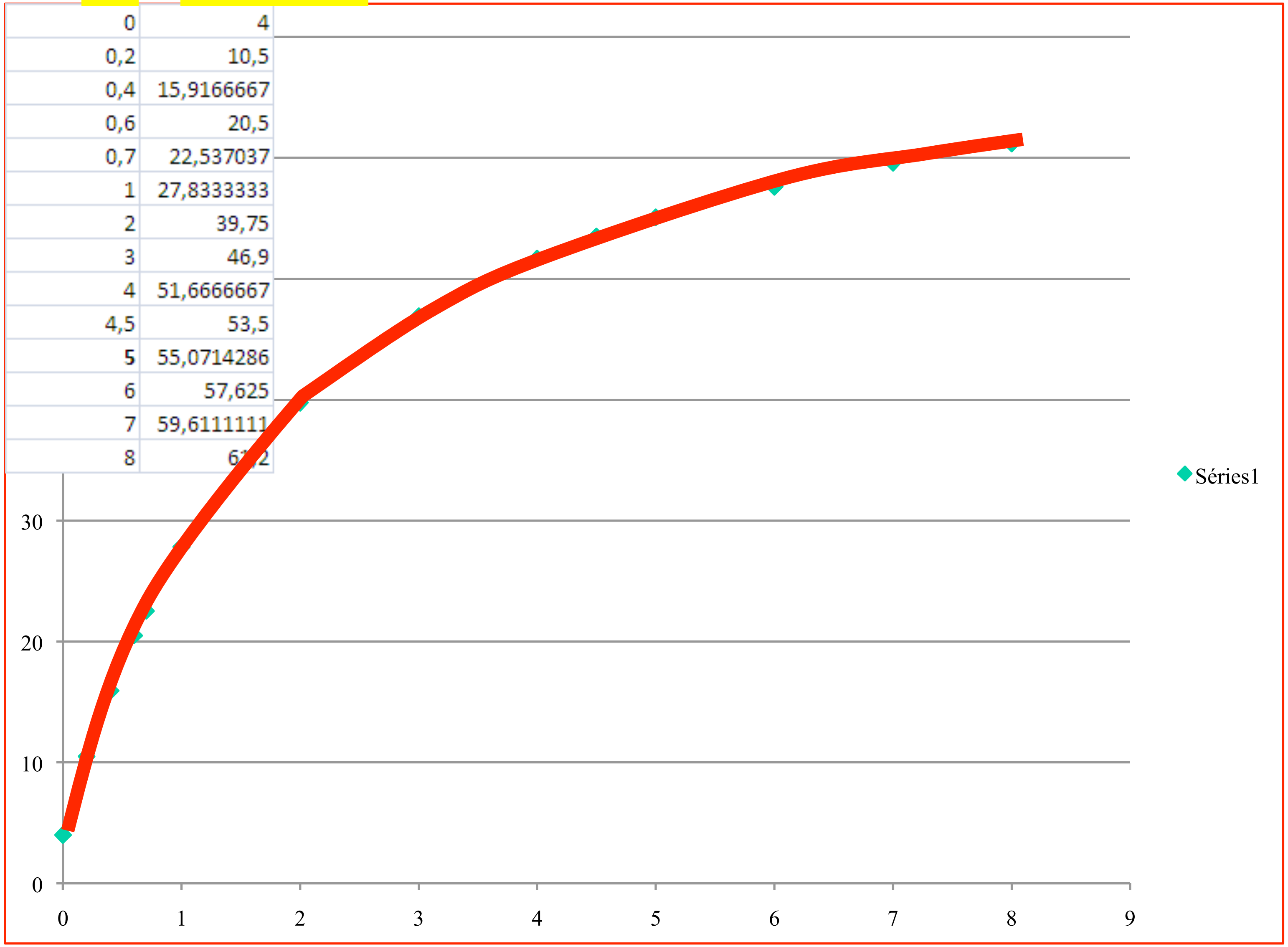


7) Very Helium-rich stars in ω Centuri ?



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

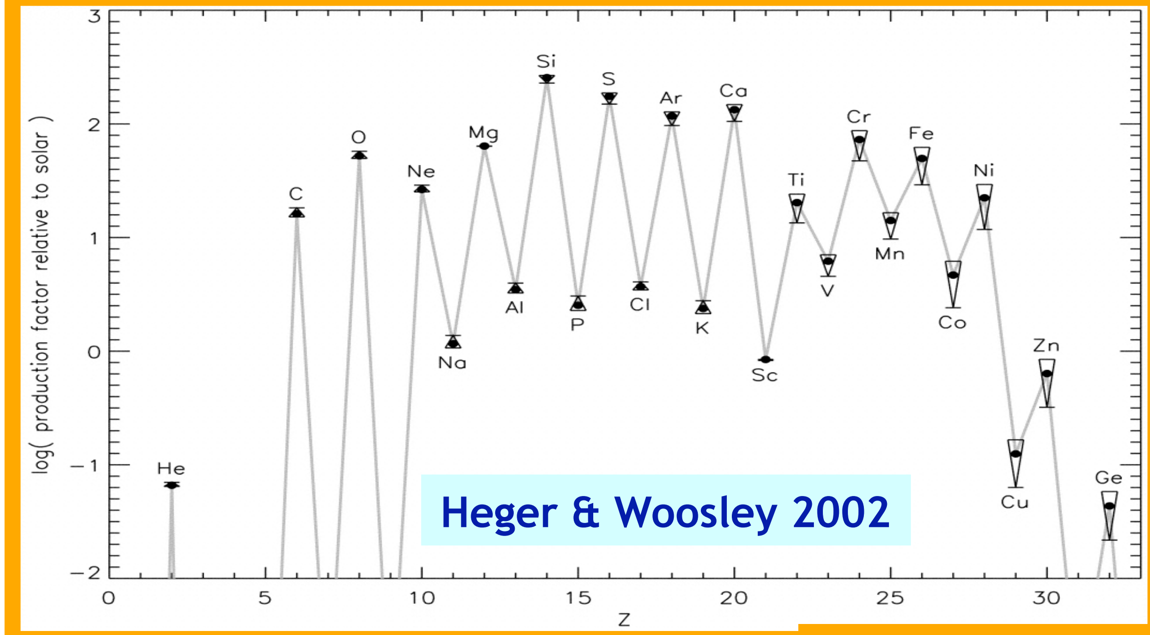
D	12C/13C
0	4
0,2	10,5
0,4	15,9166667
0,6	20,5
0,7	22,537037
1	27,8333333
2	39,75
3	46,9
4	51,6666667
4,5	53,5
5	55,0714286
6	57,625
7	59,6111111
8	61,2

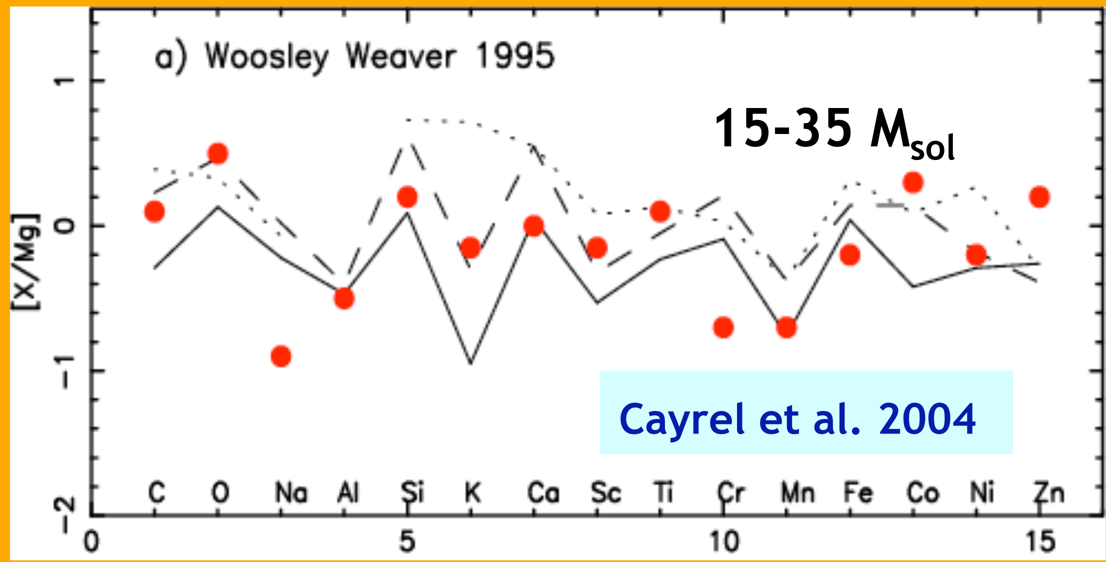


D=DILUTION FACTOR (M(ISM)/M(SOURCE)

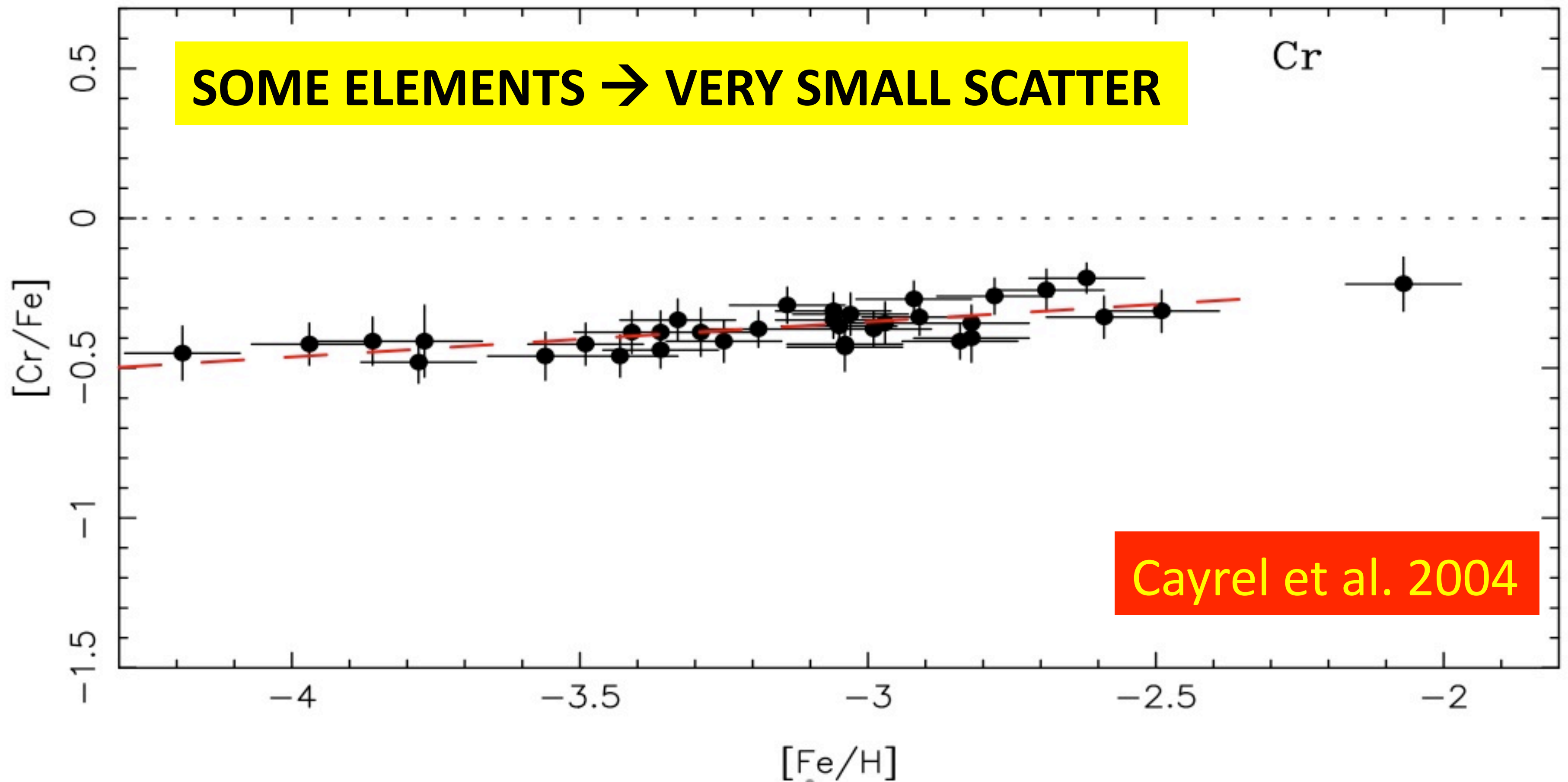
STRIKING OBSERVATIONAL FACTS

No sign of Pair Instability Supernovae

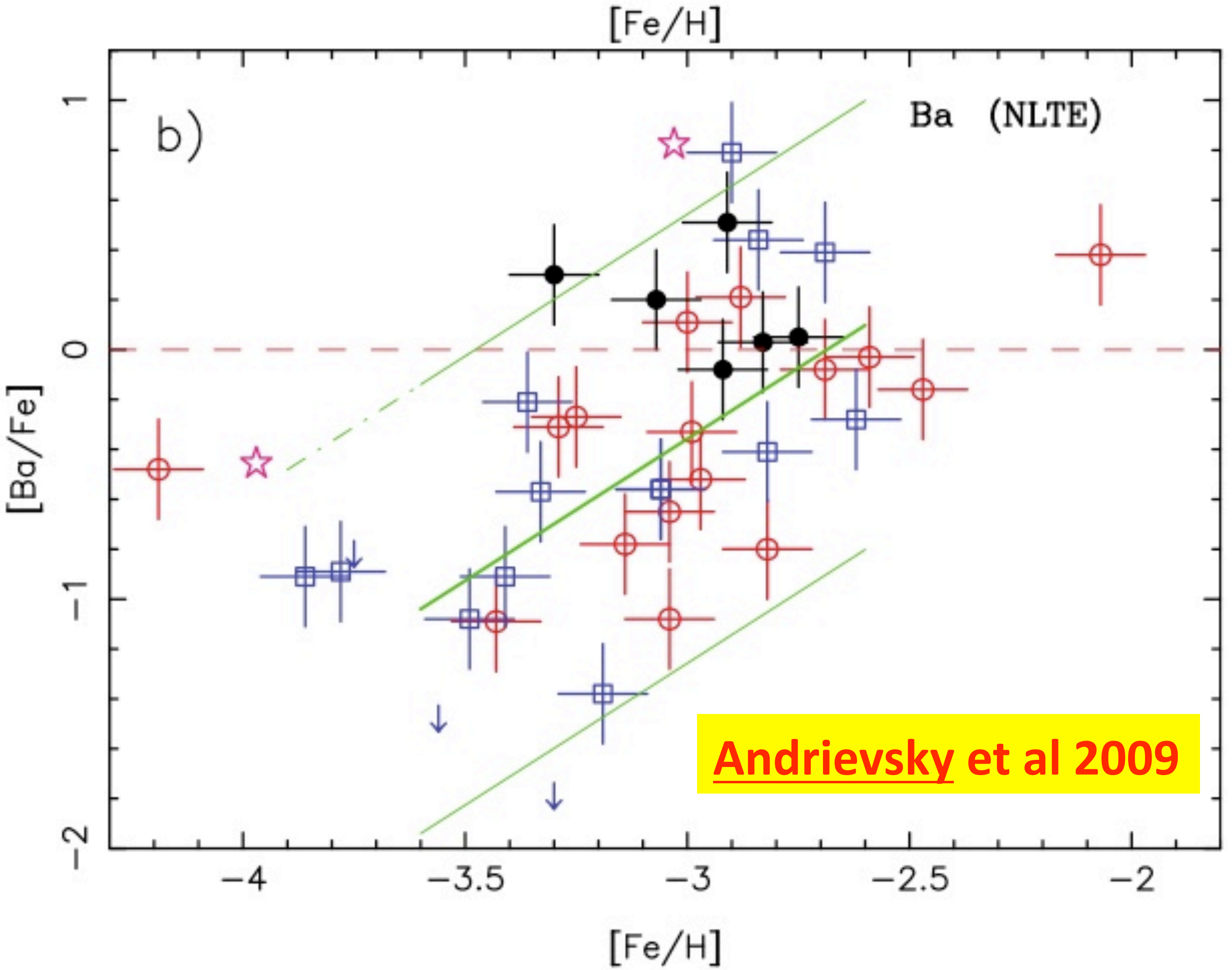




A FEW STRIKING OBSERVATIONAL FACTS

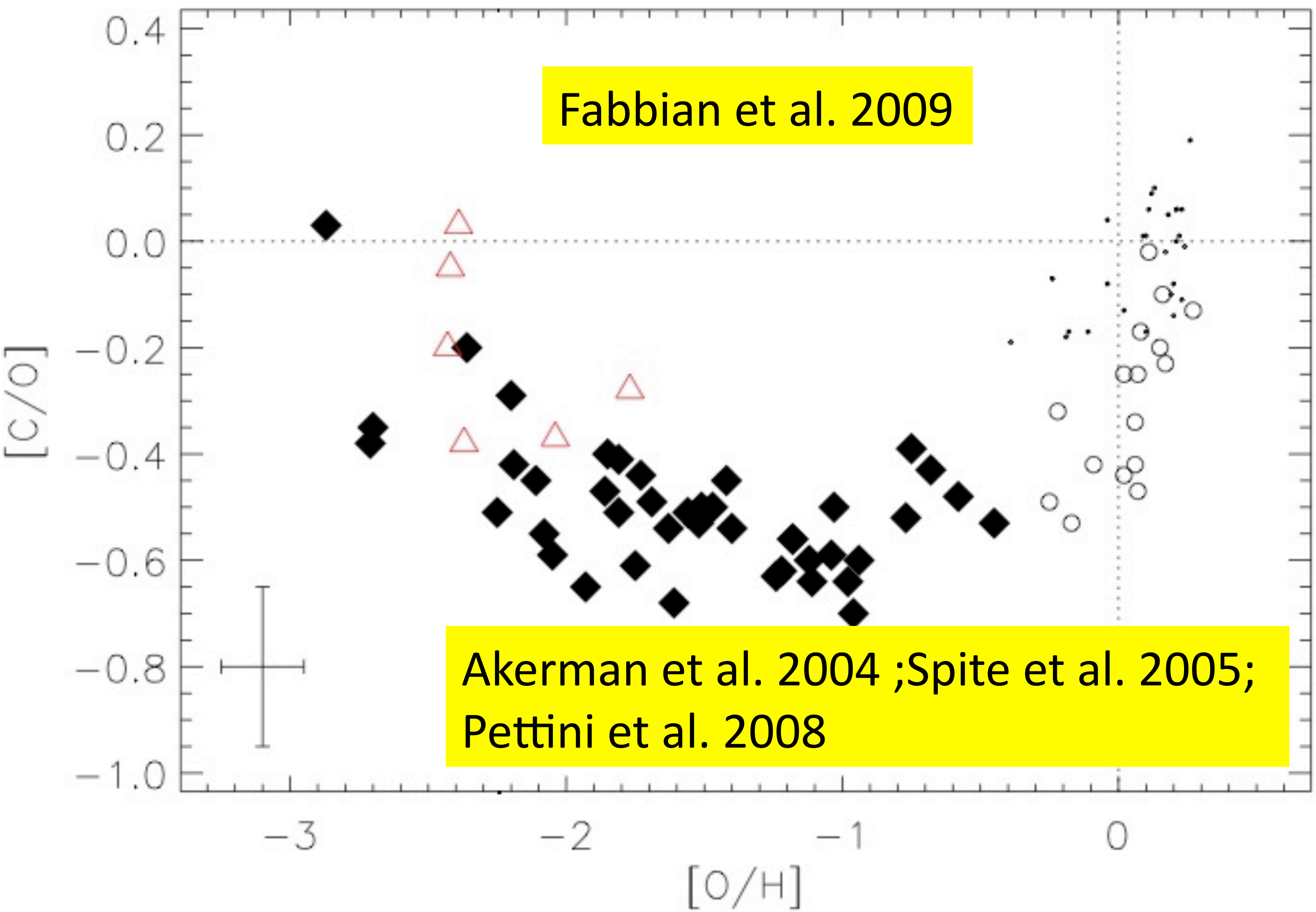


SOME ELEMENTS → IMPORTANT SCATTER



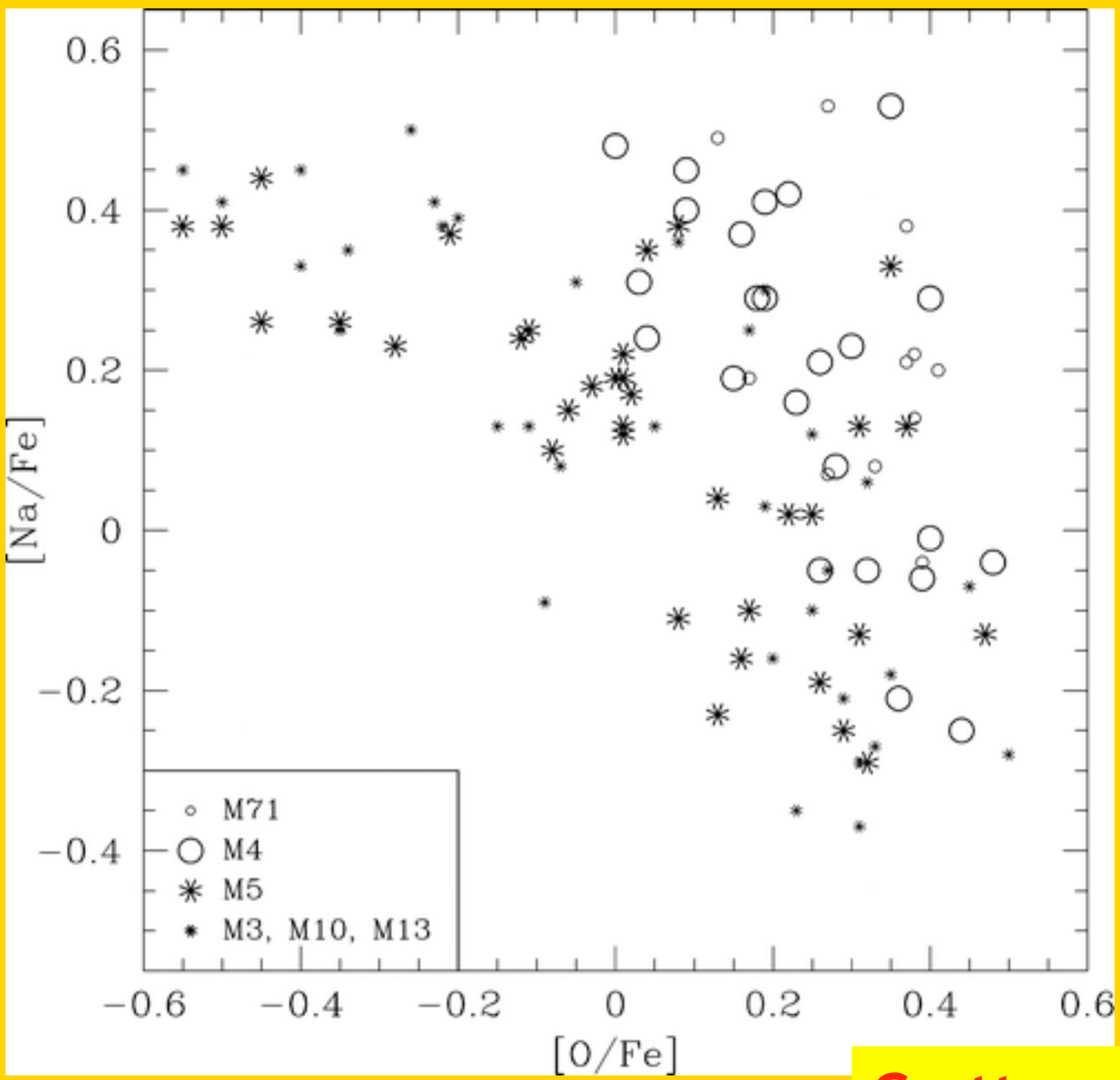
Andrievsky et al 2009

THE C/O UPTURN BELOW [O/H] = -2



STRIKING OBSERVATIONAL FACTS

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



Gratton et al 2004

ROTATION AND MASS LOSS

Radiatively driven stellar winds

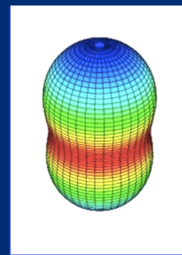
Increase of mass loss

Maeder & Meynet 2000

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

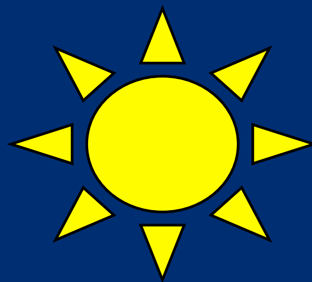
Anisotropies (fast rotation)

Owocki, 1996; Maeder, 1999



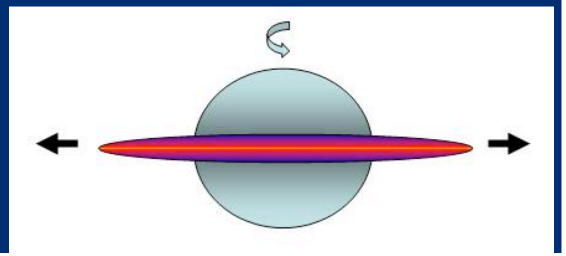
Surface enrichments

Meynet et al. 2006
Hirschi 2007

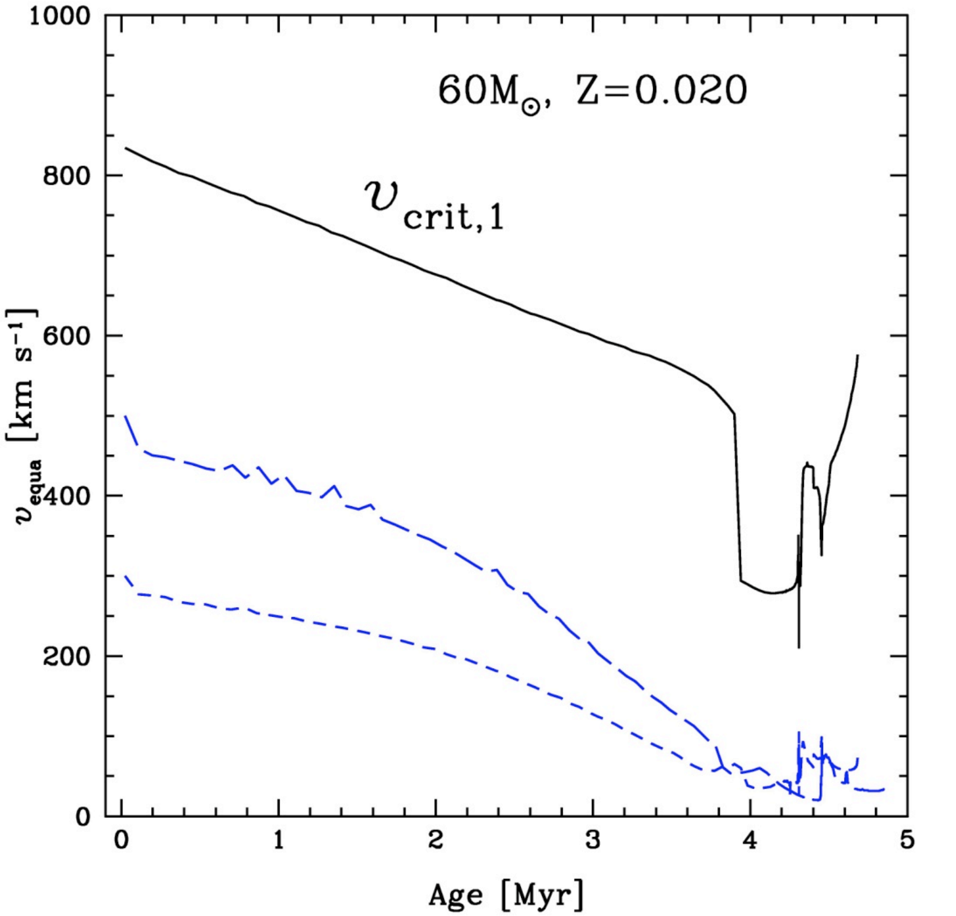


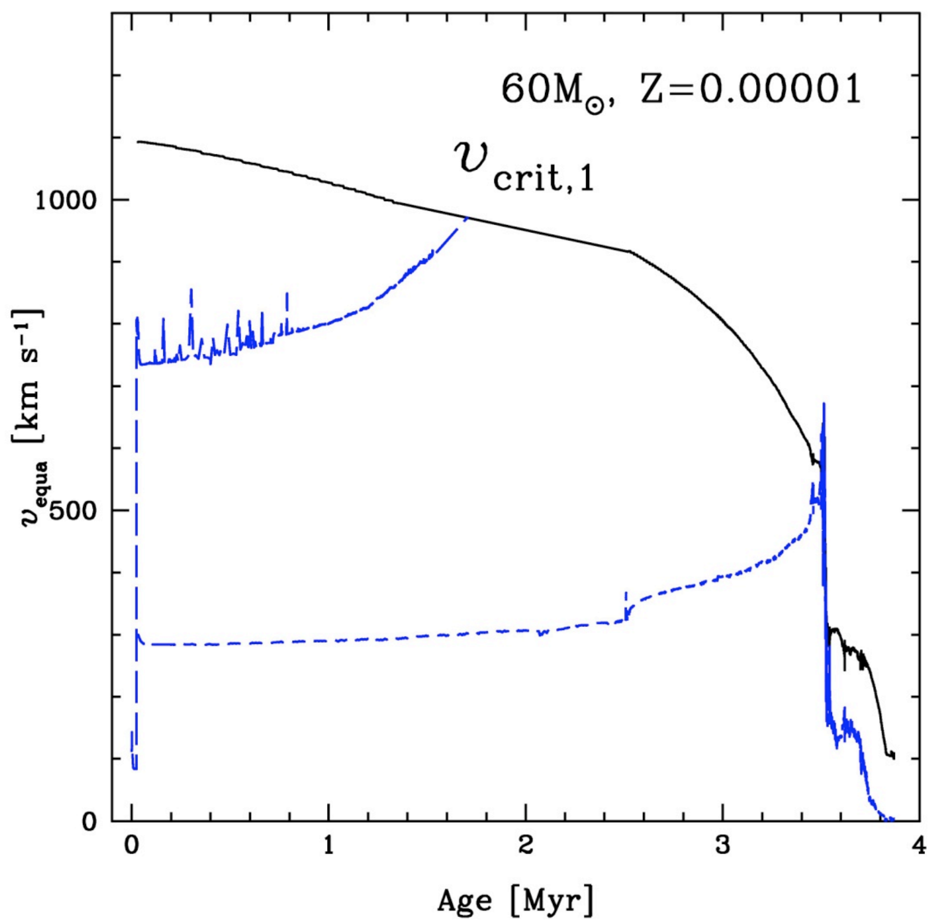
``Mechanical mass loss”

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

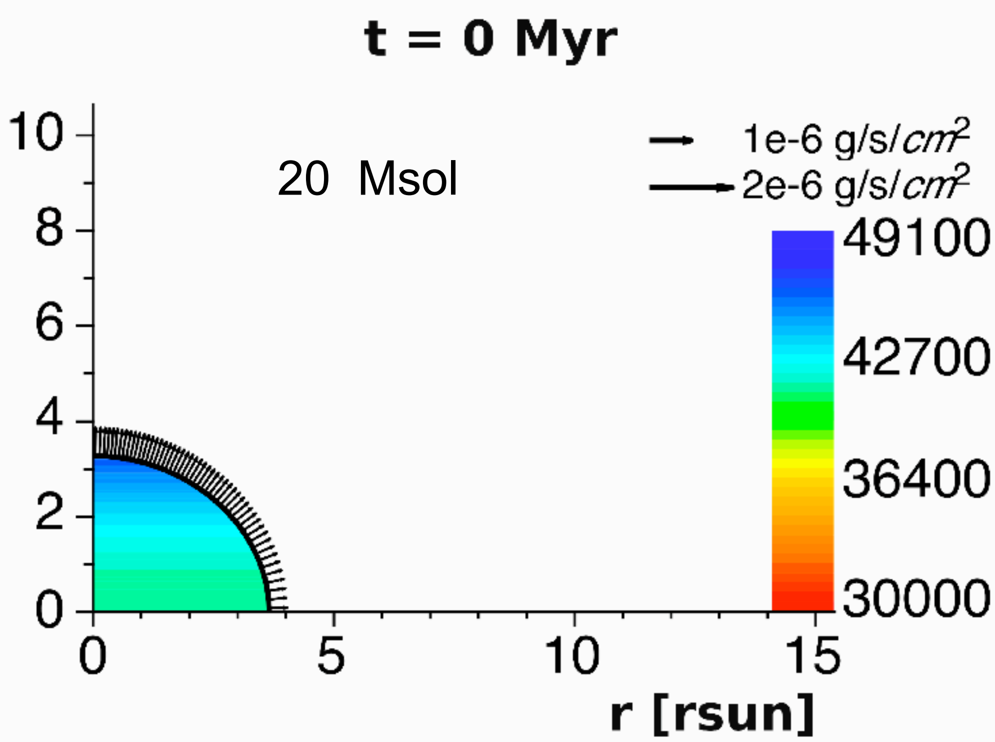


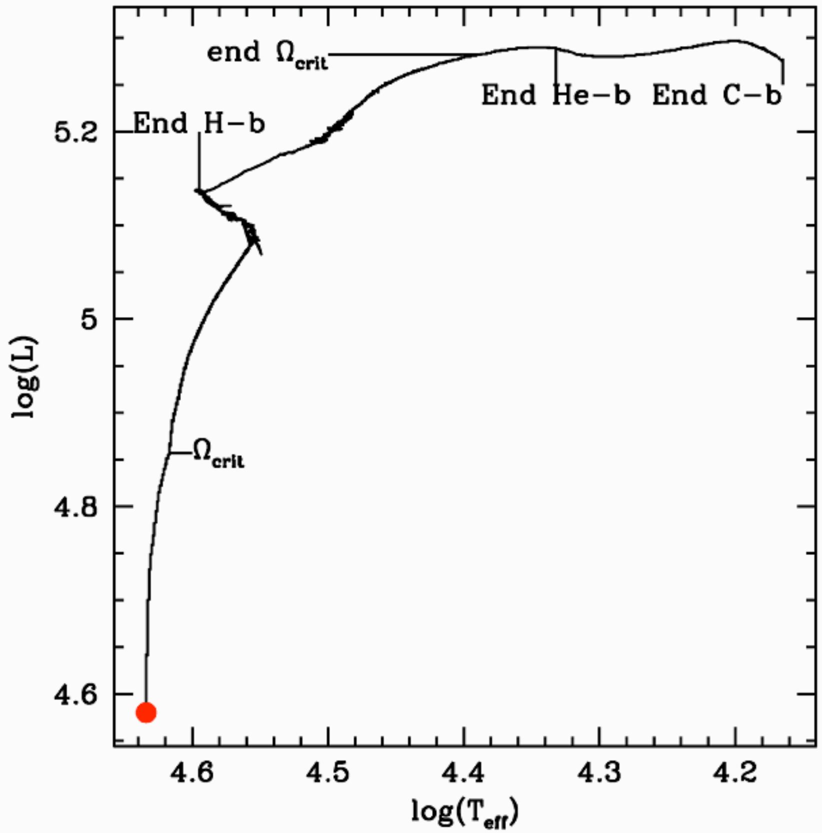
AT LOW Z: EASIER TO REACH THE CRITICAL VELOCITY



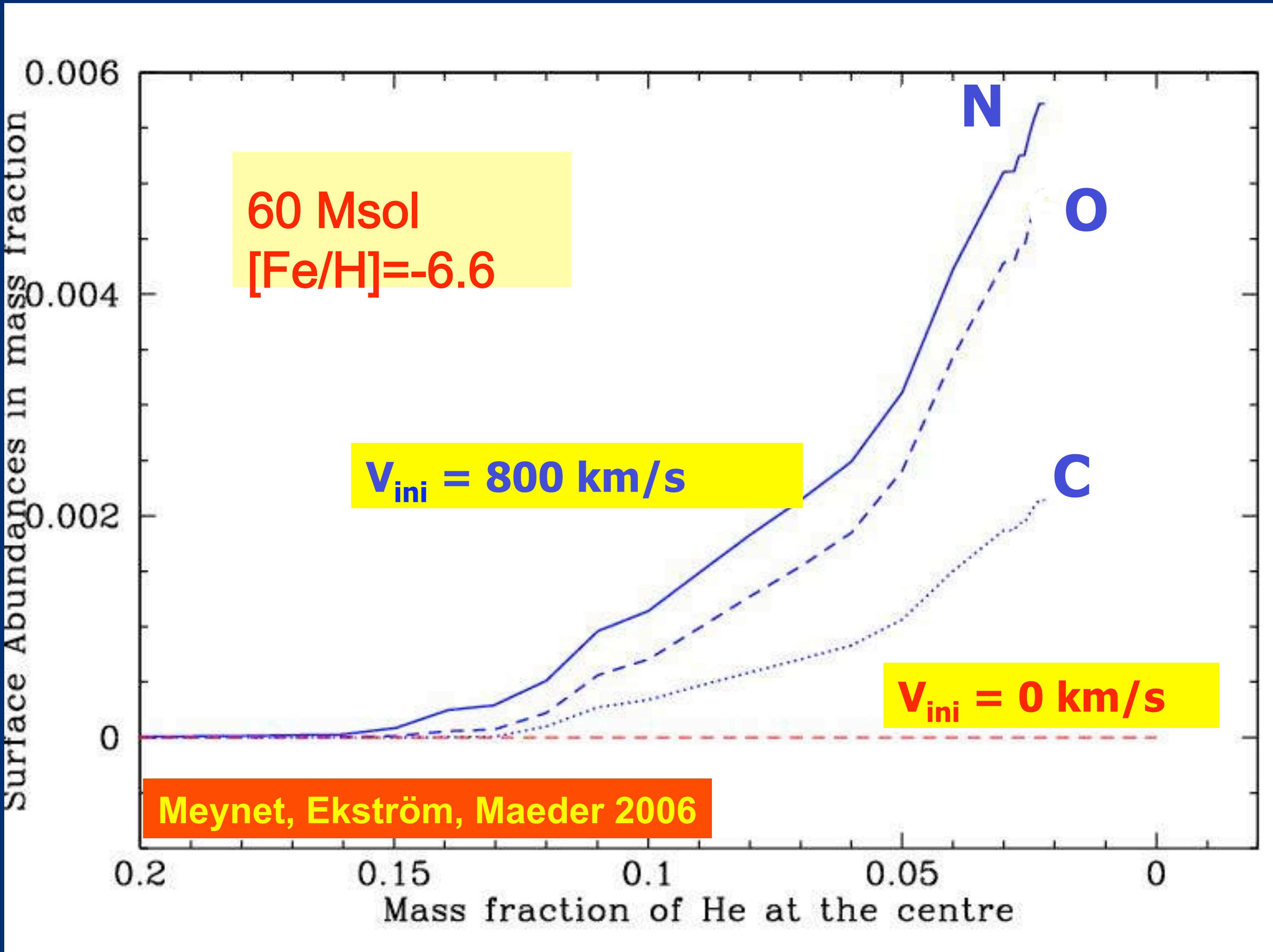


20 M Z=0.00001 velocity on the ZAMS 490 km/s, Ω/Ωcrit=0.75





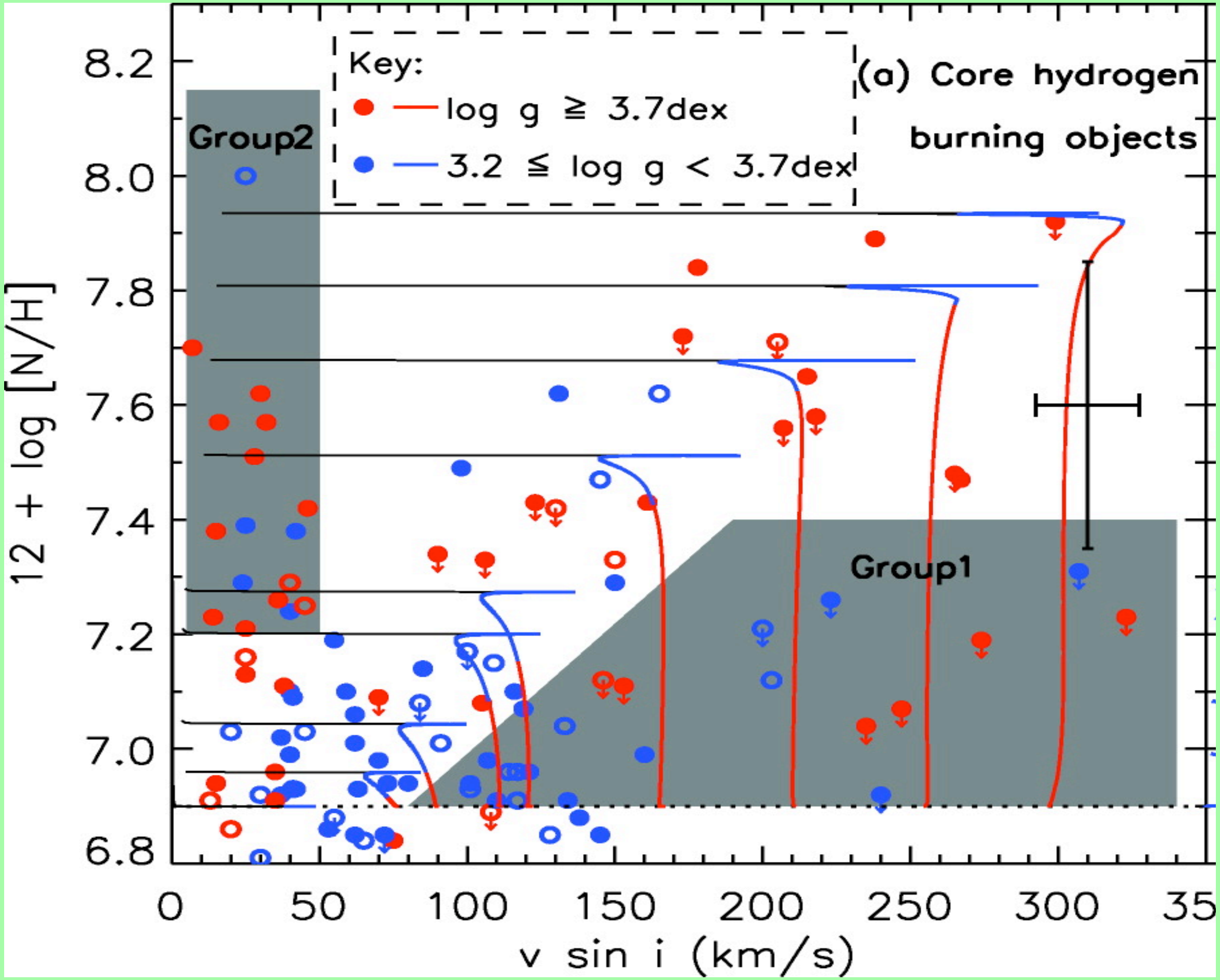
Georgy et al, in preparation


60 Msol
[Fe/H]=-6.6
N
O
C
V_ini = 800 km/s
V_ini = 0 km/s
Meynet, Ekström, Maeder 2006
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

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

Spread in masses and ages.

Sample biased toward low v sini



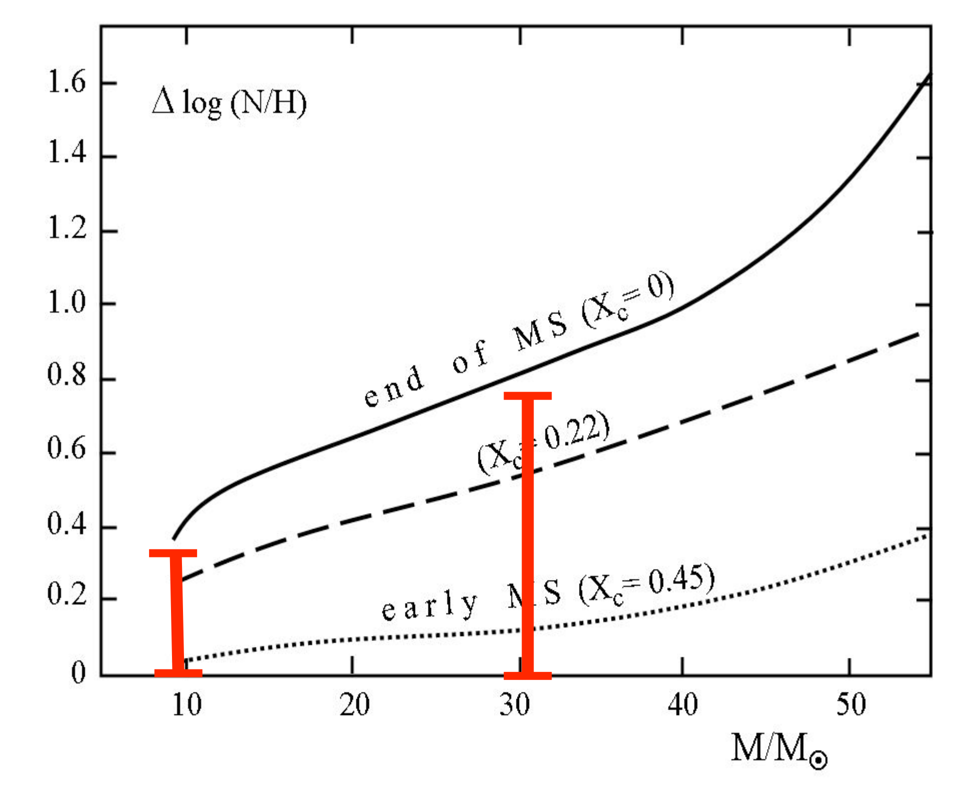
« The observation challenges the concept of rotational mixing »

Hunter et al. 2008

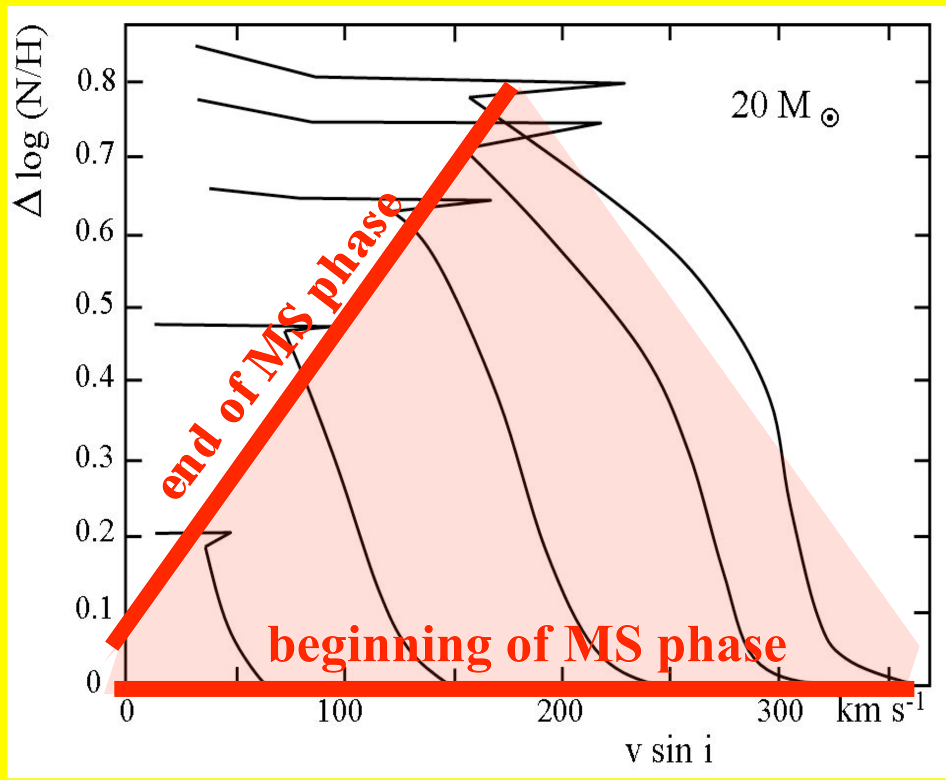
Reality: Δlog (N/H) = f(v sini, M, age, Z, binary, field ….)

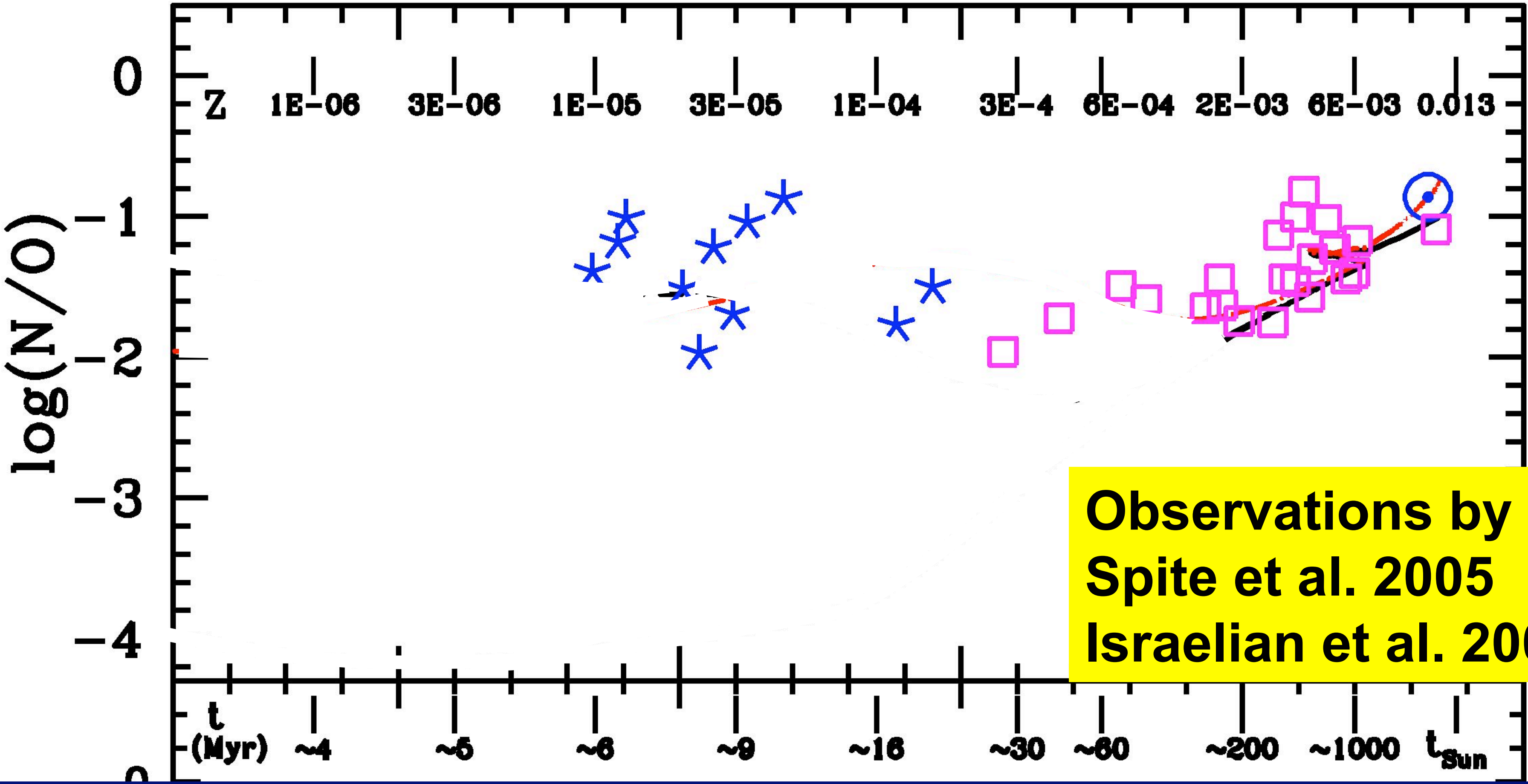
not : Δlog (N/H) = f(v sini)

Mass effect

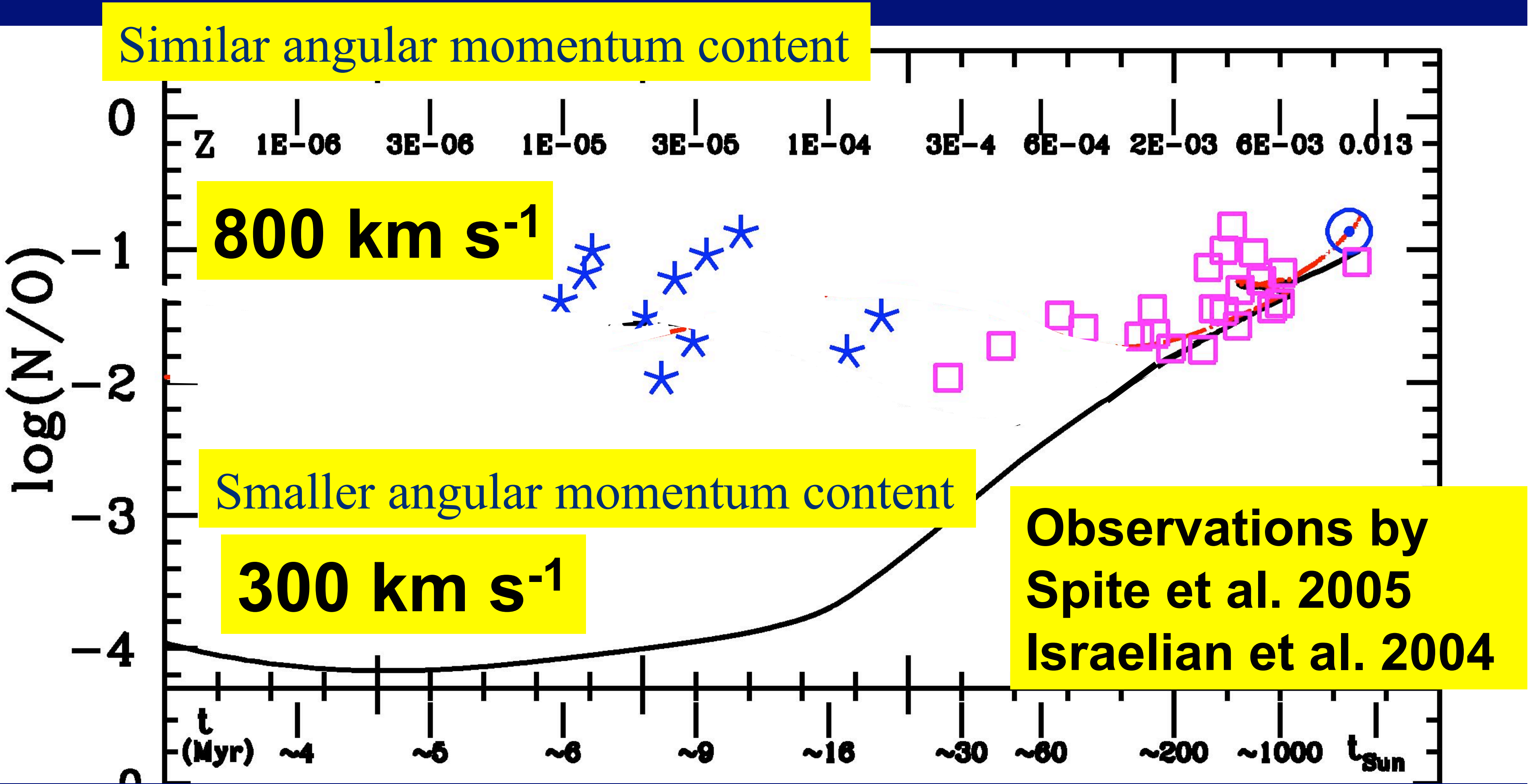


Age effect





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



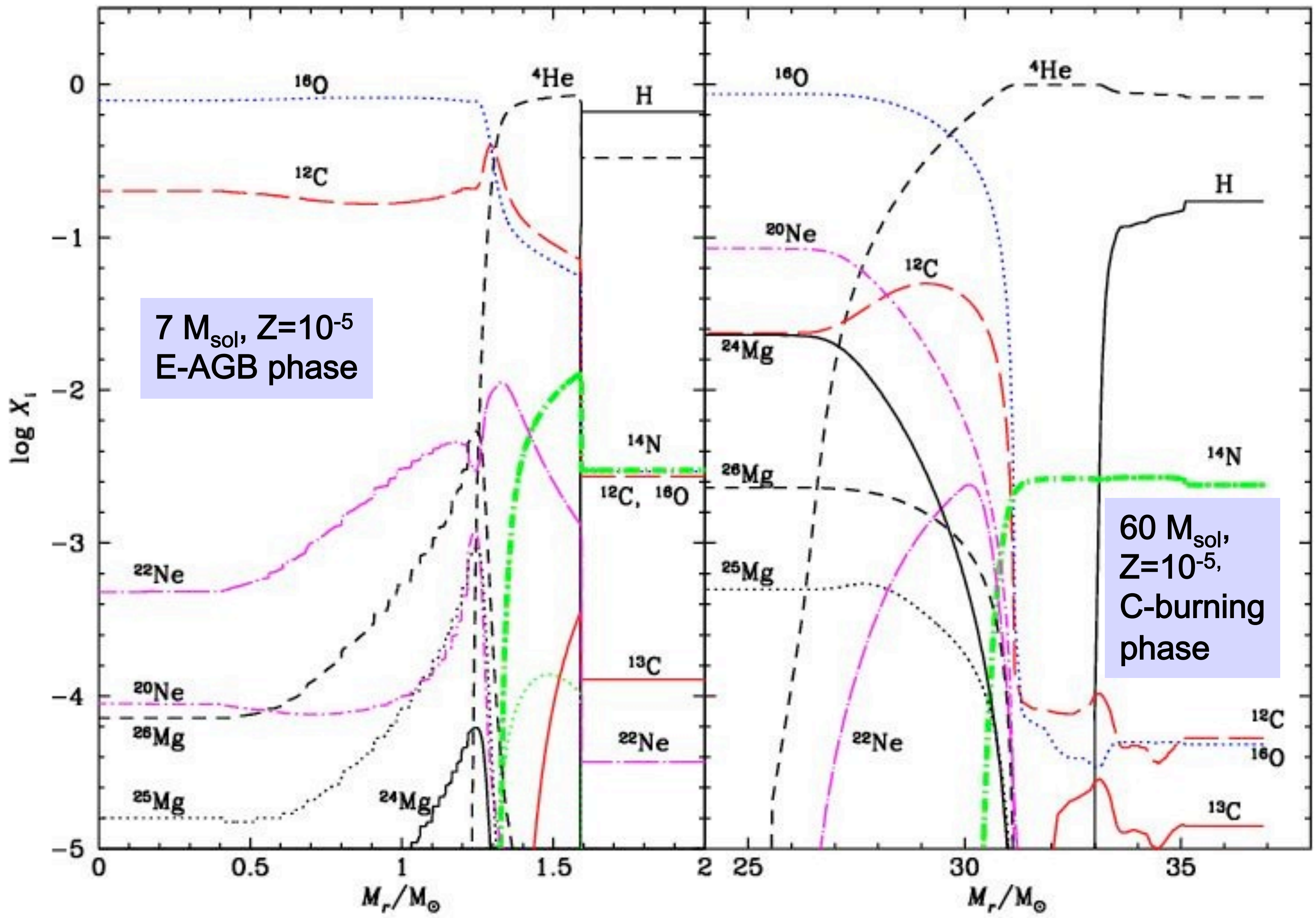
Chiappini, Hirschi, Meynet, Ekström, Maeder, Matteucci, (2006)

At low Z→ Spinstars?

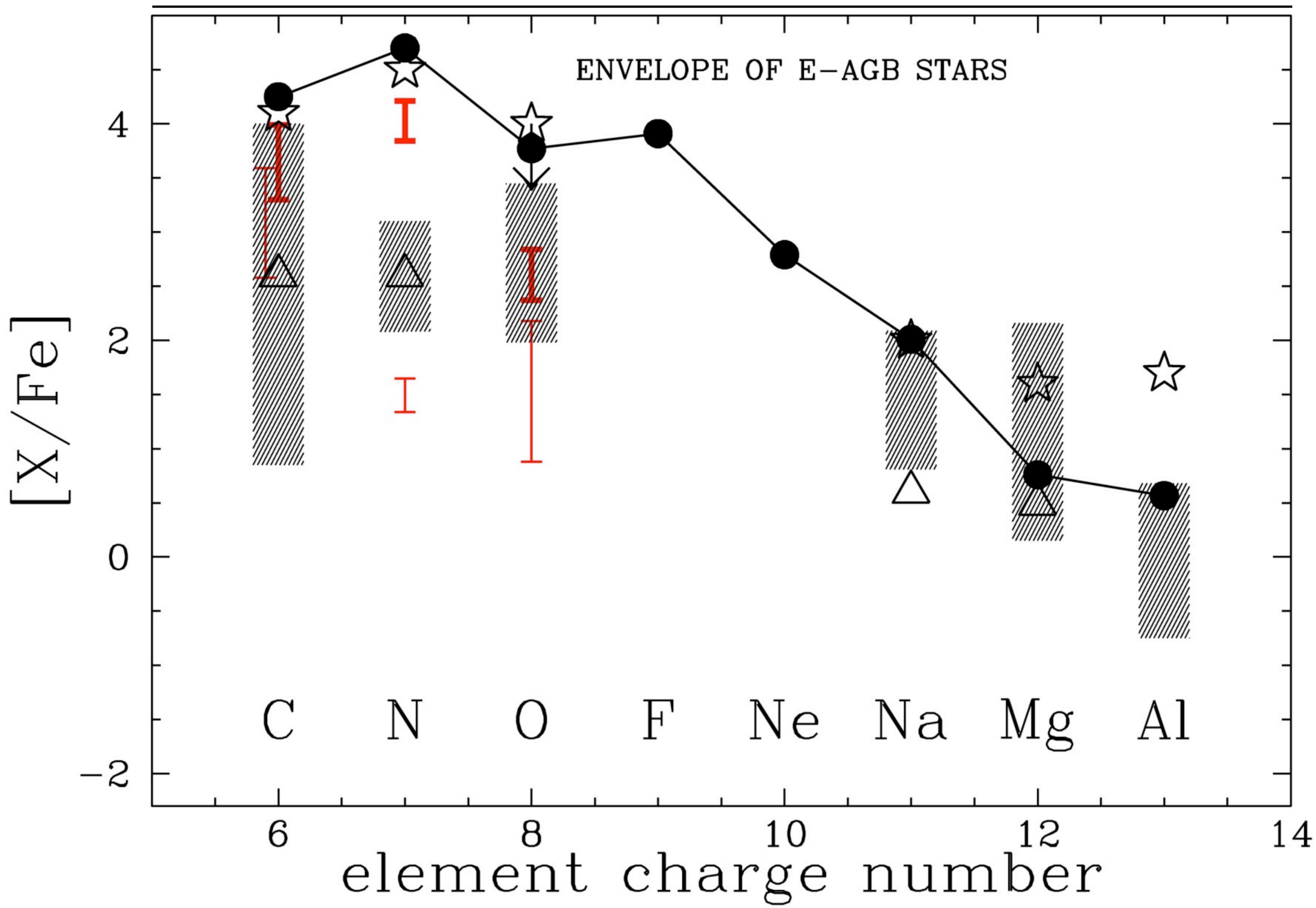
- C-rich Ultra Metal Poor Stars
- Primary nitrogen production
- Anticorrelation in Globular Clusters
- He-rich stars in Globular clusters
- Fraction of Be at low Z

HIGHER FRACTION OF FAST ROTATORS AT LOW Z?

Mass Loss increased→ nucleosynthesis
GRB
nature of SNe events?
nature of stellar remnants?
reionization?



7 M_sol, Z=10^-5
E-AGB phase
60 M_sol, Z=10^-5, C-burning phase
log X_i
M_r/M_⊙
¹⁶O
¹²C
⁴He
H
¹⁴N
¹²C, ¹⁶O
¹³C
²²Ne
²⁰Ne
²⁶Mg
²⁵Mg
²⁴Mg



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

SURFACE EFFECTS: ROTATION AND MASS LOSS

Radiatively driven stellar winds

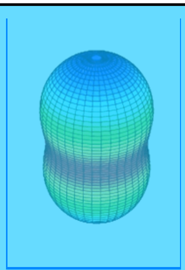
Increase of mass loss

Maeder & Meynet 2000

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

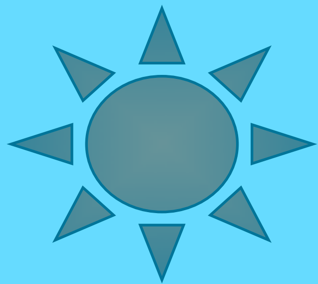
Anisotropies (fast rotation)

Owocki, 1996; Maeder, 1999



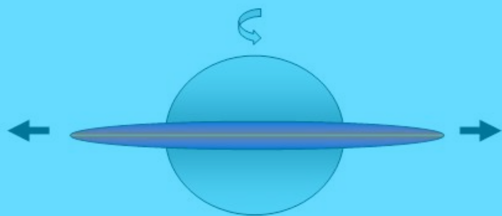
Surface enrichments

Meynet et al. 2006
Hirschi 2007



``Mechanical mass loss''

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



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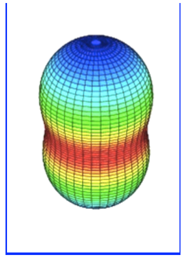

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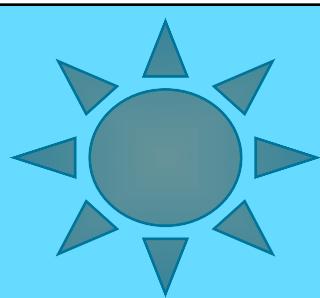

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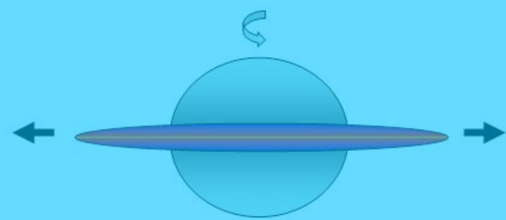
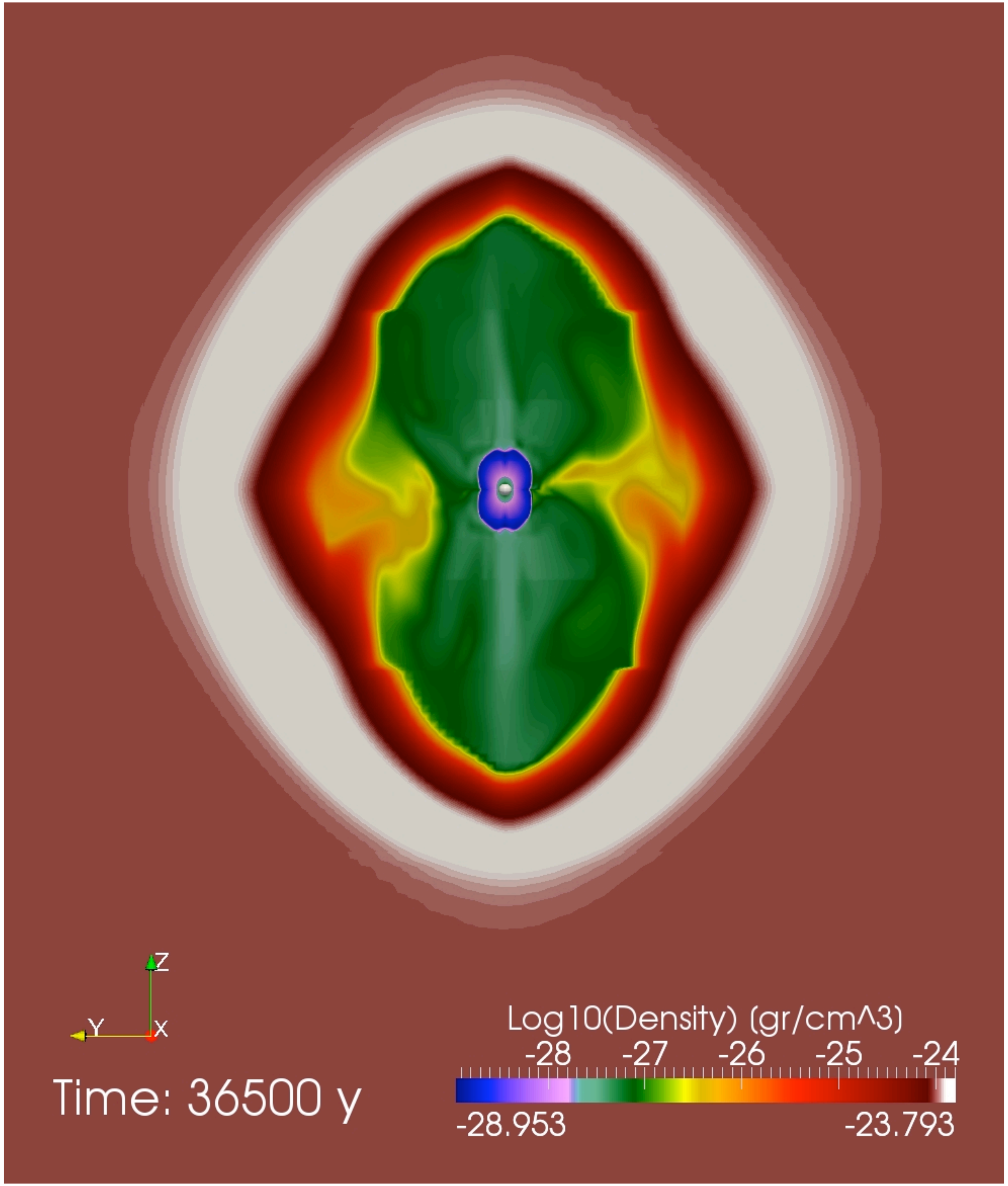
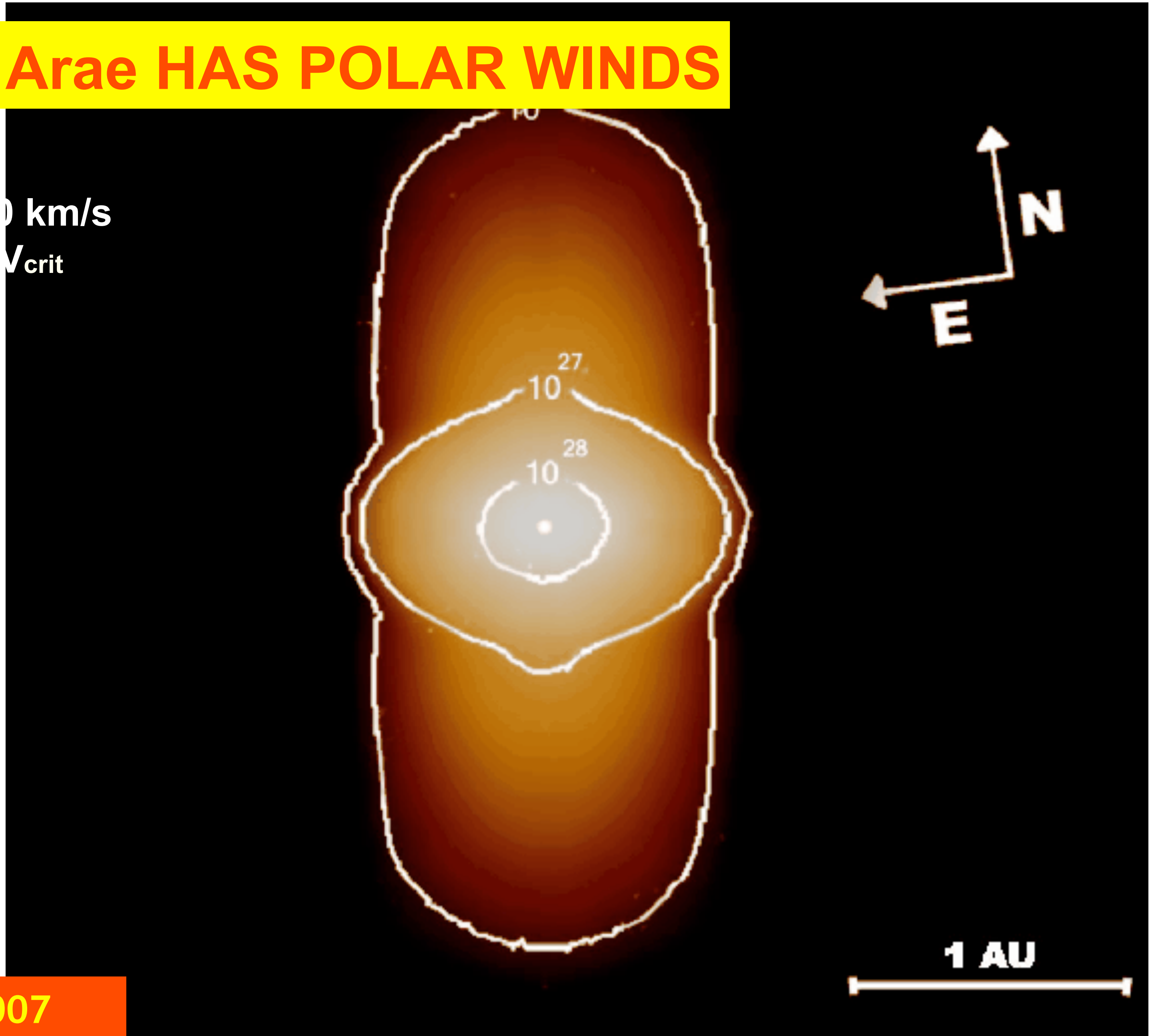



Z
Y
X
Time: 36500 y
Log10(Density) (gr/cm^3)
-28
-27
-26
-25
-24
-28.953
-23.793

α Arae HAS POLAR WINDS



ol

sol

Meilland et al. 2007

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

SURFACE EFFECTS: ROTATION AND MASS LOSS

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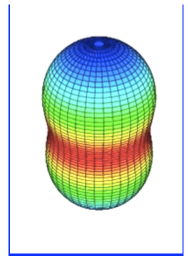
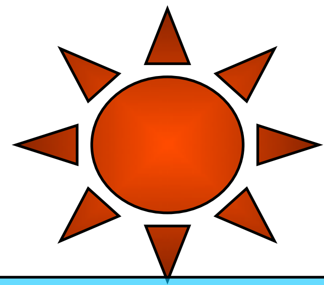


Surface enrichments

Meynet et al. 2006
Hirschi 2007



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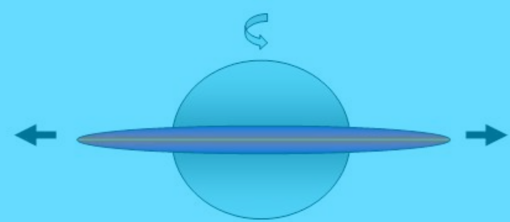

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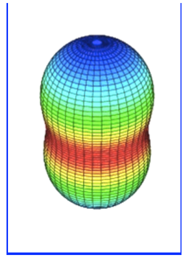

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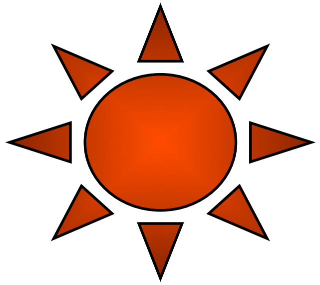
Hirschi 2007



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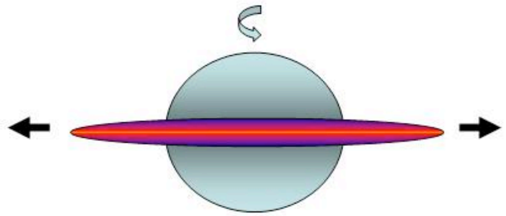
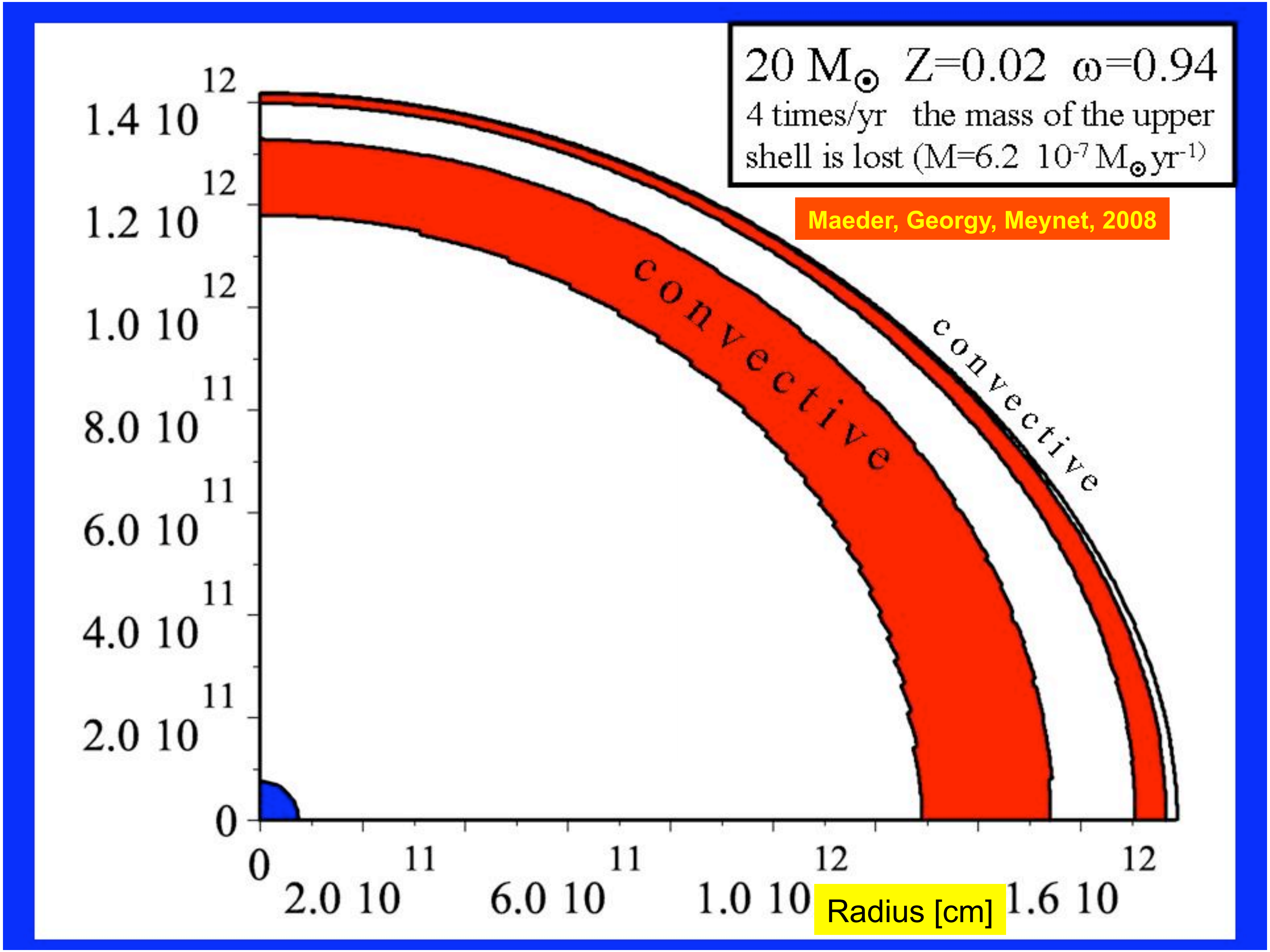
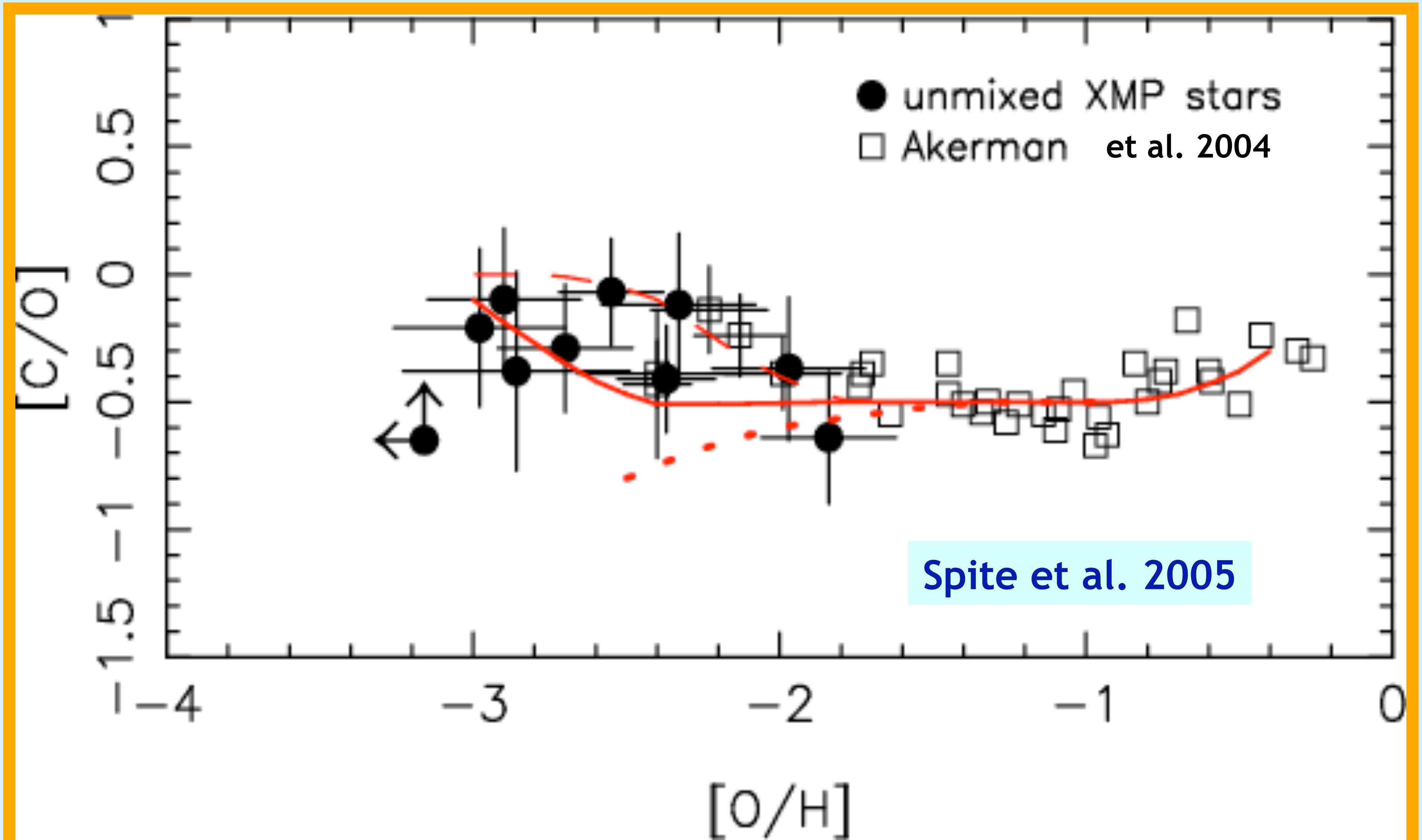




20 M⊙ Z=0.02 ω=0.94
4 times/yr the mass of the upper shell is lost (M=6.2 10-7 M⊙yr-1)
Maeder, Georgy, Meynet, 2008
convective
convective
0
2.0 10 11
6.0 10 11
1.0 10 12
1.6 10 12
Radius [cm]
1.4 10 12
1.2 10 12
1.0 10 12
8.0 10 11
6.0 10 11
4.0 10 11
2.0 10 11
0

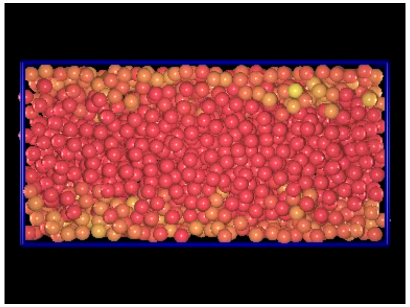
STRIKING OBSERVATIONAL FACTS

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

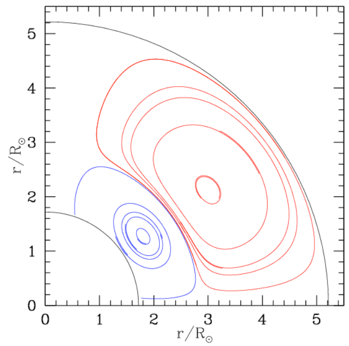


What rotation can do at low metallicity?

- Favors some nucleosynthetic paths through rotational mixing.
- Triggers important mass losses.



INTERIOR EFFECTS



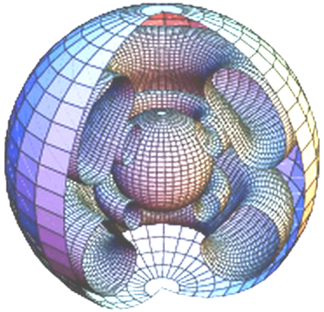
Zahn 1992 meridional circulation and shear instabilities

Meridional circulation→ thermal instability

Shear instability→ Excess of energy in differential rotation

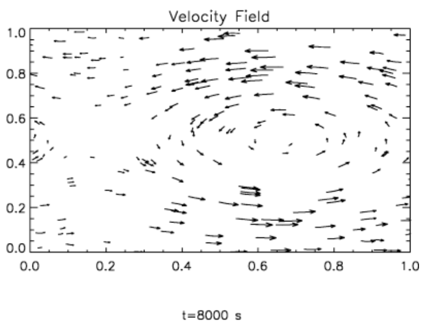
Differential rotation may amplify magnetic field in radiative regions
Spruit (1999;2002)

HOW DO THESE TRANSPORT PROCESSES DEPEND ON METALLICITY?



Angular momentum: meridional currents
Meridional currents slower in higher density regions
→Slower in more compact stars,
→ Slower at low metallicity

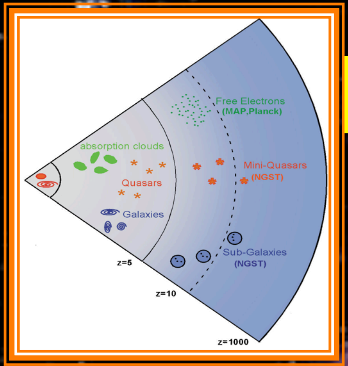
Consequences : steeper interior gradients of angular velocity
more angular momentum in the core (GRB)



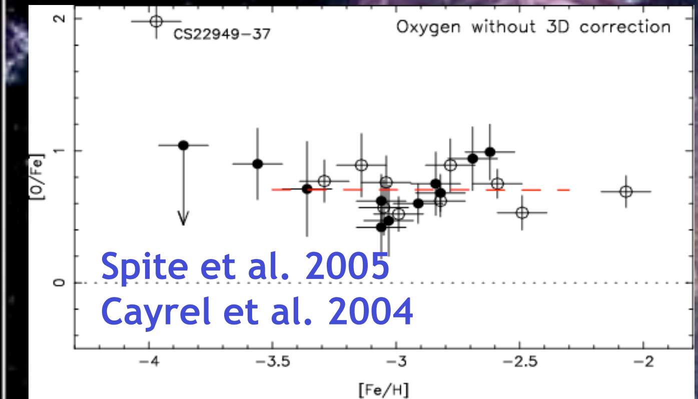
Chemical species: shear instabilities
→ Stronger at low Z
Because steeper angular velocity gradients and
Smaller spatial extension of the radiative envelope
Timescale ~R^2/D

Consequences : for a given mass, given evolutionary stage, greater
surface enrichements at lower Z,
consequences for nucleosynthesis

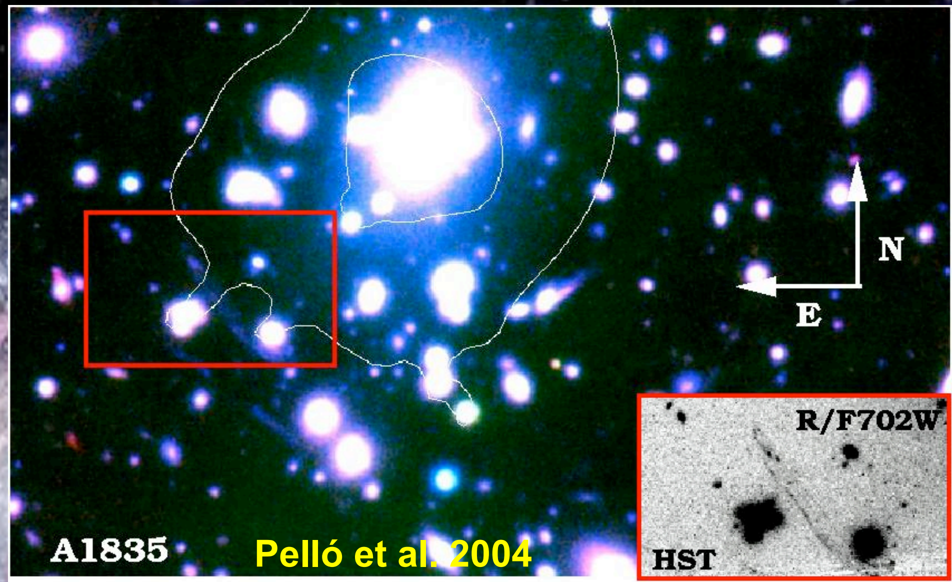
MASSIVE STAR EVOLUTION AT LOW METALLICITY



Reionization at high redshift

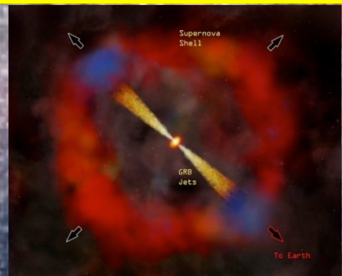


Early chemical evolution of galaxies

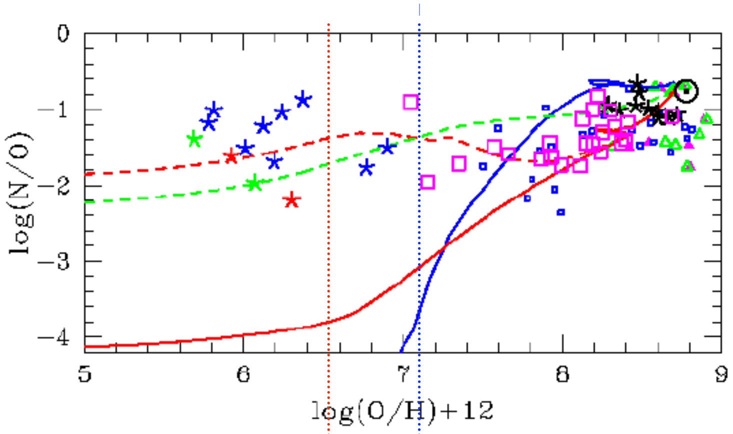


Stellar population in metal poor and/or high redshifted galaxies

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

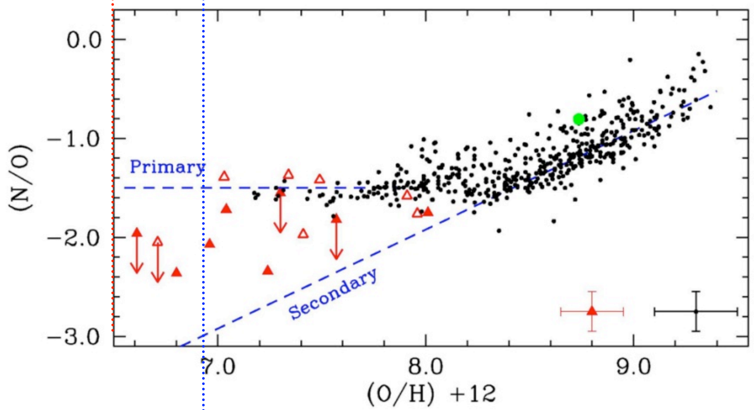


MOST IRON POOR OBJECTS



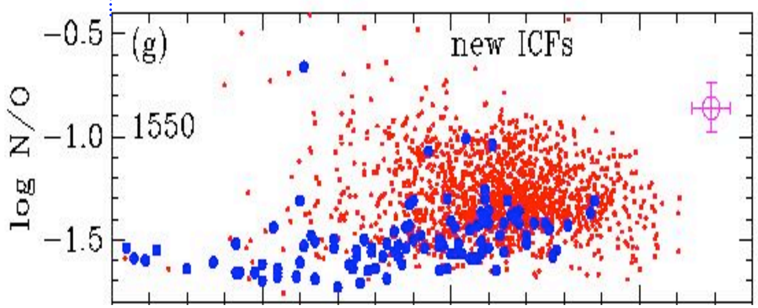
STARS IN THE HALO

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



DAMPED LYMAN ALPHA SYSTEMS

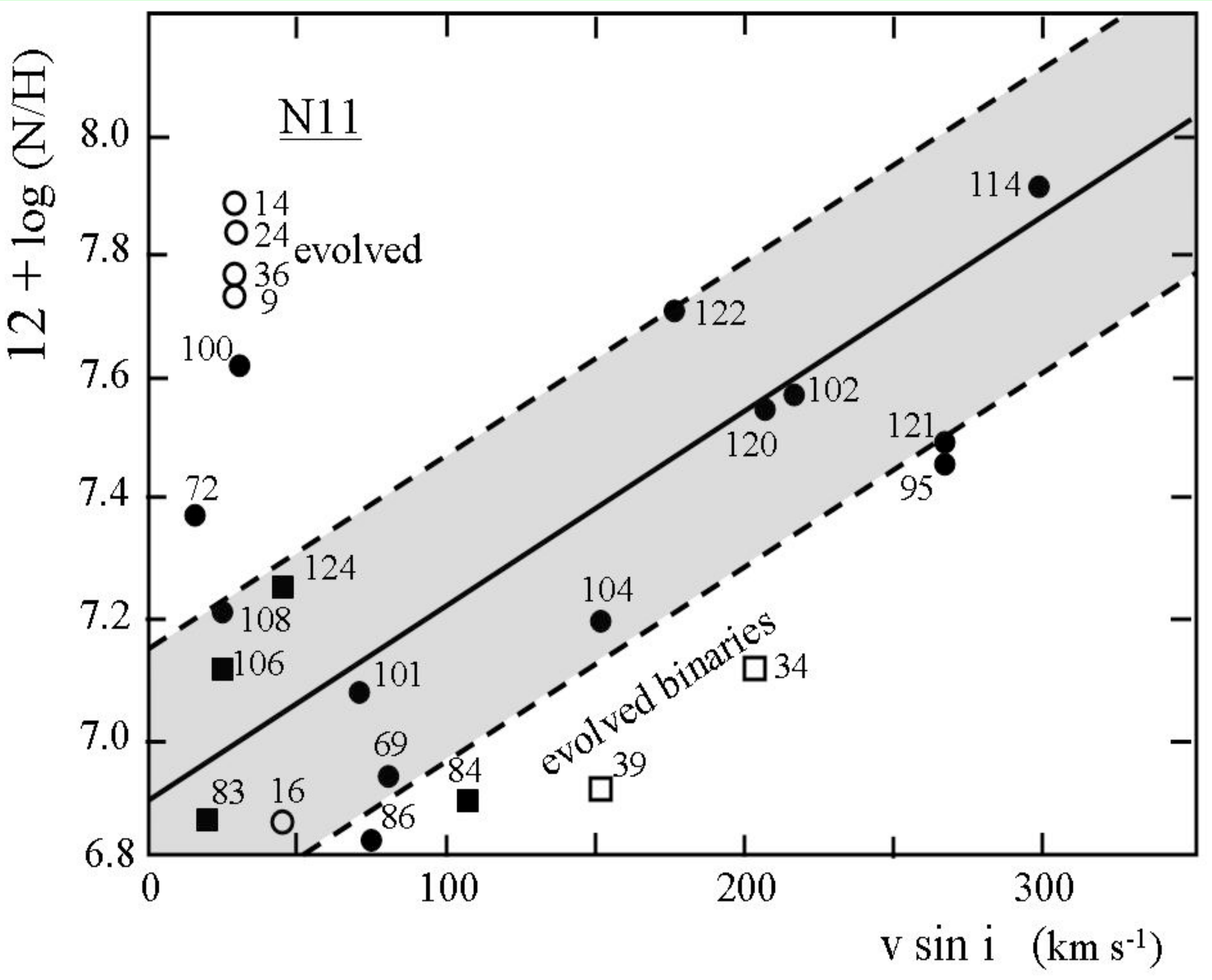
Pettini et al. (2002)
Dessauge et al. (2005)



BLUE COMPACT DWARF GALAXIES

Izotov et al (2008)

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

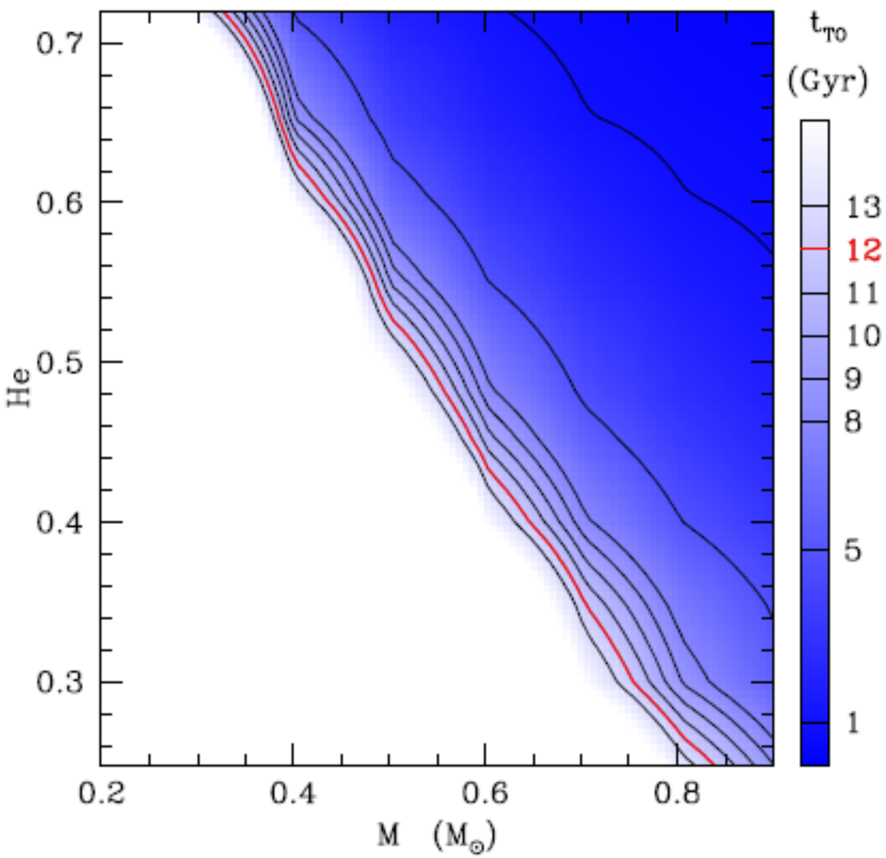


A CONSEQUENCE OF THE SPINSTAR MODEL

→ CRUMPS ARE HE-RICH Y BETWEEN 0.28-0.60

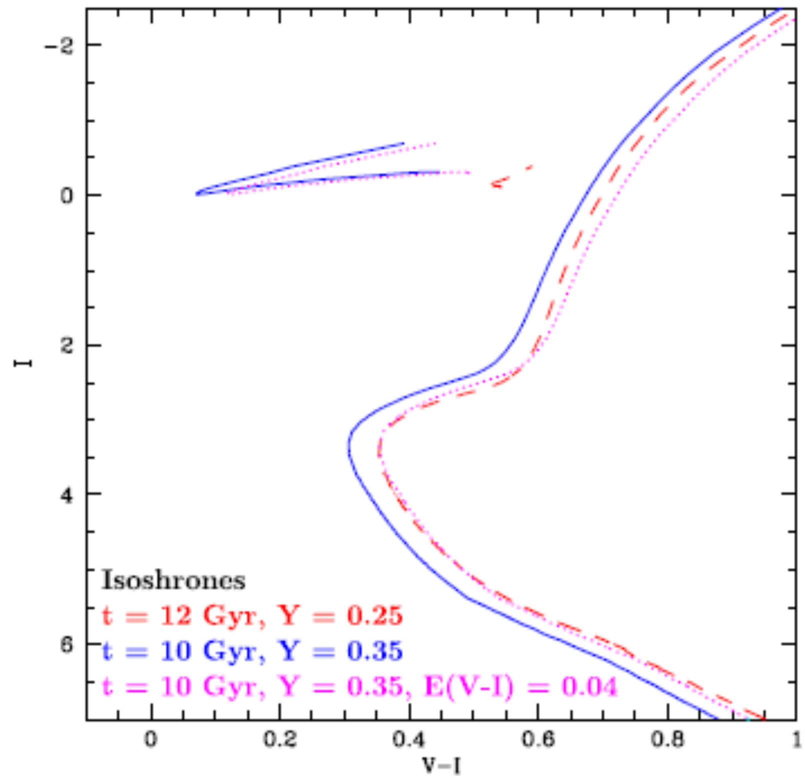
MASS DETERMINATION

He-rich shorter lifetimes



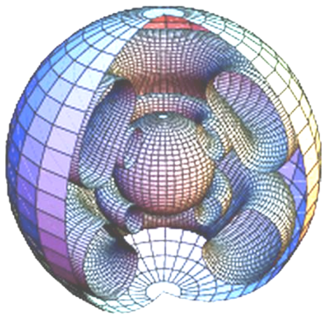
ABUNDANCE DETERMINATION

Extended Horizontal Branch

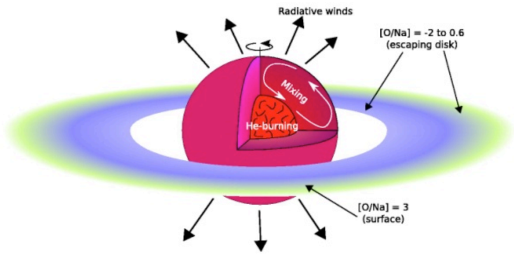


Decressin et al. 2009

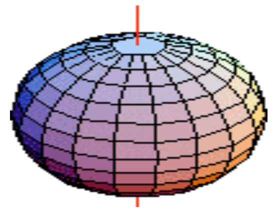
- Mixing



- Rotational mass loss→ equatorial disks



→ through opacity



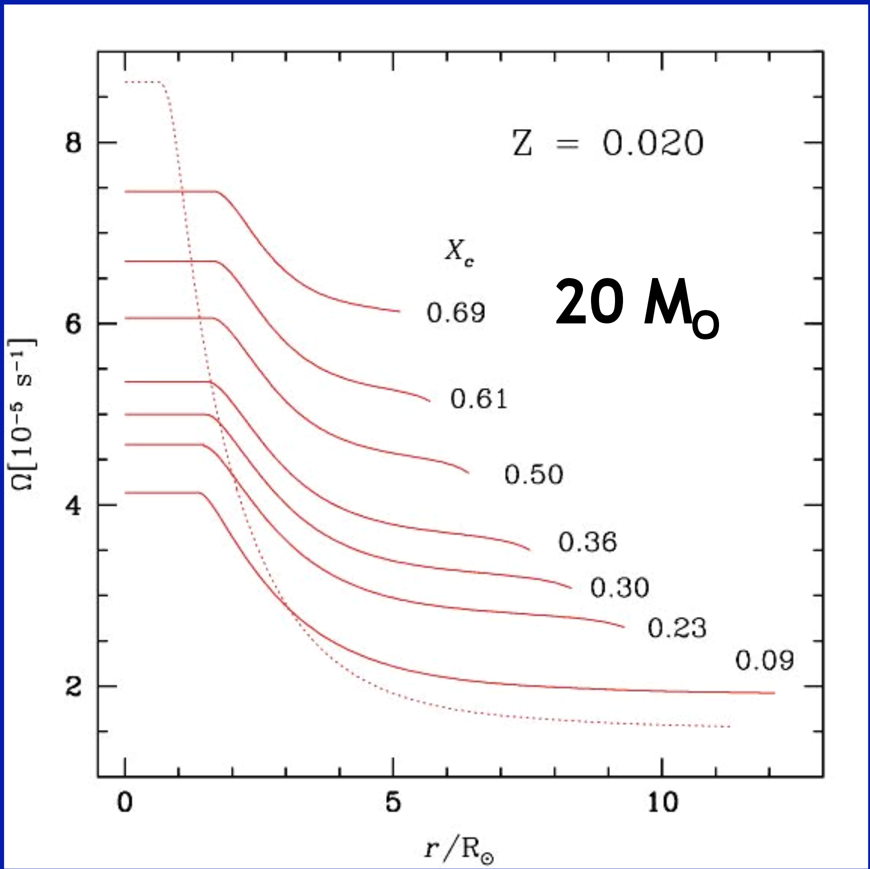
- Homogeneous evolution

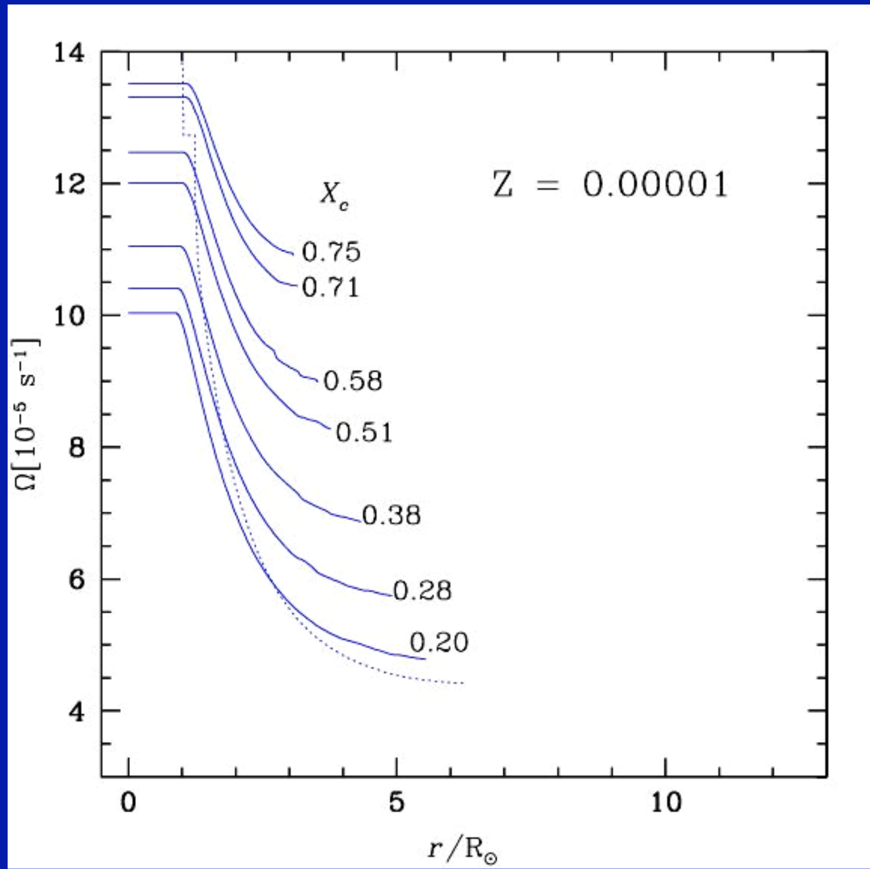
Increasing angular momentum content

IMPROVE AGREEMENT WITH WELL OBSERVED FEATURES OF MASSIVE STARS

STANDARD POP III STARS?

Gradients of Ω steeper at lower metallicity

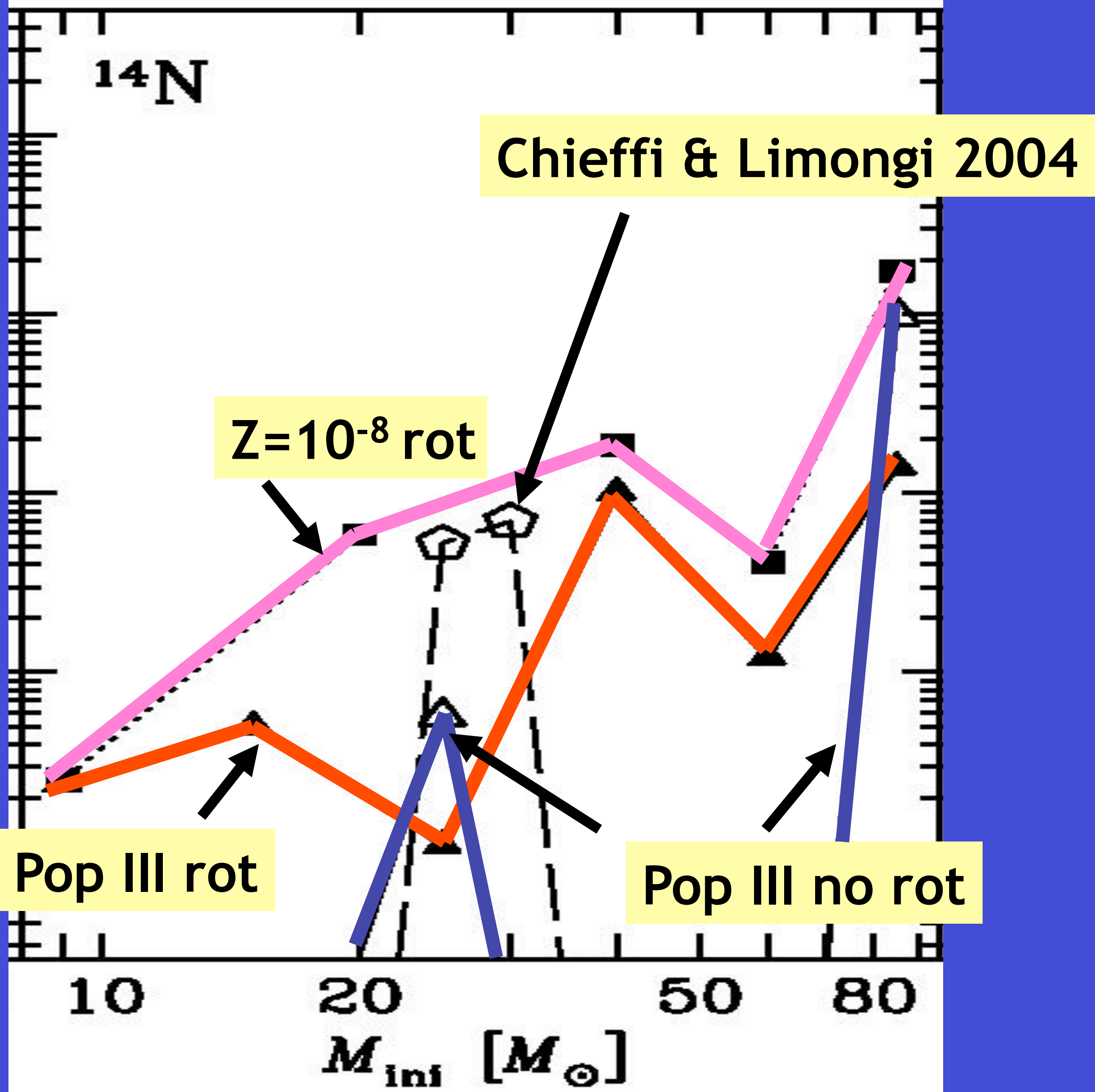




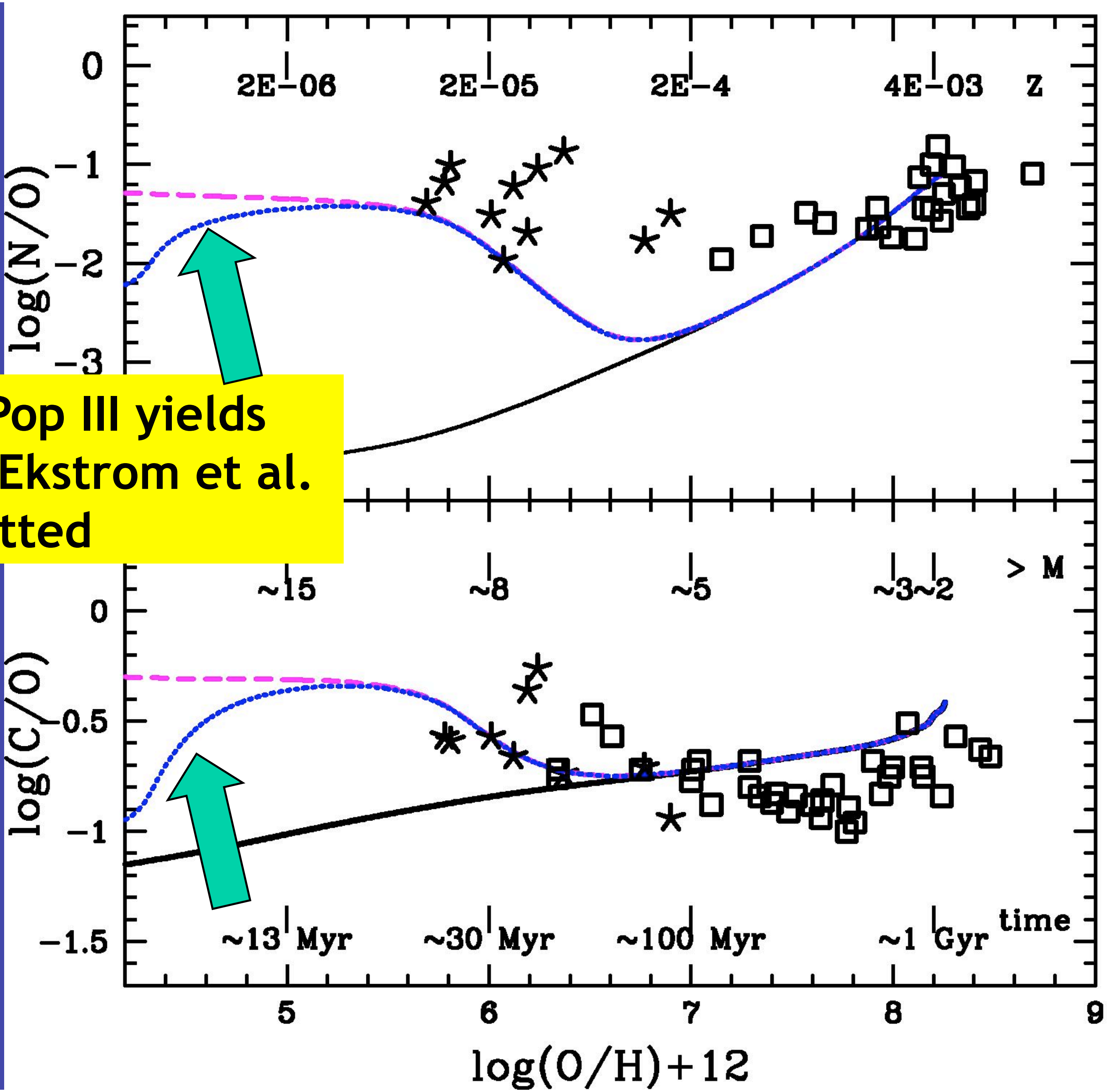
Asteroseismology of B stars:

HD 129929 : Ωcore = (3.5 ± 1.0) Ωsurf (Dupret et al. 2004)

ν Eri : Ωcore = (4 ± 1) Ωsurf (Pamyatnykh, Handler & Dziembowski 2004)



^{14}N
Chieffi & Limongi 2004
$Z=10^{-8}$ rot
Pop III rot
Pop III no rot
10
20
50
80
M_{ini} [$M_\odot$]



With Pop III yields
From Ekstrom et al.
submitted