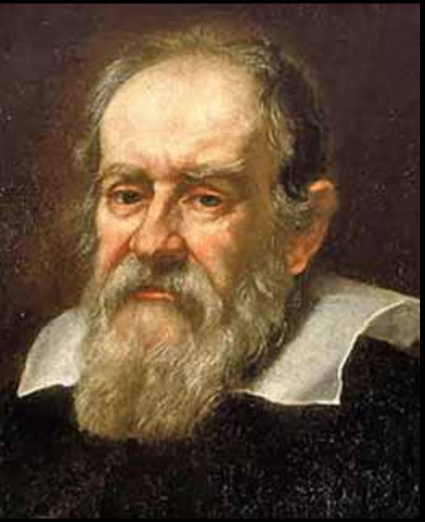
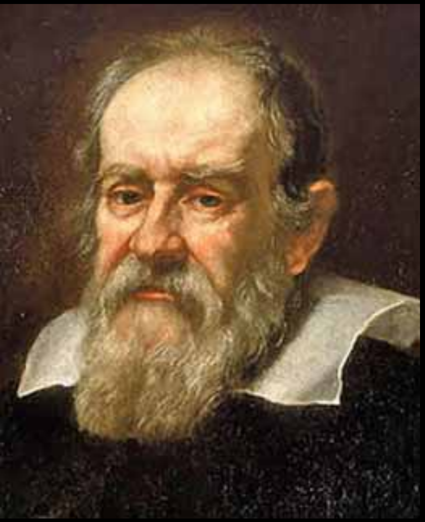




The sun, with all those planets revolving around it and dependent on it, can still ripen a bunch of grapes as if it had nothing else in the universe to do.



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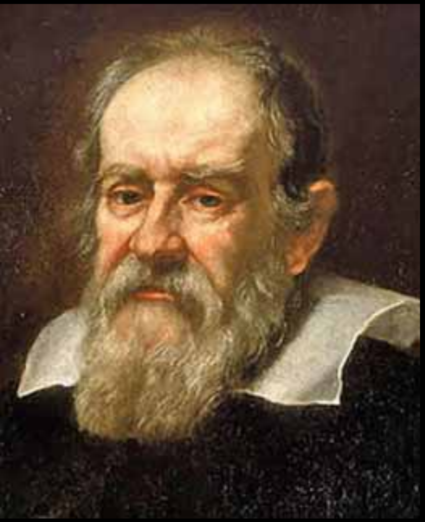
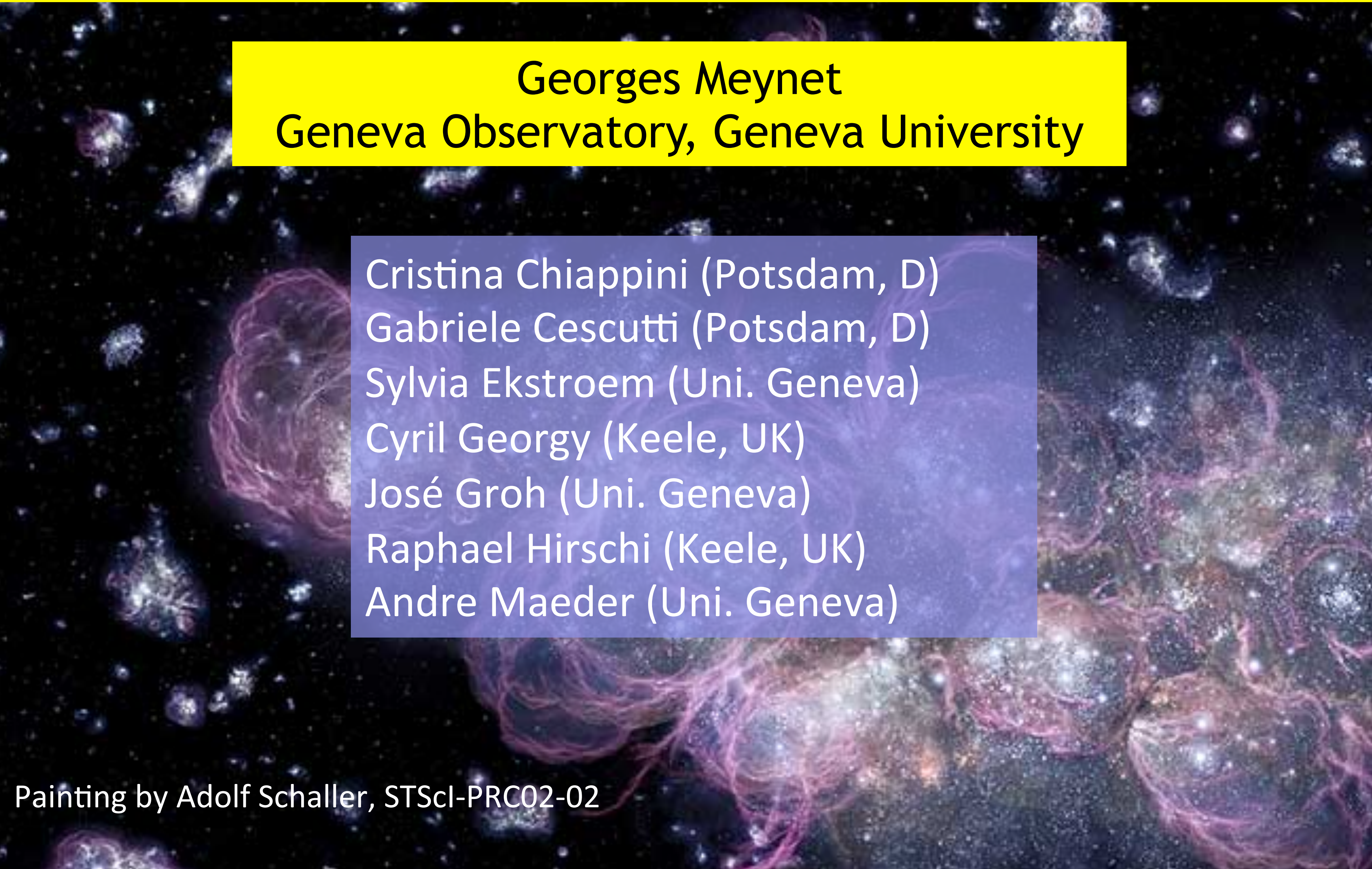


Francesca, with all the projects revolving around her and dependent on her, can still cultivate the joy of life as if she had nothing else in the universe to do.

Physics of spinstars and some consequences for the (early) chemical evolution of galaxies

Georges Meynet
Geneva Observatory, Geneva University

Cristina Chiappini (Potsdam, D)
Gabriele Cescutti (Potsdam, D)
Sylvia Ekstroem (Uni. Geneva)
Cyril Georgy (Keele, UK)
José Groh (Uni. Geneva)
Raphael Hirschi (Keele, UK)
Andre Maeder (Uni. Geneva)



Painting by Adolf Schaller, STScI-PRC02-02

SPINSTARS = STARS WHOSE EVOLUTION IS STRONGLY AFFECTED BY ROTATION

MIXING

SHEAR

$D_{shear} \sim \nabla\Omega$ $\quad t \sim R^2 / D_{shear}$

MERIDIONAL CIRCULATION

$U \sim 1/\rho$ $\quad t \sim R / U$

MASS LOSS

STELLAR WINDS

→ Anisotropie
→ Enhancement
→ Eddington limit changed
→ Indirect effects

MECHANICAL MASS LOSS

→ Equatorial mass loss

Zahn 1992; Maeder & Zahn 1998; Maeder 1999; Maeder & Meynet 2000 ; Krticka et al. 2011

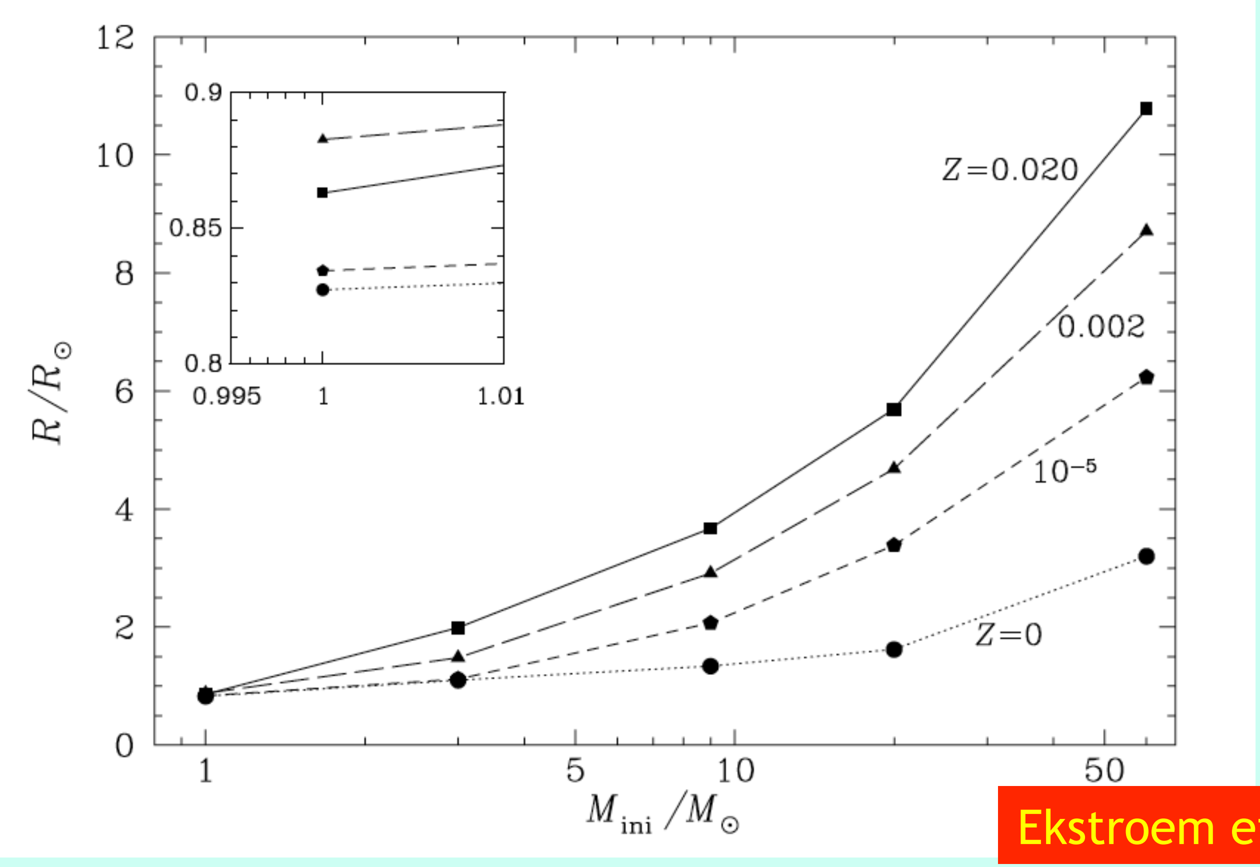
IMPORTANT IMPACT OF ROTATION IN METAL POOR REGIONS

WHY?

STARS ARE MORE COMPACT

→ Opacities smaller

→ CNO content smaller

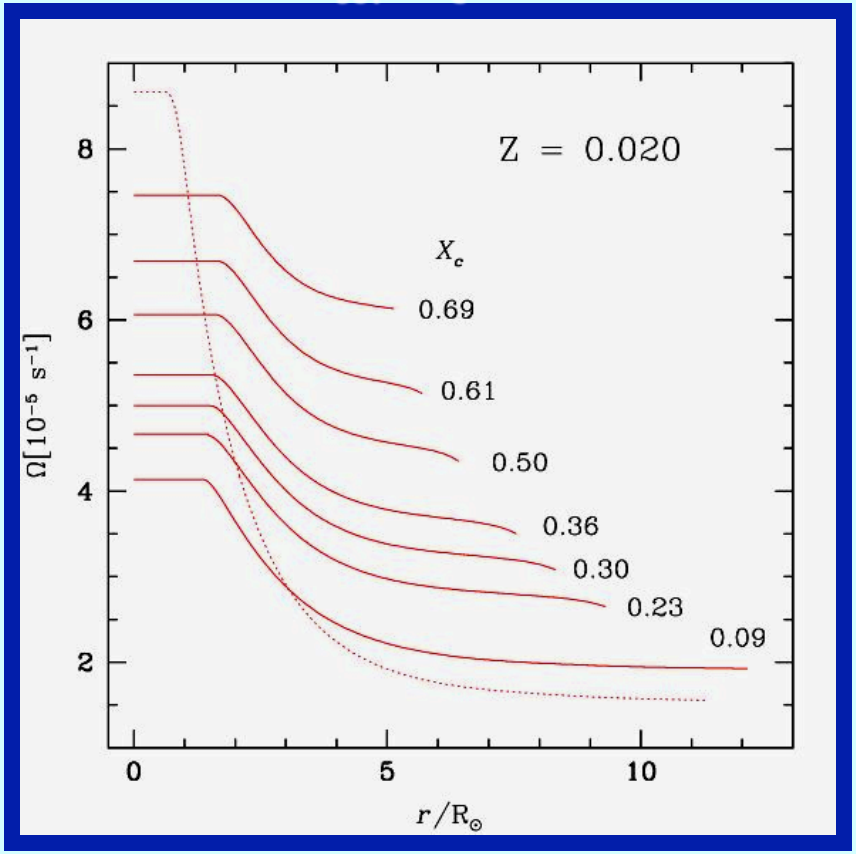


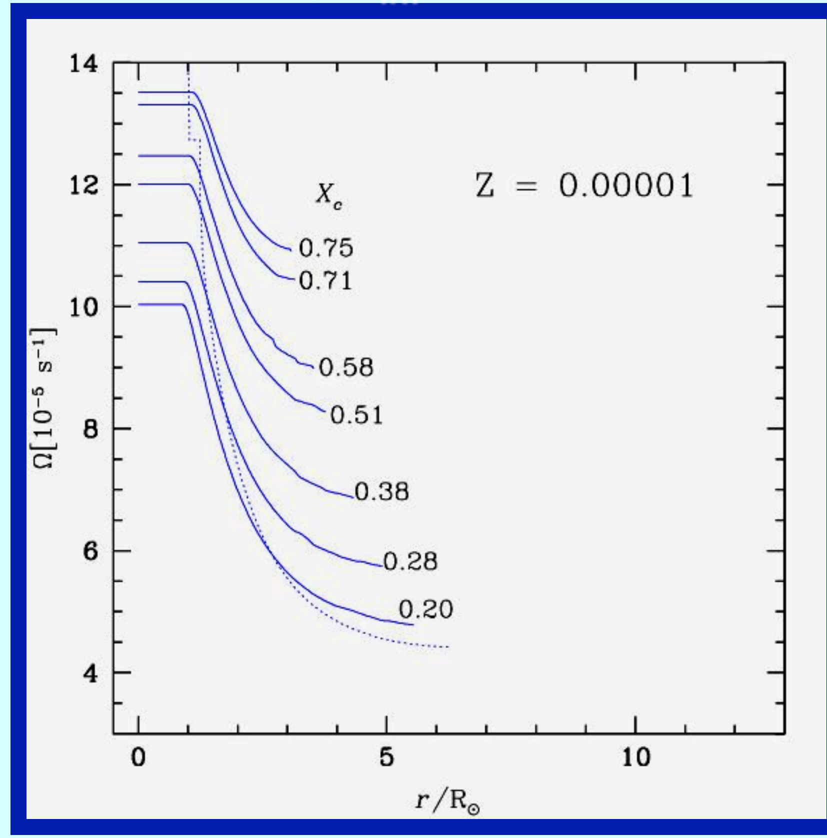
Ekstroem et al 2008

CONSEQUENCES: SHEAR MIXING STRONGER

Gradients of Ω steeper at lower metallicity

20 M_{sol}, X_c mass fraction of H at the centre, V_{ini}= 300 km/s





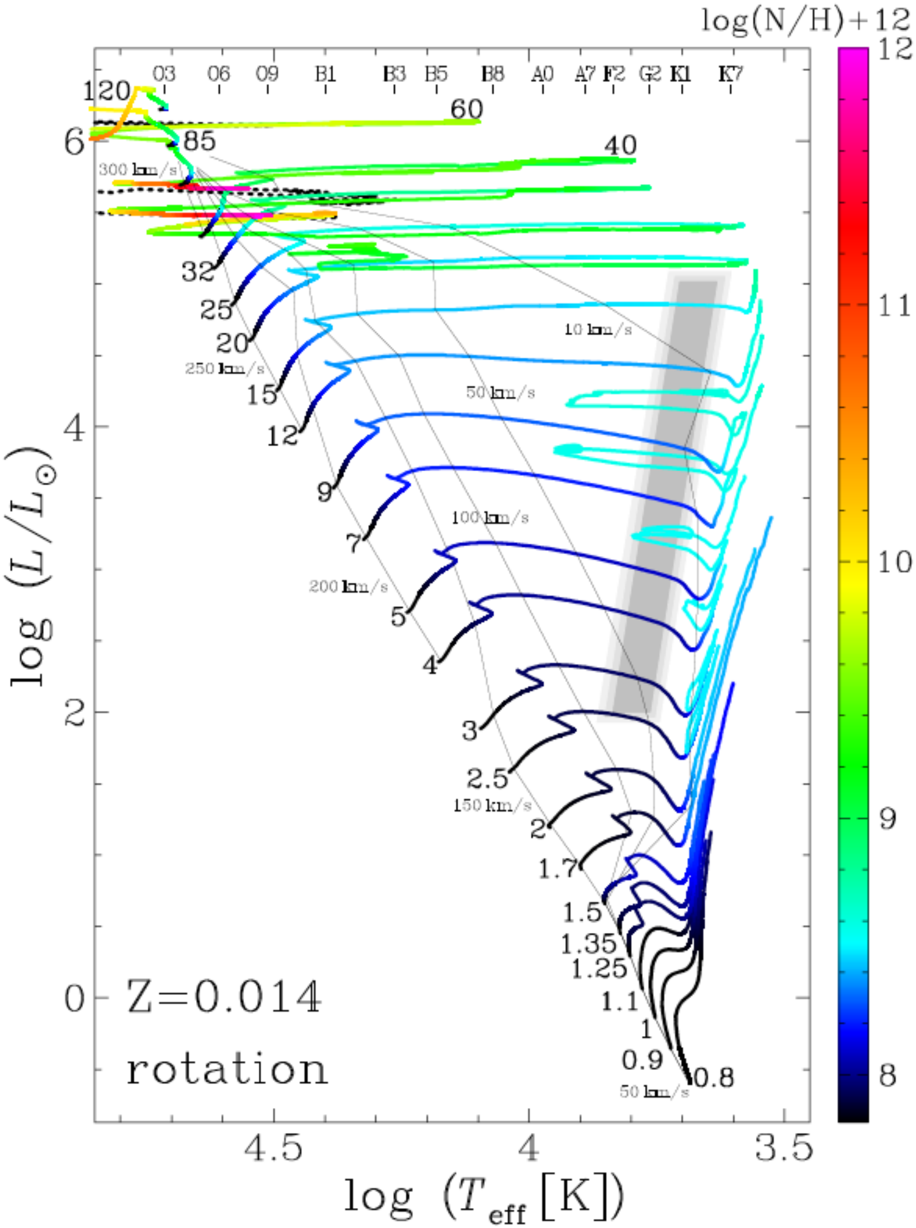
Why ?

Stars more compact, mixing timescale scales with R^2 transport of angular momentum less efficient

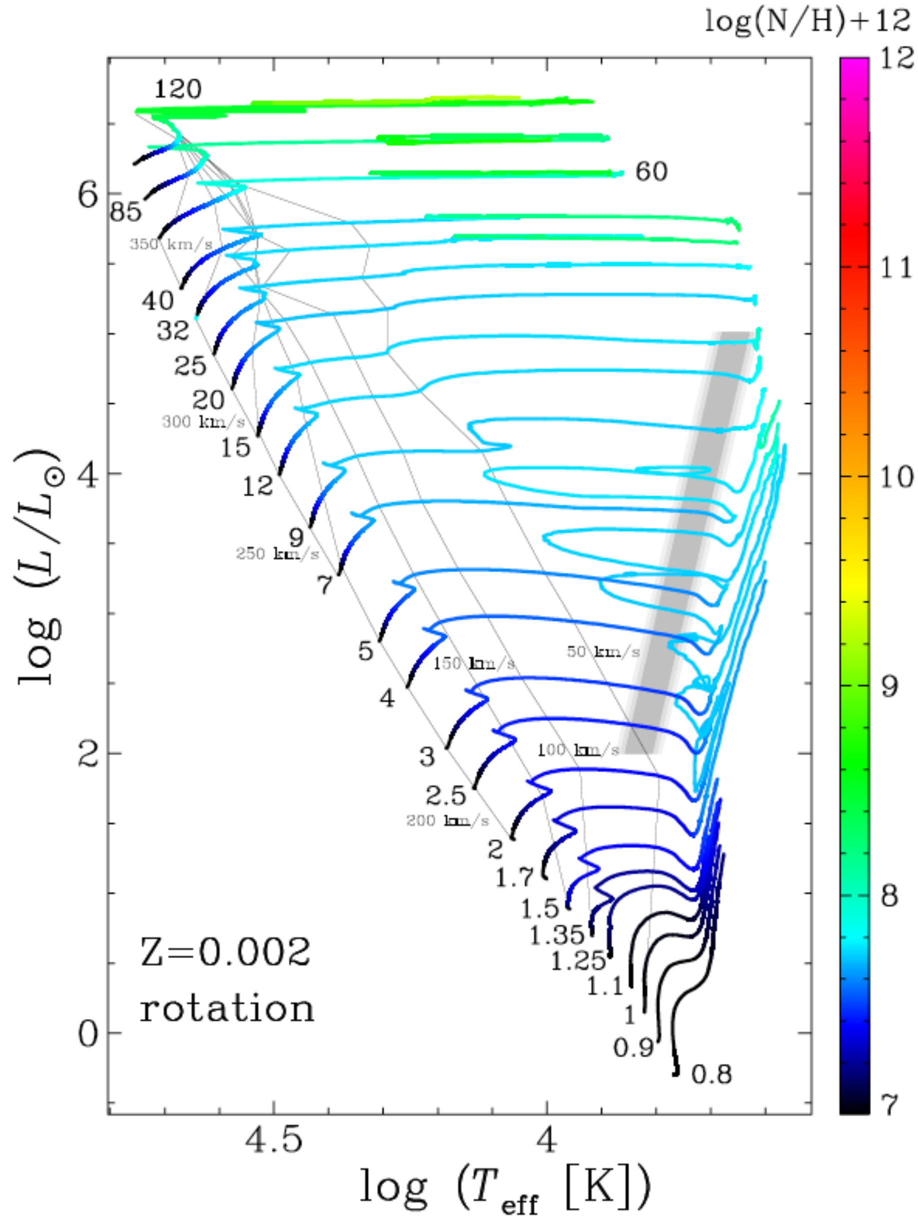
Consequences ?

More efficient mixing of the chemical elements

Ekström et al. 2012

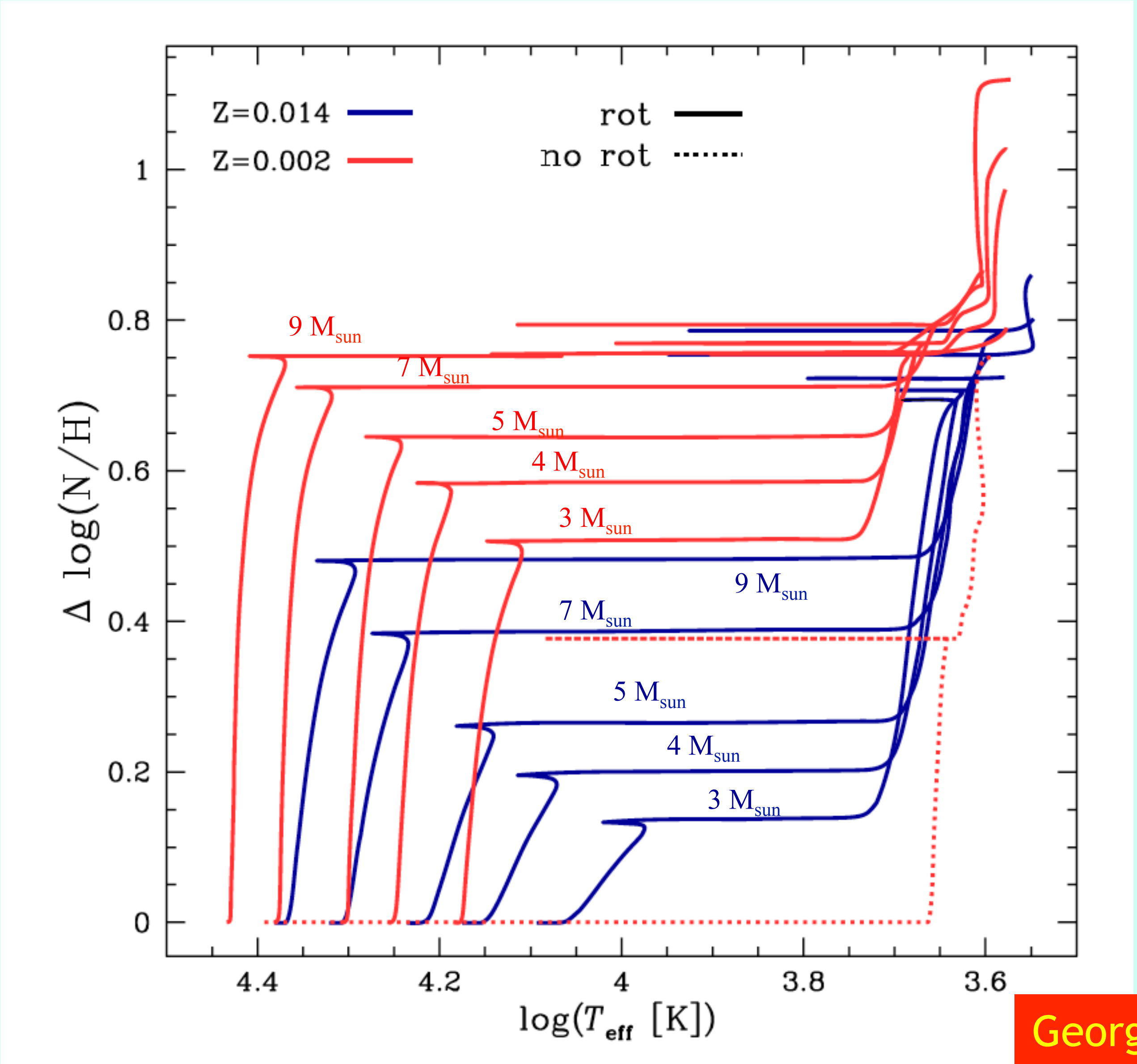


Georgy et al. 2013



AN ILLUSTRATION OF STRONGER MIXING IN METAL POOR STARS

FROM THEORETICAL MODELS



Georgy et al. 2013

A FEW RECENT DEVELOPMENTS

http://obswww.unige.ch/Recherche/evoldb/index/

Welcome to the interactive webpage for the Geneva stellar models

Through this portal, you'll access several tools designed for the Geneva stellar models. Don't hesitate to contact us if you have suggestions or comments (or to report a bug!).

We propose the following services:

- **Isochrone calculation**

  Compute a single isochrone of the desired age,
  or a sequence of isochrones giving the age range and the time steps.

- **Interpolation of a new model:**

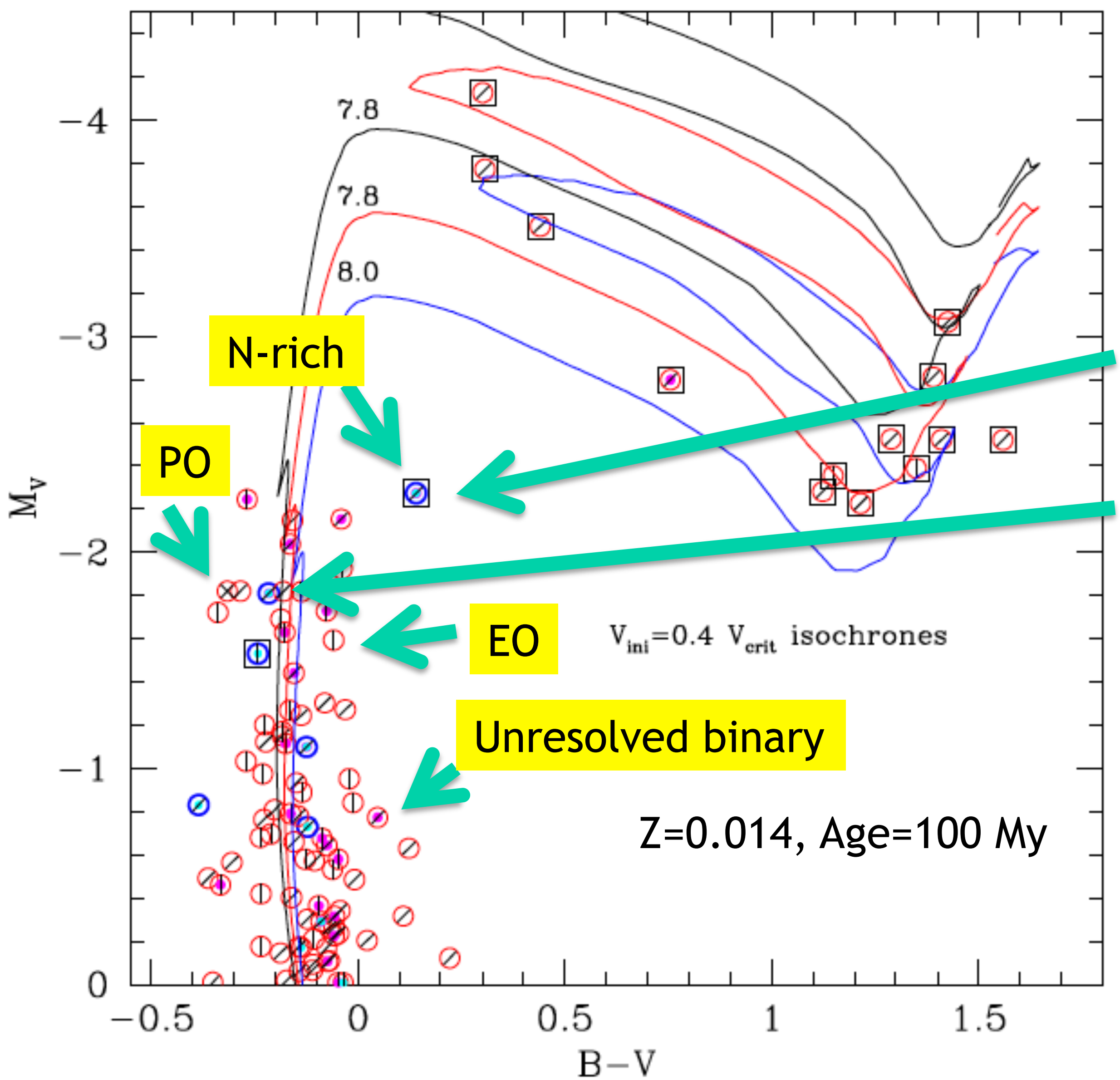
  Create a new model by interpolating between existing tracks.
  Choose the mass, rotation rate and metallicity and obtain the corresponding model track.

Please select one of the following modes:

Compute an isochrone

Submit

GePSy, Geneva Population Synthesis tool



Initial distribution of Velocities

Limb and gravity darkening accounted for

Where are the initially fast rotators?

Where are the actual fast rotators?

Where are stars seen equator.on/pole-on?

Where are the N-rich stars

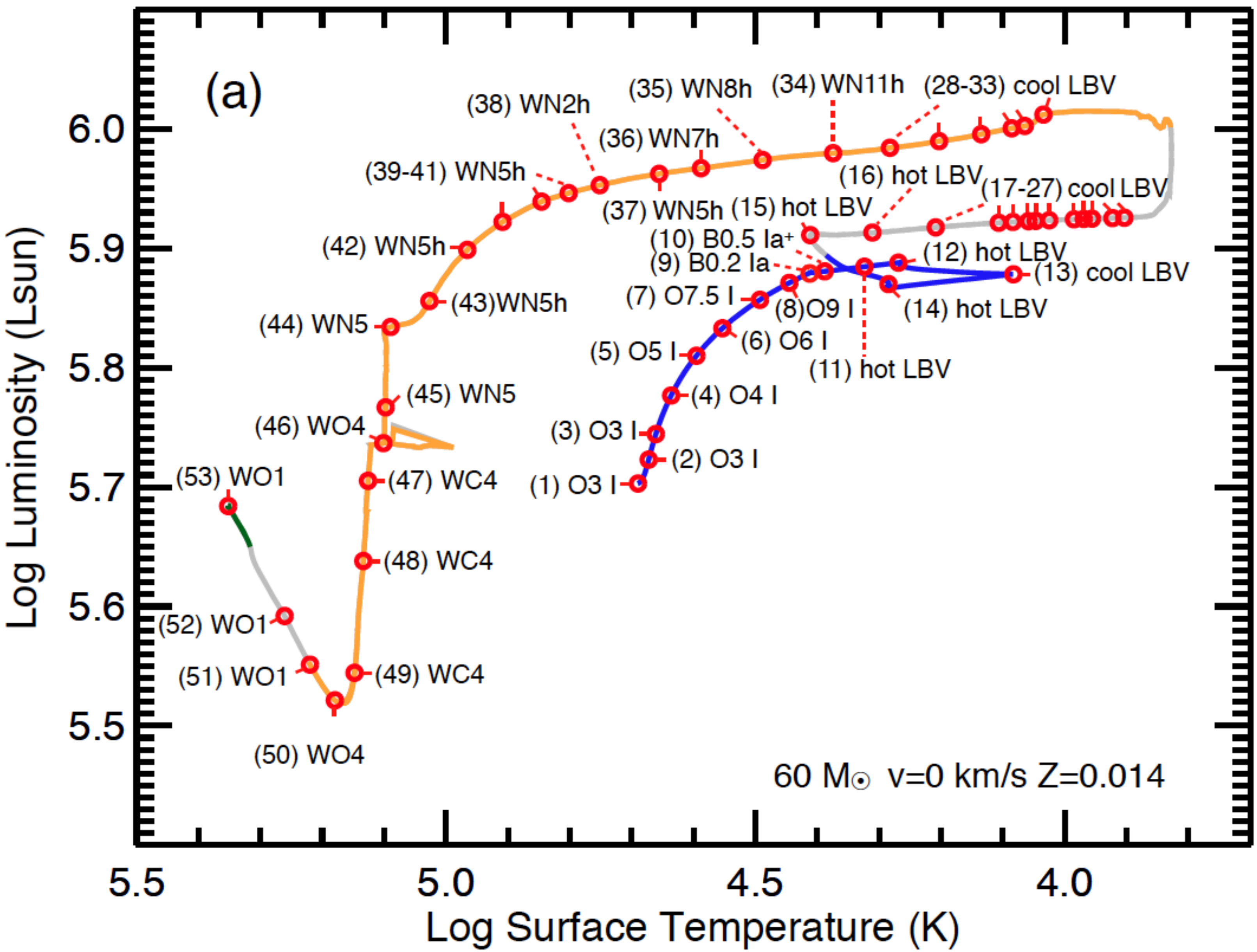
Where are the unresolved binaries?

The evolution of massive stars and their spectra

I. A non-rotating 60 $M_\odot$ star from the ZAMS to the pre-SN stage

Jose H. Groh[1], Georges Meynet[1], Sylvia Ekström[1], and Cyril Georgy[2]

Submitted



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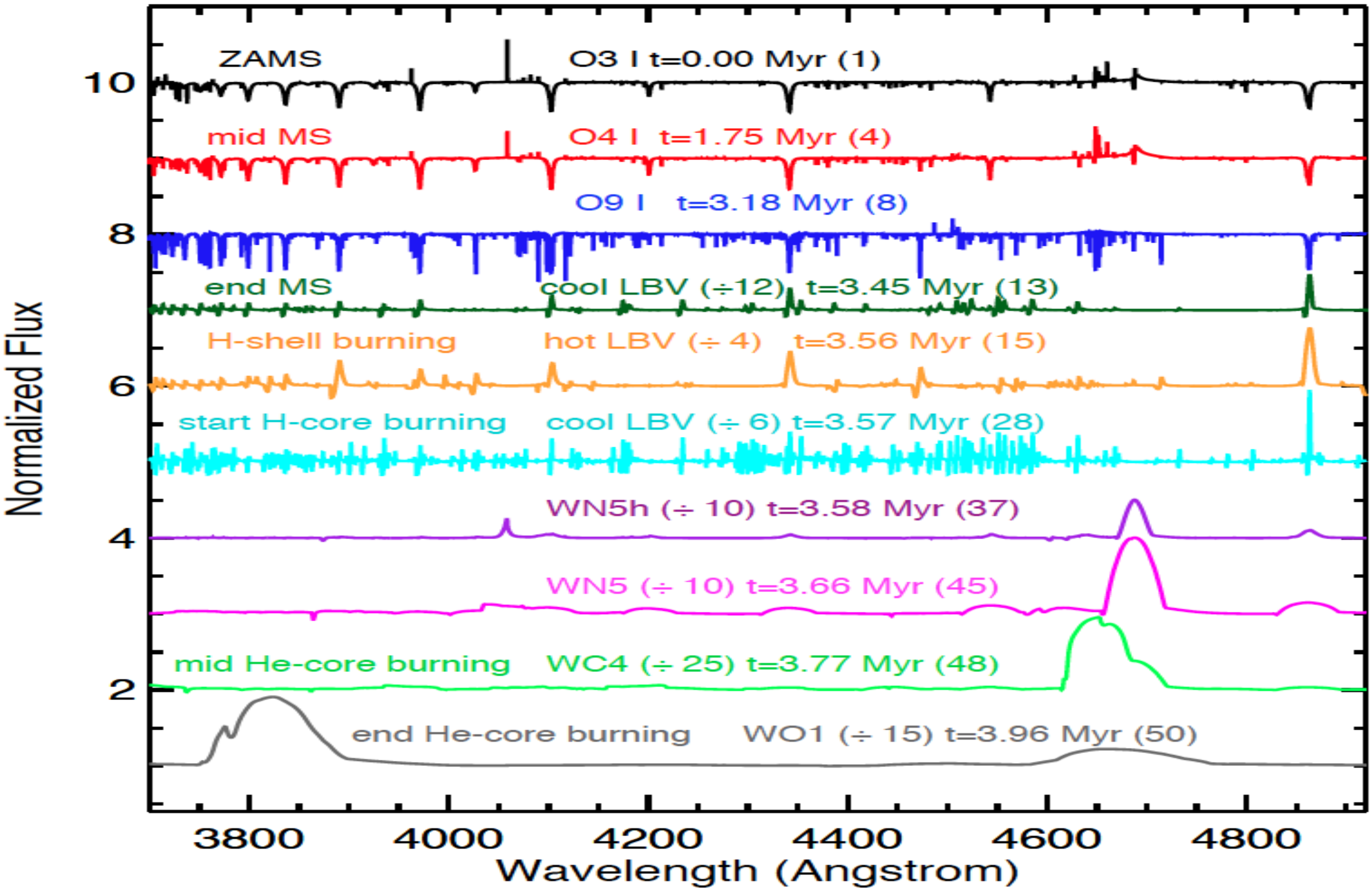

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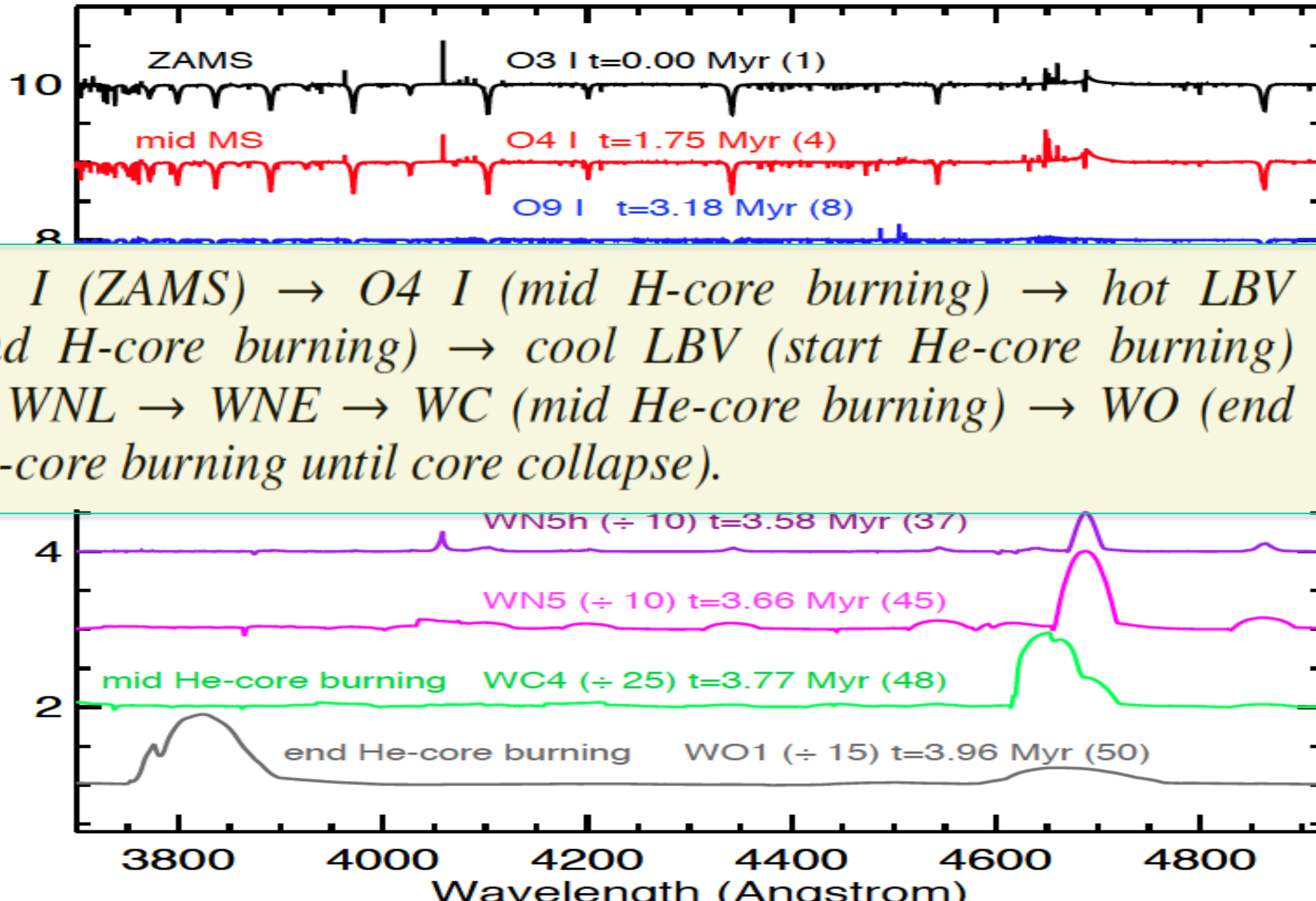
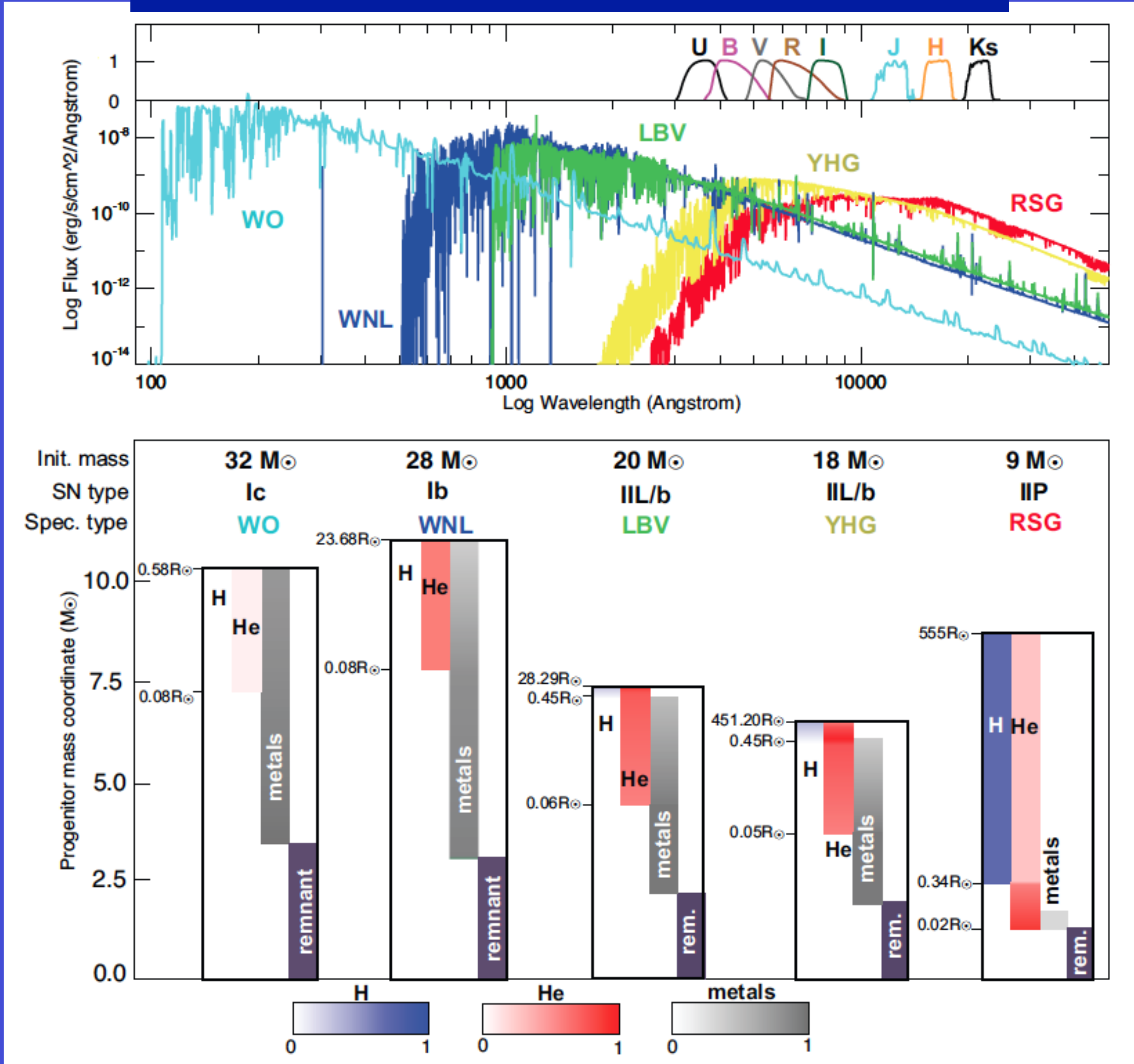


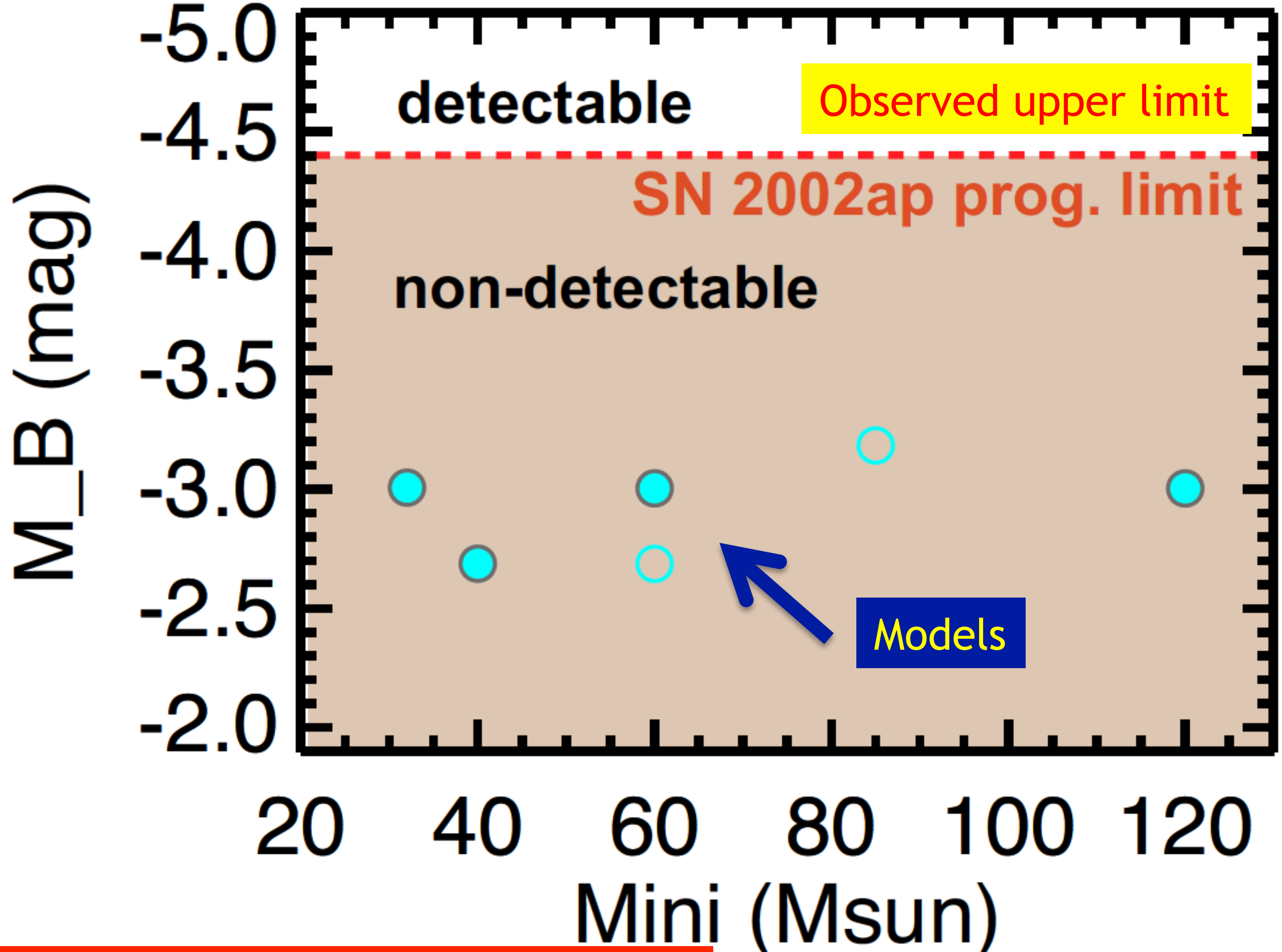
O3 I (ZAMS) → O4 I (mid H-core burning) → hot LBV (end H-core burning) → cool LBV (start He-core burning) → WNL → WNE → WC (mid He-core burning) → WO (end He-core burning until core collapse).

SPECTROSCOPIC AND PHOTOMETRIC PROPERTIES OF CORE-COLLAPSE PROGENITORS



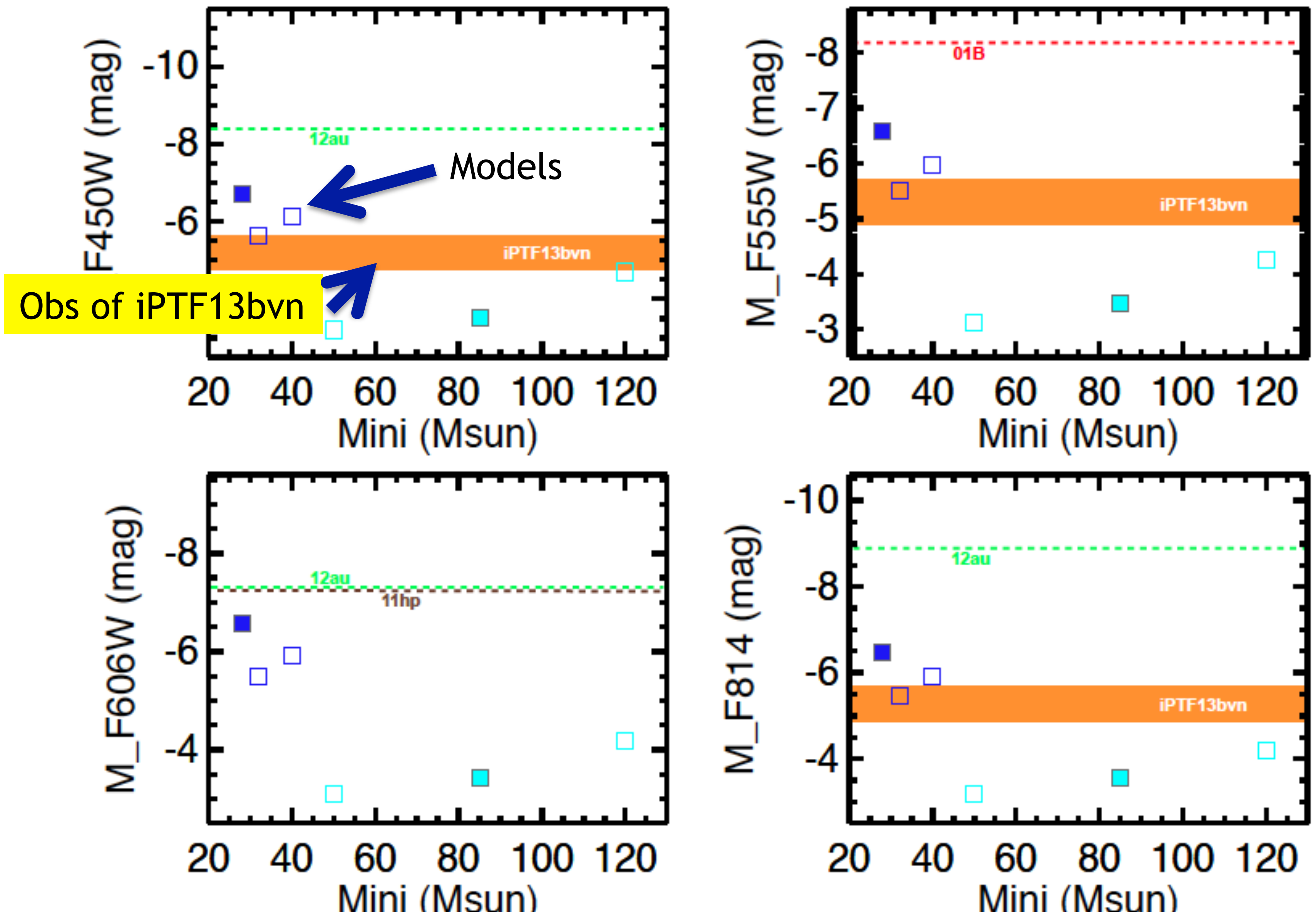
Why so few detections of type Ibc progenitors? ~13 archives images, only one detection

Pre SN are WO stars not WN or WC stars
Too low L for being detected



Groh et al, A&A in press; Yoon et al. 2012

THE ONLY PROGENITOR DETECTED SO FAR FOR A TYPE Ibc: iPTF13bvn Cao et al. 2013



Groh et al. 2013

…QUITE WELL EXPLAINED BY THEORY OF SINGLE STARS

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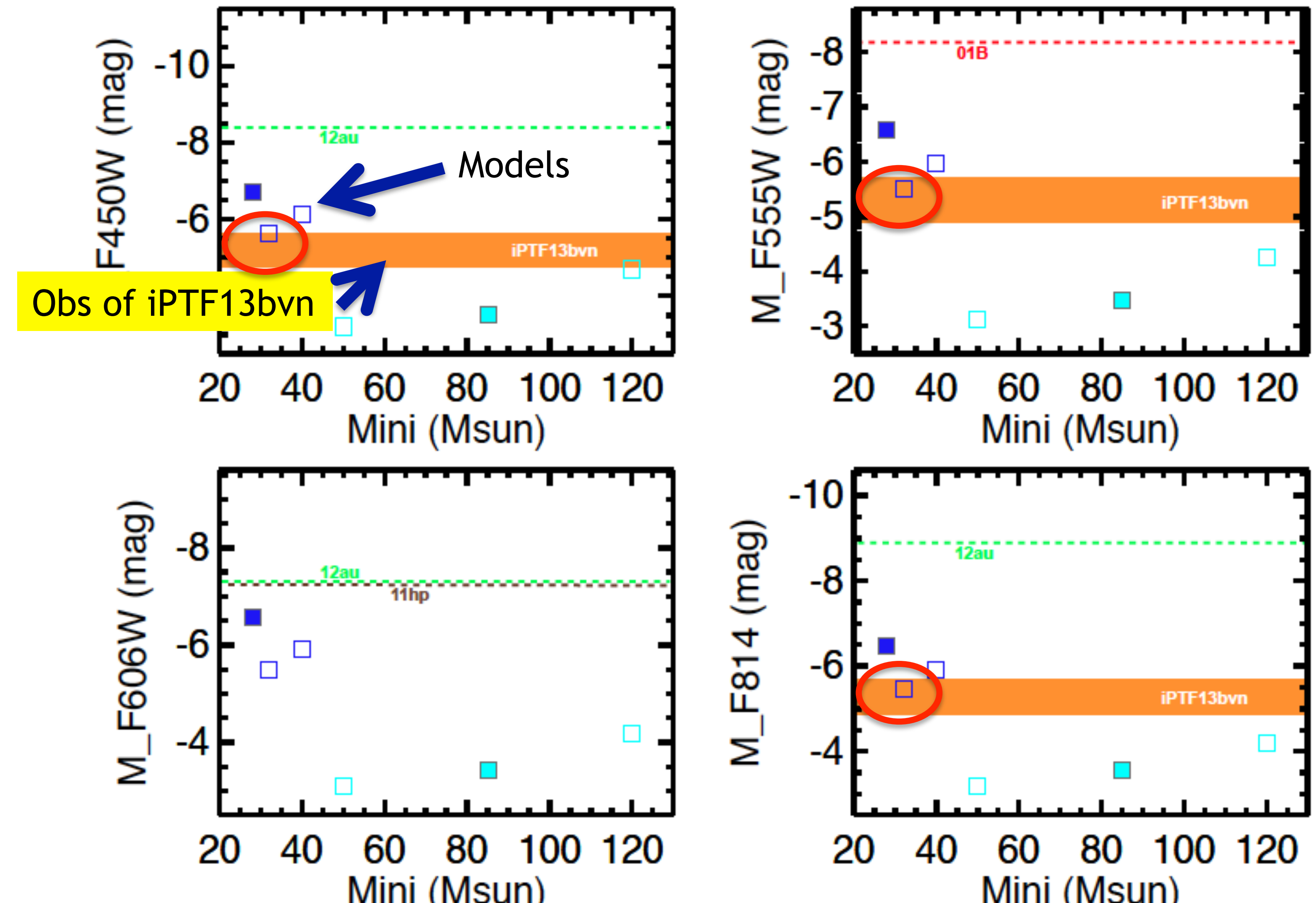
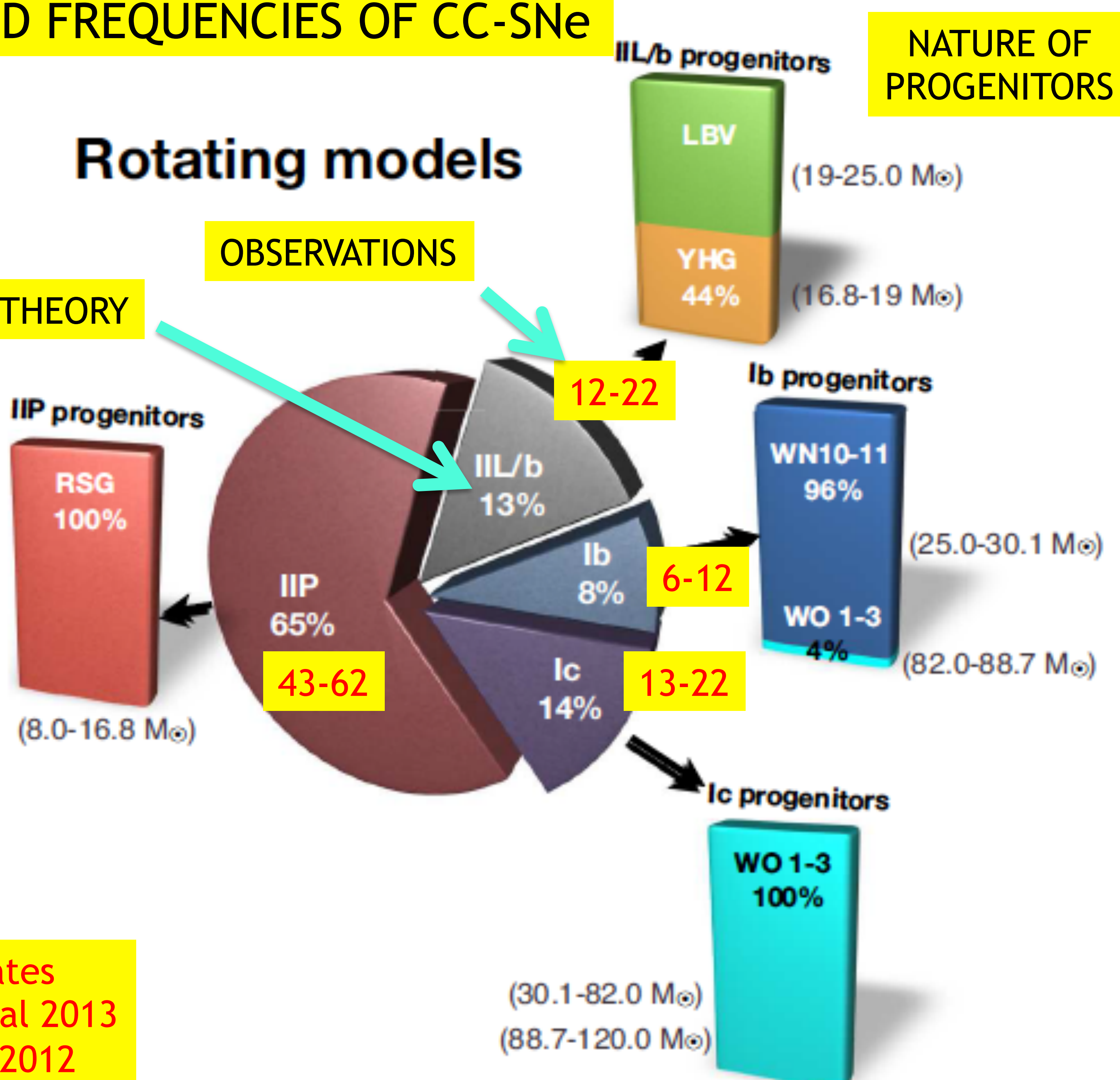


Groh et al. 2013

…QUITE WELL EXPLAINED BY THEORY OF SINGLE STARS

EXPECTED FREQUENCIES OF CC-SNe



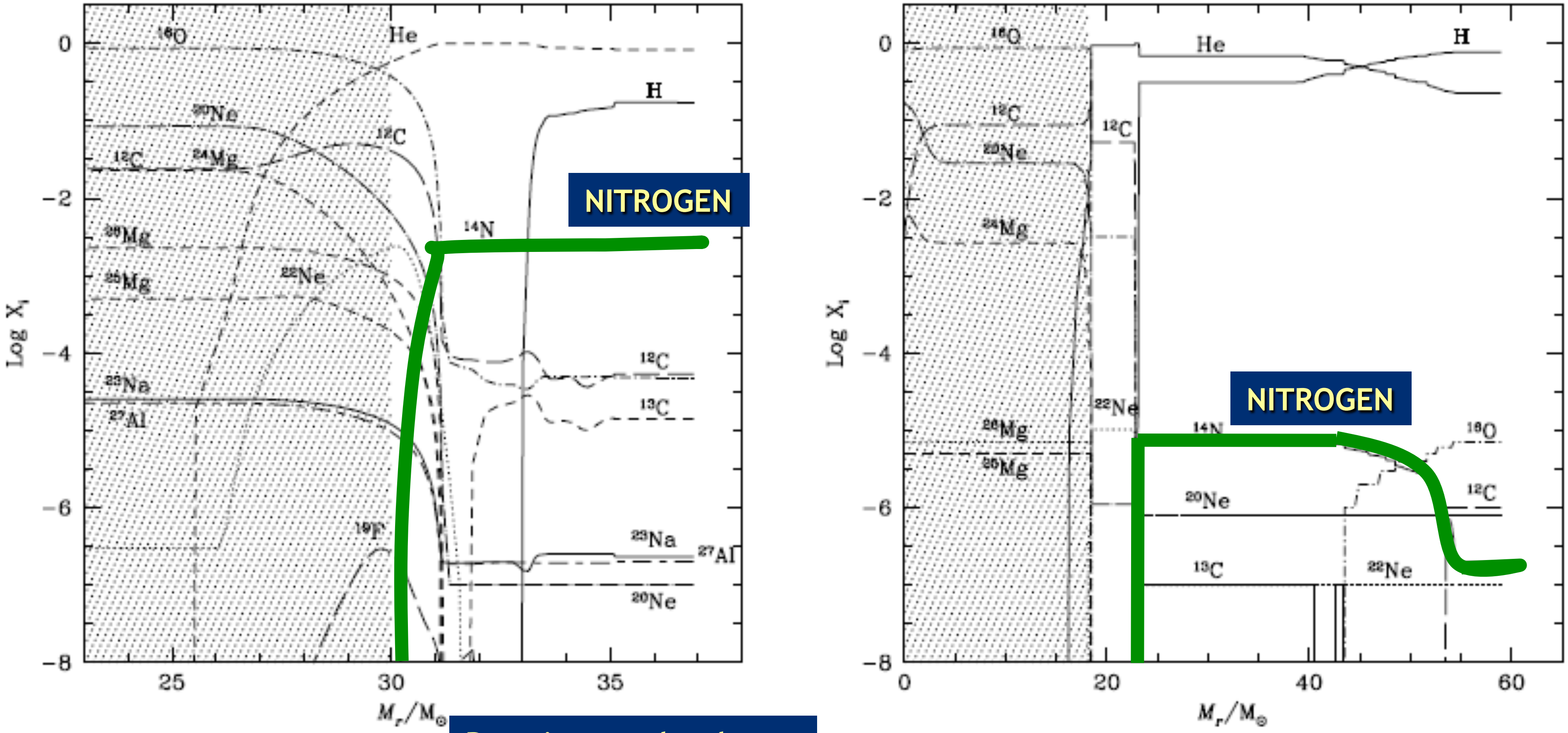
Observed rates
Eldridge et al 2013
Smith et al 2012

V/V_{crit}=0.70

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

V/V_{crit} =0

→SIMILAR MIXING IN INTERMEDIATE MASS STARS
→LOW METALLICITY REQUIRED



Rotating star has lost
Material through winds

Meynet et al. 2010

WHAT IS NEEDED FOR PRIMARY NITROGEN IN ROTATING STARS?

STRONG OMEGA GRADIENT AT THE BORDER OF THE CORE He-BURNING CORE
AT A TIME WHEN mu-GRADIENTS ARE STILL NOT TOO STRONG
→ EARLY PHASES OF CORE He-BURNING

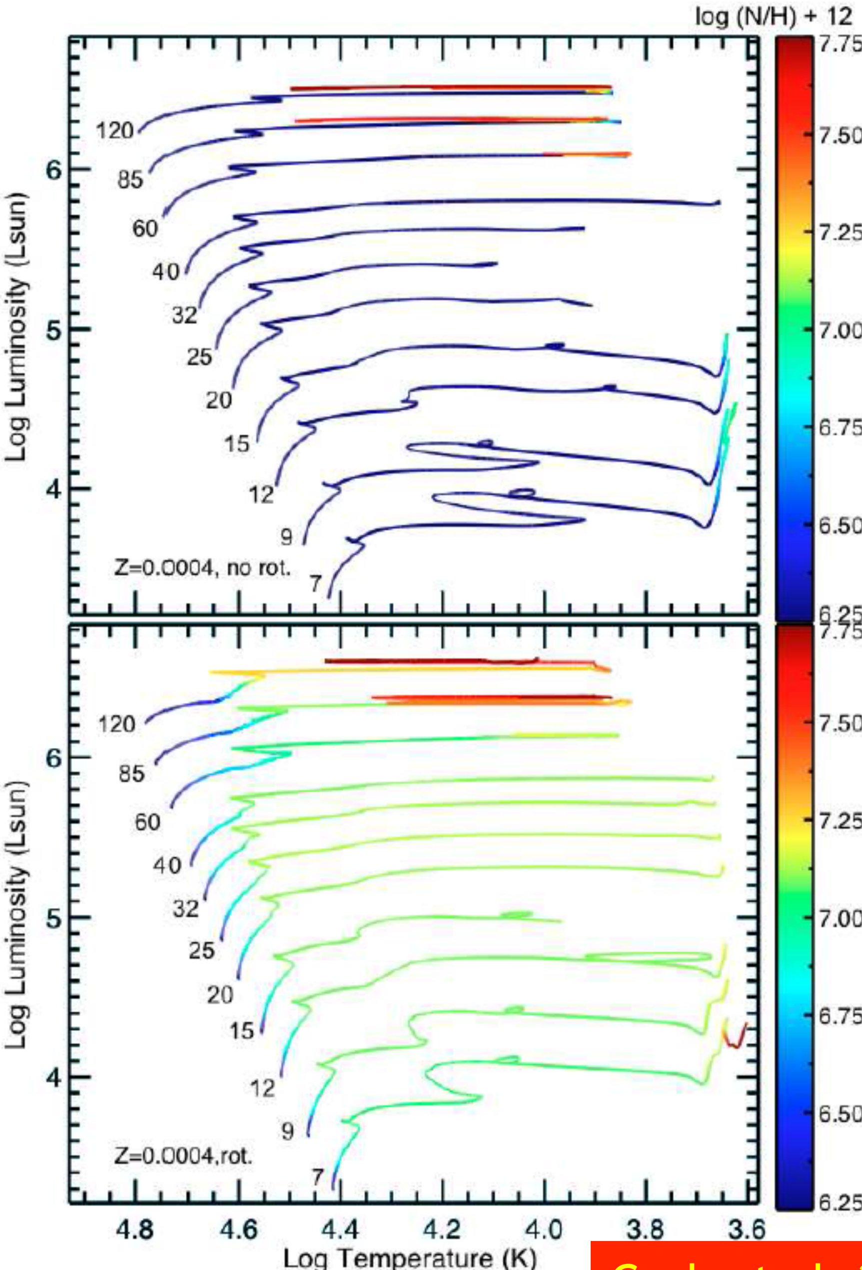
AT LOW- Z→ stars more compact→ shorter timescales

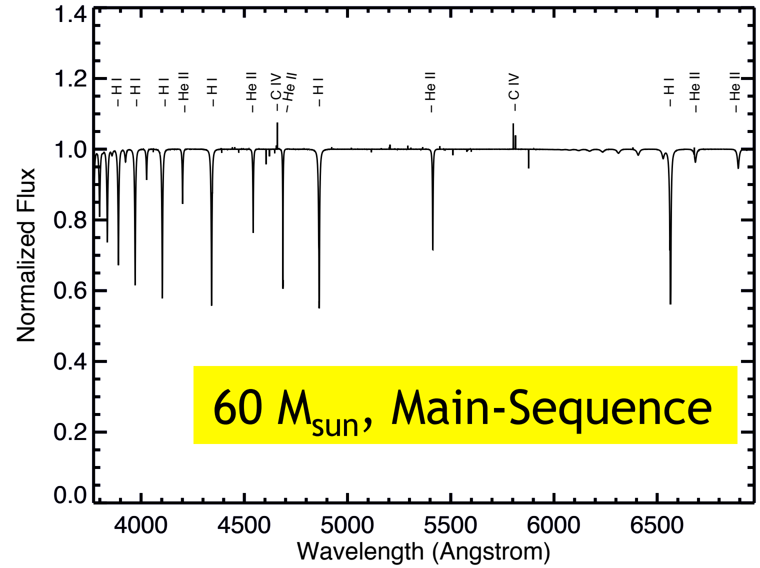
AT LOW- Z→ more angular momentum is retained in the core

AT Z=0→ less efficient N prodution because less contraction at the end MS phase

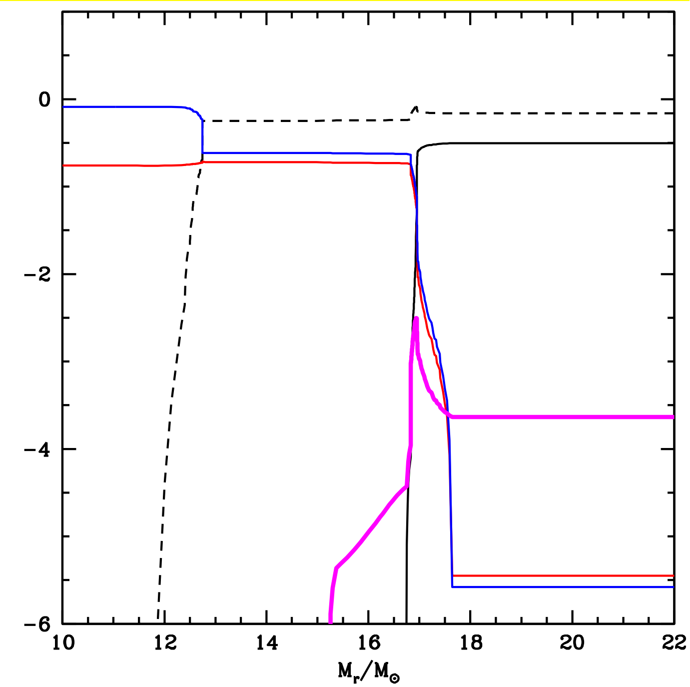
AT high Z→less efficient N production because…
→ shallower gradients and longer timescales

Z=0.0004, typical Z of I Zw18





40 M_{sun}, pre-SN, <v>~350 km s^{-1}



Groh et al. 2013

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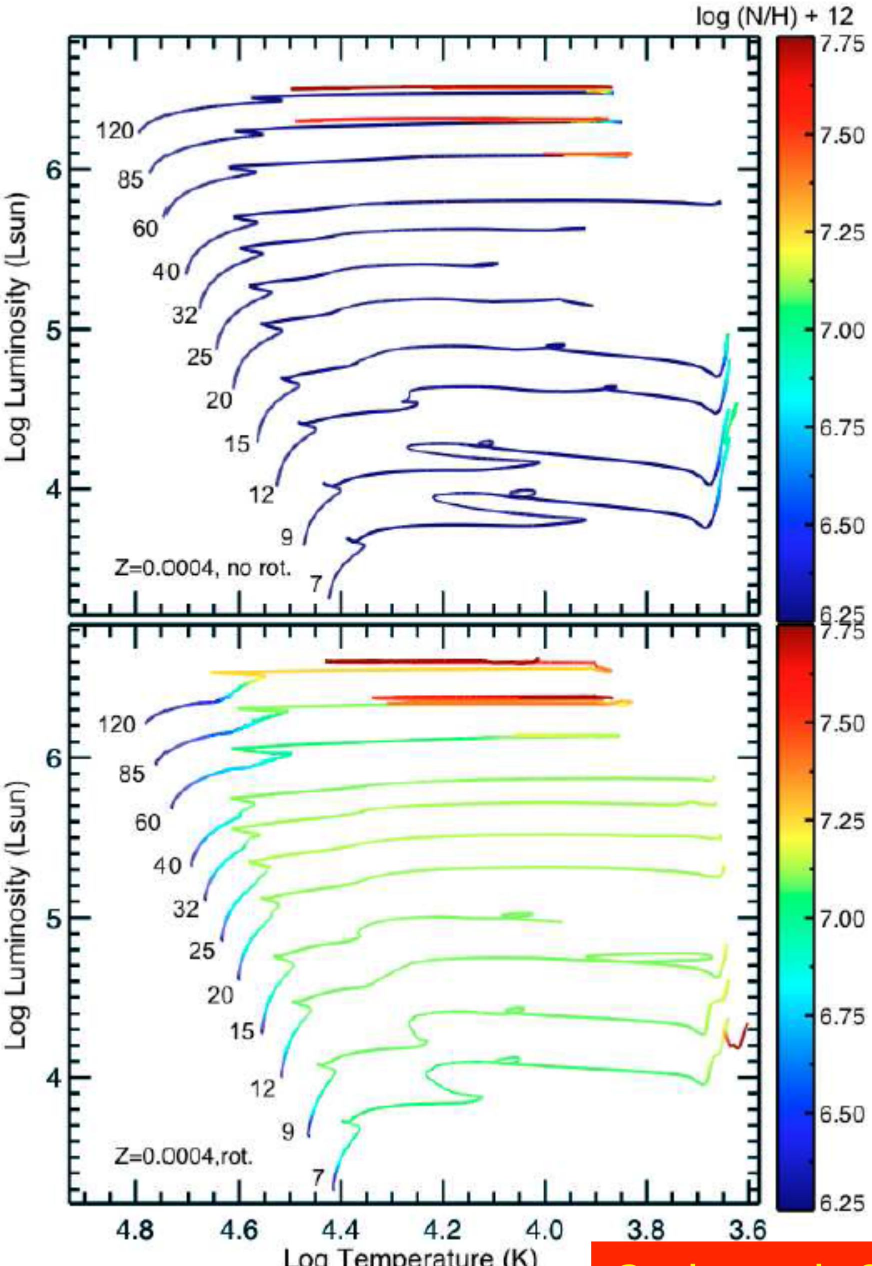

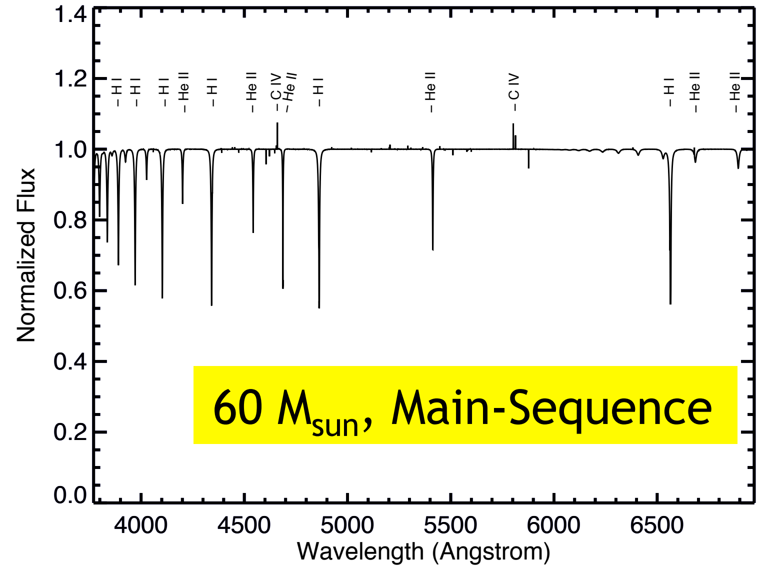

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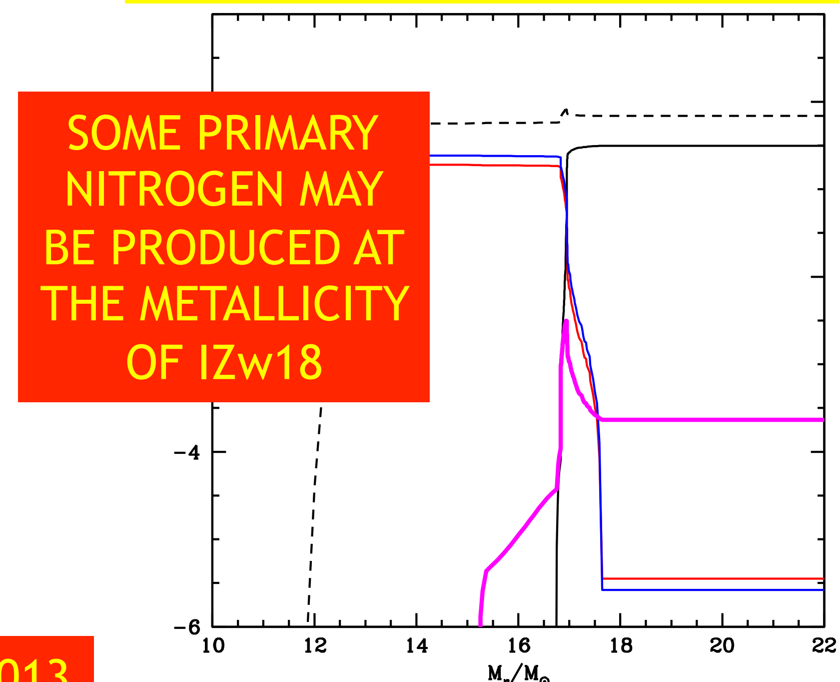


Groh et al. 2013

IMPACT OF VARIOUS PRESCRIPTIONS

$D_{\rm shear}$ from Maeder (1997, M97)

$$D_{\rm shear} = f_{\rm energ} \frac{H_P}{g\delta} \frac{K}{\left[\frac{\varphi}{\delta}\nabla_\mu + (\nabla_{\rm ad} - \nabla_{\rm rad})\right]} \left(\frac{9\pi}{32}\,\Omega\,\frac{{\rm d}\ln\Omega}{{\rm d}\ln r}\right)^2$$

where $K = \frac{4ac}{3\kappa}\frac{T^4\nabla_{\rm ad}}{\rho P\delta}$, and with $f_{\rm energ} = 1$, and $\varphi = \left(\frac{{\rm d}\ln\rho}{{\rm d}\ln\mu}\right)_{P,T} = 1$.

$D_{\rm shear}$ from Talon & Zahn (1997, TZ97)

$$D_{\rm shear} = f_{\rm energ} \frac{H_P}{g\delta} \frac{(K + D_{\rm h})}{\left[\frac{\varphi}{\delta}\nabla_\mu\left(1 + \frac{K}{D_{\rm h}}\right) + (\nabla_{\rm ad} - \nabla_{\rm rad})\right]} \left(\frac{9\pi}{32}\,\Omega\,\frac{{\rm d}\ln\Omega}{{\rm d}\ln r}\right)^2$$

with K, $f_{\rm energ}$, and φ as in (1).

$D_{\rm h}$ from Zahn (1992, Z92)

$$D_{\rm h} = \frac{1}{c_{\rm h}}\, r\, |2V(r) - \alpha U(r)| \qquad (5)$$

where $\alpha = \frac{1}{2}\frac{{\rm d}\ln(r^2\Omega)}{{\rm d}\ln r}$ and $c_{\rm h} = 1$.

$D_{\rm h}$ from Maeder (2003, M03)

$$D_{\rm h} = A\, r\, \left(r\Omega(r)\, V\, |2V - \alpha U|\right)^{1/3} \qquad (6)$$

with α as in Eq. (5) and $A = 0.002$.

$D_{\rm h}$ from Mathis et al. (2004, MZ04)

$$D_{\rm h} = \left(\frac{\beta}{10}\right)^{1/2} \left(r^2\Omega\right)^{1/2} \left(r\,|2V - \alpha U|\right)^{1/2} \qquad (7)$$

with α as in Eq. (5) and $\beta = 1.5 \cdot 10^{-6}$.

40 $M_{\rm sun}$, Z=0.00001, V(ini)= 700 km s^{-1}

Meynet et al. 2013

All models produce primary nitrogen

In most of cases (4/6), the quantities of primary nitrogen produced is about 10 times the initial content of CNO in the ejected mass.

IF MIXING IS TOO EFFICIENT → FLATTENING ALSO OF OMEGA→ LESS PRIMARY N

Some Possible Consequences

Mass loss triggered by rotation even in Pop III stars

Ekström et al. 2008

Origin of primary nitrogen, ^{13}C, ^{22}Ne in the early phases of the chemical evolution of galaxies

Meynet et al. 2006;
Chiappini et al. 2005, 2006, 2008
Cescutti and Chiappini 2010

Origin of the CEMP stars (at least the CEMP-no :no s-elements)

Meynet et al. 2006, 2010

Origin of the O-Na anticorrelation in globular clusters

Decressin et al. 2007ab

Origin of the high He-abundance in some stars in globular clusters

Maeder and Meynet 2006; Charbonnel et al. 2013

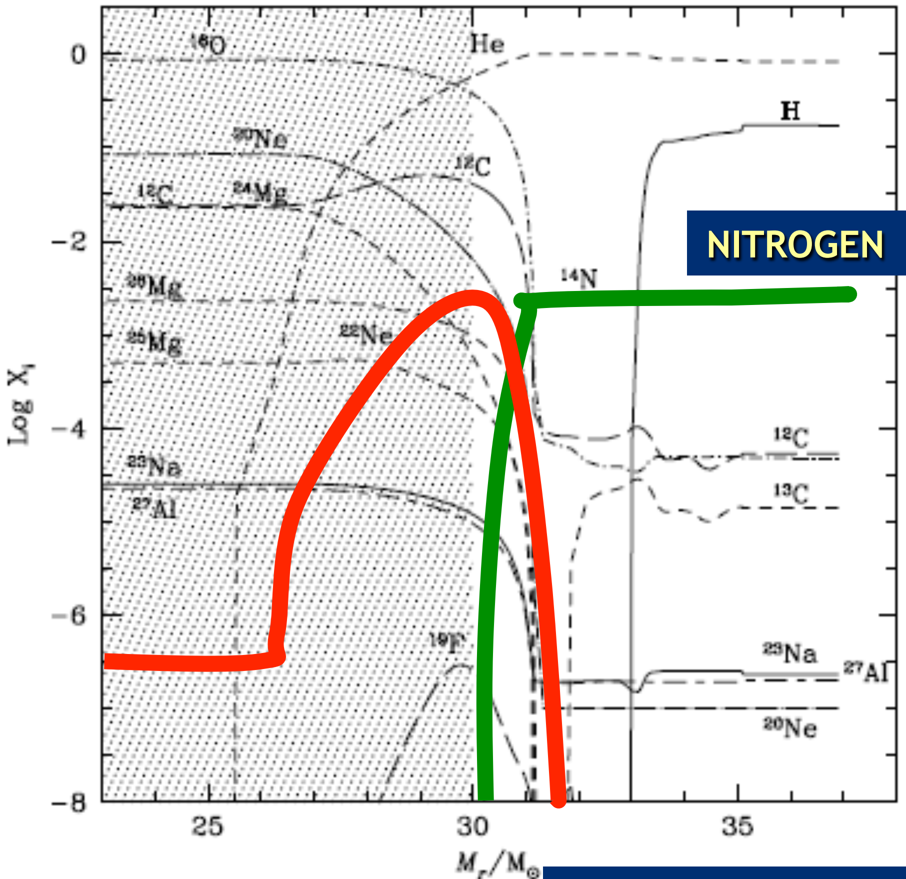
New s-process in massive metal poor rotating stars

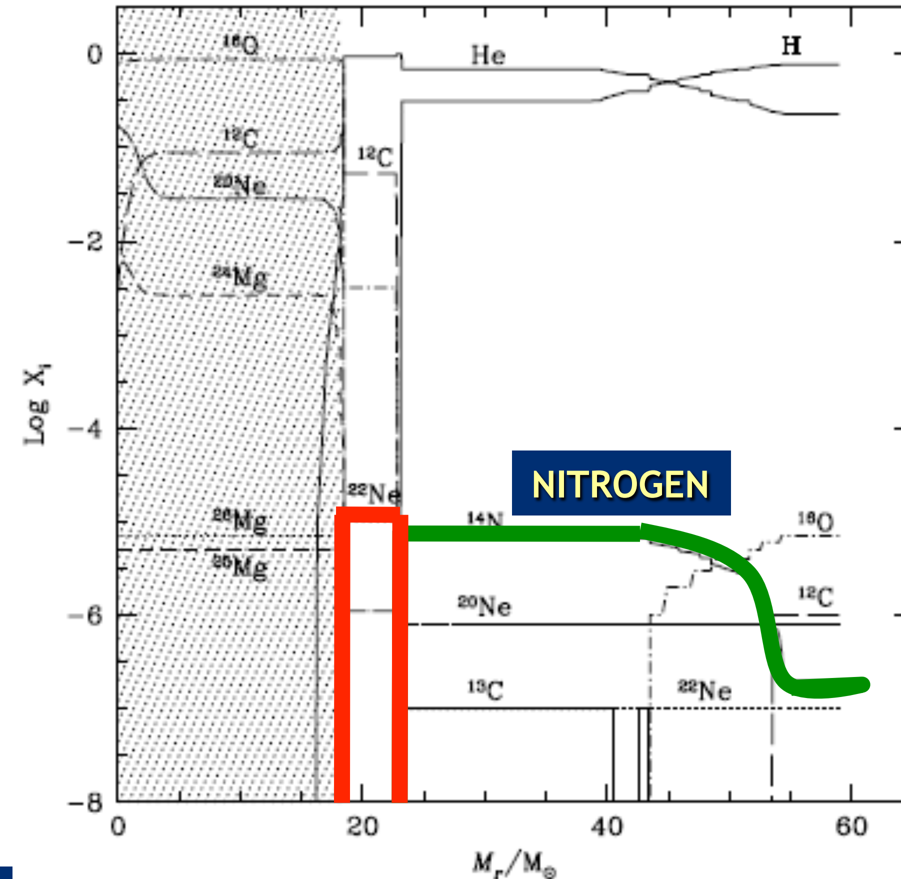
Pignatari et al. 2008; Chiappini et al. 2011;
Frischknecht et al. 2012; Cescutti et al. 2013

Primary-like evolution of Be and B

Prantzos 2012

$V/V_{crit}=0.70$ | $60\ M_{sun},\ Z=10^{-5}$ | $V/V_{crit}=0$





Rotating star has lost
Material through winds

NON-STANDARD S-PROCESS IN ROTATING MASSIVE STARS

-Integration in the Geneva stellar models of nuclear networks
with 613 isotopes up to end He-burning
with 737 isotopes from He-burning on.

Reaction library (REACLIB) from Rauscher & Thielemann (2000)

Table 3.1: Important reaction rates for the s process

Nuclear reaction	Rate source
$^{22}Ne(\alpha,n)^{25}Mg$	Jaeger et al. (2001)
$^{22}Ne(\alpha,\gamma)^{26}Mg$	NACRE
$^{14}N(\alpha,\gamma)^{18}F$	NACRE
$^{18}O(\alpha,\gamma)^{22}Ne$	NACRE
$^{17}O(\alpha,n)^{20}Ne$	NACRE
$^{17}O(\alpha,\gamma)^{21}Ne$	Caughlan & Fowler (1988)
$^{13}C(\alpha,n)^{16}O$	NACRE
$^{12}C(\alpha,\gamma)^{16}O$	Kunz et al. (2002)
$^{4}He(2\alpha,\gamma)$	Fynbo et al. (2005)
(n,γ) - experimental	KADoNiS v0.2/v0.3
(n,γ) - theoretical	Rauscher & Thielemann (2000)
β^- - constant	bet-/Nuclear Wallet Cards 7th Ed.
β^- - T-dependent	Takahashi & Yokoi (1987)/Goriely (1999)

Frischknecht 2011, PhD Thesis, Basel

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Karakas et al. 2006 lower

Descouvement 1993 lower

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Karakas et al. 2006 lower

Descouvement 1993 lower

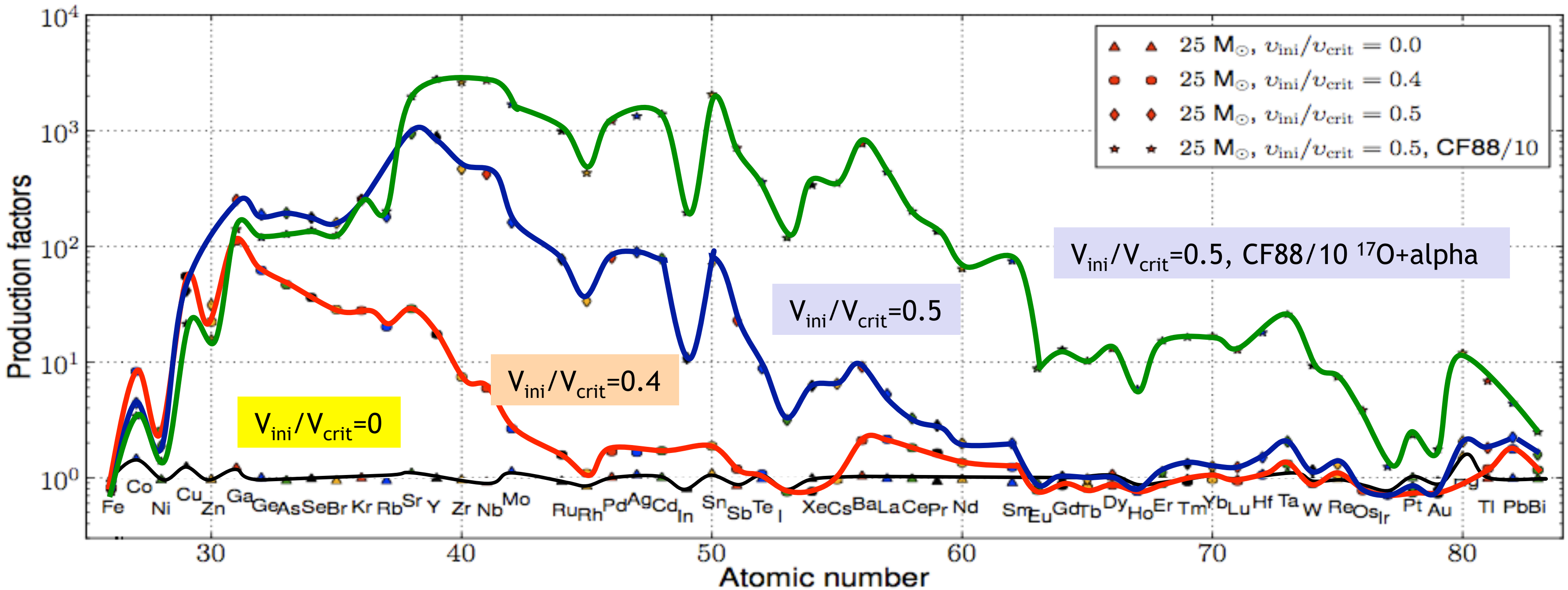
RESULTS LIKELY
ARE UNDERESTIMATED

Frischknecht 2011, PhD Thesis, Basel

NON-STANDARD S-PROCESS IN ROTATING MASSIVE STARS

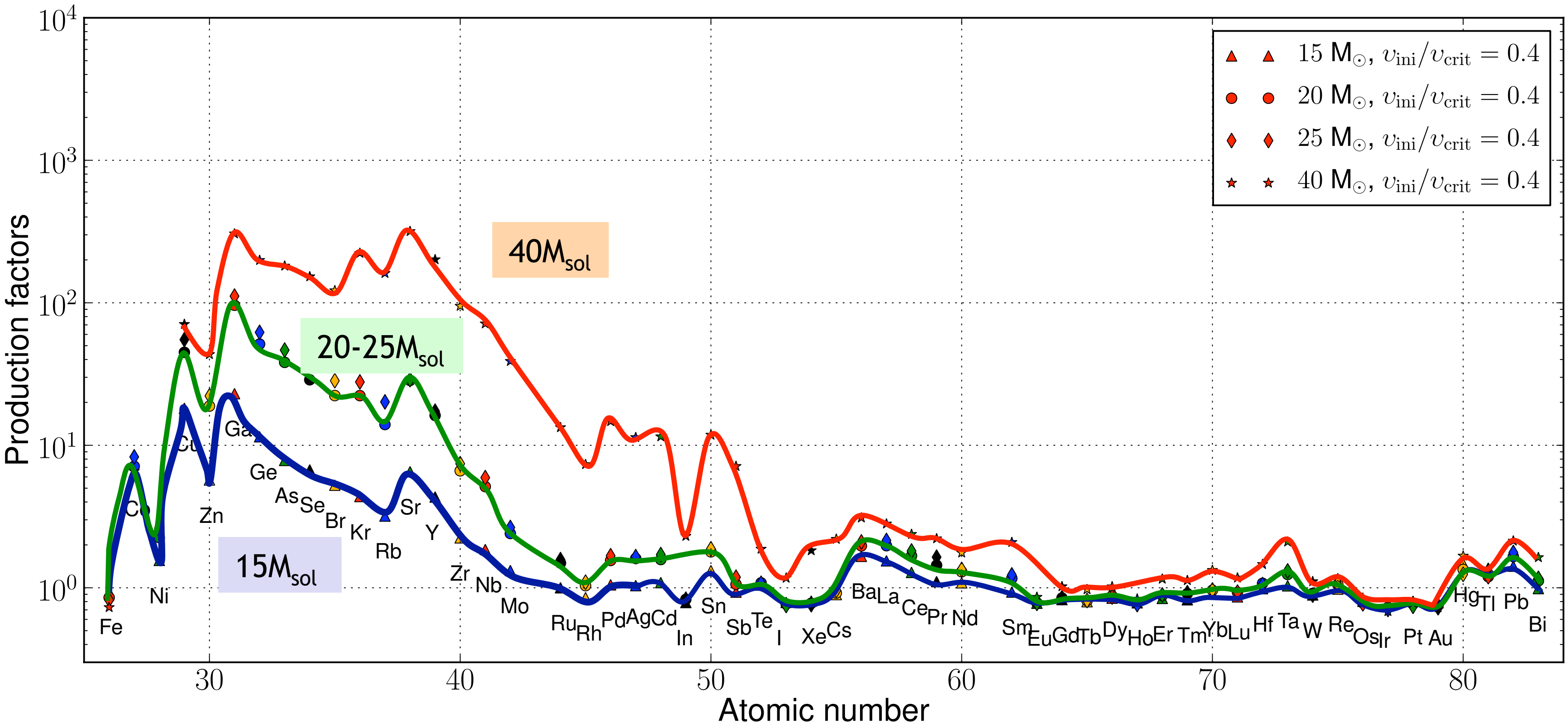
Horizontal shear diffusion coefficient Zahn (1992)
Vertical shear diffusion coefficient Talon & Zahn (1997)

$25\ M_{sol}$, $Z=10^{-5}$



Frischknecht, Hirshi and Thielemann (2012, A&A Letter)

$Z=10^{-5}$, V_{ini}/V_{crit} =0.4



Frischknecht et al. 2012

The details are making the perfection and the perfection is not a detail.

Léonard de Vinci

Extrait des carnets

Some Possible Consequences

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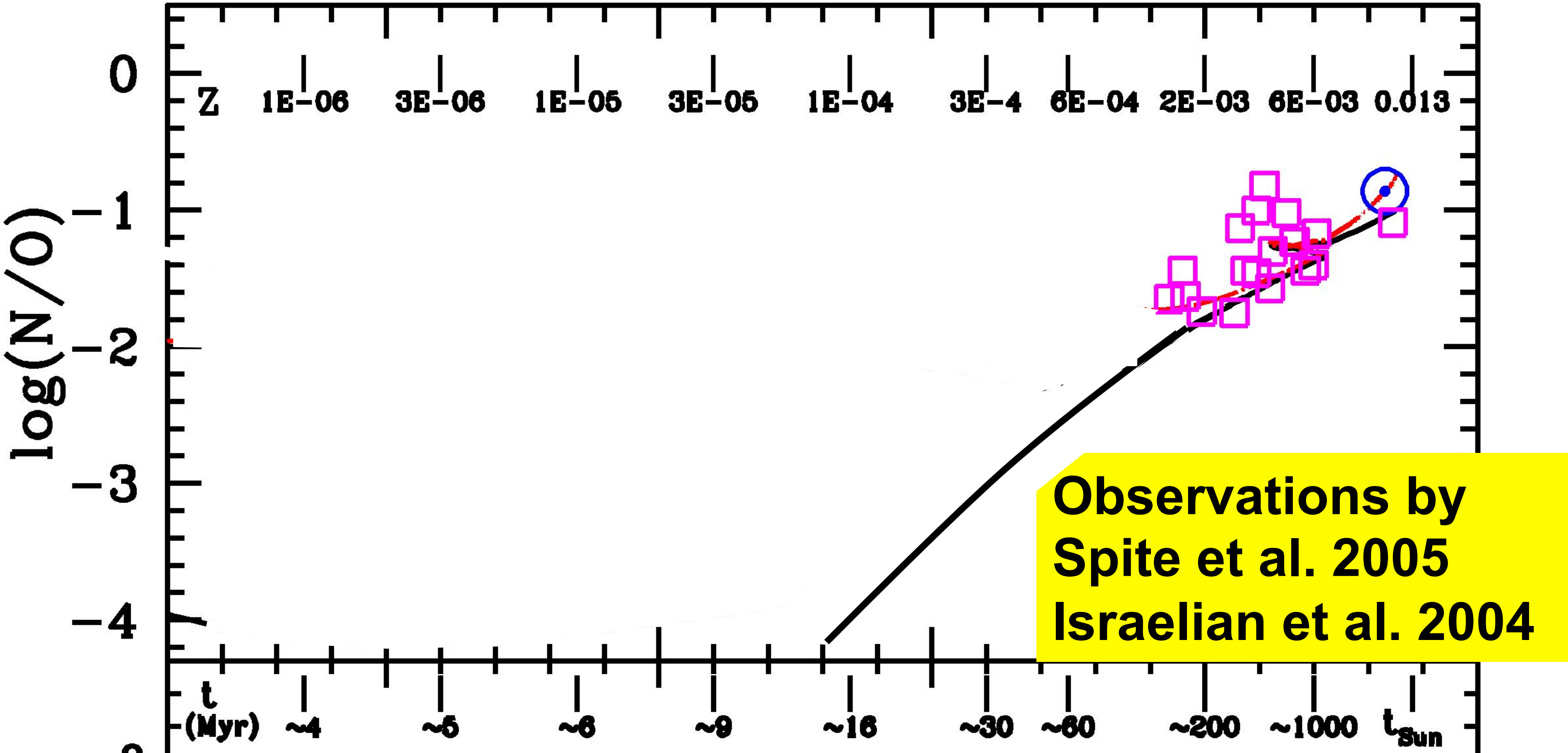
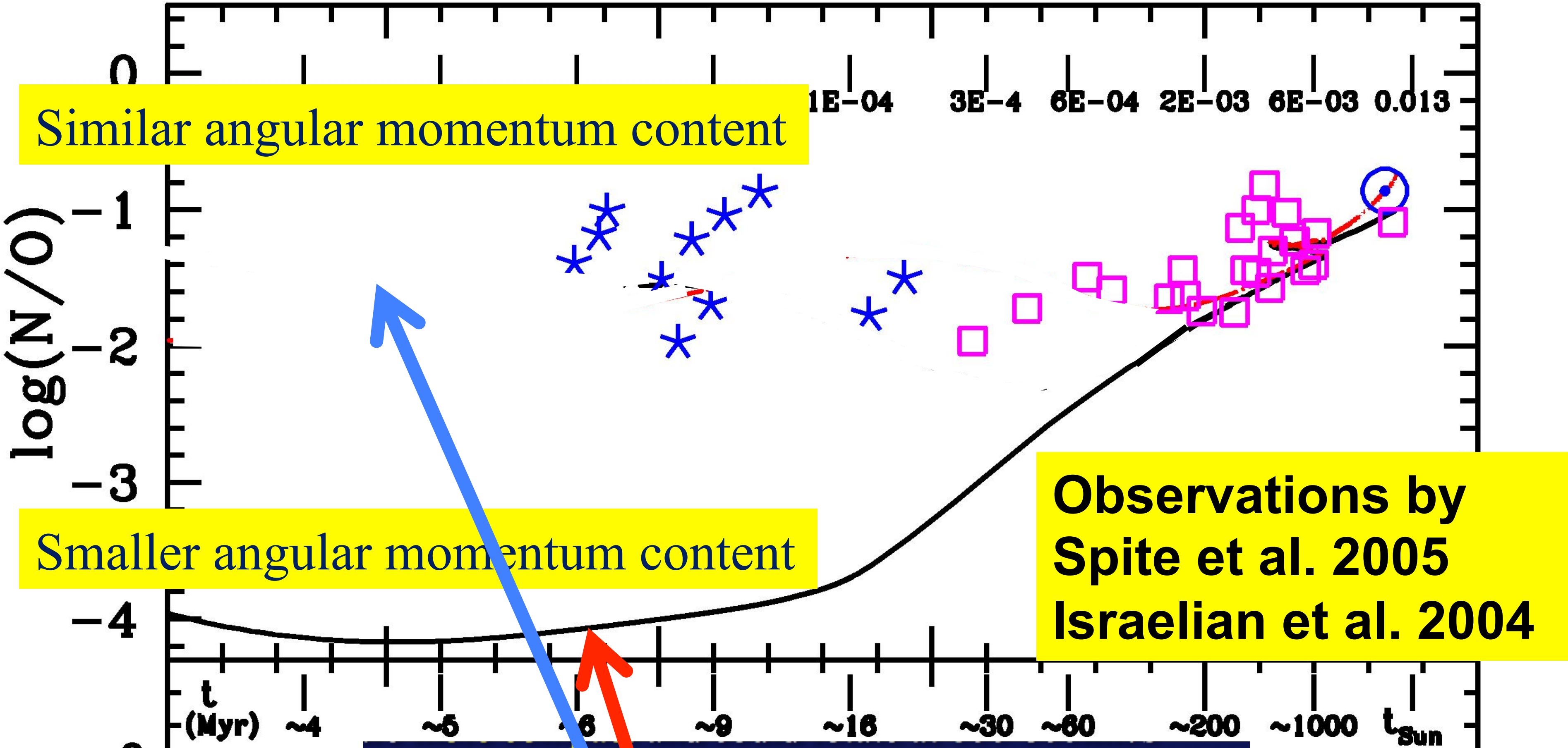
Prantzos 2012

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



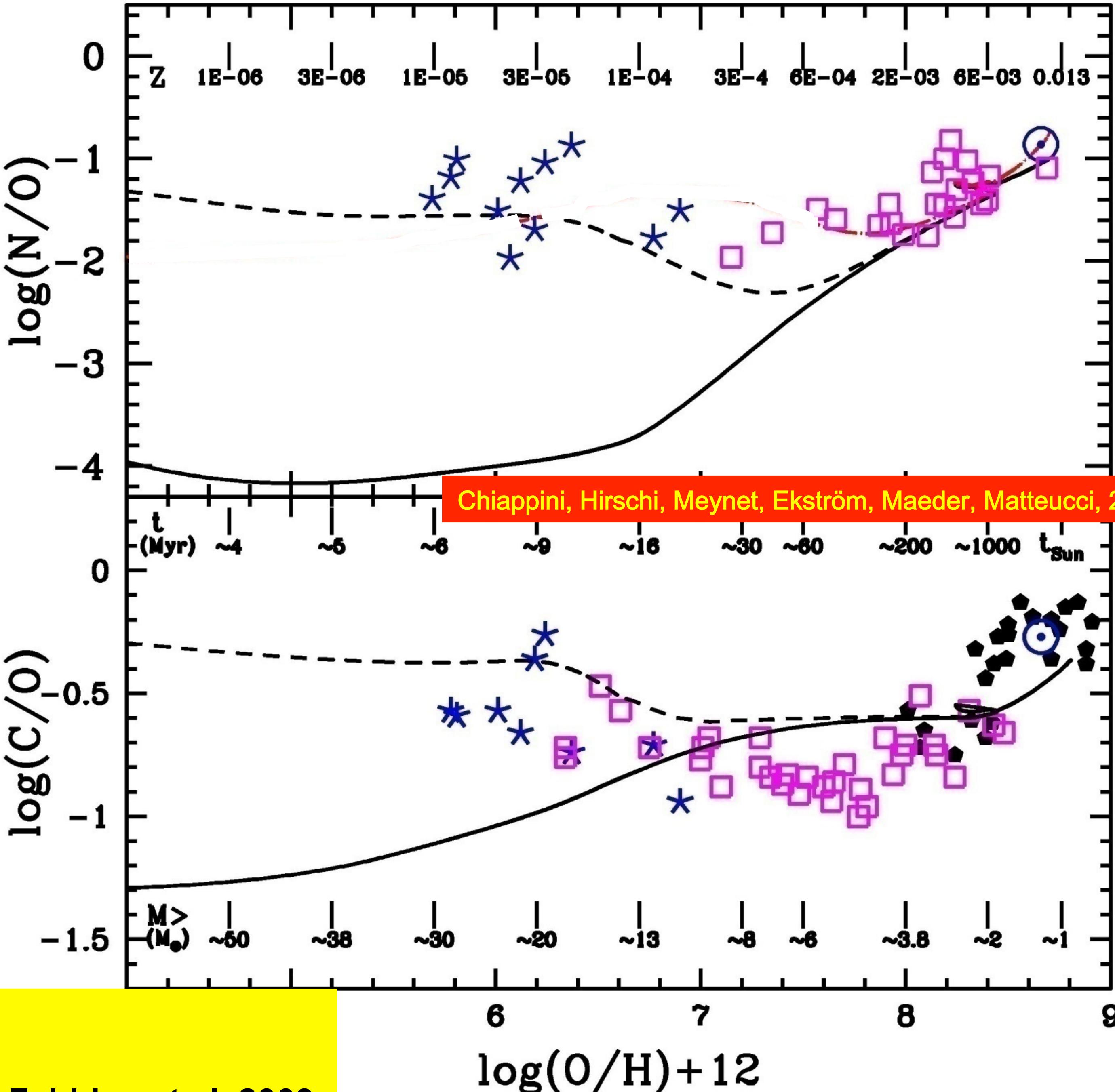
Chiappini, Hirschi, Meynet, Ekström, Maeder, Matteucci, (2006)



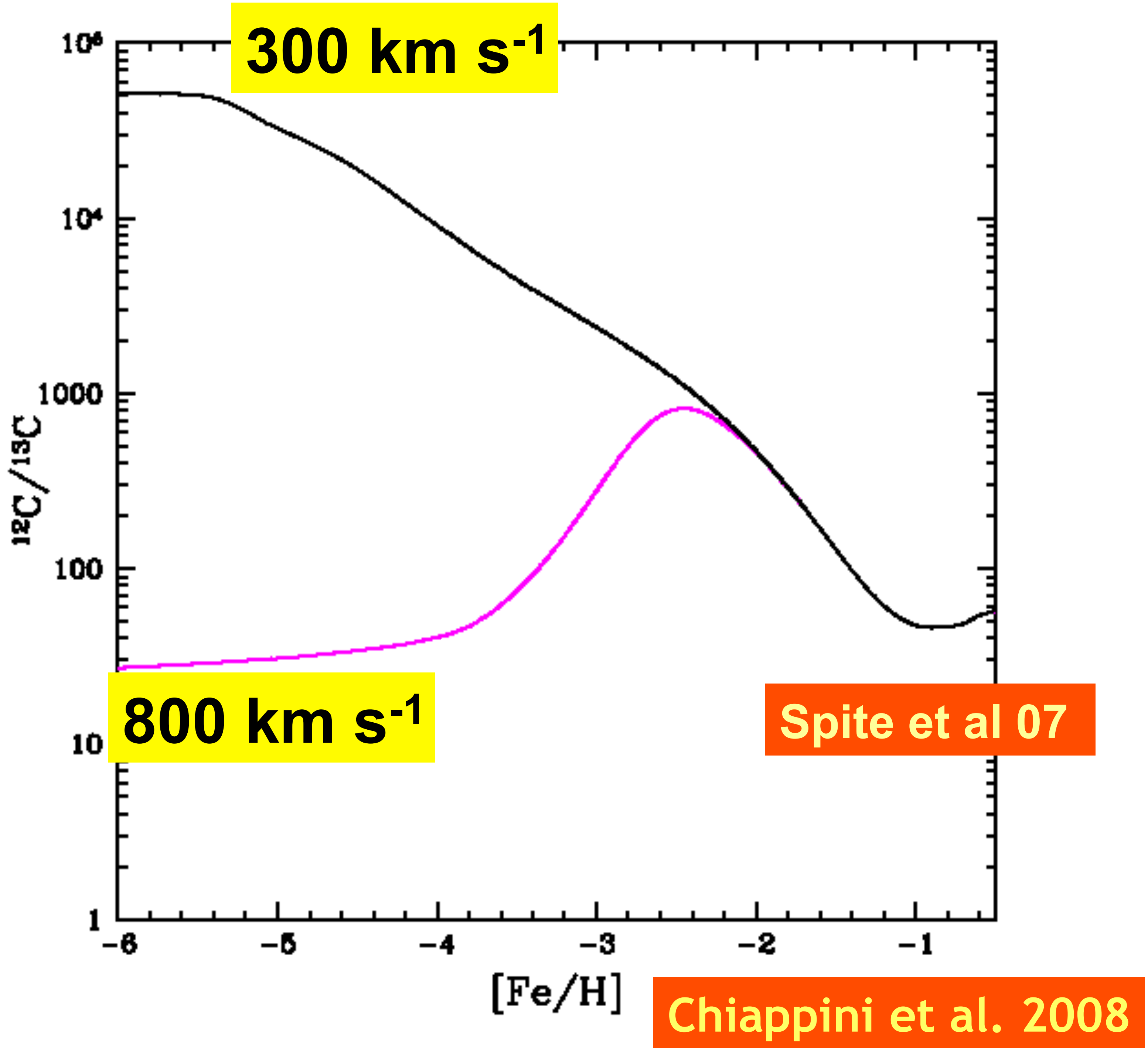
(Hirschi 2007)

M_{ini} = 20 M_{sun}: V_{ini}	Z_{ini}	J_{ini} [10^{53} erg s]
300	solar	0.36
300	10^{-8}	0.18
600	10^{-8}	0.33

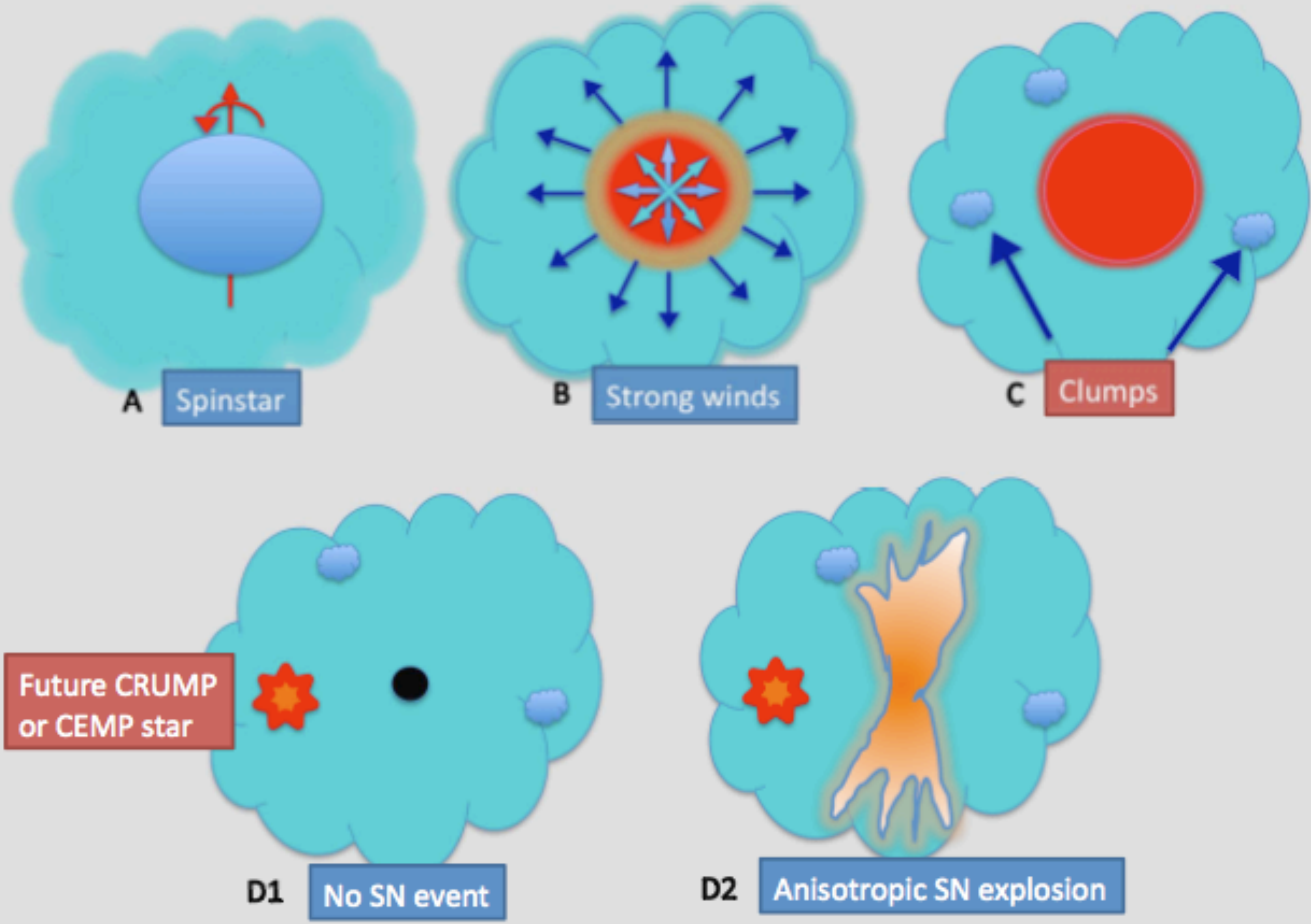
C/O



Observations from
Spite et al. 2005
Akerman et al. 2004
Nissen 2004; see also Fabbian et al. 2009



300 km s-1
800 km s-1
Spite et al 07
Chiappini et al. 2008
12C/13C
[Fe/H]

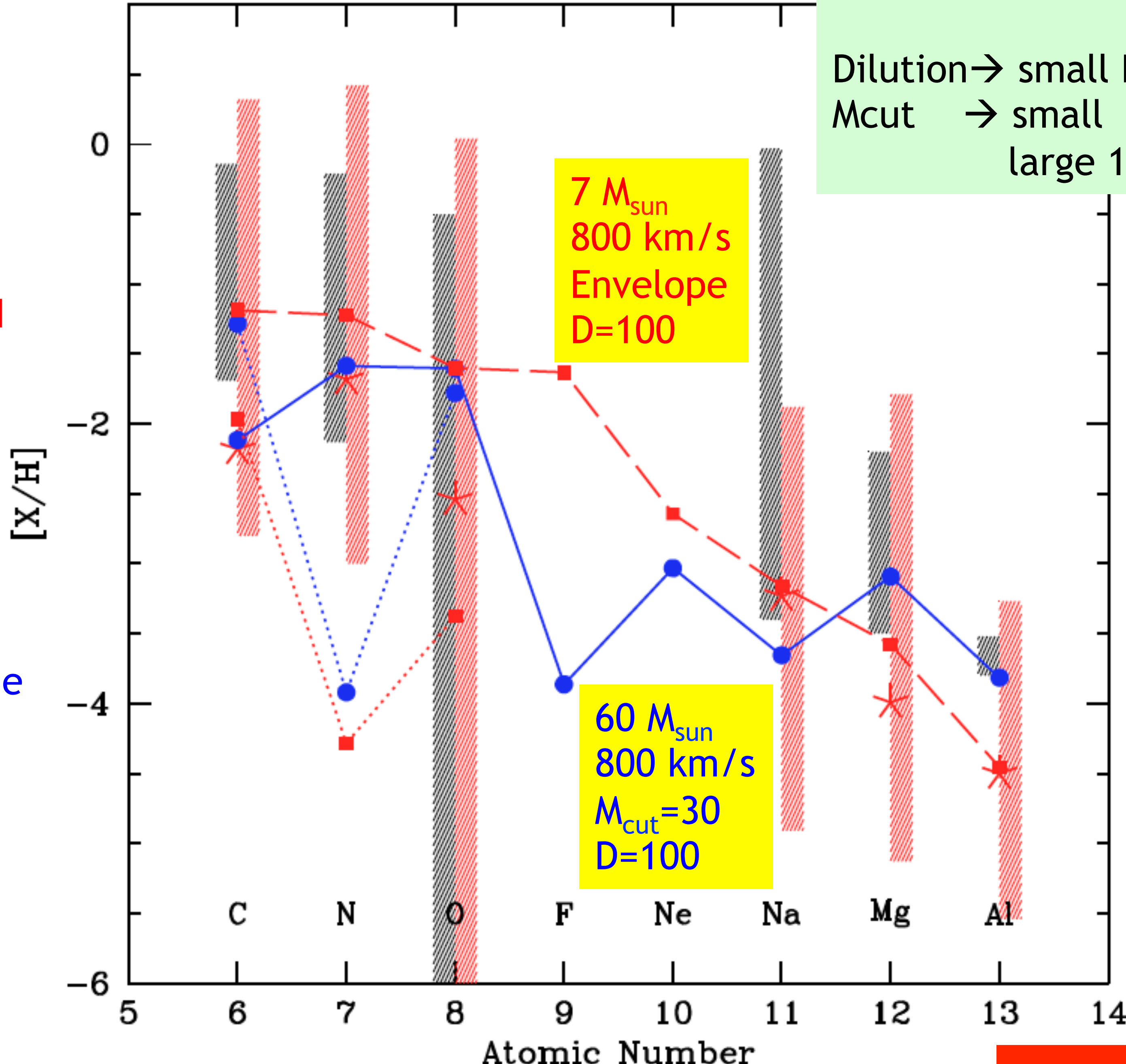

A
Spinstar
B
Strong winds
C
Clumps
Future CRUMP
or CEMP star
D1
No SN event
D2
Anisotropic SN explosion

Massive stars

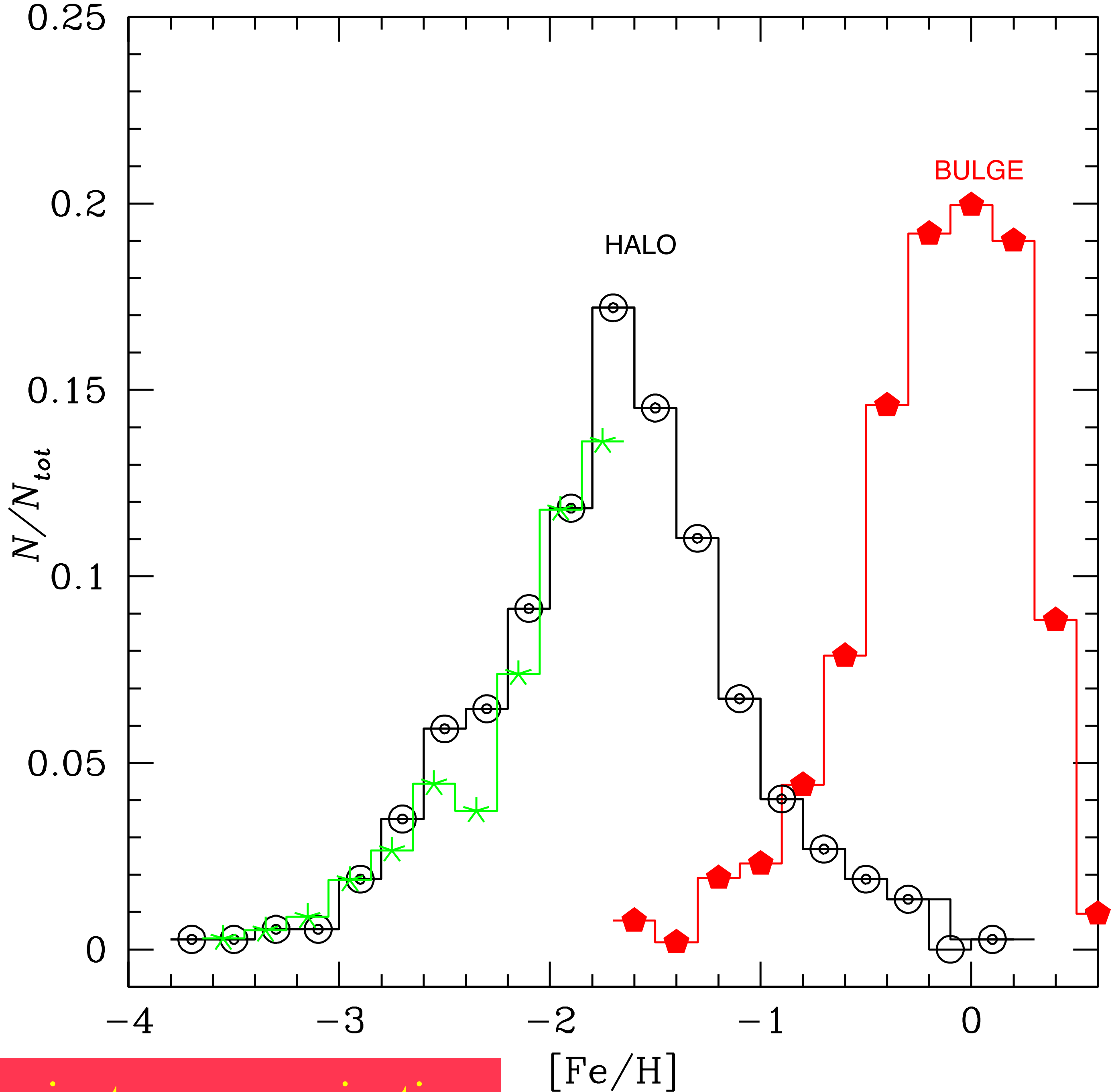
Dilution → small He-rich
Mcut → small N/C, N/O
large 12C/13C

Dotted red
7 M_{sun}
0 km/s
Envelope
D=100

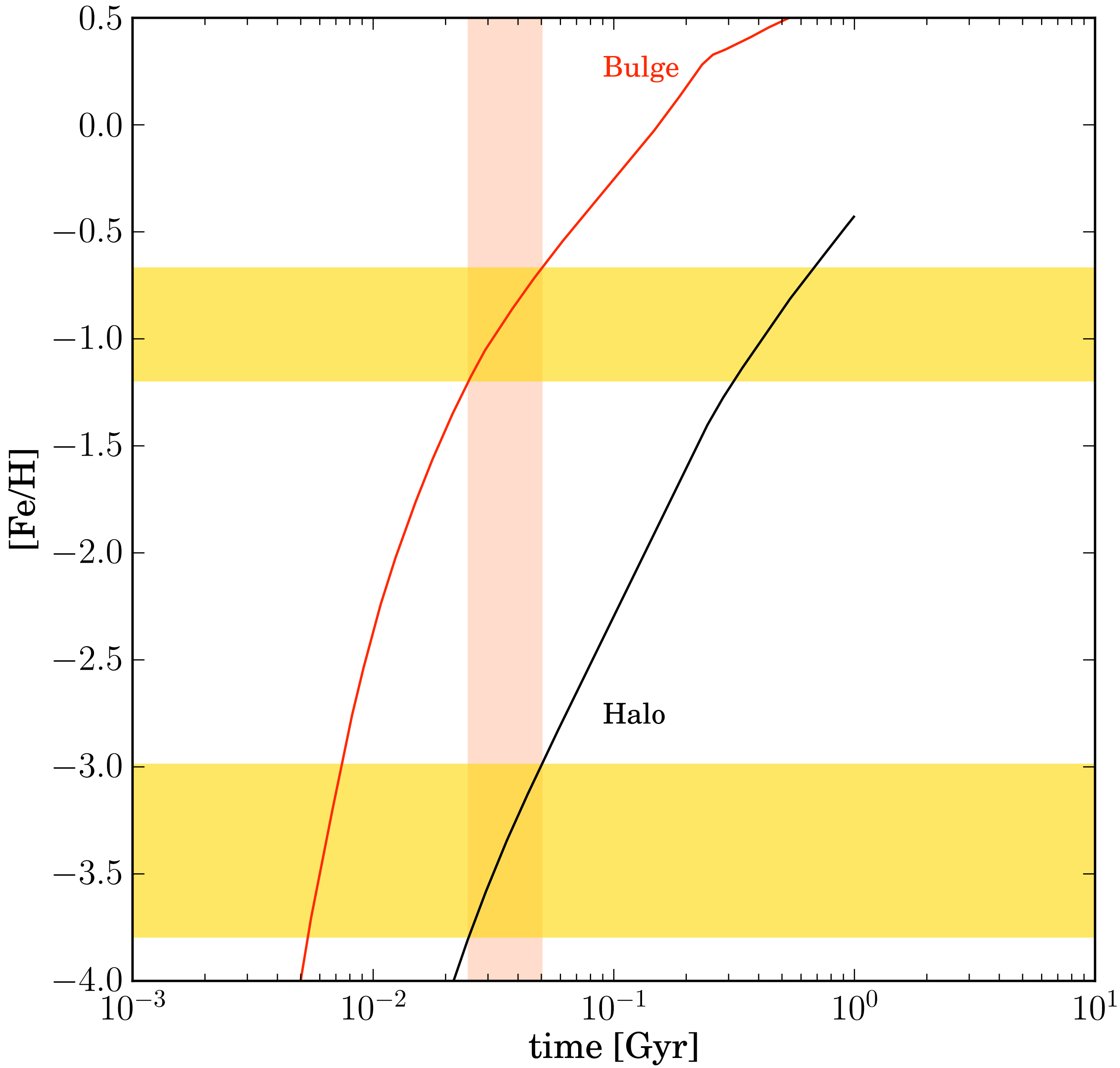
Dotted blue
60 M_{sun}
0 km/s
M_{cut}=18.2
D=100



Meynet et al. 2010



Chiappini, private communication



Models from Cescutti & Chiappini 2010; Cescutti et al. 2009

Barbuy et al. 2009

Element	B-8 (1)	B-107 (2)	B-108 (3)	B-118 (4)	B-122 (5)	B-128 (6)	B-130 (7)	F-121 (8)	
[O/Fe][1]	+0.25:	+0.5:	+0.7:	+0.3:	+0.7:	--	+0.50:	+0.5:	X
[Mg/Fe][1]	+0.10	+0.27	+0.33	+0.20	+0.20	+0.25	+0.40	+0.40	X
[Si/Fe][1]	+0.34	+0.20	+0.20	+0.29	+0.13	+0.24	+0.35	+0.27	X
[Ca/Fe][1]	+0.15	+0.04	+0.18	+0.21	+0.21	+0.16	+0.23	+0.16	X
[Ti/Fe][1]	+0.12	+0.14	+0.21	+0.11	+0.19	+0.17	+0.21	+0.16	X
[Ba/Fe][1]	+0.95	+0.50	0.0	+1.00	+0.60	+0.90	+0.25	-0.25	X
[La/Fe][1]	+0.50	+0.50	+0.30	+0.50	+0.30	--	--	0.00	X
[Y/Fe][a]	+1.20	+1.3	+1.00	+0.50	+1.20	+1.5	+1.20	+1.20	
[Sr/Fe][a]	+1.20	+1.00	+1.55	+1.50	+0.50	+1.5	--	--	
[Eu/Fe][1]	+0.50	0.00	+0.50	+0.50	+0.30	0.00	+0.80	+0.50	X
[Na/Fe][1]	+0.35	-0.30	-0.15	+0.10	+0.15	+0.10	+0.15	-0.10	X
[C/Fe][a]	< 0	< 0	< 0	< 0	< 0	< 0	< 0	< 0	

Chiappini et al., Nature 2011