The Peculiar Evolution of Low Mass EMP Stars

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Low-mass EMP/Z=0 Modelling (to 2006)
Standing on many shoulders :)

Year	Author	Mass	Metallicity	Max. Evolution	Helium
1961	Ezer (1961)	$1 \rightarrow 2000$	zero	ZAMS	0.0
1971	Ezer and Cameron	$5 \rightarrow 200$	zero	MS	0.2
1972	Ezer	3.0	zero	CHeB	0.2
1974	Cary	$2 \rightarrow 20$	zero	ZAMS	0.0, 0.23, 0.3
1974	Wagner	$0.65 \rightarrow 2.5$	$-6, -4, -2$	RGB	0.26
1975	Castellani and Paolicchi	$1 \rightarrow 100$	zero	ZAMS	0.0, 0.2, 0.4
1981	Eryurt-Ezer	3.0	zero	EAGB	0.2
1982	D'Antona and Mazzetelli	0.9, 1.0	zero	RGB, ∼DCF	0.2
1983	Guenther and Demarque	0.9	zero	MS	0.2
1984	Chieffi and Tornambe	5.0	zero	∼AGB	0.2
1985	Eryurt-Ezer and Kiziloglu	5, 7, 9	zero	CHeB	0.2
1986	Tornambe and Chieffi	$2.5 \rightarrow 8.0$	$-6, -4, -2$	EAGB	0.2
1987	Kiziloglu and Eryurt-Ezer	$0.2 \rightarrow 0.8$	zero	MS	0.2
1990	Fujimoto et al.	1.0	zero	∼DCF	0.23
1990	Hollowell et al.	1.0	zero	DCF	0.23
1993	Cassisi and Castellani	$0.7 \rightarrow 15$	$-8, -4, -2$	RGB/EAGB	0.23
1996	Cassisi et al.	$0.7 \rightarrow 1.1$	$-8, -4, -3$	∼DSF (M=0.8)	0.23
1998	Fujimoto and Iben	$0.8 \rightarrow 4$	zero	RGB/AGB	0.23
2000	Fujimoto et al.	$0.8 \rightarrow 4$	zero, $-4, -2$	DCF/DSF	0.23
2000	Weiss et al.	$0.8 \rightarrow 1.2$	zero	RGB	0.23
2001	Marigo et al.	$0.7 \rightarrow 100$	zero	∼AGB (no CHeF)[a]	0.23
2001	Chieffi et al.	$4 \rightarrow 8$	zero	DSF, ∼AGB	0.23
2001	Schlattl et al.	$0.8 \rightarrow 1.0$	zero	DCF, SRGB, ∼AGB	$0.23 \rightarrow 0.25$
2001	Goriely and Siess	3	zero	AGB s-process[b]	0.23
2002	Siess et al.	$0.8 \rightarrow 20$	zero	DSF, ∼AGB	0.235
2002	Schlattl et al.	0.8	zero, $-3, -2$	DCF	0.23
2003	Herwig	2 & 5	zero	DSF, ∼AGB	0.23?
2004	Iwamoto et al.	$1 \rightarrow 3$	-2.7	DSF, ∼AGB	0.24
2004	Picardi et al.	$0.8 \rightarrow 1.5$	zero, $-6, -5, -4$	DCF, SRGB, ∼EAGB	0.23 & 0.27
2004	Weiss et al.	0.82	zero, -5	DCF, SRGB	0.23?
2004	Suda et al.	$0.8 \rightarrow 4.0$	zero	∼DSF, ∼DSF, ∼AGB	0.23?
2006	Campbell (This study)	$0.8 \rightarrow 3+$[c]	zero, $-6, -5, -4, -3$	DCF, DSF, SRGB, AGB & Yields	0.245

PhD Thesis:
Low mass EMP Stellar Evolution & Nucleosynthesis

During my thesis I calculated a grid of stellar models including:

- Structural evolution from MS to end of TP-AGB
- Nucleosynthetic evolution for nuclides up to Sulphur 35
- Yields for the 74 included species

Stellar structure code: MONSTAR (Monash/Mt Stromlo code)

Nucleosynthesis code: MONSN ('monsoon', Monash code)

The metallicity and mass range of the grid:

$$[\mathrm{Fe/H}] = -\infty, -6.5, -5.45, -4.0, -3.0$$

$$\mathrm{M} = 0.85, 1.0, 2.0, 3.0\,\mathrm{M}_\odot$$ **→ 20 Stars**

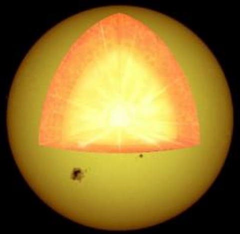
My thesis: http://users.monash.edu.au/~scamp/downloads/phd-thesis-Campbell.pdf

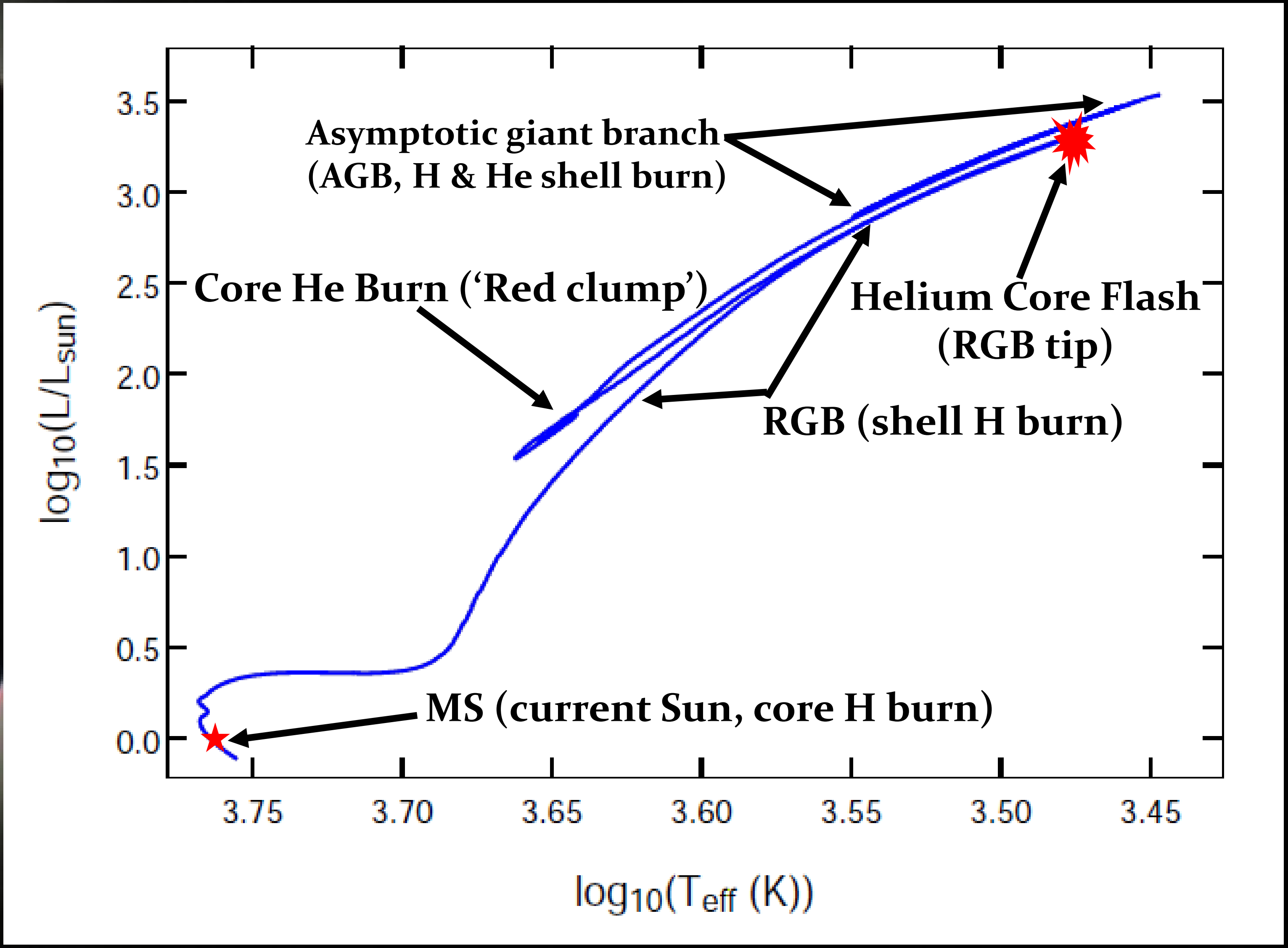
Also see Campbell & Lattanzio 2008, Campbell et al. 2010

Peculiar Evolution Example I: 0.85 $M_{\odot}$ Population III Star

NB: Using this zero metallicity model as an example,
EMP stars show similar evolutionary properties.

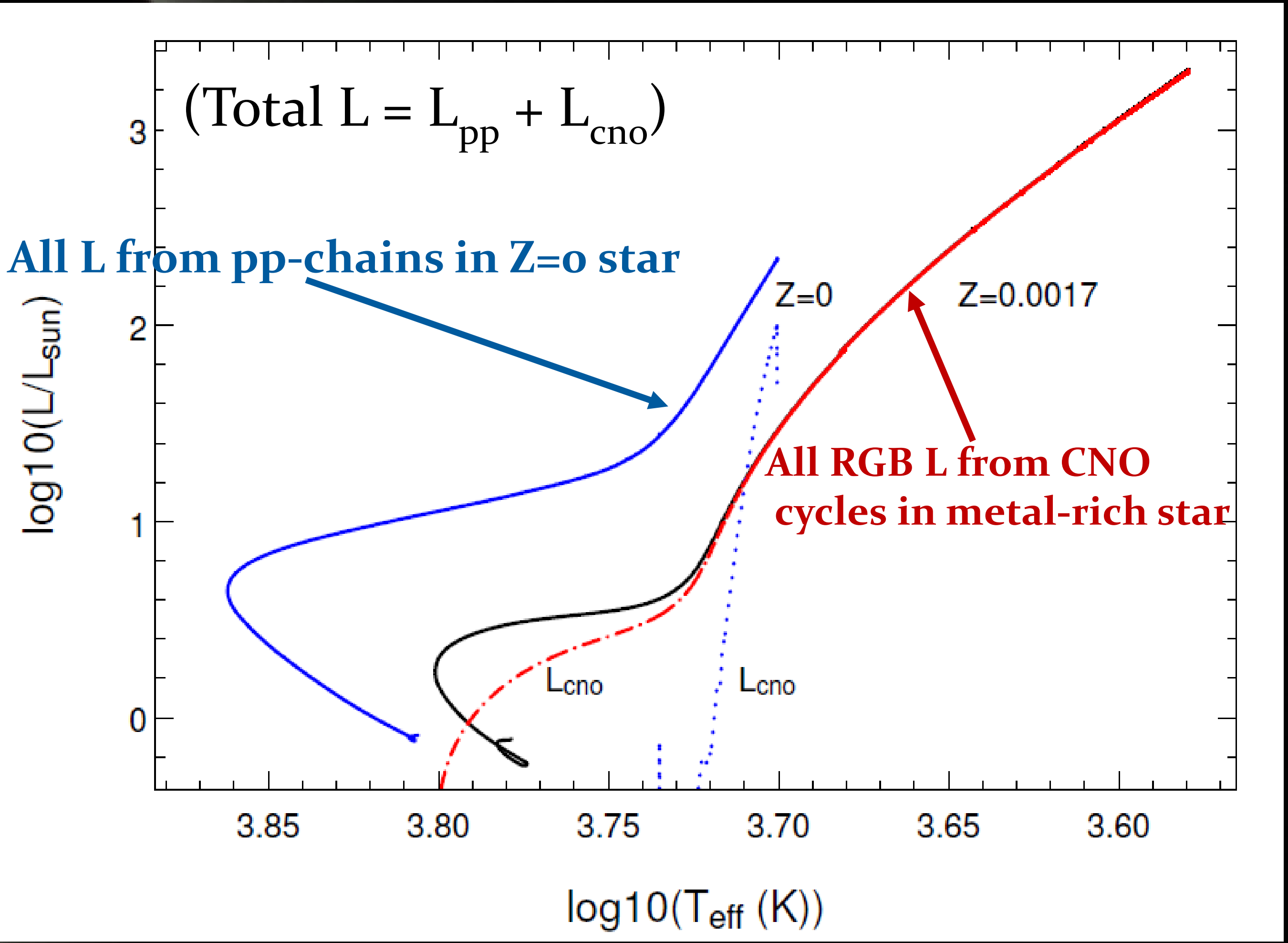
Overview of evolutionary phases: The Sun





Pop III (Z=0) 0.85 $M_\odot$: MS to RGB Tip

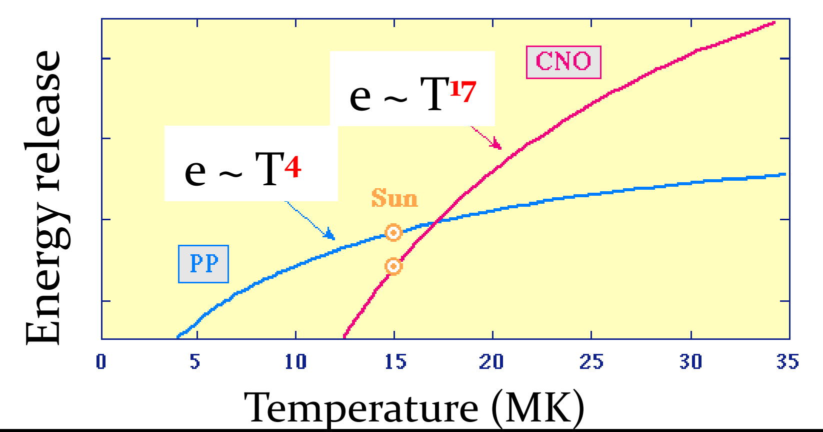
'Normal' star versus Pop III star: Hydrogen burning



- Typical Halo star mass
- Z=0 star has:
  - Higher luminosity
  - Higher surface temperature.
  - RGB tip luminosity ~ 1 dex lower.
- Major factor altering the evolution is the lower opacity of the metal-free gas.
- On the RGB the lack of CNO elements precludes the Z=0 star from burning H via the CNO cycles – until the shell becomes so hot that (some) He burning starts!

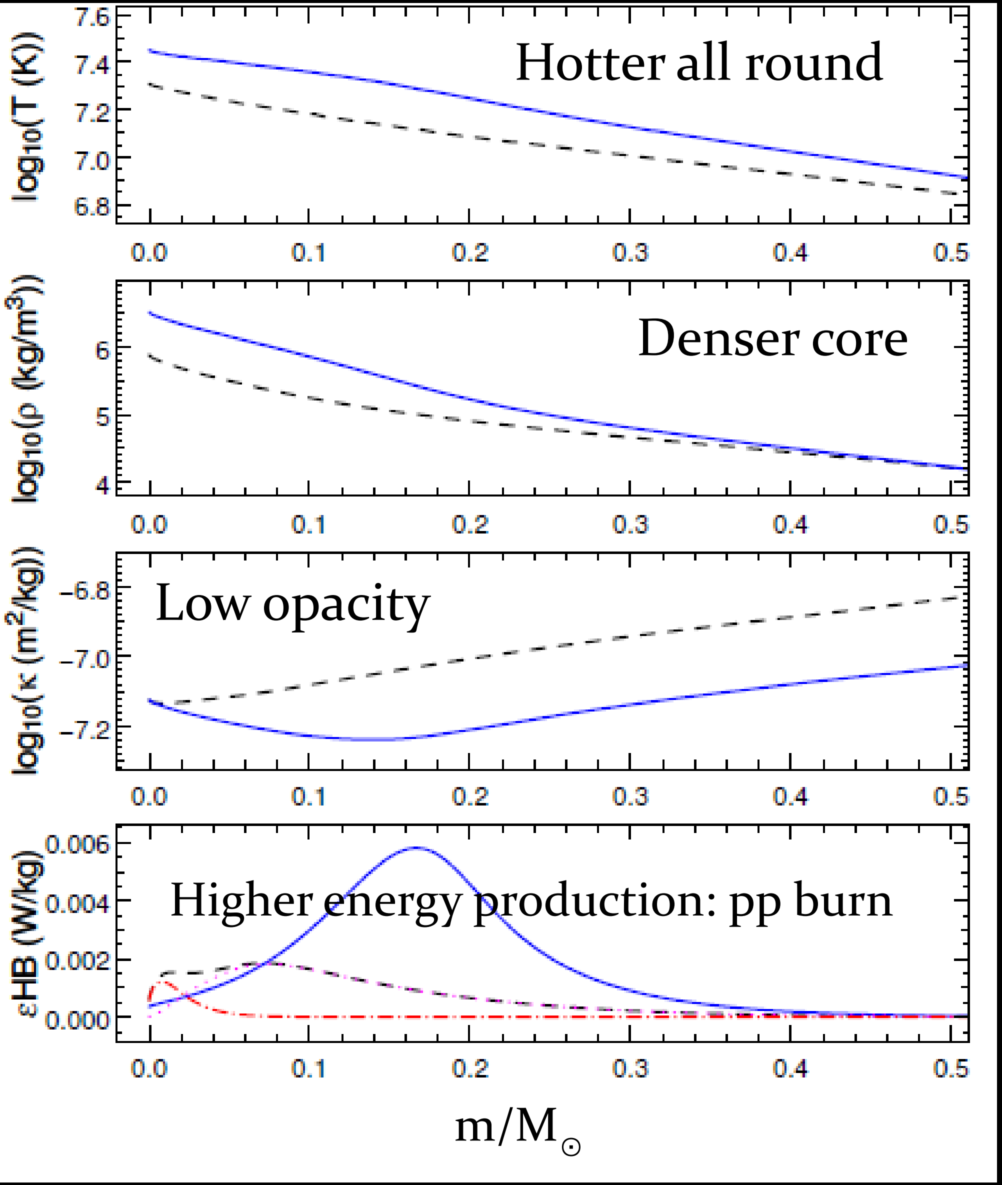
Z=0, 0.85 $M_\odot$: Internal Structure, MS

pp-chains have a *much* weaker T dependence than CNO cycle → fundamental change in structure.



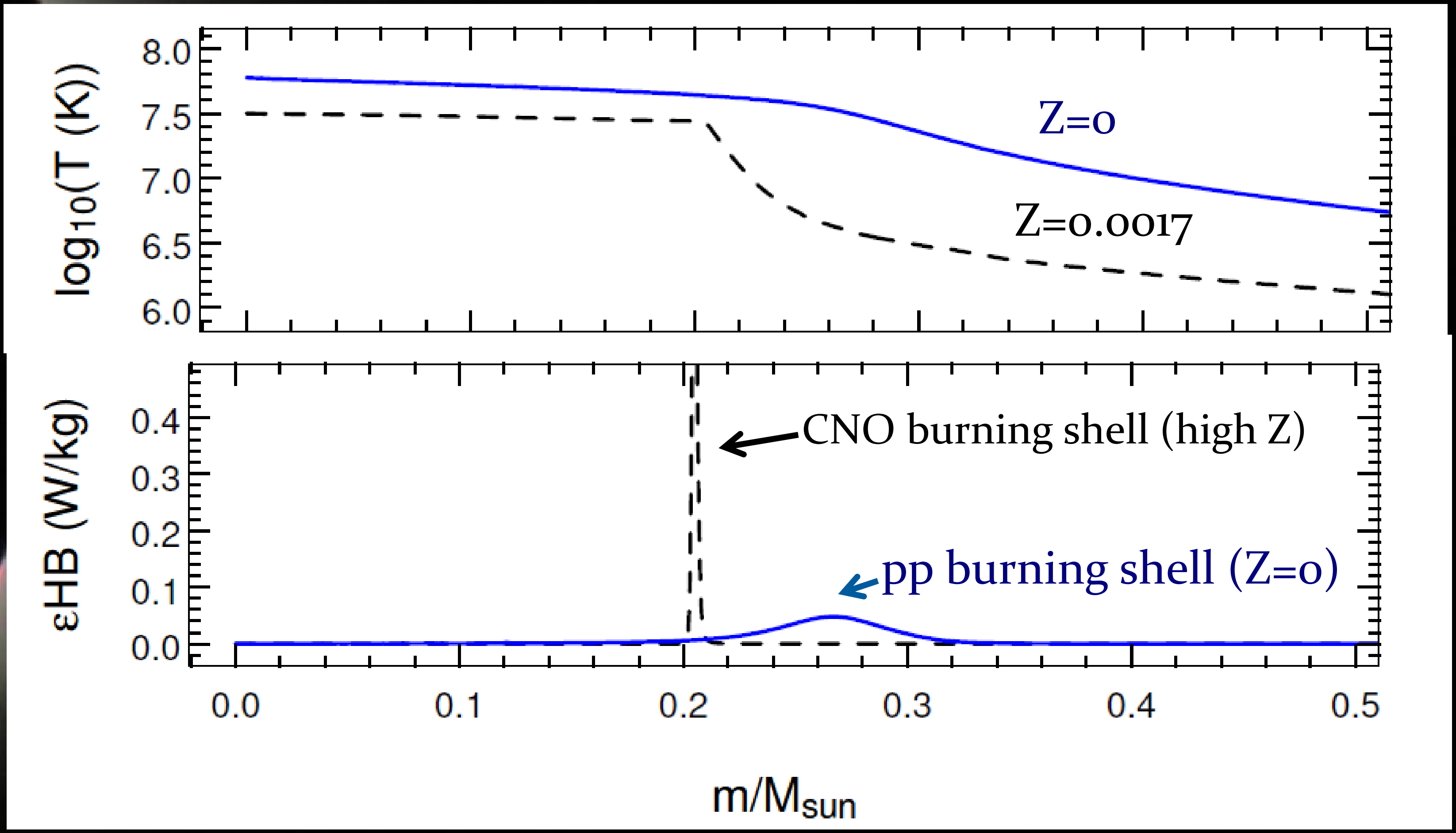
Blue = Zero metallicity
Dashed = GC metallicity

- Snapshot near end of MS
- At this stage the 'normal' star is switching to CNO H burning
- The Z=0 star cannot do this, so it continues to burn via the pp-chains, which creates a marked difference in structure



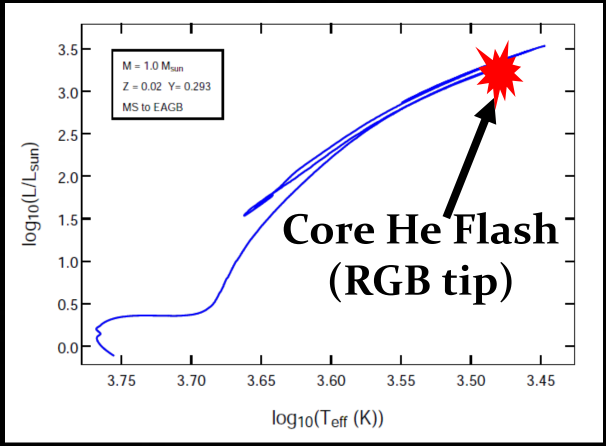
Z=0, 0.85 $M_\odot$: Internal Structure on RGB

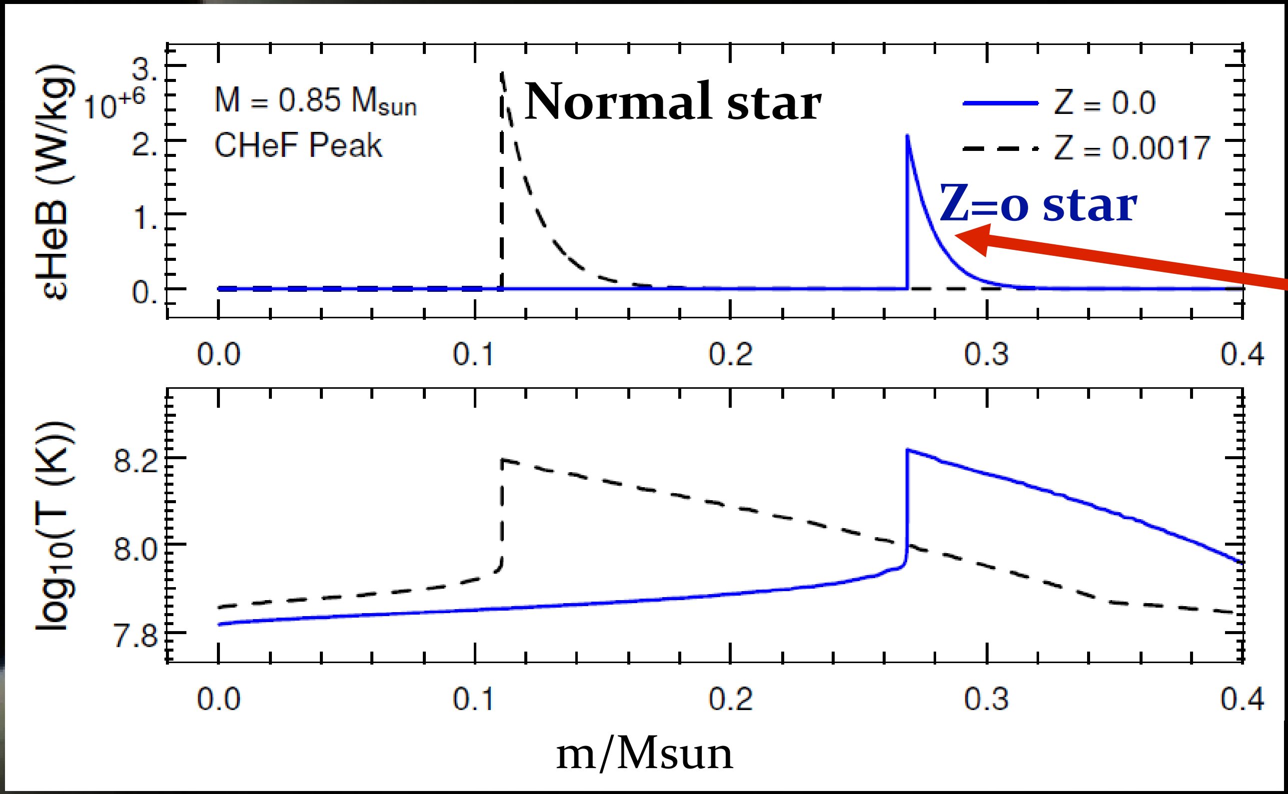
- Red giant branch structure is also very different
- The shell hydrogen burning happens over a relatively wide region of the star, again due to the pp chain reactions being only weakly sensitive to temperature, compared to the CNO cycle



Z=0, 0.85 $M_{\odot}$: Core He Flash!

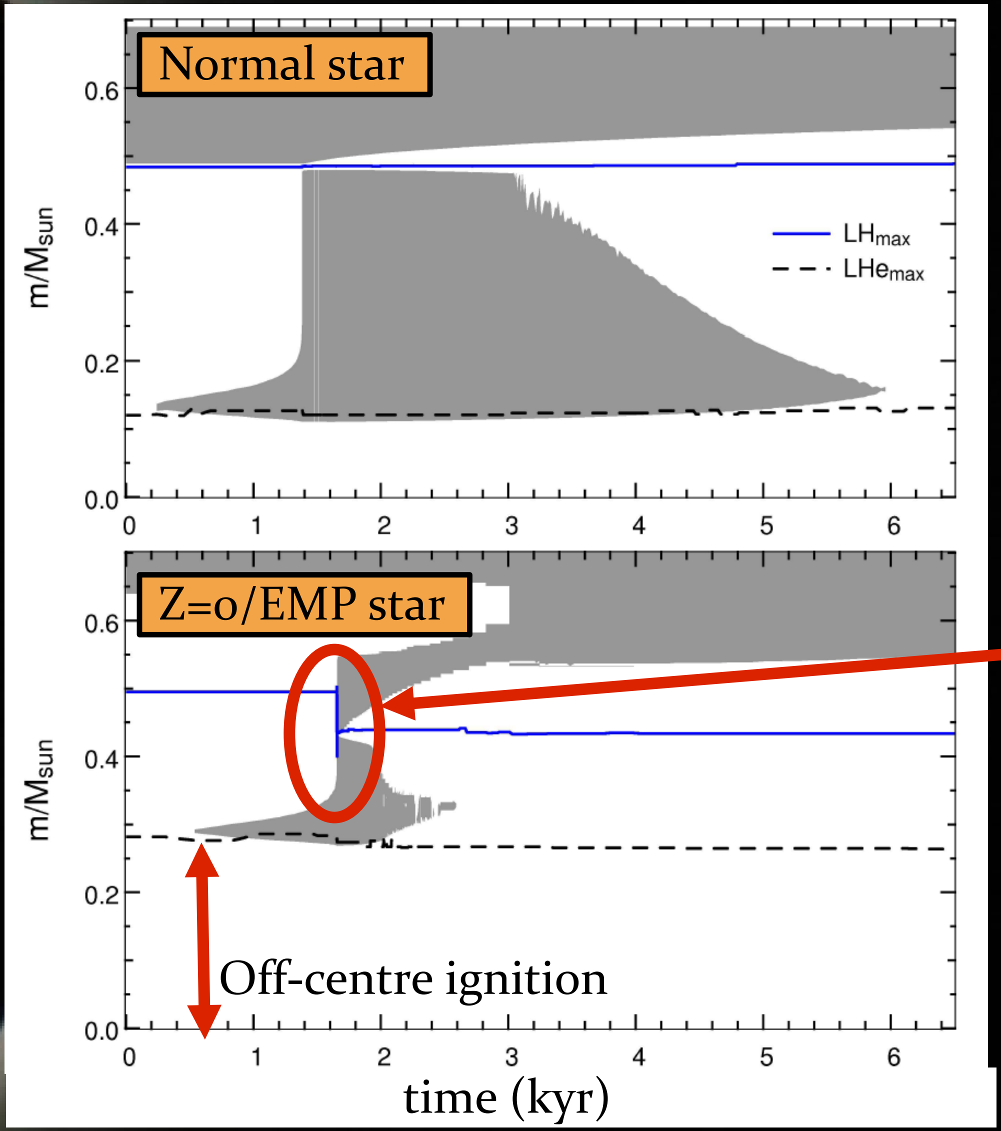
- At the top of the RGB He ignites violently, due to (partial) degeneracy of core material.
- In the Z=0 model this happens much further from the centre of the star…





Ignition way off-centre

Z=0, 0.85 $M_\odot$: Core He Flash is not normal!



Comparison between a Z=0/EMP star and a GC metallicity star

- Grey = convection
- Blue line = H burn
- Dashed line = He burn

Convection breaks out of core! → Mixes protons down to region burning helium: VERY HOT for H (~100 MK, normally H burns at ~20 MK)

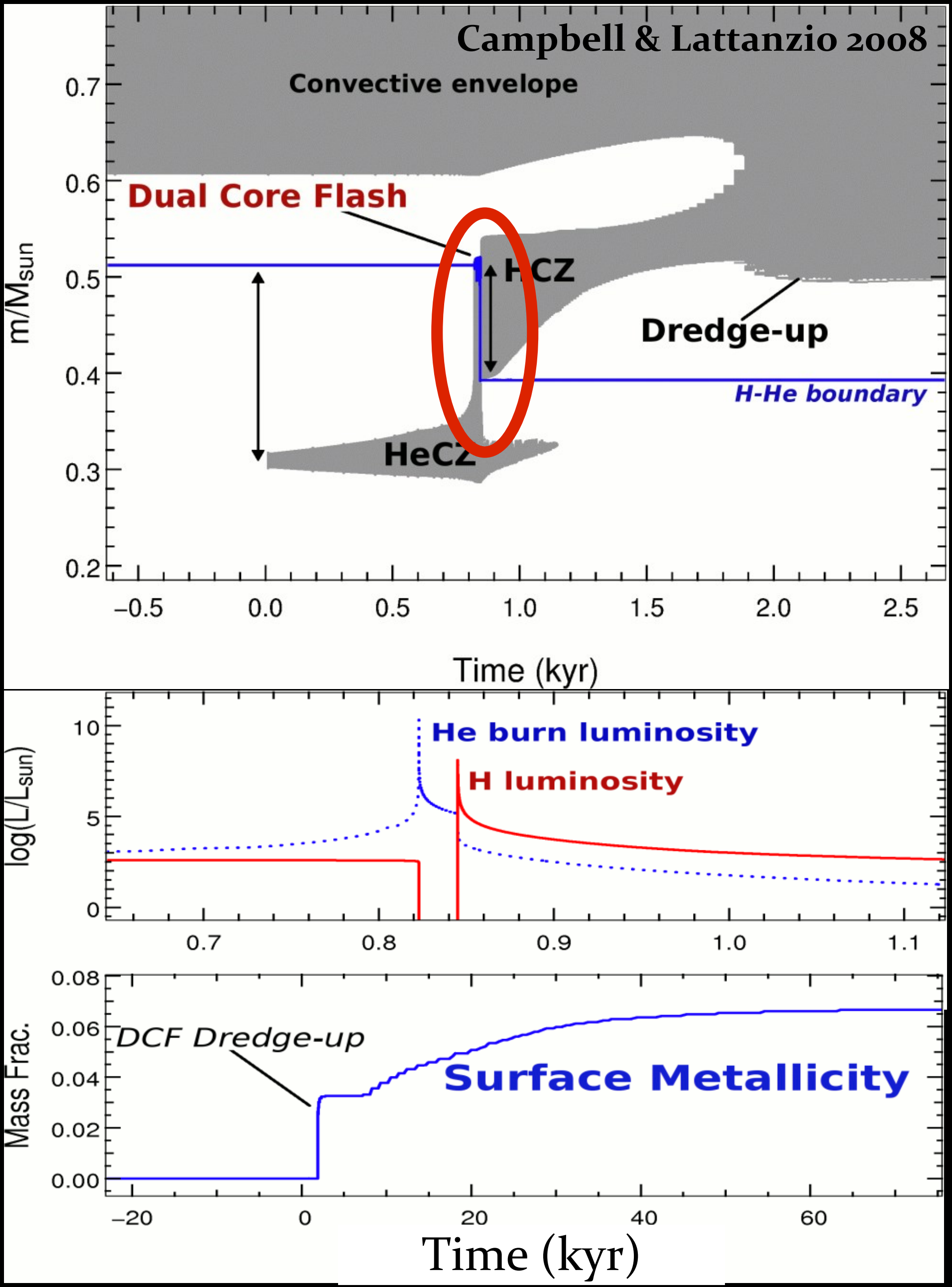
This is unique to EMP stars!

The EMP "Dual Core Flash" (DCF)

- The mixing of protons downwards into high temperature regions naturally causes very rapid H burning.

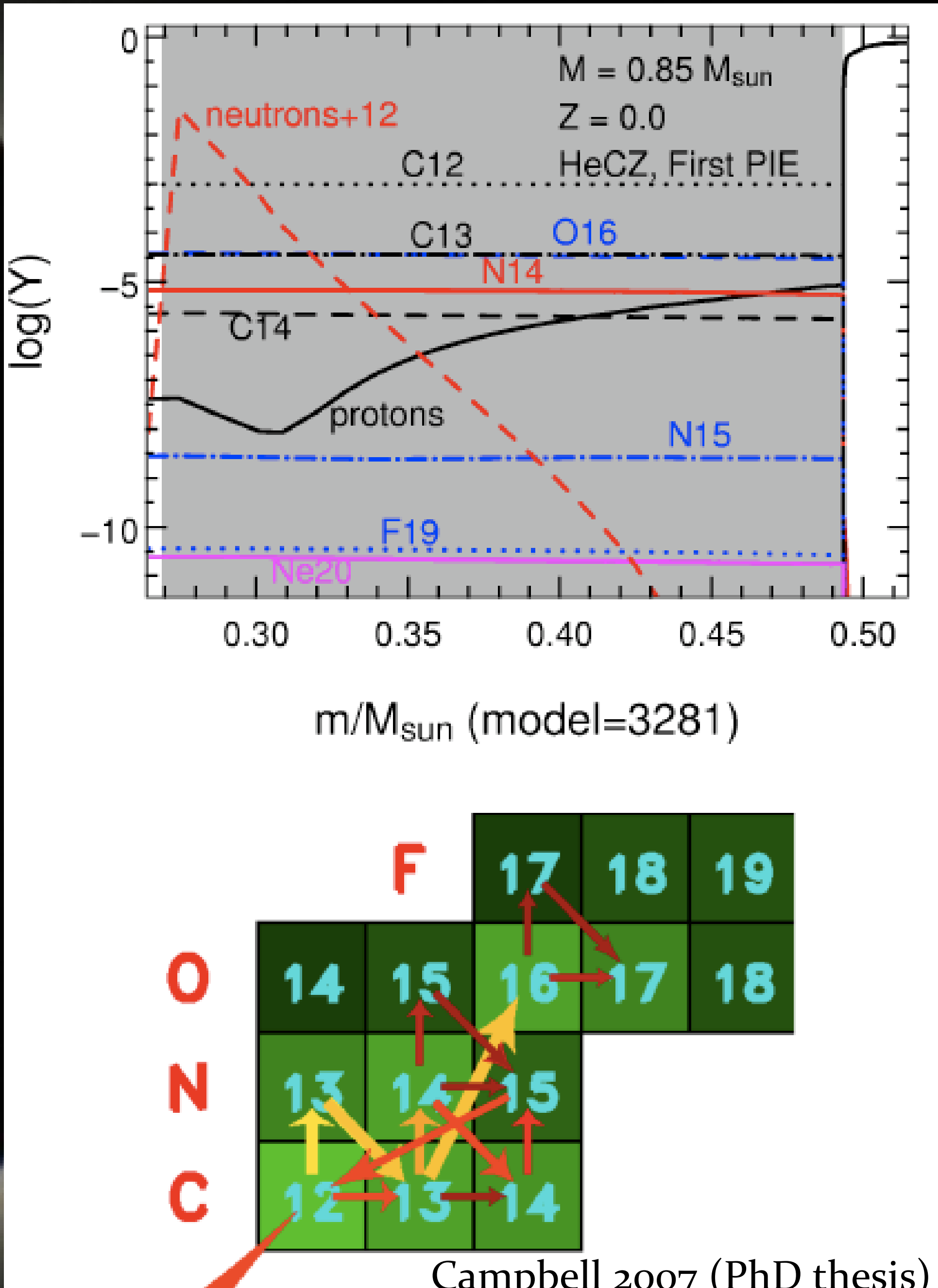
  → Hydrogen Flash!

- The He flash is still ongoing → hence name 'dual flash'.
- He burning products are mixed upwards also.
- This material is later dredged up into the envelope, polluting the surface.
- Fujimoto et al. (1990) suggested that the excess C in the CEMPs may come from these peculiar proton ingestion events (PIEs).



Again, this unique to EMP stars!

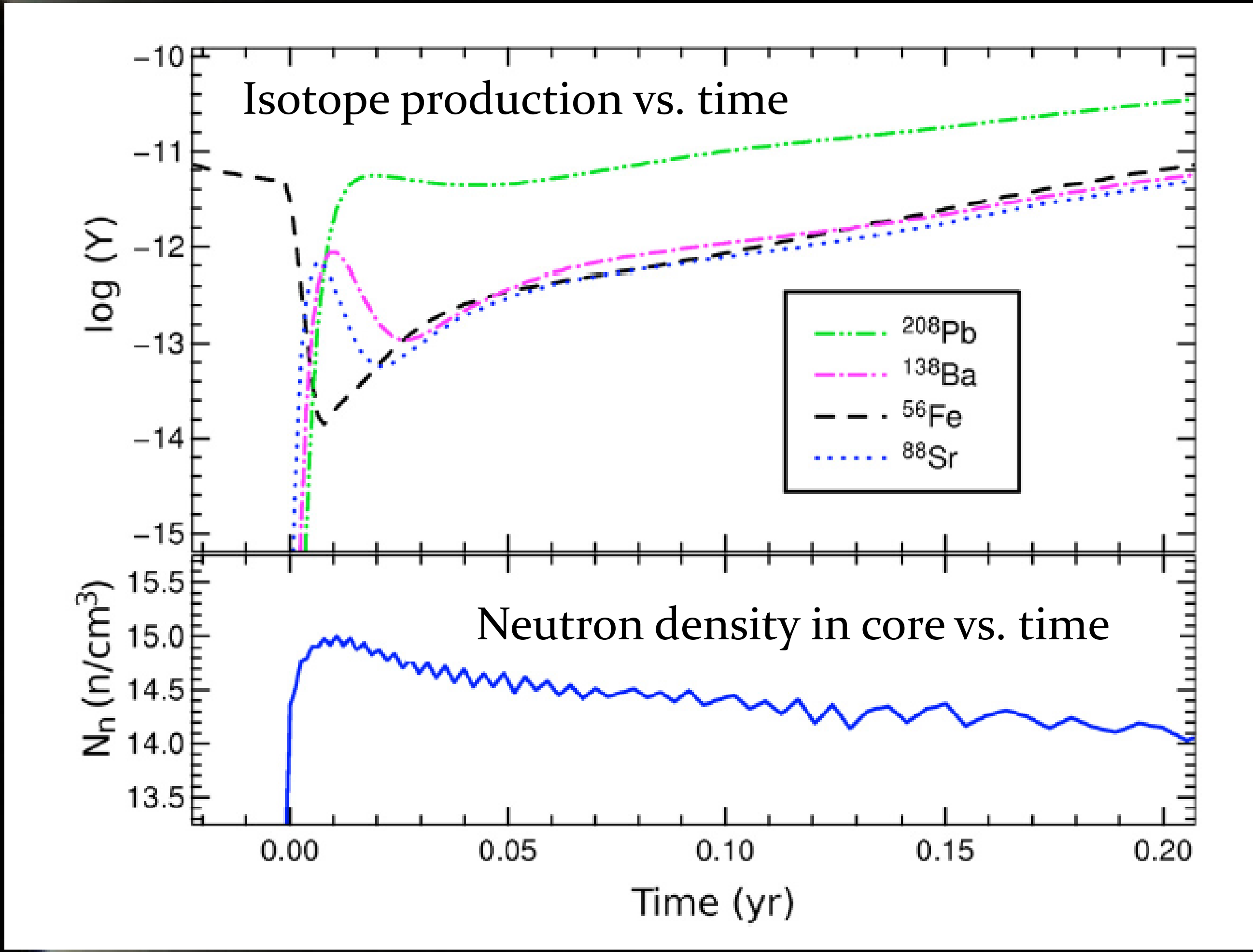
Possible s/r-Process during the DCF?



Campbell 2007 (PhD thesis)

- Fujimoto et al. (1990) also speculated that light s-process elements may be produced during a DCF, since the protons should react with the ^{12}C produced by the He burning, to produce ^{13}C.
- In this model I found that ^{13}C was produced in large amounts, and that the neutron-producing reaction $^{13}C(\alpha,n)^{16}O$ was very active during a DCF.
- Interestingly the neutron density in this rough plot from my thesis is ~10^{14} cm^{-3}.
- This neutron density is much higher than s-process densities!
- But not as high as needed for the r-process.
- This simulation had a limited nuclear network, so more investigation was required..

EMP "Neutron Superburst"



Campbell, Lugaro & Karakas 2010

- Larger network confirmed the high neutron densities:
  10^{14} to 10^{15} cm^{-3}
- So intermediate between s & r-process.
- Is this the site for CEMP i-process? – see Melanie Hampel's talk tomorrow.

CEMP s/r Mystery & the Neutron Superburst

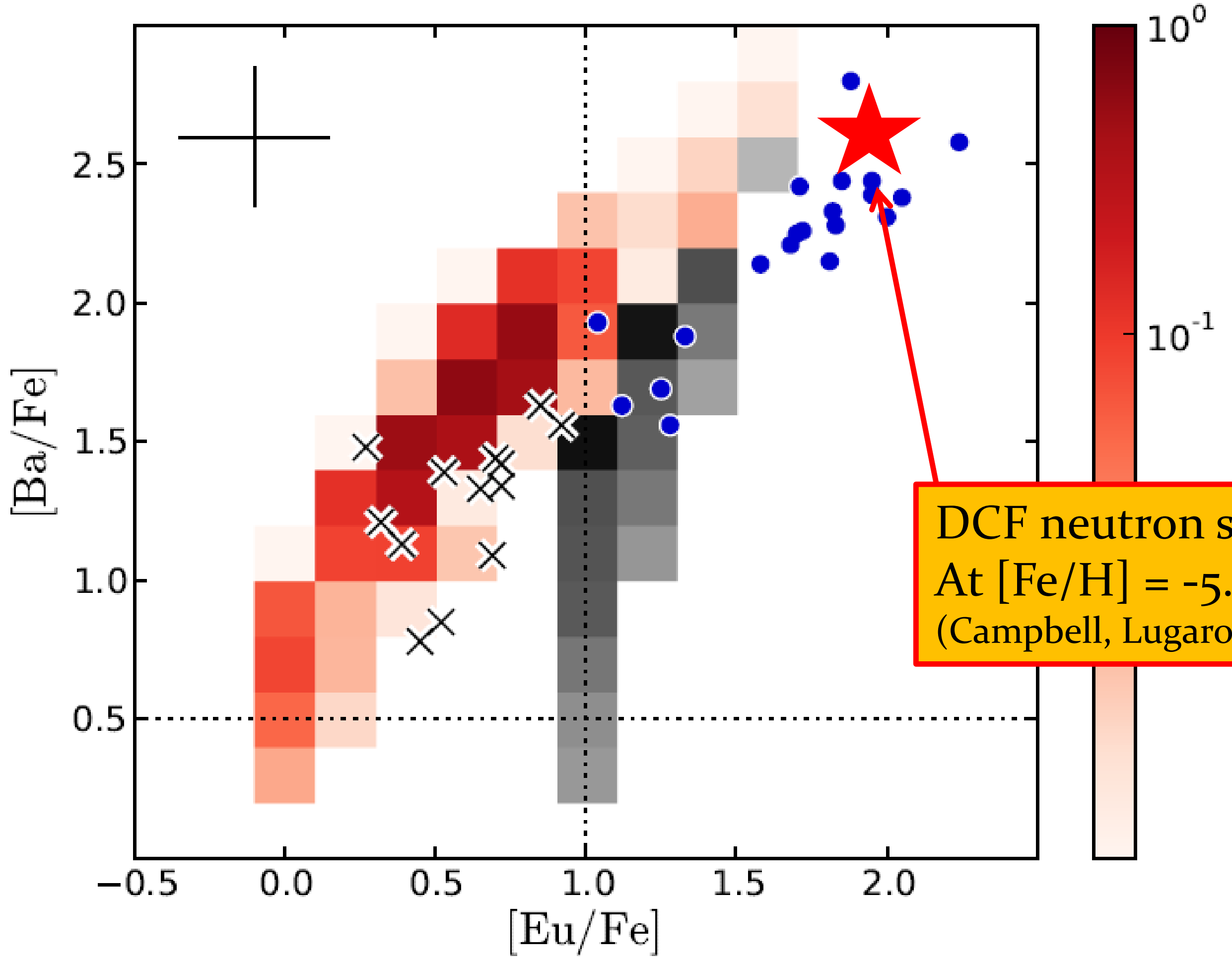
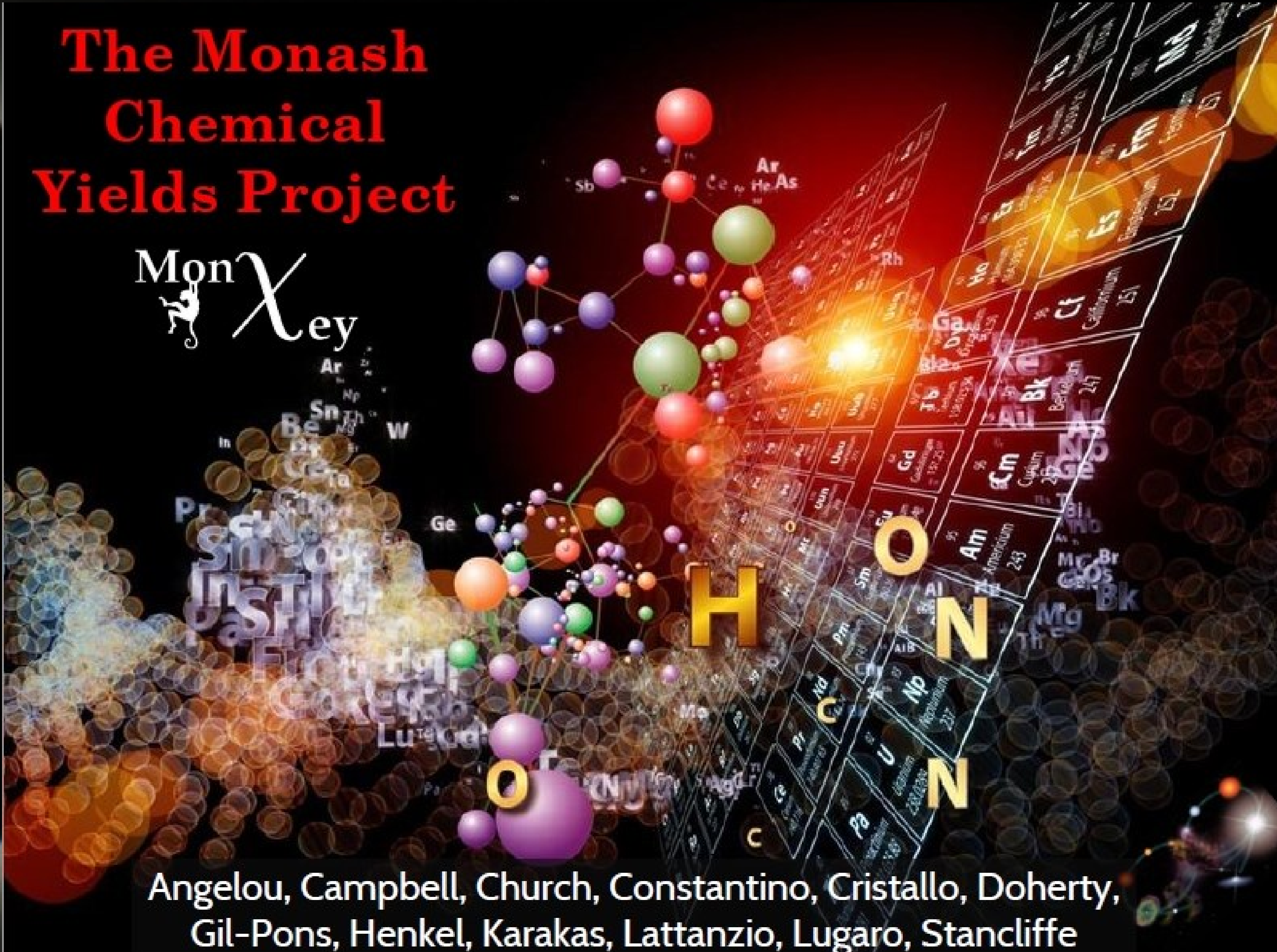


Fig. 10. Distribution of [Ba/Fe] vs. [Eu/Fe]. The red distribution represents our default model A. The grey distribution is computed with an initial enhancement of $[r/Fe]_{ini}$ = 1. The dotted lines indicate the

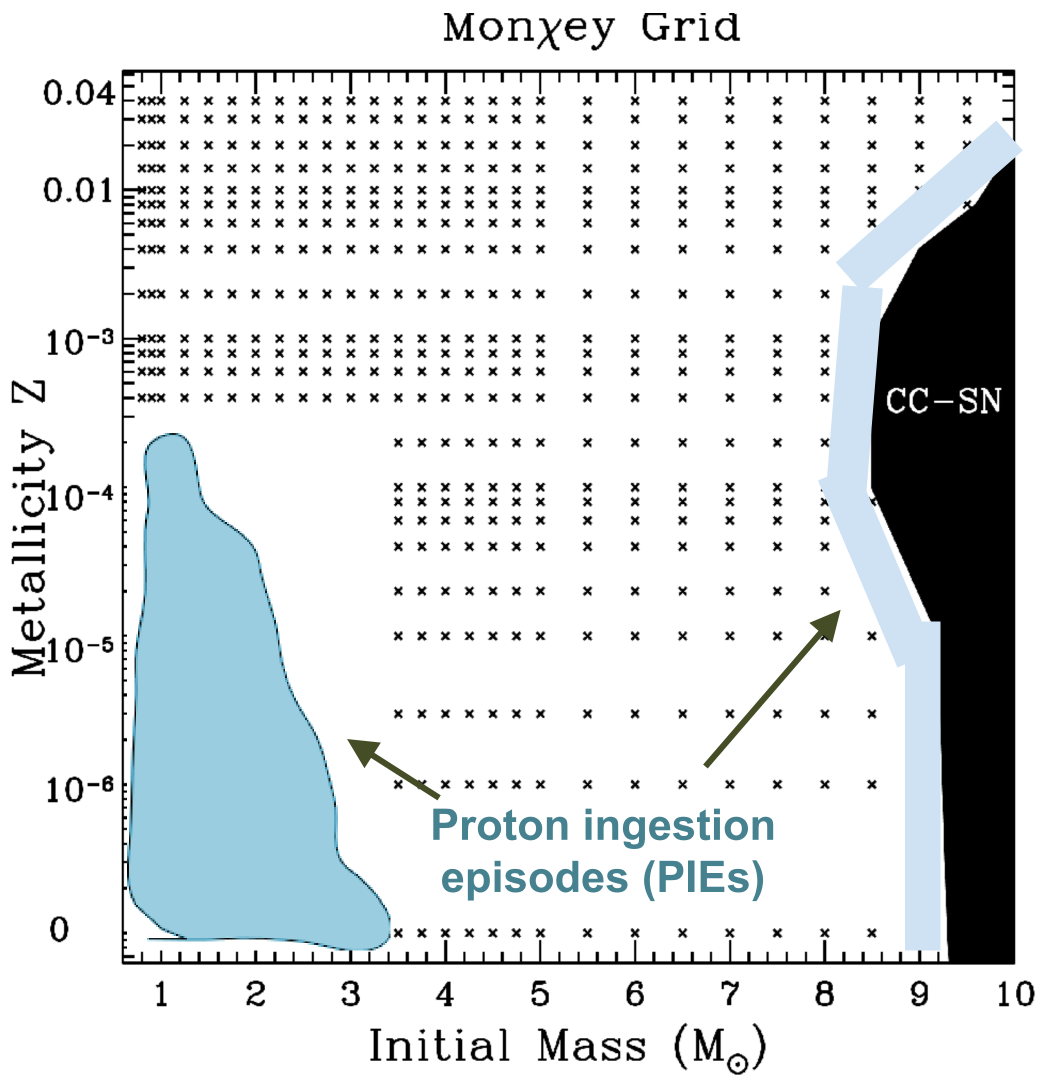
Abate, Pols, Stancliffe et al., 2015

- No neutron superburst yields included in the population synthesis – not expected at higher [Fe/H] that this study focussed on?

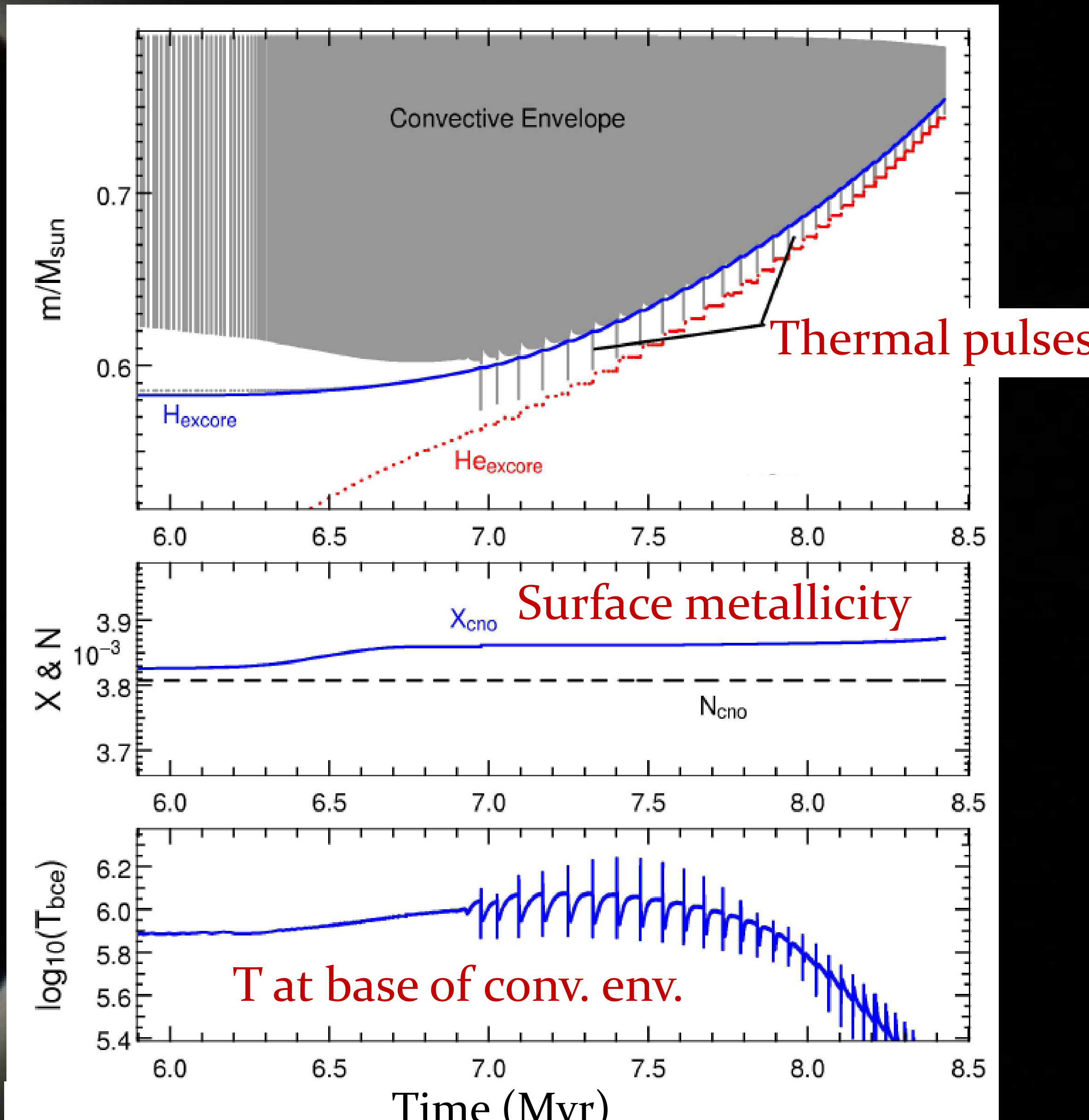
• Undiluted Z=0 model produced 5.1: 4.3, so on same line.
• More metal-'rich' models coming soon :)


The Monash
Chemical
Yields Project
MonXey
Angelou, Campbell, Church, Constantino, Cristallo, Doherty,
Gil-Pons, Henkel, Karakas, Lattanzio, Lugaro, Stancliffe

MonXey Grid: Proton ingestion episodes (PIEs)



Z=0, 0.85 $M_\odot$: AGB



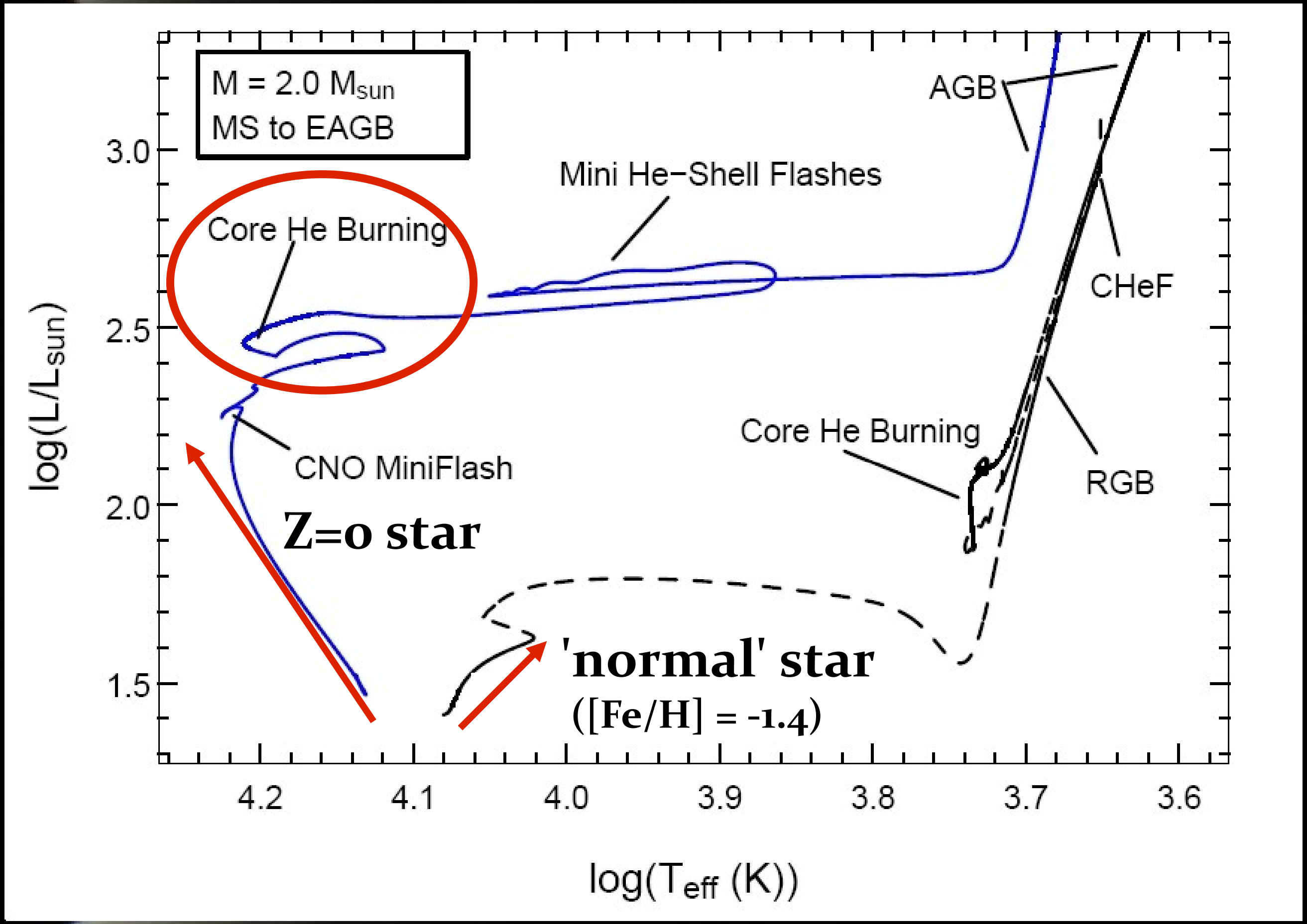
- AGB phase is fairly normal, since surface has quite high metallicity after the DCF (Z~1e-3)
- No third dredge-up in this model -- similar to high metallicity stars.
- Thus the mass lost through AGB winds has the composition of the DCF pollution: primarily C + s/i-process.
- This is unique to EMP stars.

Peculiar Evolution II:

Evolution of a 2.0 $M_\odot$ Pop III Star

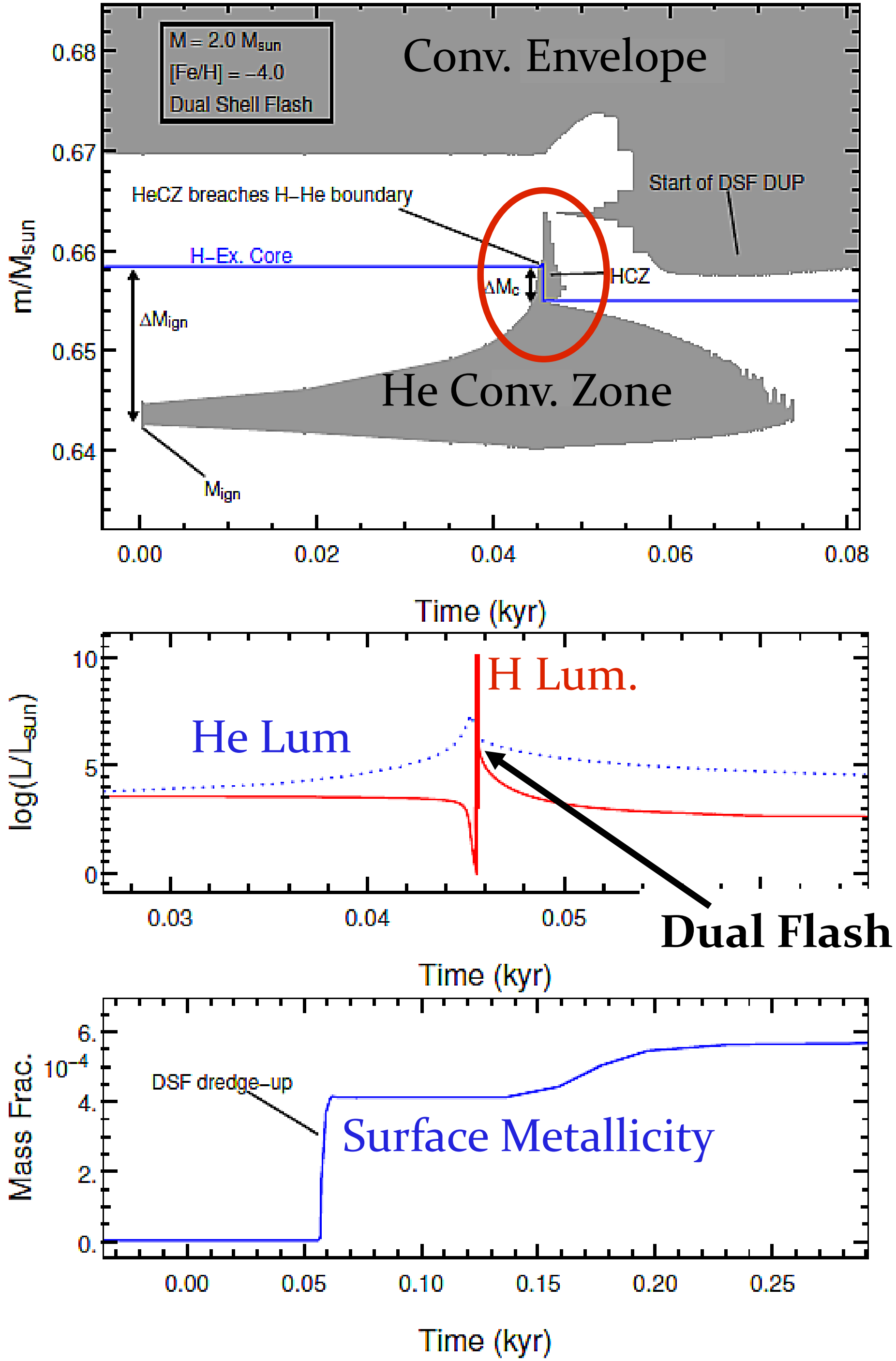
(short :)

Z=0, 2.0 $M_\odot$: MS to EAGB



- Z=0 star evolves in the opposite direction on the MS (more typical of lower-mass, pp-burning stars).
- Ignites He on the MS!
- Also it ignites He in the core before it can become a Red Giant → no RGB!
- Therefore it spends almost all its lifetime in the blue (more typical of a higher-mass star with solar Z)

The EMP AGB Dual *Shell* Flash (DSF)



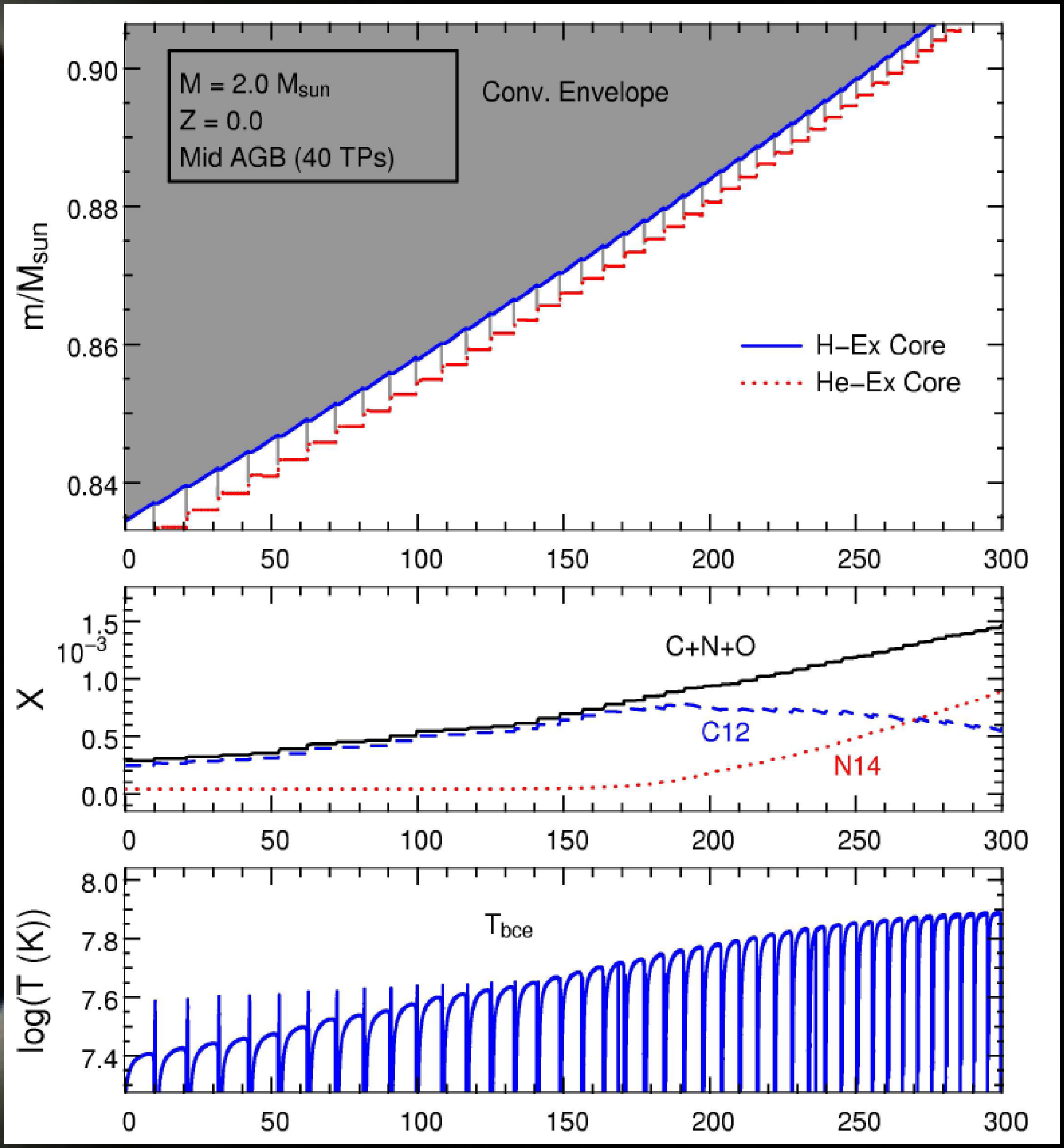
- Similar to the Dual Core Flash but this time it is the AGB shell helium flash convective zone that breaks through the H-He discontinuity
- Occurs during first few pulses of TPAGB.
- Again protons are mixed down, He burning products mixed up: So may also produce s/i-process.
- This material is also later mixed up into the envelope, polluting the surface.

AGB Stellar Structure Model:

$M = 2.0\ M_\odot$

[Fe/H] = -4.0

Z=0, 2.0 $M_\odot$: AGB



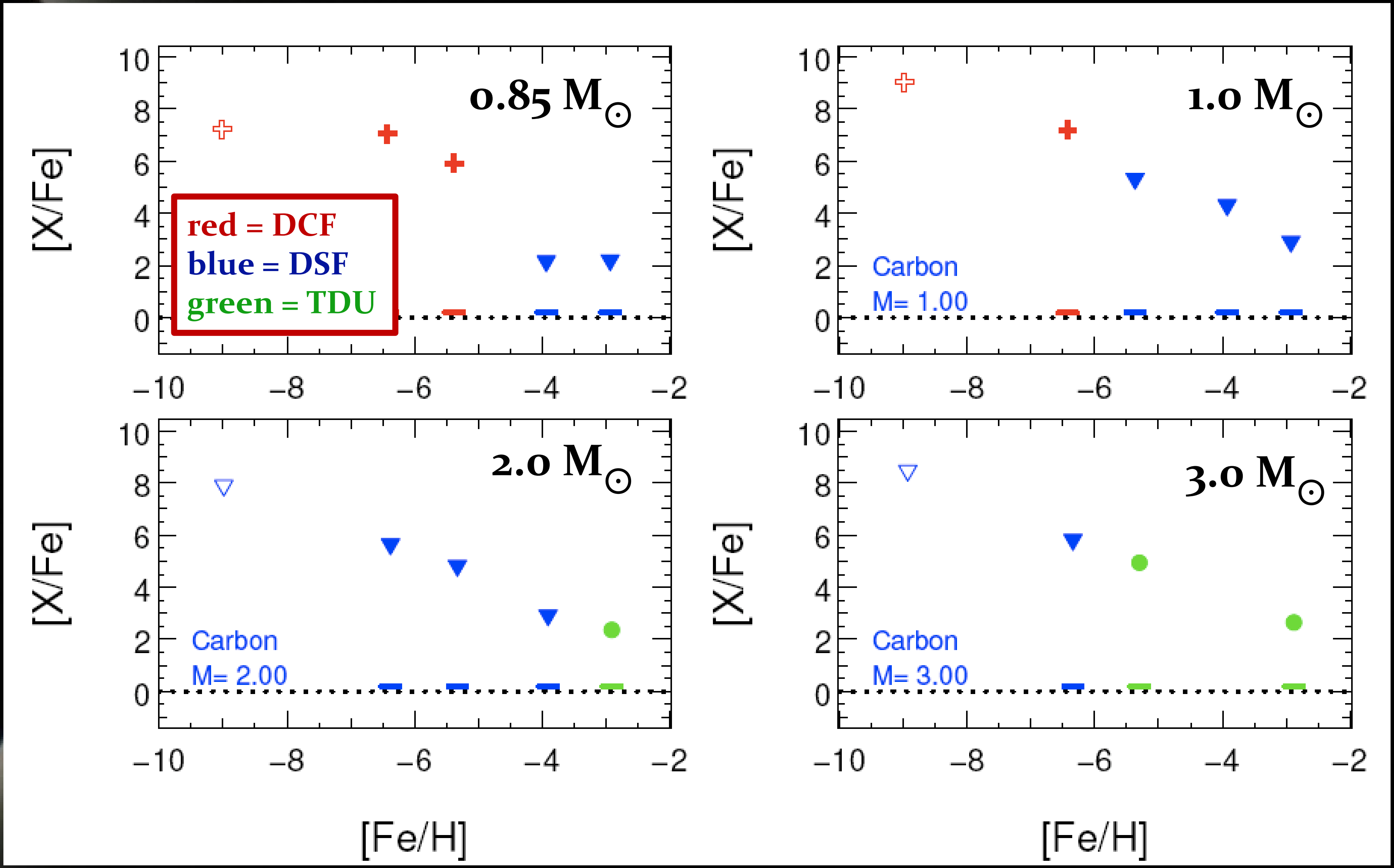
- At this higher mass TDU does occur, so the surface metallicity continually increases (initially lots of C).
- Interestingly Hot Bottom Burning (HBB) also occurs, even at this relatively low mass of 2 $M_\odot$! (usually only above 4 $M_\odot$ at solar Z). This means C→ N.
- In terms of enrichment of the AGB winds the TDU + HBB dominates over the DSF pollution.

Final Section:

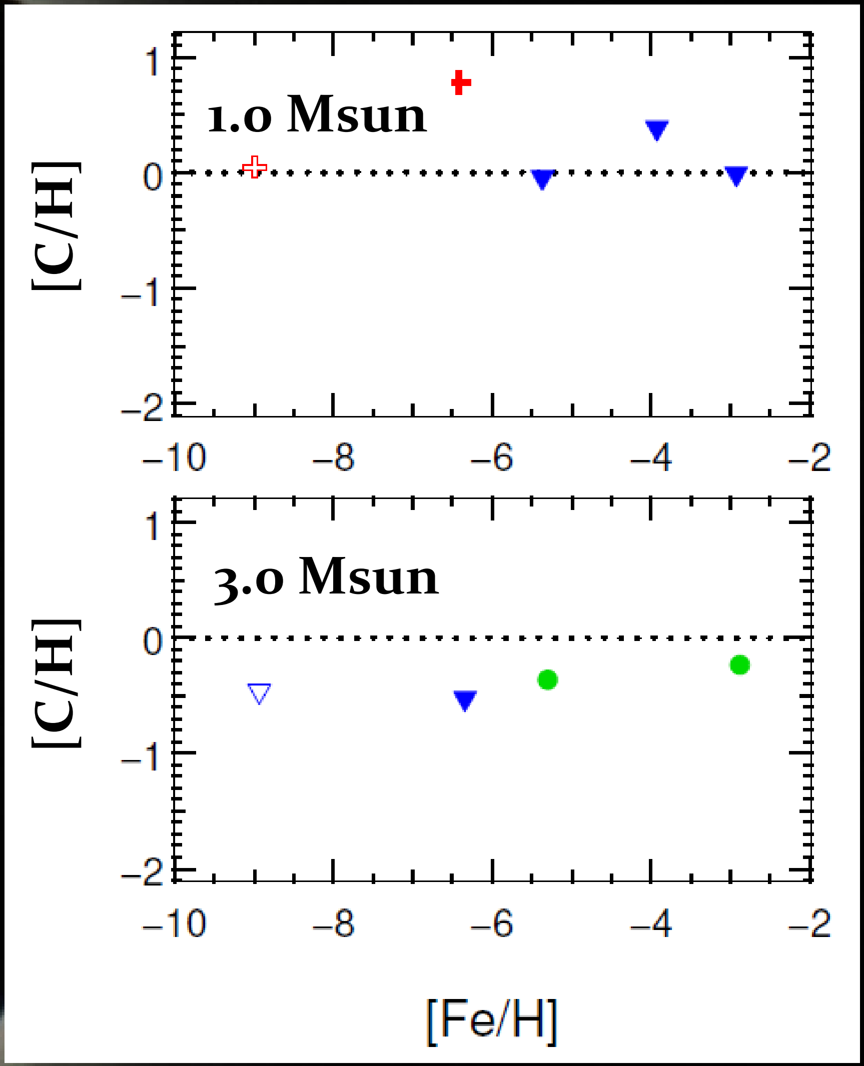
Overview of the chemical consequences of the peculiar EMP evolution

Carbon Yields Across the Grid of Models

• Yield data for many elements are available in Campbell & Lattanzio 2008



Non-Fe-scaled Carbon Yields (for Tim)



Dotted line = Solar
Red = Dual core flash pollution
Blue = Dual shell flash pollution
Green = Third dredge-up/HBB pollution

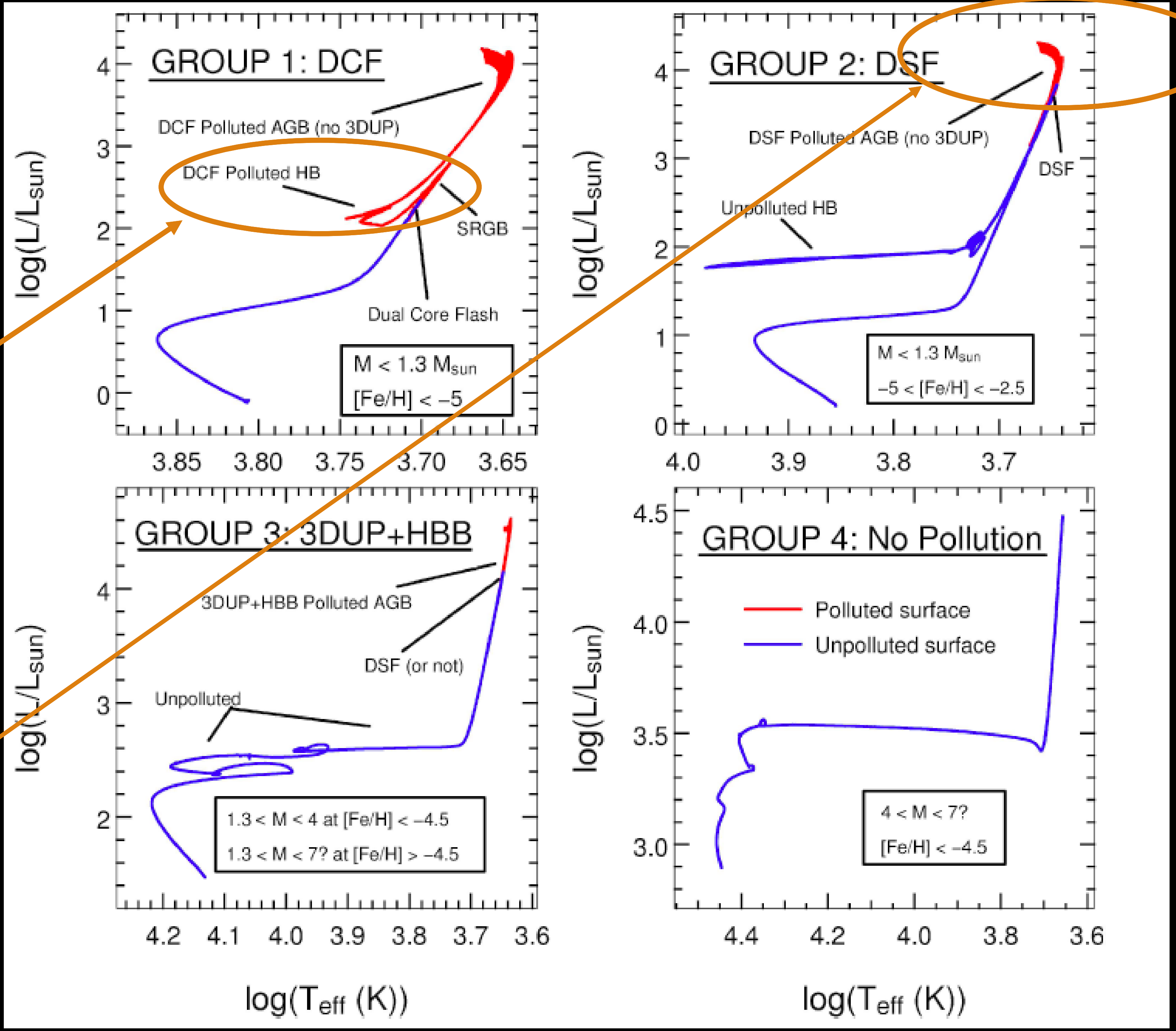
- Carbon pollution is ubiquitous & often reaches close to absolute solar abundance – even at Z=0.0!

- This 'upper envelope' of C pollution is fixed by the amount of C produced in the stellar interior, which doesn't change much with metallicity.

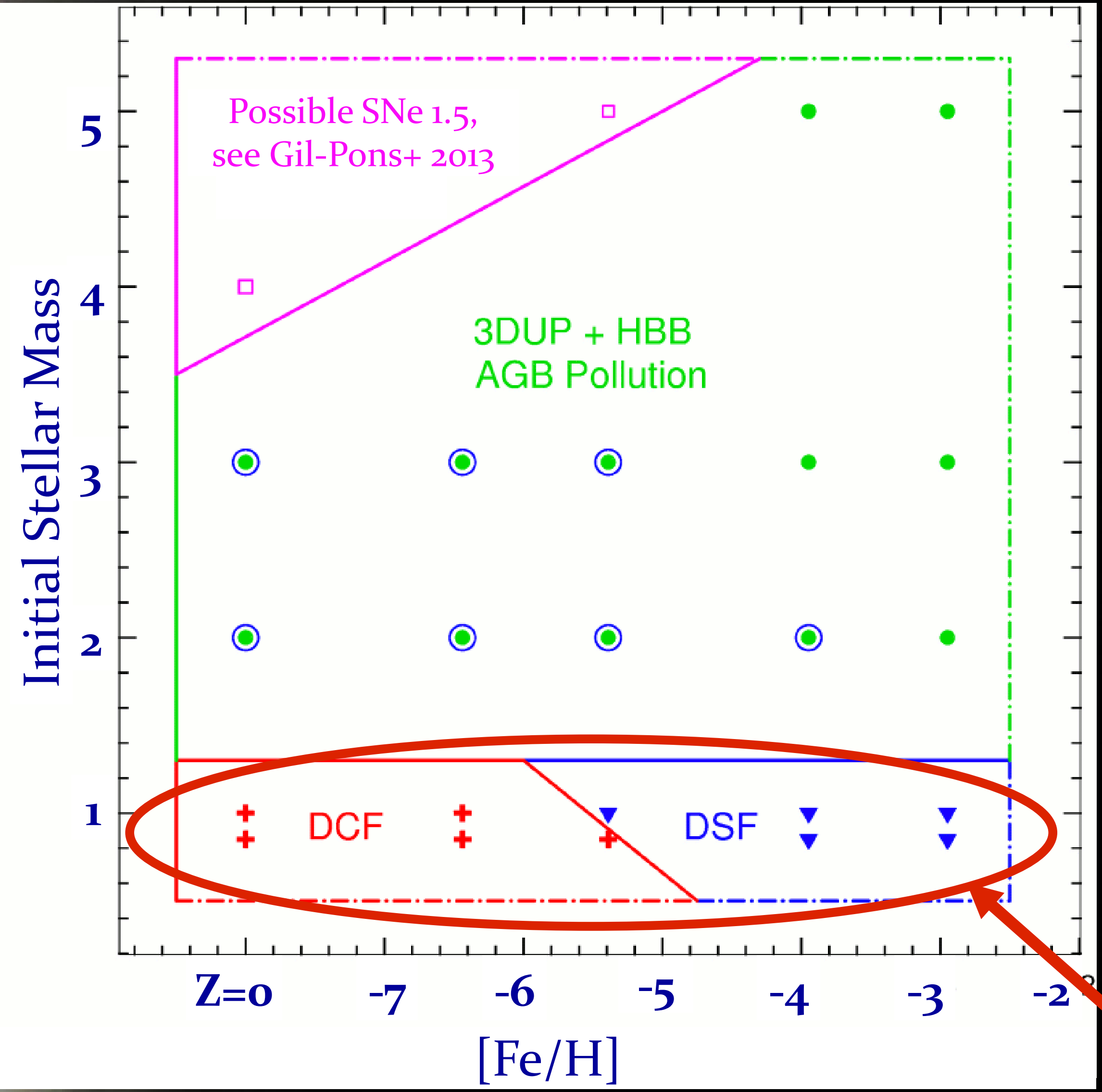
Pollution Summary of models in the HRD

Polluted for an order of magnitude longer time than AGB
→ More CEMPs

Extra source of C, in low-mass stars which would not have TDU
→ More CEMPs



Summary in Mass-Metallicity Plane



Campbell & Lattanzio 2008

- Pollution summary for the grid of models in the initial mass-[Fe/H] plane.
- Colour-coded by pollution events that contribute the most to the yields:

DCF = "Dual Core Flash" (RGB TIP)

DSF = "Dual Shell Flash" (start of AGB)

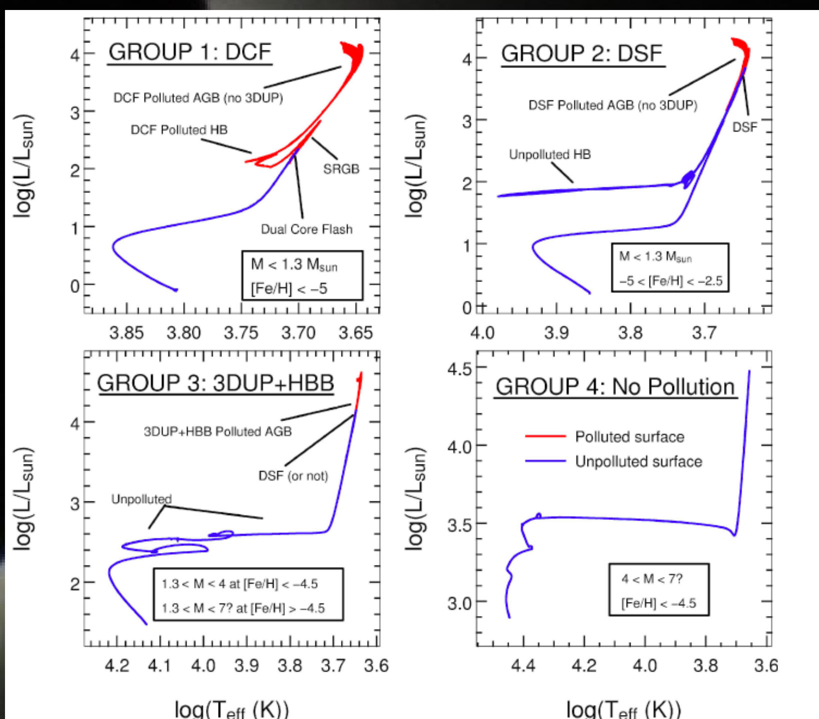
3DU = "Third dredge-up" (AGB)

HBB = "Hot Bottom Burning" (AGB)

DCF & DSF are peculiar to EMP models

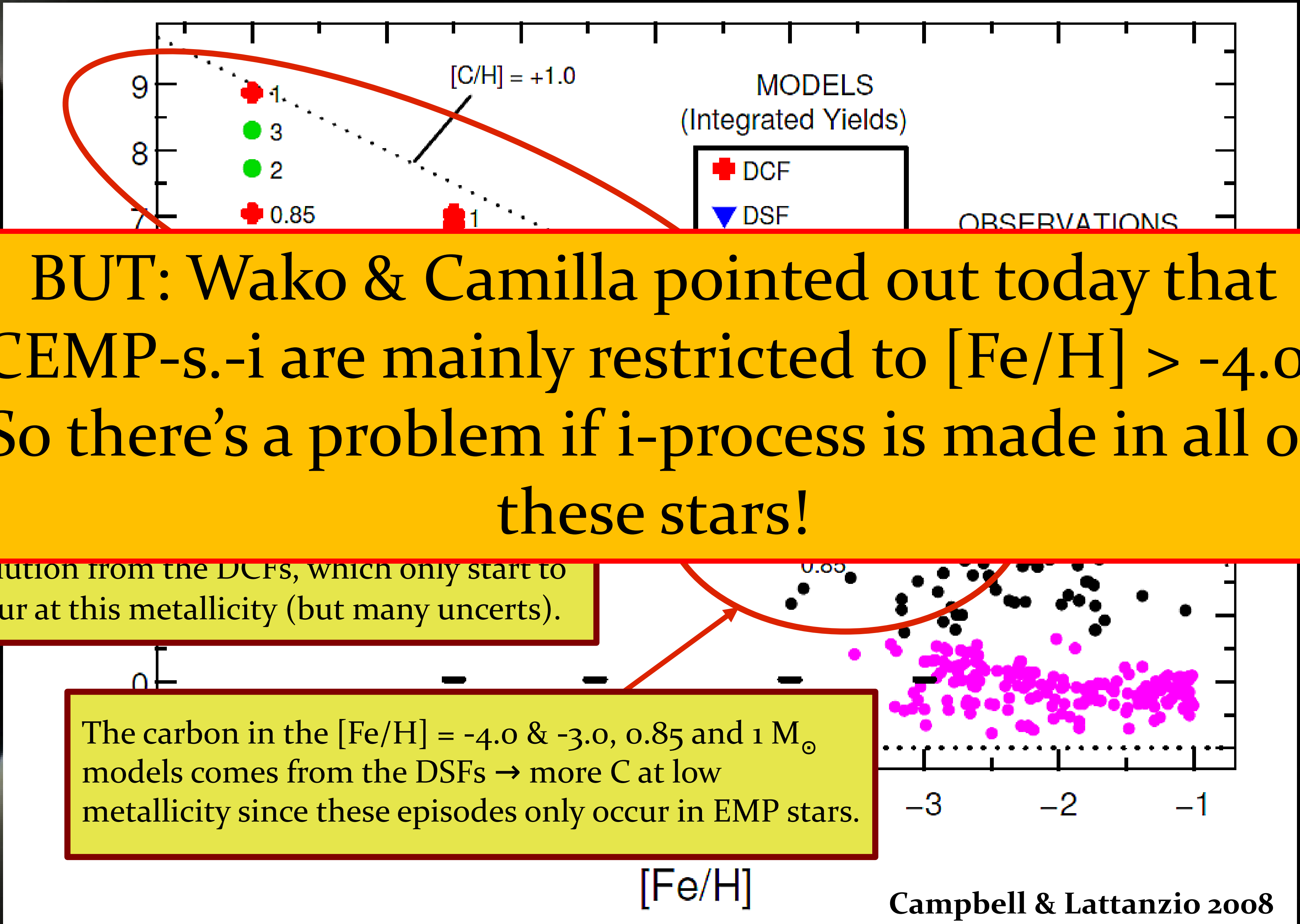
Getting the C to the EMPs: Binary mass transfer

- Stars of mass > about 0.85 Msun could have been mass donors to the currently observed CEMPs
- Roughly 50% of binary interaction occurs on AGB (Onno's talk), and given the extra sources of C in EMP stars (DCF, DSF), CEMPs would be expected to be more common at low metallicity.
- s/i-process production is also expected, in combination with the C.
- → CEMP-s explanation. Could this be an explanation for CEMP-i also?
- Question: are all CEMP-i stars in binary systems?



Credit: Star Trek TNG

Model Yields Vs Observations: [C/Fe]



BUT: Wako & Camilla pointed out today that CEMP-s.-i are mainly restricted to [Fe/H] > -4.0. So there's a problem if i-process is made in all of these stars!

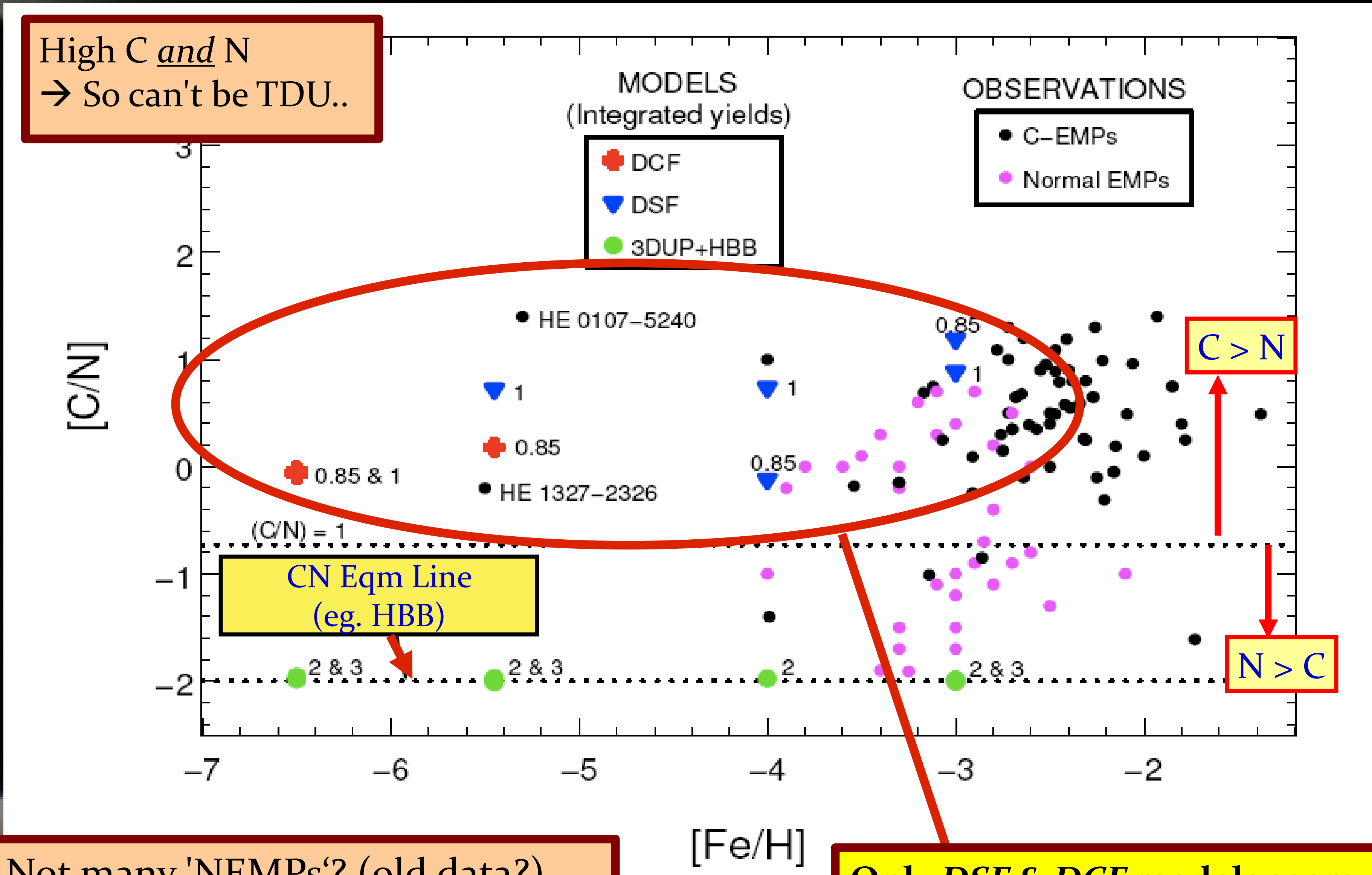
pollution from the DCFs, which only start to occur at this metallicity (but many uncerts).

The carbon in the [Fe/H] = -4.0 & -3.0, 0.85 and 1 $M_{\odot}$ models comes from the DSFs → more C at low metallicity since these episodes only occur in EMP stars.

Campbell & Lattanzio 2008

Models vs Observations: The [C/N] Constraint

High C *and* N
→ So can't be TDU..



Not many 'NEMPs'? (old data?)
→ IMF favours CEMP production?

Only *DSF & DCF* models seem to get close to observations!

Summary/Fin

- Many EMP stellar models show violent burning episodes that lead to severe surface pollution – the "Dual Flashes"

  → More ways to produce C & s/i-process isotopes at low [Fe/H].

- High neutron exposures in the dual flashes ('neutron superbursts') appear to give i-process like heavy element patterns.
- Only the models undergoing the Dual *Shell* Flash (early AGB) come close to matching the observed CEMPs at [Fe/H] > -5.0, since they produce large amounts of C as well as N, but keep N < C.
- WARNING: *Many model uncertainties*, and a huge chemical parameter space to match – I've only mentioned a few elements here..

An apt cartoon from the Melbourne artist Michael Leunig. Reproduced from a coffee mug given to me by Lisa Pinter. We note that the assumptions used in the current work are (usually) more substantial than the support for the ladder!

My thesis: http://users.monash.edu.au/~scamp/downloads/phd-thesis-Campbell.pdf