Nucleosynthesis during the peculiar core helium flash of low-mass primordial stars

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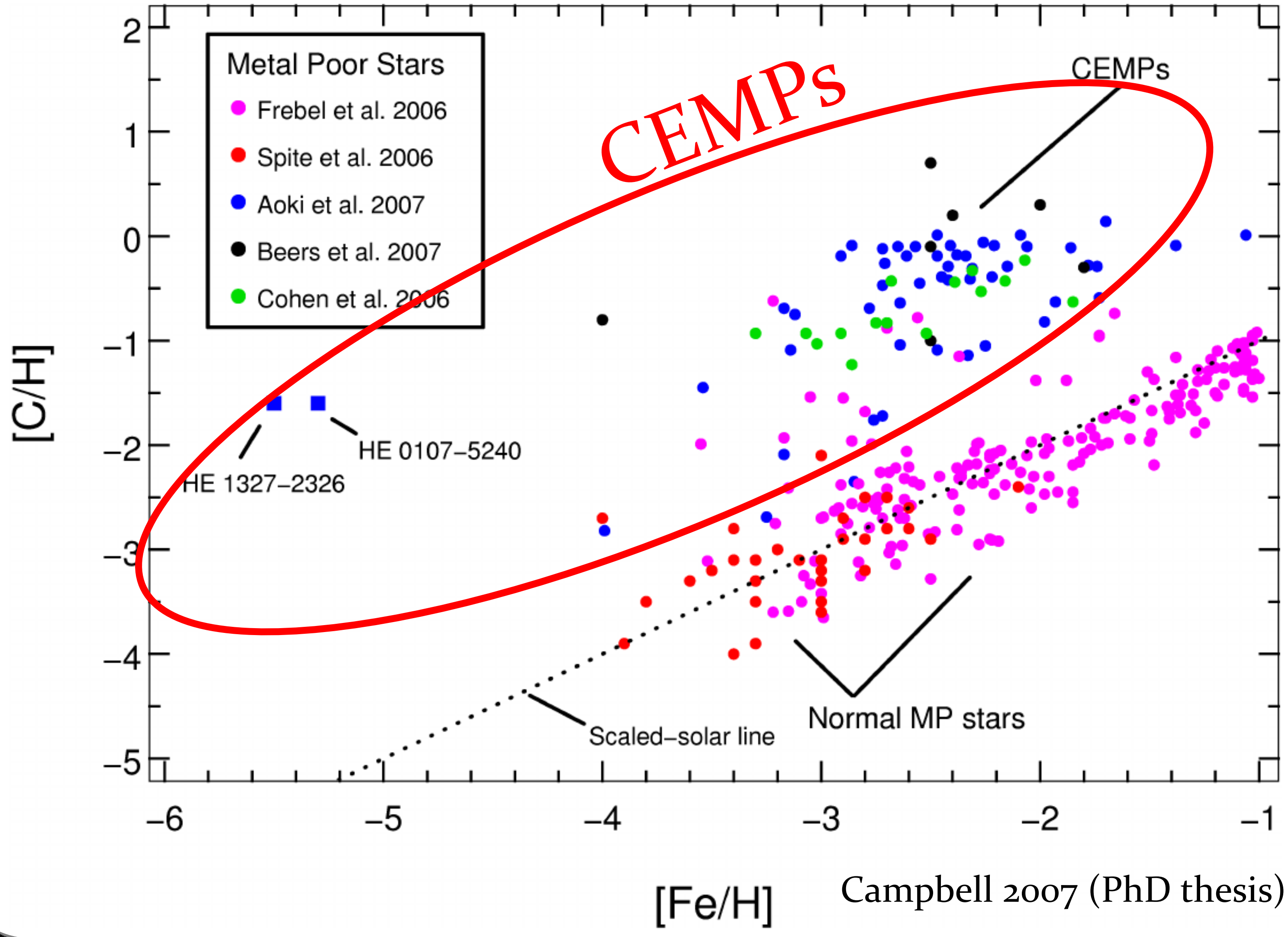
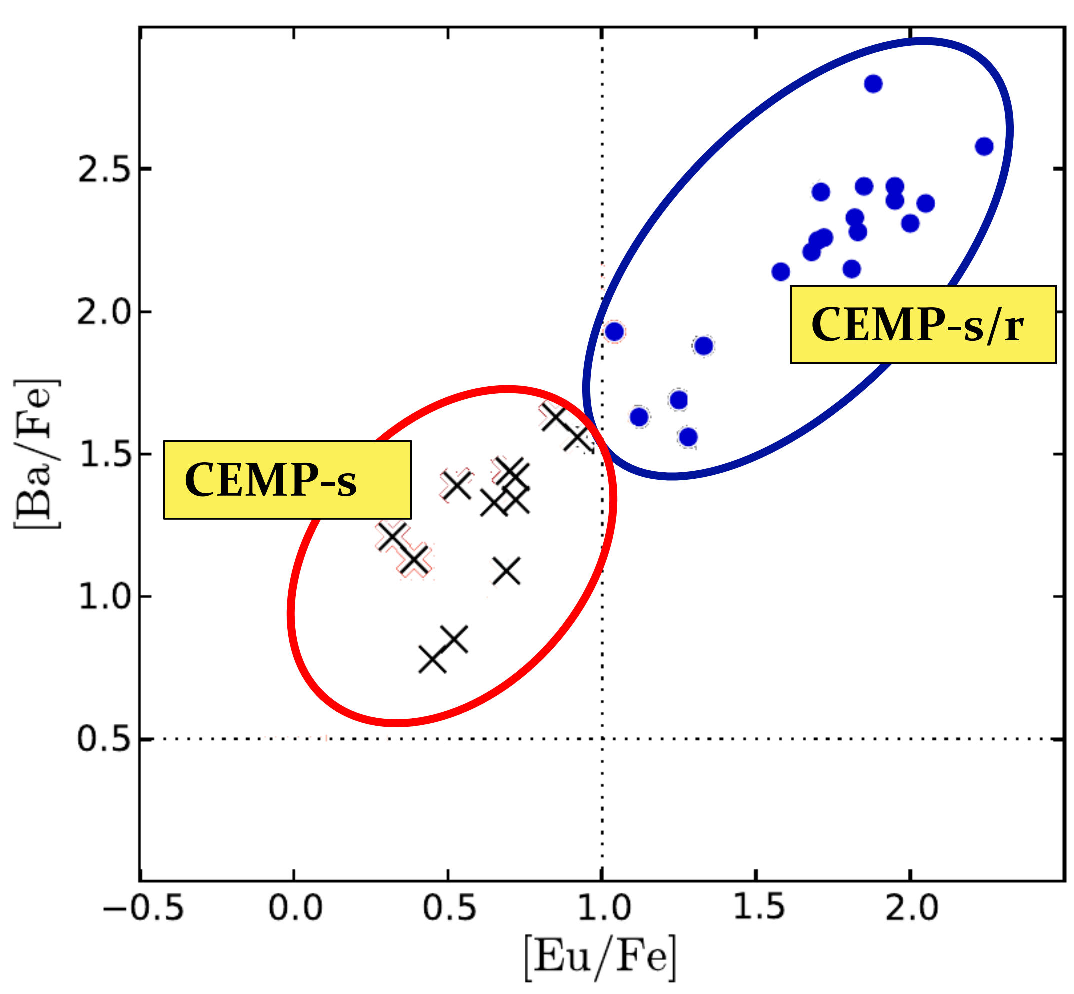
Subtitle: Beating the drum for low-mass stars!

Interestingly, EMP stars are often found to contain high levels of carbon ➔ "CEMPs"



Campbell 2007 (PhD thesis)

Also, some CEMPs are enriched in neutron-capture elements



Abate et al., 2015
Observational data from SAGA database: Suda et al. 2008, 2011

- CEMP: [C/Fe] > 0.7 dex
- CEMP-s: [Ba/Fe] > 0.5
- [Eu/Fe] < 1.0
- CEMP-s/r: [Ba/Fe] > 0.5 and [Eu/Fe] > 1.0

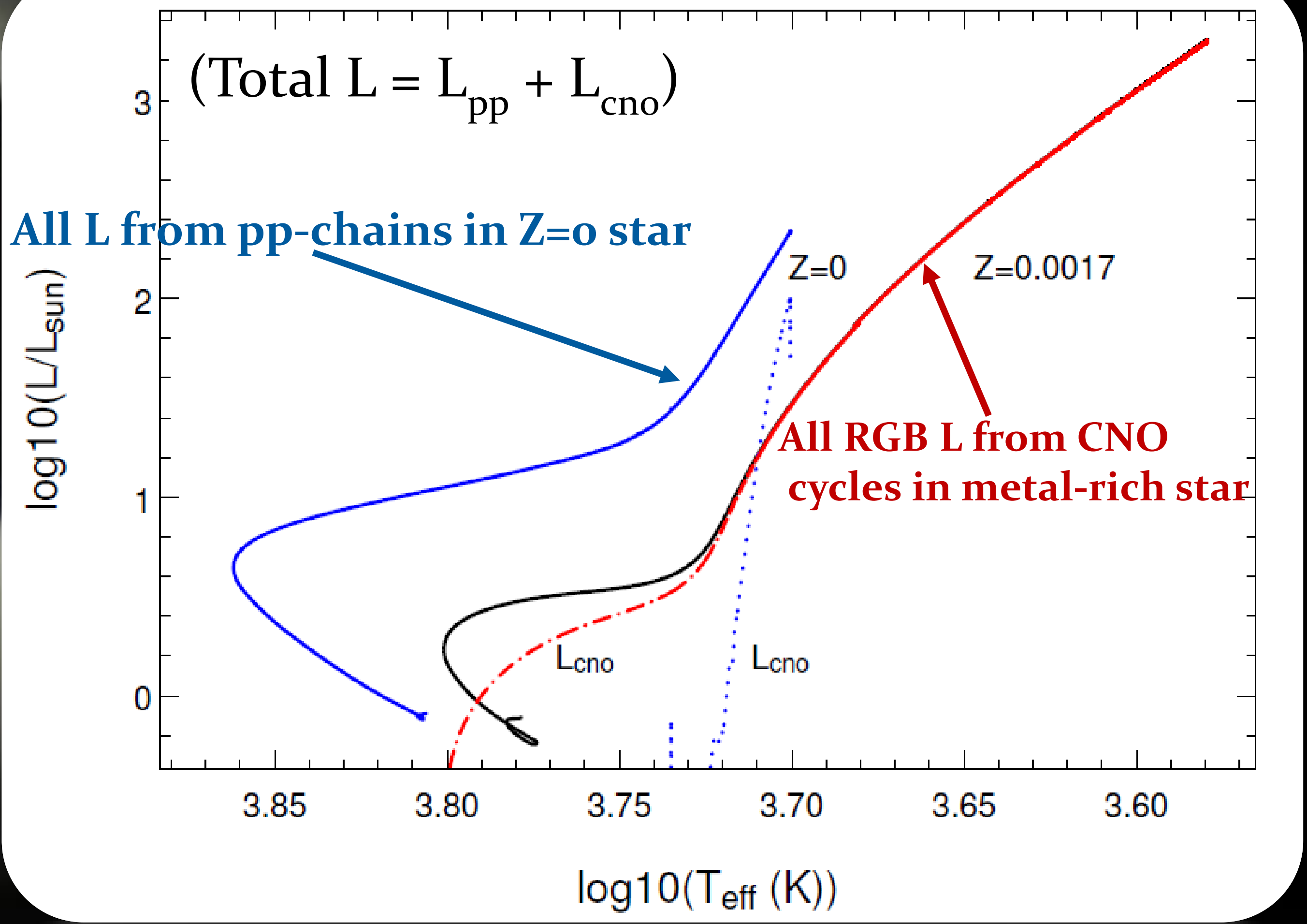
What do low-mass stellar models predict?

Case study:

Theoretical evolution of a
0.85 $M_\odot$ Population III star

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

'Normal' star versus Pop III star

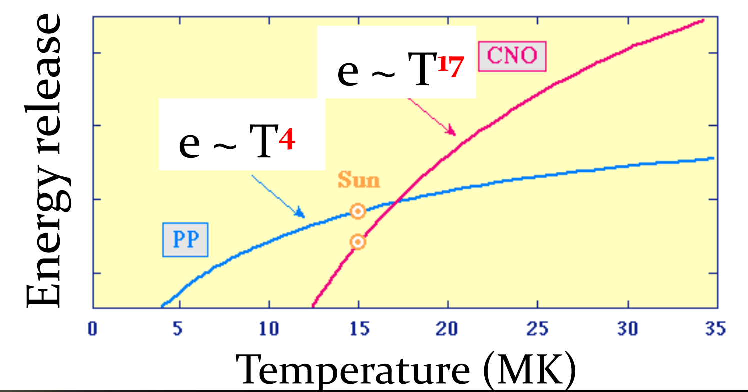


Campbell 2007 (PhD thesis)

- 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 low opacity of the metal-free gas.
- Also, the lack of CNO elements precludes the Z=0 star from burning H via the CNO cycles.

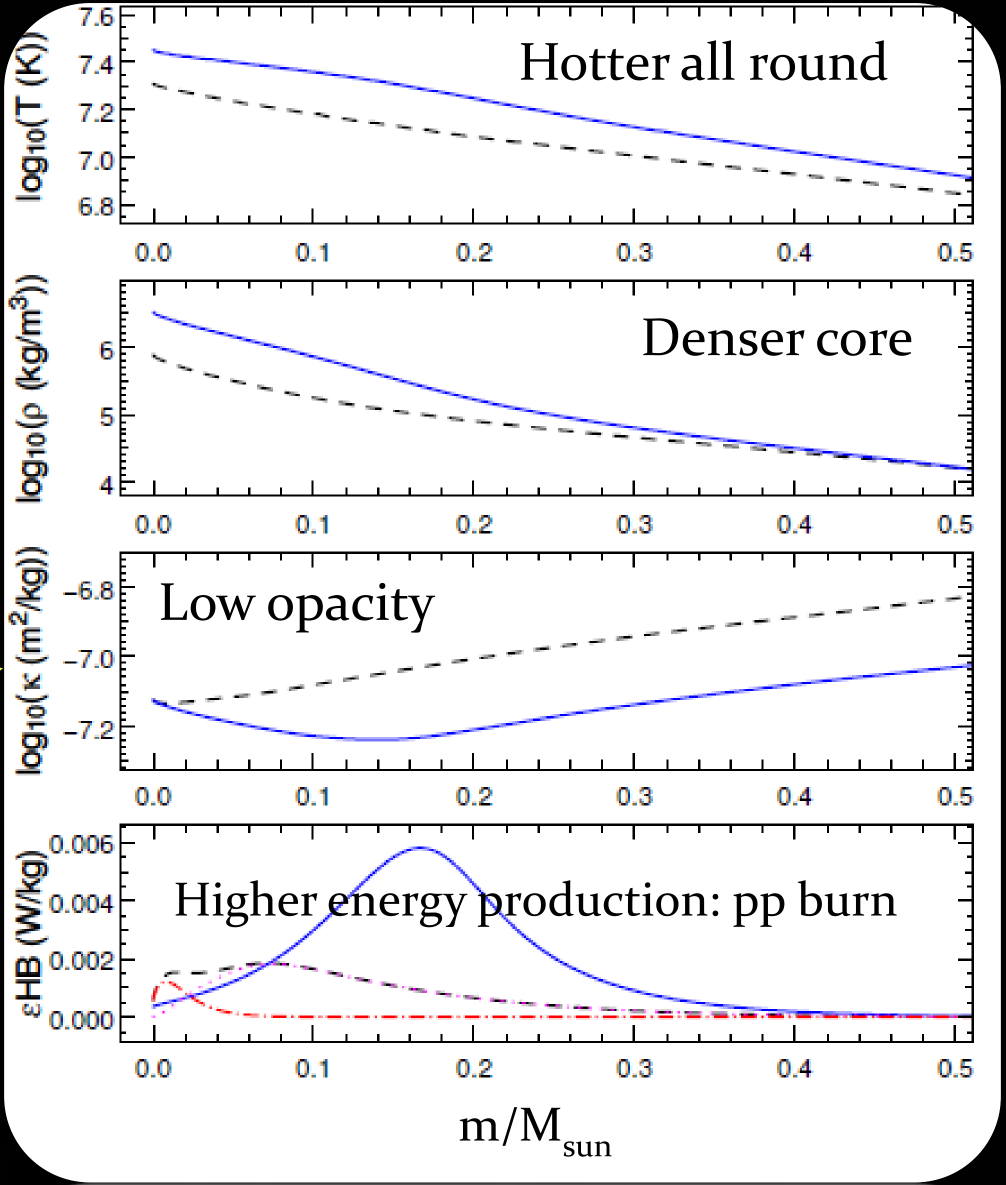
Z=0, 0.85 $M_\odot$: Internal Structure, MS

pp-chain energy release has 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

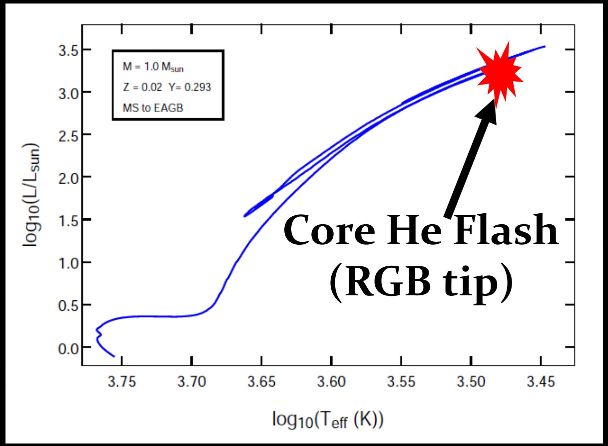


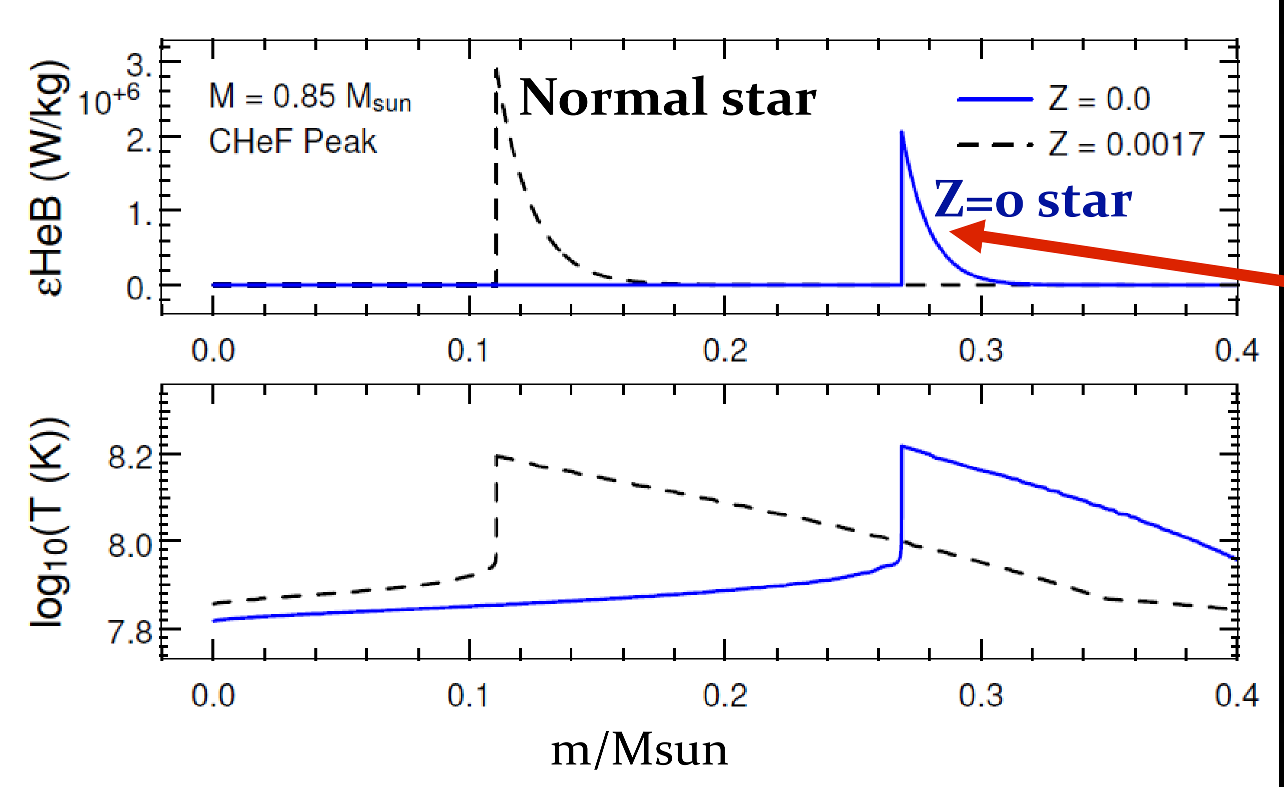
Campbell 2007 (PhD thesis)

Main Event:
The helium core-flash of the 0.85 $M_{\odot}$ Population III Star

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

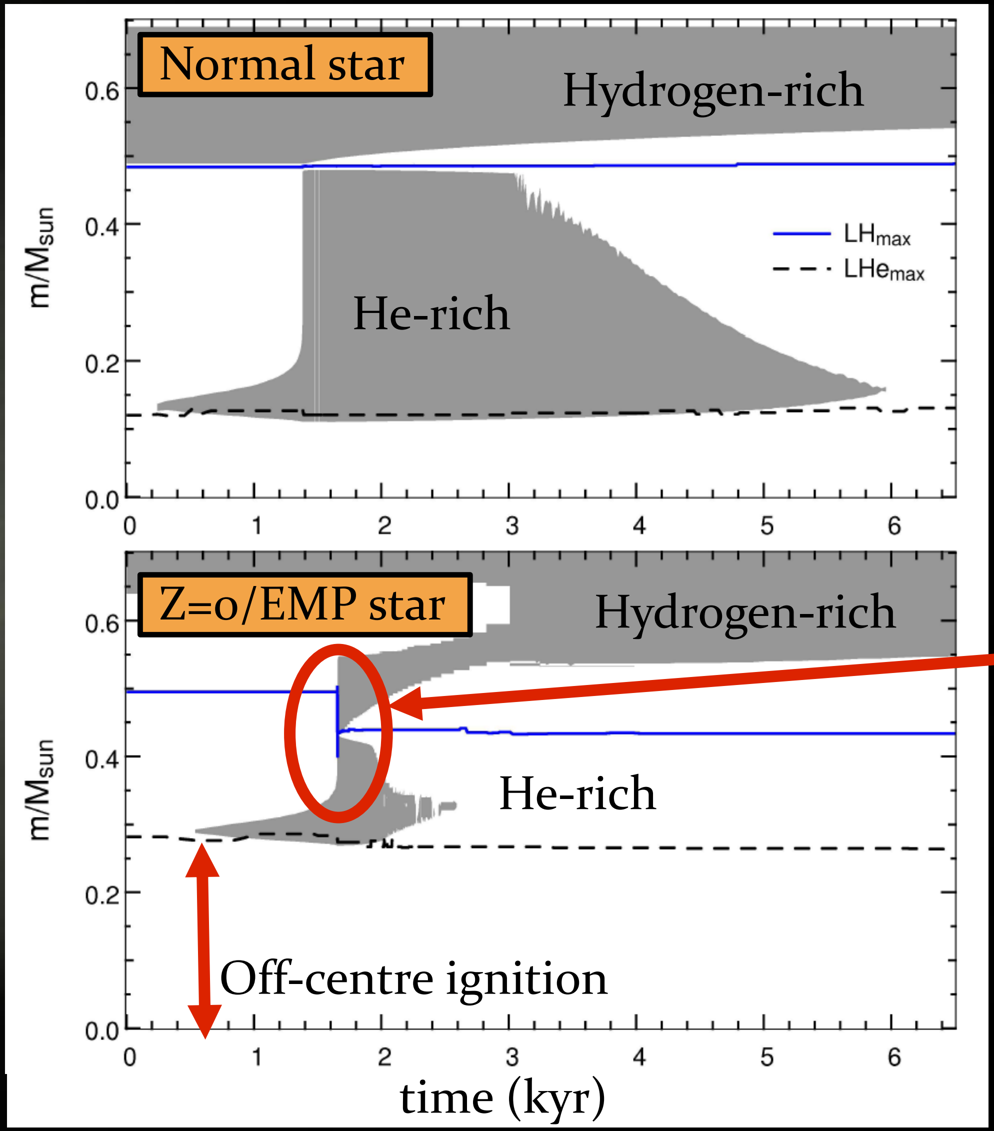
- At the top of the RGB He ignition results in a runaway burn (‘flash’) due to partial degeneracy of core material.
- In the Z=0 model this happens much further from the centre of the star…





Ignition way off-centre

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



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

- Grey shading = convection
- Blue line = H burning shell
- Dashed line = He burning shell

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

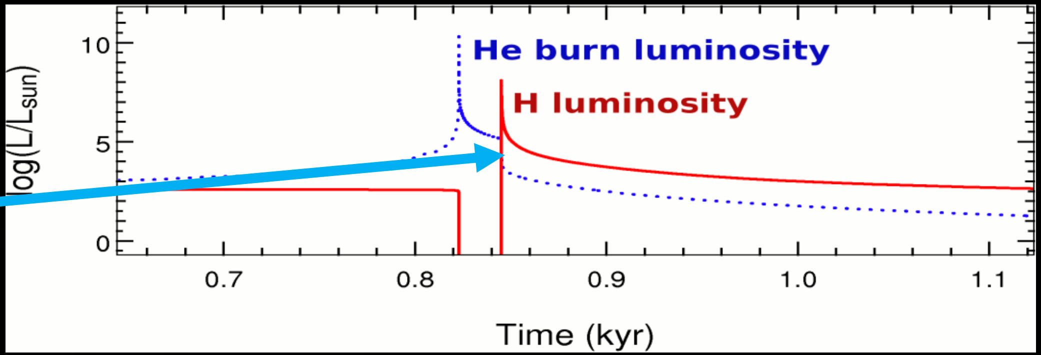
This is unique to EMP/PopIII stars!

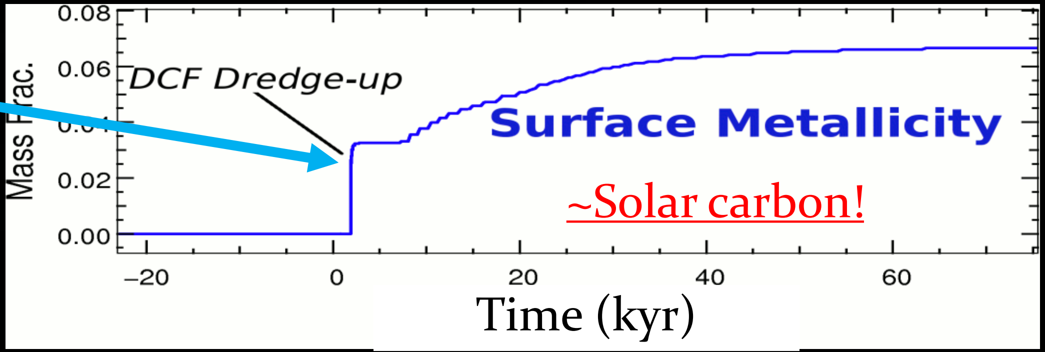
The PopIII/EMP "Dual Core Flash" (DCF)

The mixing of protons downwards into high temperature regions has 2 consequences:

1) Massive energy release:
   H burns very rapidly at such high T → 'Hydrogen Flash' → "Dual Core Flash"

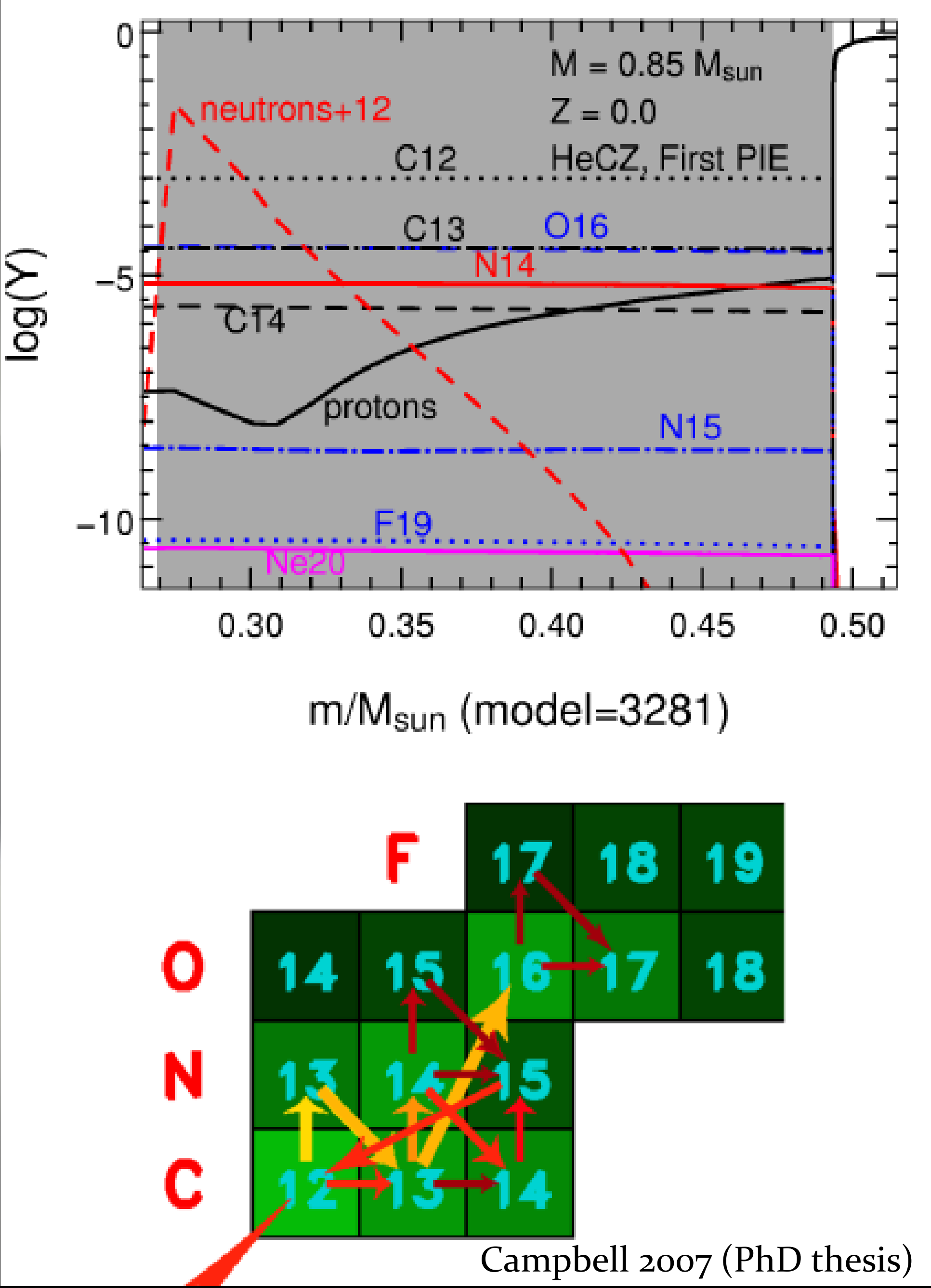
2) Interesting nucleosynthesis:
   H is not often found in such conditions, a range of isotopes can be produced → and mixed to the surface!





Campbell & Lattanzio 2008

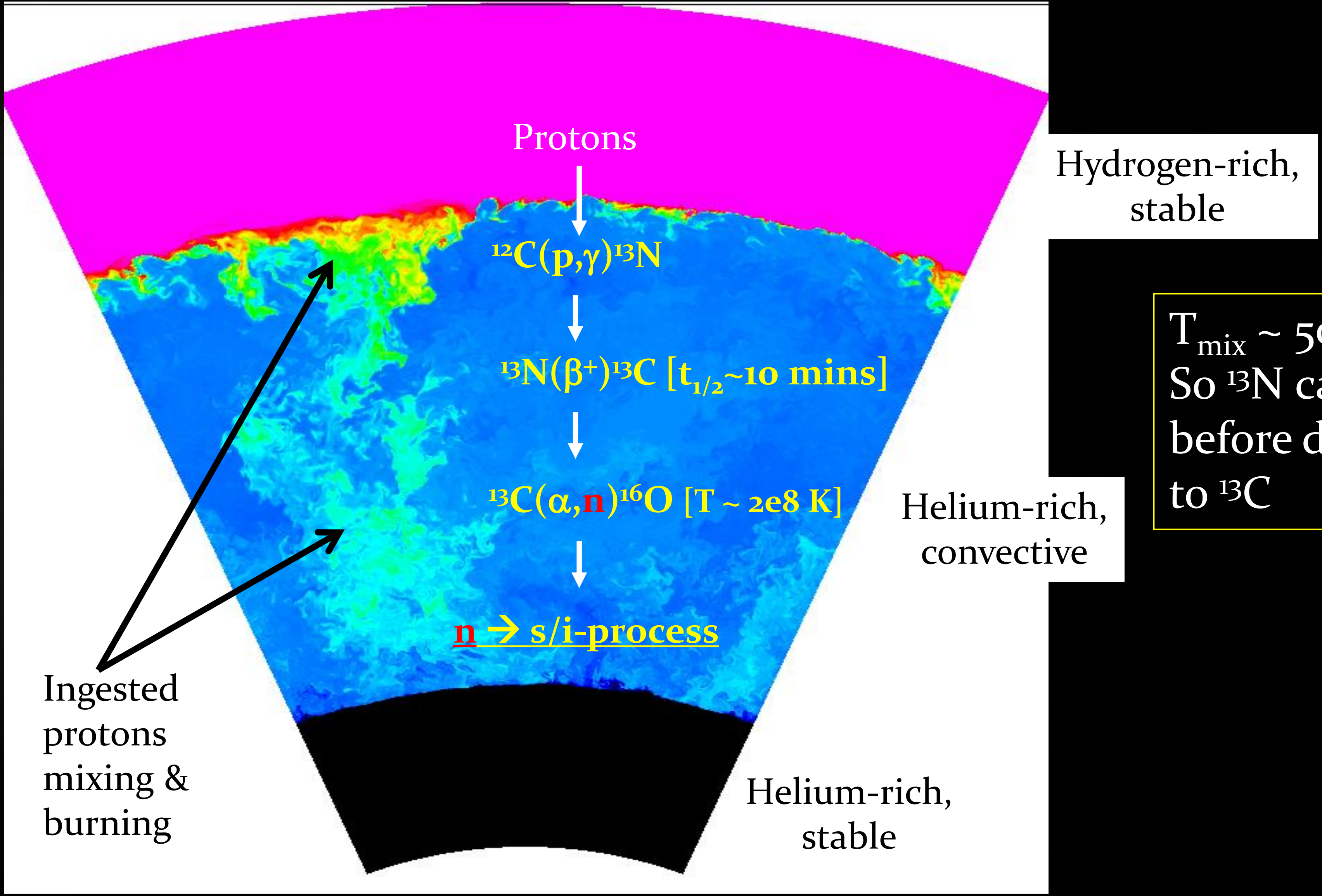
Possible s/r-Process during the DCF?



Campbell 2007 (PhD thesis)

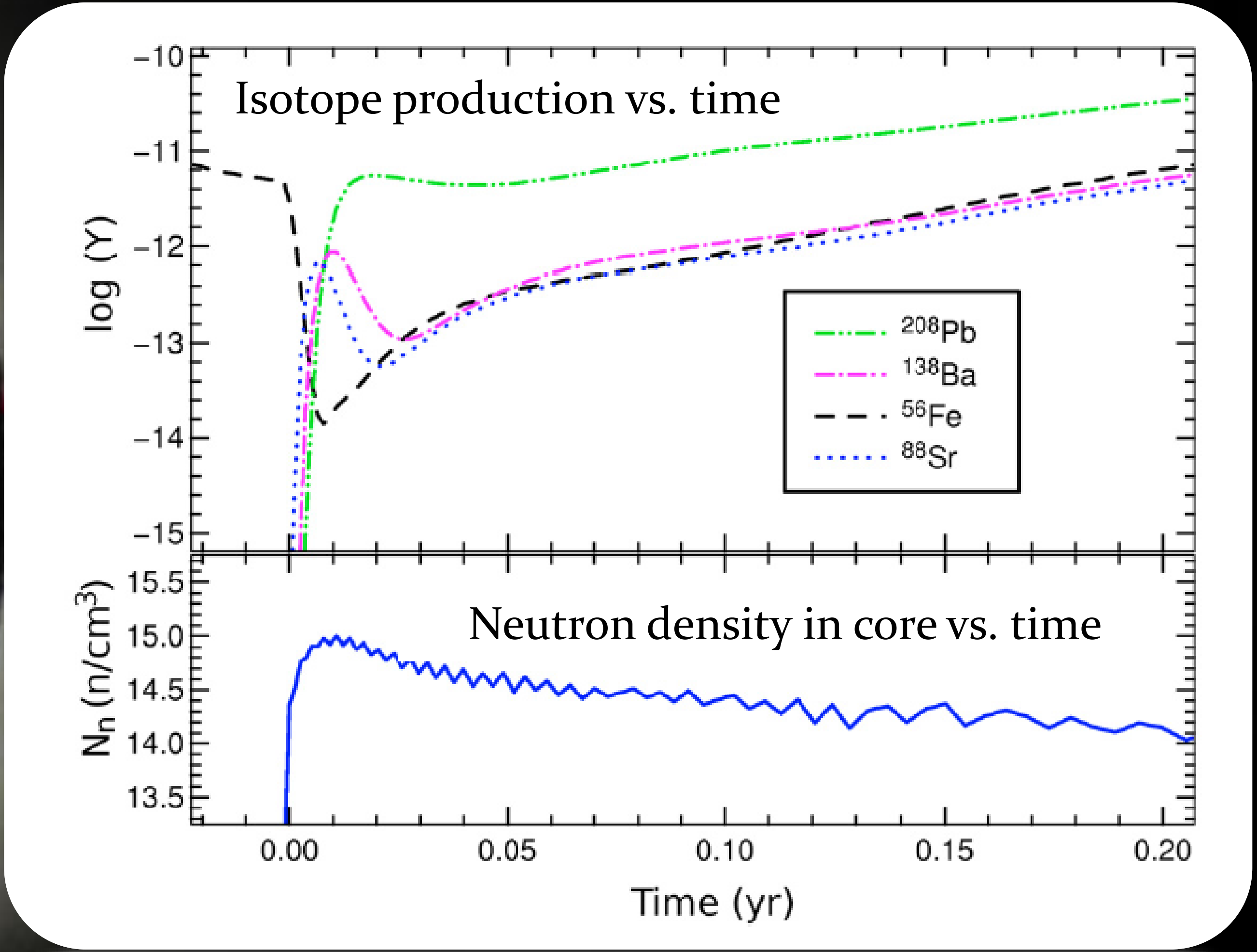
- It was suggested by Fujimoto et al (1990) that neutron-capture elements may be produced during a DCF, since the protons should be captured by ^{12}C in He burning region, to produce ^{13}C, and this can then produce neutrons.
- In this model we found that ^{13}C was produced in large amounts, and that the neutron-producing reaction $^{13}C(a,n)^{16}O$ was very active.
- Interestingly the neutron density in this model is ~10^{13} cm^{-3}.
- This is much higher than s-process densities!
- But not as high as needed for the r-process.
- This simulation had a limited nuclear network (75 isotopes, up to S), so more investigation was required..

DCF Schematic:
Mixing & Burning → Neutron-capture nucleosynthesis



T_{mix} ~ 50 min
So ^{13}N can travel before decaying to ^{13}C

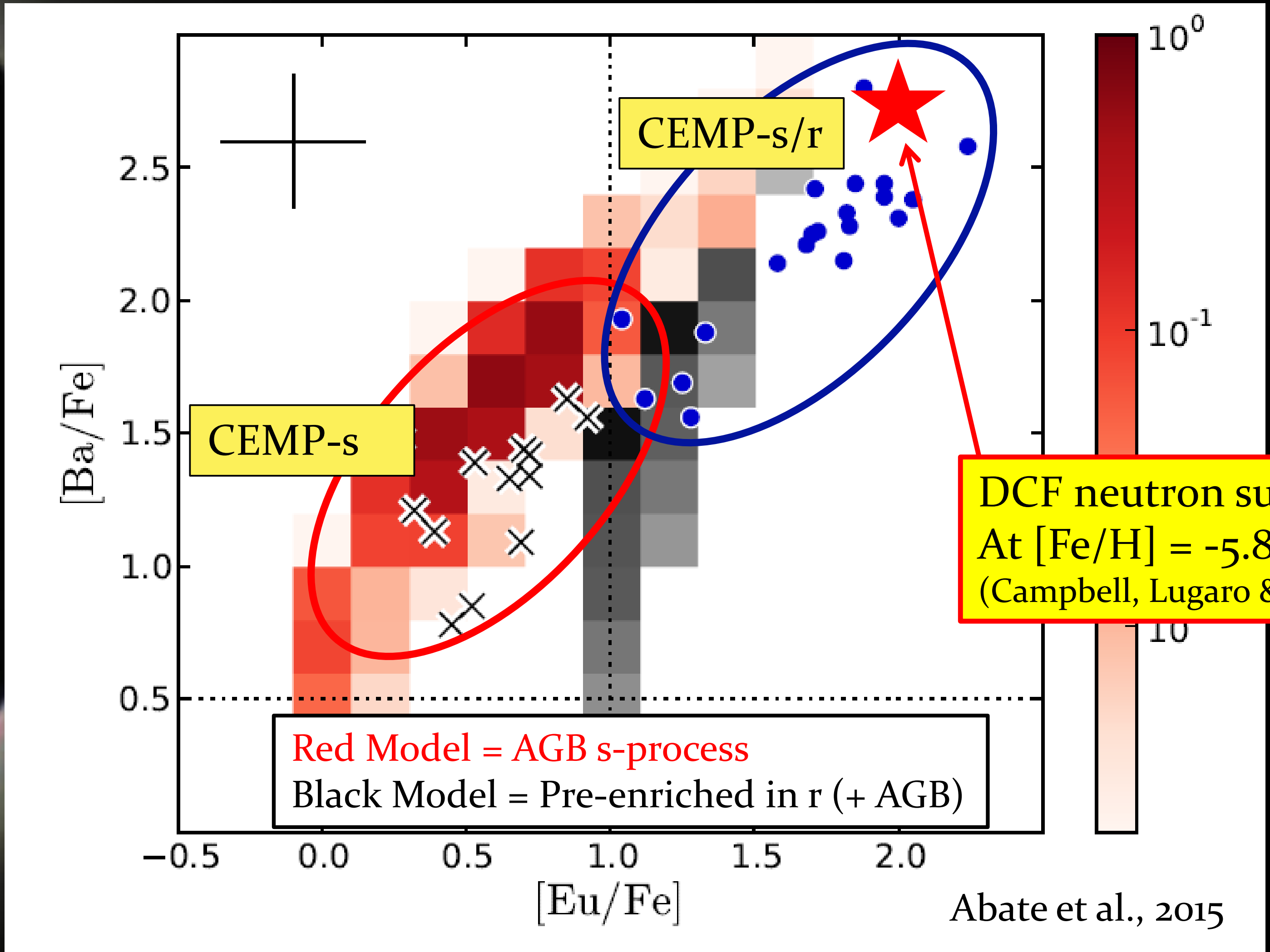
PopIII/EMP "Neutron Superburst"



Campbell, Lugaro & Karakas, 2010

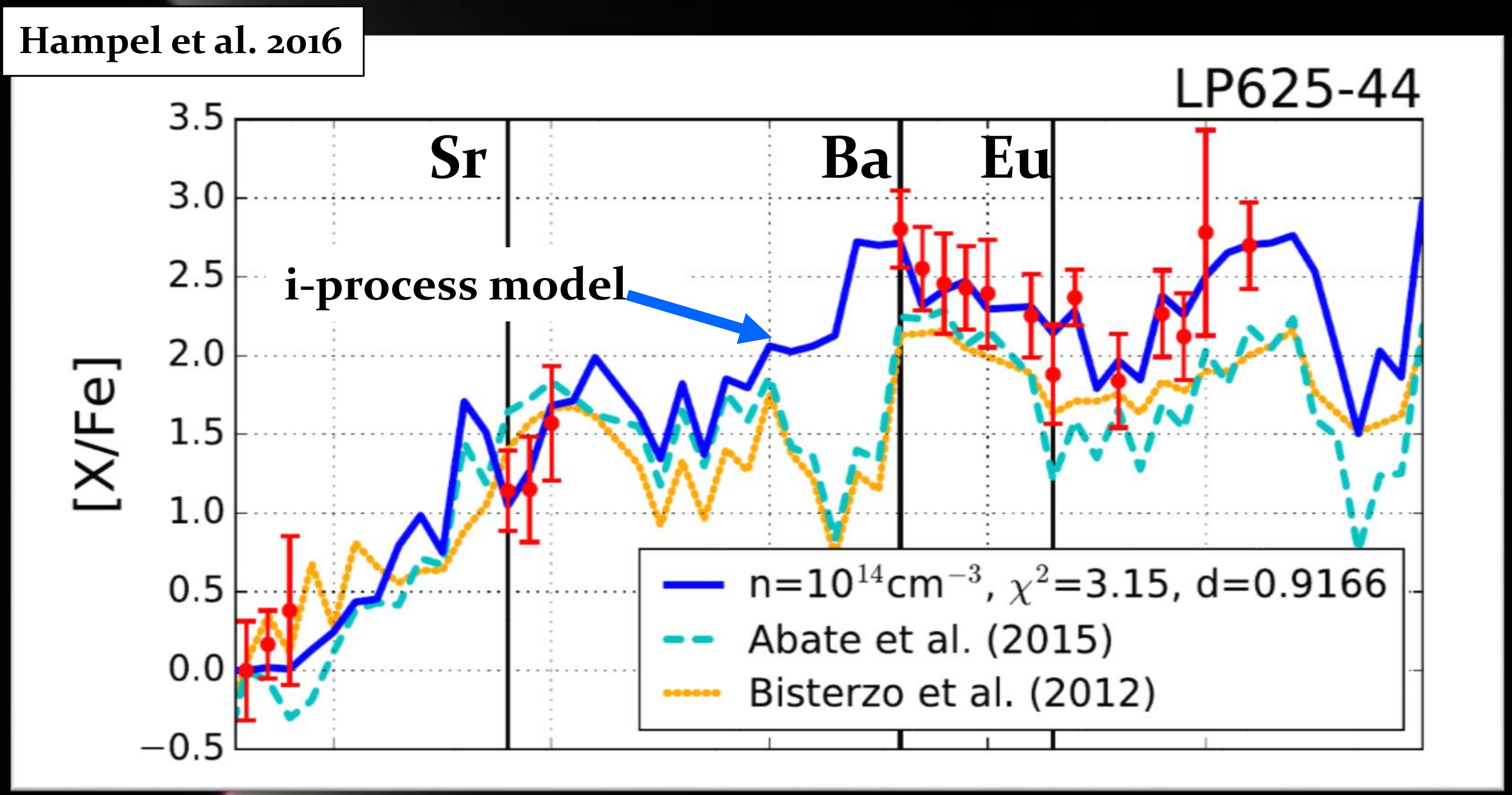
- Larger network confirmed the high neutron densities in DCFs:
  10^{13} to 10^{15} n/cm^3
- This is intermediate between s & r-process: the 'i-process' (Cowan & Rose 1977)
- At the time we didn't have a big enough network to follow the i-process properly (only 320 isotopes)…
- Note this model was [Fe/H] = -6.5, 1.0 Msun.

Back to Abate's CEMP-s, CEMP-r/s plot



- Colour scale is Population synthesis model (stellar density).
- It can produce CEMP-s stars (binaries) but can *not* produce CEMP s/r stars.
- The input to these population … tellar model yields … dels are not … the observations.
- → Could it be the 'Neutron Superburst'?? -- this this event was not included in the pop. synthesis…

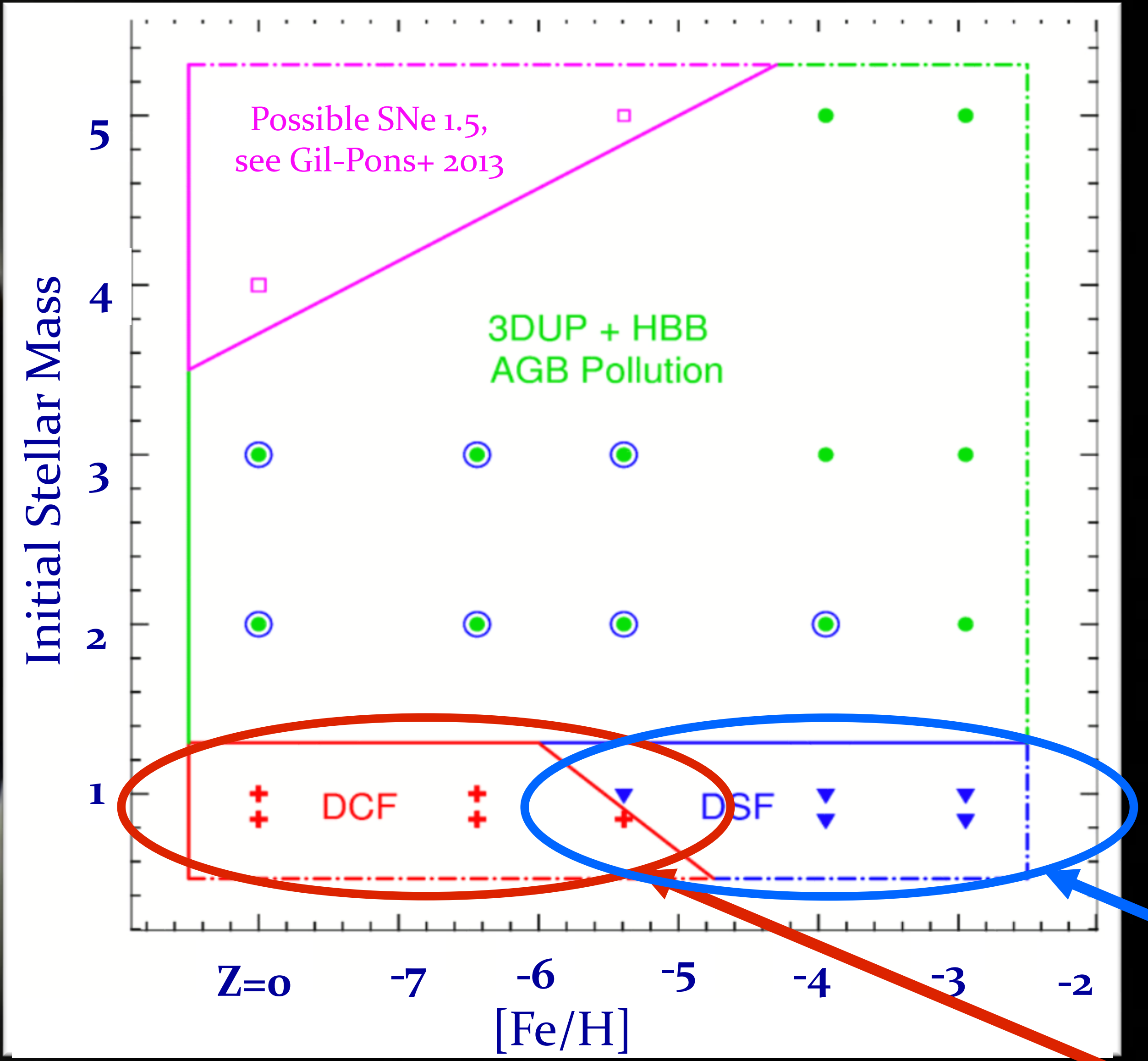
Single-Zone i-process Models



Red = Observations for star LP625-44
Blue = i-process (1-zone)
Others = s-process models

- As noted, our network was not sufficient to follow the full i-process.
- More recently a couple of groups (Dardelet+2015, Hampel+2016) have made single-zone nucleosynthesis calculations, with large i-process-capable reaction networks.
- Thermodynamic conditions are taken to represent the AGB proton-ingestion site.
- They find a very good match between observed CEMP-r/s observations and their i-process abundance patterns.
- Has been suggested to rename CEMP-r/s to CEMP-i :)

In which stars do these events happen?



Campbell & Lattanzio 2008

- Pollution summary for our grid of Z=0 and EMP models in the initial mass-[Fe/H] plane.
- Yields available! (Campbell & Lattanzio 2008)
- 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)

DSFs are similar but occur on AGB

DCFs are peculiar to EMP models → BONUS CARBON & n-capture elements!

Current Work: Stellar structure simulations coupled to a large reaction network

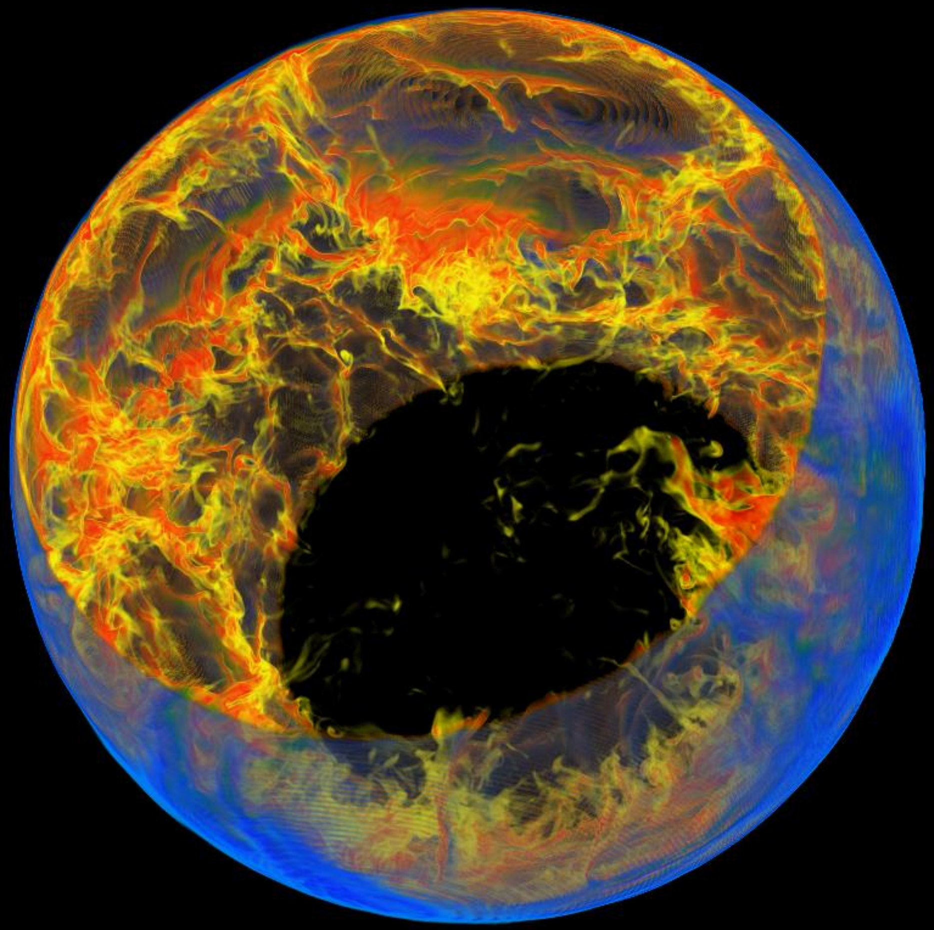
- The next step is to couple an i-process-capable network with a stellar structure calculation, for a self-consistent simulation.
- Importantly, the energy from some reactions that are not usually taken into account becomes significant, for example: $^{13}C(\alpha,n)\,^{16}O$ (Cristallo et al. 2009).
- We are currently running models using the KEPLER stellar code (Heger [Monash], Woosley, Weaver et al.), which has an adaptable nuclear network (up to Astatine).
- Kepler has recently been used for s/i-process in massive stars (Banerjee, Qian & Heger 2018).

Alexander Heger,
KEPLER code @ Monash

Caveats

- Reaction rates of unstable nuclei are mostly theoretical, so uncertain → uncertainty in abundance patterns.

- Also, the DCF is really a 3D hydrodynamical event – the assumptions about convection (MLT; cf. Meridith Joyce's talk) and mixing (diffusive) in the 1D codes must have a strong effect on the results…
- Woodward, Herwig, et al. have been working on a similar event in low-Z AGB stars, using 3D hydrodynamics (pictured right).
- Our group attempted a 3D simulation of a DCF around the same time…

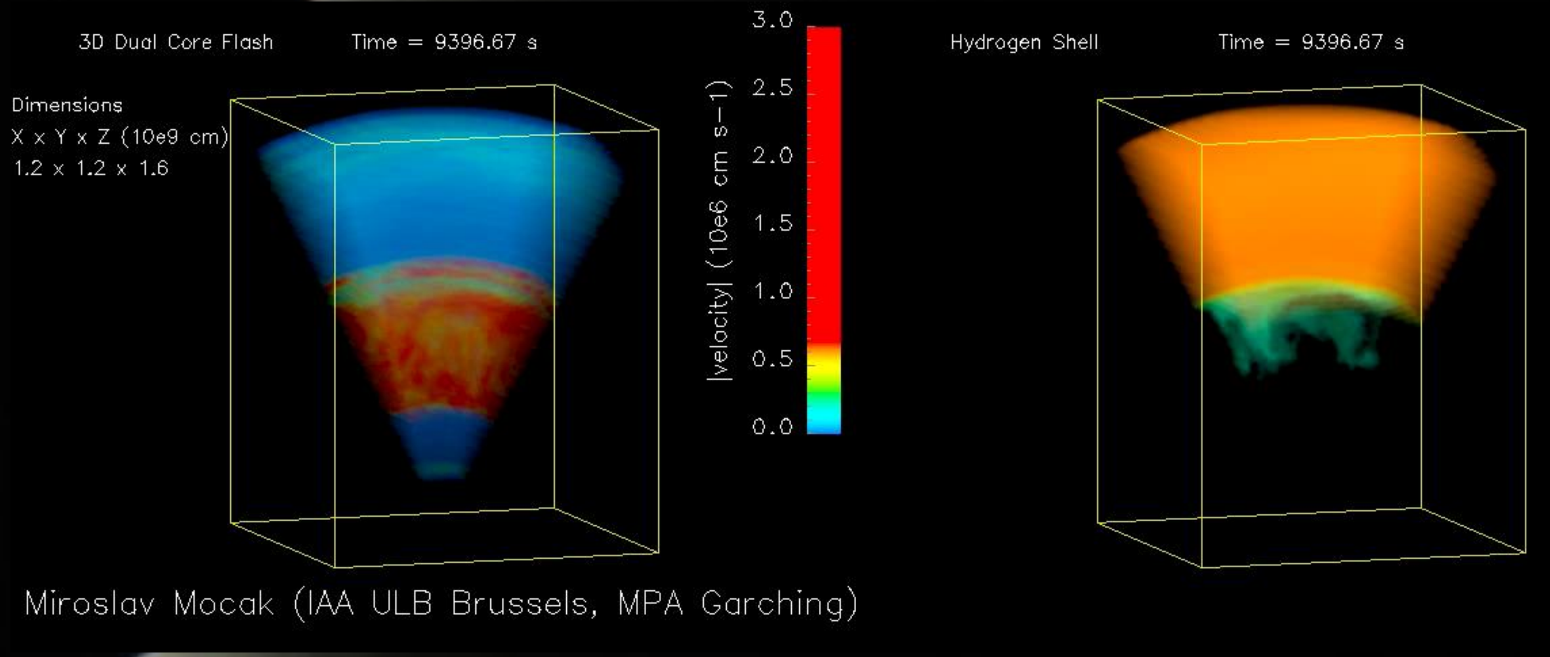


Herwig et al. 2011

Past/Future work:

Trying to get a handle on turbulent mixing & burning uncertainties using 3D Hydro Simulations

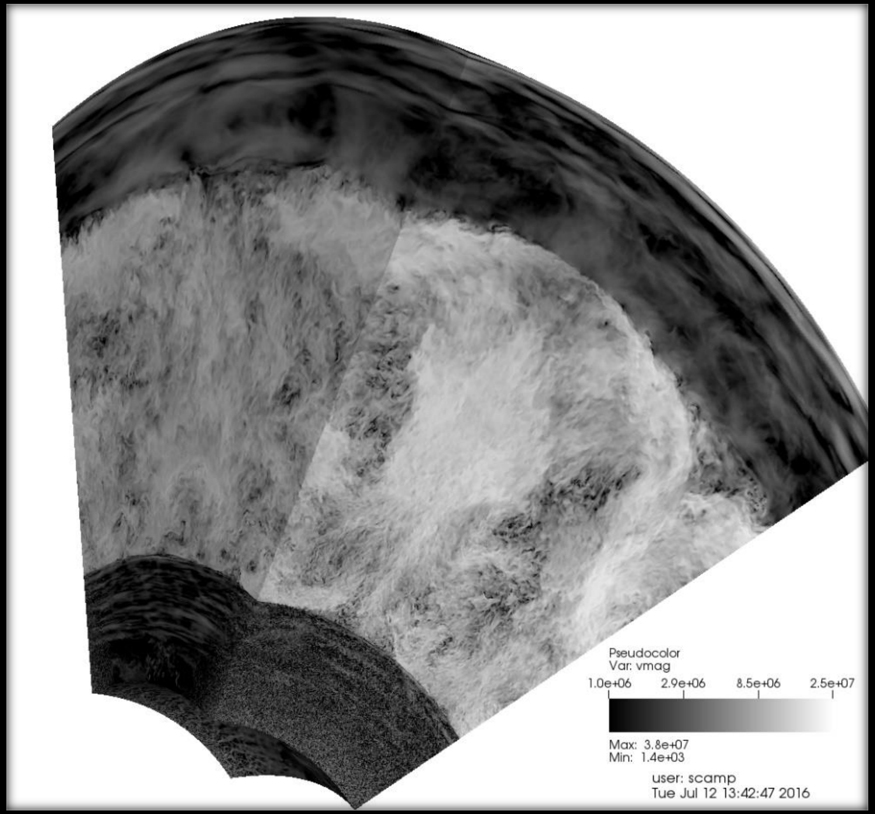
Early attempt at 3D Dual Core Flash:



Mocak, Campbell, et al., 2010

3D Hydro collaborators: Miro Mocak, Casey Meakin, Dave Arnett

Recent 3D hydro simulation, oxygen burning shell:

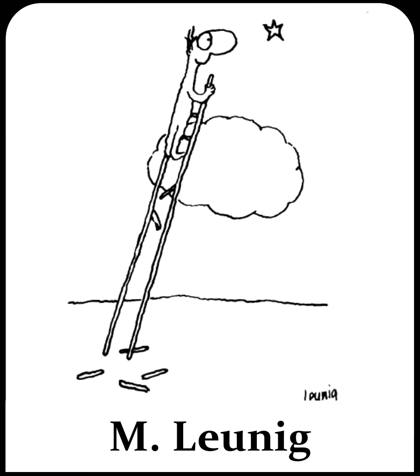


Summary/Fin

- Many EMP stellar models show violent burning episodes that lead to severe surface pollution, including carbon.
  → More ways to produce C in stars of low metallicity!
  → Way to go low-mass stars! :)
- So the existence of at least some CEMPs may be explained by this peculiar evolution of low-mass EMP stars.
- High neutron exposures in the dual flashes (‘neutron superbursts’) appear to also give i-process heavy element patterns, as identified in some CEMP stars (CEMP-s/r)

Current/future work:

- We are computing stellar models coupled to large nuclear reaction networks to model these events self-consistently.
- Also trying to reduce the model uncertainties by making 3D hydrodynamic models of these events.



Postdoc job ad!

- 3D Hydrodynamics & nucleosynthesis, at Monash Uni, Australia.
- Start latest Sep/2019.

PhD Student Ad!

- 3D hydrodynamics
- 1D stellar evolution & nucleosynthesis.

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