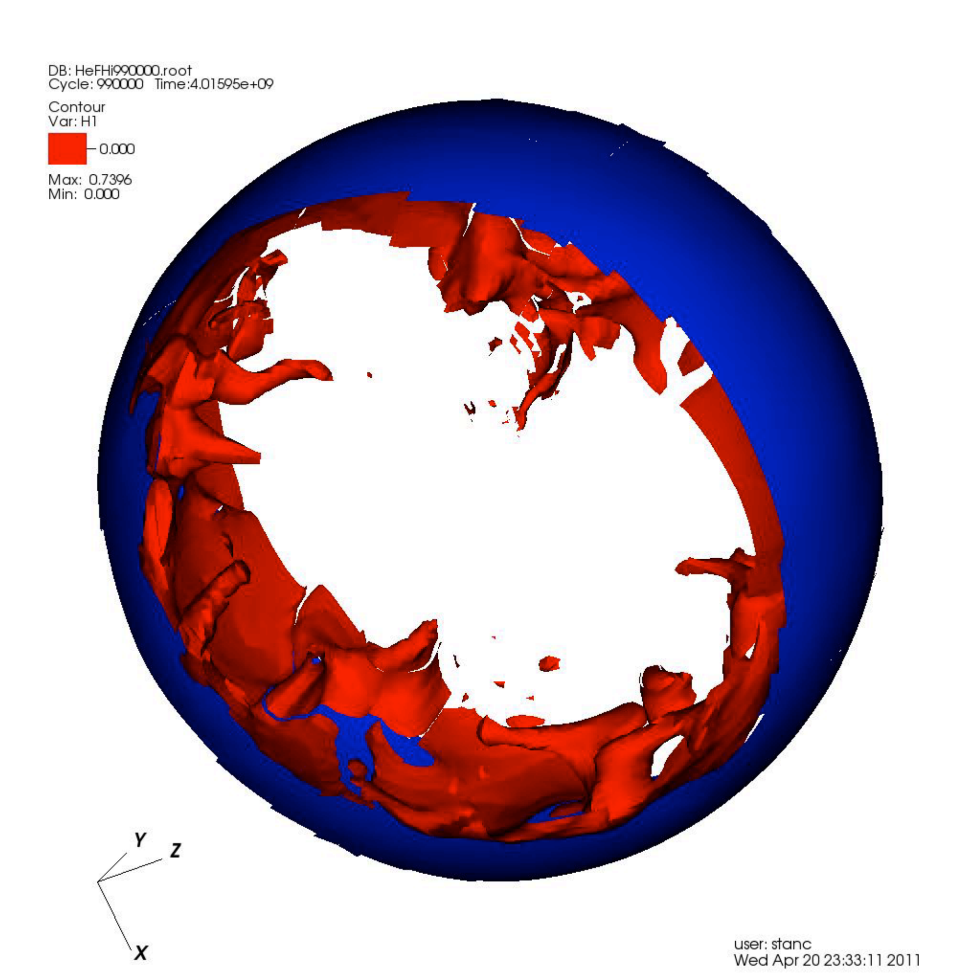
PROTON INGESTION AND NEUTRON-CAPTURE NUCLEOSYNTHESIS

Richard J. Stancliffe

Argelander Institute für Astronomie, Bonn



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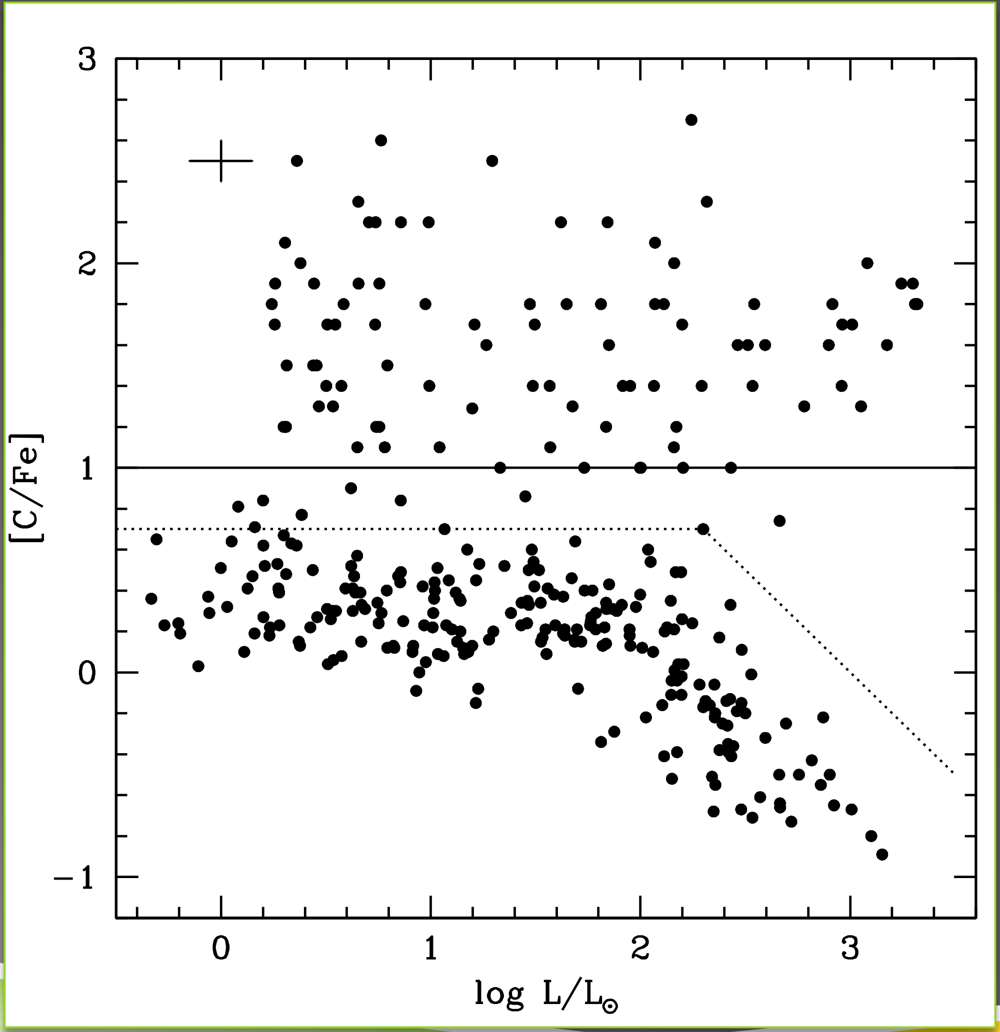
OVERVIEW

- AGB evolution
- Proton ingestion episodes
- Hydrodynamical models
- Making sense of it all…

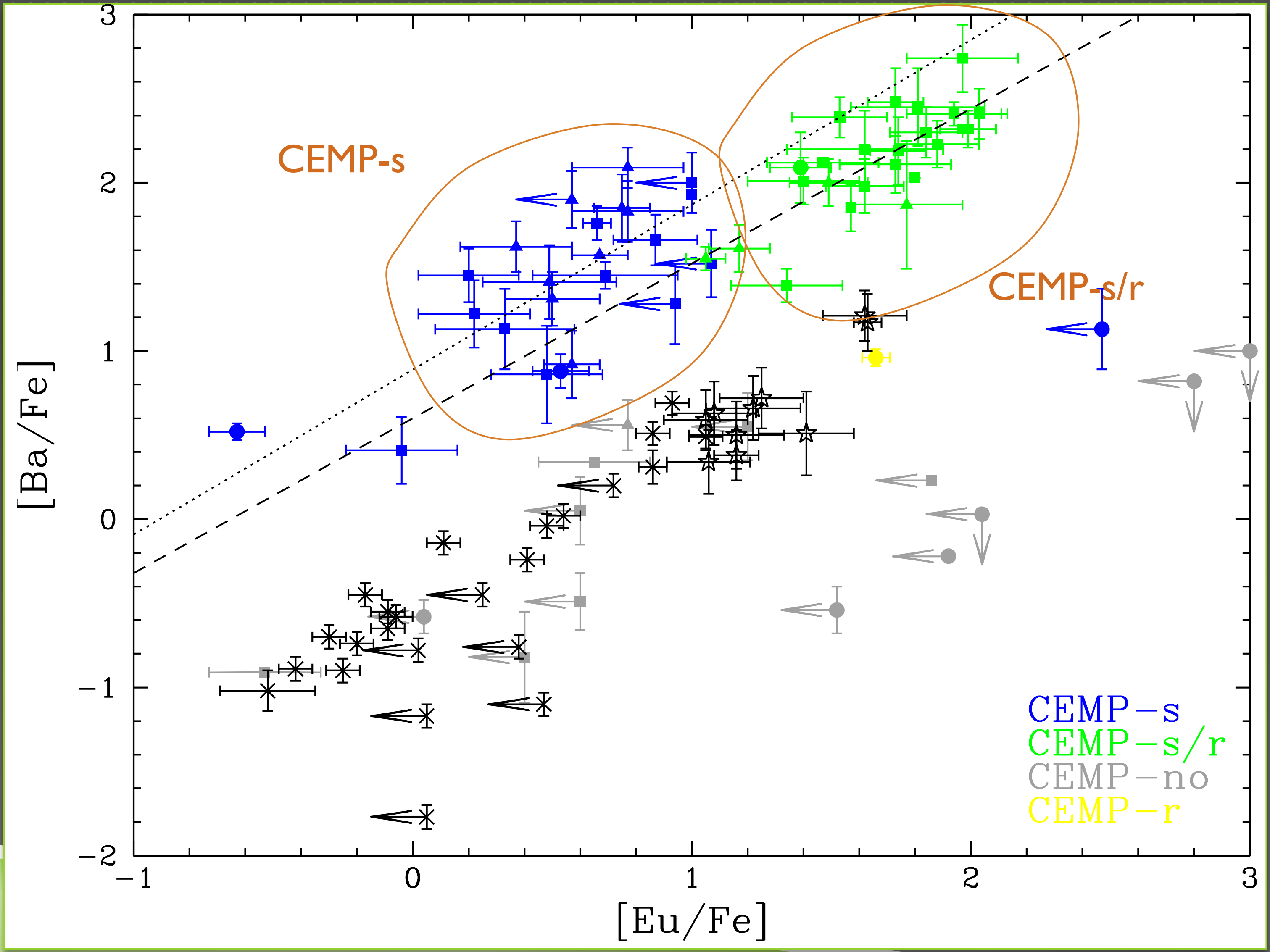
CARBON-ENHANCED STARS

- A large fraction of metal-poor stars are carbon-rich
- Perhaps as many as 20%
- Some show enrichments of heavy elements, particularly of s-process elements
- Many of these also show radial velocity variations…

Lucatello et al. (2006)



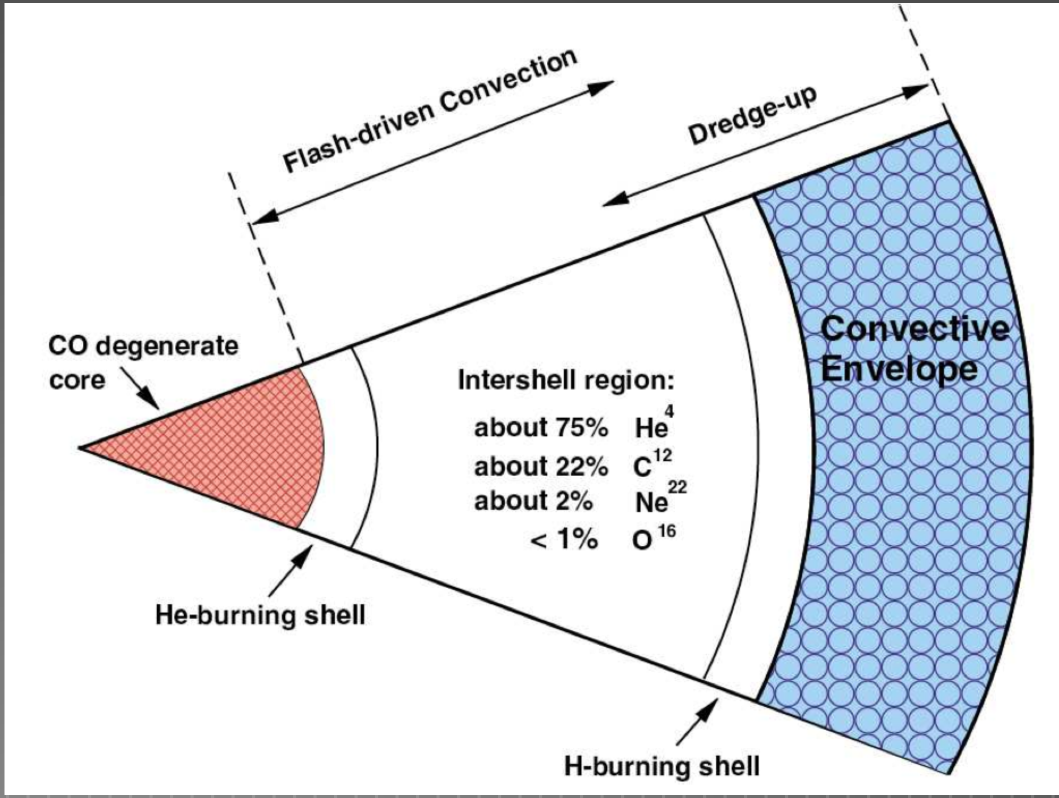
HEAVY ELEMENTS



Lugaro et al. (2012), data from Masseron et al. (2010)

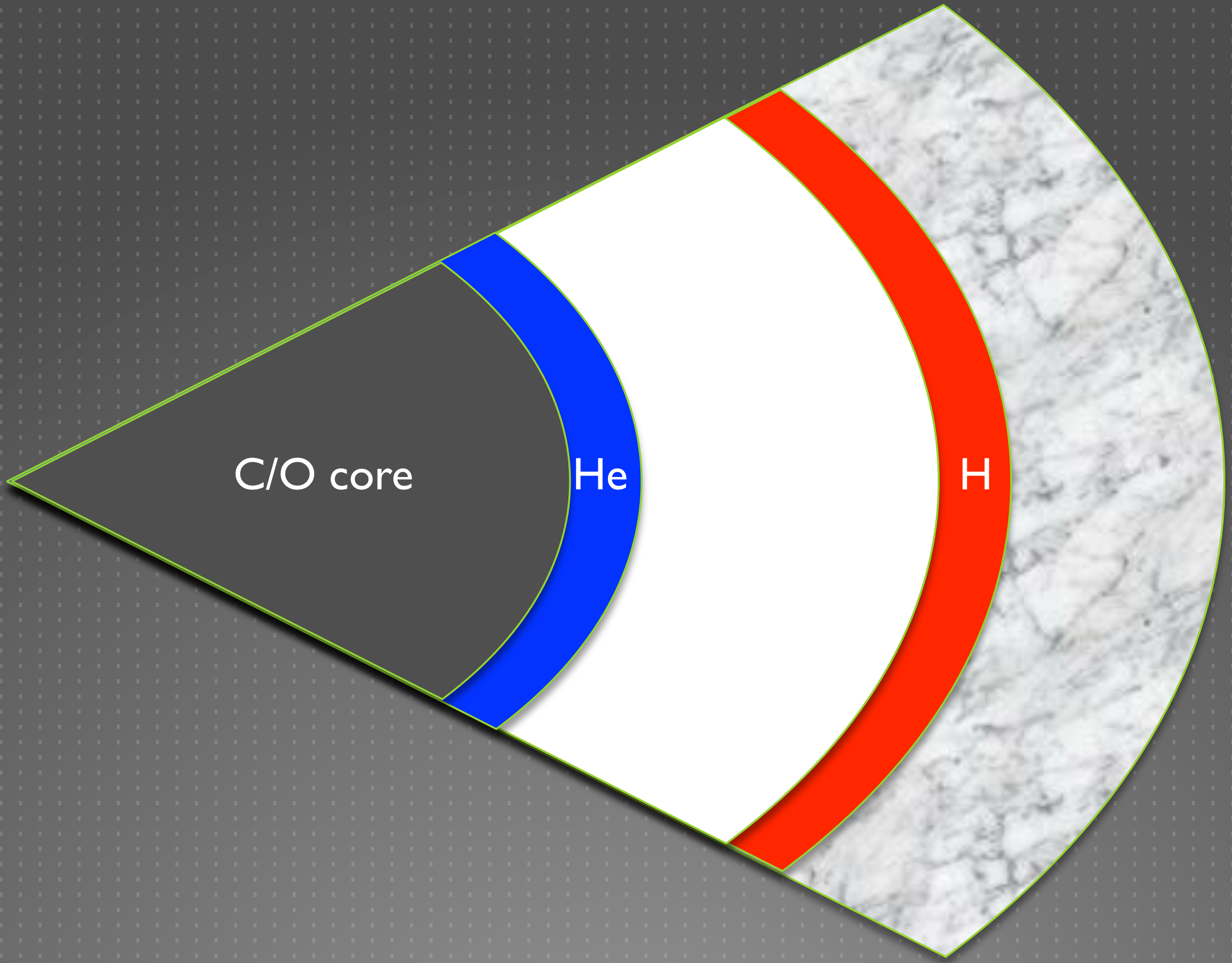
ASYMPTOTIC GIANT BRANCH STARS

- Final stage of the life of a low mass star
- Unstable double shell burning – thermal pulses
- Third dredge-up
- Strong winds erode the envelope

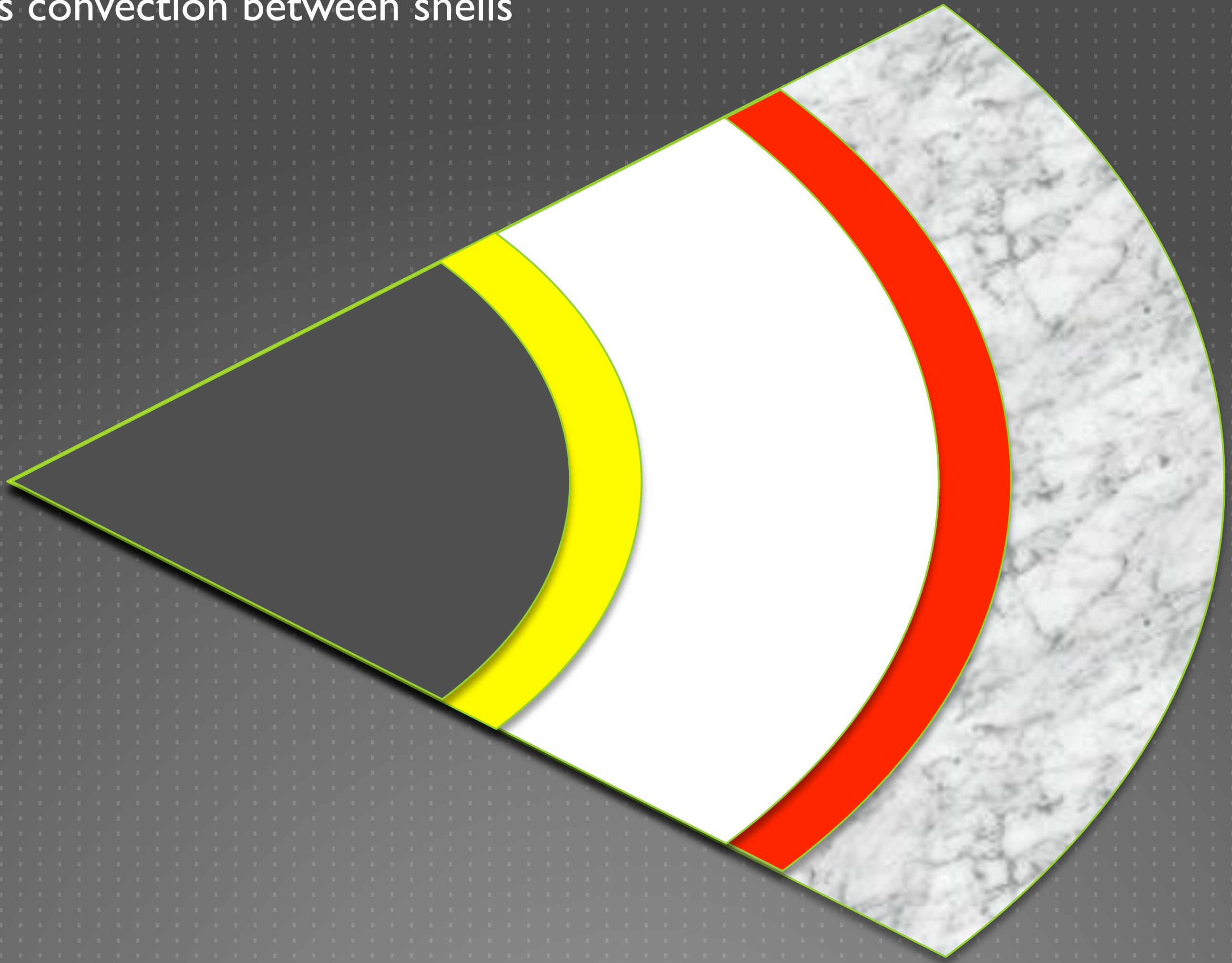


Karakas et al. (2002)

1. H-burning produces He



2. He burning ignites,
drives convection between shells



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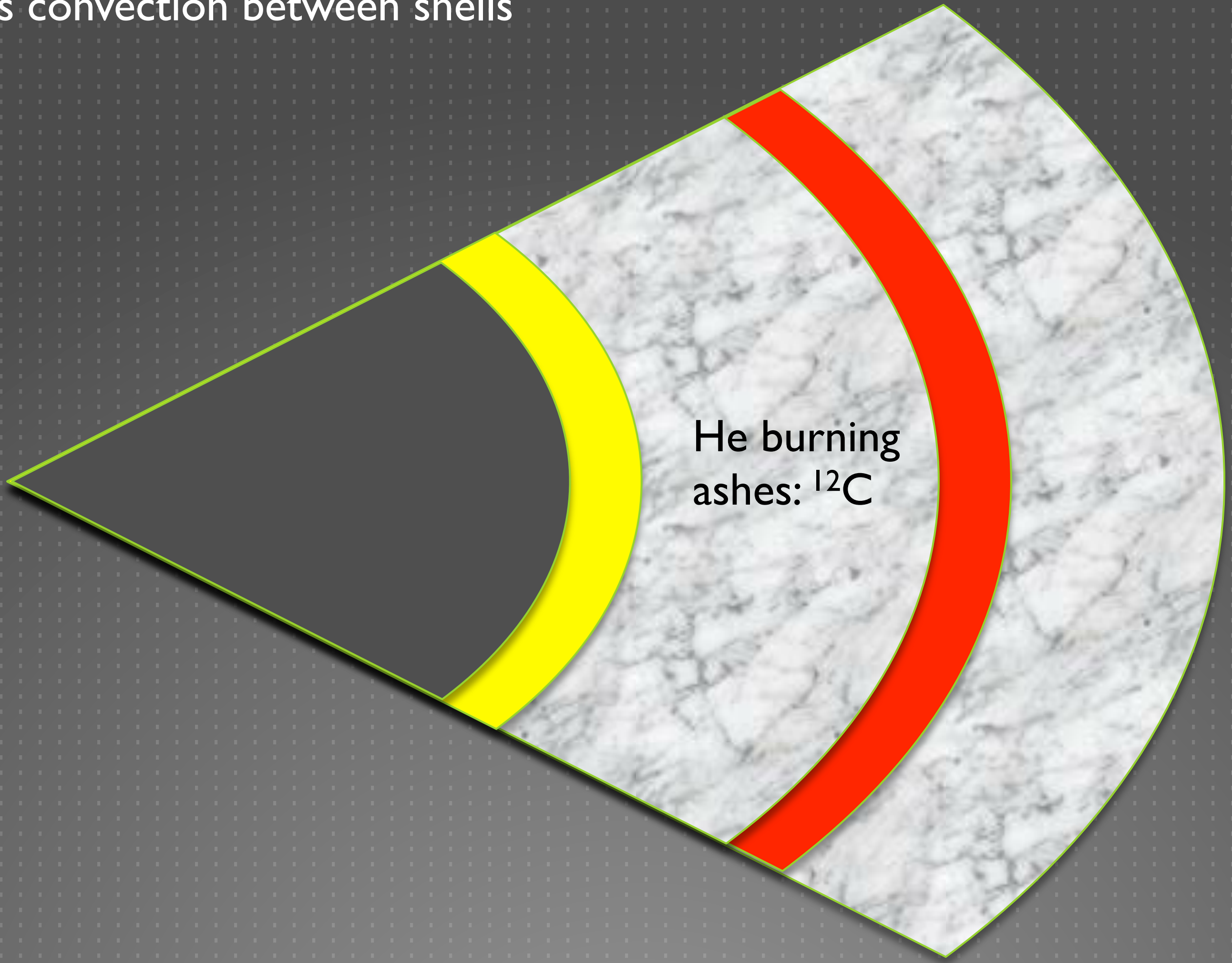
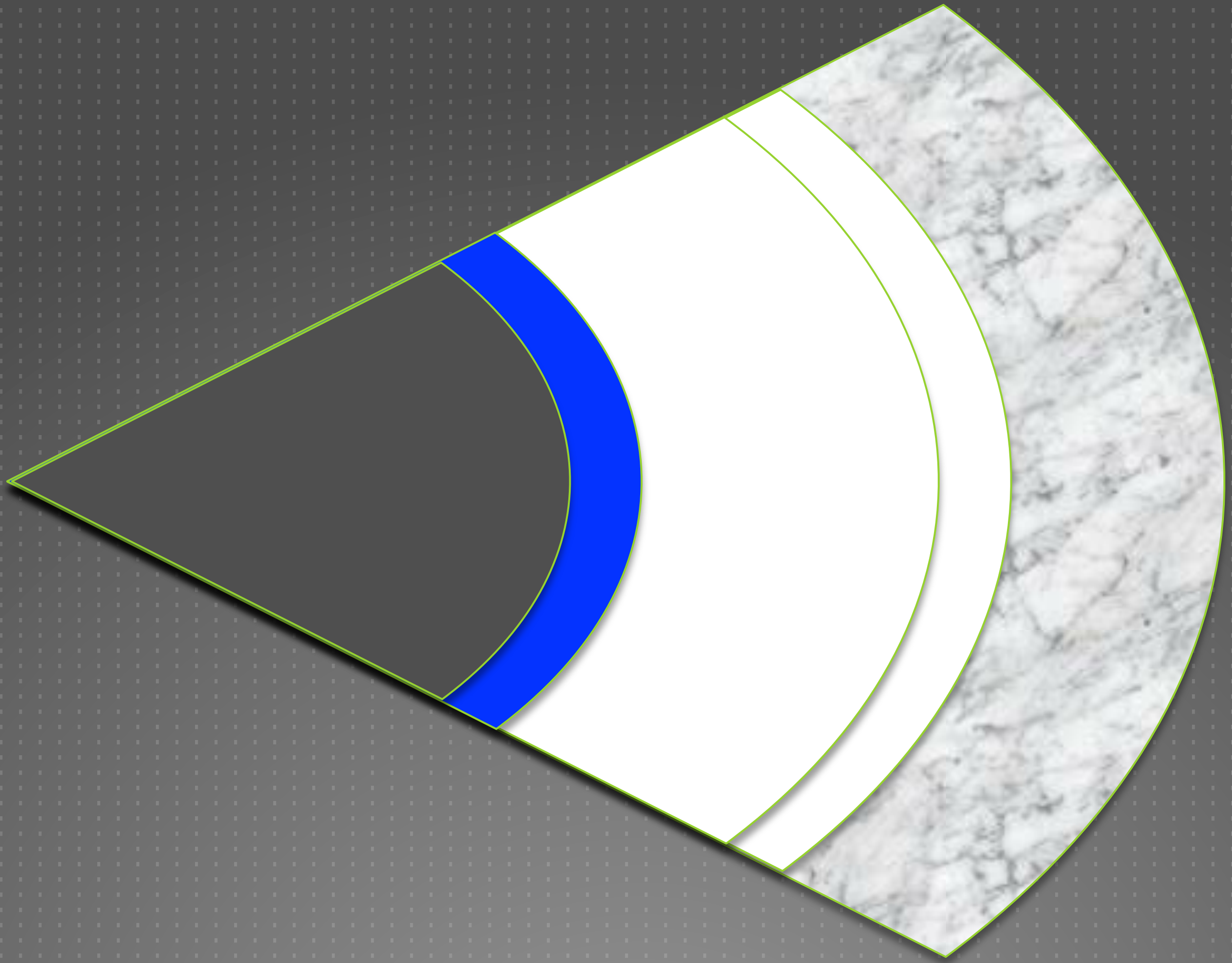
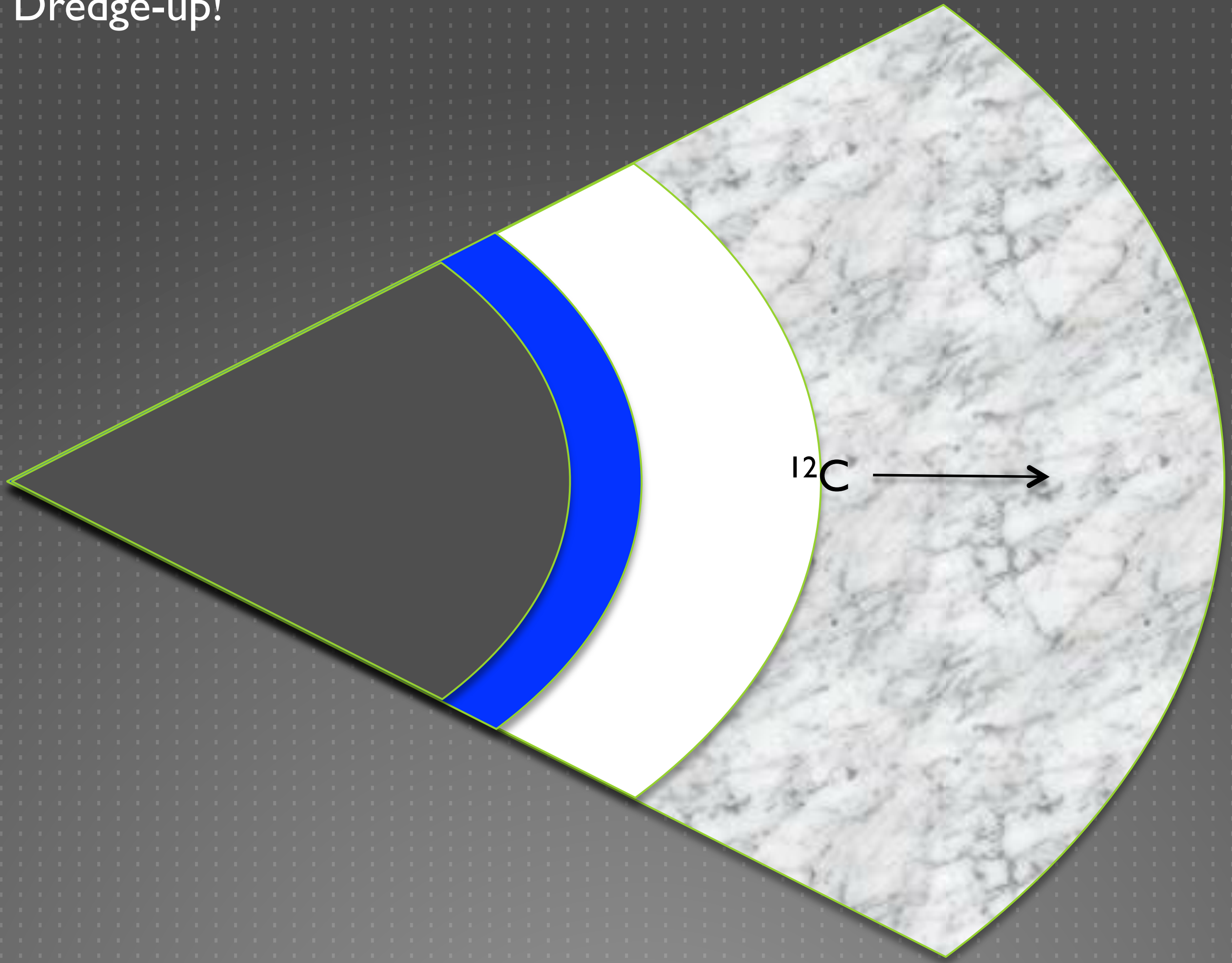


3. He-burning shuts off, expansion cools the H-shell

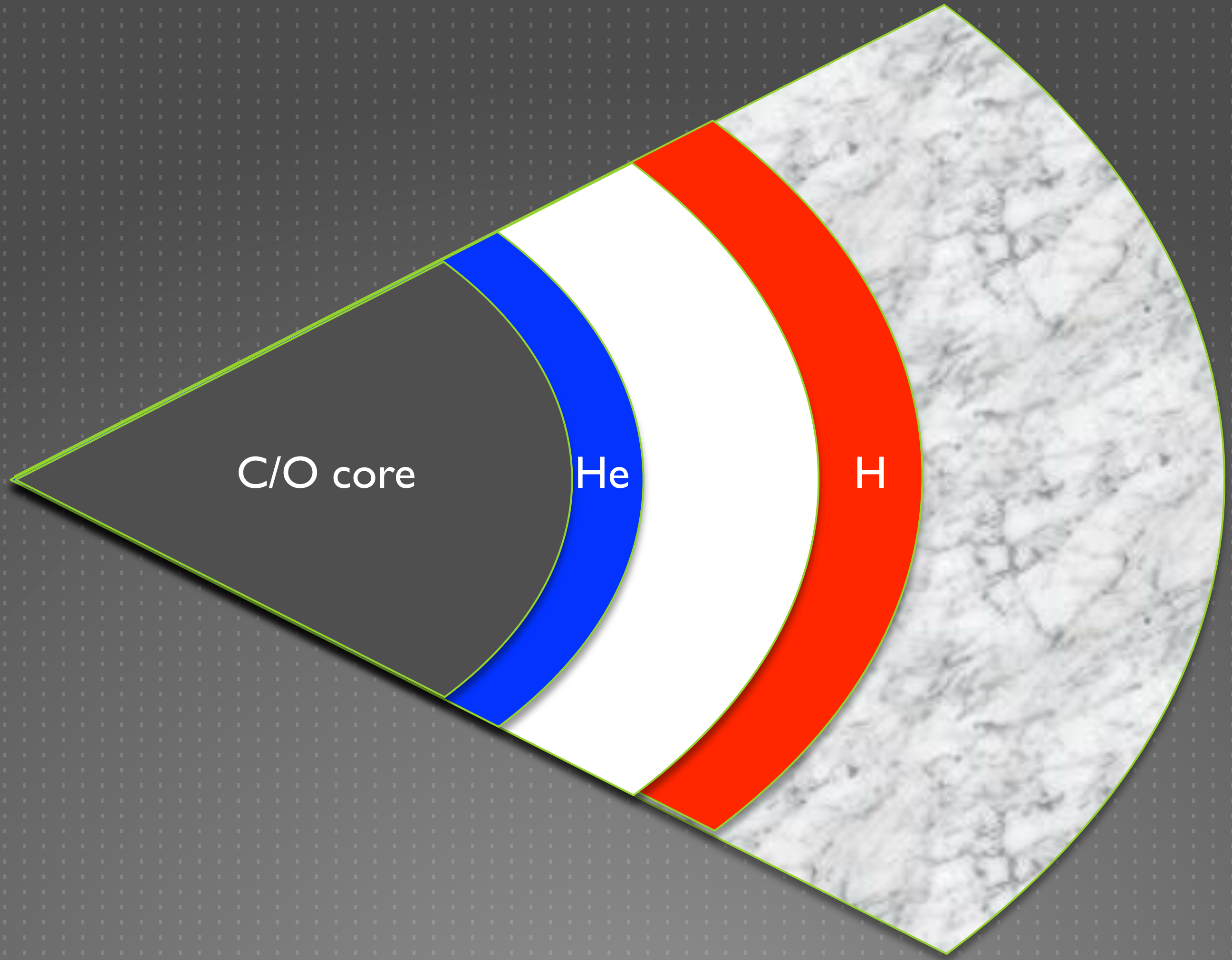


4. Convective envelope penetrates inward

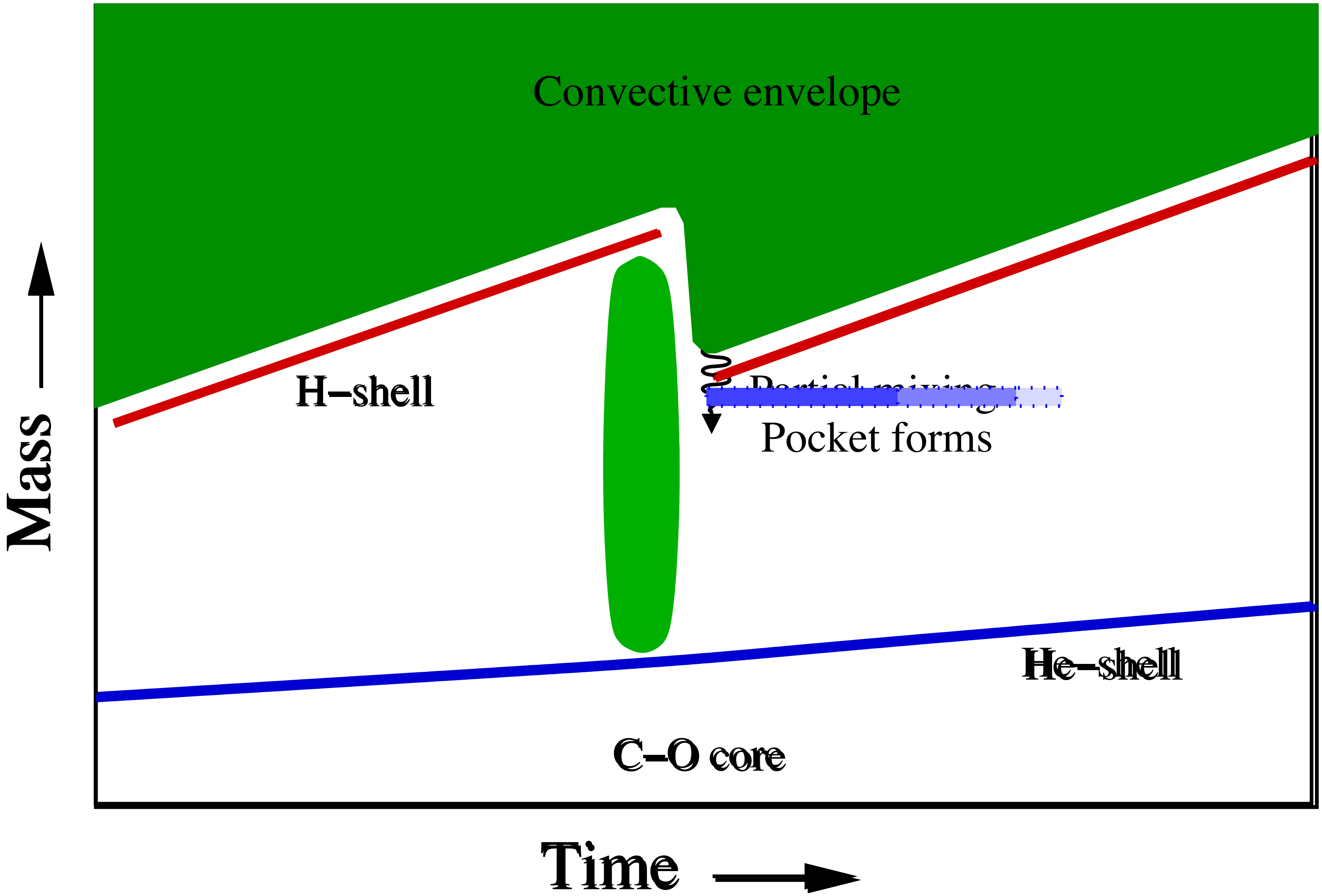
Third Dredge-up!



5. H-burning reignites and it all happens again!



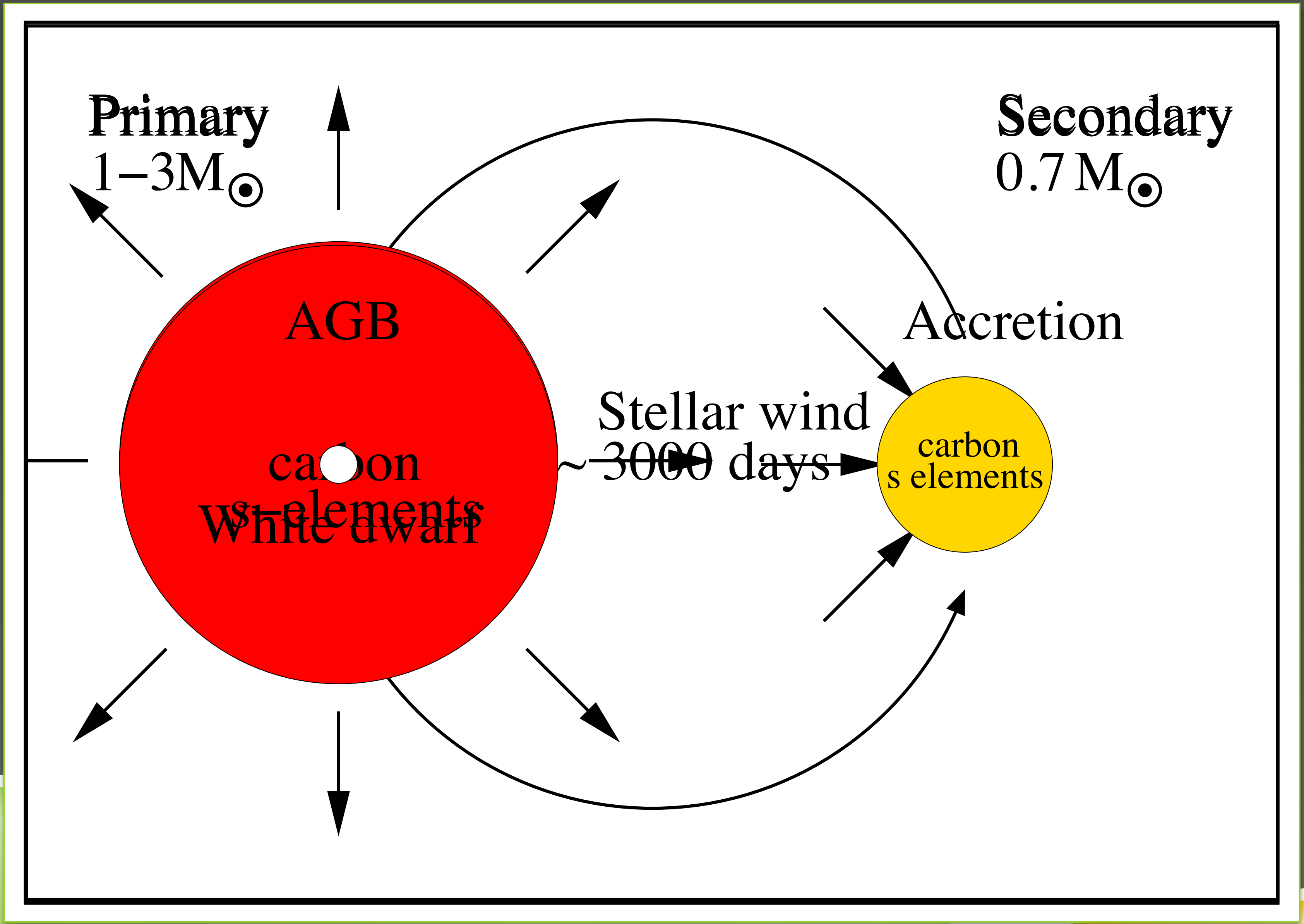
AGB NUCLEOSYNTHESIS



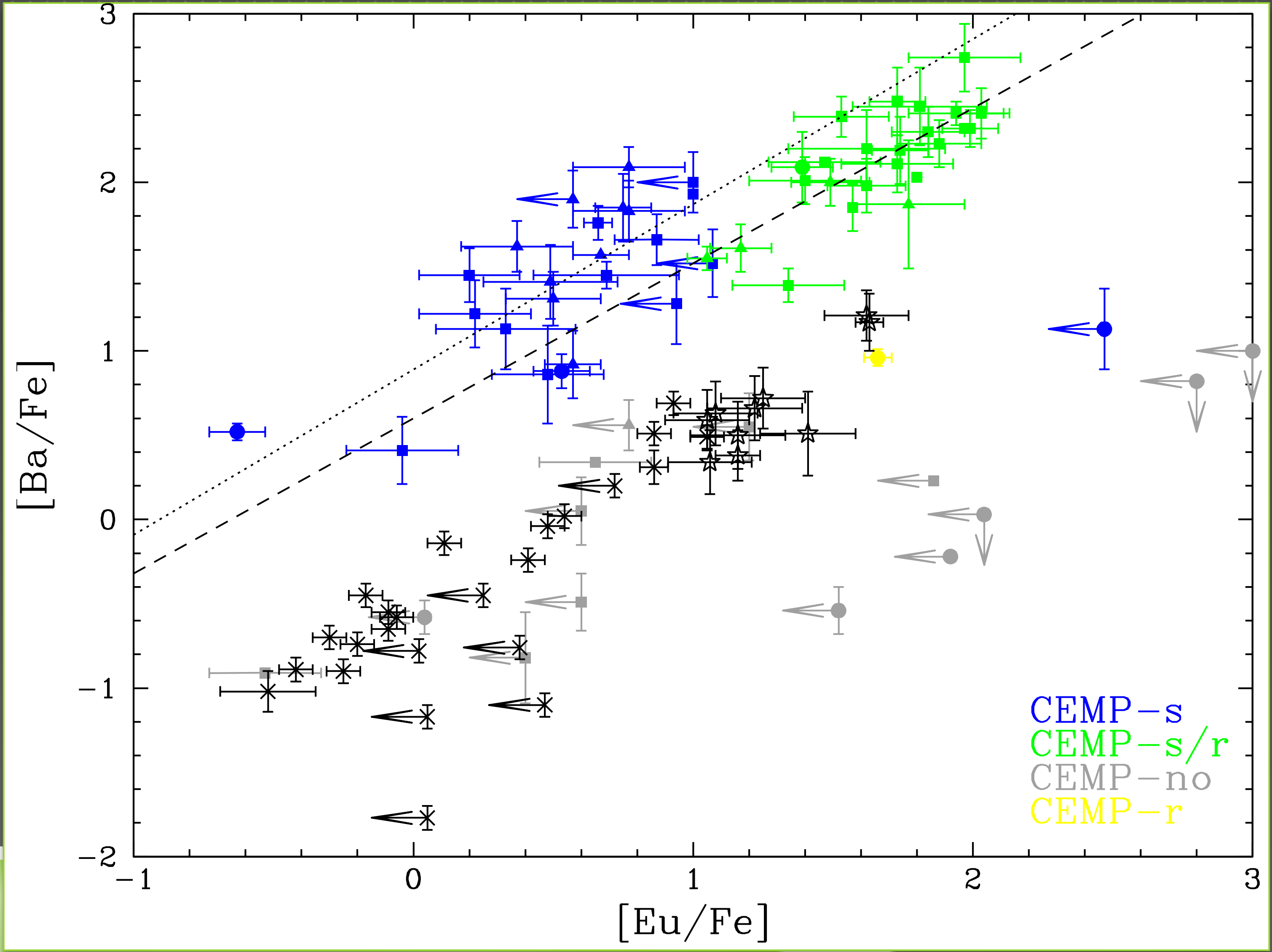
S-PROCESS NUCLEOSYNTHESIS

Neutron source: $^{13}C(a,n)^{16}O$ or $^{22}Ne(a,n)^{25}Mg$

FORMATION MECHANISM



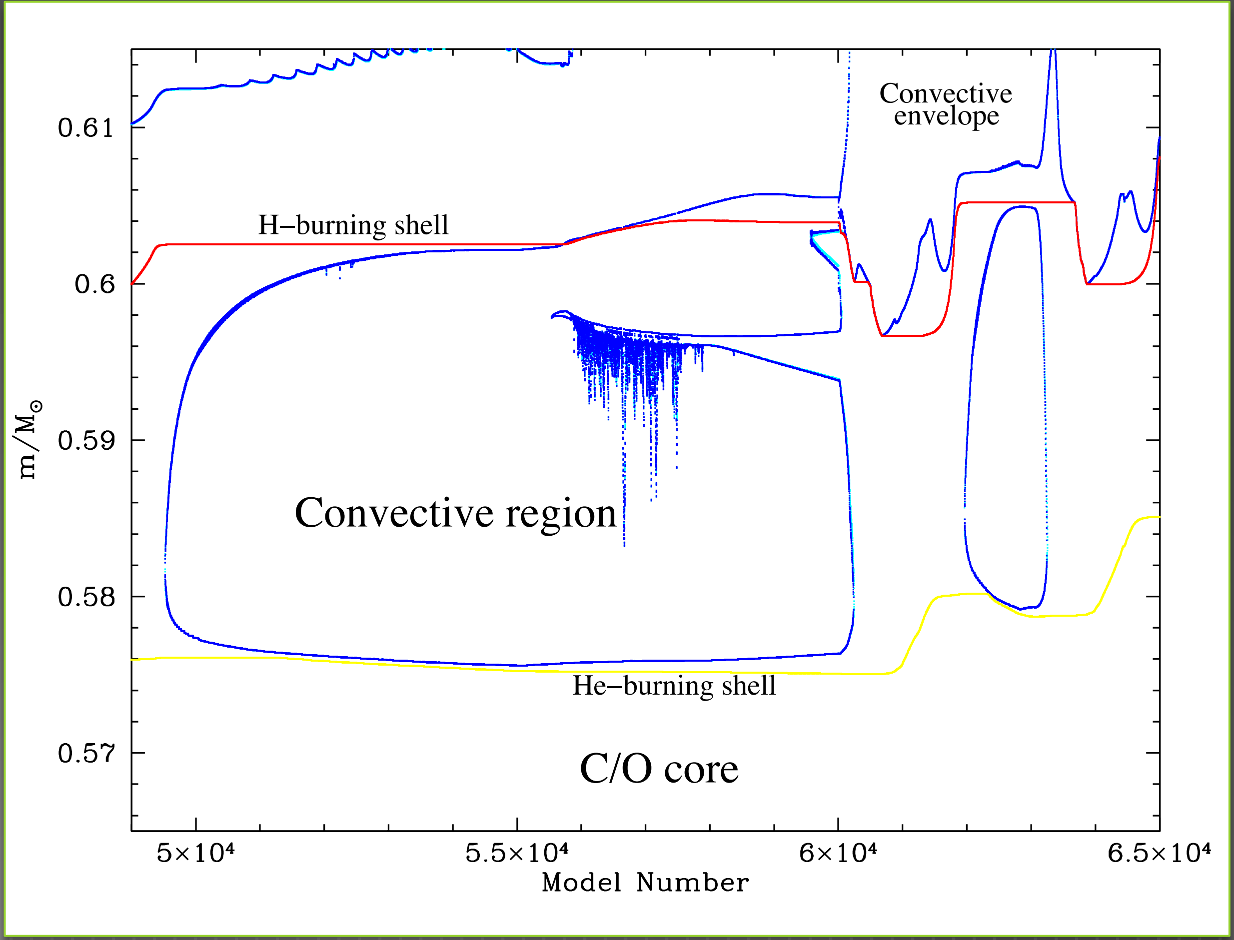
HEAVY ELEMENTS



Lugaro et al. (2012), data from Masseron et al. (2010)

EVOLUTION AT LOW-Z

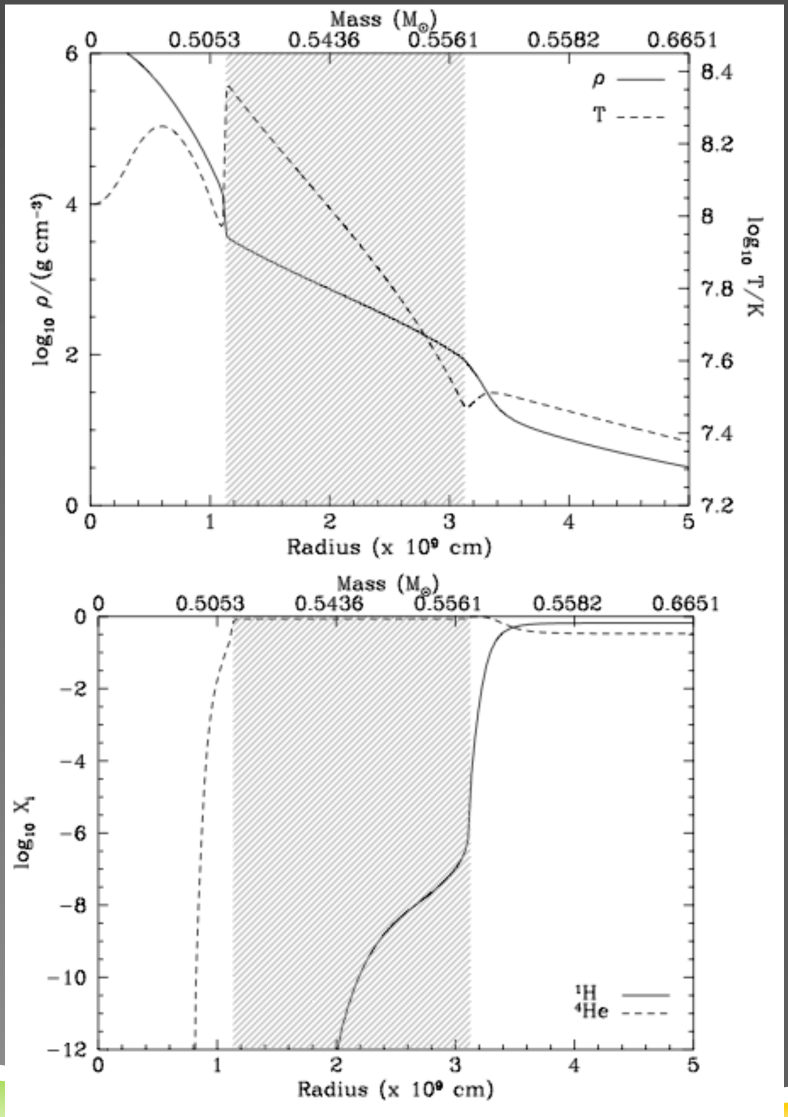
- Evolution changes at low metallicity
- He driven convection no longer trapped below the H-burning shells
- Proton can be drawn into the convective region
- Mixing, burning take place on similar timescales – hard to get this right in a 1D code!



Lau, Stancliffe & Tout (2009)

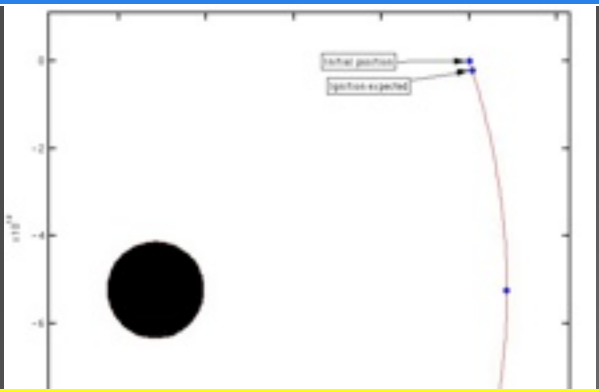
THE CASE FOR HYDRO MODELLING

- Burning/mixing occur on similar timescales
- The event is of short duration
  - Hydro can only simulate hours of star time
- Aim: take a 'snapshot' to see what the physics is and see what we should do in 1D

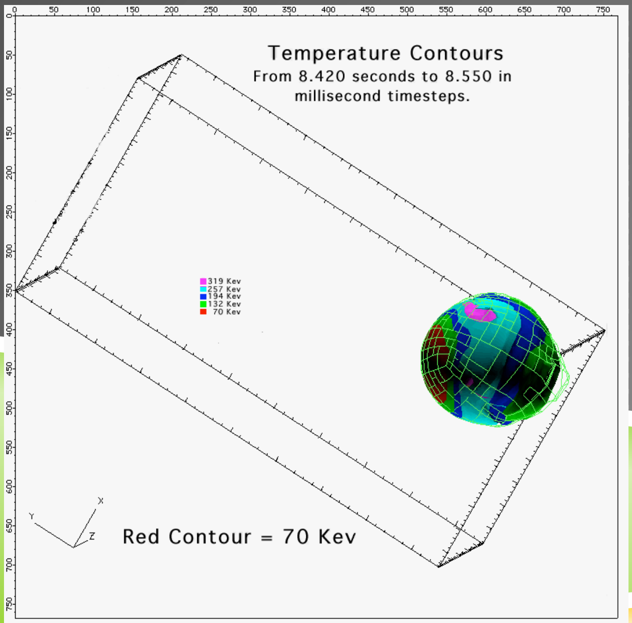


Stancliffe et al. (2011)

Djehuty
Ability to Model Whole Stars in Three Dimensions



A new GR based Type 1a like Supernova Mechanism.



Three Dimensional.

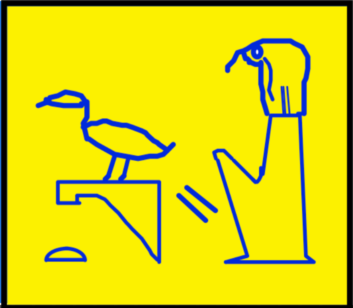
It has full basic stellar physics:

- a) Realistic Equation of State
  - i) Based on Eggleton et. al.
  - ii) Analytic with Continuous Derivatives
- b) Nuclear Energy Generation/Nucleosynthesis
- c) Energy Transport (Diffusion)
  - i) Radiative
  - ii) Conductive
- d) Self Consistent (spherical) gravity

It operates efficiently in parallel environment

Relativistically-Compressed Exploding White-Dwarf Model for SGR-A East, UCRL-JRNL-208008, David Dearborn LLNL, Jim Wilson LLNL and G Mathews Notre Dame, Ap.J. 10 Aug, 2005, Vol 629

Hydrogen Helium, Carbon, and Oxygen Burning + NSE :



7 element suite: ^{1}H, ^{3}He, ^{4}He, ^{12}C, ^{14}N, ^{16}O, ^{24}Mg

21 element suite: ^{1}H, ^{3}He, ^{4}He, ^{12}C, ^{13}C, ^{13}N, ^{14}N, ^{15}N, ^{15}O, ^{16}O, ^{17}O, ^{18}O, ^{17}F, ^{18}F, ^{19}F, ^{20}Ne, ^{22}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{56}Ni

In both element sets, the proton-proton chain is handled with the proton capture on Deuterium is assumed instant:

p (p,β ν) D (p,γ) ^{3}He
^{3}He(^{3}He,2p) ^{4}He
^{3}He(^{4}He,γ) ^{7}Be (p,^{4}He)^{4}He

The 21 element suite is suitable for the Hot CNO cycle, including leakage into ^{19}F.

^{12}C(p,γ)^{13}N	^{13}N(β, ν)^{13}C	^{13}C(p,γ)^{14}N
^{14}N(p,γ)^{15}O	^{15}O(β, ν)^{15}N	^{15}N(p,α)^{12}C
^{15}N(p,γ)^{16}O	^{16}O(p,γ)^{17}F	^{17}F(β, ν)^{17}O
^{17}O(p,α)^{14}N	^{17}O(p,γ)^{18}F	^{18}F(β, ν)^{18}O
^{18}O(p,α)^{15}N	^{18}O(p,γ)^{19}F	

The 7 element set includes only the slower rates. The beta decays on ^{13}C, ^{15}O, ^{17}F, and ^{18}F are assumed instantaneous, as are the proton captures on ^{15}N and ^{17}O:

In the 21 element set, reactions included;

^{4}He(2α,γ)^{12}C	^{12}C(γ,2α)^{4}He	^{12}C(α,γ)^{16}O
^{16}O(γ,α)^{12}C	^{16}O(α,γ)^{20}Ne	^{20}Ne(γ,α)^{16}O
^{20}Ne(α,γ)^{24}Mg	^{24}Mg(γ,α)^{20}Ne	^{24}Mg(α,γ)^{28}Si
^{28}Si(γ,α)^{24}Mg	^{28}Si(α,γ)^{32}S	^{32}S(γ,α)^{28}Si
^{14}N(α,γ)^{18}O	^{18}O(α,γ)^{22}Ne	

The following reactions are included for beginning advanced stages of massive star evolution

^{12}C(^{12}C,γ)^{24}Mg ^{12}C(^{16}O,γ)^{28}Si ^{16}O(^{16}O,γ)^{32}S

In the 7 element set, the ^{18}O(α,γ)^{22}Ne reaction is assumed to happen instantaneously, and the mass fraction change is places with all other heavy elements in ^{24}Mg

NSE following Timmes, Hoffman, and Woosley, 2000, ApJ, 129, 377-398

$$\frac{dY(^{4}He)}{dt} = -7Y(^{40}Ca)Y(^{4}He)\lambda_{\alpha\gamma}(^{40}Ca) + 7Y(^{44}Ti)\lambda_{\alpha\gamma}(^{44}Ti)$$

$$\frac{dY(^{28}Si)}{dt} = -Y(^{40}Ca)Y(^{4}He)\lambda_{\alpha\gamma}(^{40}Ca) + Y(^{44}Ti)\lambda_{\alpha\gamma}(^{44}Ti)$$

$$\frac{dY(^{56}Ni)}{dt} = +Y(^{40}Ca)Y(^{4}He)\lambda_{\alpha\gamma}(^{40}Ca) - Y(^{44}Ti)\lambda_{\alpha\gamma}(^{44}Ti)$$

Arbitrary Lagrange-Eulerian (ALE) Hydrodynamics

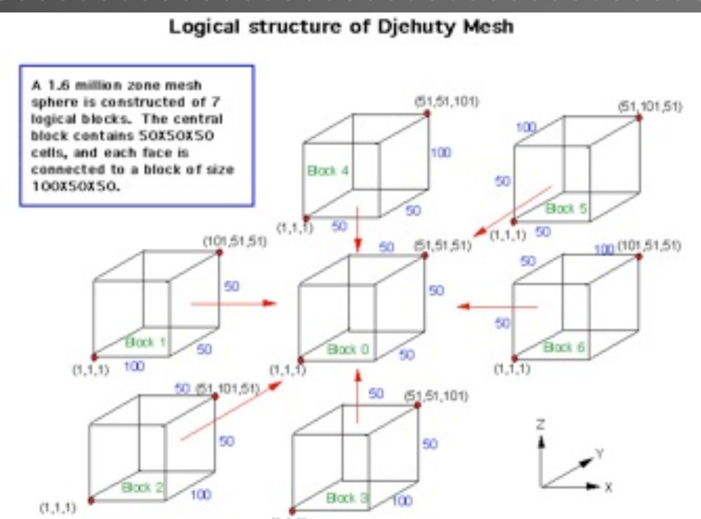
The ALE method with a predictor-corrector Lagrange-Remap formalism, is second-order accurate in both time and space.

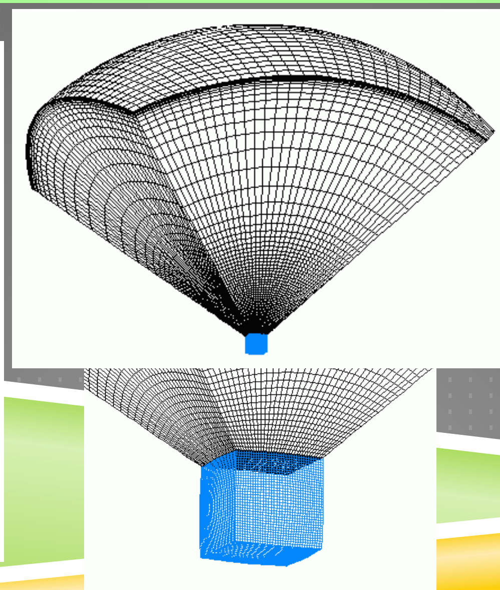
$$\dot{X}_{1/2} = \dot{X} + \ddot{X}\,\delta t_{1/2}$$
$$X_{1/2} = X + \dot{X}\,\delta t_{1/2}$$

Reevaluate force and source terms.

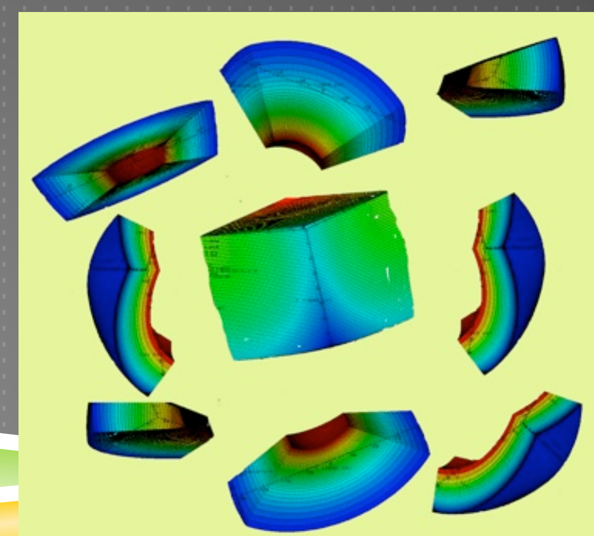
$$\dot{X} = \dot{X}_{1/2} + \ddot{X}\,\delta t$$
$$X = X + 0.5\left(\dot{X}_{1/2} + \dot{X}\right)\delta t$$

Mesh constructed of multi-block logically rectangular non-orthogonal hexahedrons.



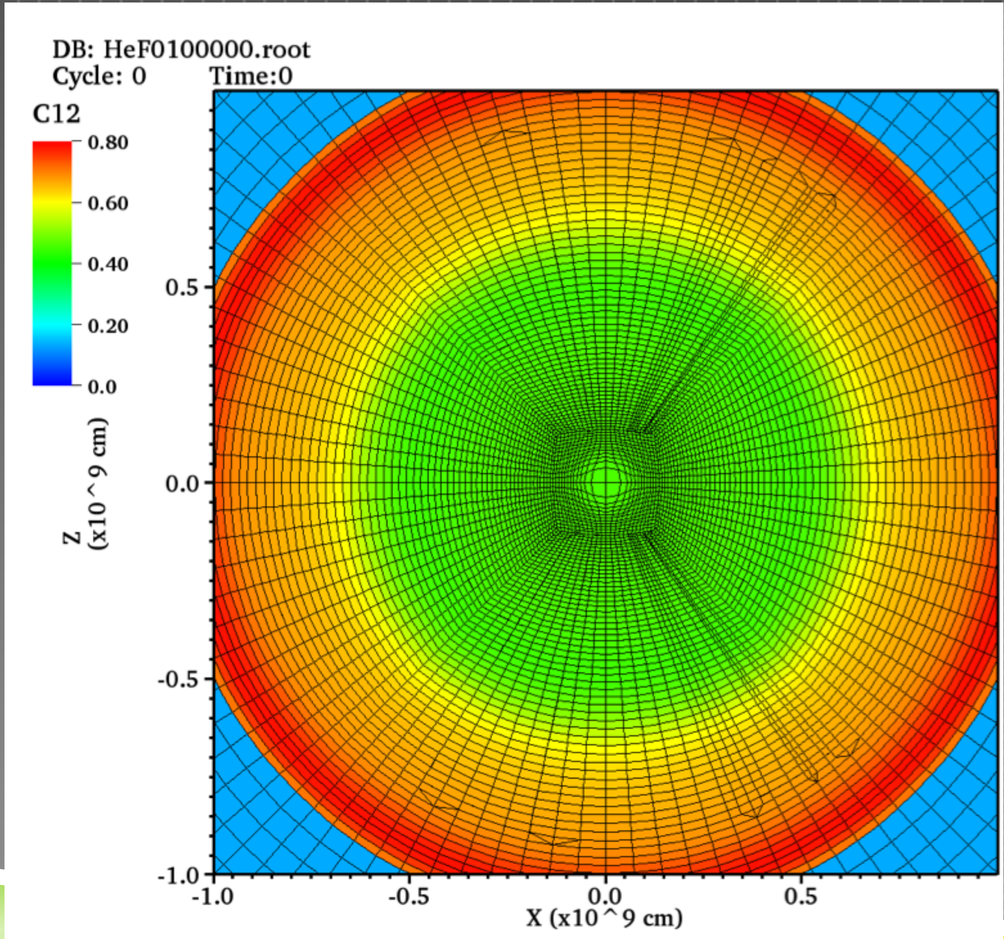


Decomposition for parallel operation, using MPI.



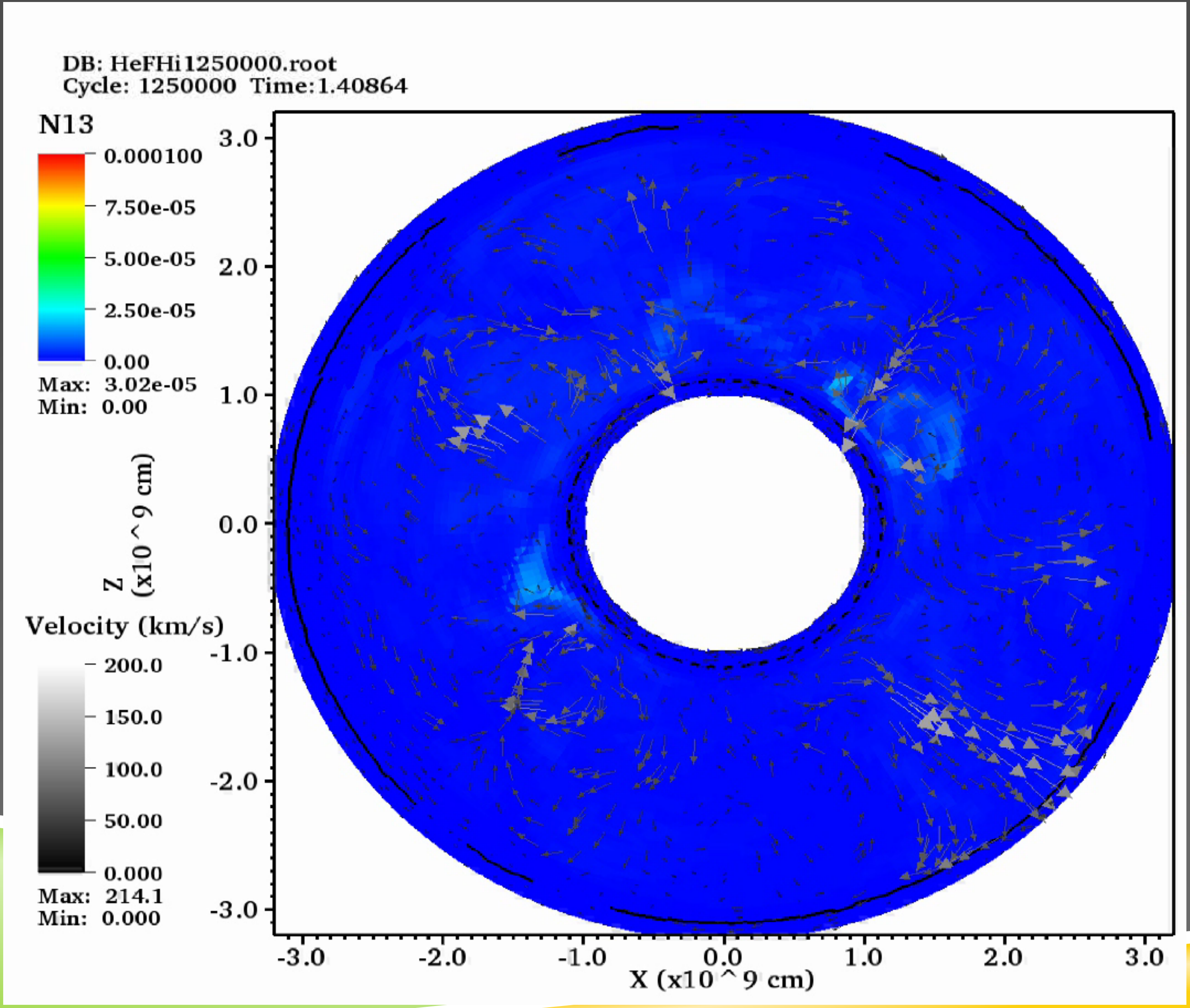
Proton ingestion episodes

- Modelled a 1 solar mass $Z=10^{-4}$ star on the asymptotic giant branch
- Threw away the convective envelope
- 40^3 zone central cube, 200 radial zones in each arm
- 144 CPUs
- Evolved for 4.5 hours of star time

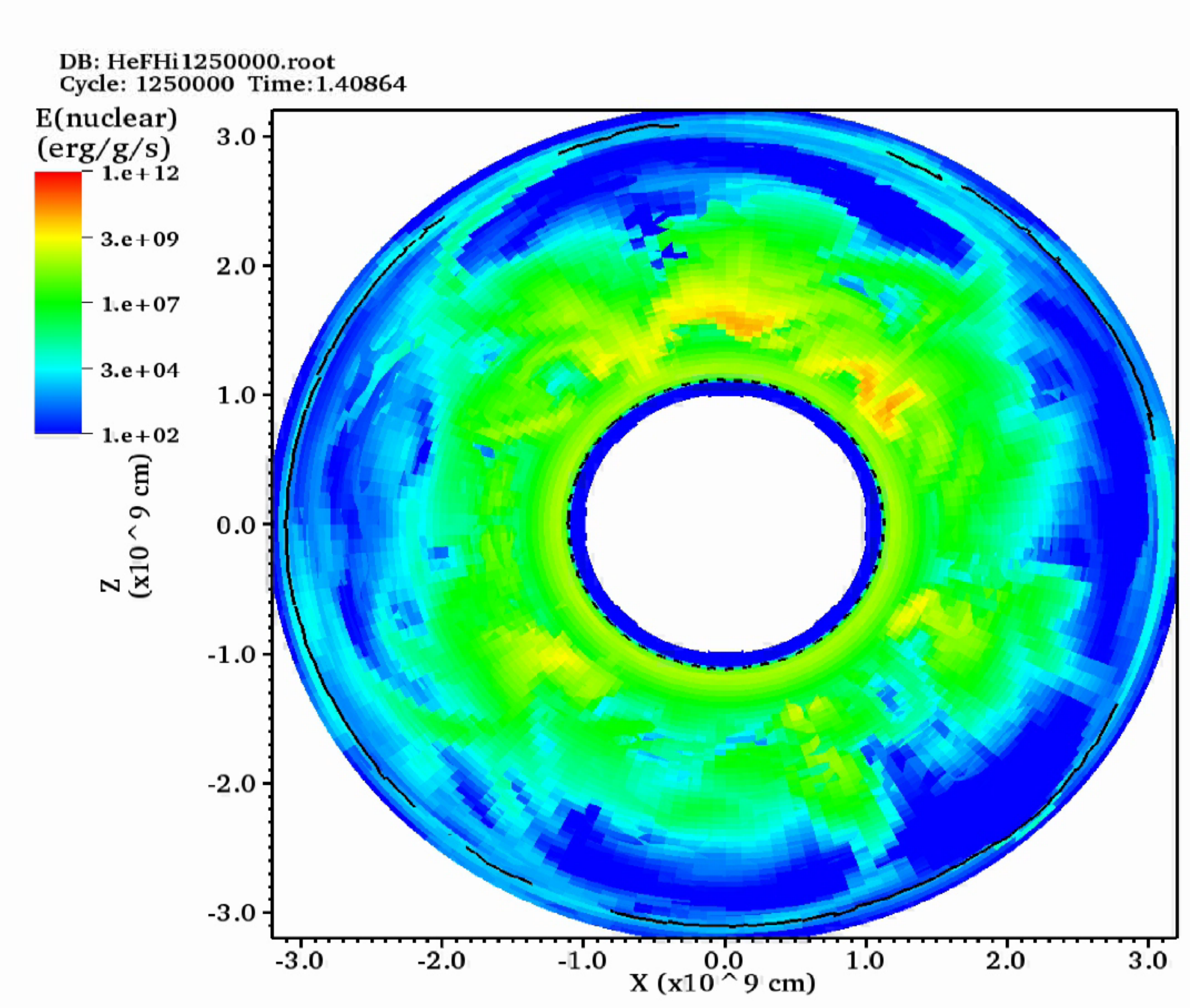


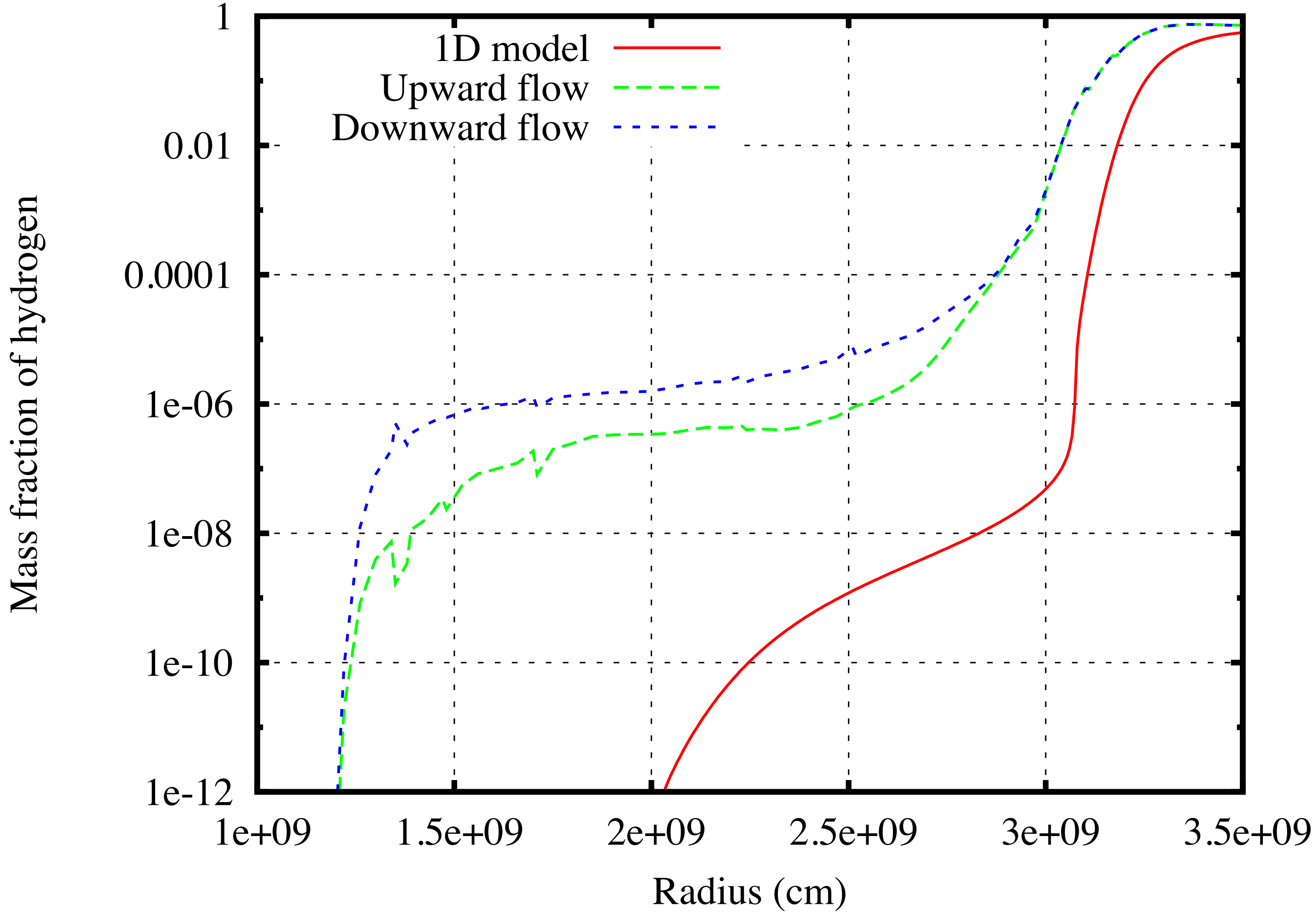
Stancliffe, Dearborn, Lattanzio, Heap & Campbell, 2011, ApJ, 742, 121

HYDRODYNAMIC SIMULATIONS



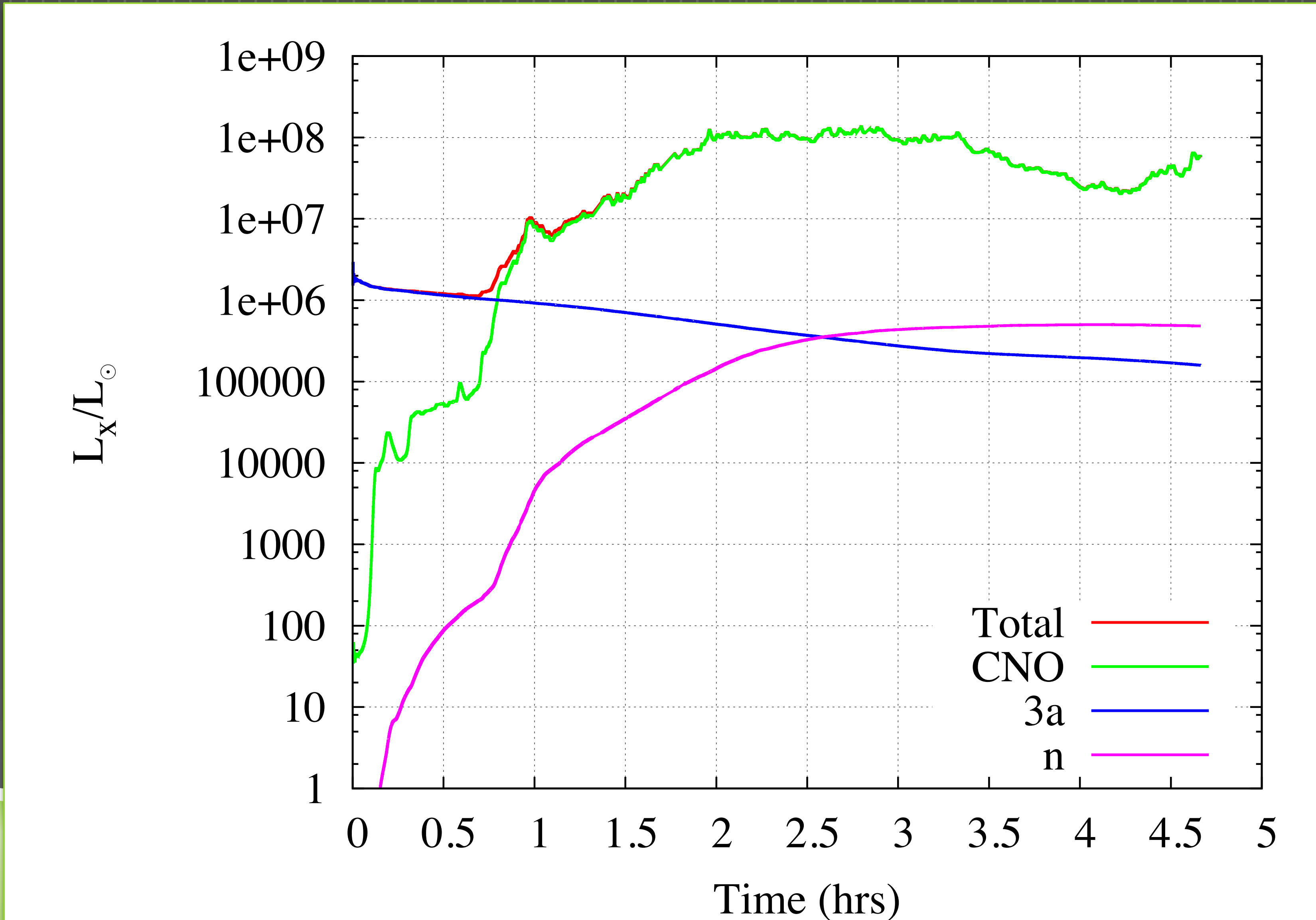
ENERGY GENERATION



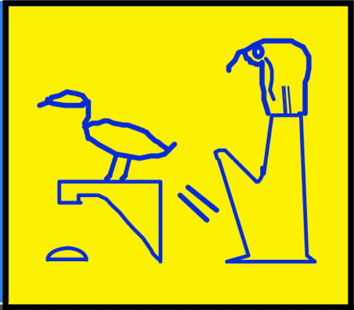


1D model
Upward flow
Downward flow
Mass fraction of hydrogen
1
0.01
0.0001
1e-06
1e-08
1e-10
1e-12
1e+09
1.5e+09
2e+09
2.5e+09
3e+09
3.5e+09
Radius (cm)

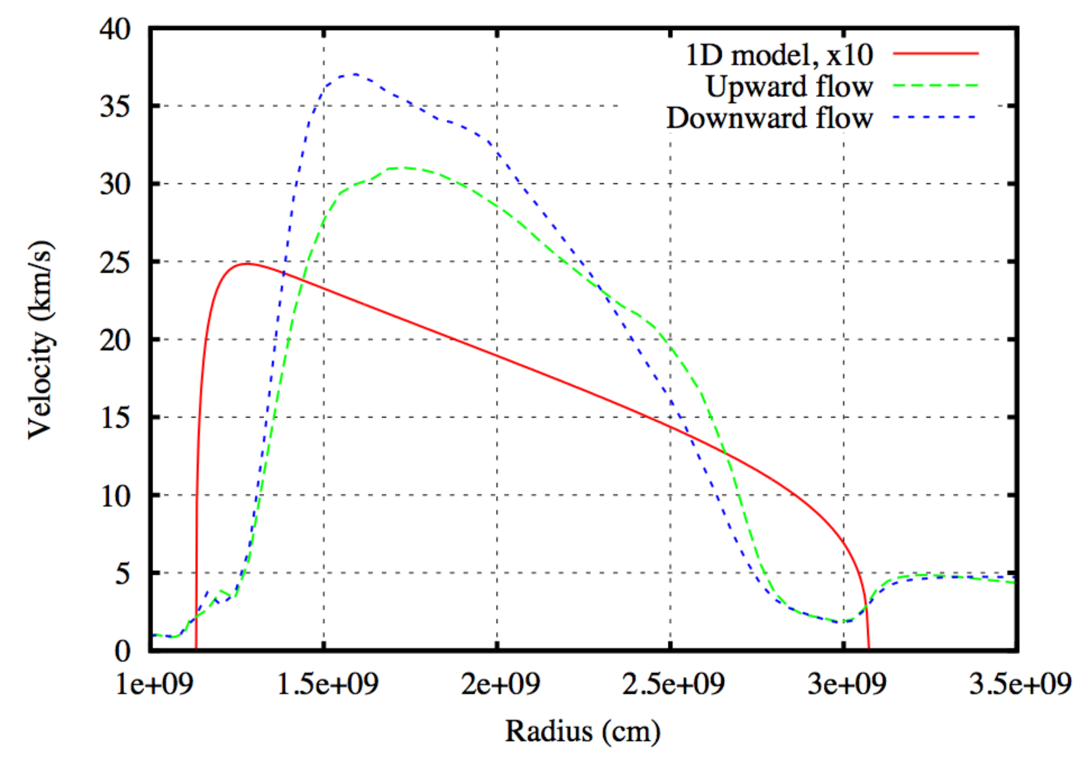
ENERGY SOURCES



Proton ingestion episodes



- No evidence that convective zone will split
- Transport by plumes is very rapid
- Energy released only at the bottom of the convective zone
- Hydrogen luminosities orders of magnitude more than the 1D models



HYDRODYNAMIC SIMULATIONS

- Transport of material is definitely not diffusive!
- Protons can travel across the intershell without burning
- H-burning energy is injected close to the He-burning shell – no different from normal helium burning
- No chance of getting the convective zone to split!
- What will this mean for nucleosynthesis???

PROSPECTS FOR NUCLEOSYNTHESIS

- Abundant 13C in the intershell
- Burning temperatures high enough for $^{13}C(a,n)^{16}O$ to be activated
- What is the neutron exposure?
- What is the resulting nucleosynthesis? – we're just starting to work on this!

SUMMARY

- CEMP(-s) stars tell us about AGB nucleosynthesis in the early Universe
- 1D stellar models are problematic at low Z
- Hydrodynamical modelling guides how we should be treating the physics
- What can we get from the neutron capture nucleosynthesis?