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H-combustion in super-AGB stars

Low- and intermediate mass stellar evolution and recurrent H-ingestion events in super-AGB thermal pulses

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KEELE UNIVERSITY — Sam Jones, Michael Bennett (Keele)

Falk Herwig

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JINA

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Nuclear astrophysics and near-field cosmology

- understanding SFH and chemical evolution in dSph galaxies
- constrain nucleosynthesis processes, e.g. Eu vs α-elements
- near-field cosmology: identify the building blocks of our galaxy

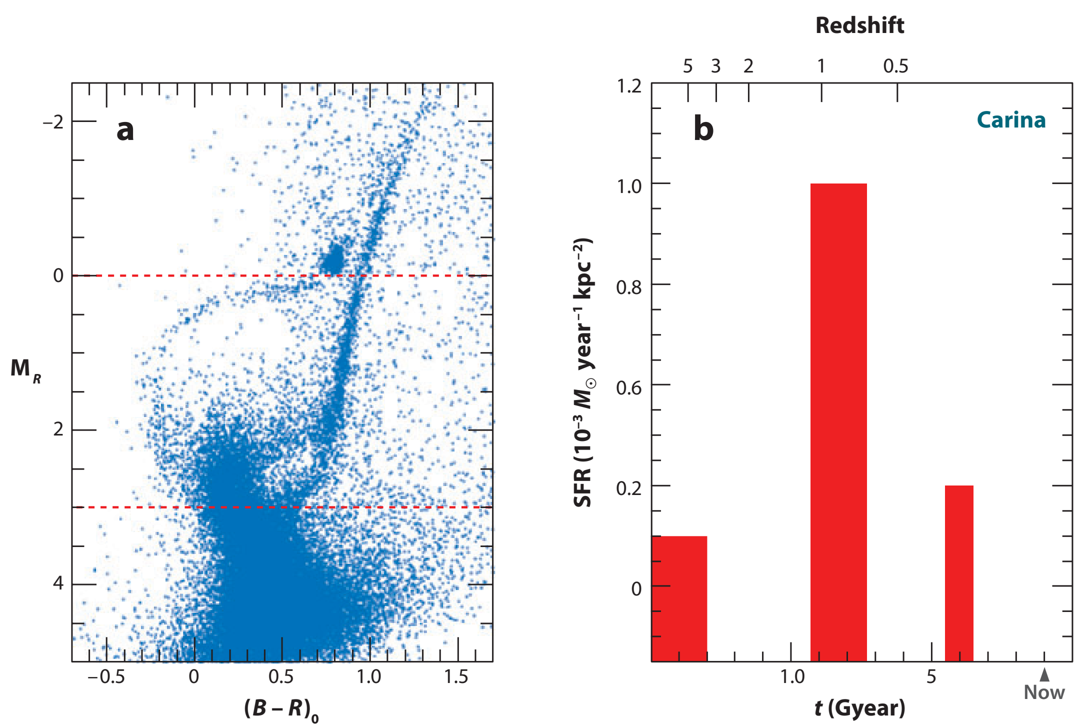
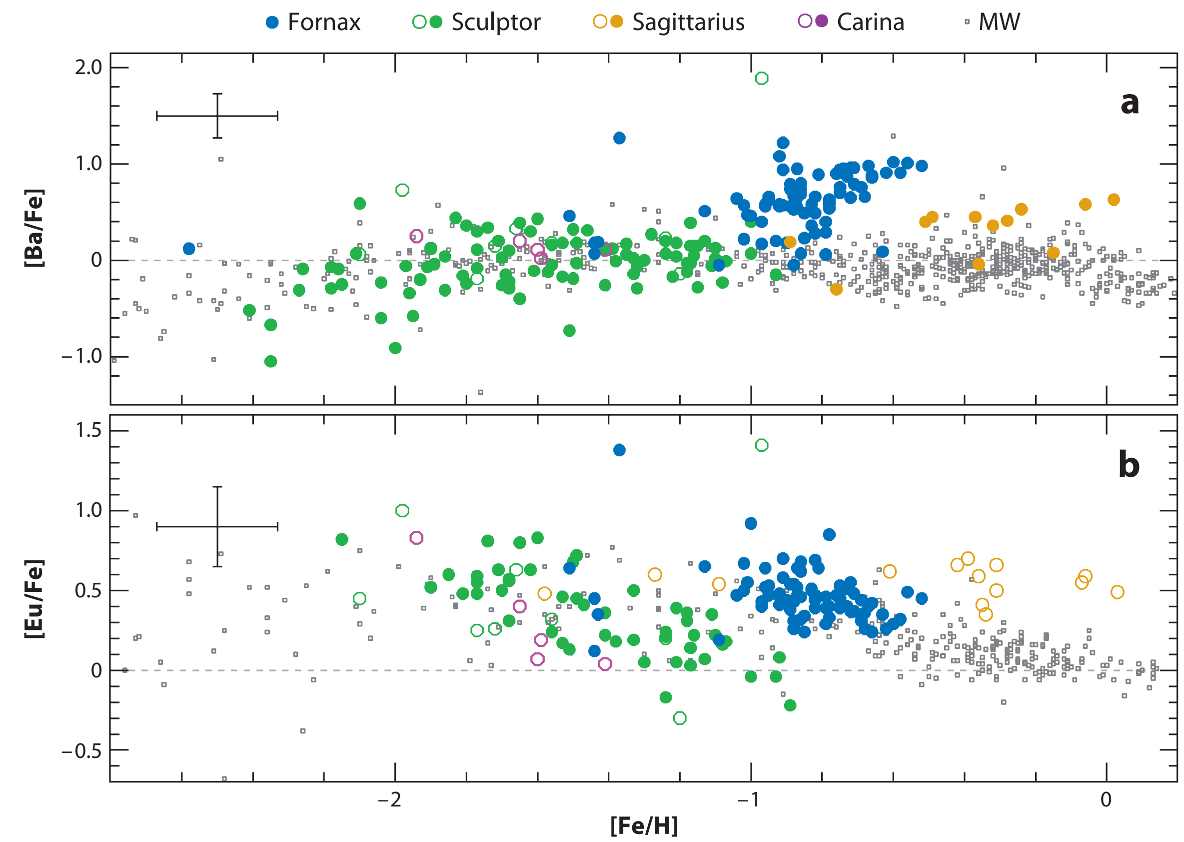
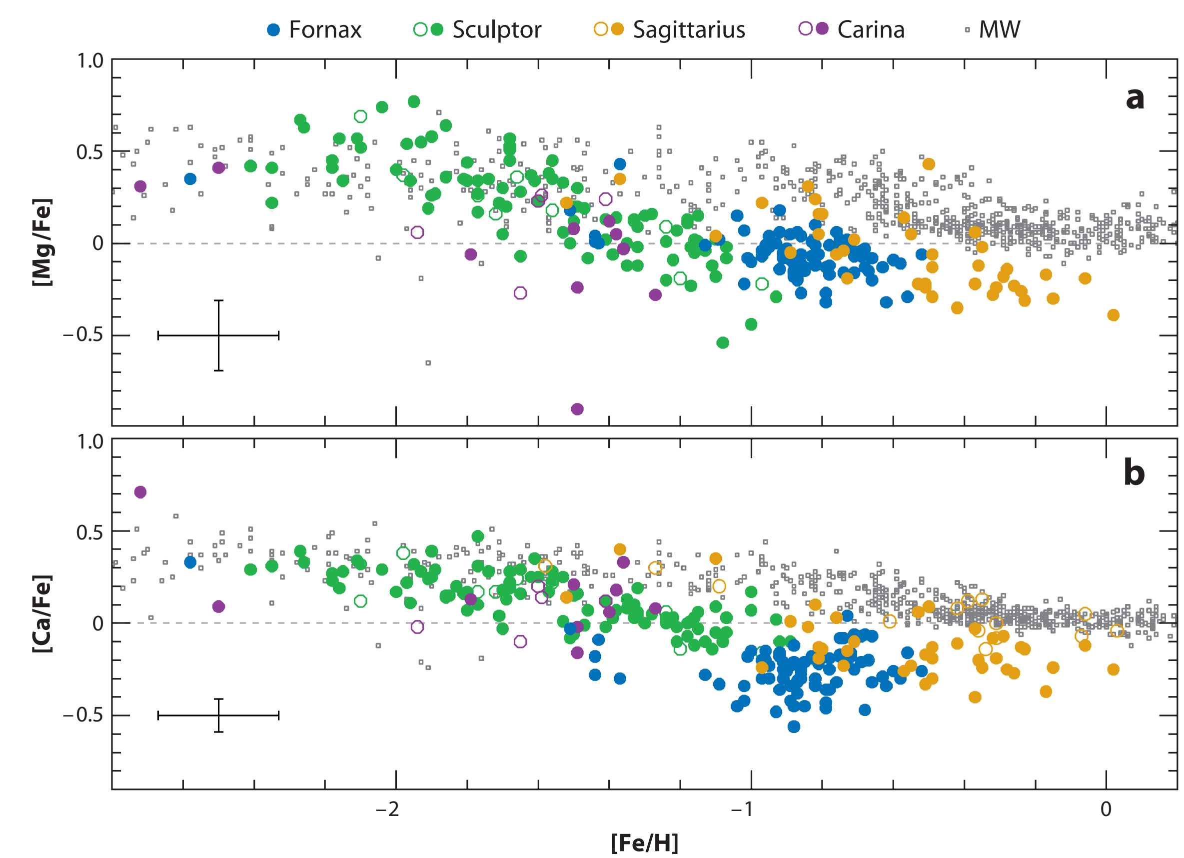


Figure 4

(*a*) A color-magnitude diagram of the Carina dwarf spheroidal (obtained by M. Mateo with the CTIO 4-m and MOSAIC camera, private communication) in the central 30′ of the galaxy. This clearly shows the presence of at least three distinct MSTOs. (*b*) The star-formation history of the central region of Carina determined by Hurley-Keller, Mateo & Nemec (1998), showing the relative strength of the different bursts. The ages are also shown in terms of redshift.

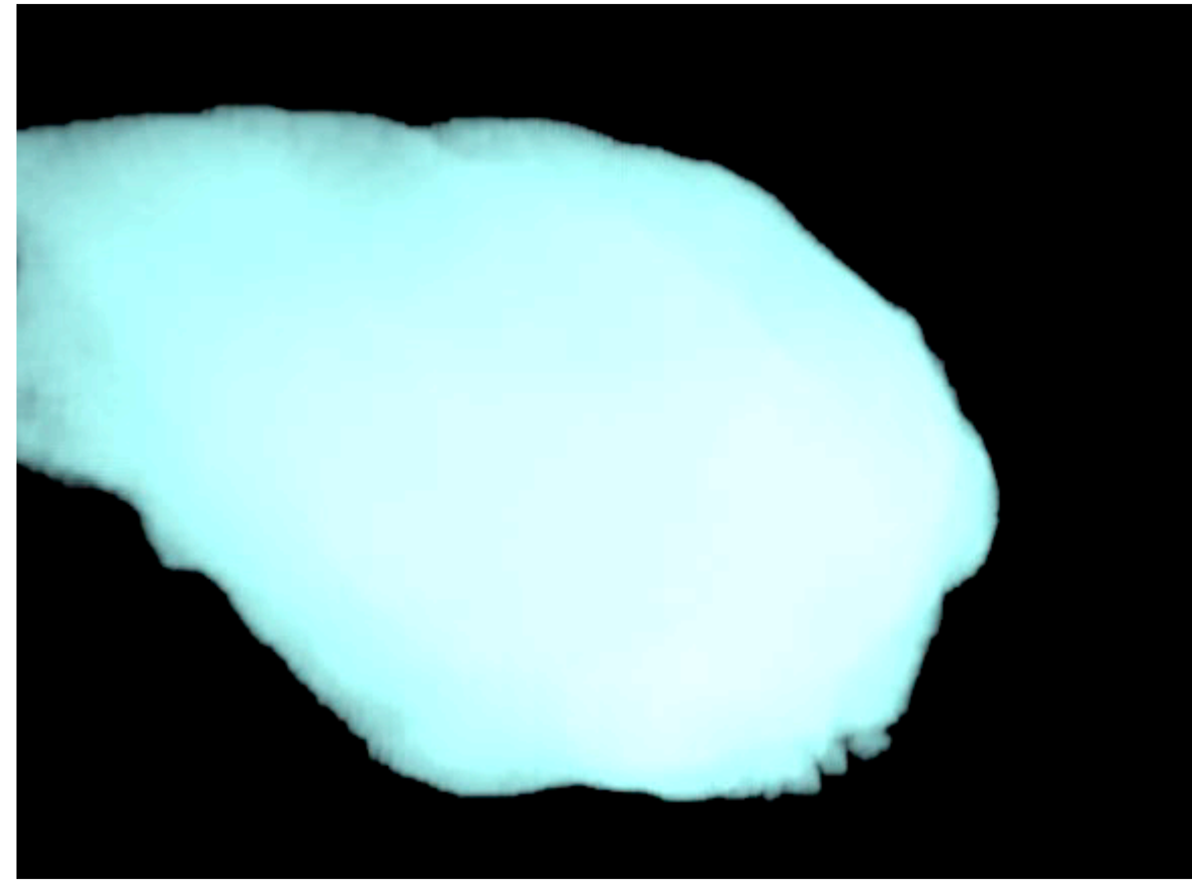




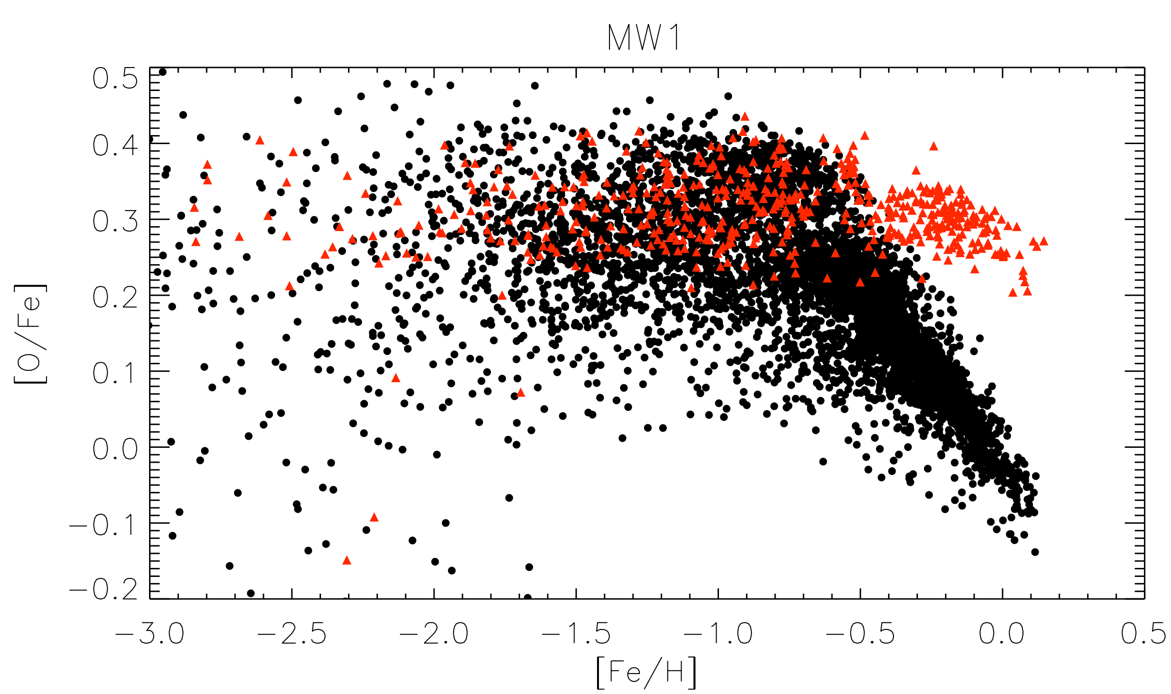
Tolstoy etal 2009 (ARAA)

The hierarchy of GCE simulation types

- analytic models, incl. one or a few zones, parameterized everything (e.g. Matteucci, Timmes, Travaglio, and many more)
- semi-analytical models, amounts to a post-processing along a cosmological merger-tree from simulations (e.g. Font etal., Tumlinson and collaborators, and many more)
- cosmological simulations with multiple tracer fields (e.g. Kobayashi, Zolotov etal. 2010)



Fabio Governato, U Washington, Seattle



"observed" halo stars in a cosmological high-resolution disc galaxy simulation, separating out in-situ stars (red triangles) and accreted stars (**black dots**)

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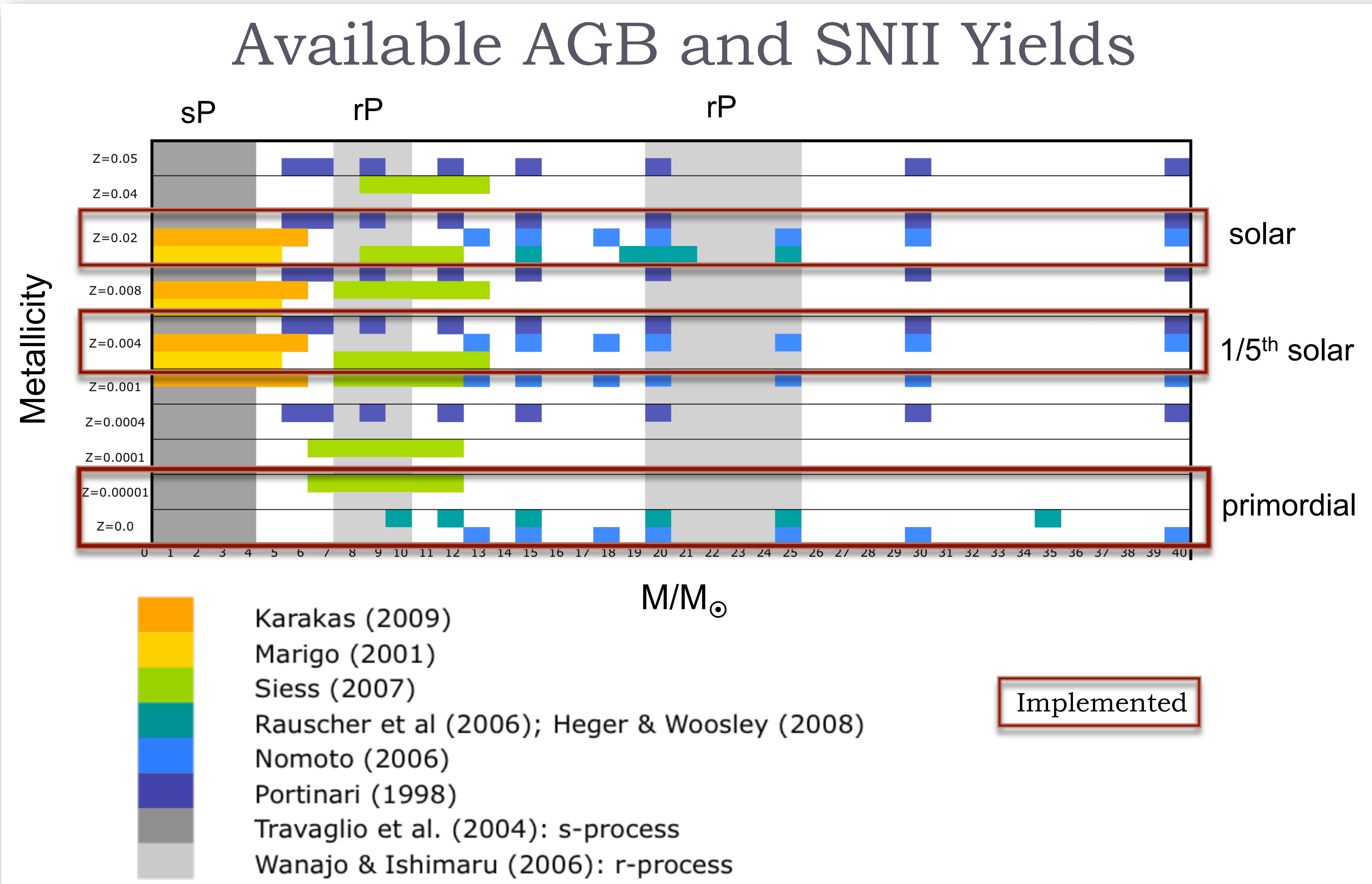
For all these applications an internally consistent simulation data set of yields is needed ....



Carolyn Peruta
Michigan State University

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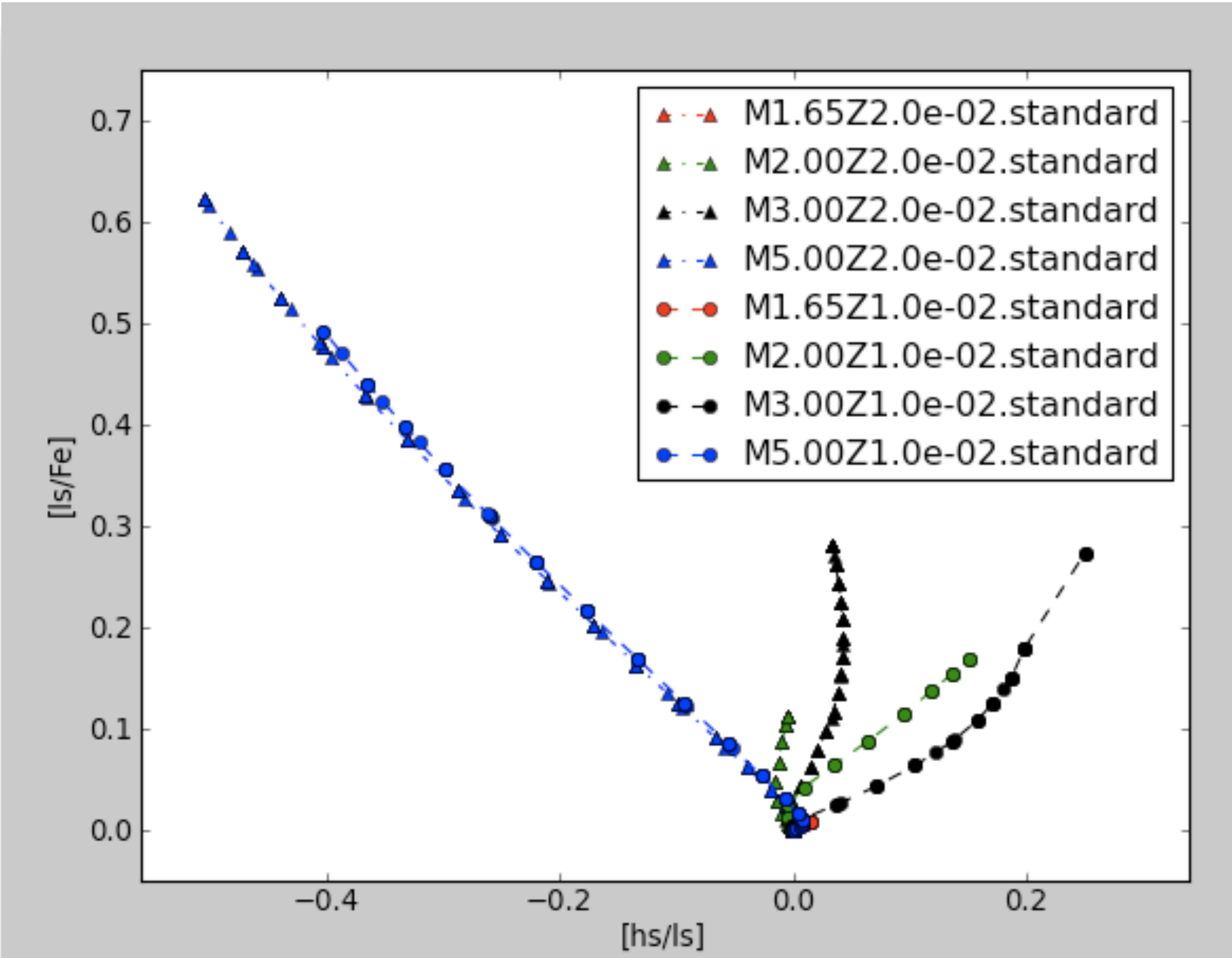
overall s-process indices in AGB stars

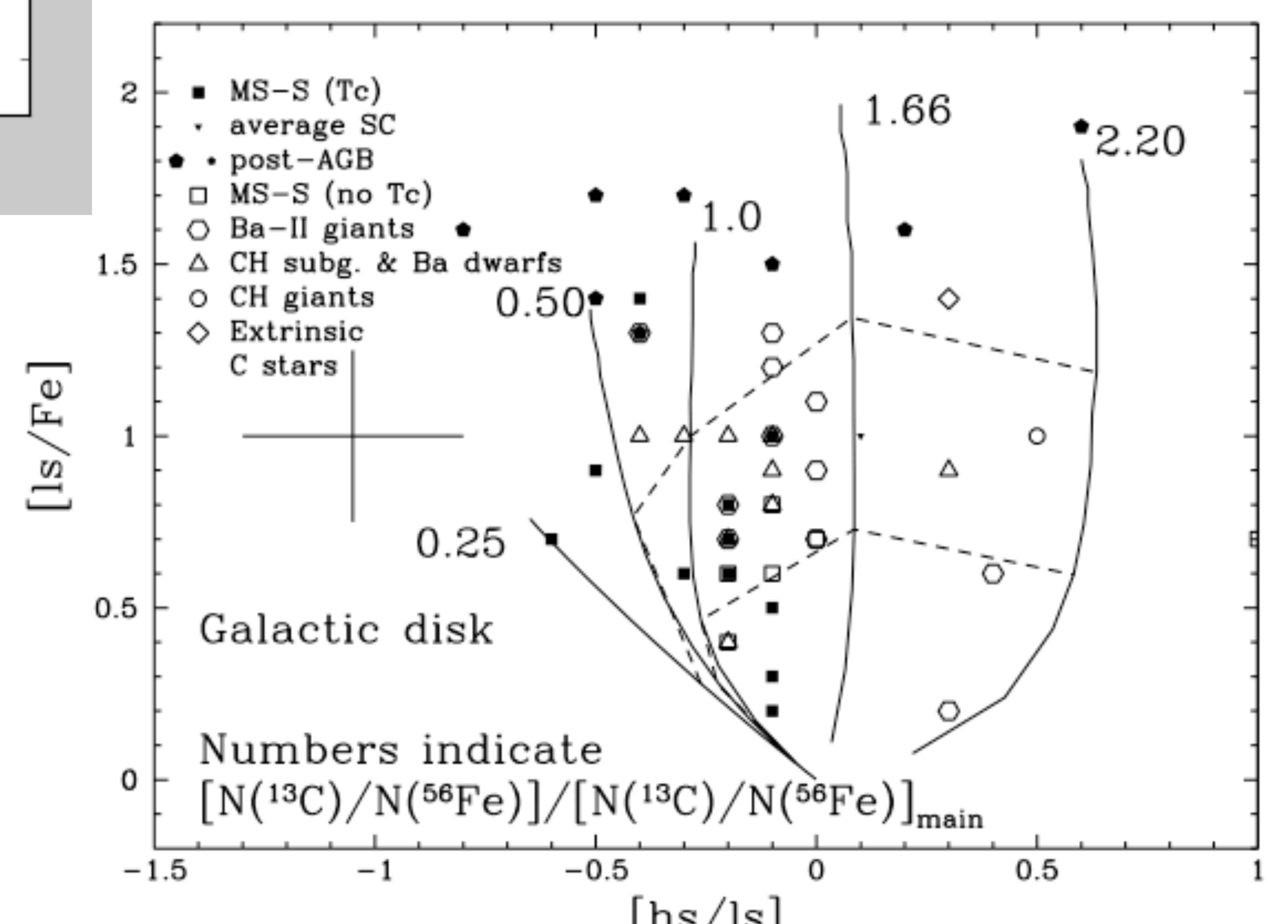
H-combustion in super-AGB stars



NuGrid: Set 1

hs: <Ba, La, Ce, Nd, La, Sm>

ls: <Y, Zr>



observations and parameterized models (Busso etal 2001)

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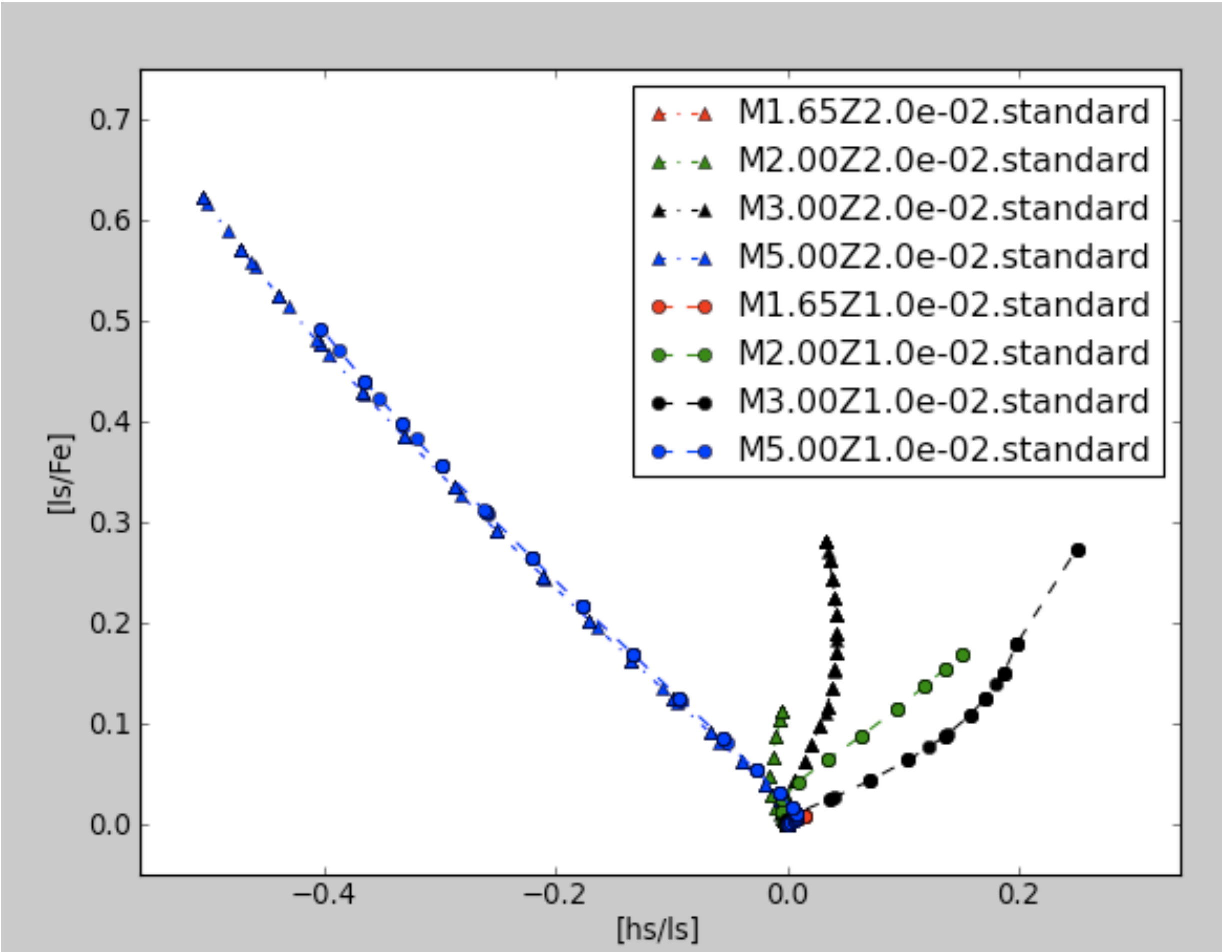
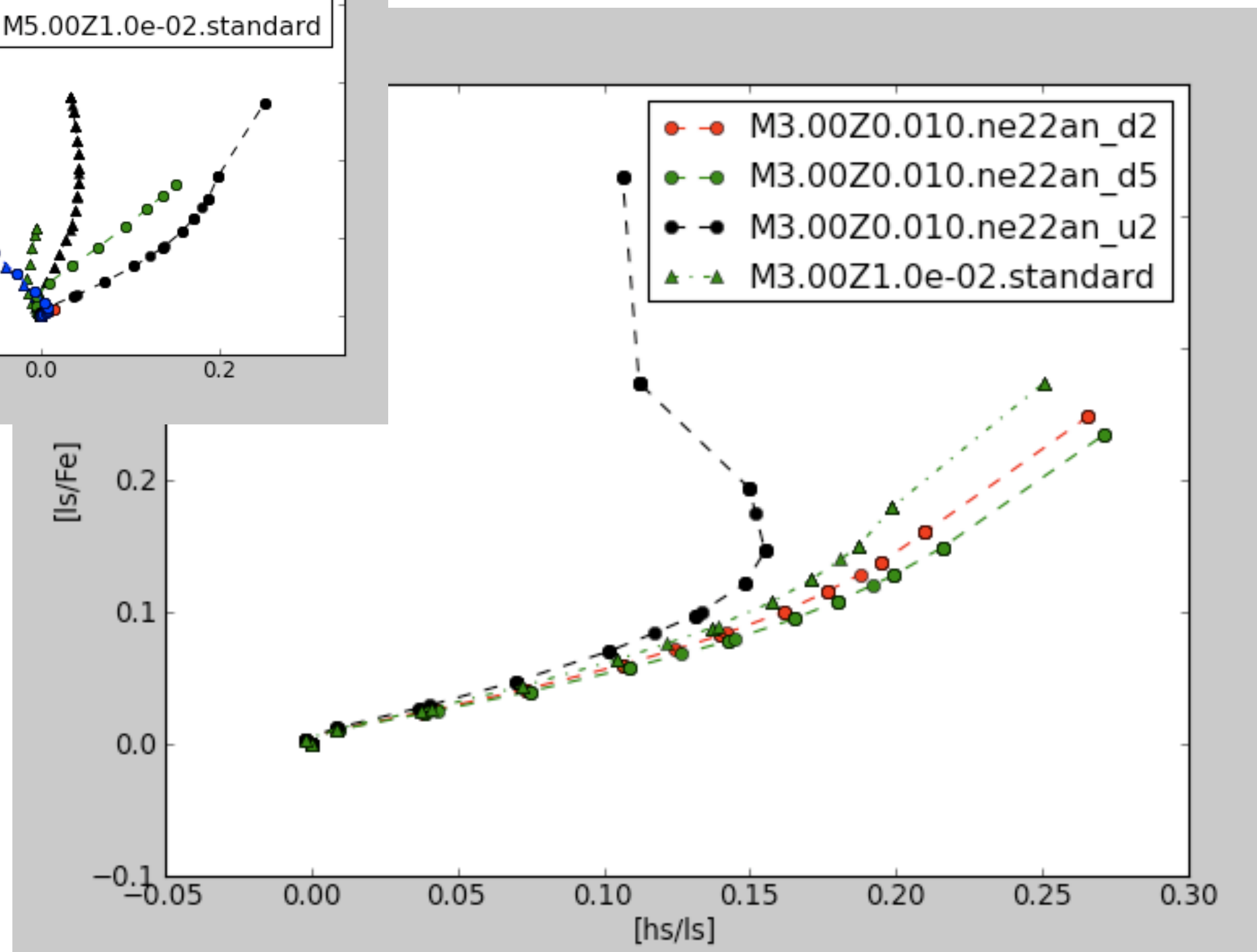
$^{22}Ne(\alpha,n)$ reaction rate uncertainty impact





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H-combustion in super-AGB stars

Branching at ^{95}Zr in AGB stars

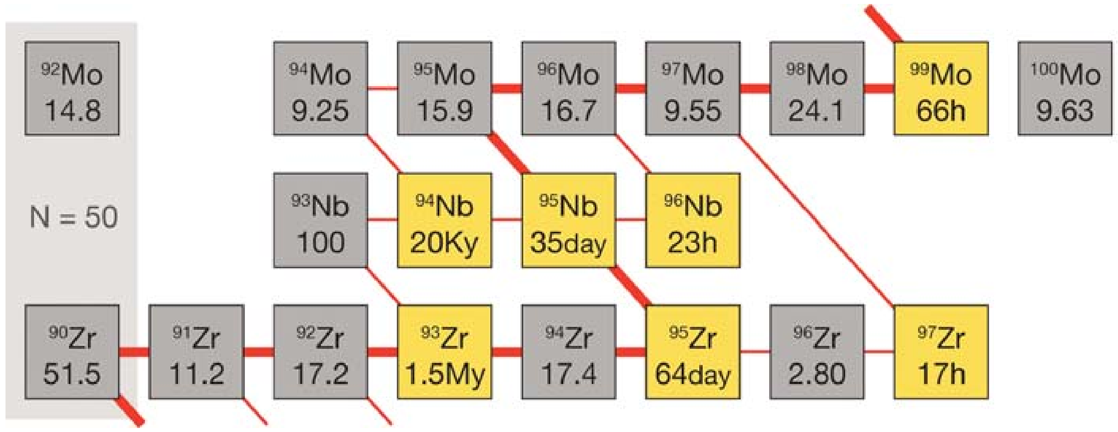
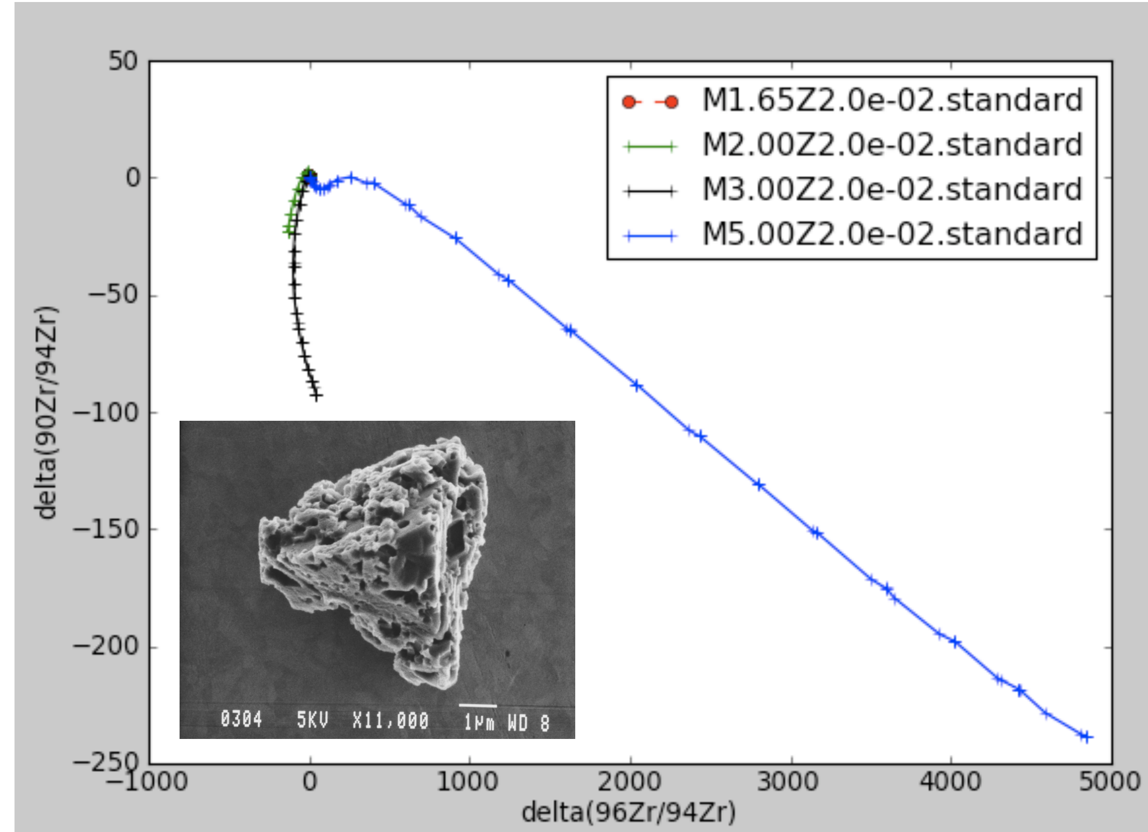
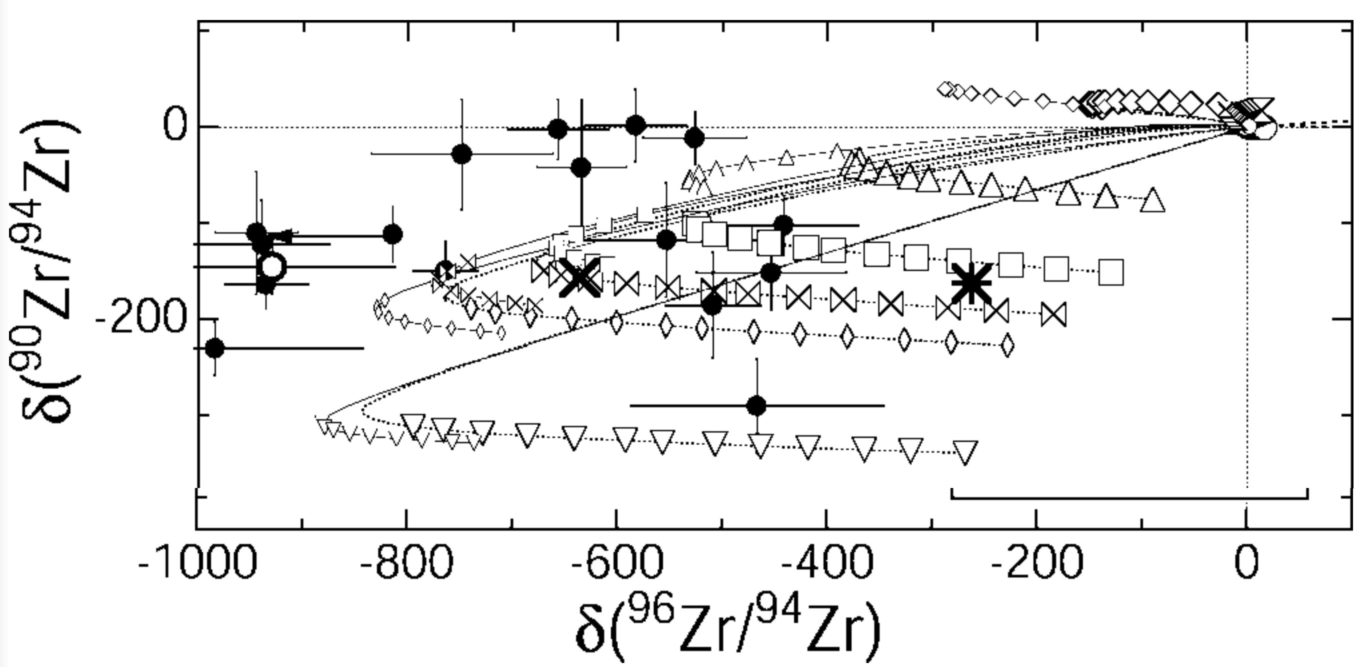
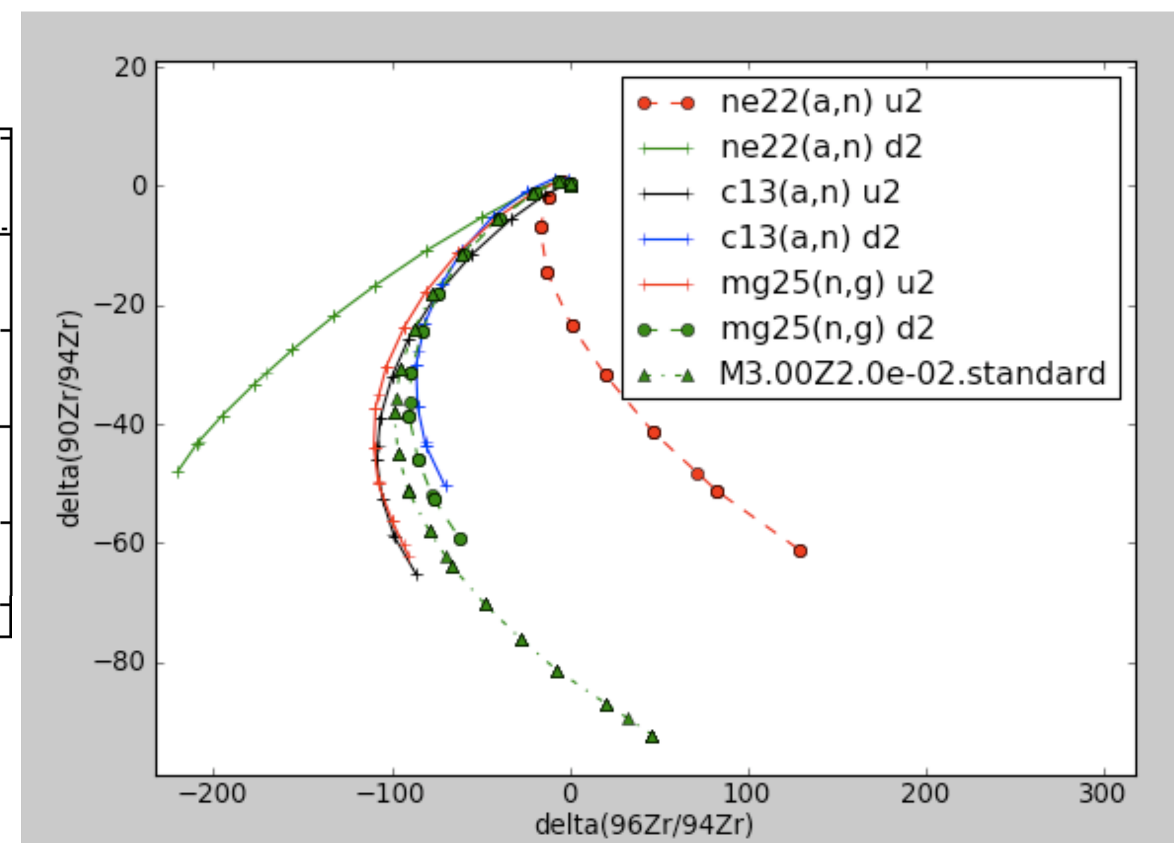


Figure 7 Detail of the chart of isotopes from zirconium to molybdenum. Unstable isotopes are represented in yellow. The *thicker red line* shows the main path of the *s* process; the *thinner red line* shows generally less important side branches. The additional numbers in the boxes give the half-life of unstable isotopes and the isotopic abundance fraction for the stable isotopes.







Lugaro etal 2003

Overview low- and intermediate mass stars I

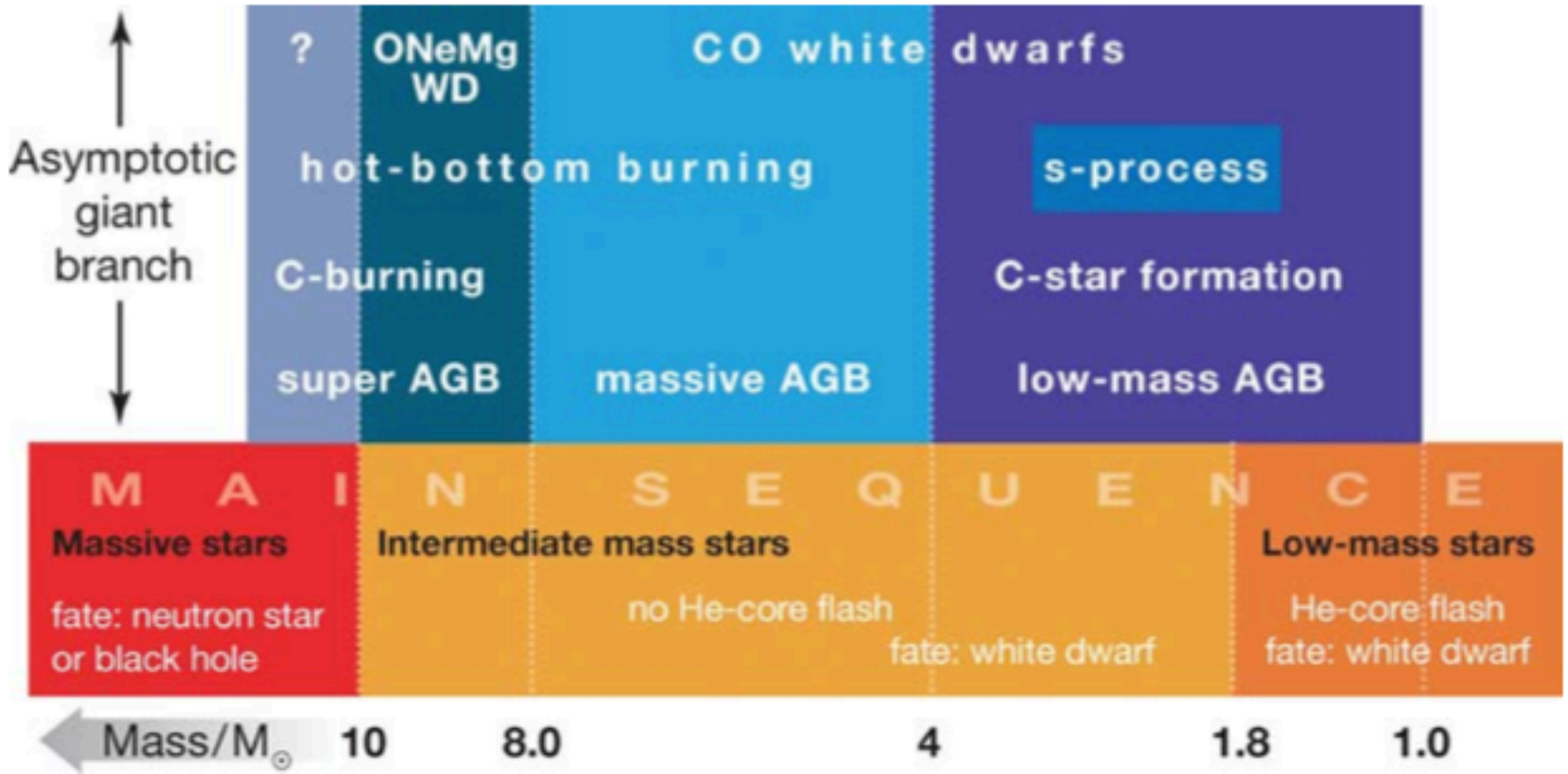


Figure 2 Classification of stars by mass on the main sequence (*lower part*) and on the AGB (*upper part*). The *lower part* shows mass designation according to initial mass. The *upper part* indicates the mass classification appropriate for AGB stars. Approximate limiting masses between different regimes are given at the bottom. These estimates are dependent on physics assumptions and input of models, as well as on metallicity. The different regimes have been labeled with some characterizing properties. The evolutionary fate of super-AGB stars is still uncertain (Section 5).

Herwig 2005, ARAA

Overview low- and intermediate mass stars II

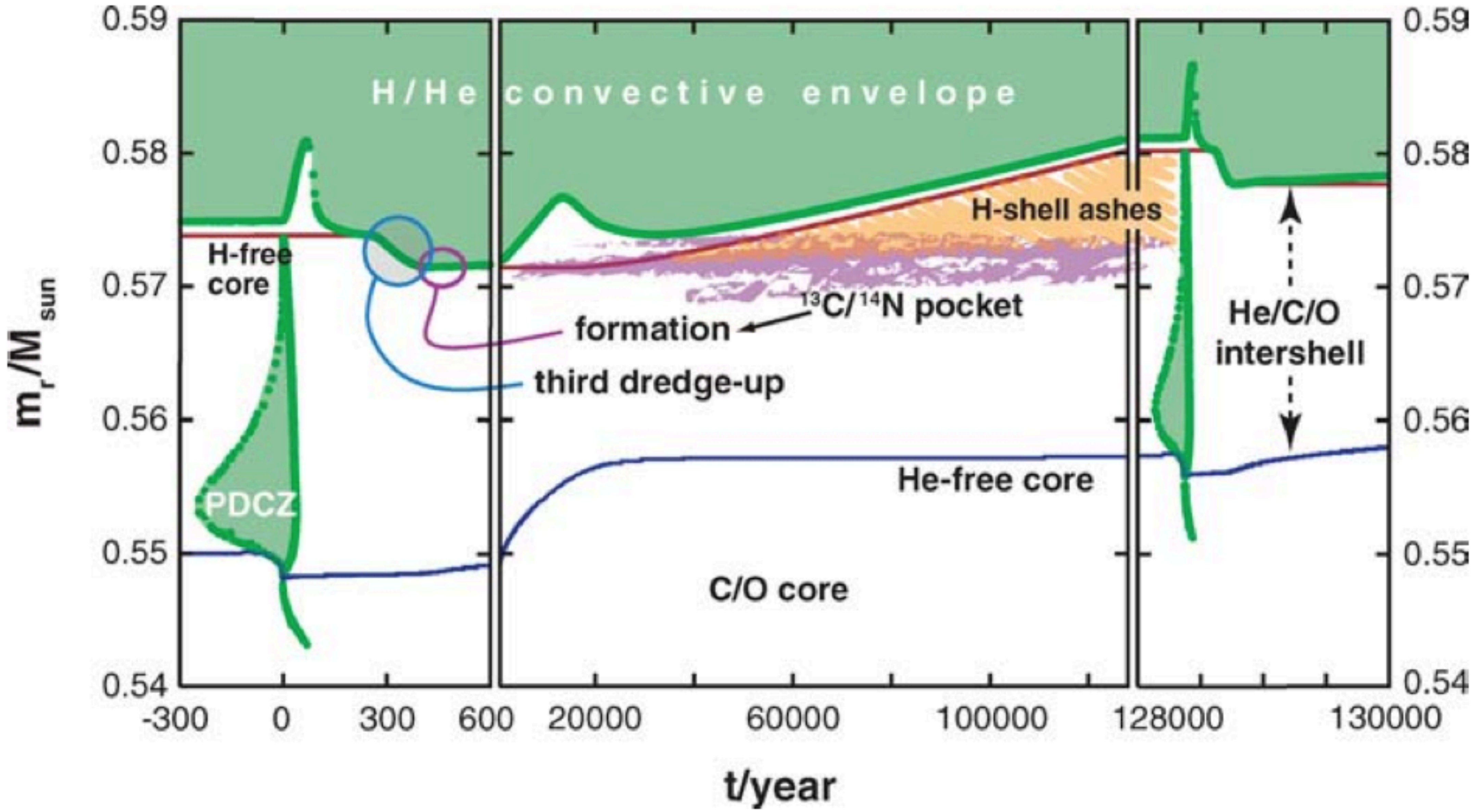
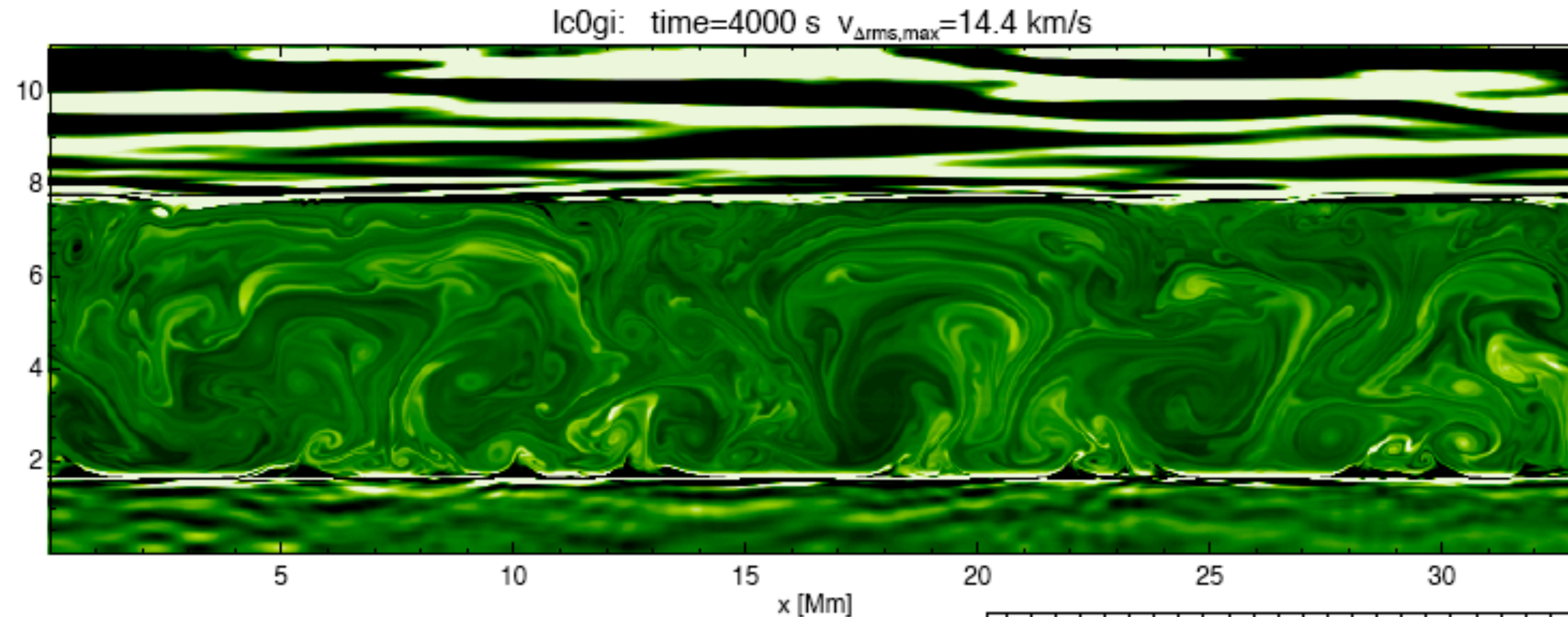


Figure 3 Thermal pulse 14, the subsequent interpulse phase and thermal pulse 15 of 2 $M_\odot$, $Z = 0.01$ sequence ET2 of Herwig & Austin (2004). The timescale is different in each panel. The *red solid line* indicates the mass coordinate of the H-free core. The *dotted green line* shows the boundaries of convection; each *dot* corresponds to one model in time. Convection zones are *light green*. The shown section of the evolution comprises 12,000 time steps. The colors indicating convection zones, layers with H-shell ashes and the region of the ^{13}C pocket match those in Figure 5.

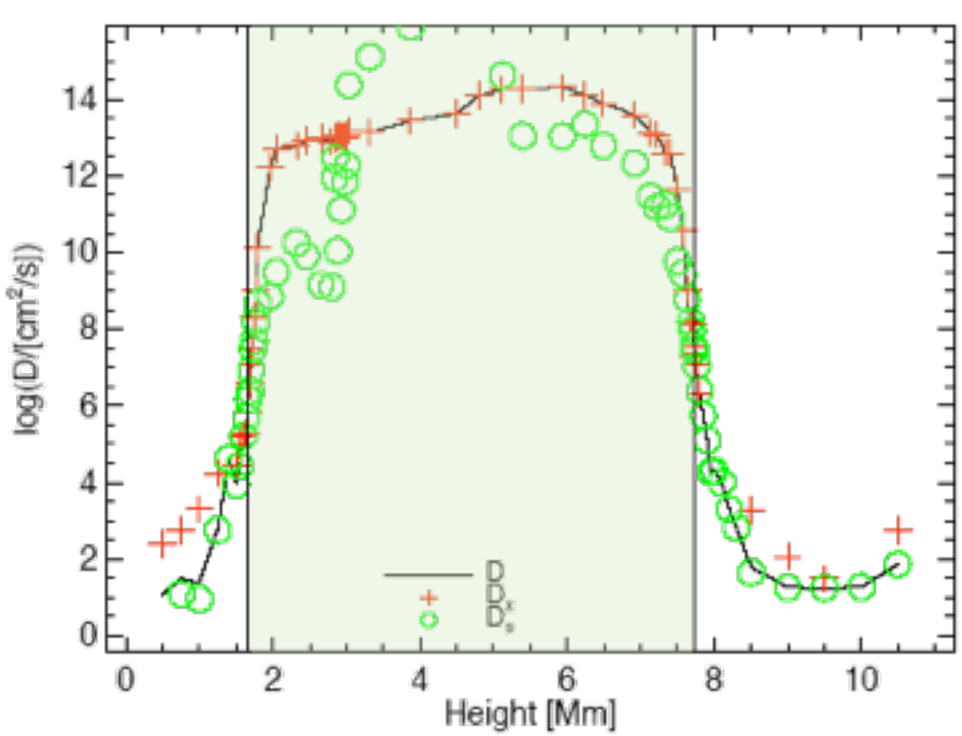
Multi-dimensional stars

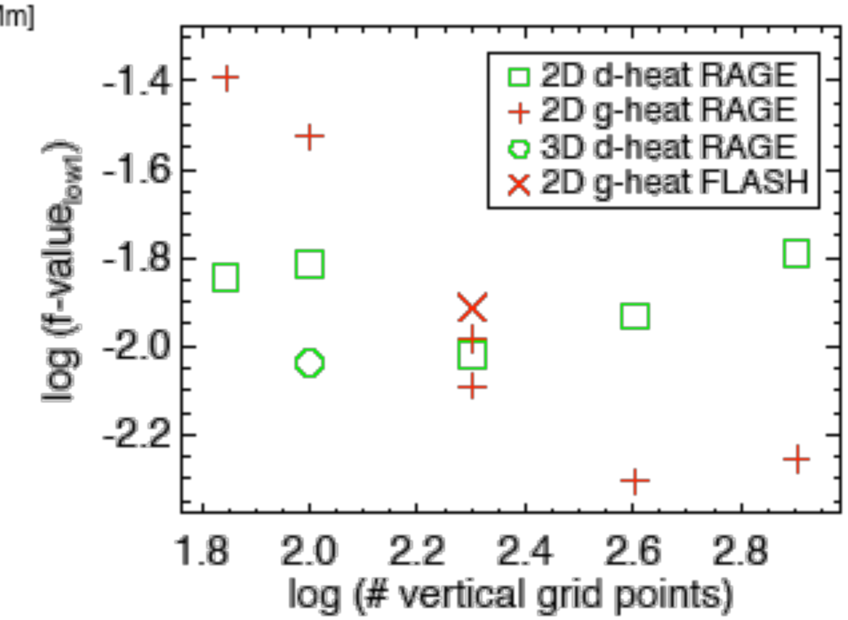
He-shell flash convection

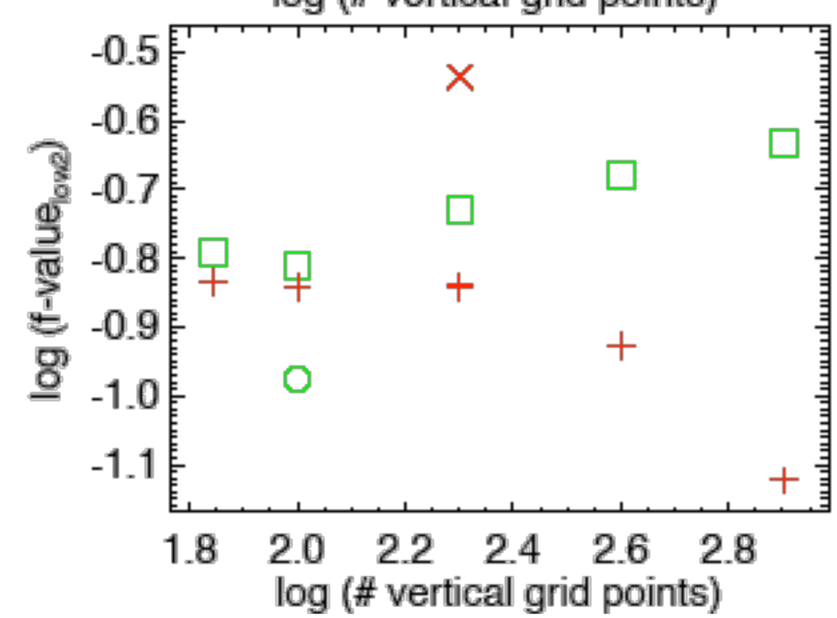
2D and 3D plane-parallel box-in-a-star (Herwig etal 2006)



2D entropy fluctuations (2400x800), realistic heating rate
Courant time scale at this resolution: ~3*10^{-3}sec -> 1.6M cycles





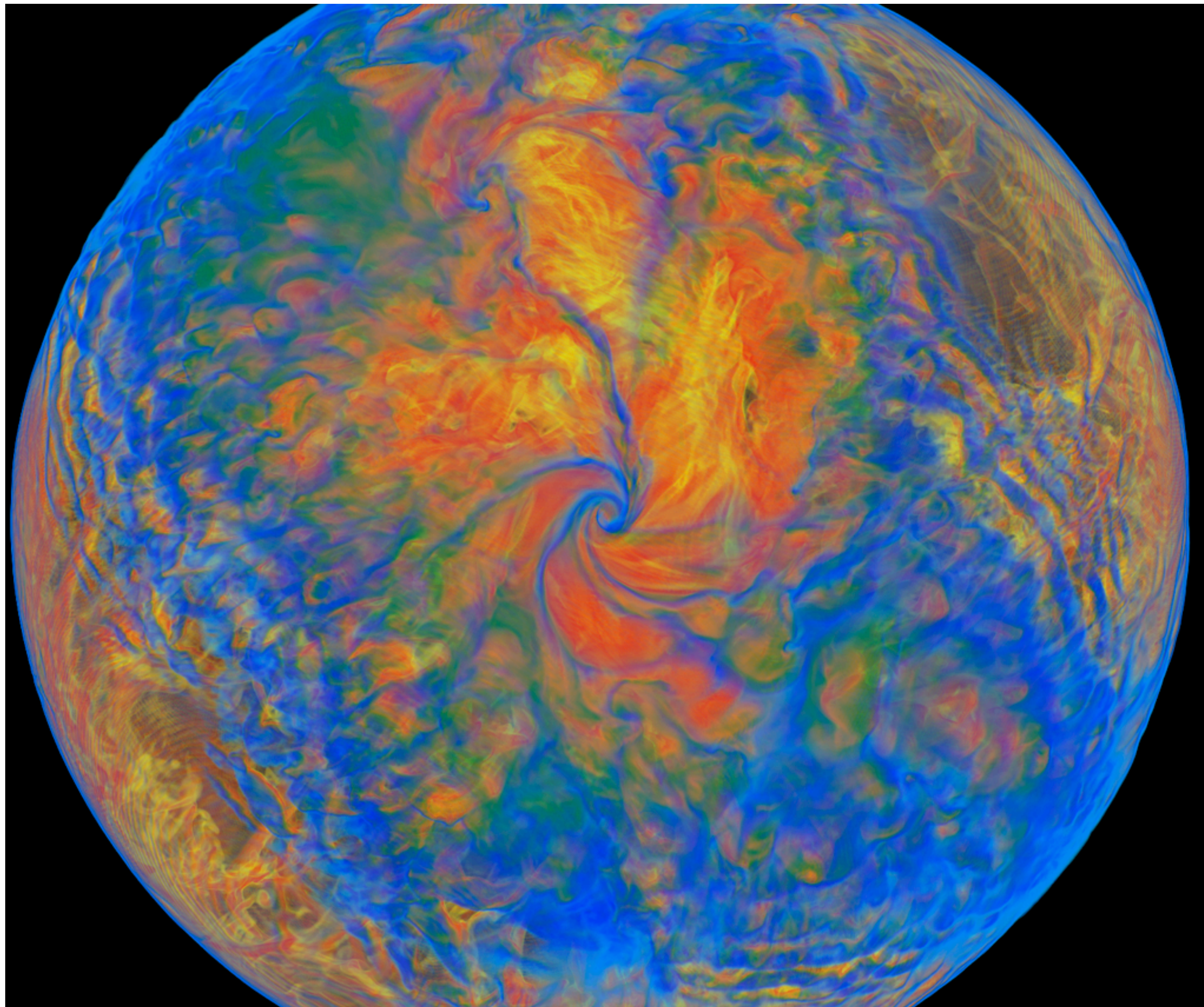


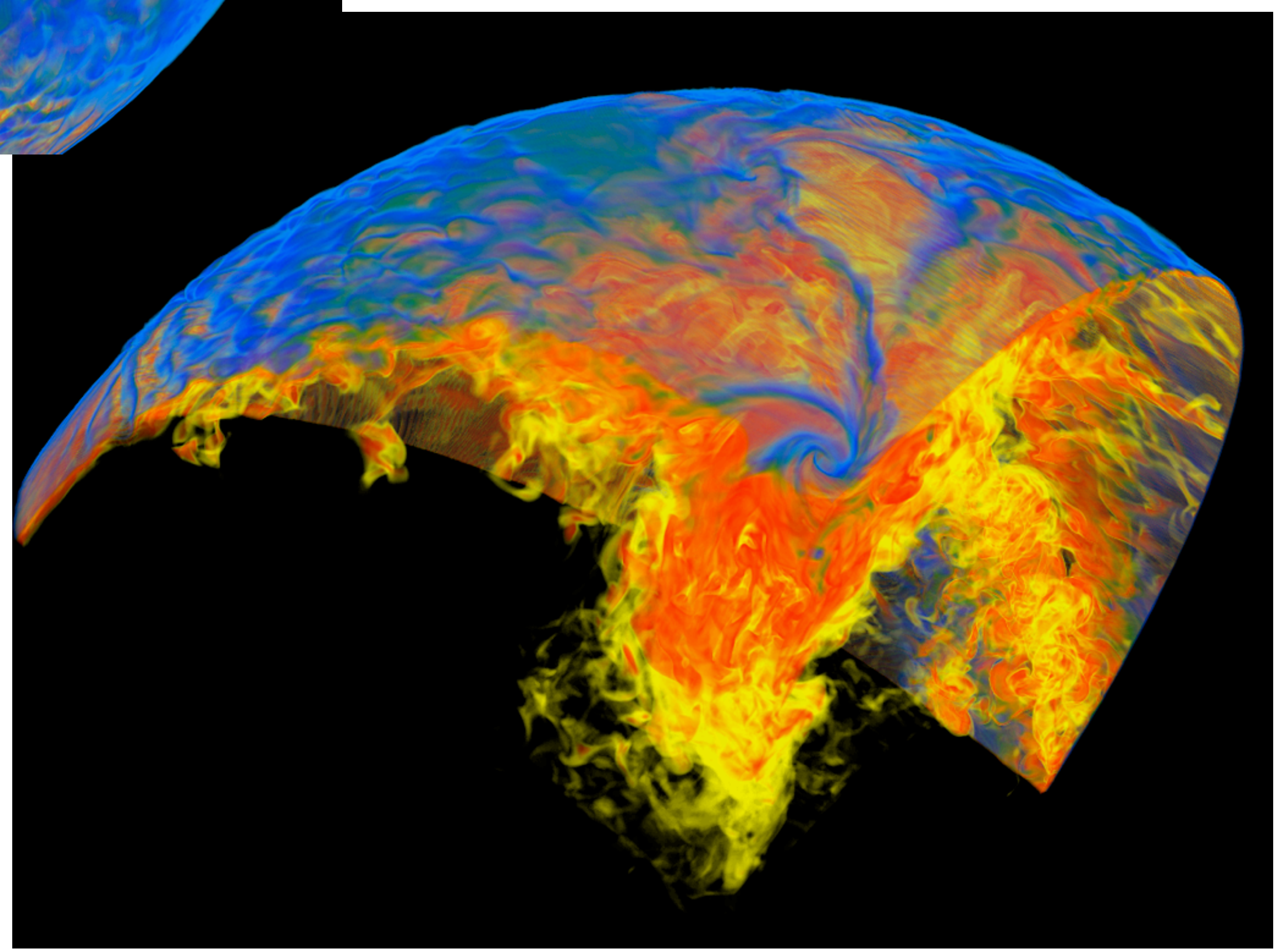
quantify "overshooting" - develop models for 1D stellar evolution

f_{top} ~ 0.10
$f_{bot,1}$ ~ 0.01
$f_{bot,2}$ ~ 0.14

Herwig etal, 2008
Freytag & Herwig, in prep

Entrainment He-shell flash convection





4π 3D simulations: concentration of fluid "above" (with Woodward, LCSE Minnesota)

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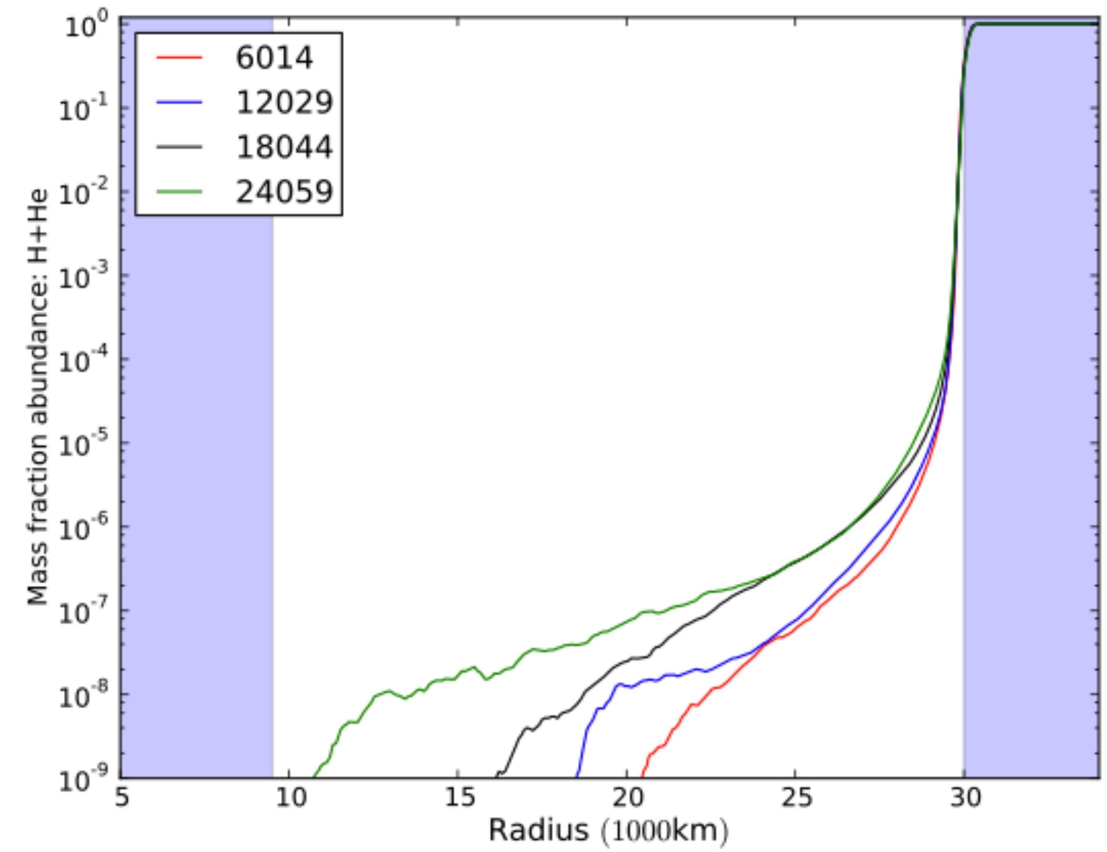
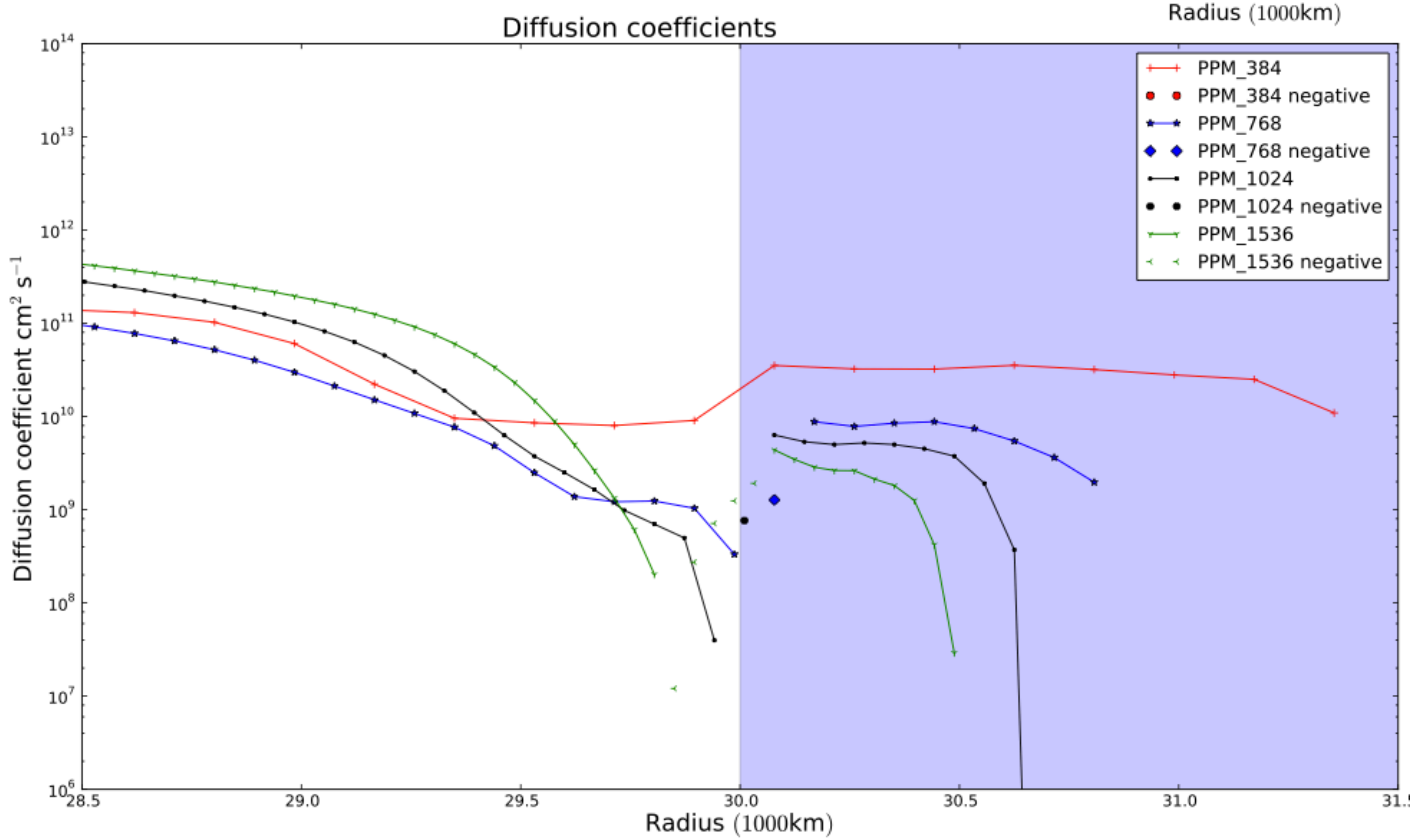
Building sub-grid models for 1D stellar evolution



diffusion coefficient analysis
(with Michael Bennett@Keele)



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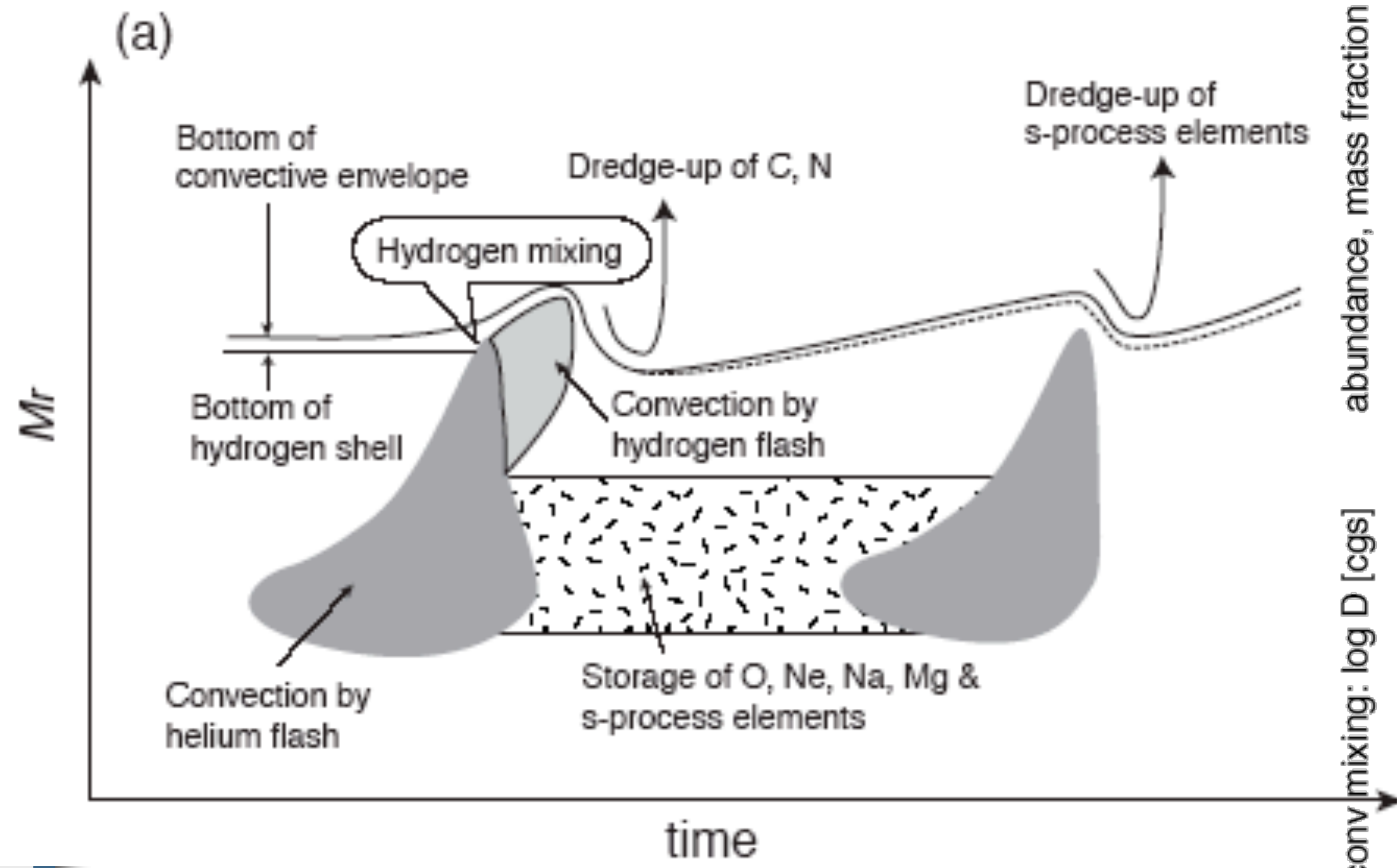
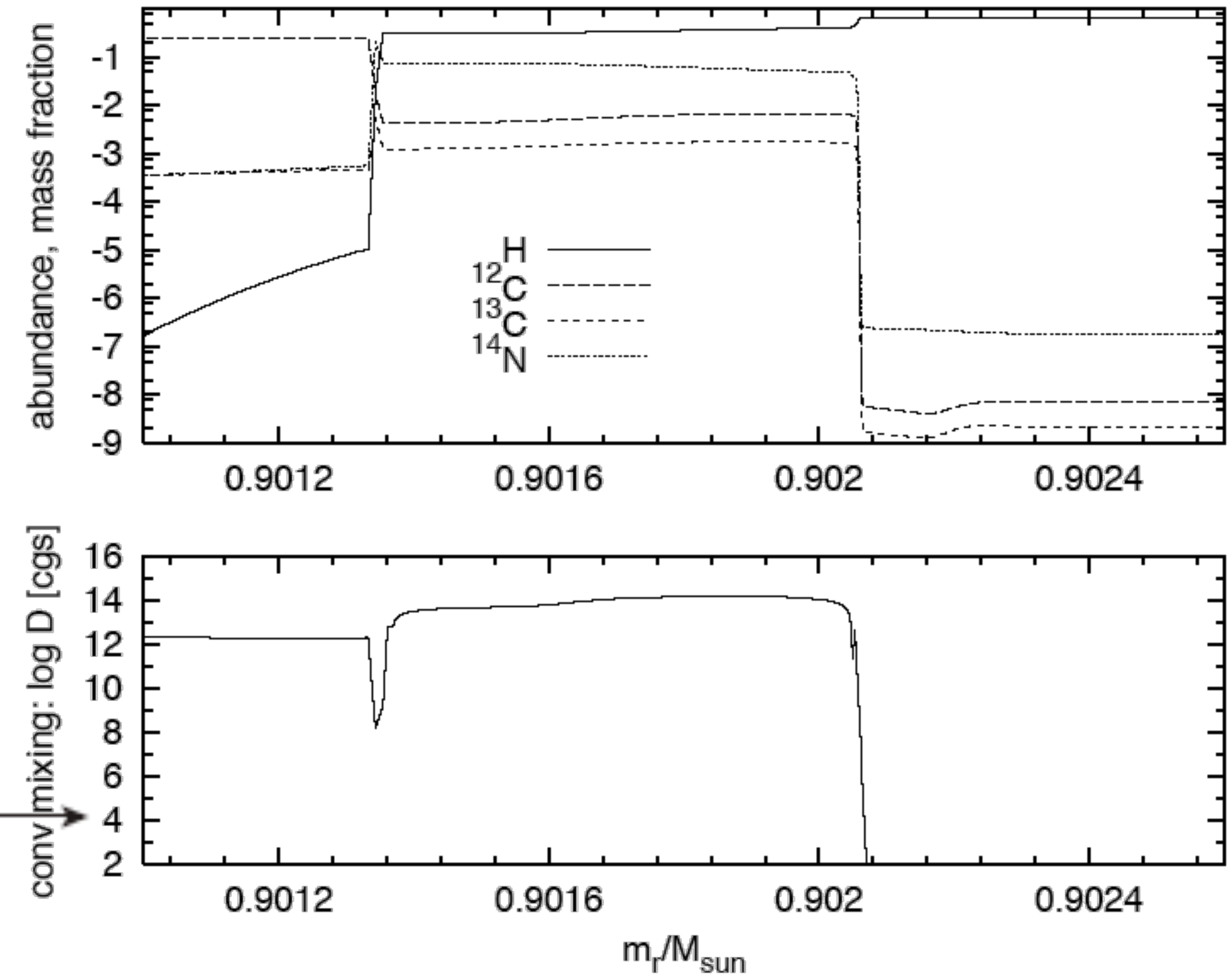
The H-ingestion (core/shell) flash in low-metallicity RGB/AGB stars





For [Fe/H] <-2.5 (Suda etal. 2004)

$5M_{sun}$, Z=0.0, 10th TP, Herwig 2002

Iwamoto etal (2004): the site for s-process in EMP AGB stars

$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(\alpha,n)^{16}O$

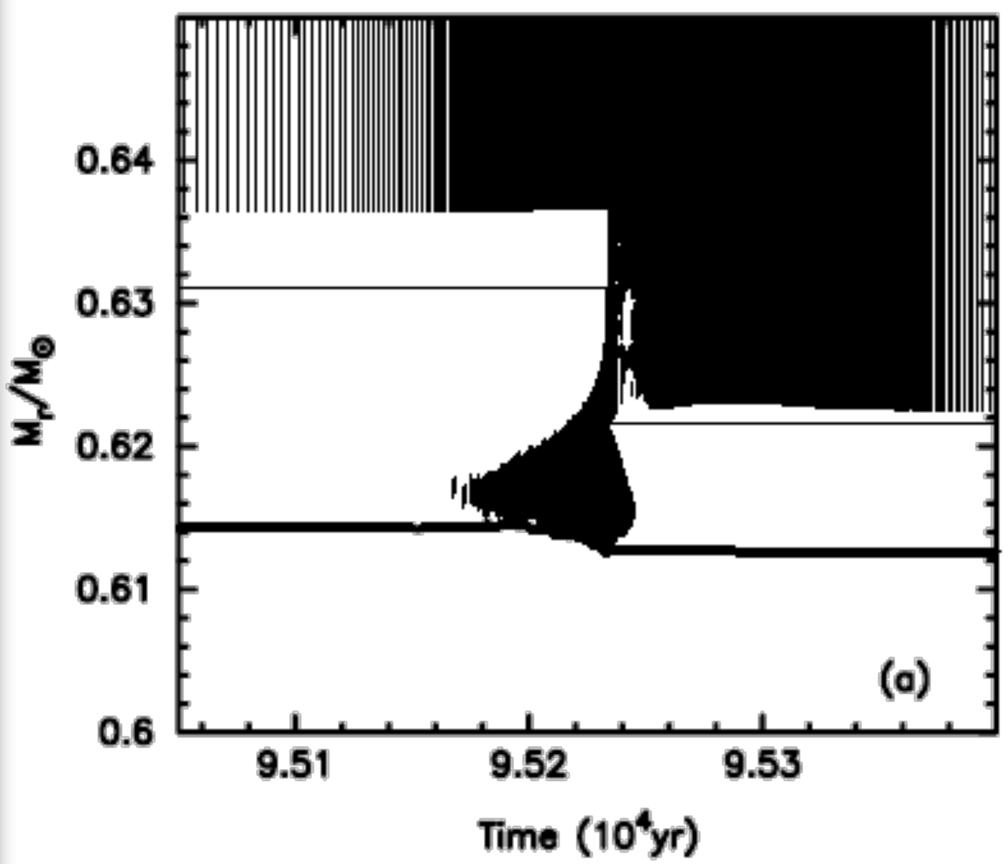
see also more recent work by:
Campbell etal
Cristallo etal
Lau etal and others

More examples

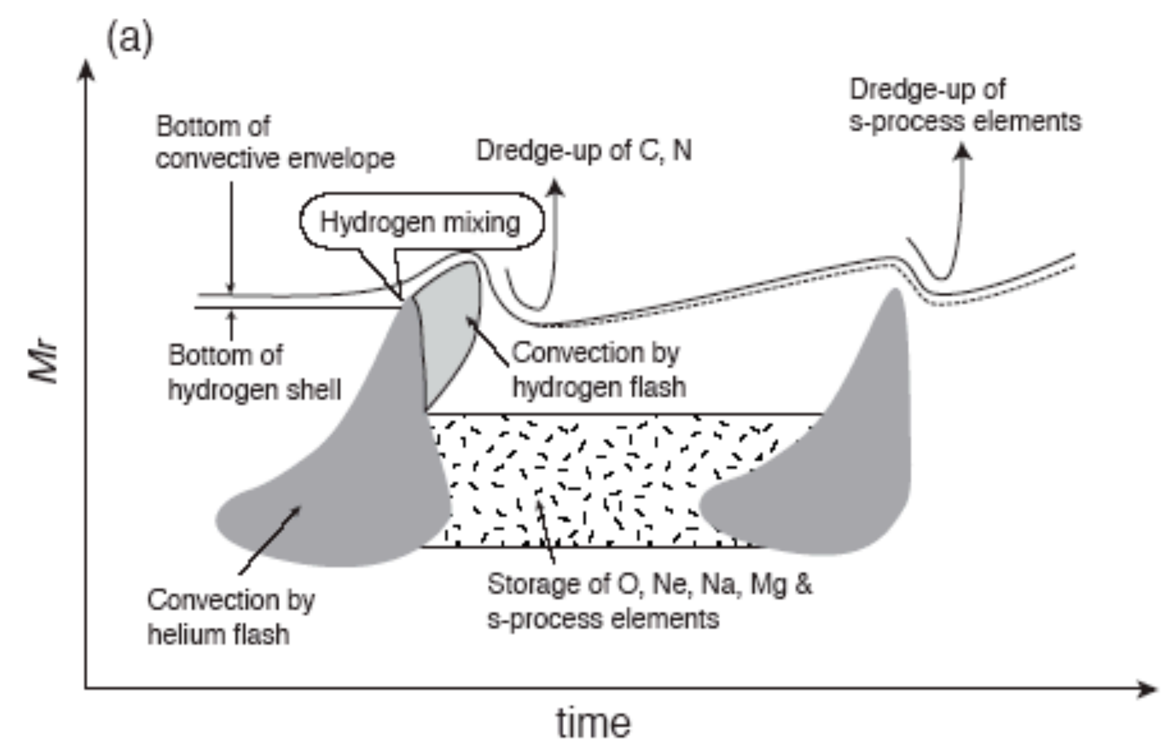
Numerous instances of convective-reactive phases in the literature, in the context of Pop III:

Fujimoto etal. (1990), Hollowell etal. (1990), Iwamoto etal (2004), Fujimoto etal (2000), Herwig (2003), Chieffi etal (2001), Weiss etal. (2004), Schlattl etal (2001), Picardie etal (2004), Suda etal (2004) …

2Msun, Z=0



Iwamoto etal. 2004



… also in massive Pop III and II.5 and X-ray bursts.

Convective-reactive event in 1M$_s$ Pop III stellar models (with MESA code, Bill Paxton)

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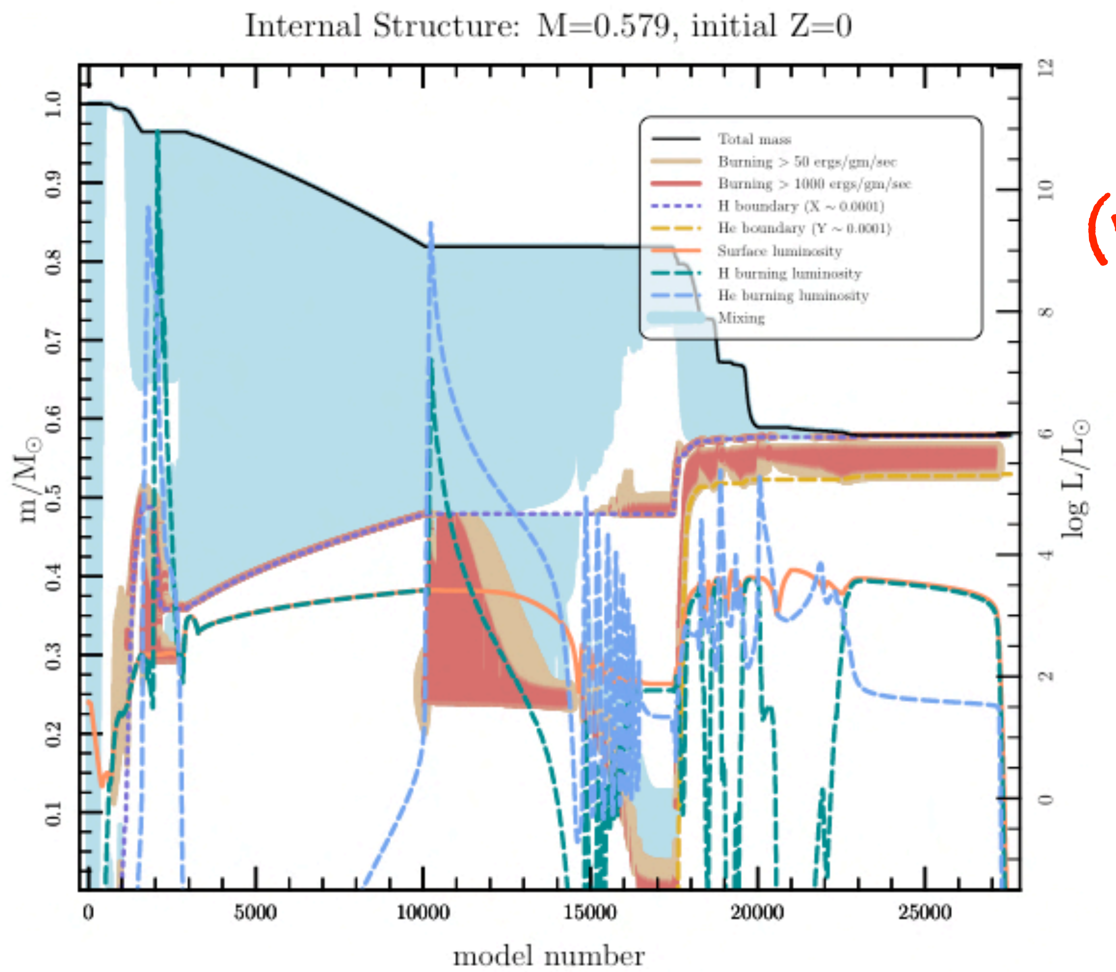
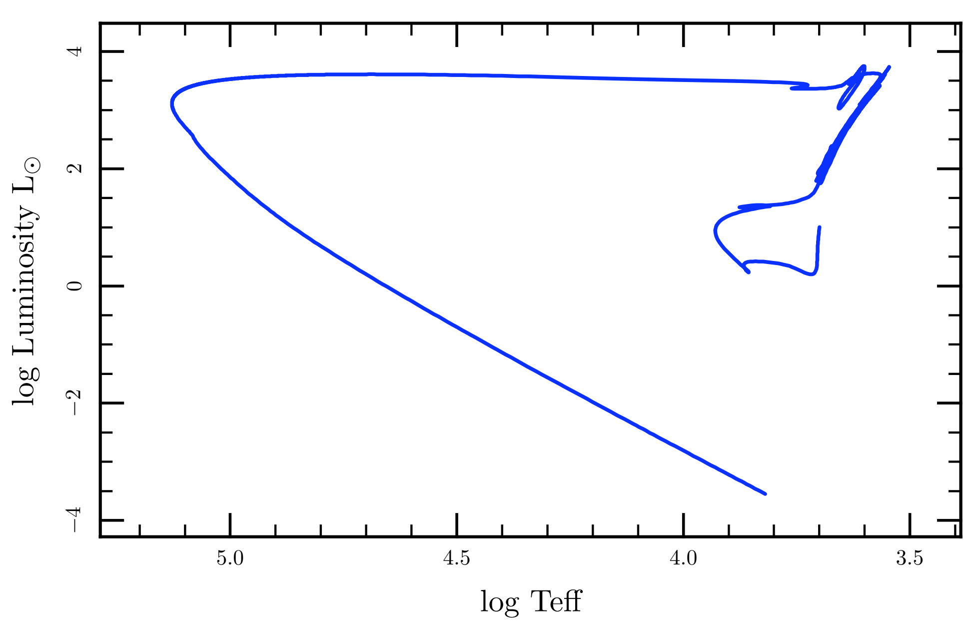
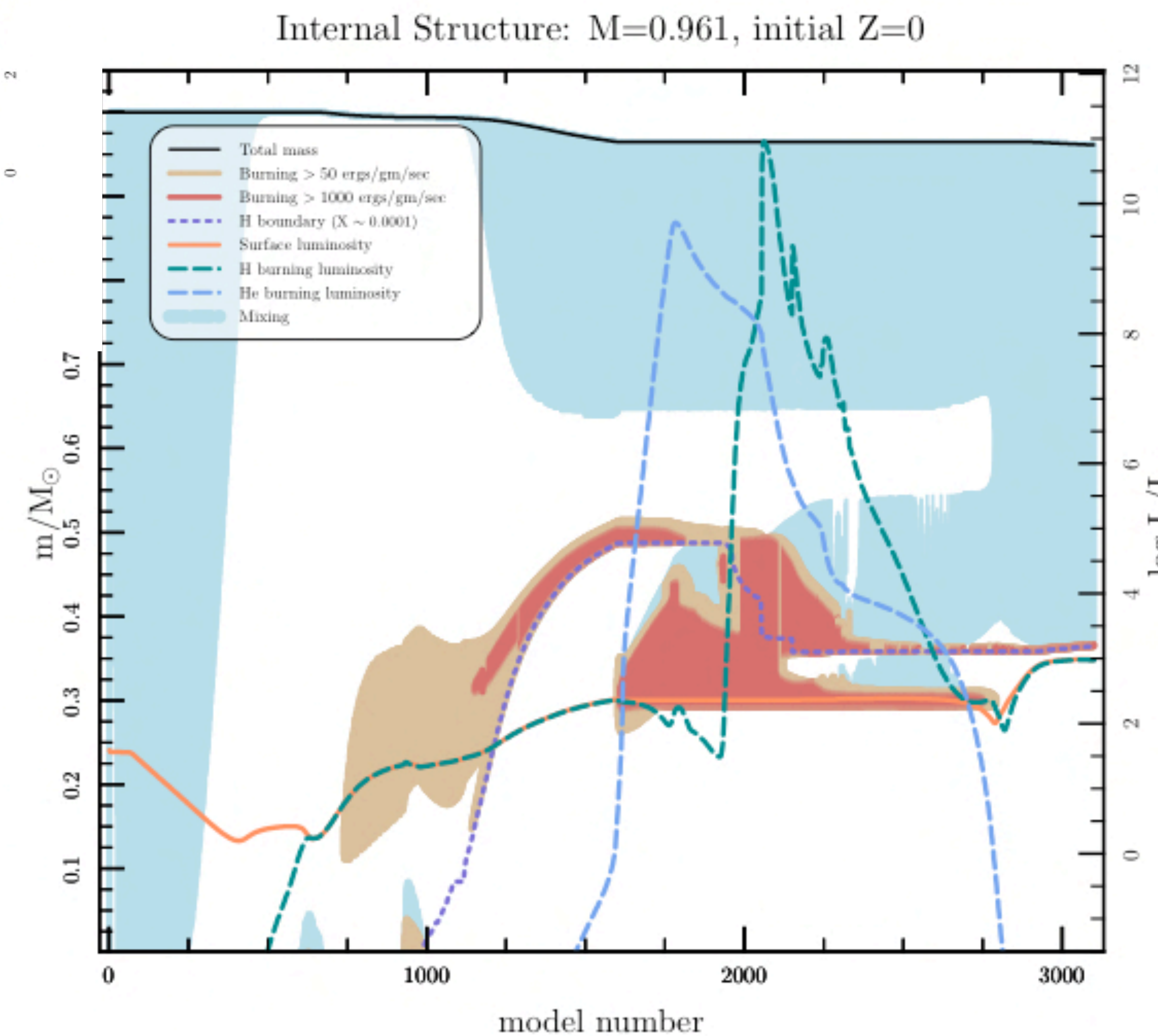






Other examples at near-solar metal content:

- X-ray bursts (Woosely etal 2004, Piro & Bildsten 2007)
- accreting white dwarfs, SNIa progenitors (Cassisi etal 1998)
- post-RGB late He-flashers (Brown etal 2001, Miller Bertolami etal 2008)
- post-AGB He-flashers (Schönberner 1979; Iben 1983, 1995; Herwig etal 1999, 2001; Miller-Bertolami etal 2006)

H-combustion in stellar evolution

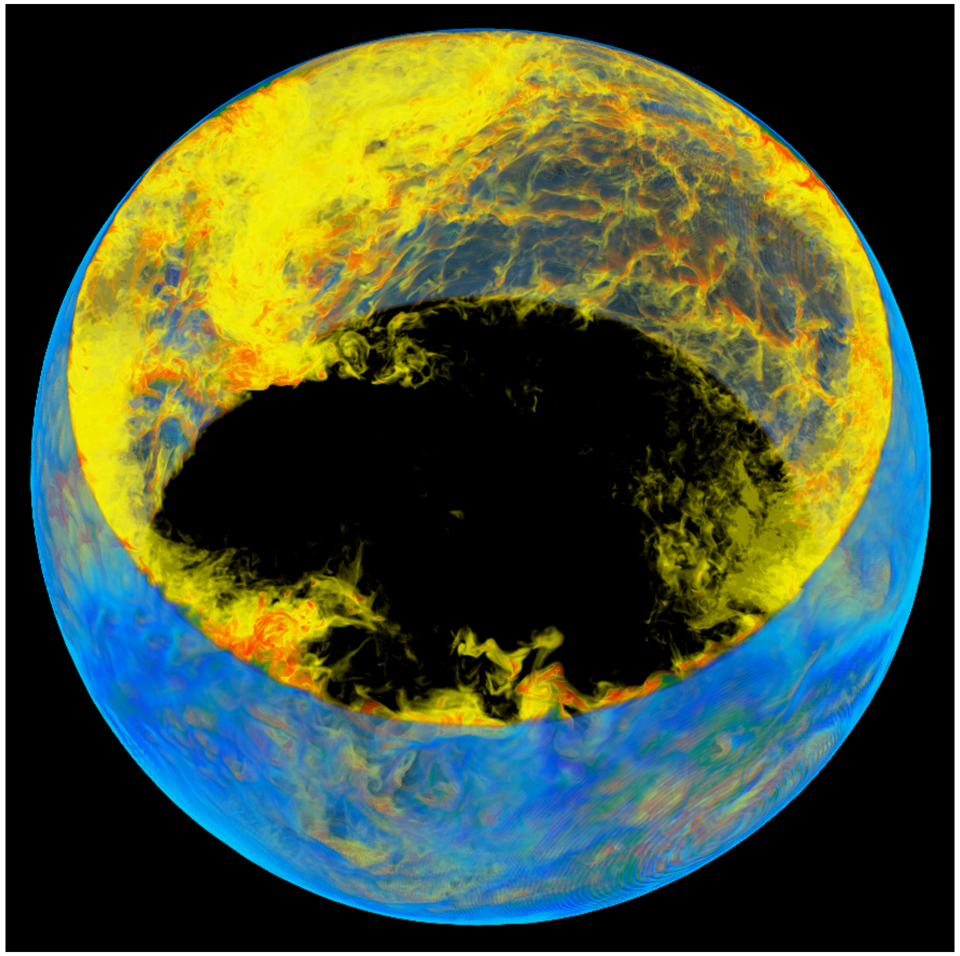
convective mixing of H into ^{12}C-rich He-convection zone
T ~ 150-300MK, t_{mix}~1000

The ratio of the mixing time scale and the reaction time scale is called the Damköhler number:

$$D_\alpha = \frac{\tau_{\rm mix}}{\tau_{\rm react}} \ .$$

Dimotakis, P. E. 2005, Annu. Rev. Fluid Mech., 37, 329

- D_α <<1: fully mixed burning, MLT appropriate
- D_α ~1 : combustion regime, MLT and 1D spherical symmetry assumption inappropriate because:
  - ★ MLT describes convection only in a time and spatially averaged sense
  - ★ in combustion fuels are not completely mixed
  - ★ fluid elements have a range of velocity - broadens the burning front
  - ★ localized energy feedback from nuclear burn feeds back into hydro



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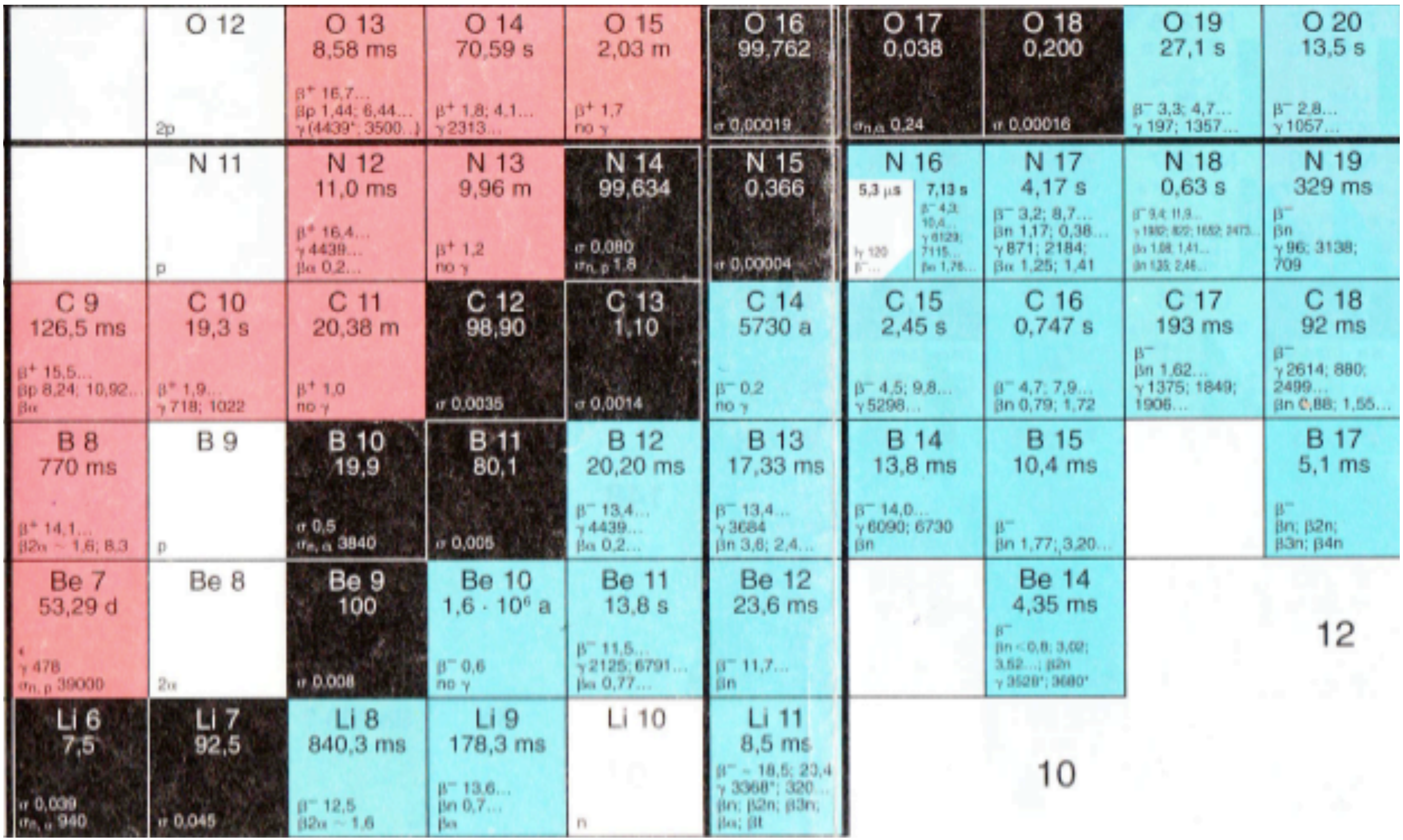
H-combustion provides naturally a neutron source under “non-standard” conditions

$^{12}C(p,\gamma)^{13}N(\beta^{+})^{13}C(\alpha,n)^{16}O$



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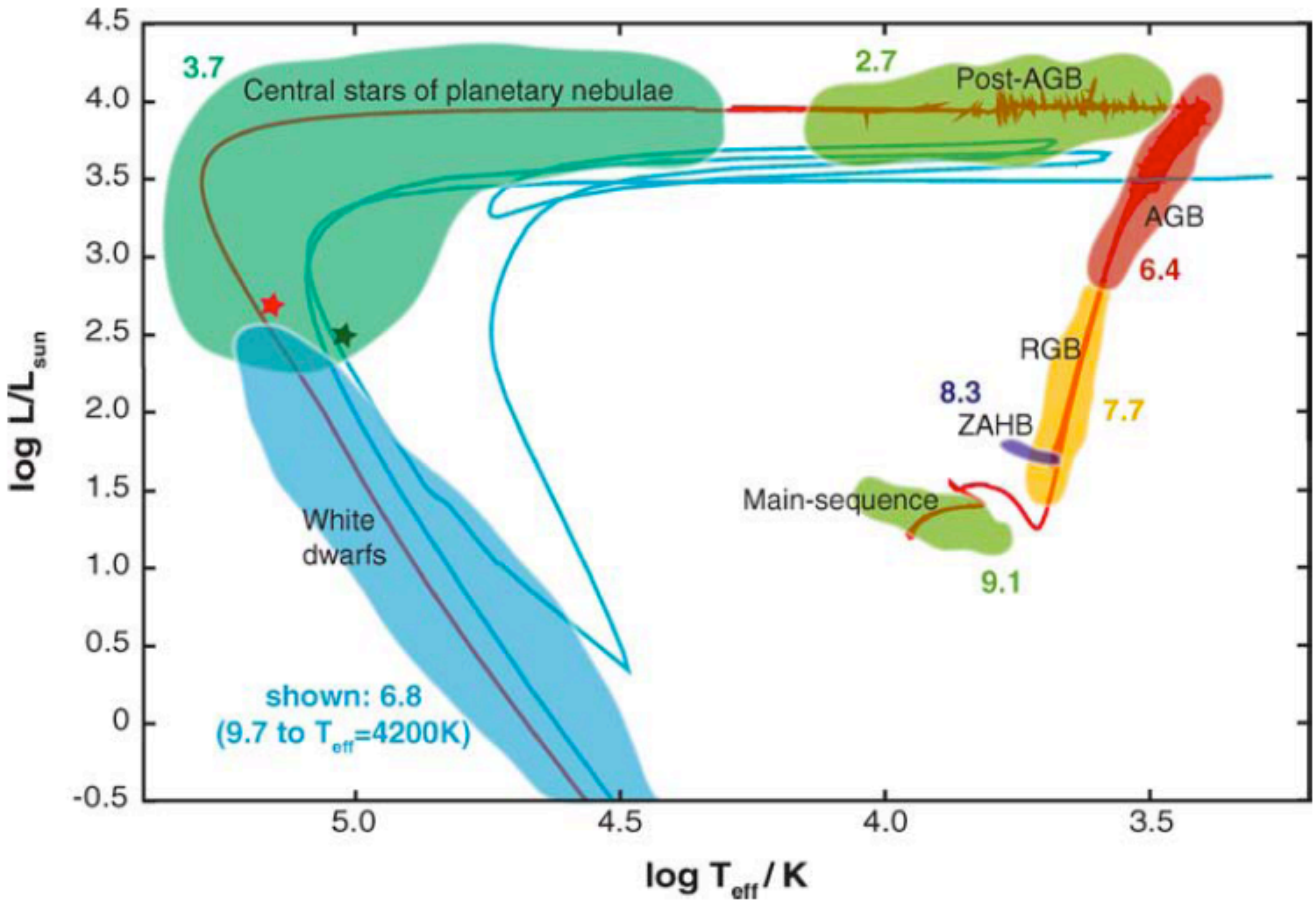
How can we better understand these H-combustion events?

Need cases with many observables that can test simulations of convective-reactive combustion!

Post-AGB flashers are such validation cases!
Sakurai's object.

Combustion in the post-AGB flasher



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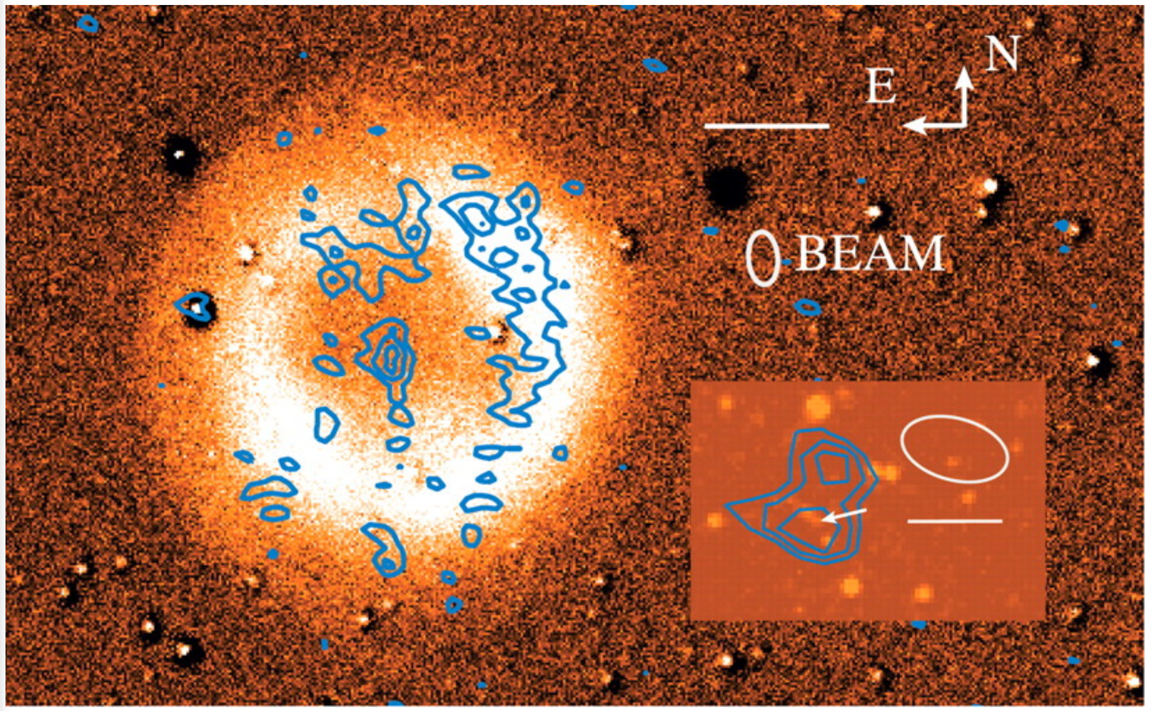
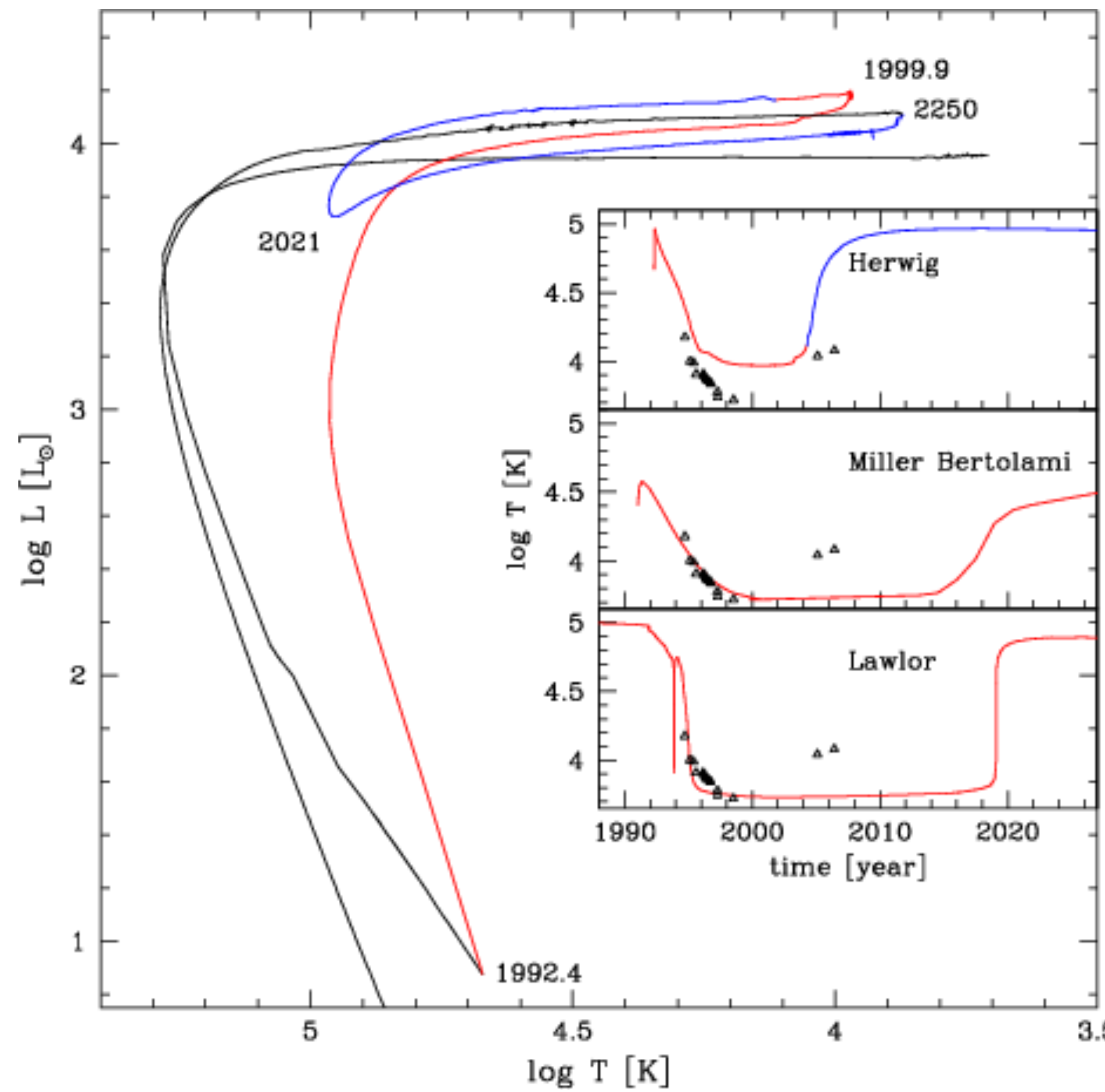
Post-AGB/young white dwarf He-shell flash object

Sakurai's object



Hajduk, Zijlstra, Herwig etal., Science 308, 231, 2005.



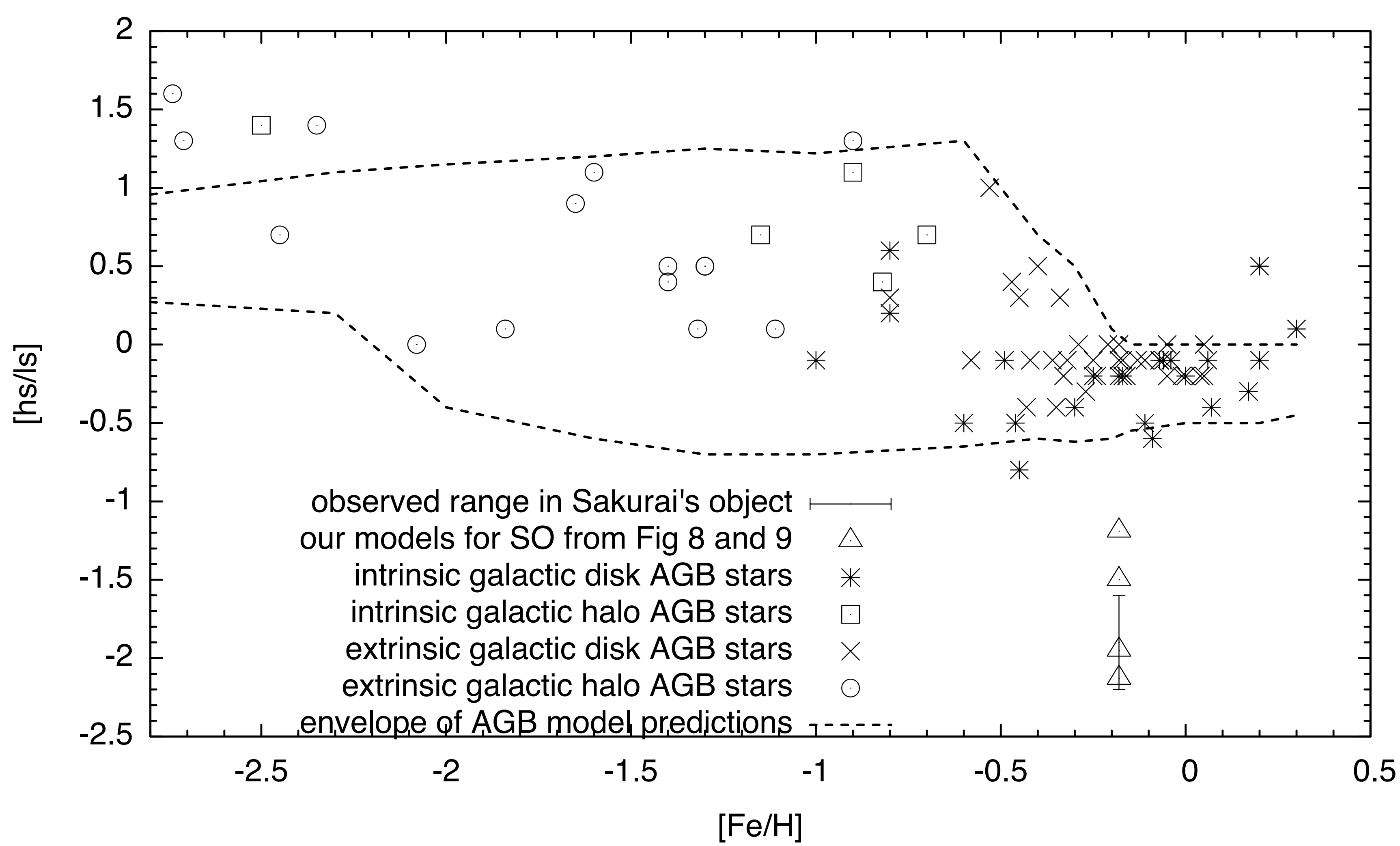
van Hoof etal 2007, 2005/06: radio observation with VLA

Highly non-solar, H-deficient abundance distribution of Sakurai's Object in 1996

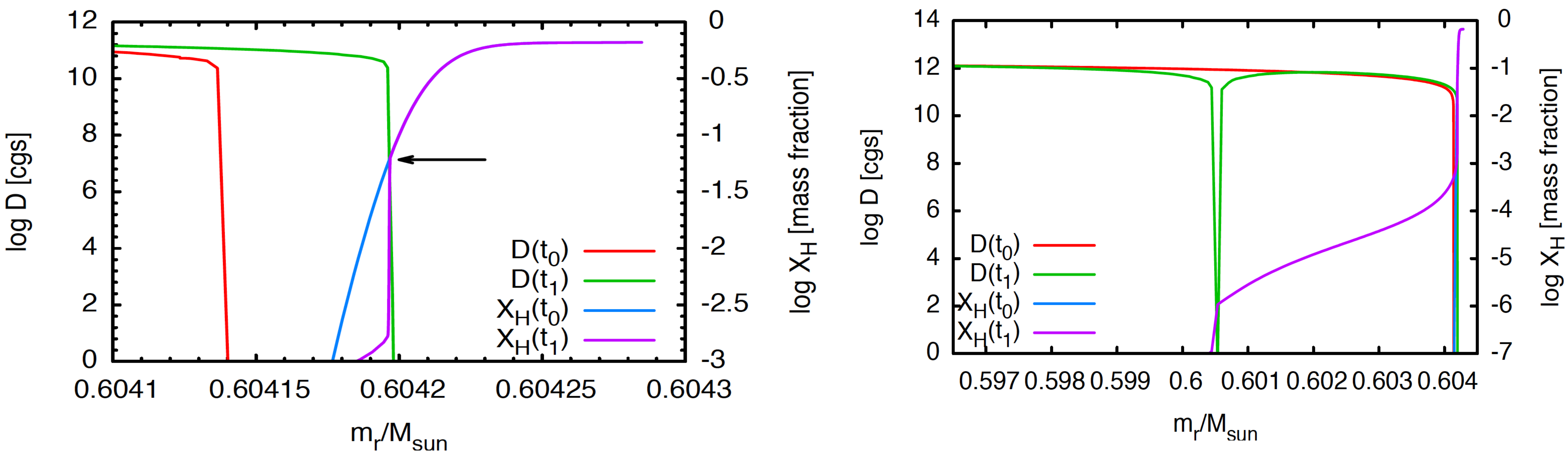
Element	Sun[a]	Sakurai's object in 1996 April 20–25	May 5–9	June 4	July 3	October 7	R CrB majority[b]	V854 Cen[c]
H	12.00	10.0	9.7	9.7	9.6	9.0	< 4.1–6.9	9.9
He	10.93	11.4[d]	11.4[d]	11.4[d]	11.4[d]	11.4[d]	11.5[d]	11.4[d]
Li	3.31	3.6	3.6	3.6	4.0	4.2	< 1.1–3.5	< 2.0
C	8.52	9.7[e] ± 0.2	9.7[e] ± 0.2	9.6[e] ± 0.2	9.7[e] ± 0.3	9.8[e] ± 0.3	8.9[e]	9.6[e]
N	7.92	9.0 ± 0.3	8.9 ± 0.4	9.0 ± 0.4	9.2 ± 0.3	8.9 ± 0.2	8.6	7.8
O	8.83	9.2 ± 0.2	9.5 ± 0.3	9.3 ± 0.4	9.3 ± 0.1	9.4 ± 0.2	8.2	8.9
Ne	8.08	9.4 ± 0.2	9.4 ± 0.3	9.5 ± 0.3	9.5 ± 0.3			
Na	6.33	6.6 ± 0.1	6.7 ± 0.1	6.5 ± 0.1	6.6 ± 0.2	6.8 ± 0.1	6.1	6.4
Mg	7.58	6.5 ± 0.4	6.6 ± 0.4	6.3 : ±0.4	6.3 : ±0.4	6.5 ± 0.3	6.4	6.2
Al	6.47	6.5 ± 0.2	6.6 ± 0.2	6.5 ± 0.3	6.6 ± 0.3	6.3	6.0	5.7
Si	7.55	7.3 ± 0.0	7.1 ± 0.2	7.1 ± 0.2	7.1 ± 0.0	7.5 ± 0.2	7.1	7.0
P	5.45	6.2	6.2 ± 0.4	6.1 ± 0.4	6.3			
S	7.33	6.8 ± 0.1	6.6 ± 0.1	6.5 ± 0.2	6.7 ± 0.1	6.9 ± 0.1	6.9	6.4
K	5.12		4.9 ± 0.0	4.7	5.0 ± 0.1	5.0 ± 0.0		
Ca	6.36	5.2 ± 0.1	5.6 ± 0.3	5.4 ± 0.3	5.6 ± 0.4	5.5 ± 0.4	5.4	5.1
Sc	3.17	3.1 ± 0.1	3.1 ± 0.1	3.2 ± 0.1	3.3 ± 0.2	3.9 ± 0.2		2.9
Ti	5.02	4.0 ± 0.1	4.1 ± 0.2	4.2 ± 0.2	4.4 ± 0.2	4.6 ± 0.2		4.1
Cr	5.67	4.5 ± 0.1	4.5 ± 0.2	4.7 ± 0.2	4.8 ± 0.2	5.1 ± 0.2		4.2
Fe	7.50	6.4 ± 0.2	6.4 ± 0.2	6.4 ± 0.2	6.6 ± 0.2	6.6 ± 0.3	6.5	6.0
Ni	6.25	6.1 ± 0.3	6.1 ± 0.4	5.9 ± 0.2	6.0 ± 0.2	6.2 ± 0.2	5.9	5.9
Cu	4.21		5.0 ± 0.3	5.0 ± 0.2	5.1 ± 0.0	5.0 ± 0.1		
Zn	4.60	4.9 ± 0.2	4.8 ± 0.2	4.9	5.1	5.4	4.3	4.4
Rb	2.60		< 3.7	4.2		4.6		
Sr	2.97	4.7 : ±0.1	4.9 : ±0.2	5.0 : ±0.4		5.4 : ±0.0		2.2
Y	2.24	3.2 ± 0.3	3.3 ± 0.3	3.3 ± 0.3	3.7 ± 0.2	4.2 ± 0.2	2.1	2.2
Zr	2.60	3.0 ± 0.2	3.0 ± 0.3	3.2 ± 0.2	3.3 ± 0.2	3.5 ± 0.3		2.1
Ba	2.13	1.5 ± 0.1	1.5 ± 0.2	1.5 ± 0.2	1.8 ± 0.1	1.9 ± 0.4	1.6	1.3
La	1.17		< 1.6		1.3	1.5		0.4

Asplund etal 1999

Observational constraints: Ratio of heavy (hs = <Ba,La>) to light s-process elements (ls = <Rb,Sr,Y,Zr>) is very low (Asplund etal. 1999). Other observed abundances (e.g. Li, P, Cu, Zn up and S, Ti, Cr and Fe down) are also **anomalous in a way that can not be reconciled with any known s-process production site during the progenitor AGB evolution** (Busso etal. 2001). In particular, no or very few neutrons would be released in the early-split convection scenario predicted from stellar evolution.



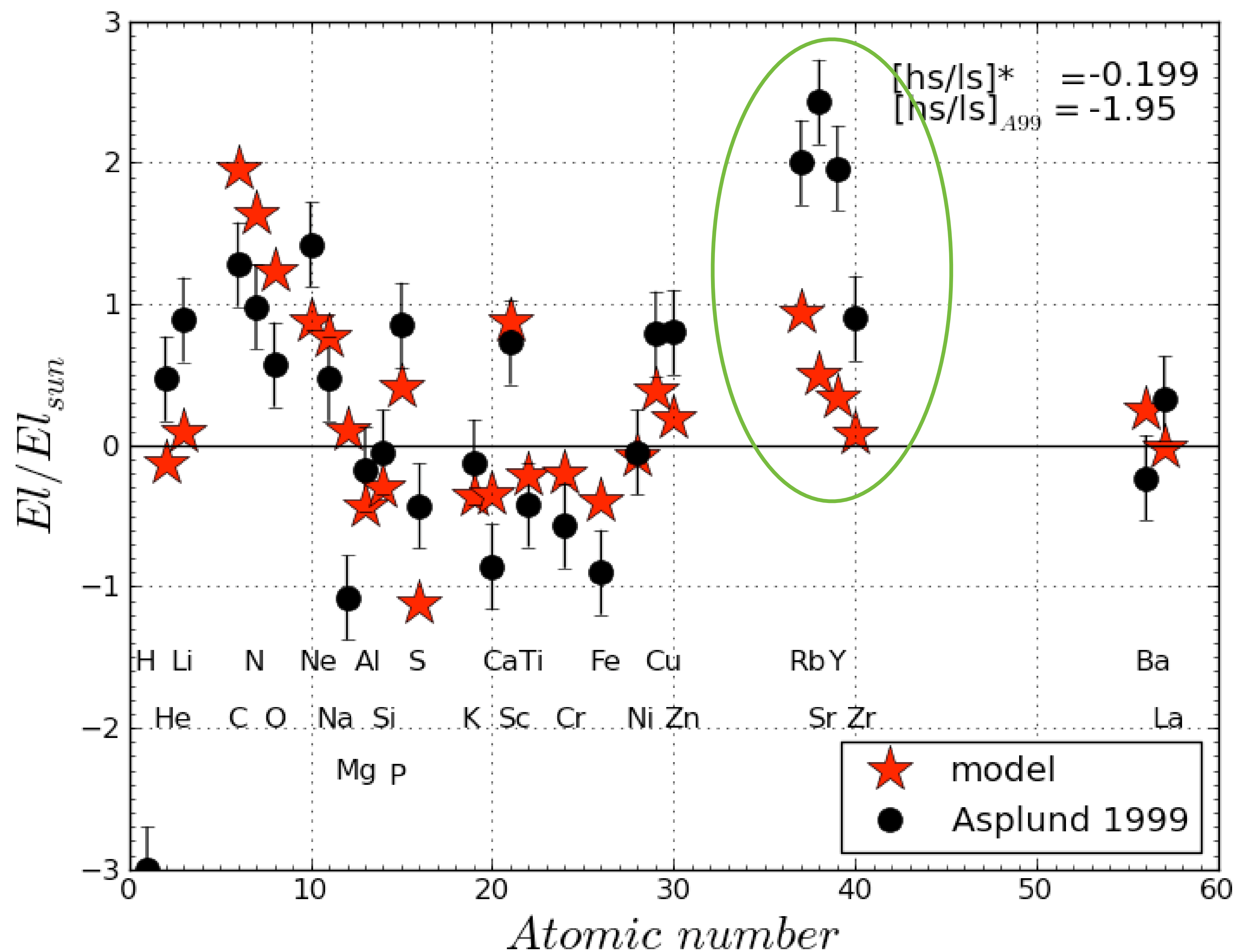
Stellar evolution picture of the HIF in Sakurai's object



Stellar evolution predictions for the nuclear combustion in Sakurai's object: Convective diffusion coefficient and H abundance profile at the beginning of the H-ingestion flash (t_0) and at the time when the split of the convection zone appears at $t_1 = t_0 + 8.58 \times 10^5$s. In our 1D models mixing through this split is not possible. Left panel: the outer section of the convection zone showing the location of the split as a deep dip in D; right panel: just the interface of the outer boundary of the convection zone.

Abundance distribution according to stellar evolution mixing

Can not reproduce observed abundance pattern



Herwig etal 2011, ApJ

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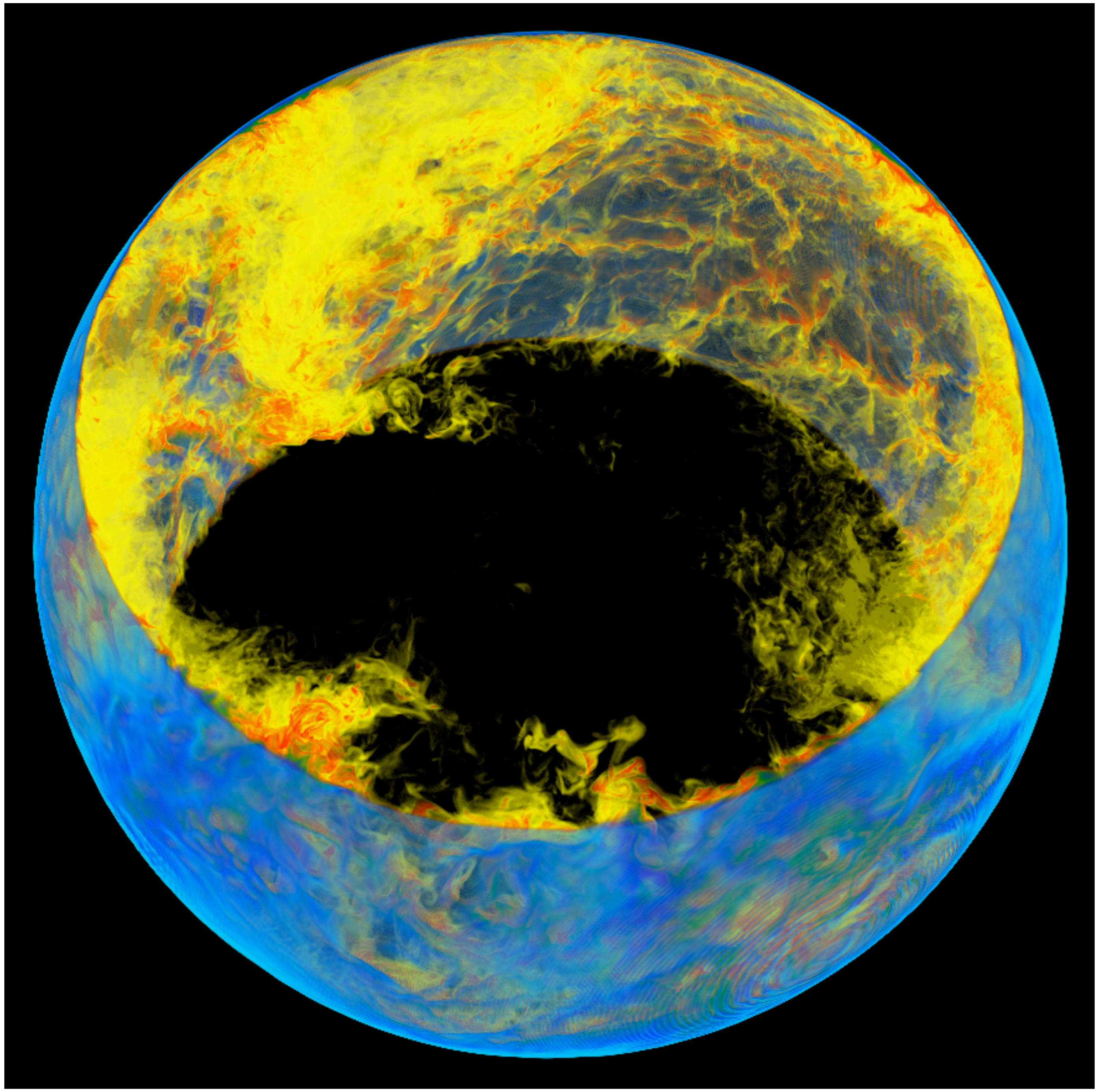
Multi-dimensional stars

abundance of H-rich material entrained from above into convection zone at ~20ks

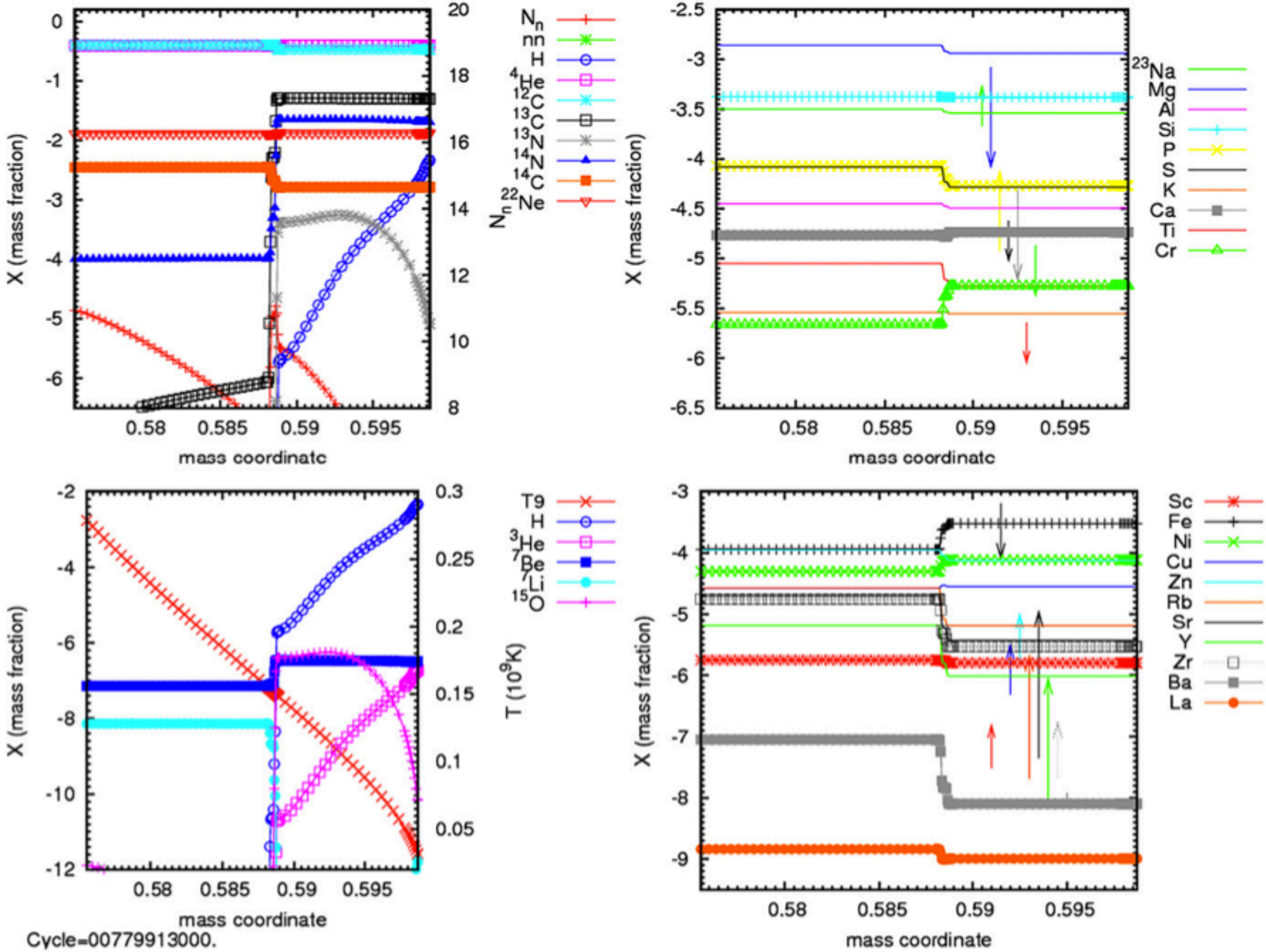
Next generation He-shell flash convection

i. 3D 4π star-in-a-box simulations (e.g. Herwig etal 2010, arXiv:1002.2241)
ii. compressible gas dynamics PPM code Paul Woodward (http://www.lcse.umn.edu)
iii. high accuracy PPB advection scheme
iv. 2 fluids, with individual, realistic material densities
v. 576^3 cartesian grid, simulated time total 60ks
vi. Ma ~ 0.03, 11H_P in conv. zone



http://www.lcse.umn.edu/index.php?c=movies

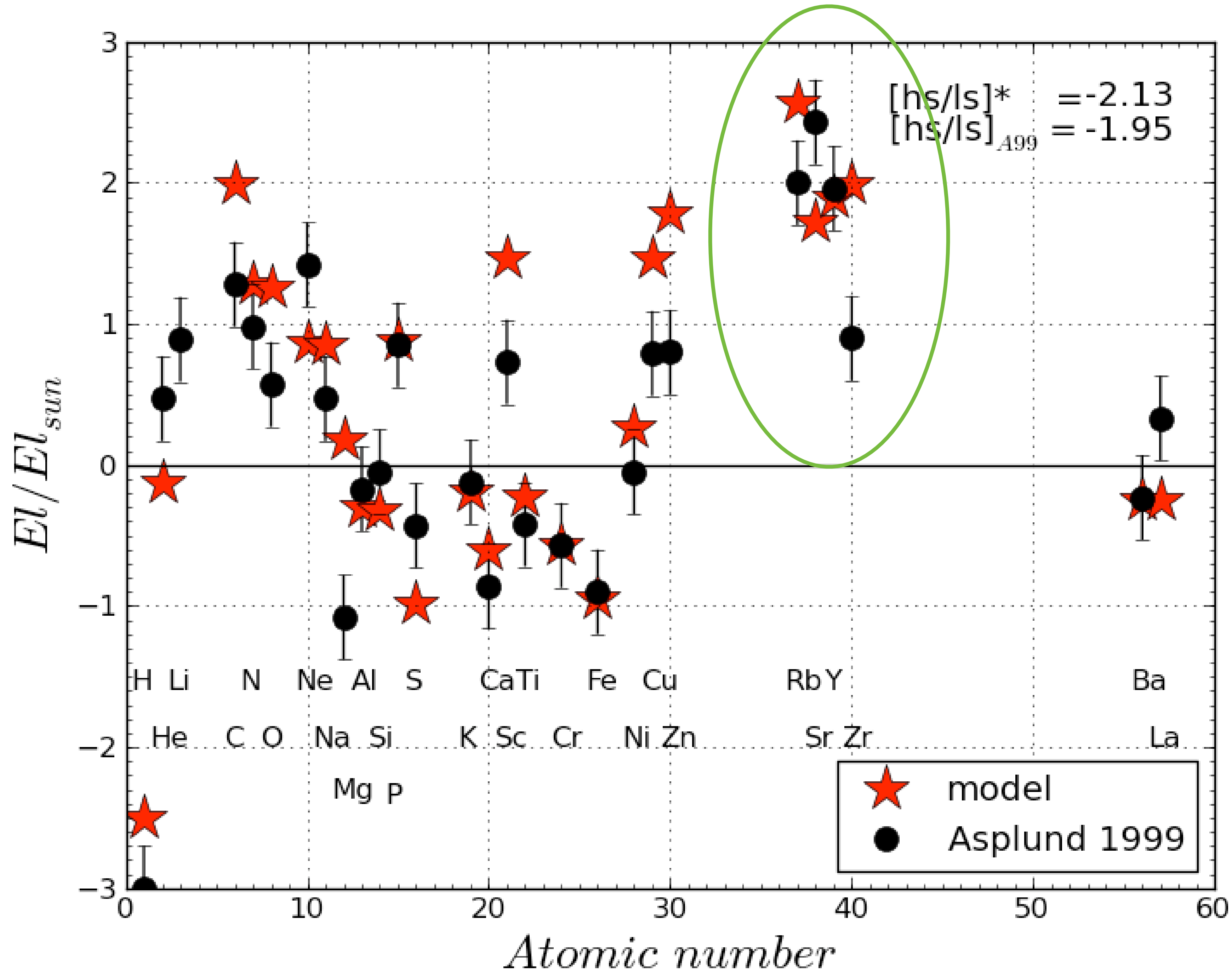
H-combustion in super-AGB stars



Herwig etal 2011, ApJ

Abundance distribution according to delayed split assumption

Most abundance patterns, including low [hs/ls] can be reproduced.



For full details see: Herwig etal 2010, arXiv:1002.2241

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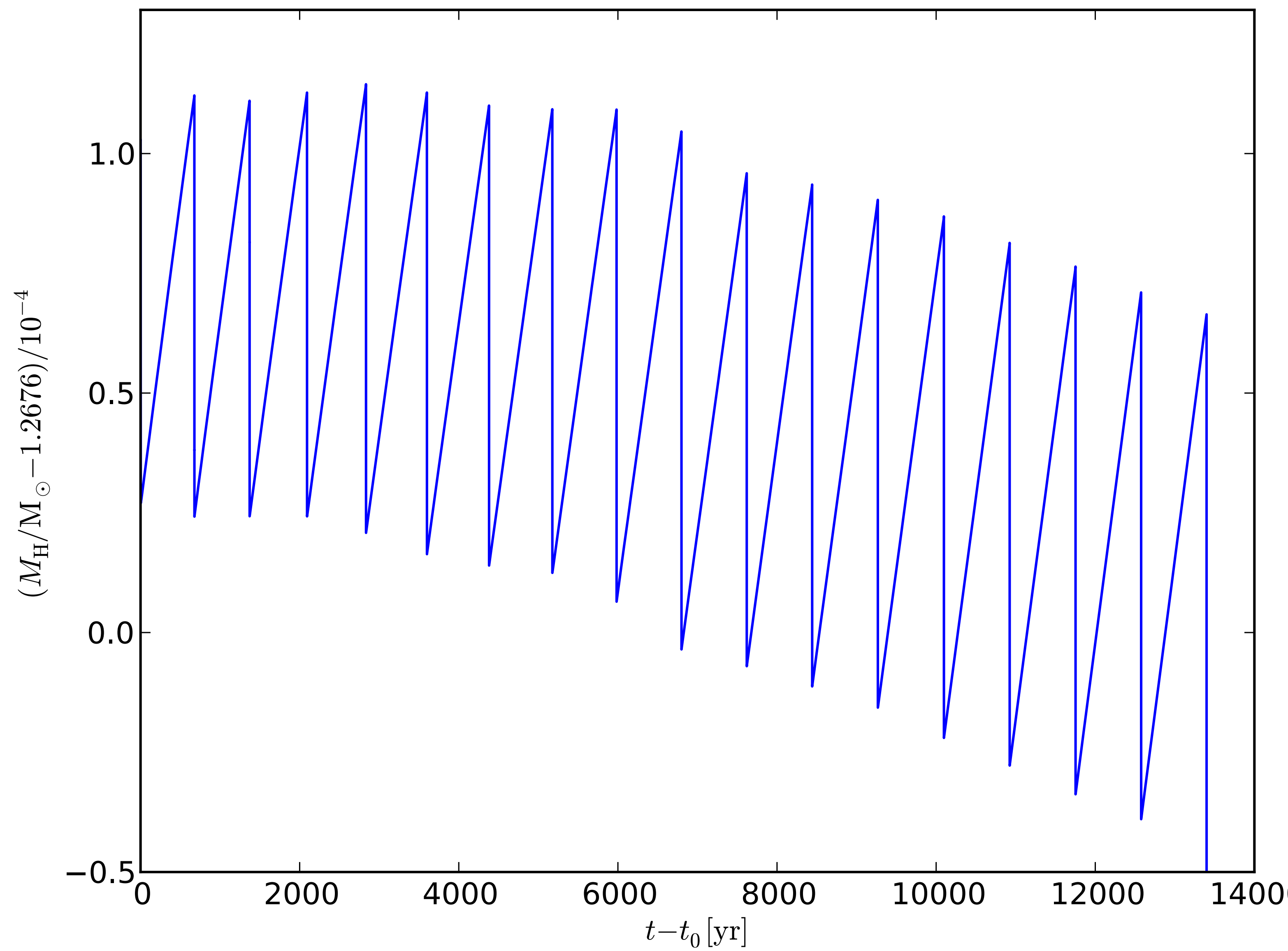
H-combustion in super-AGB stars

Super-AGB star models at low metallicity

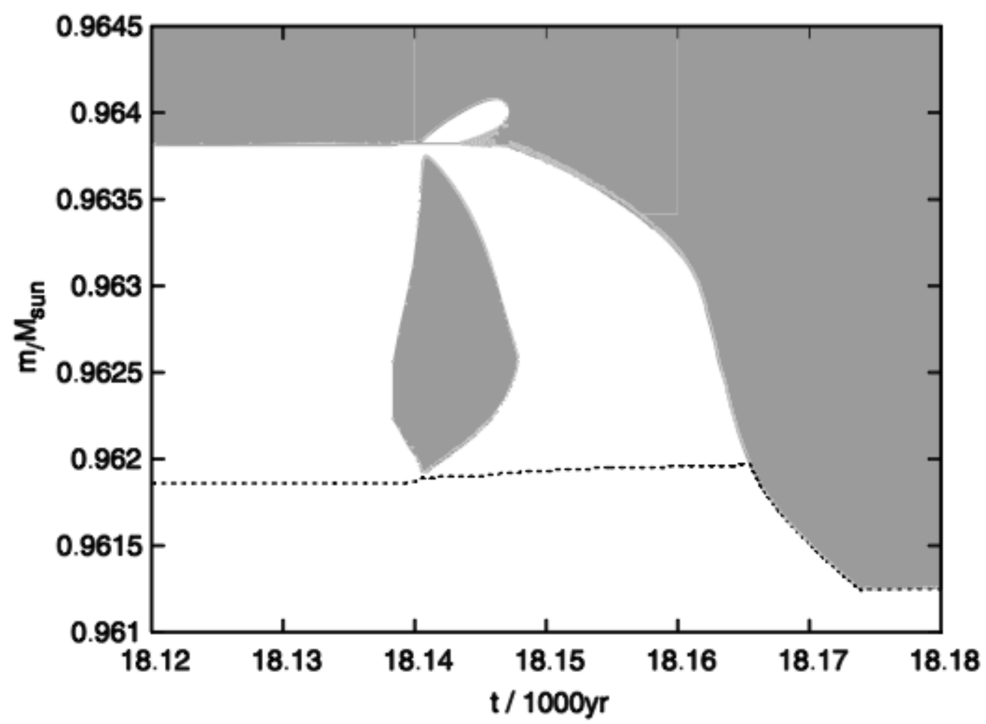
- stellar evolution (with MESA), $M_{ini}=7M_\odot$
- [Fe/H]=-1.7, α-enhanced initial abundance1st, 2nd dredge-ups, 'dredge-out' → CNO abundance env. 1st TP ⊙ - 0.5dex
- convective boundary mixing (tiny: f=0.002/0.004)

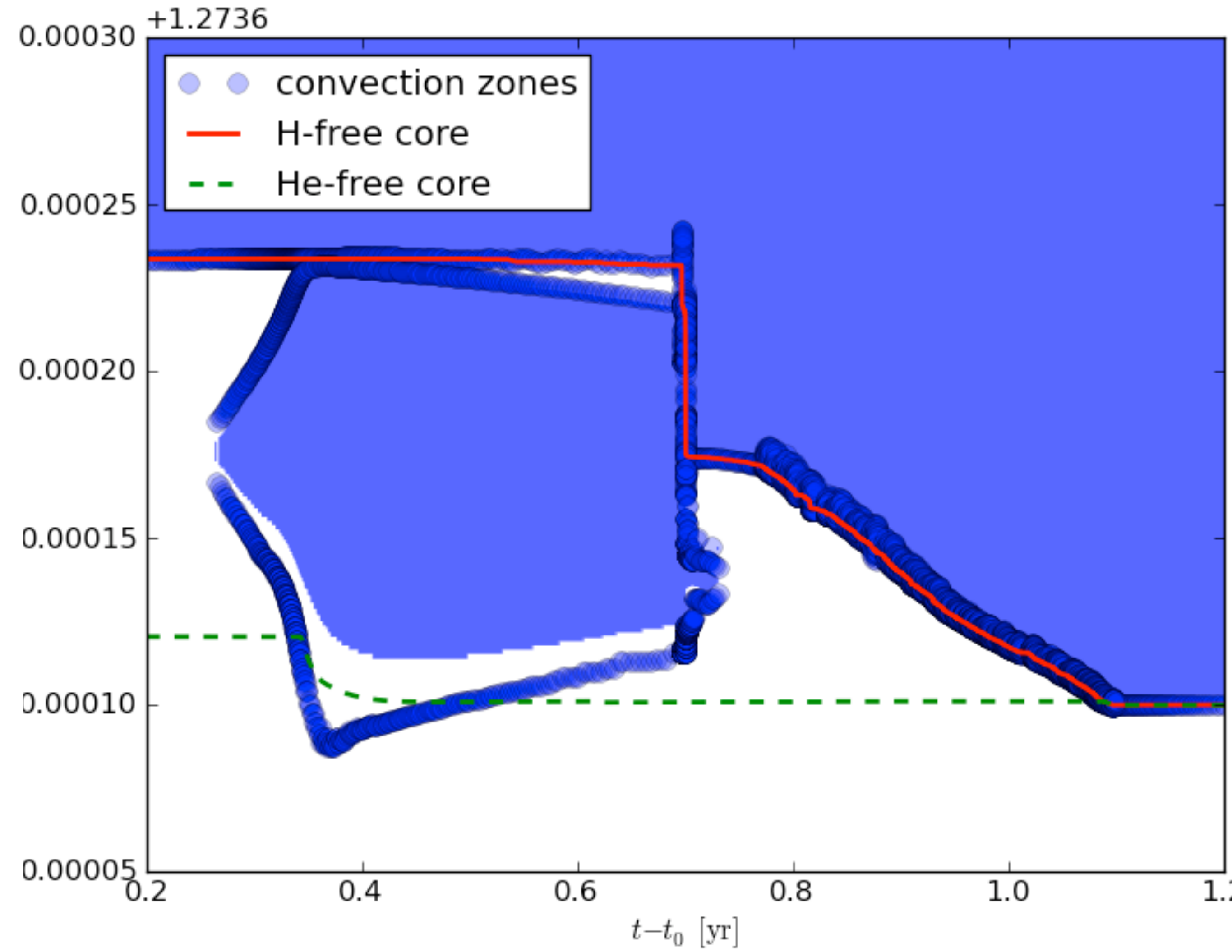
Healthy thermal pulses with 3rd dredge-up



H-combustion in super-AGB star models

- hot dredge-up with H-mixing into still live He-shell flash convection zone
- H-burning $L_{peak} \sim 10^9 L_\odot$
- recurrent! followed after all of the

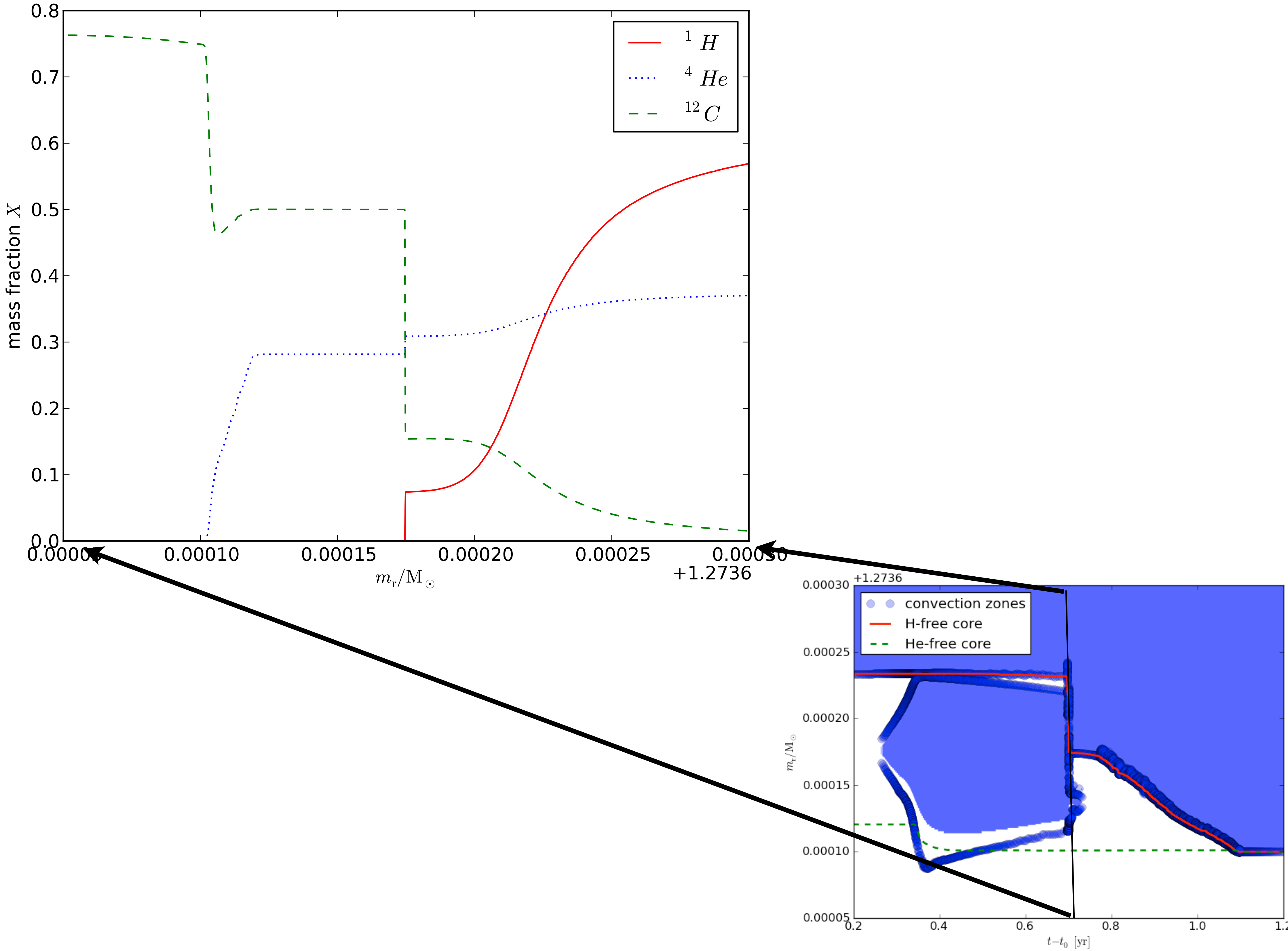




Herwig etal.submitted

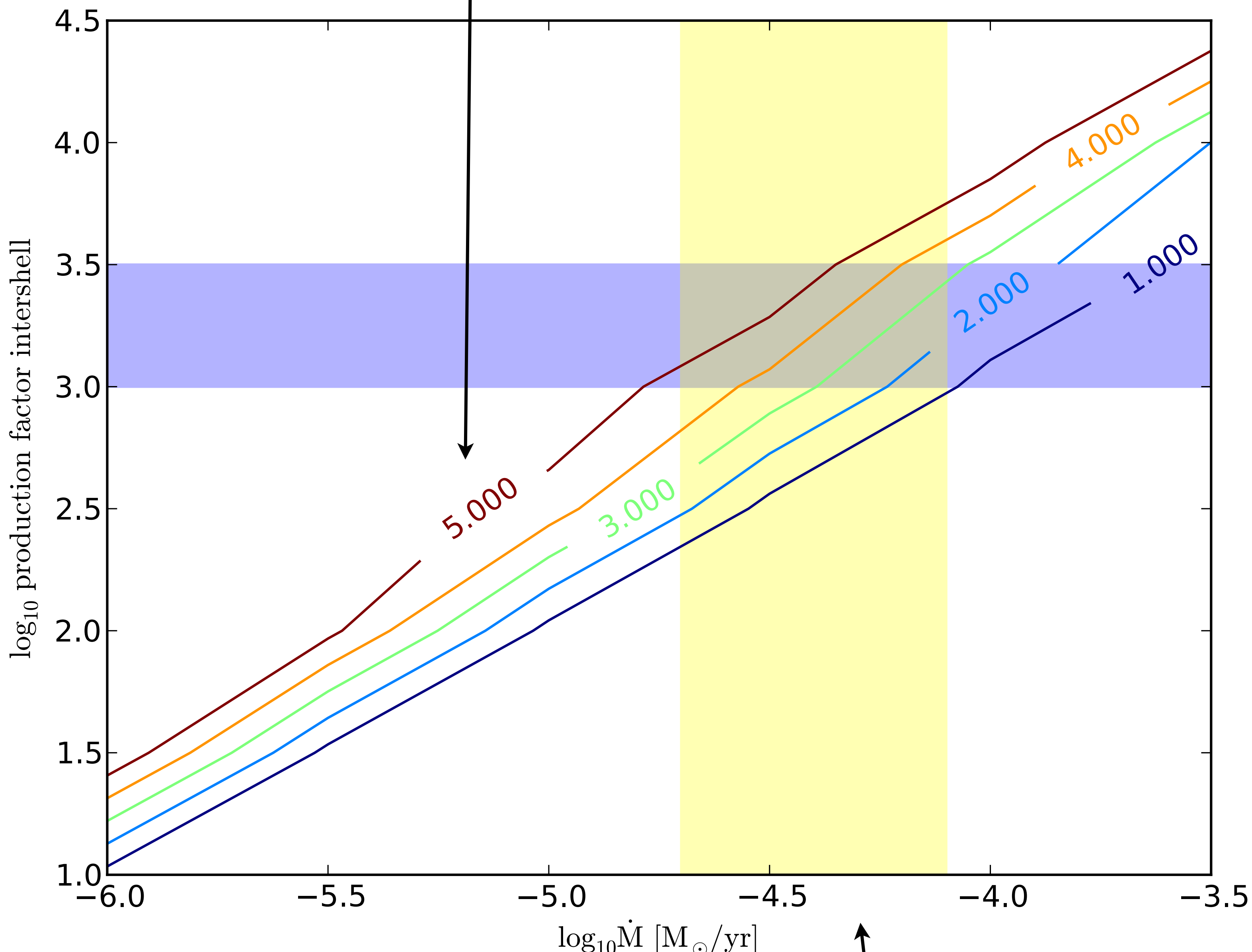
$5 M_\odot$, [Fe/H]=-2/3,
Herwig 2004

Abundance profile in burn/mix H-combustion layer



Mix- and envelope-enrichment model

log(overabundance) in ejecta

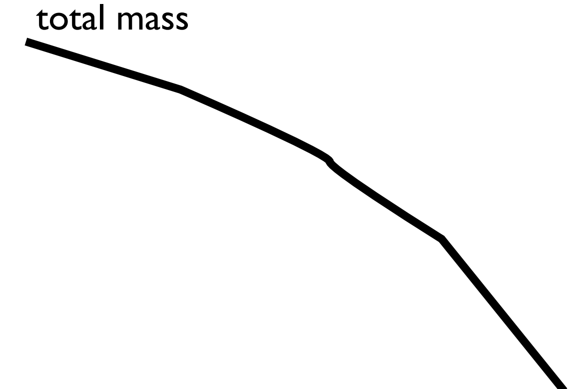


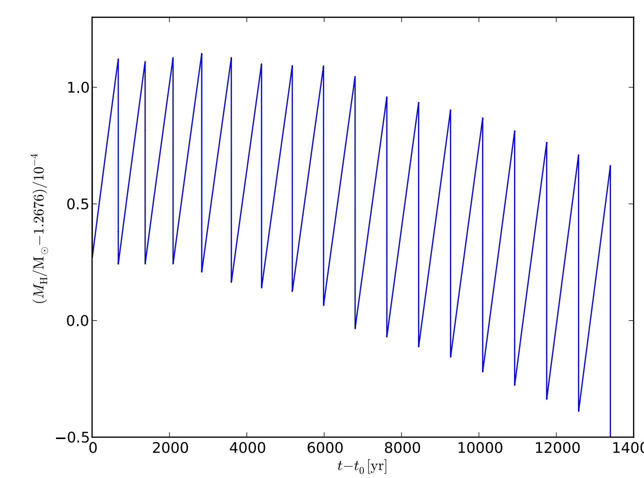
range of mass loss for luminous M-type giants (van Loon etal. 2005)

$\log(\dot{M})$=-5 (-4) ⇒

800 (80) TPs

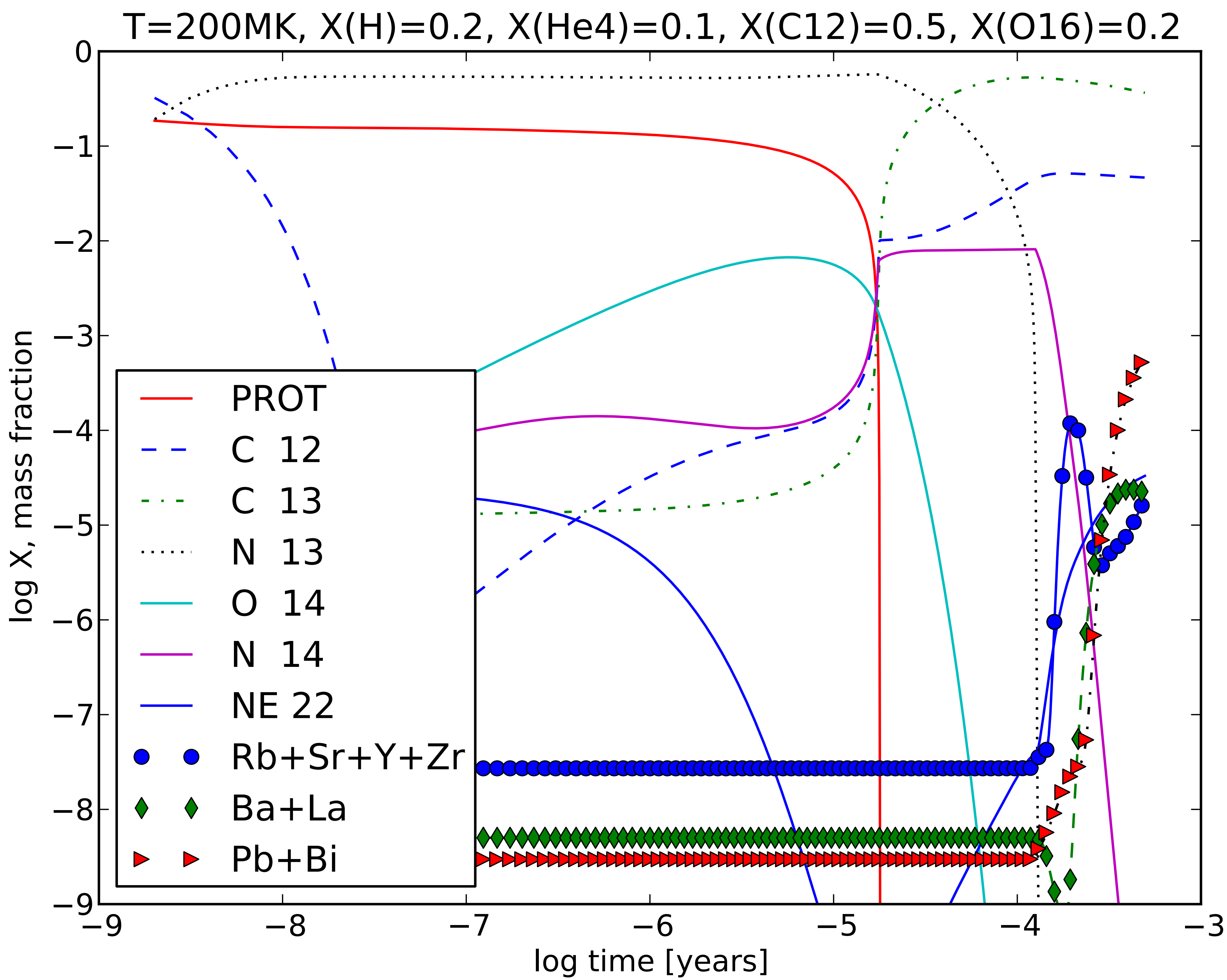
total mass



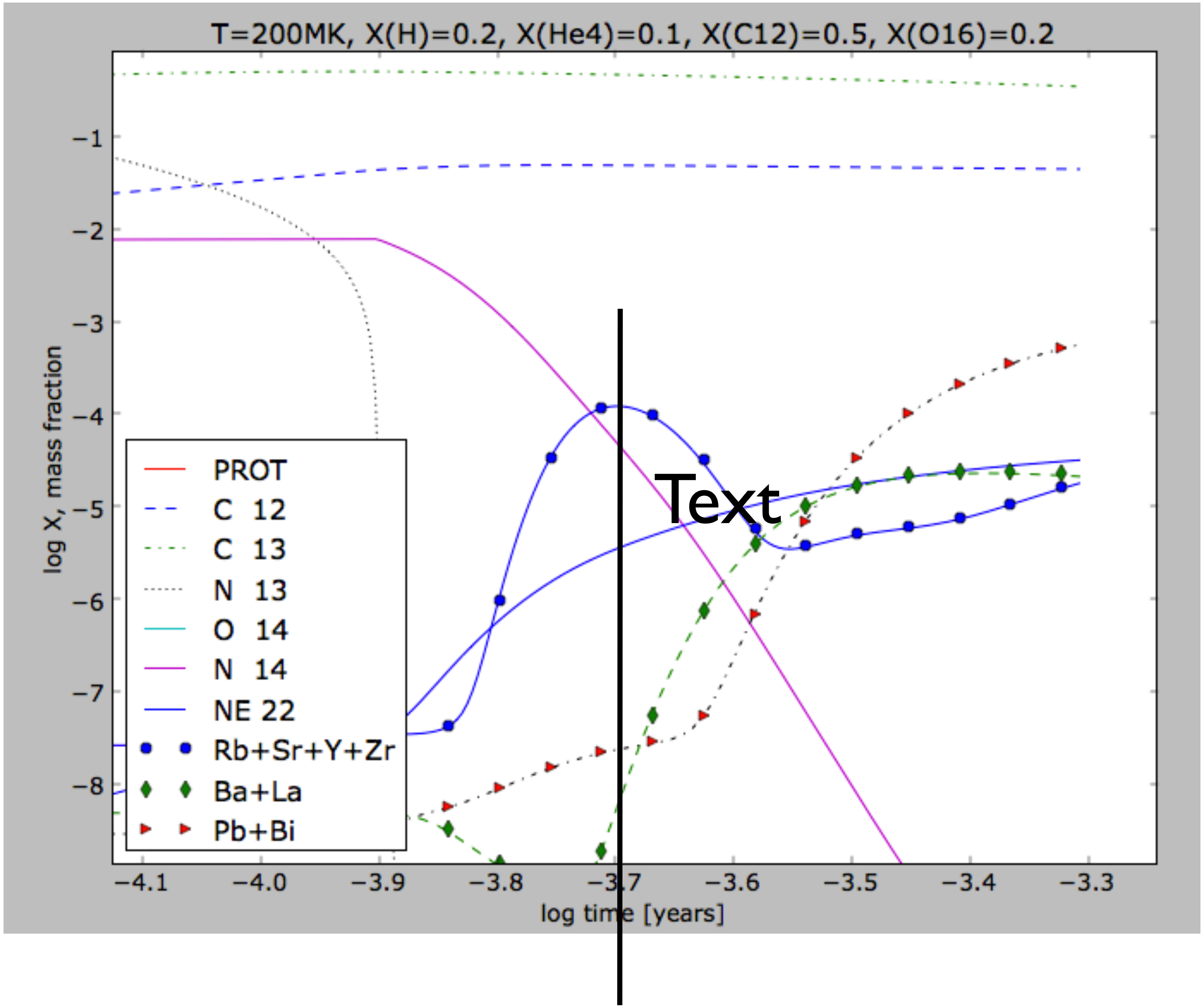


Herwig etal.submitted

One-zone nucleosynthesis of H-combustion



One-zone nucleosynthesis of H-combustion



$N_n \sim 10^{15} cm^{-3}$

6200s

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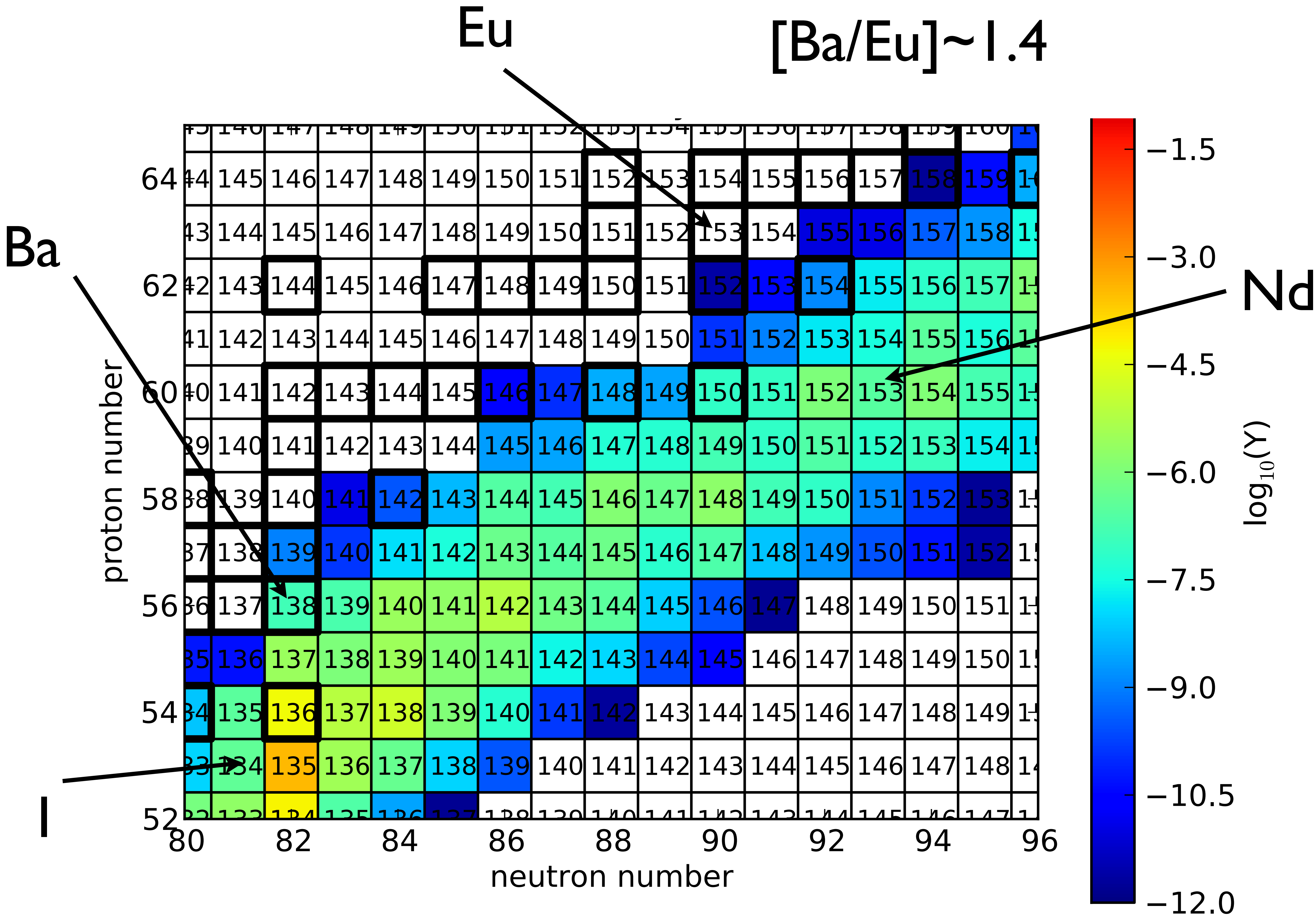
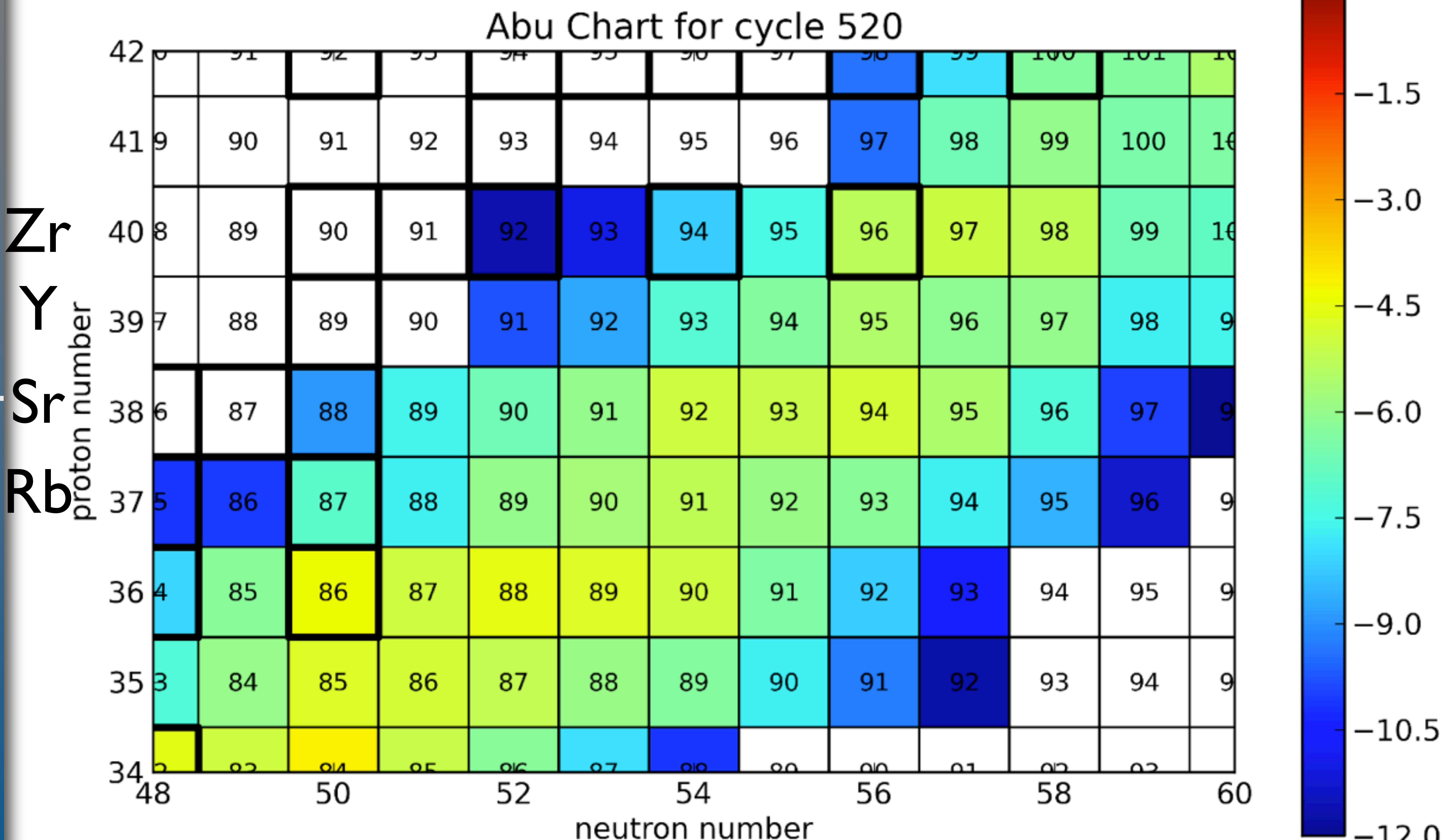
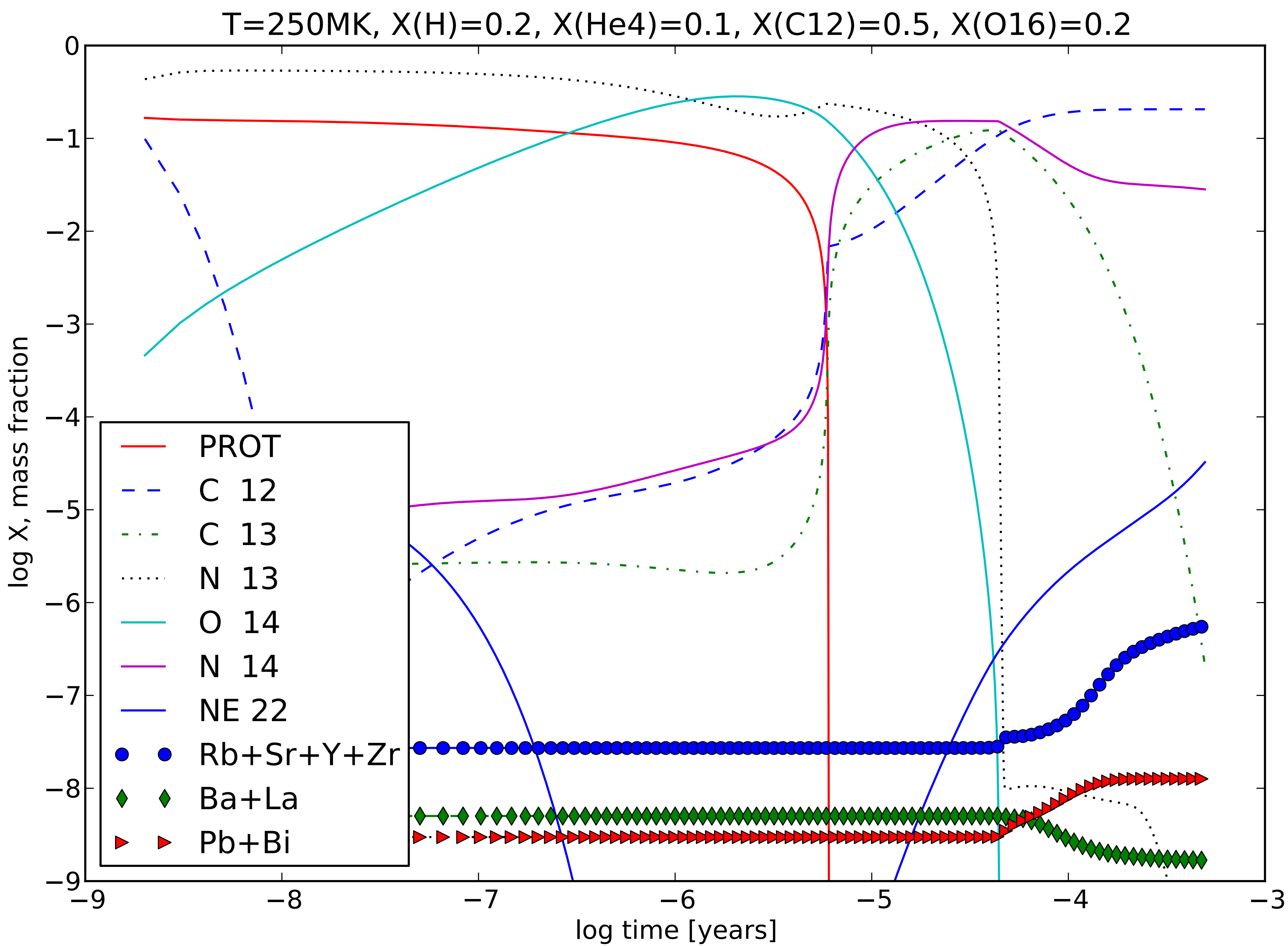
H-combustion in super-AGB stars



H-combustion in super-AGB stars



One-zone nucleosynthesis of H-combustion



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Conclusions

H-combustion is

- n-capture conditions between s and r
- non-standard
- has been shown to result in excess first peak production in Sakurai's object
- shows in a wide range of low-metallicity environments, including possibly the super-AGB stars
- combustion events may very well show a spread, including leaking into second or third peak in some cases

☞ possible contribution to (low-Z) LEPP