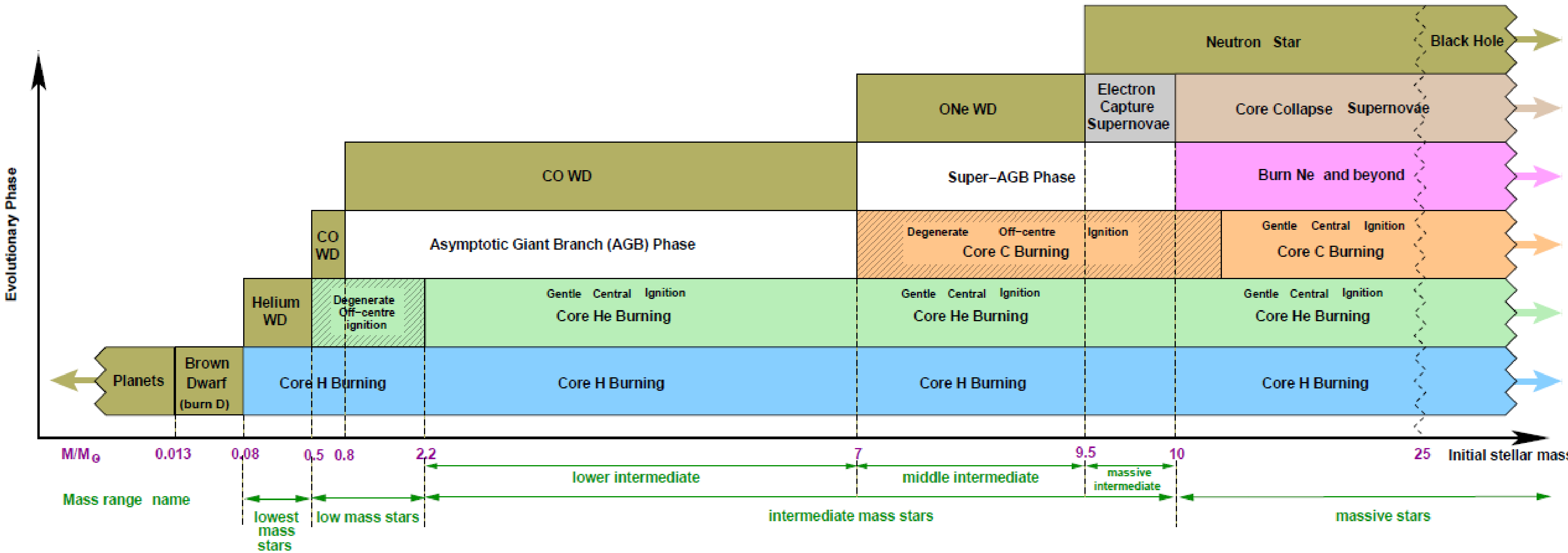
Stars becoming White Dwarfs and neutron capture processes

Marco Pignatari & NuGrid

E.A. Milne Center for Astrophysics
University of Hull

Brainstorming on Compact objects, their equation of state, related explosive events, and their nucleosynthesis – Basel 2016

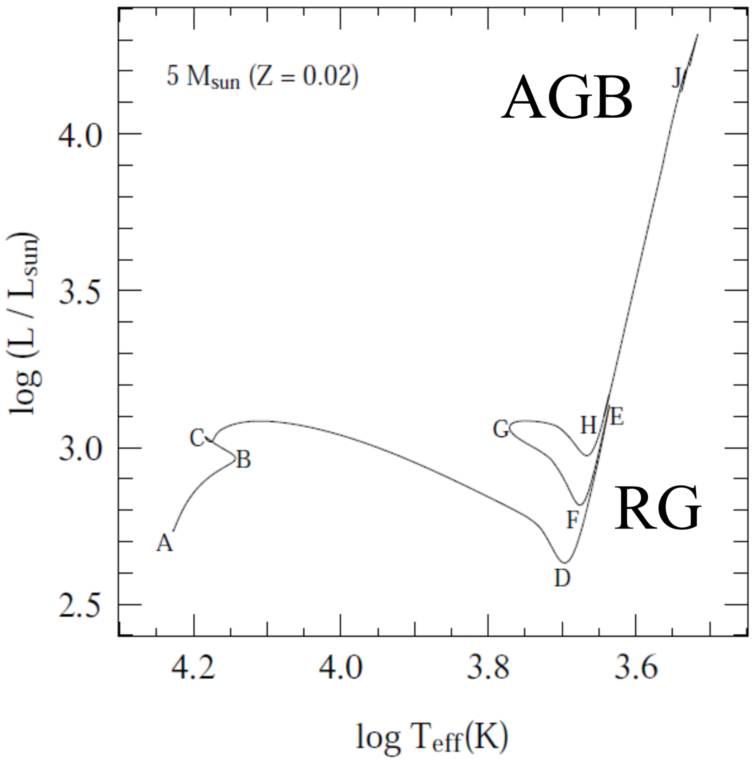
Stars forming WDs

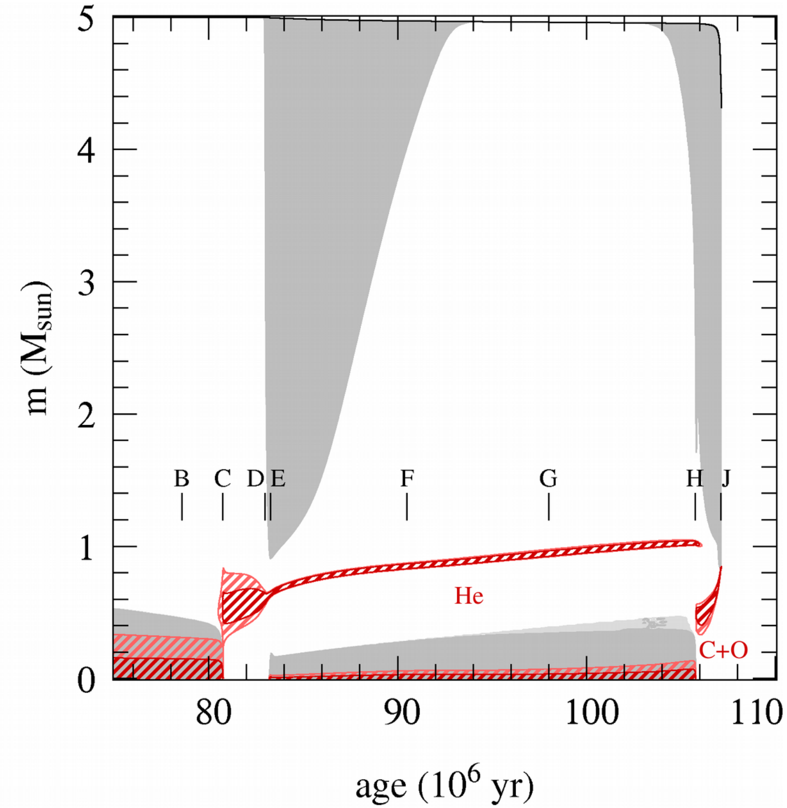


Karakas & Lattanzio 2014, PASA

Intermediate & Low-Mass Stars

5 M_o star: Evolution through H- and He-burning

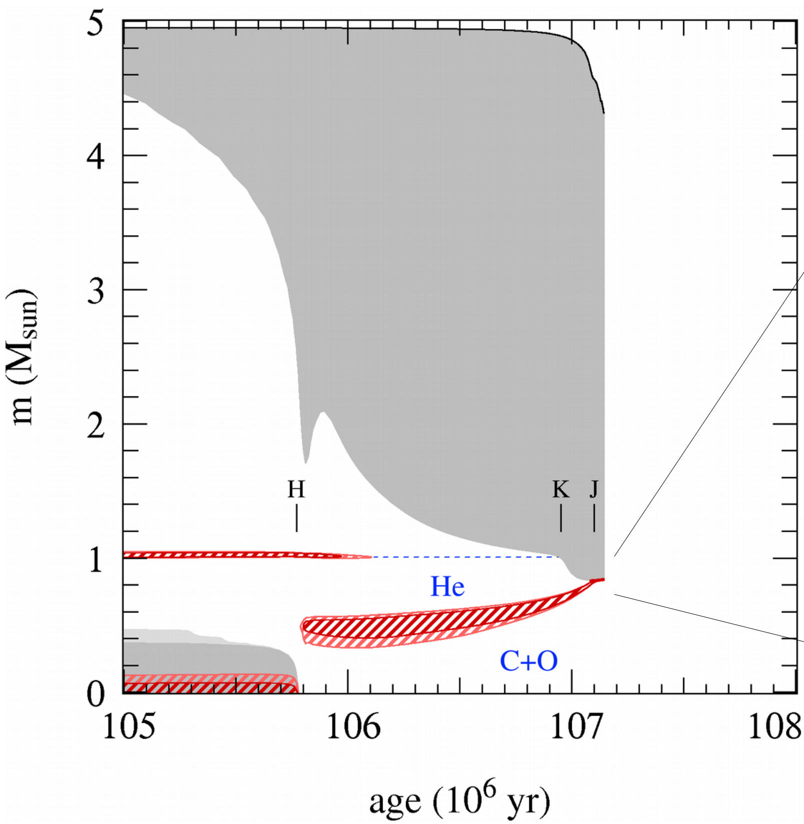




From SE notes, O. Pols (2009)

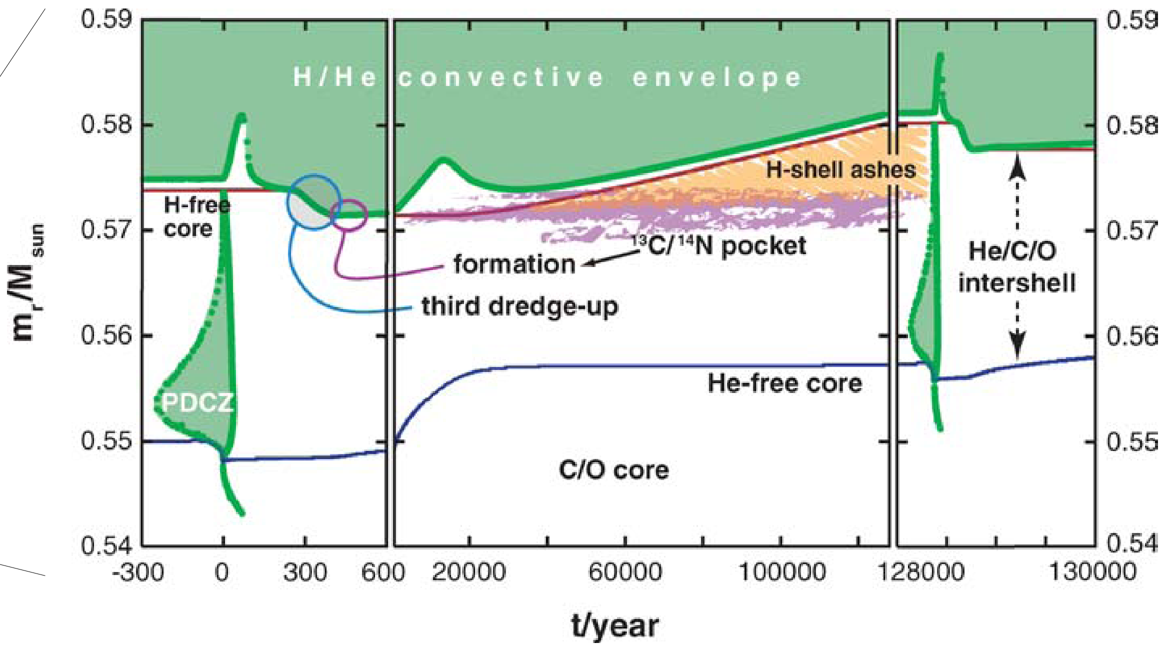
Intermediate & Low-Mass Stars

5 M_o star: AGB phase



From SE notes, O. Pols (2009)

Structure in AGB phase



Herwig, ARAA, 2005

Herwig ARAA 2005

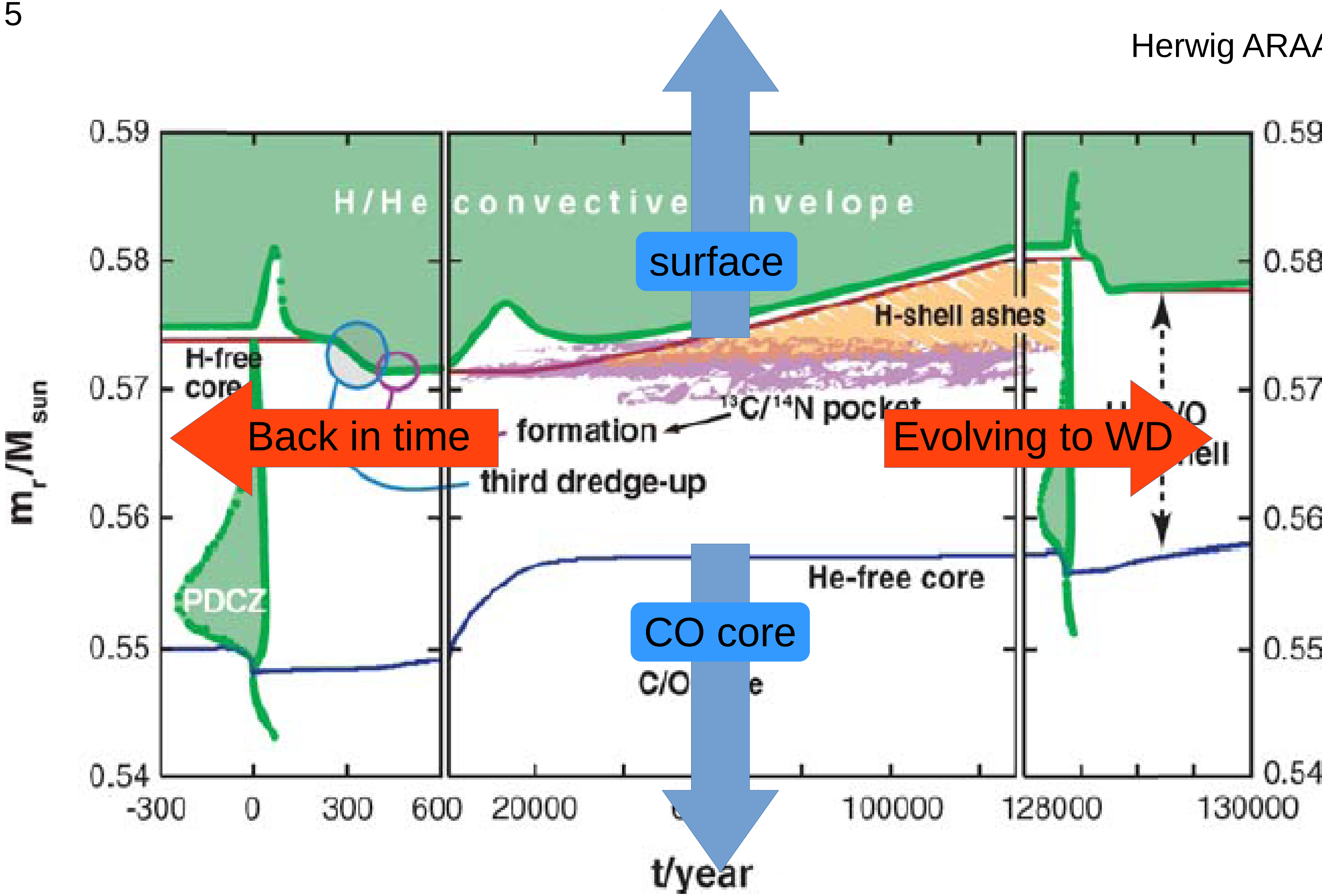
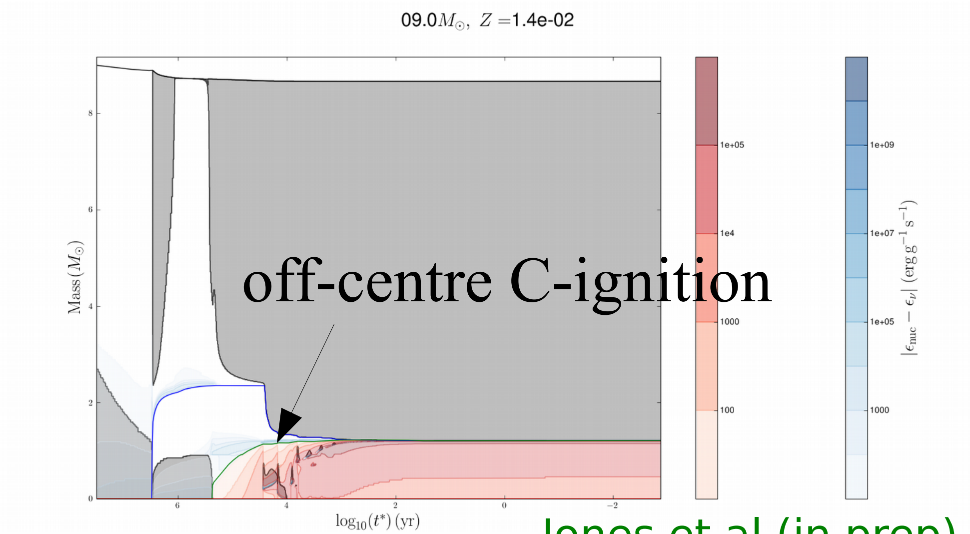


Figure 3 Thermal pulse 14, the subsequent interpulse phase and thermal pulse 15 of 2 $M_\odot$, $Z = 0.01$ sequence ET2 of Herwig & Austin (2004). The timescale is different in each panel.

SAGB & ECSN progenitors

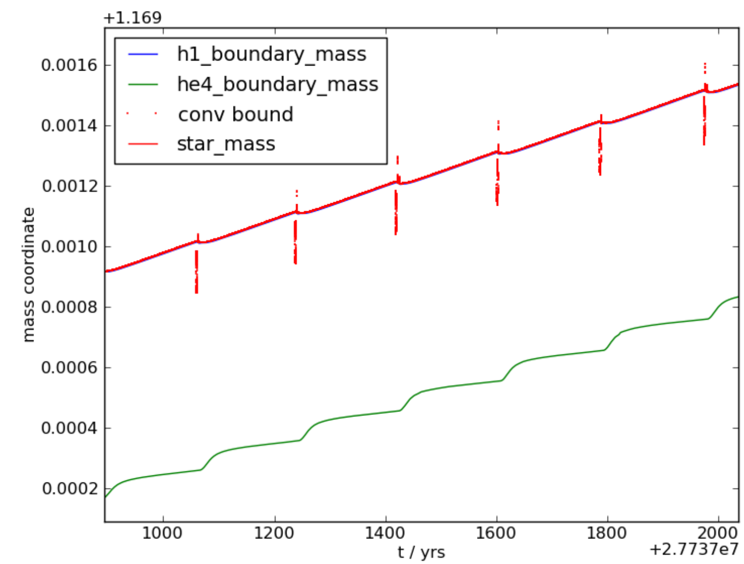
$M_{up} \leq M \leq M_{mas}$; $M_{up} \approx 8M_{sun}$, $M_{mas} \approx 10M_{sun}$ (TRANSITION MASSES)

Early evolution like AGBs;



Jones et al (in prep)

TP-phase → core growth
Dep. on Mdot ↔mixing



Jones et al (subm.)

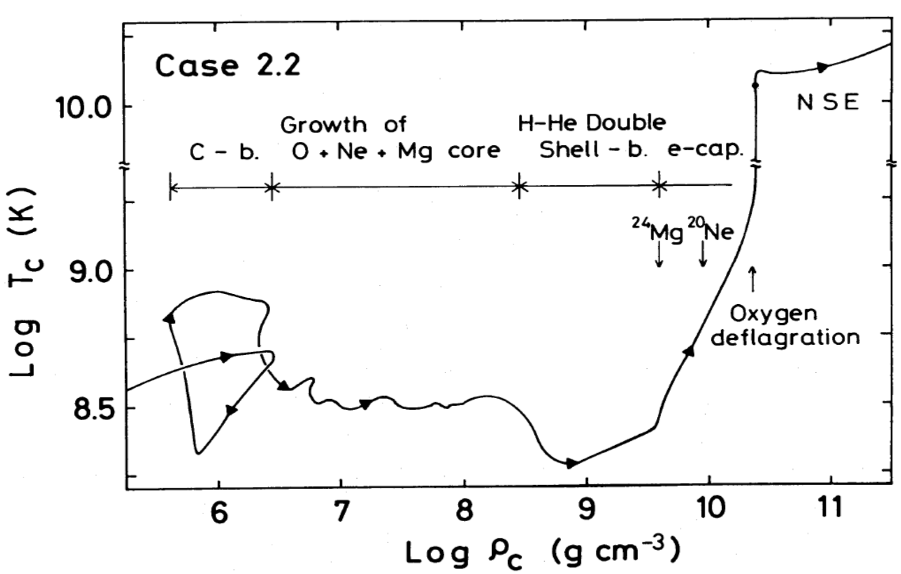
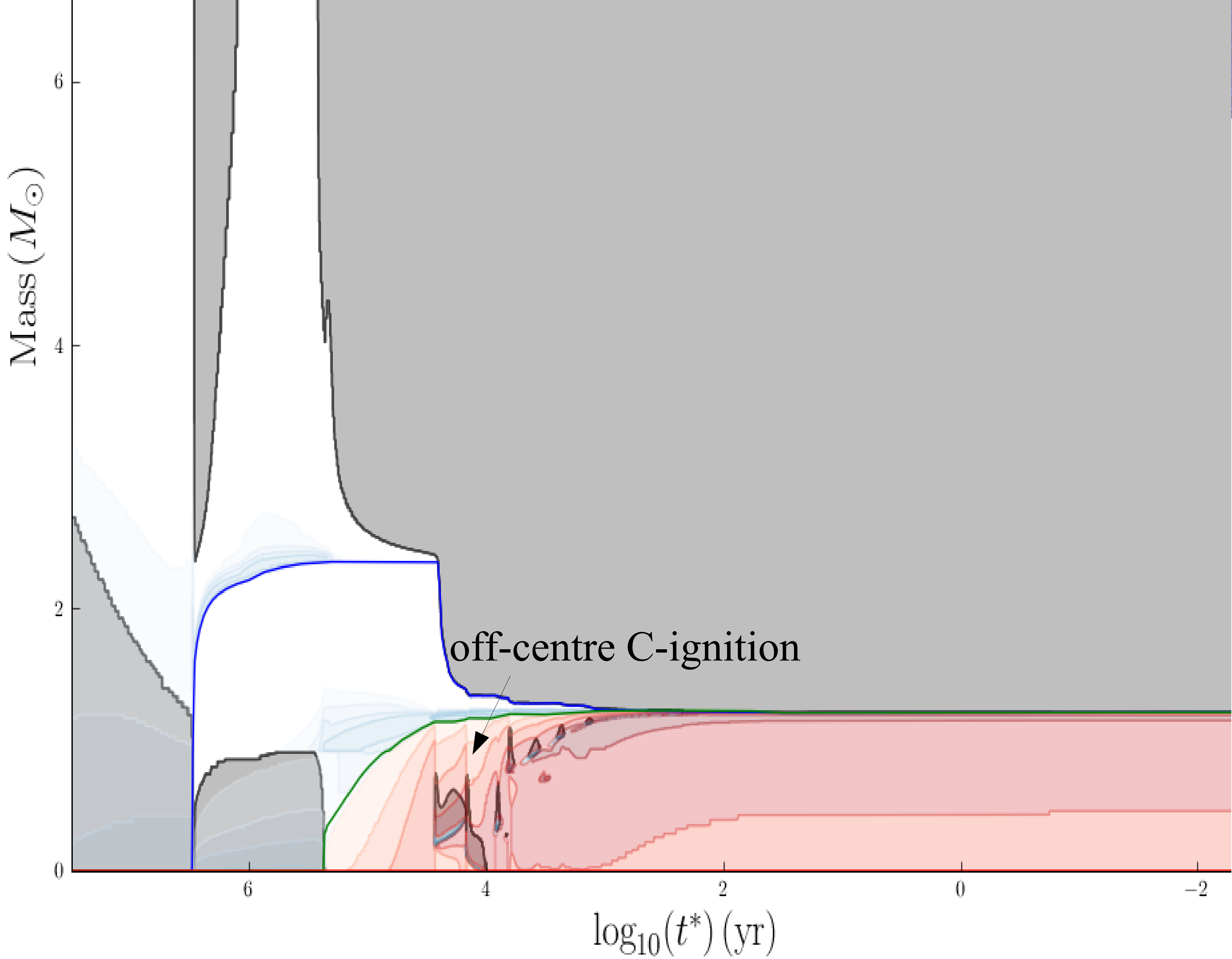


FIG. 4.—Evolutionary track in the central density and temperature diagram

Critical ONeMg core mass = M_{crit} = 1.375

(Miyaji et al. 1980; Nomoto 1984)

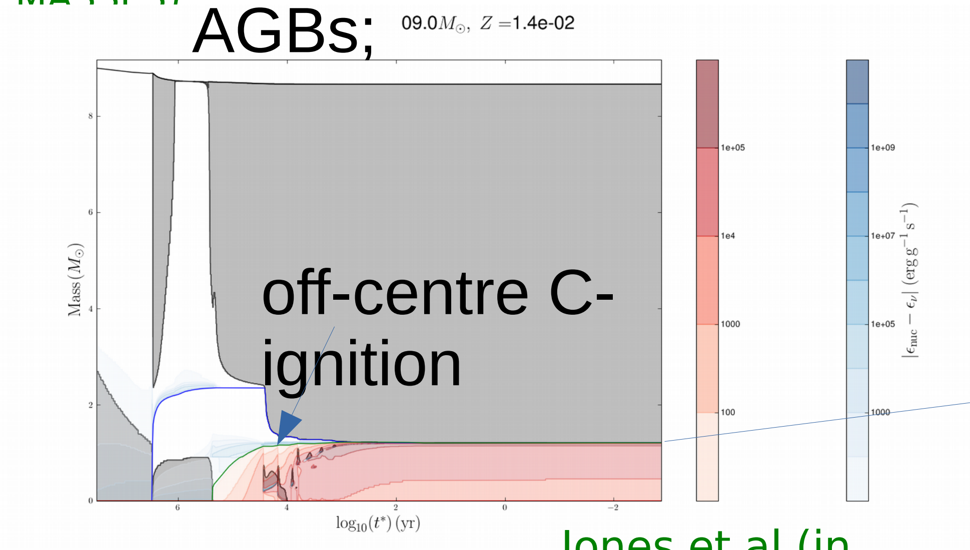
See also: Miyaji (1980); Nomoto(1984, 1987); Miyaji & Nomoto (1987); Garcia-Berro, Ritossa and Iben (1990s); Eldridge & Tout (2004); L. Siess (2006, 2007, 2009, 2010), Poelarends (2008); Doherty et al. (2010) ...



Mass $(M_\odot)$
6
4
2
0
off-centre C-ignition
6
4
2
0
−2
$\log_{10}(t^*)$ (yr)

$M_{up} \leq M \leq M_{mas}$; $M_{up} \approx 8M_{sun}$, $M_{mas} \approx 10M_{sun}$ (TRANSITION MASSES)

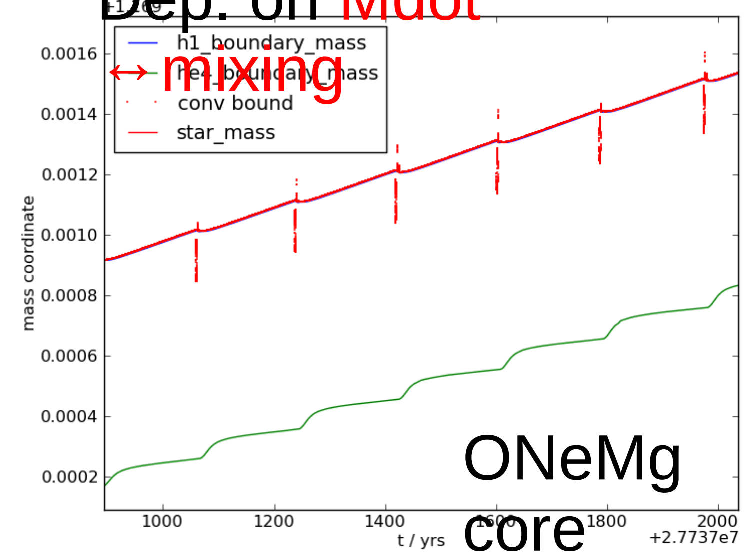
Early evolution like AGBs;



off-centre C-ignition

Jones et al (in prep)

TP-phase → core growth
Dep. on Mdot
↔ mixing



ONeMg core

Jones et al (in prep)

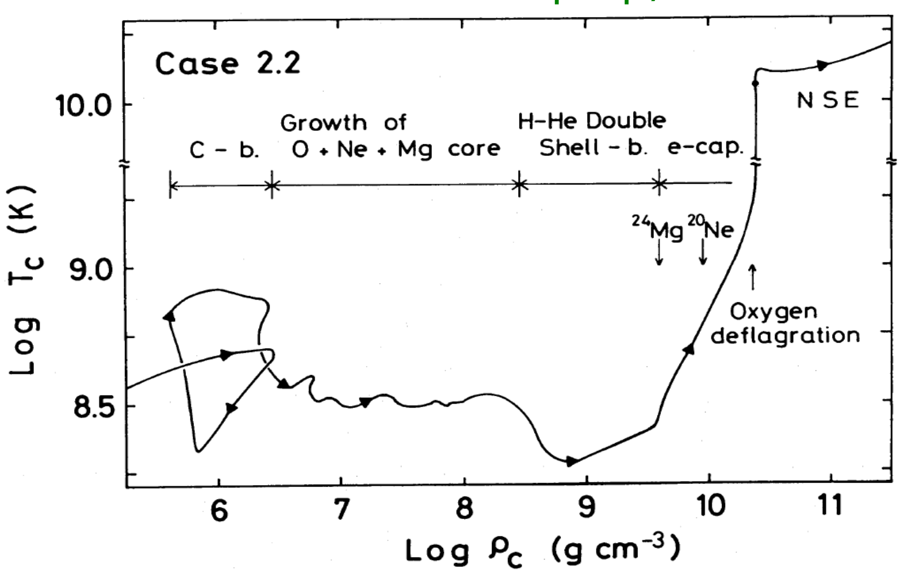


FIG. 4.—Evolutionary track in the central density and temperature diagram

Critical ONeMg core mass = M_{crit} = ~1.375
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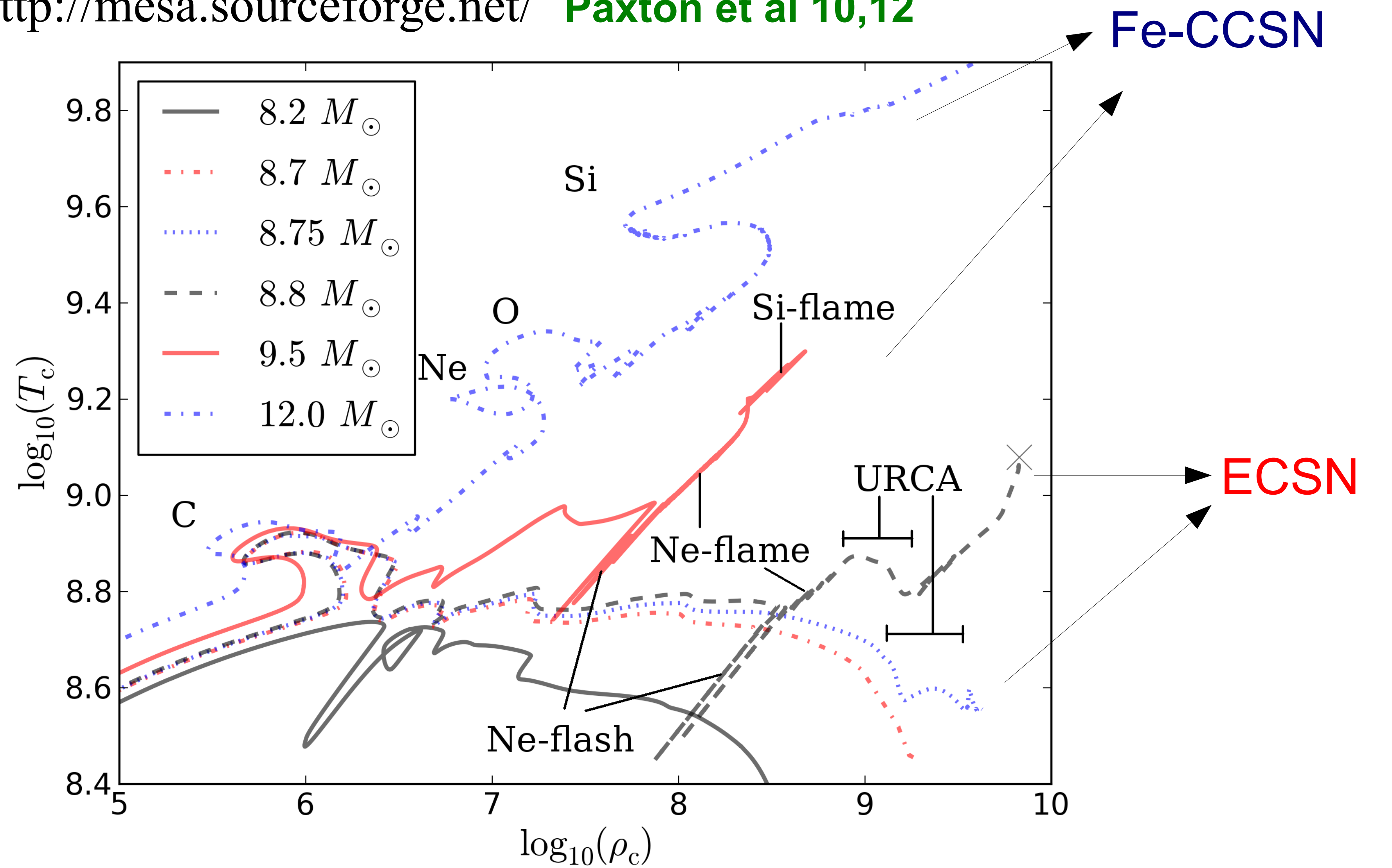
Fate of Least-Massive MS: ECSN/Fe-CCSN?

7-15 M_o models ← MESA stellar evolution code:

http://mesa.sourceforge.net/ **Paxton et al 10,12**



Both SAGB and failed massive stars may produce ECSN

Jones et al. (2013), ApJ 772, 150

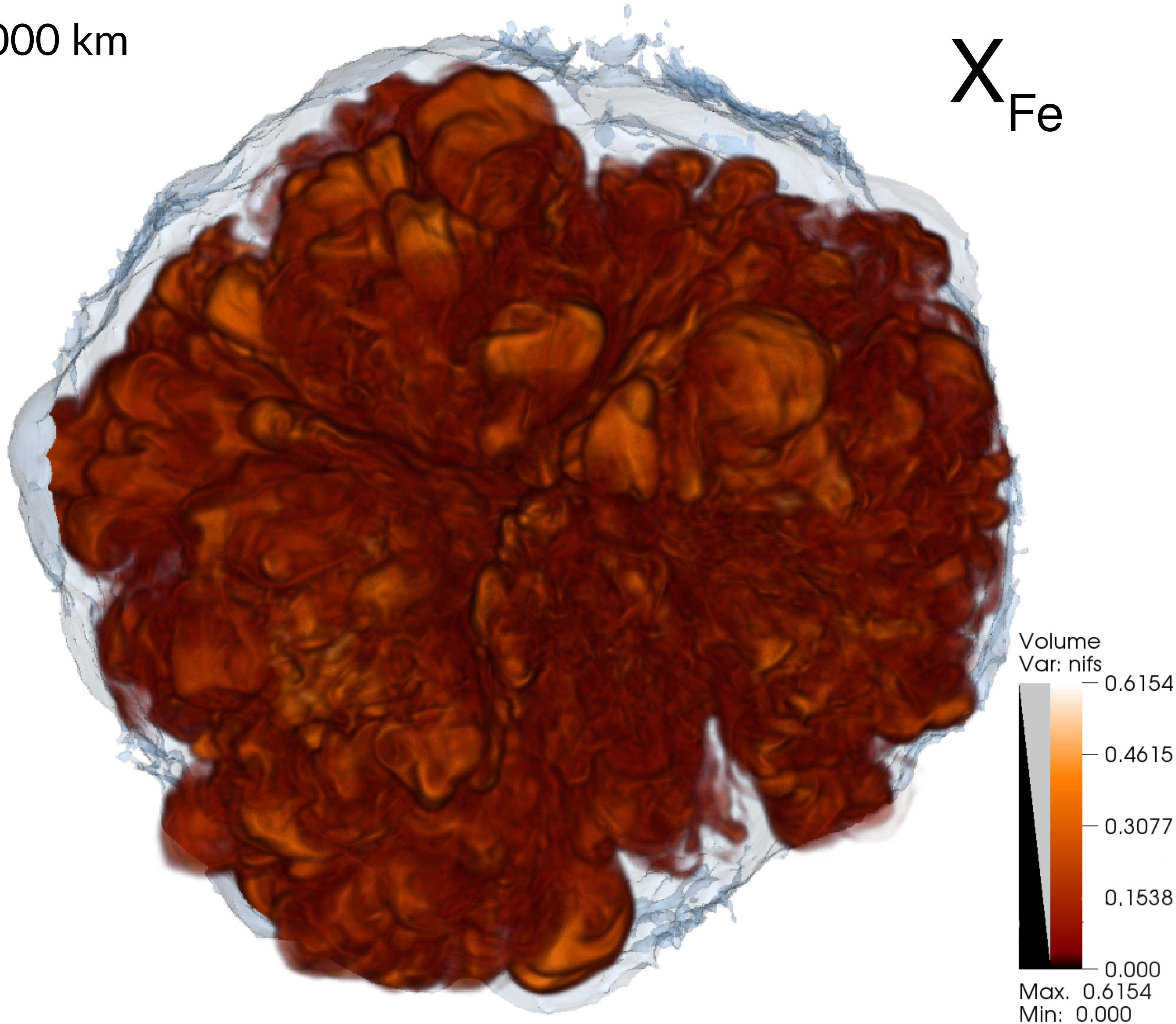
Scale: 400,000 km
Time: 60 s

O DEFLAGRATION

3D 4π: 512^3

THERMONUCLEAR EXPLOSION?

X_{Fe}



DIAGNOSTICS

S. Jones, FKR, RP, IRS, STO, PVFE
arXiv:1602.05771

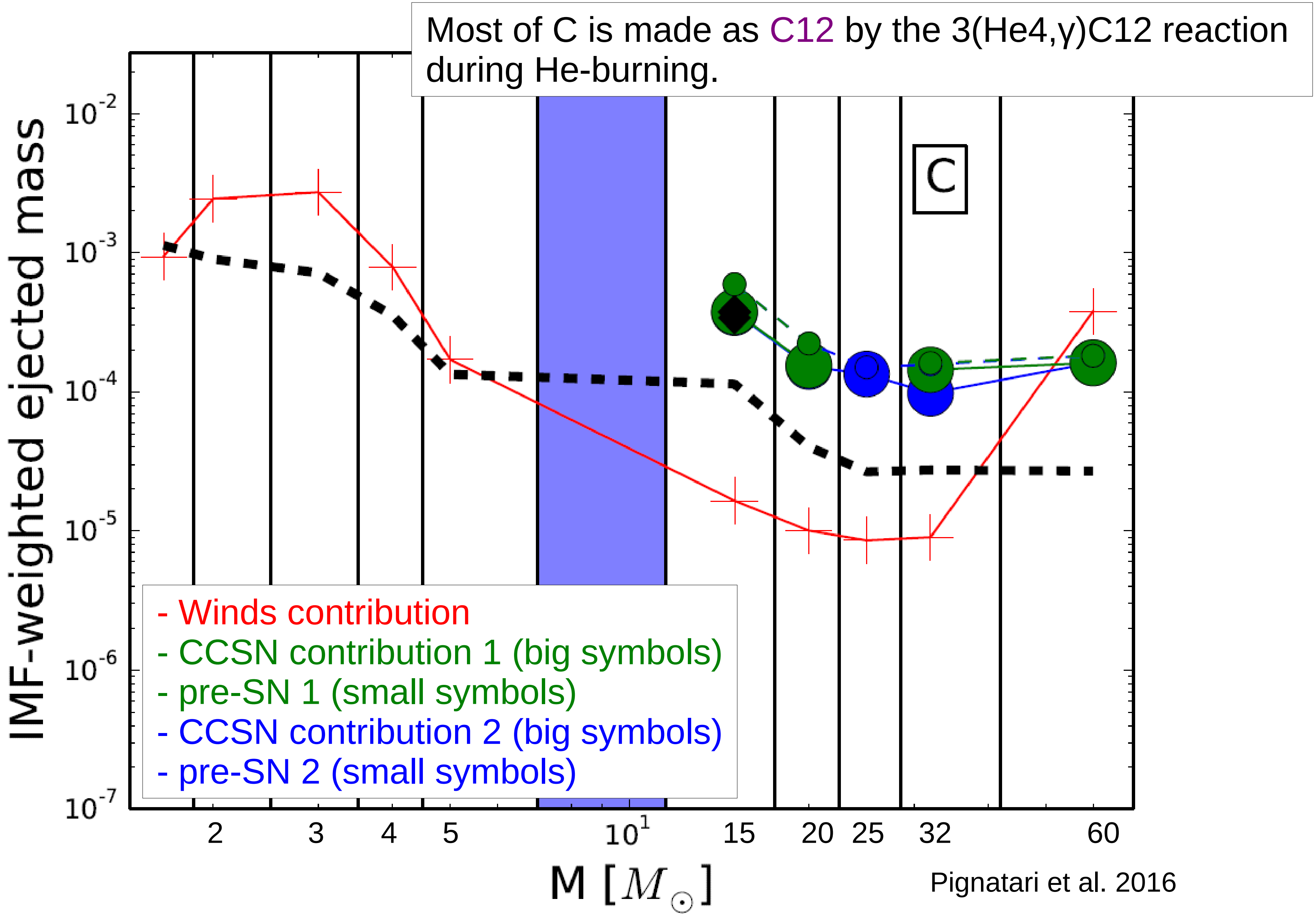
Bound ONeFe remnants

id.	res.	$\log_{10} \rho_c^{\rm ini}$ (g cm^{-3})	CC (Y/N)	$M_{\rm rem}$	$M_{\rm rem}^{\rm Ni}$ ($M_\odot$)	$M_{\rm ej}$	$M_{\rm ej}^{\rm Ni}$	$\langle Y_{\rm e,re}$
G13	256^3	9.90	N	0.653	0.168	0.735	0.236	0.49
G14	512^3	9.90	N	0.462	0.137	0.929	0.349	0.49
G15	256^3	9.90	Y	1.231	0.217	0.158	0.044	0.49
J01	256^3	9.95	N	0.606	0.157	0.798	0.254	0.49
J02	256^3	9.95	Y	1.297	0.227	0.100	0.021	0.49
H01*	256^3	10.3	N	1.401	0.032	0.000	0.000	0.47

Core collapse

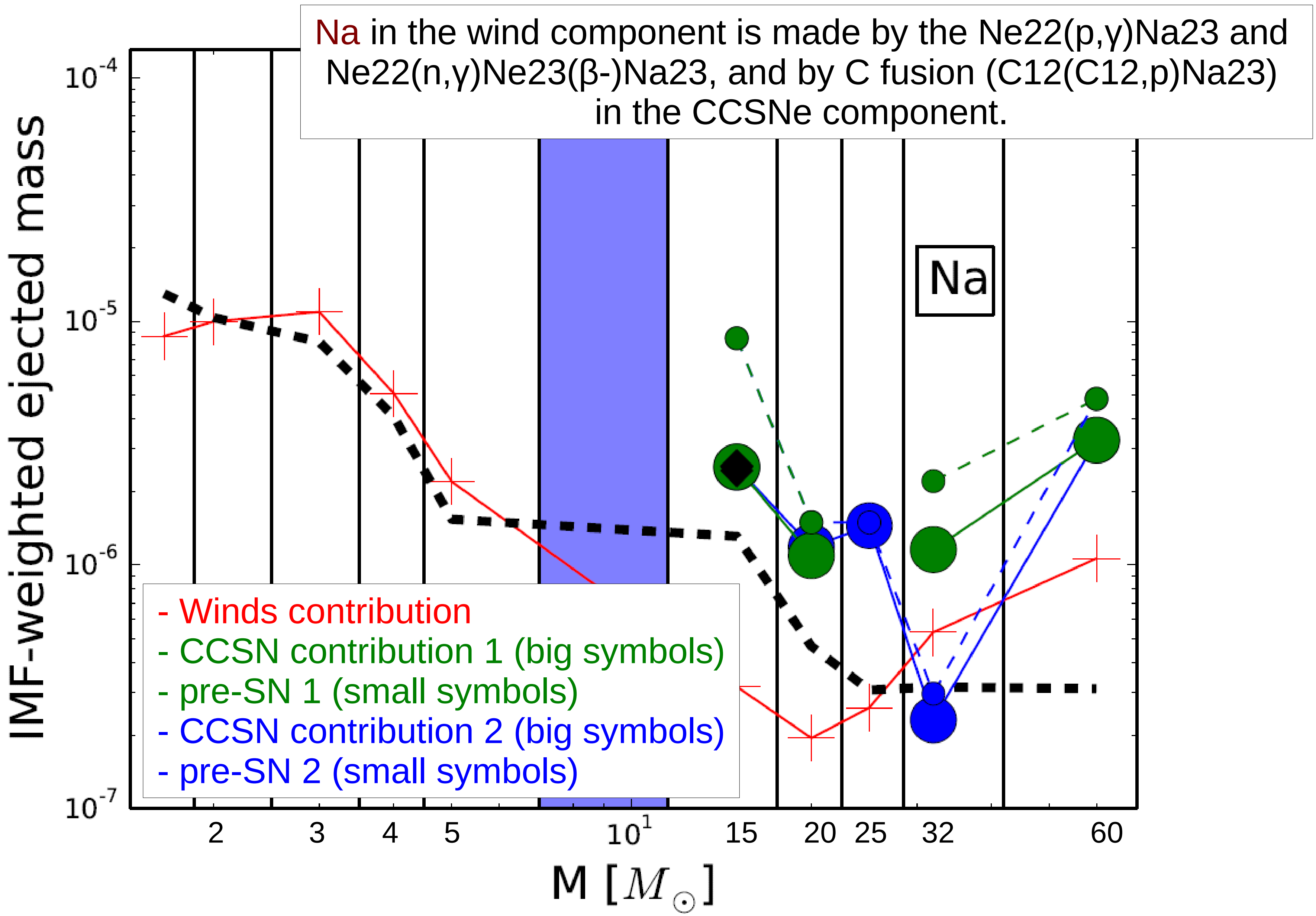
What would these things actually **look like**? Faint SN1a? Have we seen them? → **Radiative transfer calculations required**

What do AGB stars make?

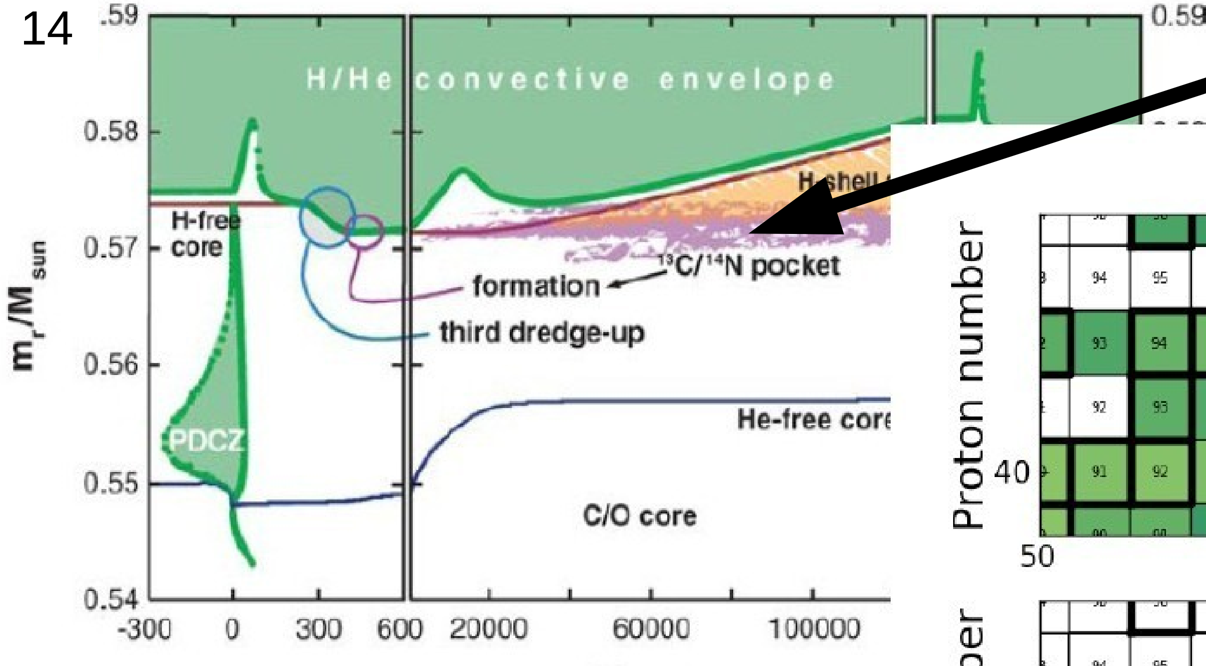


Pignatari et al. 2016

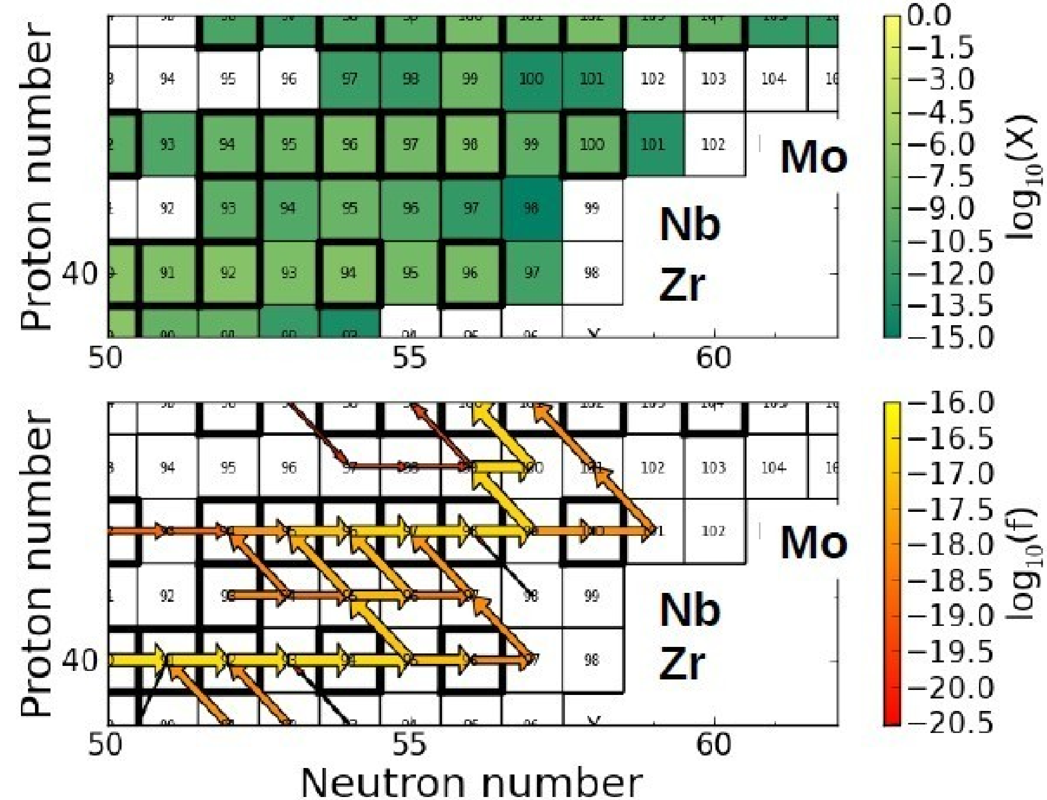
No GCE here, but it is already possible to get some general indications.

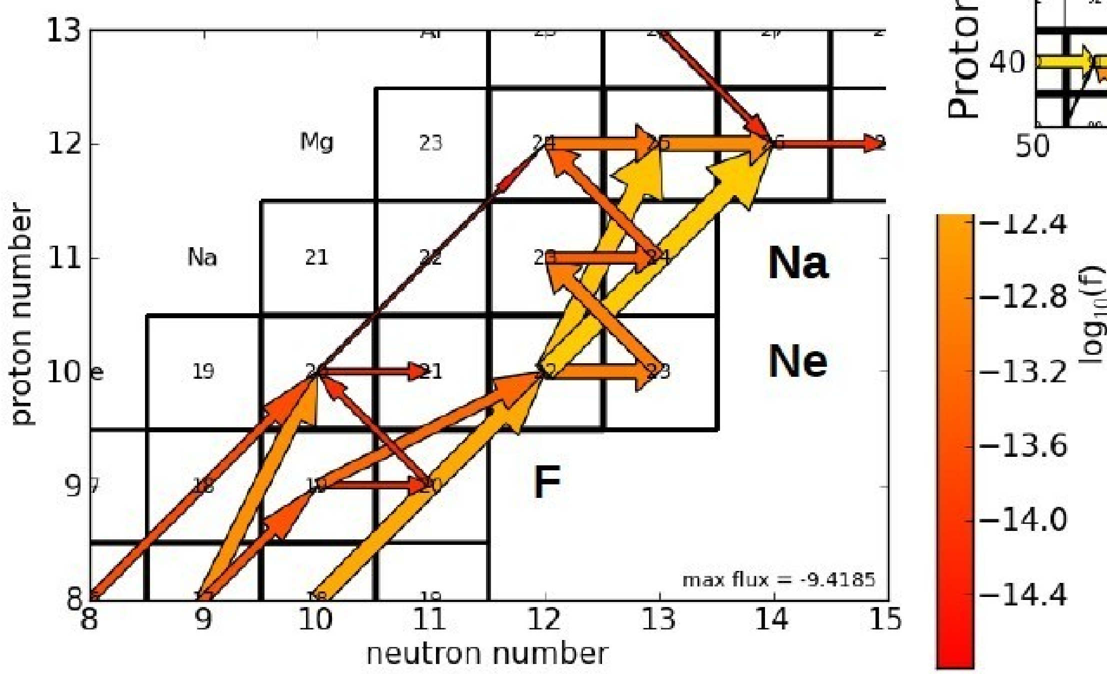


and then N, F, ^{22}Ne …. and the main s process.



C13(a,n) main neutron source in C13-pocket

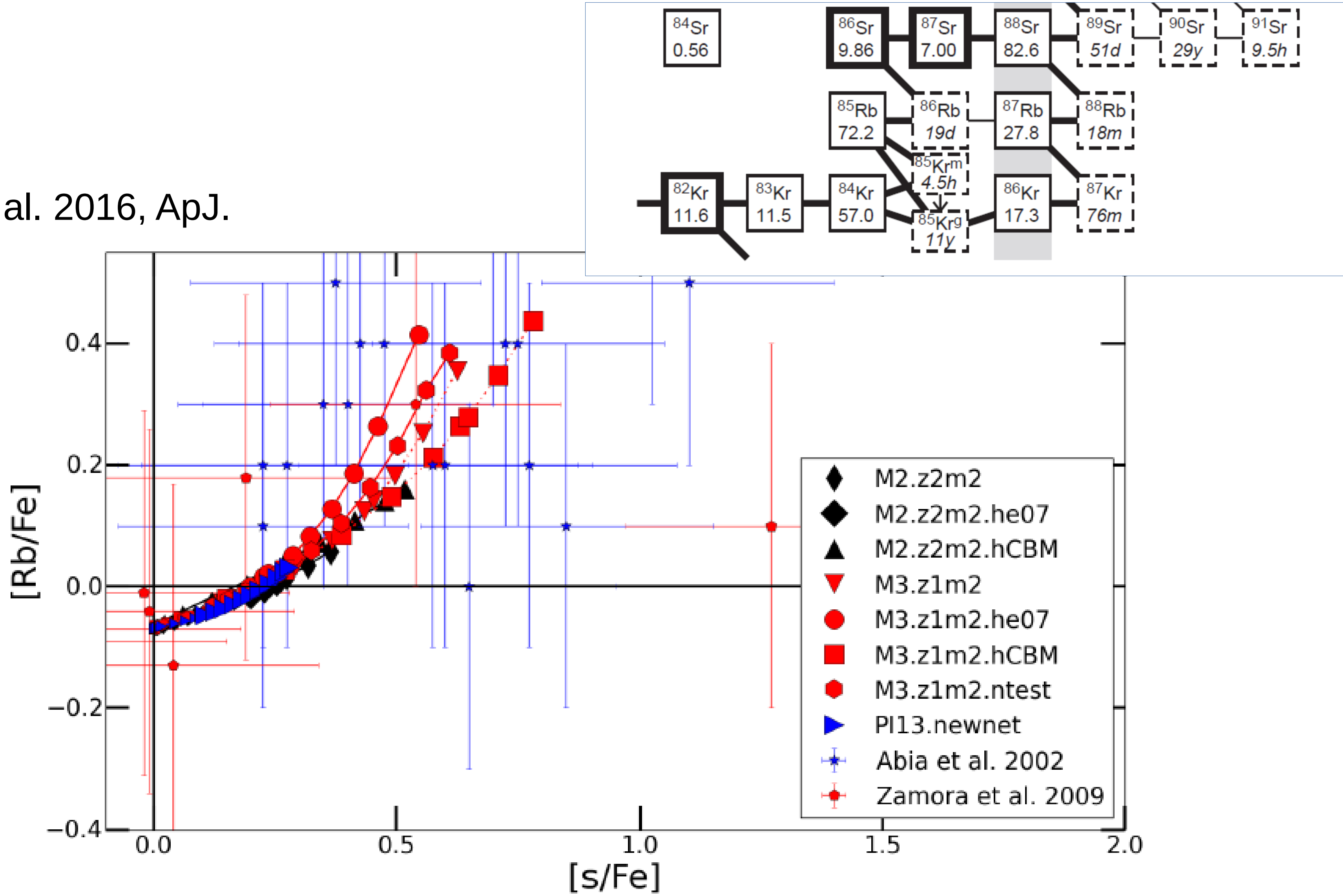




s-process during the Thermal Pulse Ne22(a,n)Mg25 activation -

N_n peak > 10^{10} cm^{-3}

Battino et al. 2016, ApJ.

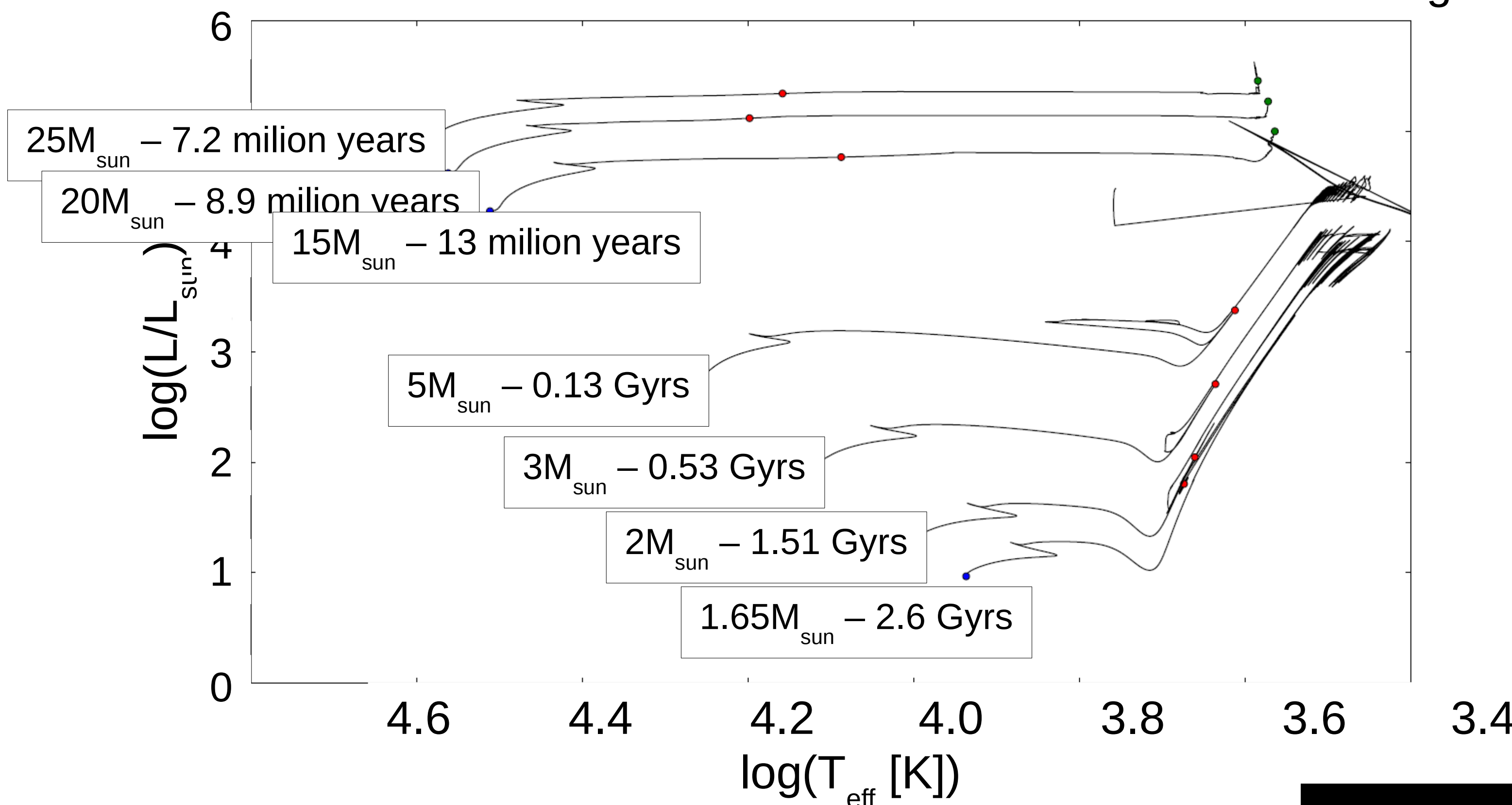


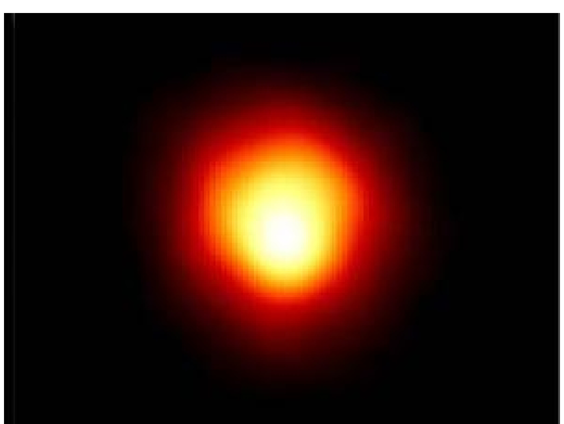
- The [Rb/Fe] dependends on: (1) CBM below the TP; (2) Ne22(a,n); (3) Kr85(n,γ)
- The [s/Fe] depends on: (1) the production efficiency of the C13-pocket (2) mass loss; ...

We can learn a lot about physics processes relevant for AGB stars by comparing theoretical predictions with observations.

AGB stars take longer to evolve compared to massive stars (→ GCE). But super AGB stars evolution time is fast!

HR diagram





Betelgeuse (α-Ori):

- 19 M_{sun}
- 650 lyr
- 1180 R_{sun}

CWLeo (IRC+10216):

- 400 lyr
- 250 R_{sun}

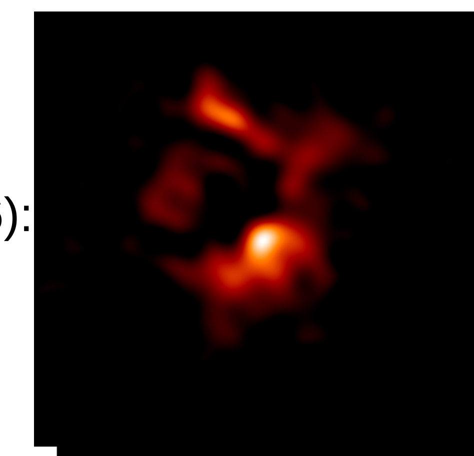
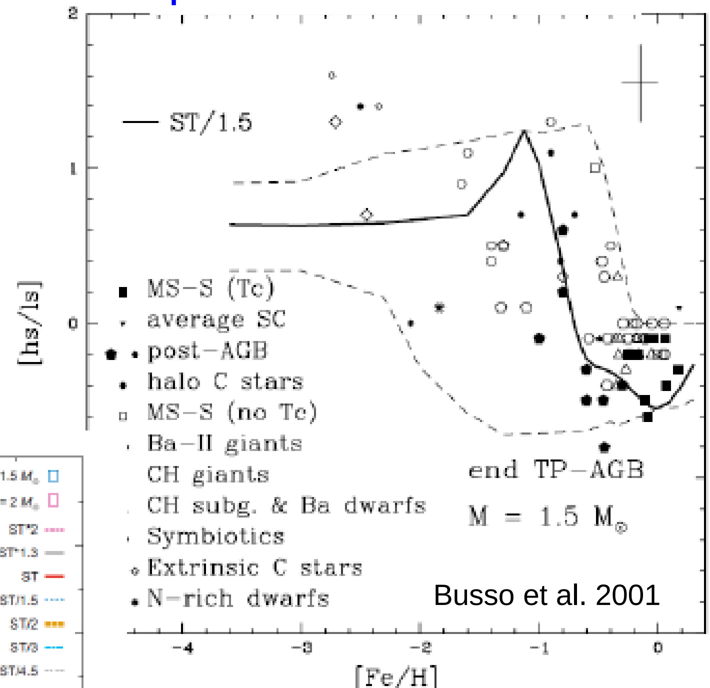


Image: A. Dupree/CFA/R. Gilliland/STScI/NASA/ESA

Tuthill et al. 2000, A&A, Keck Telescope

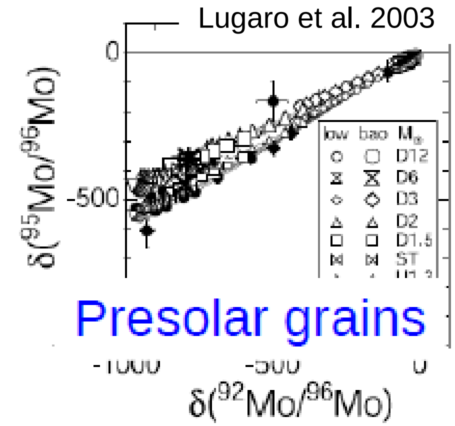
It is possible to observe the intrinsic s-process nucleosynthesis in AGB stars at different metallicities, without GCE degeneracy.

Ba stars, MS-S stars, post-AGB stars...

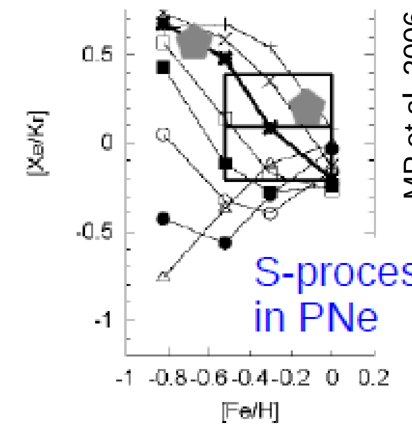


Busso et al. 2001

Lugaro et al. 2003



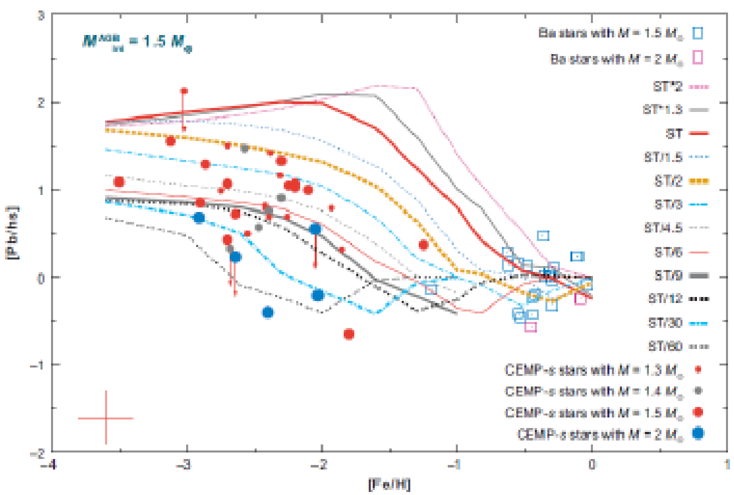
Presolar grains



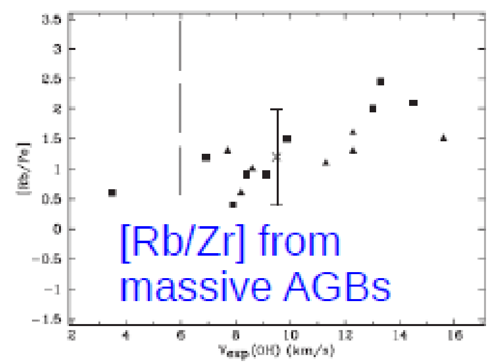
MP et al. 2006

S-process in PNe

CEMP-s stars

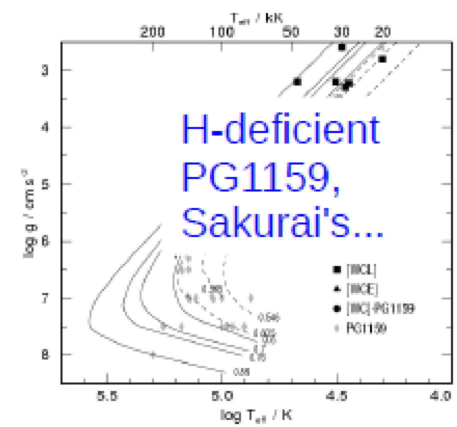


Sneden et al. 2008



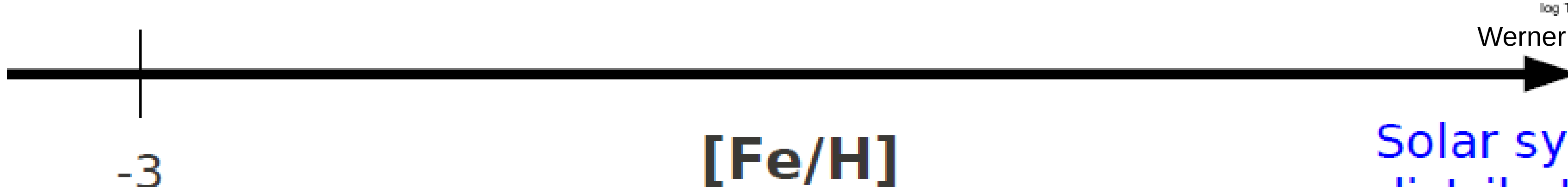
[Rb/Zr] from massive AGBs

Garcia-Hernandez et al. 2006



H-deficient PG1159, Sakurai's...

Werner & Herwig 2006



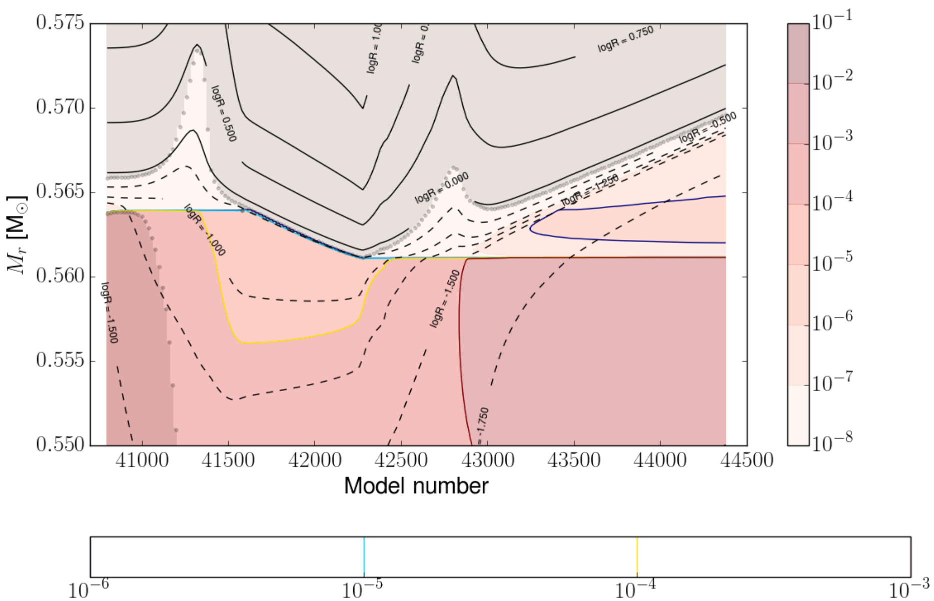
Solar system distribution

e.g., Bisterzo et al. 2014

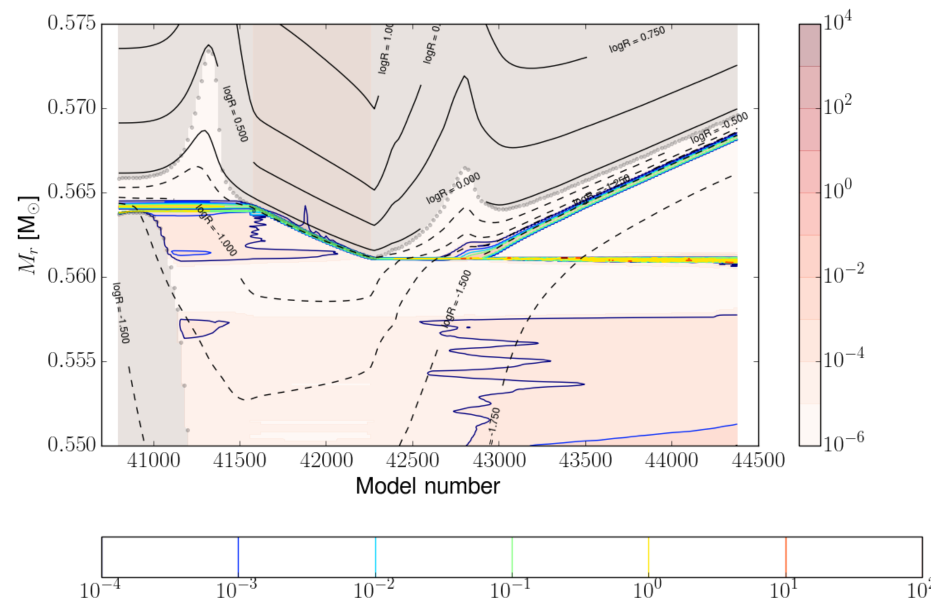
Effects of Rotation (and B-fields)?

Herwig et al 2000, Decressin et al, Piersanti et al 2013

Omega contour map

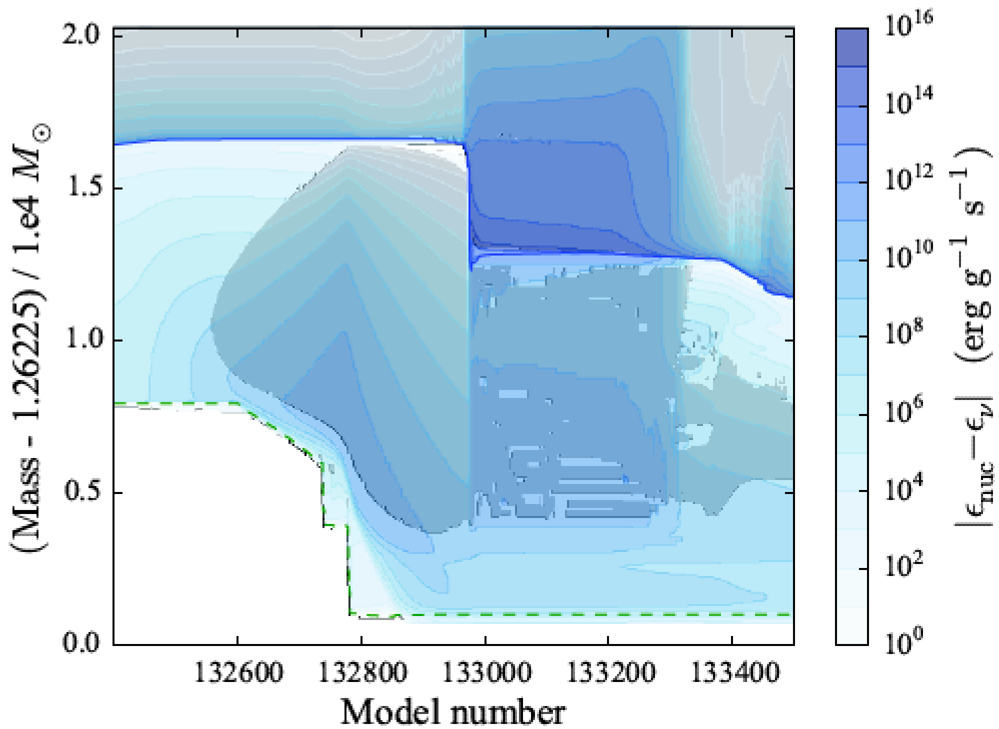


Mu contour map



Rotation decreases s process production & may explain observed scatter

If you think AGB stars are complicated, let's look at super AGB stars...



Convective structure and nuclear energy generation during a thermal pulse in which hydrogen is ingested into the pulse-driven convection zone (PDCZ). Model: initial mass 7Msun, Metallicity $Z=10^{-4}$ (Jones et al. 2015, MNRAS).

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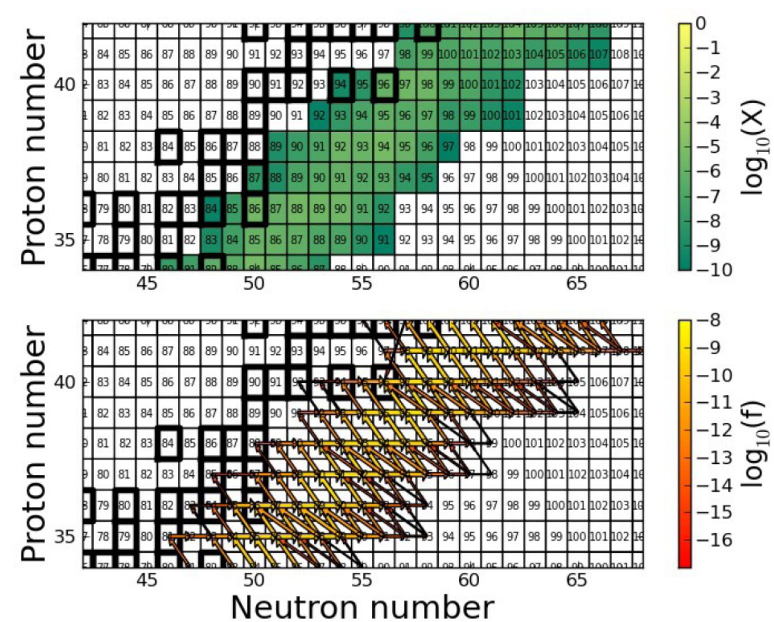
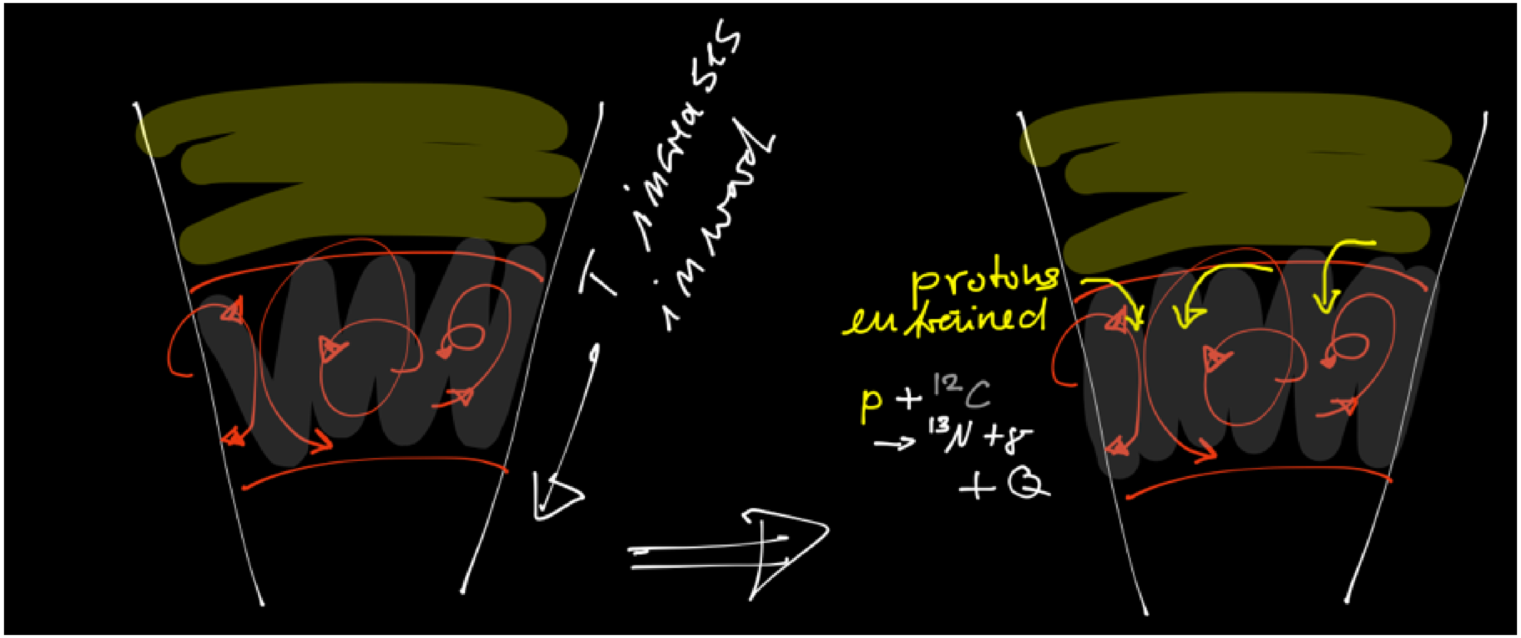


The intermediate neutron capture process (or i process, Cowan & Rose 1977 ApJ) is activated.



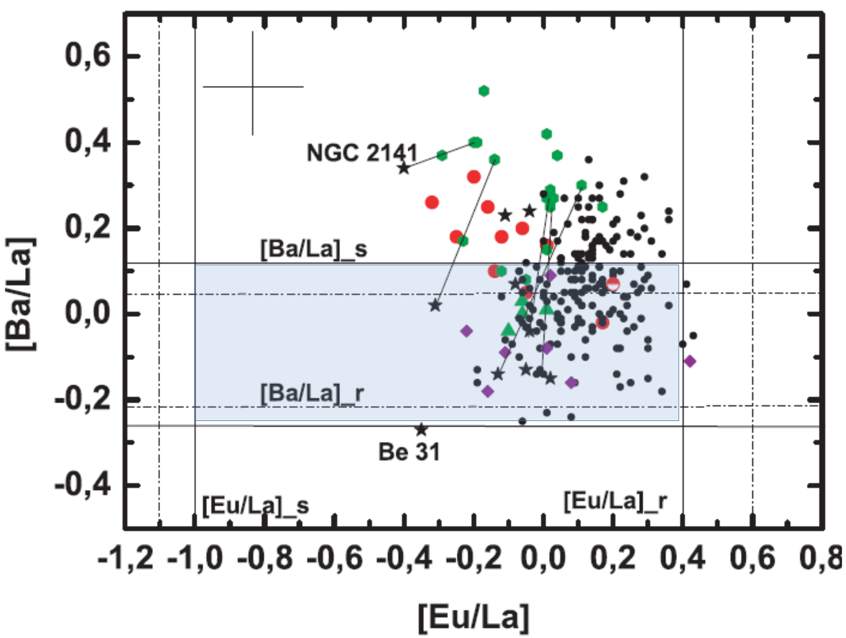
N13 and/or C13 are mixed in regions with typical He-burning temperatures, <u>together with Fe-seed rich and i-process poor material.</u>

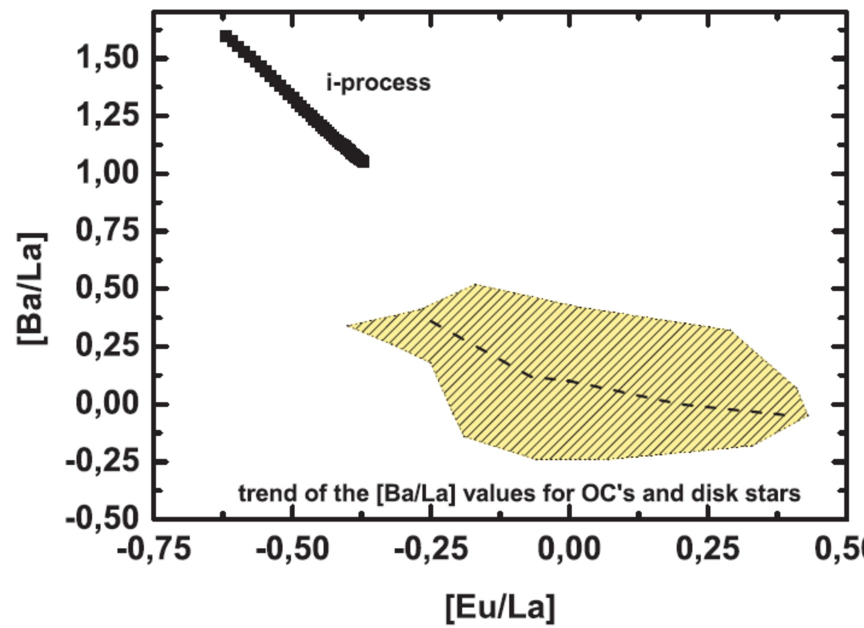
The C13(α,n)O16 is activated, producing neutron densities ~ 10^{14}-10^{16} cm^{-3}.

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **446,** 3651–3668 (2015) doi:10.1093/mnras/stu2337

New insights on Ba overabundance in open clusters.* Evidence for the intermediate neutron-capture process at play?

T. Mishenina,[1,2] M. Pignatari,[3]† G. Carraro,[4,5] V. Kovtyukh,[1,2]‡ L. Monaco,[4] S. Korotin,[1,2] E. Shereta,[1] I. Yegorova[4] and F. Herwig[6,7]†



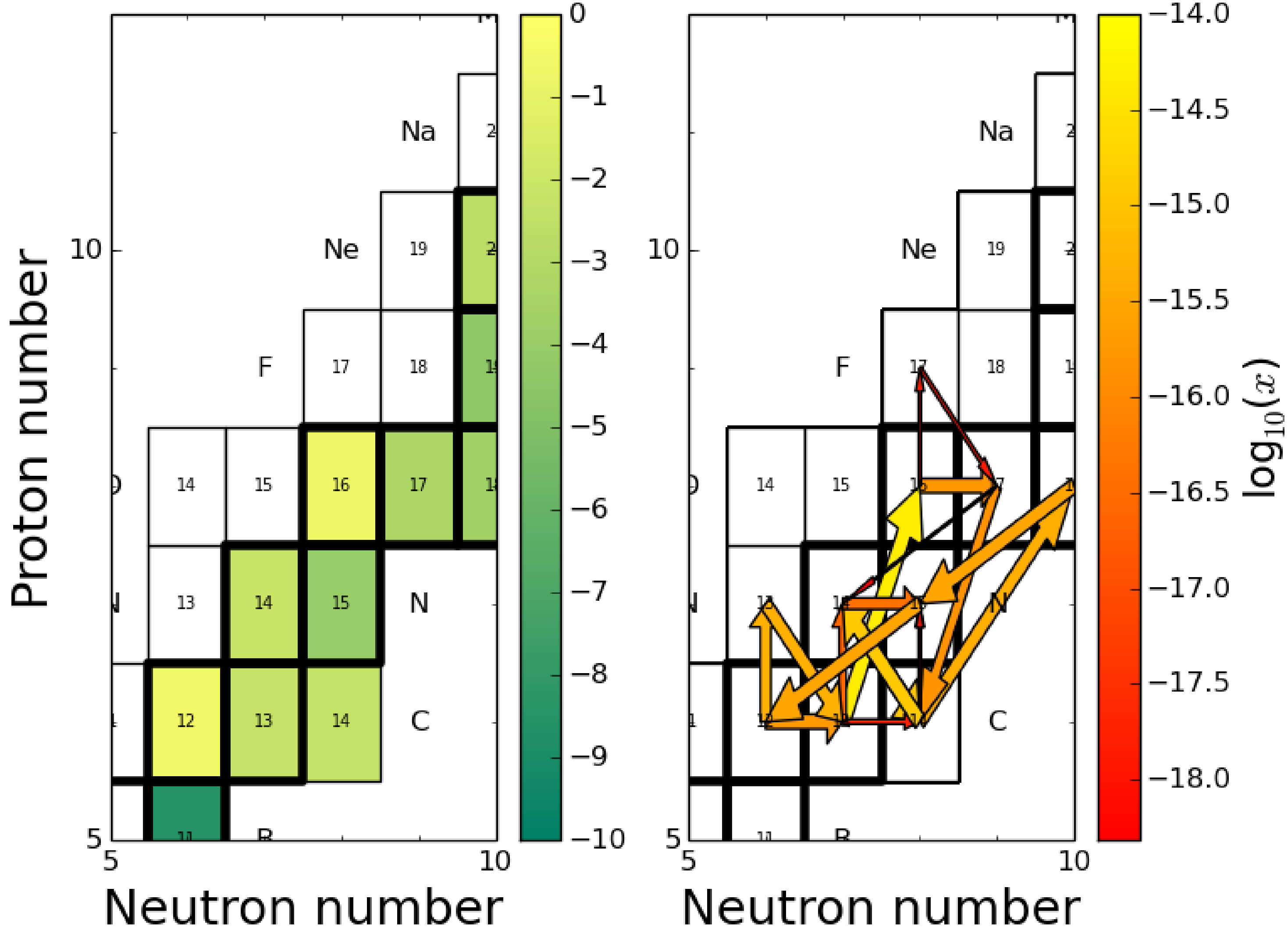


<u>Observing the i process signature in OCs:</u>
The i process might be relevant for GCE!

Summary

- AGB stars are challenging for theoretical stellar simulations. The crucial nucleosynthesis is happening in few 10^4 Km on top of the CO core.
- Observations of AGB stars allow to test physics recipes included in the models and the nuclear reaction network (e.g., convective-boundary mixing due to gravity waves, rotation and magnetic field).
- The observation s-process elements provide an ideal diagnostic for stellar models and relevant nuclear reaction rates.
- Super AGB stars are even more challenging. They are potential carrier of the i process.
- Is the i process relevant for GCE?

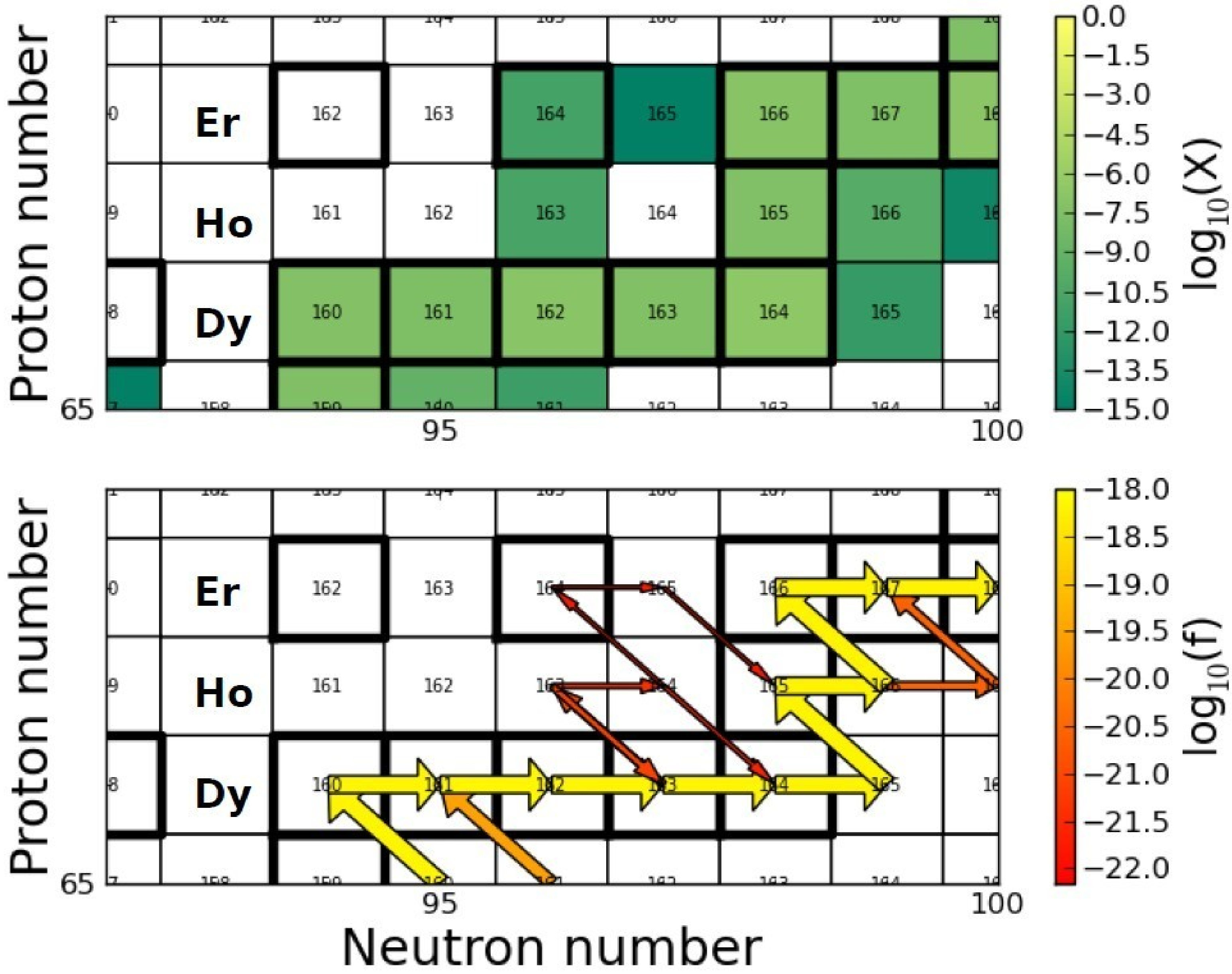
Some detail about the nucleosynthesis in the C13-pocket:



Fluxes integrated over the all life of a C13-pocket trajectory
Efficient activation of the C13(alpha,n)O16 neutron source

Initial abundances:
C12=0.30
C13=0.03
N14=0.01
...

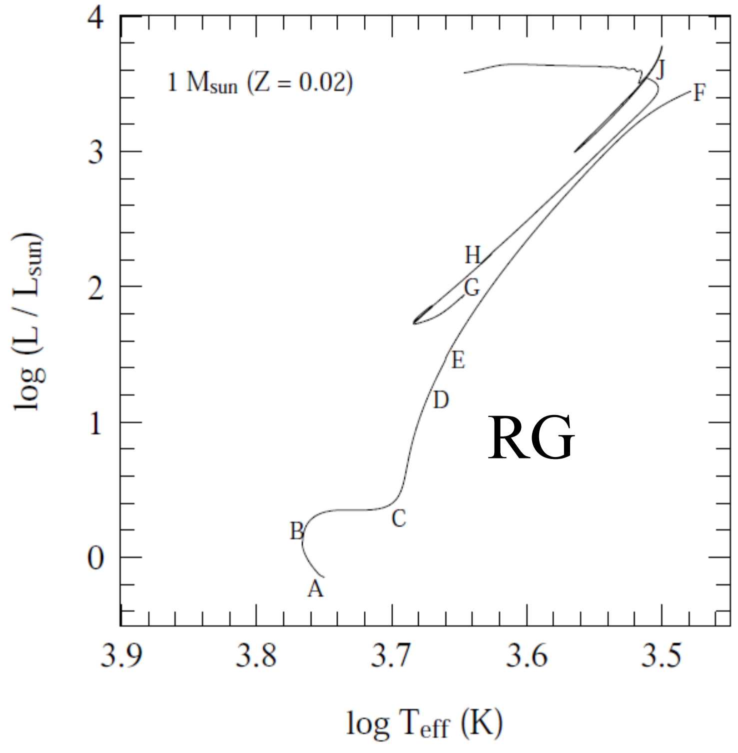
An example of the s process path

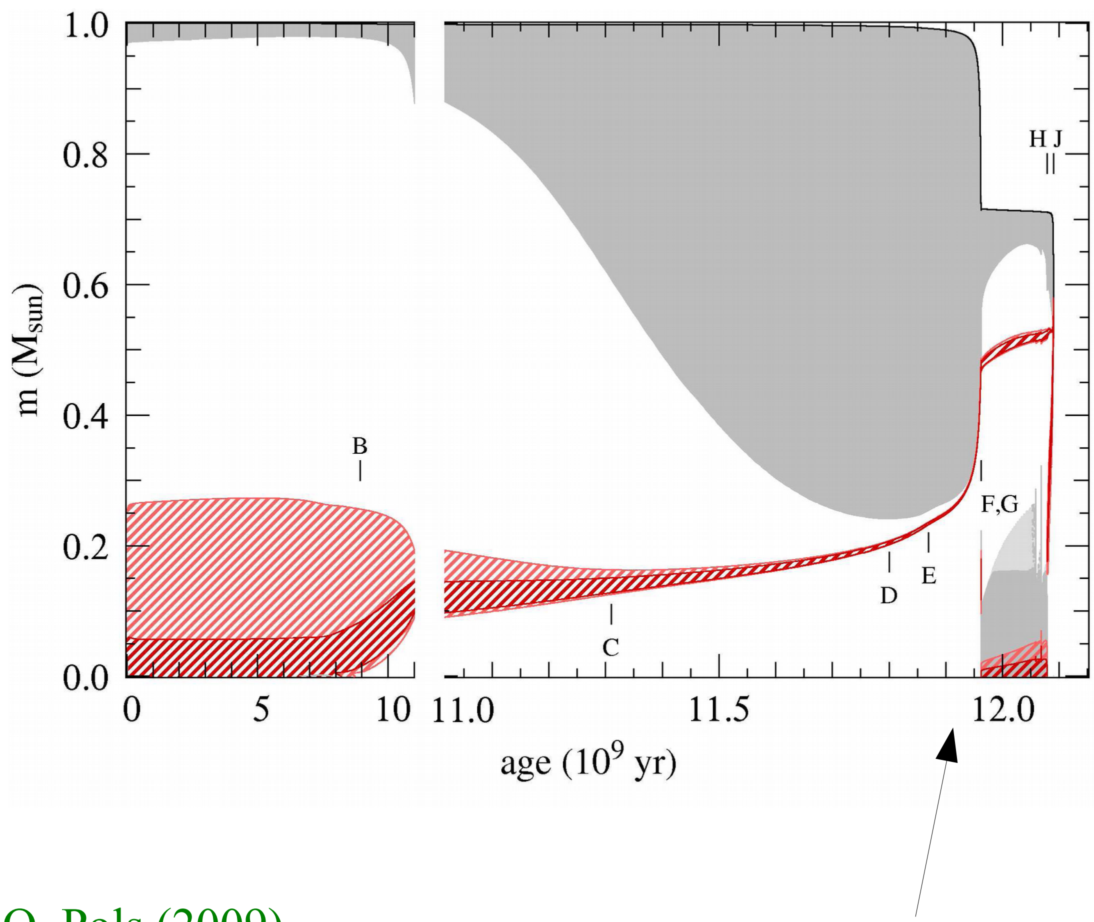


It can be more complicated than what you think.

Intermediate & Low-Mass Stars

1 M_o star: Evolution through H- and He-burning





From SE notes, O. Pols (2009)

He-flash at point F → G