The i process: modelling and observational constraints

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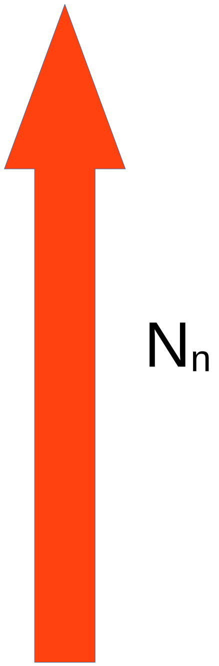
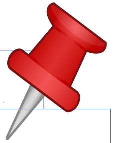
List of neutron capture processes

- The r process (neutrino-wind, NS mergers, jet-SNe, etc) - $N_n > 10^{20}$ n cm^{-3};
- The n process (explosive He-burning in CCSN) -

  10^{18} n cm^{-3} < N_n < few 10^{20} n cm^{-3};
- The i process (H ingestion in convective He burning conditions) - 10^{13} n cm^{-3} < N_n < 10^{16} n cm^{-3};
- Neutron capture triggered by the Ne22(α,n)Mg25 in massive AGB stars and super-AGB stars - $N_n < 10^{14}$ n cm^{-3};
- The s process (s process in AGB stars, s process in massive stars and fast rotators) – N_n < few 10^{12} n cm^{-3}.





1977

THE ASTROPHYSICAL JOURNAL, **212**:149–158, 1977 February 15

PRODUCTION OF ^{14}C AND NEUTRONS IN RED GIANTS

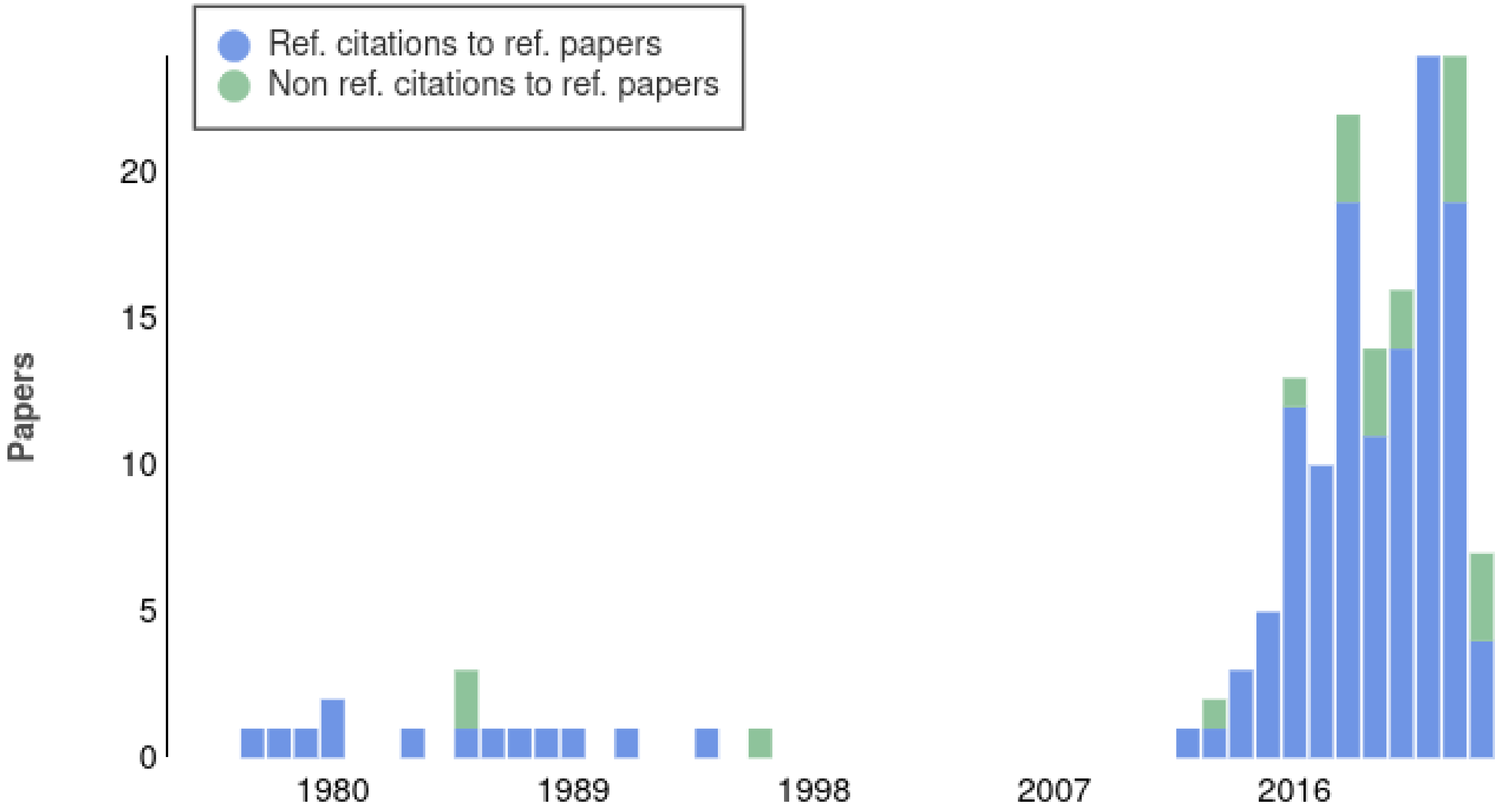
JOHN J. COWAN AND WILLIAM K. ROSE
Astronomy Program, University of Maryland, College Park
Received 1976 June 28

ABSTRACT

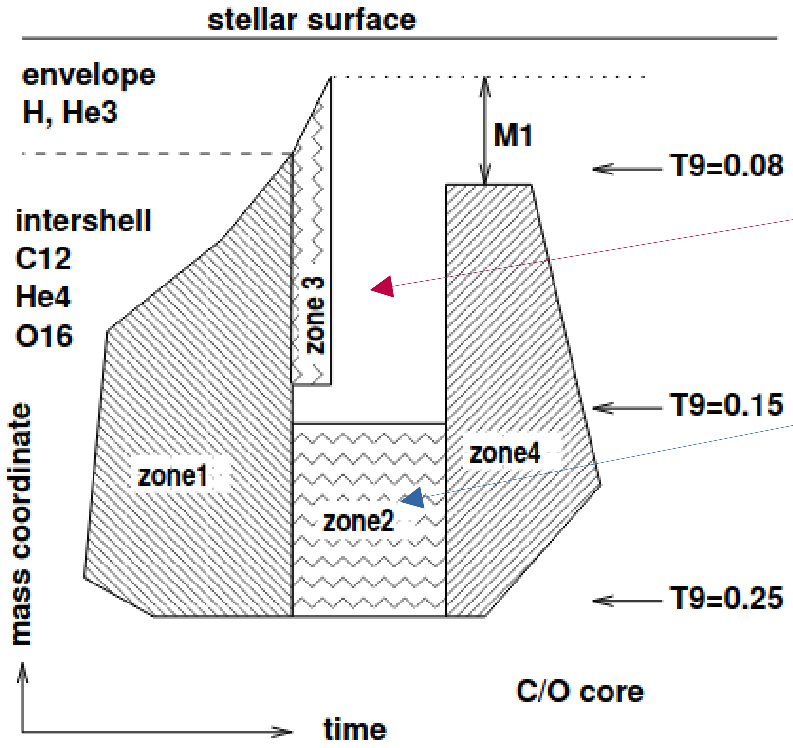
We have examined the effects of mixing various amounts of hydrogen-rich material into the intershell convective region of red giants undergoing helium shell flashes. We find that significant amounts of ^{14}C can be produced via the ^{14}N$(n, p)^{14}$C reaction. If substantial portions of this intershell region are mixed out into the envelopes of red giants, then ^{14}C may be detectable in evolved stars.

We find a neutron number density in the intershell region of $\sim 10^{15}$–10^{17} cm^{-3} and a flux of $\sim 10^{23}$–10^{25} cm^{-2} s^{-1}. This neutron flux is many orders of magnitude above the flux required for the classical *s*-process, and thus an intermediate neutron process (*i*-process) may operate in evolved red giants. The neutrons are principally produced by the ^{13}C$(\alpha, n)^{16}$O reaction.

In all cases studied we find substantial enhancements of ^{17}O. These mixing models offer a plausible explanation of the observations of enhanced ^{17}O in the carbon star IRC 10216. For certain physical conditions we find significant enhancements of ^{15}N in the intershell region.



Source: NASA ADS



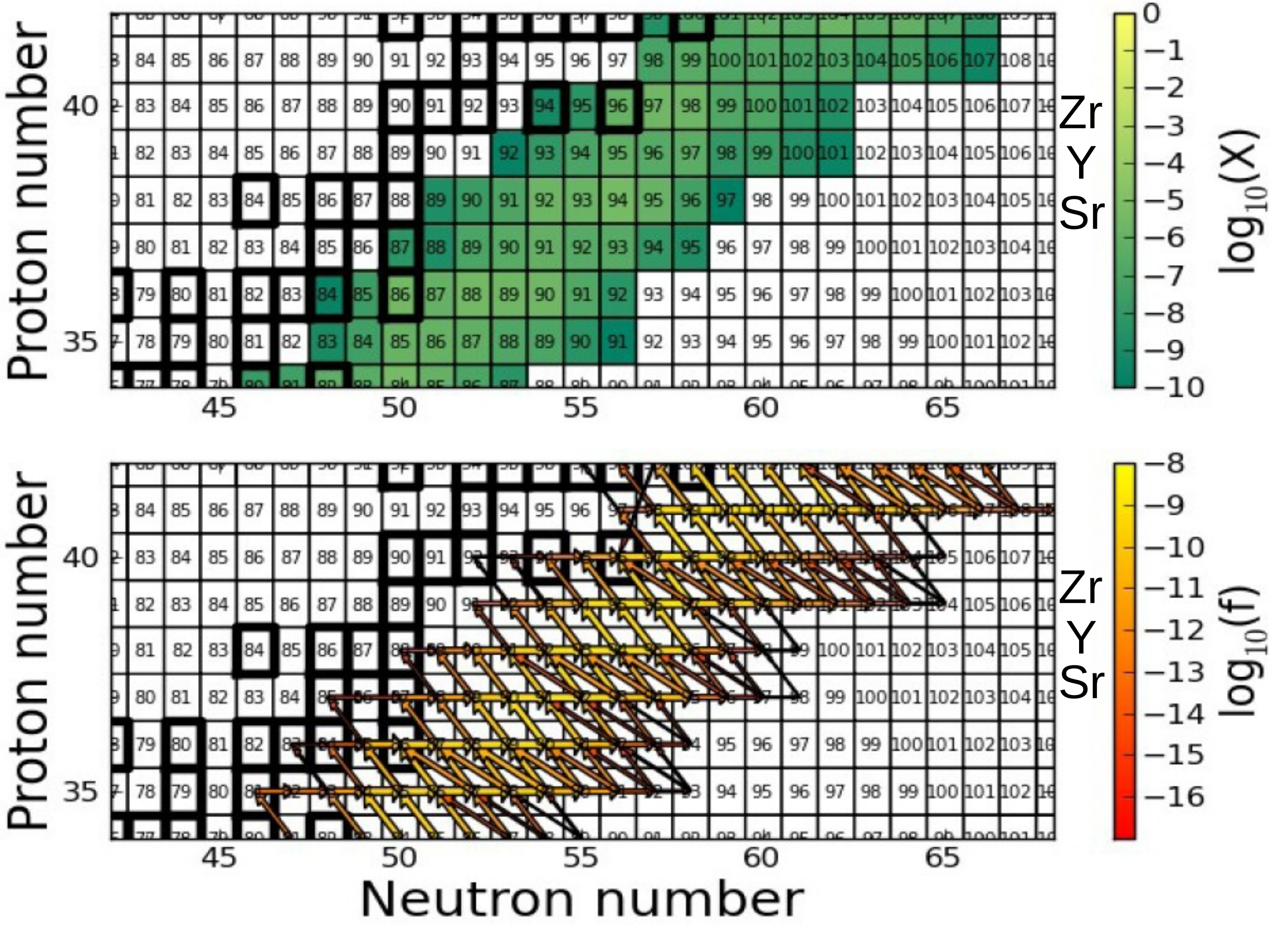
C12+p → N13
N13 → C13

C13(a,n)O16
i-process ~ 10^{14}-10^{15} neutrons cm^{-3}

N13 and/or C13 are mixed <u>for hours-months</u> (site dependent) in regions with typical He-burning temperatures (T9 ~ 0.25-0.3 GK), <u>together with Fe-seed rich material.</u>

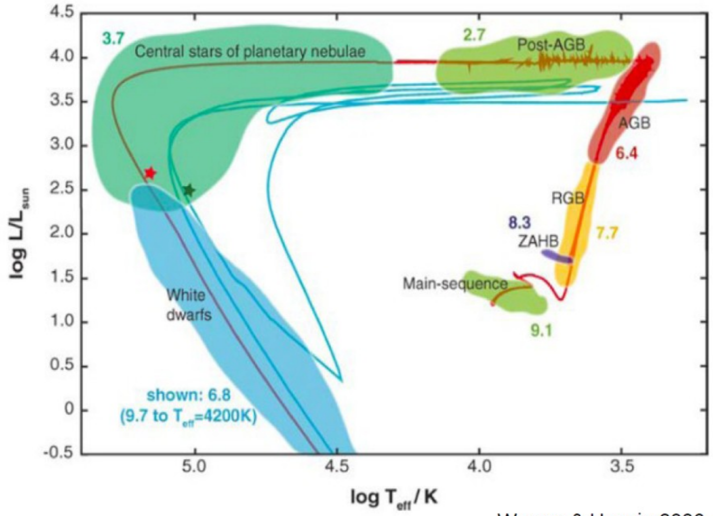
Main source of neutrons: C13(α,n)O16

Nucleosynthesis properties of the i process: Se-Nb



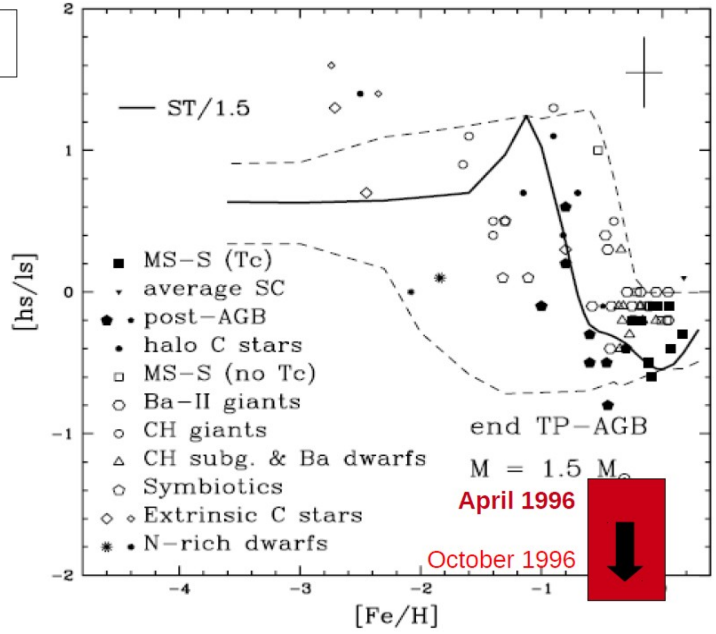
H-ingestion sites:
(with the potential i-process production)

- Post AGB stars, all Z (e.g., Fujimoto+ 1977, Iben+ 1982, Miller Bertolami+ 2006, Herwig+ 2011, Herwig+ 2014, Woodward+ 2015)
- Low mass stars and AGB stars, low Z and Z = 0 (e.g., Hollowell+ 1990, Fujimoto+ 2000, Suda+ 2004, Campbell & Lattanzio 2008, Cristallo+2009, Herwig+ 2014, Woodward+ 2015, Lugaro+ 2015, Abate+ 2016, Choplin+ 2021, Karinkuzhi+ 2021...)
- Super AGB stars, low Z (Jones+ 2016)
- Massive stars, all Z (e.g., Woosley & Weaver 1995, Limongi & Chieffi 2012, Pignatari+ 2015, Roederer+ 2016, Clarkson+ 2018, Banerjee+ 2018, Clarkson+ 2021)
- Stellar binaries: iRAWDs, all Z (Denissenkov+ 2017, 2019, Côté+ 2018, Battino+ 2020, Stephens+ 2021)



Werner & Herwig 2006, PASP

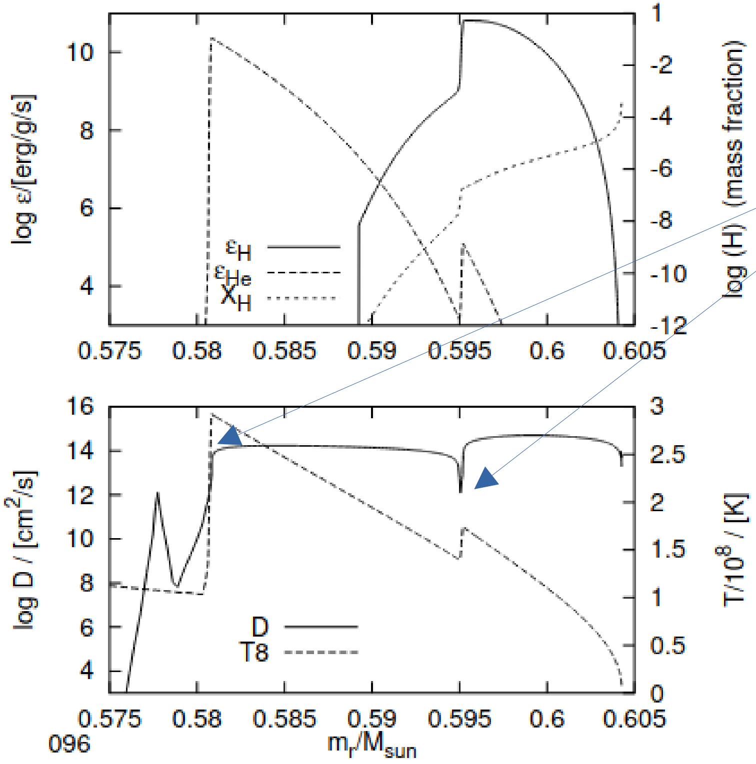
hs = Ba peak
ls = Sr peak



Busso et al. 2001, ApJ 557 versus
Asplund et al. 1999 A&A 343

First clear observational evidence of the i process:
the Sakurai's Object (post-AGB star after VLTP).
Not relevant for GCE but ideal benchmark
for hydrodynamics simulations and to define
relevant nuclear reaction rates.

1D simulations of VLTPs: no i-process



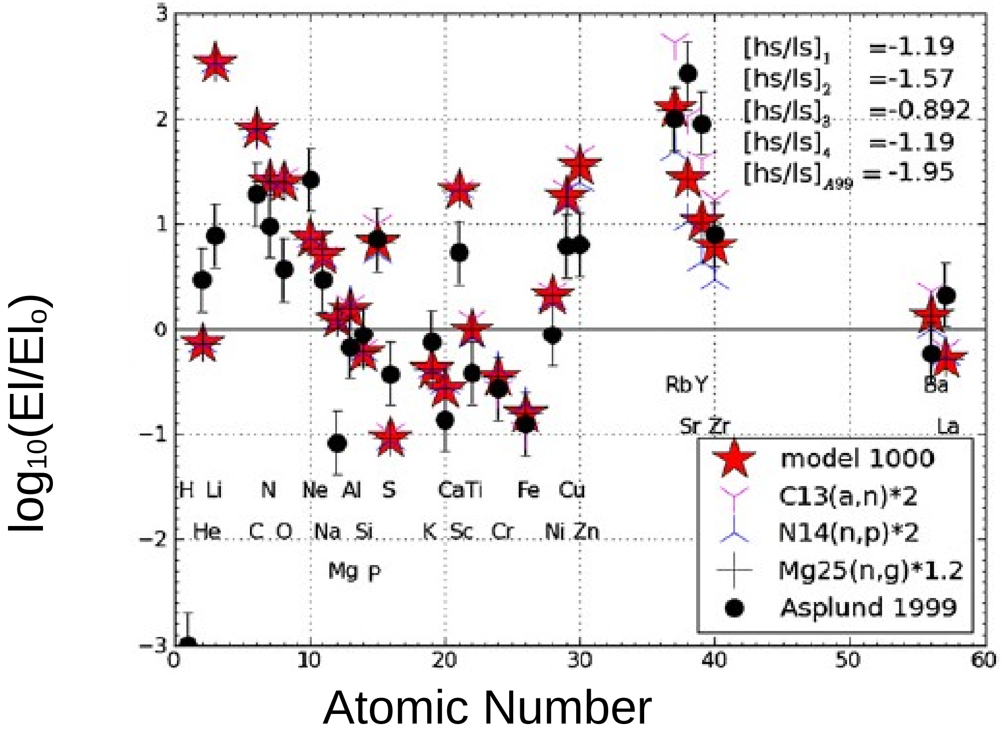
As soon as some H in ingested,
The He-burning convective zone
Is “splitted” in two.

C13 is made by C12+p, but C13
never reaches the bottom of the
He-burning zone.

NO I-PROCESS!

See e.g., Herwig+1999, Miller Bertolami+ 2006

Simulations from the Sakurai's Object (2009)

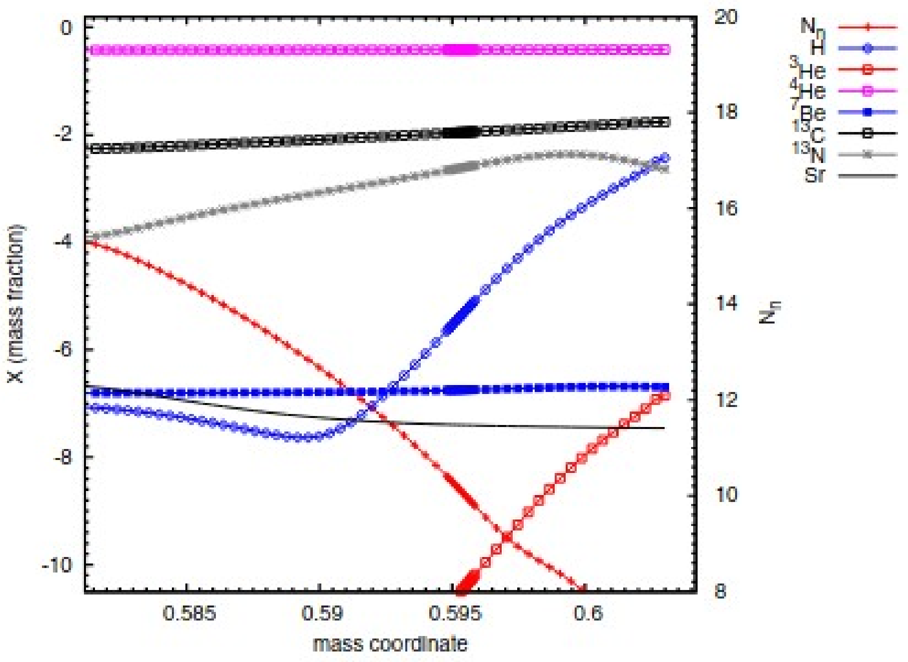


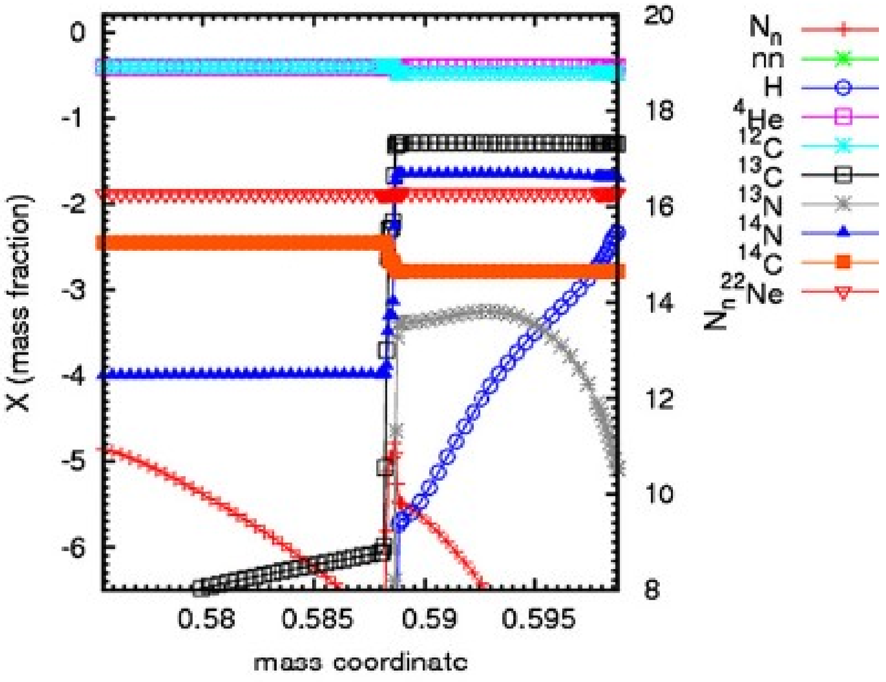
- High neutron densities:
  $N_n \sim 10^{15}$ cm^{-3}
- neutrons by the $^{13}C(\alpha,n)^{16}O$:
  i process

How??

Herwig, MP et al. 2011 ApJ

Basics of the computational experiment

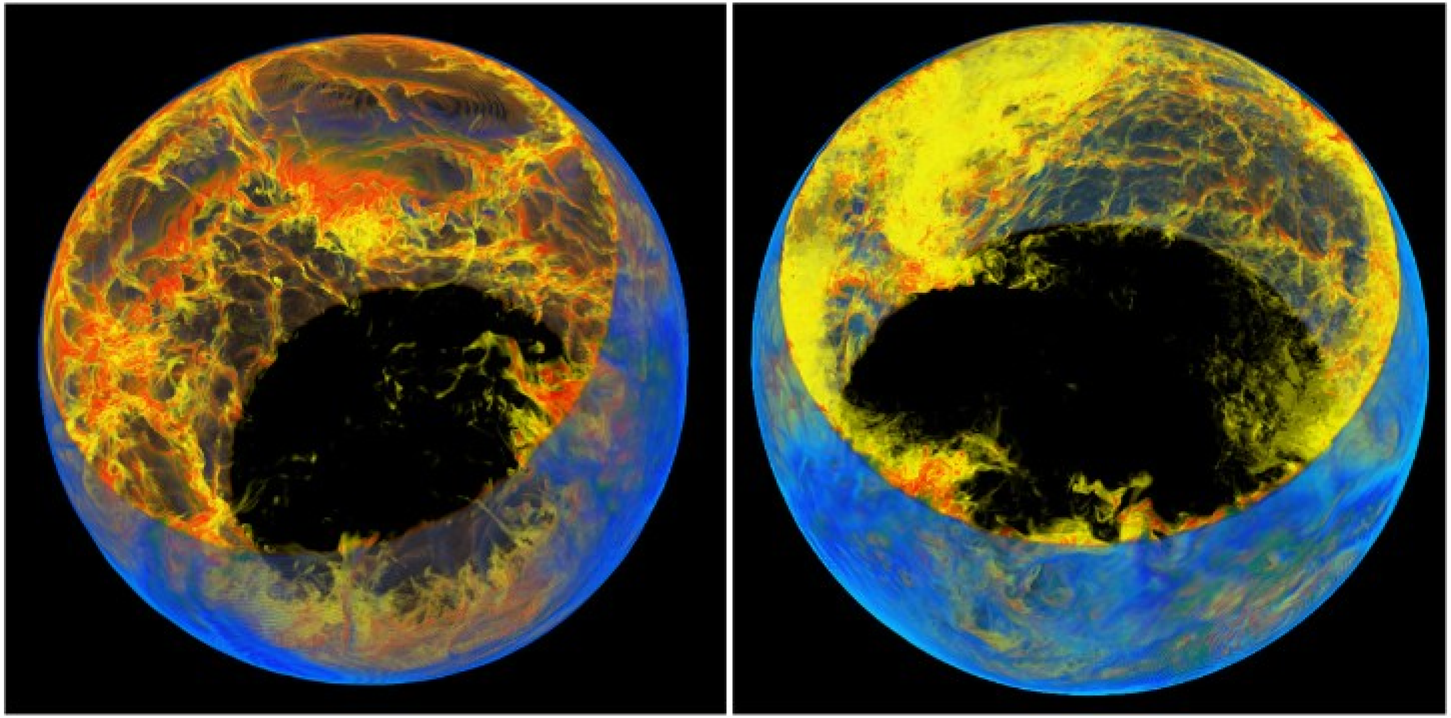




- M_{ing} = 5.3*10^{-10} Msun/s
- Time-step of the stellar code reduced by a factor of a 1000 to resolve the nucleosynthesis

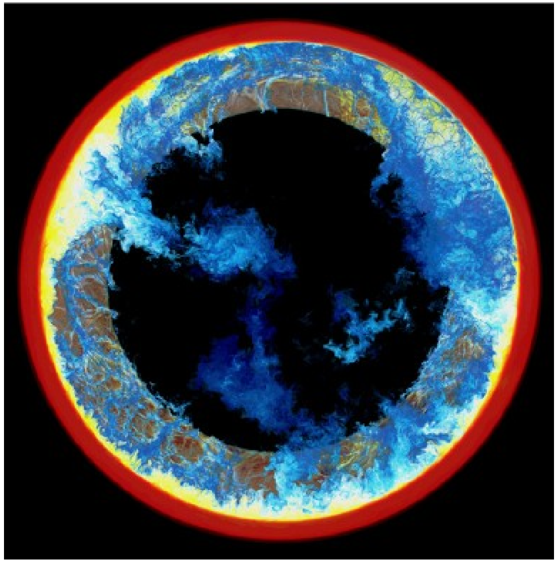
- “Split” activated at 800-1200 minutes from the start of the H-ingestion

H11: approach motivation



3D simulations for ~300 minutes:
strong variations in the H-ingestion efficiency at different positions and times

Results for the hydrodynamics of H ingestion from ten years ago:
(Cost of a resolved simulation of H ingestion for 20 hr star time: ~ 500K $)



- Defined the dependence of the entrainment rate on grid resolution of H-rich material at the top convection boundary and the subsequent advection into deeper He-rich layers. Data to inform 1D models.

The i-process crisis:

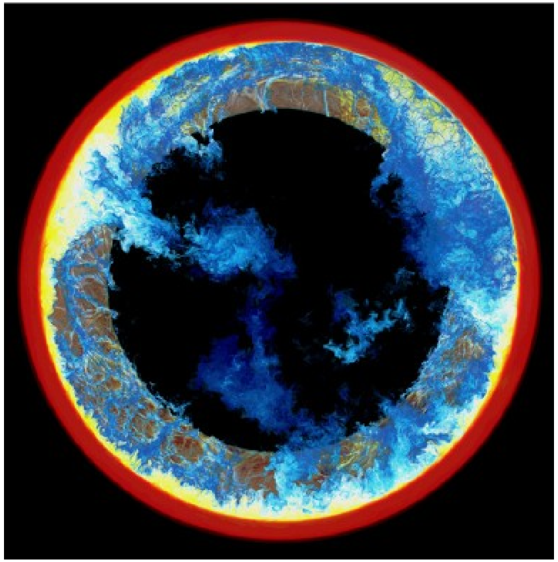
Herwig+2014 and Woodward+2015 results for hydro are questioning post-AGB stars as i-process sites?

+ Herwig et al. 2014, ApJL 792
+ Woodward et al. 2015, ApJ 798, 49

+ For other hydrodynamics simulations of H ingestion (at low metallicity): Mokak et a. 2011 A&A, Stancliffe et al. 2011 ApJ

Results for the hydrodynamics of H ingestion from ten years ago:

(Cost of a resolved simulation of H ingestion for 20 hr star time: ~ 500K $)



+ Herwig et al. 2014, ApJL 792
+ Woodward et al. 2015, ApJ 798, 49

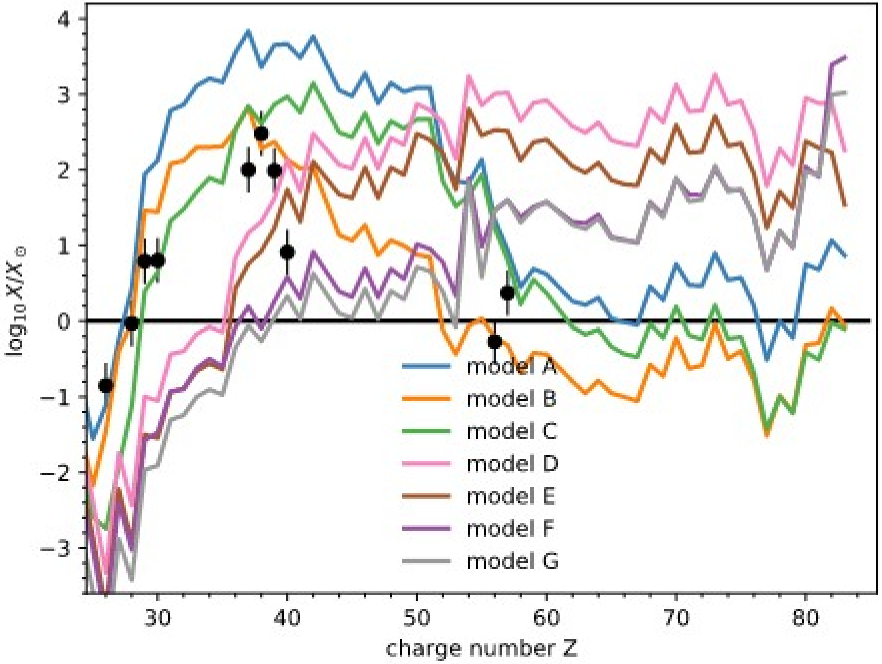
The i-process crisis:

- H11: to get the observed i-process pattern, H-ingestion rate M_{ing}= 5.3*10^{-10} Msun/s.

- W15: M_{ing}= 4.4*10^{-13} Msun/s at the beginning;
- H14: Formation of instability (GOSH) where the split forms in 1D models (at ~ 800 minutes), which boost and drive M_{ing} up to ~ 7*10^{-11} Msun/s before the simulations stop.

- The M_{ing} is not constant!
- How does the star evolve once the GOSH instabilities start to take over?
- This should apply also to low-Z AGB stars?

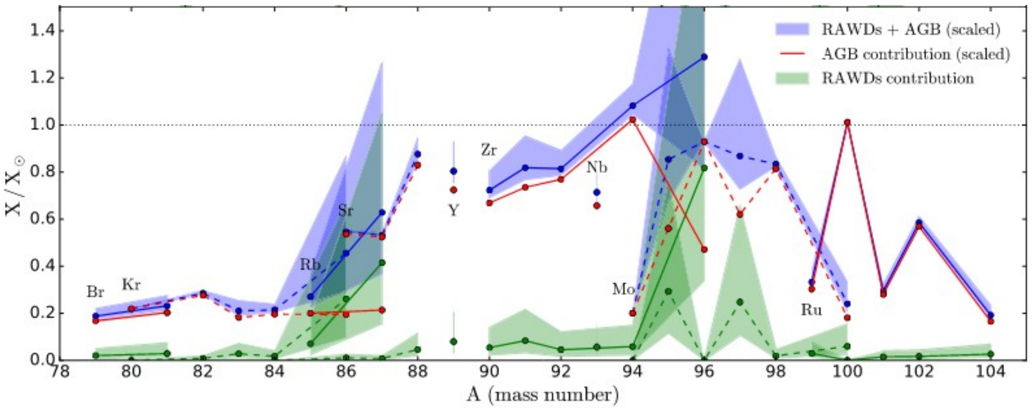
What is the Sakurai's object?



Sakurai's object vs iRAWDs (Denissenkov+2019)

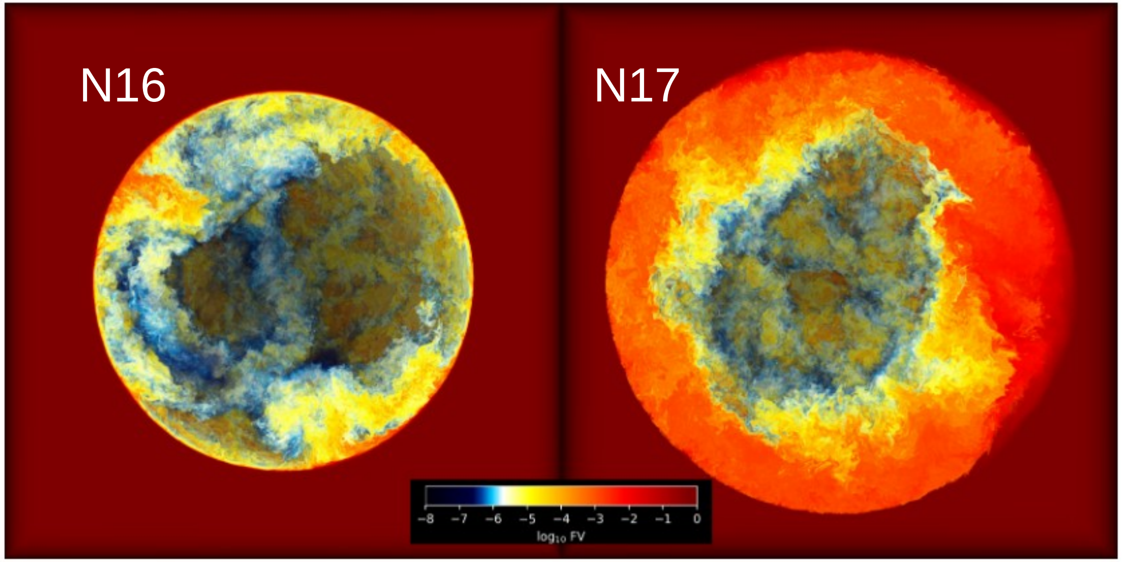
RAWD: **R**apidly **A**ccreting **W**hite **D**warf
$M_{acc} \sim 10^{-7}$ Msun/year

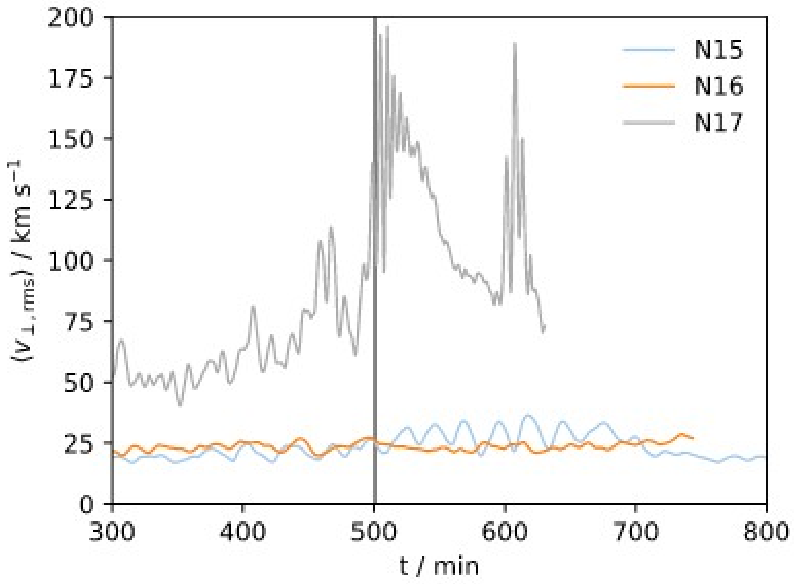
Challenging scenario:
The Sakurai's object is not a stellar binary.



iRAWDs: impact on GCE (Cote+2018 ApJ)

RAWDs





N16: $\dot{M}_{ing}$ ~ 7.2*10^{-12} Msun/s
N17: $\dot{M}_{ing}$ up to ~ 1.08*10^{-10} Msun/s

Stephens+ 2021

Most of the times there is no GOSH,
but sometimes there is also in RAWDs.

0-order rule to navigate all this

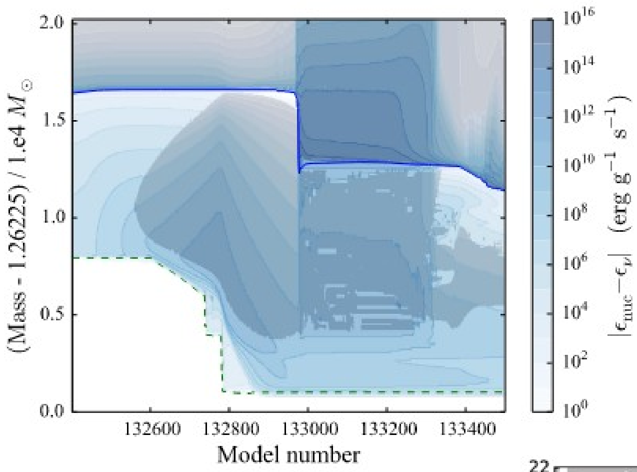
As general indication, if the L_{C12+p} is comparable or larger than L_{3He4} the stellar structure is strongly affected. Indicatively, in a He-burning environment in low mass stars this would correspond to:

$$M_{ing} \sim 5*10^{-11} Msun/s$$

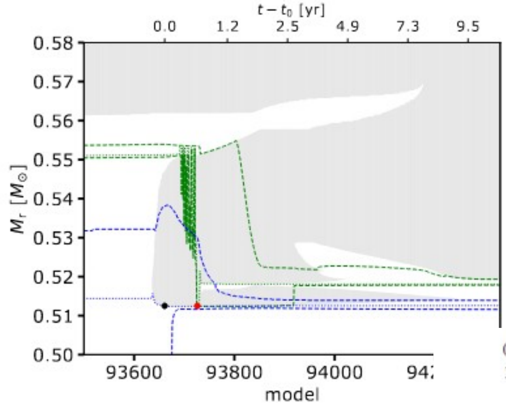
(Woodward+ 2015)

However, also for conditions significantly below this, we might have a GOSH (and a split of the He-burning convective region).

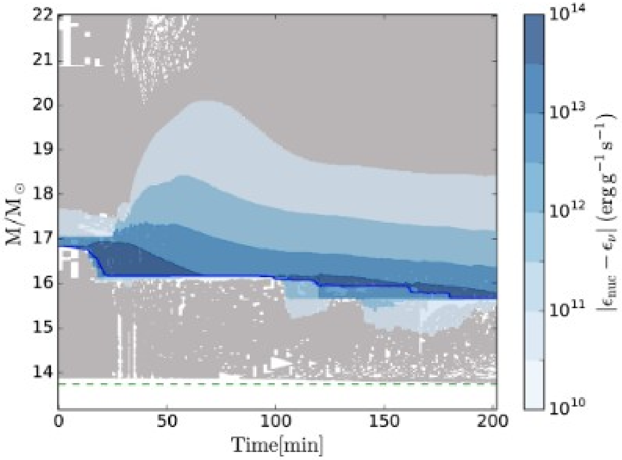
What about other stellar sources?



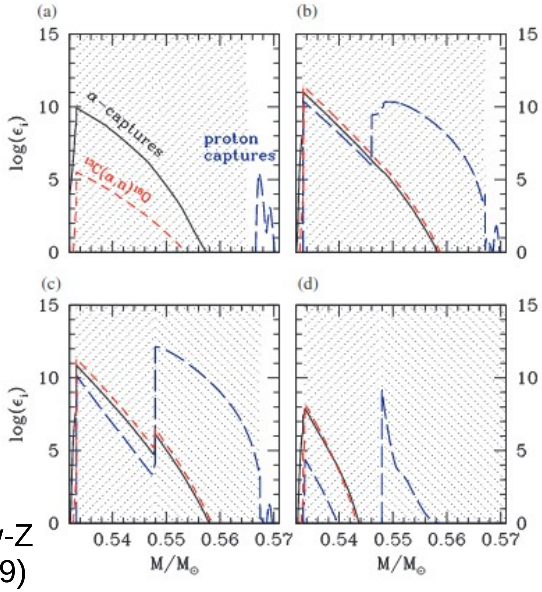
Super-AGB stars (Jones+2016)



AGB stars low-Z
(Choplin+ 2021)

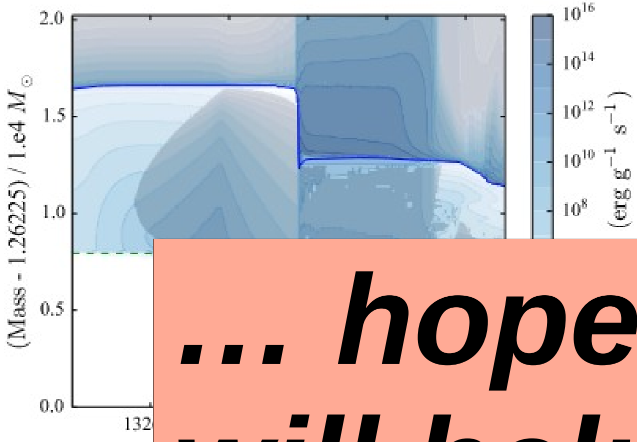


Massive stars
(Clarkson & Herwig 2021)

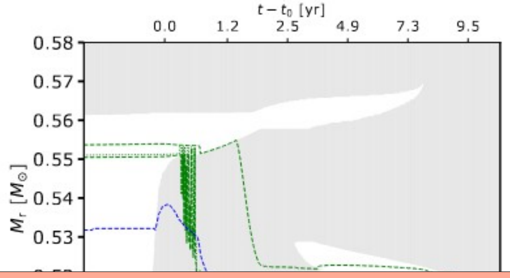


AGB stars low-Z
(Cristallo+2009)

What about other stellar sources?

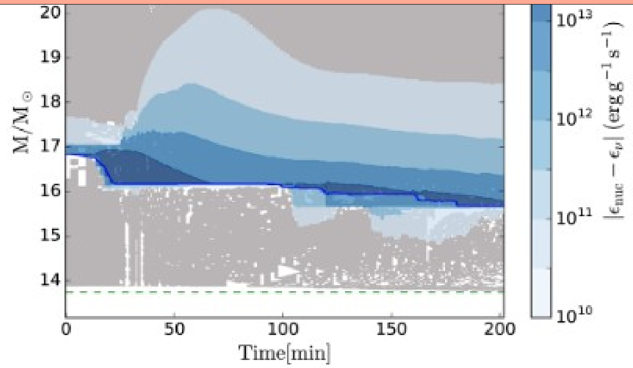


Super-AGB sta

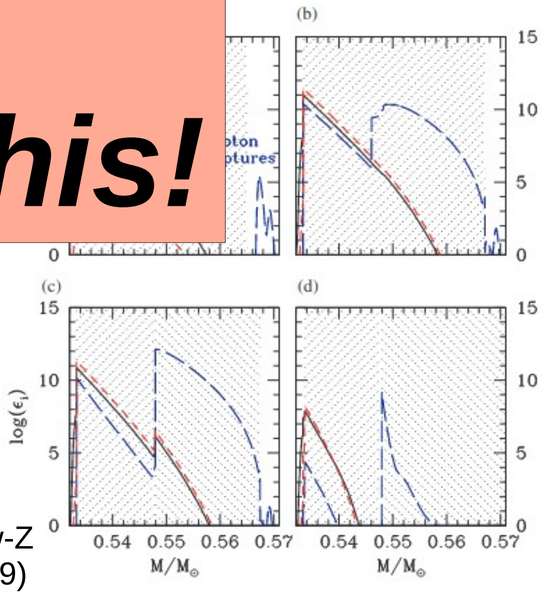


AGB stars low-Z
(Choplin+ 2021)

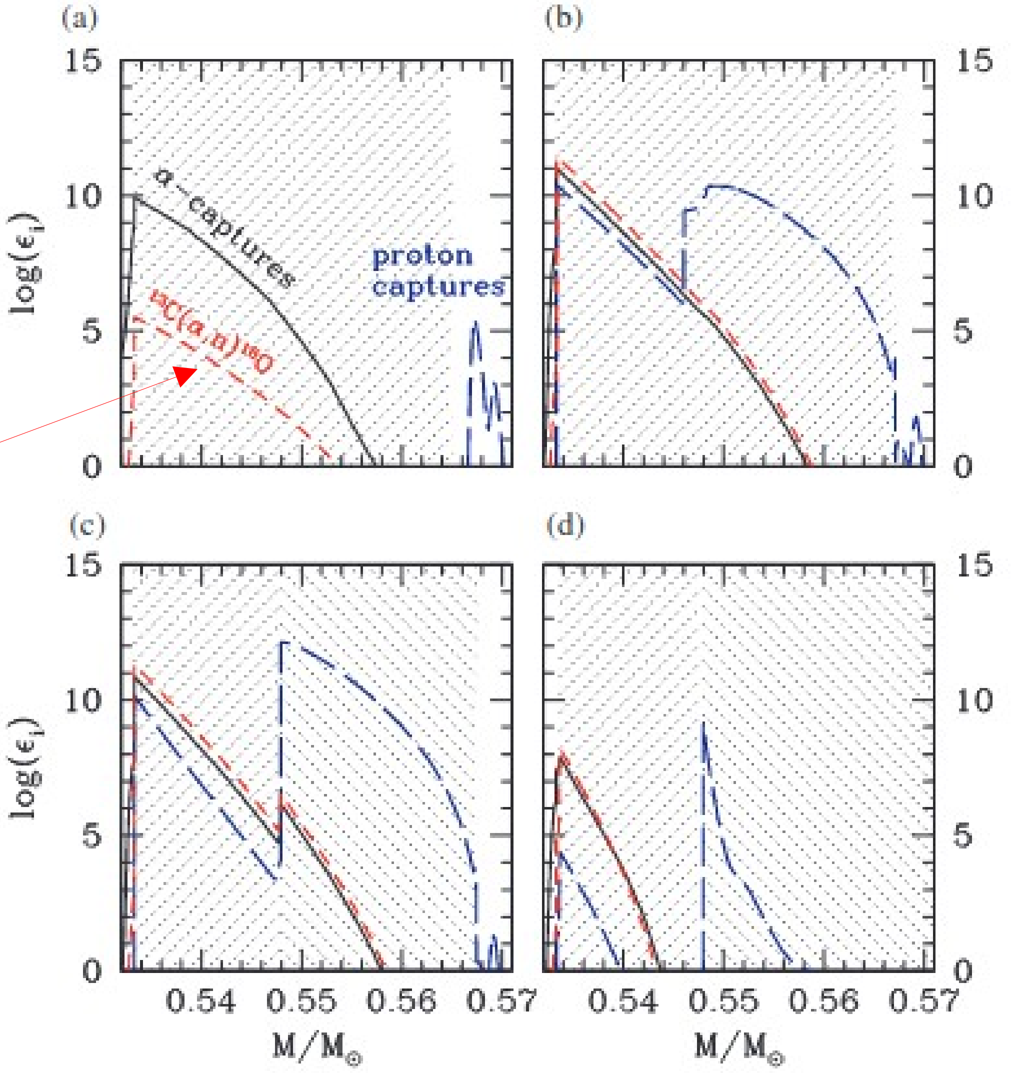
... hopefully, CeNAM will help to explore this!



Massive stars
(Clarkson & Herwig 2021)



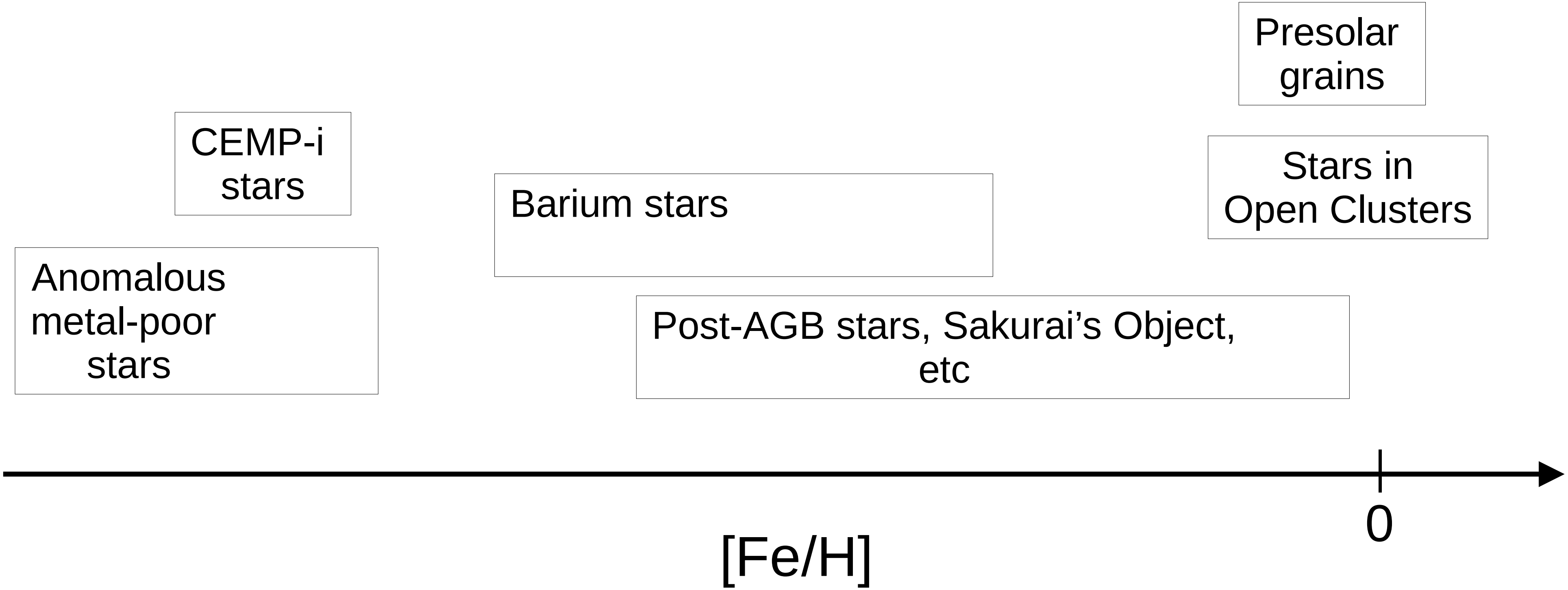
AGB stars low-Z
(Cristallo+2009)



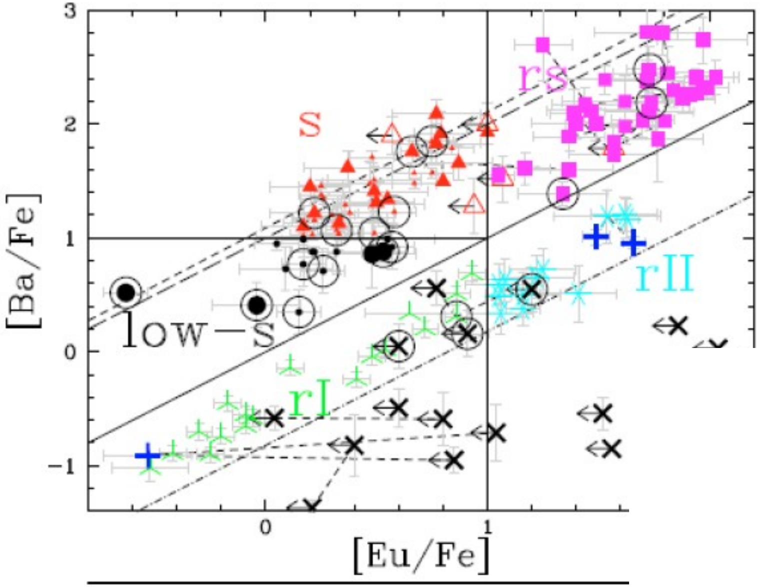
C13(α,n)O16 could be an energy source!

AGB stars low-Z (Cristallo+2009)

Observation of i-process signature



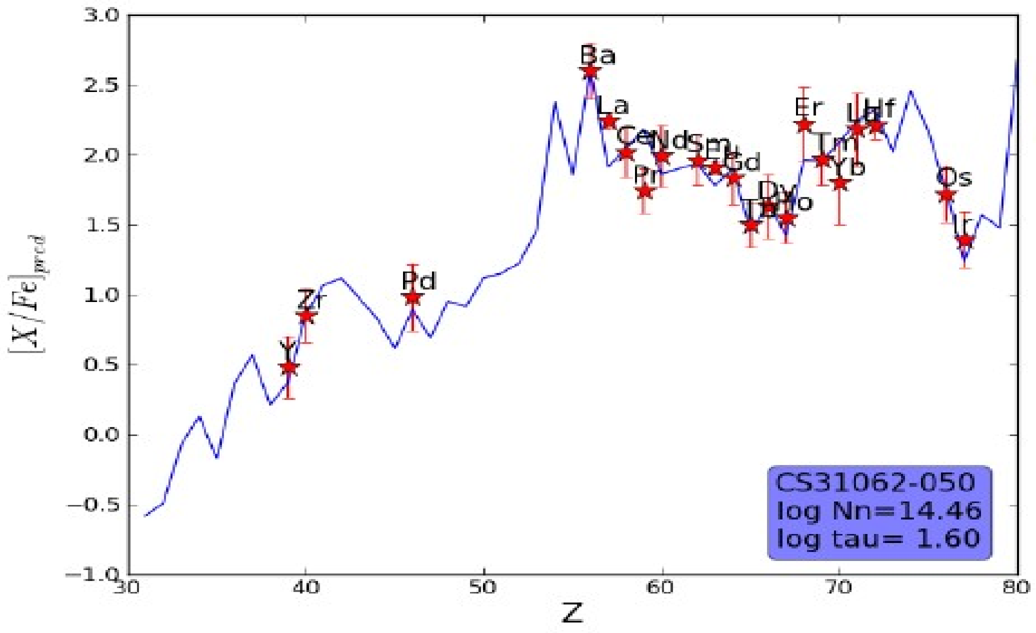
CEMP-rs stars → CEMP-i stars



Masseron et al. 2010

Among the CEMP-rs stars, several have clear i-process pattern, no s+r. For many candidates we do not have enough elements measured.

CEMP-i (Dardelet, et al. 2014, NIC PoS 145)
<u>One-zone calculation (1 minute in my laptop)</u>



<u>CEMP-rs/i (low mass AGB primary):</u>
e.g., Cristallo+ 2009, Bisterzo et al. 2012, Lugaro et al. 2012, Abate et al. 2016, Hampel et al. 2016, Caffau+ 2019, Choplin+ 2021, Karinkuzhi+ 2021

<u>Additional scenarios: iRAWDs, massive stars?</u>

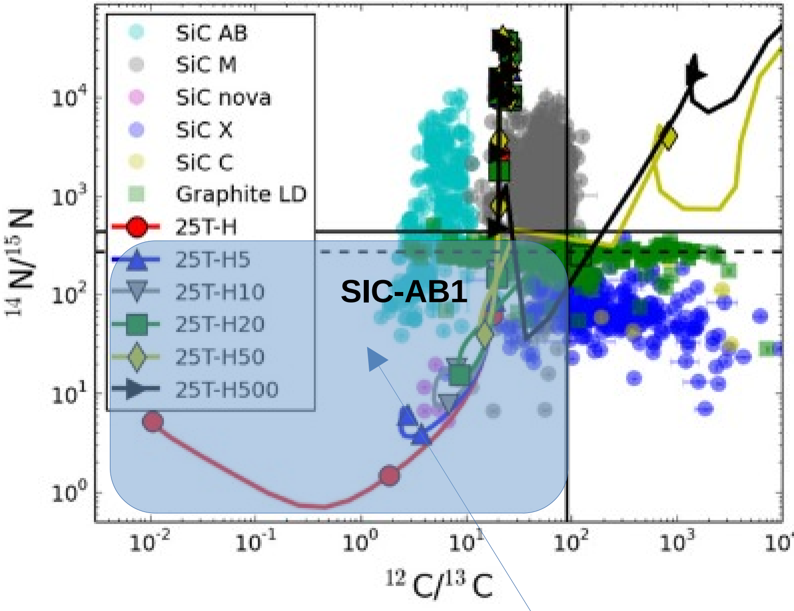
Without putting constraints on the i-process source(s), based on the nuclear reaction rates, we can say that:

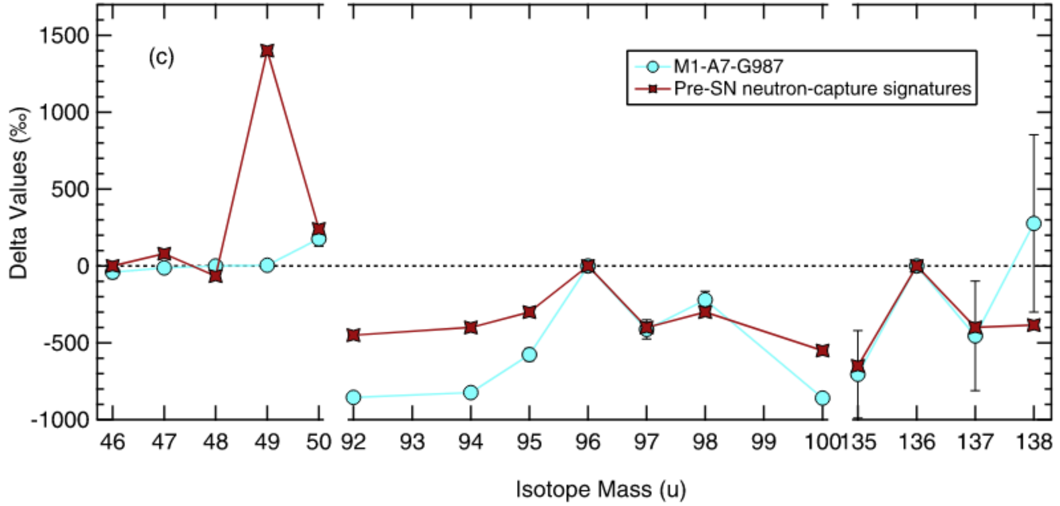
1) Typical abundance signatures in CEMP-s stars <u>cannot</u> be reproduced by i-process conditions

2) The abundance pattern of r-process stars <u>cannot</u> be reproduced by the i-process conditions

3) there are CEMP-sr stars that are not consistent with an s+r abundance pattern, and they are reproduced by the i process.

Is there always i-process after an H-ingestion event? NO





Pignatari+2015 ApJL

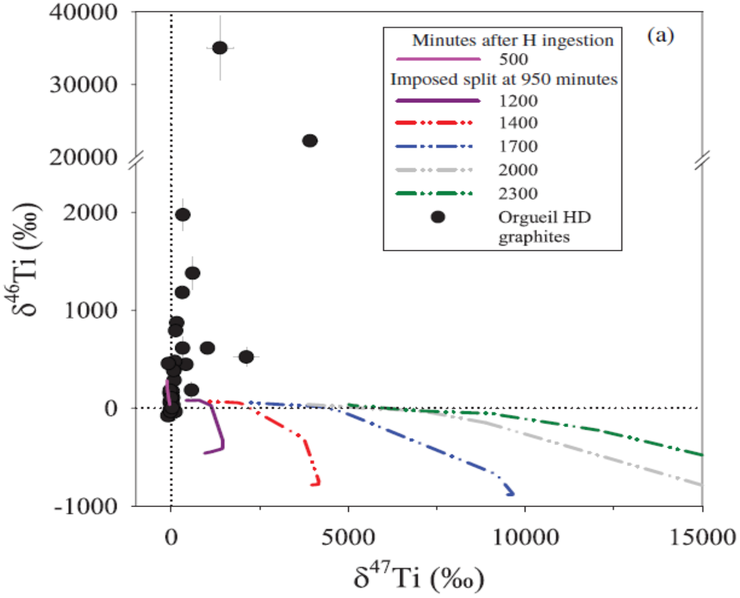
H-ingestion
+SN explosion

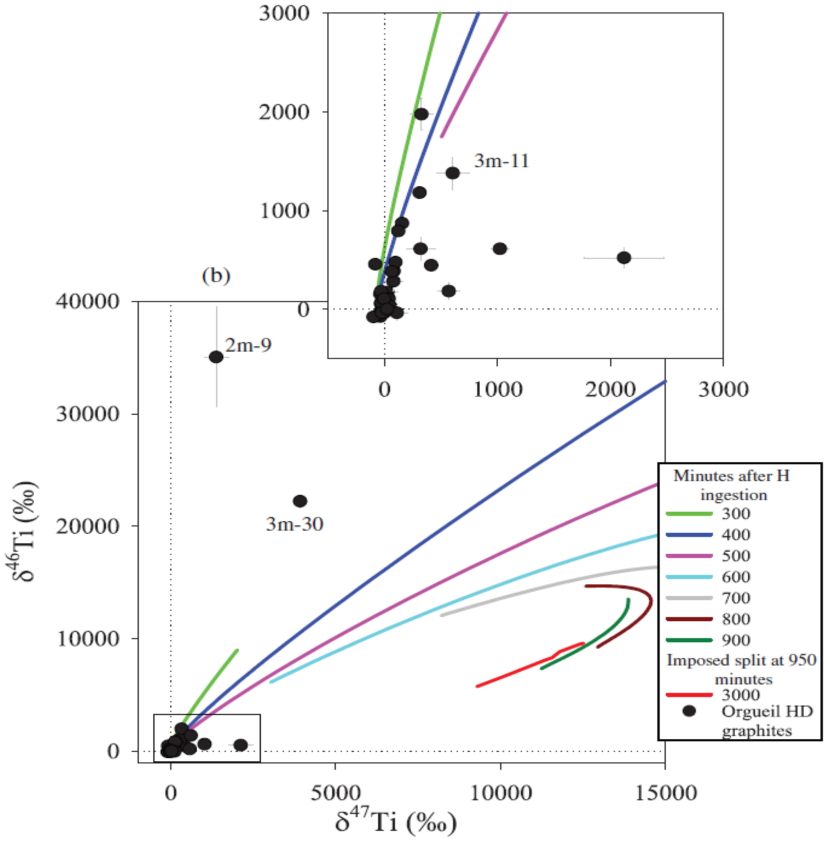
SiC-AB1 grains from massive stars show Mo and Ba with s-process signature of the preSN He shell. NO I-PROCESS! (and NO N-PROCESS!)
Liu, N. et al. 2019 ApJ 2018

Jadhav et al. 2013, ApJL
(Presolar HD graphites)

During SIMS measurements, <u>was not possible to resolve the stable isobars ^{46,48}Ca from the ^{46,48}Ti peaks.</u>

^{47}V 32.60 m β+	^{48}V 15.97 d β+	^{49}V 329.05 d β+	^{50}V 0.25 50 mb	^{51}V 99.75 38 mb
^{46}Ti 8.25 26.8 mb	^{47}Ti 7.44 64.4 mb	^{48}Ti 73.72 31.8 mb	^{49}Ti 5.41 22.1 mb	^{50}Ti 5.18 3.6 mb
^{45}Sc 100 69 mb	^{46}Sc 83.79 d β-	^{47}Sc 3.35 d β-	^{48}Sc 1.82 d β-	^{49}Sc 57.20 m β-
^{44}Ca 2.09 9.4 mb	^{45}Ca 162.62 d 17.5 mb, β-	^{46}Ca 0.004 5.3 mb	^{47}Ca 4.54 d β-	^{48}Ca 0.187 0.87 mb
^{43}K 22.30 h β-	^{44}K 22.13 m β-	^{45}K 17.30 m β-	^{46}K 1.75 m β-	^{47}K 17.50 s β-



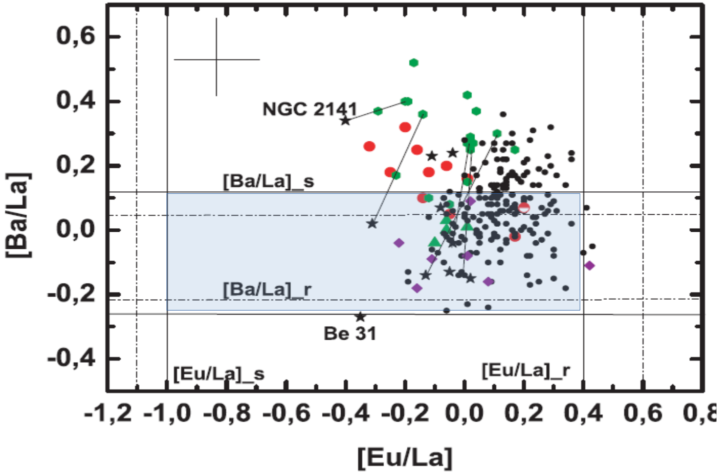


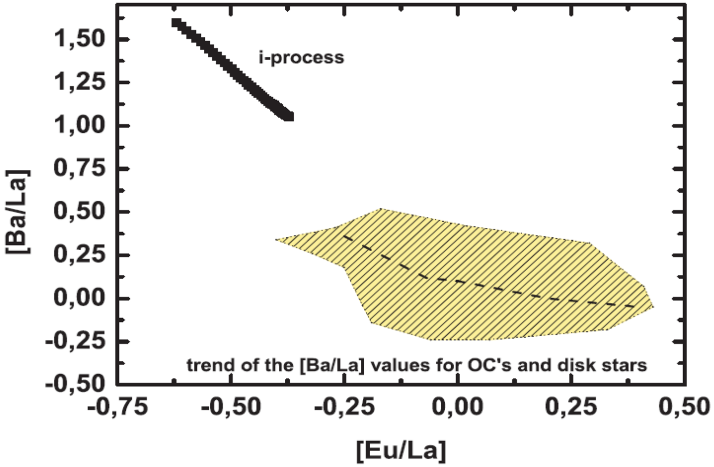
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

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?

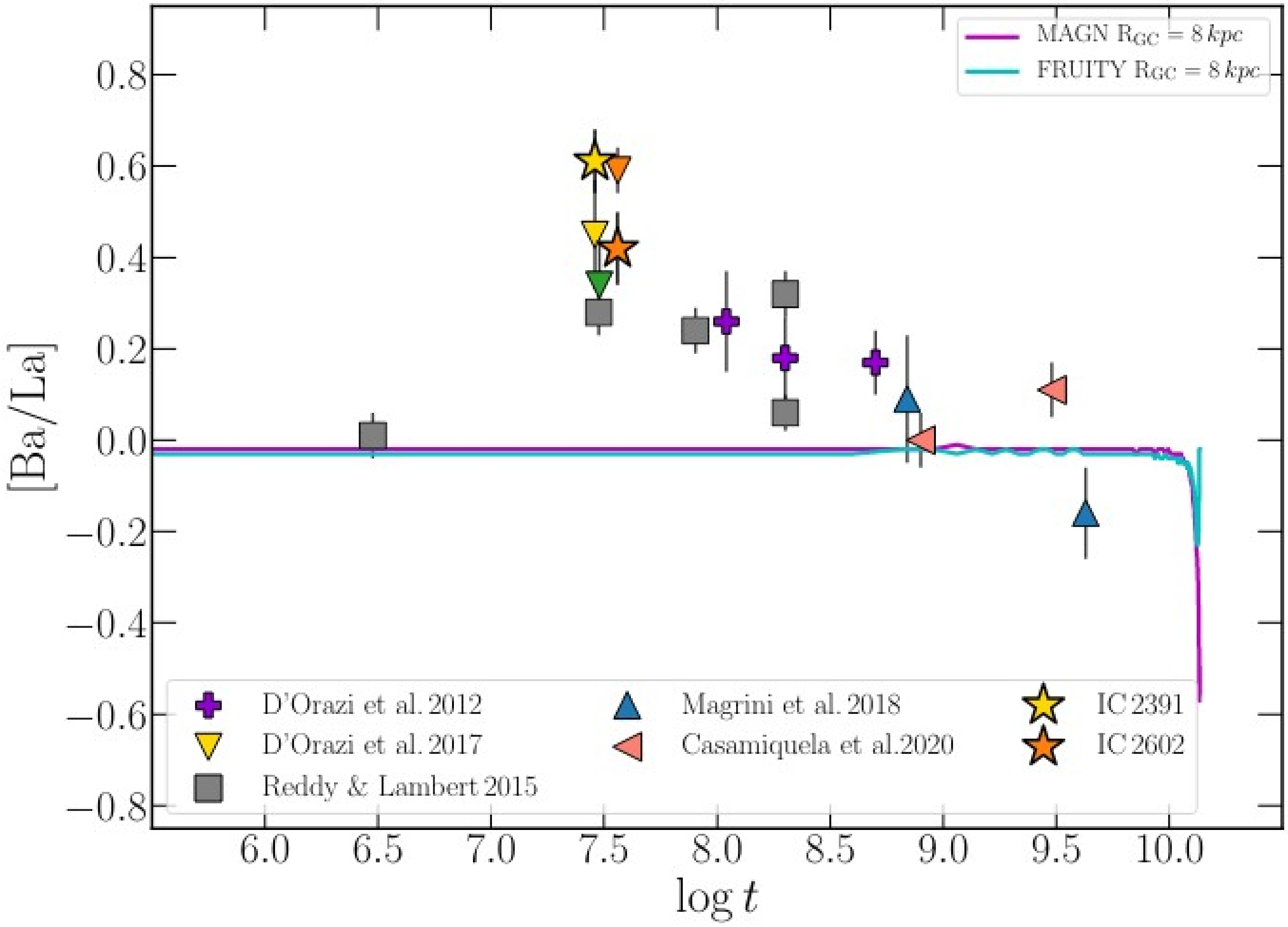
T. Mishenina,[1,2] M. Pignatari,[3]† G. Carraro,[4,5] V. Kovtyukh,[1,2]‡ L. Monaco,[4] S. Korotin,[1,2] E. Shereta,[1] I. Yegorova[4] and F. Herwig[6,7]†





<u>Observing the i process signature in OCs:</u>
Results of high Ba and low La and Ce <u>**confirmed**</u> recently by D'Orazi+ 2017 A&A, <u>**questioned**</u> by Reddy & Lambert 2017 ApJ. See also Maiorca+ 2012, Overbeek+ 2016… Baratella+2021 Under debate...

<u>**- What source?**</u>
- Still uncertainties about the spectroscopic observation of Ba



Baratella+ 2021 A&A

Beyond Bi, only the r-process can go?

A&A 667, L13 (2022)
https://doi.org/10.1051/0004-6361/202244928

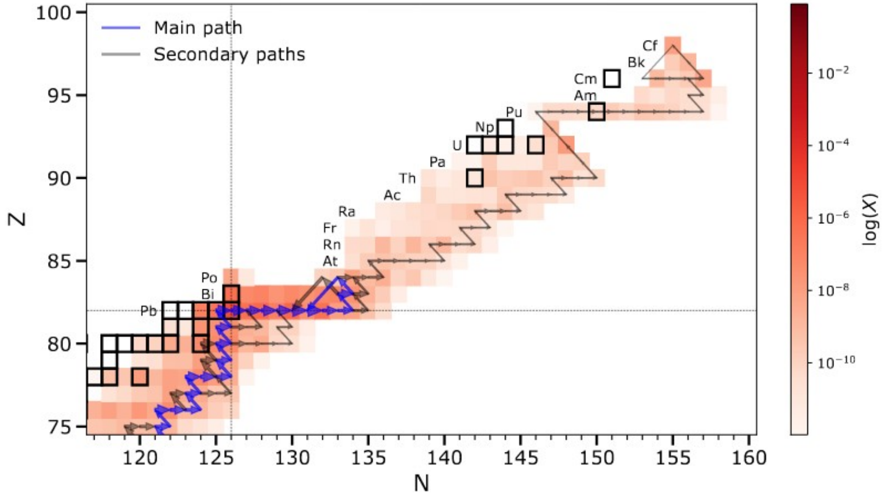
Astronomy & Astrophysics

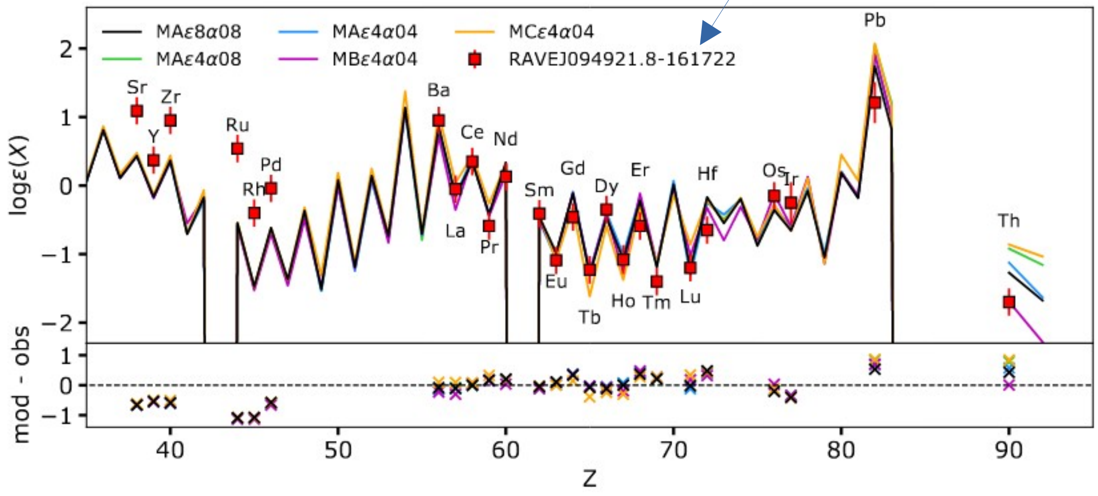
LETTER TO THE EDITOR

Synthesis of thorium and uranium in asymptotic giant branch stars

A. Choplin, S. Goriely, and L. Siess

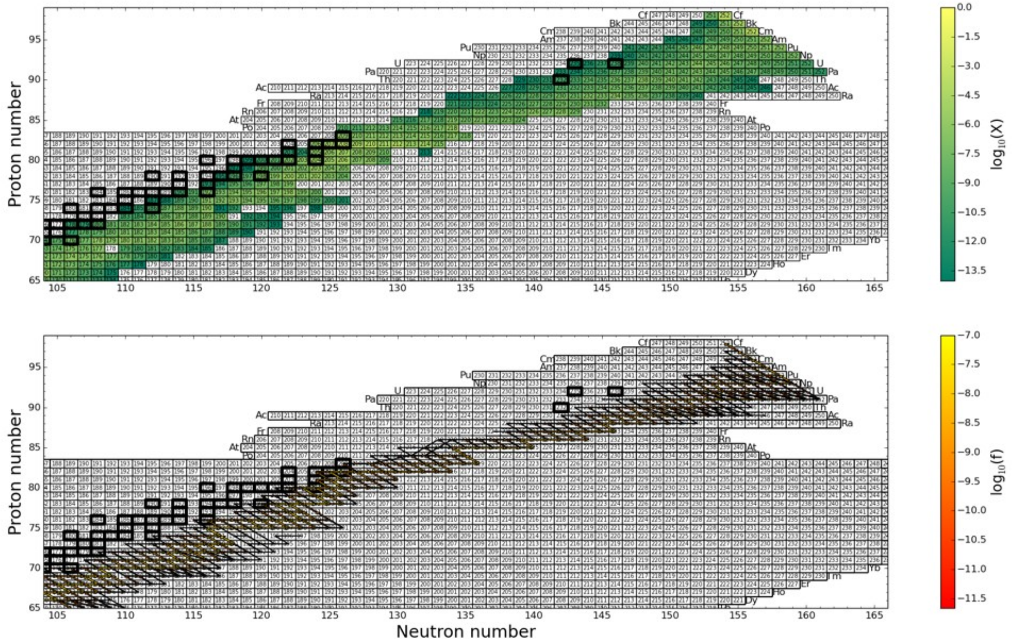
CEMP-rs star



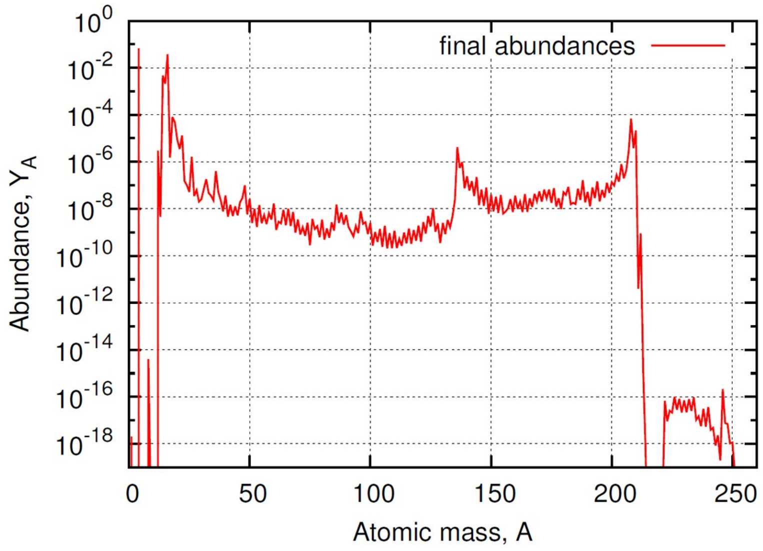


The i process can make Actinides including Th and U, **but how much**?

In i-process conditions bottlenecks in the Po-At region can be bypassed (see also **Kiss & Trócsányi 2010**)



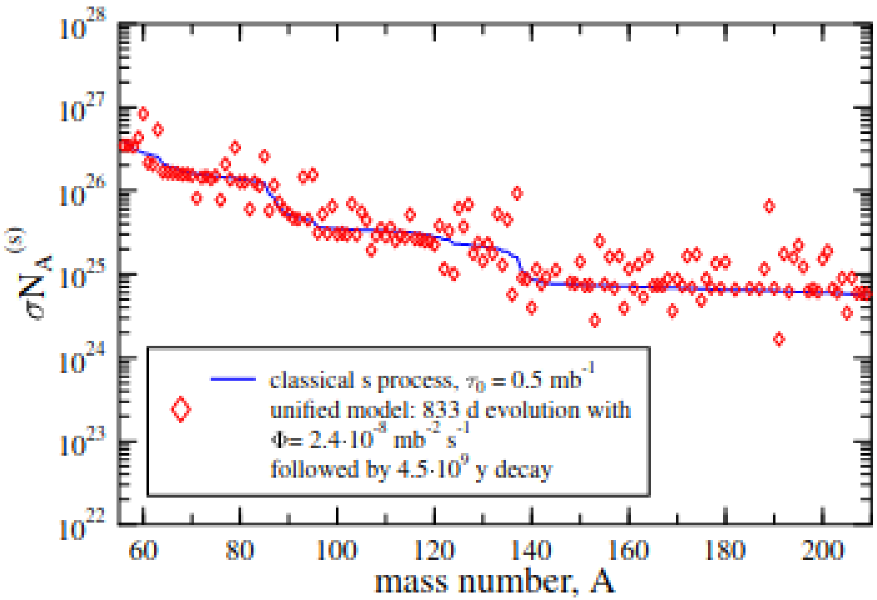
@ MP NuGrid run (2016):
Similar unpublished results by Stancliffe et al.



@ Oleg Korobkin run (2017):
Idea confirmed using full r-process net

From the i-process workshop at TRIUMF (2019)

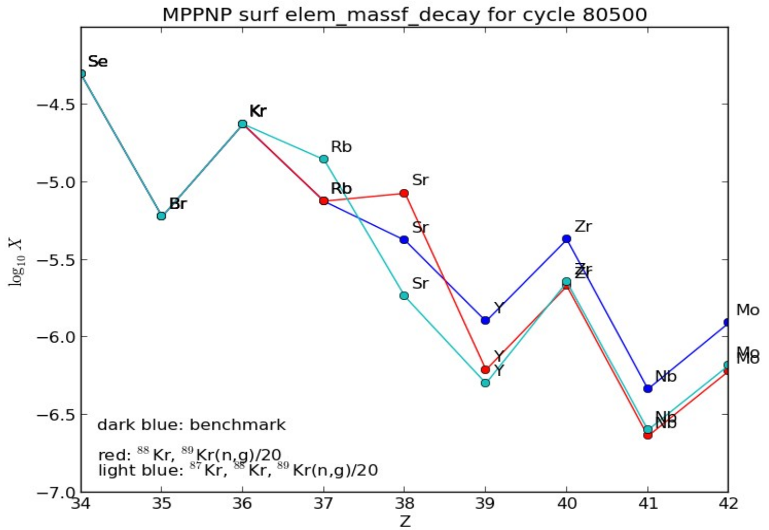
Kiss & Trócsányi 2010:
Journal of Physics: Conference Series, Volume 202, Issue 1



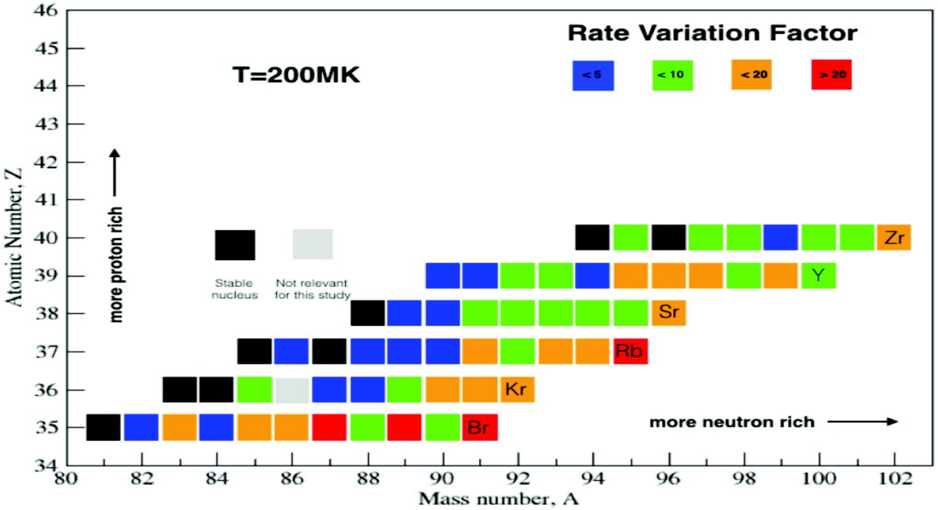
No follow-up full publication… The astrophysical scenario was missing.

decay quickly. However, some nuclei with long life time, such as ^{235}U and ^{238}U, remain for a long time. The abundances of such nuclei depend strongly on the neutron density. For the relatively modest value of $N_n = 10^{11}\,\mathrm{n\,cm}^{-3}$ the abundances of uranium isotopes is negligible as compared to the observable abundances of elements [8]. The observed abundances can be obtained with the model with the parameter value $\Phi \simeq 3 \cdot 10^{-5}\,\mathrm{mb}^{-2}\mathrm{s}^{-1}$ corresponding to $N_n \simeq 10^{14}\,\mathrm{n\,cm}^{-3}$ that is still six orders of magnitude smaller than the typical neutron density in supernovae [4].

Denissenkov et al. 2018 JPhG 45

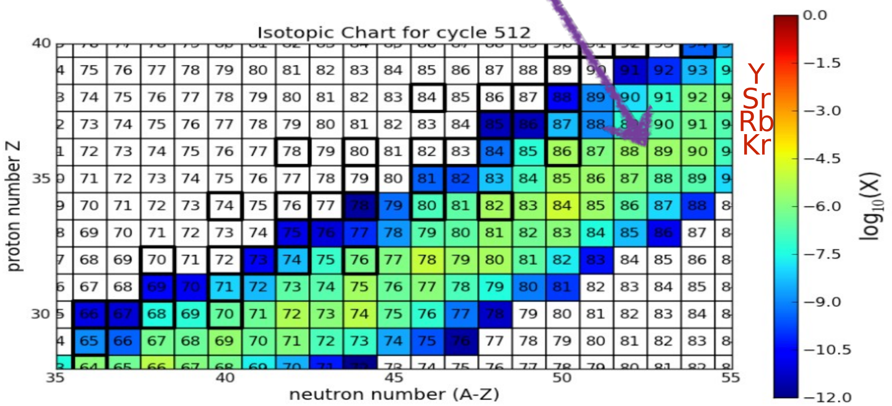


- nuclear data uncertainty impact: Kr89(n,γ)Kr90



Rate variation factor, based on uncertainty estimation.

Nuclear data needs for 1st-peak elements i process



Nuclear uncertainties studies (i-process)

- Bertolli+ 2013 arXiv (low Z, no site specific, N=82 zone)
- Denissenkov+ 2018 JPhG 45 (post AGBs, N=50 zone)
- McKay+ 2020 MNRAS 491 (no site specific, 32 < Z < 48)
- Goriely+ 2021 A&A 654 (low Z AGB, no Z specific)
- Denissenkov+ 2021 MNRAS 503 (iRAWDs, 56 < Z < 74)

Summary

- There are different i-process stellar sites: we cannot expect a robust i-process pattern.
- There is observational evidence that there may be H-ingestion without i-process (presolar grains from massive stars)
- Stellar modelling: a long way to go before validating all the potential i-process sites with multi-dimensional hydrodynamical simulations. However, it is possible to derive the information from 3D hydrodynamics simulations to validate 1D models (➔ CeNAM).
- The GCE i-process contribution could be hiding in the solar r-process (better: non-s process) residual. All the way up to U and Th? What about Ba in open clusters?
- What is the range of neutron exposures that can be reached by the i-process in the different stellar sites for different metallicities?
- Impact of nuclear uncertainties: a lot can be done for this in the next years.

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