WP3: Computational Program

Astrophysical reaction rates and nucleosynthesis simulations for appropriate stellar models

Impact on questions **Q1** and **Q2**

Is there a nuclear solution to the cosmological lithium problem?

How did first-generation stars produce CNO elements?

WP3: Tasks (T)

- T3.1: Reaction rates calculations from available experimental data (PDRA1 – year 1 & 2)
- T3.2: Novel assessment of Li and CNO nucleosynthesis in zero-metallicity stars (PDRA3 & MP – year 3+)
  - M = 15, 40, 60, 80, 140 $M_\odot$ + M = 150, 200, 250, 500, 750 and 1000 $M_\odot$, Z = 0 -- MESA + NuGrid
- T3.3: Stellar simulations to quantify the impact of nuclear uncertainties (PDRA3 & MP – year 3+)
  - Impact on the stellar energy budget considering the rates provided by T3.1 on a subset of models (15, 80, 200, 1000 $M_\odot$)

$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu$$
$$^{2}\mathrm{D} + {}^{1}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma$$

$$^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2\,{}^{1}\mathrm{H}$$

$\boxed{\mathrm{ppI}}$

$$^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$$

To make and destroy...

$$^{7}\mathrm{Be} + e^{-} \rightarrow {}^{7}\mathrm{Li} + \nu$$
$$^{7}\mathrm{Li} + {}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$

$\boxed{\mathrm{ppII}}$

$$^{7}\mathrm{Be} + {}^{1}\mathrm{H} \rightarrow {}^{8}\mathrm{B} + \gamma$$
$$^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be}^{*} + e^{+} + \nu$$
$$^{8}\mathrm{Be}^{*} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$

$\boxed{\mathrm{ppIII}}$

The Cameron-Fowler Beryllium Transport Mechanism

$$^{7}\mathrm{Li}\,(p,\alpha)^{4}\mathrm{He} \;=\; \mathrm{ppII}$$

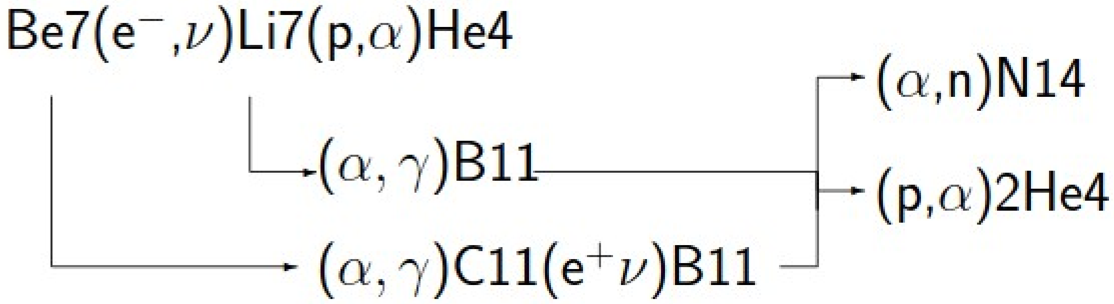
$$^{3}\mathrm{He}\,(\alpha,\gamma)^{7}\,\mathrm{Be}\,(\beta^{-},\nu)^{7}\,\mathrm{Li}$$

$$^{7}\mathrm{Be}\,(p,\gamma)^{8}\mathrm{B}\,(\beta^{+}\nu)^{8}\mathrm{Be}\,(\alpha)^{4}\mathrm{He} \;=\; \mathrm{ppIII}$$

To make without destroying

Lattanzio+ 2015 MNRAS 446

… in H-depleted stellar material:

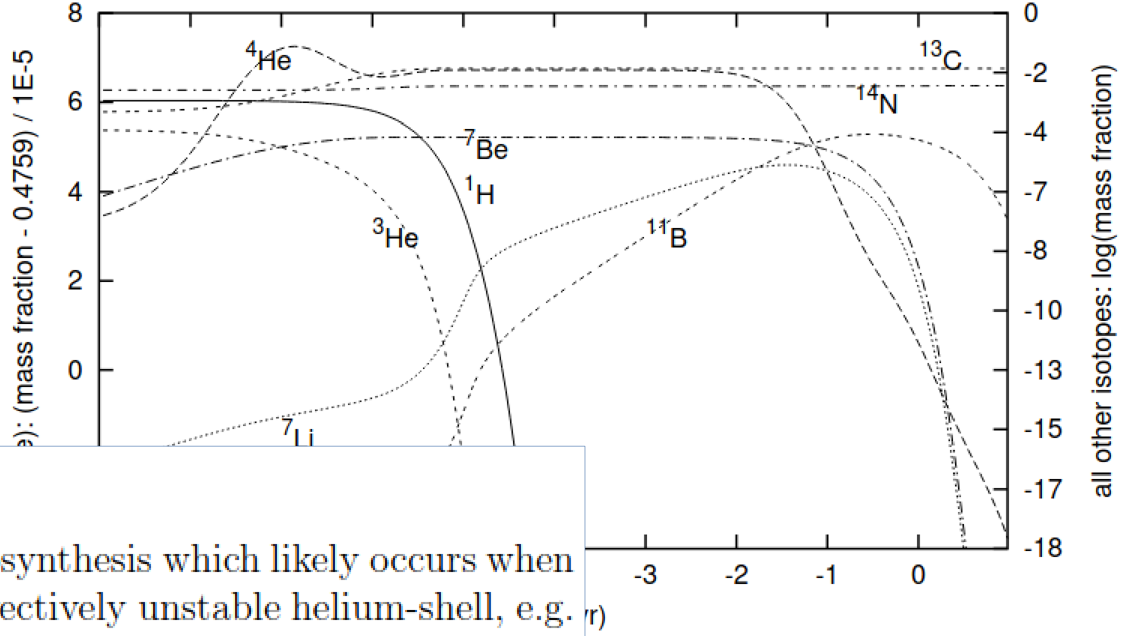


Herwig & Langer 2001 Nuc Phys A 688

To make and destroy…
or to make without destroying?

Convective proton and ^{3}He ingestion into helium burning: Nucleosynthesis during a post-AGB thermal pulse

Falk Herwig[a,b,*] and Norbert Langer[c]

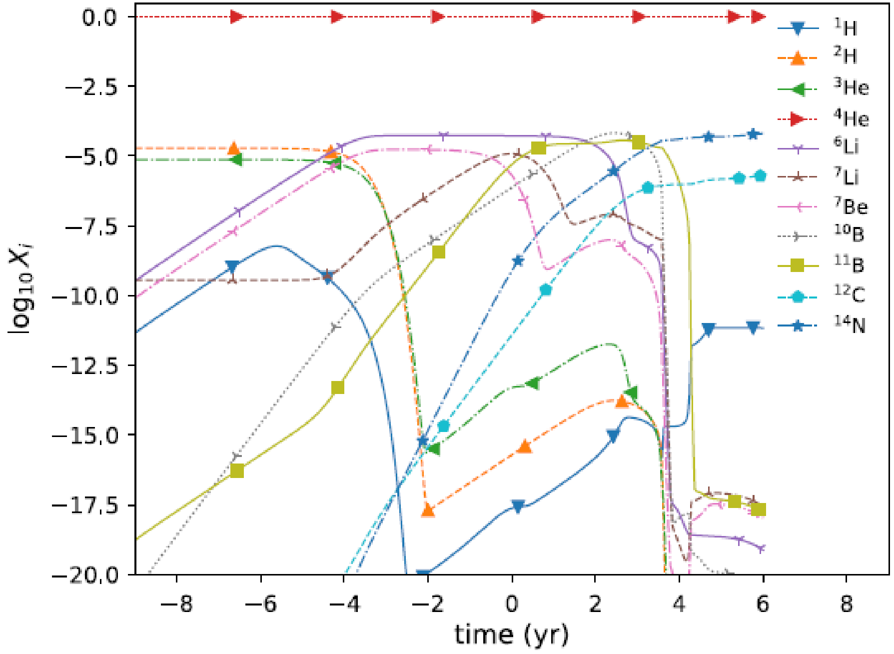


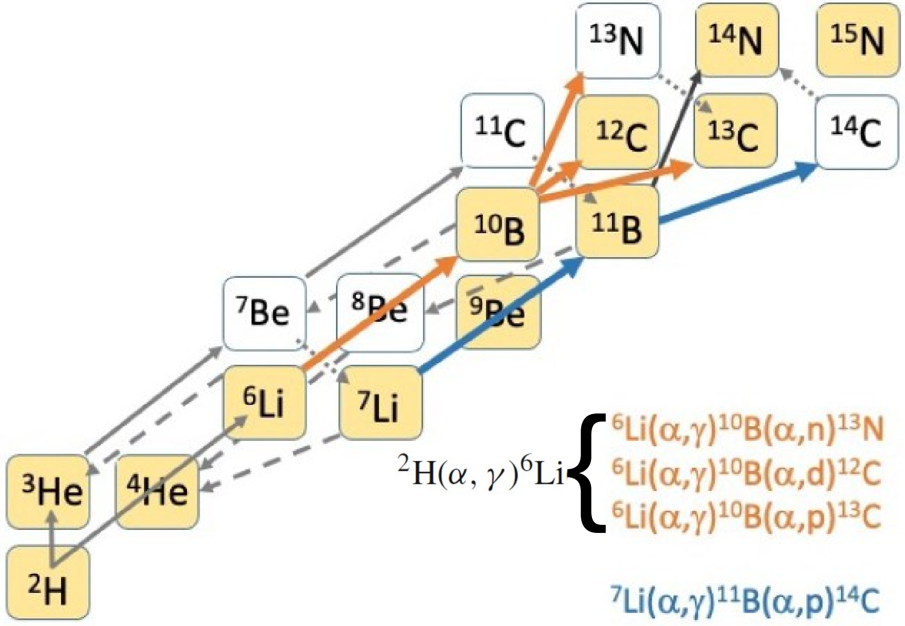
3. Conclusions

We have presented a new mode of light element nucleosynthesis which likely occurs when unprocessed material is ingested into an active and convectively unstable helium-shell, e.g. during a very late post-AGB thermal pulse. We have, however, not yet modelled in detail the mixing processes which ultimately bring the lithium into the atmosphere. Given the fragile constitution of lithium, most other sources of lithium in stars like *Sakurai's* object can be ruled out. We thus conclude that the proposed mechanism might be responsible for some of the lithium abundance anomalies observed in stars.

Also considering the impact of the Li6 channel:

(see discussion in Wiescher+ 2021 Eur. Phys. J. A)



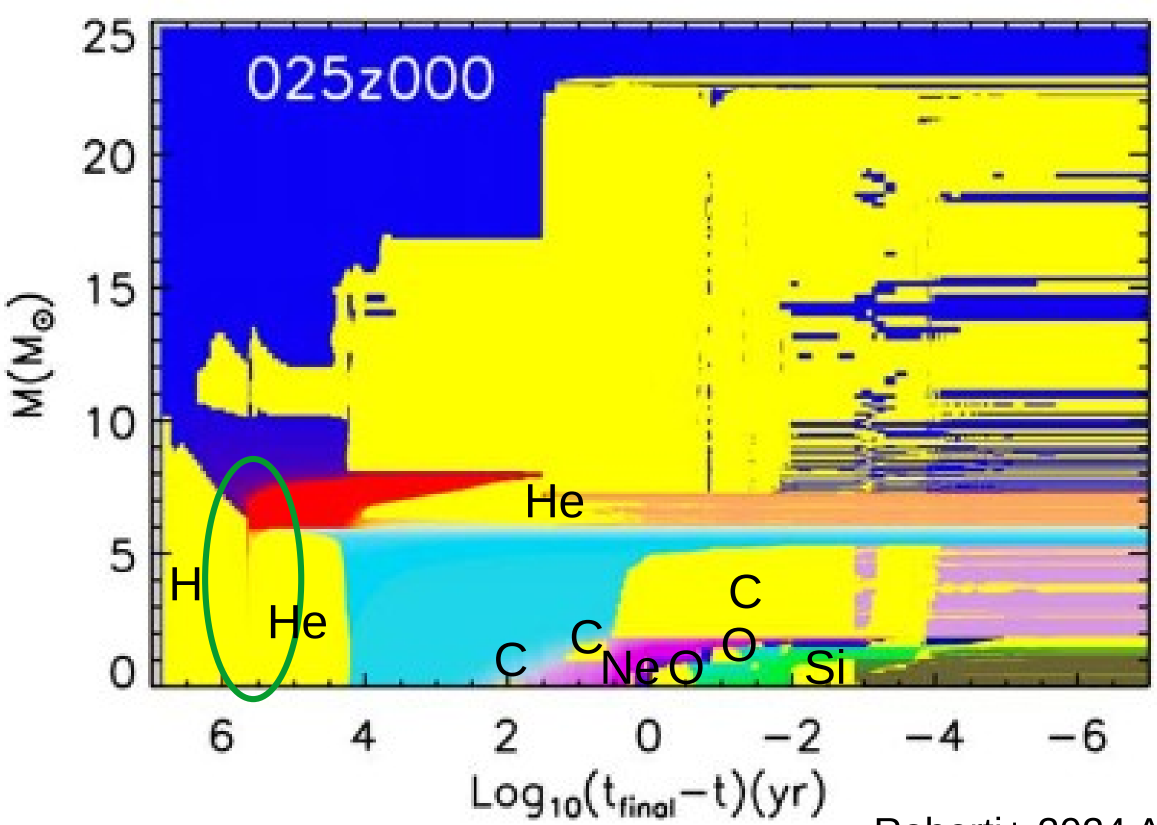


Q2: How did first-generation stars produce CNO elements?

For [Fe/H] > −5, CNO cycle dominates over pp-chain for intermediate-mass and massive stars.

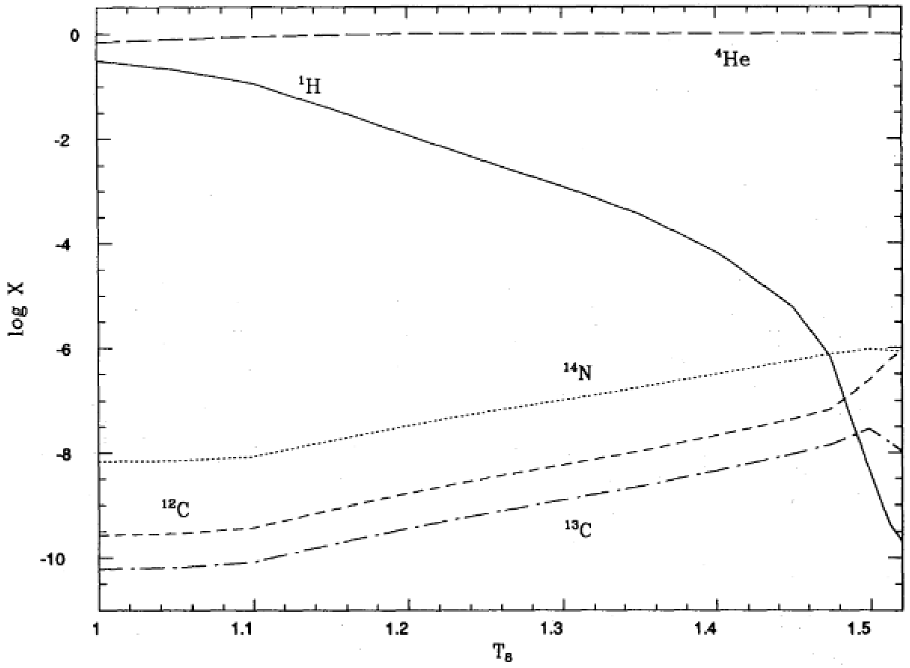
For [Fe/H] < −5, pp-chain only cannot power the stellar structure properly

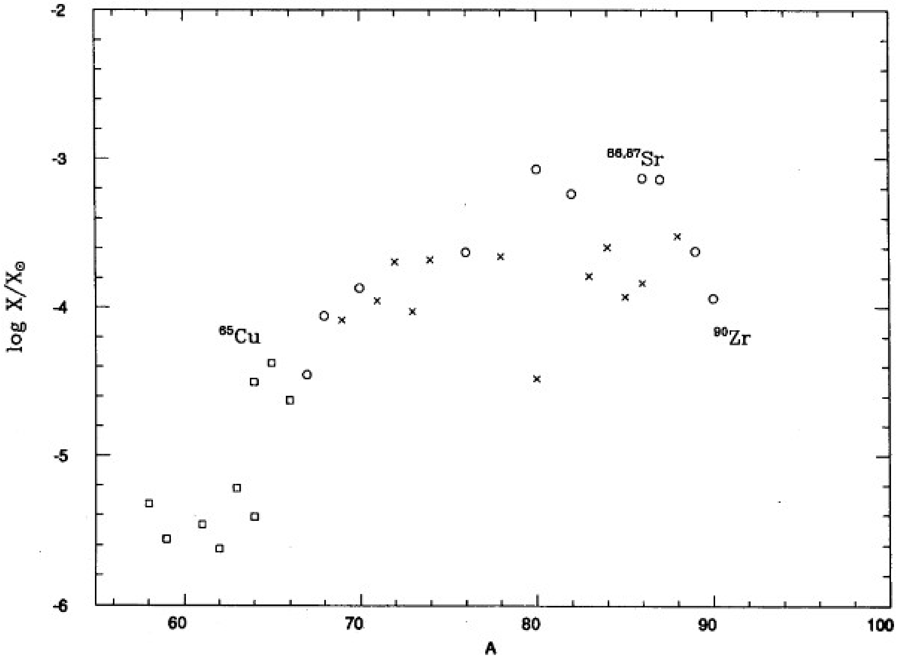
He-fusion starts to work at the end of central H burning → primary C12 → CNO cycle activated



Roberti+ 2024 ApJS 270

Example of a possible impact:
S-process production from the C13 made at the end of H burning





Baraffe+ 1992 A&A 258

… more in general, we can explore the production of the first heavy elements.

Q2: Is there a nuclear solution to the cosmological lithium problem?

The Astrophysical Journal, 653:300–315, 2006 December 10

FROM FIRST STARS TO THE SPITE PLATEAU: A POSSIBLE RECONCILIATION OF HALO STARS OBSERVATIONS WITH PREDICTIONS FROM BIG BANG NUCLEOSYNTHESIS

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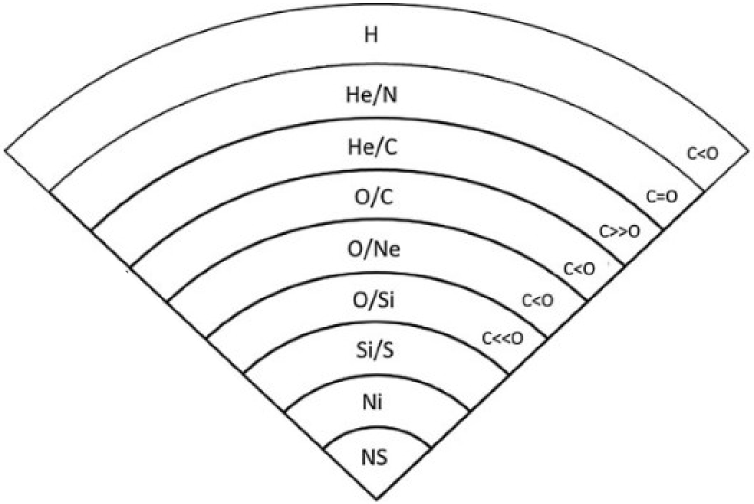
J. W. Truran
Department of Astronomy and Astrophysics, University of Chicago, 933 East 56th Street, Chicago, Il, 60637; and Physics Division, Argonne National Laboratory, 9700 South Cass Road, Argonne, IL 60439-4863; truran@nova.uchicago.edu

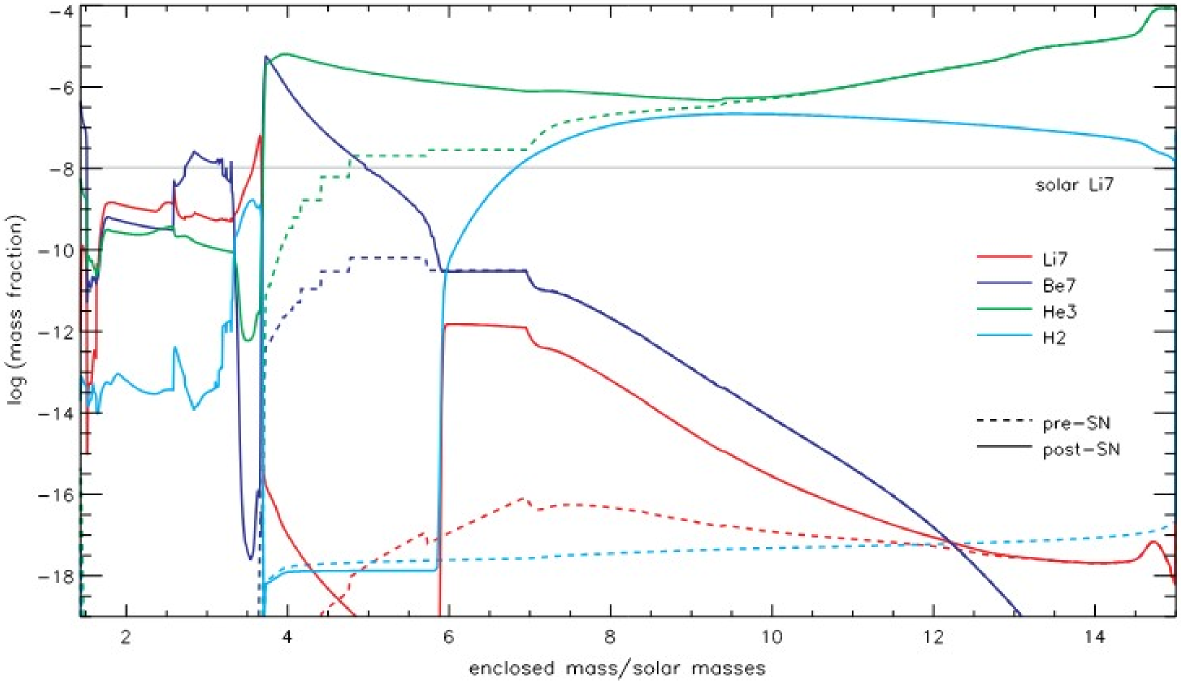
and

J. W. Ferguson



… from Piau+ 2006, page 306:

“Hence, it may be premature to conclude that lithium production cannot have had an early impact. Bearing the above in mind, we neglected 7 Li-production processes in our discussion.”



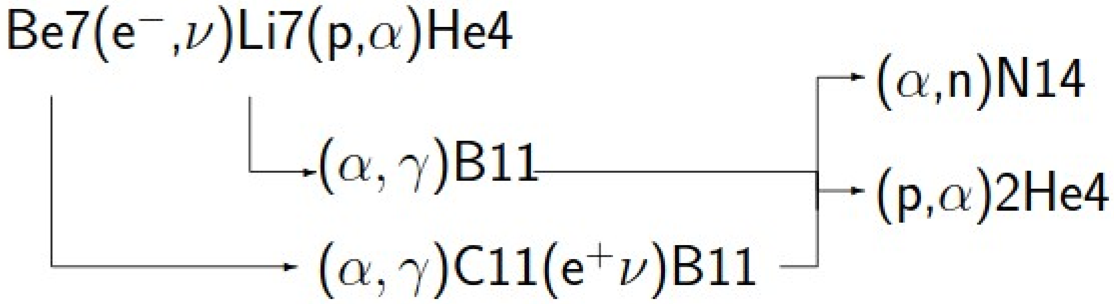
Heger & Woosley 2010 ApJ 724

Production channels:

$$^{4}\mathrm{He}(\nu_{\mu,\tau},n)^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$$

$$\bar{\nu}_{\mathrm{e}}(\mathrm{p},\mathrm{e}^{+})\mathrm{n}(\mathrm{p},\gamma)^{2}\mathrm{H}(\mathrm{p},\gamma)^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$$

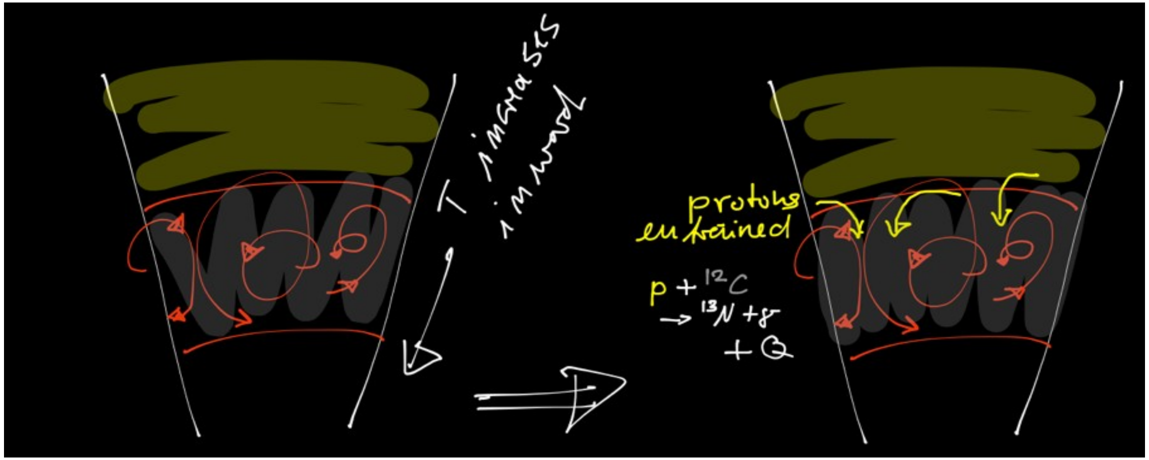
… in H-depleted stellar material:

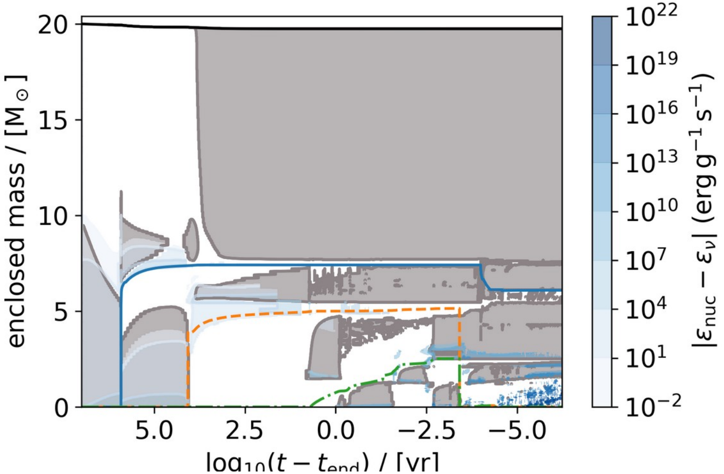


Herwig & Langer 2001 Nuc Phys A 688

To make and destroy…

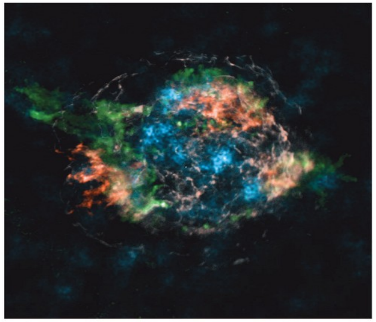
or to make without destroying?





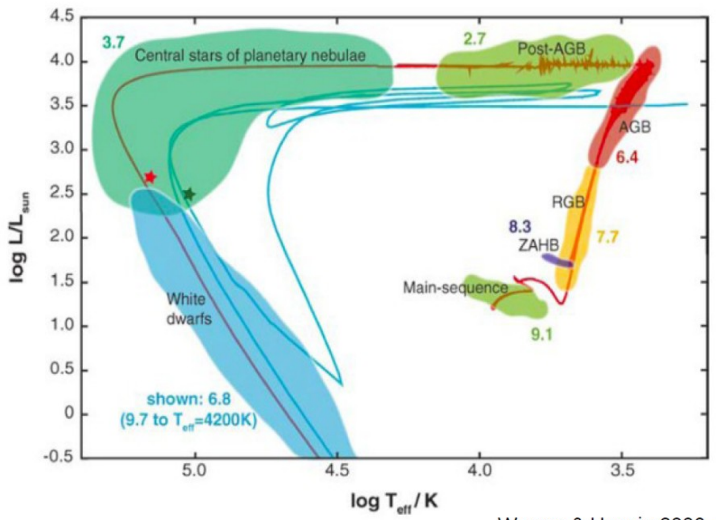
<u>H-ingestion</u>: Ingestion of H in a convective He environment.
→ High production of Li7, C13, N14, N15 (?), Al26 (?)

<u>Example</u>: 20Msun star
From Ritter+2018



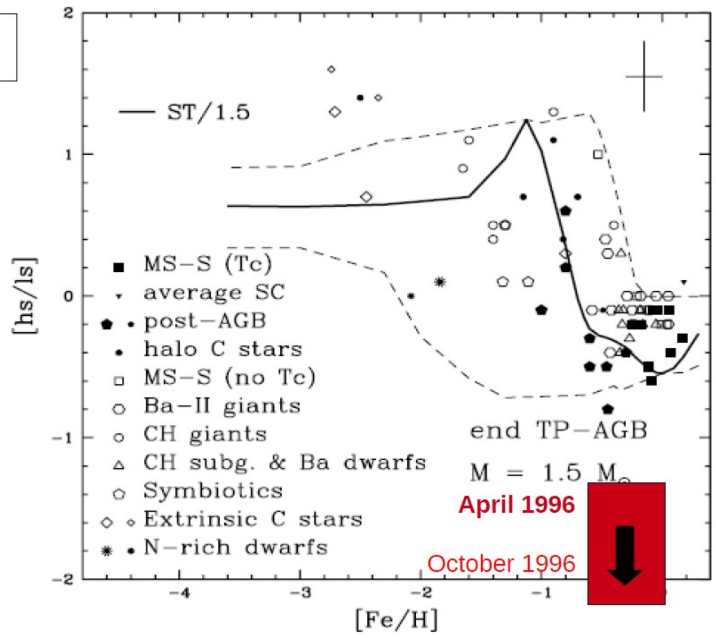
SN shock in the former He shell when H still present, temperature rising up to ~ 1.-1.2 GK.

Mixture of H-burning and He-burning in explosive conditions (timescale ~ 1 sec).



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 H-ingestion:
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.

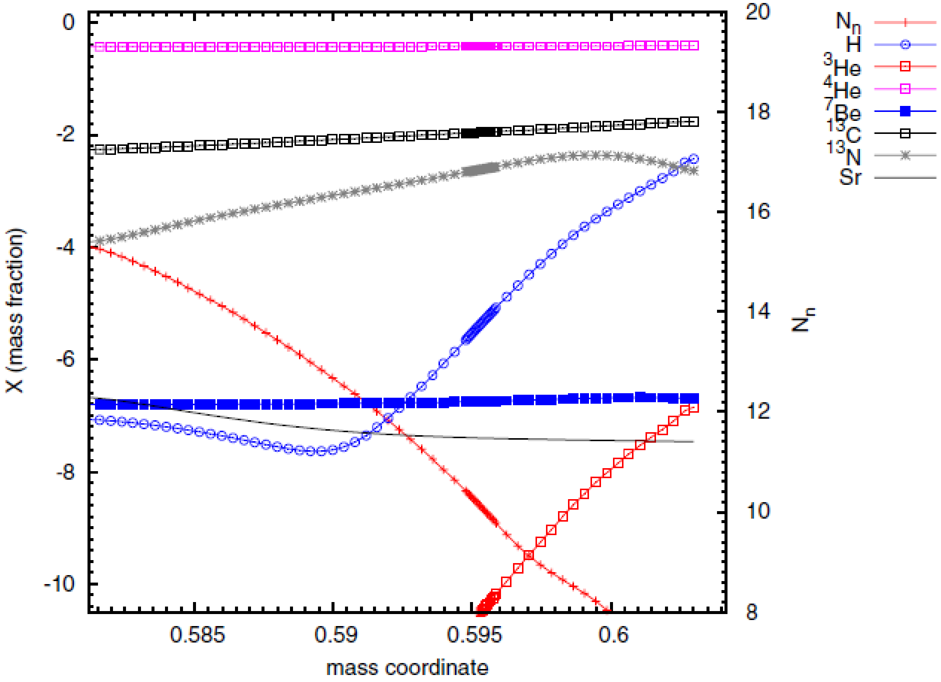
The Astrophysical Journal, 727:89 (15pp), 2011 February 1 doi:10.1088/0004-637X/727/2/89

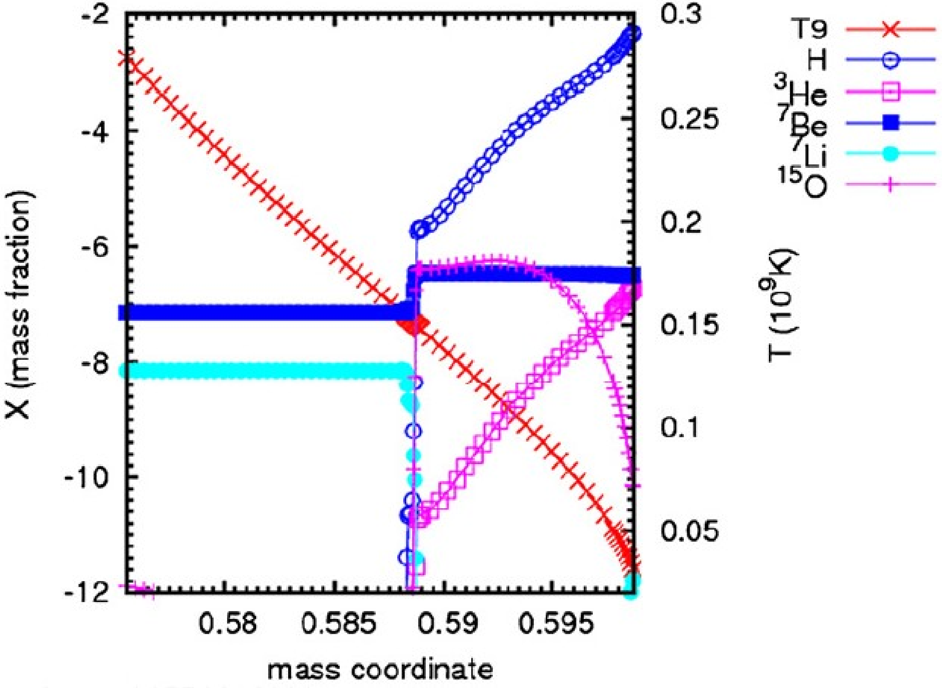
CONVECTIVE–REACTIVE PROTON–^{12}C COMBUSTION IN SAKURAI'S OBJECT (V4334 SAGITTARII) AND IMPLICATIONS FOR THE EVOLUTION AND YIELDS FROM THE FIRST GENERATIONS OF STARS

Falk Herwig[1,10], Marco Pignatari[1,2,3,10], Paul R. Woodward[4], David H. Porter[5], Gabriel Rockefeller[6,7,10], Chris L. Fryer[6,7,10], Michael Bennett[8,10], and Raphael Hirschi[8,9,10]

Element	Sun[a]	Sakurai's object in 1996					R CrB	V854 Cen[c]
		April 20–25	May 5–9	June 4	July 3	October 7	majority[b]	
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]

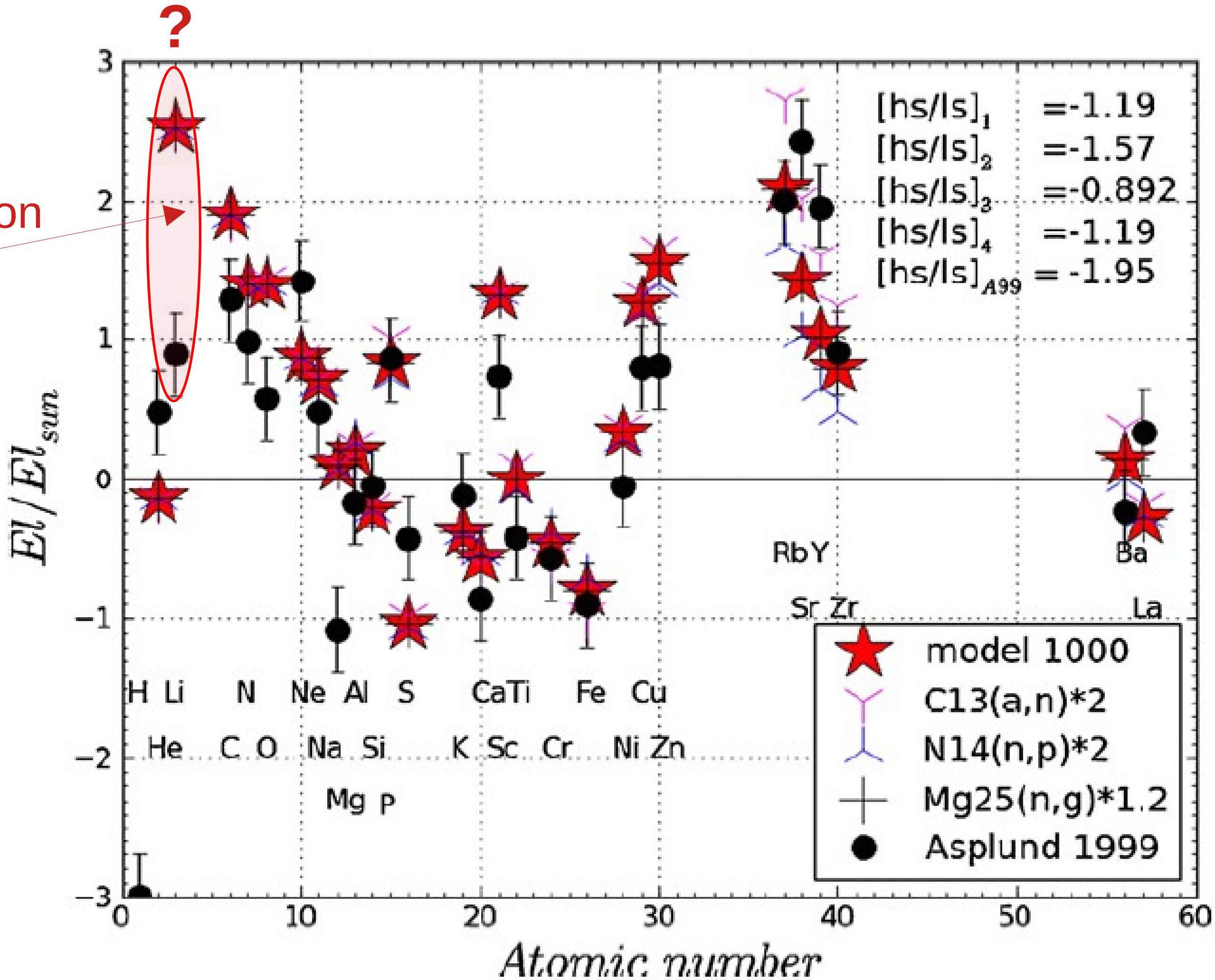
Asplund+ 1999 A&A 343



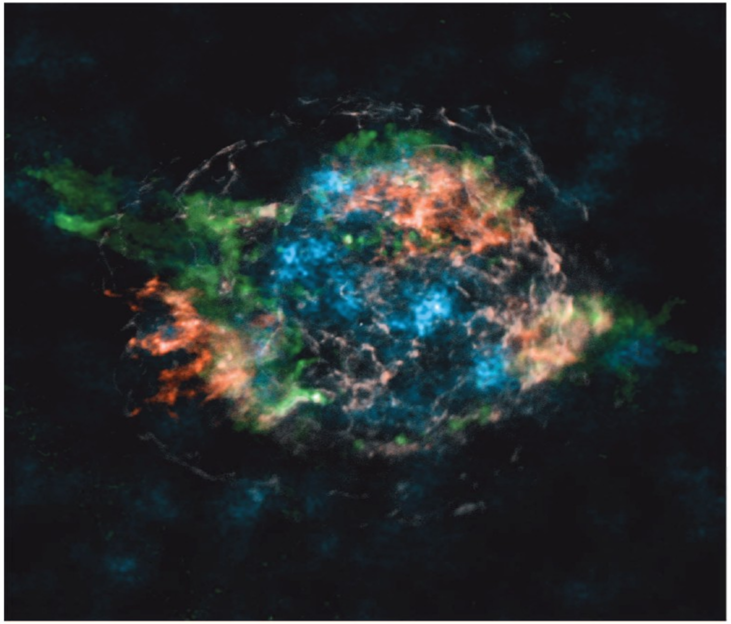


Herwig+ 2011 ApJ 727

Nuclear reaction rate issue?



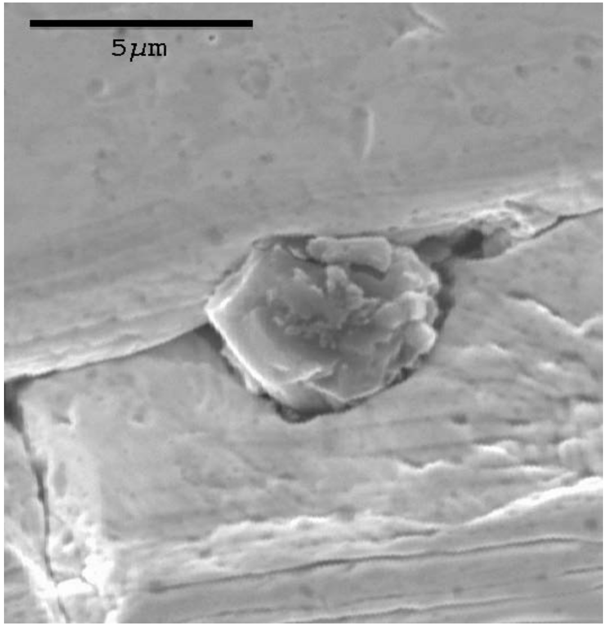
CCSN remnant



Cas A
11000 ly
~ 300 years ago

See Grefenstette et al. 2014, Nature
(NuSTAR data)

Presolar grain from an old CCSN



From Reto Trappitsch (Uni of Chicago)

unknown
? - (today in a lab)
~ 4.5-5 Gyrs ago

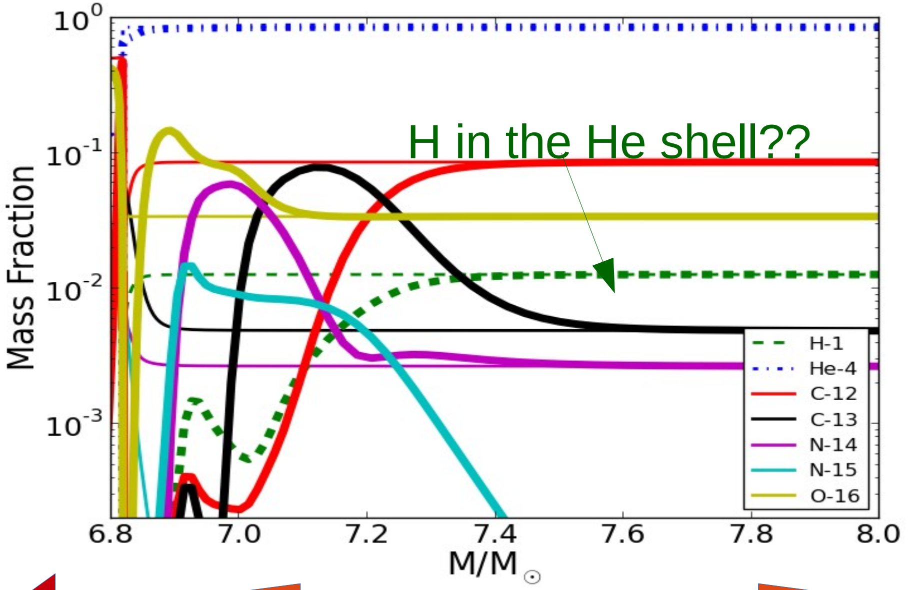
Zinner 2014, Tr. Geochem.

The Astrophysical Journal Letters, 808:L43 (6pp), 2015 August 1 doi:10.1088/2041-8205/808/2/L43

CARBON-RICH PRESOLAR GRAINS FROM MASSIVE STARS: SUBSOLAR $^{12}C/^{13}C$ AND $^{14}N/^{15}N$ RATIOS AND THE MYSTERY OF ^{15}N

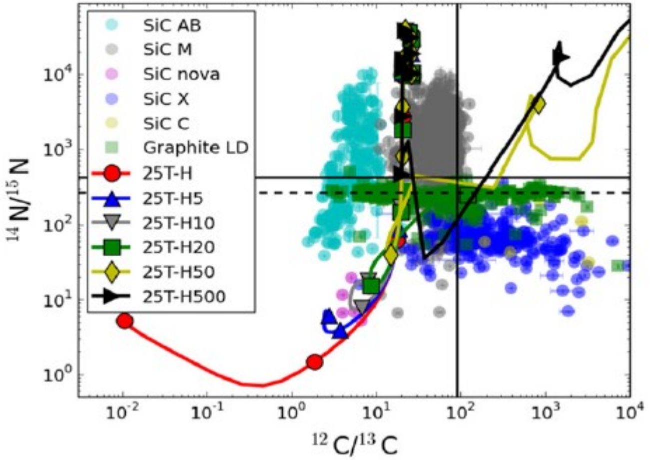
M. Pignatari[1,2,13], E. Zinner[3], P. Hoppe[4], C. J. Jordan[5,14], B. K. Gibson[5,14], R. Trappitsch[6,13], F. Herwig[7,8,13], C. Fryer[9,13], R. Hirschi[10,11,13,14], and F. X. Timmes[8,12,13]

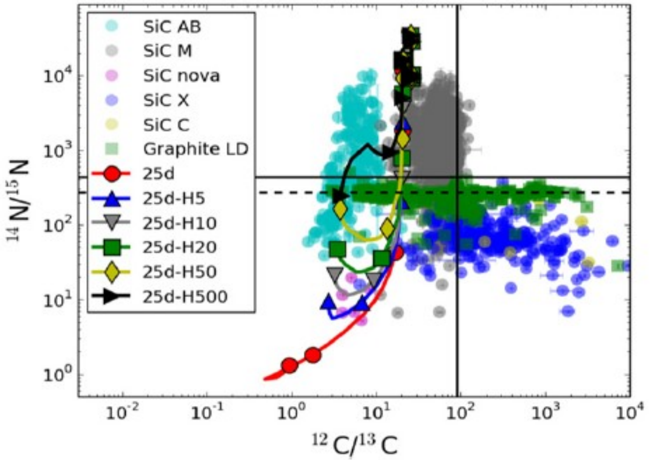
Model 25T
Metallicity = Z=0.02
Explosive He shell nucleosynthesis with H ingested still alive

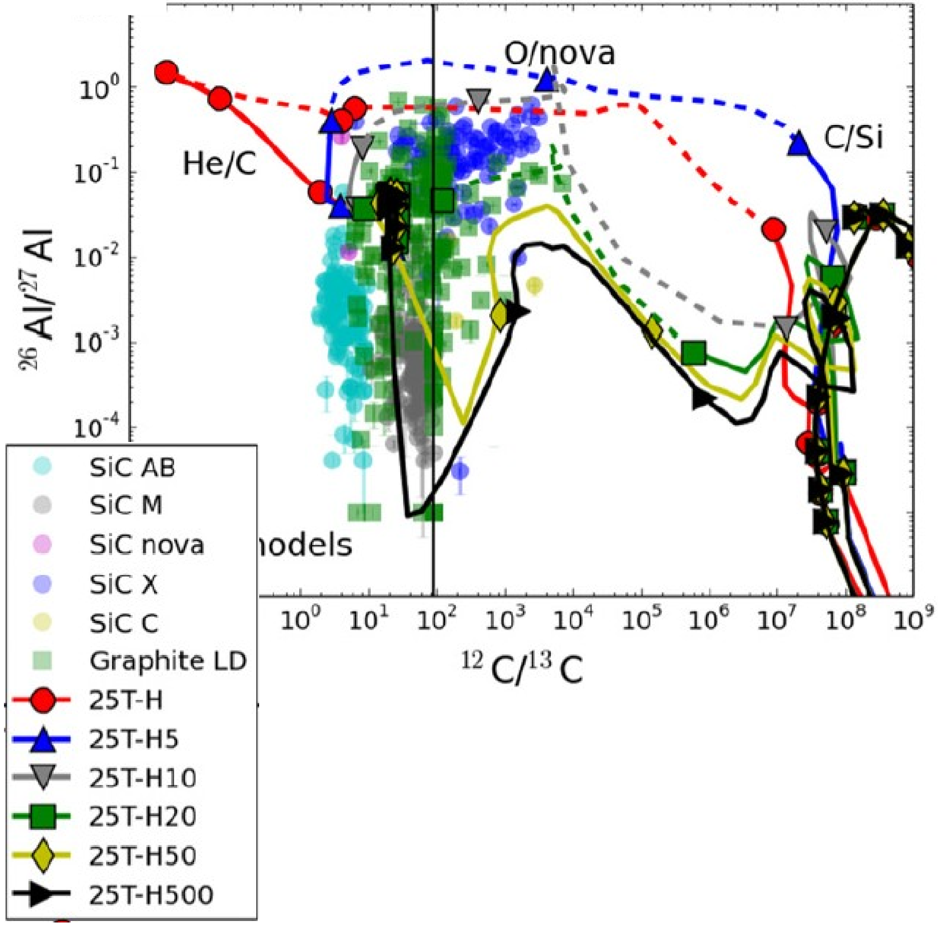


Centre of the star

He-shell layers

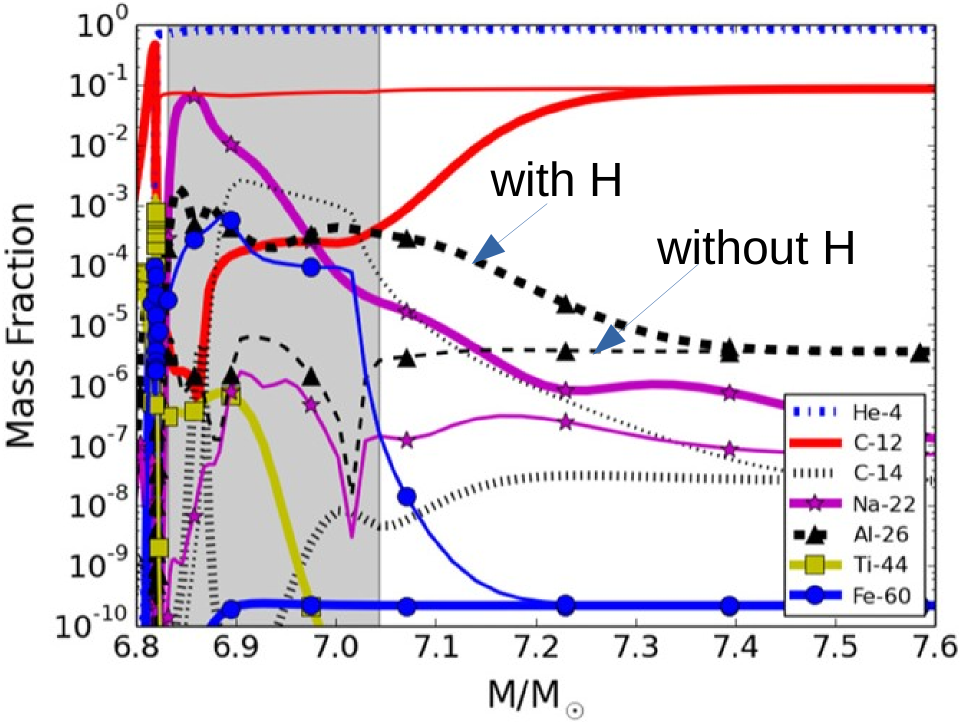


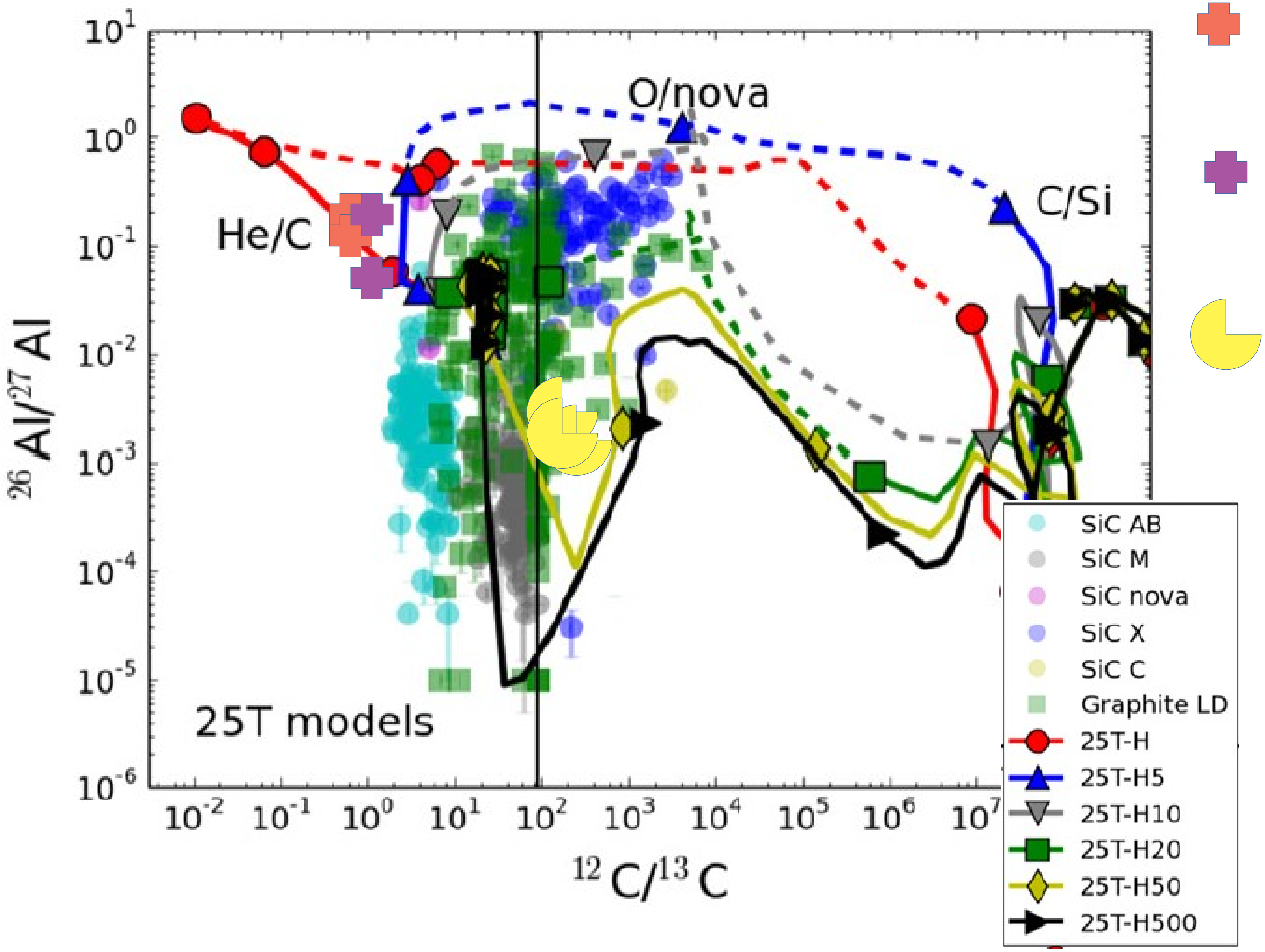




Without H (standard)
+ He burn
+ neutron burst
+ C14, Al26, Fe60

With H
+ He-H burn
+ no n burst
+++ Na22, Al26





CO Nova
Denissenkov et al. 2014

One Nova
Denissenkov et al. 2014

AGB stars
Ritter et al. 2018

H-ingestion sites:
(with the potential Li production)

- <u>Post AGB stars</u>, all Z (e.g., Fujimoto+ 1977, Iben+ 1982, Miller Bertolami+ 2006, Herwig+ 2011, Herwig+ 2014, Woodward+ 2015)
- <u>Low mass stars and AGB stars</u>, 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...)
- <u>Super AGB stars</u>, low Z (Jones+ 2016)
- <u>Massive stars</u>, all Z (e.g., Woosley & Weaver 1995, Limongi & Chieffi 2012, Pignatari+ 2015, Roederer+ 2016, Clarkson+ 2018, Banerjee+ 2018, Clarkson+ 2021)
- <u>Stellar binaries</u>: iRAWDs, all Z (Denissenkov+ 2017, 2019, Côté+ 2018, Battino+ 2020, Stephens+ 2021)

Choplin+ 2024 Galaxies 12

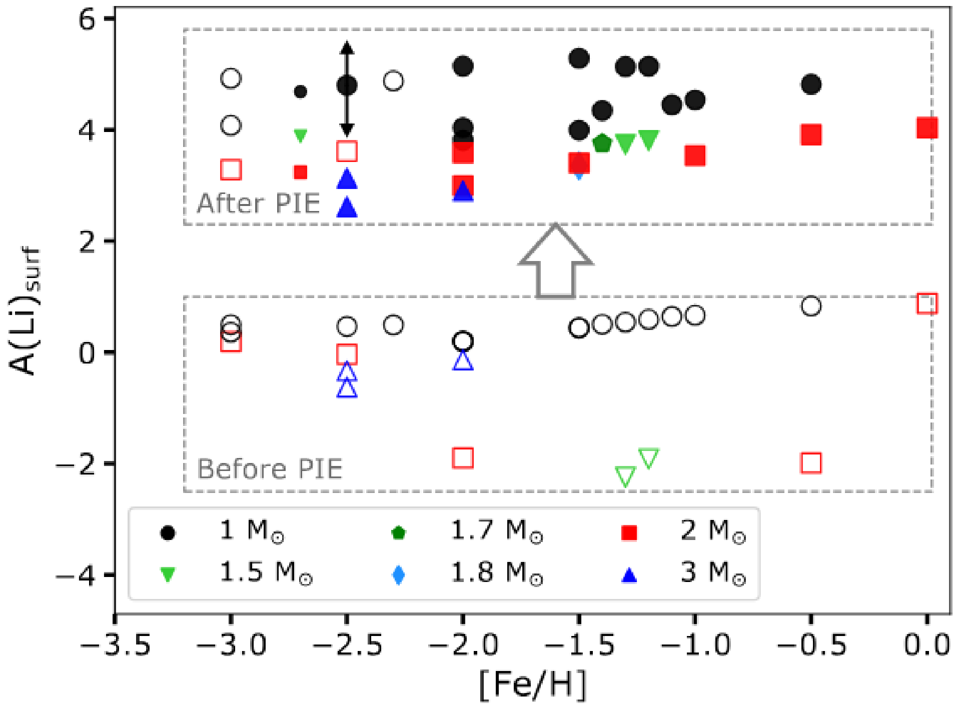
galaxies

MDPI

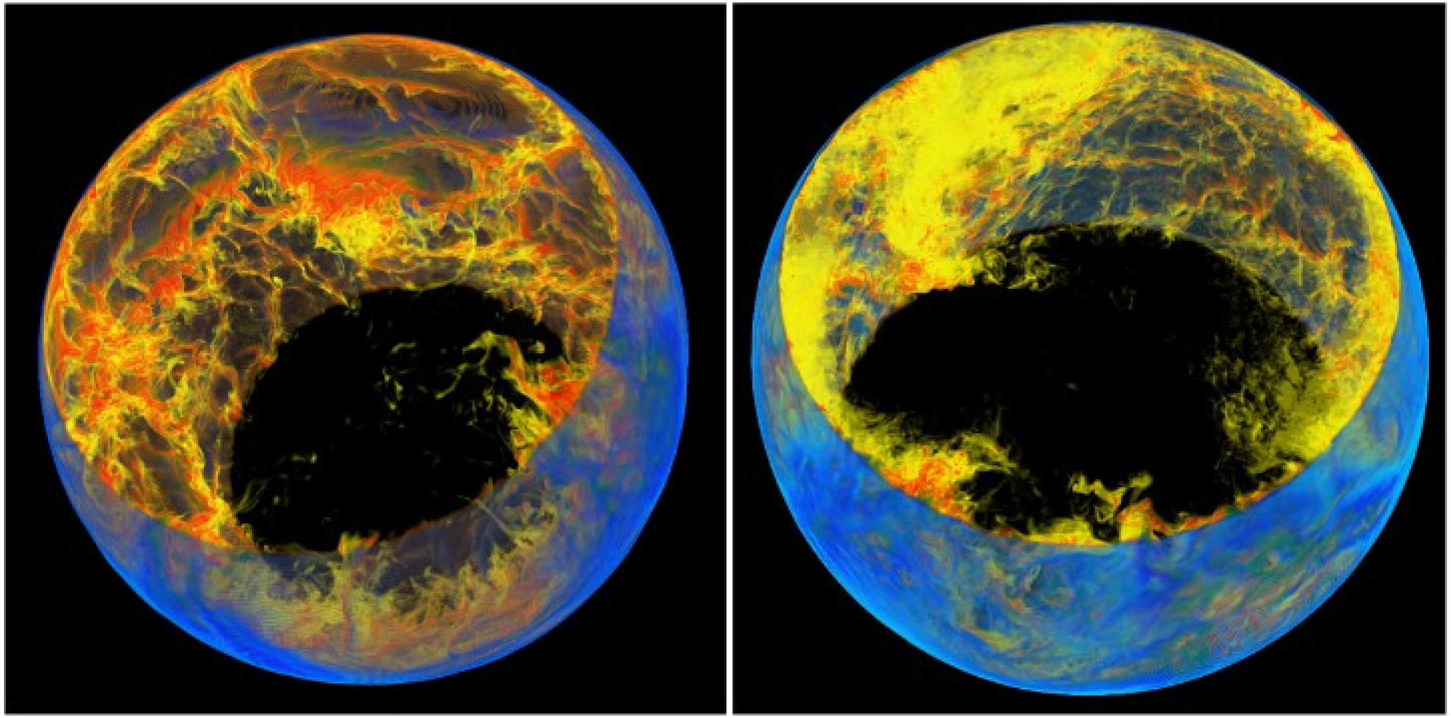
Article

Production of Lithium and Heavy Elements in AGB Stars Experiencing PIEs

Arthur Choplin *, Lionel Siess, Stephane Goriely and Sebastien Martinet



H-ingestion: 3D hydro required



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

Q2: Is there a nuclear solution to the cosmological lithium problem?

No, we will probably make it worse,
But NUCLEAR will allow to better define Li production in stellar simulations.

WP3: Computational Program

Astrophysical reaction rates and nucleosynthesis simulations for appropriate stellar models

Impact on questions **Q1** and **Q2**

Is there a nuclear solution to the cosmological lithium problem?

How did first-generation stars produce CNO elements?