Nuclear Astrophysics 2
(Neutron-capture) Nucleosynthesis in massive stars

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The n_TOF Nuclear Physics Winter School, 21-26 January 2024

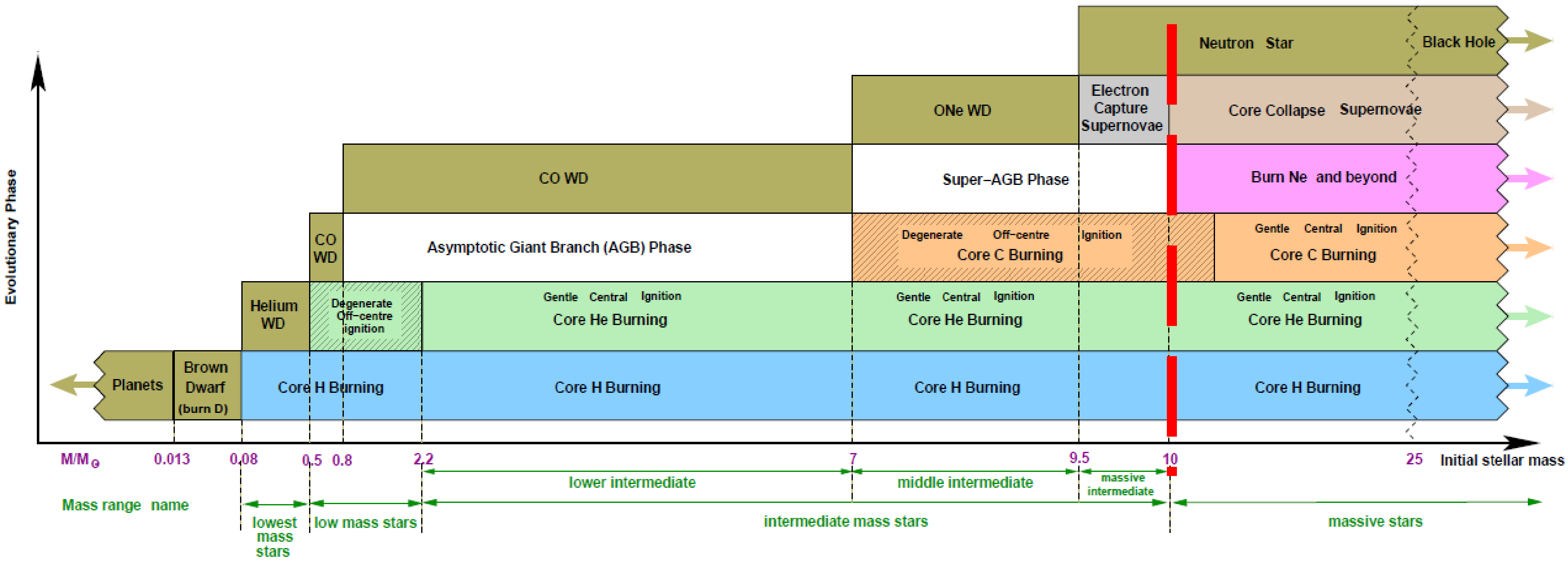
Outline

- Introduction to massive stars - basic features
- Stars & nucleosynthesis as computational experiments
- Neutron-capture processes in massive stars:
  - introduction and observations
  - Connection with Galactic Chemical Evolution
- The s-process, n-process, i-process, r-processes… (we will see how far we will go with this)

Initial stellar mass vs Evolution phases

Oscar’s lecture on Monday
(Nuclear Astrophysics 1)

Nuclear Astrophysics 2



Karakas & Lattanzio 2014, PASA

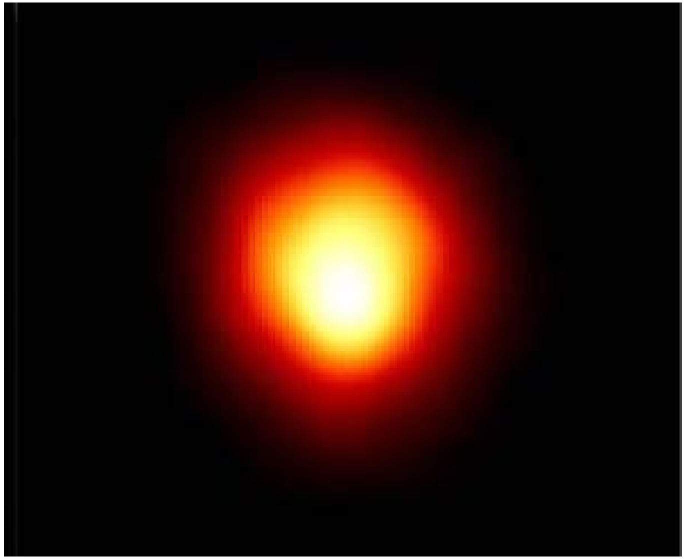
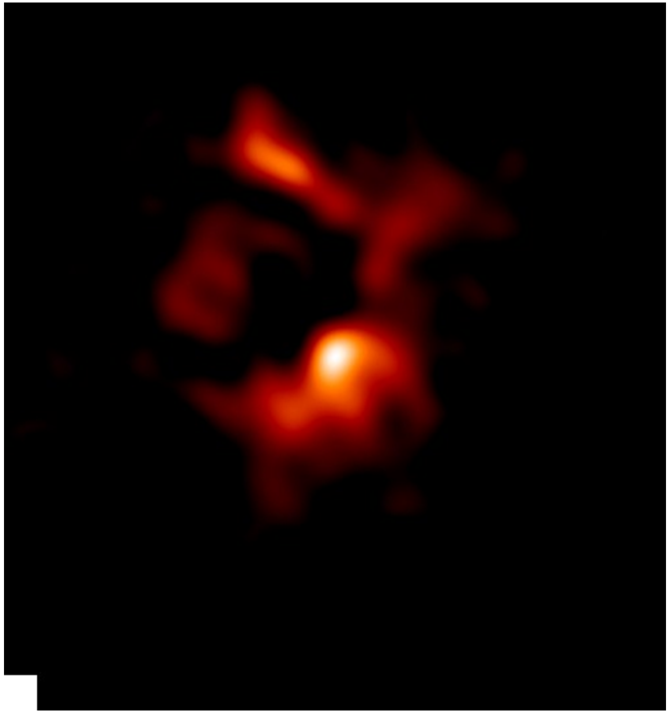


Image: A. Dupree/CFA/R. Gilliland/STScI/NASA/ESA

Betelgeuse (α-Ori):

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



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

CWLeo (IRC+10216):

- 400 lyr
- 250 R_{sun}

Sun: 1 M_{sun} ; 1 AU ; 1 R_{sun}

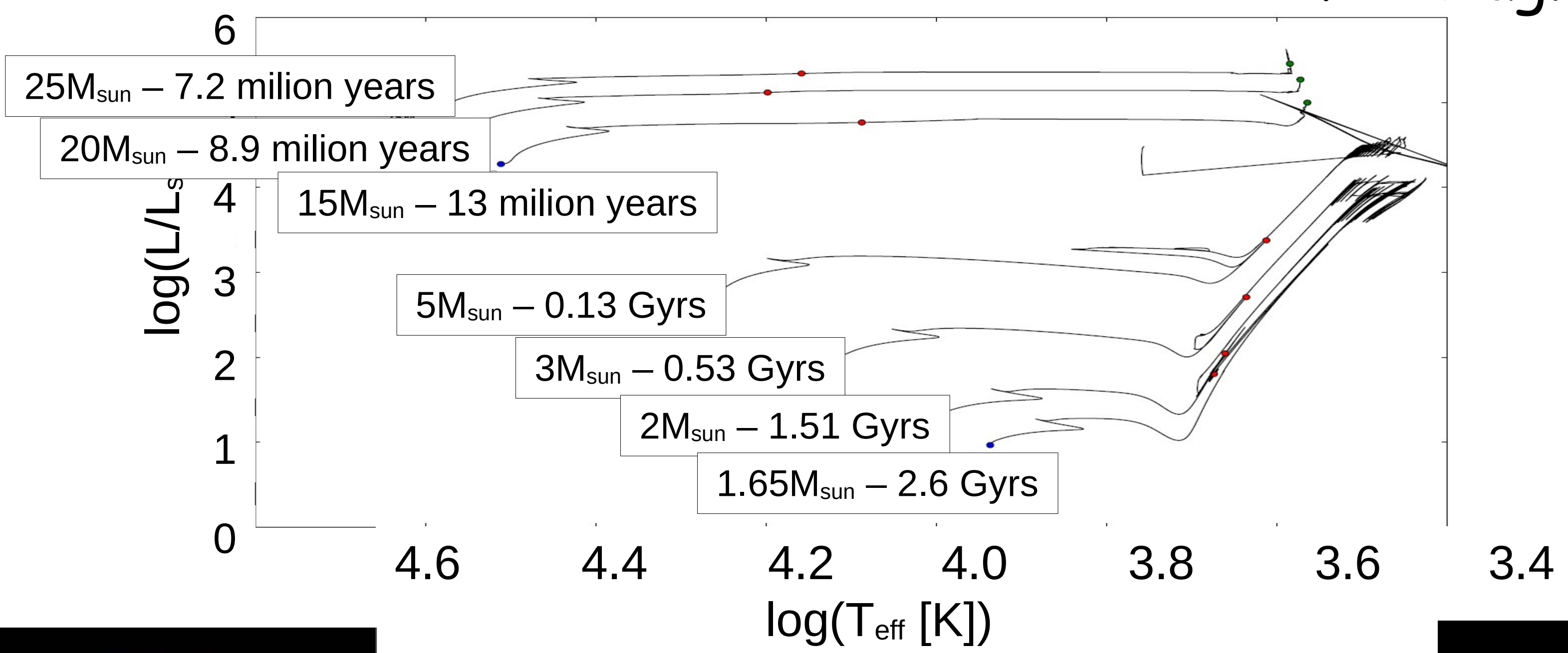
1 M_{sun} ~ $2*10^{30}$ Kg

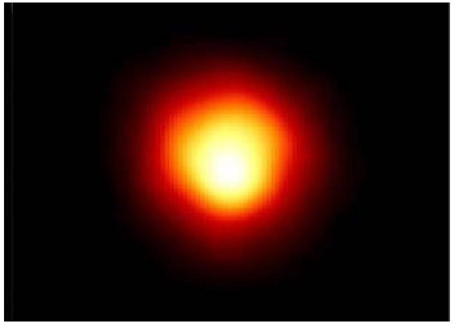
1 AU = 1./63241,1 lyr

1 lyr = $9,461*10^{12}$ Km

1 R_{sun} = 695700 Km

HR diagram





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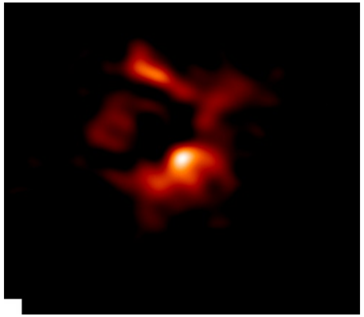
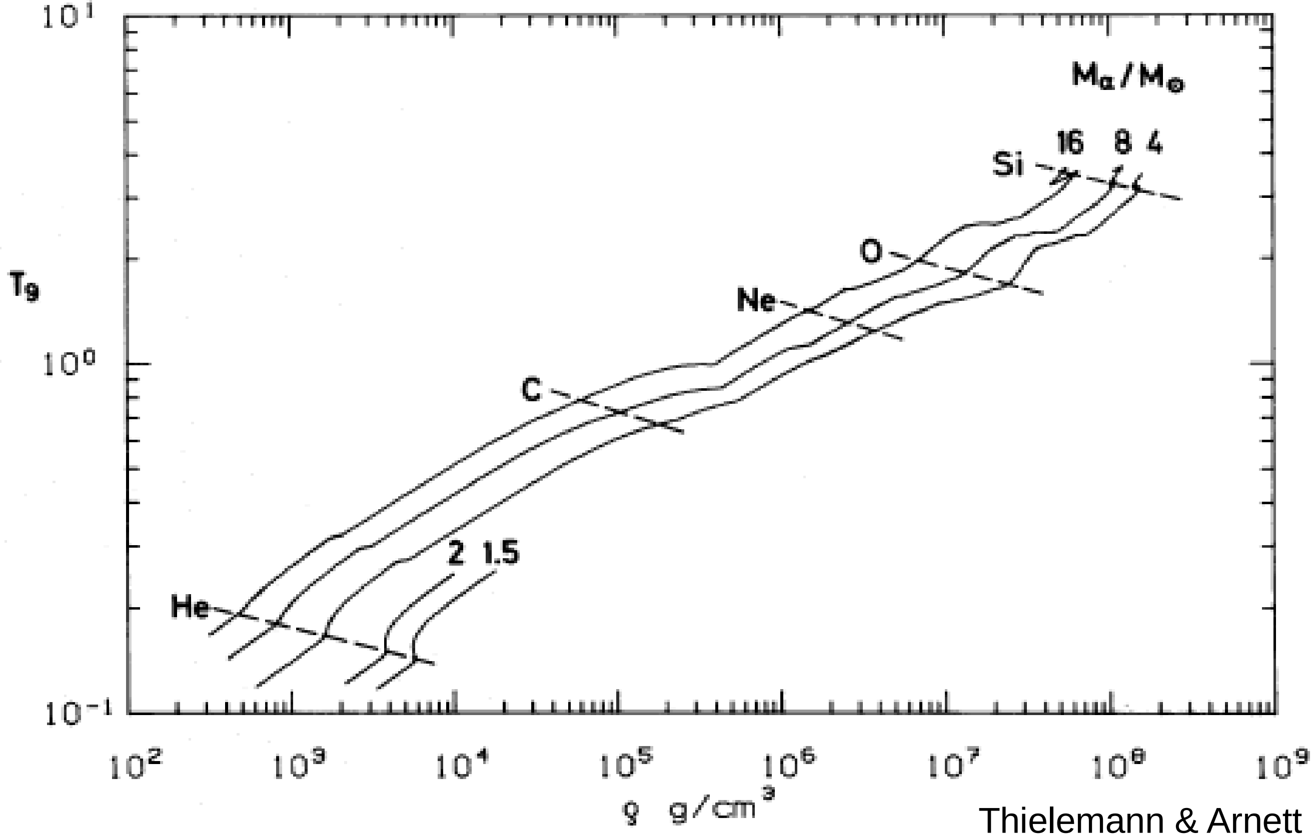
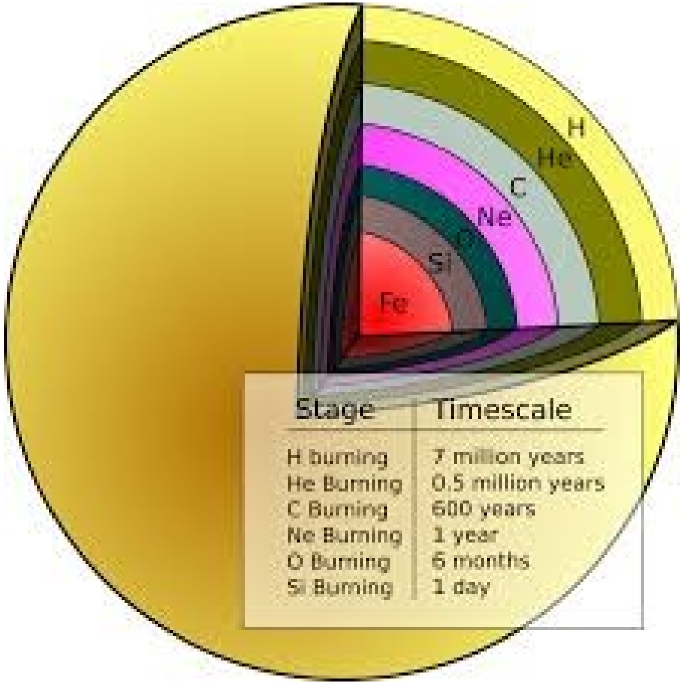


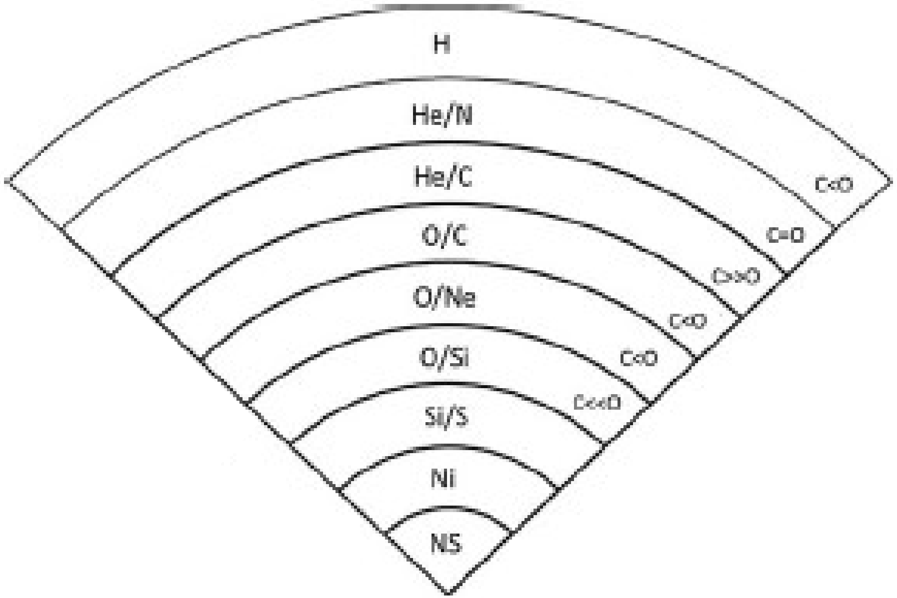
Tuthill et al. 2000, A&A, Keck Telescope

Structure evolution inside



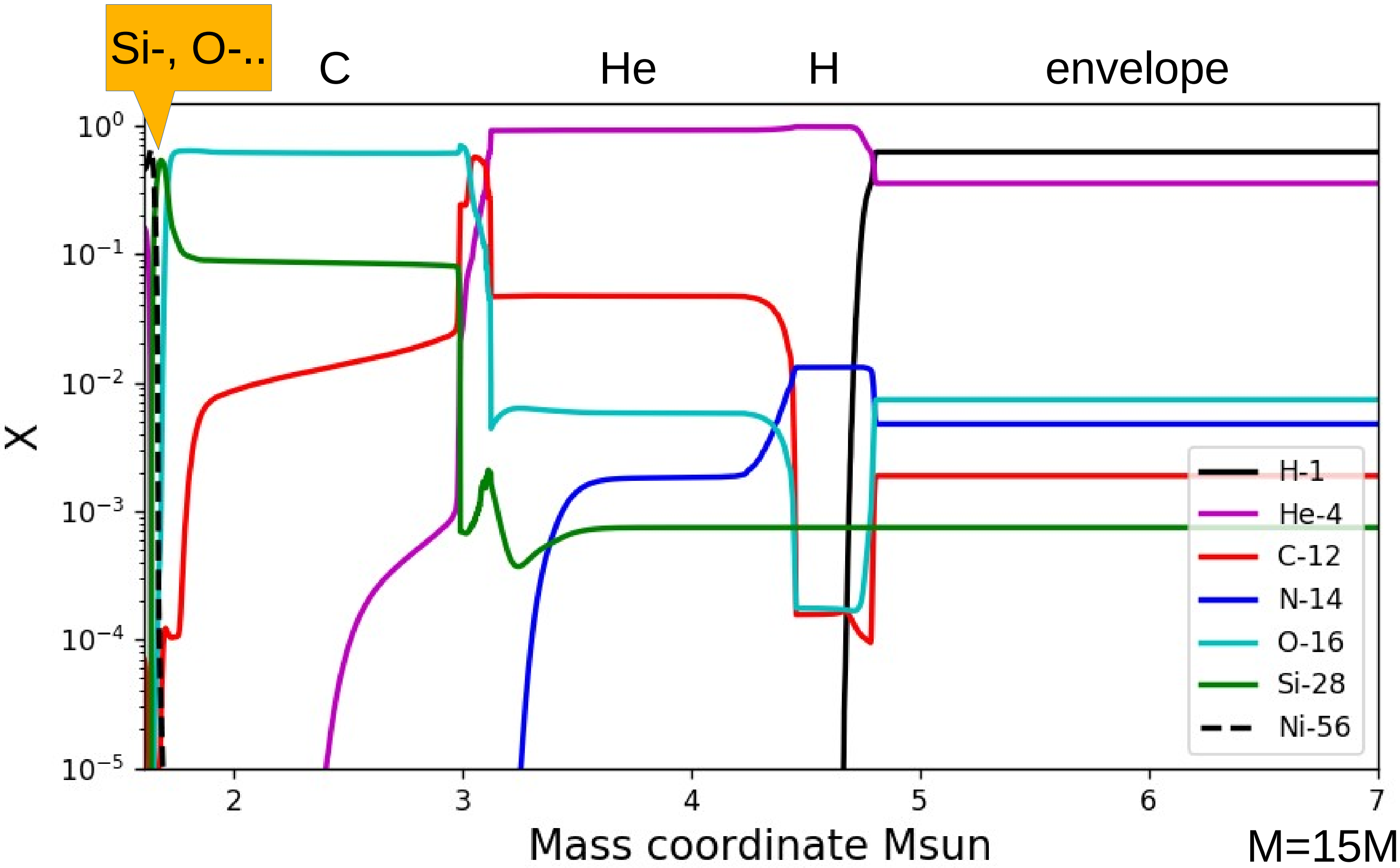
Thielemann & Arnett 1985 ApJ





> 10 solar masses
before SN explosion

> 10 solar masses
after SN explosion



M=15Msun, Z=0.02
Ritter+2018 MNRAS
MESA progenitor
Fryer+12 explosion

Low-mass stars
Intermediate-mass stars
High-mass stars

Nuclear burning stages

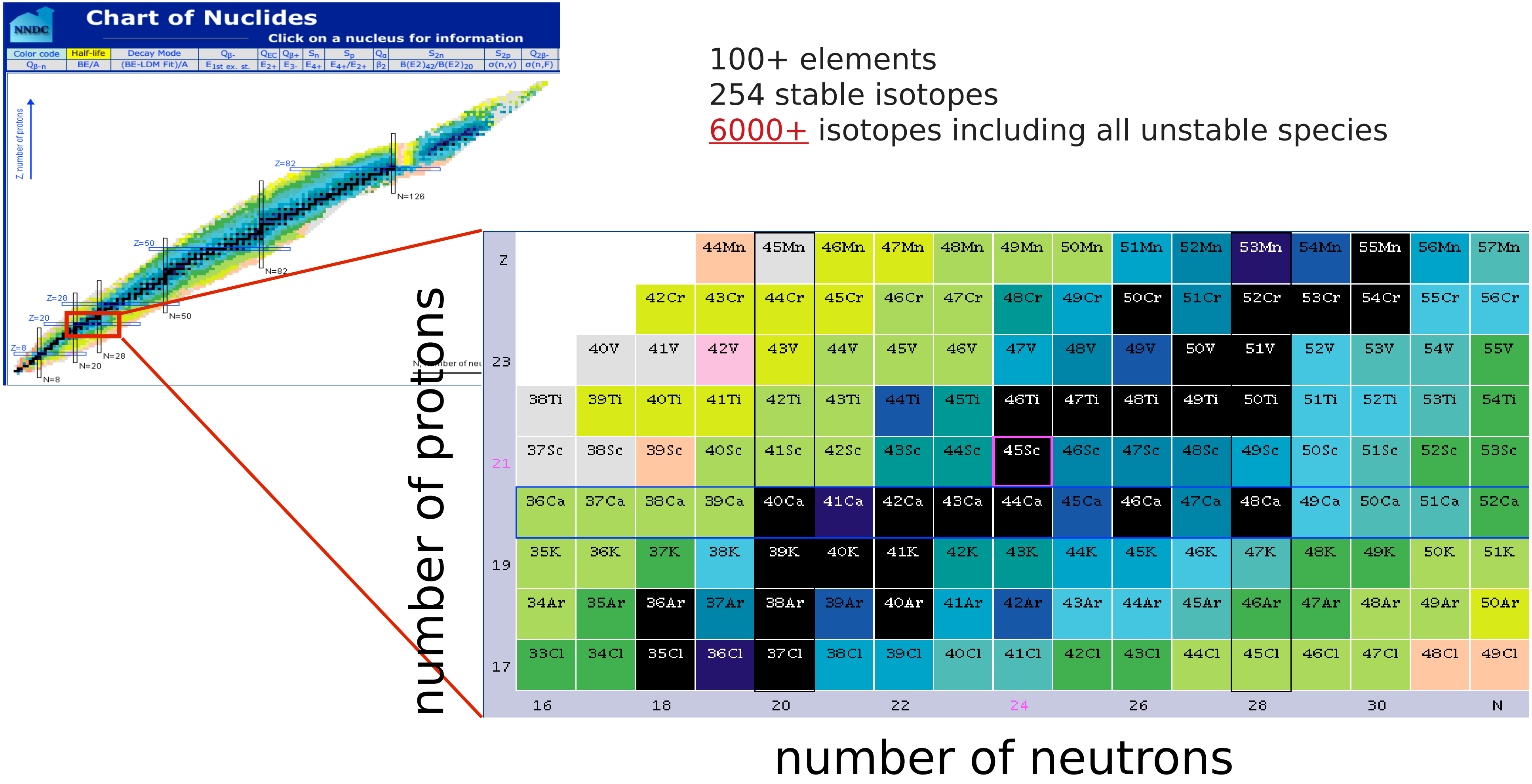
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^{4}He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2–0.3	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si, S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)\ldots$

From: Alex Heger

See also Jones et al. 2013, ApJ

What is the origin of all the elements and the isotopes?

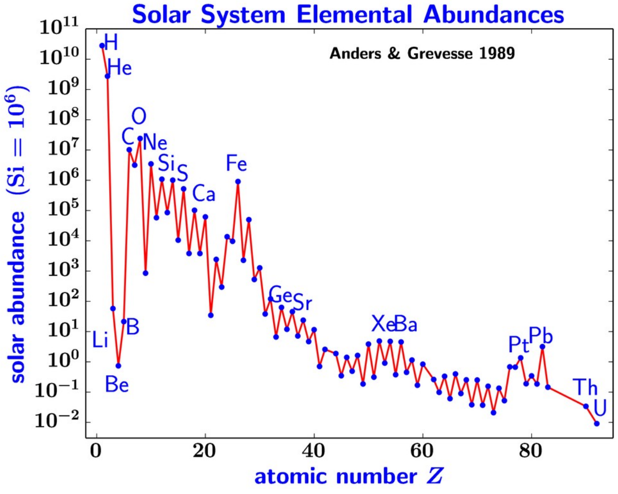
100+ elements
254 stable isotopes
6000+ isotopes including all unstable species

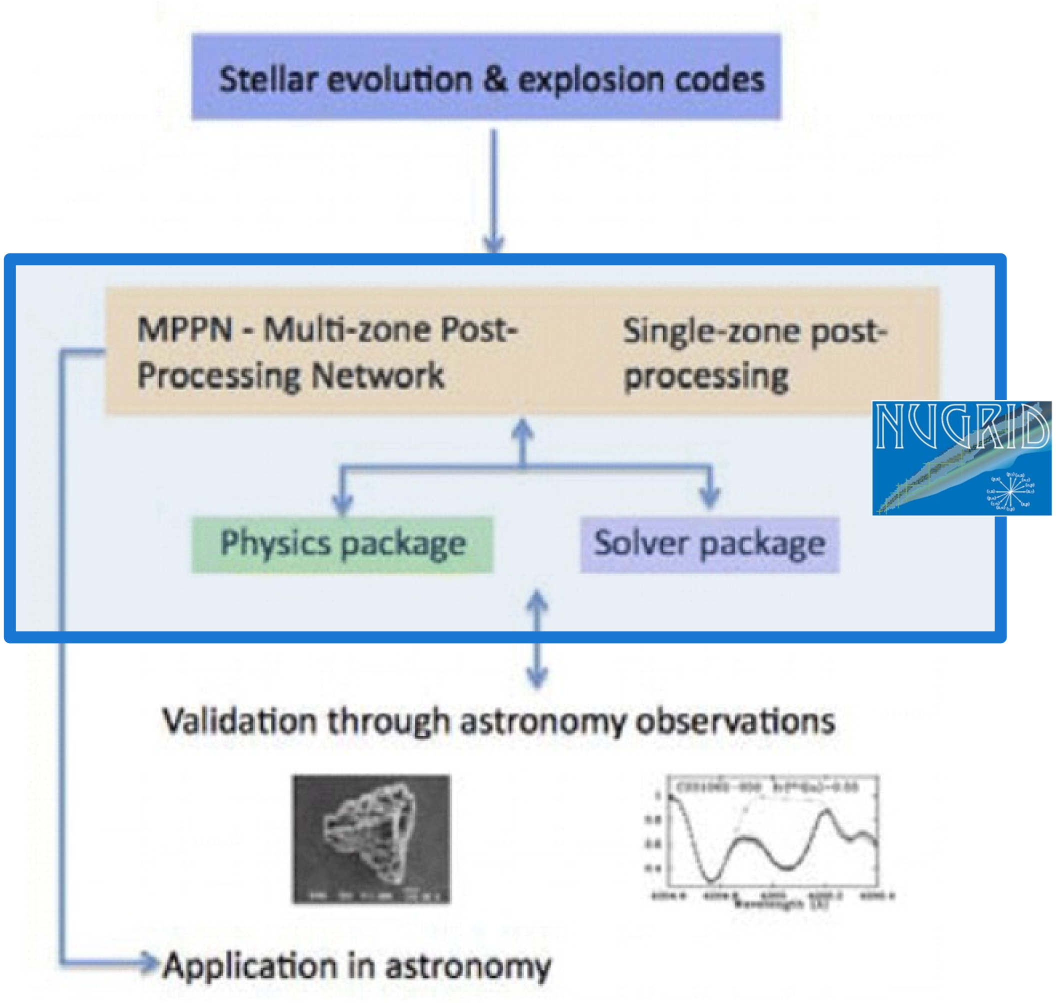


Production of elements **and isotopes** in stars

GCE

Comparison with observations





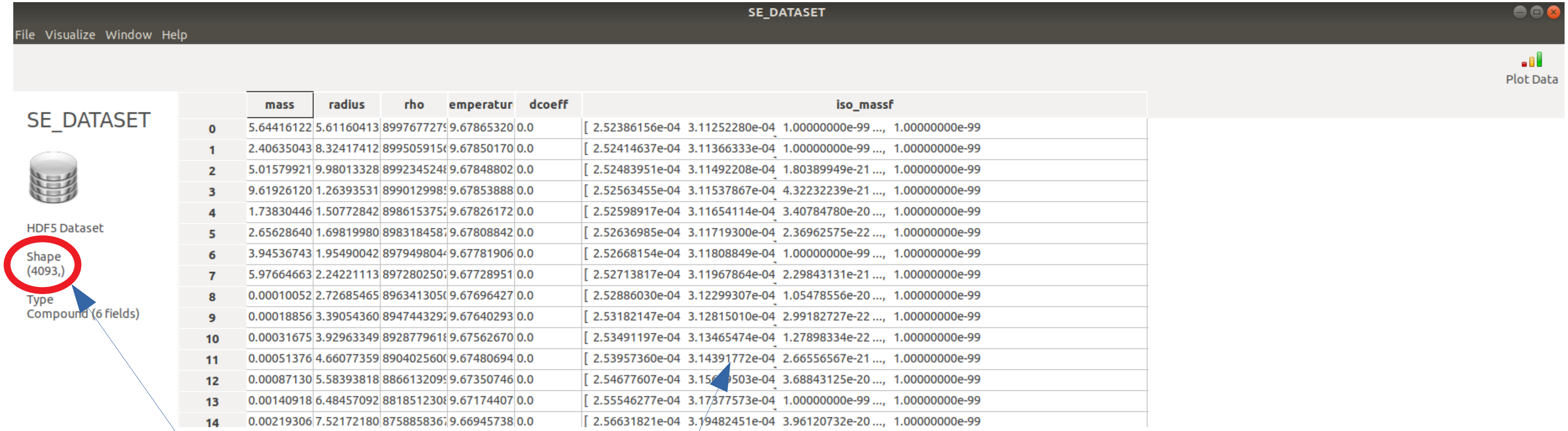
Labs for computational experiments in nucleosynthesis

Locally:
Some simple calculations (e.g., single trajectories);
Nuclear sensitivity studies (light configurations);
Vizualization.

Viper-HPC @Hull
available via
ChETEC-INFRA

HPC:
Full stellar models;
Stellar yields sets for GCE;
Visualization.

Data in hdf5: looking at one file with, e.g., HDF compass ...



	mass	radius	rho	emperatur	dcoeff	iso_massf
0	5.64416122	5.61160413	899767727	9.67865320	0.0	[2.52386156e-04 3.11252280e-04 1.00000000e-99 ..., 1.00000000e-99
1	2.40635043	8.32417412	899505915	9.67850170	0.0	[2.52414637e-04 3.11366333e-04 1.00000000e-99 ..., 1.00000000e-99
2	5.01579921	9.98013328	899234524	9.67848802	0.0	[2.52483951e-04 3.11492208e-04 1.80389949e-21 ..., 1.00000000e-99
3	9.61926120	1.26393531	899012998	9.67853888	0.0	[2.52563455e-04 3.11537867e-04 4.32232239e-21 ..., 1.00000000e-99
4	1.73830446	1.50772842	898615375	9.67826172	0.0	[2.52598917e-04 3.11654114e-04 3.40784780e-20 ..., 1.00000000e-99
5	2.65628640	1.69819980	898318458	9.67808842	0.0	[2.52636985e-04 3.11719300e-04 2.36962575e-22 ..., 1.00000000e-99
6	3.94536743	1.95490042	897949804	9.67781906	0.0	[2.52668154e-04 3.11808849e-04 1.00000000e-99 ..., 1.00000000e-99
7	5.97664663	2.24221113	897280250	9.67728951	0.0	[2.52713817e-04 3.11967864e-04 2.29843131e-21 ..., 1.00000000e-99
8	0.00010052	2.72685465	896341305	9.67696427	0.0	[2.52886030e-04 3.12299307e-04 1.05478556e-20 ..., 1.00000000e-99
9	0.00018856	3.39054360	894744329	9.67640293	0.0	[2.53182147e-04 3.12815010e-04 2.99182727e-22 ..., 1.00000000e-99
10	0.00031675	3.92963349	892877961	9.67562670	0.0	[2.53491197e-04 3.13465474e-04 1.27898334e-22 ..., 1.00000000e-99
11	0.00051376	4.66077359	890402560	9.67480694	0.0	[2.53957360e-04 3.14391772e-04 2.66556567e-21 ..., 1.00000000e-99
12	0.00087130	5.58393818	886613209	9.67350746	0.0	[2.54677607e-04 3.15[illegible]503e-04 3.68843125e-20 ..., 1.00000000e-99
13	0.00140918	6.48457092	881851230	9.67174407	0.0	[2.55546277e-04 3.17377573e-04 1.00000000e-99 ..., 1.00000000e-99
14	0.00219306	7.52172180	875885836	9.66945738	0.0	[2.56631821e-04 3.19482451e-04 3.96120732e-20 ..., 1.00000000e-99

data: [4093 rows x (5 x 1 dp + 1 x 5134 dp)] x **1 evolution step**

Example: 1D stellar model (CCSN progenitor)

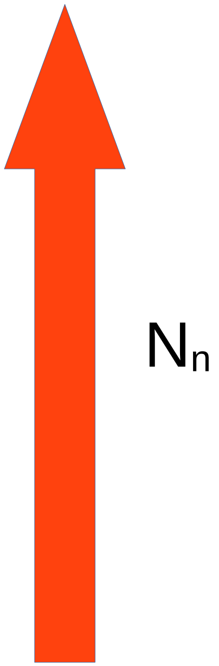
Additional things to consider (data maintenance and visualization)

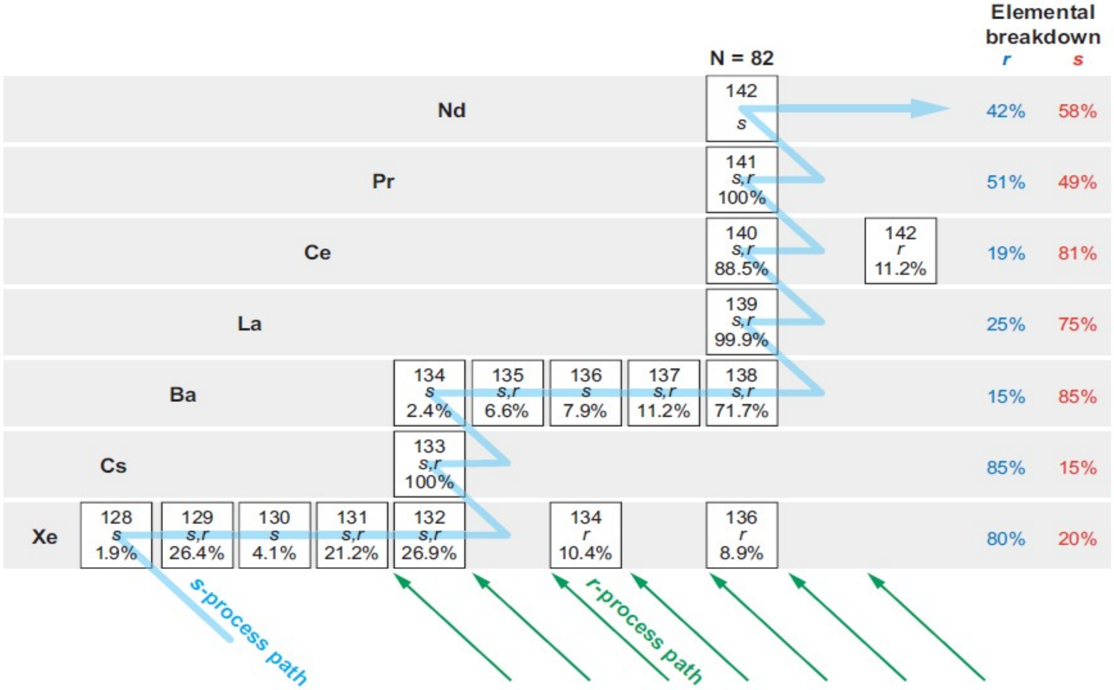
- Reproducibility of the results:
  - Long term data storage
  - Visualization:
    - Can you make the same plots after 3 year ?
    - Can you reproduce the same plots made 3 year ago?
- data accessibility to collaborators

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} .





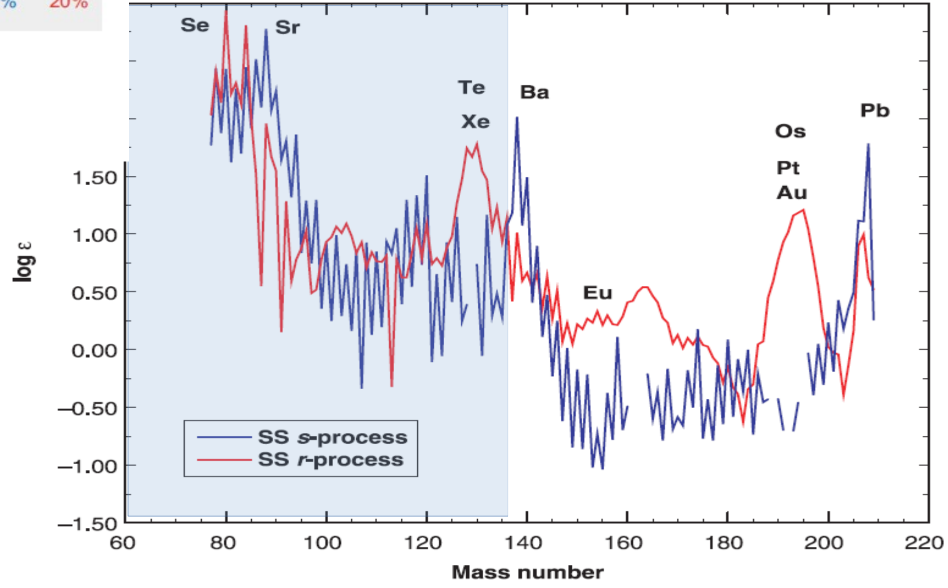
MACS from experiments

s-process pattern

r-process pattern in the Sun

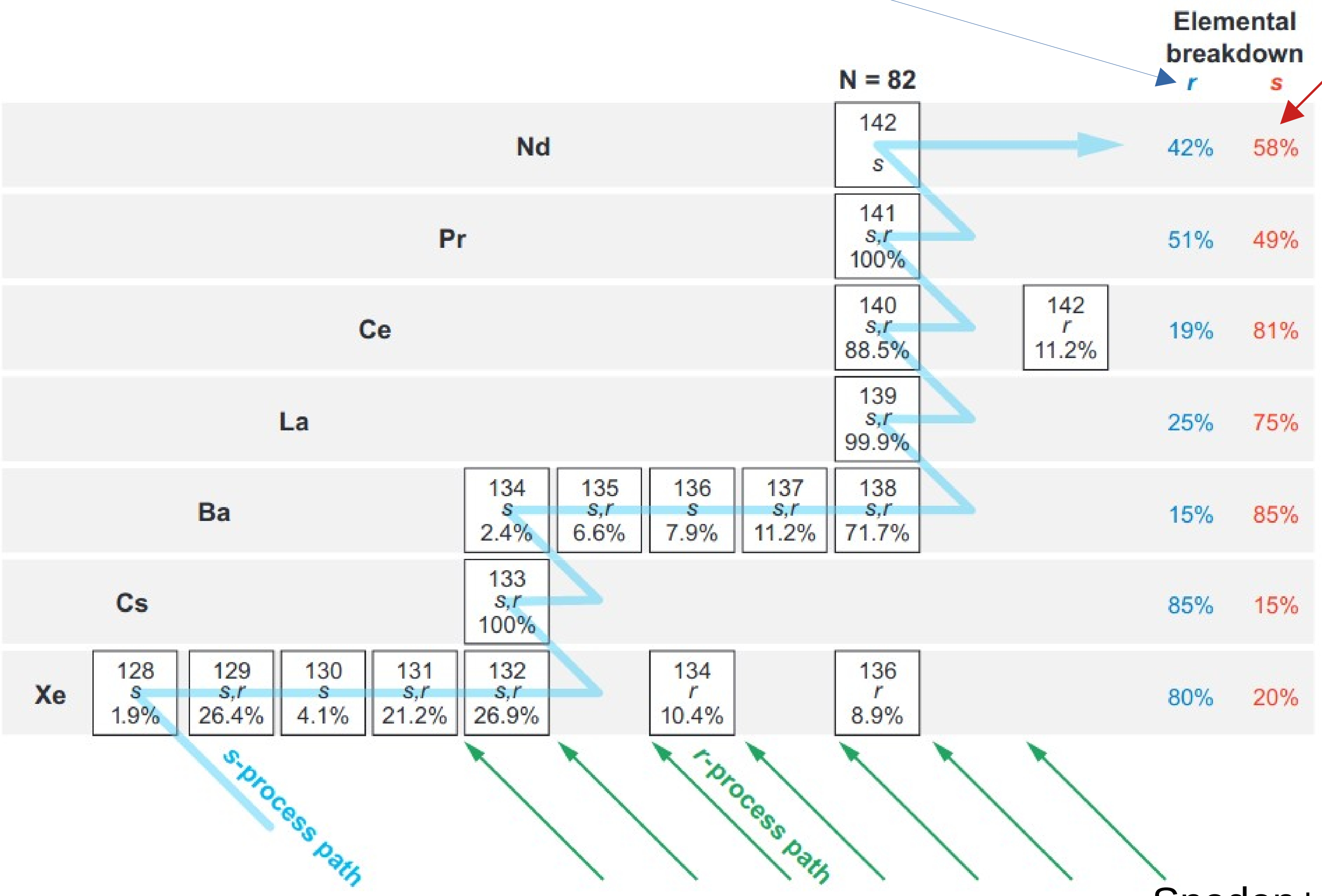
r-process pattern in old stars

Sneden & Cowan 2003



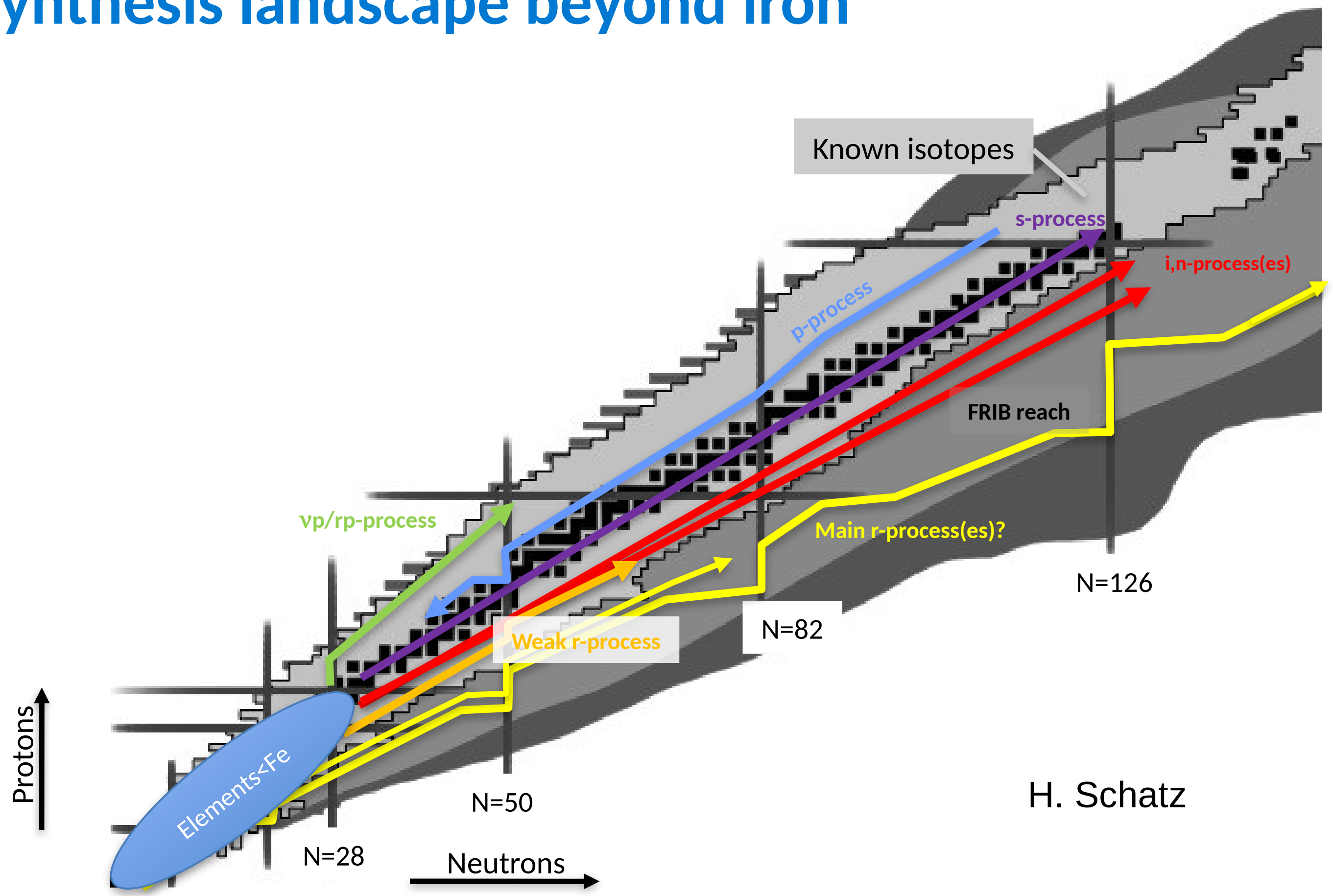
r = solar - s

S-process
Models + GCE



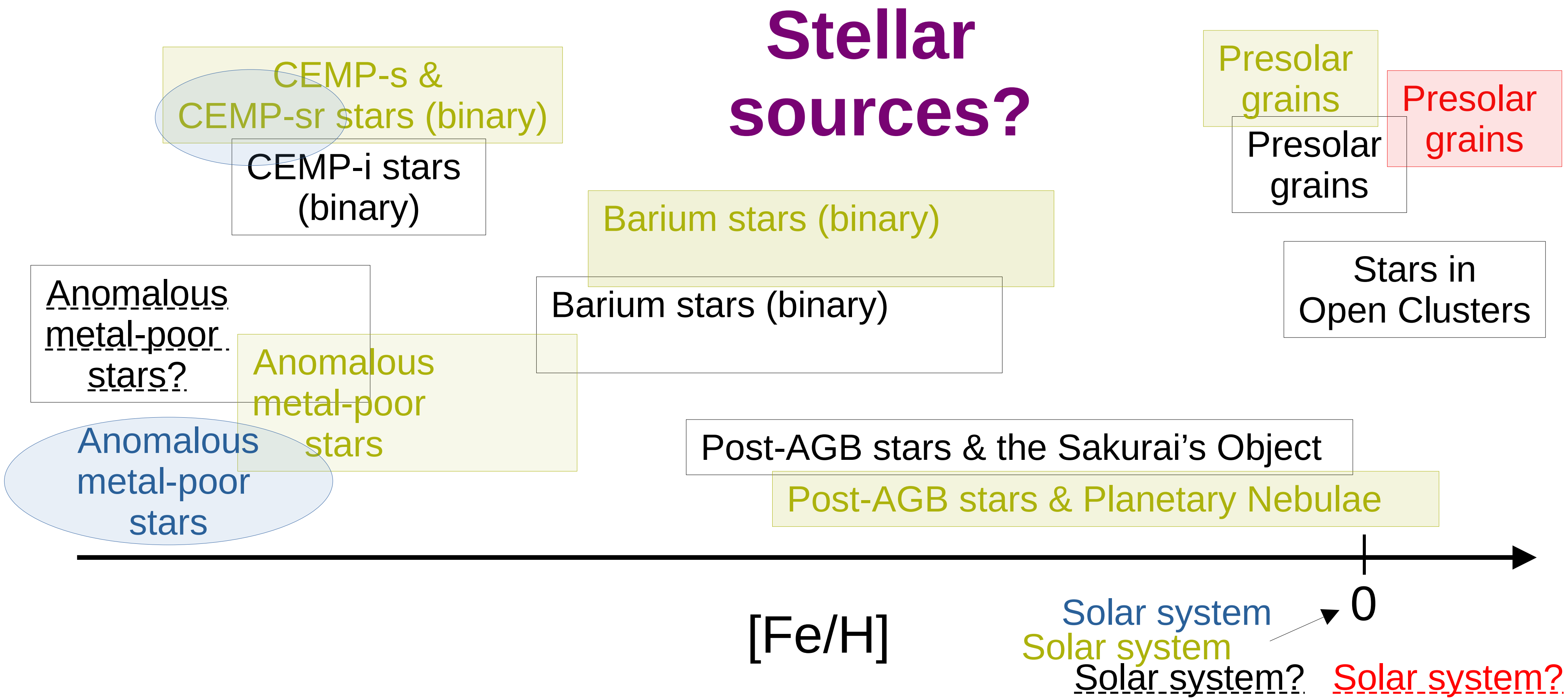
Sneden+ 2008 ARAA

Nucleosynthesis landscape beyond iron



H. Schatz

Observation of s- i- n- & r-process signatures



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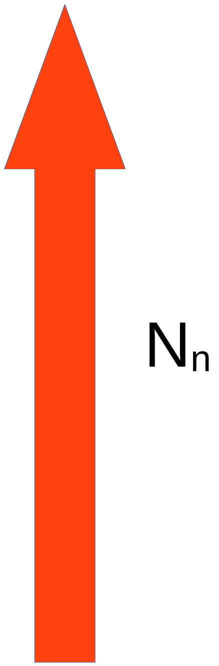
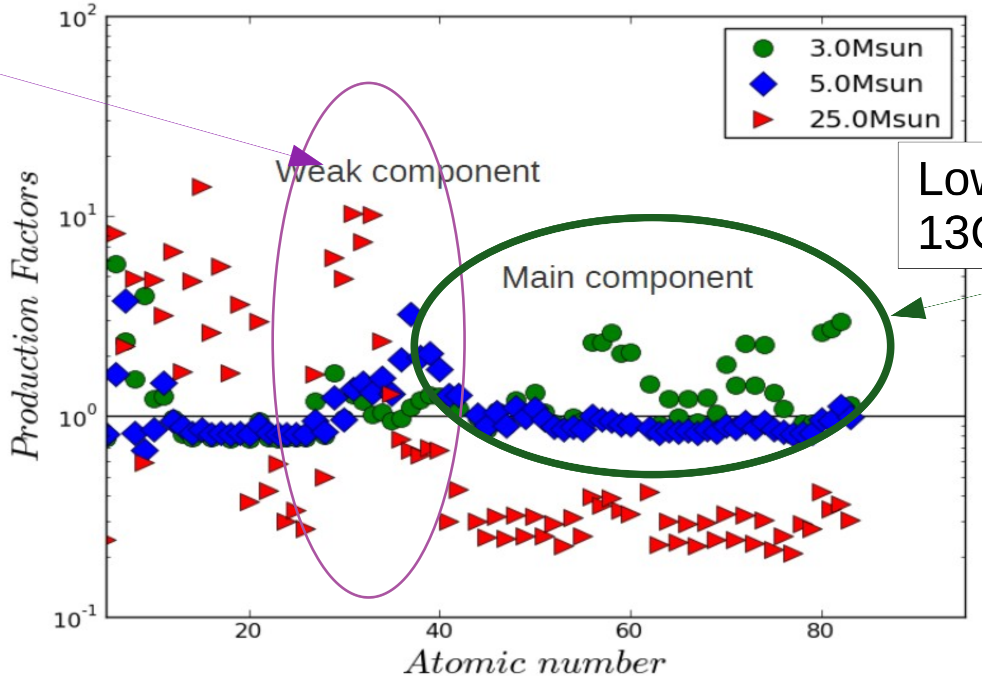


massive stars… or
22Ne(α,n)25Mg



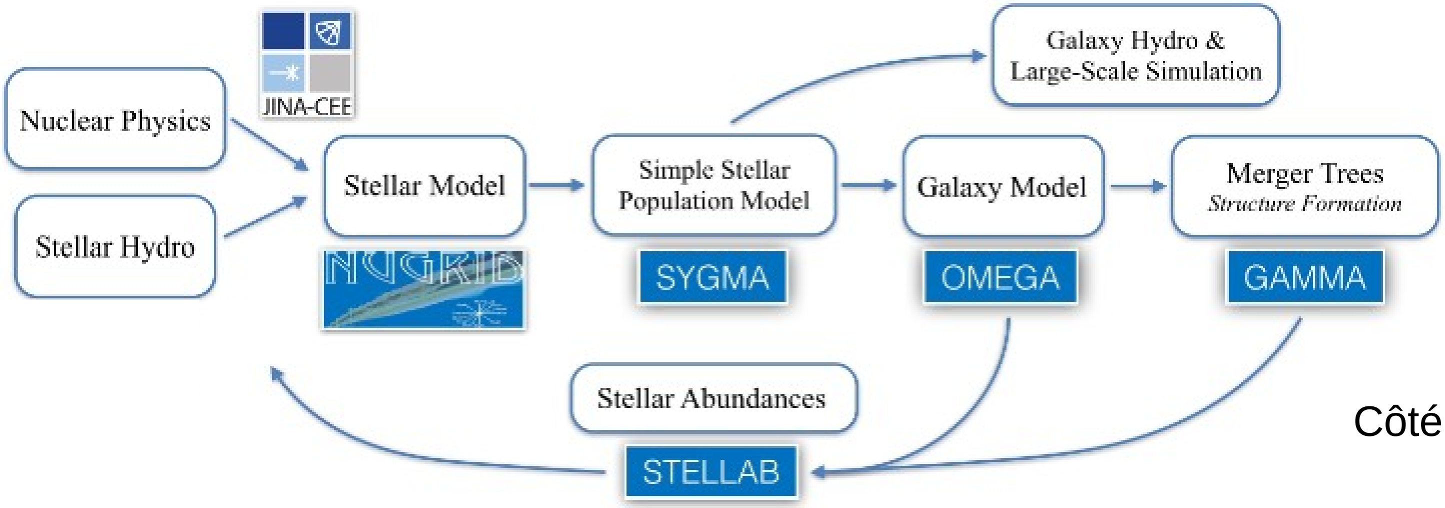
Low-mass AGB stars… or
13C(α,n)16O & 22Ne(α,n)25Mg

MP+2016, ApJS

Elemental production factors for a low mass AGB star, a massive AGB stars, and a massive star (Z=0.01).

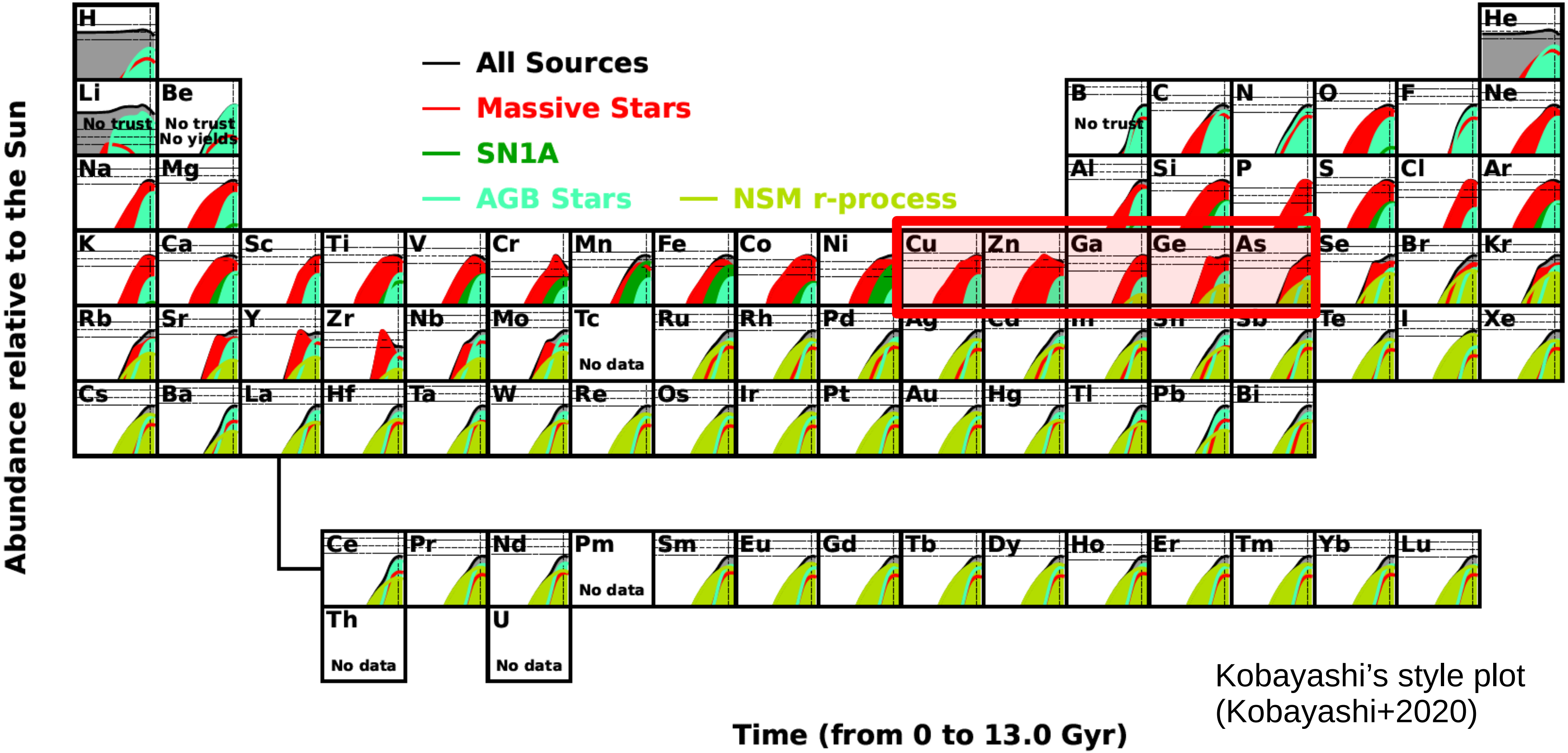
Open-source codes
http://nugrid.github.io/NuPyCEE
https://github.com/becot85/JINAPyCEE

Chemical Evolution Pipeline

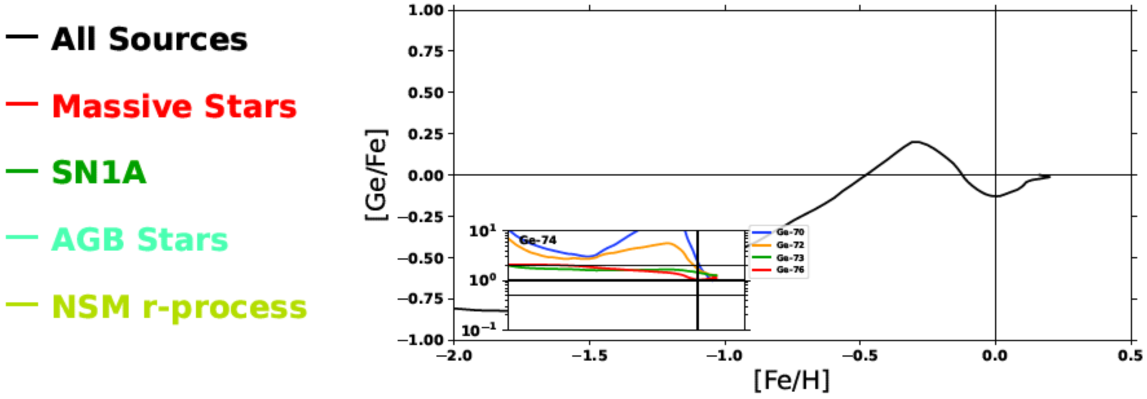


Côté+ 2017

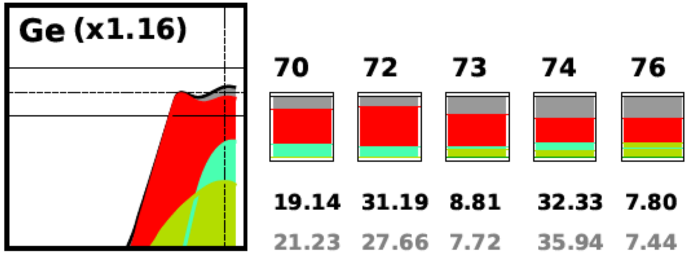
- **SYGMA** - **S**tellar **Y**ields for **G**alactic **M**odeling **A**pplications (Ritter, Côté, Herwig, et al. 2017)
- **OMEGA** - **O**ne-zone **M**odel for the **E**volution of **GA**laxies (Côté, O'Shea, Ritter, et al. 2017)
- **GAMMA** - **G**alaxy **A**ssembly with **M**erger-trees for **M**odeling **A**bundances (Côté, Silvia, O'Shea, et al. 2017)
- **STELLAB** - **STELL**ar **AB**undances, observational data plotting tool

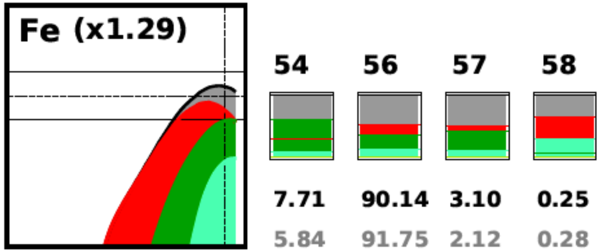


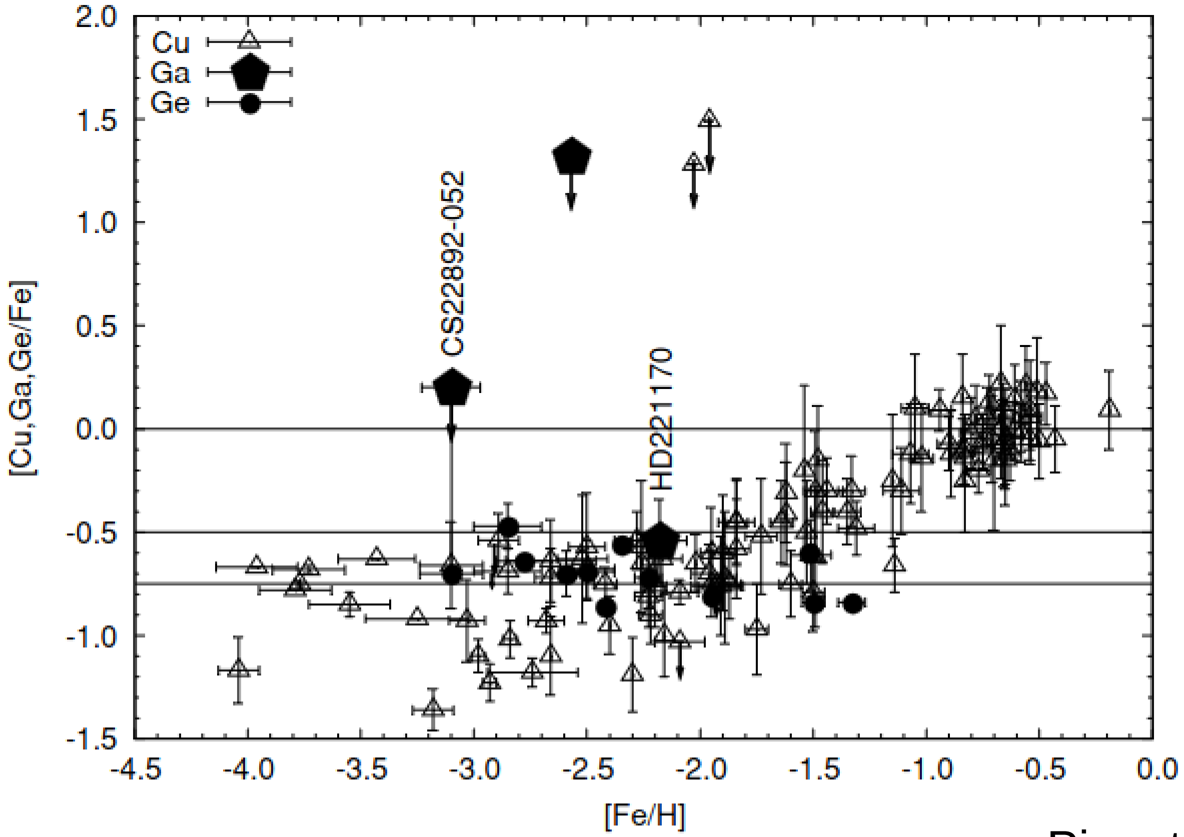
Kobayashi’s style plot
(Kobayashi+2020)



Prantzos's style plots
(Prantzos+2020)



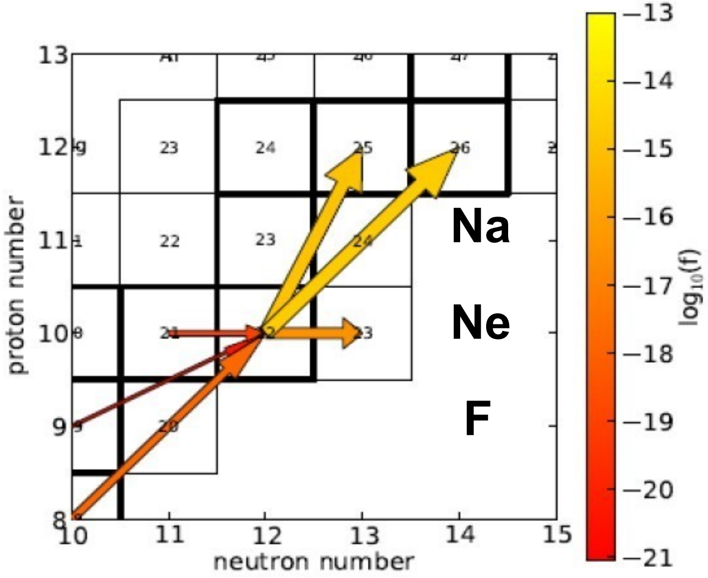




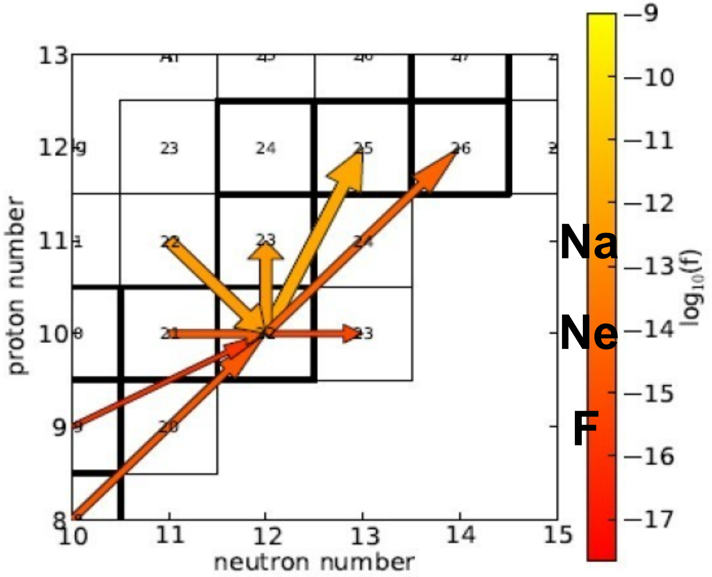
Pignatari+ 2010 ApJ

12

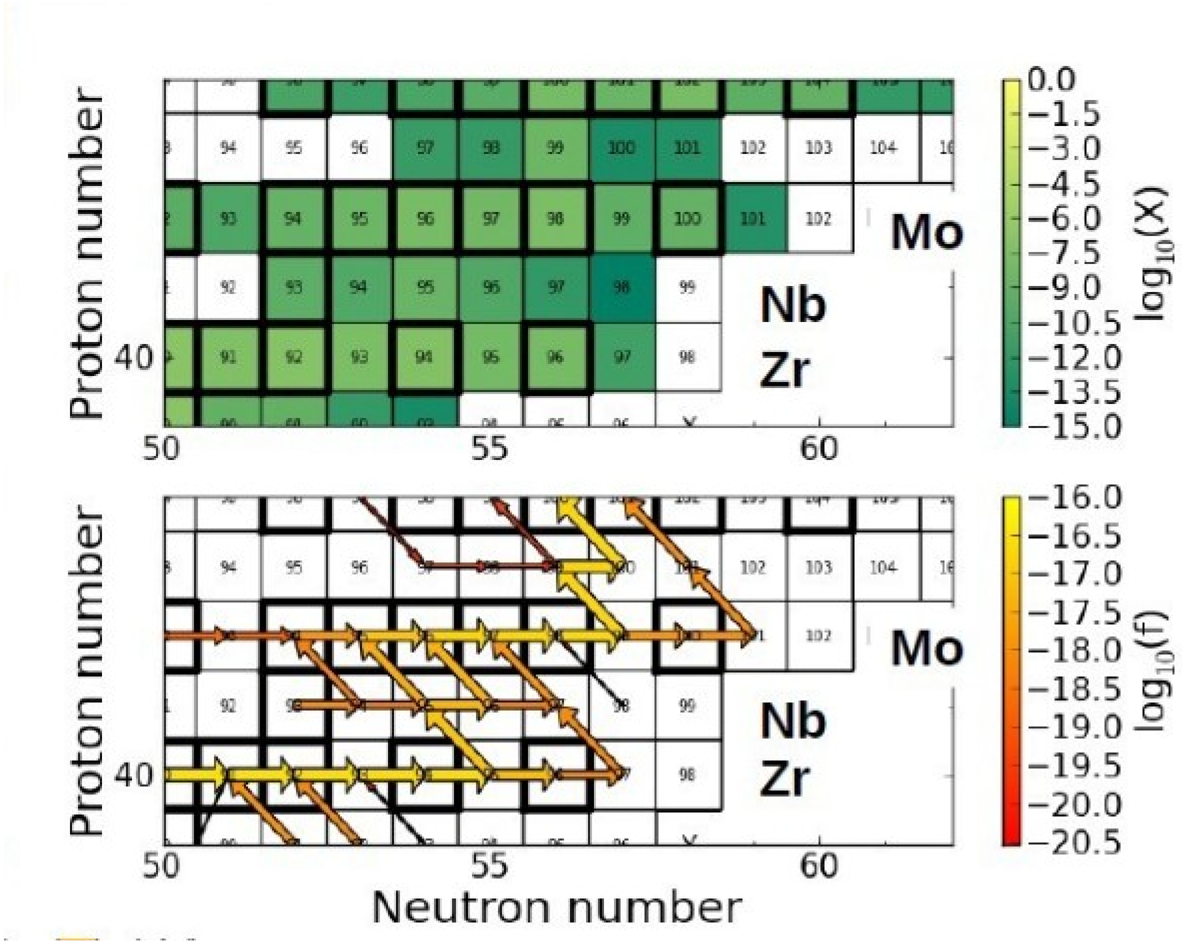
Ne22(α,n)Mg25: main neutron source of the weak s-process in massive stars.



Ne22 nucleosynthesis in He-burning conditions (T9 ~ 0.3)



Ne22 nucleosynthesis in C-burning conditions (T9 ~ 1)



Proton number
40
50
55
60
Mo
Nb
Zr
0.0
−1.5
−3.0
−4.5
−6.0
−7.5
−9.0
−10.5
−12.0
−13.5
−15.0
$\log_{10}(X)$
Proton number
40
50
55
60
Neutron number
Mo
Nb
Zr
−16.0
−16.5
−17.0
−17.5
−18.0
−18.5
−19.0
−19.5
−20.0
−20.5
$\log_{10}(f)$

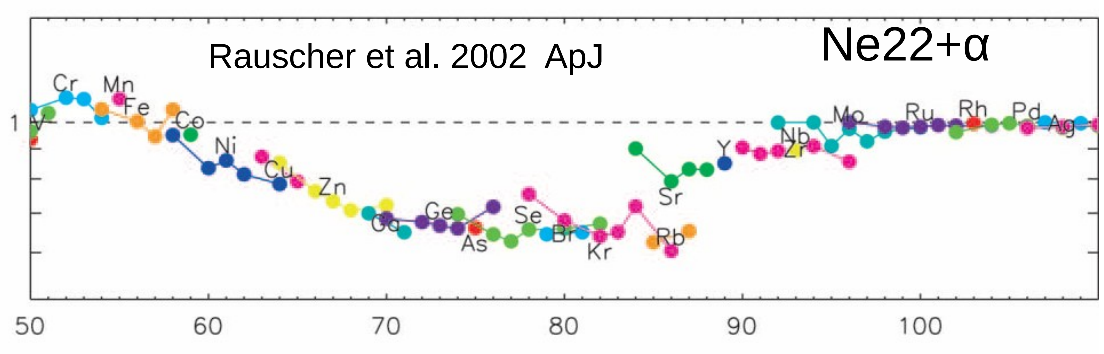
22Ne(α,n)25Mg rate ($cm^3\ mol^{-1}\ s^{-1}$) & 22Ne(α,n)25Mg / 22Ne(α,γ)26Mg

T9	Kaeppeler+1994	Longland+2012	Talwar+2016	Adsley+2021
0.3	4.14e-11* (3.39)	3.36e-11 (2.97)	3.33e-11 (0.59)	1.05e-11 (1.23)
1.0	5.27e-02* (145)	6.64e-02 (162)	8.68e-02 (207)	1.33e-01 (344)

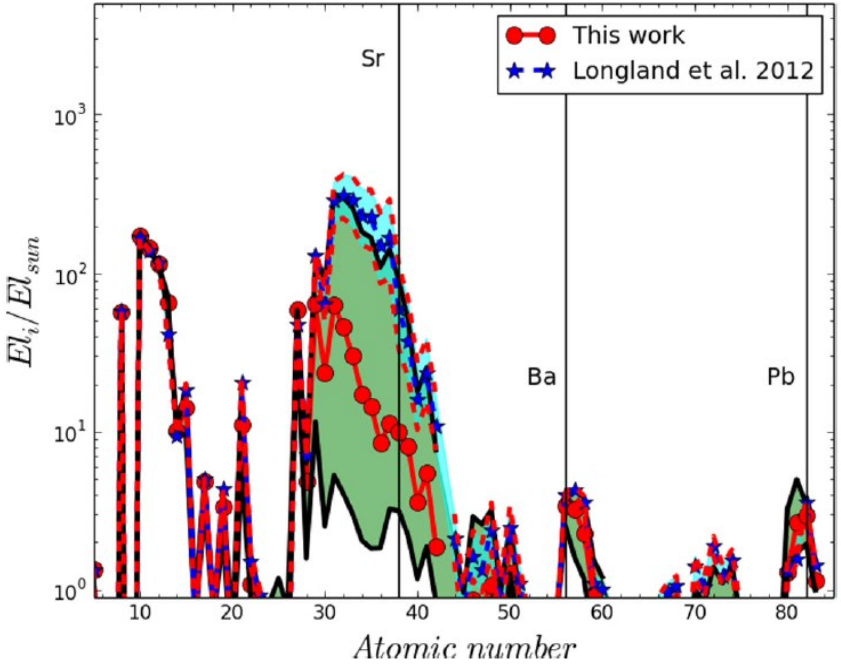
(*): From Kaeppeler+1994, typically used the lower limit, where the 633 keV resonance is neglected

- **In low-mass AGB stars: only partial 22Ne(α,n)25Mg activation**
- **In massive stars:**
  - **At 0.3 GK both rates and their relative ratios are important**
  - **At 1.0 GK the 22Ne(α,γ)26Mg is not relevant**

Nuclear uncertainties have large impact on the s-process products of massive stars



Talwar+ 2016 PRC



Eur. Phys. J. A (2023) 59:302
https://doi.org/10.1140/epja/s10050-023-01206-1

THE EUROPEAN PHYSICAL JOURNAL A

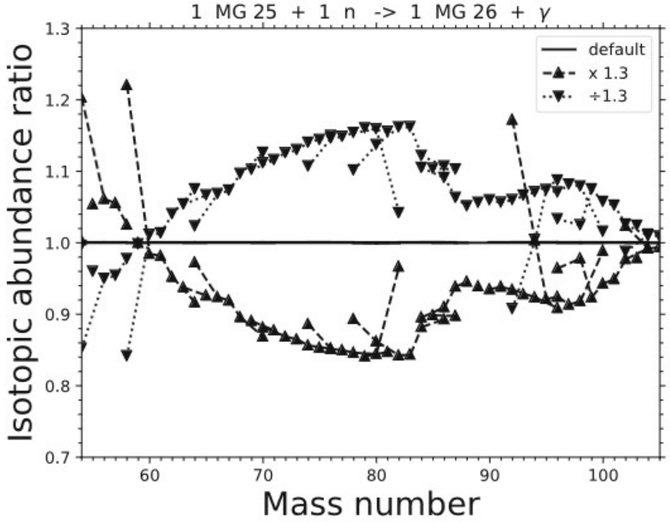
Regular Article - Experimental Physics

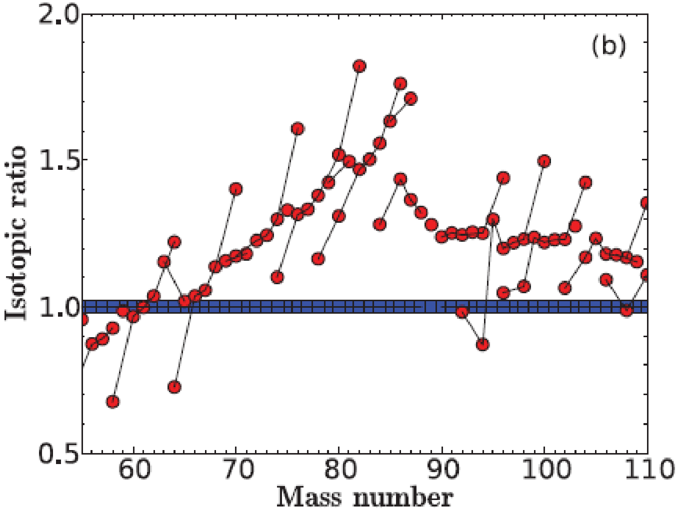
The s process in massive stars, a benchmark for neutron capture reaction rates

Marco Pignatari[1,2,3,a,b], Roberto Gallino[4], Rene Reifarth[5,6]

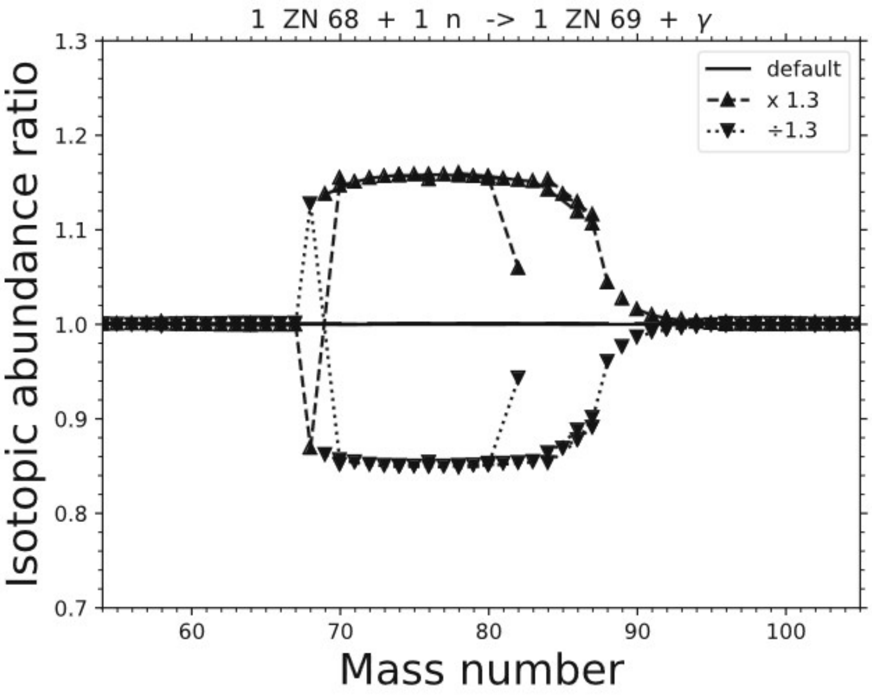
EPJA volume
in honour of
Franz Käppeler

Sensitivity study: 86 neutron-capture rates in the mass regions C-Si & Fe - Zr

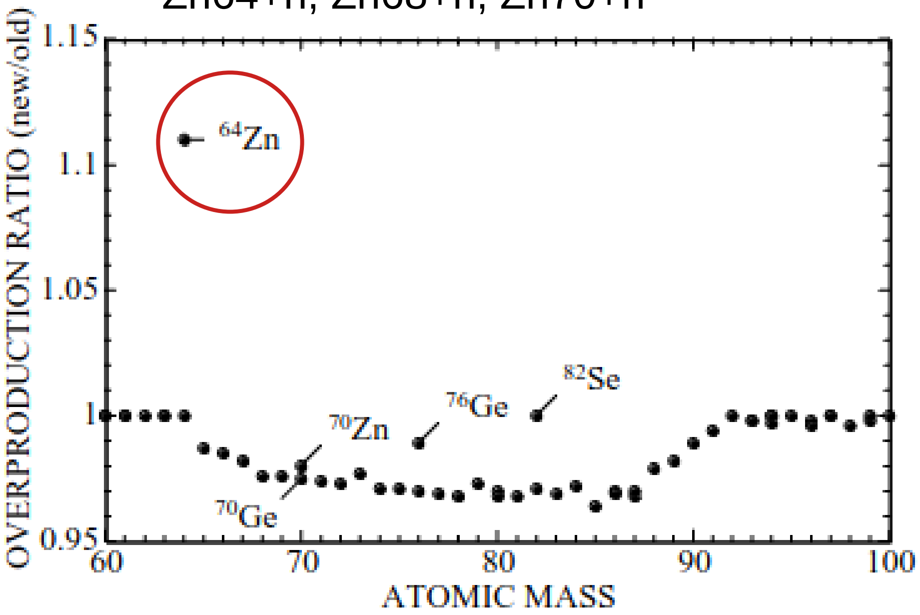




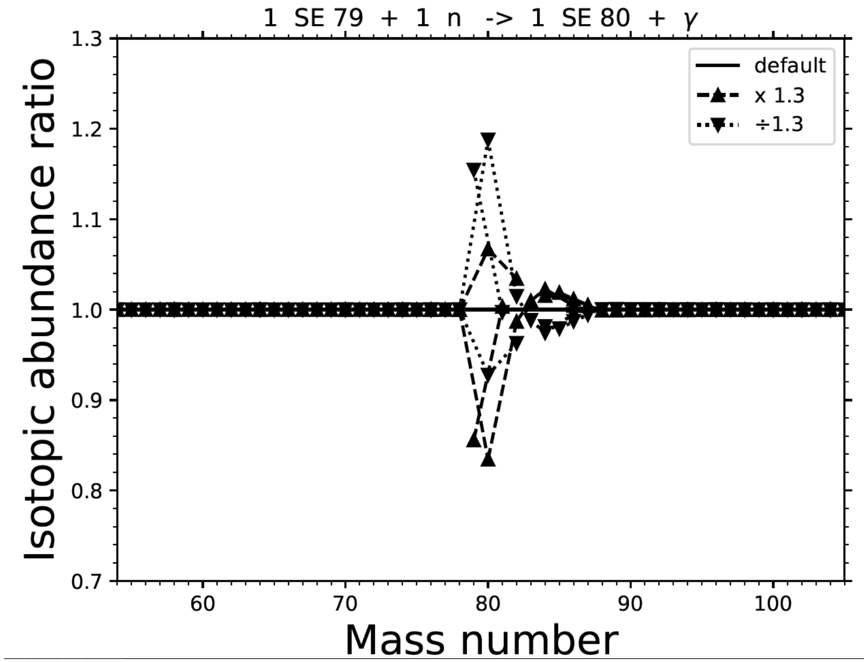
Massimi+2012 n_TOF:
24Mg+n, 25Mg+n, 26Mg+n



Reifarth+2012 Act. (NETZ calculations)
Zn64+n, Zn68+n, Zn70+n

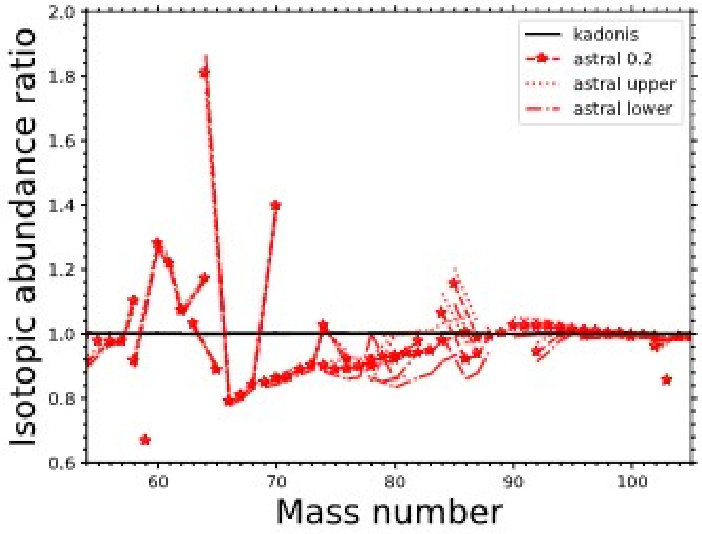


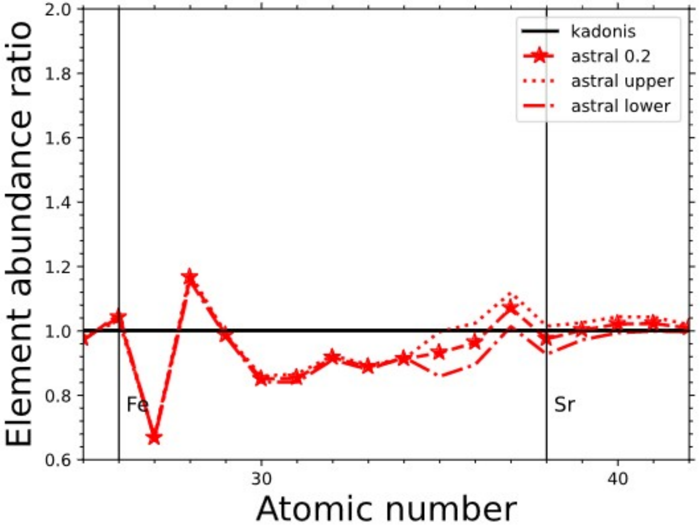
… n_TOF data?

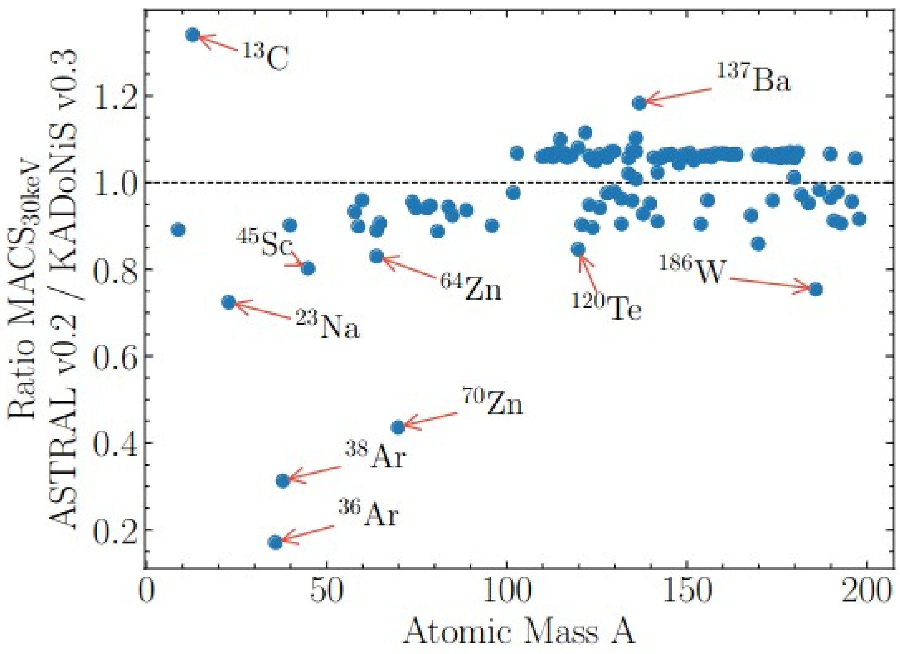


^{80}Rb 33.40 s β+	^{81}Rb 4.57 h β+	^{82}Rb 1.27 m β+	^{83}Rb 86.20 d β+	^{84}Rb 33.10 d β+
^{79}Kr 1.46 d 959 mb, β+	^{80}Kr 2.28 267 mb	^{81}Kr 229.02 ka 607 mb, β+	^{82}Kr 11.58 90 mb	^{83}Kr 11.49 243 mb
^{78}Br 6.46 m β+	^{79}Br 50.69 622 mb	^{80}Br 17.68 m β-	^{81}Br 49.31 239 mb	^{82}Br 1.47 d β-
^{77}Se 7.63 418 mb	^{78}Se 23.77 109 mb	^{79}Se 294.99 ka 263 mb, β-	^{80}Se 49.61 42 mb	^{81}Se 18.45 m β-
^{76}As 1.09 d β-	^{77}As 1.62 d β-	^{78}As 1.51 h β-	^{79}As 9.01 m β-	^{80}As 15.20 s β-

n_TOF: status experiment?
Lerendegui-Marco+ 2023







Vescovi+2023 ASTRAL

… all data available in Zenodo: https://zenodo.org/records/10124711

NuGrid Nucleosynthesis Grid collaboration

Published November 14, 2023 | Version v1

Dataset | Open

Output from paper: The s process in massive stars, a benchmark for neutron capture reaction rates

Pignatari, Marco[1]; Gallino, Roberto[2]; Reifarth, Rene[3]

Show affiliations

Title: "The s process in massive stars, a benchmark for neutron capture reaction rates"; Authors: Marco Pignatari, Roberto Gallino, Rene Reifarth

---

Content: tar.gz package including a README file and two folders. The folders contain all the abundance plots associated to the work Pignatari, Gallino & Reifarth, 2023 The European Physical Journal A, Special Issue on: 'From reactors to stars' in honor of Franz Kaeppeler.

Files

Files (16.0 MB)

Name	Size	Download all
impact_cross_sections_weaks.tar.gz md5:e62303d4589229b0f7ad1220fe8c4715	16.0 MB	Download

Additional details

Identifiers	DOI 10.5281/zenodo.10124711
Dates	Created 2023-11-14

Versions

Version v1 — Nov 14, 2023
10.5281/zenodo.10124711

Cite all versions? You can cite all versions by using the DOI 10.5281/zenodo.10124710. This DOI represents all versions, and will always resolve to the latest one. Read more.

External resources

Indexed in

OpenAIRE

Communities

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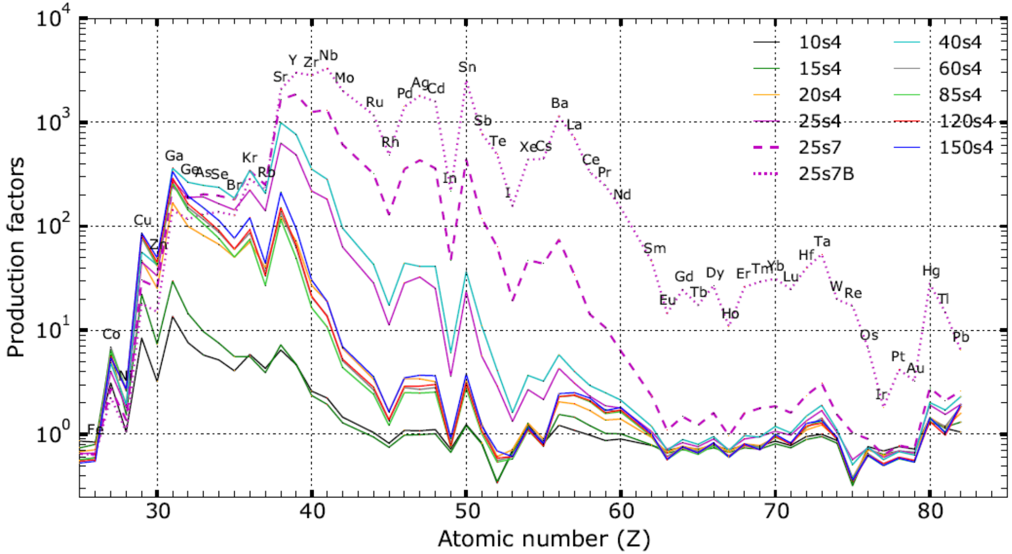
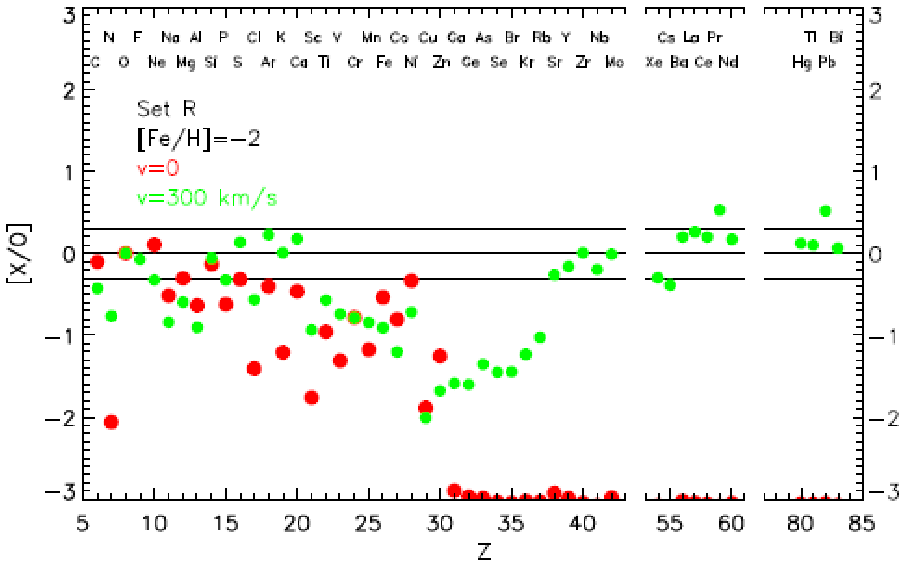
Details

DOI
DOI 10.5281/zenodo.10124711

Enhanced s process due to rotation in massive stars at low metallicity



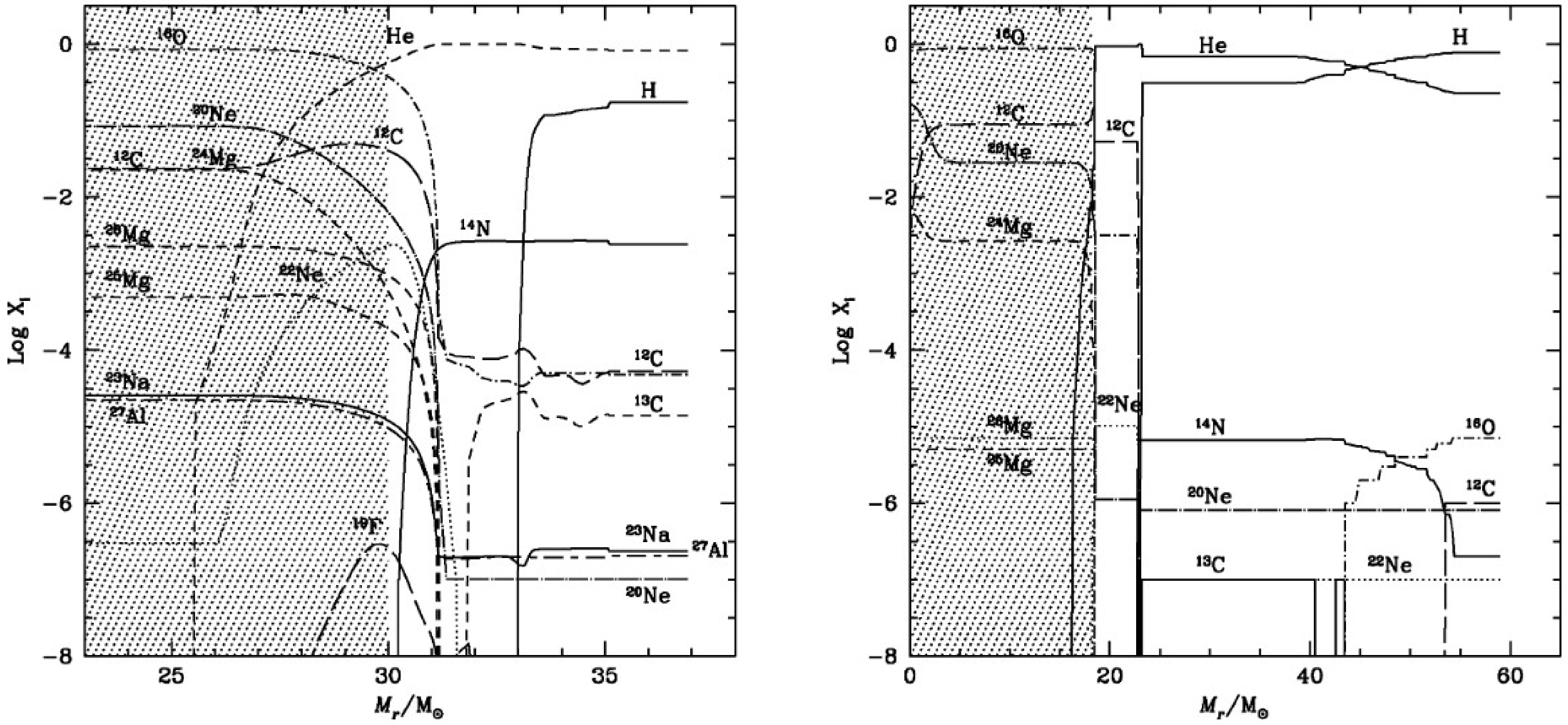
Choplin+ 2018 A&A



Limongi & Chieffi 2018 ApJ

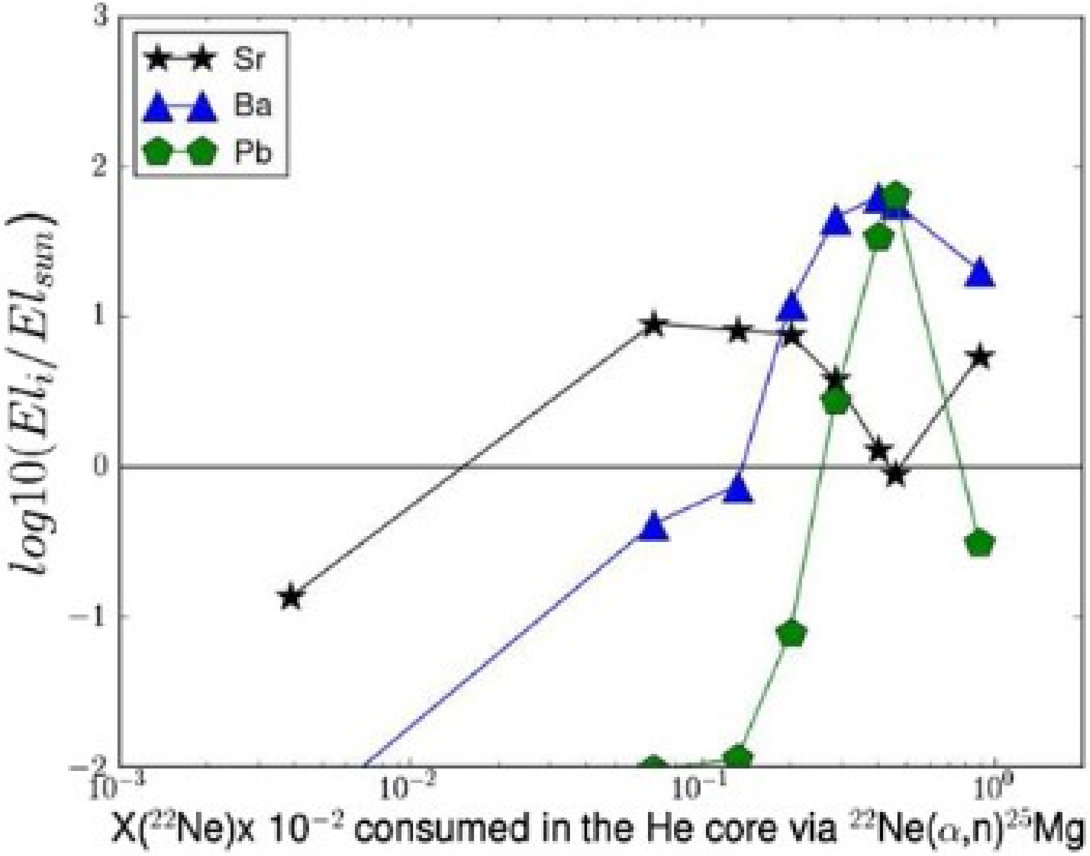
See also Pignatari+ 2008 ApJL, Frischknecht+ 2016 MNRAS

Why the s-process is boosted in fast-rotating massive stars?



Meynet+ 2010

22Ne+α:
impact on the s-process in fast-rotating massive stars

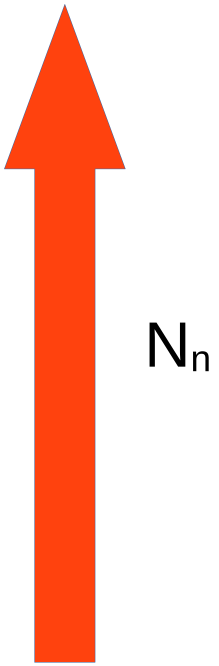


Pignatari+2013 ApJ

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} .



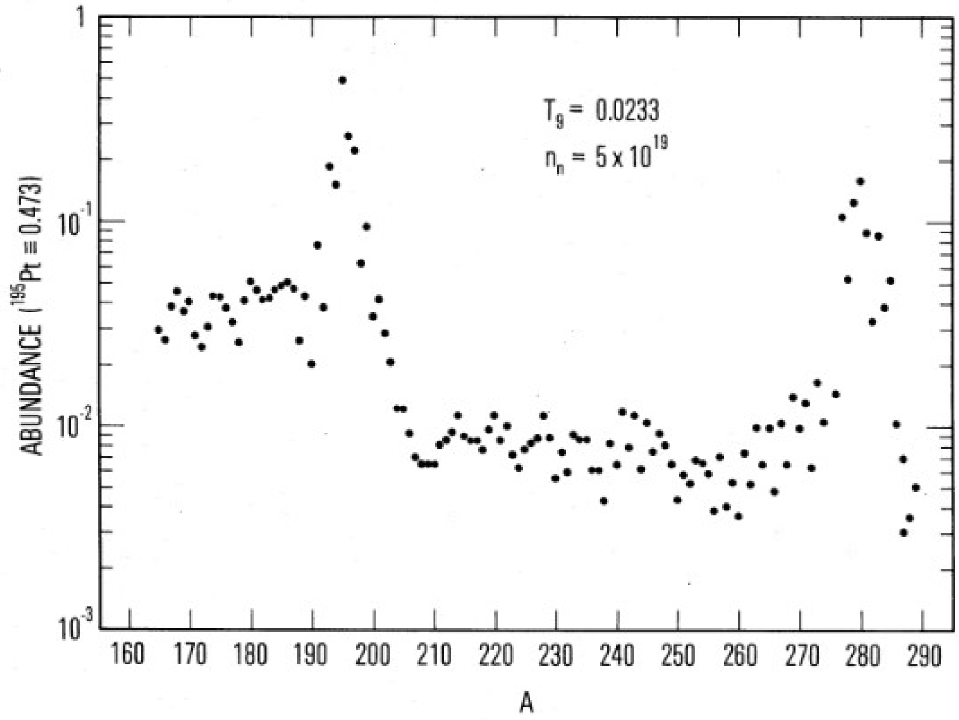
THE ASTROPHYSICAL JOURNAL, 209:846–849, 1976 November 1

1976

A POSSIBLE ALTERNATIVE TO THE *r*-PROCESS

J. B. BLAKE
Space Sciences Laboratory, The Aerospace Corporation
AND
D. N. SCHRAMM
Enrico Fermi Institute, University of Chicago
Received 1976 March 10

n process



Possible stellar sites proposed: CCSNe or Novae

Connecting the n-process with the stellar site

Astron. Astrophys. 74, 175–185 (1979)

ASTRONOMY AND ASTROPHYSICS

Meteoritic Anomalies and Explosive Neutron Processing of Helium-burning Shells*

F.-K. Thielemann[1], M. Arnould[2]***, and W. Hillebrandt[1]

THE ASTROPHYSICAL JOURNAL, 248:315–320, 1981 August 15

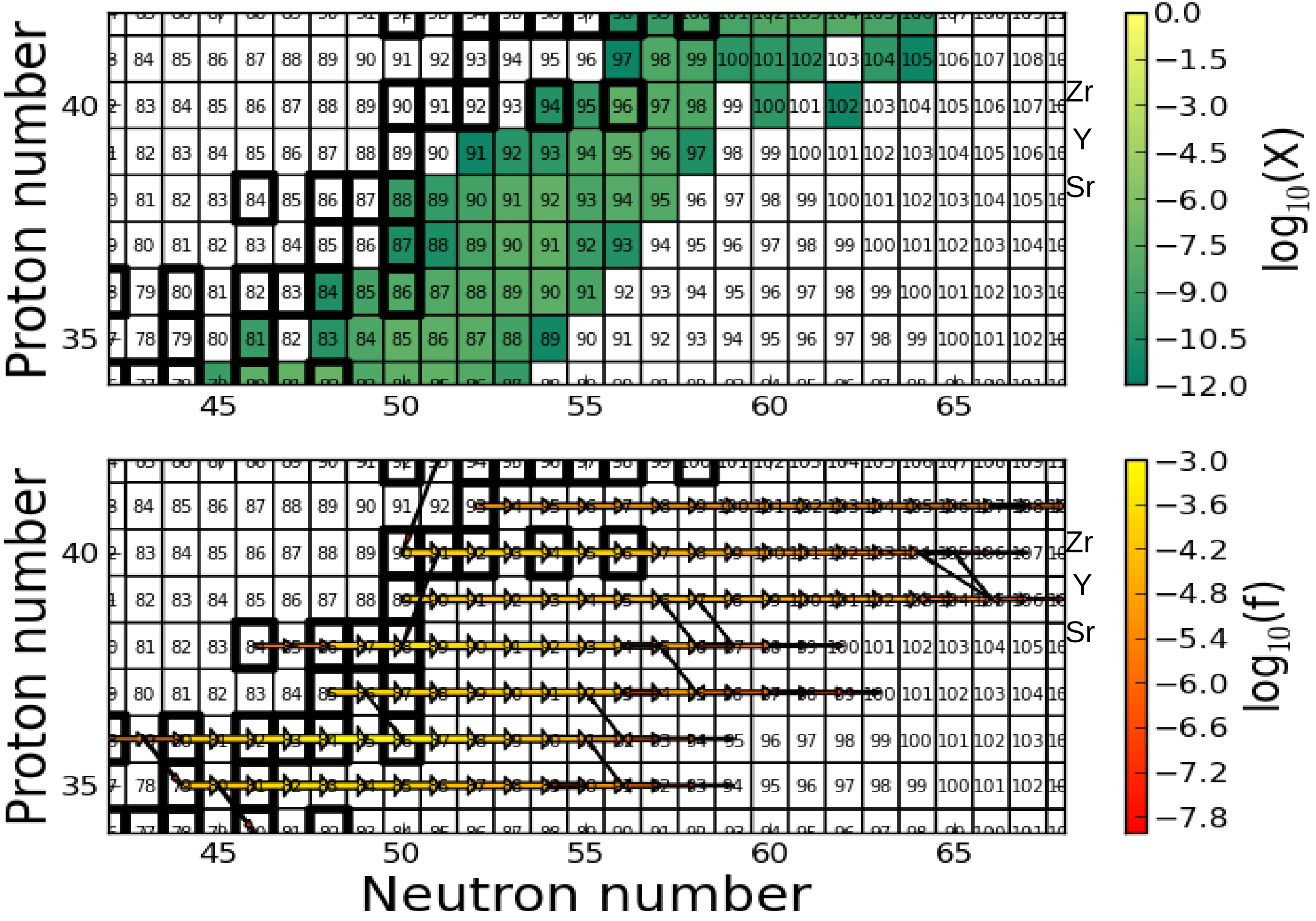
NUCLEOSYNTHESIS OF NEUTRON-RICH HEAVY NUCLEI DURING EXPLOSIVE HELIUM BURNING IN MASSIVE STARS

J. B. BLAKE
Space Sciences Laboratory, The Aerospace Corporation
S. E. WOOSLEY
Lick Observatory, University of California at Santa Cruz, and Lawrence Livermore Laboratory
T. A. WEAVER
Lawrence Livermore Laboratory
AND
D. N. SCHRAMM
Enrico Fermi Institute, University of Chicago
Received 1980 November 6; accepted 1981 March 2

Main results:

- The n-process is associated to the explosive He-burning in CCSNe;
- The main neutron source is the 22Ne(α,n)25Mg.
- The r-process abundances are not reproduced

Nucleosynthesis properties of the n process



What are the observational signatures of the n-process?

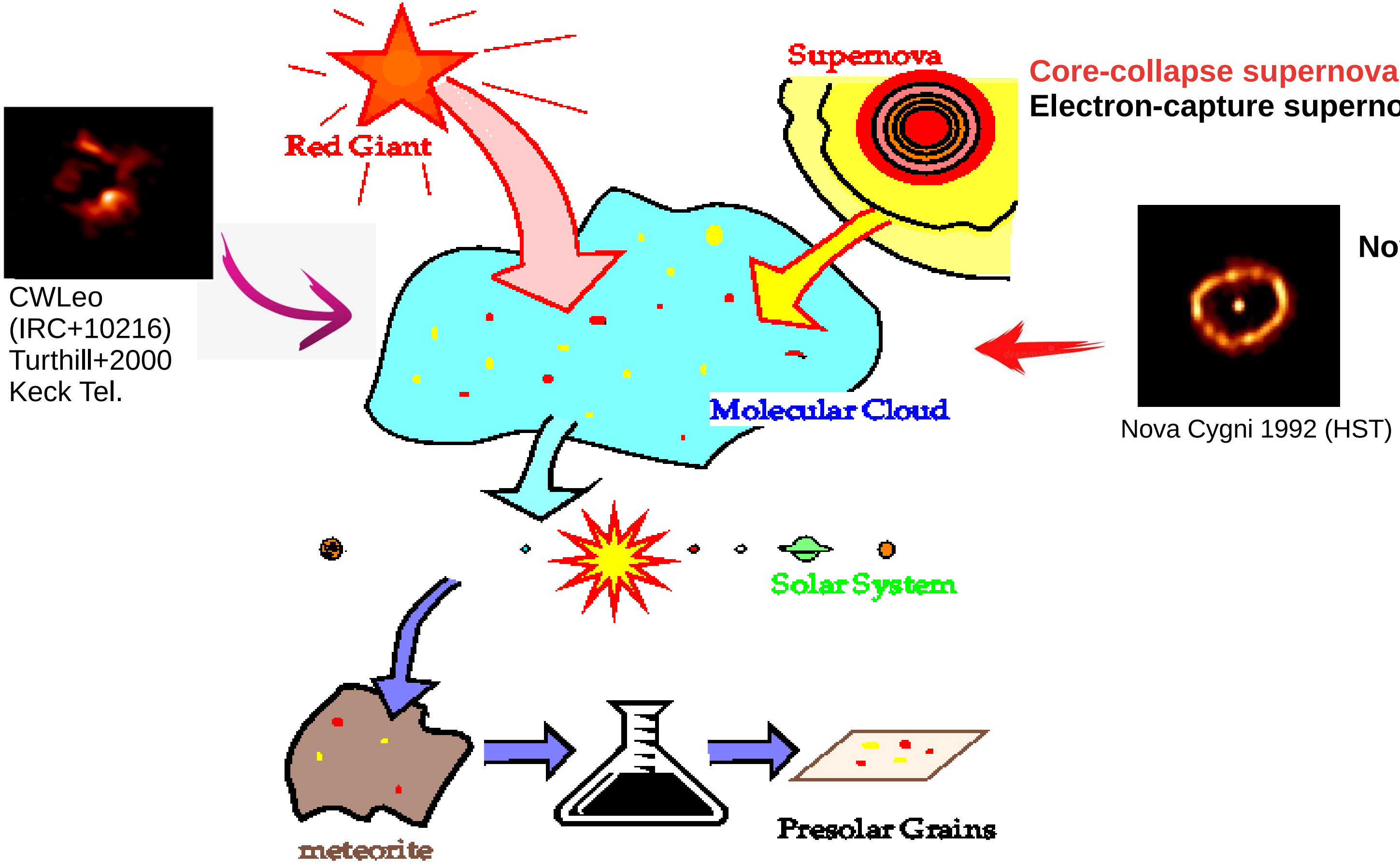
- The impact on GCE is not expected to be relevant
- Signature on C-rich presolar grains
- Contribution to the Short-Lived Radionuclides (SLRs – 0.1-100Myr) in the Galaxy and in the Early Solar System

The presolar grain journey from stars to us

AGB stars
Post-AGB stars
...

Core-collapse supernovae
Electron-capture supernovae (?)

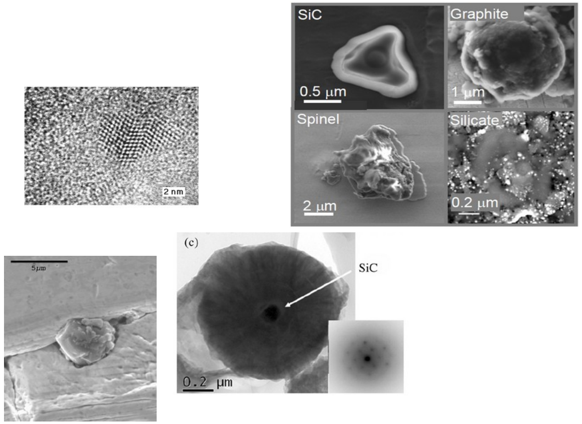
Novae



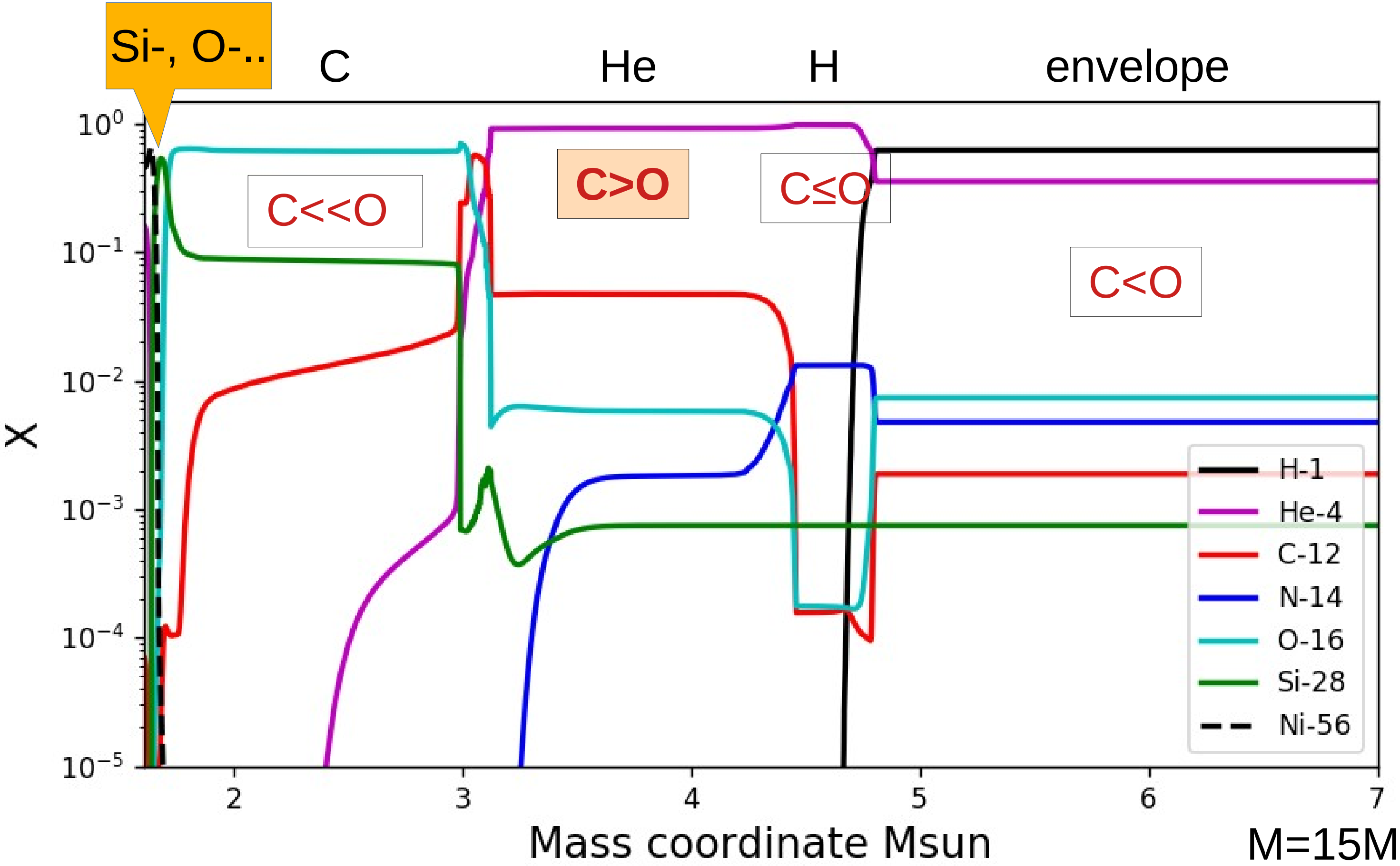
Adapted from L. Nittler

Grains formed from part of the material ejected, in the timescale of few months-one year after the explosion. **Not to be compared with integrated stellar yields!**

Grains formed in winds and to be compared with surface abundance from stellar models

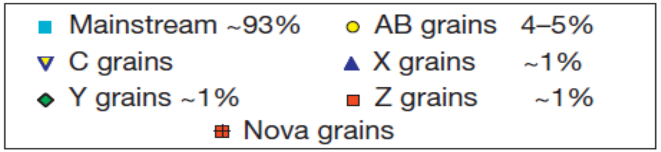


Presolar grains zoo

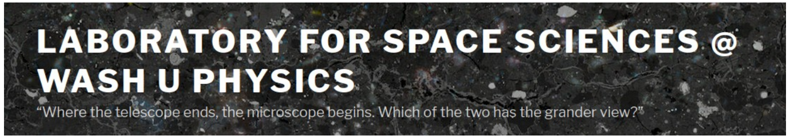


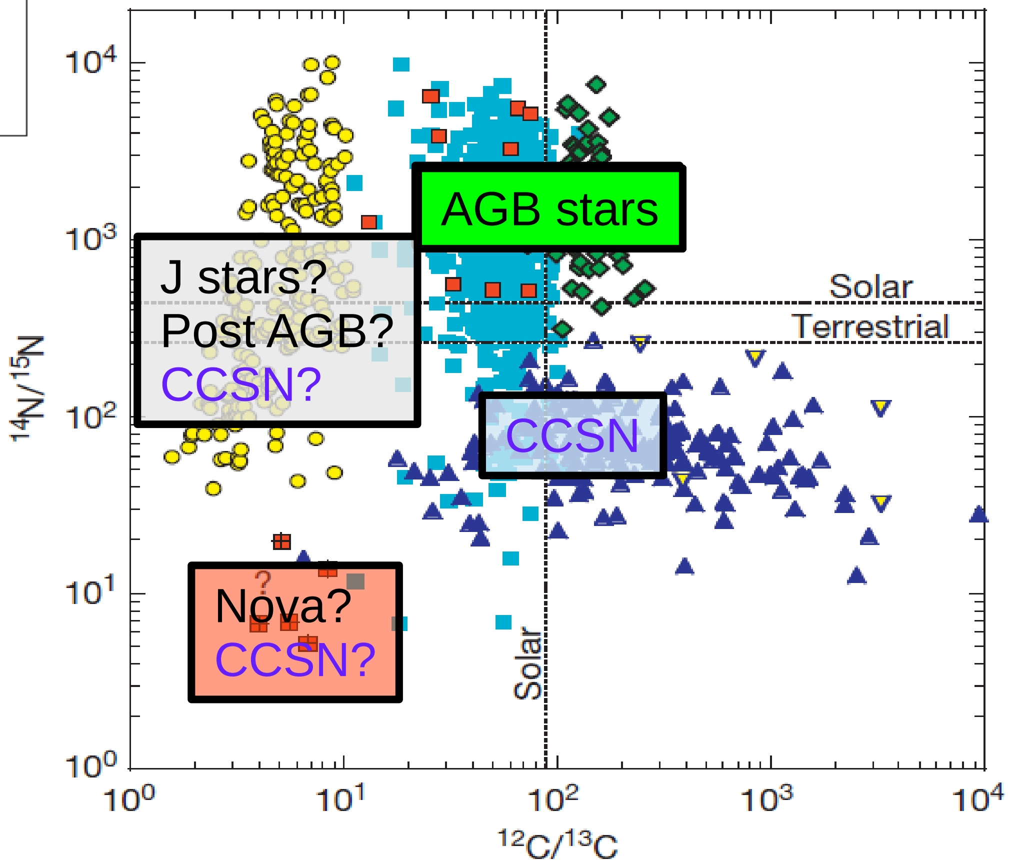
M=15Msun, Z=0.02
Ritter+2018 MNRAS
MESA progenitor
Fryer+12 explosion

The analysis to disentangle the origin of different types of presolar grains is based on the comparison between their **isotopic** composition and stellar models.



St. Louis Presolar Grains database:
Hynes & Gyngard 2009 LPIS 40
Stephan et al. 2020, LpIS 51

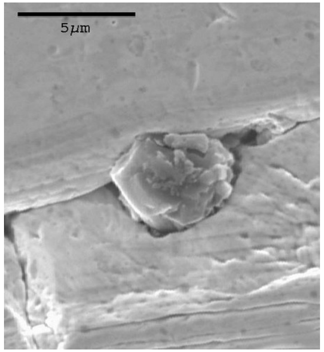




https://presolar.physics.wustl.edu/presolar-grain-database/

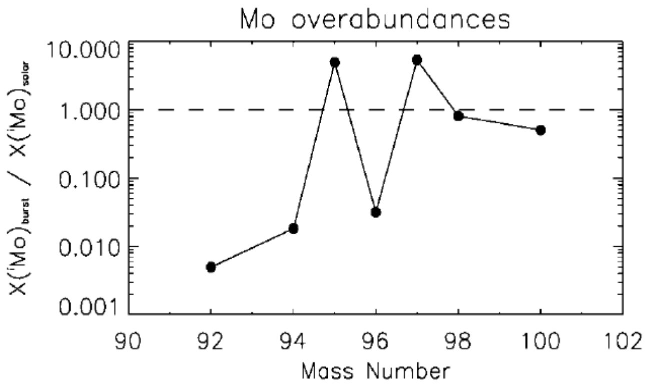
Zinner 2014, Treat. Geochem 1.4

The n-process: n-capture signature in presolar SiC-X grains from CCSNe



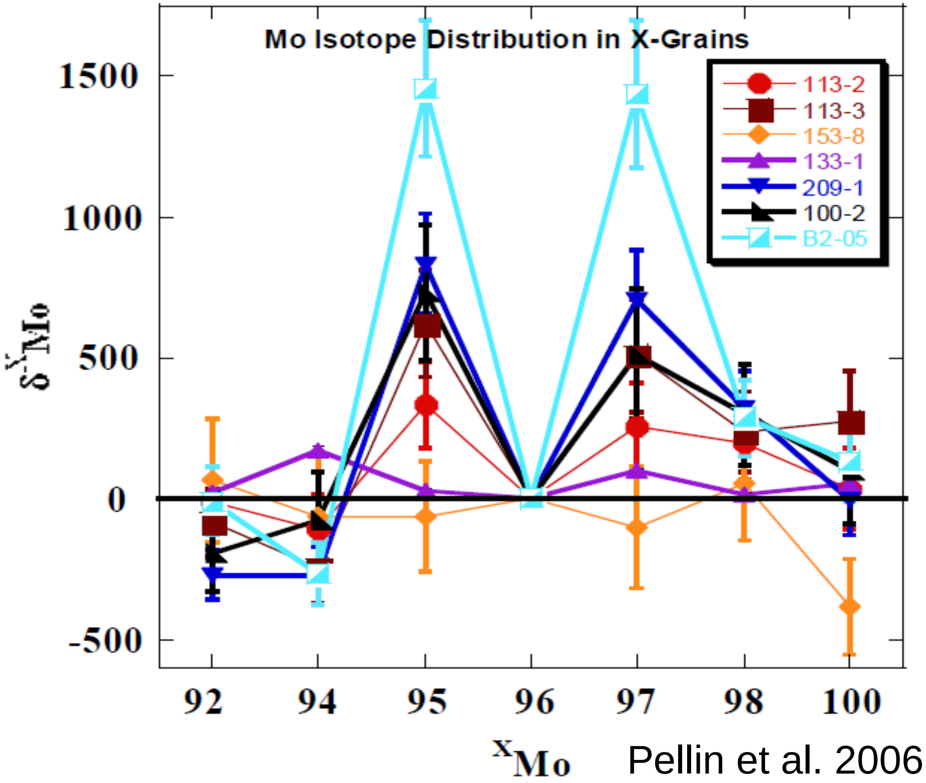
R. Trappitsch (Brandeis University)

n-process signature in the explosive He shell:
e.g., Sr, Zr, Mo, Ru, Ba

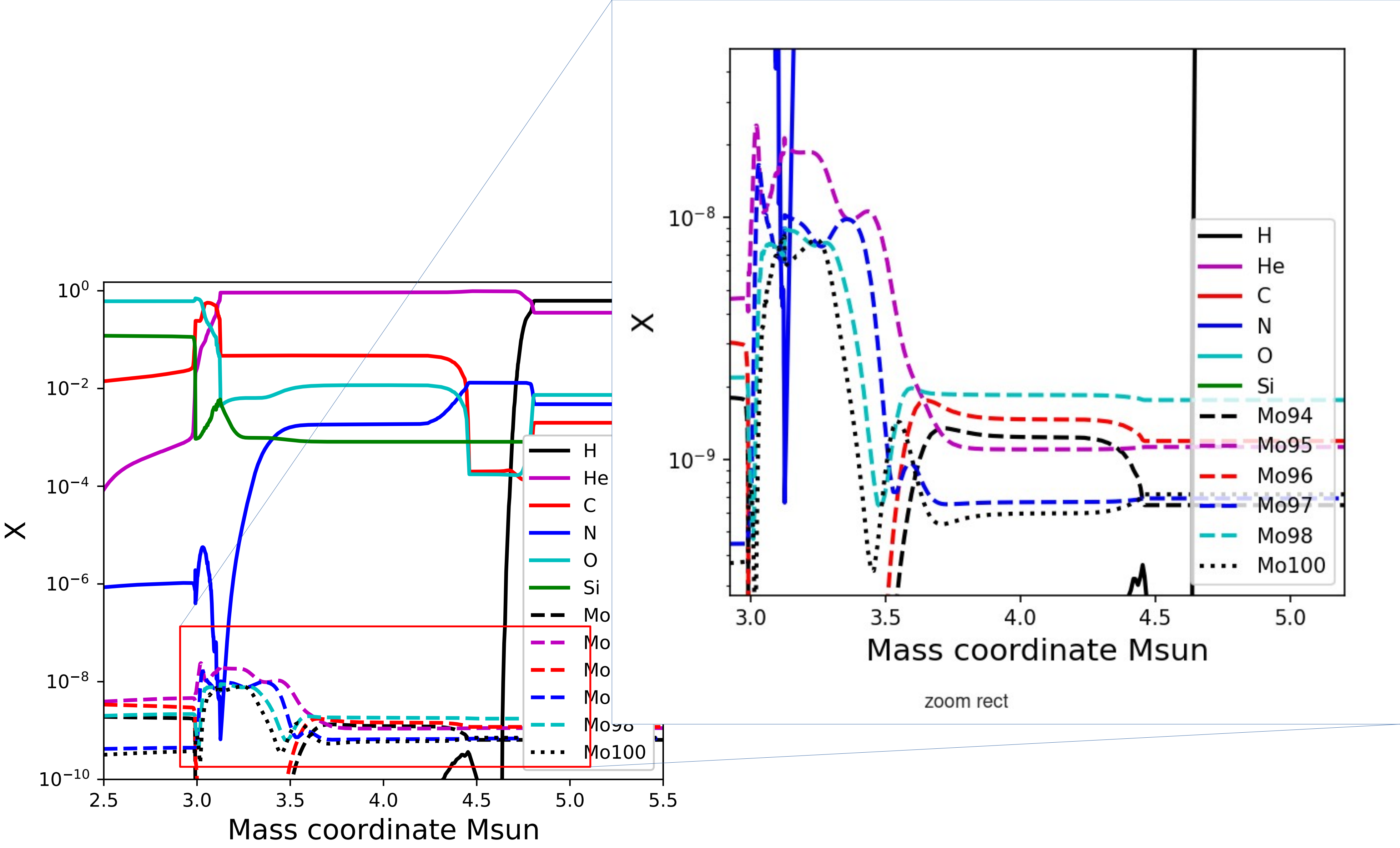


Meyer et al. 2000, ApJL

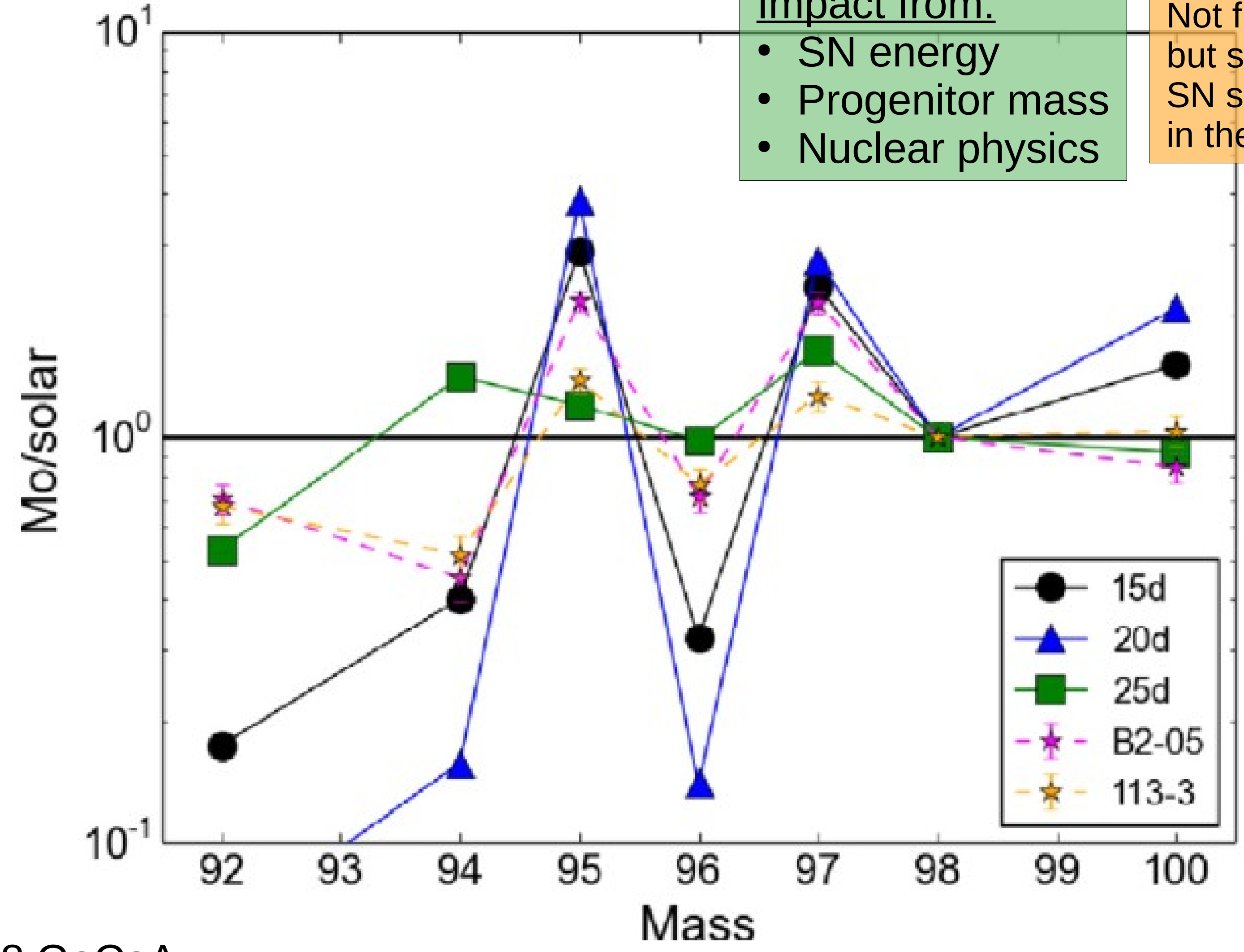
NO-s & NO-r



Pellin et al. 2006 LPI



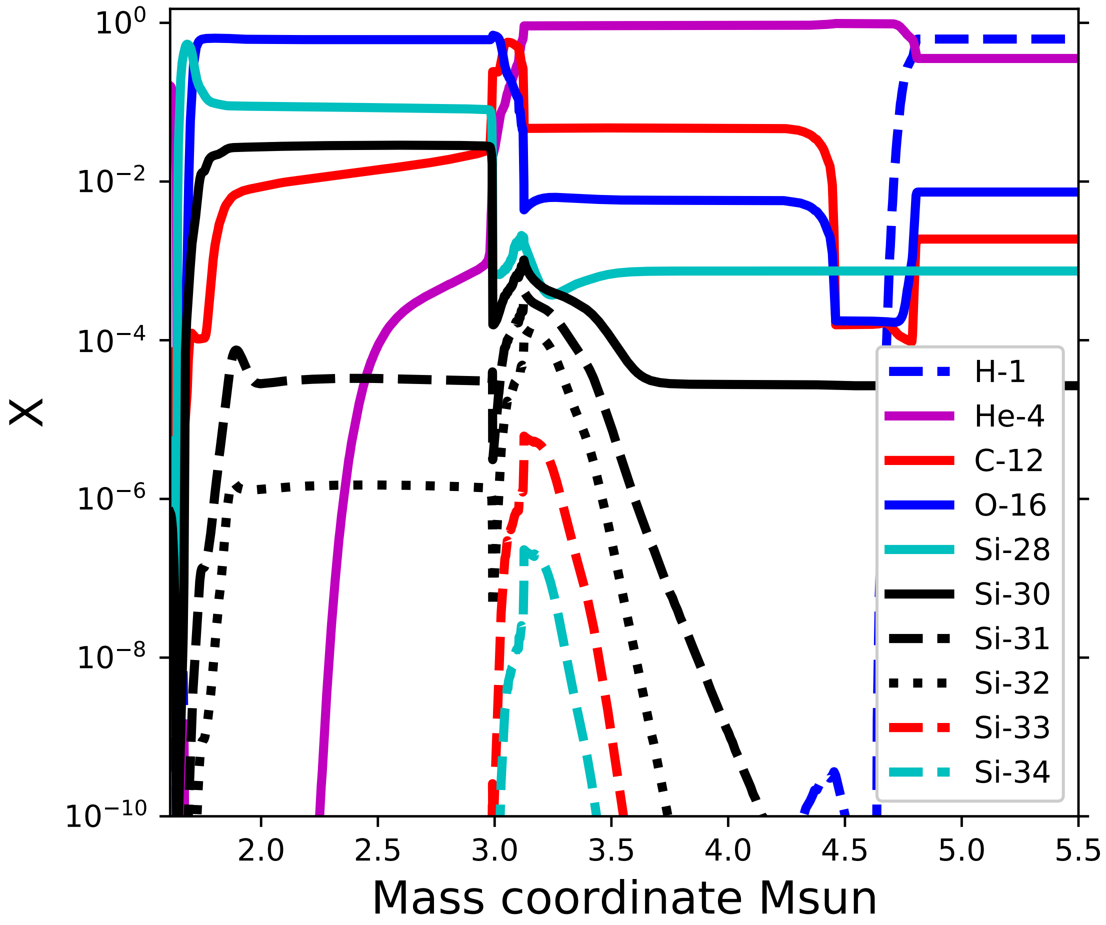
X
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
2.5
3.0
3.5
4.0
4.5
5.0
5.5
Mass coordinate Msun
H
He
C
N
O
Si
Mo
Mo
Mo
Mo
Mo98
Mo100
X
10^{-8}
10^{-9}
3.0
3.5
4.0
4.5
5.0
Mass coordinate Msun
H
He
C
N
O
Si
Mo94
Mo95
Mo96
Mo97
Mo98
Mo100
zoom rect



Impact from:
- SN energy
- Progenitor mass
- Nuclear physics

Not from 1 trajectory, but snapshot of SN shock conditions in the He shell layers.

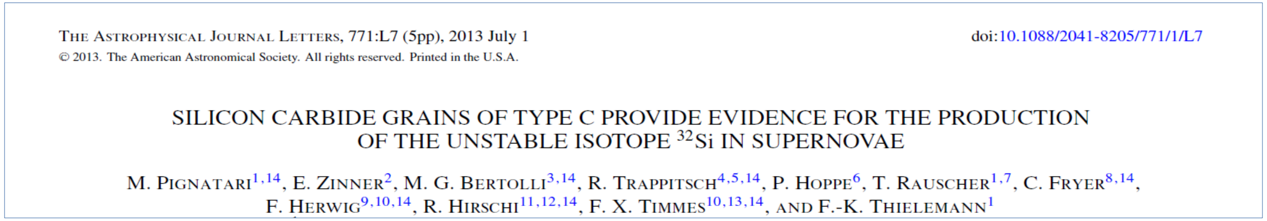
Pignatari+ 2018 GeCoA



M=15Msun, Z=0.02
Ritter+2018 MNRAS
MESA progenitor
Fryer+12 explosion

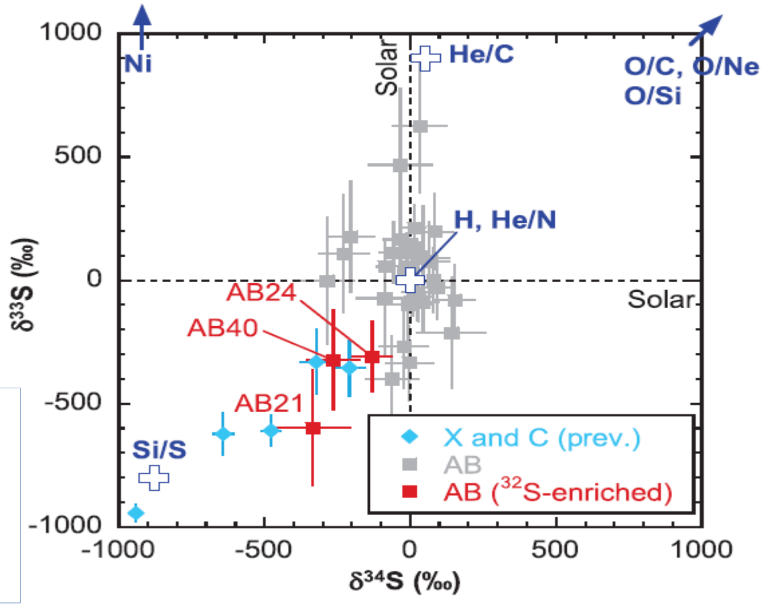
Neutron captures in the He shell ejecta: Signature of radioactive Si32 found in presolar SiC-C grains

Constrain the explosive nucleosynthesis conditions in the C-rich He shell of the progenitor CCSN.


The Astrophysical Journal Letters, 771:L7 (5pp), 2013 July 1 doi:10.1088/2041-8205/771/1/L7

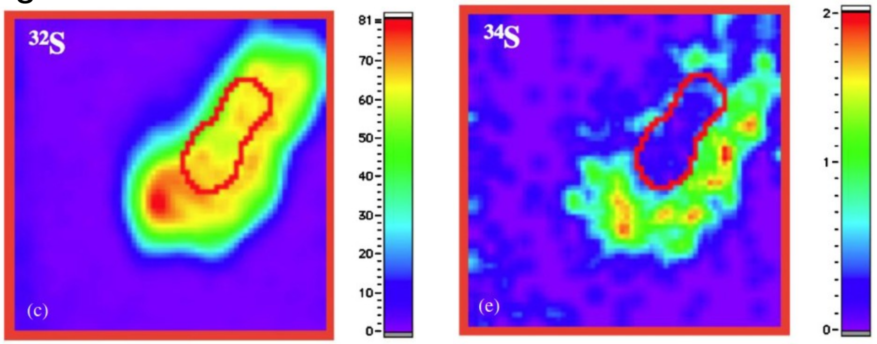
SILICON CARBIDE GRAINS OF TYPE C PROVIDE EVIDENCE FOR THE PRODUCTION OF THE UNSTABLE ISOTOPE ^{32}Si IN SUPERNOVAE

M. Pignatari[1,14], E. Zinner[2], M. G. Bertolli[3,14], R. Trappitsch[4,5,14], P. Hoppe[6], T. Rauscher[1,7], C. Fryer[8,14], F. Herwig[9,10,14], R. Hirschi[11,12,14], F. X. Timmes[10,13,14], and F.-K. Thielemann[1]

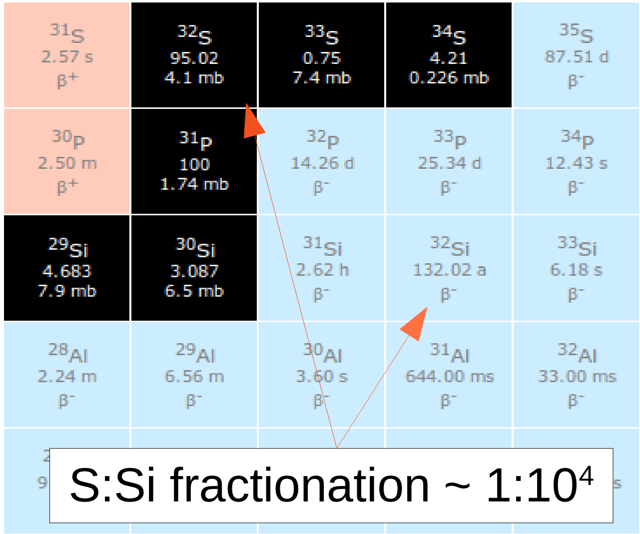


(see also Fujiya et al. 2013, ApJL for SiC AB grains)

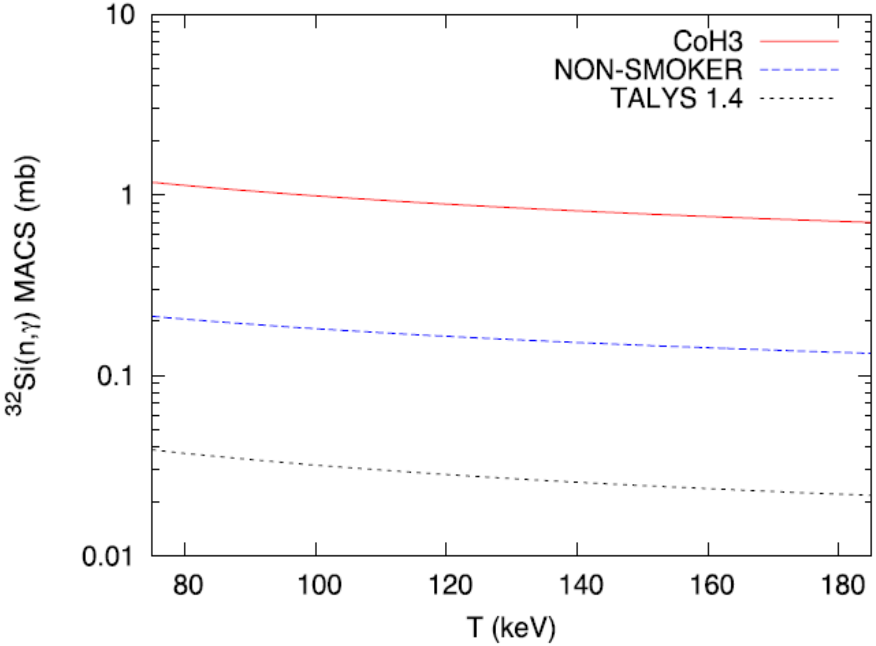
C grain a1-5-7

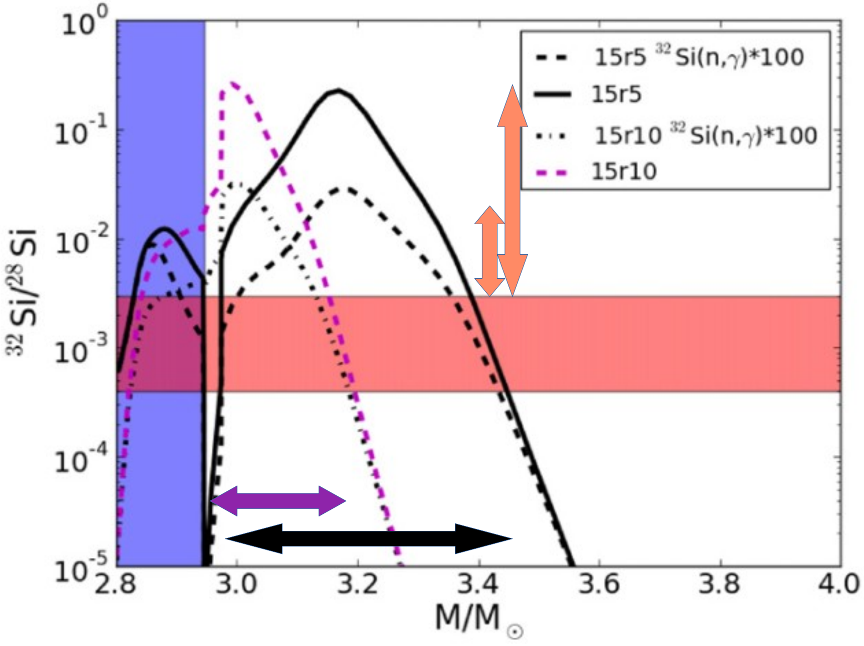


NanoSIMS images, Xu et al. 2015, ApJ



Signature of radioactive Si32 found in presolar SiC-C grains



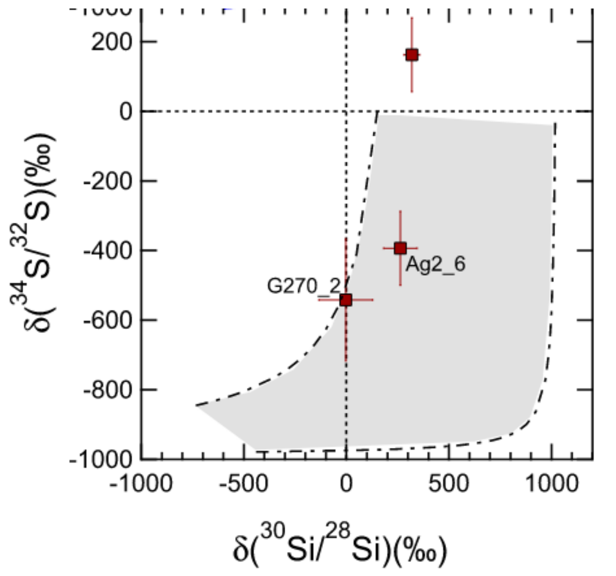


Si32(n,γ)Si33 changes by a factor of 100.

Impact from the direct capture component?
Xu+2014 PRC 90

- The SN energy controls the extension of the C-rich region with high Si32/Si28.
- The Si31(n,γ)Si32 and Si32(n,γ)Si33 rates control the amount of Si32-enrichment in the Si32-rich layers.

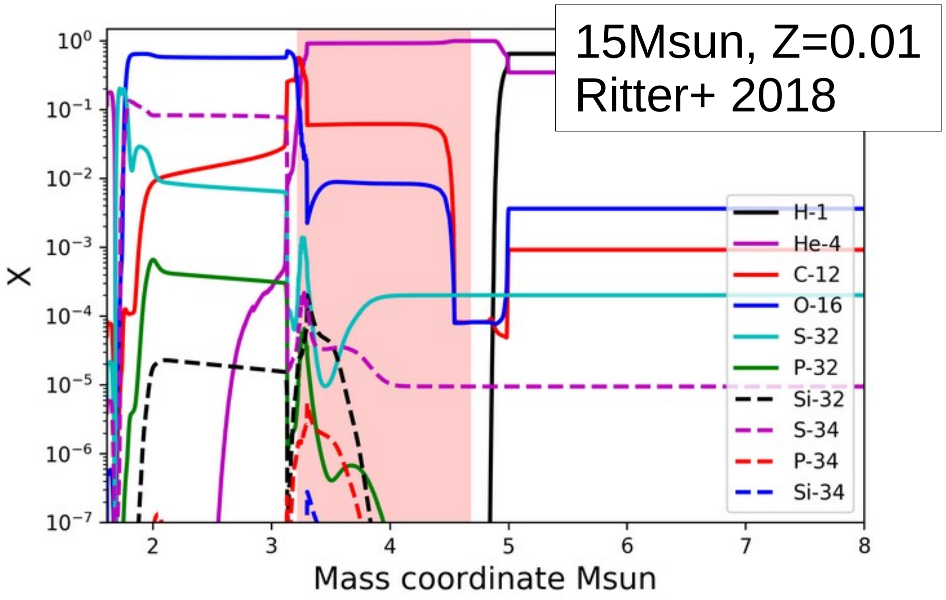
Novae signature or n-process in presolar grains?



Liu+ 2016 ApJ 820

- S34/S32: Gillespie+ 2017 Phys Rev C
- S33/S32: Kennington+ 2020 Phys Rev Lett.

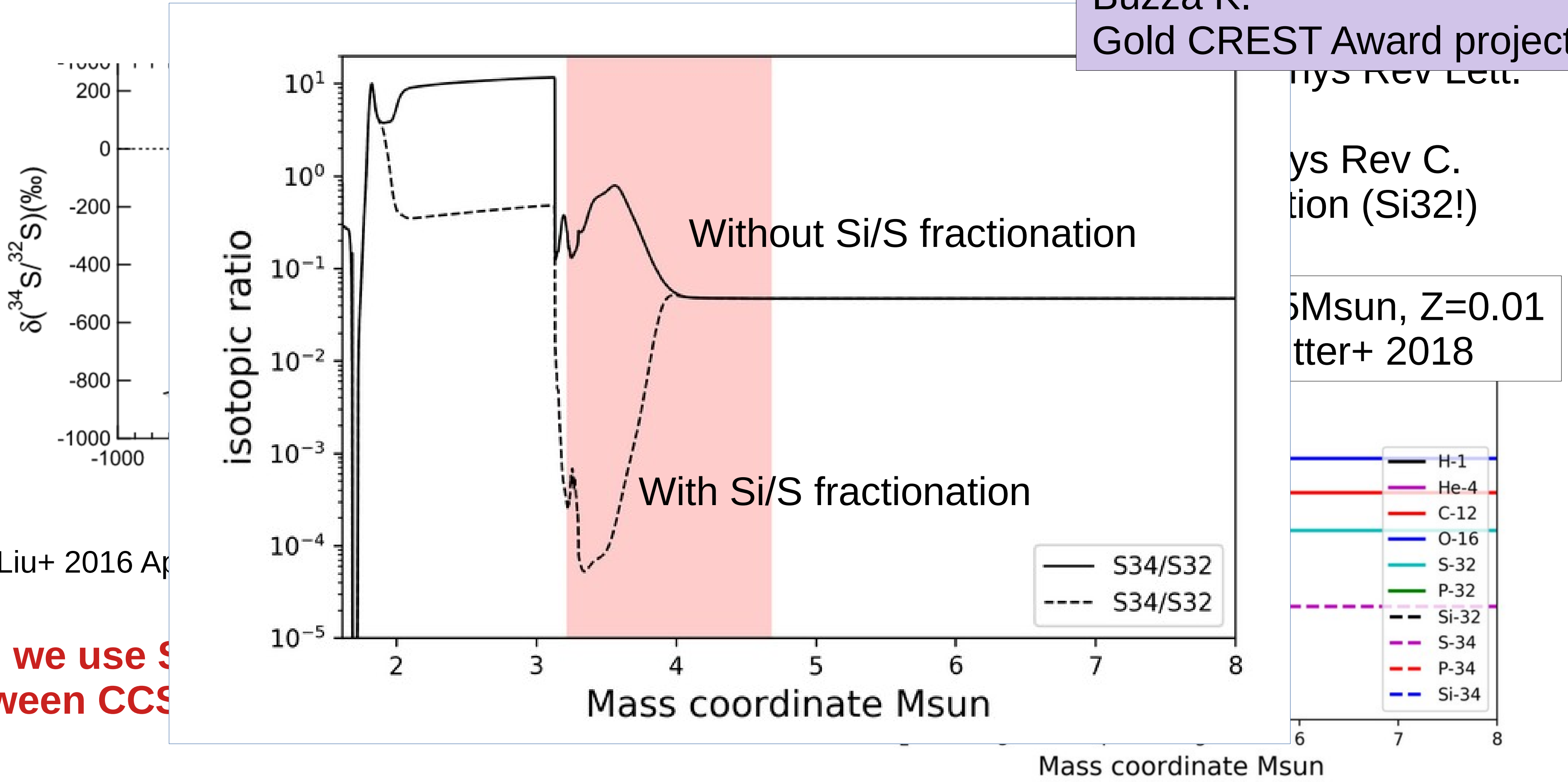
However, see Richter+ 2020 Phys Rev C.
Take into account Si/S fractionation (**Si32!**)



Can we use S-isotopic ratios to distinguish between CCSN and nova origin of grains?

CCSNe or Novae?

Buzza K.
Gold CREST Award project



Liu+ 2016 Ap

Can we use S
between CCS

SLRs in the ESS

Progress in Particle and Nuclear Physics 102 (2018) 1–47

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

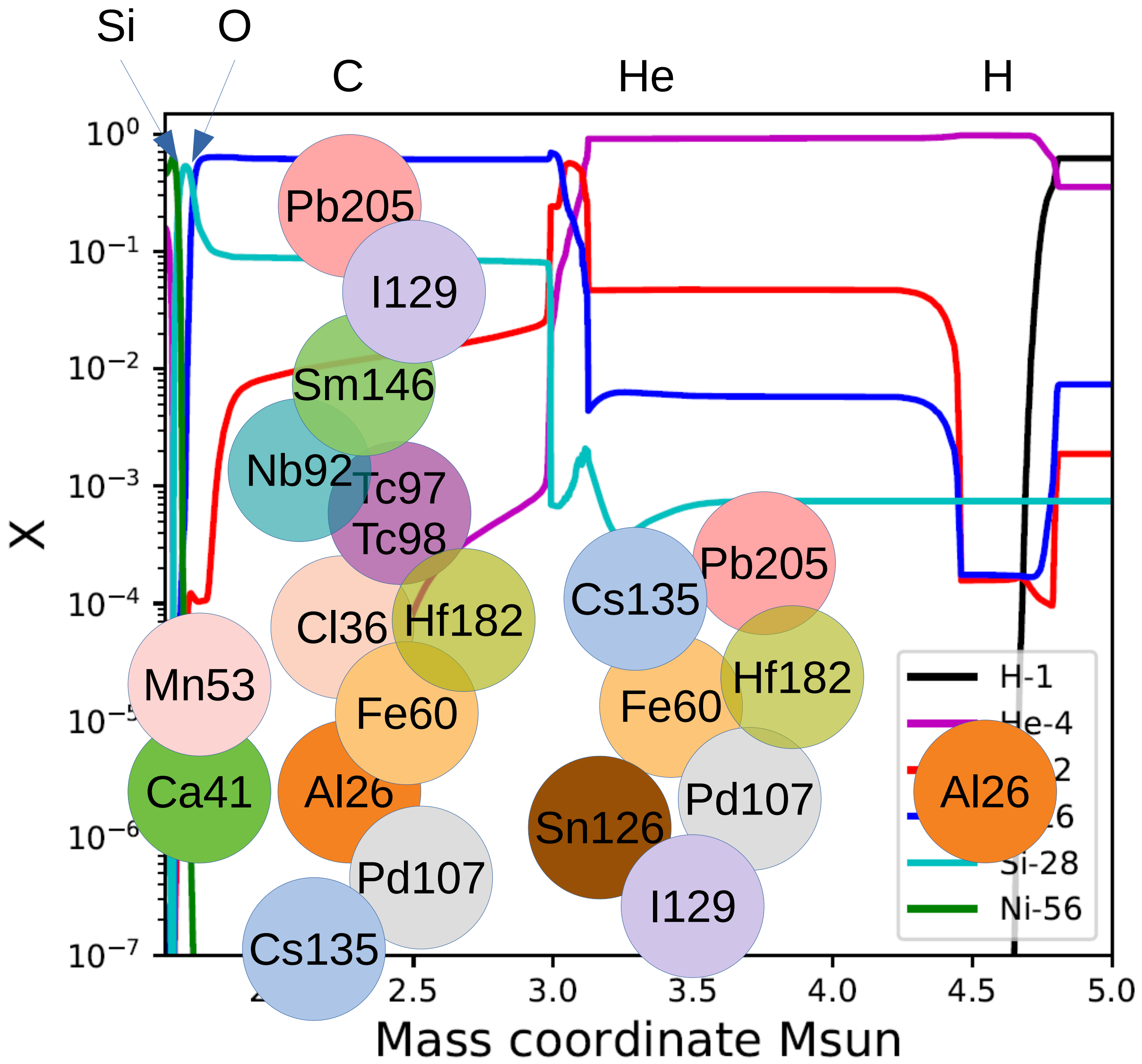
Review

Radioactive nuclei from cosmochronology to habitability

M. Lugaro [a,b,*], U. Ott [c,d], Á. Kereszturi [a]

Check for updates

A really good review to know more about this..

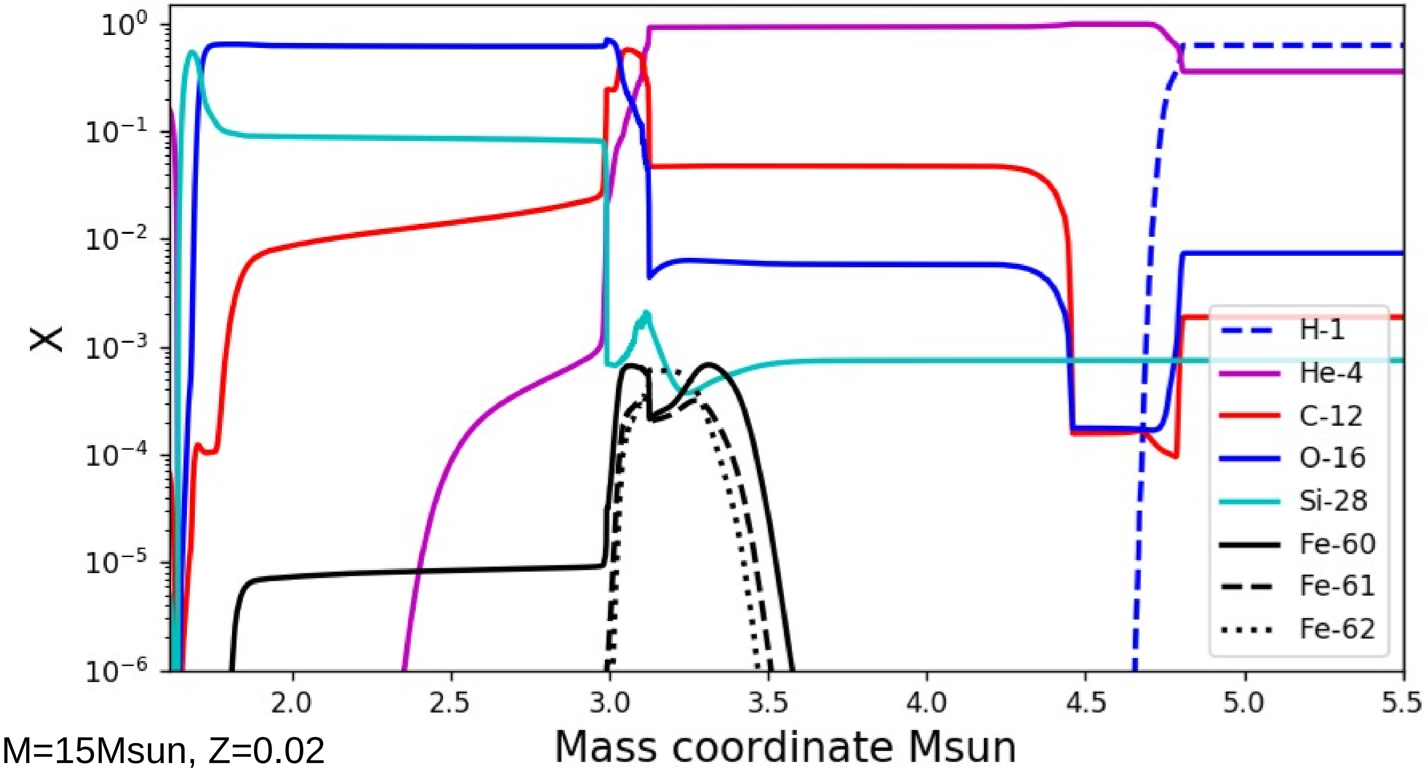


M = 15Msun, Z=0.02
CCSN model
Ritter et al. 2018 MNRAS

For an updated list of SLRs measures in the early solar system:
Lugaro et al 2018 PPNP (and references there)

Lawson et al. 2022, MNRAS (Hull/Konkoly/Los Alamos):
build the map of the CCSNe ejecta based on SLRs

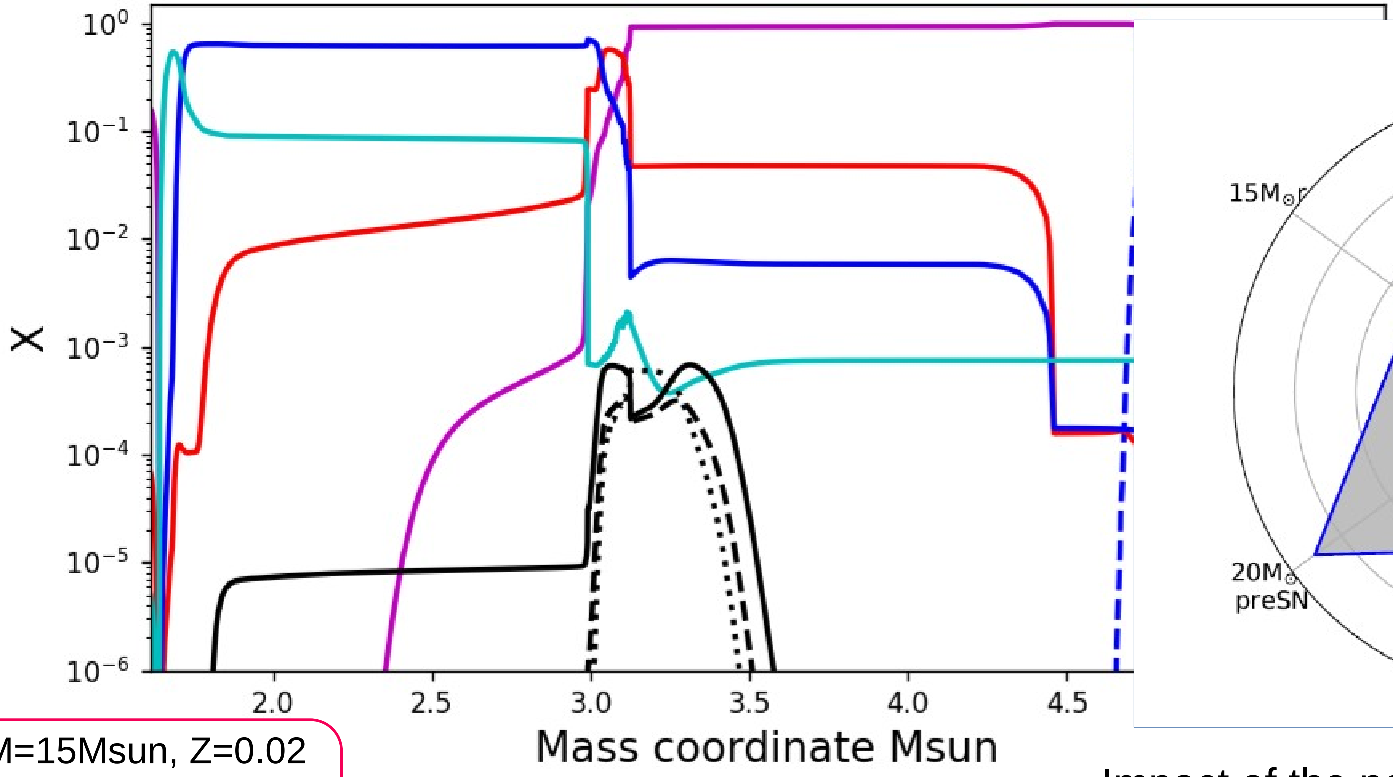
Neutron burst driven by the Ne22(α,n): Fe60

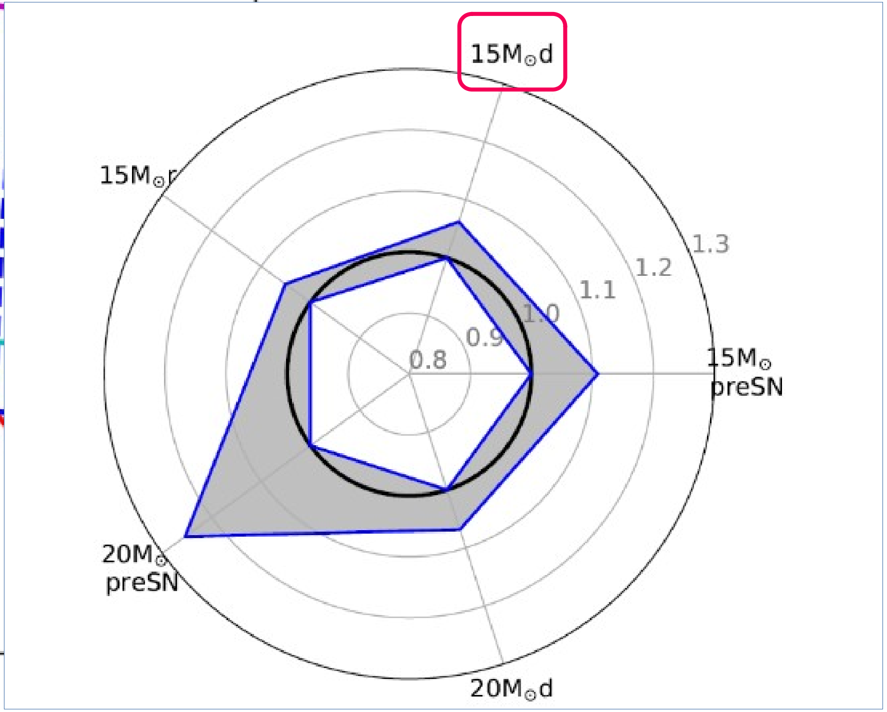


M=15Msun, Z=0.02
Ritter+2018 MNRAS
MESA progenitor
Fryer+12 explosion

^{60}Ni 26.223 30 mb	^{61}Ni 1.14 82 mb	^{62}Ni 3.634 22.3 mb	^{63}Ni 100.11 a 31 mb, β^-
^{59}Co 100 38 mb	^{60}Co 5.27 a β^-	^{61}Co 1.65 h β^-	^{62}Co 1.50 m β^-
^{58}Fe 0.282 12.1 mb	^{59}Fe 44.50 d β^-	^{60}Fe 1.50 Ma β^-	^{61}Fe 5.98 m β^-

Neutron burst driven by the Ne22(α,n): Fe60

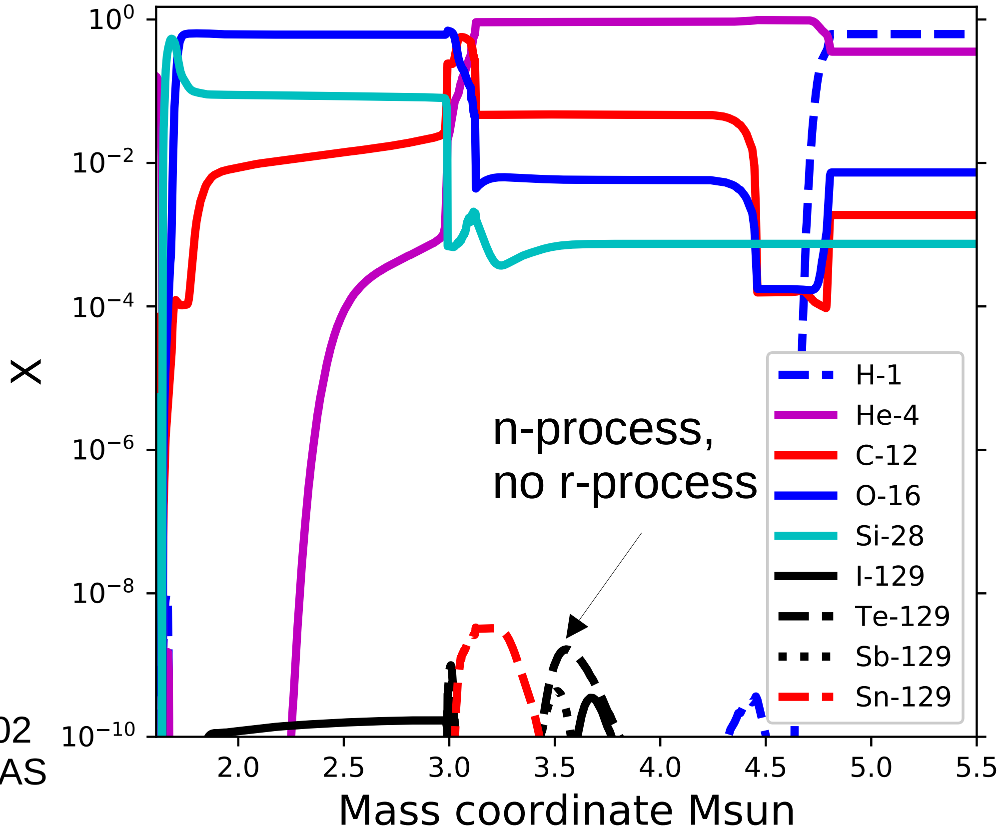




M=15Msun, Z=0.02
Ritter+2018 MNRAS
MESA progenitor
Fryer+12 explosion

Impact of the new Fe59(n,γ)Fe60 on Fe60 yields:
Yan+ 2021, ApJ 919
(see also Jones+ 2019 MNRAS)

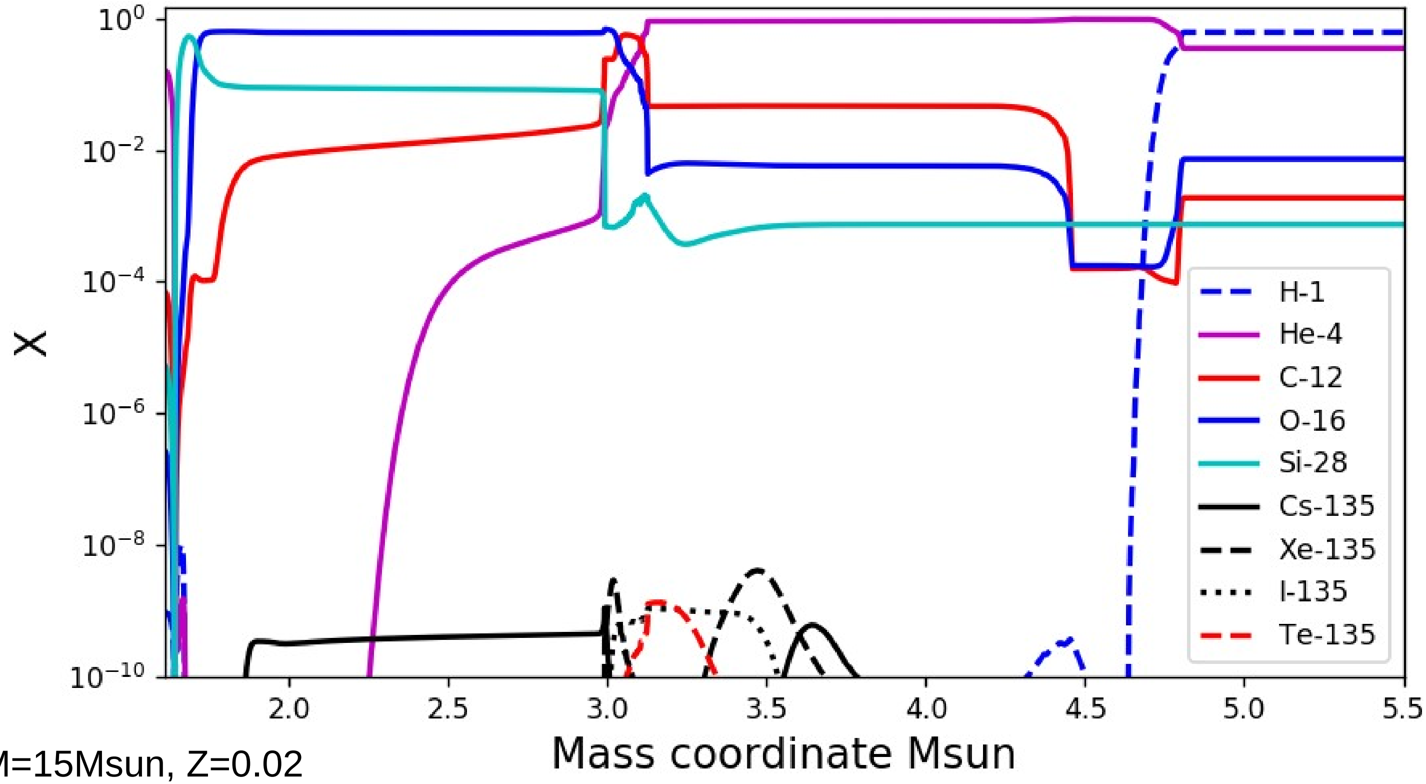
Neutron burst driven by the Ne22(α,n): I129



^{128}Xe 1.91 248 mb	^{129}Xe 26.4 472 mb	^{130}Xe 4.071 141 mb	^{131}Xe 21.232 340 mb	^{132}Xe 26.909 64.6 mb
^{127}I 100 635 mb	^{128}I 24.99 m β^-	^{129}I 15.70 Ma 441 mb, β^-	^{130}I 12.36 h β^-	^{131}I 8.02 d β^-
^{126}Te 18.84 81.3 mb	^{127}Te 9.35 h β^-	^{128}Te 31.74 44.4 mb	^{129}Te 1.16 h β^-	^{130}Te 34.08 14.7 mb

M=15Msun, Z=0.02
Ritter+2018 MNRAS
MESA progenitor
Fryer+12 explosion

Neutron burst driven by the Ne22(α,n): Cs135

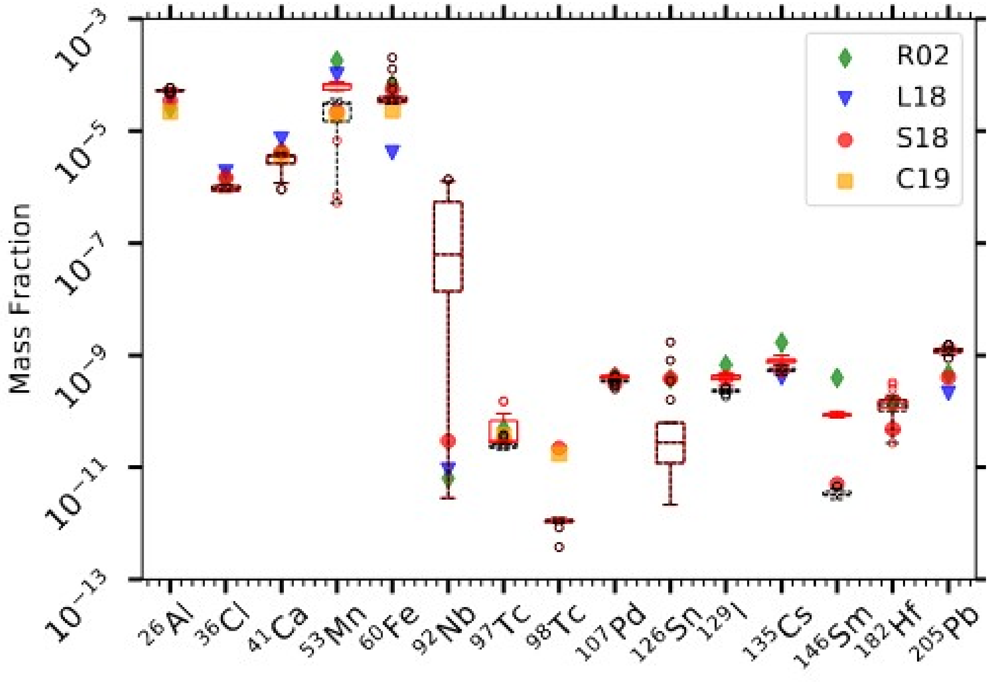


M=15Msun, Z=0.02
Ritter+2018 MNRAS
MESA progenitor
Fryer+12 explosion

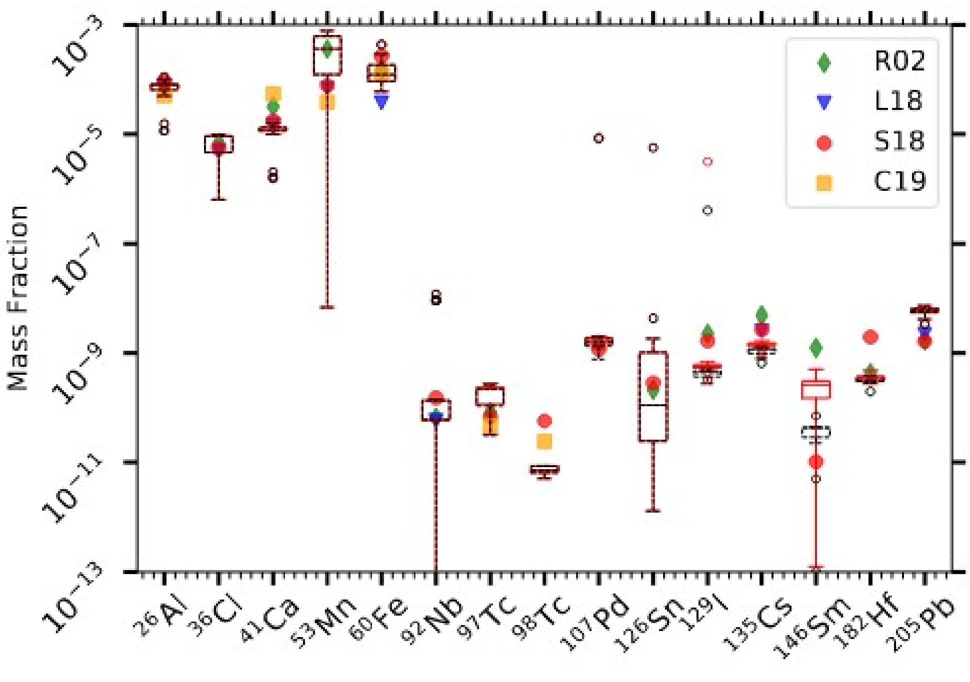
^{134}Ba 2.417 176 mb	^{135}Ba 6.592 455 mb	^{136}Ba 7.854 61.2 mb	^{137}Ba 11.232 76.3 mb
^{133}Cs 100 509 mb	^{134}Cs 2.07 a 664 mb, β^-	^{135}Cs 2.30 Ma 198 mb, β^-	^{136}Cs 13.04 d β^-
^{132}Xe 26.909 64.6 mb	^{133}Xe 5.24 d 127 mb, β^-	^{134}Xe 10.436 20.2 mb	^{135}Xe 9.14 h β^-

Lawson+2022 MNRAS 511

Lawson+2022
Rauscher+2002
Limongi&Chieffi2018 (NR)
Sieverding+2018
Curtis+2019



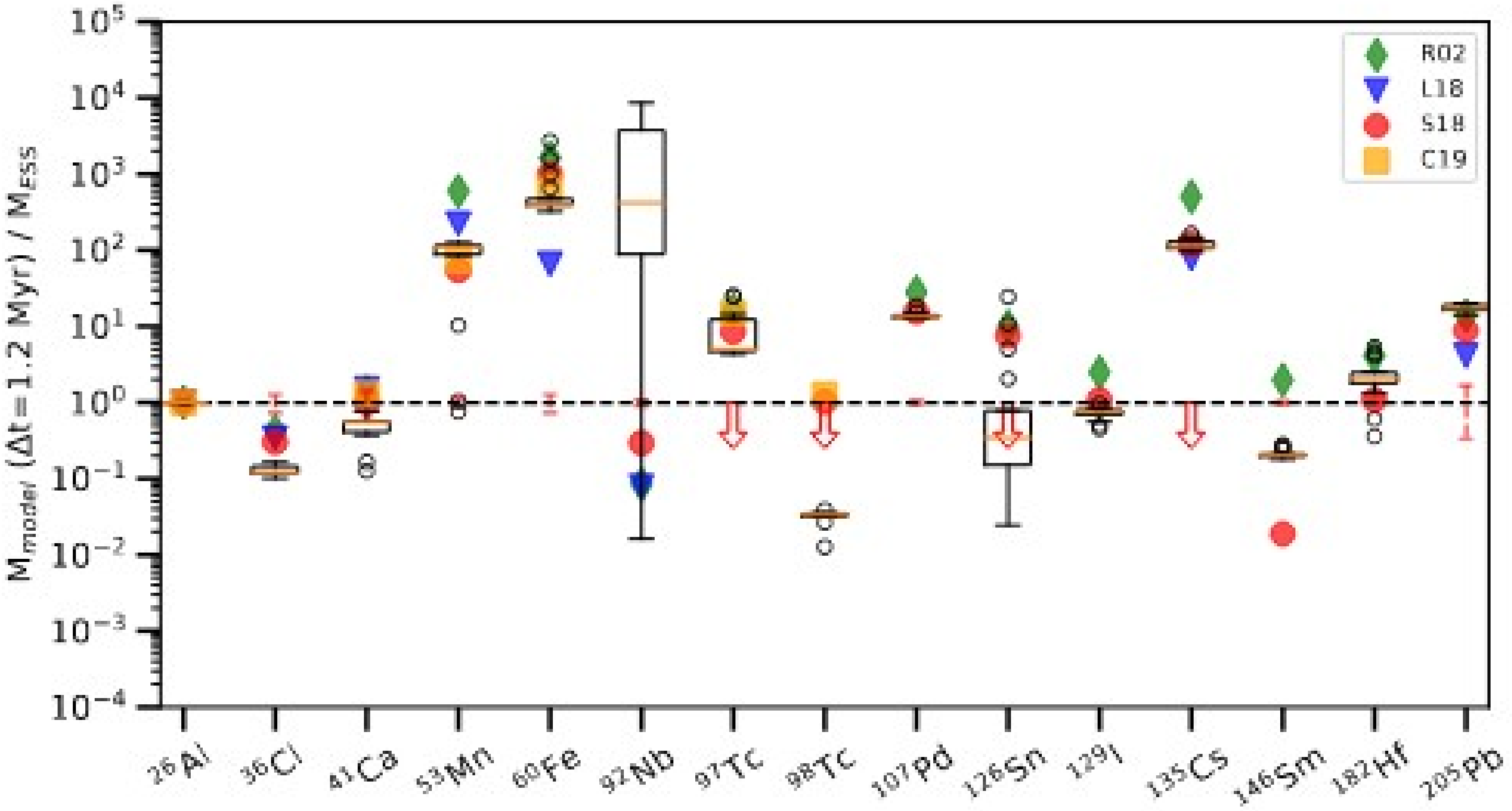
15Msun

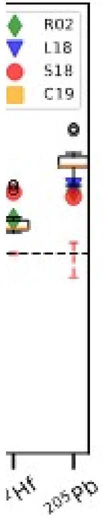


25Msun

Lawson+2022

Lawson+ 2023, MNRAS in prep.





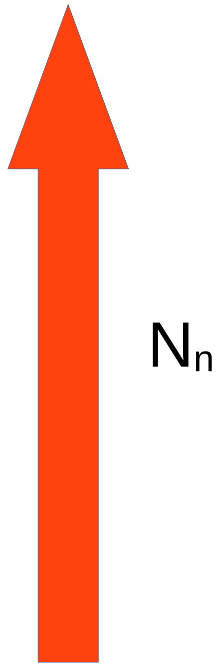
Nuclear uncertainty studies (n-process)

- None specific over group of isotopes
- Possibly good overlap with the i process “local” needs for the (n,γ) rates. There are more studies available now covering different mass regions. To be verified.
- Basic impact study for the Si32 production: Pignatari+ 2013 ApJL

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} .



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

1977

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

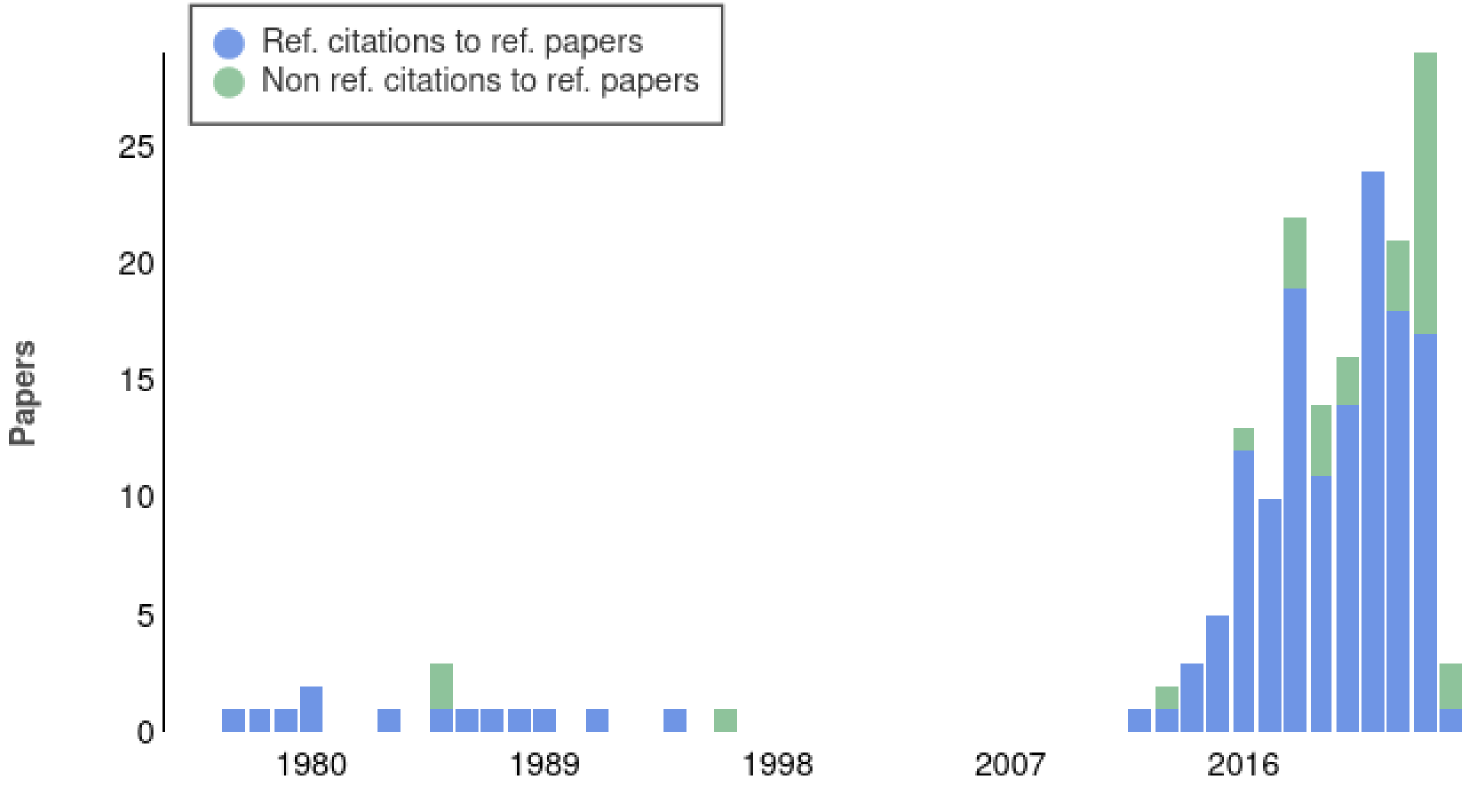
JOHN J. COWAN AND WILLIAM K. ROSE
Astronomy Program, University of Maryland, College Park
Received 1976 June 28

ABSTRACT

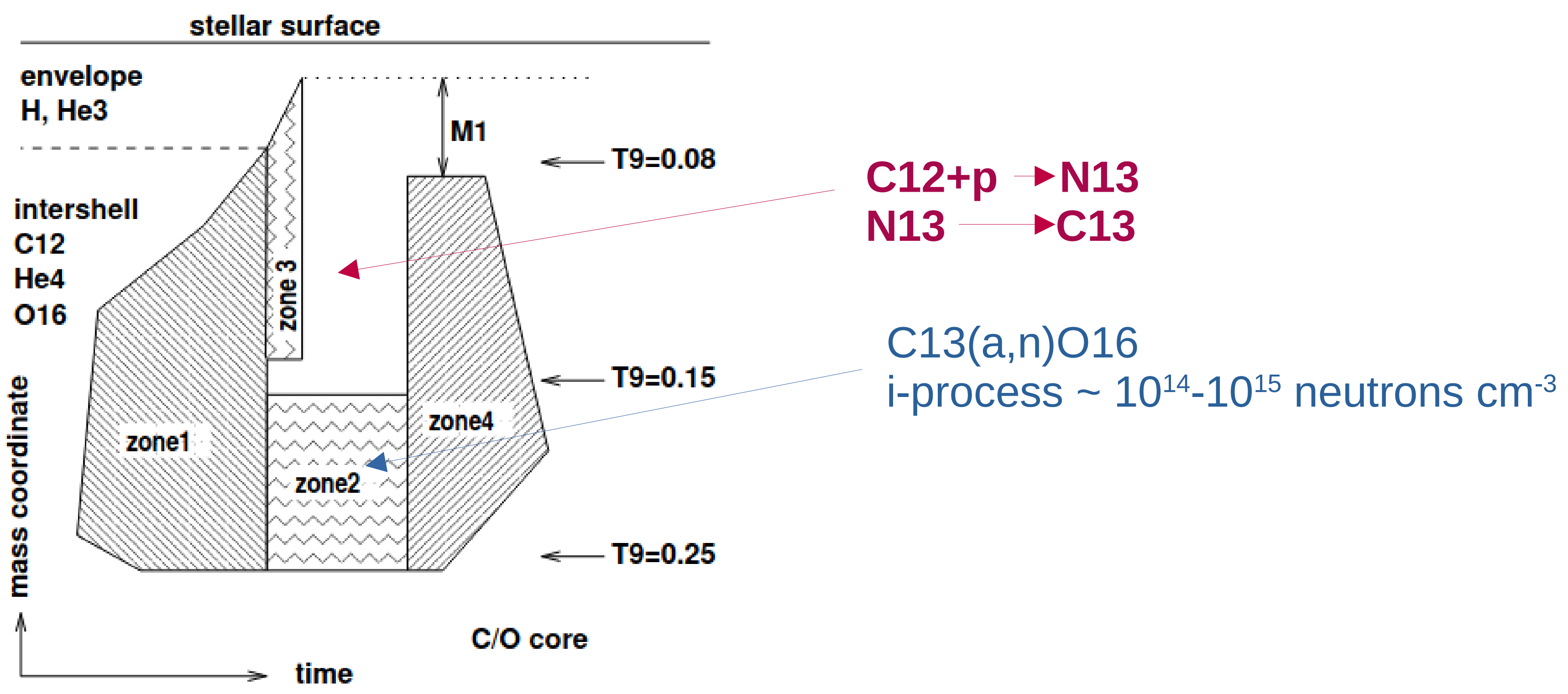
We have examined the effects of mixing various amounts of hydrogen-rich material into the intershell convective region of red giants undergoing helium shell flashes. We find that significant amounts of ^{14}C can be produced via the ^{14}N$(n, p)^{14}$C reaction. If substantial portions of this intershell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



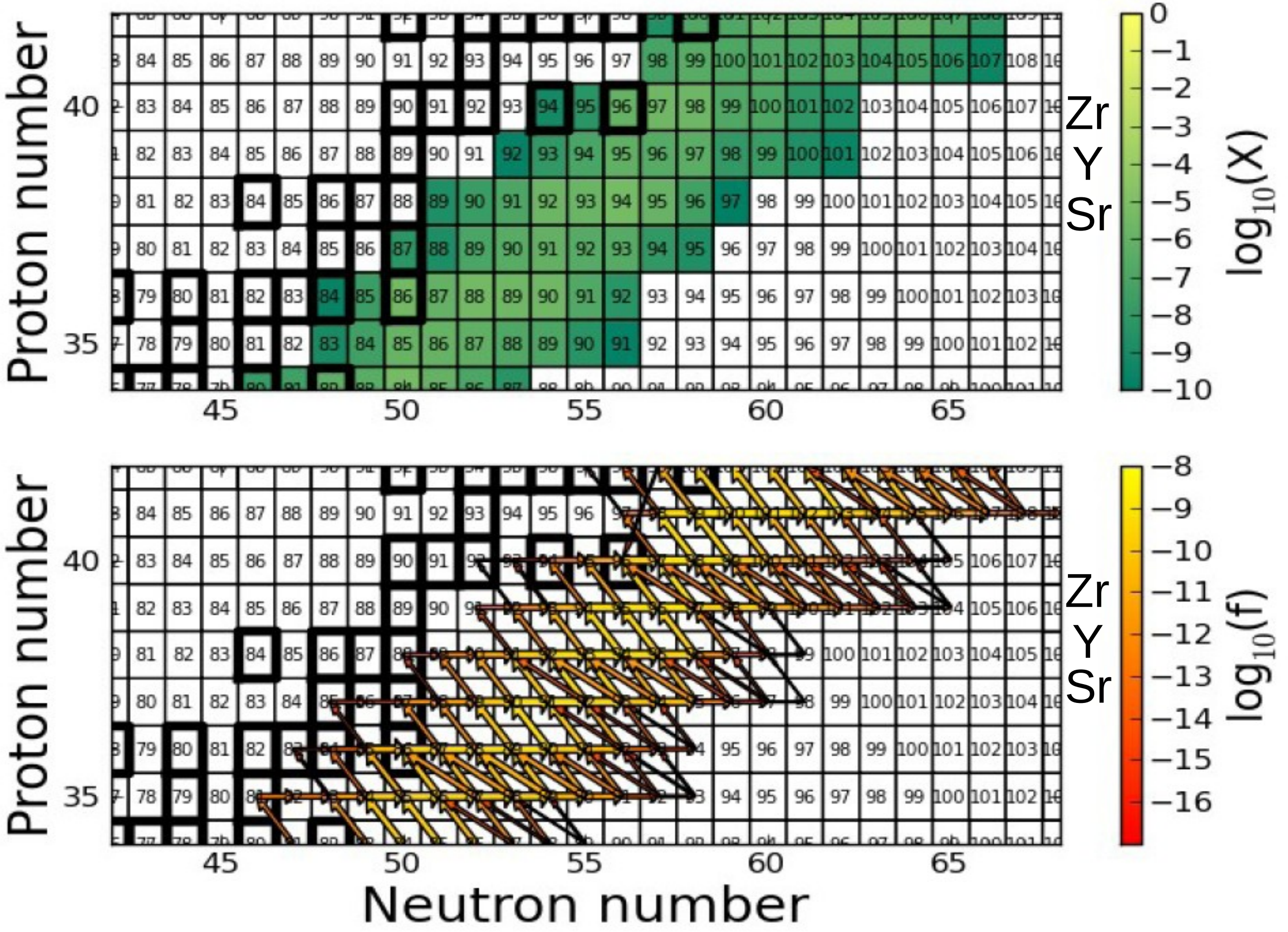
Source: NASA ADS



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>

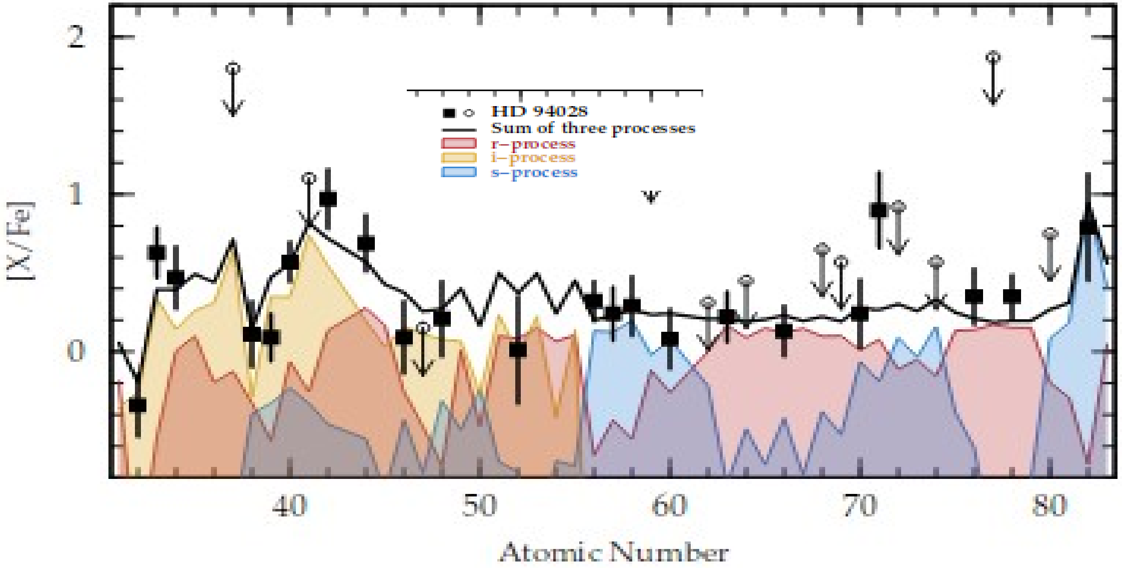
Main source of neutrons: C13(α,n)O16

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)



Roederer+ 2016 ApJ

-HD94028 ([Fe/H]~-1.6)

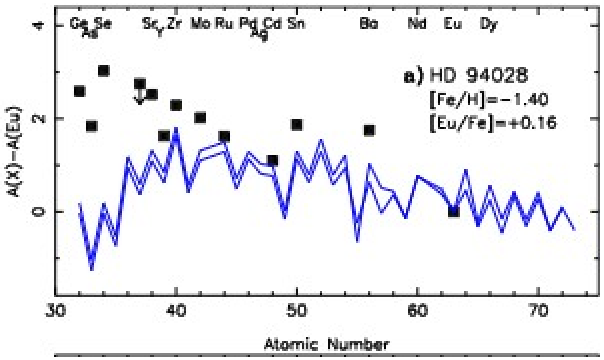
- [C/Fe] ~ solar

- No WD companion detected

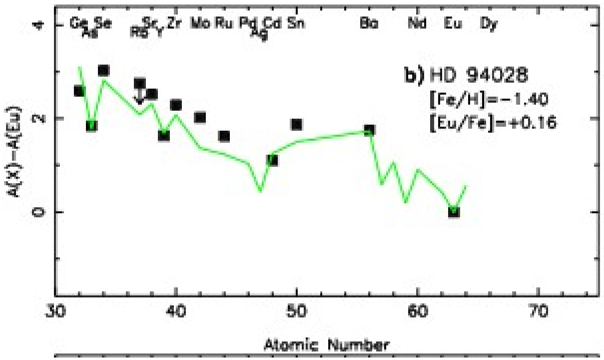
- The abundance pattern of HD 94028 cannot be explained by s+r process. Another process is needed.
- [As/Ge] = 0.99 ± 0.23 dex
- The only tested process that can get these ratios is the i process

... followup studies

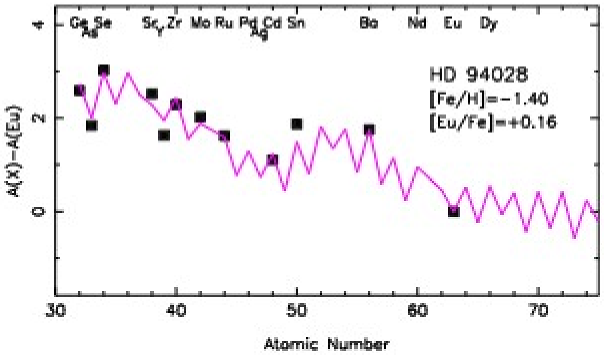
- Han+2018 ApJ 856: the weak r-process + s-process + r-process may also work
- Peterson+ 2020 A&A 638: revision of the abundances, revision of [Fe/H] and As a bit smaller. The solution of Roederer+ 2016 still works.



HD94028 vs r-process

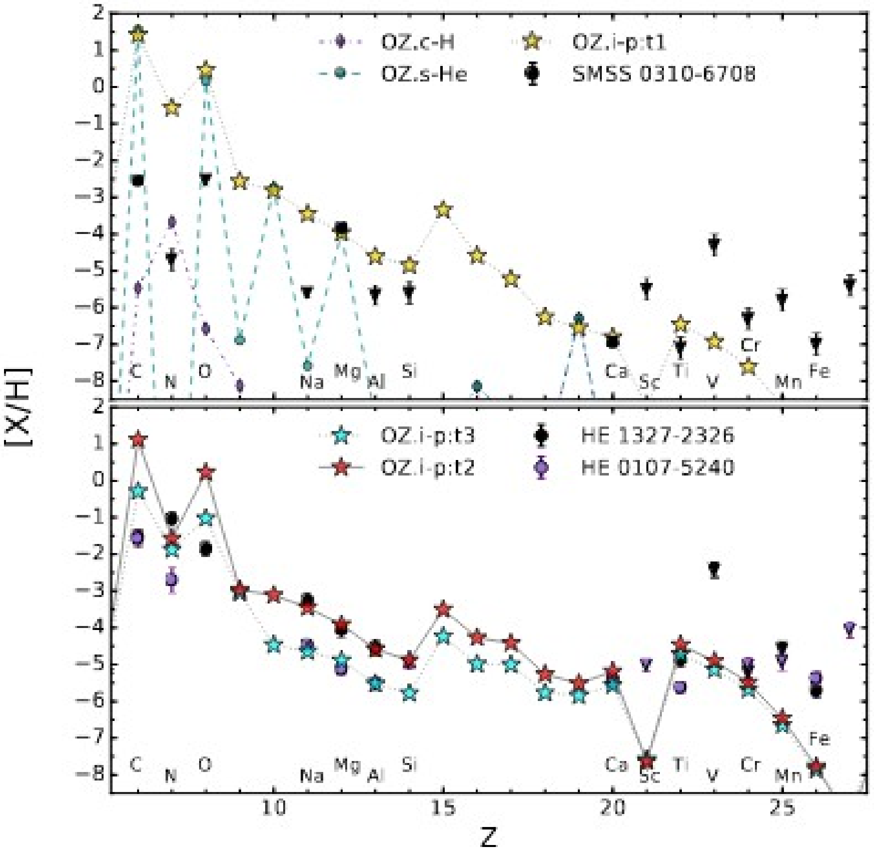


HD94028 vs solar residual



HD94028 vs Roederer's mix

Does the i-process explain the pattern of SMSS J0313-6708 (the Most Iron-Poor Stars)? **No** -- Clarkson+ 2018 MNRAS

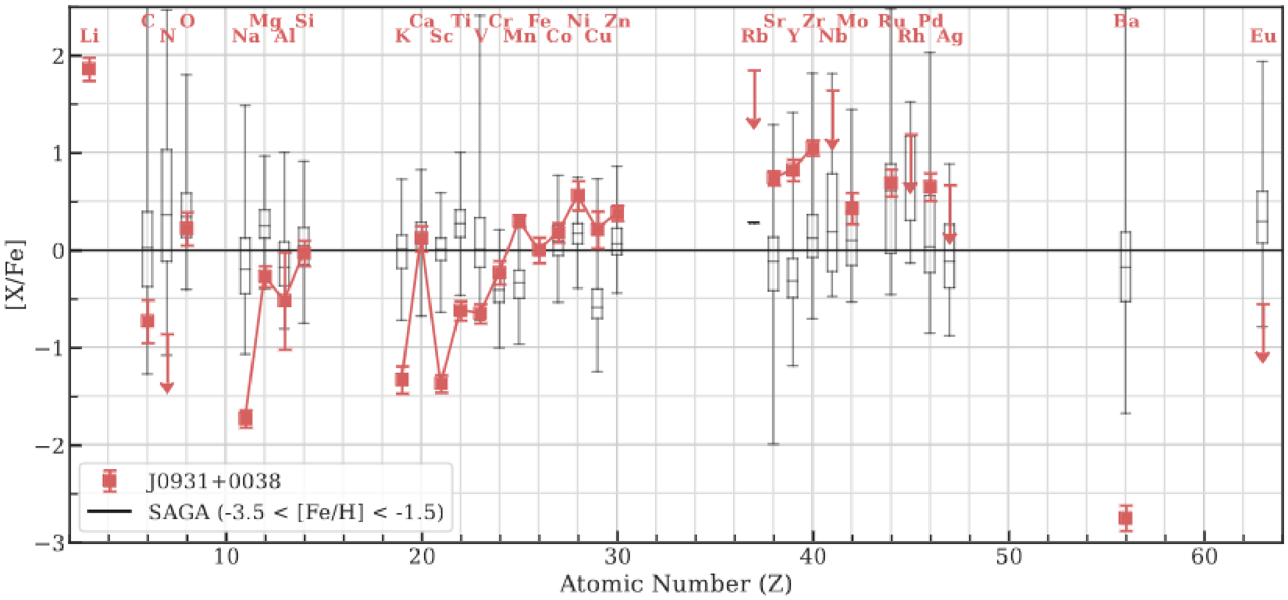


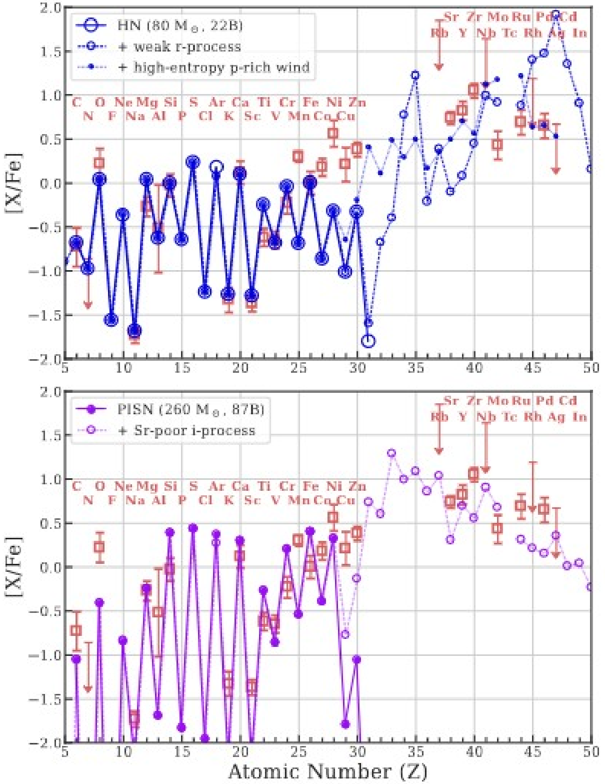
No comprehensive set of 3D hydrodynamic models for H-ingestion in massive stars.
What does it happen to the star after H is ingested in He-burning regions?

Possible outcome: Global Oscillation of Shell H-ingestion (GOSH)
Clarkson & Herwig 2021

J0931+0038 (Ji et al., 2024 ApJL acceted)

- [Fe/H] = -1.76 +/- 0.13;
- most likely carries the signature of a high-mass star (> 50 Msun)

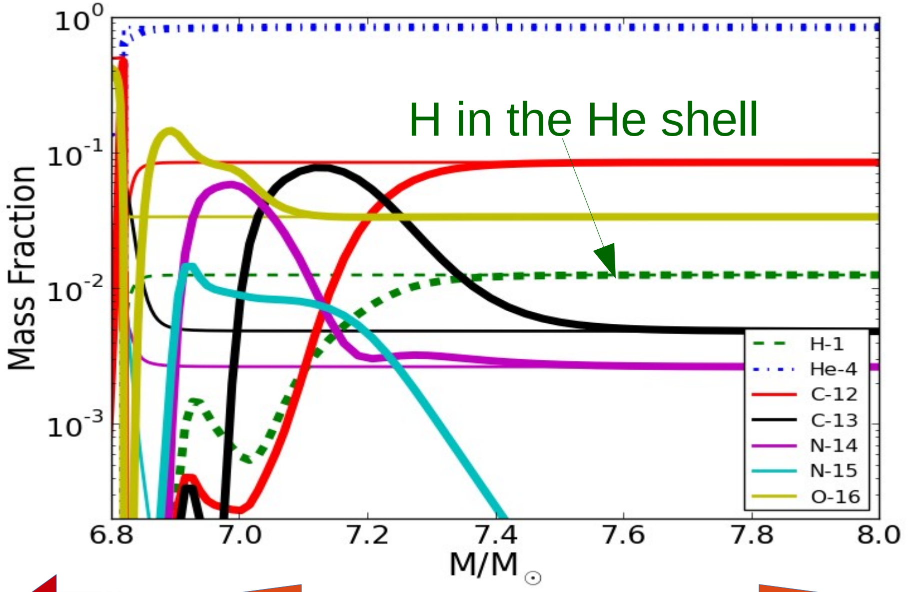




i-process for heavy elements: best of the worse...

H-ingestion+CCSN explosion
Pignatari+ 2015 ApJL

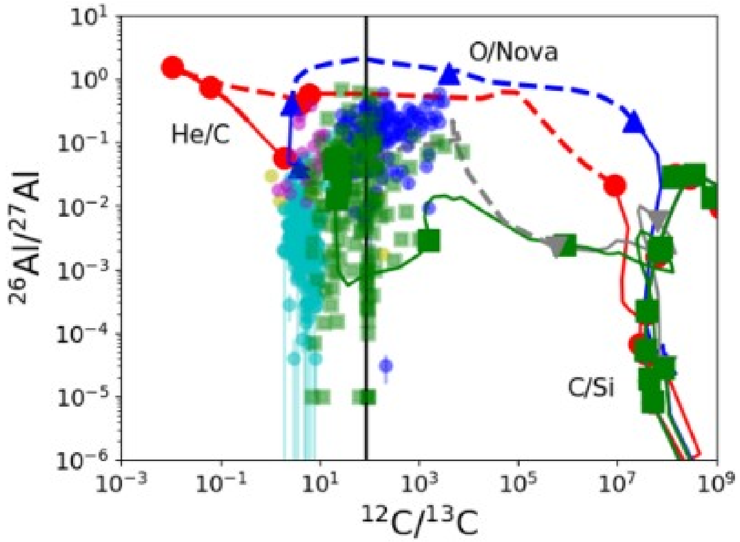
Model 25T
Metallicity = Z=0.02
Explosive He shell nucleosynthesis
with H ingested still alive



Centre of the star

He-shell layers

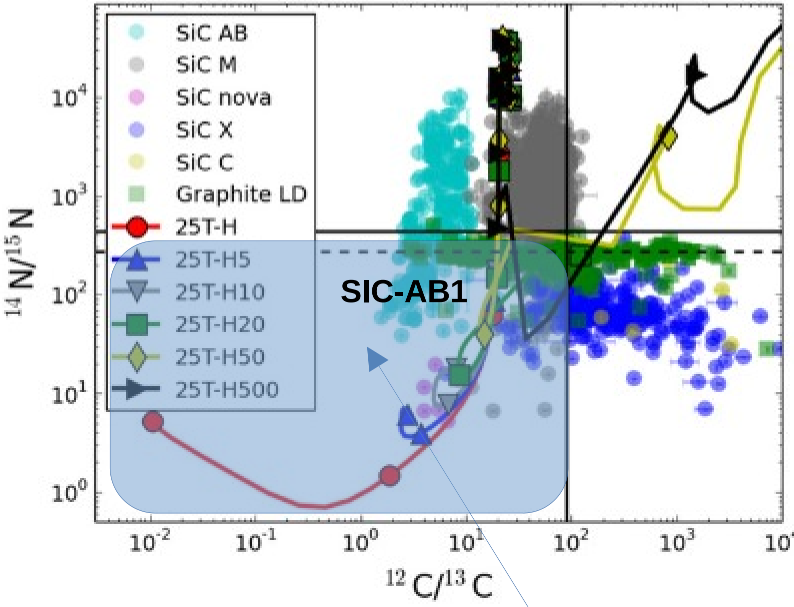
Schofield+2022 MNRAS
(see also Hoppe+2023 ApJL)



Nuclear physics in action:
With H alive in the He shell during the SN explosion, the **Ne22+p** dominates over the **Ne22+α** → No n-process

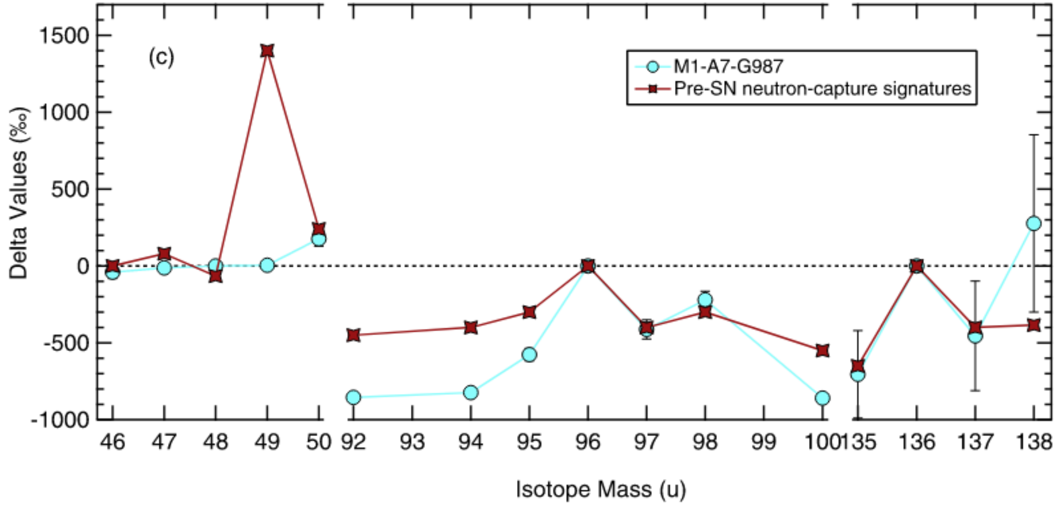
Predicted in 2015, confirmed in 2019!

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



Pignatari+2015 ApJL

H-ingestion
+SN explosion



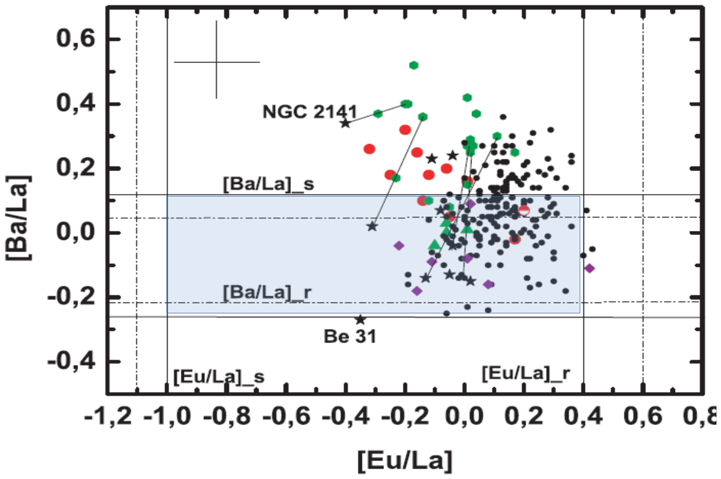
SiC-AB1 grains from massive stars show Mo and Ba with s-process signature of the preSN He shell. NO I-PROCESS! (and NO N-PROCESS!)

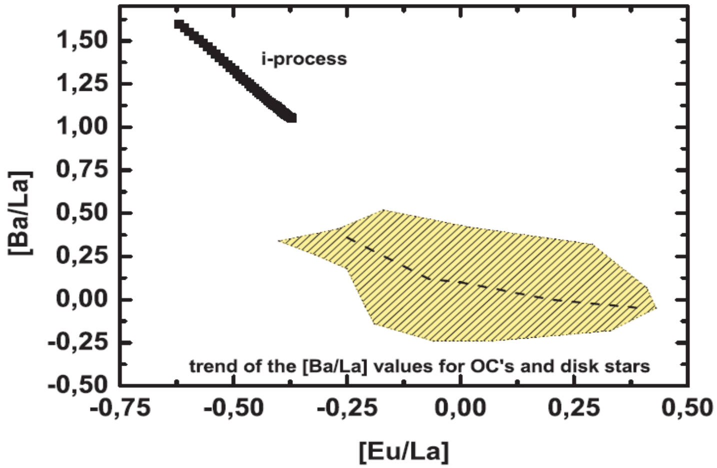
Liu, N. et al. 2019 ApJ 2018

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†]

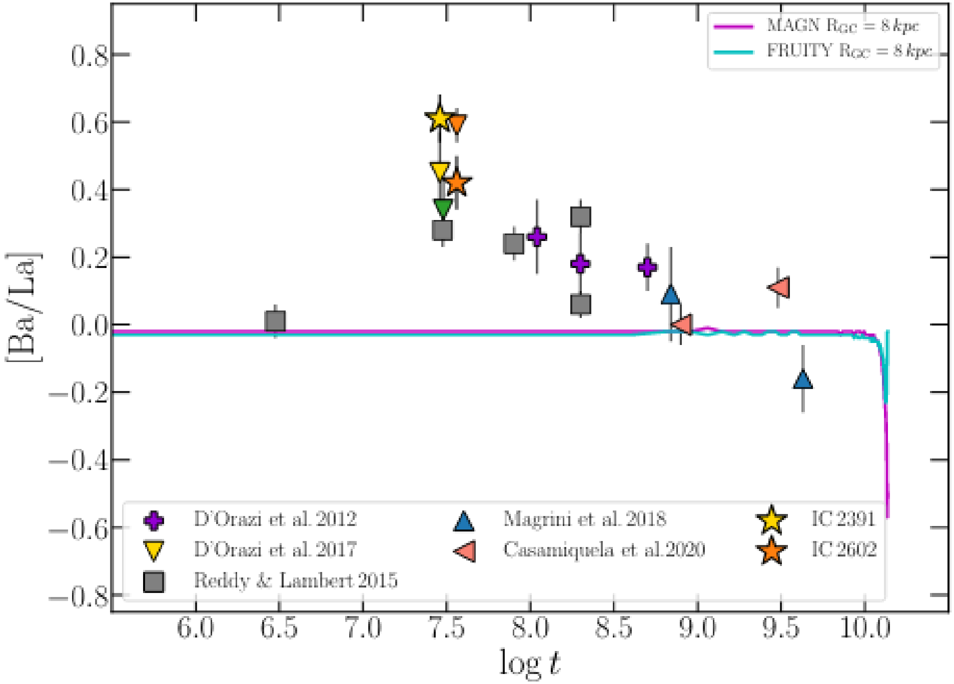




<u>Observing the i process signature in OCs:</u>
Results of high Ba and low La and Ce **<u>confirmed</u>** recently by D'Orazi+ 2017 A&A, **<u>questioned</u>** by Reddy & Lambert 2017 ApJ. See also Maiorca+ 2012, Overbeek+ 2016… Baratella+2021 Under debate...

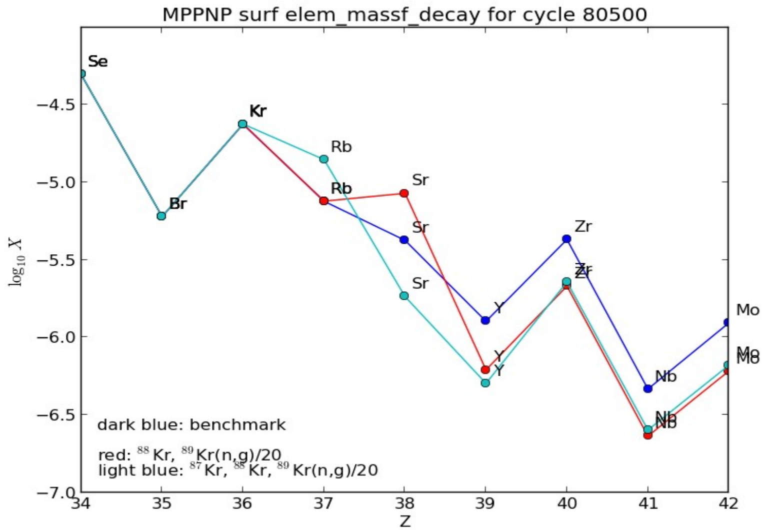
<u>- What source?</u>
- Still uncertainties about the spectroscopic observation of Ba

Baratella+ 2021 A&A, OCs...

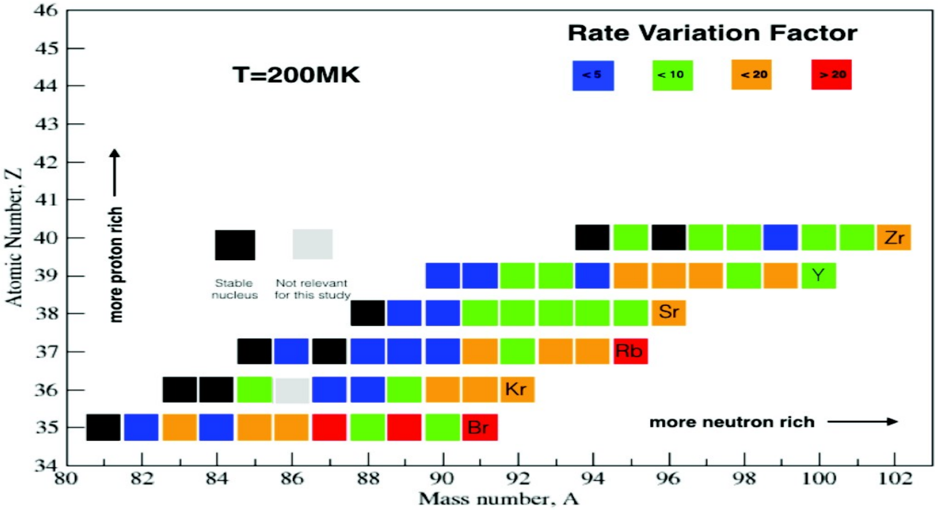


Issues with observation of Ba for now cannot explain the high [Ba/La]

Denissenkov et al. 2018 JPhG 45

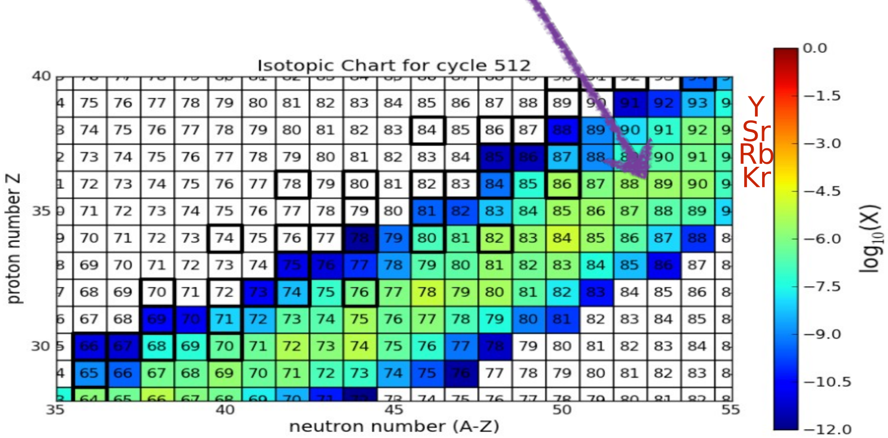


- nuclear data uncertainty impact: Kr89(n,γ)Kr90



Rate variation factor, based on uncertainty estimation.

Nuclear data needs for 1st-peak elements i process



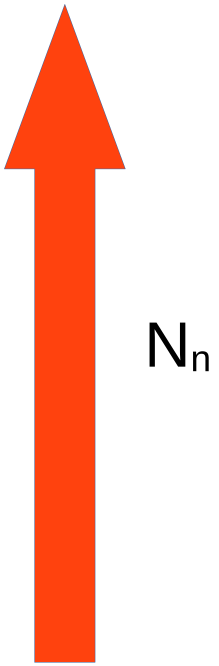
Nuclear uncertainties studies (i-process)

- 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, $56 < Z < 74$)

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} .



CCSN remnant

Cassiopea A

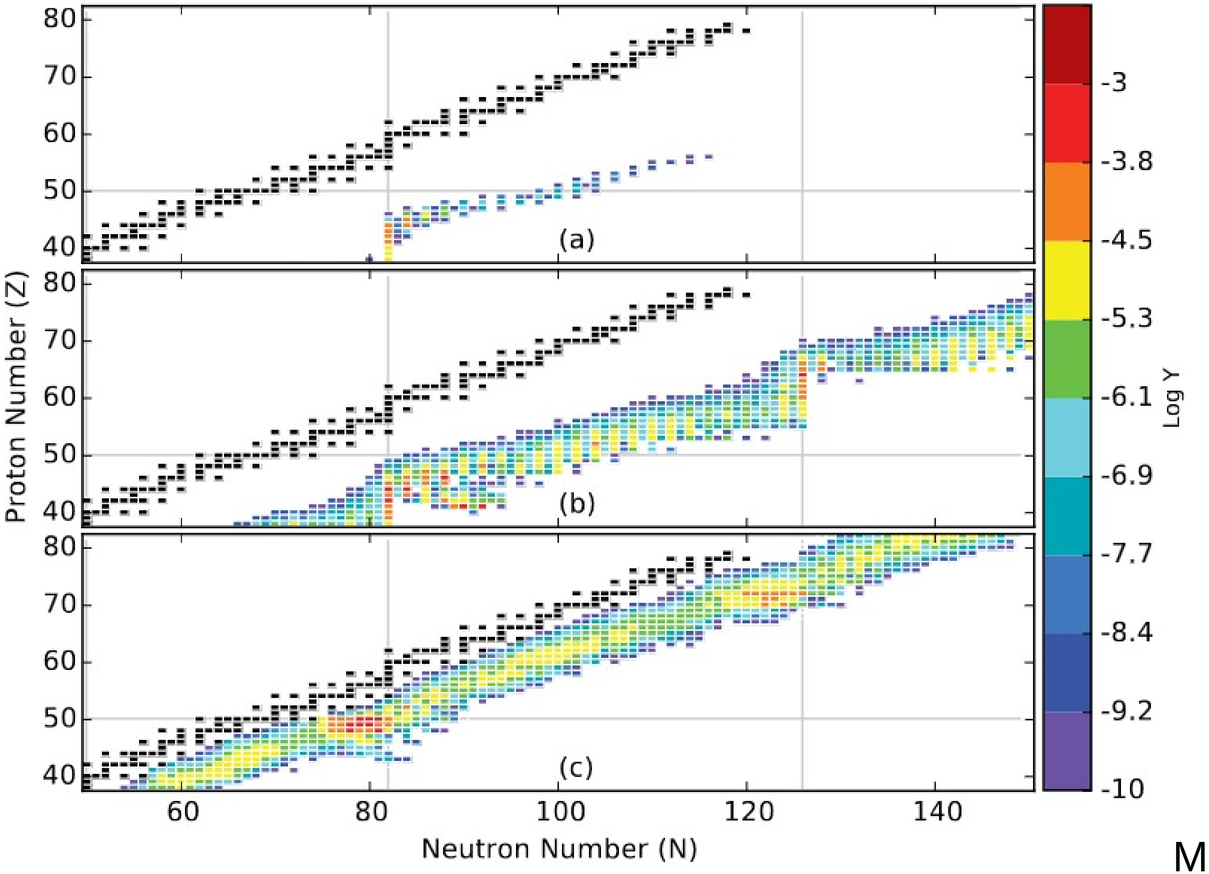
11000 ly

~ 300 years ago

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

“Where, oh where has the r-process gone?”

Qian & Wasserburg 2006



Mumpower+ PPNP 2016

Why making the r-process is so difficult?

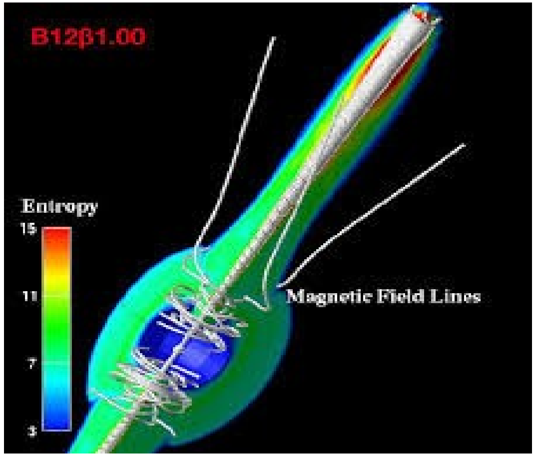
- Today the most supported scenarios are Neutron-Star mergers, Magnetically Driven Jets from exotic Supernovae, etc but not typical CCSNe (e.g., Cowan+2021).
- Neutrino-driven winds from CCSNe do not seem to have the conditions to host the r-process. Why?

$2\alpha(n,\gamma)^9Be(\alpha,n)^{12}C$.... from Woosley & Hoffman 1992 ApJ:

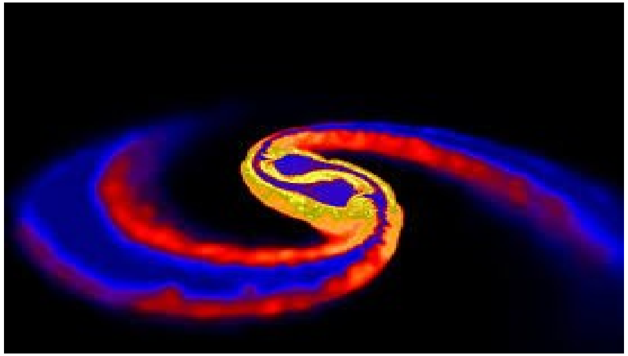
bound nuclei, and the final composition will differ from what would be calculated in NSE. This is the α-rich freeze-out. [If the mass fractions of free neutrons and α-particles are both large, the assembly of α-particles to ^{12}C may be amplified by a factor typically of order 10 by the neutron-catalyzed reaction sequence $^4He(\alpha n, \gamma)^9Be(\alpha, n)^{12}C$ (Delano & Cameron 1971 and Appendix A below), but the requirements on density remain approximately the same.]

The r-process sources: short summary

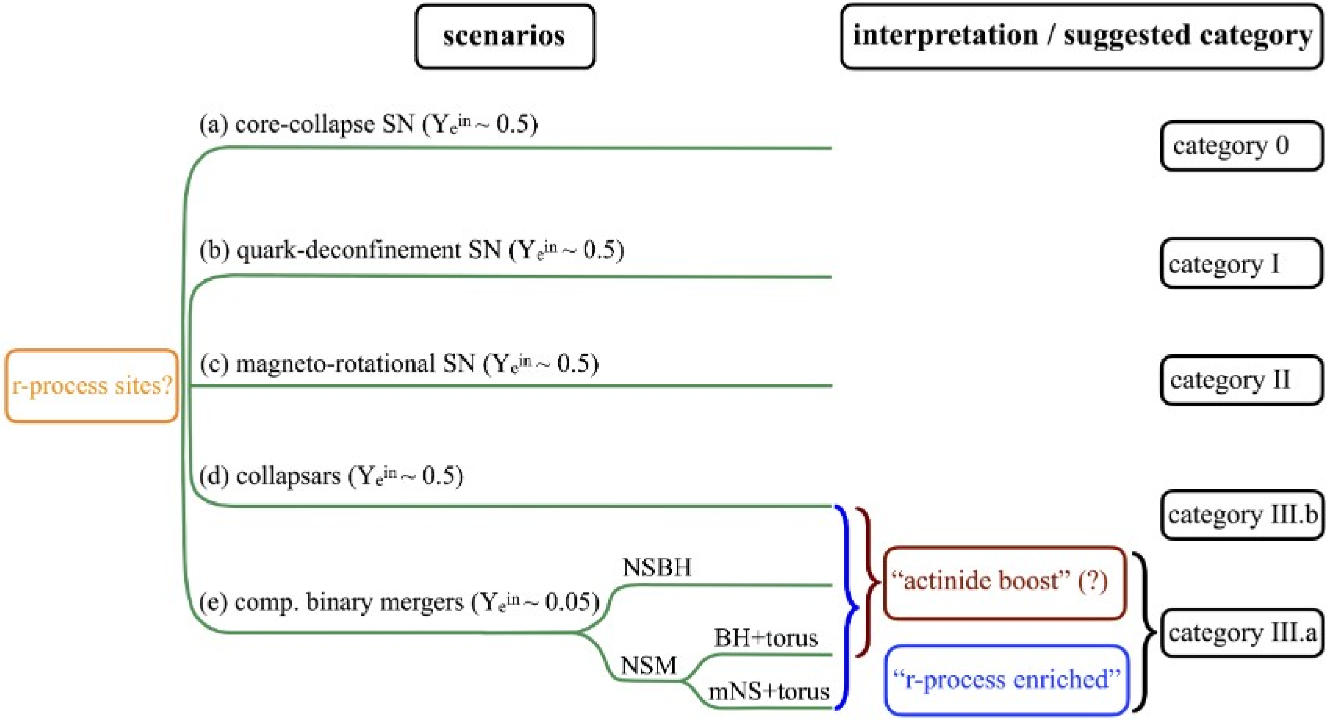
Anomalous Supernovae:
e.g., jetSNe → magnetars
0.2 ≤ protons/neutrons ≤ 0.4



Neutron Star Mergers:
protons/neutrons ≤ 0.1



How many r-processes?



Weak r-process/ νp-process

Coproduction of Eu and Fe

Limited Eu made

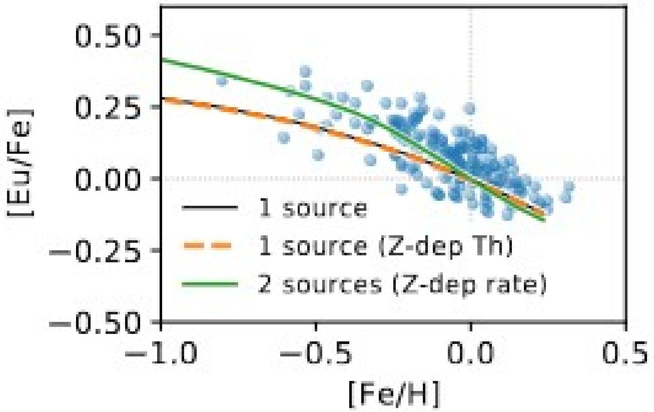
Average high Sr/Eu consistent with weak r-process & [Eu/Fe] < 0

r-II stars ([Eu/Fe] > 1) and r-I stars (0 < [Eu/Fe] < 1)

Strong r-process (production up to the actinides)

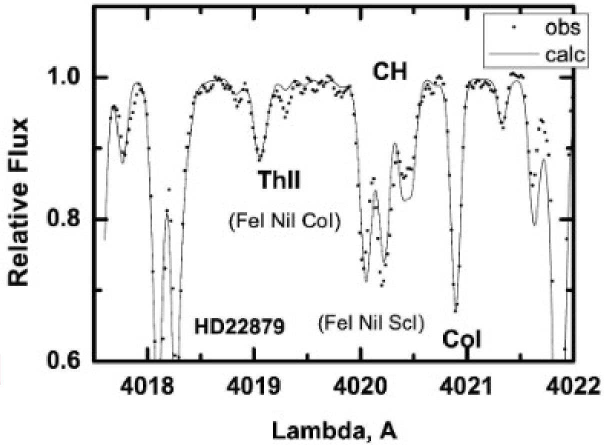
Using observations from metal-poor stars: Farouqi+ 2022 A&A

...and using Eu and Th observations from stars in the MW disk: Mishenina+ 2022 MNRAS

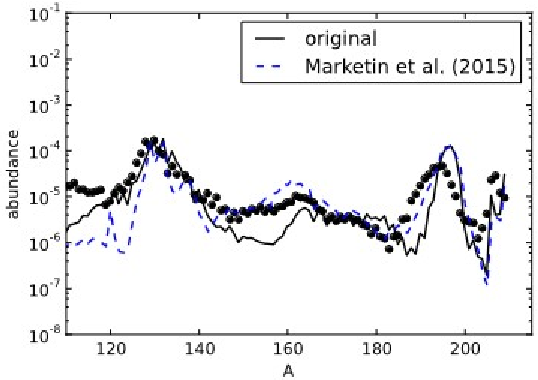


Possible result: there could be two r-process sources active in the MW disk: one Th-poor, and one Th-rich, both carrying Eu.

Challenge: Th-II line blended by Fe-I, Ni-I and Co-I lines!

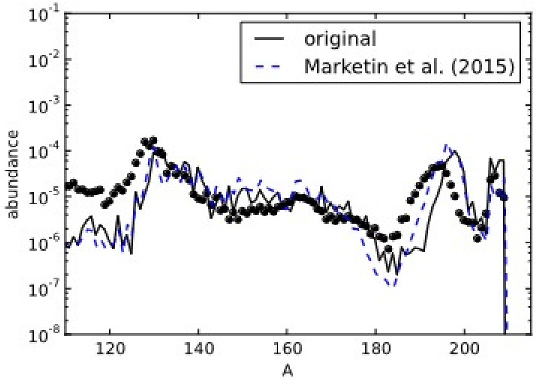


Nuclear experiments and theory for the r-process: challenging and/or impossible?



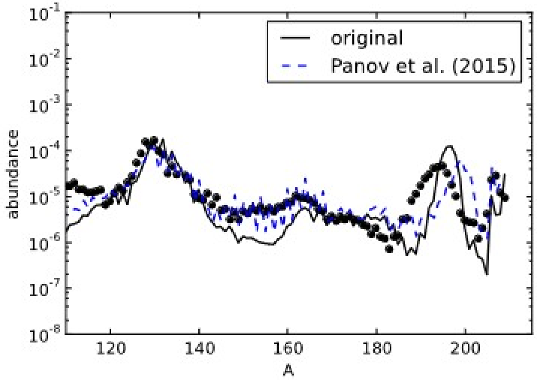
(a) FRDM, Marketin (2015)

ABLA07



(b) HFB-14, Marketin (2015)

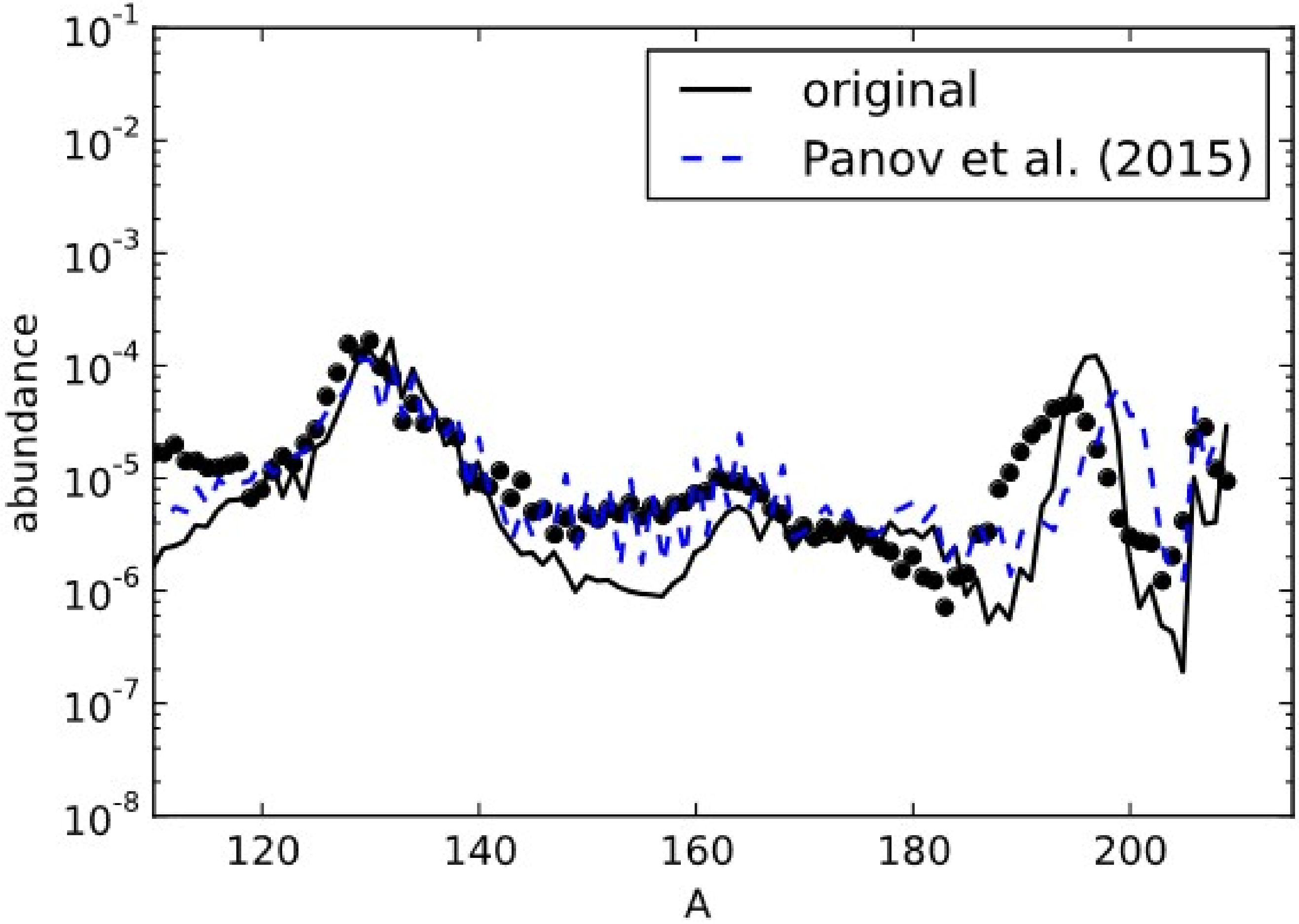
ABLA07



(c) FRDM, Panov (2015)

ABLA07

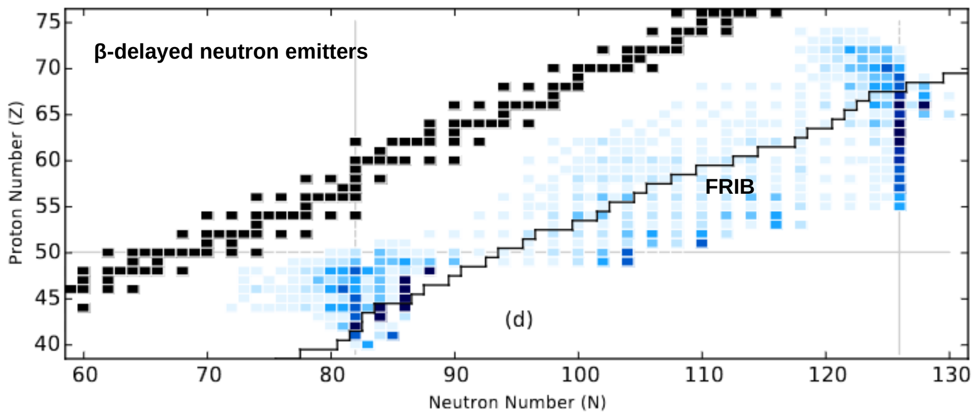
Eichler+ ApJ 2015

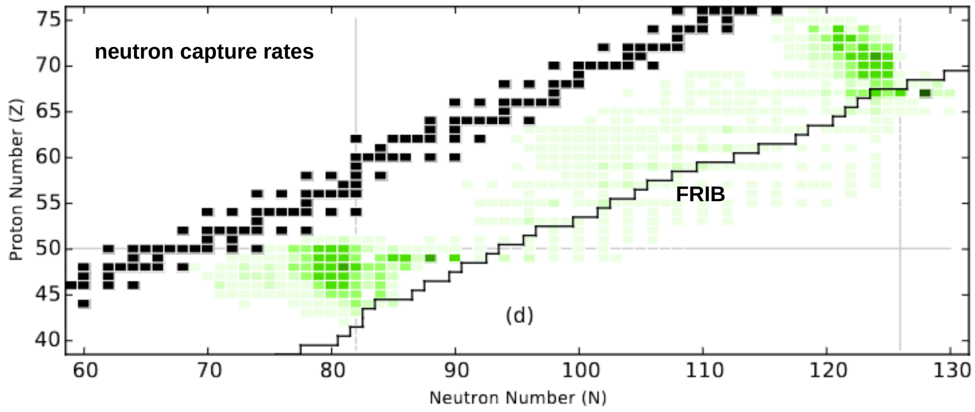


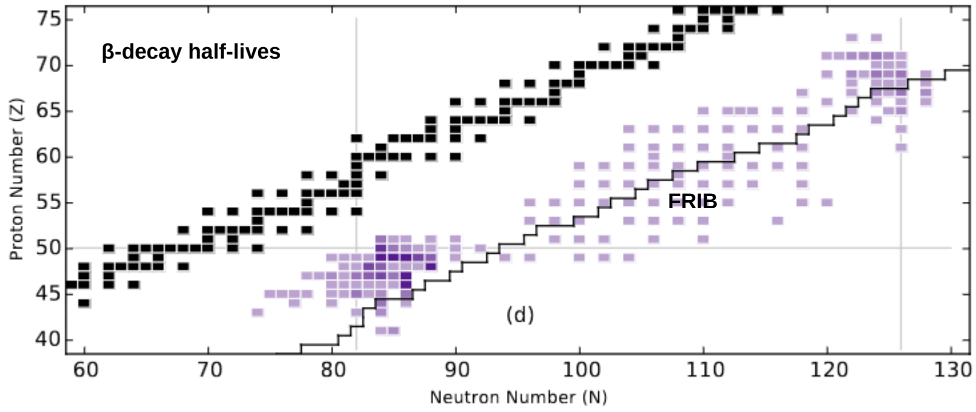
(c) FRDM, Panov (2015)

ABLA07

Nuclear experiments and theory for the r-process: challenging and/or impossible?

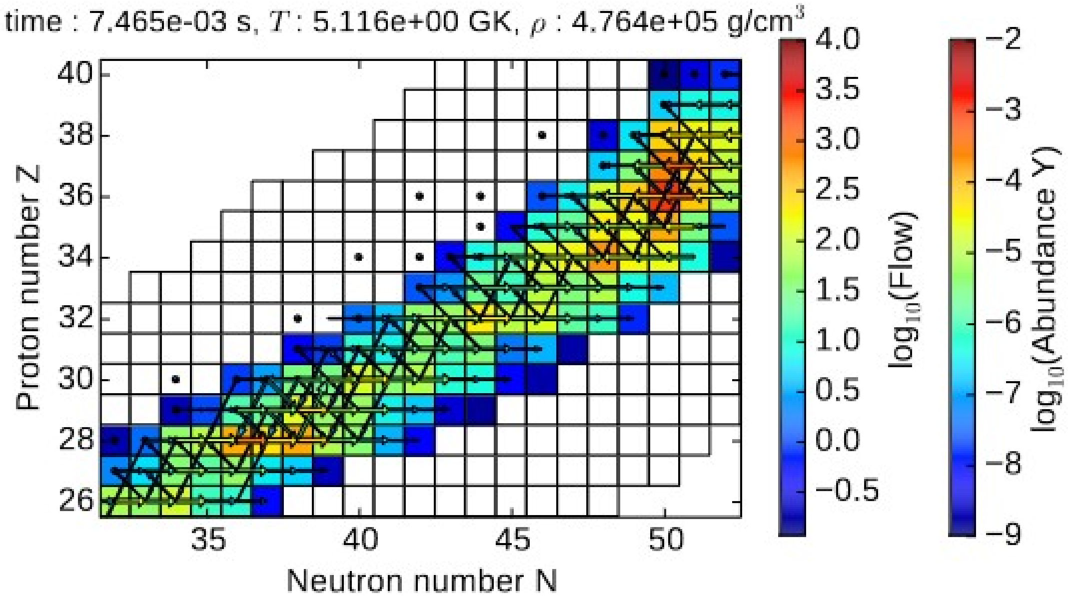


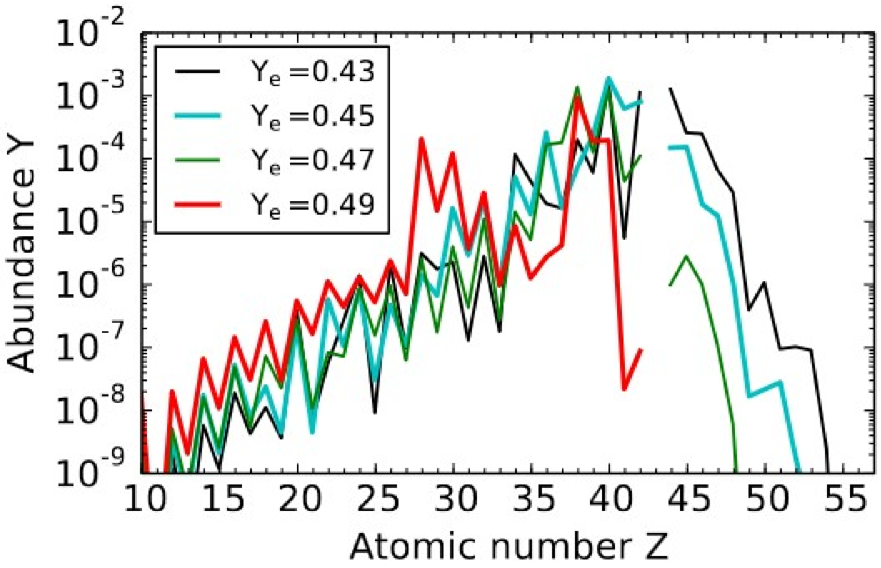




Mumpower+ PPNP 2016

Modern weak r-process in CCSNe:
combination of neutron captures and alpha-captures

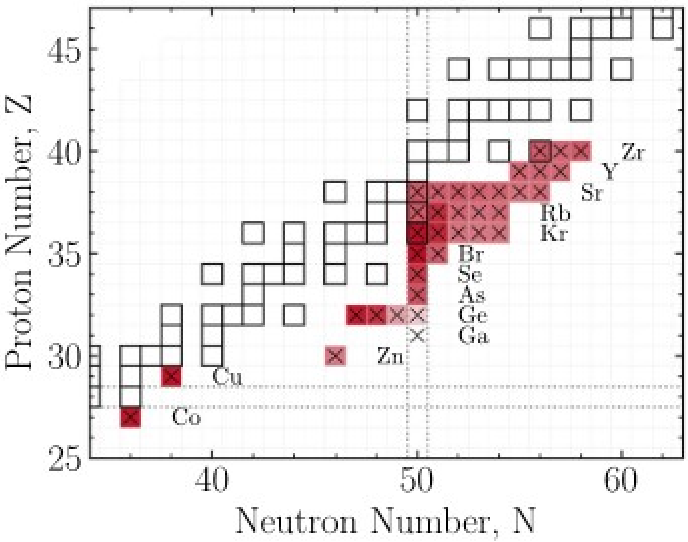




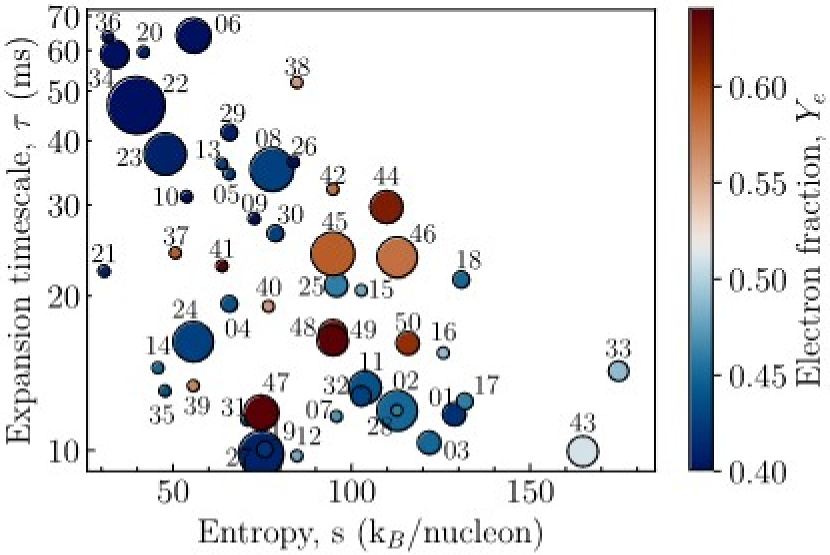
Bliss+ 2017

(α,n) reactions affecting elemental ratios in the neutrino-driven wind ejecta: wish list

Caveat: neutrino-driven winds ejecta dominated by proton-rich ejecta?



Psaltis+ 2022

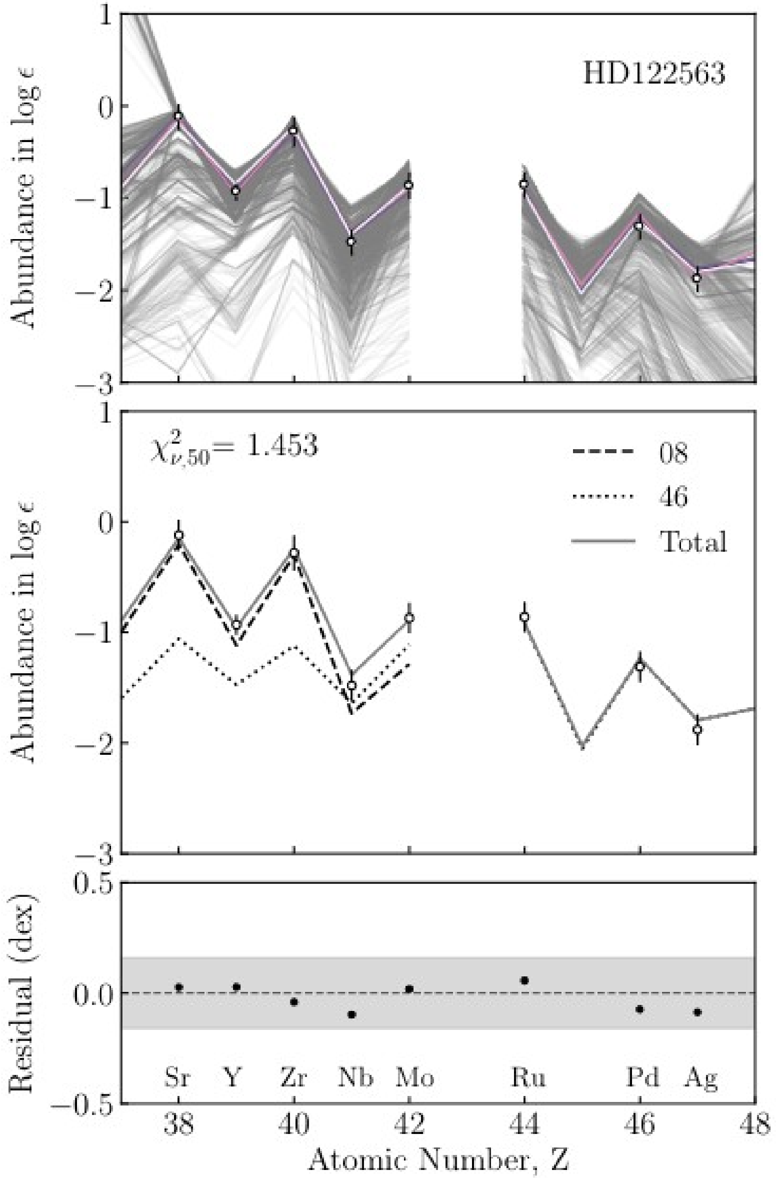


Psaltis+ 2023

Main Goal:
find the combinations reproducing the abundance patterns in metal-poor stars.

What can we learn?

Psaltis+ 2023



Outline

- Introduction to massive stars basic features
- Stars & nucleosynthesis as computational experiments
- Neutron-capture processes in massive stars:
  - introduction and observations
  - Connection with Galactic Chemical Evolution
- The s-process, n-process, i-process, r-processes…