Impact of Stellar Yields on Galactic Chemical Evolution

Marco Pignatari

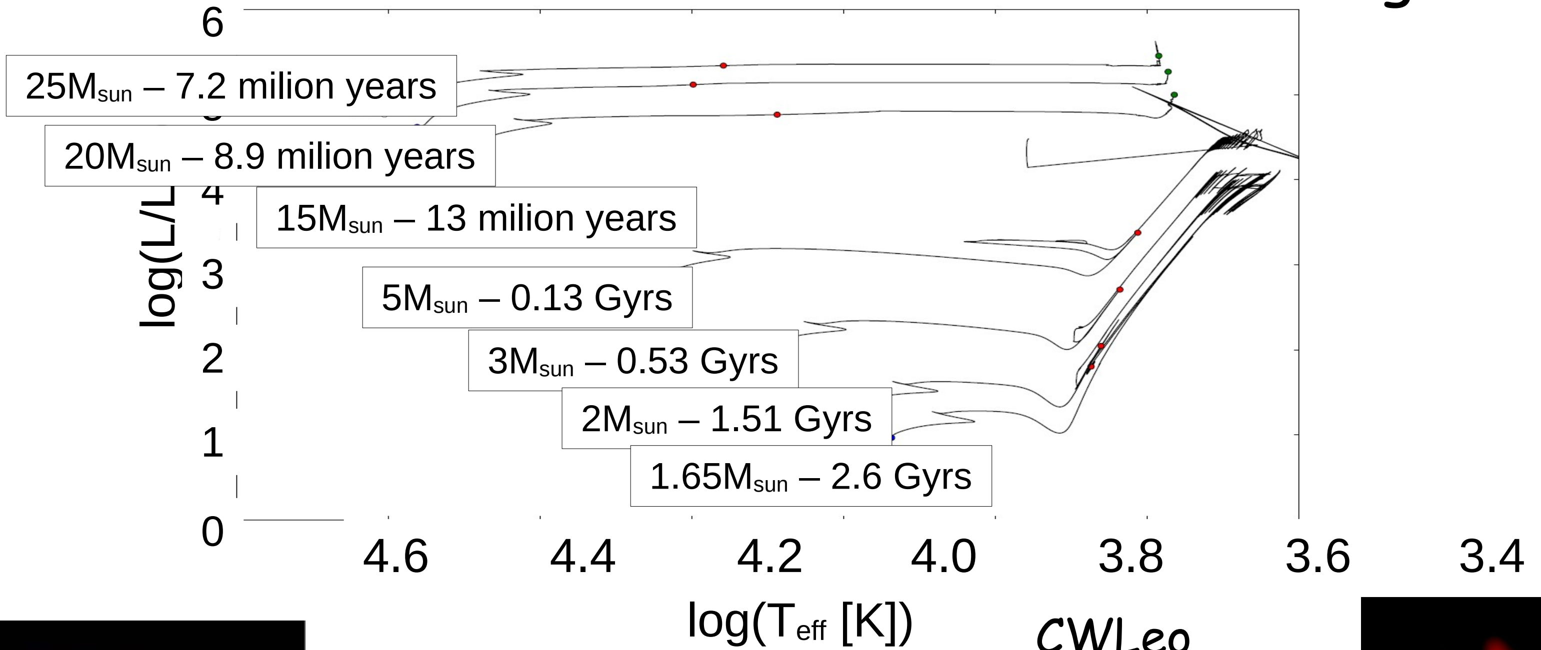
- @Konkoly Observatory, CSFK HUN-REN & MTA Centre of Excellence, Budapest, Hungary

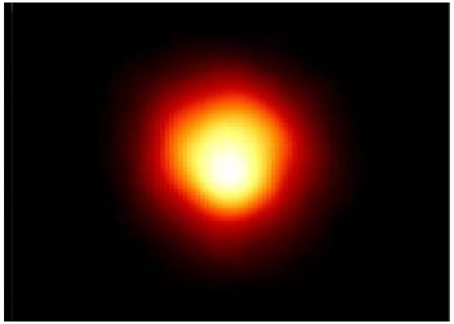
Nuclear Physics in Astrophysics XI (NPA-XI), 15-20 September 2024

Messages to remember

- Stellar yields are a crucial source of uncertainty for Galactic Chemical Evolution (GCE) of element and isotope abundances.
- Uncertainties vs errorbars: why stellar yields are not provided with errorbars? It is really hard to provide comprehensive errors for stellar yields!
- The GCE results not fitting the observations for “good” reasons are usually more useful than the “good” GCE results for “wrong” reasons.
- Example 1: [Mg/Si] vs [C/O] & Si isotopes in presolar SiC grains
- Example 2: C-O-Si shell merger in massive stars: does it happen in real stars?
- Example 3: Short-Lived Radioactive isotopes.
- **Can we use GCE to learn about stars? Yes, if we use the right elemental and isotopic ratios.**

HR diagram





Betelgeuse (α-Ori):

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

CWLeo (IRC+10216):

- 400 lyr
- 250 R_{sun}

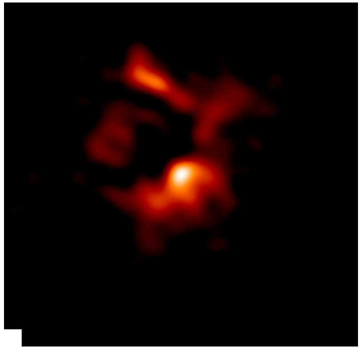
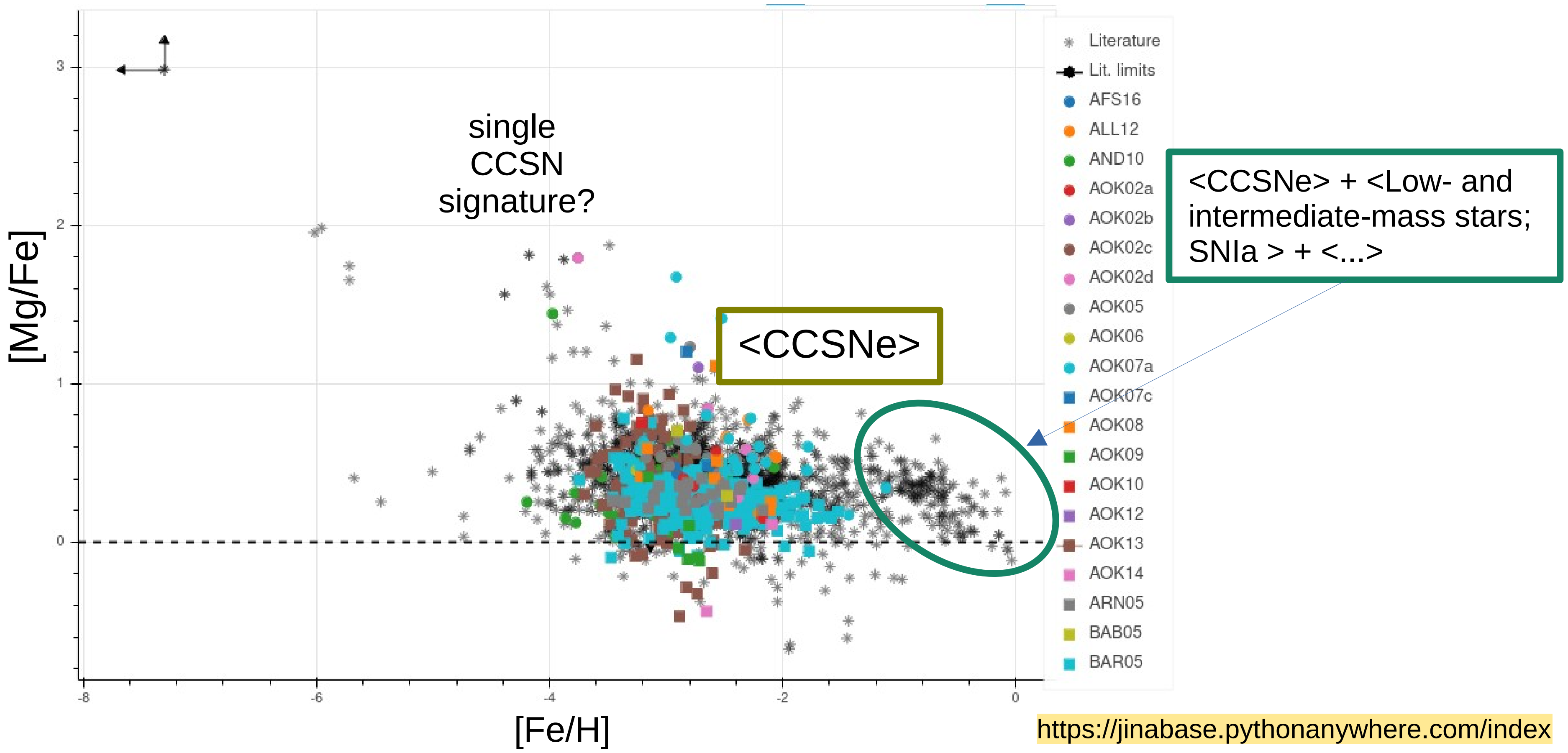


Image: A. Dupree/CFA/R. Gilliland/STScI/NASA/ESA

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

GCE keeps memory of the different stellar generations contributing to the production of elements.

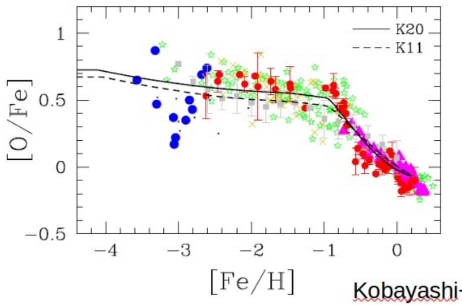
$$[A/B] = \log(n_A/n_B) - \log(n_A/n_B)_\odot$$



https://jinabase.pythonanywhere.com/index

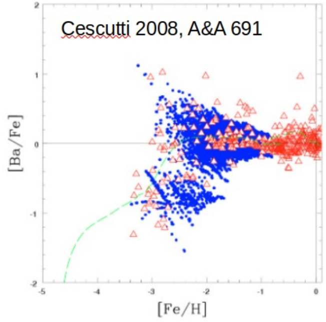
Complementary GCE approaches:

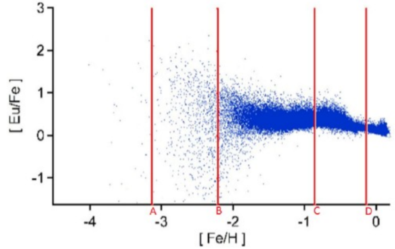
1) Homogeneous approach: assumption of instantaneous gas mixing



Kobayashi+ 2020, ApJ 900

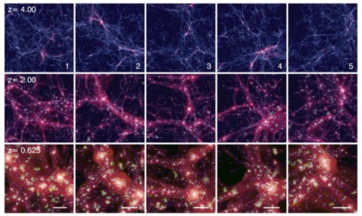
2) Inhomogeneous approach: evolution of a large number of gas volumes



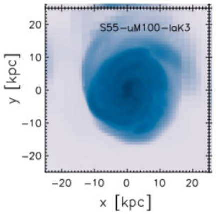


Wehmeyer+ 2015, MNRAS 452

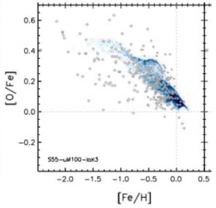
3) 3D Chemodynamical Models: “self-consistent” treatment of the chemical and dynamical evolution of a system.



Lee+ 2021, ApJ 908, Horizon 5 Gpc scale



Few+ 2014, MNRAS 444, MW scale & the solar neighbourhood



Typical “star particle” Size ≥ 10^5-10^6 Msun

Stellar yields and GCE

Timmes+ 1995 ApJS 98, Gibson+ 1997 MNRAS 290, Chiappini+ 2005 A&AL 27 …

A&A 522, A32 (2010)
DOI: 10.1051/0004-6361/201014483
© ESO 2010
Astronomy & Astrophysics

Quantifying the uncertainties of chemical evolution studies

II. Stellar yields

D. Romano[1,2], A. I. Karakas[3], M. Tosi[2], and F. Matteucci[4,5]

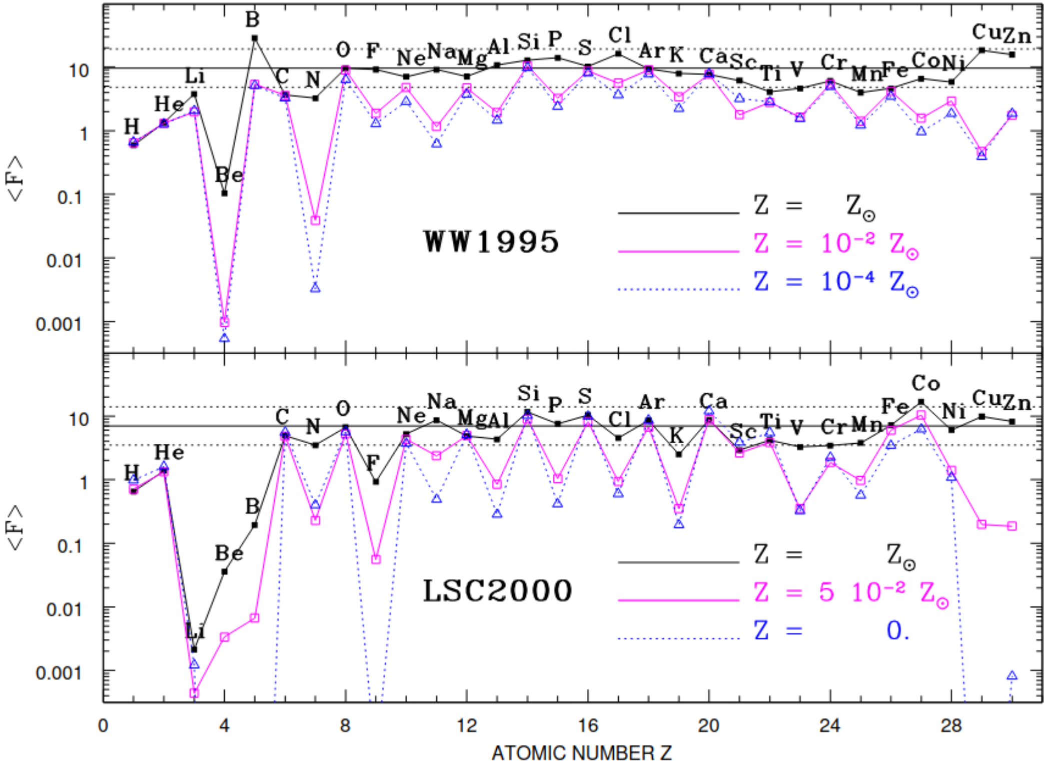
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **451**, 3693–3708 (2015) doi:10.1093/mnras/stv1102

Galactic chemical evolution: stellar yields and the initial mass function

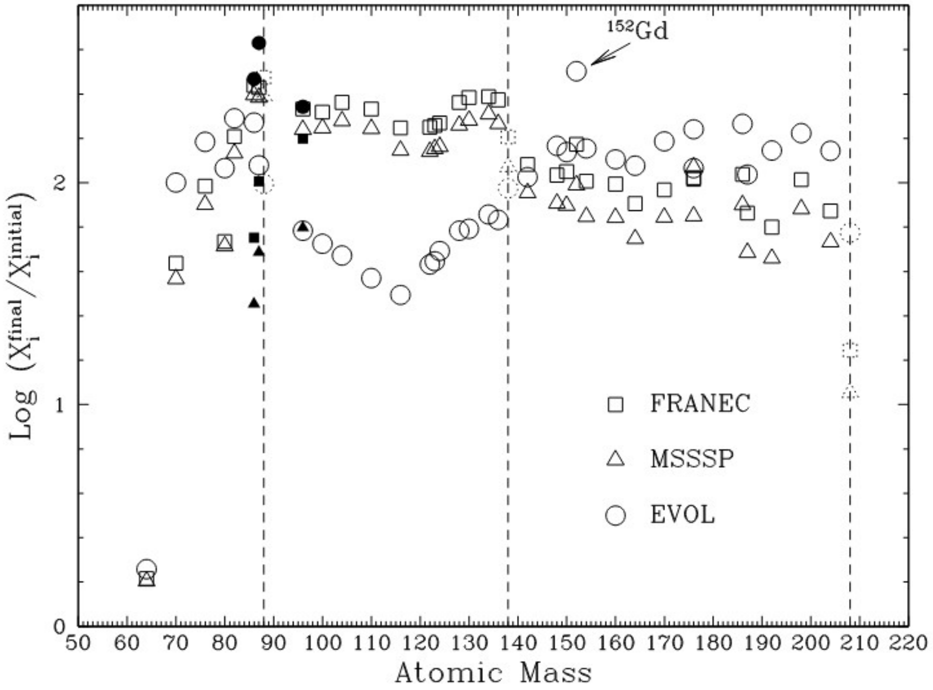
Mercedes Mollá,[1,2★] Oscar Cavichia,[2,3★] Marta Gavilán[4] and Brad K. Gibson[5]

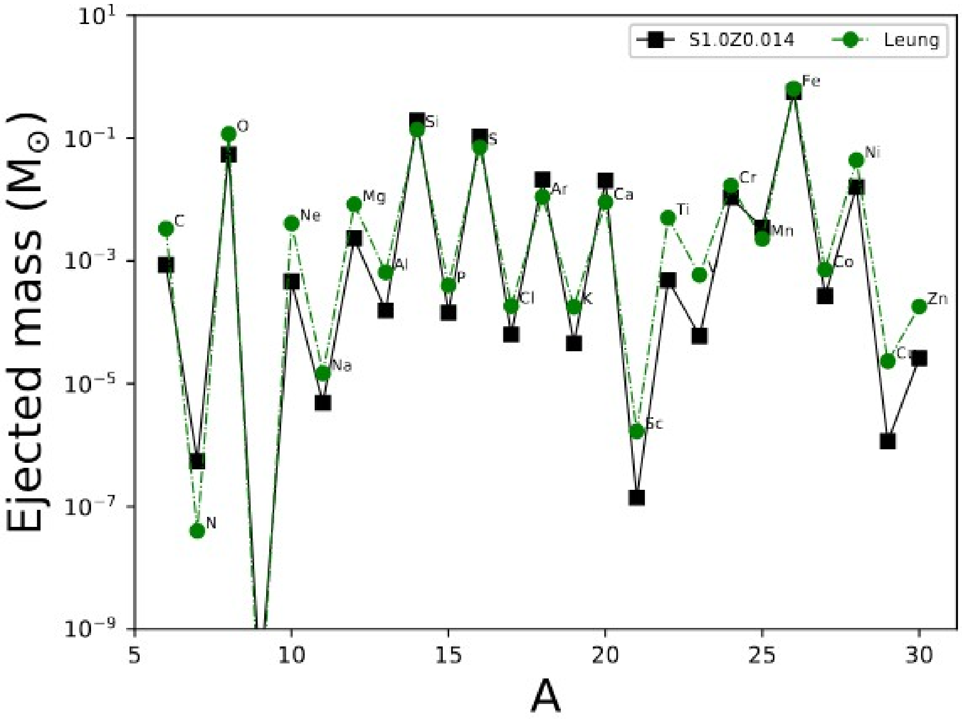
… to Prantzos+ 2018 MNRAS 476, Gronow+ 2021 A&A 656, ….

Approach:
produce GCE models using different stellar yields sets, to evaluate the impact of their variations on GCE predictions.



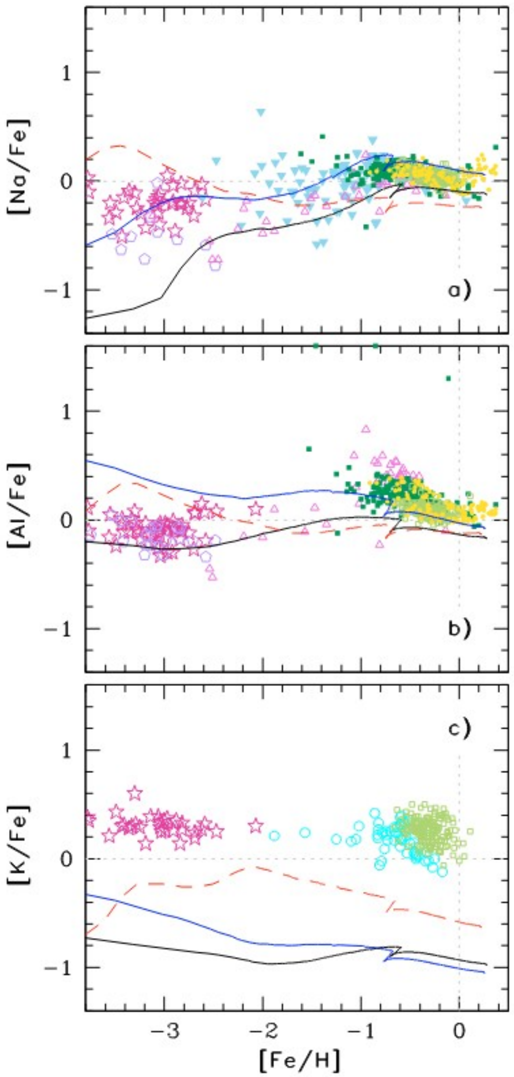
Goswami & Prantzos 2000 A&A 359





Lugaro+ 2003 ApJ 586
AGB stars: FRANEC vs MSSSP vs EVOL

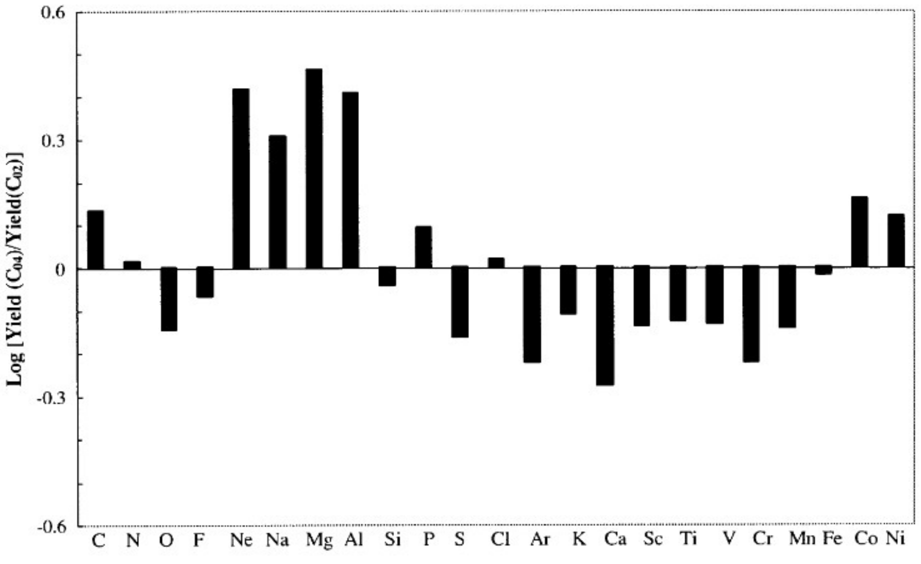
Keegans+ 2023 APJS 268
SubCh SNIa: Leung & Nomoto 2020 ApJ 861 vs Shen+ 2018 ApJ 854

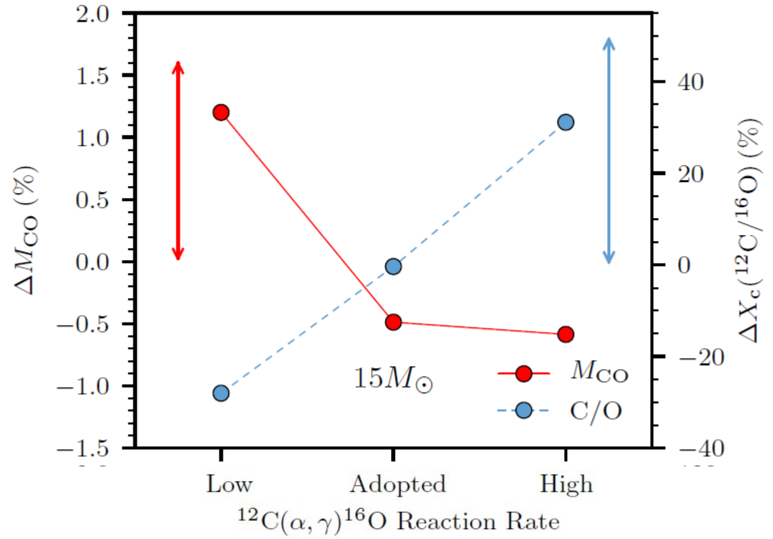


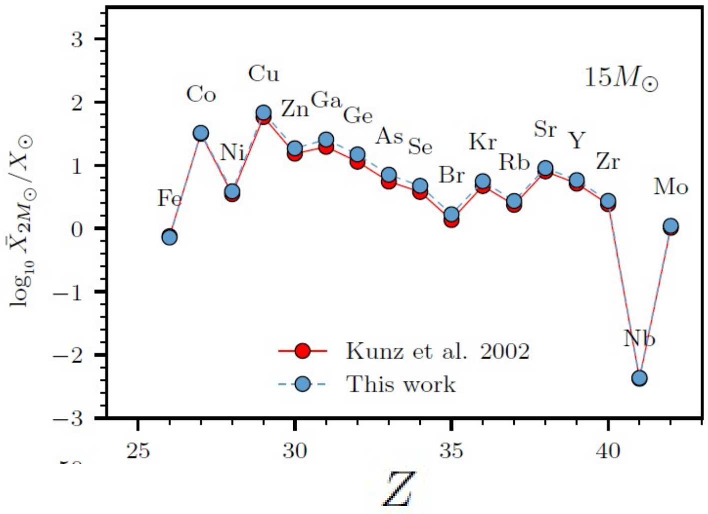
When trying to reproduce the elements (well.. the [element/Fe]):

- The yield sets allowing to fit better the observations for an element may not work for another element (e.g., Na vs Al).
- For some elements, there are no yields configuration to use for GCE that are consistent with observations (e.g., K).

Romano+ 2010 A&A 522





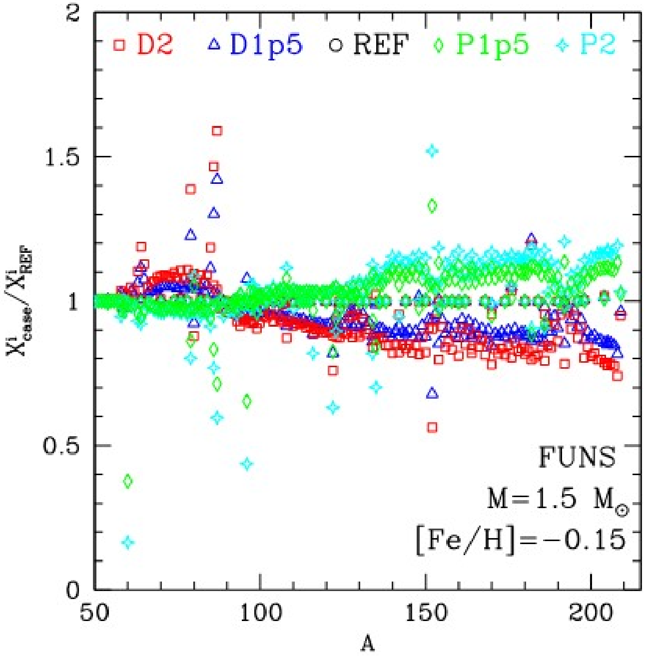


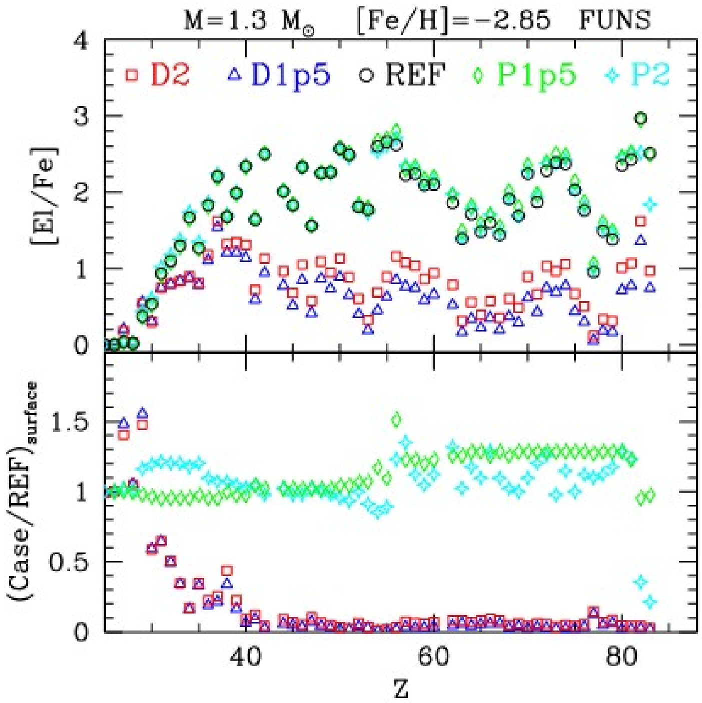
Case 1: $^{12}C(\alpha,\gamma)^{16}O$, from Imbriani+ 2000 ApJ 558 and Deboer+ 2017 RMP 89

See A Choplin, F. Herwig and S. Martinet talks

The i-process happening here.
The impact is model dependent!

Typical AGB star with s-process





Case 2: $^{13}C(\alpha,n)^{16}O$, from Cristallo+ 2018 ApJ 2018

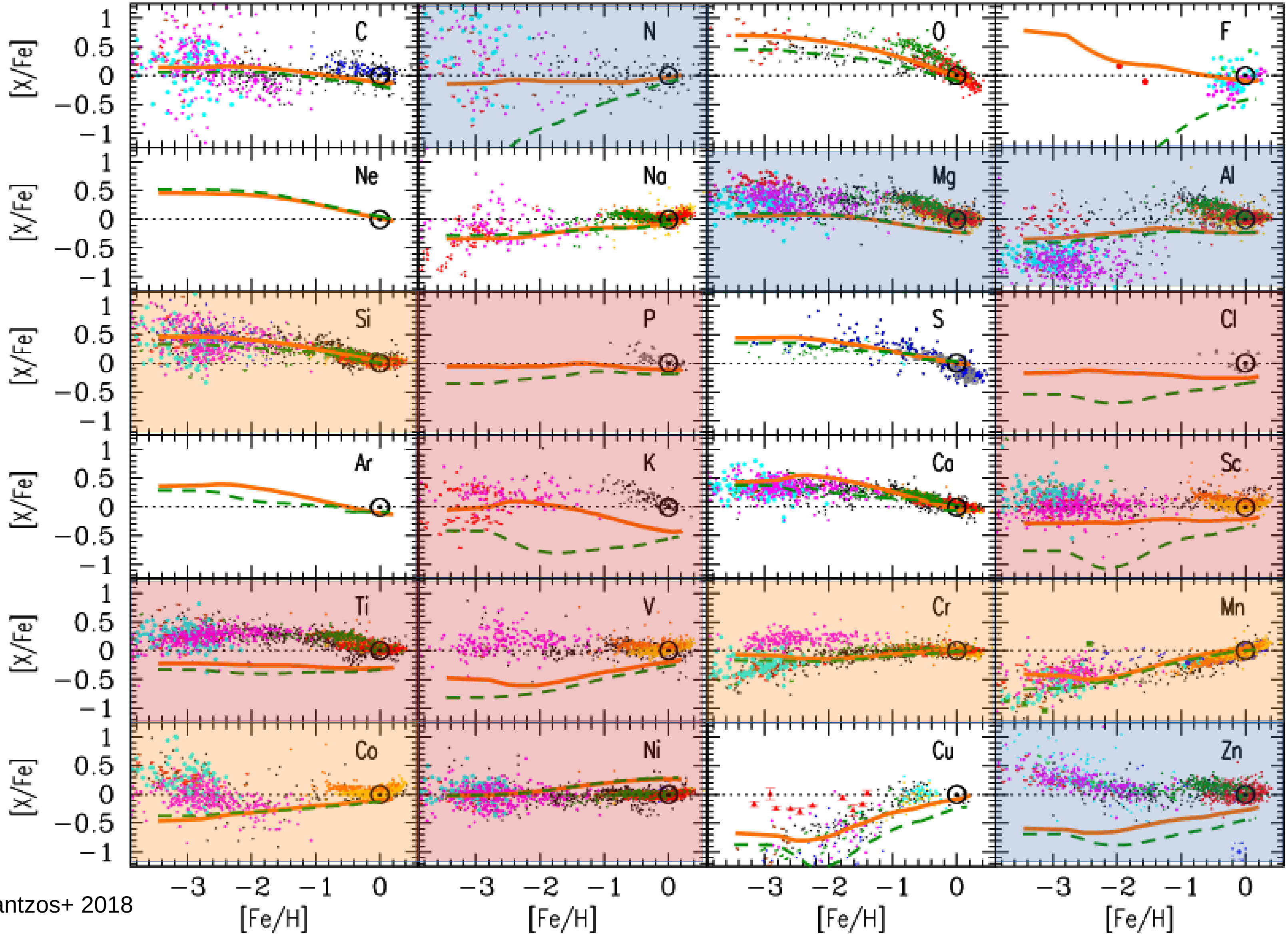
See also M. Wiedeking talk for the $^{66}Ni(n,\gamma)^{67}Ni$ rate

State-of-the-art: GCE vs obs.

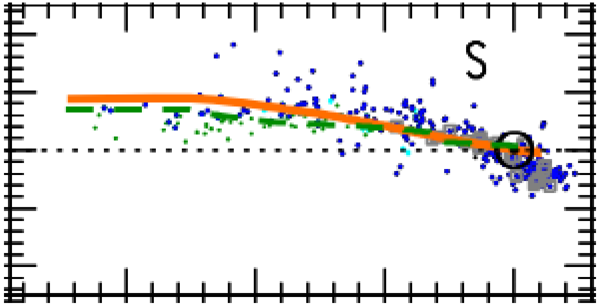
Always an issue

Dispersion at low Z

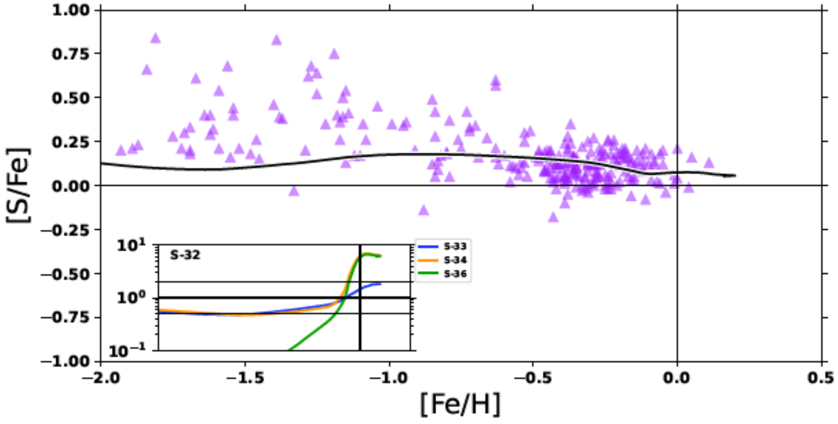
Issue using some yields, or often for some Z

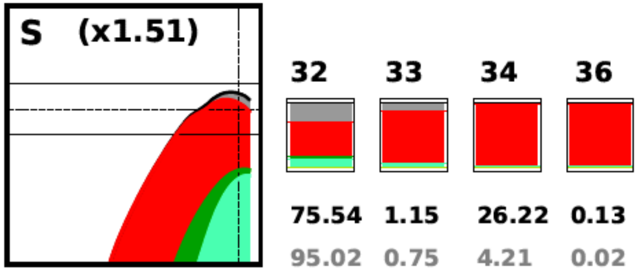


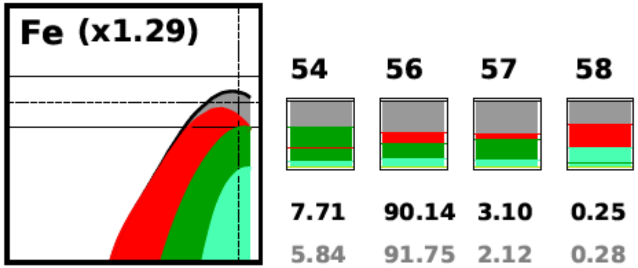
Prantzos+ 2018



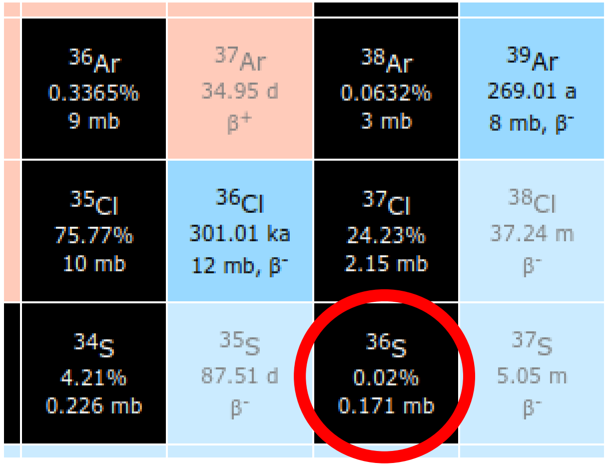
— All Sources
— Massive Stars
— SN1A
— AGB Stars
— NSM r-process







Reifarth+ 2000 ApJ 528
The ^{34}S(n,γ)^{35}S rate made life really hard for ^{36}S.



Preliminary: No statistics yet!

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **524**, 6295–6330 (2023) https://doi.org/10.1093/mnras/stad2167
Advance Access publication 2023 July 21

The chemical evolution of the solar neighbourhood for planet-hosting stars

Marco Pignatari,[1,2,3,4,5★] Thomas C. L. Trueman,[1,3,4] Kate A. Womack,[3] Brad K. Gibson,[3,5] Benoit Côté,[1,4,5,6] Diego Turrini,[7,8,9] Christopher Sneden,[10] Stephen J. Mojzsis,[1,2,11] Richard J. Stancliffe,[4,12] Paul Fong,[3,4] Thomas V. Lawson,[3,4,13] James D. Keegans,[4,14] Kate Pilkington,[15] Jean-Claude Passy,[16] Timothy C. Beers[5,17] and Maria Lugaro[1,2,18,19]

- **16 authors**
- **5 PhD/young PDRA**
- **Target communities: nuclear astrophysics & planet formation/modeling**

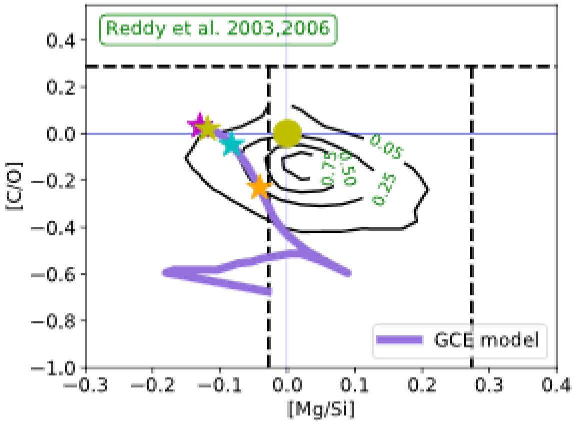
Experimental Astronomy (2022) 53:225–278
https://doi.org/10.1007/s10686-021-09754-4

ORIGINAL ARTICLE

Exploring the link between star and planet formation with Ariel

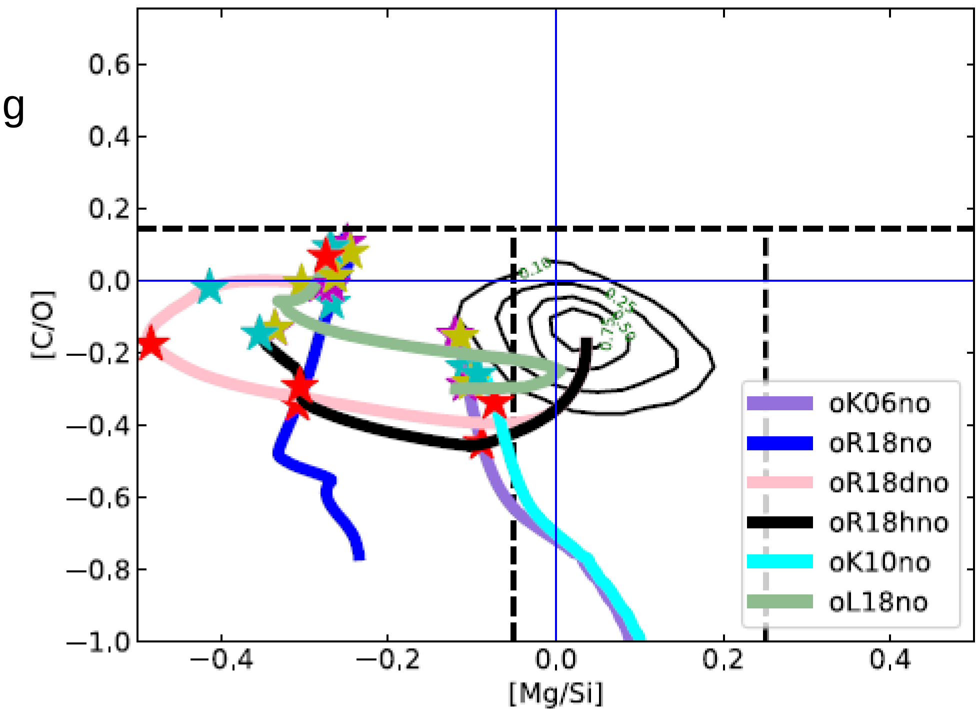
Diego Turrini[1,2] · Claudio Codella[3] · Camilla Danielski[4] · Davide Fedele[2,3] · Sergio Fonte[1] · Antonio Garufi[3] · Mario Giuseppe Guarcello[5] · Ravit Helled[6] · Masahiro Ikoma[7] · Mihkel Kama[8,9] · Tadahiro Kimura[7] · J. M. Diederik Kruijssen[10] · Jesus Maldonado[5] · Yamila Miguel[11,12] · Sergio Molinari[1] · Athanasia Nikolaou[13,14] · Fabrizio Oliva[1] · Olja Panić[15] · Marco Pignatari[16,17,18] · Linda Podio[3] · Hans Rickman[19] · Eugenio Schisano[1] · Sho Shibata[7] · Allona Vazan[20] · Paulina Wolkenberg[1]

Received: 30 June 2020 / Accepted: 13 April 2021 / Published online: 15 October 2021



Effect of stellar yields & the Mg puzzle

- 6 stellar yield sets
- the solar [C/O] is obtained using 3 sets
- by using 2 other sets we get closer to the solar [Mg/Si], but none of them show enough Mg



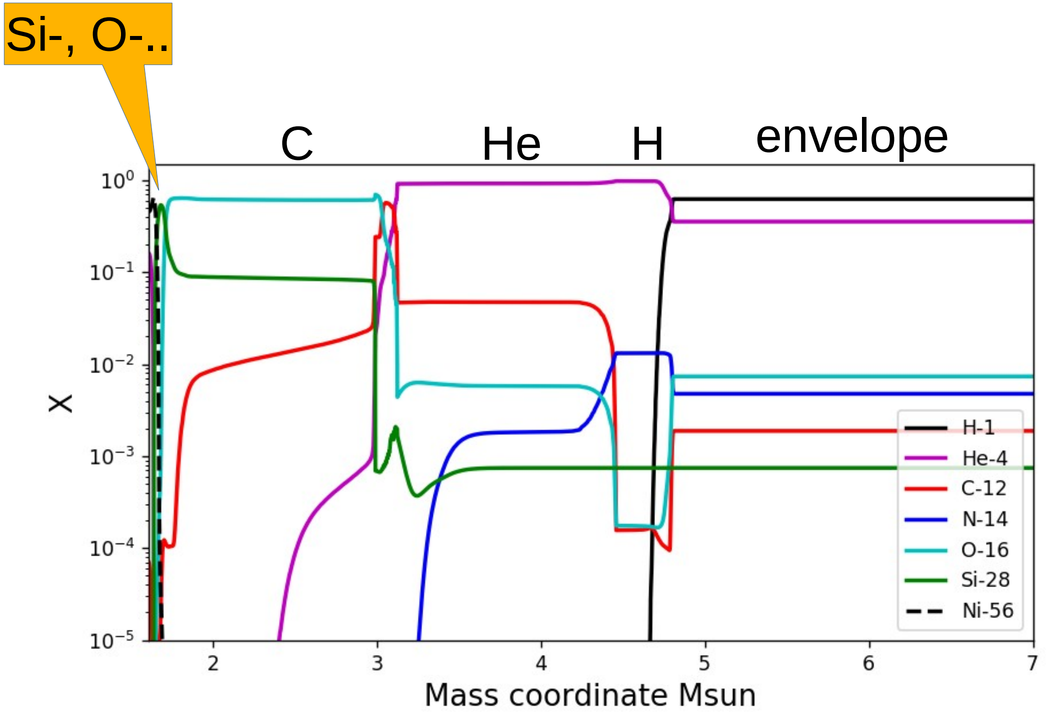
Mg puzzle!

Old problem, identified first from using WW95 CCSNe yields

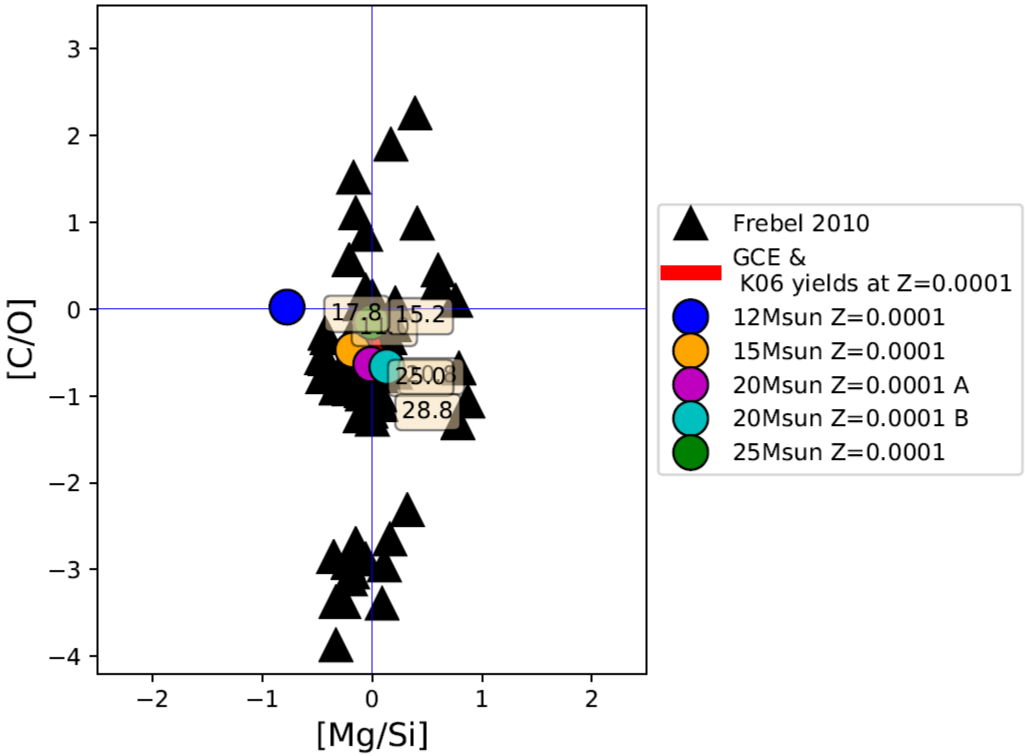
See also poster #55 by F.P. Jost et al.

Nuclear astrophysics point of view: it should not be that difficult..

- **C**: product of 3α→ ^{12}C reaction (preSN partial He-burning)
- **O**: product of the $^{12}C(\alpha,\gamma)^{16}O$ reaction (preSN He-burning)
- **Mg**: product of the $^{20}Ne(\alpha,\gamma)^{24}Mg$ reaction (preSN C/Ne-burning)
- **Si**: product of $^{16}O+^{16}O$ (explosive O-burning)

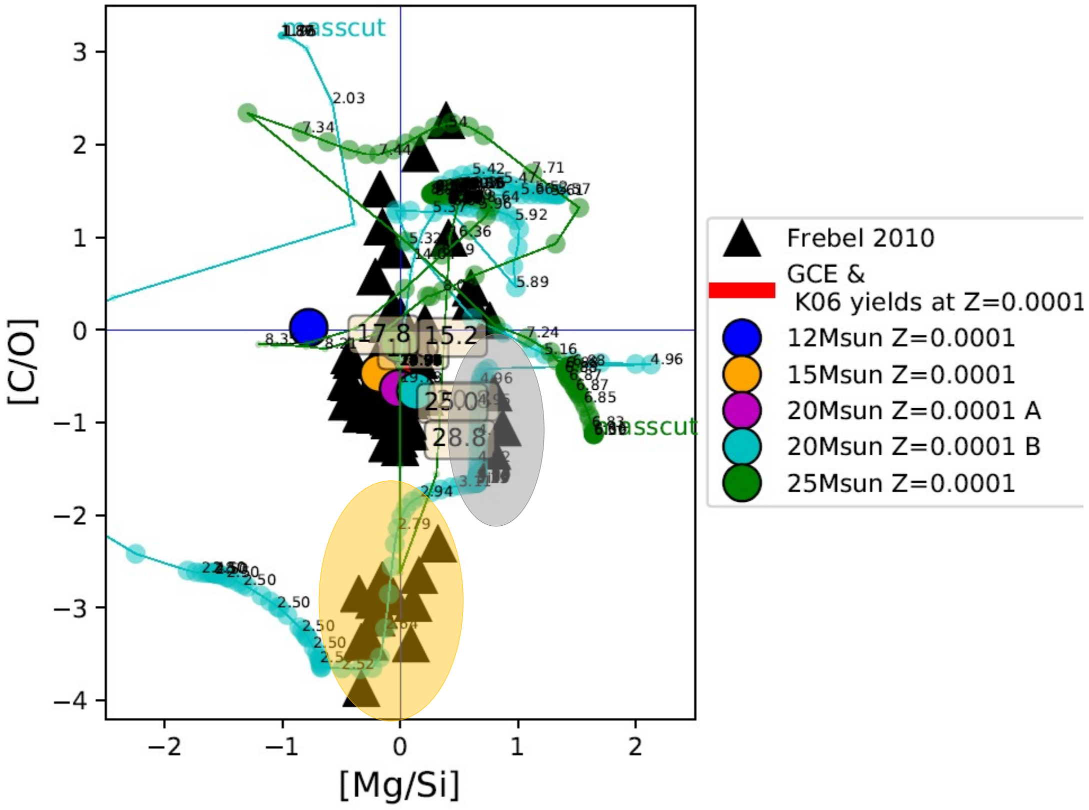


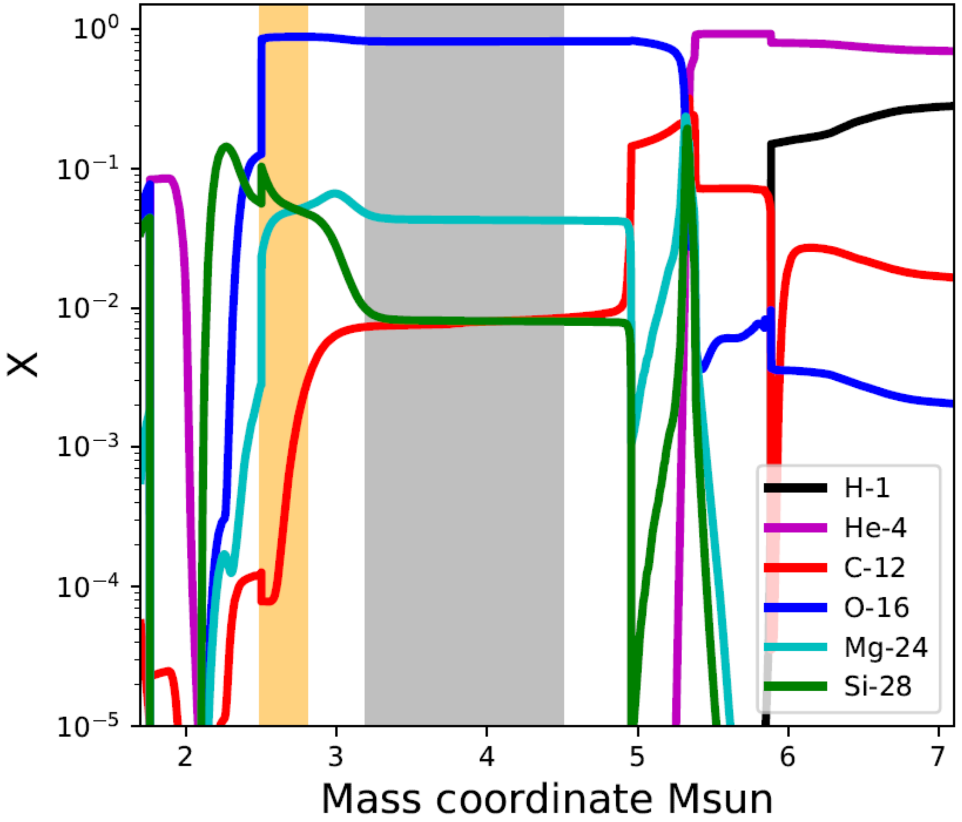
M=15Msun, Z=0.02
Ritter+2018 MNRAS 480
MESA progenitor
Fryer+12 explosion



1D CCSN integrated yields Ritter+ 2018

Work in progress: comparison with stellar archaeology data - Pignatari+ in prep.

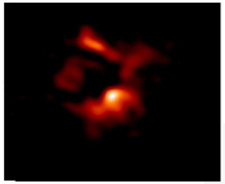




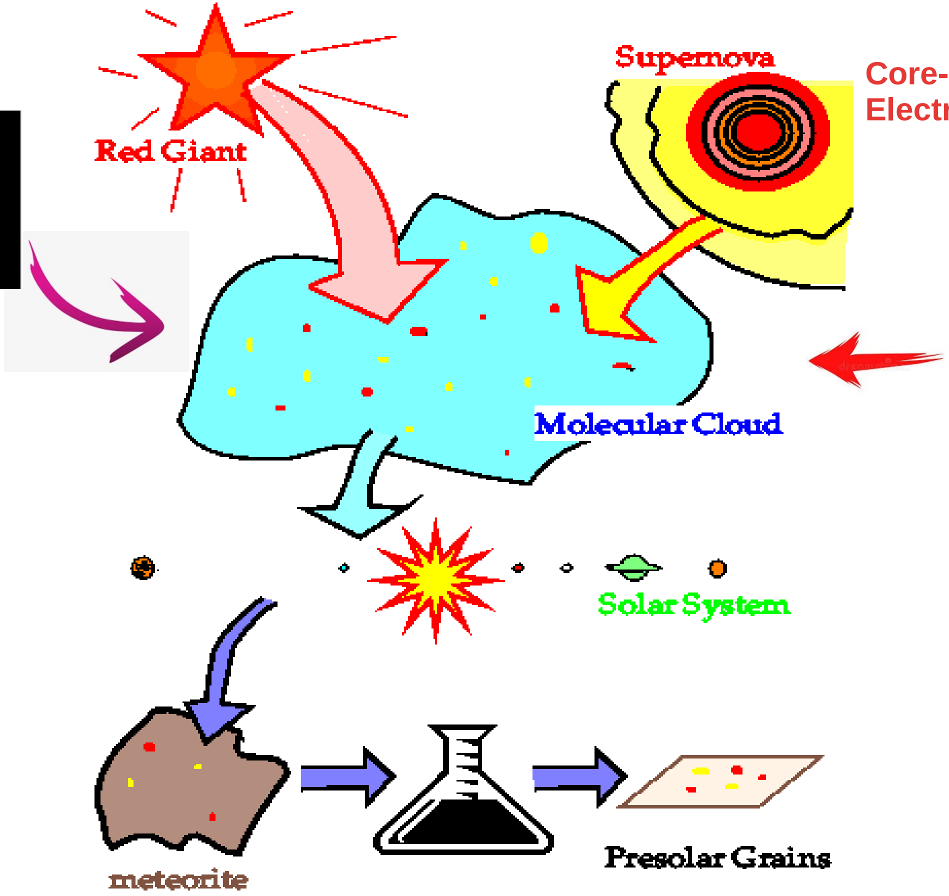
Work in progress: comparison with stellar archaeology data - Pignatari+ in prep.

The presolar grain journey from stars to us

AGB stars
Post-AGB stars
...

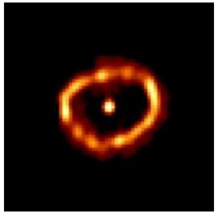


CWLeo
(IRC+10216)
Turthill+2000
Keck Tel.



Core-collapse supernovae
Electron-capture supernovae (?)

Novae



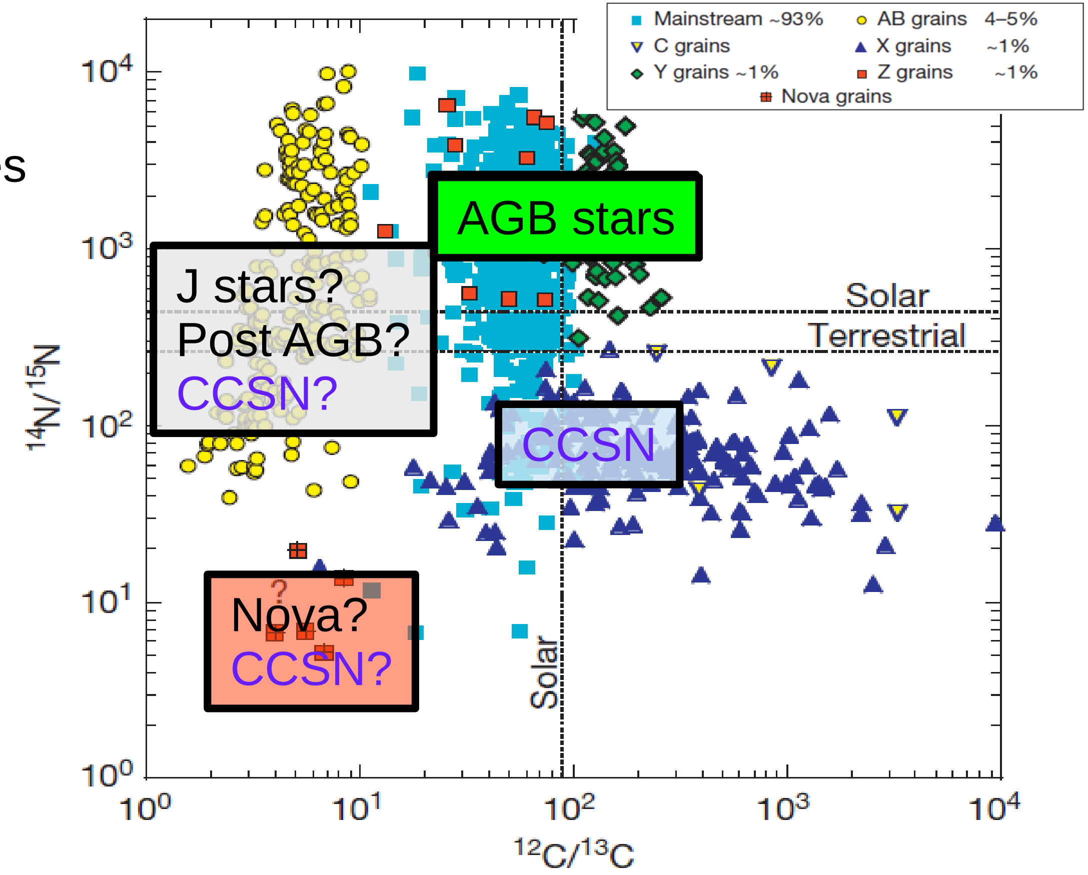
Nova Cygni 1992 (HST)

See the previous talk
by R. Trappitsch!

L. Nittler

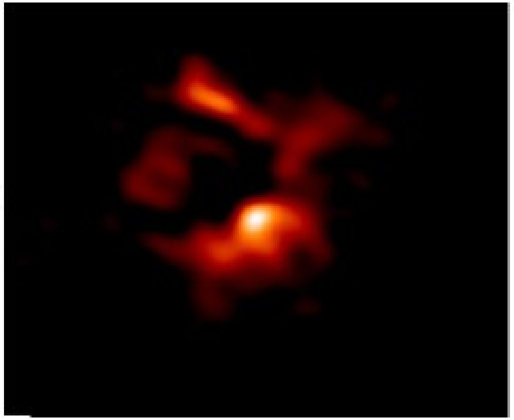
Working with presolar grains

- Study of nucleosynthesis isotopic anomalies in bulk grains and single grains
- Study of meteoritic anomalies, carried by different types of presolar grains
- Study of isotopic signatures not modified by intrinsic nucleosynthesis in the parent star (GCE study for stars that we cannot observe anymore, died "shortly" before the formation of the Sun)



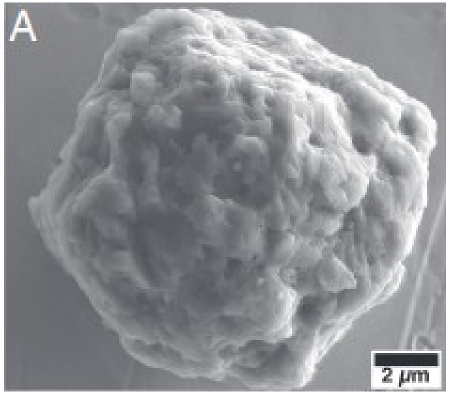
Zinner 2014, Treat. Geochem 1.4
https://presolar.physics.wustl.edu/presolar-grain-database/

Time GCE window provided by grains



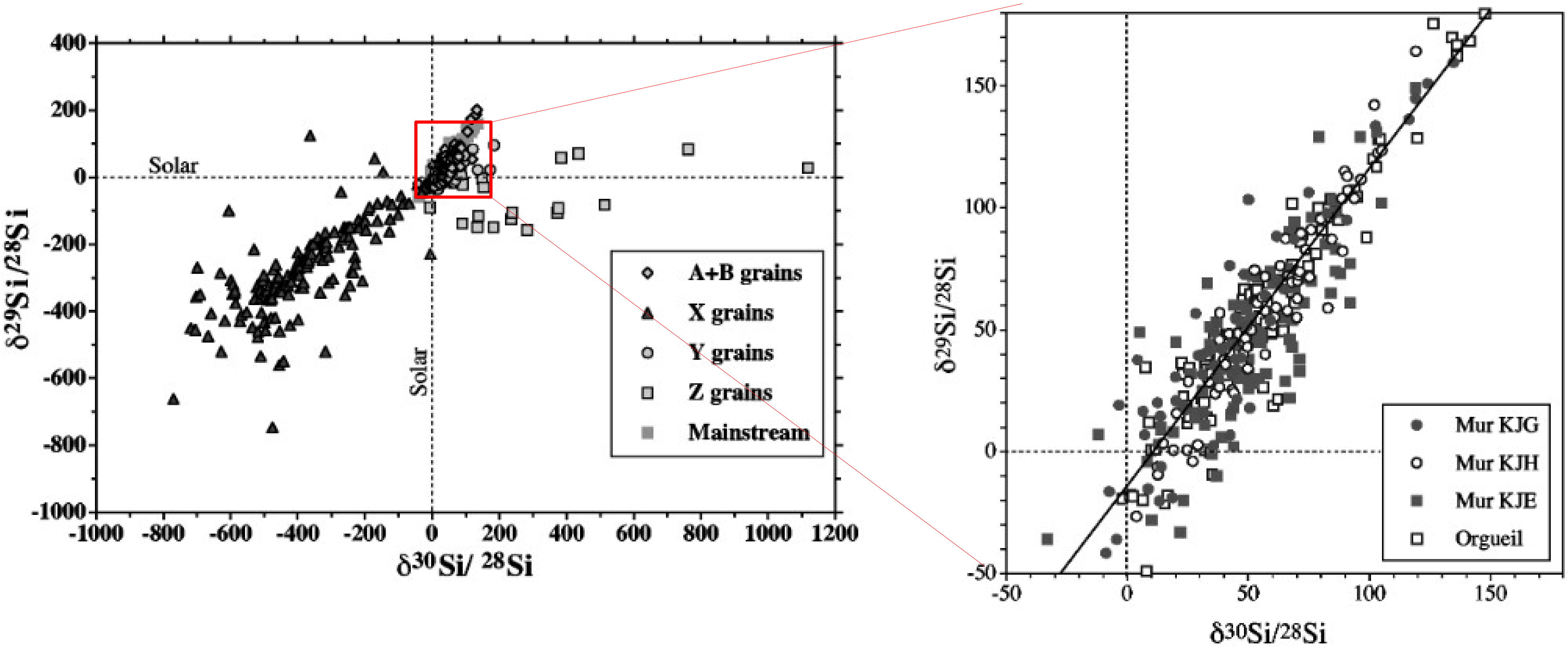
3 Gyr > τ > 0.5 Gyr

< 0.3 Gyr in the ISM
(Heck+ 2020, PNAS 117)



ESS

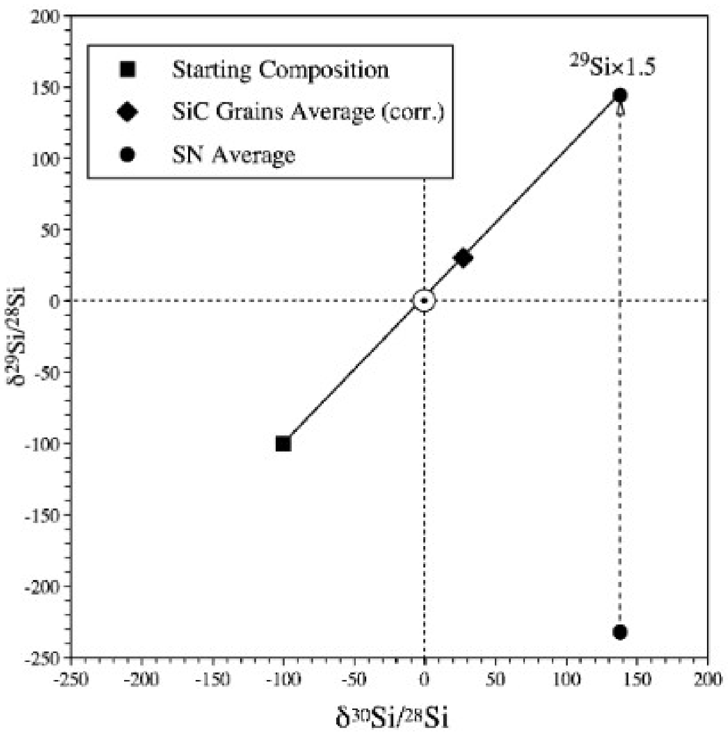
GCE with presolar grains



Lugaro+ 1999, ApJ 527

δ abundances = ((isotope1/isotope2)/solar ratio - 1)*1000

Scenarios to explain the Si isotope scatter:



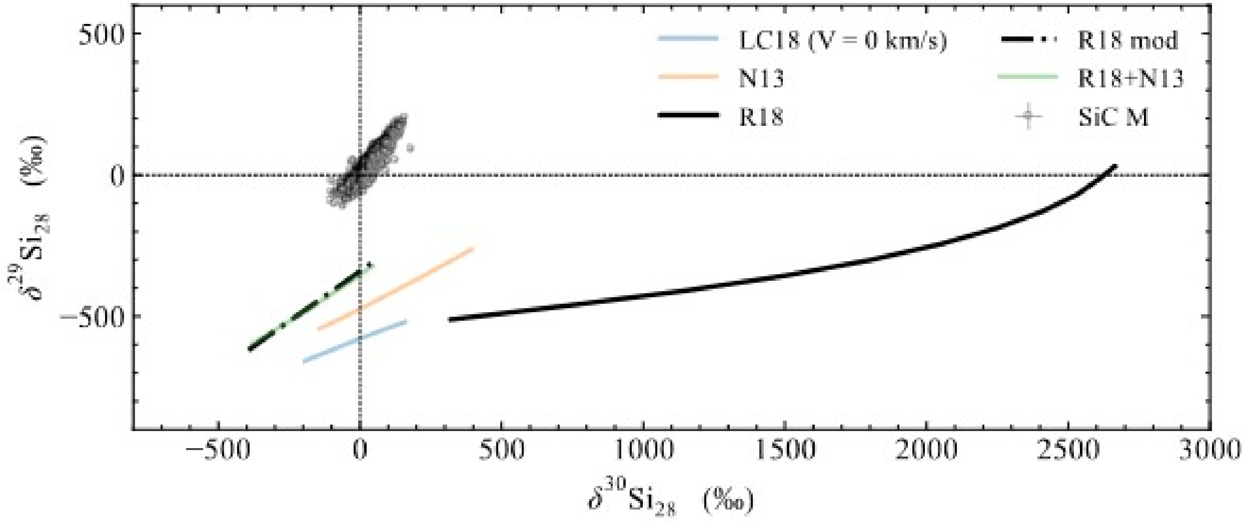
Lugaro+ 1999 ApJ 527

- Clayton 1997 ApJ 484: stars diffused outward from more metal-rich part of the disks (the Sun was born at 6.6 kpc), i.e., giving higher Si29 and Si30 with respect to Si28;
- Alexander & Nittler 1999 ApJ 526: Cl97 may work, but other processes may be at play;
- Lugaro+ 1999 ApJ 527: effect of heterogeneous GCE from CCSNe contribution ...

  … and moving further using the isotopes from two elements (Nittler 2005 ApJ 618) ;
- Clayton 2003 ApJ 598: mixing line due to a merger between a metal-poor dwarf galaxy and the Milky Way disk 5-6 Gyr ago;
- Lewis+ 2013 ApJL 768, reviewing the problem and supporting the role of migration in shaping the observed scatter.

Open-source GCE codes OMEGA

http://nugrid.github.io/NuPyCEE
https://github.com/becot85/JINAPyCEE



Fok, H.K.+ 2024, submitted

See poster #86 by Spelta et al.

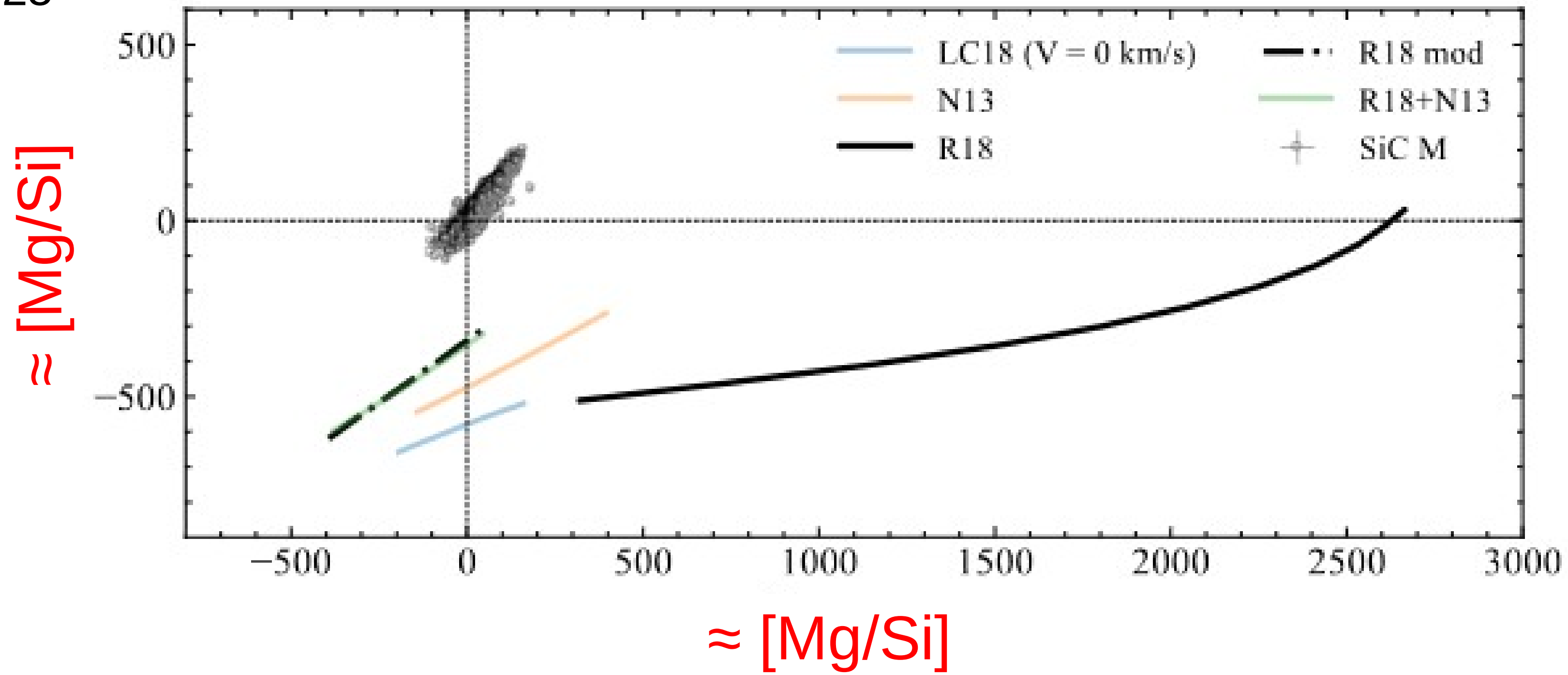
Results affected by nuclear uncertainties, among others by the $^{30}Si(n,\gamma)^{31}Si$ rate

▼ Comment

Rec. value is from GKD03. MACS vs. kT table from GKD03, but extended above kT=30 keV with norm. energy dependence from endfb71. Note that there is discrepancy between the activation measurement from BSR02b and the TOF value from GKD03. **A further investigation is required!!!**
Last review: August 2014

▼ List of all available values

original	renorm.	year	type	Comment	Ref
1.82 ± 0.33		2003	c	Linac, TOF, Au: Sat.; DC component is 0.48 (30) mb; no res. at 2.235 keV found	GKD03
3.51 ± 0.15 kT= 25 keV	3.24 ± 0.14	2002,2015	c	VdG, Act., Au:RaK88 corrected by 632 mb/586 mb= 1.0785; DC component at kT= 30 keV is 0.36 mb	BSR02b



Comment

Rec. value is from GKD03. MACS vs. kT table from GKD03, but extended above kT= 50 keV with norm. energy dependence from endfb71. Note that there is discrepancy between the activation measurement from BSR02b and the TOF value from GKD03. **A further investigation is required!!!**
Last review: August 2014

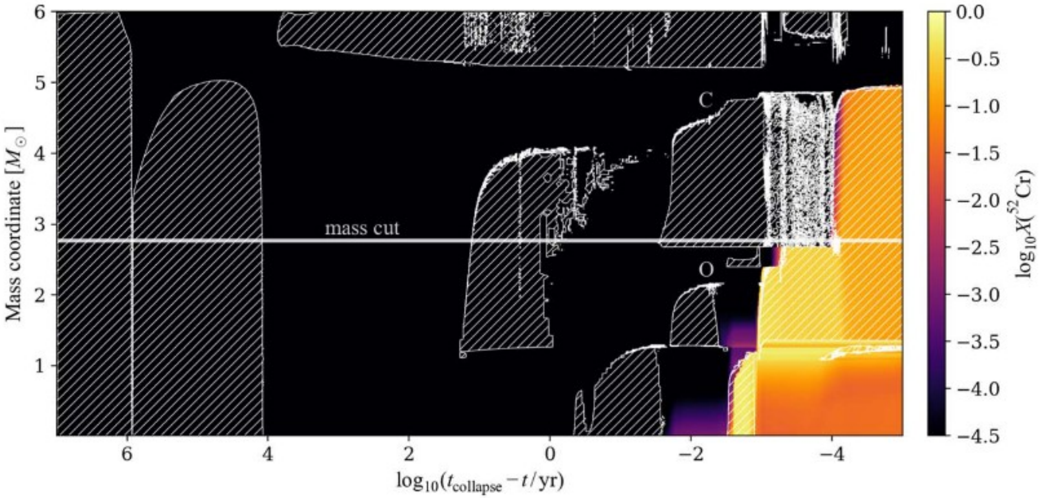
List of all available values

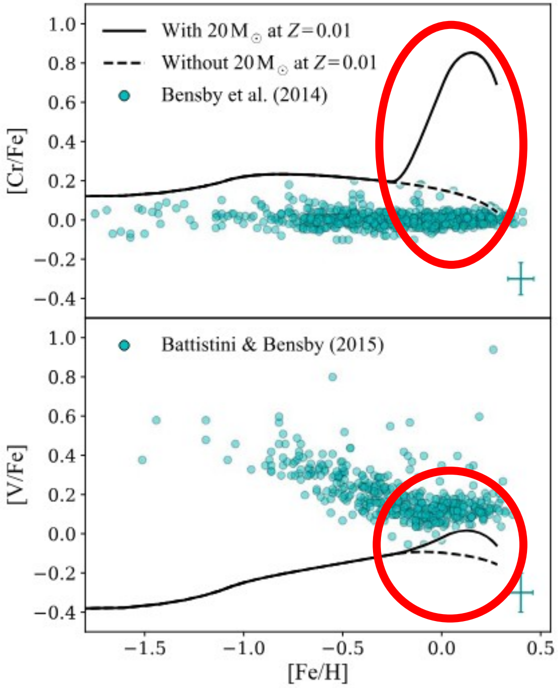
original	renorm.	year	type	Comment	Ref
1.82 ± 0.33		2003	c	Linac, TOF, Au: Sat.; DC component is 0.48 (30) mb; no res. at 2.235 keV found	GKD03
3.51 ± 0.15 kT= 25 keV	3.24 ± 0.14	2002,2015	c	VdG, Act., Au:RaK88 corrected by 632 mb/586 mb= 1.0785; DC component at kT= 30 keV is 0.36 mb	BSR02b

The Astrophysical Journal, 892:57 (6pp), 2020 March 20
https://doi.org/10.3847/1538-4357/ab77ac
© 2020. The American Astronomical Society. All rights reserved.

Chromium Nucleosynthesis and Silicon–Carbon Shell Mergers in Massive Stars

Benoit Côté[1,2,3,4,8], Samuel Jones[5,8], Falk Herwig[3,6,8], and Marco Pignatari[1,3,7,8]
[1] Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, MTA Centre for Excellence, Konkoly Thege Miklos 15-17, H-1121 Budapest, Hungary





<u>Result from GCE</u>: major shell mergers in massive stars including Si shell material should be a rare event.

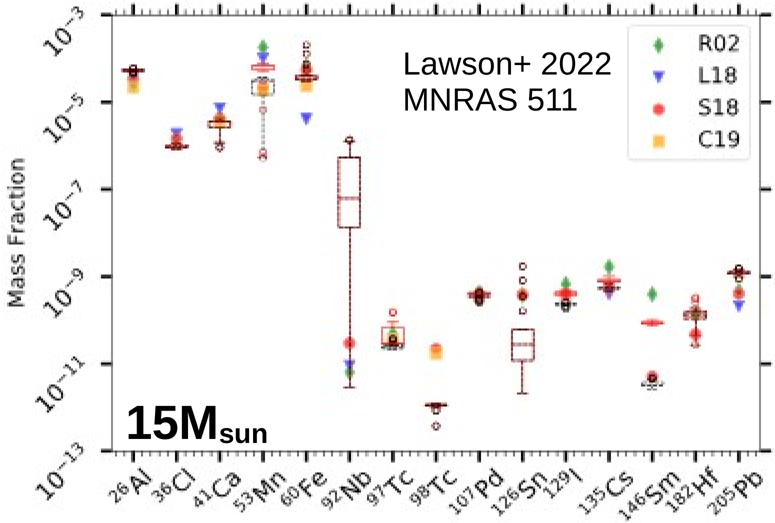
GCE of short-lived-radioactive isotopes ($T_{1/2}$ ~ 0.1-100 million years) observed in the Early Solar System (Lugaro+ 2018 PrPNP 102)

GCE contribution may be relevant for species with $T_{1/2} \geq 2$ Myr

SLR	Daughter	Reference	$T_{1/2}$ (Myr)
^{26}Al	^{26}Mg	^{27}Al	0.72
^{36}Cl	^{36}S	^{35}Cl	0.30
^{41}Ca	^{41}K	^{40}Ca	0.099
^{53}Mn	^{53}Cr	^{55}Mn	3.7
^{60}Fe	^{60}Ni	^{56}Fe	2.6
^{92}Nb	^{92}Zr	^{92}Mo	34
^{97}Tc	^{97}Mo	^{98}Ru	4.2
^{98}Tc	^{98}Ru	^{98}Ru	4.2
^{107}Pd	^{107}Ag	^{108}Pd	6.5
^{126}Sn	^{126}Te	^{124}Sn	0.23
^{129}I	^{129}Xe	^{127}I	15
^{135}Cs	^{135}Ba	^{133}Cs	2.3
^{146}Sm	^{142}Nd	^{144}Sm	68
^{182}Hf	^{182}W	^{180}Hf	8.9
^{205}Pb	^{205}Tl	^{204}Pb	17

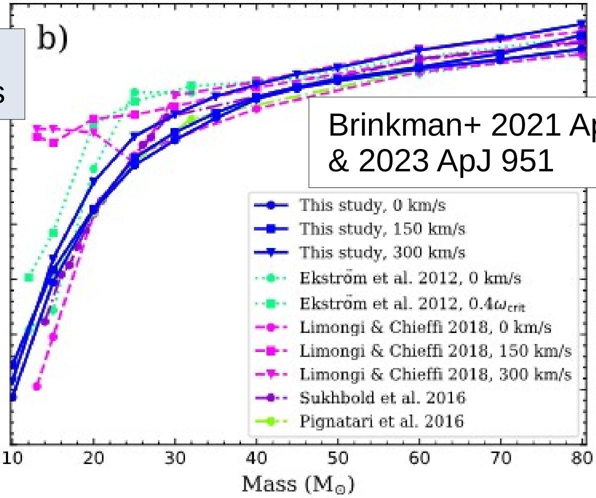
See the talks by B. Wehmeyer and A. Vasini

SLRs yields variation from CCSNe

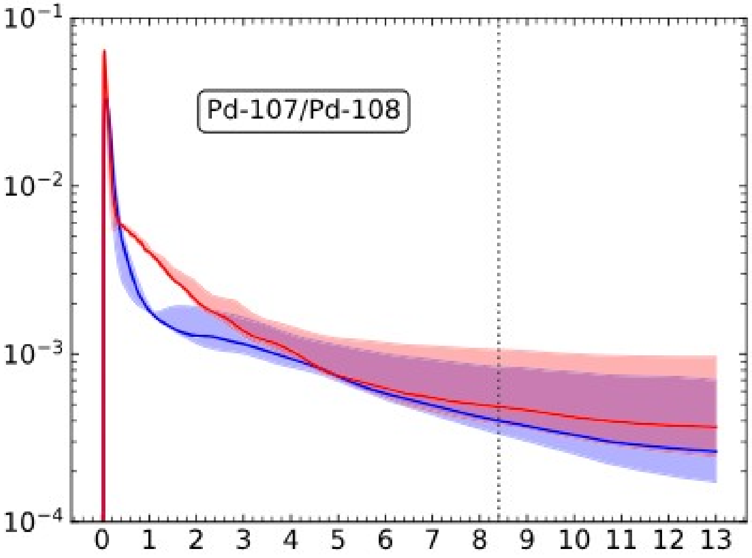


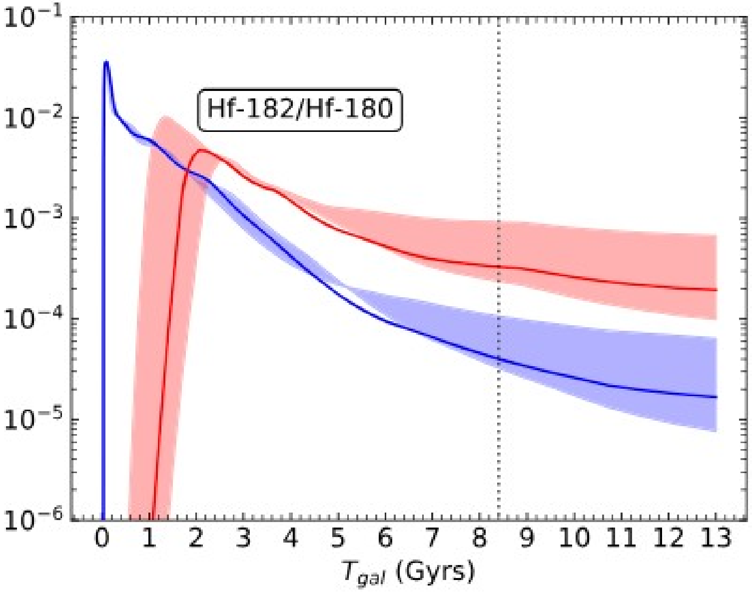
SLRs yields from massive star winds

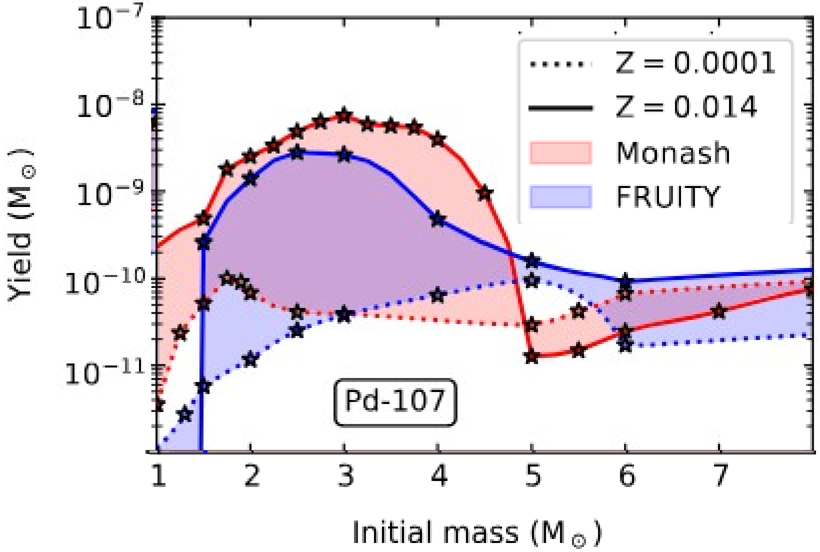
See the talk from E. Higgins

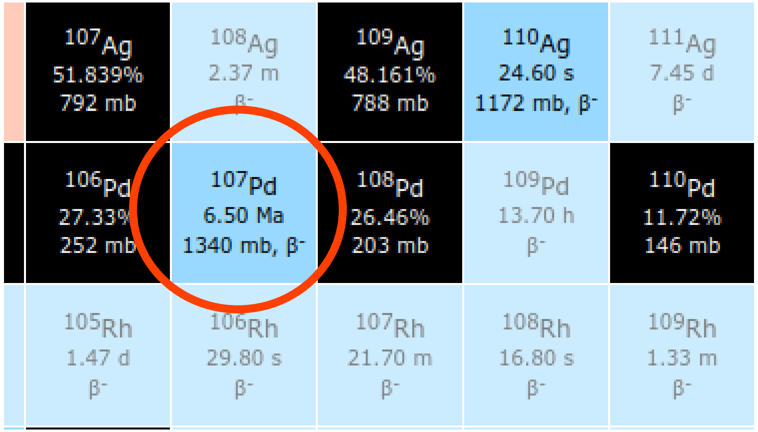


Brinkman+ 2021 ApJ 923 & 2023 ApJ 951



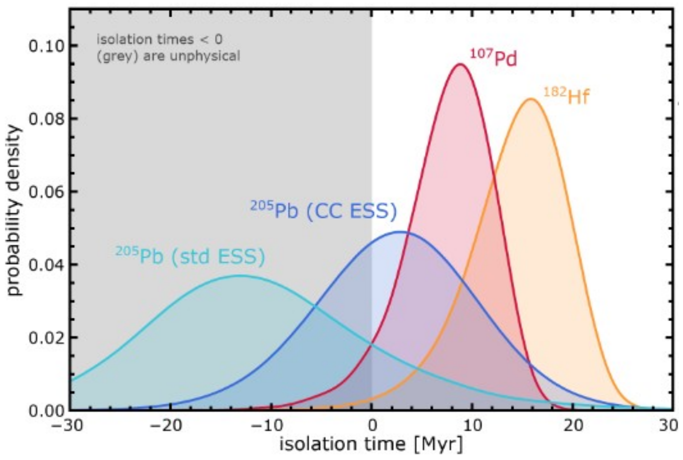






Trueman+2022 ApJ 924

See Posters #88 by Thomas Neff and #254 by Guy Leckenby & Iris Dillmann



^{205}Bi 15.31 d β^+	^{206}Bi 6.24 d β^+	^{207}Bi 32.90 a β^+	^{208}Bi 367.91 ka β^+	^{209}Bi 100% 2.7 mb
^{204}Pb 1.4% 89.5 mb	^{205}Pb 17.30 Ma 125 mb, β^+	^{206}Pb 24.1% 14.5 mb	^{207}Pb 22.1% 9.7 mb	^{208}Pb 52.4% 0.36 mb
^{203}Tl 29.524% 124 mb	^{204}Tl 3.78 a 215 mb, β^-	^{205}Tl 70.476% 54 mb	^{206}Tl 4.20 m β^-	^{207}Tl 4.77 m β^-
^{202}Hg 29.86% 63.2 mb	^{203}Hg 46.60 d 98 mb, β^-	^{204}Hg 6.87% 42 mb	^{205}Hg 5.14 m β^-	^{206}Hg 8.15 m β^-
^{201}Au 26.00 m β^-	^{202}Au 28.80 s β^-	^{203}Au 1.00 m β^-	^{204}Au 39.80 s β^-	^{205}Au 31.00 s β^-

Message to take home: before these results it was impossible to generate robust ^{205}Pb s-process yields from AGB stars.
Now results are getting good!

See also Casanovas-Hoste+ 2024 PRL 133
for the new 204Tl MACS (C. Domingo-Pardo's talk)

Messages to remember

- Stellar yields are a crucial source of uncertainty for Galactic Chemical Evolution (GCE) of element and isotope abundances.
- Uncertainties vs errorbars: why stellar yields are not provided with errorbars? It is really hard to provide comprehensive errors for stellar yields!
- The GCE results not fitting the observations for “good” reasons are usually more useful than the “good” GCE results for “wrong” reasons.
- Example 1: [Mg/Si] vs [C/O] & Si isotopes in presolar SiC grains
- Example 2: C-O-Si shell merger in massive stars: does it happen in real stars?
- Example 3: Short-Lived Radioactive isotopes.
- **Can we use GCE to learn about stars? Yes, if we use the right elemental and isotopic ratios.**