Galactic Chemical Evolution: impact of stellar yields and link with the Galactic Habitable Zone

Marco Pignatari

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“Molecules and planets in the outer Galaxy: is there a boundary of the Galactic Habitable Zone?” - 12-14 November 2024, Florence, Italy

Messages to remember

S. Viti &
E. Spitoni's talks

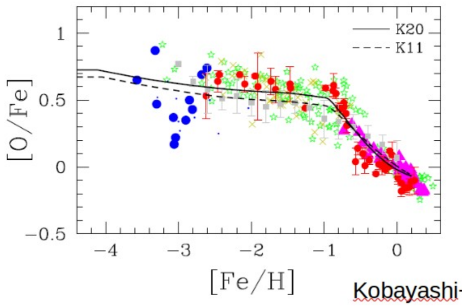
L. Colzi's talk

- Stellar yields are a crucial source of uncertainty for Galactic Chemical Evolution (GCE) of elements and isotopes.
- Uncertainties vs errorbars: why stellar yields are not provided with errorbars? It is really hard to provide comprehensive errors for stellar yields!
- **Integrated yields of Core-Collapse Supernovae are not safe to be used for GCE studies in the form they are usually provided. But the CCSNe models and the ejected yields are ok.**
- A good example: [Mg/Si] vs [C/O] in the solar neighbourhood & Si isotopes in presolar SiC grains.
- GCE of the radioactive heat-sources for planets: what is the Th/Eu trend in the MW disk?

E. Delgago Mena's talk

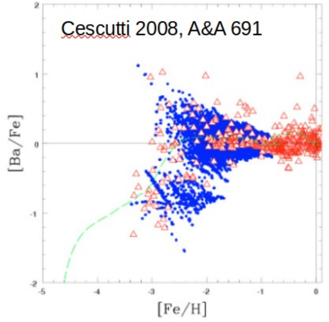
Complementary GCE approaches:

1) Homogeneous approach: assumption of instantaneous gas mixing

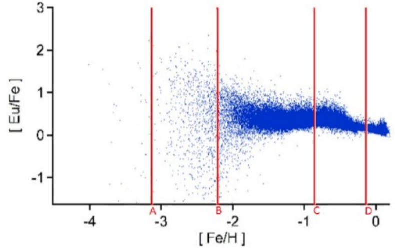


Kobayashi+ 2020, ApJ 900

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

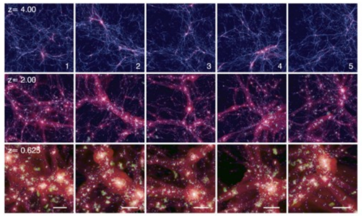


Cescutti 2008, A&A 691

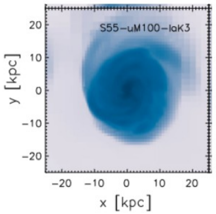


Wehmeyer+ 2015, MNRAS 452

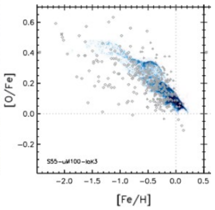
3) 3D Chemodynamical Models: "self-consistent" treatment of the chemical and dynamical evolution of a system.



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

E. Spitoni, M. Palla & R. Yates talks

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

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]

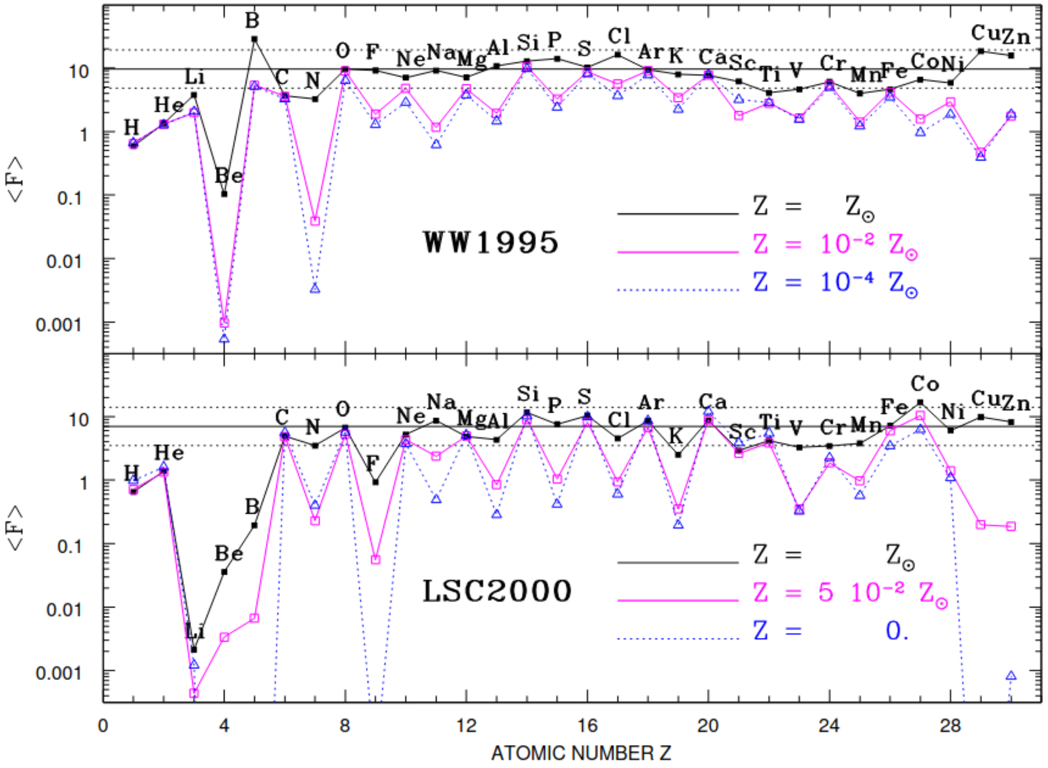
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **451**, 3693–3708 (2015) doi:10.1093/mnras/stv1102

Galactic chemical evolution: stellar yields and the initial mass function

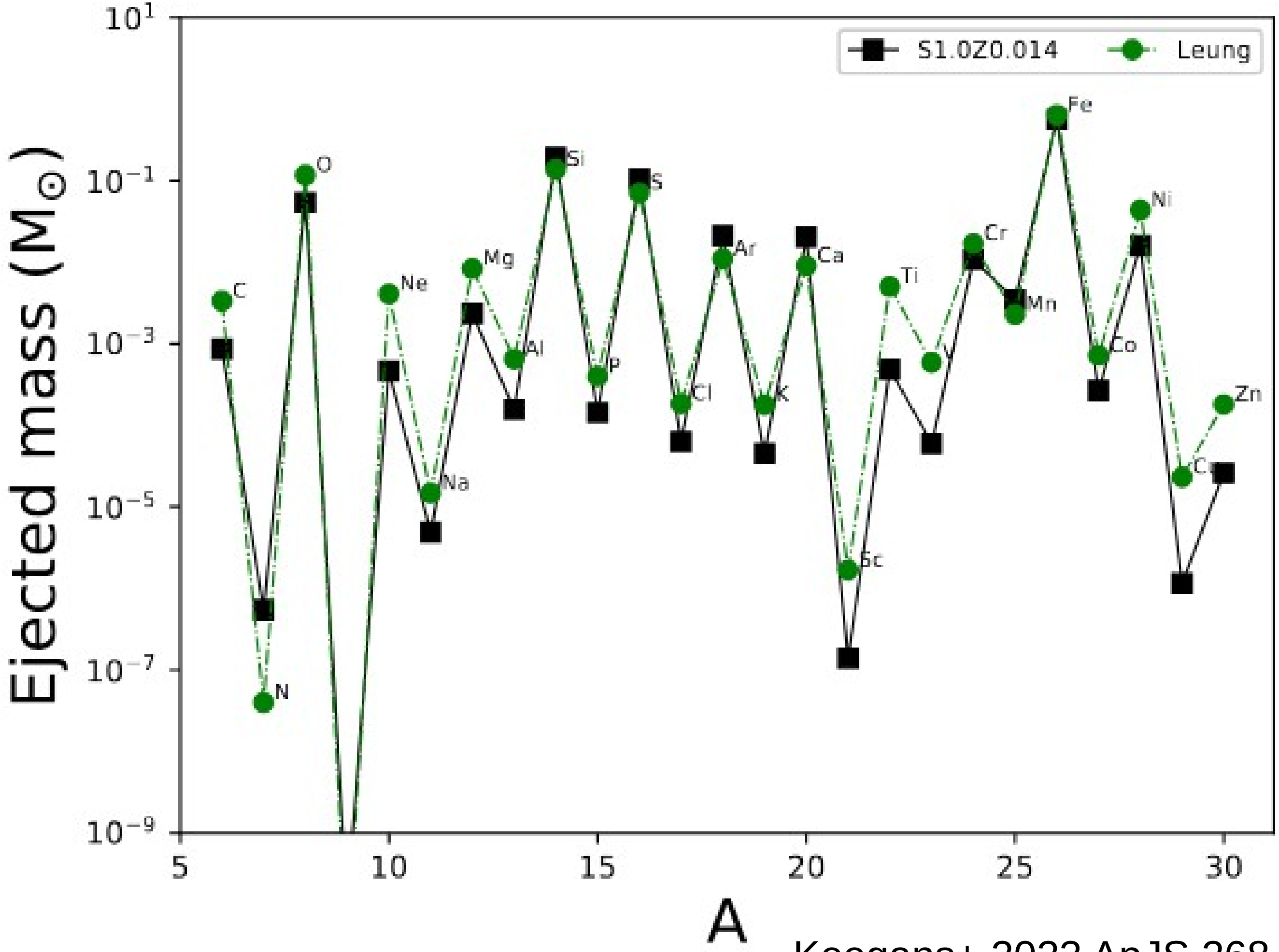
Mercedes Mollá,[1,2★] Oscar Cavichia,[2,3★] Marta Gavilán[4] and Brad K. Gibson[5]

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

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

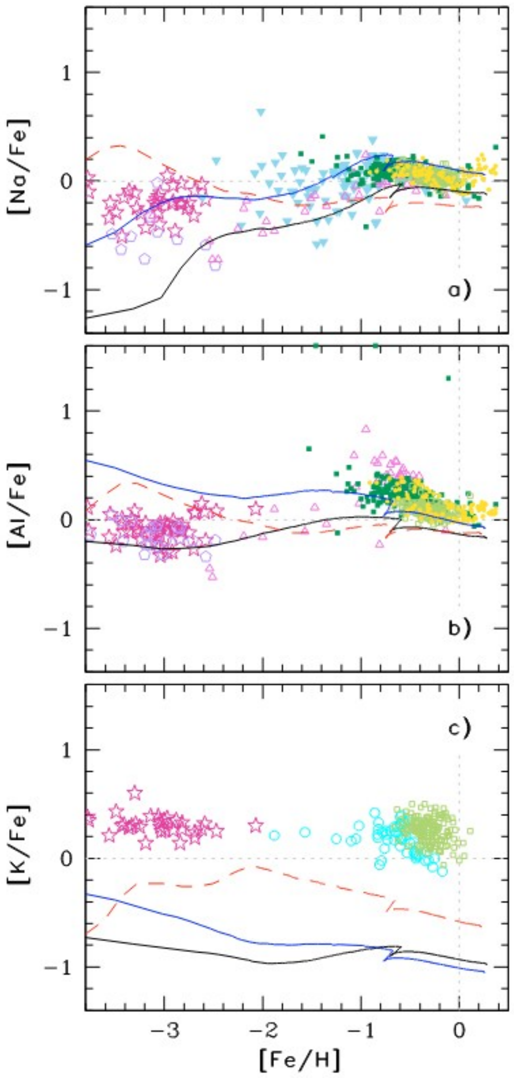


Goswami & Prantzos 2000 A&A 359



What difference is relevant for GCE?

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



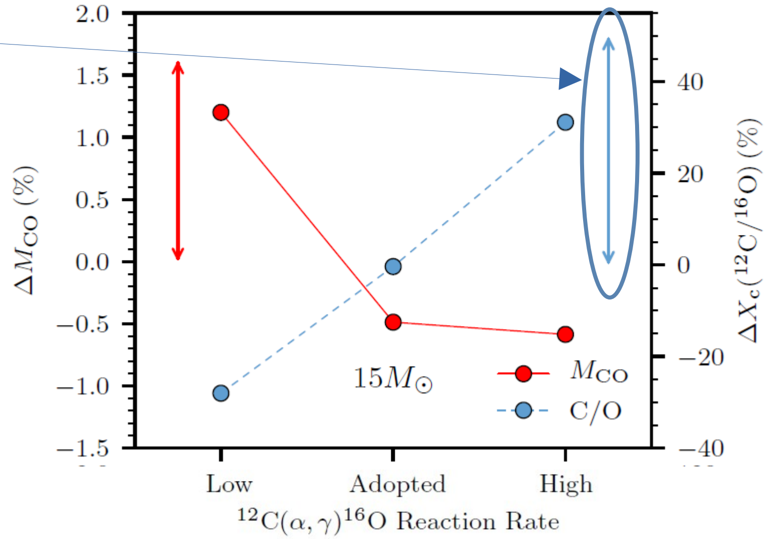
When trying to reproduce the elements (well.. the [element/Fe]):

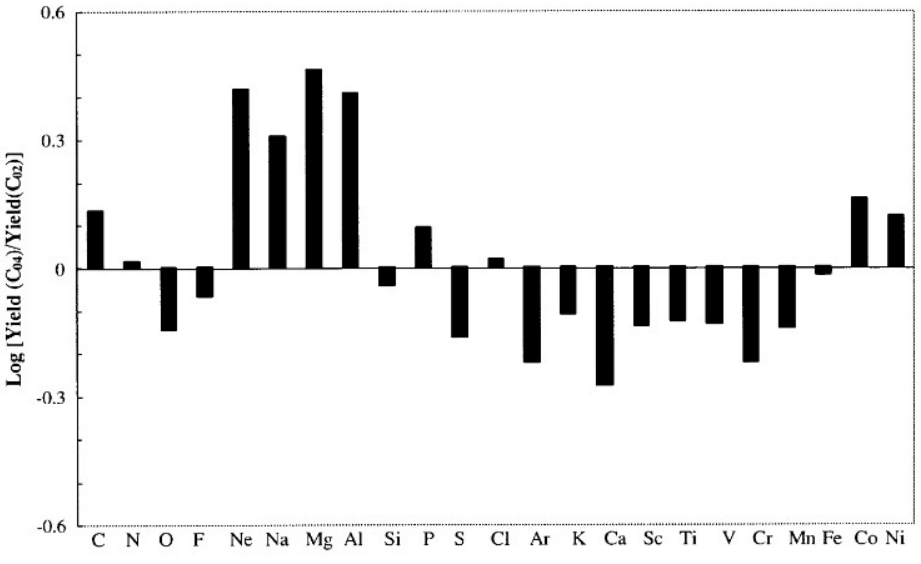
- The yield sets allowing to fit better the observations for an element may not work for another element (e.g., Na vs Al).
- For some elements, there are no yields configuration to use for GCE that are consistent with observations (e.g., K).

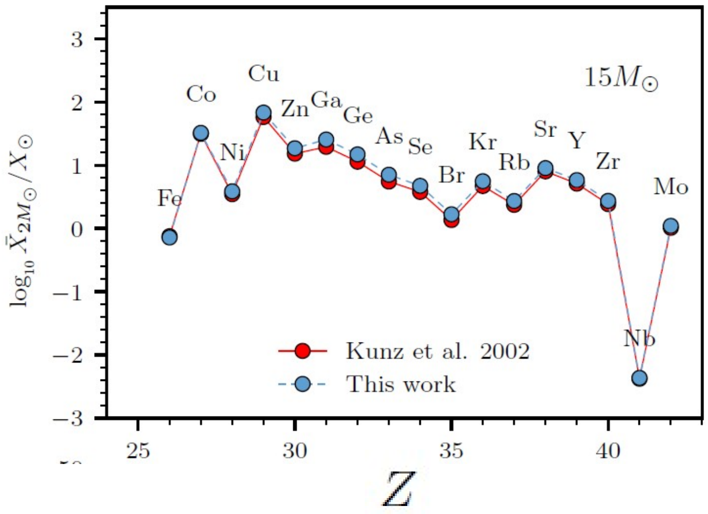
Romano+ 2010 A&A 522

Impact of nuclear reaction rates

Even with ~20% uncertainty, still strong non-linear variations between models are possible







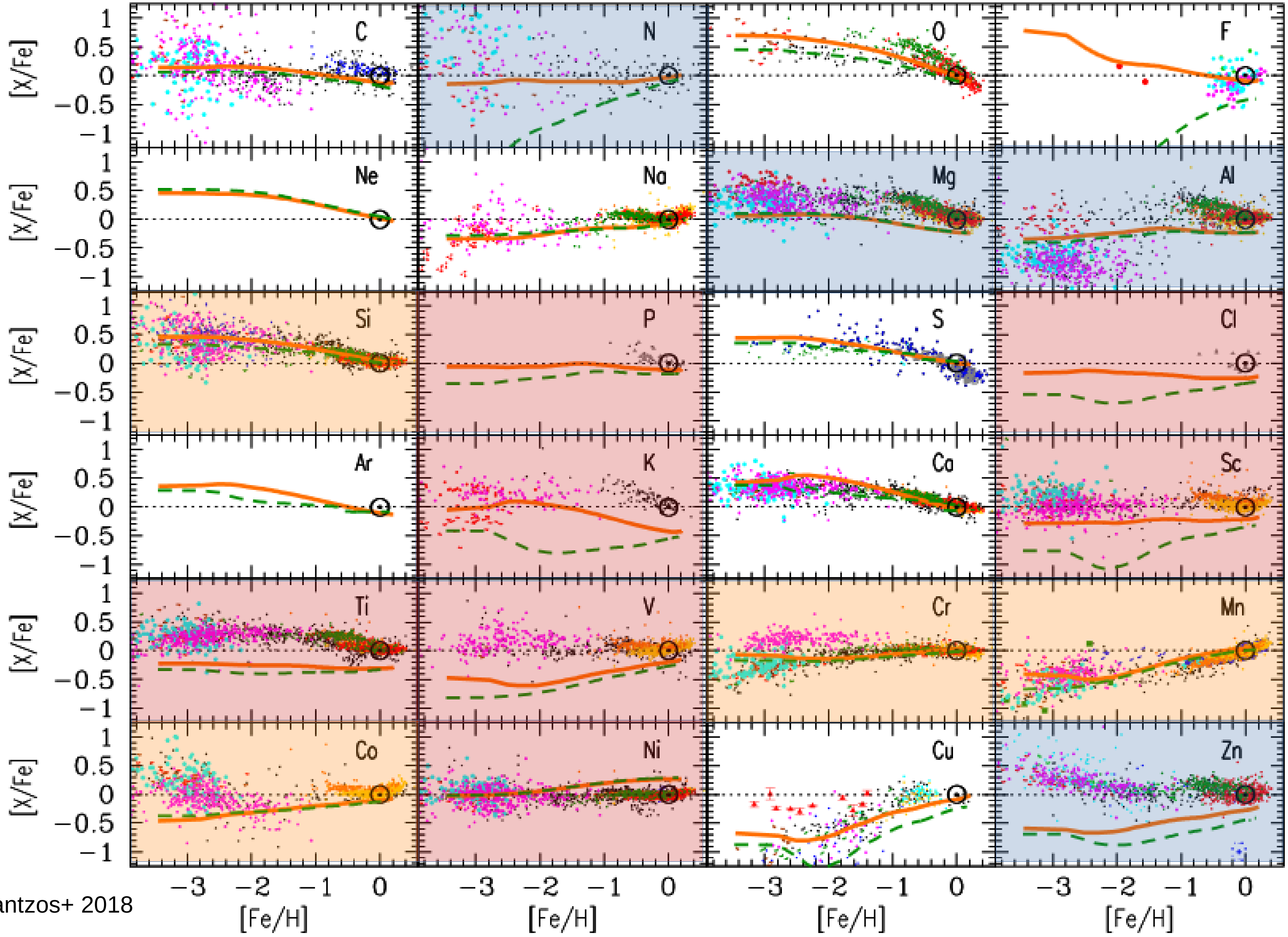
The impact of the $^{12}C(\alpha,\gamma)^{16}O$, from Imbriani+ 2000 ApJ 558 and Deboer+ 2017 RMP 89

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

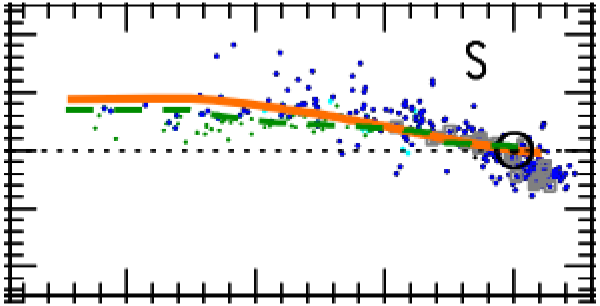
Always an issue

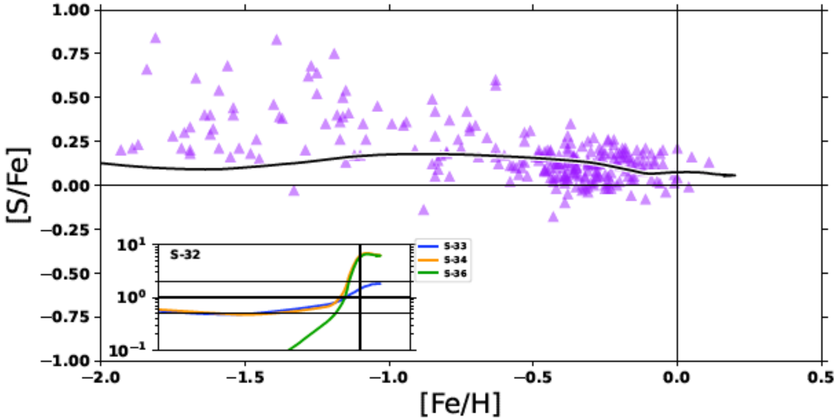
Dispersion at low Z

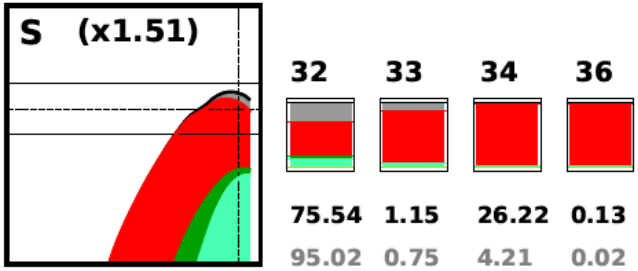
Issue using some yields, or often for some Z

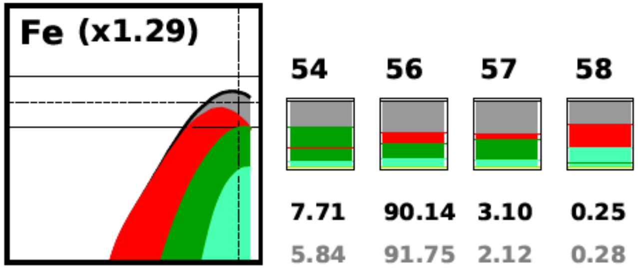


Prantzos+ 2018







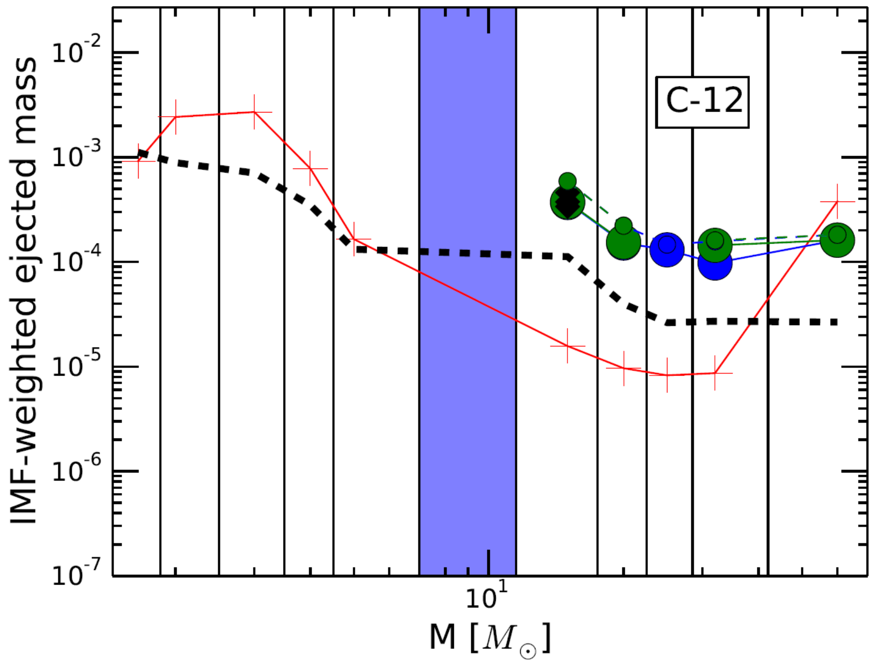


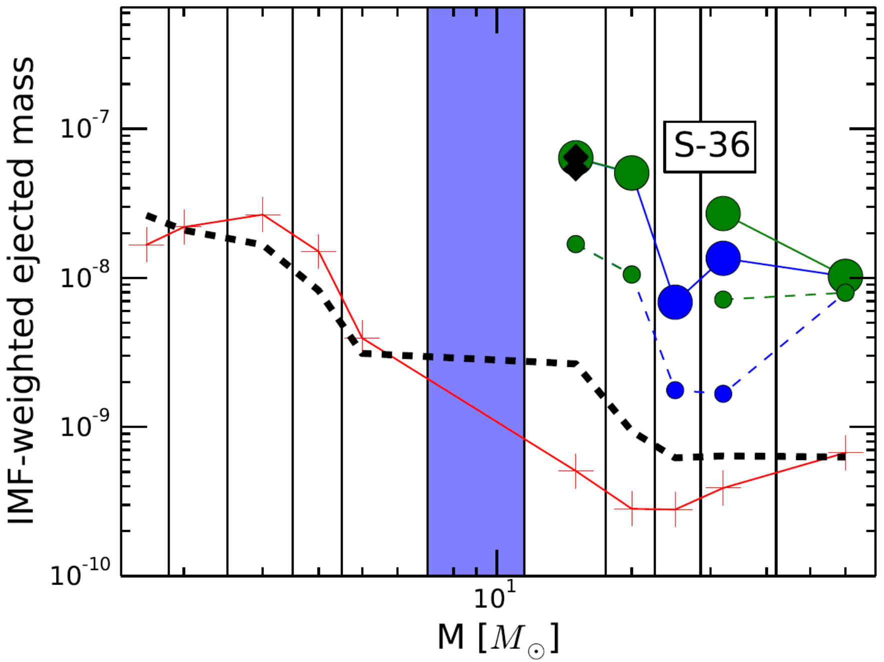
Reifarth+ 2000 ApJ 528
The $^{34}S(n,\gamma)^{35}S$ rate made life really hard for ^{36}S.

^{36}Ar 0.3365% 9 mb	^{37}Ar 34.95 d β+	^{38}Ar 0.0632% 3 mb	^{39}Ar 269.01 a 8 mb, β-
^{35}Cl 75.77% 10 mb	^{36}Cl 301.01 ka 12 mb, β-	^{37}Cl 24.23% 2.15 mb	^{38}Cl 37.24 m β-
^{34}S 4.21% 0.226 mb	^{35}S 87.51 d β-	^{36}S 0.02% 0.171 mb	^{37}S 5.05 m β-

Preliminary: No statistics yet!

Pignatari+ 2016, ApJS 225





S32/S36 ≈ S/S36 ≈ S/C

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

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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**

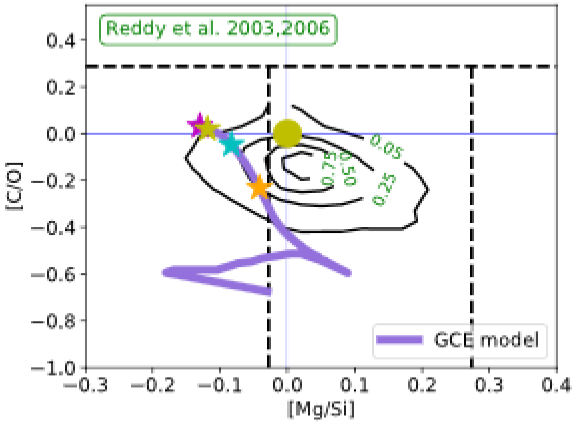
Experimental Astronomy (2022) 53:225–278
https://doi.org/10.1007/s10686-021-09754-4

ORIGINAL ARTICLE

Exploring the link between star and planet formation with Ariel

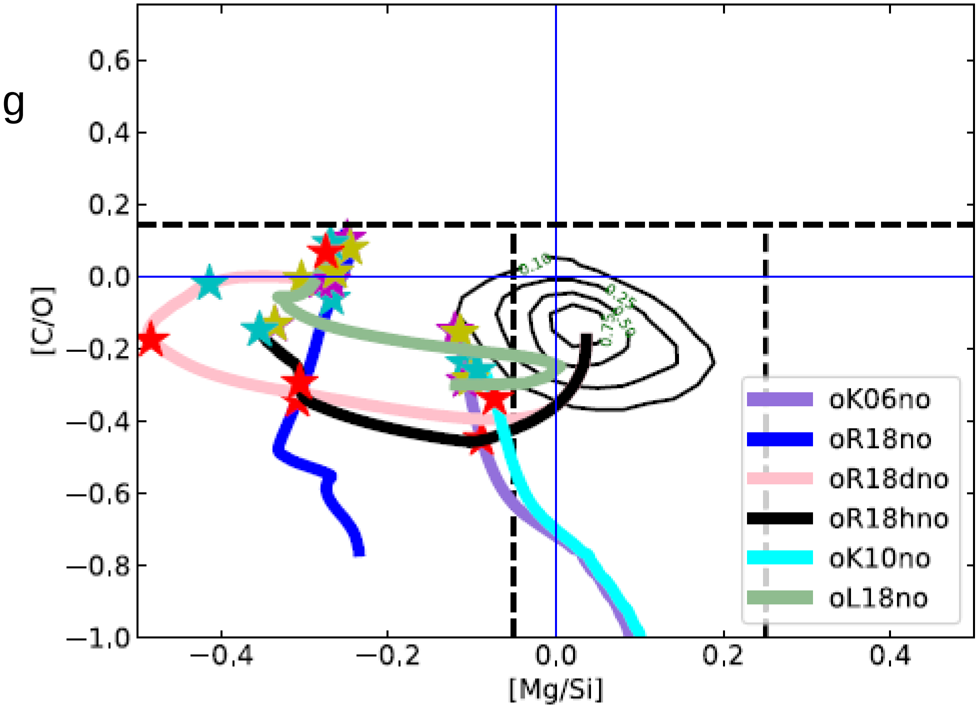
Diego Turrini[1,2] · Claudio Codella[3] · Camilla Danielski[4] · Davide Fedele[2,3] · Sergio Fonte[1] · Antonio Garufi[3] · Mario Giuseppe Guarcello[5] · Ravit Helled[6] · Masahiro Ikoma[7] · Mihkel Kama[8,9] · Tadahiro Kimura[7] · J. M. Diederik Kruijssen[10] · Jesus Maldonado[5] · Yamila Miguel[11,12] · 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 4 sets
- by using 2 other sets we get closer to the solar [Mg/Si], but none of them show enough Mg

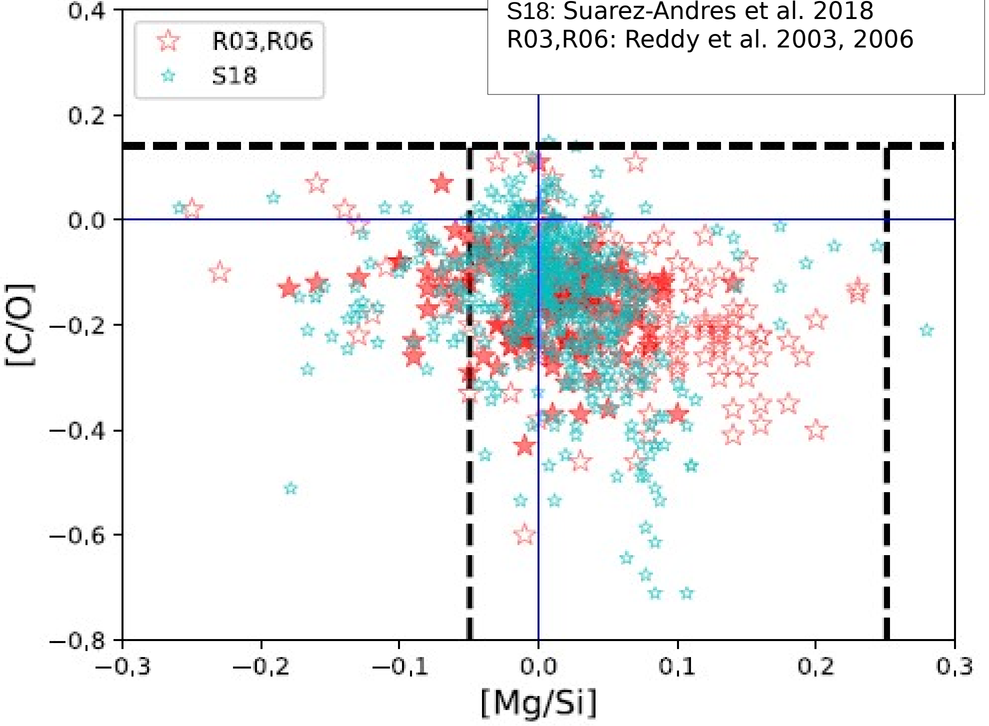


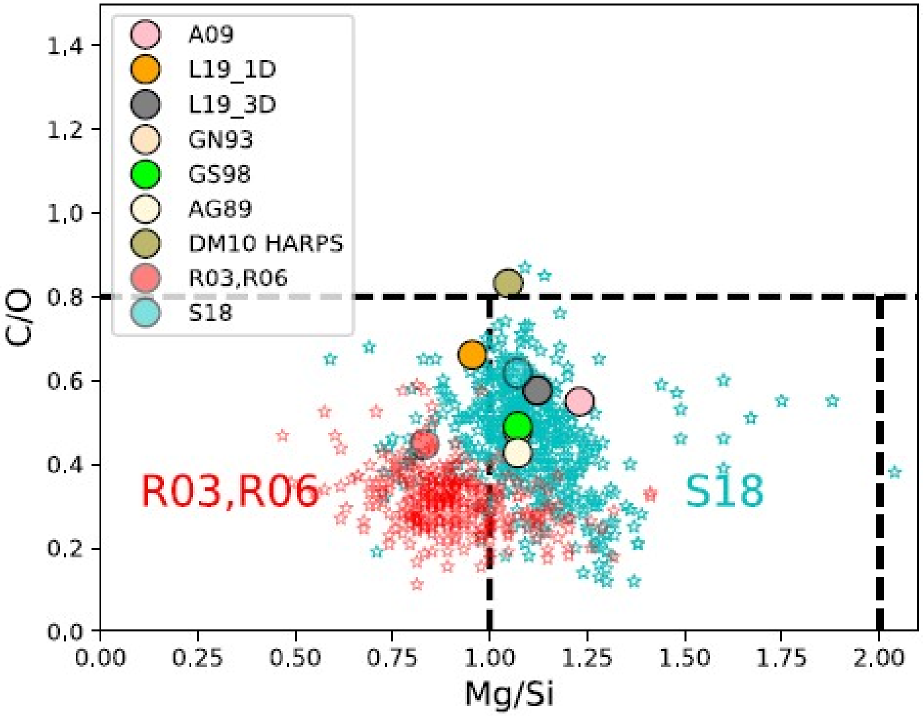
Mg puzzle!

Old problem, identified first from using WW95 CCSNe yields (e.g., Gibson+ 1997 MNRAS 290 and several works following)

The zoo of solar normalizations

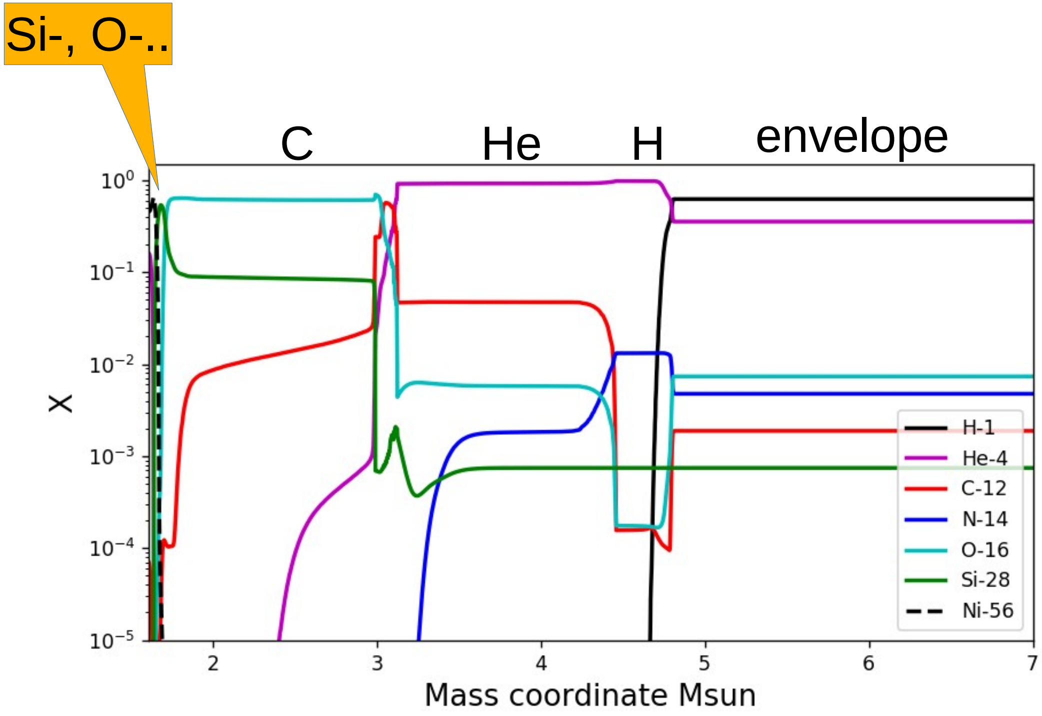
S18: Suarez-Andres et al. 2018
R03,R06: Reddy et al. 2003, 2006





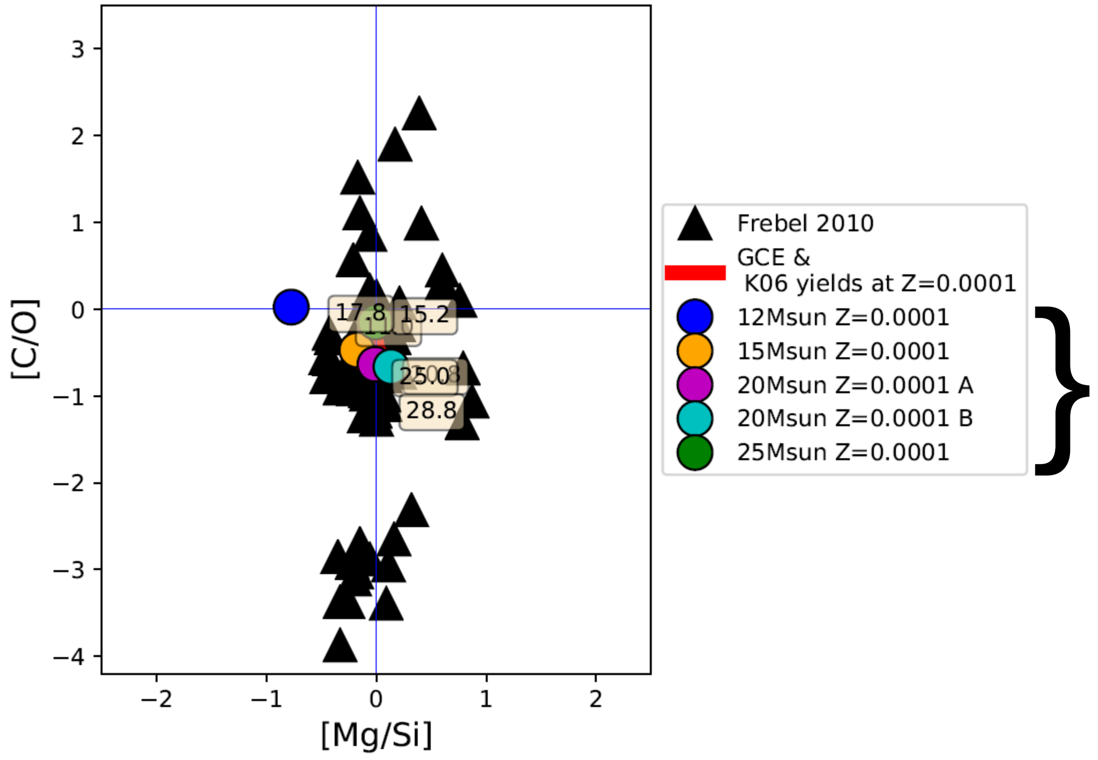
Nuclear astrophysics point of view: it should not be that difficult..

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

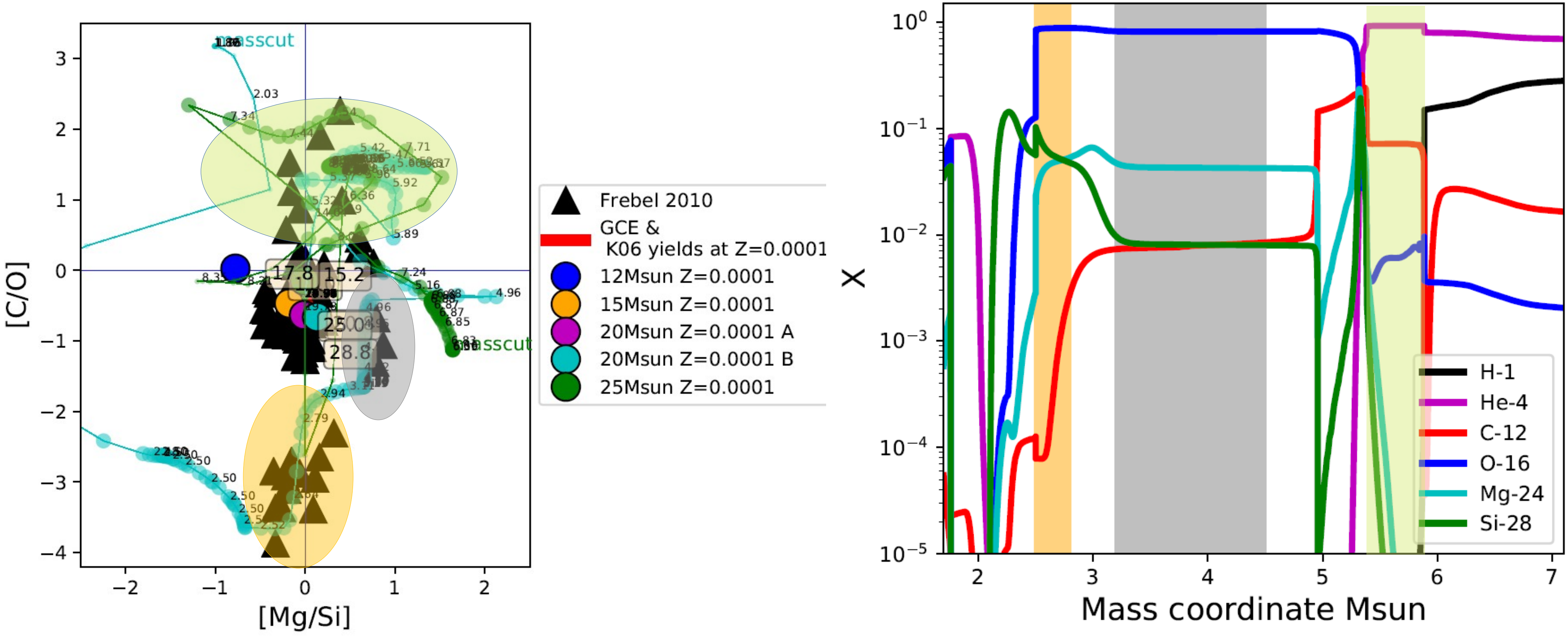


M=15Msun, Z=0.02
Ritter+2018 MNRAS 480
MESA progenitor
Fryer+12 explosion

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



1D CCSN integrated yields Ritter+ 2018



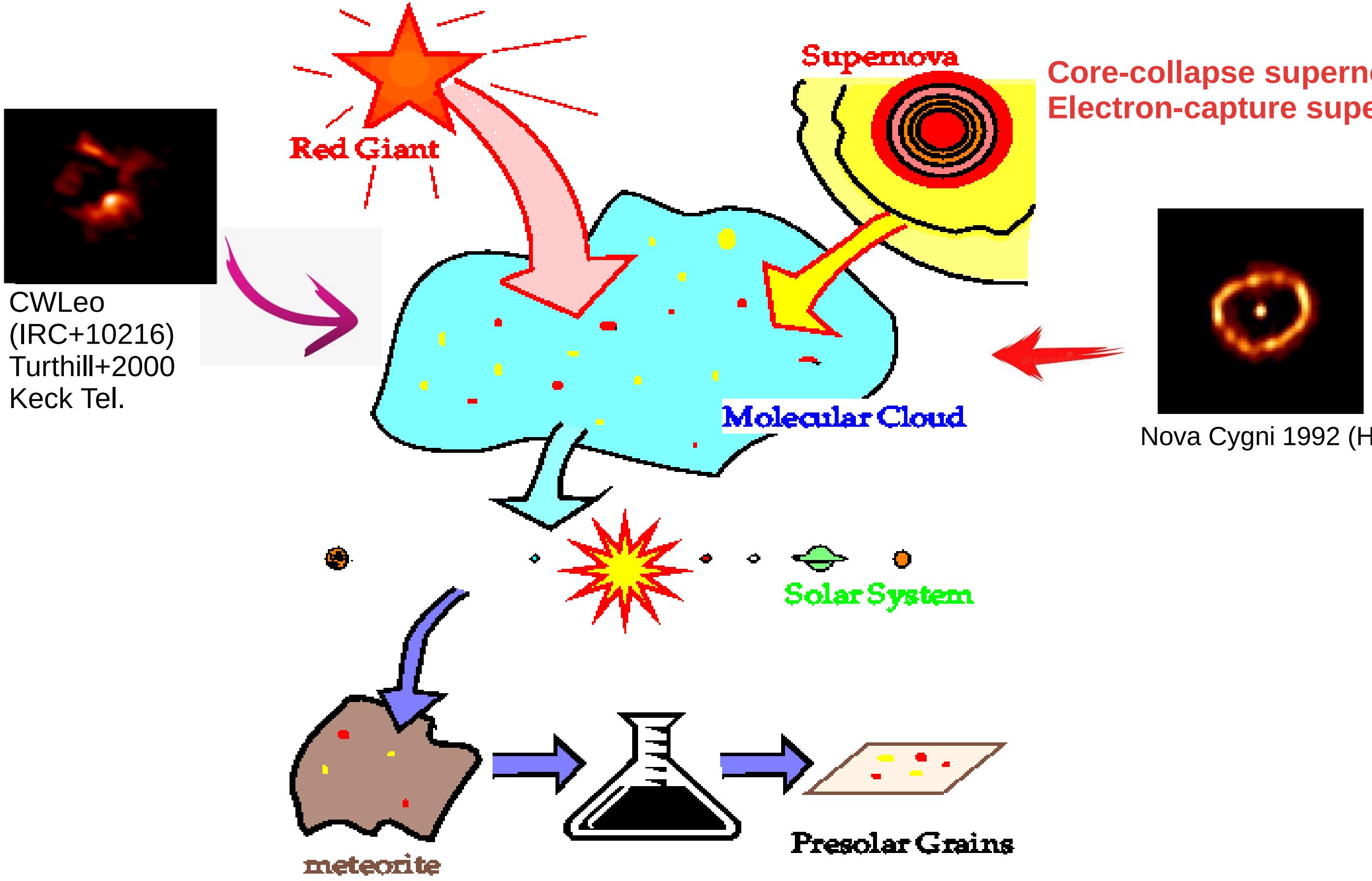
Work in progress: comparison with stellar archaeology data - Pignatari+ in prep.

The presolar grain journey from stars to us

AGB stars
Post-AGB stars
...

Core-collapse supernovae
Electron-capture supernovae (?)

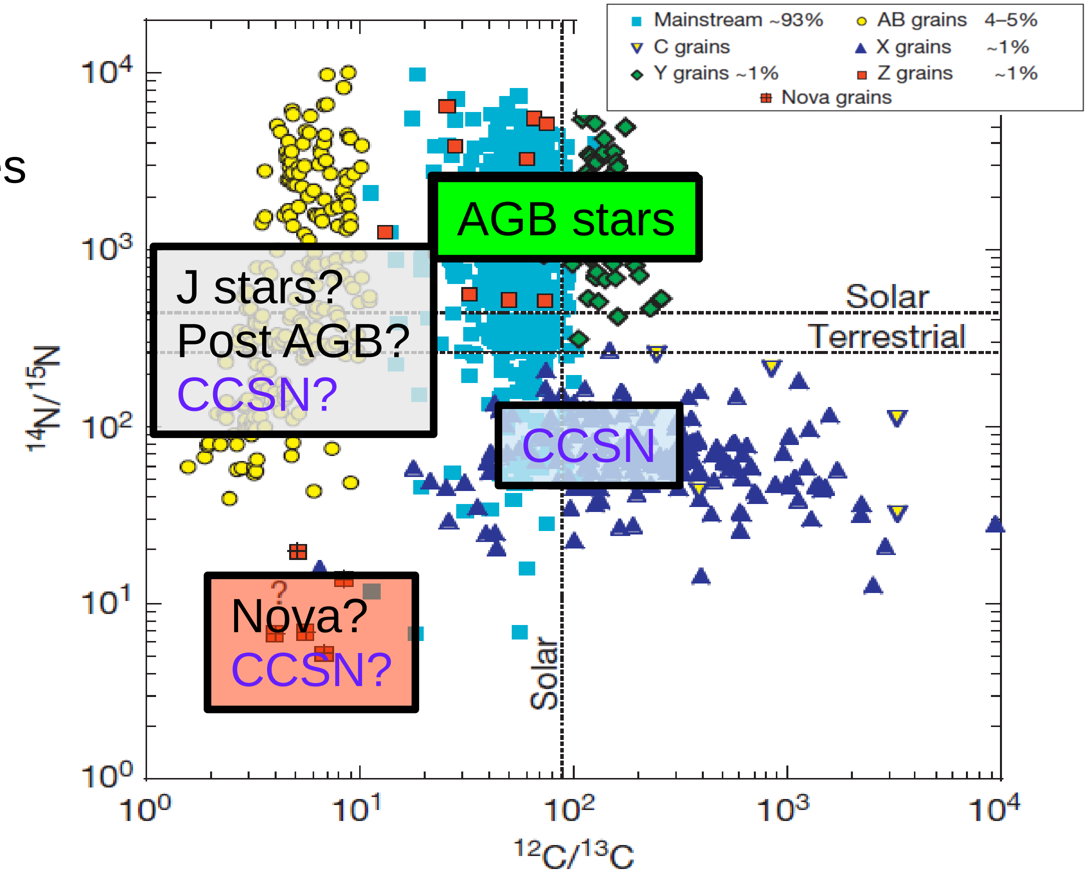
Novae



L. Nittler

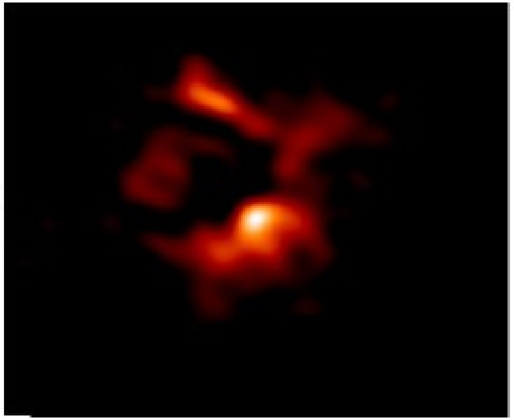
Working with presolar grains

- 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)



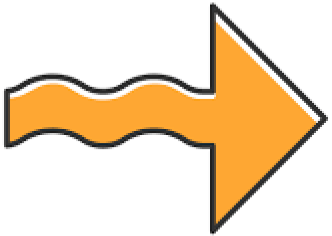
Zinner 2014, Treat. Geochem 1.4
https://presolar.physics.wustl.edu/presolar-grain-database/

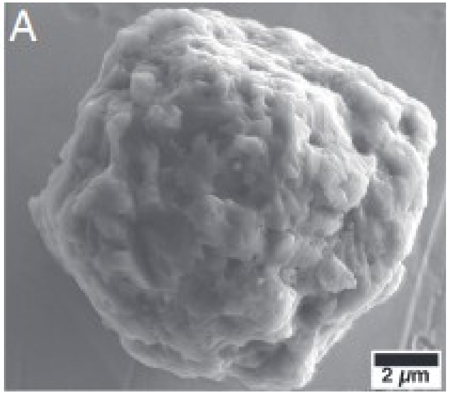
Time GCE window provided by grains



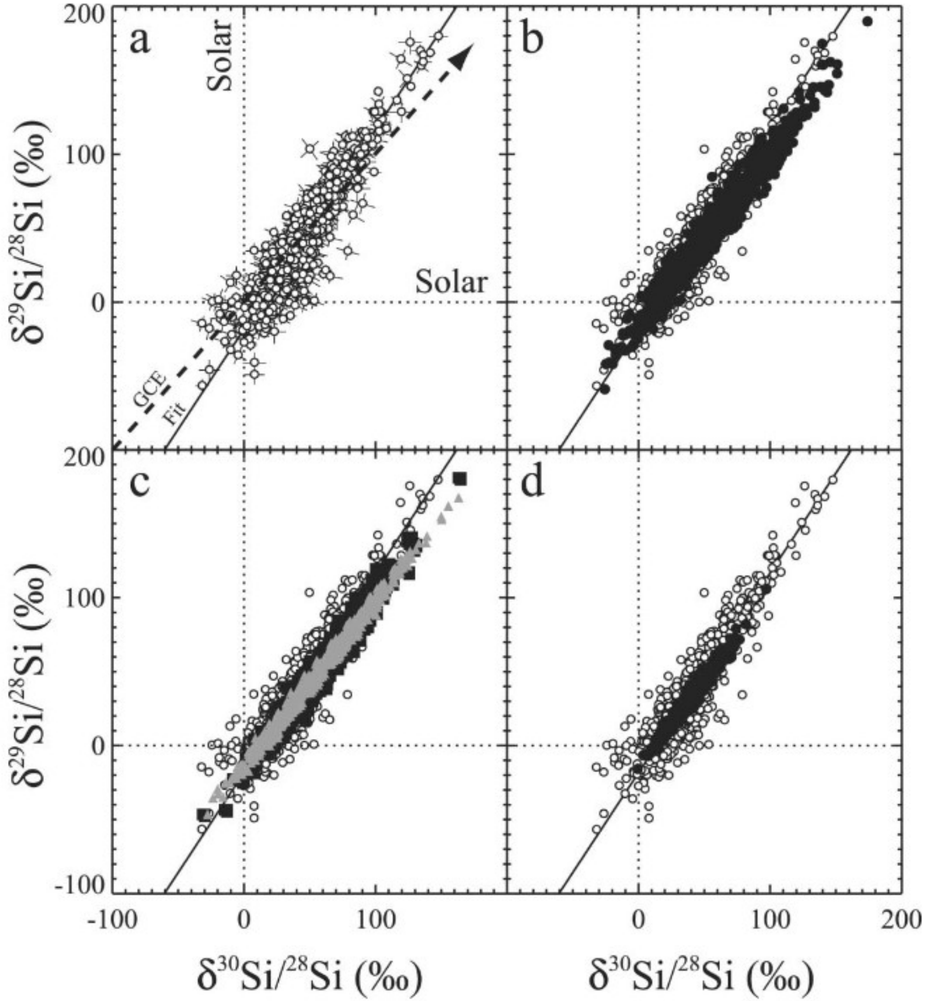
3 Gyr > τ > 0.5 Gyr

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

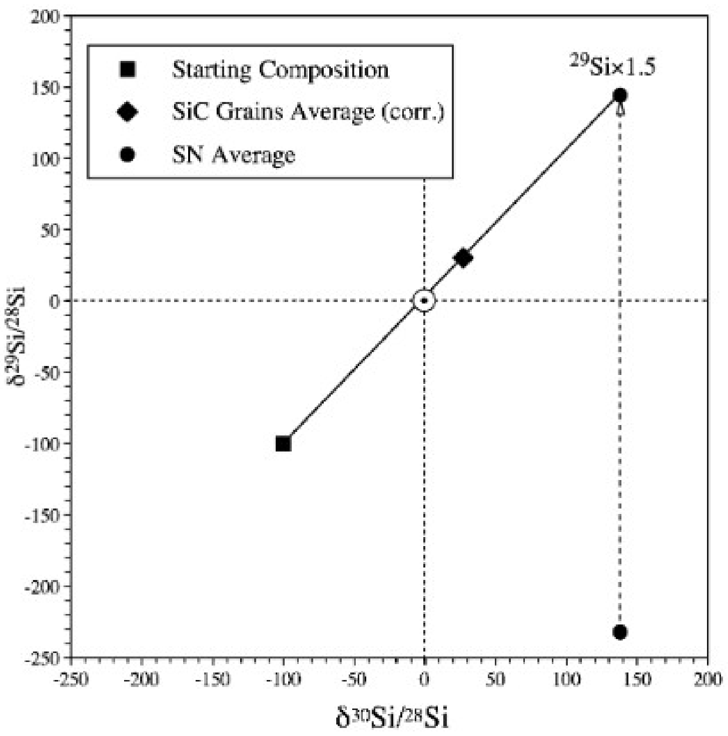




ESS



Nittler+ 2005 ApJ 618



Lugaro+ 1999 ApJ 527

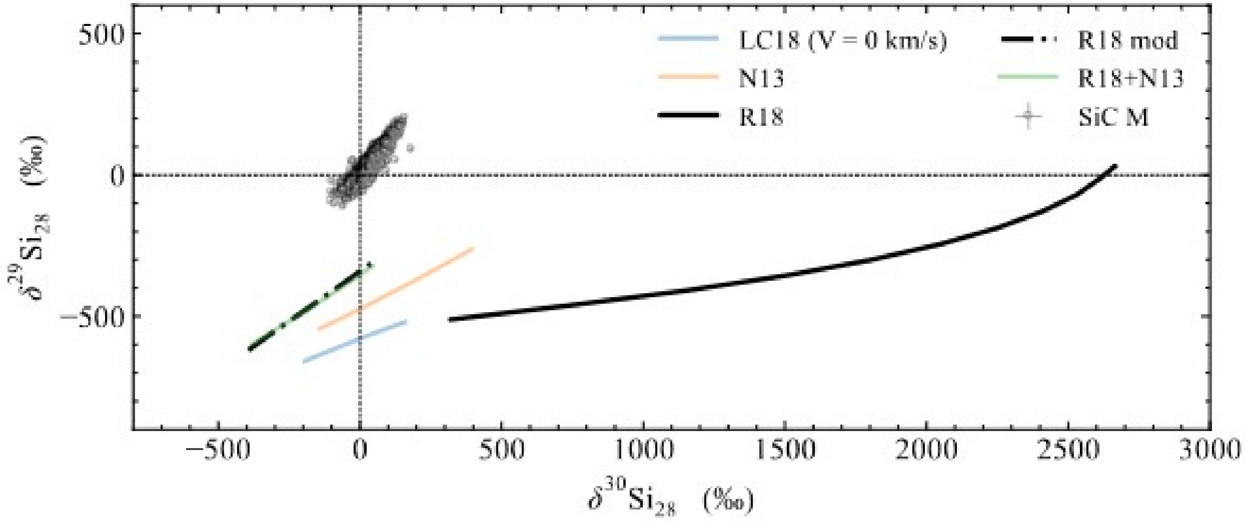
Scenarios to explain the Si isotopic ratios measured:

- 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, ApJL accepted

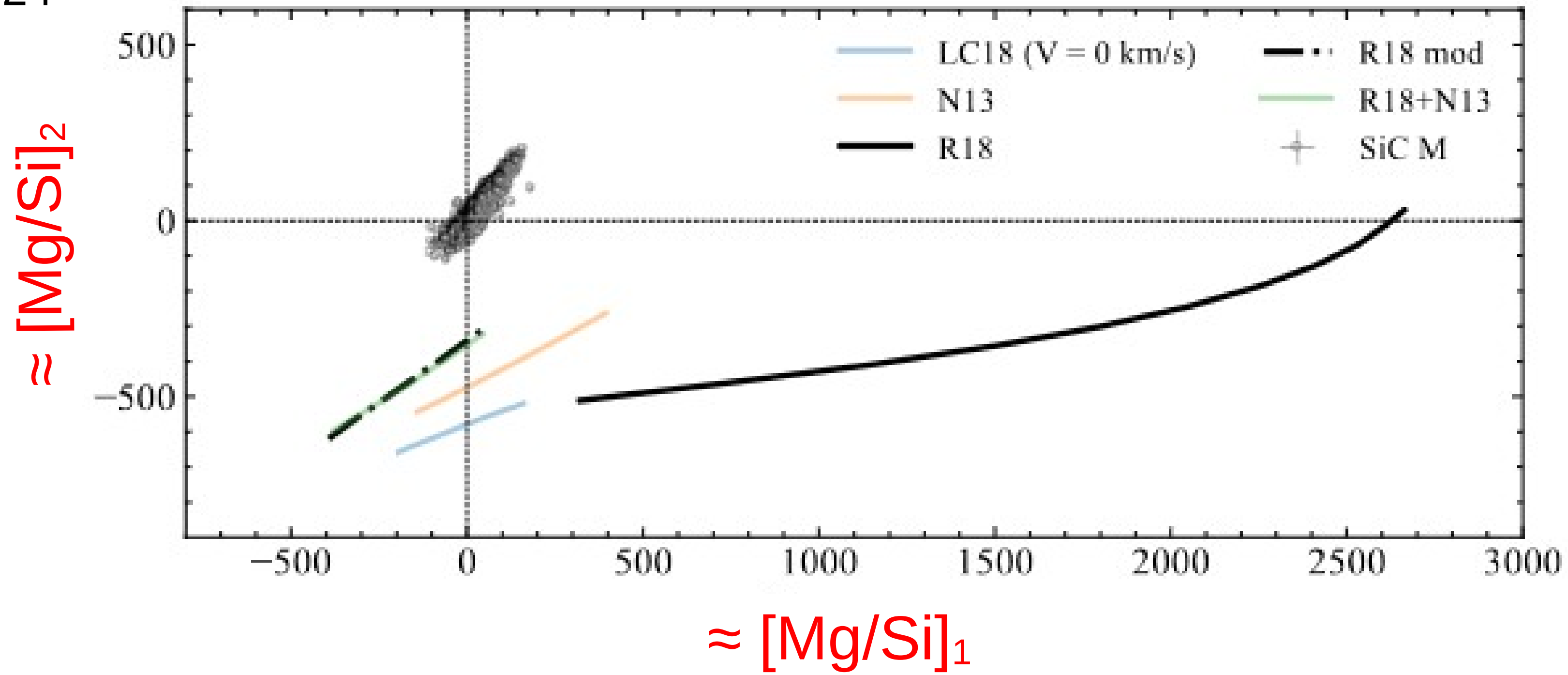
Results affected by nuclear uncertainties, among others by the $^{30}Si(n,\gamma)^{31}Si$ rate

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


LC18 (V = 0 km/s)
N13
R18
R18 mod
R18+N13
SiC M
500
0
−500
−500
0
500
1000
1500
2000
2500
3000
≈ [Mg/Si]2
≈ [Mg/Si]1

GCE of radioactive heat-source isotopes

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ROYAL ASTRONOMICAL SOCIETY
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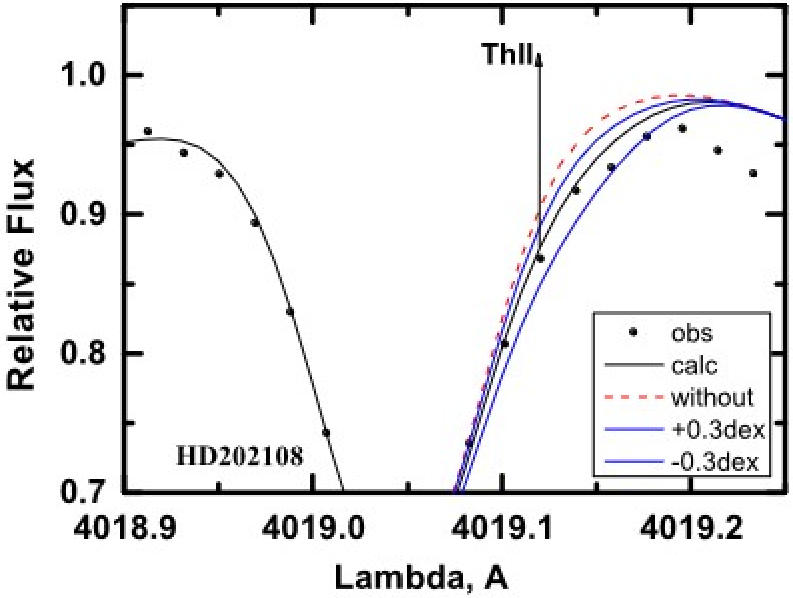
Advance Access publication 2022 August 25
https://doi.org/10.1093/mnras/stac2361

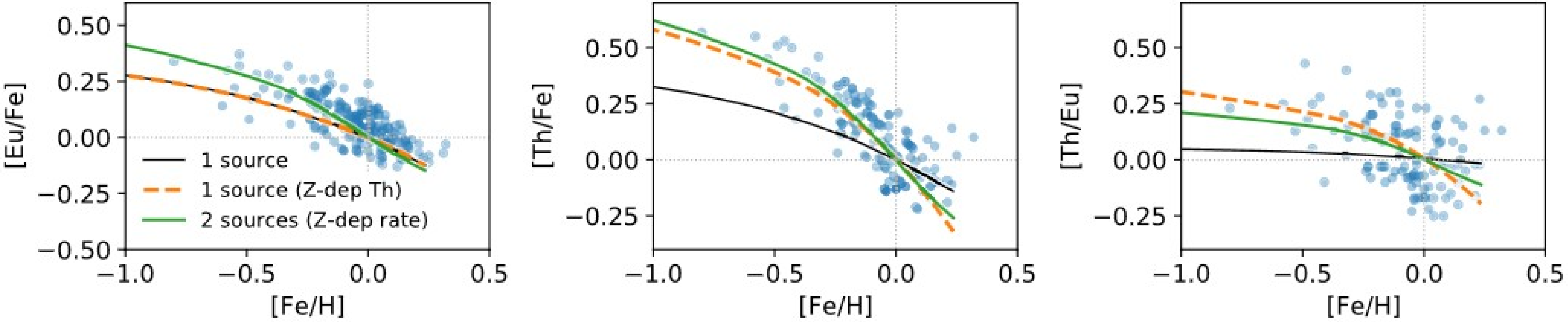
Enrichment of the Galactic disc with neutron-capture elements: Gd, Dy, and Th

T. Mishenina,[1★] M. Pignatari,[2,3,4,5★†] T. Gorbaneva,[1] B. Côté,[2,5,6†] A. Yagüe López,[2,7†]
F.-K. Thielemann[8,9] and C. Soubiran[10]

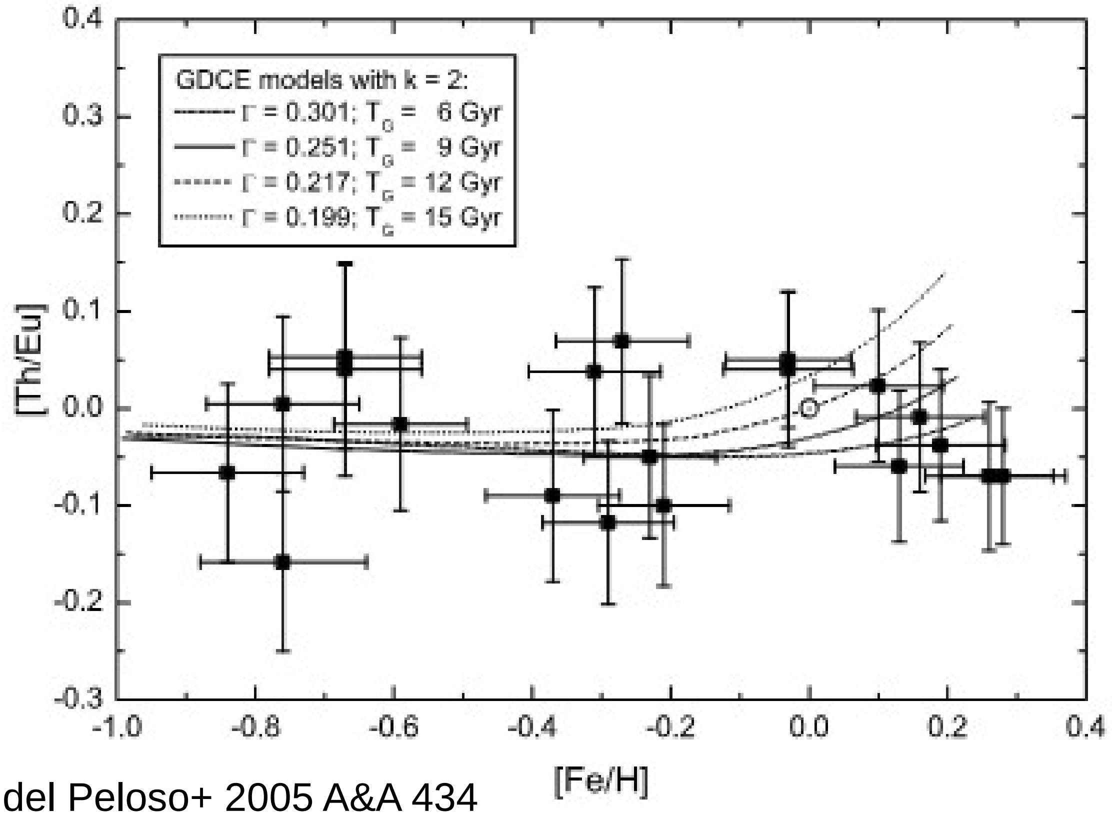
Talk by E. Delgado Mena



Blend with Co, Fe, Ni, Mn lines!



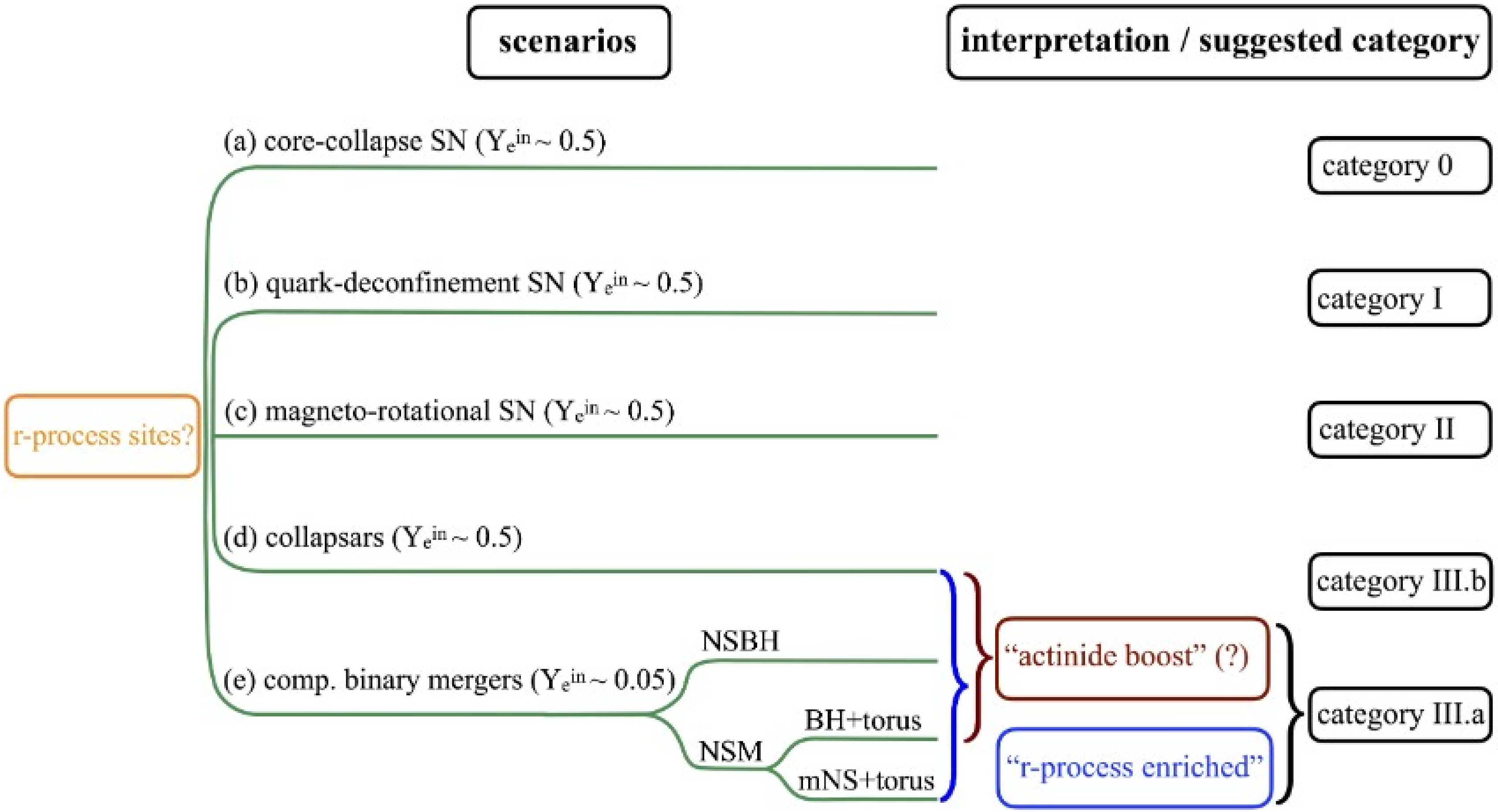
What is the [Th/Eu] trend in the MW disk?



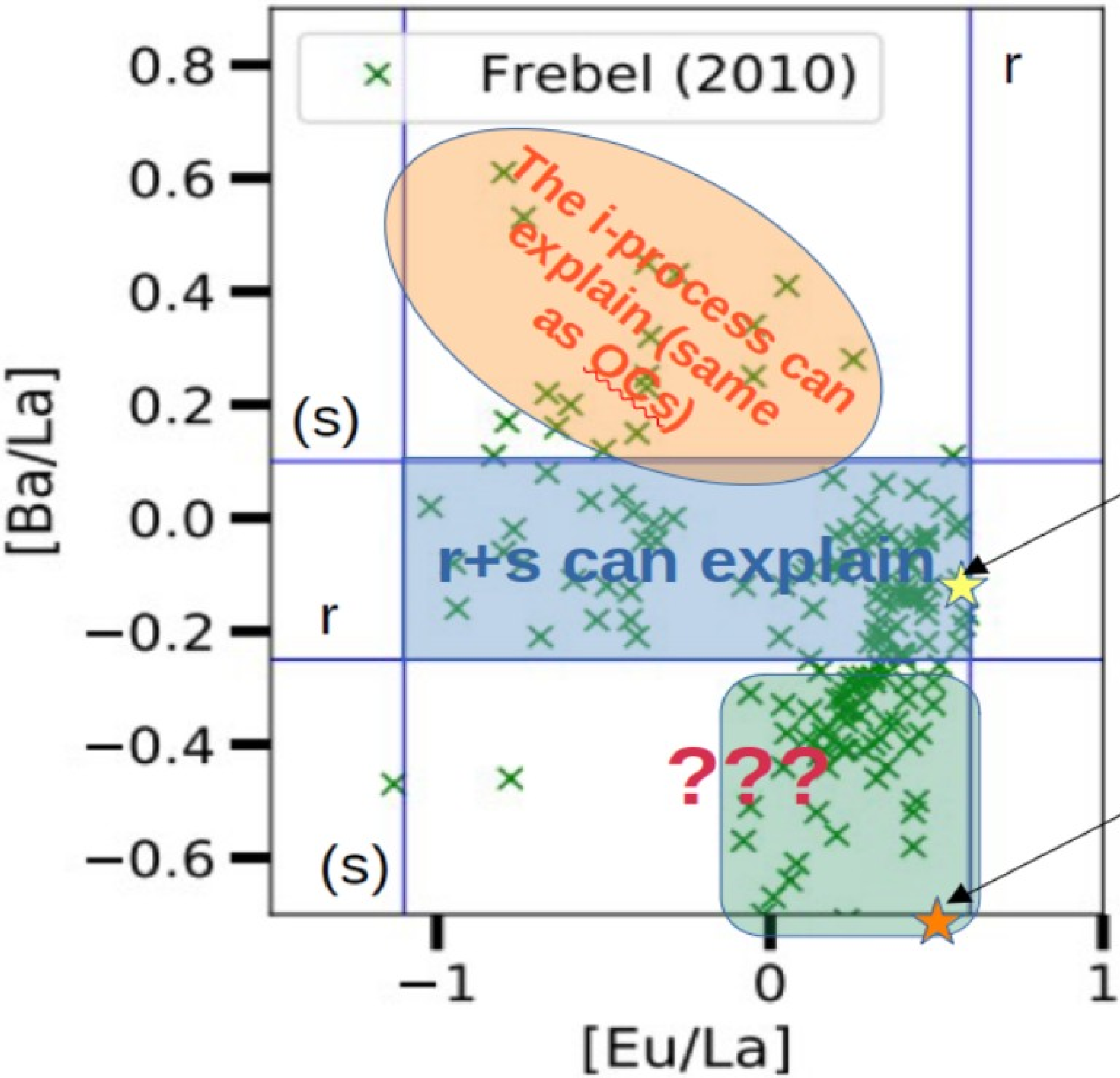
del Peloso+ 2005 A&A 434

See also Frank+ 2014 Icar 243, Unterborn+ 2015 ApJ 806, Botelho+ 2019 MNRAS 482

A&A 663, A70 (2022)



Farouqi+ 2022 A&A 663



CS 22892-052
(r-II star)

HE 1523-0901
(r-II star)

Mishenina+ 2024 A&A 687

Messages to remember

- Stellar yields are a crucial source of uncertainty for Galactic Chemical Evolution (GCE) of elements and isotopes.
- Uncertainties vs errorbars: why stellar yields are not provided with errorbars? It is really hard to provide comprehensive errors for stellar yields!
- **Integrated yields of Core-Collapse Supernovae are not safe to be used for GCE studies in the form they are usually provided. But the CCSNe models and the ejected yields are ok.**
- A good example: [Mg/Si] vs [C/O] in the solar neighbourhood & Si isotopes in presolar SiC grains.
- GCE of the radioactive heat-sources for planets: what is the Th/Eu trend in the MW disk?

ANNOUNCING:
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A <u>NEW</u> ERC Synergy project, starting in 2025 and running for 6 years!

cPI. Steve Mojzsis (CSFK, Hungary)

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Planetary geochemistry and nuclear astrophysics of exoplanets.

PI. Fabrice Gaillard (CNRS, France)

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Laboratory experiments of outgassing from planetary interiors

PI. Kevin Heng (LMU, Germany)

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