Impact of newly measured reaction rates on the nucleosynthesis of ^{26}Al in stars

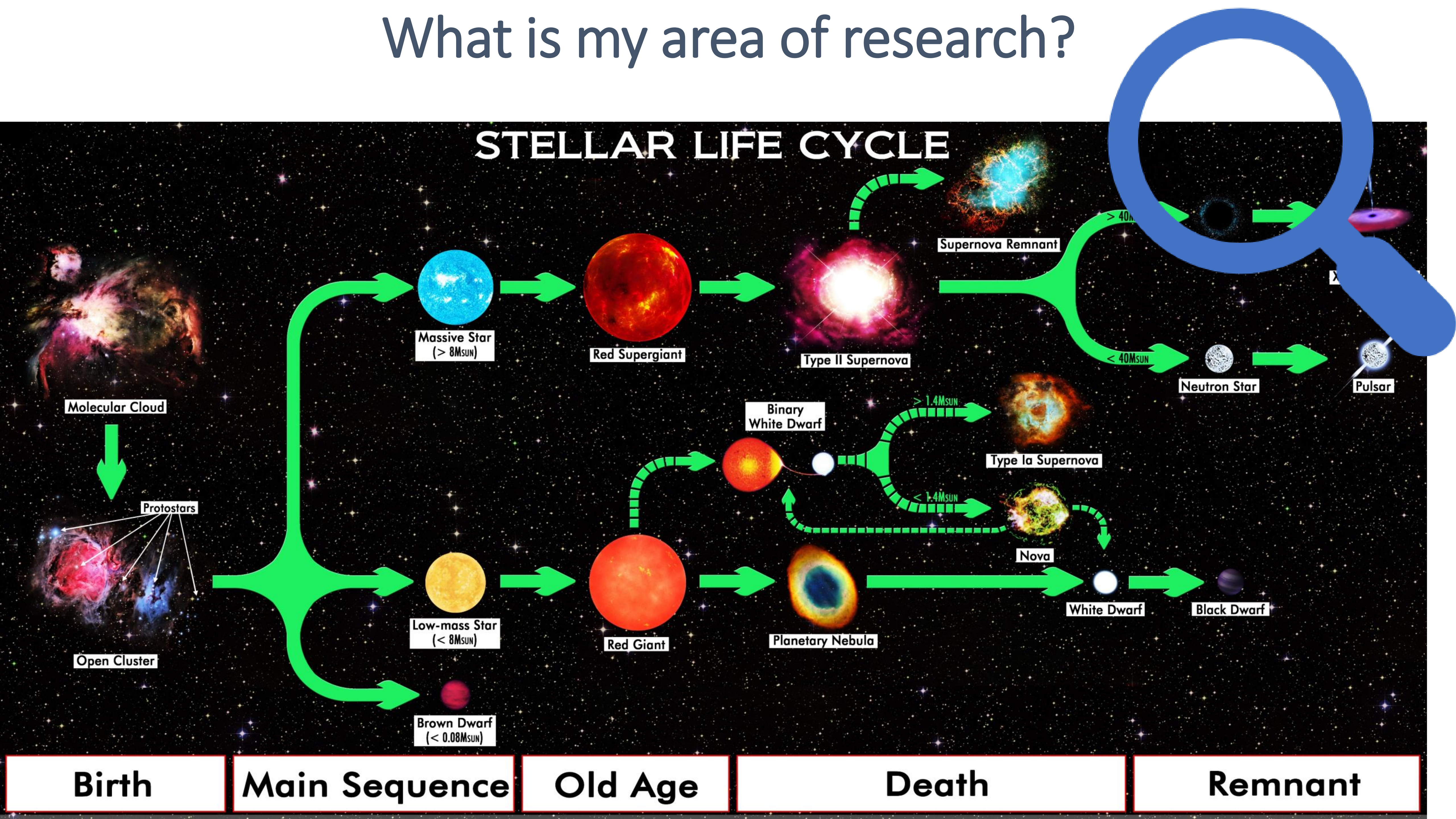
Umberto Battino, The University of Hull, NuGrid Collaboration

“Inaugural workshop on Nuclear Astrochemistry”, 29/2/2023, Trento

UNIVERSITY OF HULL

NUGRID

What is my area of research?



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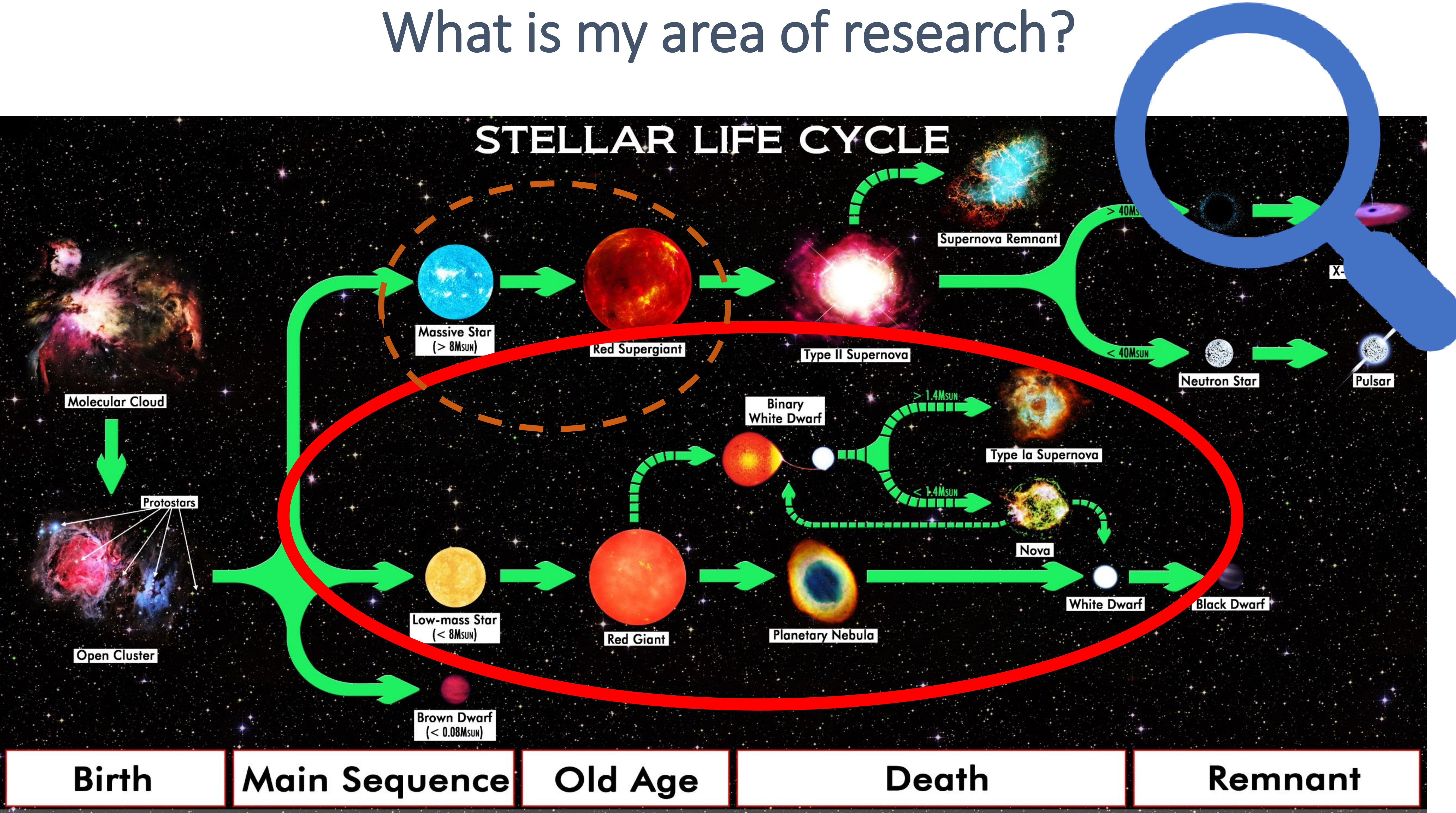
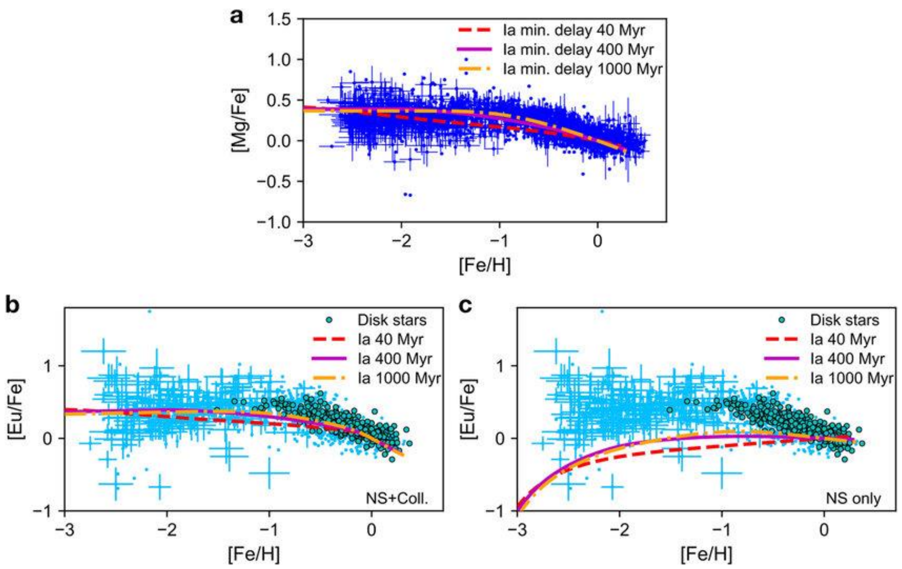
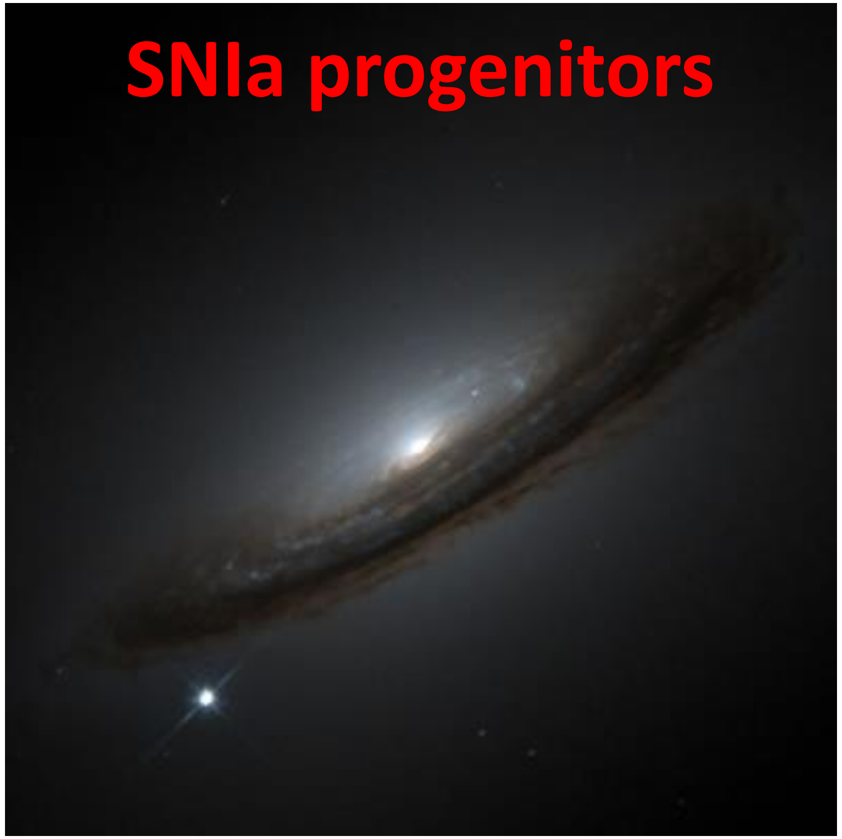


Wider relevance to the field I work in

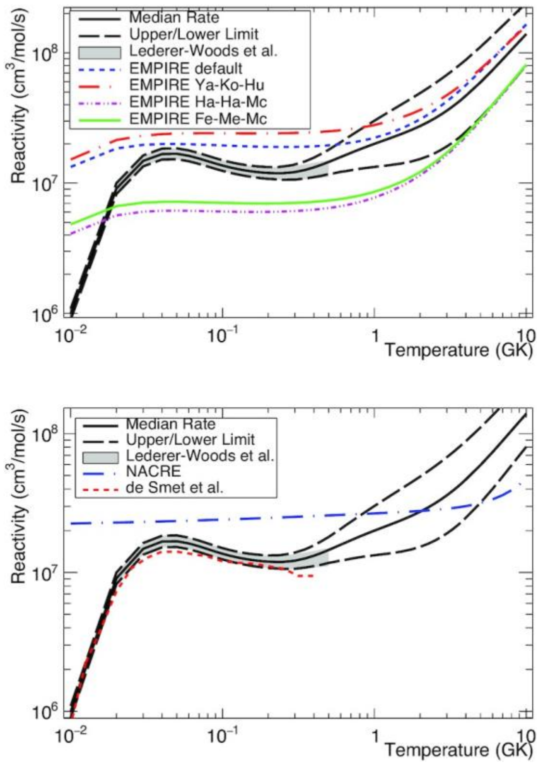
GCE



Siegel et al. *Nature* **569**, 241–244 (2019).

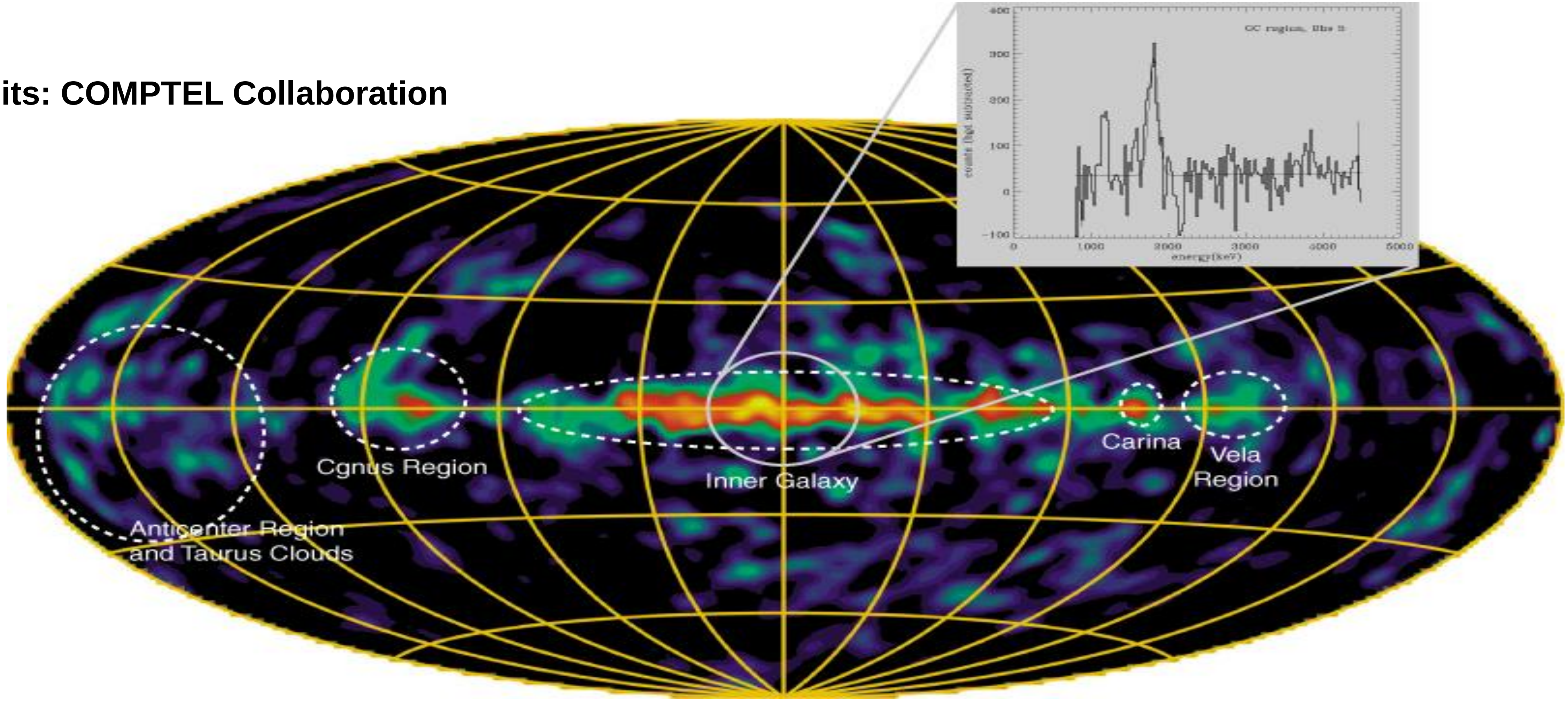


Nuclear impact/ sensitivity studies

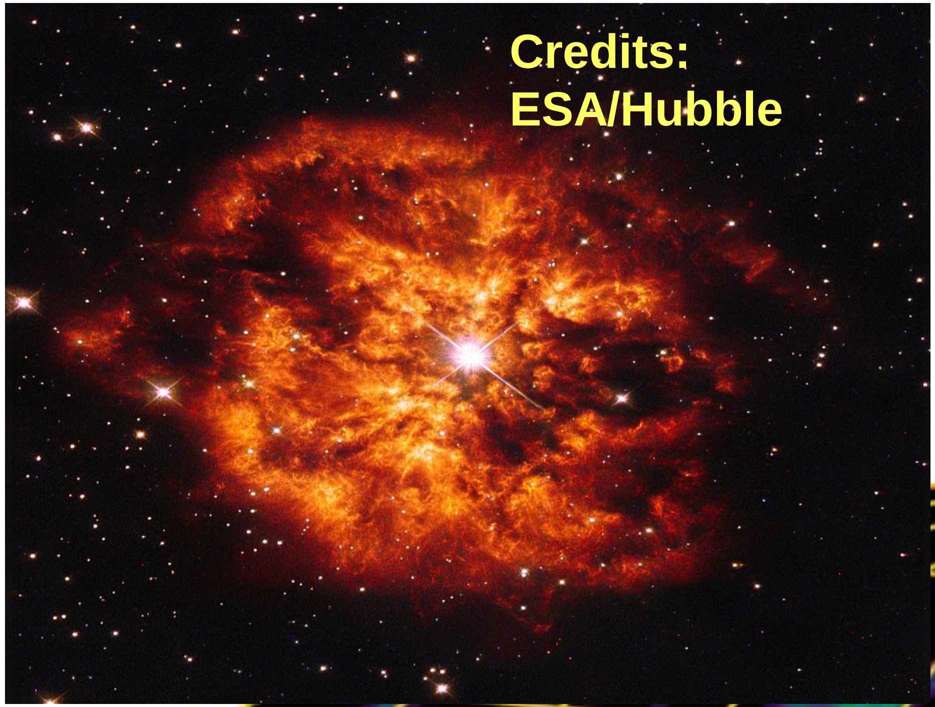


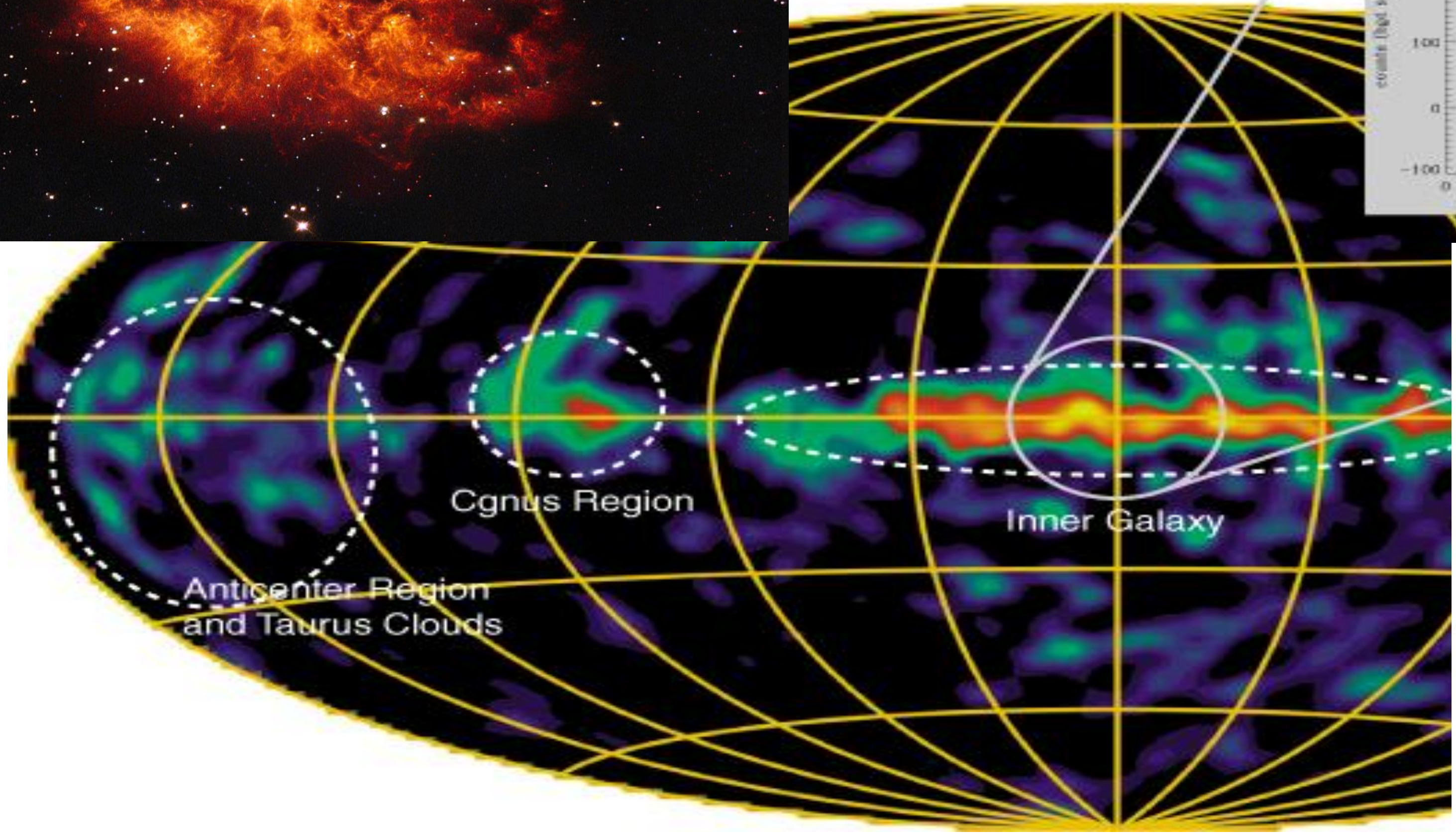
^{26}Al in the Galaxy

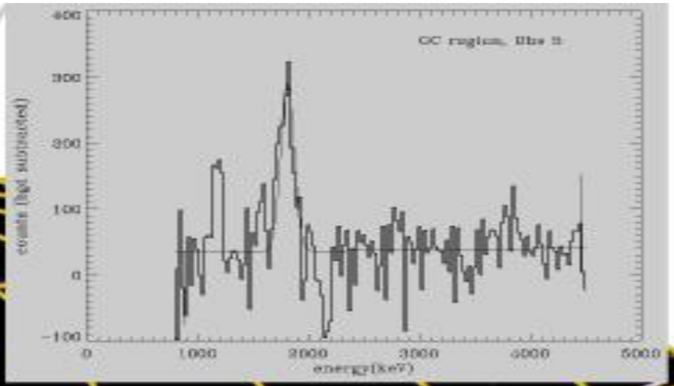
Credits: COMPTEL Collaboration

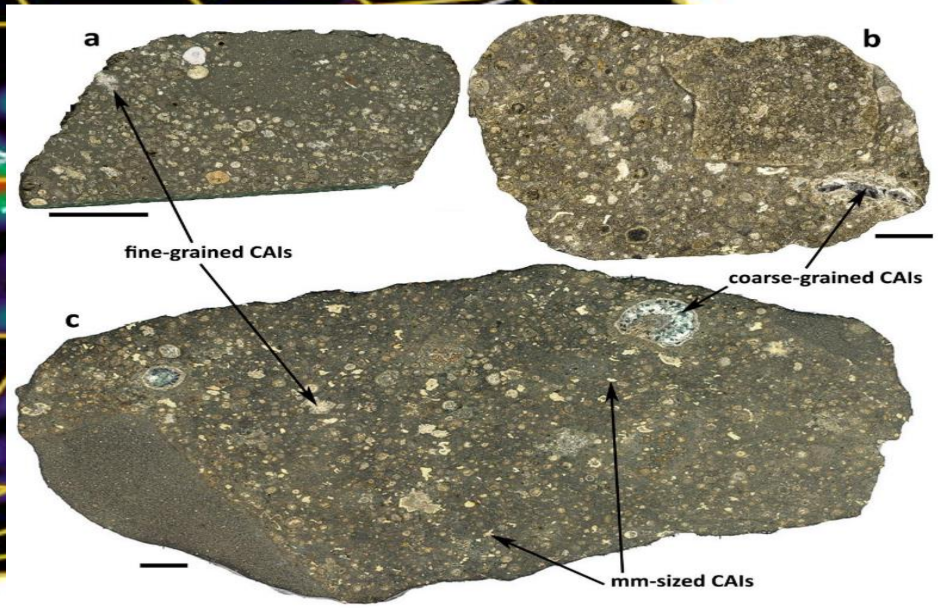


in the Galaxy









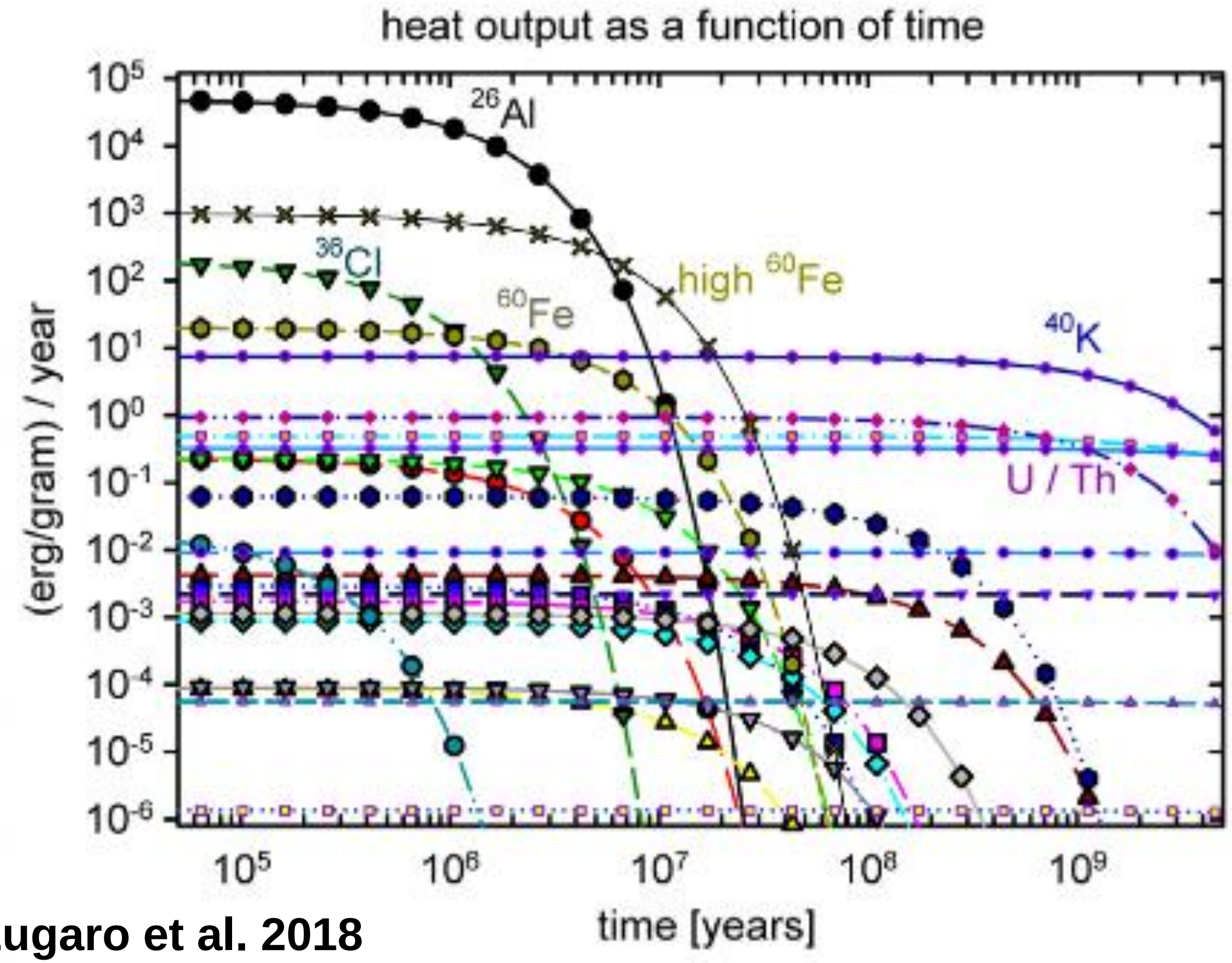
Charnoz et al. 2015

Link between ^{26}Al radioactivity and habitability

- The dominant process contributing to the very early melting of planetesimals was the decay of ^{26}Al (figure from Lugaro+ 2018).

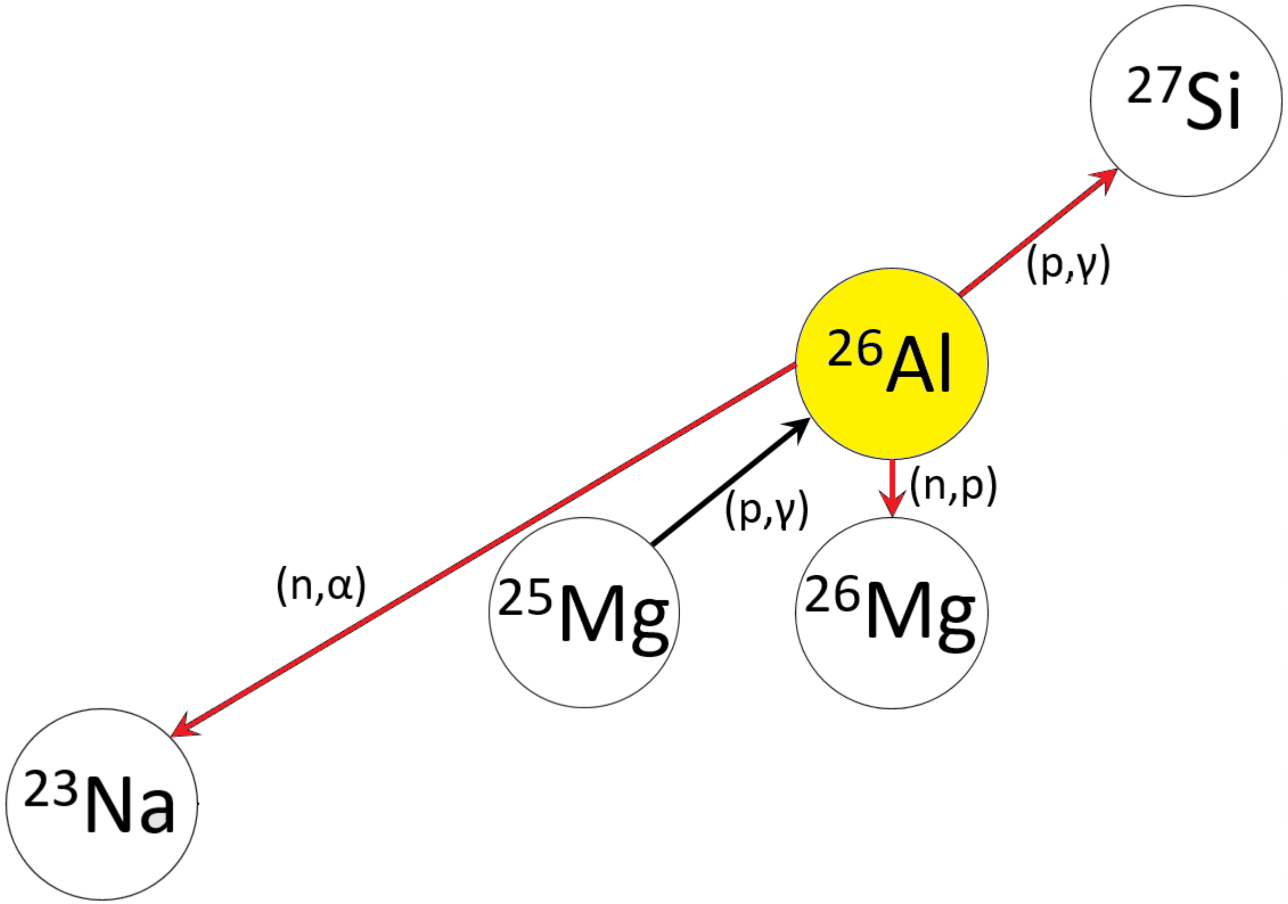
- Melt even relatively small planetesimals (Lichtenberg+ 2016), modified the mineral content, melted ice to liquid water producing a variety of molecules (Monteux+ 2017).

- Key heat source in the early solar-system and central role in the thermal evolution of young planetary bodies in the Solar System.



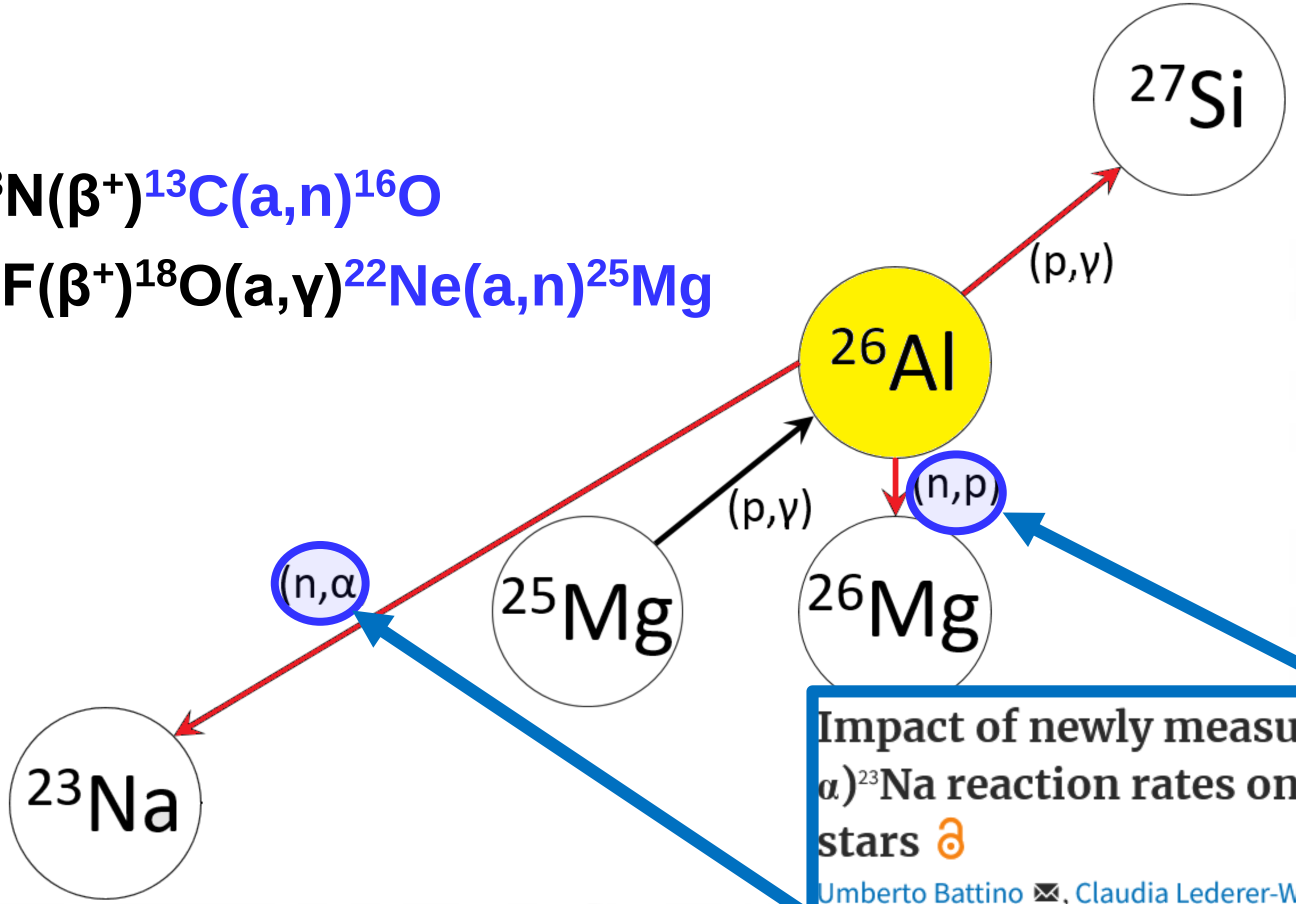
Lugaro et al. 2018

Main production/destruction nuclear reaction



Main production/destruction nuclear reaction

- $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(a,n)^{16}O$
- $^{14}N(a,\gamma)^{18}F(\beta^+)^{18}O(a,\gamma)^{22}Ne(a,n)^{25}Mg$



Impact of newly measured $^{26}Al(n,p)^{26}Mg$ and $^{26}Al(n,\alpha)^{23}Na$ reaction rates on the nucleosynthesis of ^{26}Al in stars

Umberto Battino, Claudia Lederer-Woods, Marco Pignatari, Benjámin Soós, Maria Lugaro, Diego Vescovi, Sergio Cristallo, Philip J Woods, Amanda Karakas

Monthly Notices of the Royal Astronomical Society, Volume 520, Issue 2, April 2023, Pages 2436–2444, https://doi.org/10.1093/mnras/stad106

Published: 12 January 2023 **Article history ▾**

TOPICAL REVIEW • OPEN ACCESS

Progress on nuclear reaction rates affecting the stellar production of ^{26}Al

A M Laird[29,1], M Lugaro[2,3,4], A Kankainen[5], P Adsley[6,7], D W Bardayan[8], H E Brinkman[2,9], B Côté[2,3,10,11], C M Deibel[12], R Diehl[13], F Hammache[14] + Show full author list

Published 28 February 2023 • © 2023 The Author(s). Published by IOP Publishing Ltd
Journal of Physics G: Nuclear and Particle Physics, Volume 50, Number 3
Citation A M Laird *et al* 2023 *J. Phys. G: Nucl. Part. Phys.* **50** 033002
DOI 10.1088/1361-6471/ac9cf8

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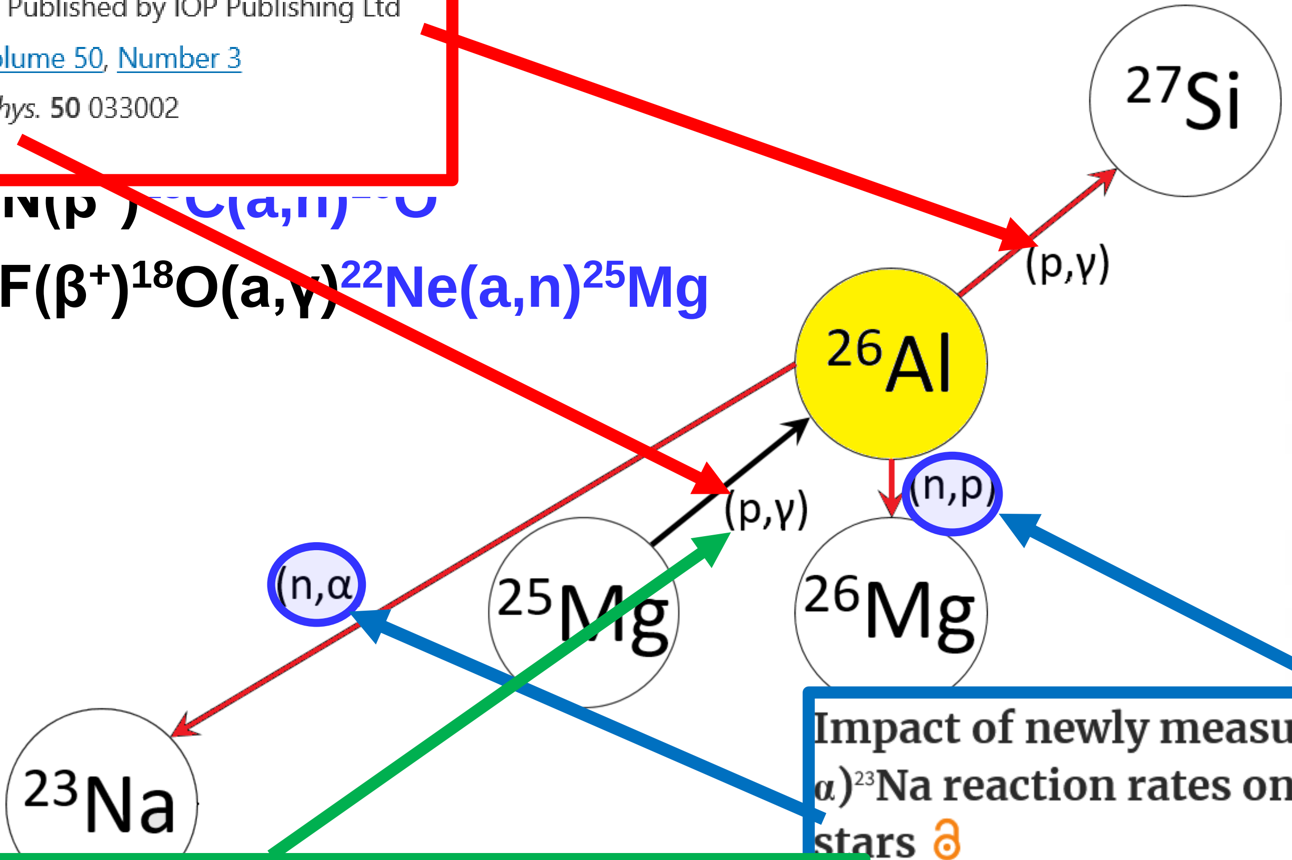

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Updated reaction rate of ^{25}Mg(p,γ)^{26}Al and its astrophysical implication

H. Zhang *et al.*

Phys. Rev. C **107**, 065801 – Published 5 June 2023

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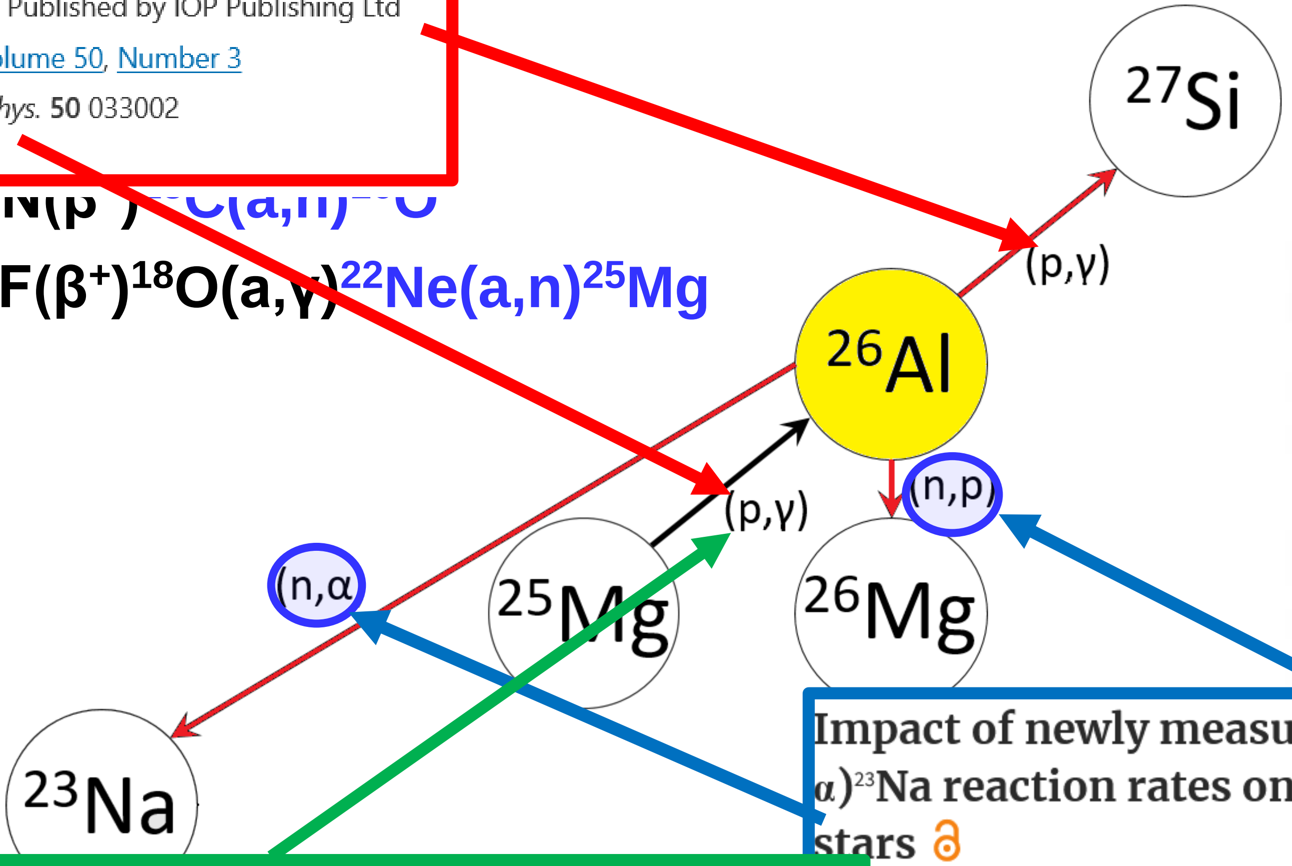
...ion nuclear reaction

- ...C(p,γ)...N(β...)...C(a,n)...O
- ^{14}N(a,γ)^{18}F(β$^+$)^{18}O(a,γ)^{22}Ne(a,n)^{25}Mg



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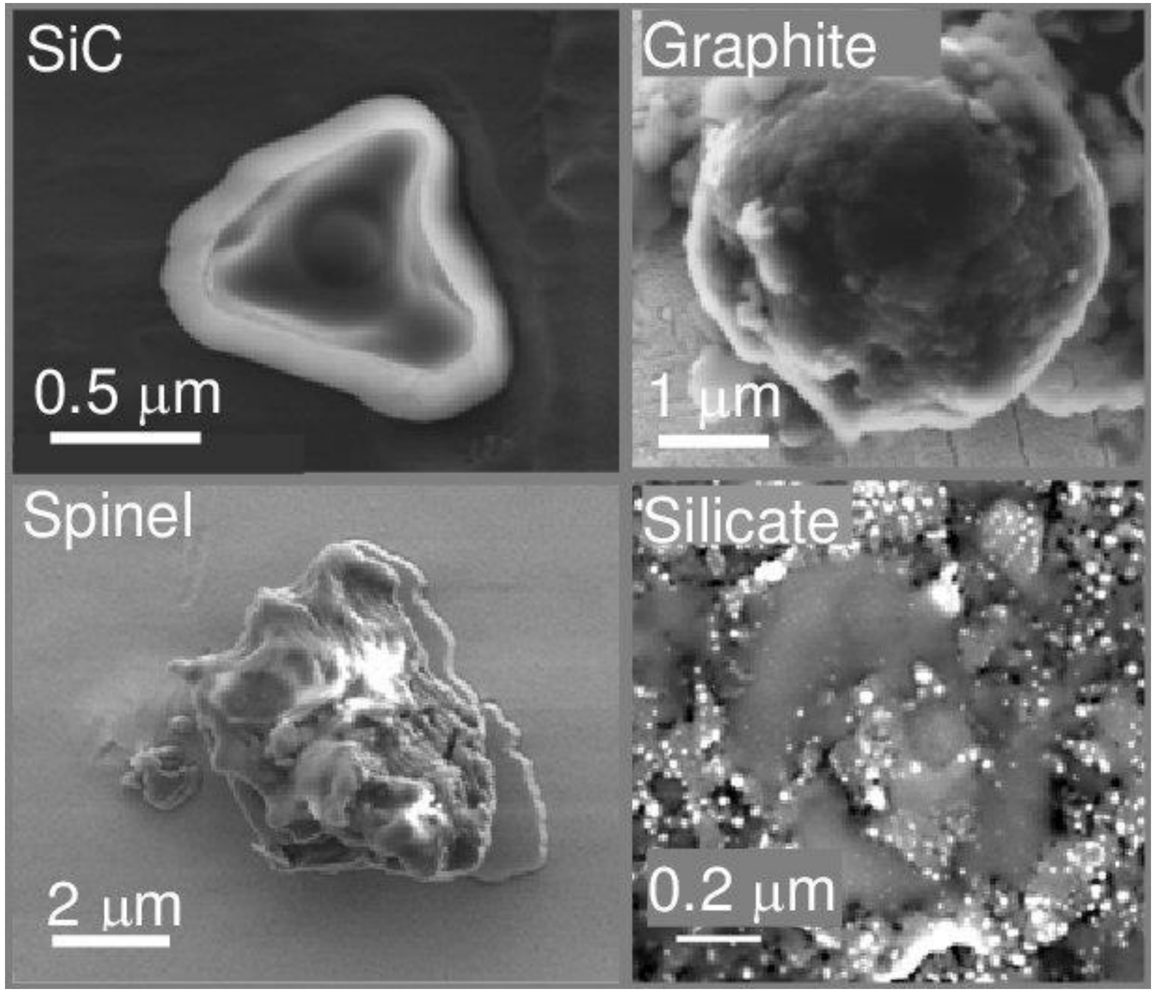
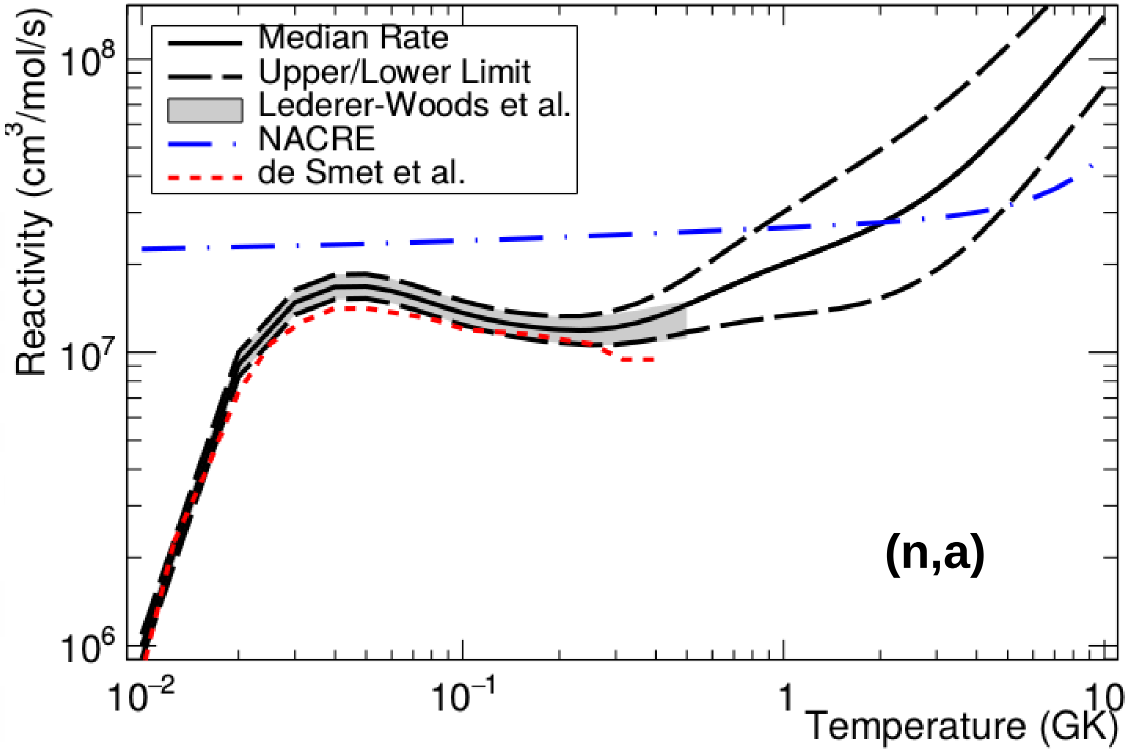
Astrophysical impact

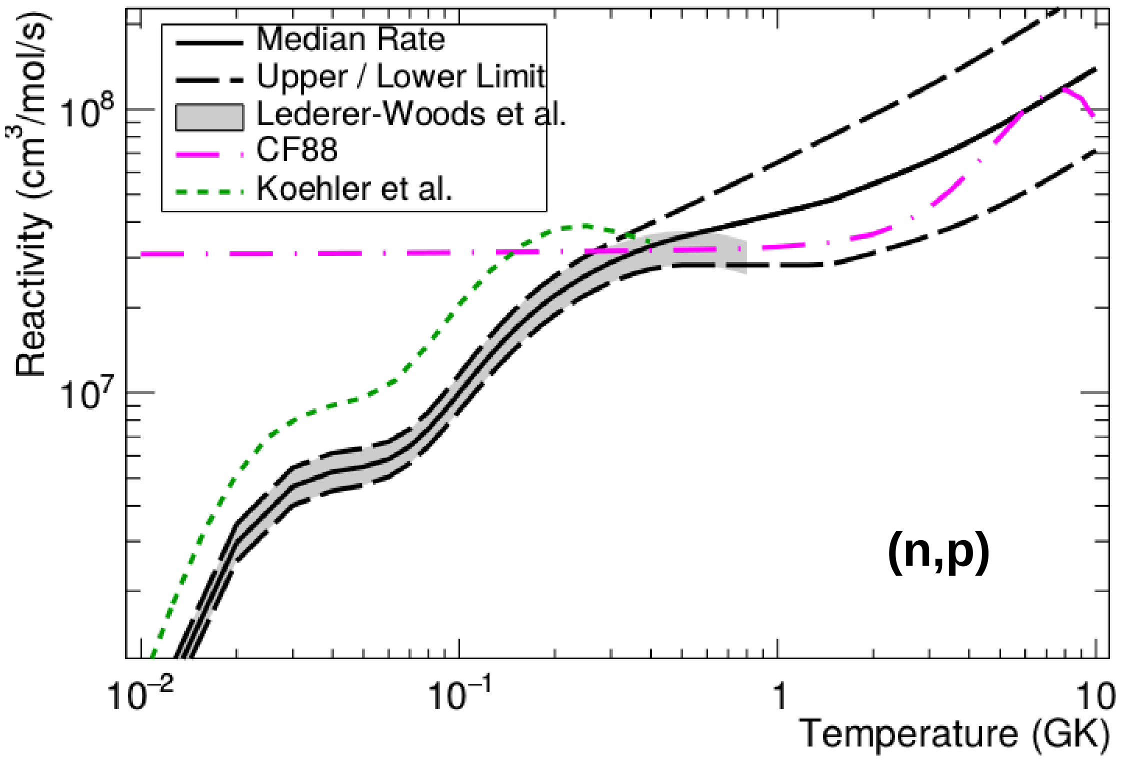
Massive stars



Presolar grains from AGB stars

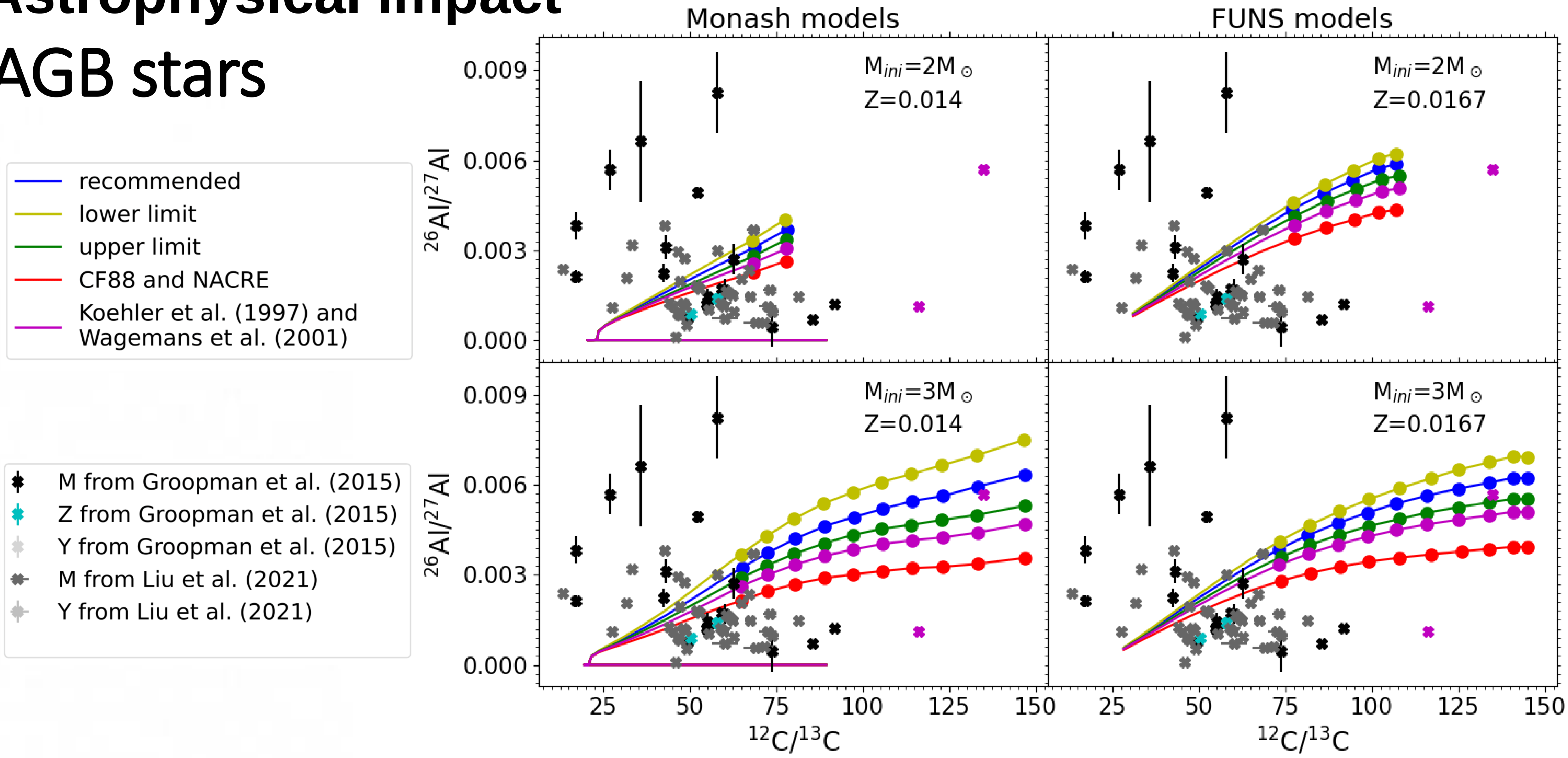
^{26}Al(n,a/n,p): New measurements at CERN (n_TOF)



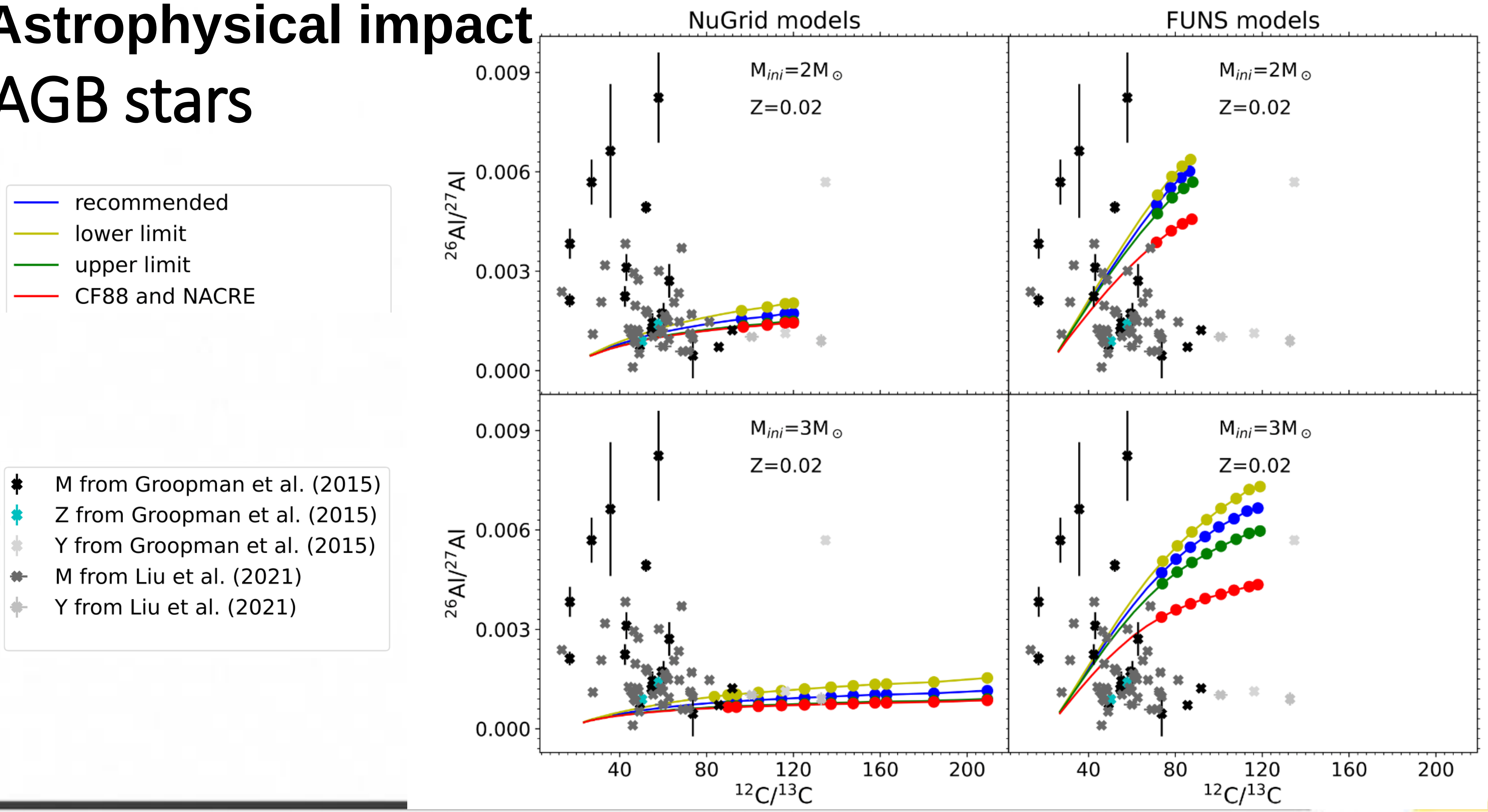


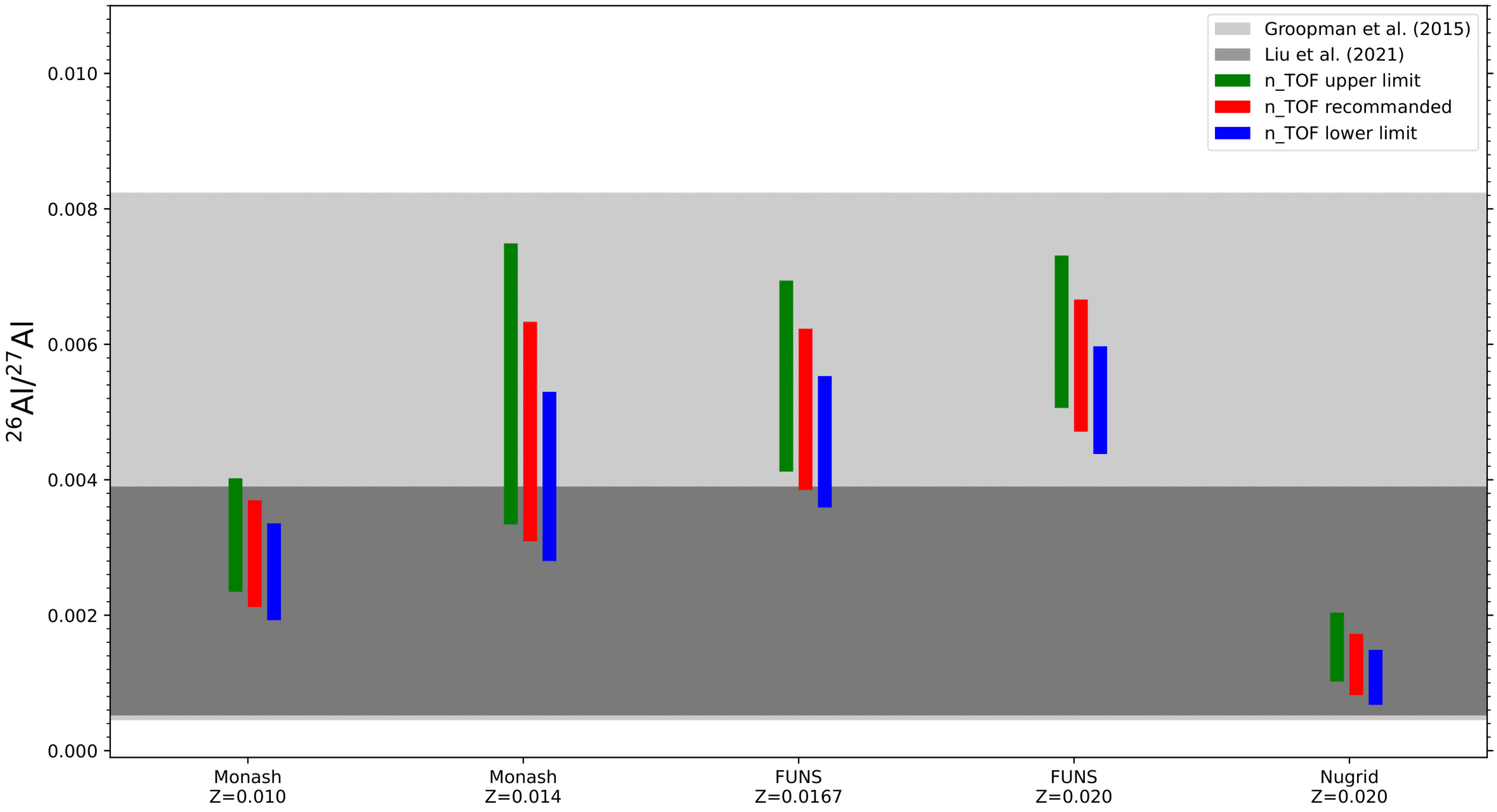
- Experimental data only cover low temperatures → Combined with Hauser-Feshbach models data for high T
- Lower rates at lower T → less efficient ^{26}Al destruction → higher ^{26}Al/^{27}Al ratio in presolar grains

Astrophysical impact
AGB stars



Astrophysical impact
AGB stars

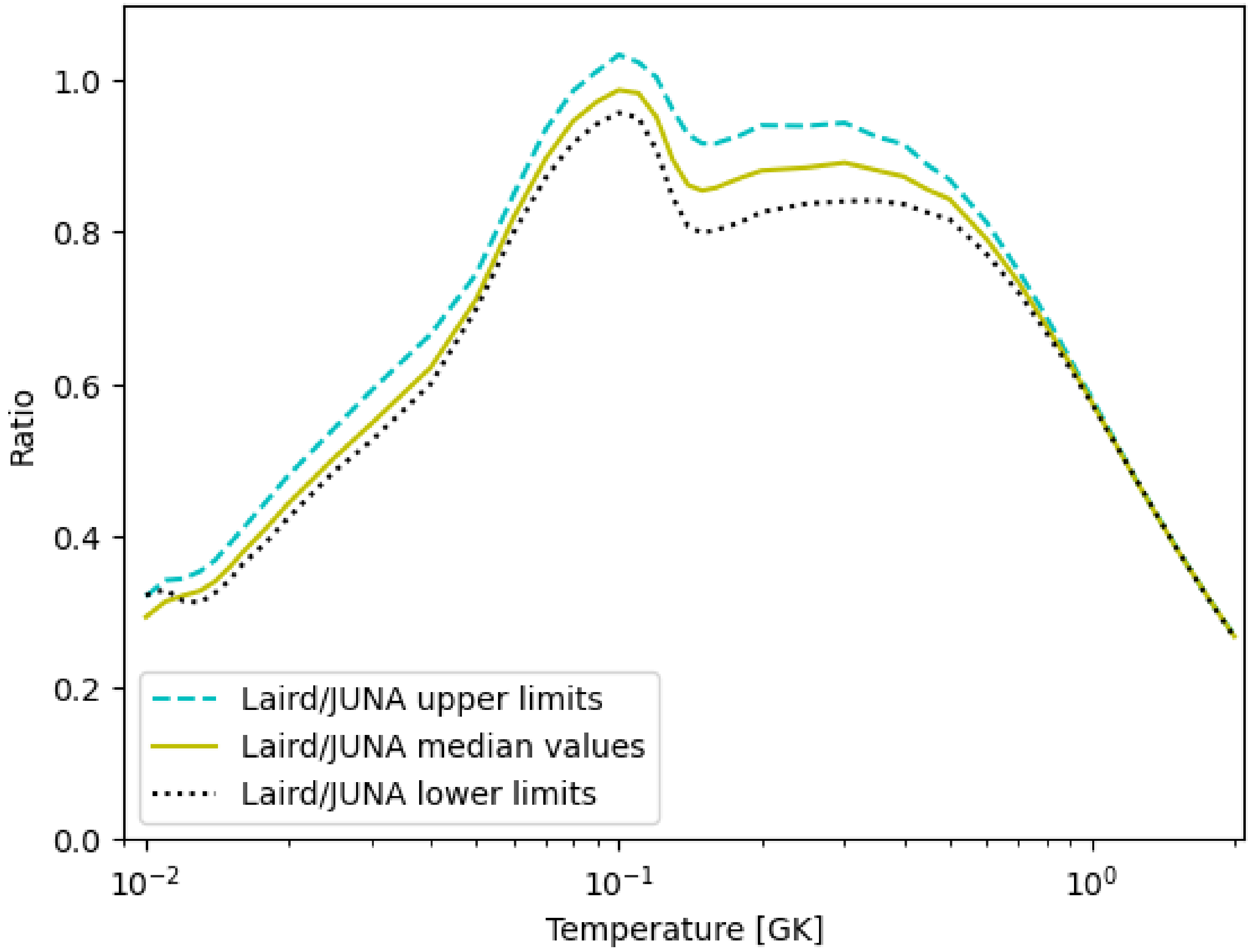




Groopman et al. (2015)
Liu et al. (2021)
n_TOF upper limit
n_TOF recommanded
n_TOF lower limit
0.010
0.008
0.006
0.004
0.002
0.000
$^{26}Al/^{27}Al$
Monash Z=0.010
Monash Z=0.014
FUNS Z=0.0167
FUNS Z=0.020
Nugrid Z=0.020

$^{25}Mg(p,\gamma)^{26}Al$

- ^{26}Al in CCSNe is usually produced between explosive Ne and C zones. In our models, this happens at temperatures 1.74 < T/GK < 2.60.
- In this temperature range the rate from Laird+2023 is around a factor of three lower than the rate from JUNA.
- Mainly due to the shifted resonance energy computed taking the difference in electron binding energies before and after the reaction into account as described in Laird+2023. This was not included by Zhang+2023, but can cause an appreciable difference in the resonance energy (and therefore the reaction rate).



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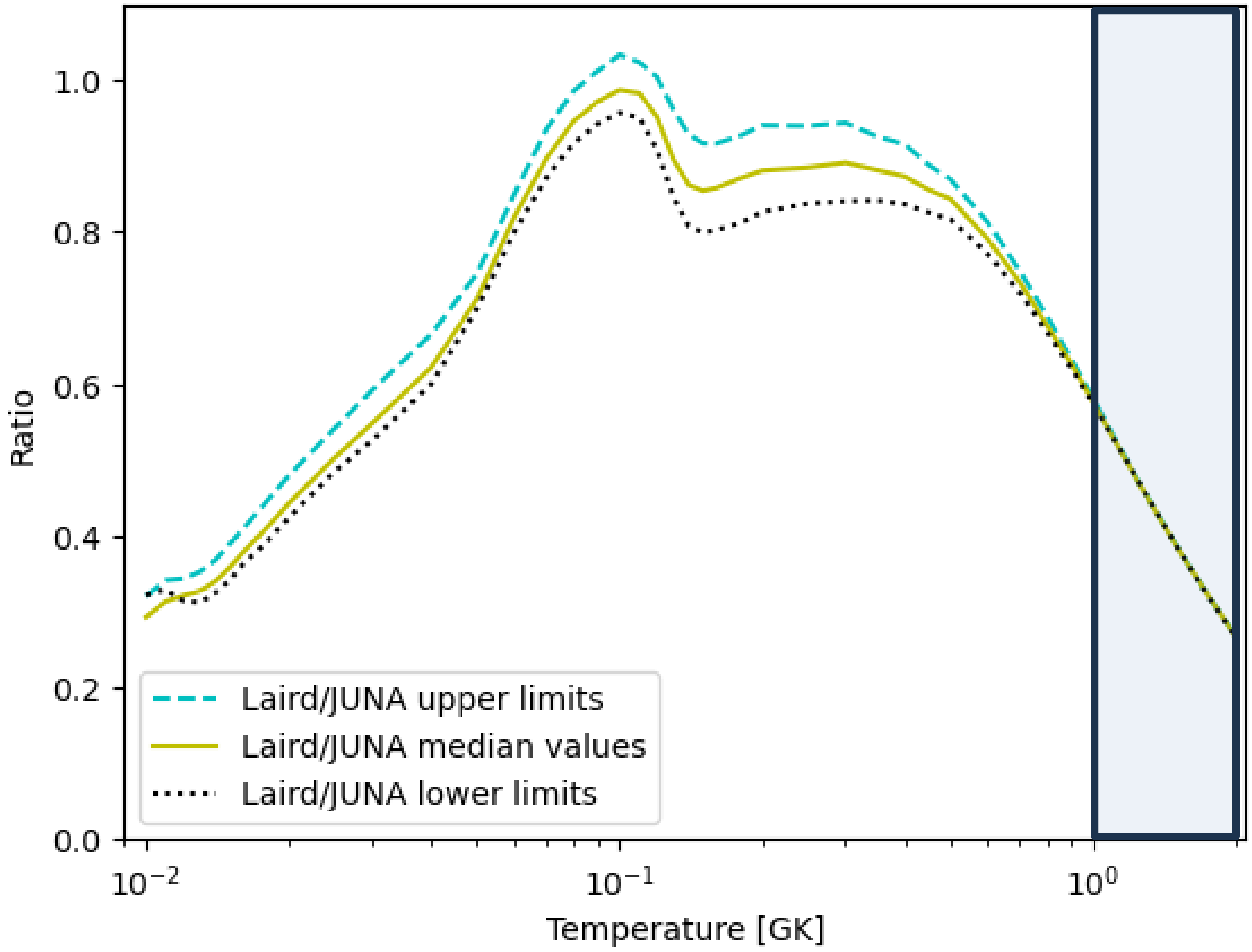


Collective impact on explosive nucleosynthesis

- Abundances in mass fraction of key nuclear species as a function of the internal mass coordinate in the CCSN models exploding with 1.2 and 3×10^{51} erg.

- The gray shaded areas represent each explosive burning stage; the vertical dotted line identifies the location of the mass-cut.

- **STANDARD**: ^{25}Mg(p,γ)^{26}Al and ^{26}Al (p,γ)^{27}Si from Iliadis+2010, ^{26}Al (n,p)^{26}Mg and ^{26}Al(n,a)^{23}Na from Caughlan & Folwler 1988 and NACRE respectively

- **LA-BA**: ^{25}Mg(p,γ)^{26}Al and ^{26}Al (p,γ)^{27}Si from Laird+2023, ^{26}Al (n,p)^{26}Mg and ^{26}Al(n,a)^{23}Na from Battino+2023

- **JU-LA-BA**: Same as LA-BA, but ^{25}Mg(p,γ)^{26}Al from Zhang+2023 (JUNA)

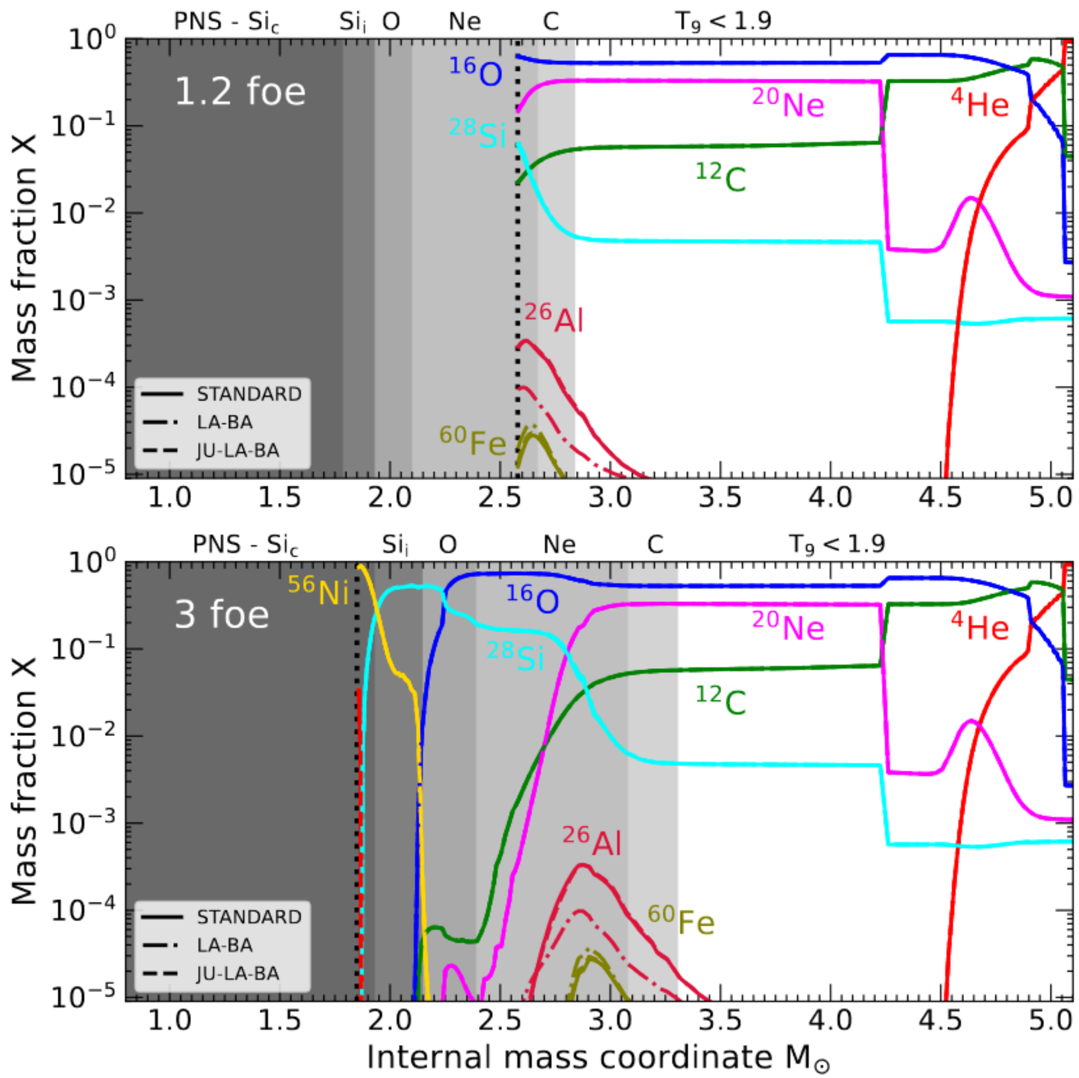
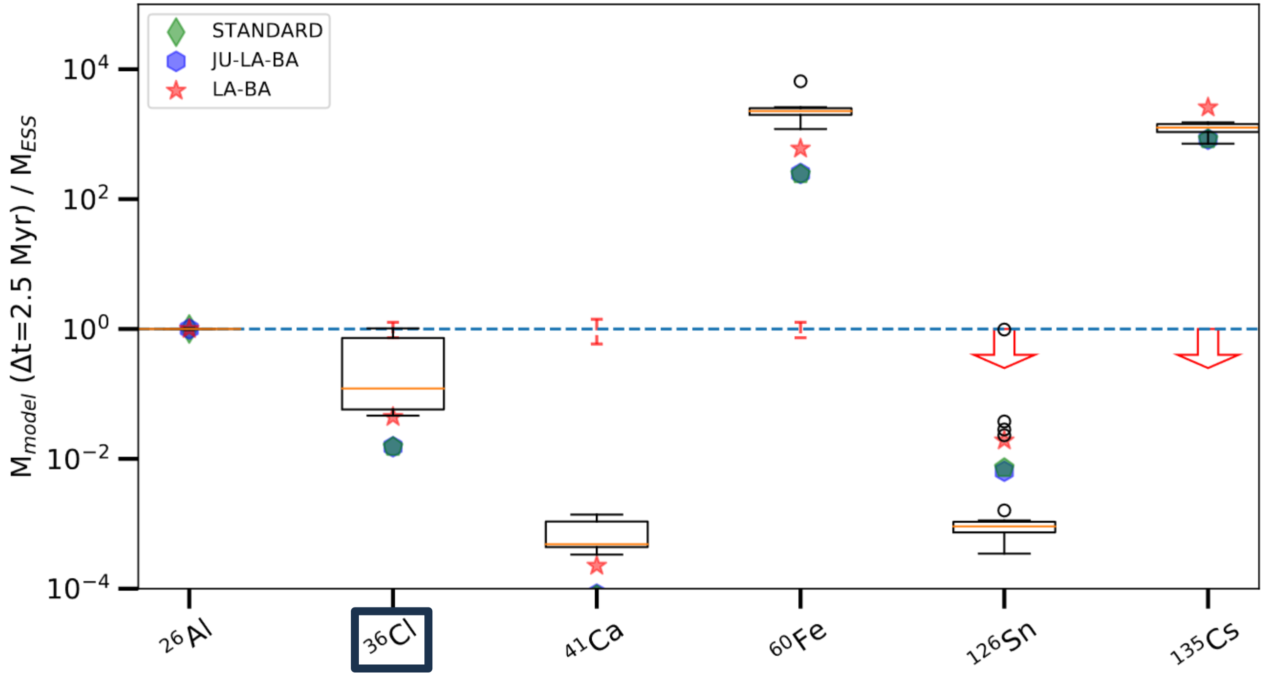


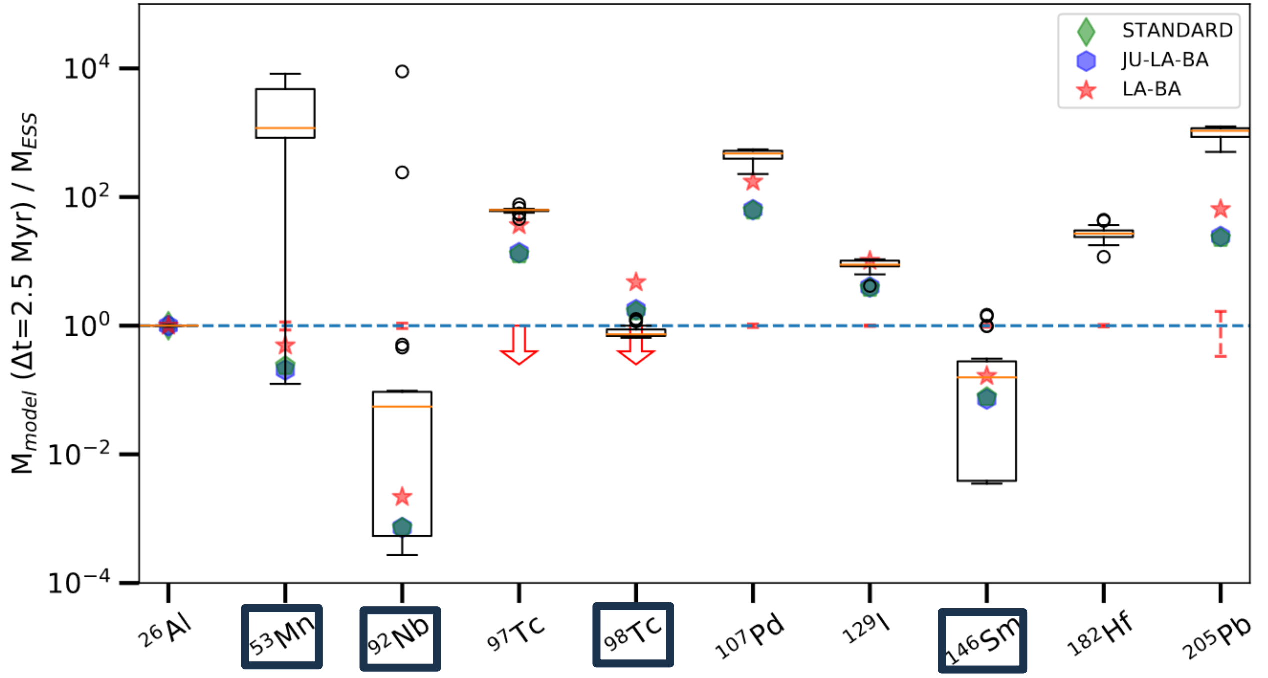
Table 2. Total explosive ejected yields (in $M_\odot$) of ^{26}Al and other key species of our models for different selections of nuclear reaction rates (see main text for more details).

Specie	STANDARD	JU-LA-BA	LA-BA
	1.2×10^{51} erg		
^{20}Ne	5.60e-01	5.60e-01	5.60e-01
^{23}Na	1.07e-02	1.07e-02	1.07e-02
^{24}Mg	9.32e-02	9.32e-02	9.29e-02
^{25}Mg	1.66e-02	1.67e-02	1.70e-02
^{26}Mg	1.65e-02	1.64e-02	1.64e-02
^{26}Al	7.02e-05	7.17e-05	2.71e-05
^{27}Al	1.14e-02	1.14e-02	1.13e-02
^{28}Si	2.13e-02	2.14e-02	2.17e-02
^{29}Si	3.17e-03	3.16e-03	3.10e-03
^{30}Si	1.96e-03	1.95e-03	1.90e-03
^{60}Fe	1.19e-05	1.21e-05	1.30e-05
	3×10^{51} erg		
^{20}Ne	4.79e-01	4.79e-01	4.78e-01
^{23}Na	8.80e-03	8.80e-03	8.77e-03
^{24}Mg	9.81e-02	9.77e-02	9.66e-02
^{25}Mg	1.44e-02	1.45e-02	1.49e-02
^{26}Mg	1.44e-02	1.44e-02	1.43e-02
^{26}Al	9.68e-05	9.69e-05	3.60e-05
^{27}Al	1.20e-02	1.19e-02	1.18e-02
^{28}Si	2.82e-01	2.83e-01	2.84e-01
^{29}Si	4.99e-03	4.98e-03	4.95e-03
^{30}Si	6.94e-03	6.93e-03	6.82e-03
^{60}Fe	1.14e-05	1.17e-05	1.30e-05

$^{25}Mg(n,\gamma)^{26}Mg$ ~100 times lower than $^{26}Al(n,p)^{26}Mg$ and $^{26}Al(n,a)^{23}Na$ at T/GK > 1

SRLs comparison to ESS

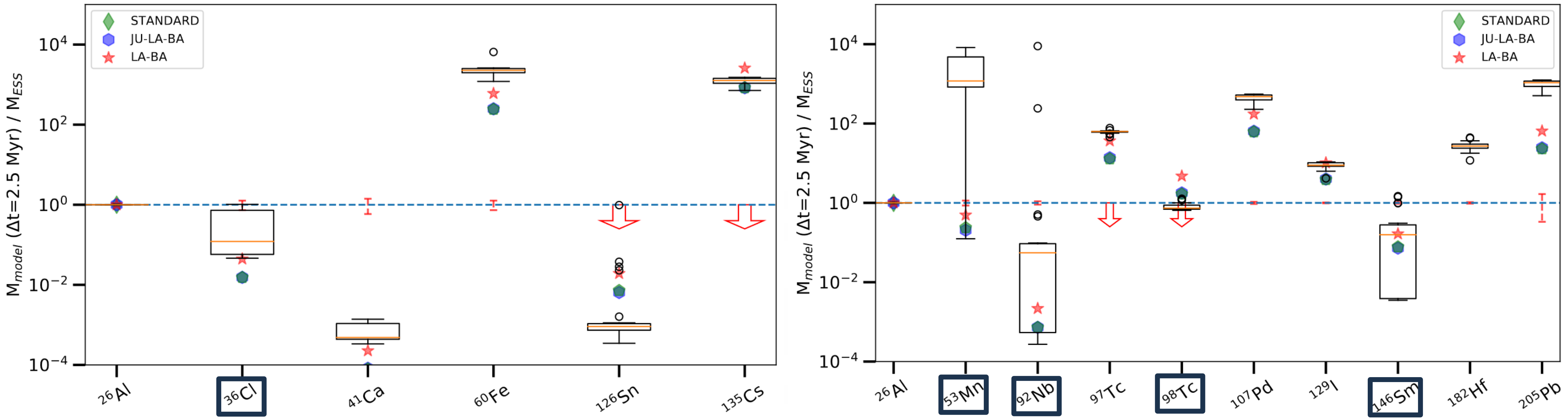




Only 5 out of the 14 SLRs considered here are consistent with their observed ESS values.

Two potential solutions: 1) A different astrophysical scenario able to perform better against observations;
2) An additional pollution event producing more ^{26}Al and less of the overproduced SLRs (such as ^{60}Fe) that happened close in time (within ~2.5 Myr) and space to a CCSN.

SRLs comparison to ESS



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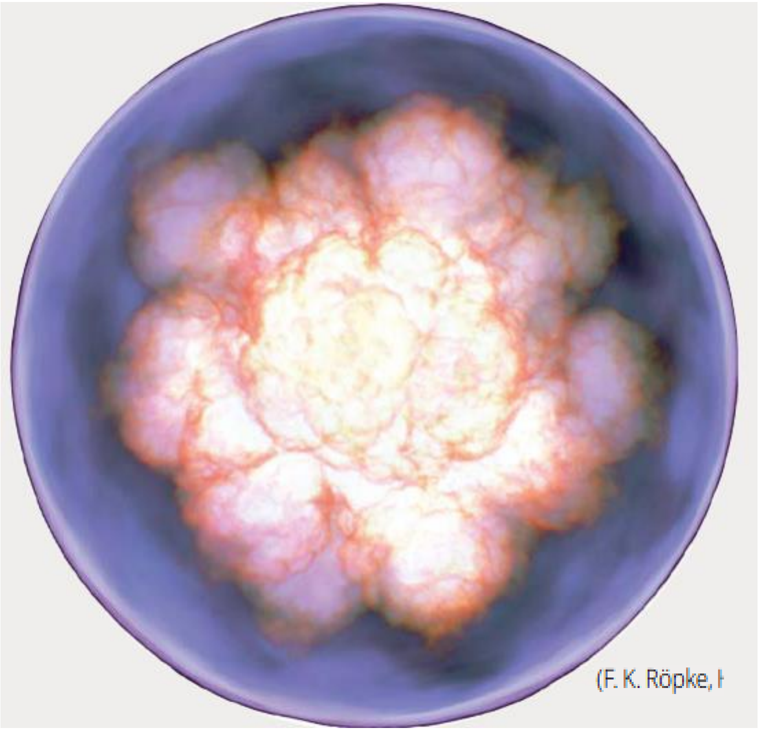
Different astrophysical scenario?



Near-Chandrasekhar mass SNIa?

H-accretor → but only ~6% of SN Ia from there, see e.g. Johansson et al. (2016))

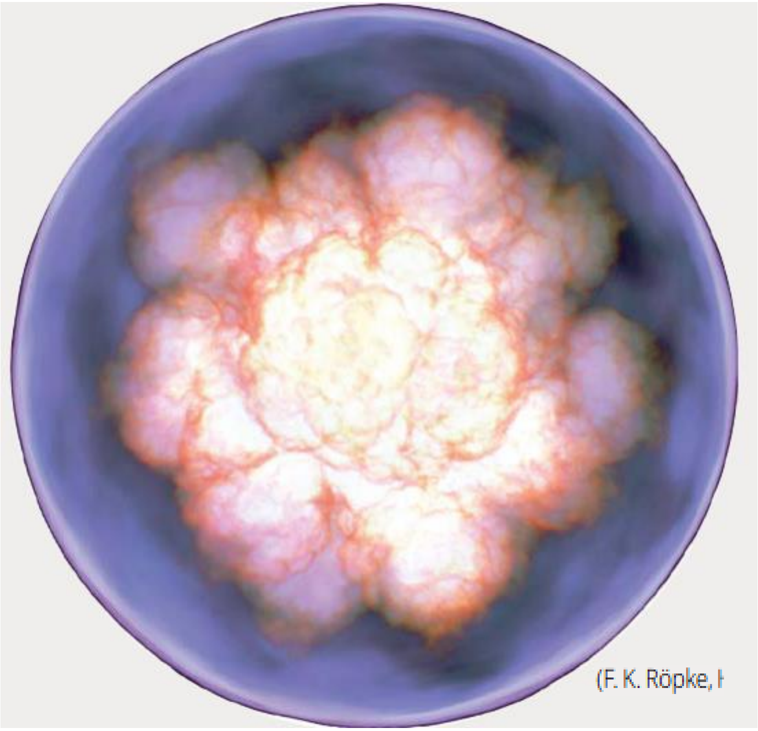
Slow WD merger → Accretion disk formation
→ Final outcome depends on accretion rate and WD mass ratio (see e.g. Piersanti+2003)

Core-collapase SN from rotating WR stars?

Rotationally enhanced mass-loss → Less ^{1}H and ^{14}N to form ^{22}Ne

→ Possibly less ^{60}Fe and ^{135}Cs?

Different astrophysical scenario?



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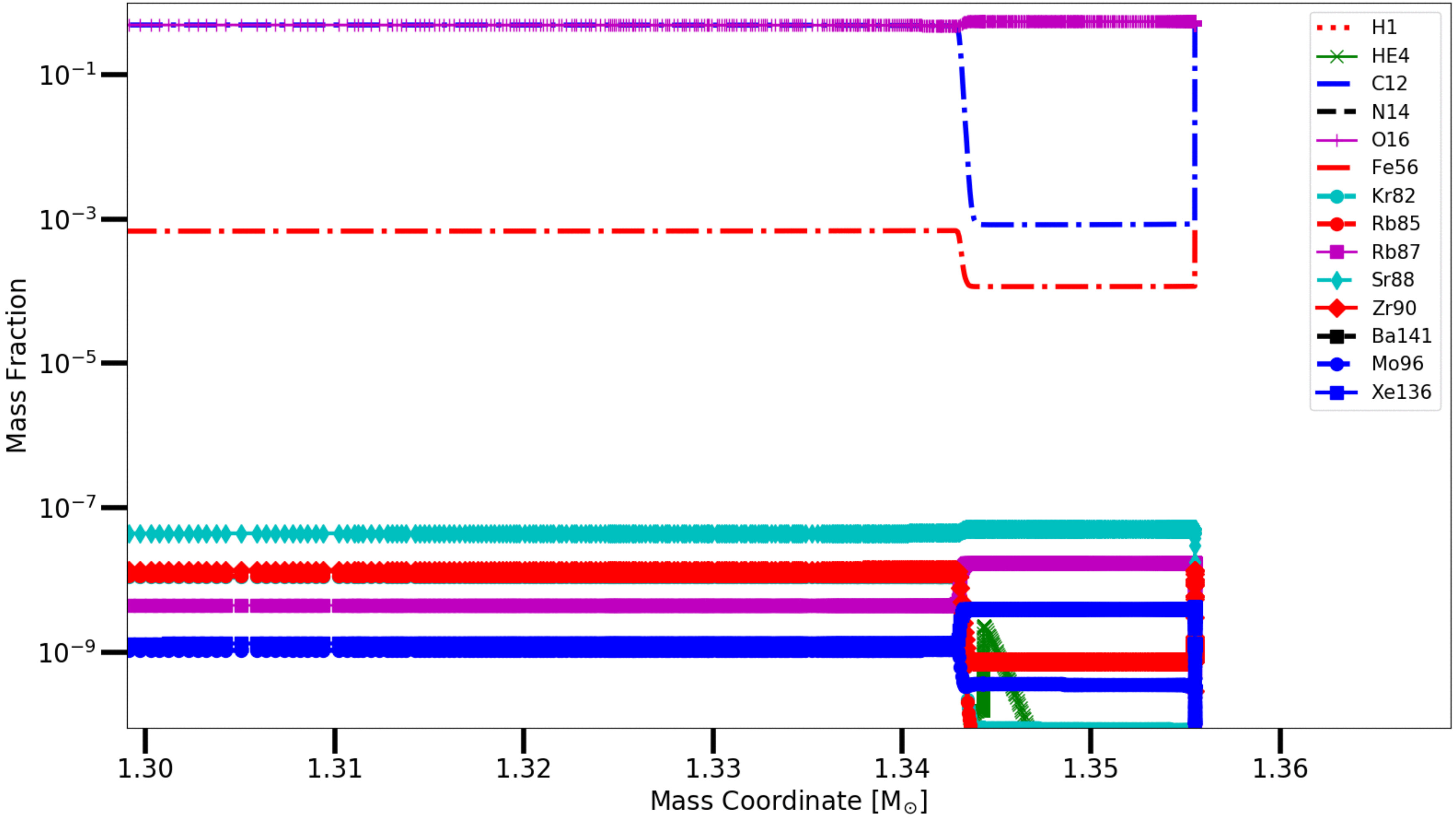
Trans-Fe element nucleosynthesis on near-Chandrasekhar SNIa progenitors

Battino et al.; EPJ Web Conf., 260 (2022)



Summary

- We presented new reactivities for the **^{26}Al(n, p)^{26}Mg** and **^{26}Al(n, α)^{23}Na** nuclear reactions and tested their effect on stellar nucleosynthesis → significant impact on low-mass AGB nucleosynthesis.
- The measurement of n-capture cross-section of ^{26}Al by n_TOF is smaller at AGB nucleosynthesis temperature → Higher ^{26}Al/ ^{27}Al → ***Now possible to explain most of the measured range in SiC with the same stellar code***
- We computed the evolution of a high-mass star (20Msun, Z=0.01345) and the nucleosynthetic yields ejected by its explosion at 1.2 and 3×10^{51} erg. We included all the updated rates of the relevant nuclear reactions for ^{26}Al nucleosynthesis, i.e. **^{26}Al(n, p)^{26}Mg** and **^{26}Al(n, α)^{23}Na** , **^{26}Al(p, γ)^{27}Si** and **^{25}Mg(p, γ) ^{26}Al**.
- Only minor differences are present between the STANDARD and JU-LA-BA case, while in the LA-BA case we notice a **substantial decrease** in the ejected amount of ^{26}Al, almost a factor of three compared to the JU-LA-BA case, which is consistent with the difference up to a factor of three between the ^{25}Mg(p, γ) ^{26}Al reaction rates by Laird+2023 and Zhang+2023.
- Only **5 out of the 14 SLRs** considered here are consistent with their observed ESS values, but different progenitors need to be explored (e.g. rotating WR stars or SNIa) → **How critical was this for life on Earth?**
- Large stellar uncertainties still affect ^{26}Al production for CCSN (and AGB stars),
- Full results in **Battino et al. 2023** (MNRAS **520**,2436–2444) and **Battino et al. 2024** (submitted to MDPI Universe)

New rates available on ChANUREPS (http://chanureps.chetec-infra.eu/)

$^{26}Al_g(n,p)^{26}Mg$

Battino et al. 2023

This $^{26}Al(n,p)^{26}Mg$ nuclear reaction rate has been obtained by combining experimental results and theoretical predictions of the respective ground state reaction cross-sections. Its evaluation is primarily based on the recent high-precision measurement at the nTOF-CERN facility and is supplemented by theoretical calculations and a previous experiment (Trautvetter et al. 1986) at higher neutron energies.

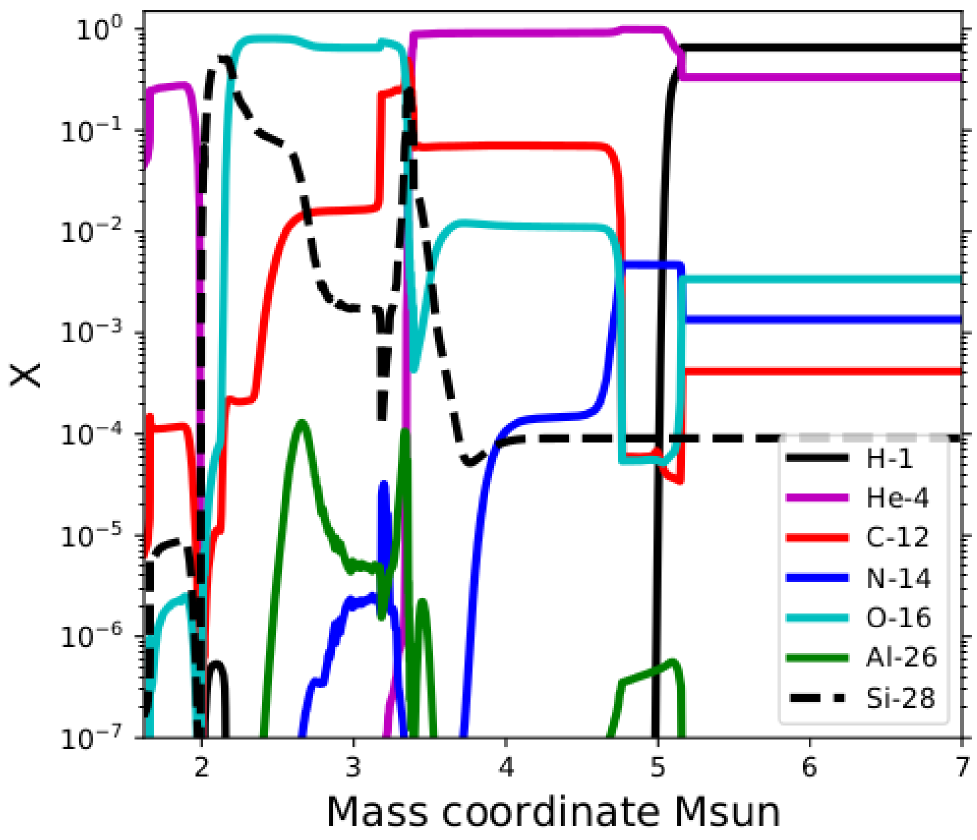
Link to the paper

Download "26Al_np"

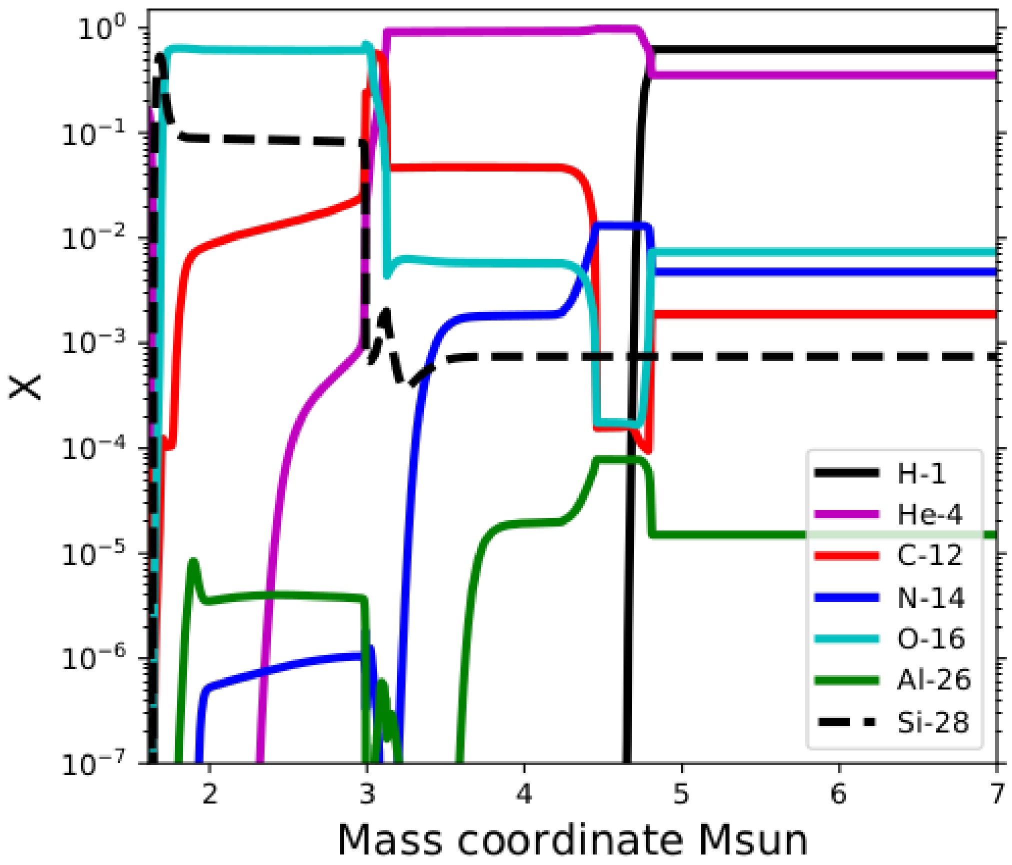
Al26np.txt – Downloaded 1 time – 2.88 KB

Massive stars

Ritter+2018



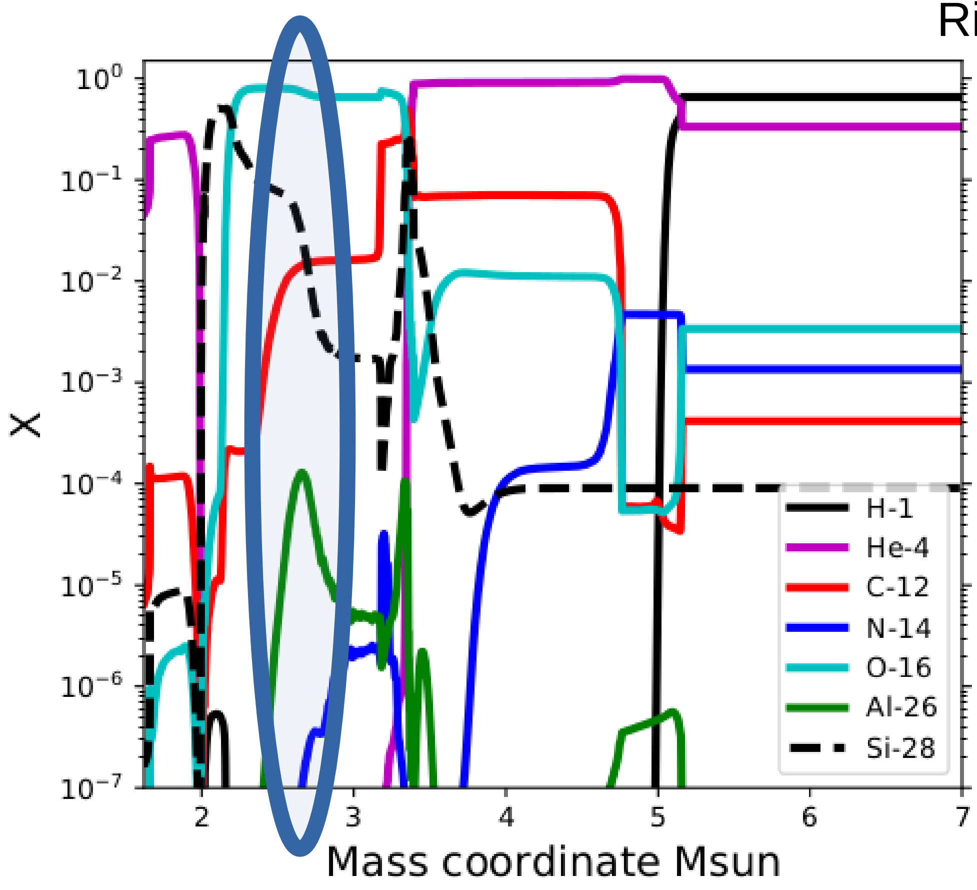
M=15 Msun; Z=0.006



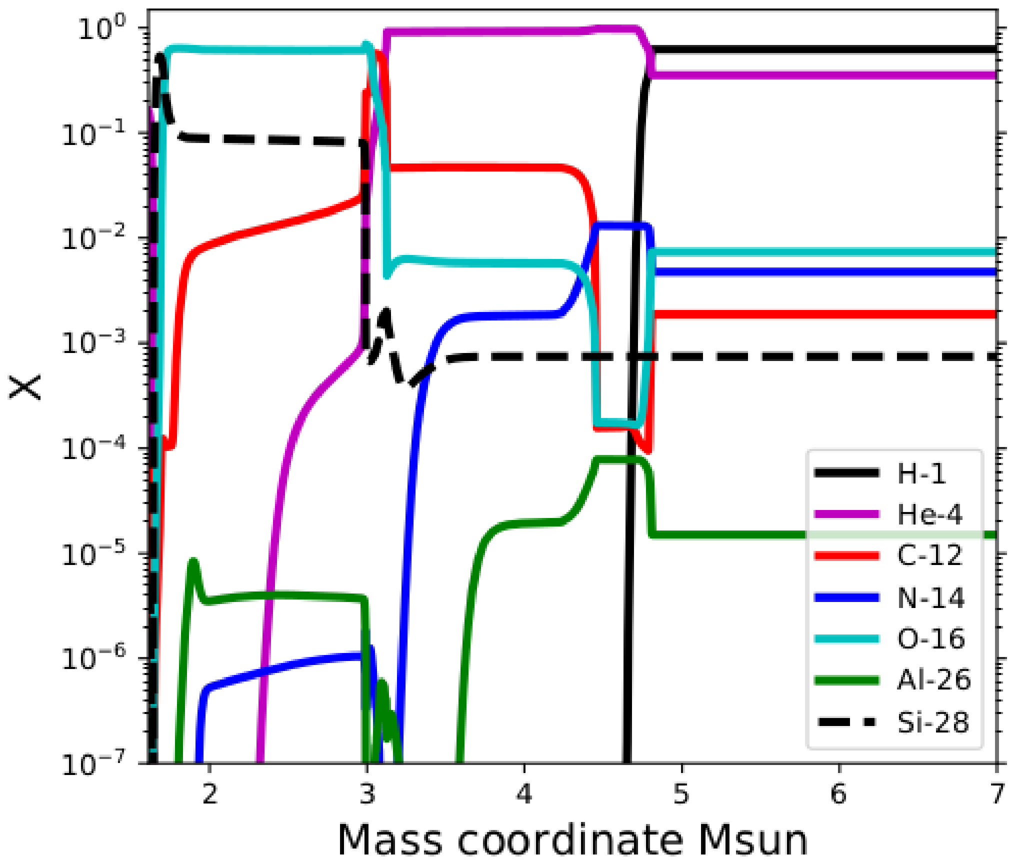
M=15 Msun; Z=0.02

Massive stars

Ritter+2018



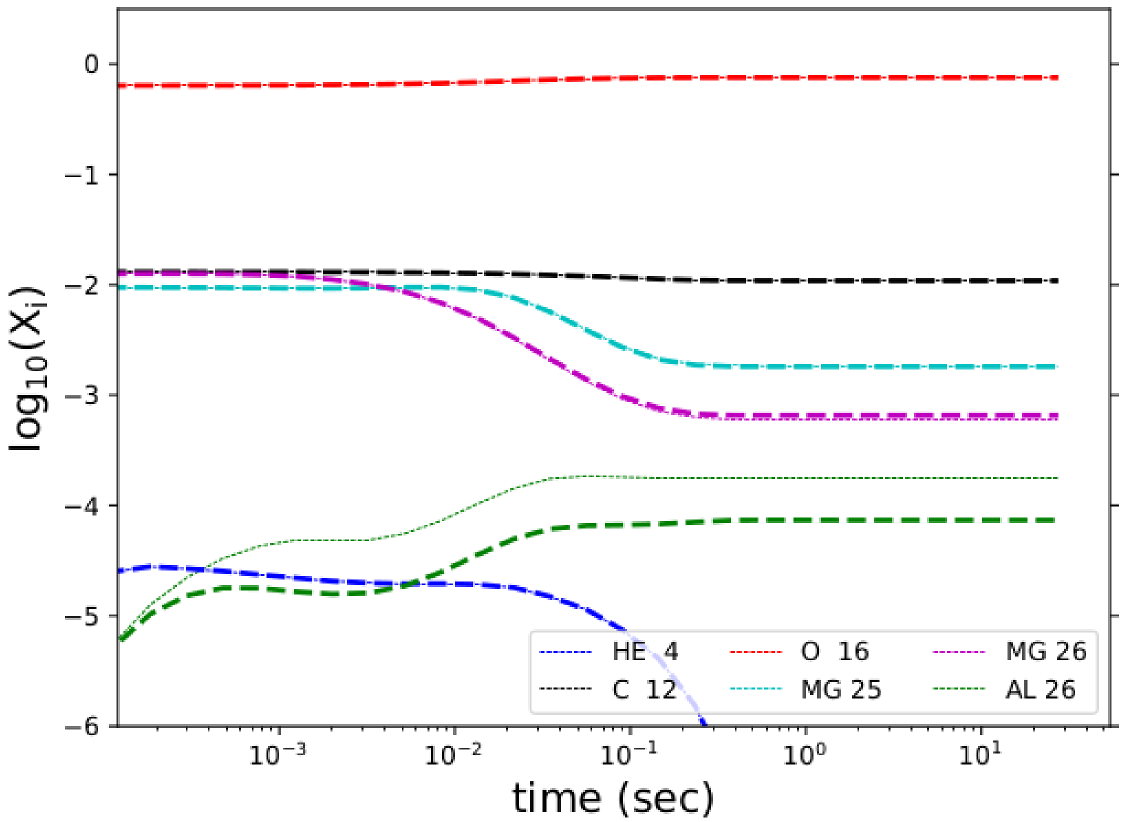
M=15 Msun; Z=0.006



M=15 Msun; Z=0.02

Massive stars

M=15 Msun; Z=0.006



- The final ^{26}Al abundance in mass fraction is varying by about a **factor of 2.4**
- ^{26}Al abundance obtained by Ritter et al. emloying CF88 and NACRE is very close to what is obtained with our lower limits…
- ...^{26}Al abundance decreases with our new rates → **opposite of what happens in AGB stars**, as our new rates are higher than the older rates at high temperatures typical of CCSN explosions