Short-lived Radioisotopes from Massive Stars and Type Ia Supernovae

Umberto Battino (Keele University, NuGrid Collaboration)

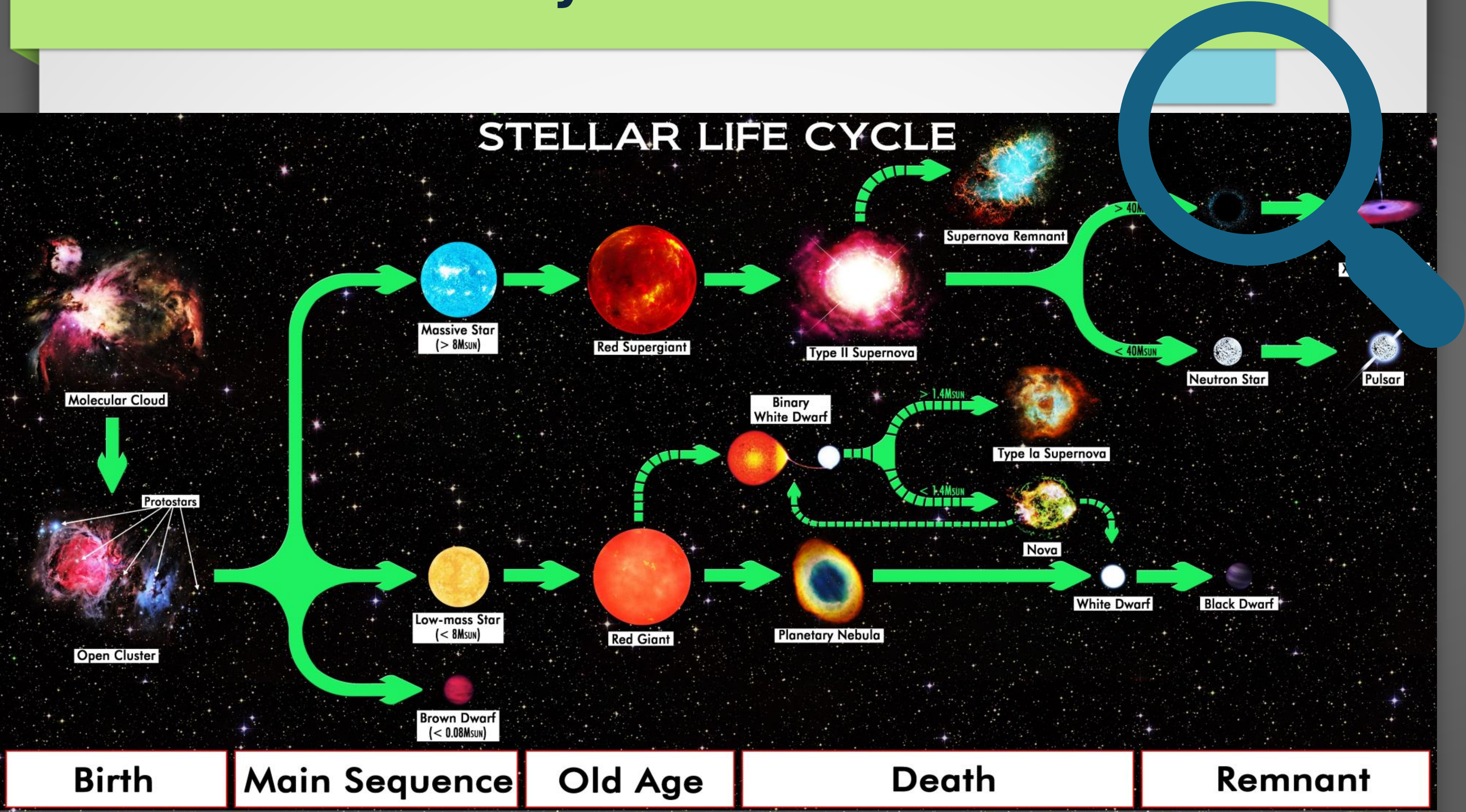
Selected Topics in Nuclear and Atomic Physics 2024

4-8 Oct 2024; Fiera di Primiero (TN)

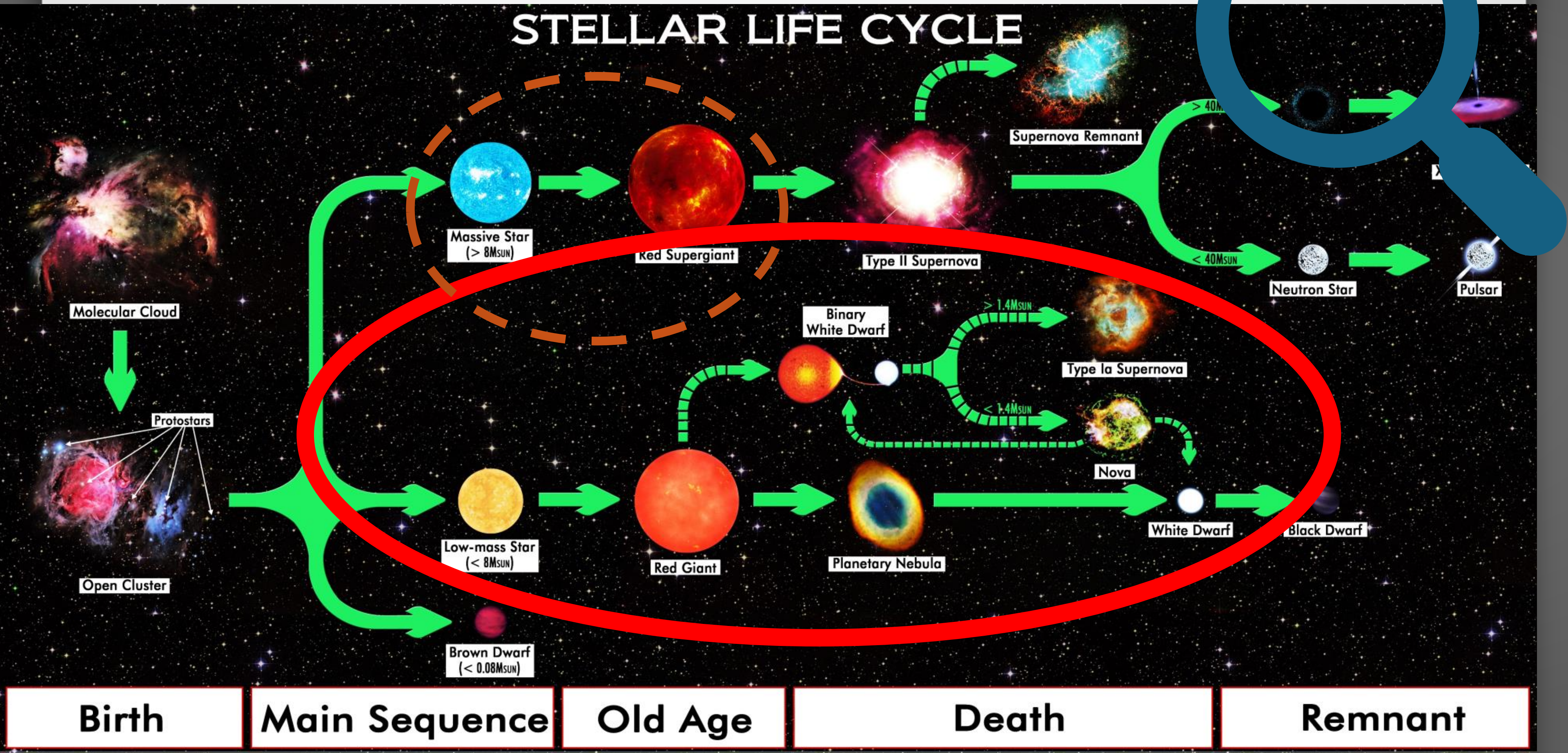
Keele University

NUGRID

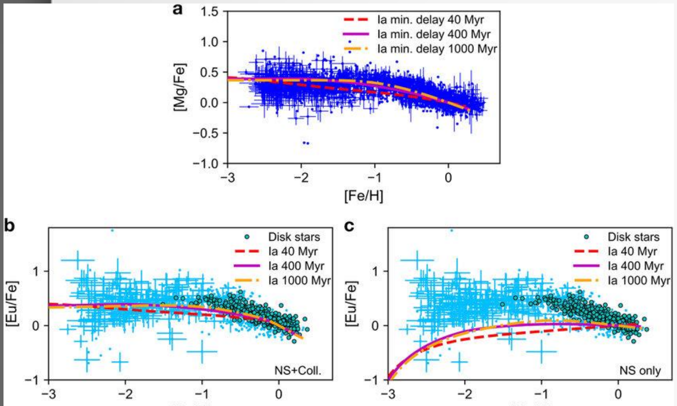
What is my area of research?



What is my area of research?

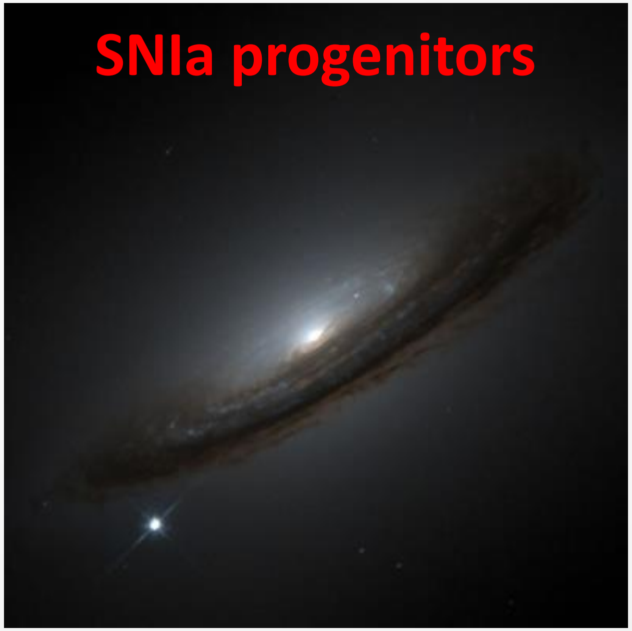


Wider relevance to the field I work in



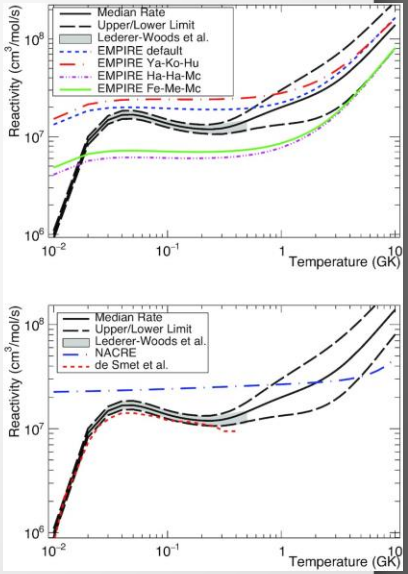
Siegel et al. *Nature* **569**, 241–244 (2019).

Galactic Chemical Evolution (GCE)



SNIa progenitors

Nuclear impact/ sensitivity studies

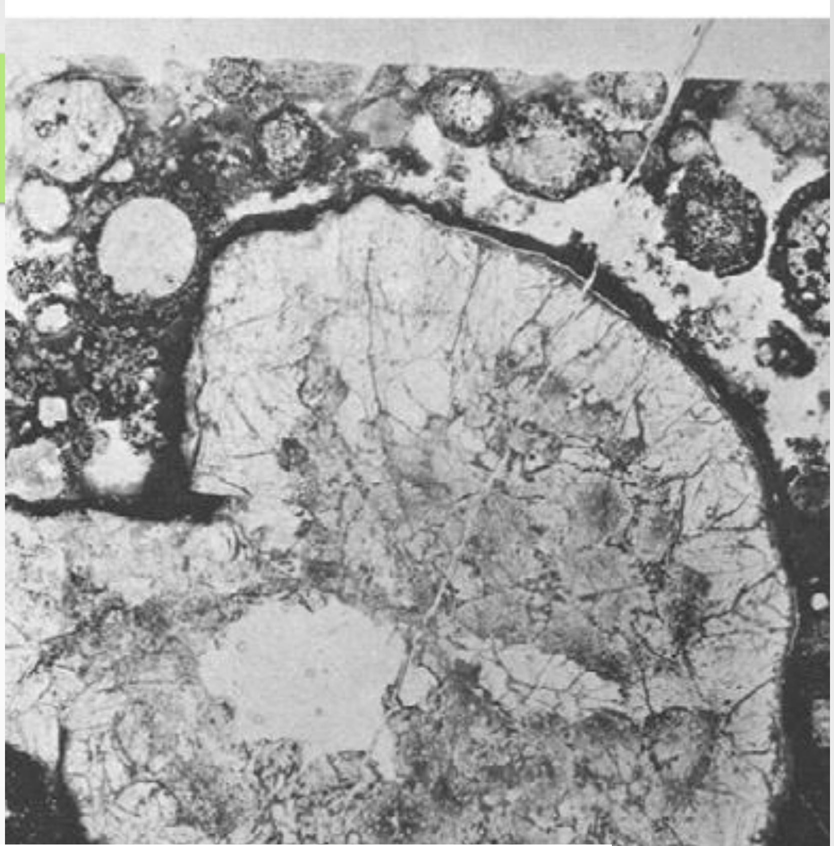


Introduction

- The meticulous examination of meteoric rocks reveals an intriguing aspect of our Solar System: it was rich in **radioactive nuclei** when it formed 4.6 billion years ago.

- Many of these nuclei were short-lived, becoming extinct within a few hundred million years of the Solar System's formation (Dauphas & Chaussidon 2011).

- By analyzing meteorites for the byproducts of their decay, we can deduce the original abundances of these short-lived radionuclides (SLRs), which have half-lives of less than 100 million years.



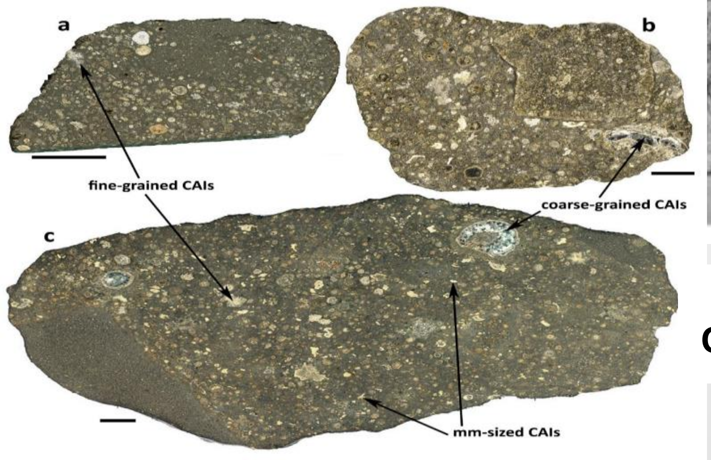


Figure 1: Representative scanned slabs of CV and CK carbonaceous chondrites used to establish the CAI size distributions in Chaumard et al. (2014) and the present study. (a) Allende, (b) NWA 2900, and (c) TNZ 057. Scale bars are 1 cm. Numerous CAIs are visible as whitish inclusions, with several examples of cm-sized and mm-sized CAIs labeled with arrows. Dark mm-sized grains of pyroxene are visible within coarse-grained CAIs, whereas grains are indistinguishable in fine-grained CAIs.

Marks et al. 2011
Charnoz et al. 2015

—Intr

- The meticulo meteoric rocks r aspect of our S rich in **radioact** formed 4.6 billion

- Many of these lived, becoming hundred million System's forma Chaussidon 2011

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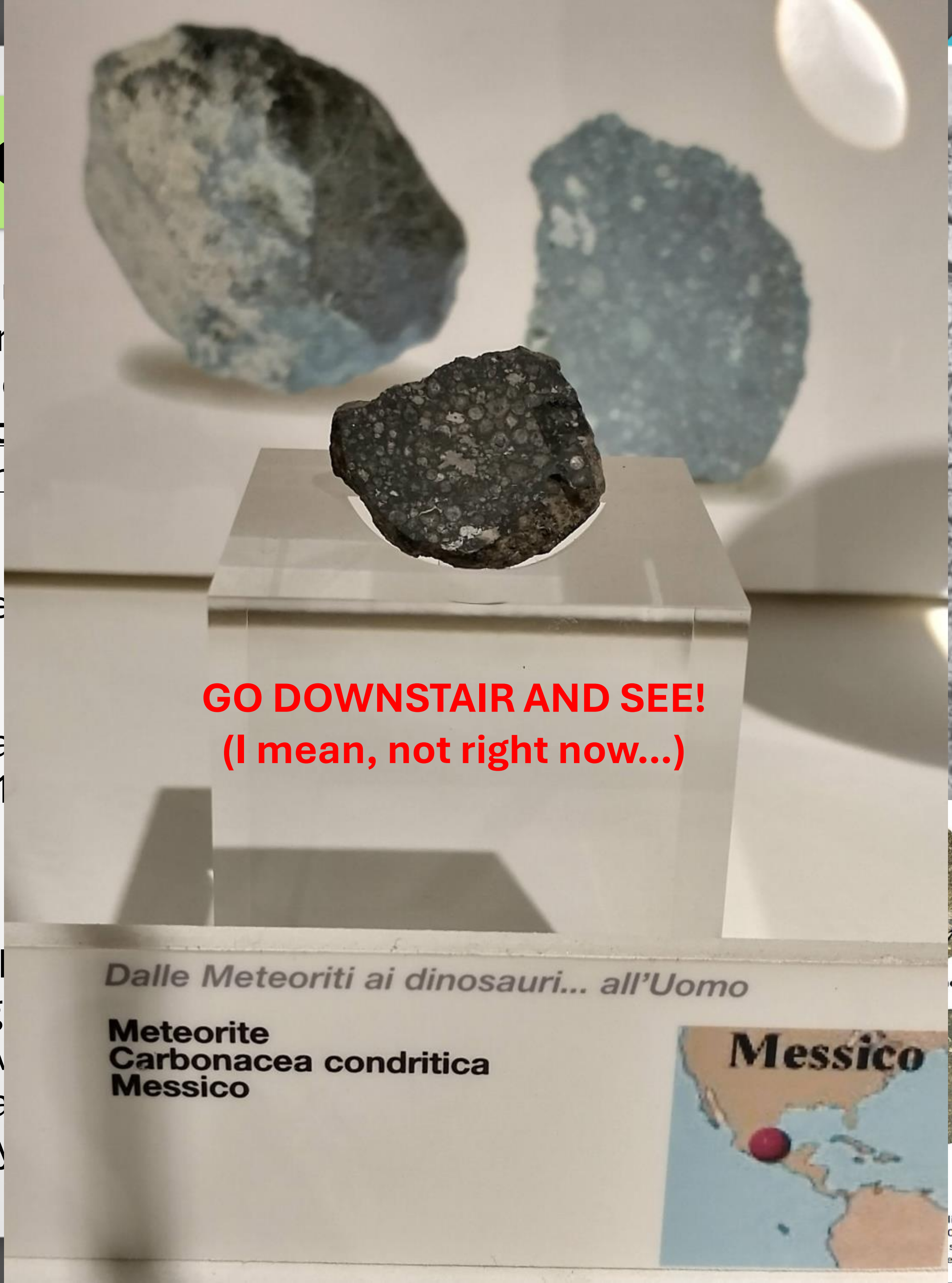
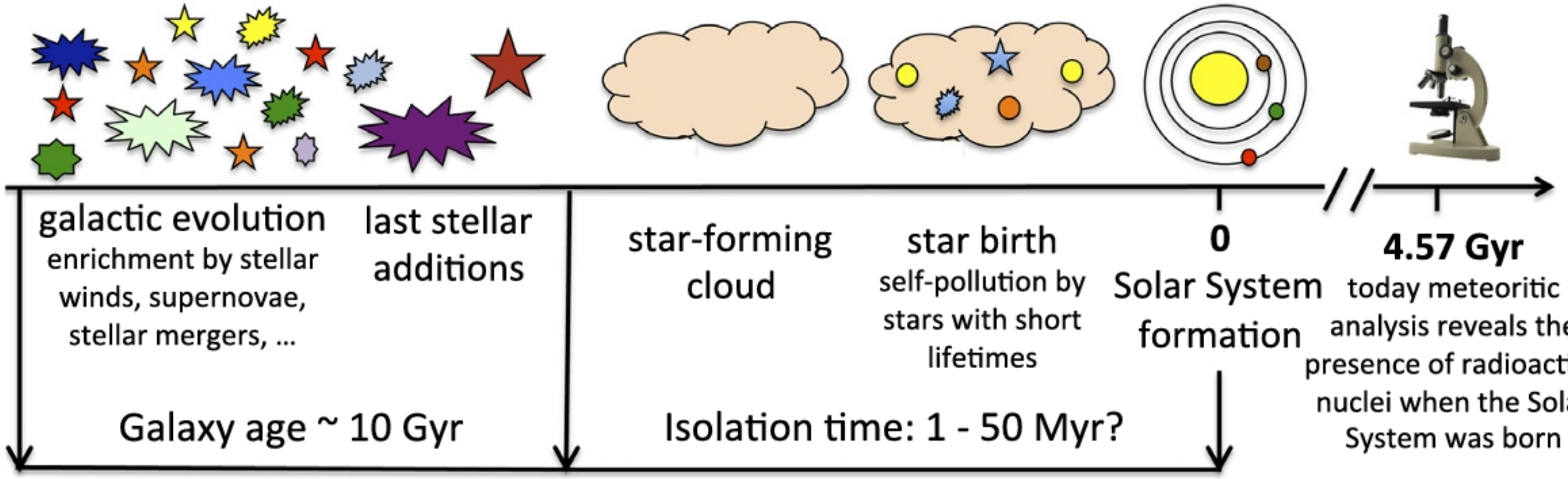


GO DOWNSTAIR AND SEE!
(I mean, not right now...)

Marks et al. 2011
Charnoz et al. 2015

SLRs and the Solar System's history

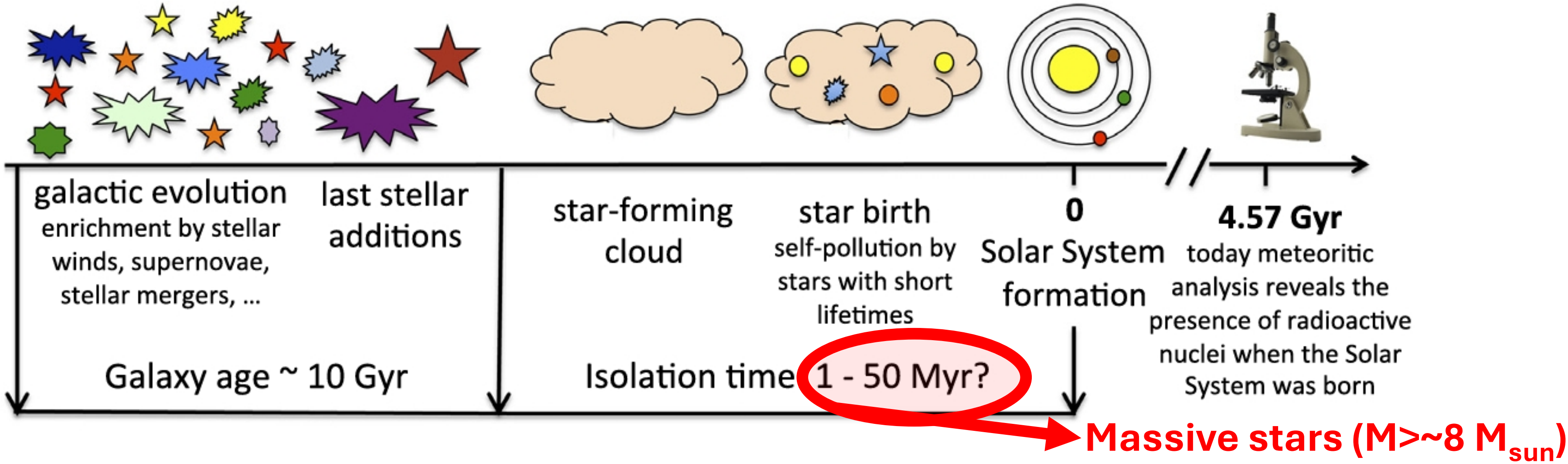


- SLRs serve as chronometers and fingerprints, shedding light on the **Solar System's history and birth environment** (Lugaro et al. 2018).

- Comparing SLR abundances in the early Solar System (ESS) to those predicted by galactic chemical evolution (hereafter GCE) allows us to calculate the "isolation time" elapsed from the formation of the molecular cloud where the Sun originated and the formation of the Sun itself.

- This isolation time is determined by the exponential decay of SLRs (Côté et al. 2019a,b), providing insights into the separation of molecular cloud material from the rest of the galactic interstellar medium influenced by stellar nucleosynthetic events.

SLRs and the Solar System’s history



galactic evolution
enrichment by stellar winds, supernovae, stellar mergers, ...

last stellar additions

Galaxy age ~ 10 Gyr

star-forming cloud

star birth
self-pollution by stars with short lifetimes

Isolation time 1 - 50 Myr?

0
Solar System formation

4.57 Gyr
today meteoritic analysis reveals the presence of radioactive nuclei when the Solar System was born

Massive stars (M>~8 M_{sun})

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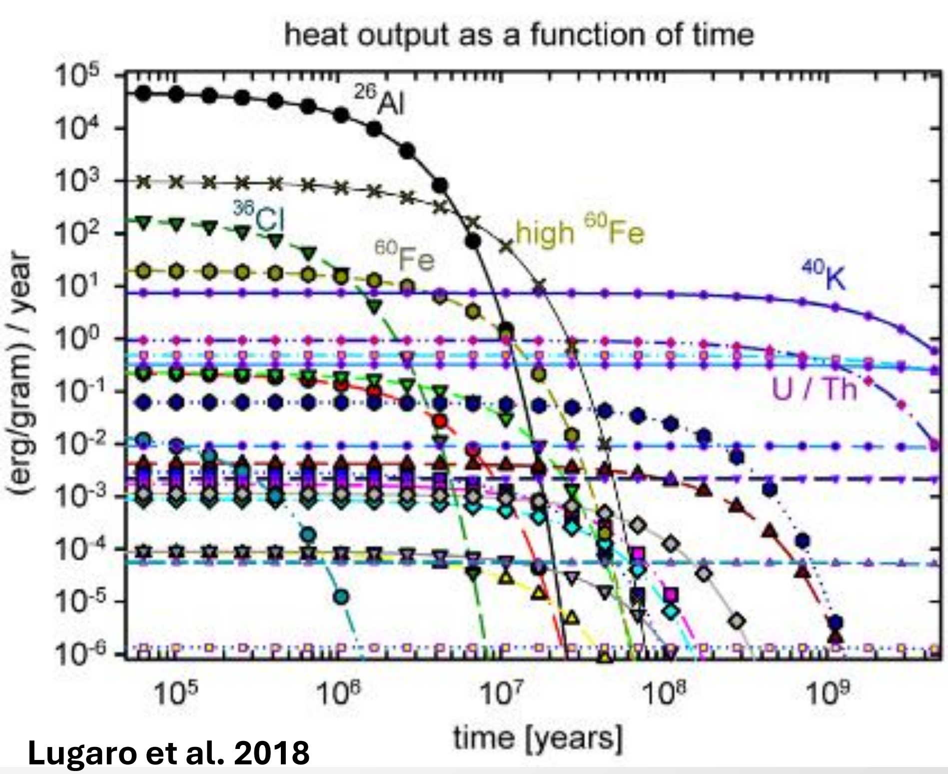
SLRs and habitability

- The dominant process contributing to the very early melting of planetesimals was the decay of **^{26}Al**.

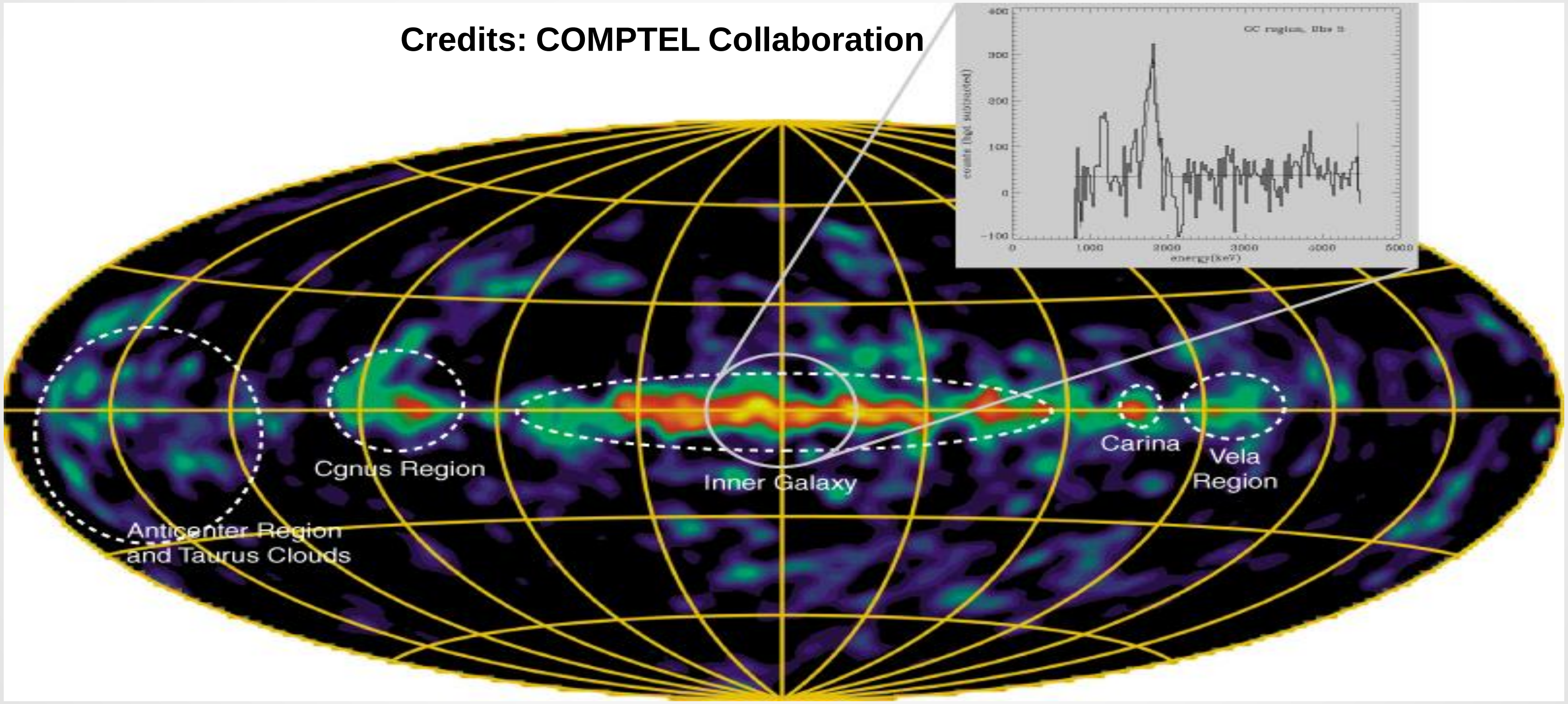
- Melt even relatively small planetesimals (Lichtenberg+ 2016), modified the mineral content, melted ice to liquid water producing a variety of molecules (Monteux+ 2017).

- **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

^{26}Al and Stellar Nucleosynthesis

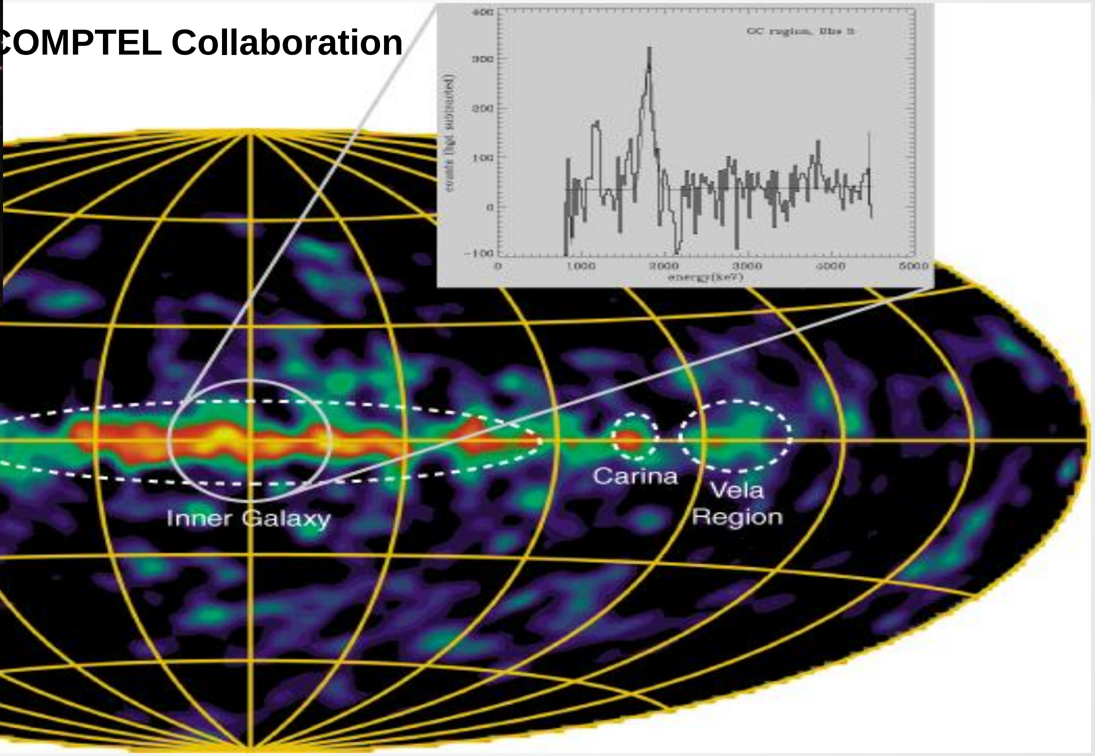


Credits: COMPTEL Collaboration

^{26}Al and Stellar Nucleosynthesis

Credits: ESA/Hubble

Credits: COMPTEL Collaboration

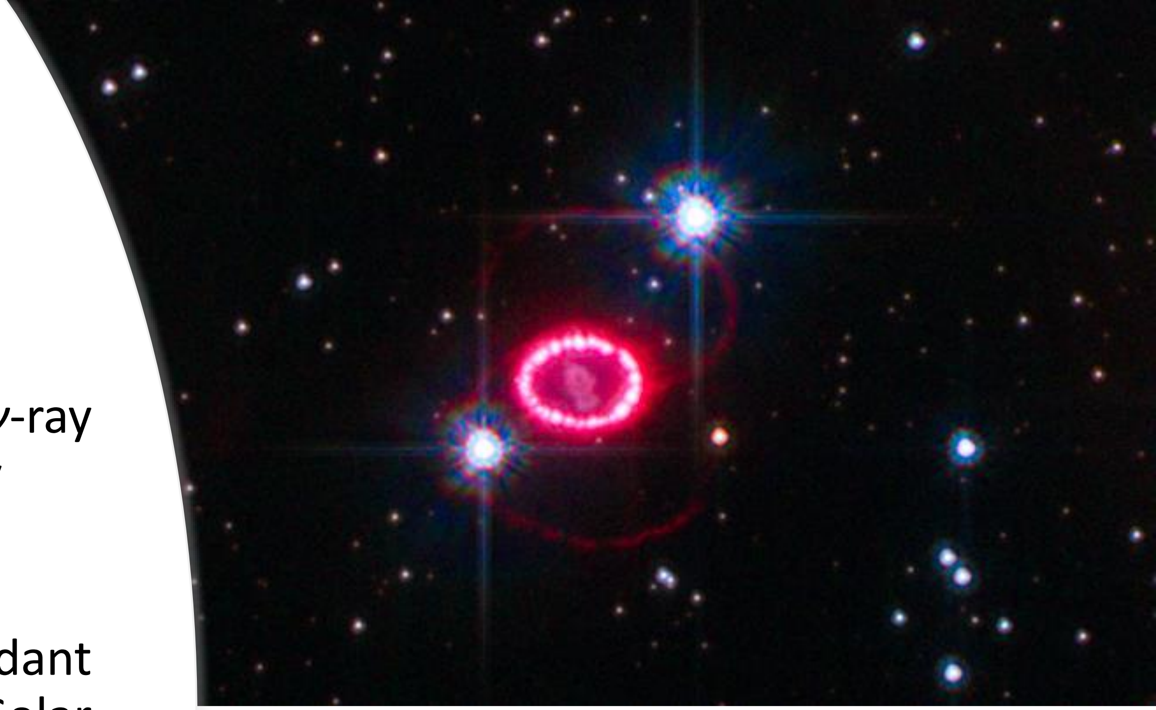


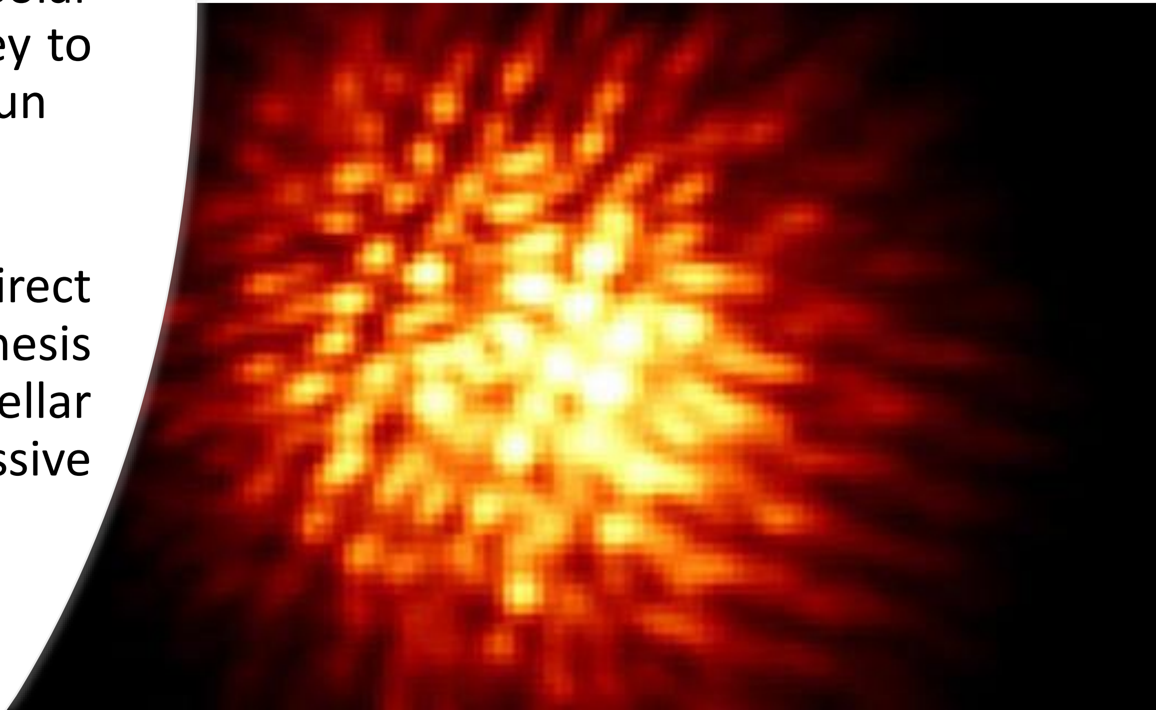
Why ^{26}Al?

- Subject of interest in both γ-ray astrophysics and cosmochemistry

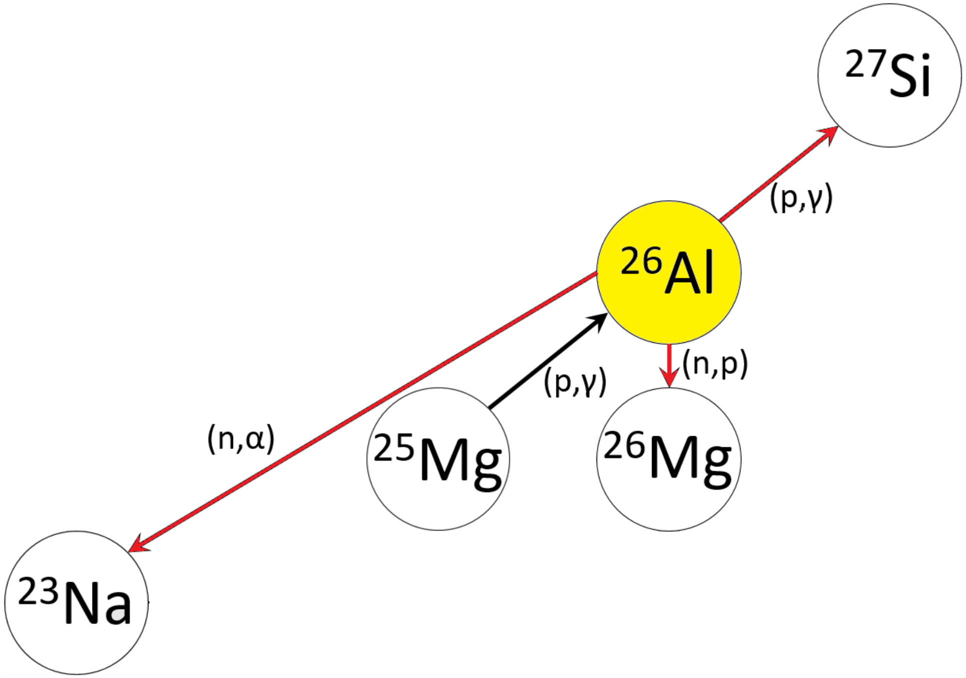
- Live ^{26}Al was highly abundant during the early stages of the Solar System → Its understanding is key to unveil birth environment of the Sun

- 1809 keV line emission as a direct tracer of ongoing nucleosynthesis processes enriching the interstellar medium, especially from massive stars and related explosions.





Main production/destruction nuclear reaction



tion nuclear reaction

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

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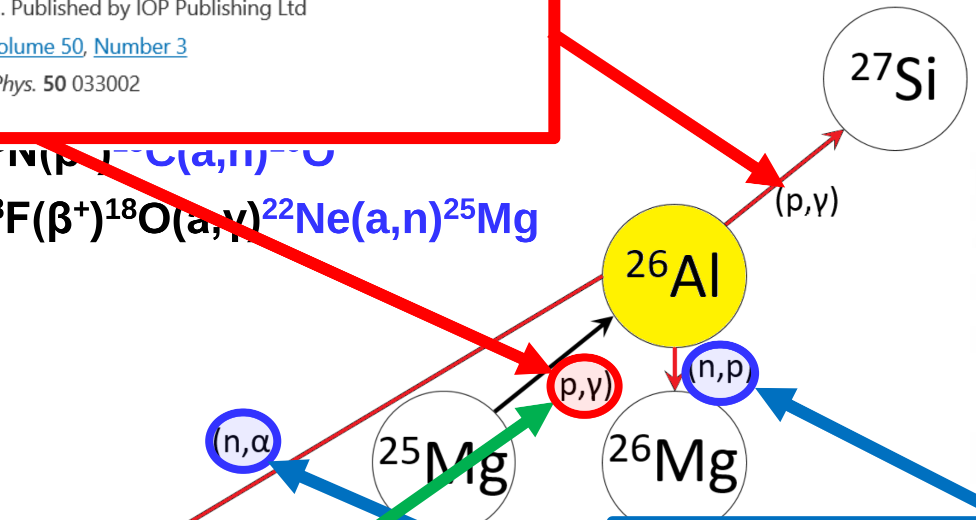
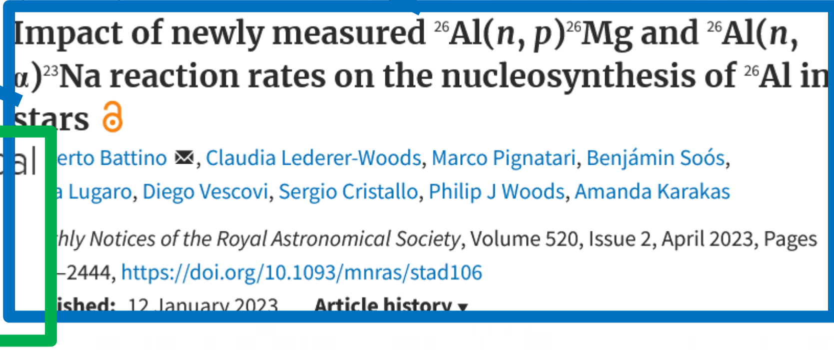
Journal of Physics G: Nuclear and Particle Physics, Volume 50, Number 3

Citation A M Laird *et al* 2023 *J. Phys. G: Nucl. Part. Phys.* **50** 033002

DOI 10.1088/1361-6471/ac9cf8

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





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

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

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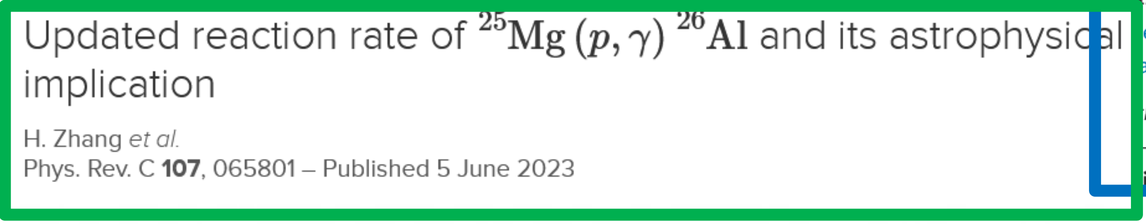

Updated reaction rate of ^{25}Mg(p, γ) ^{26}Al and its astrophysical implication

H. Zhang *et al.*
Phys. Rev. C **107**, 065801 – Published 5 June 2023

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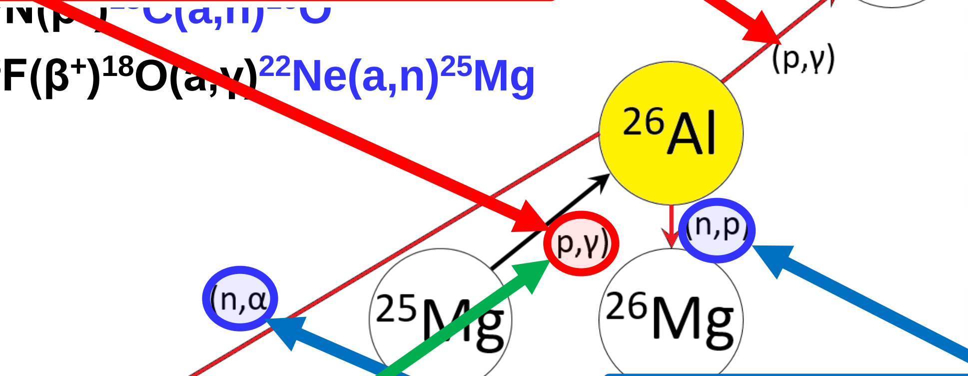
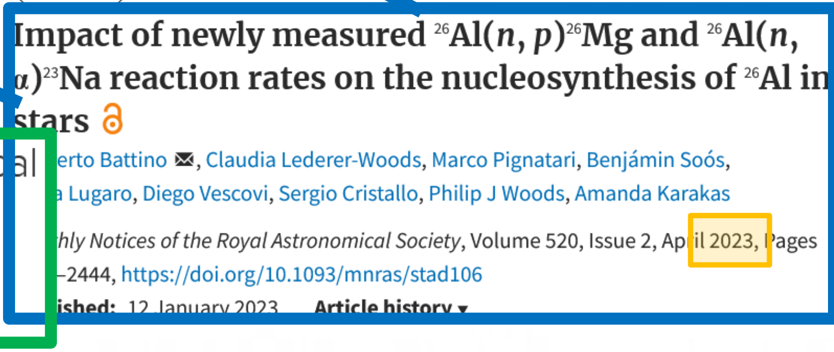
- C(p,γ) N(p C(a,n) O
- ^{14}N(a,γ)^{18}F(β$^+$)^{18}O(a,γ)^{22}Ne(a,n)^{25}Mg





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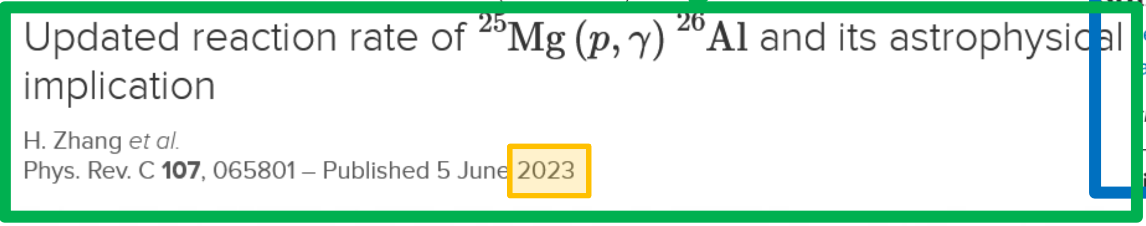

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$^{25}Mg(p,\gamma)^{26}Al$

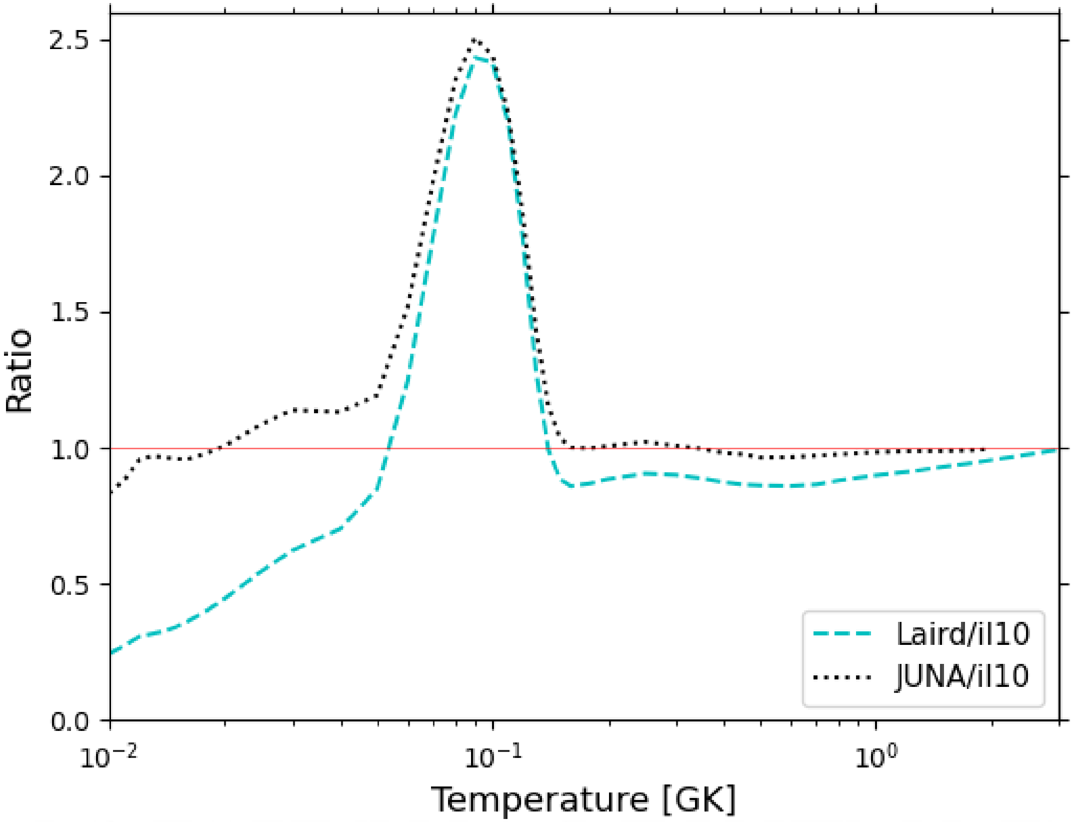
- ^{26}Al in CCSNe is usually produced between explosive Ne and C zones. In our models, this happens at temperatures 1.74 < T/GK < 2.60.

- We extended the rate from Laird+2023 beyond 0.7 GK including resonance information from Iliadis+ 2010 (same high T inputs used by JUNA)

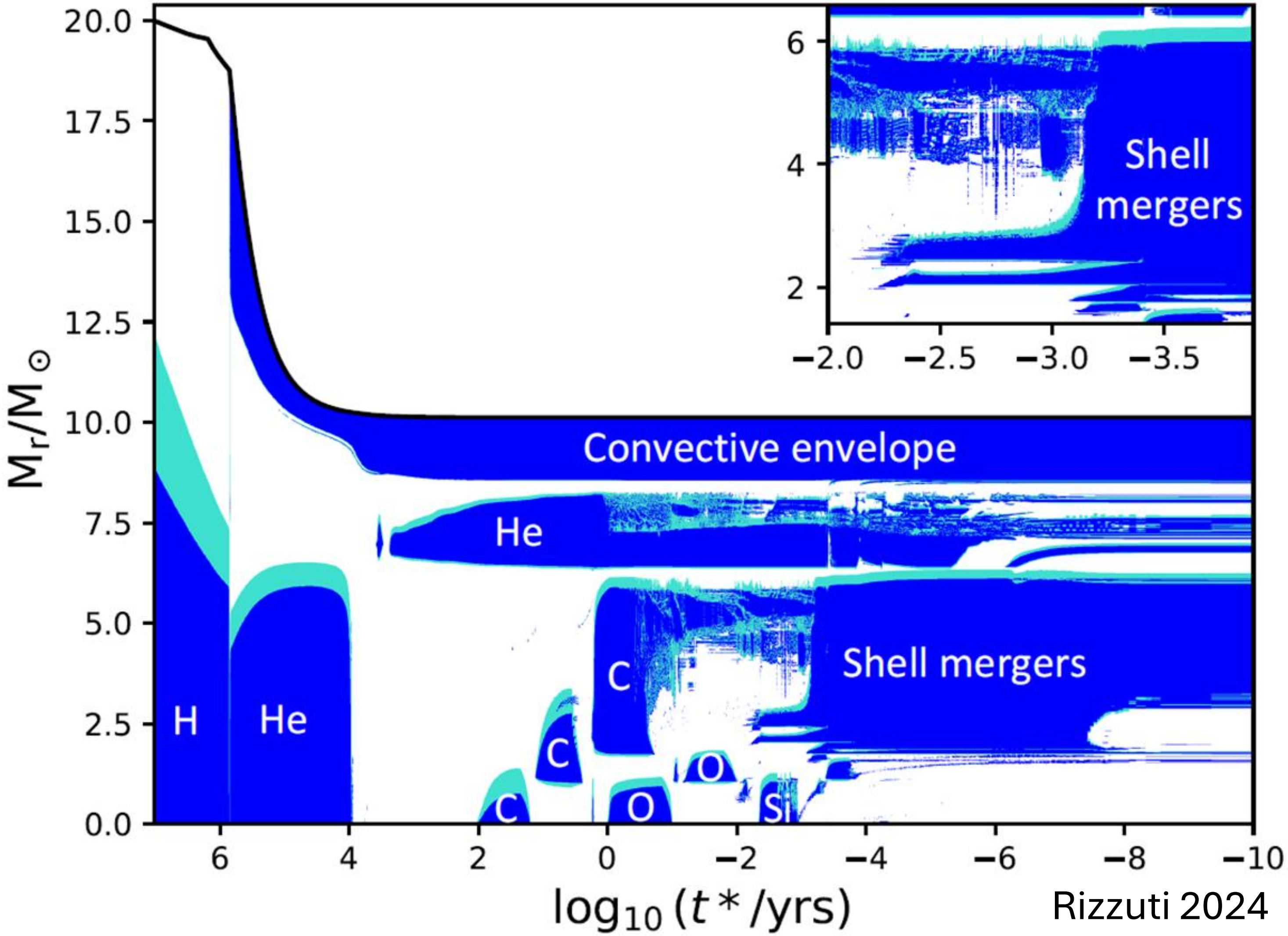
- Difference at low T mainly due to the shifted resonance energy computed taking into account the difference in electron binding energies before and after the reaction (see Laird+2023).

- Very similar reaction rates at high T (of interest for ^{26}Al)

- New extended rate available in Battino+2024

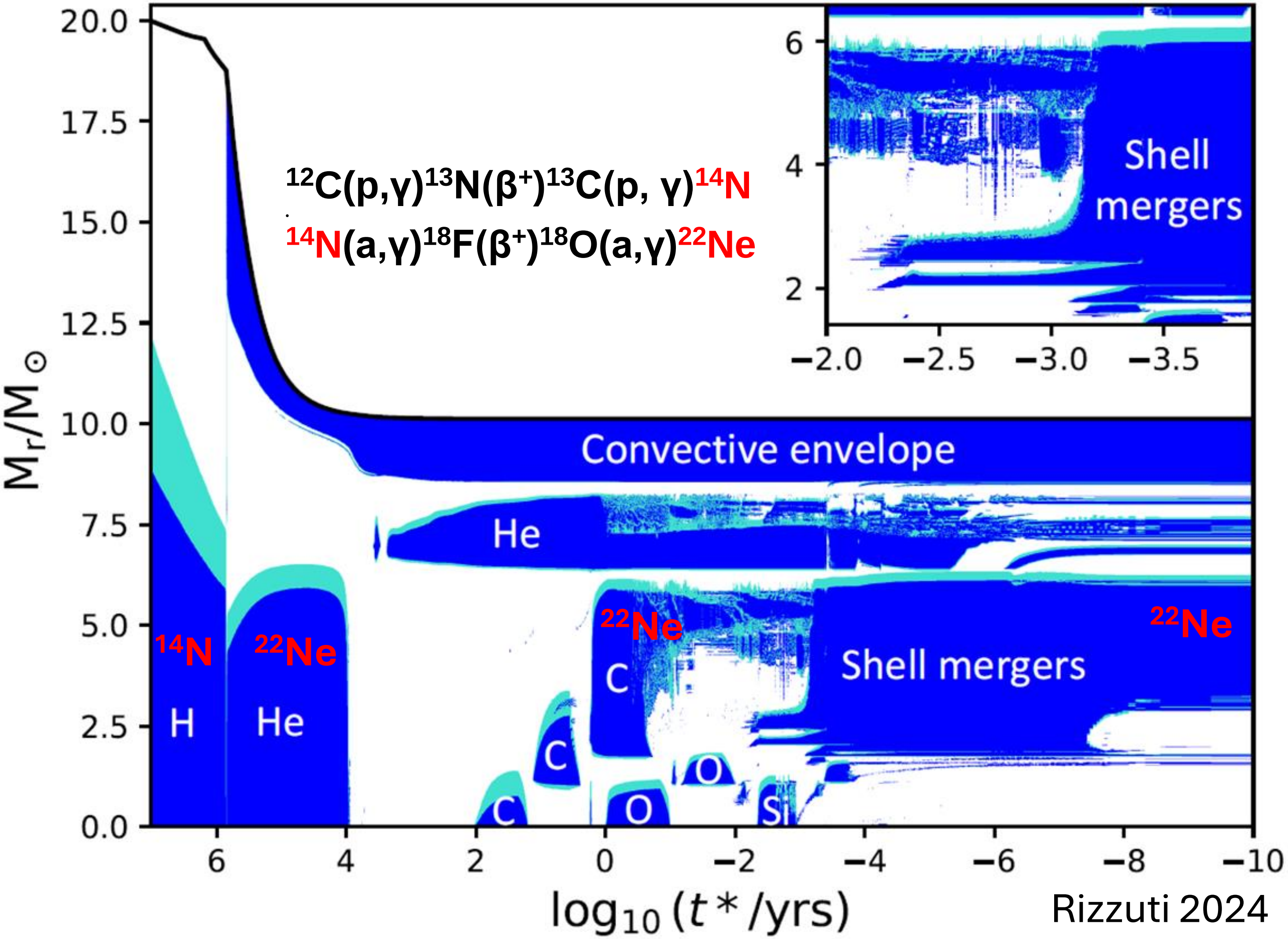


^{26}Al(n,p/a)



Rizzuti 2024

^{26}Al(n,p/a)

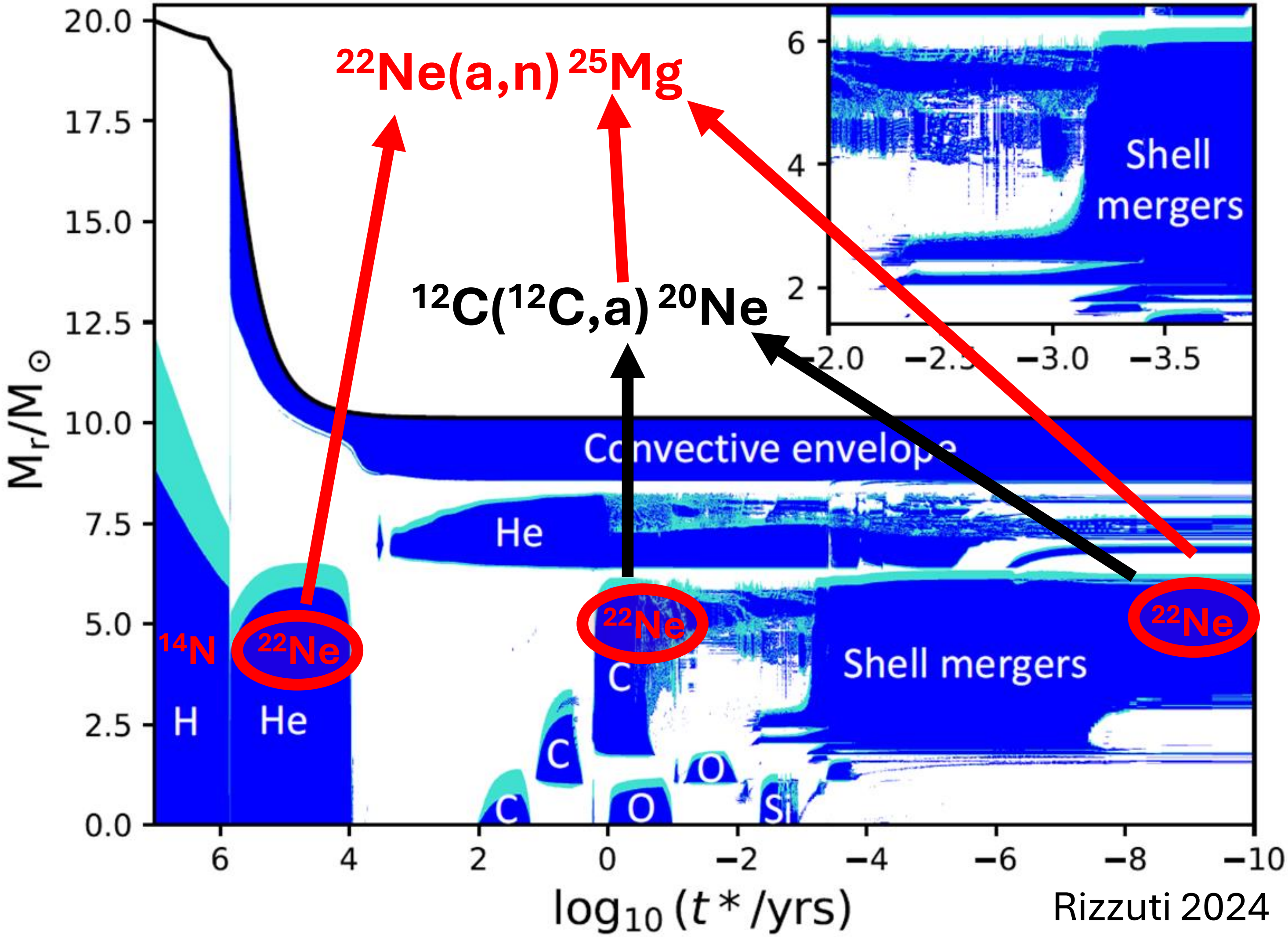


^{12}C(p,γ)^{13}N(β$^+$)^{13}C(p, γ)^{14}N

^{14}N(a,γ)^{18}F(β$^+$)^{18}O(a,γ)^{22}Ne

Rizzuti 2024

^{26}Al(n,p/a)



Rizzuti 2024

Collective impact on explosive nucleosynthesis

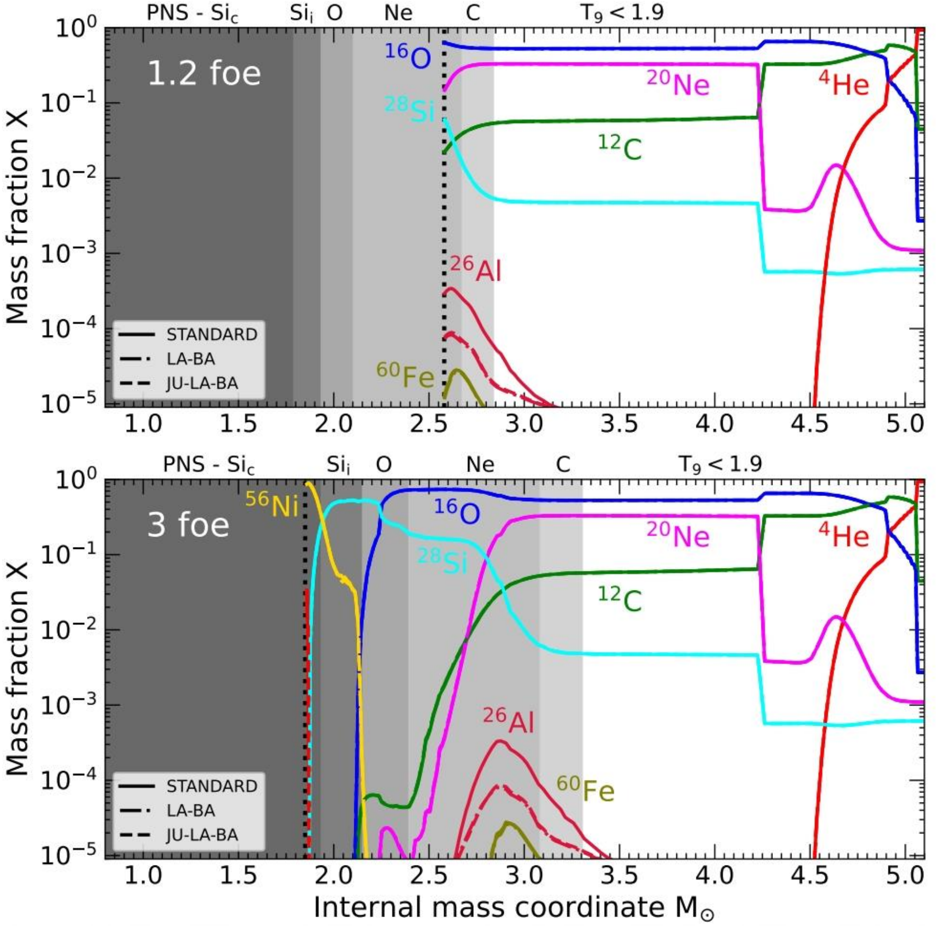
- Abundances in mass fraction of key nuclear species as a function of the internal mass coordinate in the CCSN models exploding with 1.2 and 3×10^{51} erg.

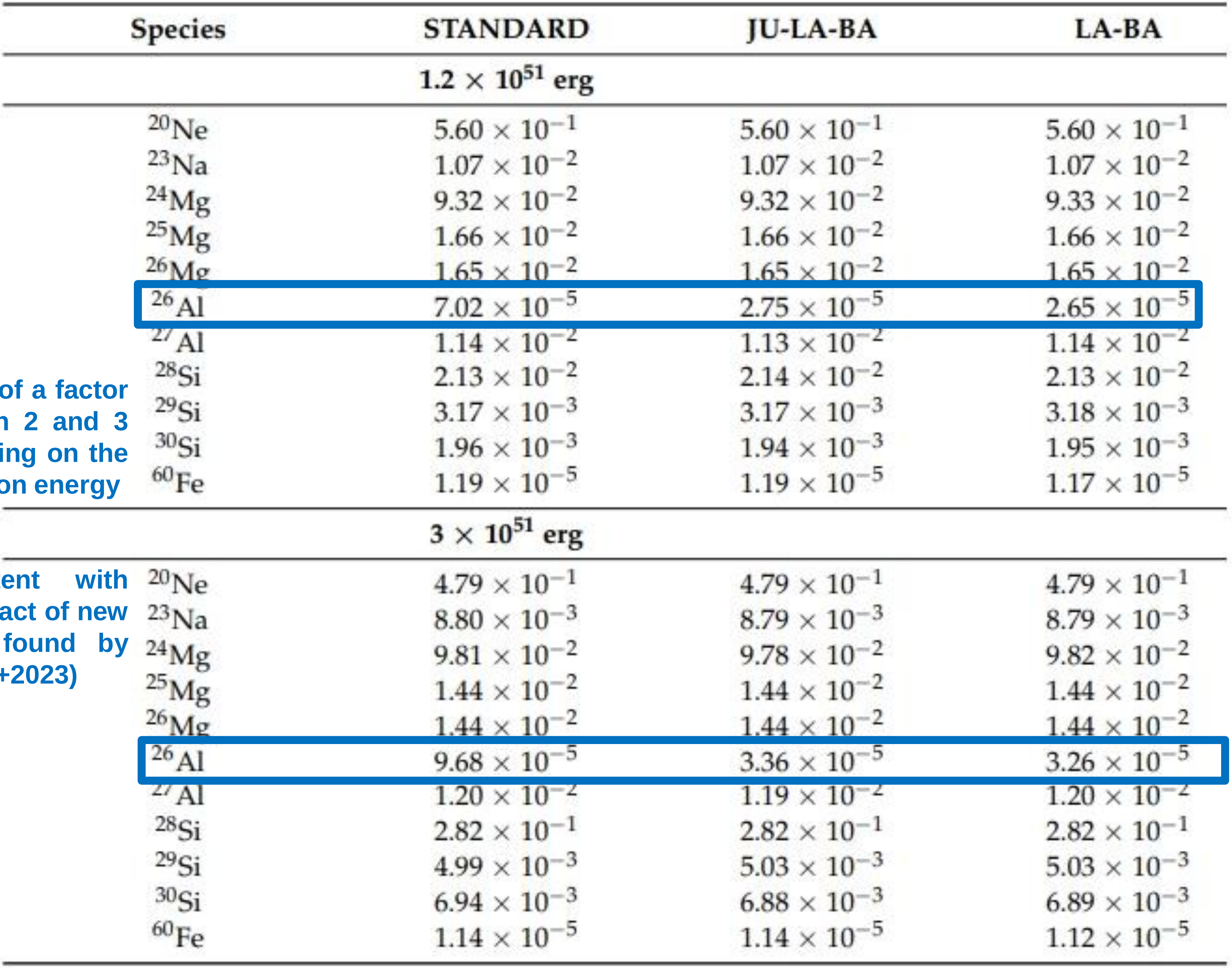
- The gray shaded areas represent each explosive burning stage; the vertical dotted line identifies the location of the mass-cut.

- **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)



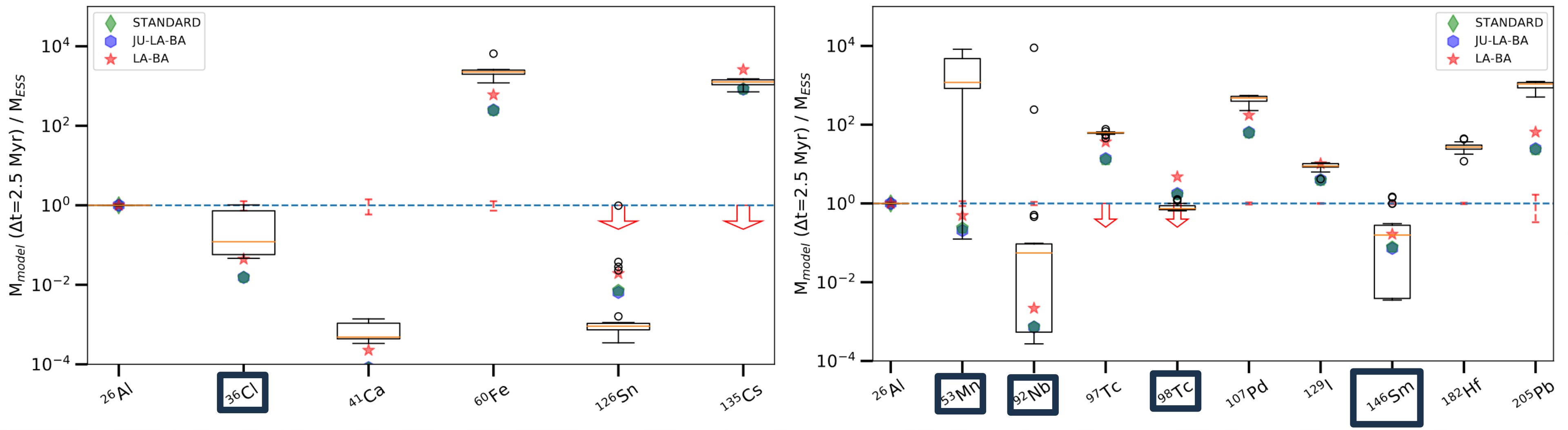


Species	STANDARD	JU-LA-BA	LA-BA
1.2×10^{51} erg			
^{20}Ne	5.60×10^{-1}	5.60×10^{-1}	5.60×10^{-1}
^{23}Na	1.07×10^{-2}	1.07×10^{-2}	1.07×10^{-2}
^{24}Mg	9.32×10^{-2}	9.32×10^{-2}	9.33×10^{-2}
^{25}Mg	1.66×10^{-2}	1.66×10^{-2}	1.66×10^{-2}
^{26}Mg	1.65×10^{-2}	1.65×10^{-2}	1.65×10^{-2}
^{26}Al	7.02×10^{-5}	2.75×10^{-5}	2.65×10^{-5}
^{27}Al	1.14×10^{-2}	1.13×10^{-2}	1.14×10^{-2}
^{28}Si	2.13×10^{-2}	2.14×10^{-2}	2.13×10^{-2}
^{29}Si	3.17×10^{-3}	3.17×10^{-3}	3.18×10^{-3}
^{30}Si	1.96×10^{-3}	1.94×10^{-3}	1.95×10^{-3}
^{60}Fe	1.19×10^{-5}	1.19×10^{-5}	1.17×10^{-5}
3×10^{51} erg			
^{20}Ne	4.79×10^{-1}	4.79×10^{-1}	4.79×10^{-1}
^{23}Na	8.80×10^{-3}	8.79×10^{-3}	8.79×10^{-3}
^{24}Mg	9.81×10^{-2}	9.78×10^{-2}	9.82×10^{-2}
^{25}Mg	1.44×10^{-2}	1.44×10^{-2}	1.44×10^{-2}
^{26}Mg	1.44×10^{-2}	1.44×10^{-2}	1.44×10^{-2}
^{26}Al	9.68×10^{-5}	3.36×10^{-5}	3.26×10^{-5}
^{27}Al	1.20×10^{-2}	1.19×10^{-2}	1.20×10^{-2}
^{28}Si	2.82×10^{-1}	2.82×10^{-1}	2.82×10^{-1}
^{29}Si	4.99×10^{-3}	5.03×10^{-3}	5.03×10^{-3}
^{30}Si	6.94×10^{-3}	6.88×10^{-3}	6.89×10^{-3}
^{60}Fe	1.14×10^{-5}	1.14×10^{-5}	1.12×10^{-5}

Impact of a factor between 2 and 3 depending on the explosion energy

Consistent with the impact of new ^{26}Al+n found by Battino+2023)

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;

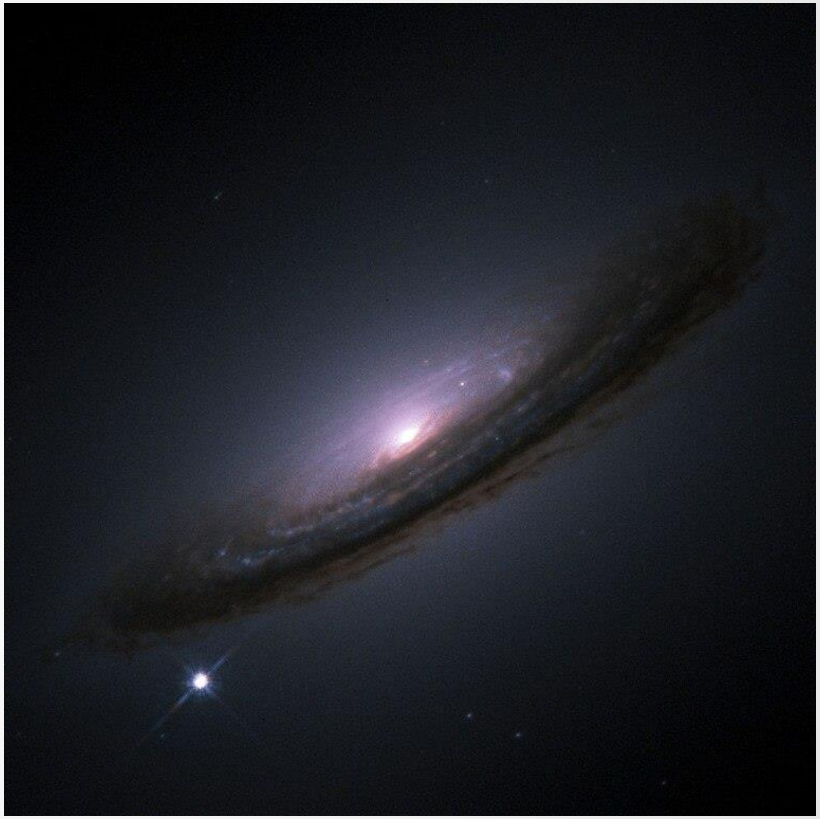
2) An additional event producing more ^{26}Al and less of the overproduced SLRs (such as ^{60}Fe) that happened close in time and space to a CCSN.

Type Ia Supernova and habitability

- 2/3 of the iron content in the Milky Way was produced by the explosion of white dwarfs in binary systems as **type Ia supernovae**.

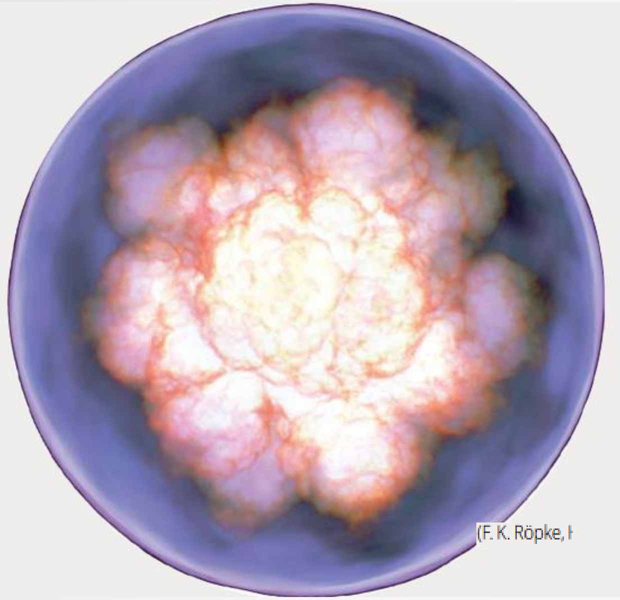
- Iron is a crucial ingredient for planetary magnetic-field generation, the formation of proteins and enzyme systems (Wade et al. 2021) → central role played in the origin of the Solar System and in the emergence of life as we know it on Earth.

- Additionally, due to their characteristic lightcurves, SNe Ia are standardizable candles for cosmic-distance measurements → evidence for the accelerated expansion of the Universe (Nobel Prize Physics, 2011)



NASA/ESA, The Hubble Key Project Team
The High-Z Supernova Search Team

SNe Ia progenitors

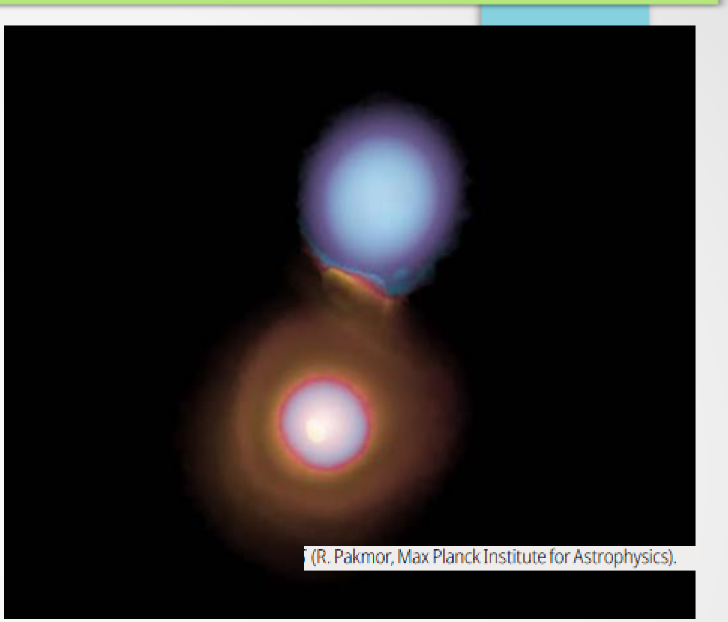


(F. K. Röpke,

Near-Chandrasekhar mass events

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)



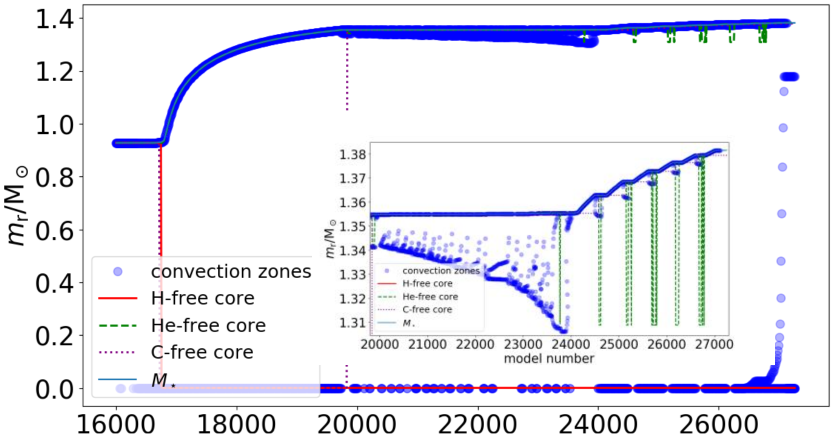
(R. Pakmor, Max Planck Institute for Astrophysics).

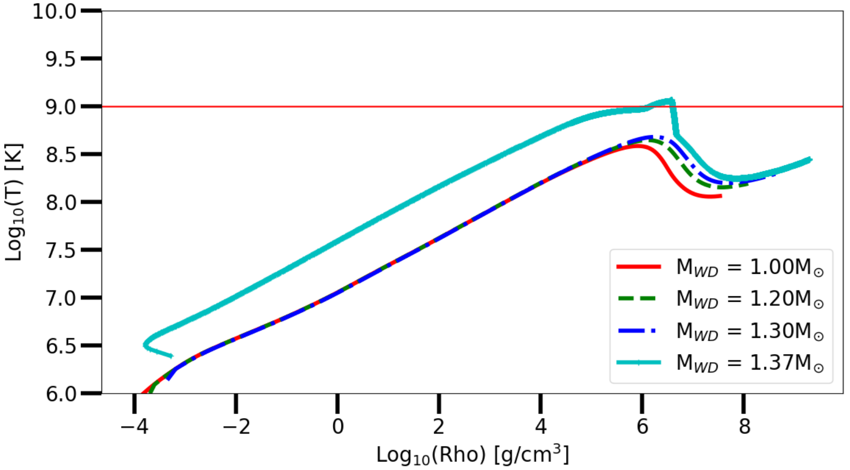
Sub-Chandrasekhar mass events

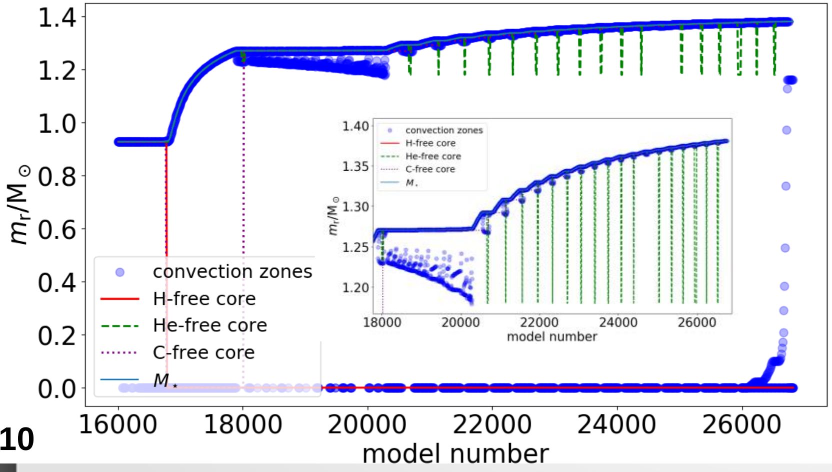
He-accretor → Double-detonation (see Fink+2010; Magee+2021)

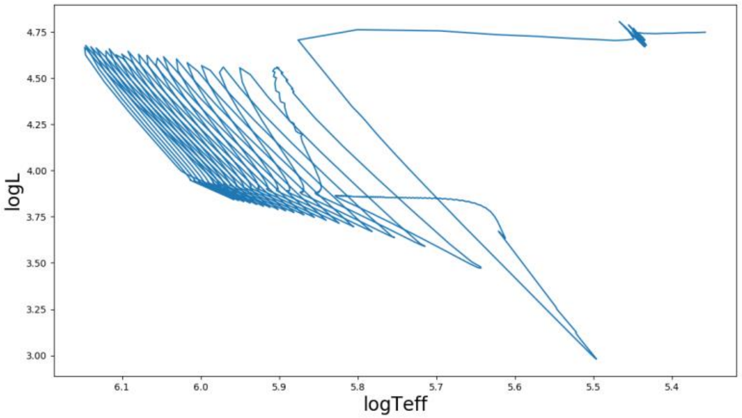
Violent merger → Prompt detonation during the merger process (if mass ratio q > ~0.8; see Pakmor et al. 2010, 2011, 2012, 2013)

Slow WD merger

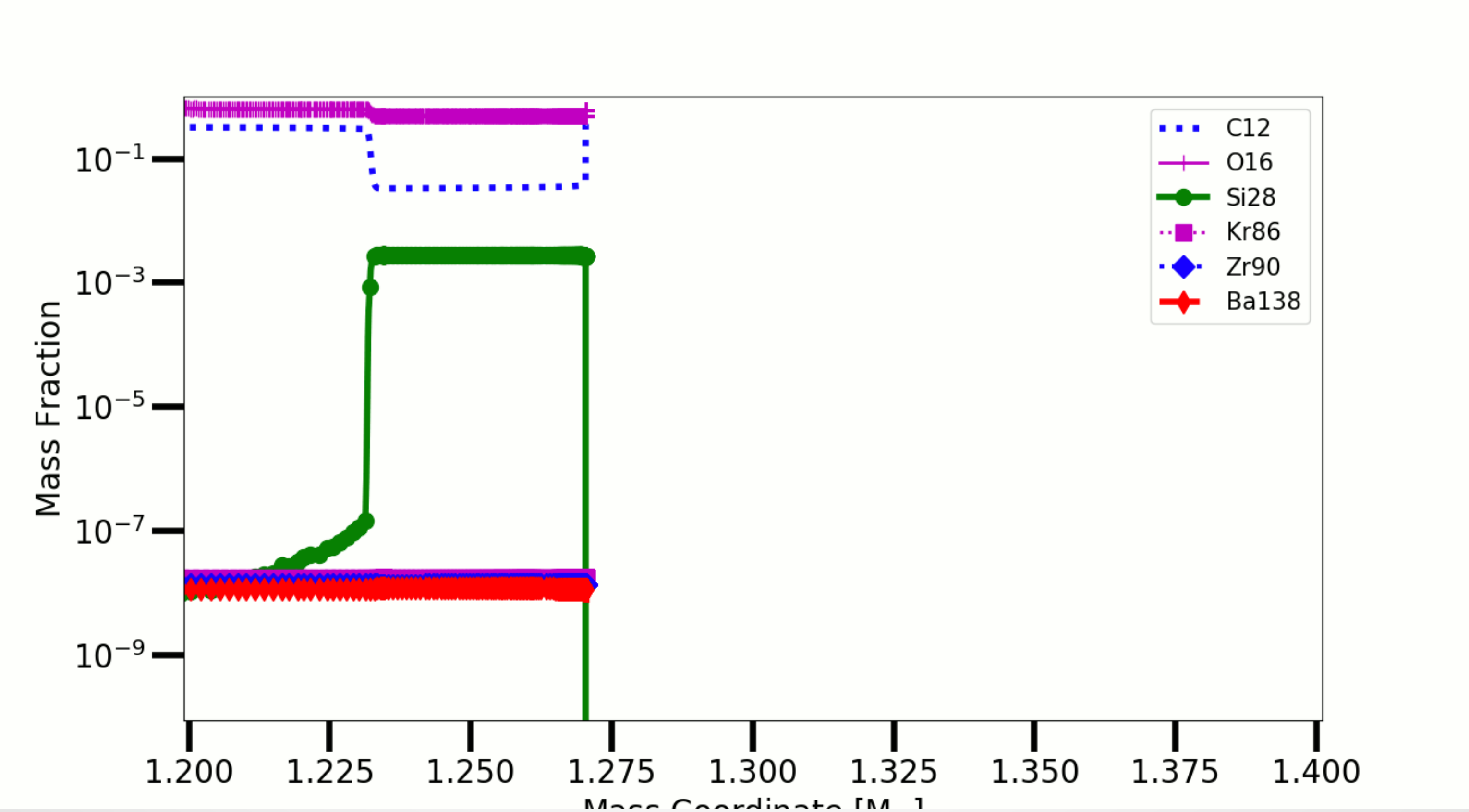






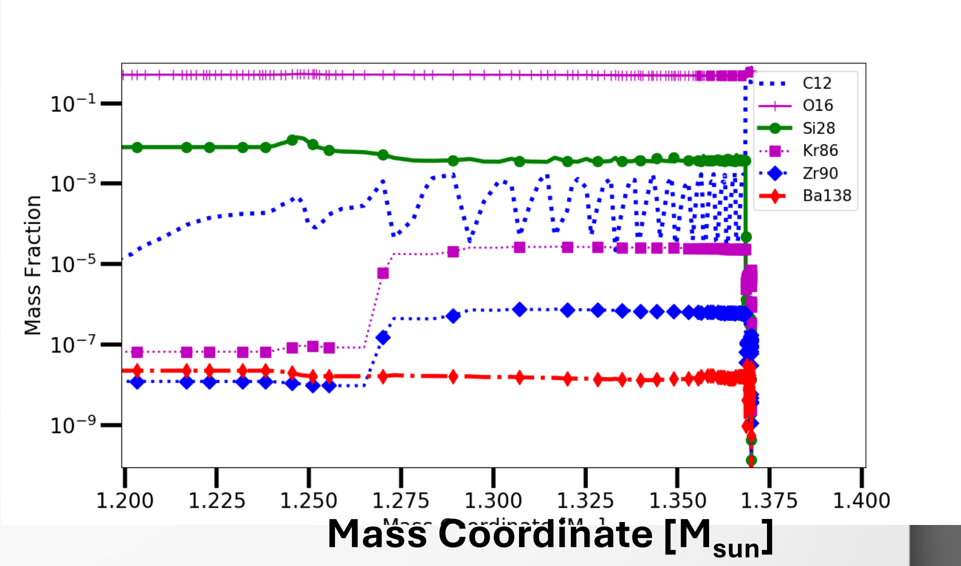


Trans-Fe element nucleosynthesis



^{28}Si and ^{44}Ti nucleosynthesis

- Due to its half-life of 59 years, ^{44}Ti decay radiation has the capability to sustain late-time supernova light curves and can be observed in young supernova remnants.
- Produced during the explosion by alpha-capture chains starting from ^{12}C/^{16}O/^{20}Ne
- The detection of ^{44}Ti can uniquely constrain the nature of SNe Ia progenitors (Kosakowski et al. 2023)
- E.g., by comparing the predictions of stellar models relying on up-to-date (nuclear) physics inputs to observations of young supernova remnants by satellite-based gamma spectrometers, such as the Compton Spectrometer and Imager (COSI, launch scheduled for 2027).



SURFACE ^{28}SI ENHANCEMENT MUST BE TAKEN INTO ACCOUNT WHEN SETTING INITIAL ABUNDANCES TO SIMULATE NEAR-CHANDRASEKHAR EXPLOSIONS!

(Here enriched by 20 to 30 times compared to solar)

Summary and future perspectives

- We computed the evolution of a high-mass star (20 Msun, 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**.

- We noticed a **substantial decrease** in the ejected amount of ^{26}Al, between a factor of two and three (depending on the explosion energy) when the newest rates are adopted → Consistent with the impacts of the new nTOF ^{26}Al+n reaction rates found by Battino+2023.

- Only **5 out of the 14 SLRs** considered here are consistent with their observed ESS values, but different progenitors need to be explored... rotating WR stars? (Rotationally enhanced mass-loss → Less ^{1}H and ^{14}N to form ^{22}Ne → Possibly less ^{60}Fe and ^{135}Cs?) → **How critical was the progenitor nature for life on Earth?**

- Relevant uncertainties still affect ^{26}Al production, both stellar and nuclear (e.g. the ^{22}Ne+alpha rates adopted)

- Full results in **Battino et al. 2023** (MNRAS **520**,2436–2444) and **Battino et al. 2024** (Universe 2024, 10, 204.)

Summary and future perspectives

- Large production of trans-Fe elements on slow white dwarf mergers → First, preliminary, results in **Battino et al. 2022** (NIC-XVI proceedings)
- What impact on GCE? A new observable 'smoking gun' of a Chandrasekhar explosion?
- Great deep and all-sky surveys are about to start!! (LSST, 4MOST-TiDES etc…)
- Surface C-burning also leeds to high production (20 to 30 times compare to the initial solar abundances) of ^{28}Si → Possible relevant impact of ^{44}Ti production

VERA C. RUBIN OBSERVATORY

LSST Legacy Survey of Space and Time

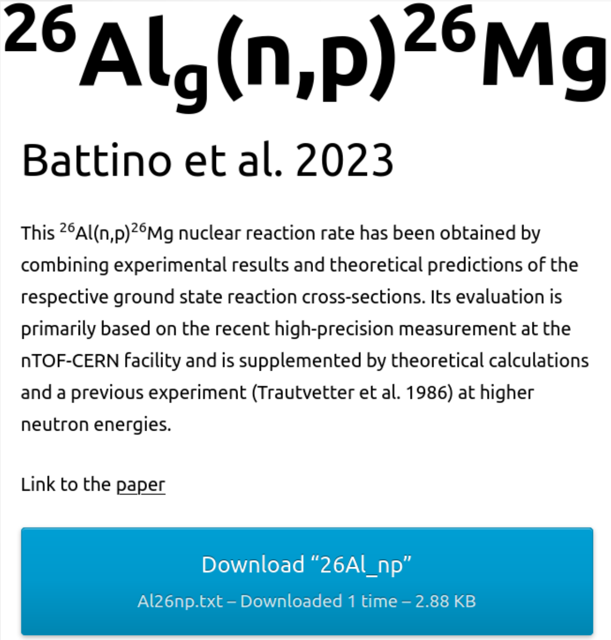
4MOST

Grazie!

Thank you!!

New rates available on ChANUREPS

(http://chanureps.chetec-infra.eu/)



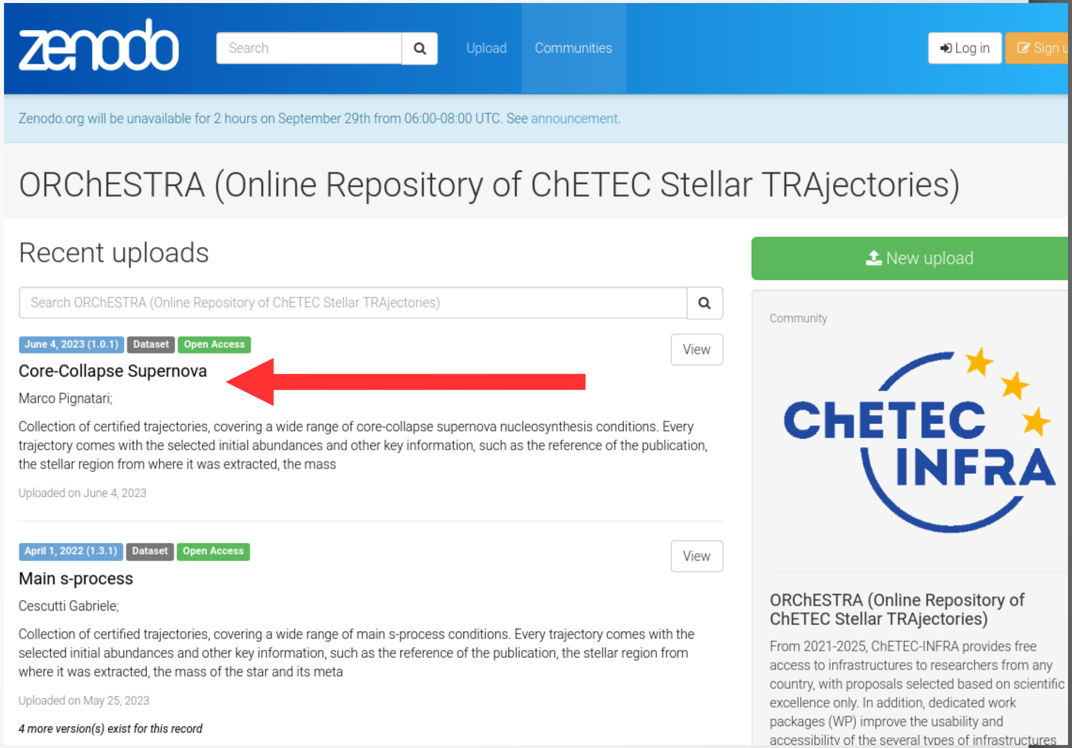
$^{26}Al_g(n,p)^{26}Mg$

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

Massive star trajectory available on OrCHESTRA



Zenodo.org will be unavailable for 2 hours on September 29th from 06:00-08:00 UTC. See announcement.

ORChESTRA (Online Repository of ChETEC Stellar TRAjectories)

Recent uploads

Core-Collapse Supernova

Marco Pignatari;

Collection of certified trajectories, covering a wide range of core-collapse supernova nucleosynthesis conditions. Every trajectory comes with the selected initial abundances and other key information, such as the reference of the publication, the stellar region from where it was extracted, the mass

Uploaded on June 4, 2023

Main s-process

Cescutti Gabriele;

Collection of certified trajectories, covering a wide range of main s-process conditions. Every trajectory comes with the selected initial abundances and other key information, such as the reference of the publication, the stellar region from where it was extracted, the mass of the star and its meta

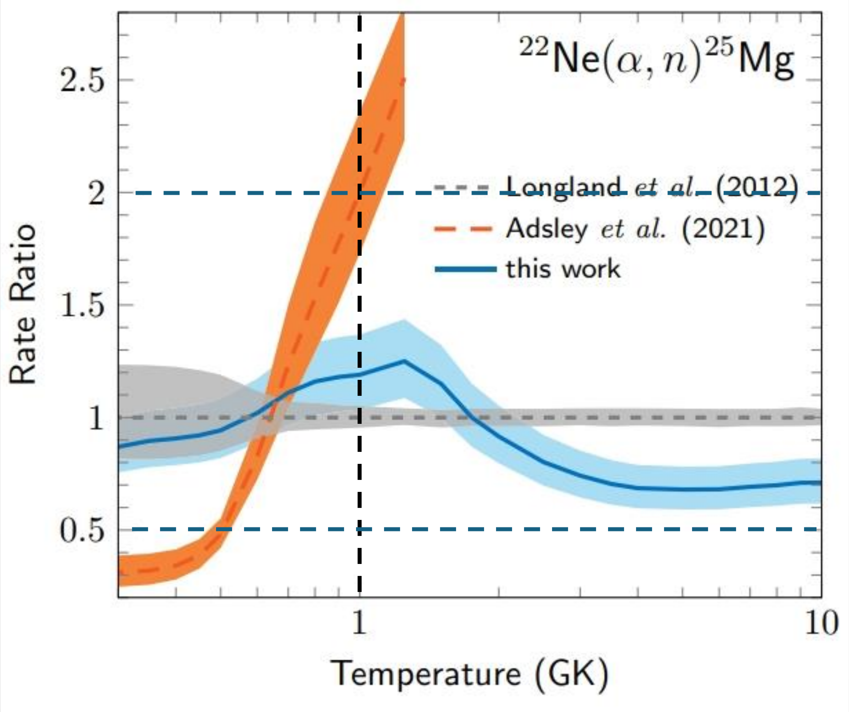
Uploaded on May 25, 2023

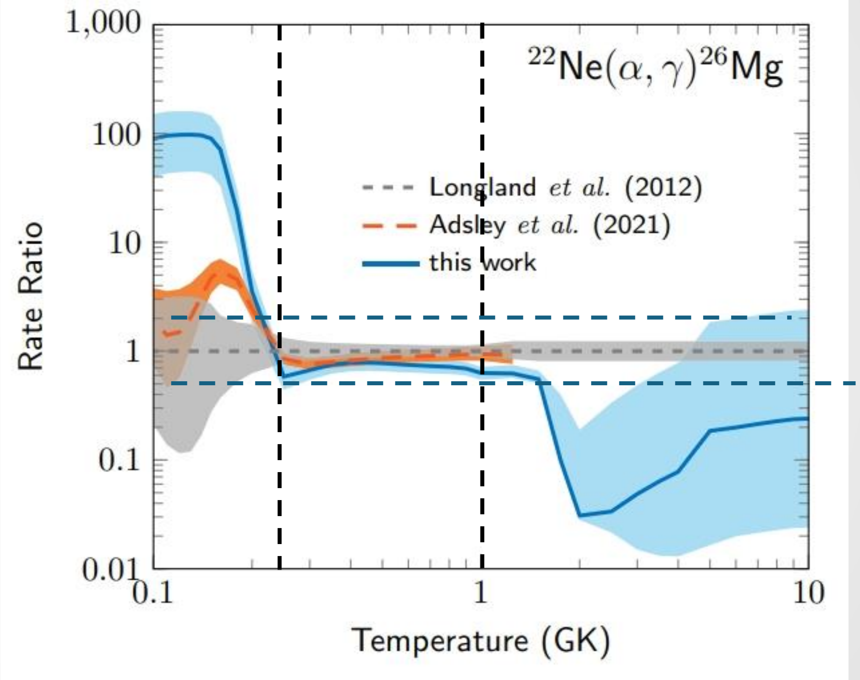
4 more version(s) exist for this record

ORChESTRA (Online Repository of ChETEC Stellar TRAjectories)

From 2021-2025, ChETEC-INFRA provides free access to infrastructures to researchers from any country, with proposals selected based on scientific excellence only. In addition, dedicated work packages (WP) improve the usability and accessibility of the several types of infrastructures

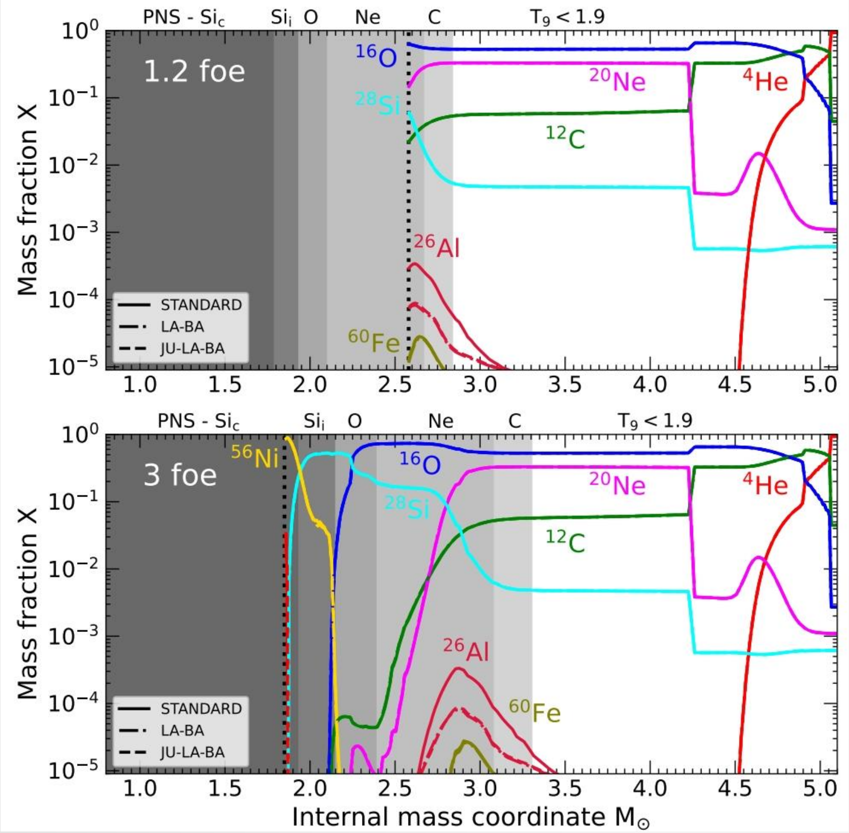
Impact of ^{22}Ne+alpha rates

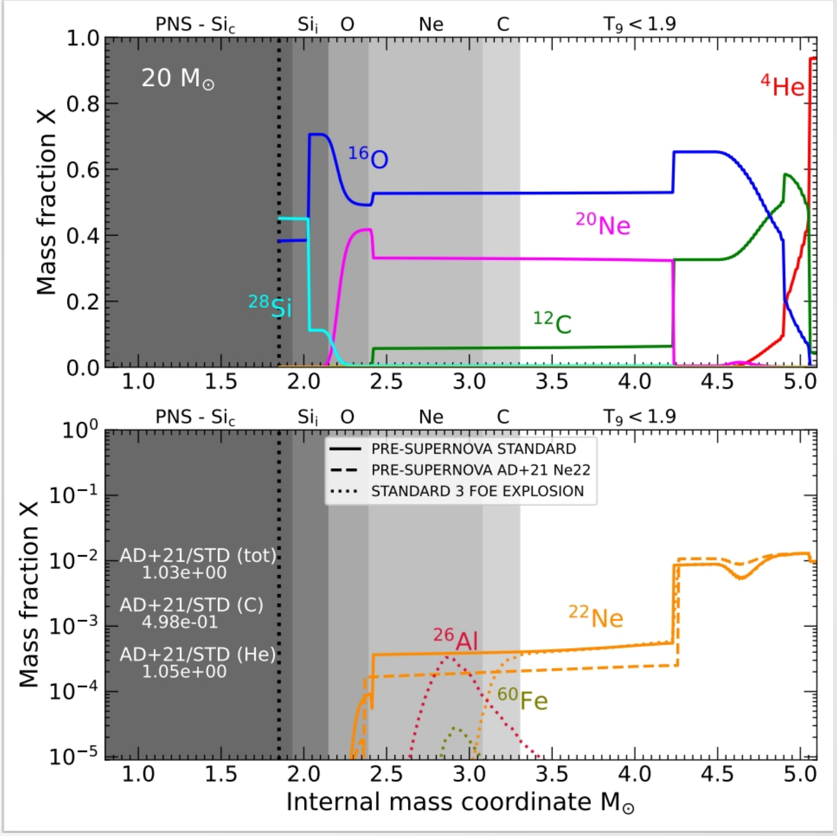




Wiescher et al.; 2023

Explosive CCSN nucleosynthesis





Battino + 2024

~Factor of two impact on ^{26}Al abundance

→ Impact on ^{60}Fe/^{26}Al

(to be compared with INTEGRAL data!)