Possible neutron capture measurements at n_TOF for astrophysics

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Meeting nazionale n_TOF
Bologna – Italia, 21-22 Novembre 2024

Origin of the heavy elements

s(low) process

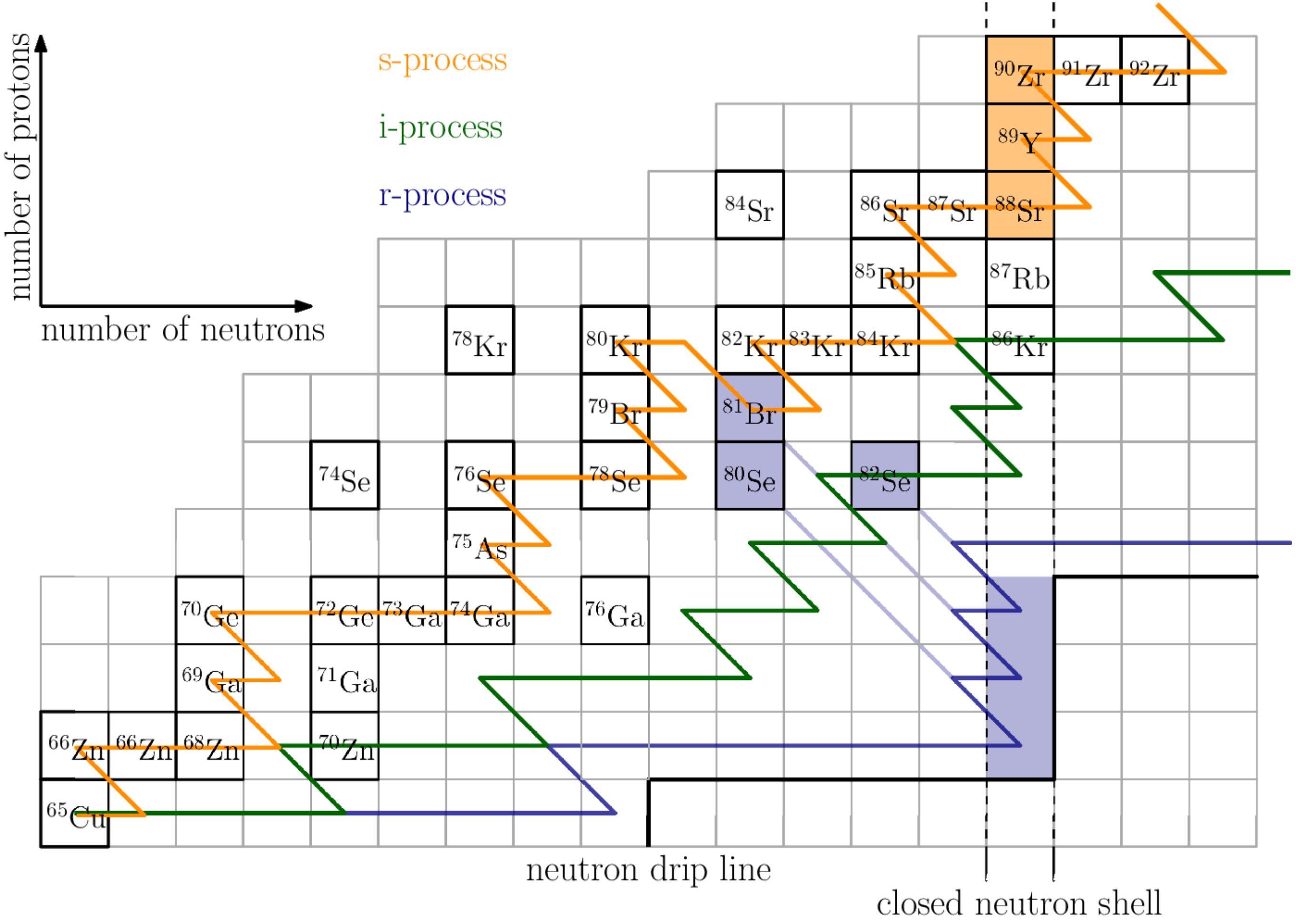
- Mild neutron density n_n~10^7
- Asymptotic giant branch (AGB) and massive stars

i(ntermediate) process

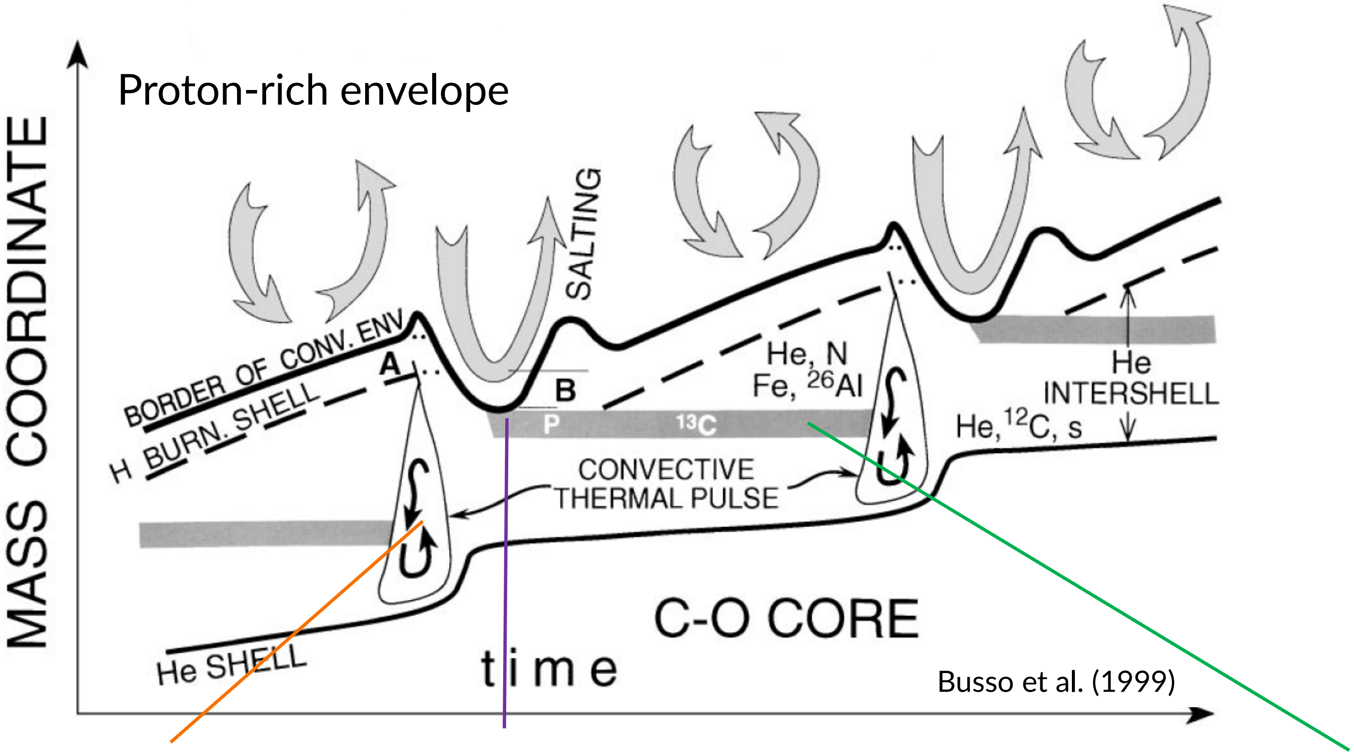
- Intemerdiate neutron density n_n~10^{15}
- AGB, rapidly accreting white dwarfs, massive stars, etc.

r(apid) process

- High neutron density $n_n \gtrsim 10^{21}$
- Supernovae and compact binary mergers



s-Processing in AGB stars



Busso et al. (1999)

- What?
  Low-Mass Stars
- When?
  Asymptotic Giant Branch (AGB)
- How?
  Thermally Pulsing (TP)

He-flash — Protons — $^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C$ — ^{13}C-pocket

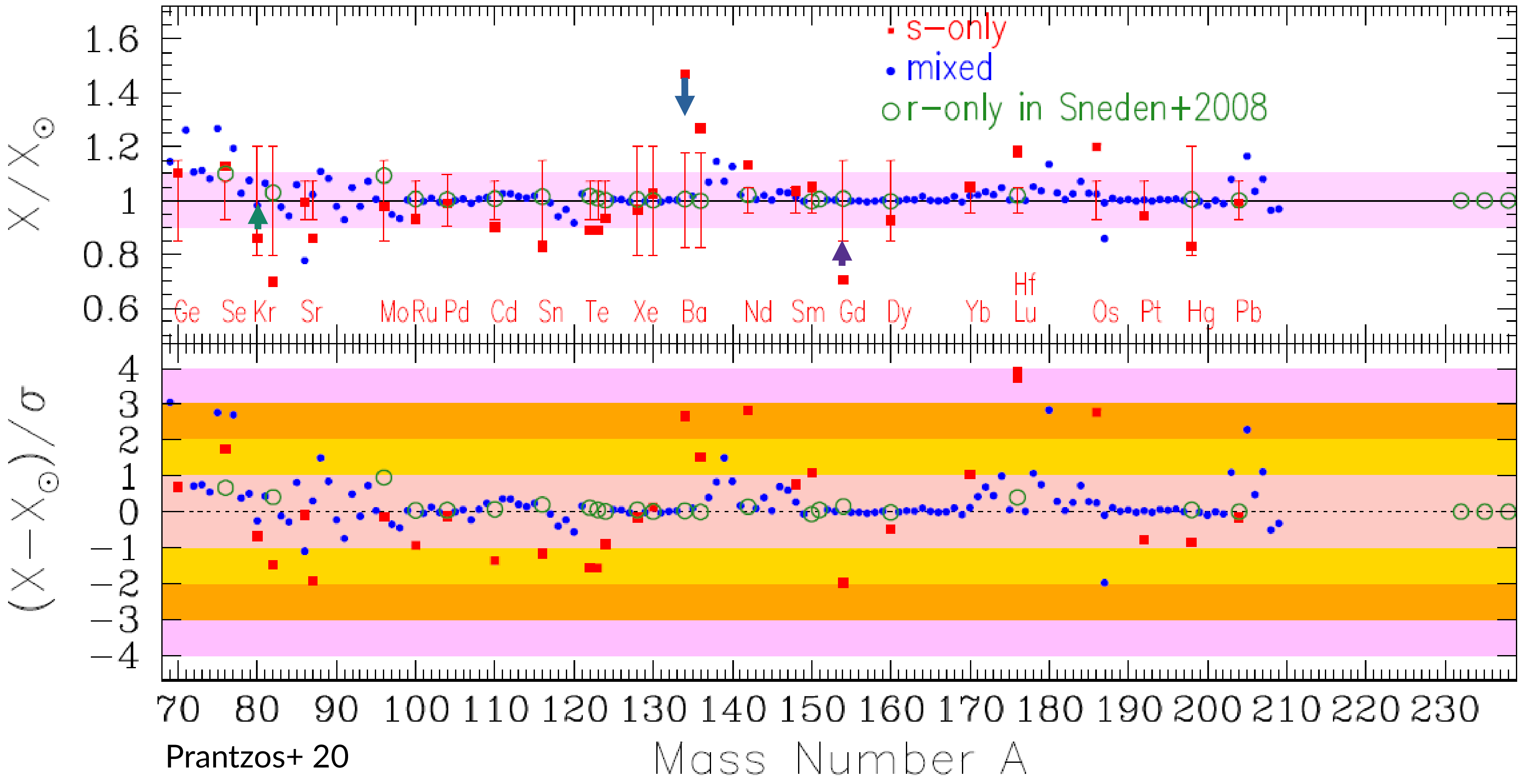
$^{22}Ne(\alpha,n)$ — $^{13}C(\alpha,n)$ → Heavy elements!!

Comparison to solar distribution

Mazzone+ 20

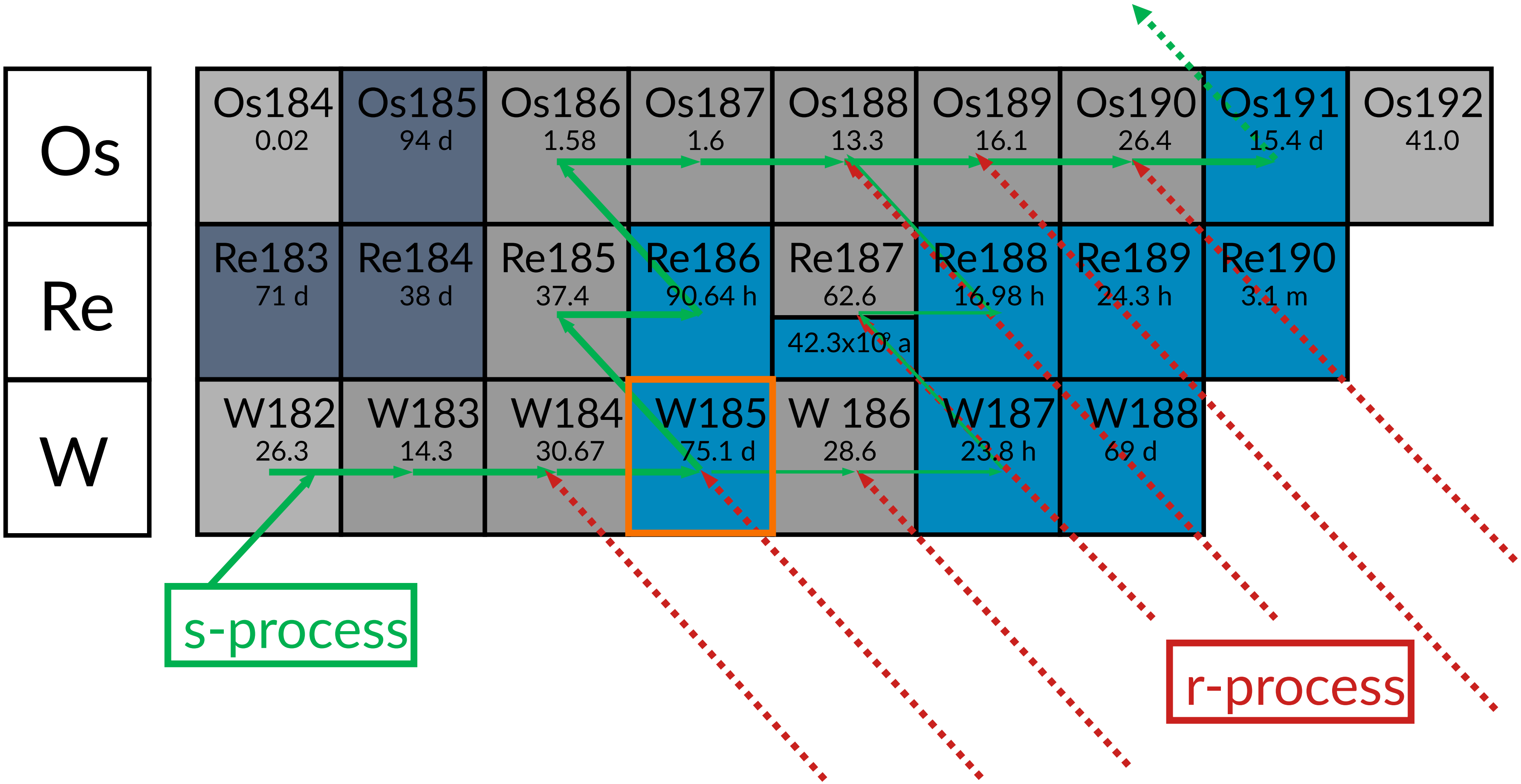
Tessler+ 21

Taioli+ 22



Prantzos+ 20

Branchings in the s-process



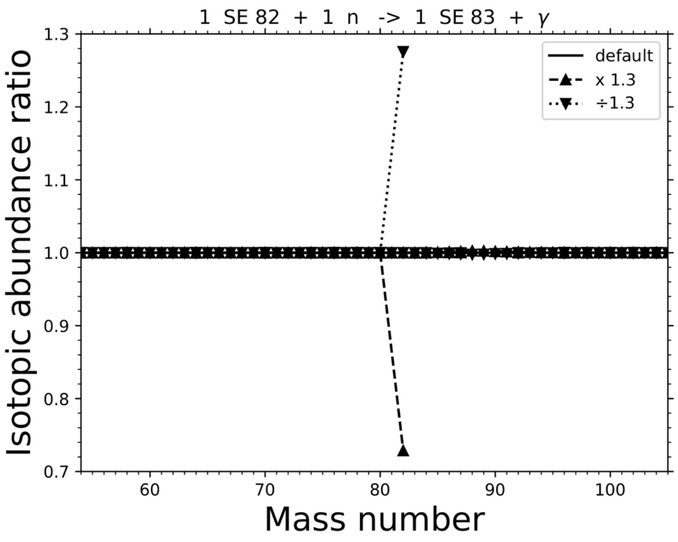
Os	Os184 0.02	Os185 94 d	Os186 1.58	Os187 1.6	Os188 13.3	Os189 16.1	Os190 26.4	Os191 15.4 d	Os192 41.0
Re	Re183 71 d	Re184 38 d	Re185 37.4	Re186 90.64 h	Re187 62.6 42.3x10^9 a	Re188 16.98 h	Re189 24.3 h	Re190 3.1 m	
W	W182 26.3	W183 14.3	W184 30.67	W185 75.1 d	W 186 28.6	W187 23.8 h	W188 69 d		

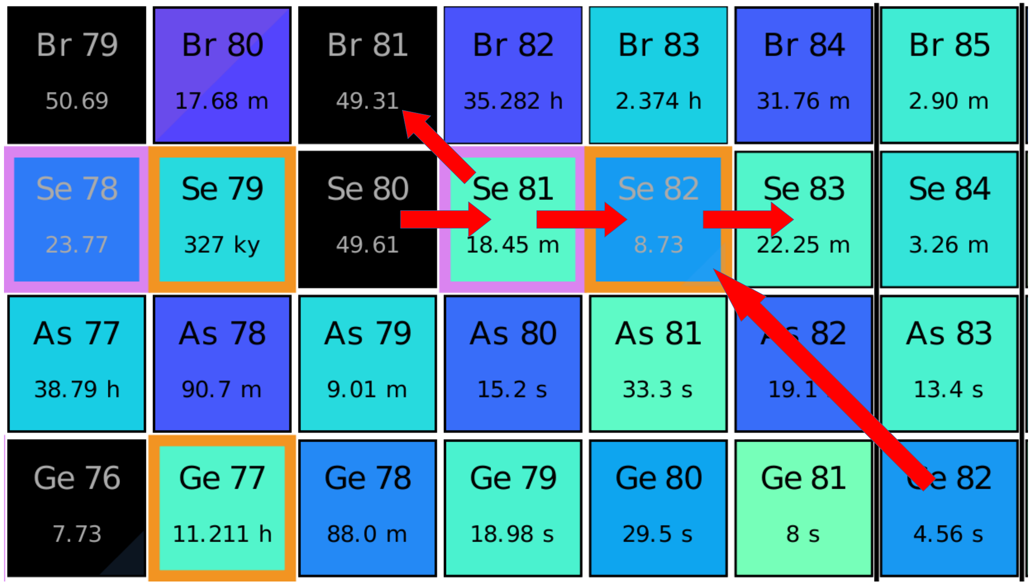
- **Branching points**: if $\tau_n \sim \tau_\beta$ several paths are possible

^{82}Se

- ^{82}Se is a stable nucleus
- Its production during the s-process largely depends on the branching at ^{79}Se and ^{81}Se
- Its solar value is mostly of r-process origin (88,9%; see Prantzos+ 20)
- It can be produced via the i-process
- Its abundance is mostly determined by the ^{82}Se(n,γ) (Pignatari+ 23, Martinet+ 24)

Pignatari+ 23, EPJA





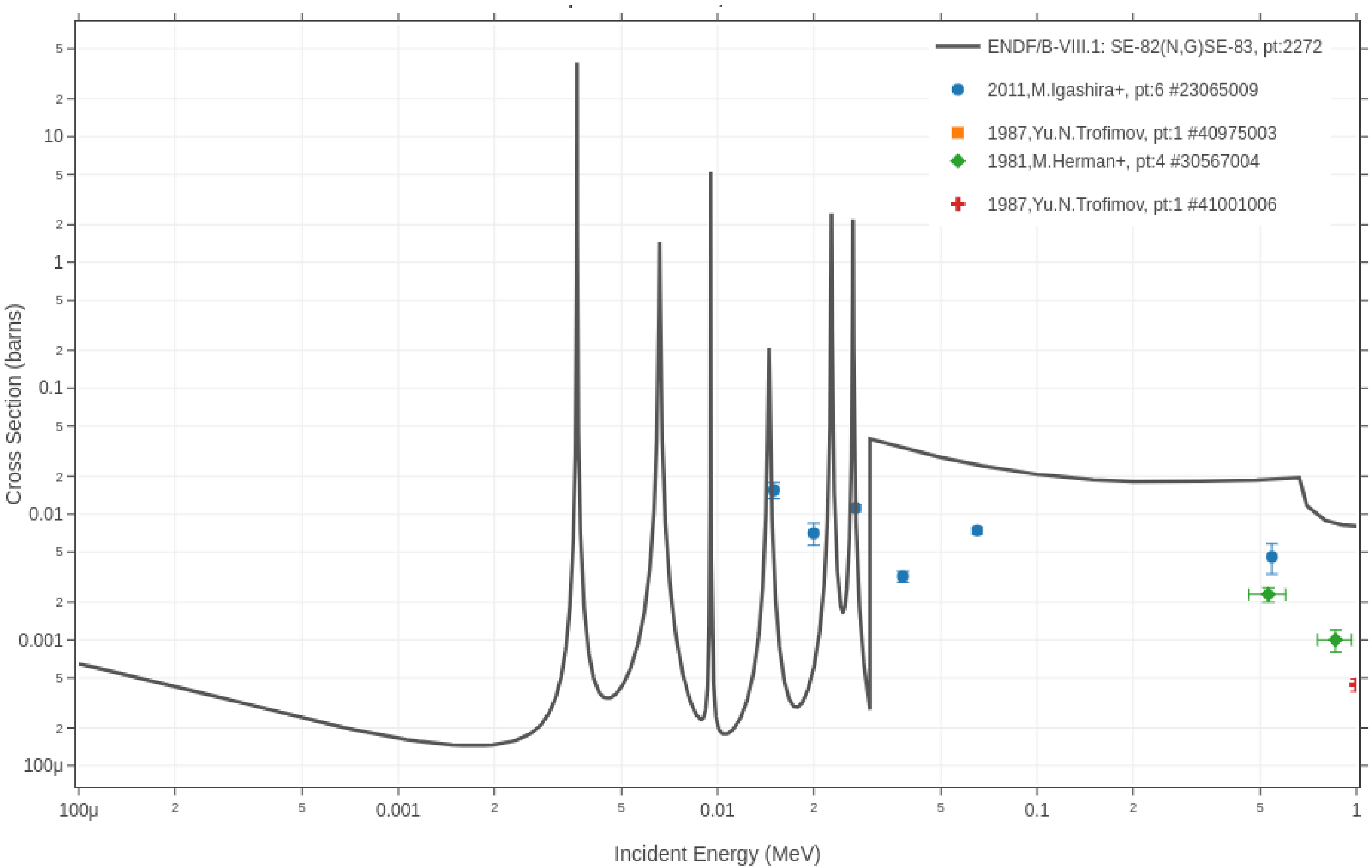
Br 79 50.69	Br 80 17.68 m	Br 81 49.31	Br 82 35.282 h	Br 83 2.374 h	Br 84 31.76 m	Br 85 2.90 m
Se 78 23.77	Se 79 327 ky	Se 80 49.61	Se 81 18.45 m	Se 82 8.73	Se 83 22.25 m	Se 84 3.26 m
As 77 38.79 h	As 78 90.7 m	As 79 9.01 m	As 80 15.2 s	As 81 33.3 s	As 82 19.1	As 83 13.4 s
Ge 76 7.73	Ge 77 11.211 h	Ge 78 88.0 m	Ge 79 18.98 s	Ge 80 29.5 s	Ge 81 8 s	Ge 82 4.56 s

Martinet+ 24, A&A

🟪	Mild Impact
🟧	Medium Impact
🟥	High Impact

^{82}Se

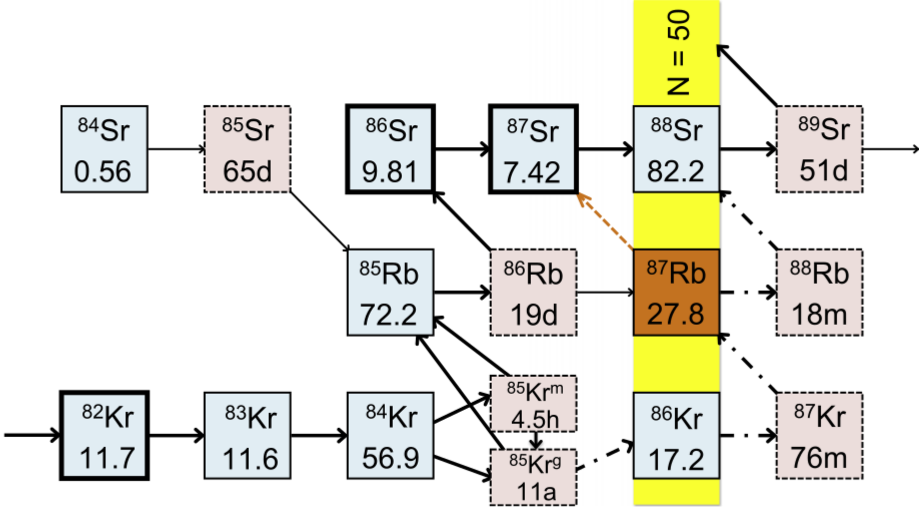
- ^{82}Se MACS adopted in the astrophysical codes is theoretical

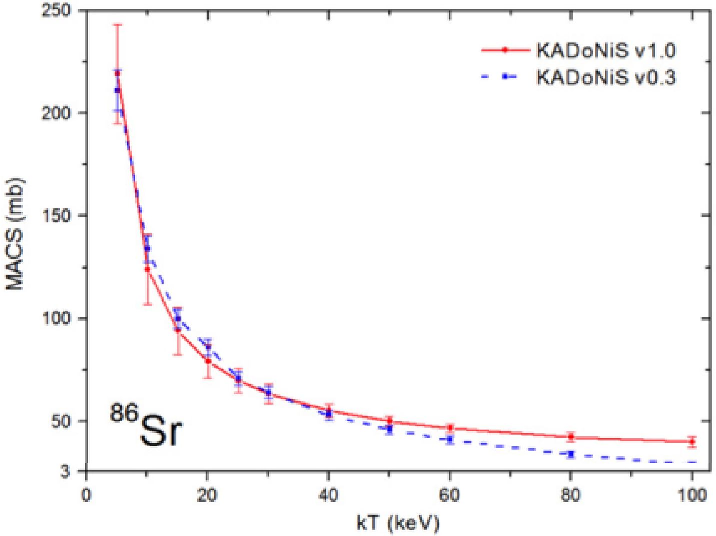


^{86,87,88}Sr

Liu+ 15, ApJ

- ^{86,87,88}Sr are produced during the main s-process
- ^{88}Sr has very low cross section → bottleneck, difficult measurement
- Extremely precise measurements of strontium isotopic ratios in presolar grains
- Measurements already proposed by us in 2022 and 2023 but ^{87}Sr proposal by Gunsing+ recently approved by INTC
- ^{86}Sr MACS evaluation based on TOF measurements by Macklin 89

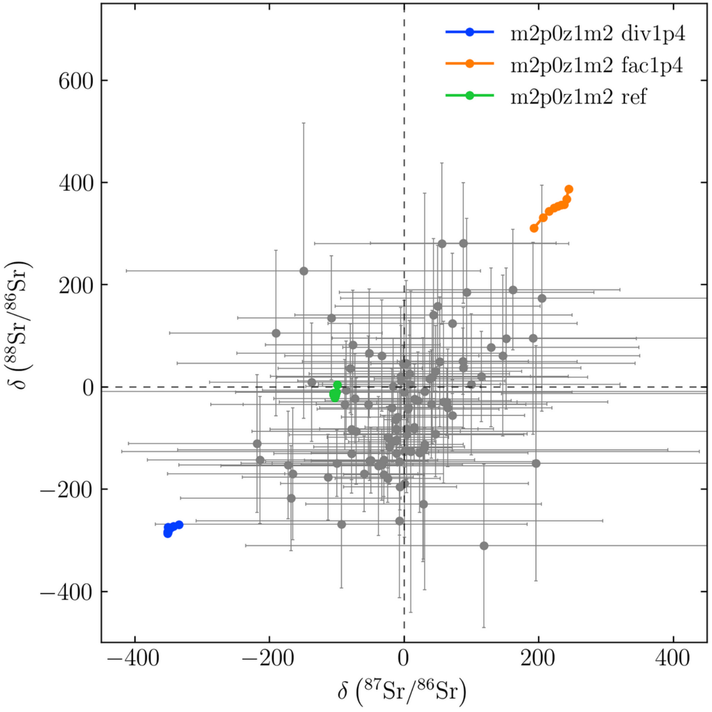


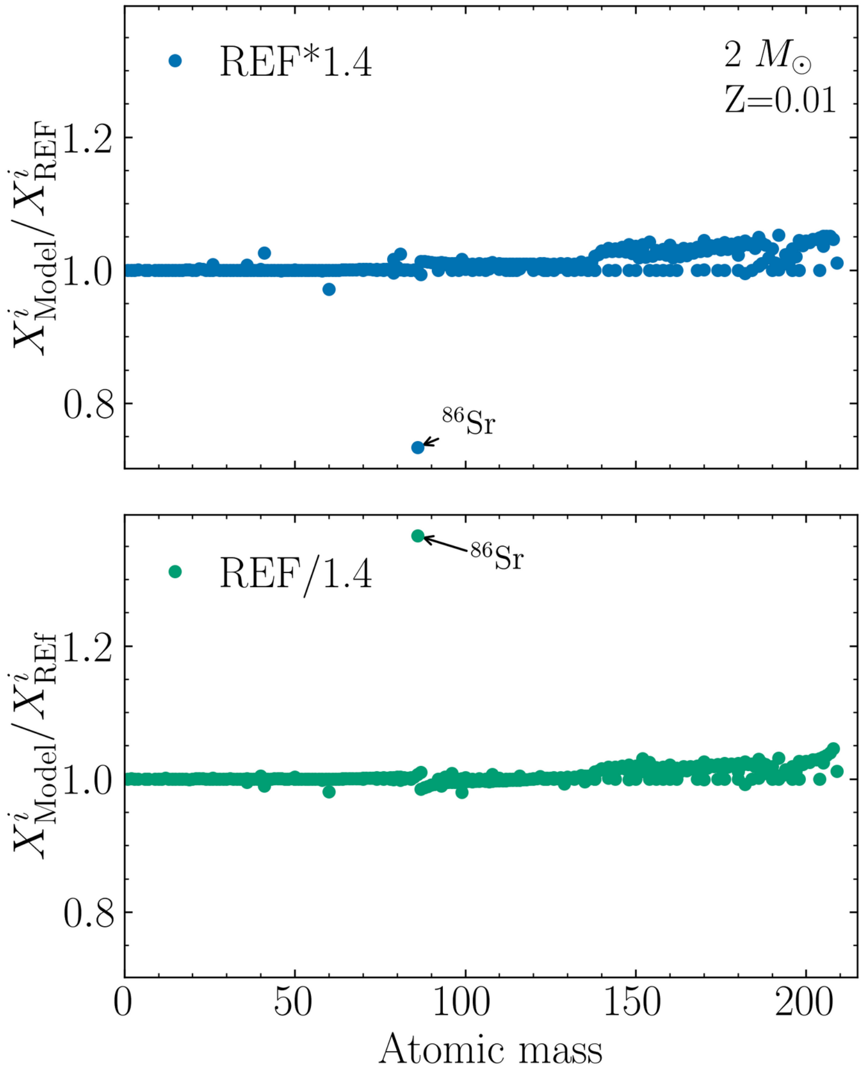


^{86}Sr

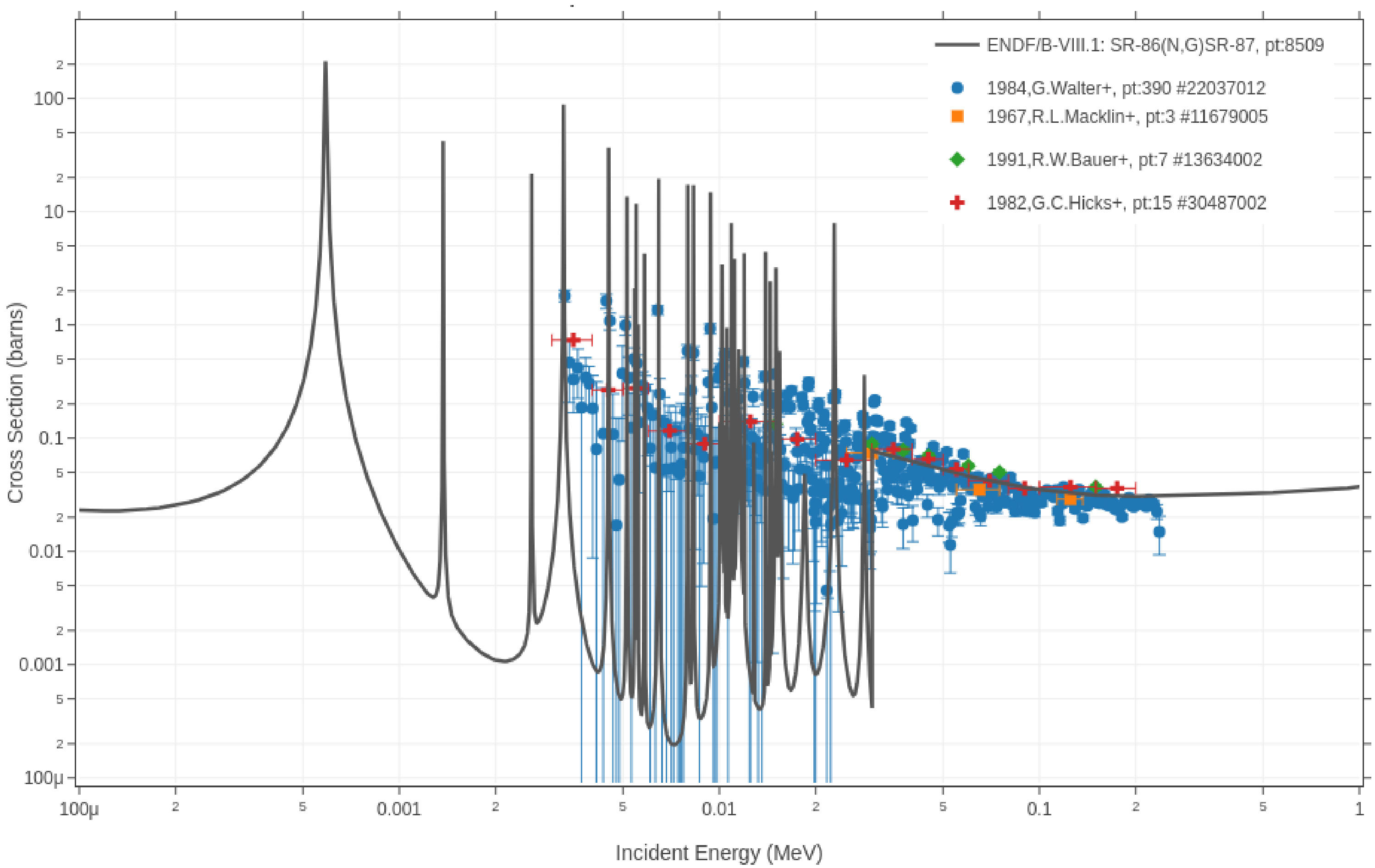
- ^{86}Sr is a reference term for Sr isotopic ratio

- Tests varying the ^{86}Sr MACS by ±40%





^{86}Sr


ENDF/B-VIII.1: SR-86(N,G)SR-87, pt:8509
1984,G.Walter+, pt:390 #22037012
1967,R.L.Macklin+, pt:3 #11679005
1991,R.W.Bauer+, pt:7 #13634002
1982,G.C.Hicks+, pt:15 #30487002
Cross Section (barns)
100
10
1
0.1
0.01
0.001
100μ
Incident Energy (MeV)
100μ
0.001
0.01
0.1
1
2
5

^{99}Tc

- The half life of ^{99}Tc is 0.21 Myr
- 0.11 Myr at 100 MK
- 4.5 years at 300 MK

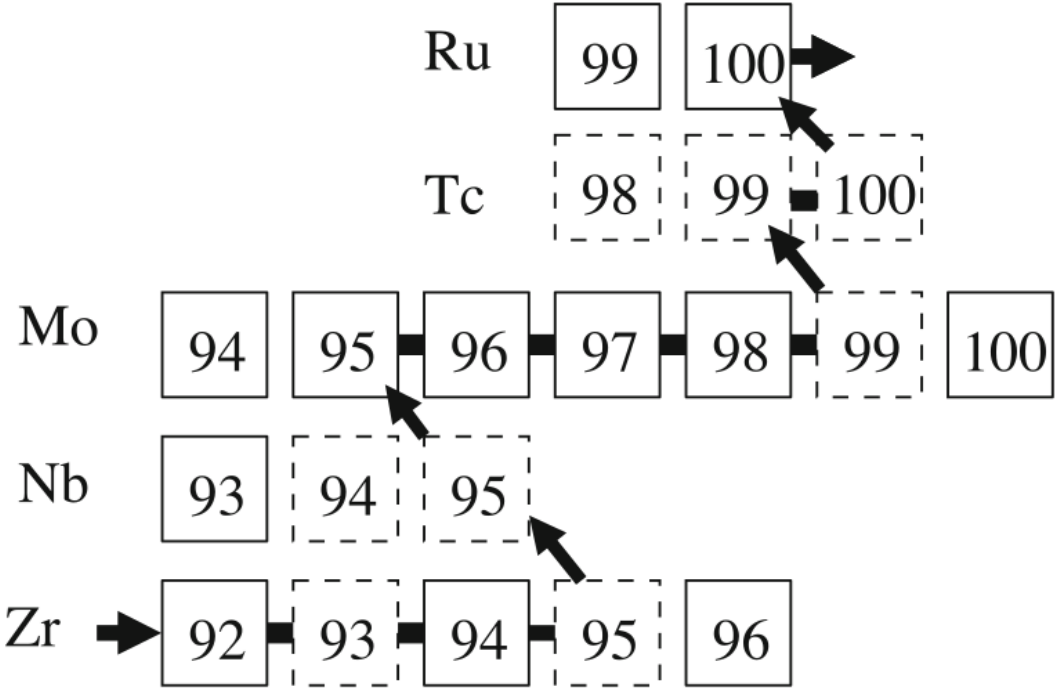
→ The neutron-capture path of the branching point is mostly open, producing ^{100}Tc, which quickly decays into ^{100}Ru, thus skipping ^{99}Ru

→ Radiogenic decay of ^{99}Tc produces ^{99}Ru

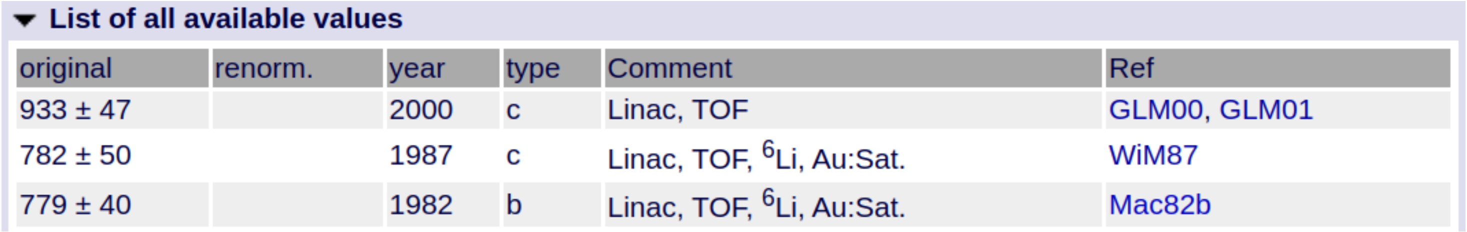
→ Observation of Tc in AGB stars

→ Presence of ^{99}Tc in single stardust SiC grains at the time of their formation discovered via laboratory analysis of the Ru isotopic composition of these grains (Savina+ 04)

Lugaro & Chieffi 18, ASSL

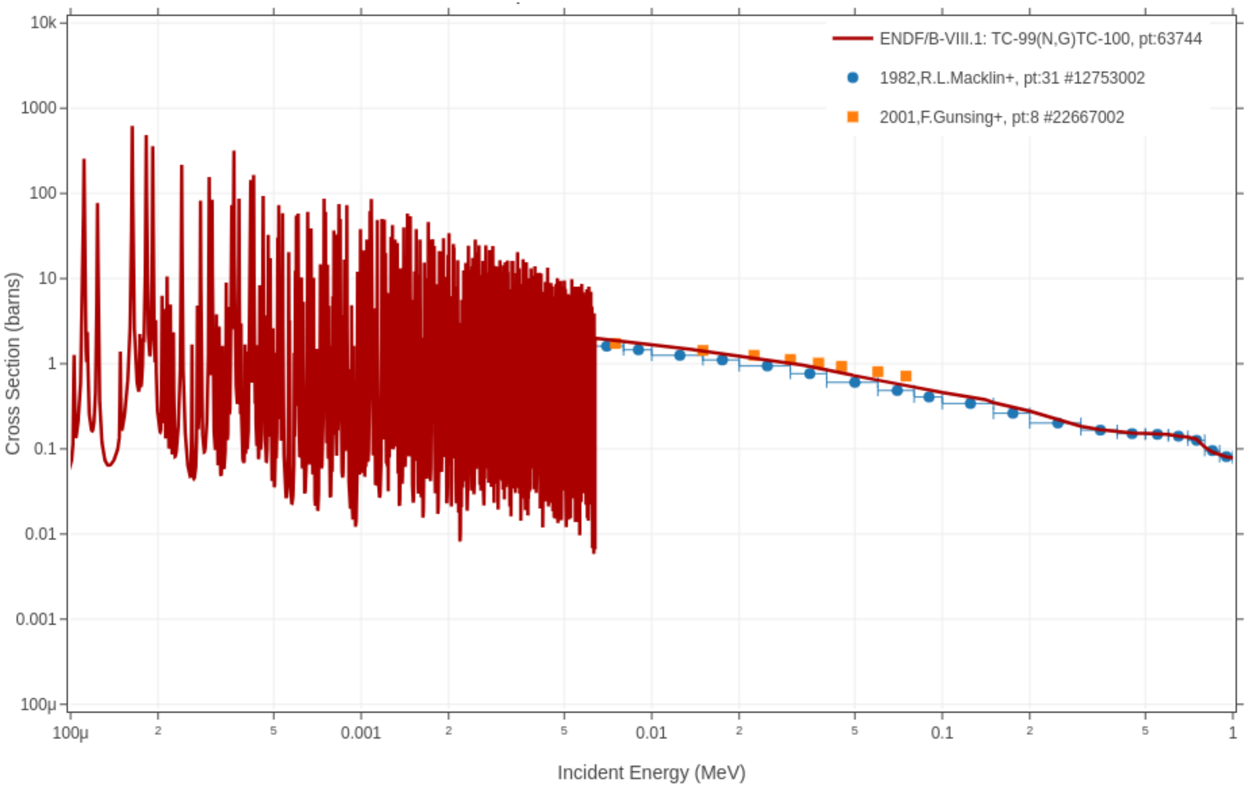


^{99}Tc



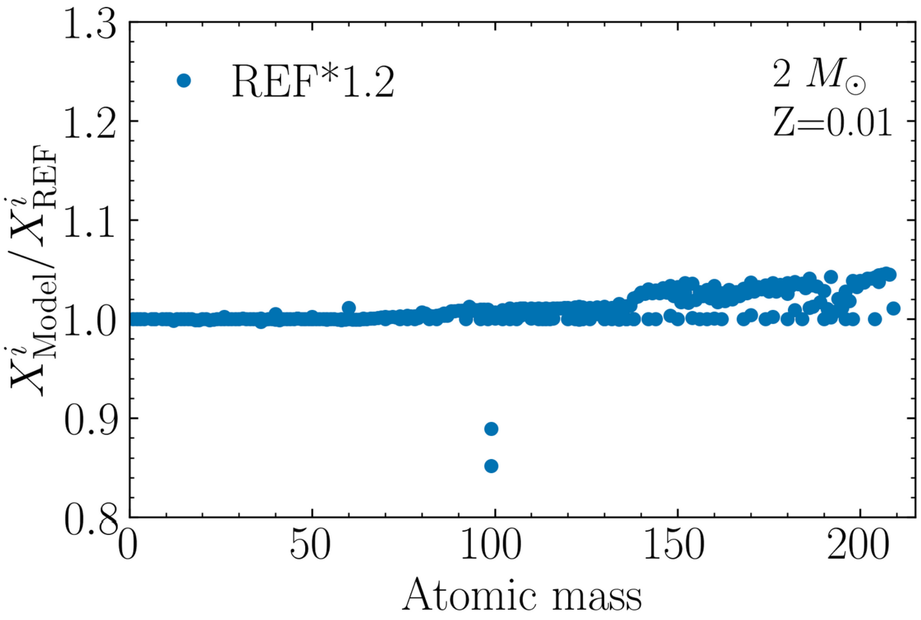
▼ **List of all available values**

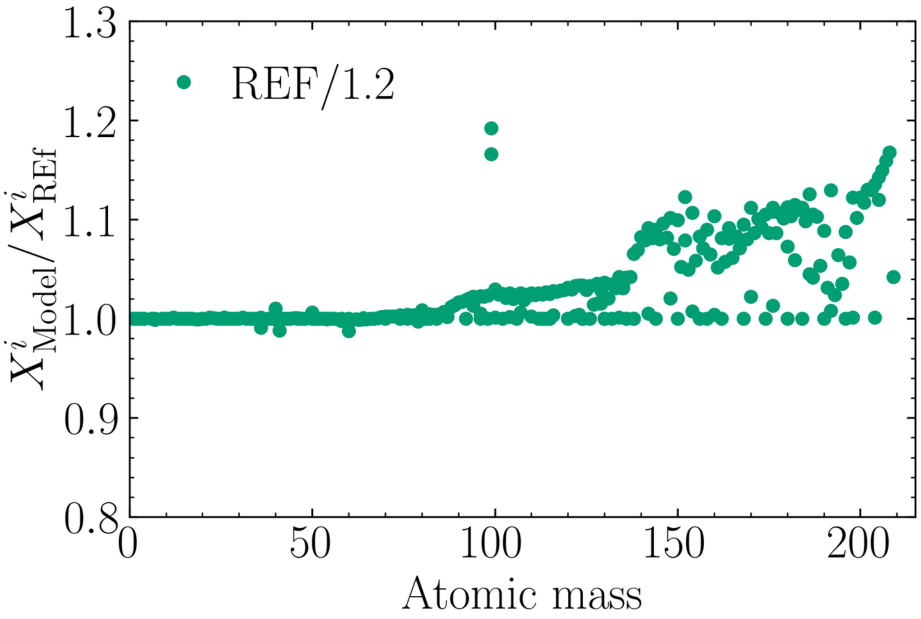
original	renorm.	year	type	Comment	Ref
933 ± 47		2000	c	Linac, TOF	GLM00, GLM01
782 ± 50		1987	c	Linac, TOF, ^{6}Li, Au:Sat.	WiM87
779 ± 40		1982	b	Linac, TOF, ^{6}Li, Au:Sat.	Mac82b



^{99}Tc

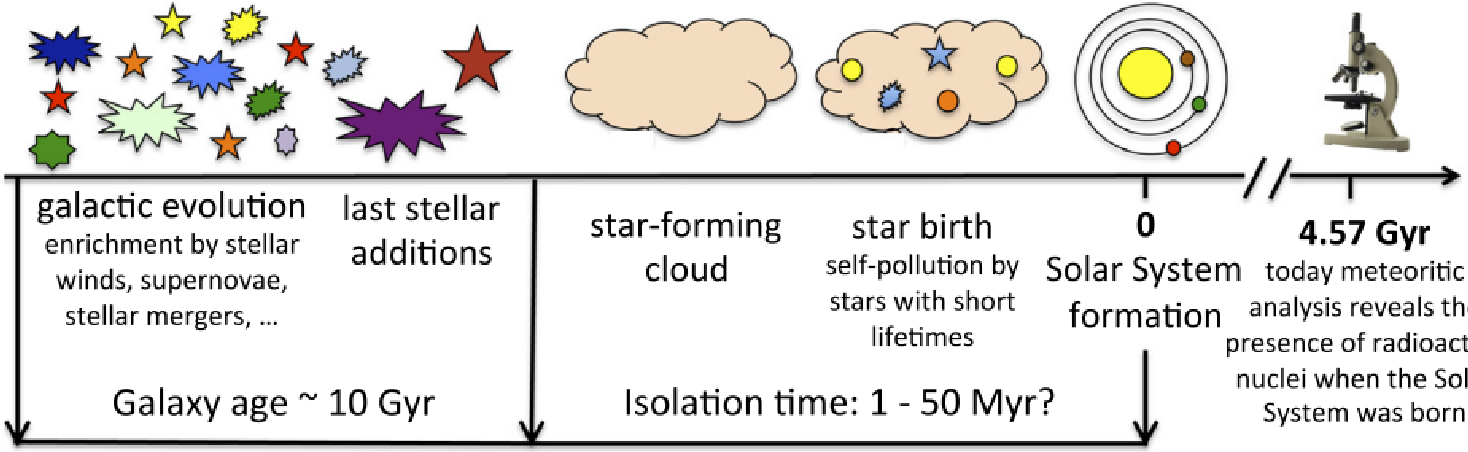
Tests varying the ^{99}Tc MACS by ±20%





The Early Solar System

Lugaro+ 18, PrPNP



- Many short-lived radionuclides (SLRs) were present in the first few million years of Solar System history
- Their presence is inferred through excesses in daughter isotopes (compared to normal terrestrial isotopic composition) in various materials found in primitive meteorites
- Their abundances have profound impact on the timing of stellar nucleosynthesis events prior to Solar System formation, chronology of events in the early Solar System, early solar activity, heating of early-formed planetesimals, and chronology of planet formation

The Early Solar System

- Neutron captures produce significant abundances of **^{41}Ca**, **^{60}Fe**, **^{107}Pd**, **^{135}Cs**, **^{182}Hf**, and **^{205}Pb**
- The survival of ^{135}Cs and ^{205}Pb in stellar environments is very uncertain because of the strong temperature and density dependence of their half lives, decreasing by orders of magnitudes in stellar conditions and determined only theoretically
- ^{41}Ca, ^{107}Pd, and ^{205}Pb are produced by neutron captures on the stable isotopes
- ^{60}Fe, ^{135}Cs, and ^{182}Hf can be reached via the activation of branching points at ^{59}Fe, ^{134}Cs, and ^{181}Hf

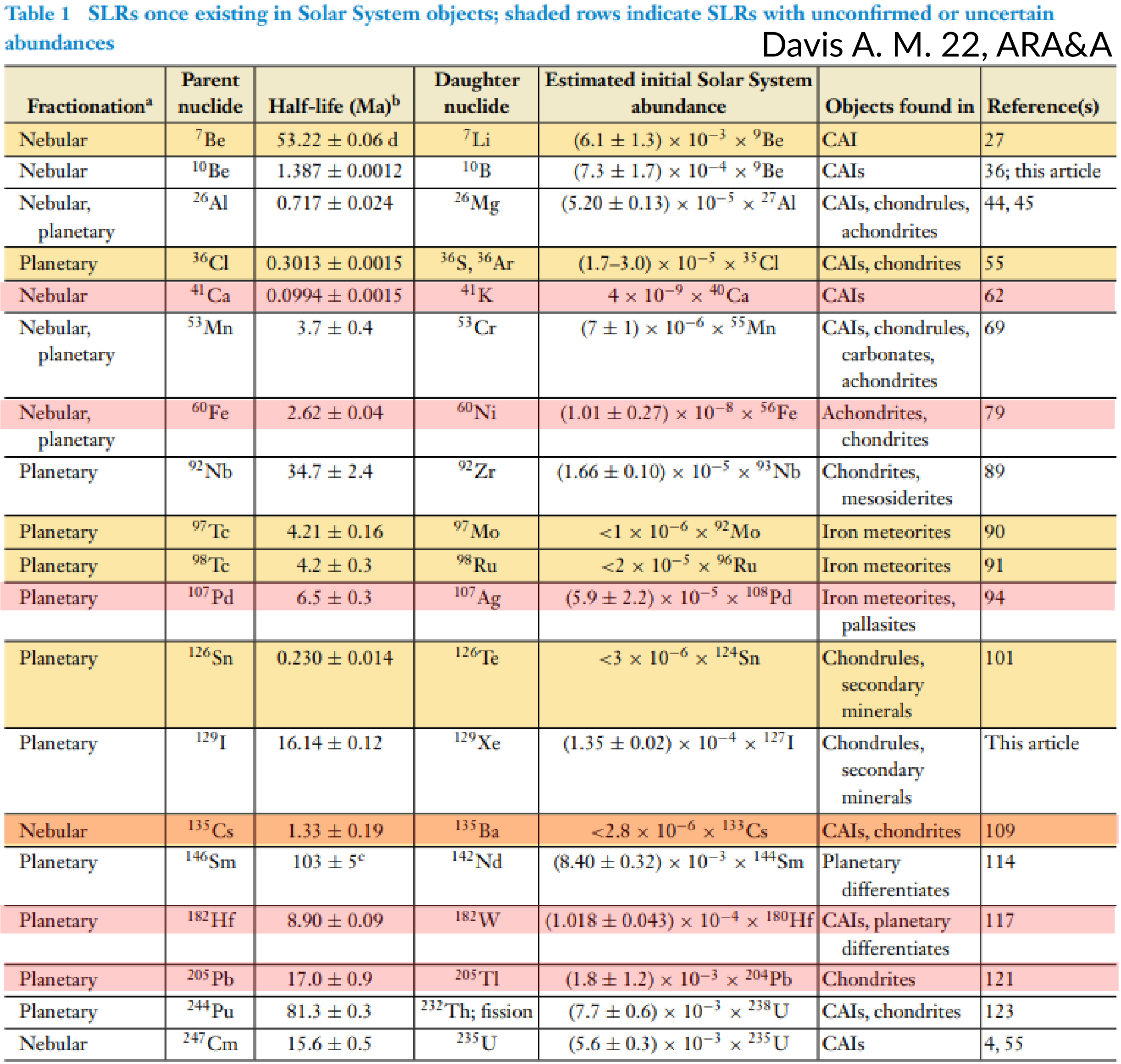


Table 1 SLRs once existing in Solar System objects; shaded rows indicate SLRs with unconfirmed or uncertain abundances

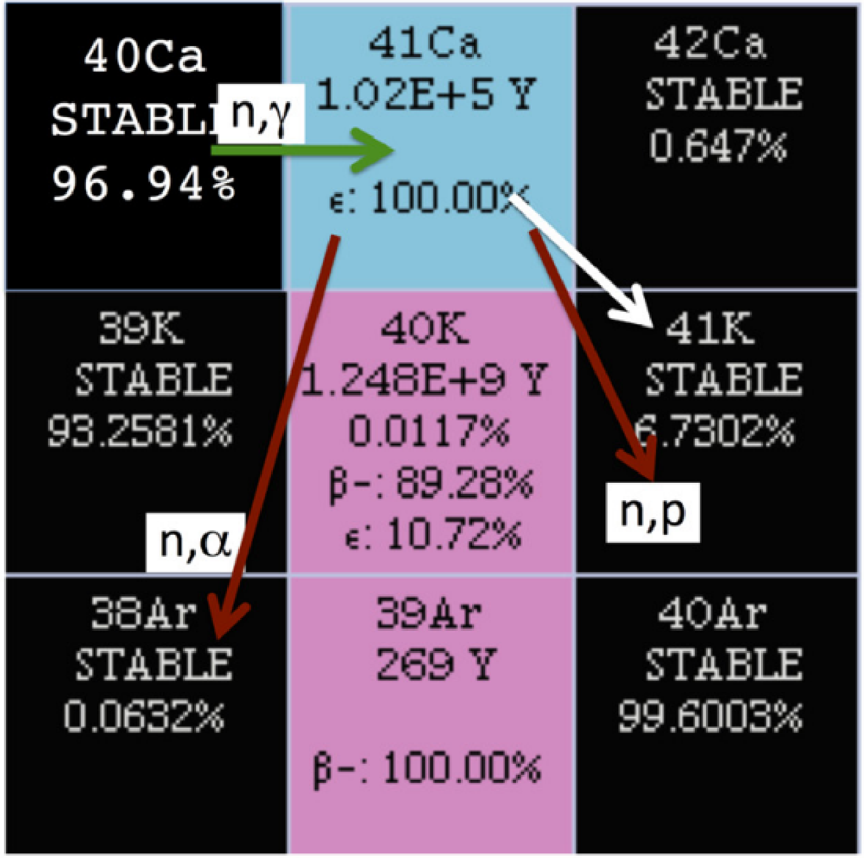
Fractionation[a]	Parent nuclide	Half-life (Ma)[b]	Daughter nuclide	Estimated initial Solar System abundance	Objects found in	Reference(s)
Nebular	^{7}Be	53.22 ± 0.06 d	^{7}Li	$(6.1 \pm 1.3) \times 10^{-3} \times {}^{9}$Be	CAI	27
Nebular	^{10}Be	1.387 ± 0.0012	^{10}B	$(7.3 \pm 1.7) \times 10^{-4} \times {}^{9}$Be	CAIs	36; this article
Nebular, planetary	^{26}Al	0.717 ± 0.024	^{26}Mg	$(5.20 \pm 0.13) \times 10^{-5} \times {}^{27}$Al	CAIs, chondrules, achondrites	44, 45
Planetary	^{36}Cl	0.3013 ± 0.0015	^{36}S, ^{36}Ar	$(1.7\text{–}3.0) \times 10^{-5} \times {}^{35}$Cl	CAIs, chondrites	55
Nebular	^{41}Ca	0.0994 ± 0.0015	^{41}K	$4 \times 10^{-9} \times {}^{40}$Ca	CAIs	62
Nebular, planetary	^{53}Mn	3.7 ± 0.4	^{53}Cr	$(7 \pm 1) \times 10^{-6} \times {}^{55}$Mn	CAIs, chondrules, carbonates, achondrites	69
Nebular, planetary	^{60}Fe	2.62 ± 0.04	^{60}Ni	$(1.01 \pm 0.27) \times 10^{-8} \times {}^{56}$Fe	Achondrites, chondrites	79
Planetary	^{92}Nb	34.7 ± 2.4	^{92}Zr	$(1.66 \pm 0.10) \times 10^{-5} \times {}^{93}$Nb	Chondrites, mesosiderites	89
Planetary	^{97}Tc	4.21 ± 0.16	^{97}Mo	$<1 \times 10^{-6} \times {}^{92}$Mo	Iron meteorites	90
Planetary	^{98}Tc	4.2 ± 0.3	^{98}Ru	$<2 \times 10^{-5} \times {}^{96}$Ru	Iron meteorites	91
Planetary	^{107}Pd	6.5 ± 0.3	^{107}Ag	$(5.9 \pm 2.2) \times 10^{-5} \times {}^{108}$Pd	Iron meteorites, pallasites	94
Planetary	^{126}Sn	0.230 ± 0.014	^{126}Te	$<3 \times 10^{-6} \times {}^{124}$Sn	Chondrules, secondary minerals	101
Planetary	^{129}I	16.14 ± 0.12	^{129}Xe	$(1.35 \pm 0.02) \times 10^{-4} \times {}^{127}$I	Chondrules, secondary minerals	This article
Nebular	^{135}Cs	1.33 ± 0.19	^{135}Ba	$<2.8 \times 10^{-6} \times {}^{133}$Cs	CAIs, chondrites	109
Planetary	^{146}Sm	103 ± 5[c]	^{142}Nd	$(8.40 \pm 0.32) \times 10^{-3} \times {}^{144}$Sm	Planetary differentiates	114
Planetary	^{182}Hf	8.90 ± 0.09	^{182}W	$(1.018 \pm 0.043) \times 10^{-4} \times {}^{180}$Hf	CAIs, planetary differentiates	117
Planetary	^{205}Pb	17.0 ± 0.9	^{205}Tl	$(1.8 \pm 1.2) \times 10^{-3} \times {}^{204}$Pb	Chondrites	121
Planetary	^{244}Pu	81.3 ± 0.3	^{232}Th; fission	$(7.7 \pm 0.6) \times 10^{-3} \times {}^{238}$U	CAIs, chondrites	123
Nebular	^{247}Cm	15.6 ± 0.5	^{235}U	$(5.6 \pm 0.3) \times 10^{-3} \times {}^{235}$U	CAIs	4, 55

Davis A. M. 22, ARA&A

^{41}Ca(n,p) & ^{41}Ca(n,α)

- ^{41}Ca is long-lived radioactive nuclei lighter than iron
- Important also for ^{41}K/^{39}K excesses measured in presolar grains from supernovae (Amari+ 96)
- Can be made by neutron captures on ^{40}Ca (half life of 0.1 Myr), which is stable and with relatively high solar abundance
- Neutron captures also destroy ^{41}Ca via different channels, the predominant being ^{41}Ca(n,α)^{38}Ar
- Experimental estimates for the neutron-capture cross section is available (e.g. de Smet et al. 2006),
- Electron-capture rate of ^{41}Ca is expected to vary significantly for different temperatures and densities relevant to stellar conditions
- Theoretical computations by Fuller+ 82

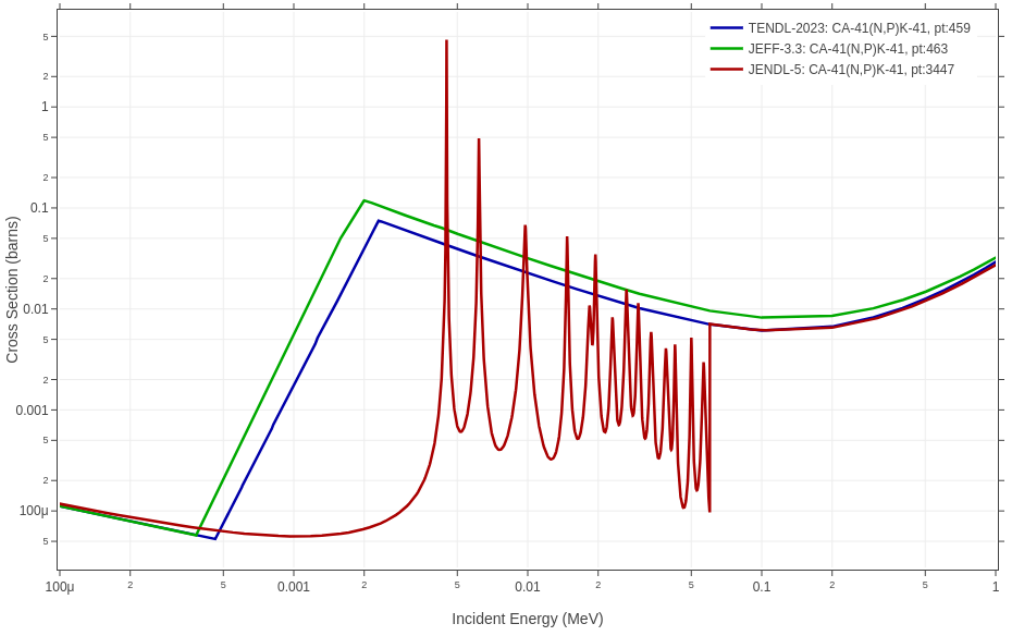
Lugaro+ 18, PrPNP

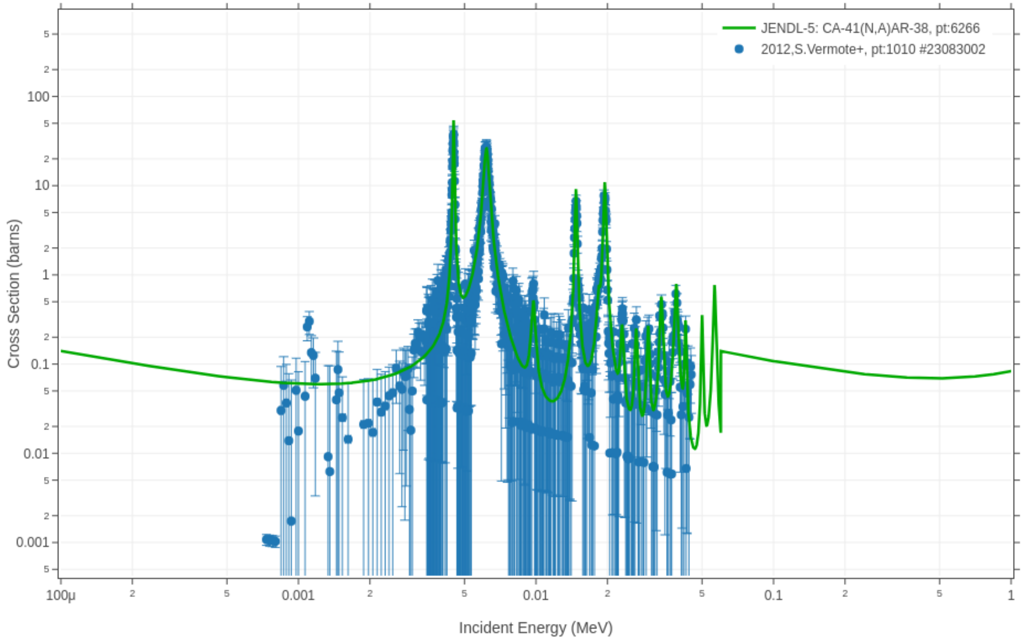


40Ca STABL 96.94%	41Ca 1.02E+5 Y ε: 100.00%	42Ca STABLE 0.647%
39K STABLE 93.2581%	40K 1.248E+9 Y 0.0117% β-: 89.28% ε: 10.72%	41K STABLE 6.7302%
38Ar STABLE 0.0632%	39Ar 269 Y β-: 100.00%	40Ar STABLE 99.6003%

^{41}Ca(n,p) & ^{41}Ca(n,α)

- Thermal n-capture cross sections from Wagemans+ 98
- ^{41}Ca(n,α)^{38}Ar reaction cross section up to 80 keV measured at GELINA (Vermote+ 12)
- Studied via inverse kinematics → ^{38}Ar(α,n)^{41}Ca and ^{38}Ar(α,p)^{41}K (Talwar+ 18)





^{107}Pd

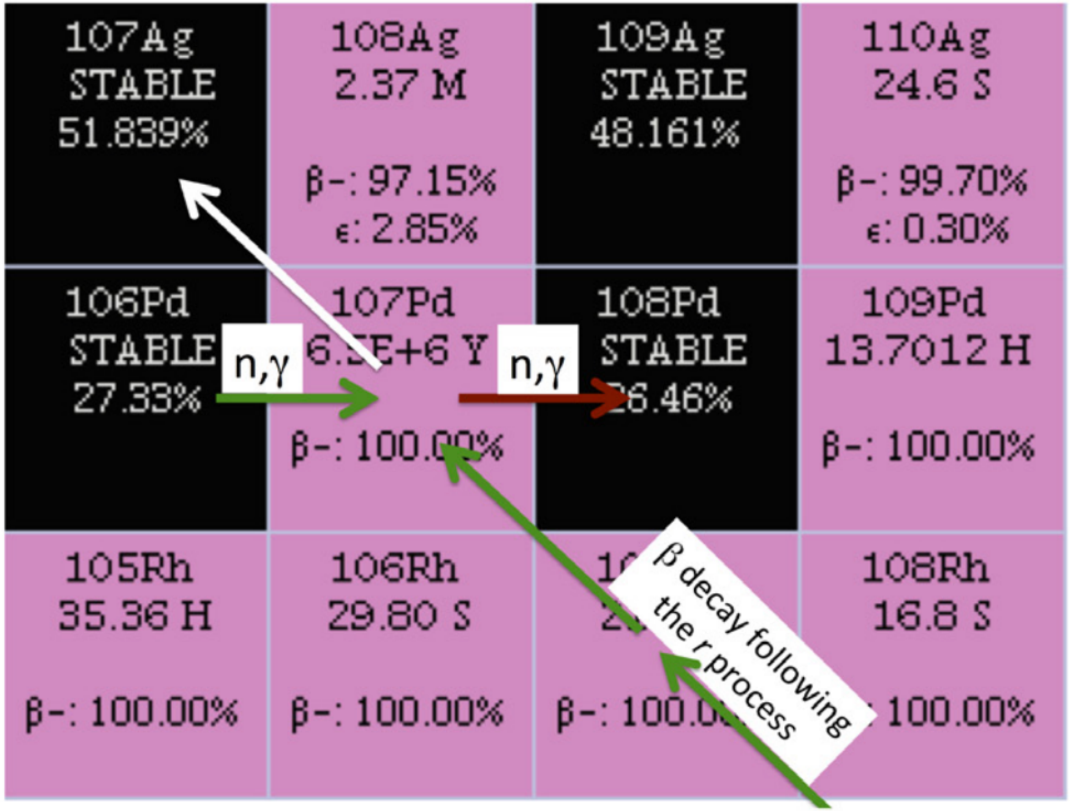
- Too long-living ($T_{1/2}$ = 6.5 Myr, down to 700 years at 300 MK) to act as a branching point during the s-process

➔ Behaves as a stable nucleus

- Experimentally determined neutron-capture cross section (Macklin 1985)

➔ Its radiogenic decay is responsible for production of ^{107}Ag

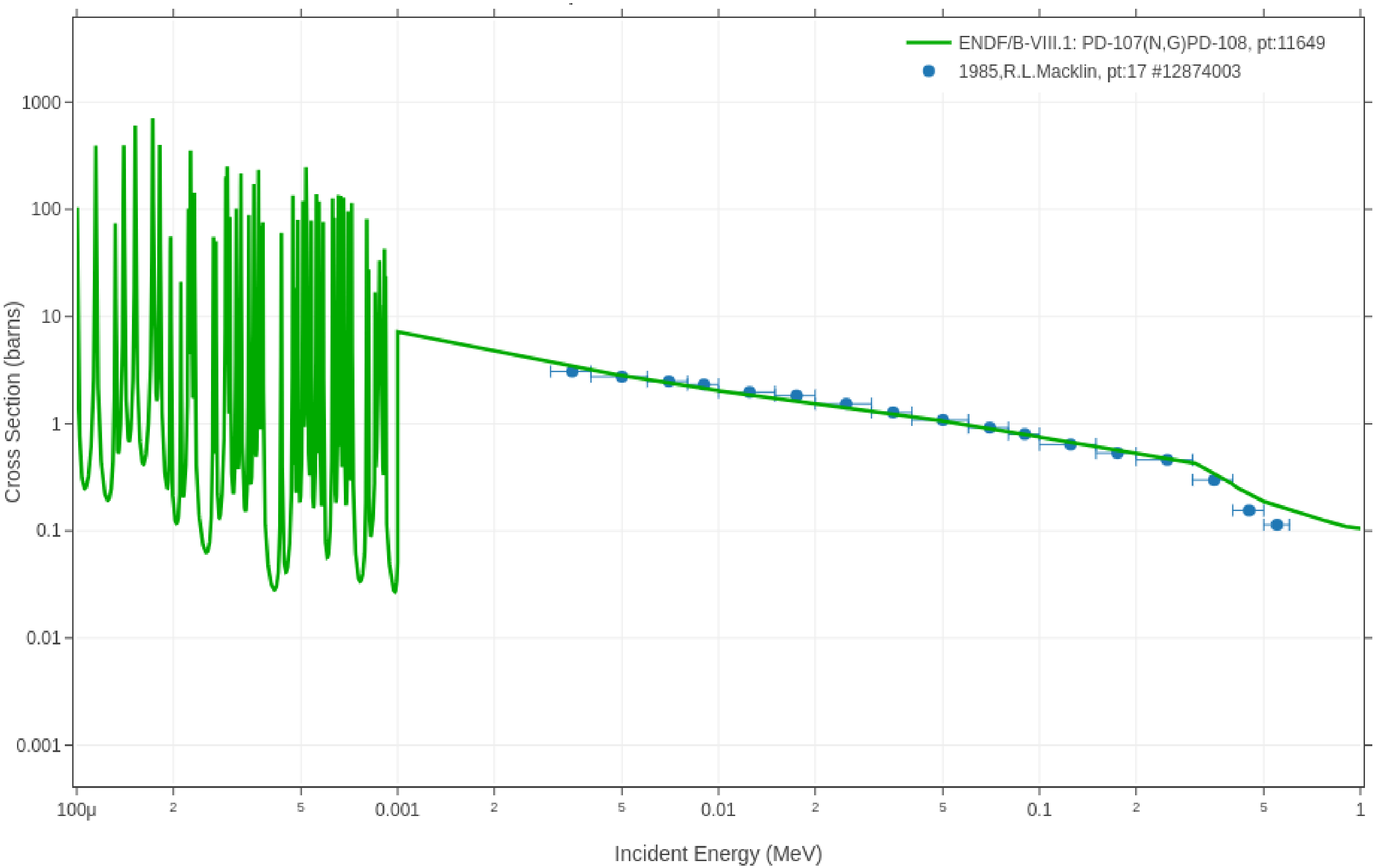
Lugaro+ 18, PrPNP



107Ag STABLE 51.839%	108Ag 2.37 M β-: 97.15% ϵ: 2.85%	109Ag STABLE 48.161%	110Ag 24.6 S β-: 99.70% ϵ: 0.30%
106Pd STABLE 27.33%	107Pd 6.5E+6 Y β-: 100.00%	108Pd STABLE 26.46%	109Pd 13.7012 H β-: 100.00%
105Rh 35.36 H β-: 100.00%	106Rh 29.80 S β-: 100.00%	1 2 β-: 100.0	108Rh 16.8 S 100.00%

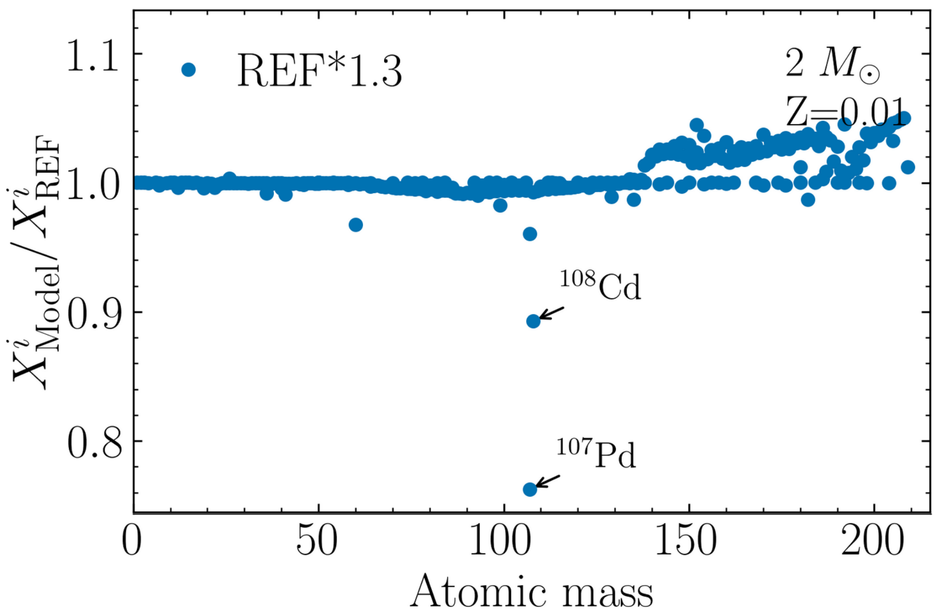
^{107}Pd

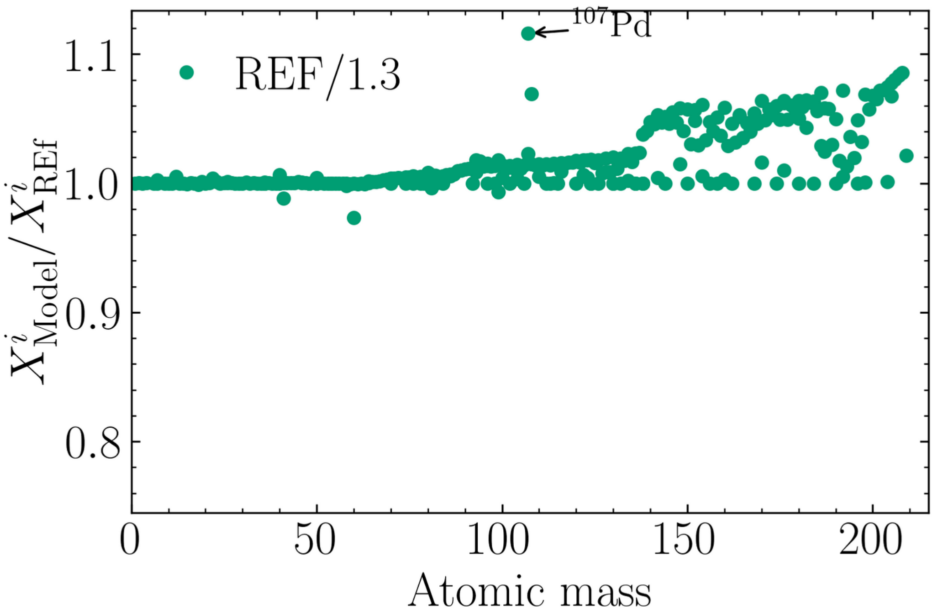
- Experimentally determined neutron-capture cross section (Macklin 1985)



^{107}Pd

- Tests varying the ^{107}Pd MACS by ±30%

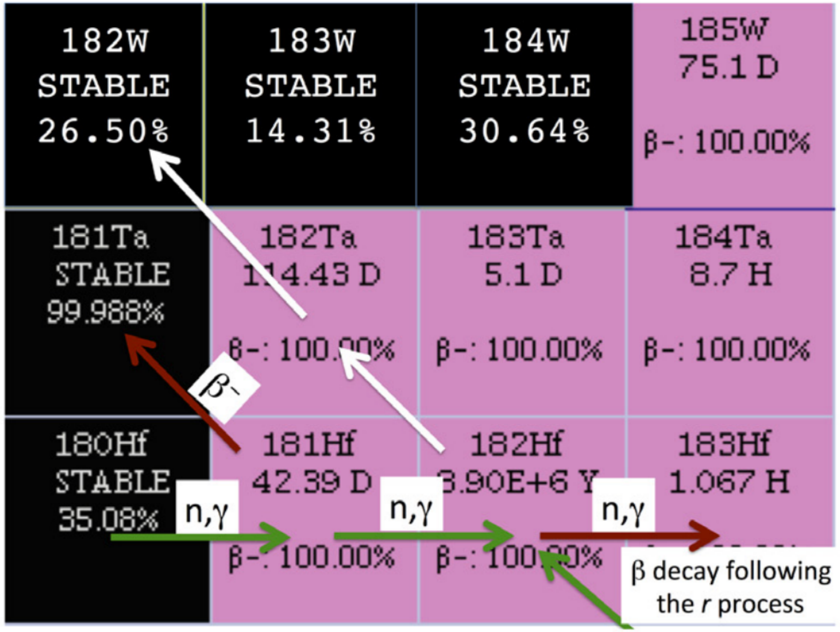




^{182}Hf

- Production of ^{182}Hf via activation of the branching point at ^{181}Hf

Lugaro+ 18, PrPNP



- The half life of ^{181}Hf, is believed to strongly decrease from 42 days to ~2 days in stellar conditions, mostly via population of an excited state at 68 keV (TY 87)

- However, the more recent, detailed experiments of Bondarenko+ 02 on the nuclear structure of ^{181}Hf suggested that this energy level does not exist

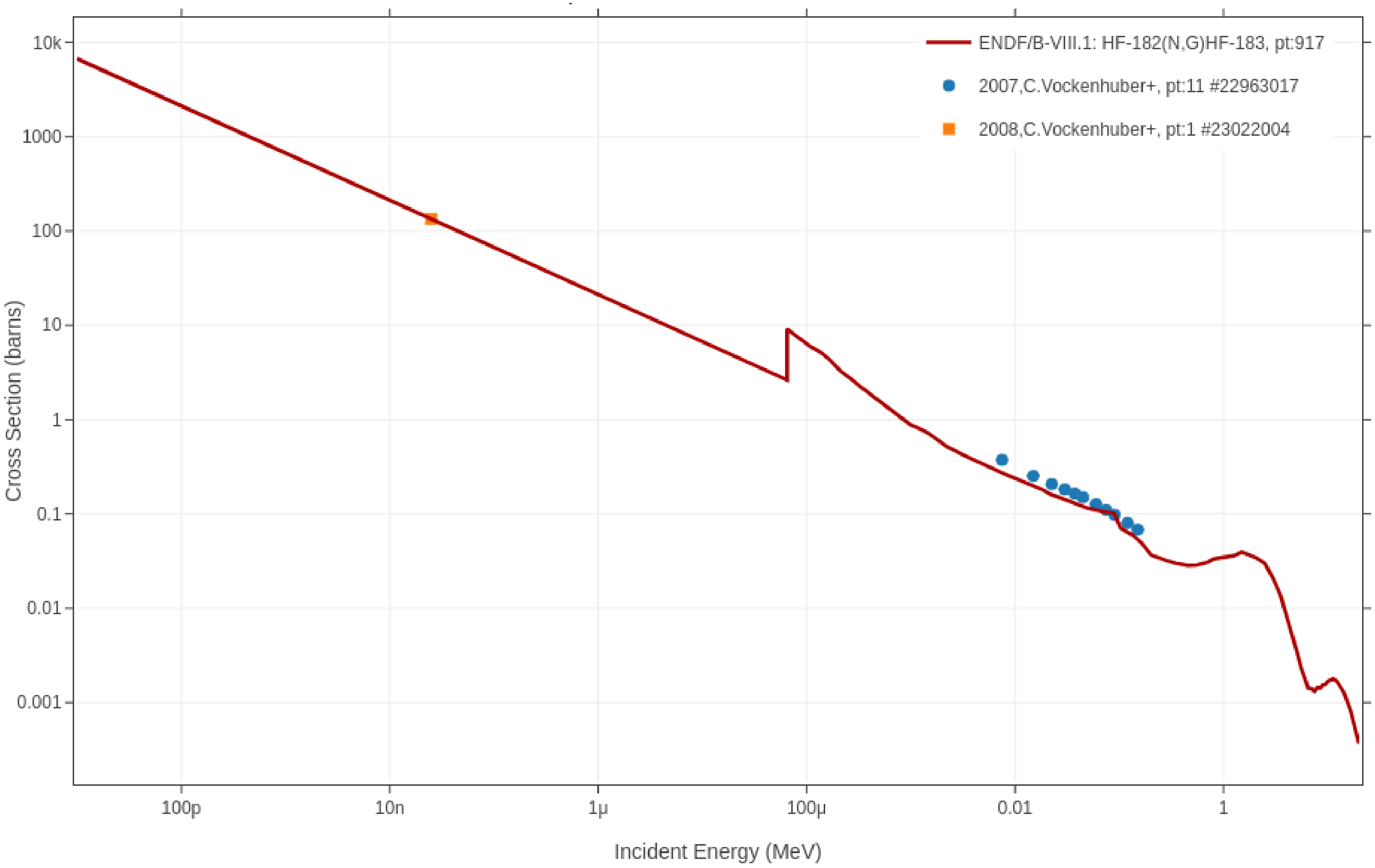
→ Possible large production of ^{182}Hf to the s-process in AGB stars

→ This may resolve the discrepancy between the abundances of ^{129}I and ^{182}Hf in the early solar system and allow to time the latest r- and s-process events that contributed to the build-up of solar system matter before the formation of the Sun (see discussion in Lugaro+ 14 and Vescovi+ 18)

- Its decay into ^{182}W is of importance also for determing the solar r-process residual of this isotope

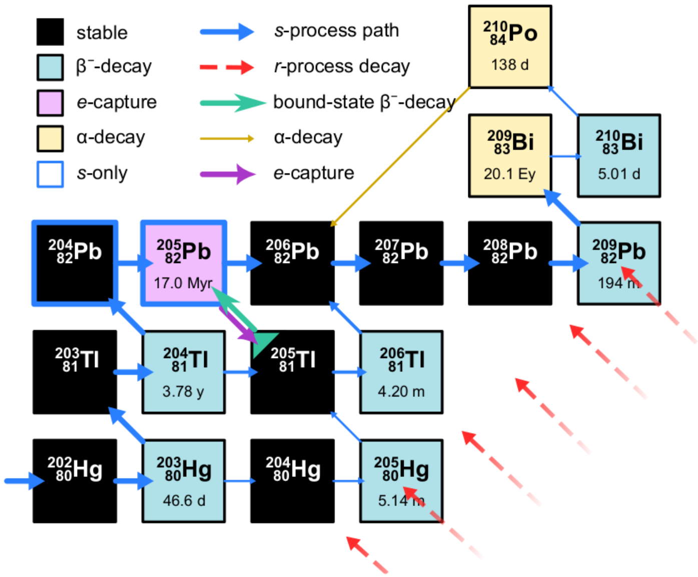
^{182}Hf

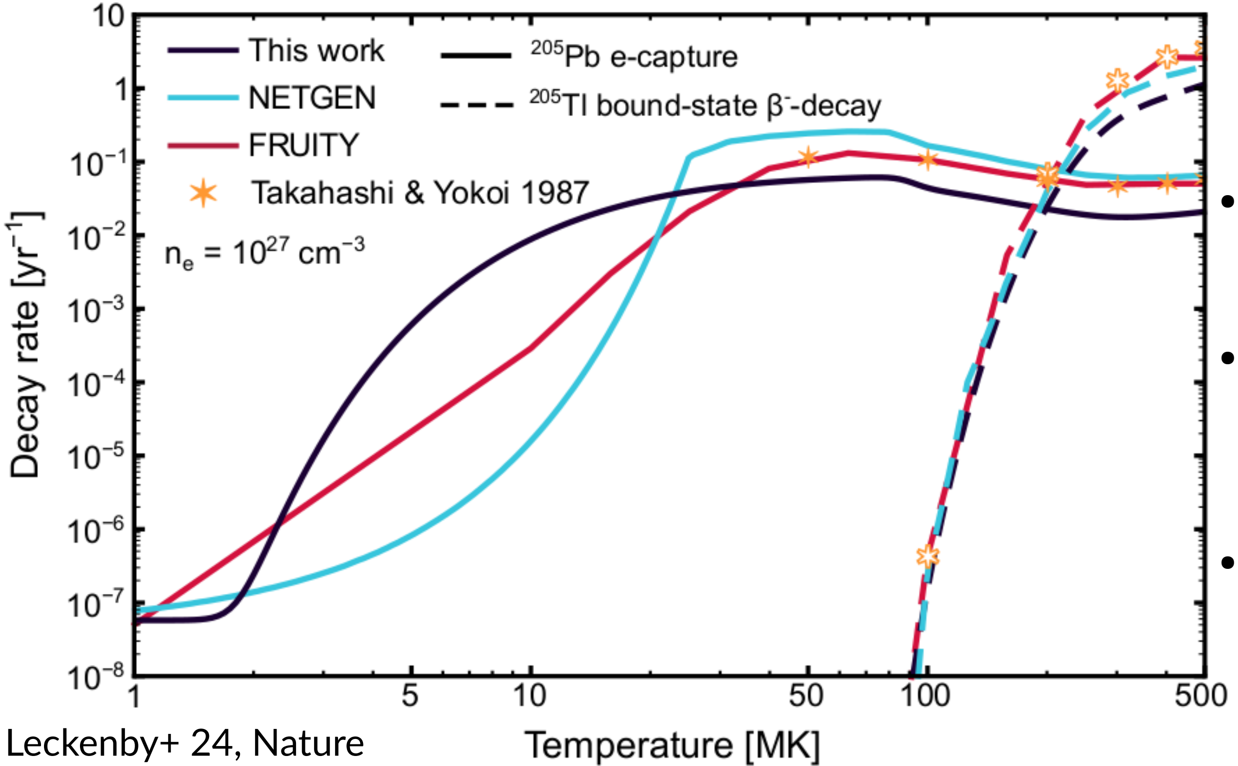
- Experimentally determined n-capture cross section via activation technique (Vockenhuber+ 07)



^{205}Pb

- Despite its long terrestrial half-life ($T_{1/2}$ = 17 Myr) of **^{205}Pb acts as a branching point** because of the strong dependence on temperature and electron density
- **^{205}Tl becomes unstable during TPs** and its β^- decay is competing with the β^+ decay of ^{205}Pb



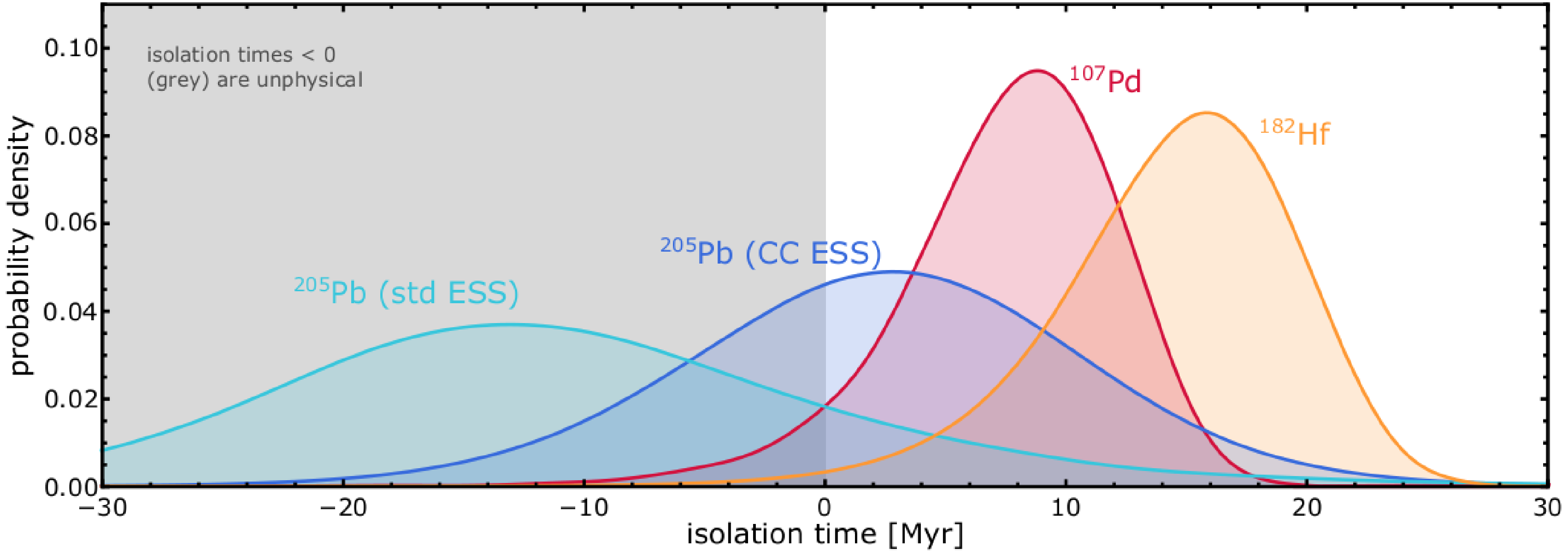


Leckenby+ 24, Nature

- **Measured for the first time** the bound-state β^- decay of ^{205}Tl
- The measured half-life is **4.7 times larger** than the previous theoretical estimate (291 days vs. 58 days)
- Diverging behavior at low temperatures due to the different extrapolation to the terrestrial value (log versus linear)

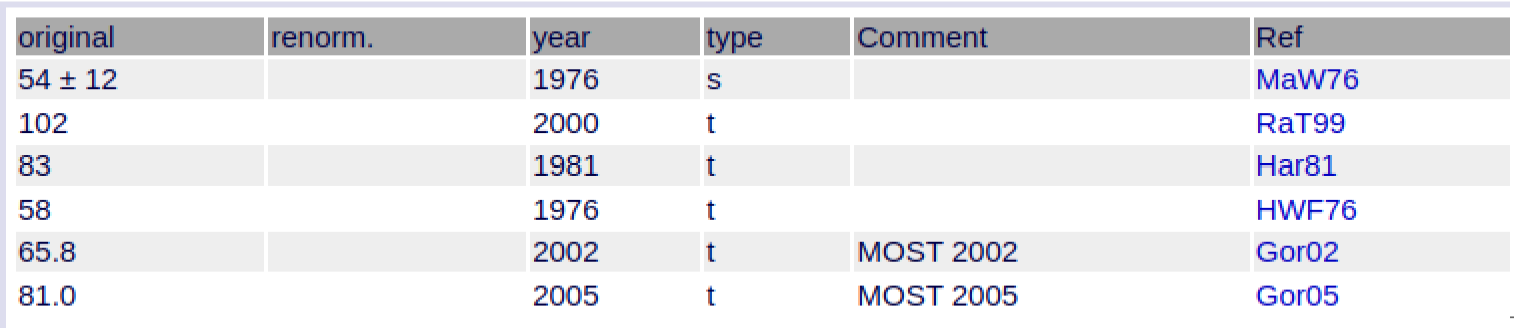
^{205}Pb

Leckenby+ 24, Nature



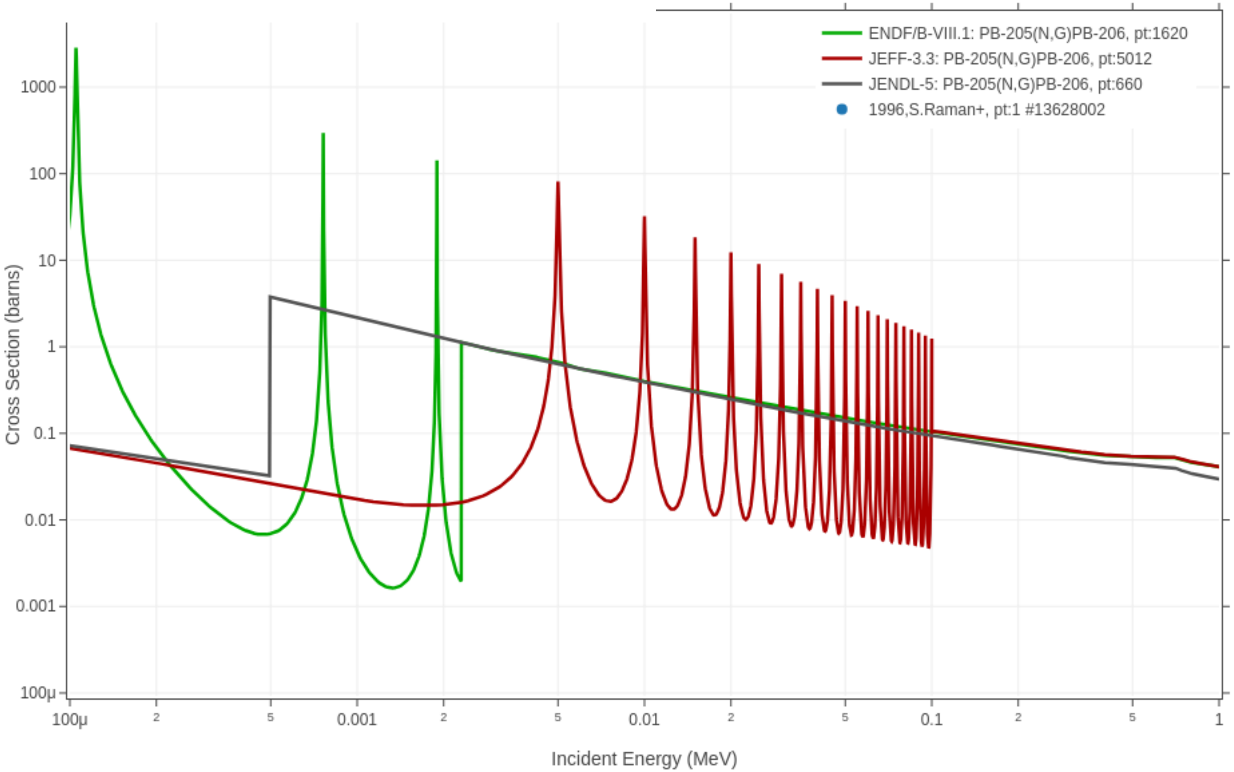
- Plugging in new yields in basic GCE models and comparing to the ^{205}Pb/^{204}Pb ratio from meteorites, the isolation time of Solar material inside its parent molecular cloud can be determined
- **Positive isolation times** that are consistent with the other s-process short-lived radioactive nuclei found in the early Solar System

^{205}Pb



original	renorm.	year	type	Comment	Ref
54 ± 12		1976	s		MaW76
102		2000	t		RaT99
83		1981	t		Har81
58		1976	t		HWF76
65.8		2002	t	MOST 2002	Gor02
81.0		2005	t	MOST 2005	Gor05

- Theoretical (n,γ) cross section



^{205}Pb

- Tests varying the ^{205}Pb MACS by a factor 2