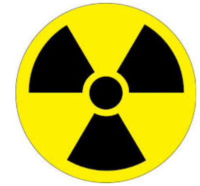
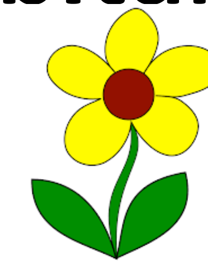
Radionuclides 
from cosmochronology to habitability



Maria Lugaro

Konkoly Observatory, Hungarian Academy of Sciences

and

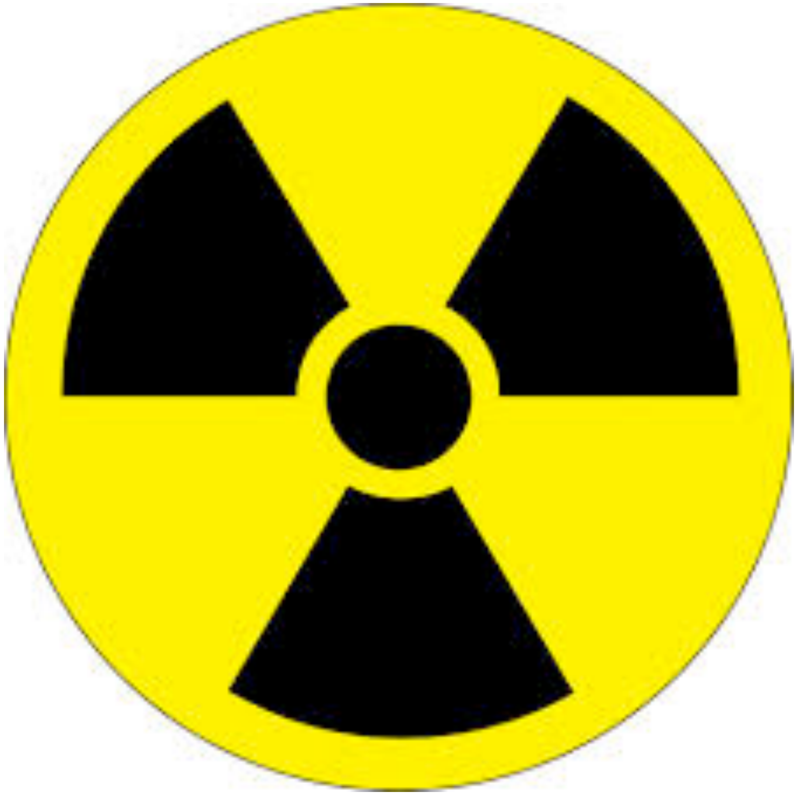
Monash University, Australia

In collaboration with:

Ulrich Ott (University of West Hungary), *Alexander Heger* (Monash), *Marco Pignatari* (University of Hull), *Dean Osrin* (Monash), *Stephane Goriely* (Universite' Libre de Bruxelles), *Kai Zuber* (Technische Universitat Dresden), *Zsolt Fülöp and György Gyürky* (Atomki, MTA), *Amanda Karakas* (Monash), *Claudia Travaglio* (Turin Observatory), *Brad Gibson* (University of Hull), *Carolyn Doherty* (Konkoly), *John Lattanzio* (Monash)

$$dN/dt = -N/\tau$$

N=abundance
τ = mean life



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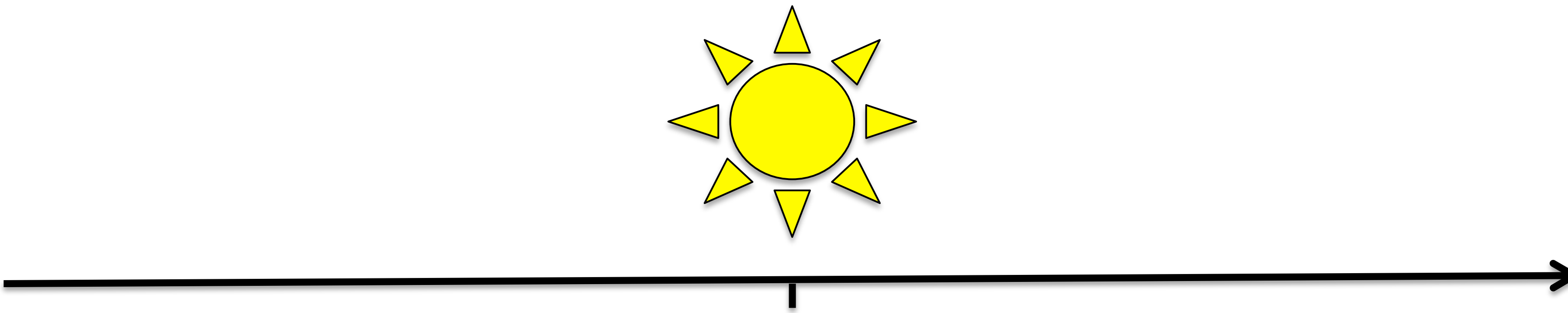
$$[\ \ln(N_1) - \ln(N_0)\ ]\ \tau = t_0 - t_1$$

N_1 and N_0 = abundances of the radionuclide at times t_1 and t_0



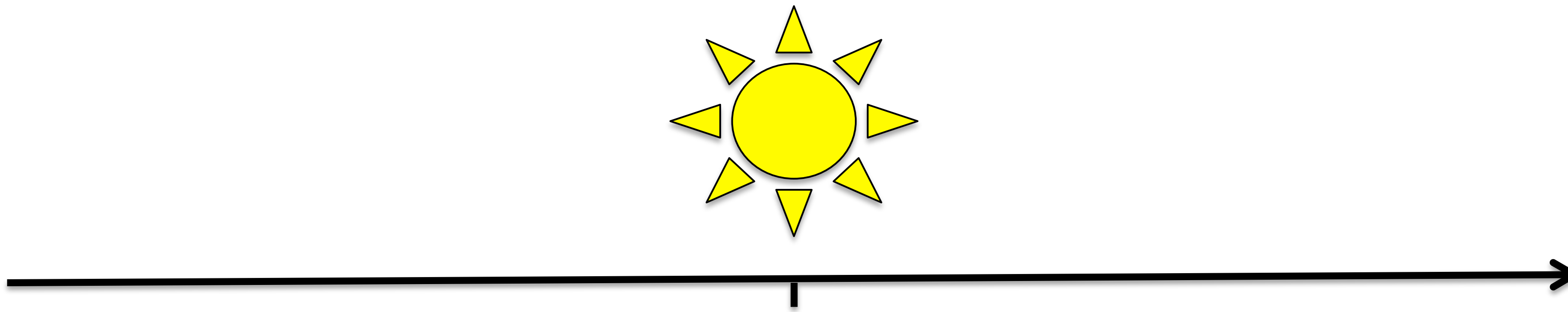
t_0

birth of the Sun

N_0 are available from meteoritic analysis

Isotope	τ (Myr)	Reference isotope	Initial Solar System ratio
^{247}Cm	22.5	^{235}U	$(1.1 \pm 0.3) \times 10^{-4}$ (27%)
^{244}Pu	80	^{238}U	$(6.8 \pm 1.0) \times 10^{-3}$ (15%)
^{182}Hf	13	^{180}Hf	$(9.72 \pm 0.44) \times 10^{-5}$ (4%)
^{146}Sm	98 or 149	^{146}Sm	$(8.86 \pm 0.5) \times 10^{-3}$ (5%)
^{129}I	23	^{127}I	$(1.19 \pm 0.20) \times 10^{-4}$ (15%)
^{107}Pd	9.4	^{108}Pd	$(5.9 \pm 2.2) \times 10^{-5}$ (37%)
^{92}Nb	50	^{92}Mo	$(3.6 \pm 1.2) \times 10^{-5}$ (33%)
^{53}Mn	5.3	^{55}Mn	$(6.28 \pm 0.66) \times 10^{-6}$ (10%)
^{60}Fe	3.8	^{56}Fe	10^{-9} - 10^{-6}
^{41}Ca	0.15	^{40}Ca	~ 4.2×10^{-9}
^{26}Al	1.03	^{27}Al	$(5.23 \pm 0.13) \times 10^{-5}$ (2.5%)

Detailed chronology of planetary growth from micrometer-sized dust to terrestrial planets



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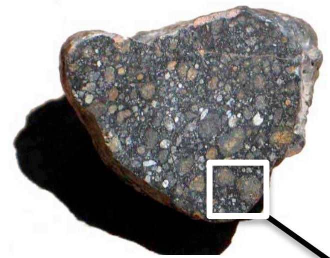
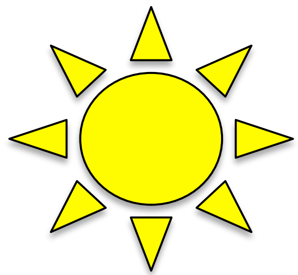
Detailed chronology of planetary growth from micrometer-sized dust to terrestrial planets





t_0

birth of the Sun

N_0 is available from meteoritic analysis

t_1

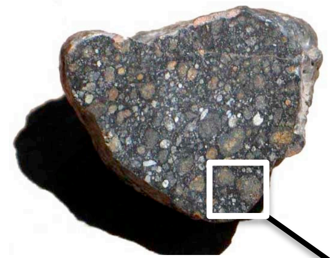
chondrule formation

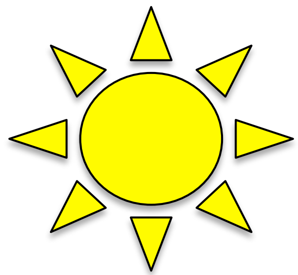
~ 1 Myr

Dauphas & Chaussidon 2011, Annual Reviews of Earth and Planetary Science

Detailed chronology of planetary growth from micrometer-sized dust to terrestrial planets

?





t_0

birth of the Sun

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t_1

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~ 1 Myr

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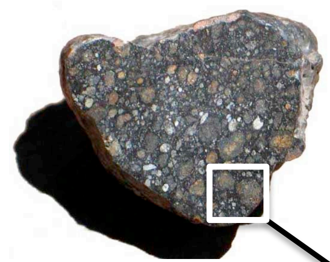
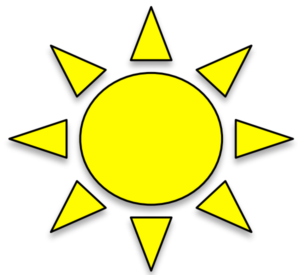
Detailed chronology of the events that predated the birth of the Sun



Detailed chronology of planetary growth from micrometer-sized dust to terrestrial planets



t_1

What is t_1? How do we determine N_1?

t_0

birth of the Sun

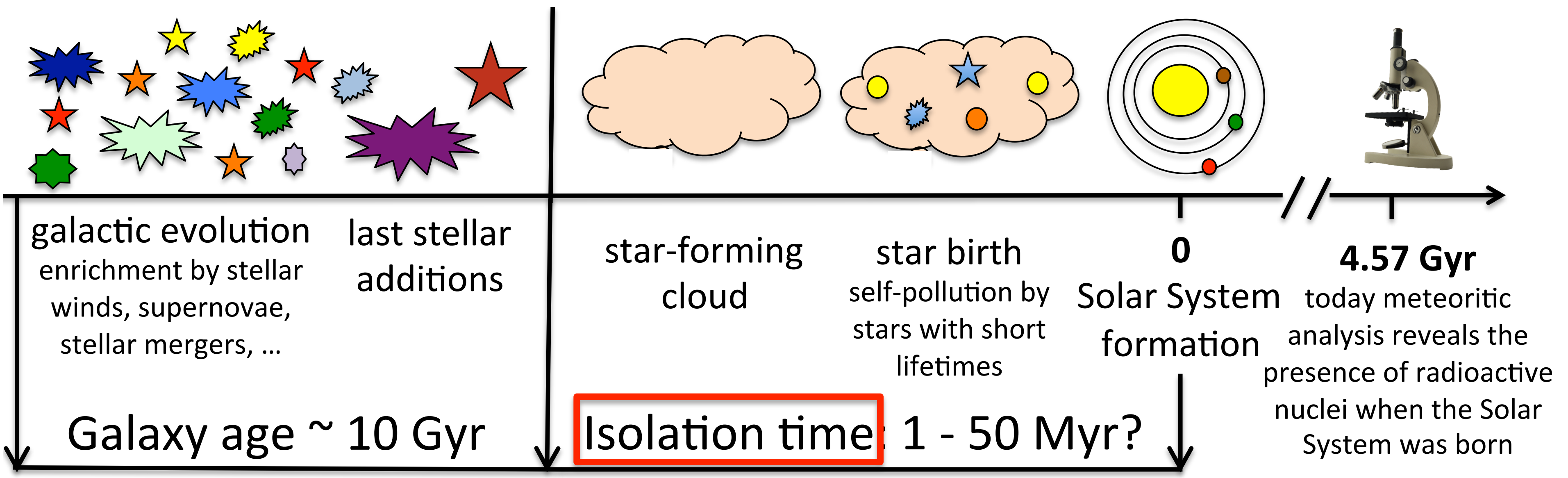
N_0 is available from meteoritic analysis

t_1

chondrule formation ~ 1 Myr

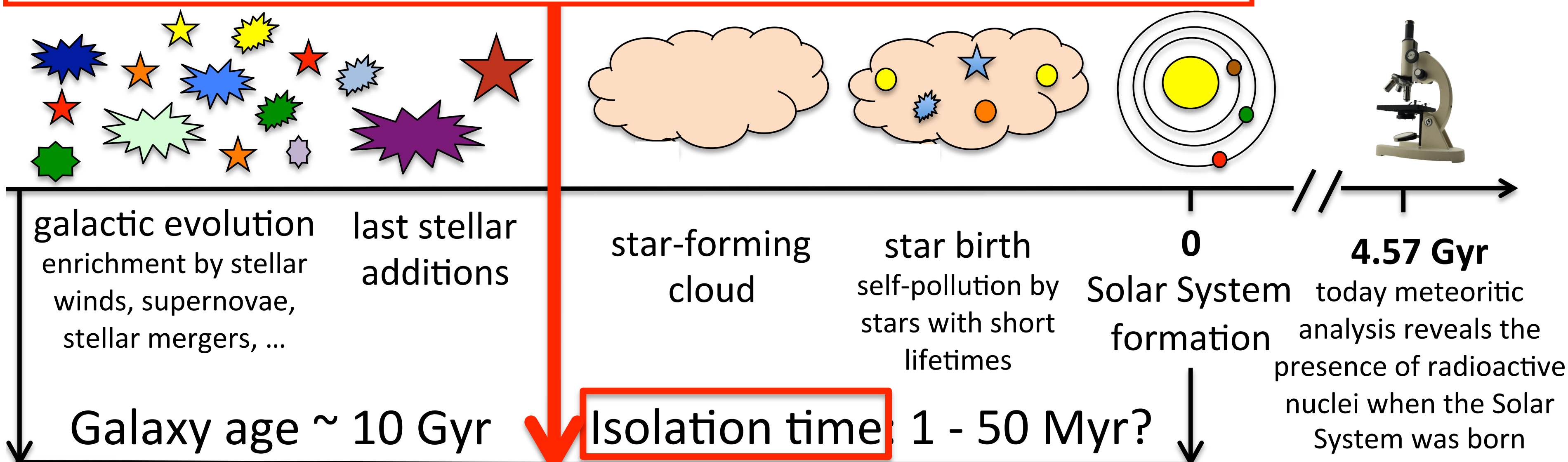
Dauphas & Chaussidon 2011, Annual Reviews of Earth and Planetary Science

Qualitative chronology of the events that predated the birth of the Sun



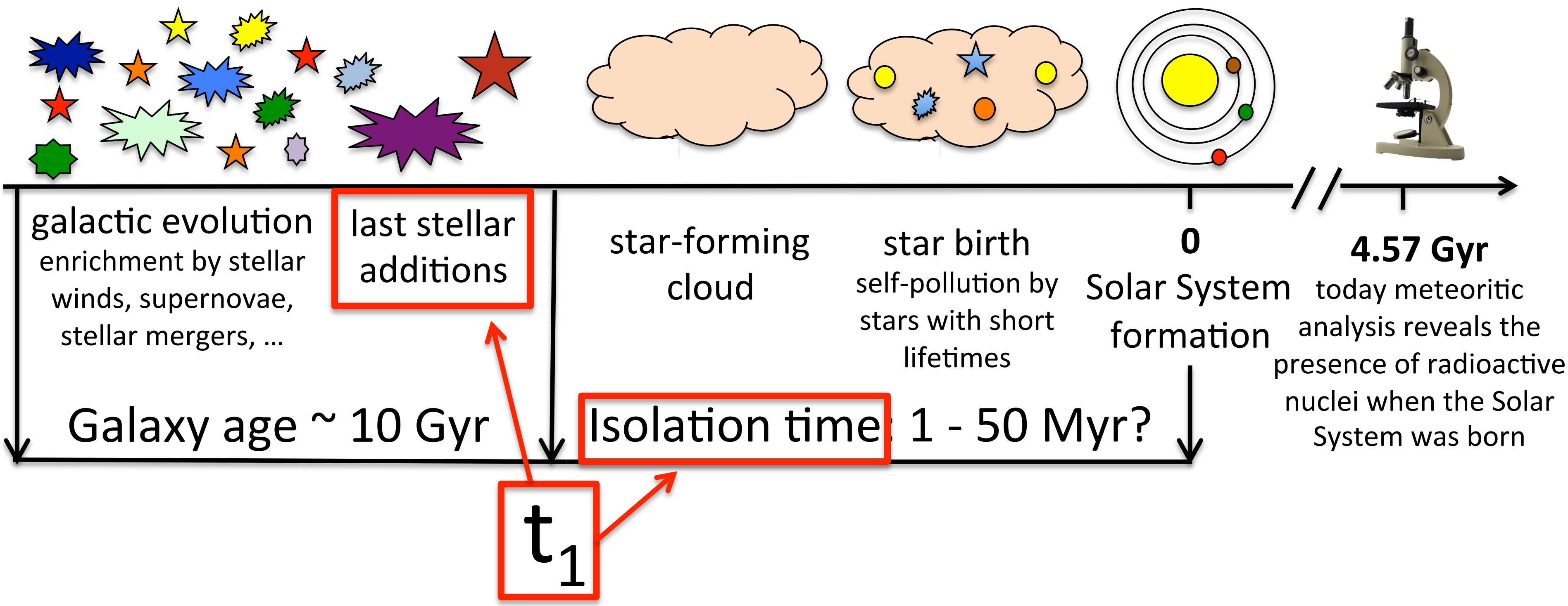
Qualitative chronology of the events that predated the birth of the Sun

The circumstances of the birth of the Sun



- Small star-forming clouds live as short as 4-5 Myr.
- More massive clouds have longer lifetimes, up to 40 Myr.
- A protracted isolation timescale would imply that our Sun was born in a high-mass stellar nursery.

Qualitative chronology of the events that predated the birth of the Sun



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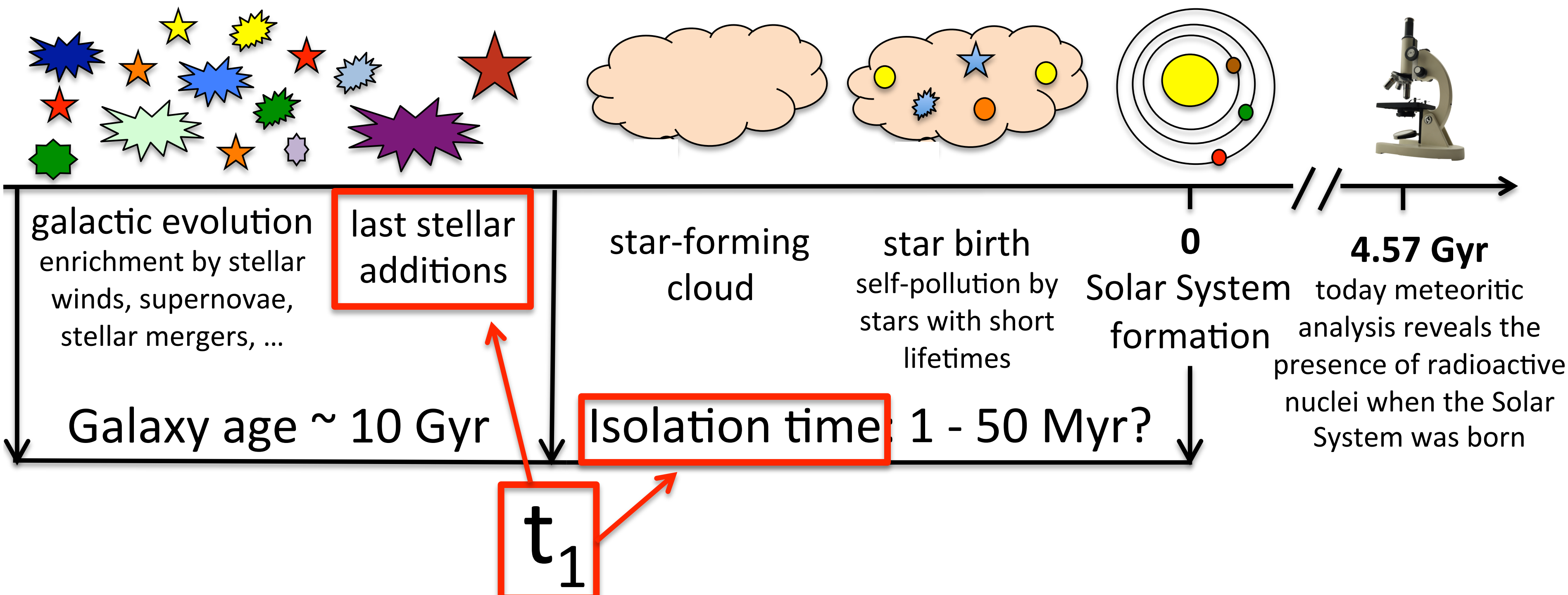
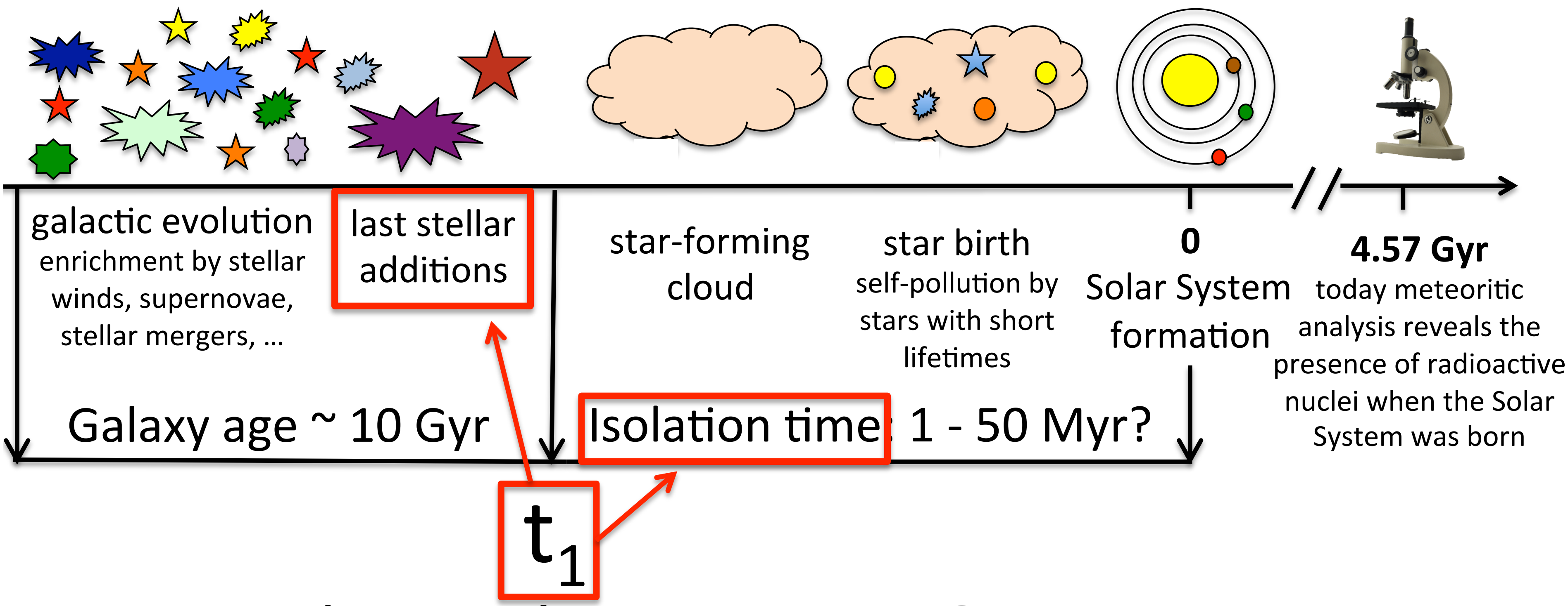


How do we determine N_1?

Qualitative chronology of the events that predated the birth of the Sun



How do we determine N_1?

Stellar Nucleosynthesis + Galactic Chemical Evolution

Isotope	τ (Myr)	Reference isotope	Initial Solar System ratio
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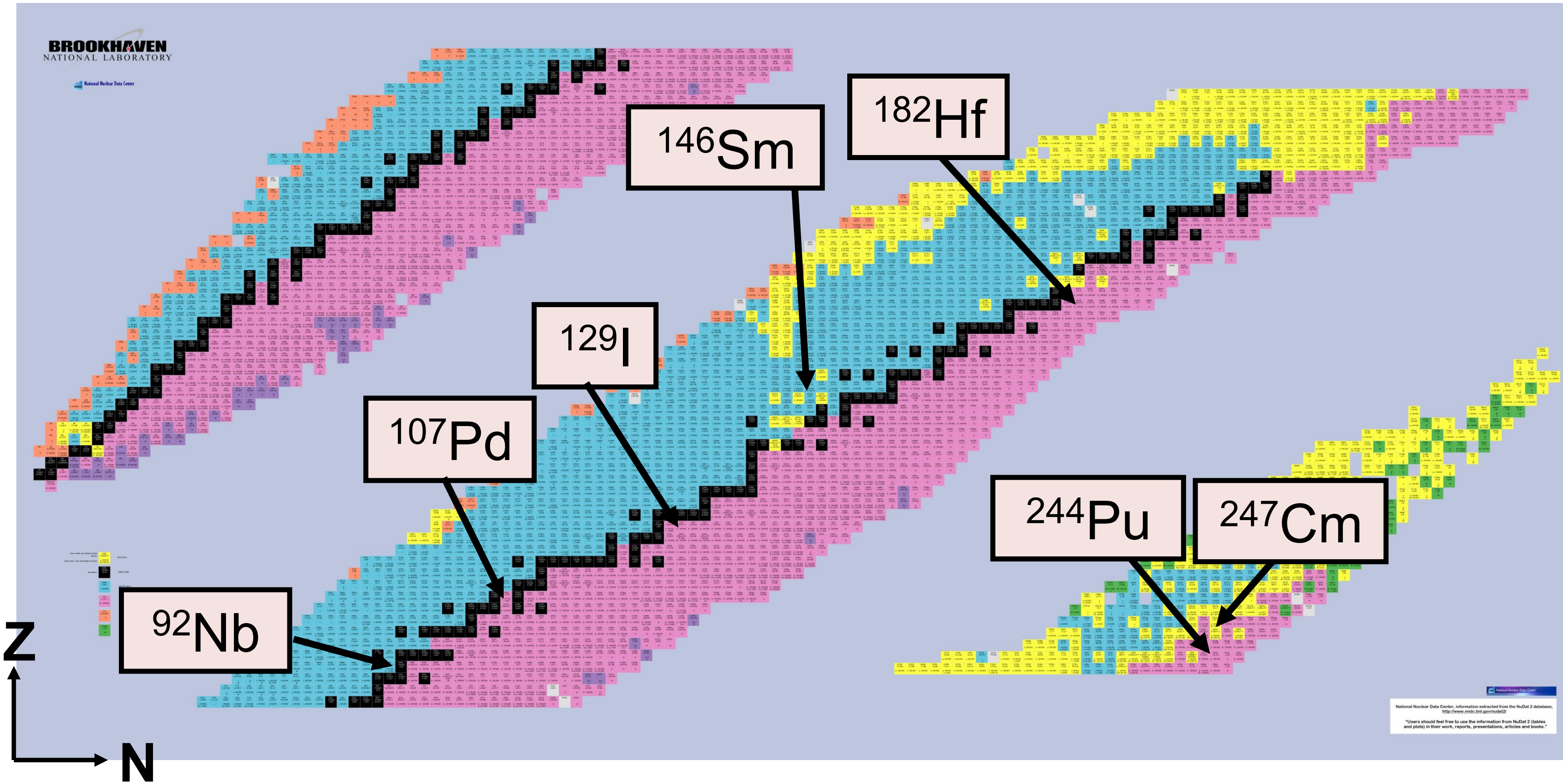
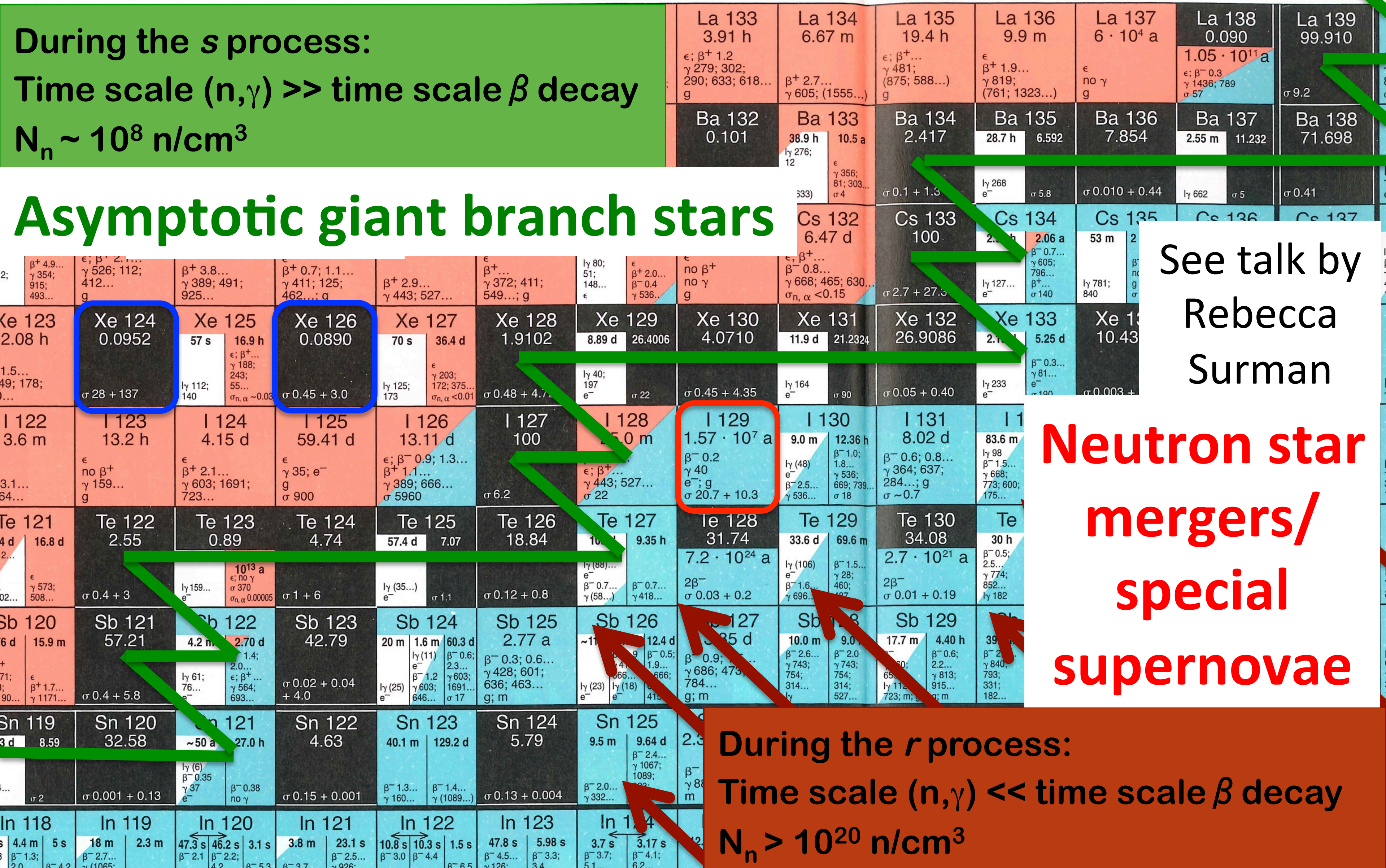
The nuclei heavier than Fe are produced by neutron captures: ***rapid*** (supernovae/neutron star mergers) or ***slow*** (AGB stars)



A few exceptions produced by the ***p* process** (supernovae): disintegrations (γ process) or proton captures

Slow and Rapid neutron captures



During the *s* process:
Time scale (n,γ) >> time scale β decay
$N_n \sim 10^8$ n/cm^3

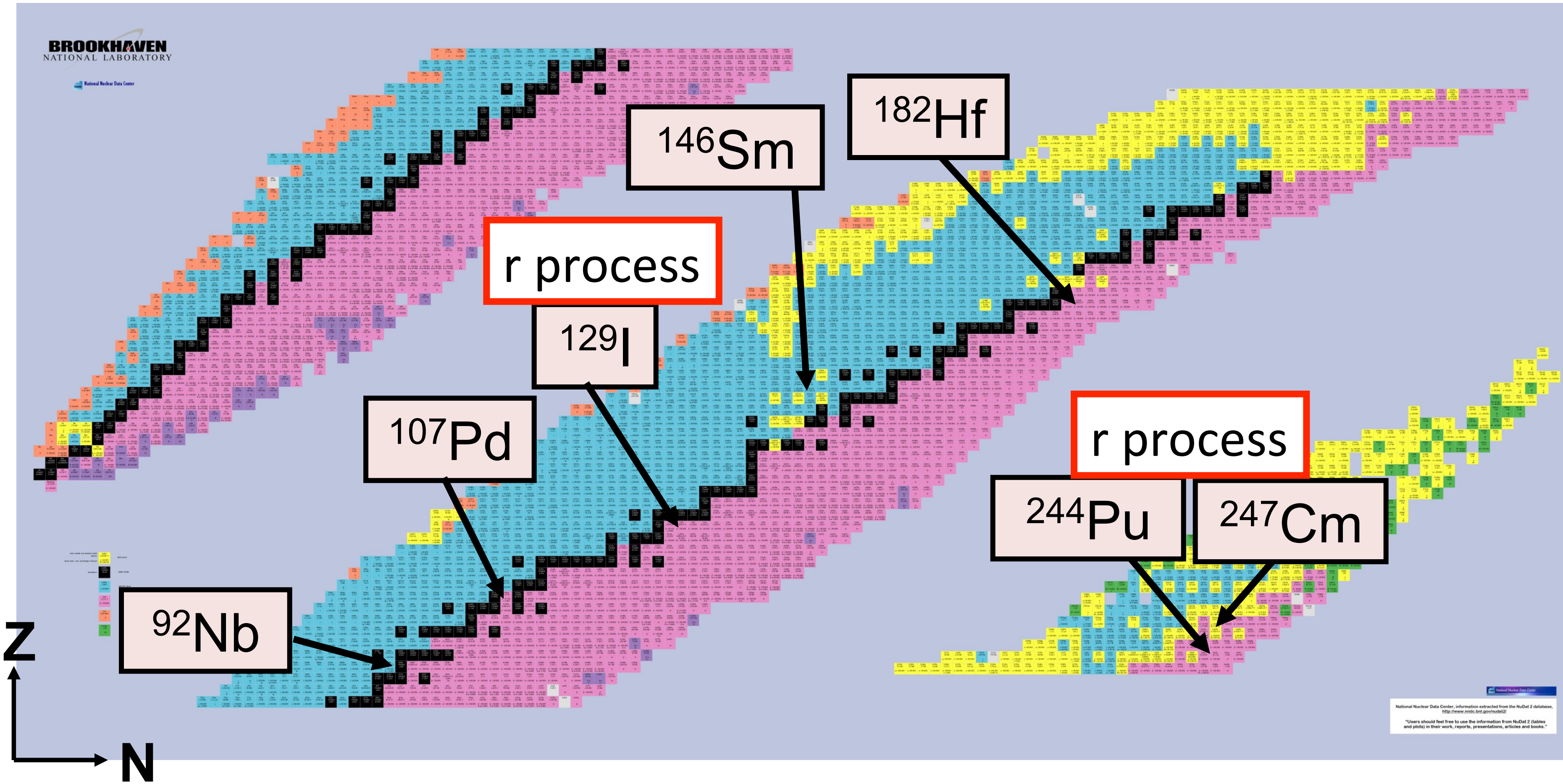
Asymptotic giant branch stars

See talk by Rebecca Surman

Neutron star mergers/ special supernovae

During the *r* process:
Time scale (n,γ) << time scale β decay
$N_n > 10^{20}$ n/cm^3

The nuclei heavier than Fe are produced by neutron captures:
rapid (supernovae/neutron star mergers) or ***slow*** (AGB stars)



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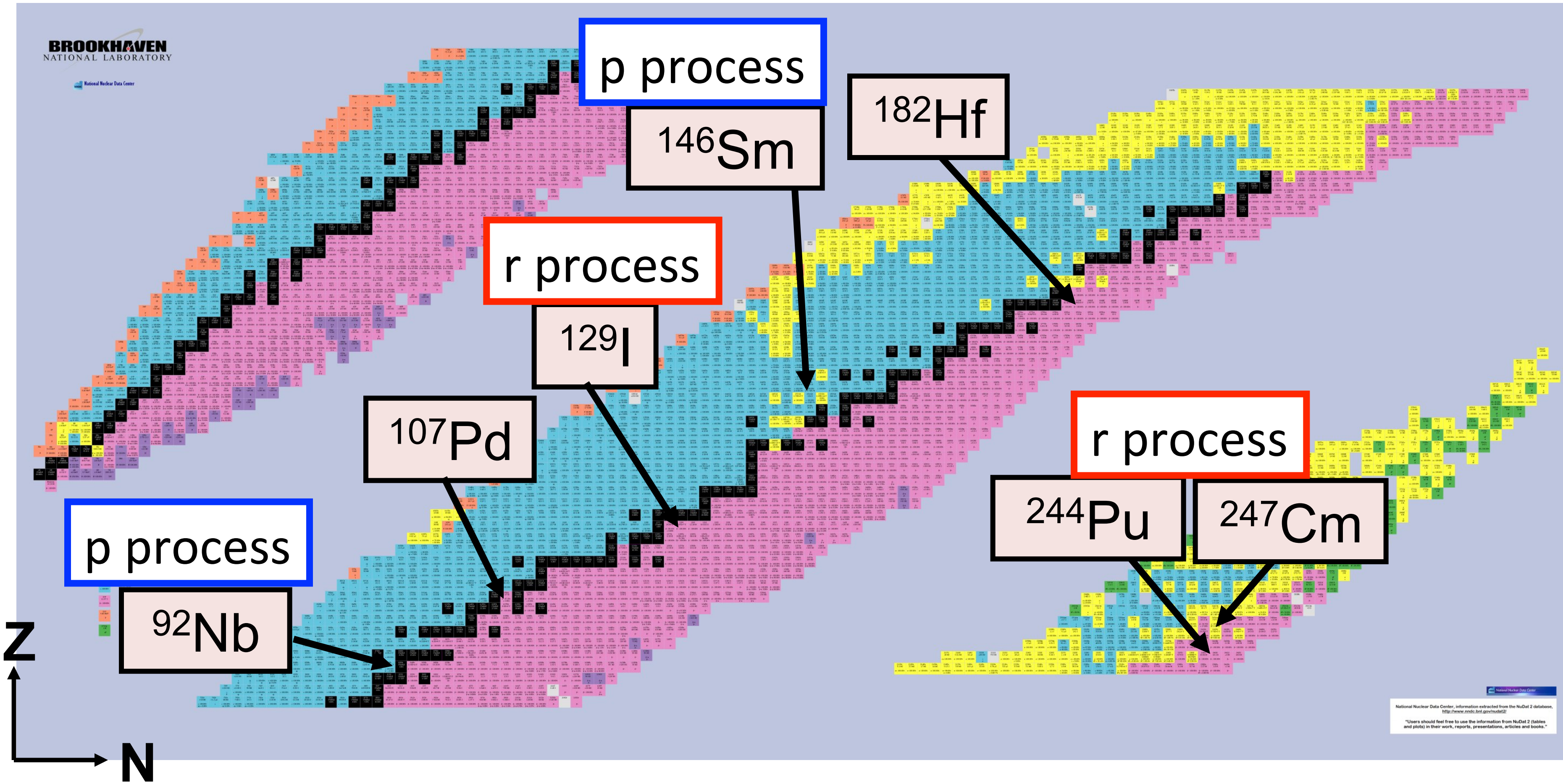

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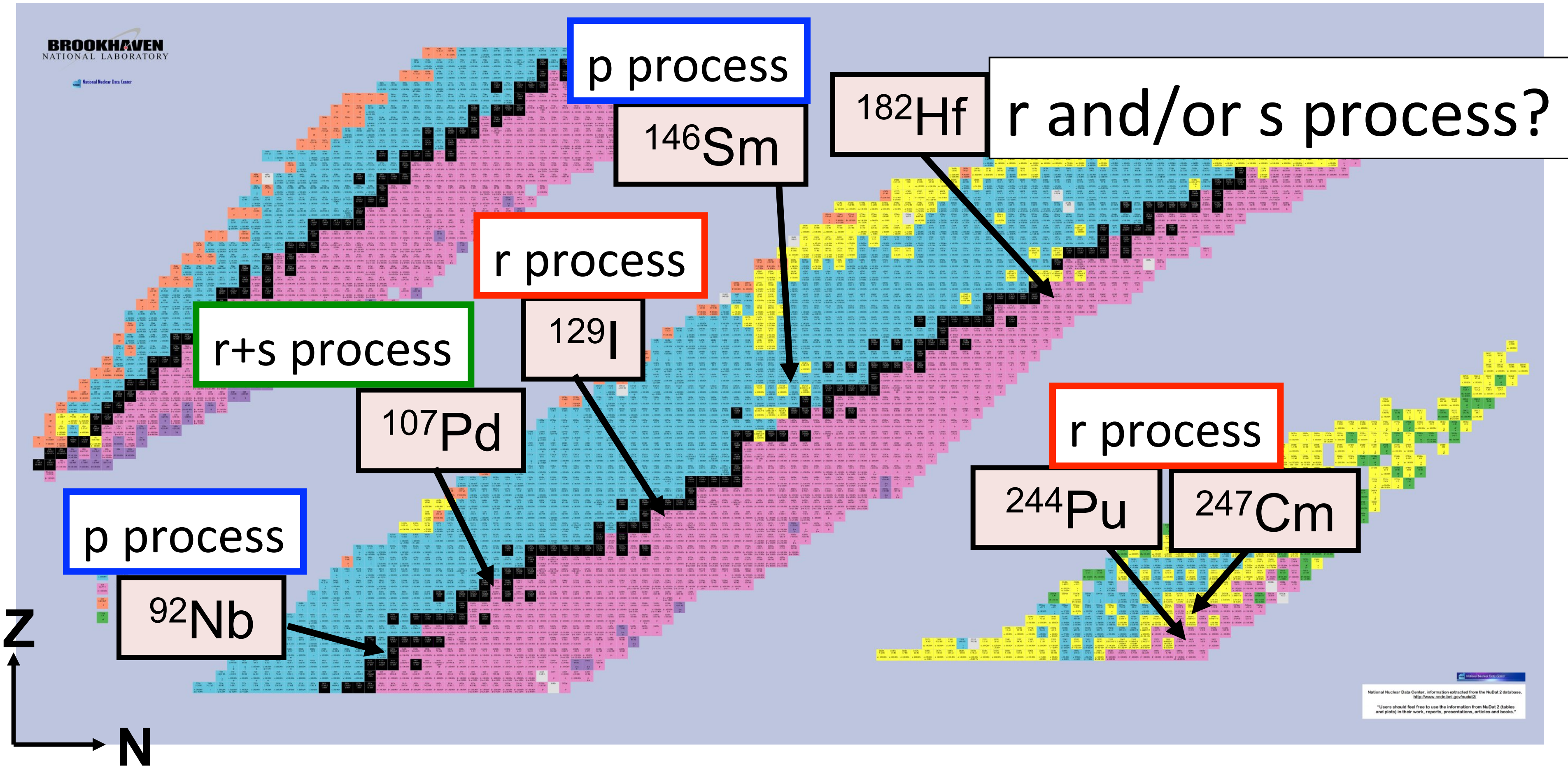

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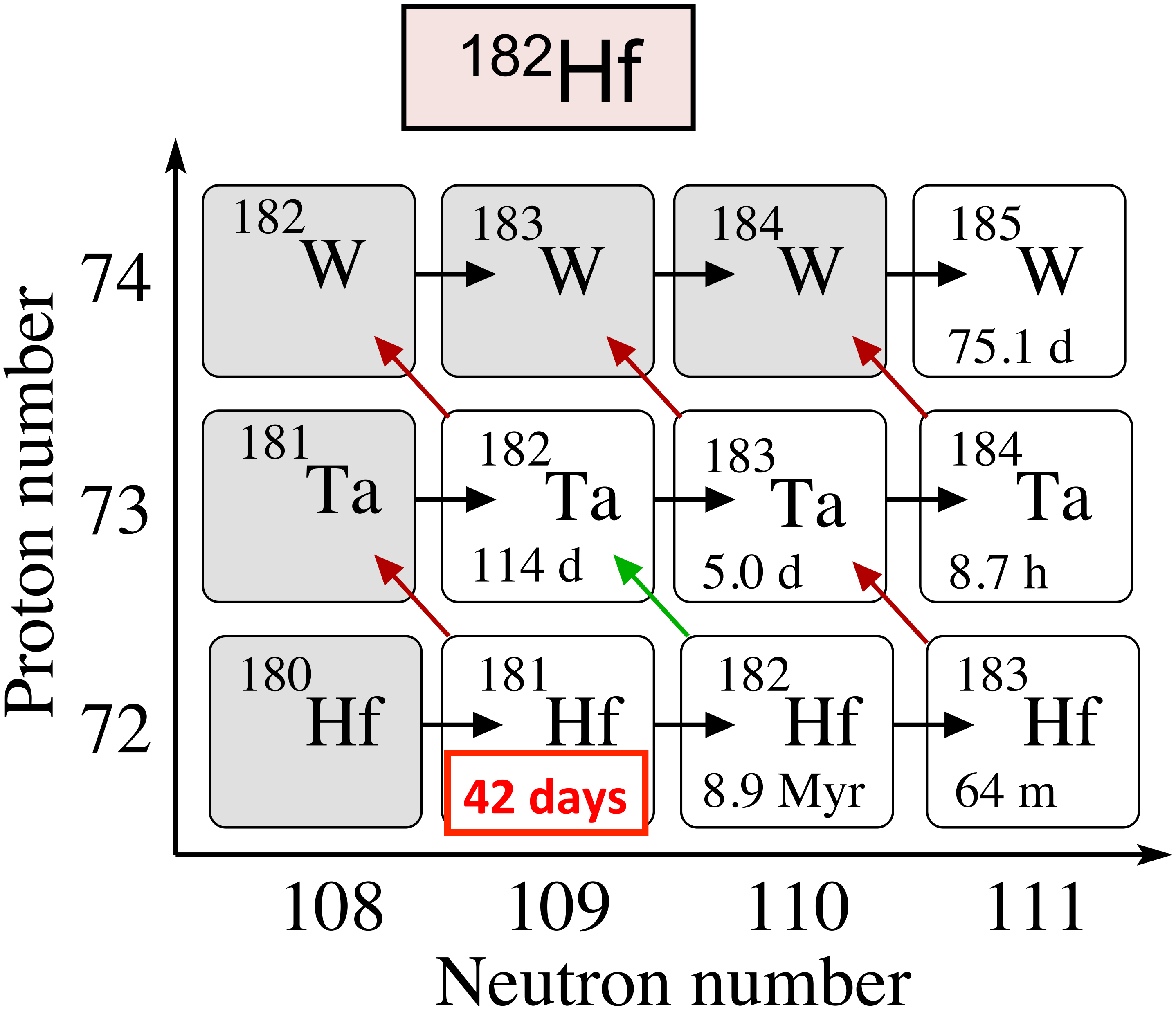
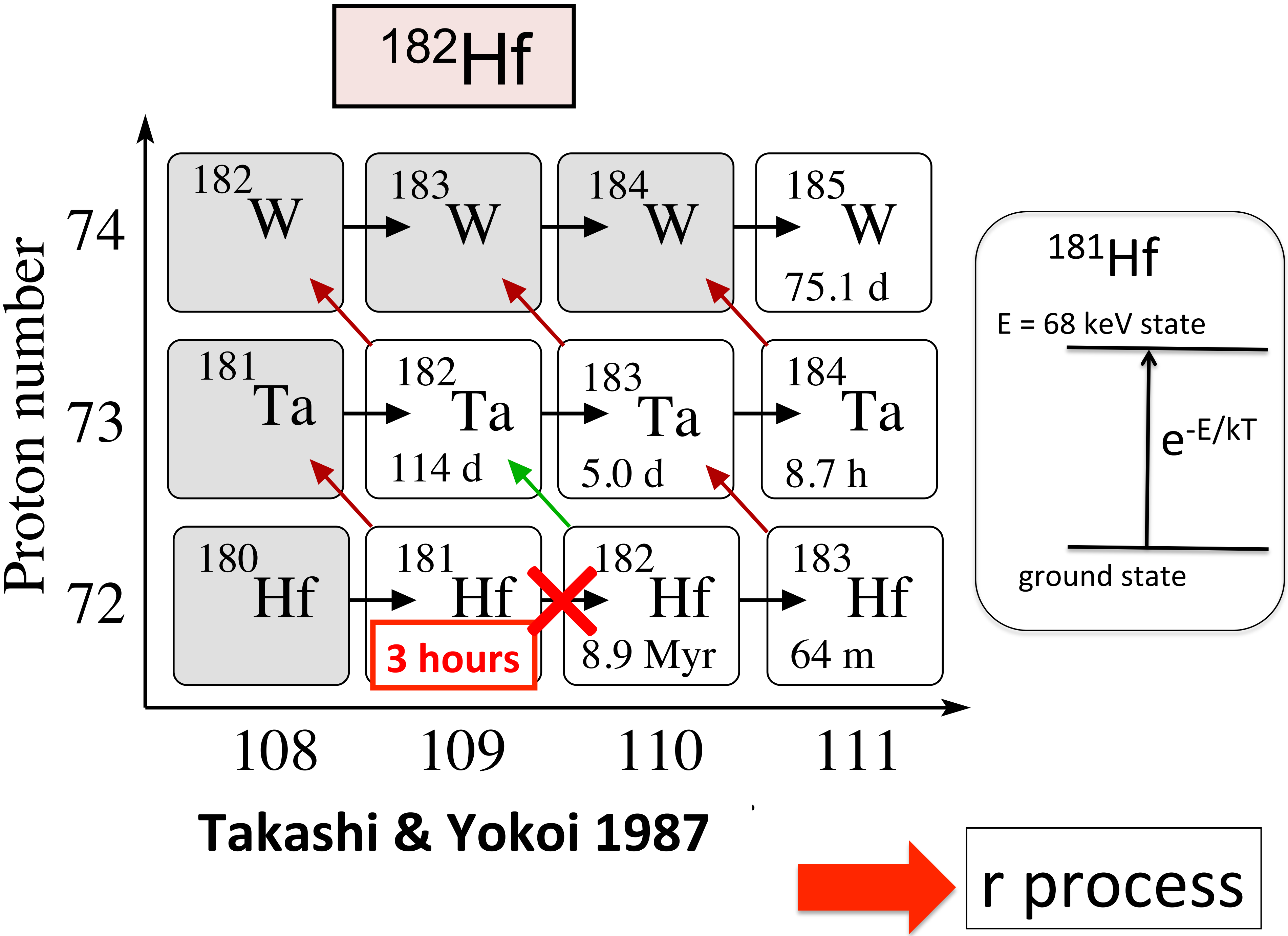
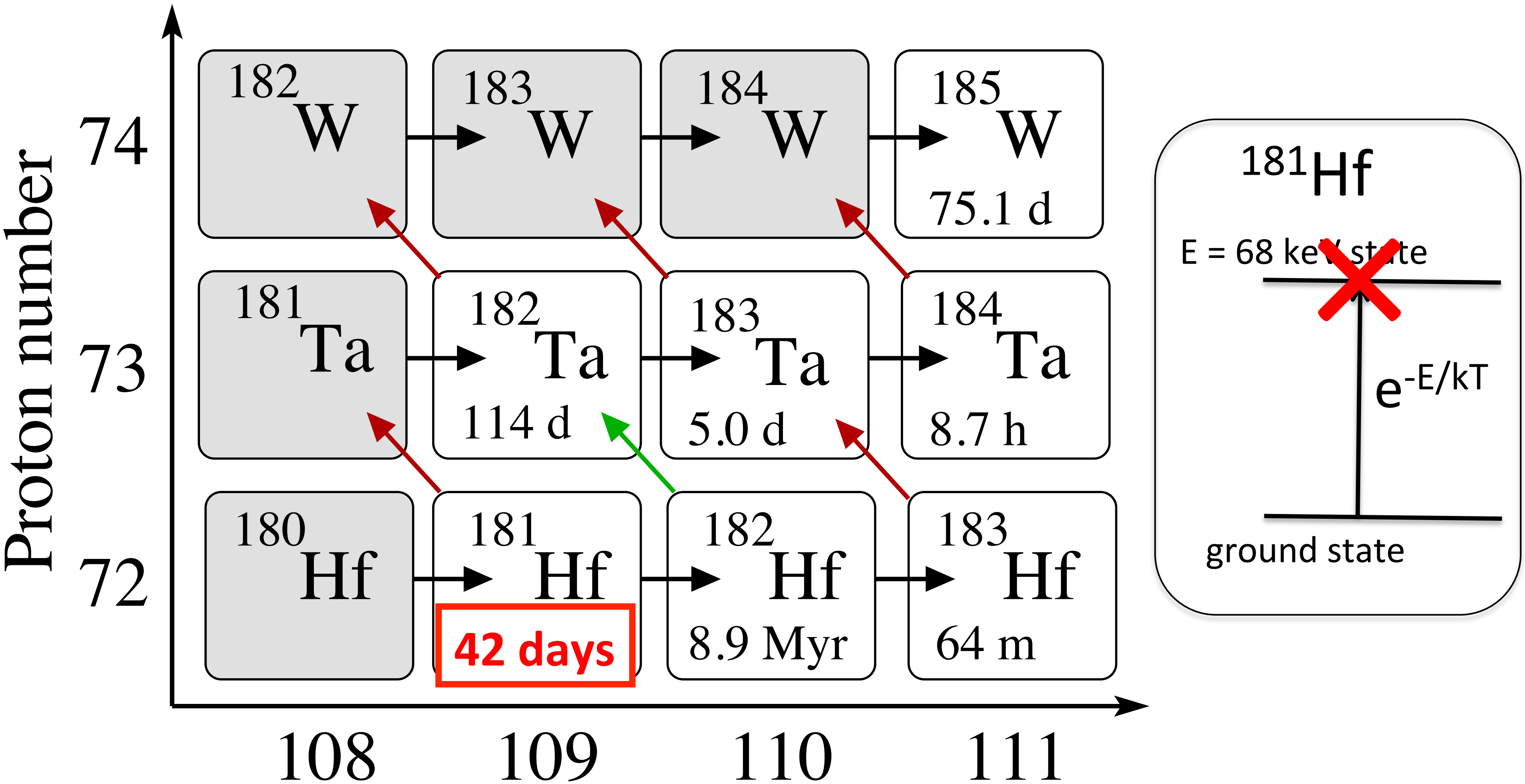


182Hf
182 W
183 W
184 W
185 W
75.1 d
181 Ta
182 Ta
114 d
183 Ta
5.0 d
184 Ta
8.7 h
180 Hf
181 Hf
42 days
182 Hf
8.9 Myr
183 Hf
64 m
Proton number
74
73
72
108
109
110
111
Neutron number



182Hf
Proton number
74
73
72
108
109
110
111
182 W
183 W
184 W
185 W 75.1 d
181 Ta
182 Ta 114 d
183 Ta 5.0 d
184 Ta 8.7 h
180 Hf
181 Hf
3 hours
182 Hf 8.9 Myr
183 Hf 64 m
181Hf
E = 68 keV state
e-E/kT
ground state
Takashi & Yokoi 1987
r process

^{182}Hf

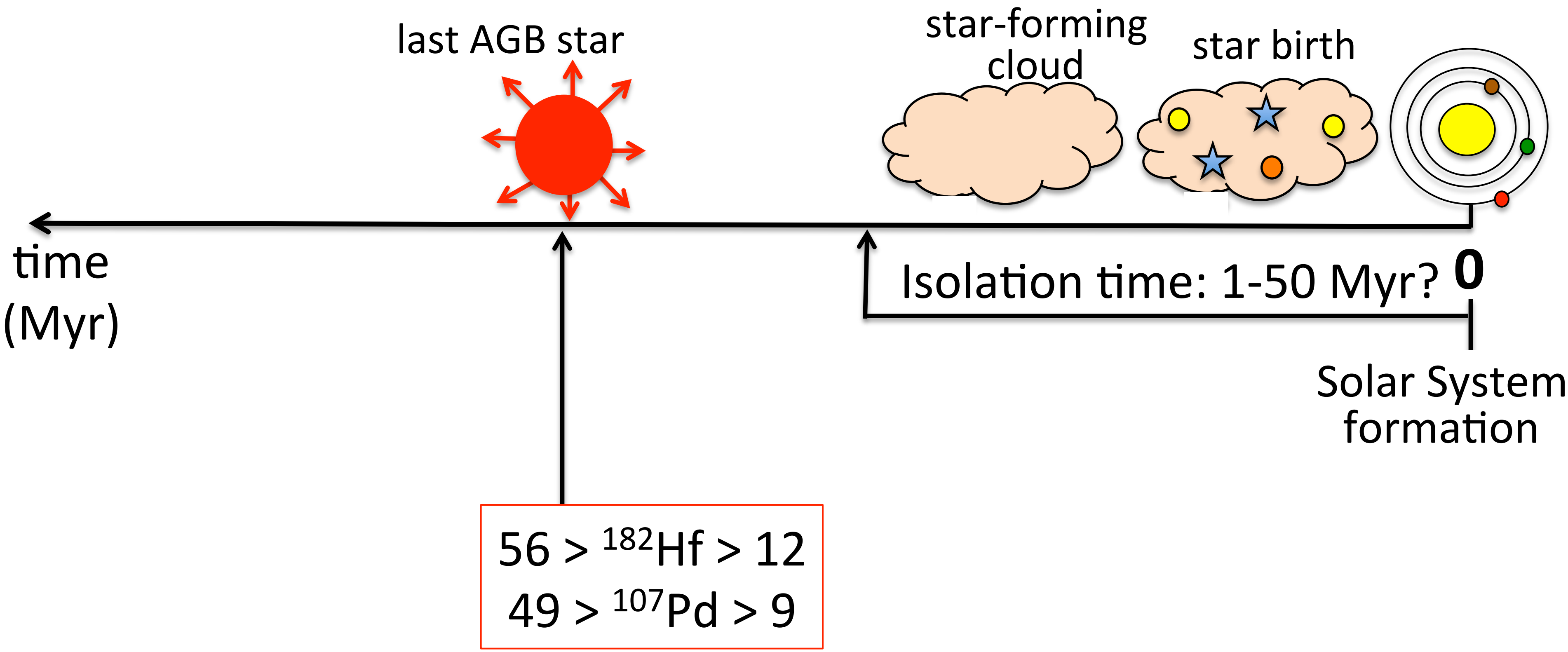


The 68 keV state does not exist (Bondarenko et al. 2002)

s process

The prehistory of the Solar System

updated from Lugaro et al. (2014, Science); Lugaro et al. (2016, PNAS)

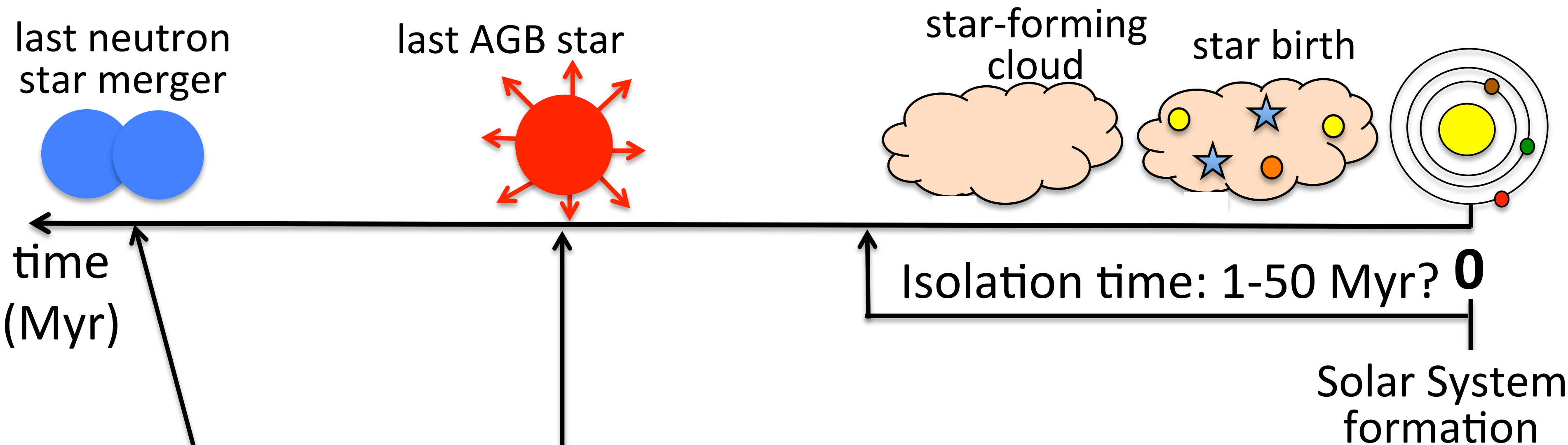


Uncertainties from:

- missing galactic chemical evolution predictions
- *s*-process production: ^{22}Ne+α; decay rate and neutron capture on ^{181}Hf, neutron captures on ^{107,108}Pd

The prehistory of the Solar System

updated from Lugaro et al. (2014, Science); Lugaro et al. (2016, PNAS)



150 > ^{129}I > 76

337 > ^{244}Pu > 73

205 > ^{247}Cm > 100

56 > ^{182}Hf > 12

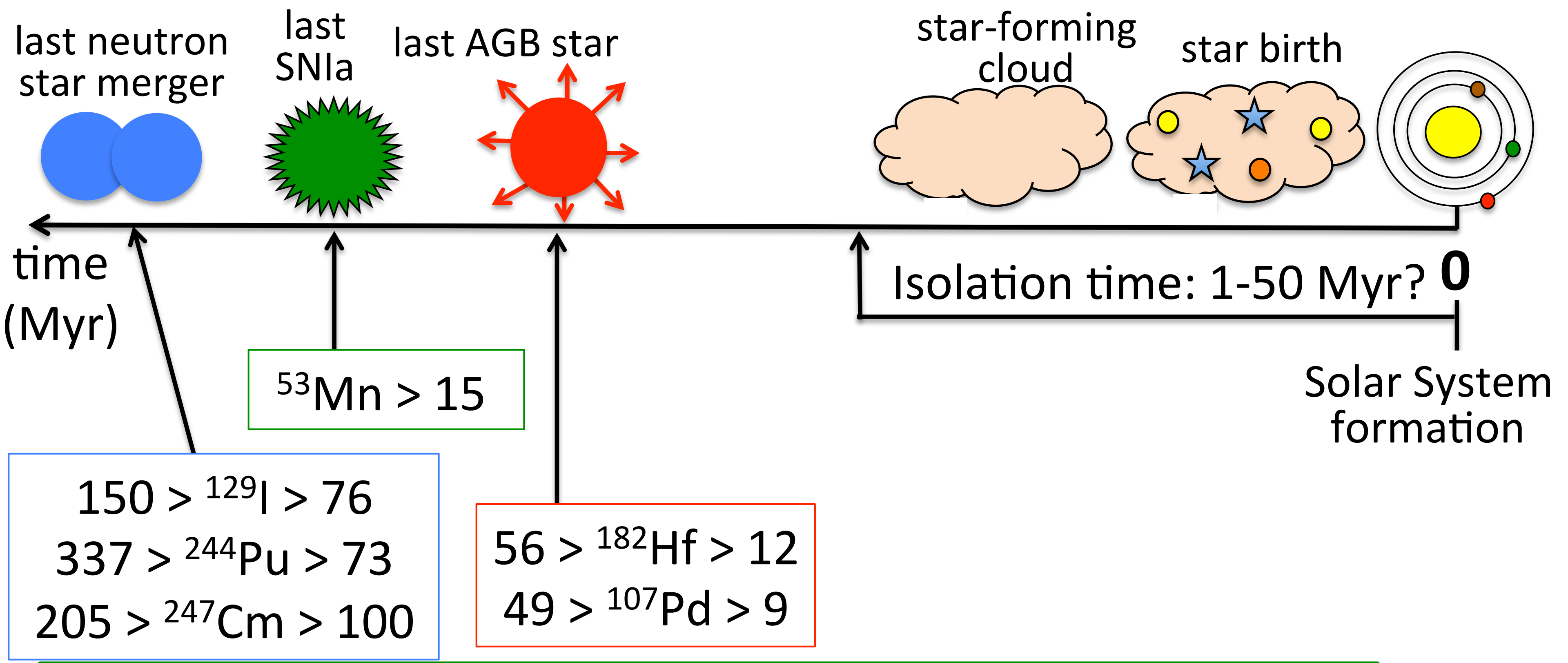
49 > ^{107}Pd > 9

Uncertainties from:

- missing galactic chemical evolution predictions
- the actinides *r*-process production yields (Goriely & Janka 2016)

The prehistory of the Solar System

updated from Lugaro et al. (2014, Science); Lugaro et al. (2016, PNAS)

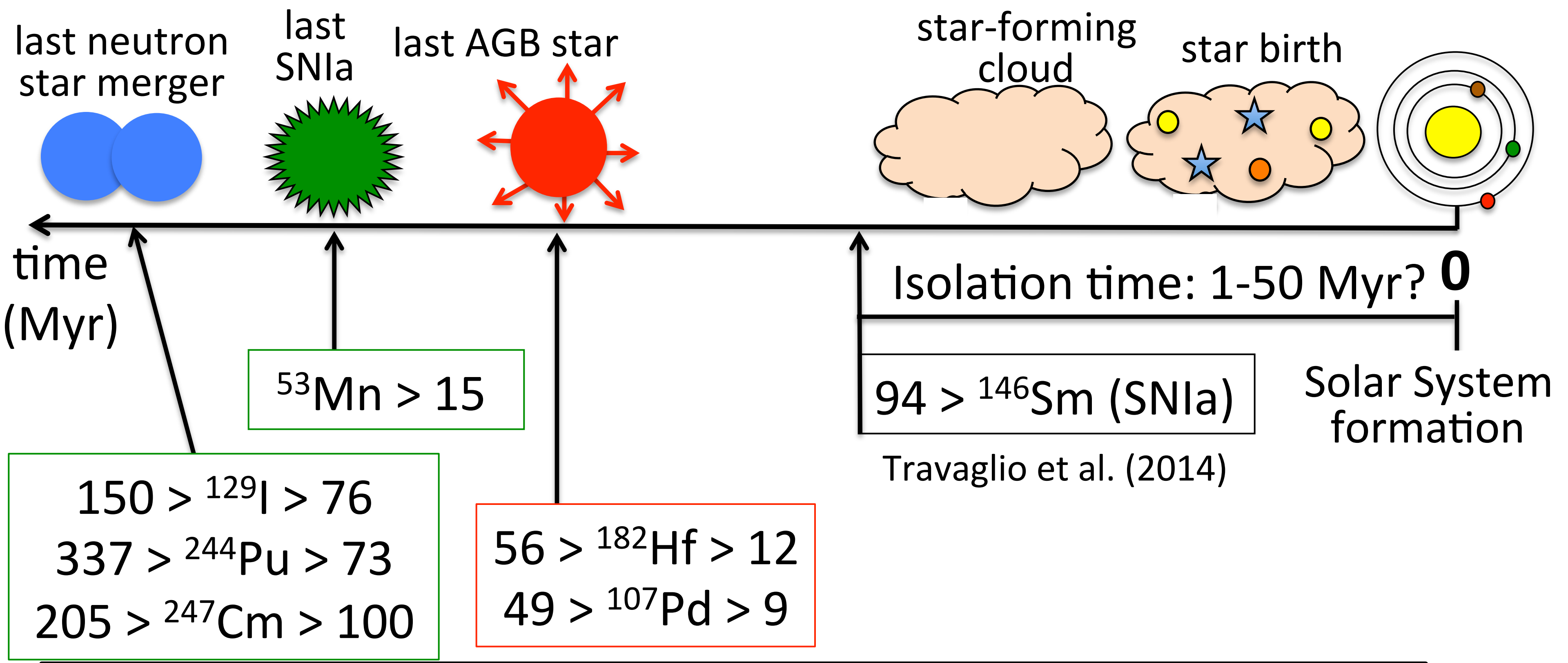


Uncertainties from:

- missing galactic chemical evolution predictions
- the half life of ^{53}Mn
- the $^{32}S(\beta+)^{32}P$ decay rate (Parikh et al. 2013)

The prehistory of the Solar System

updated from Lugaro et al. (2014, Science); Lugaro et al. (2016, PNAS)

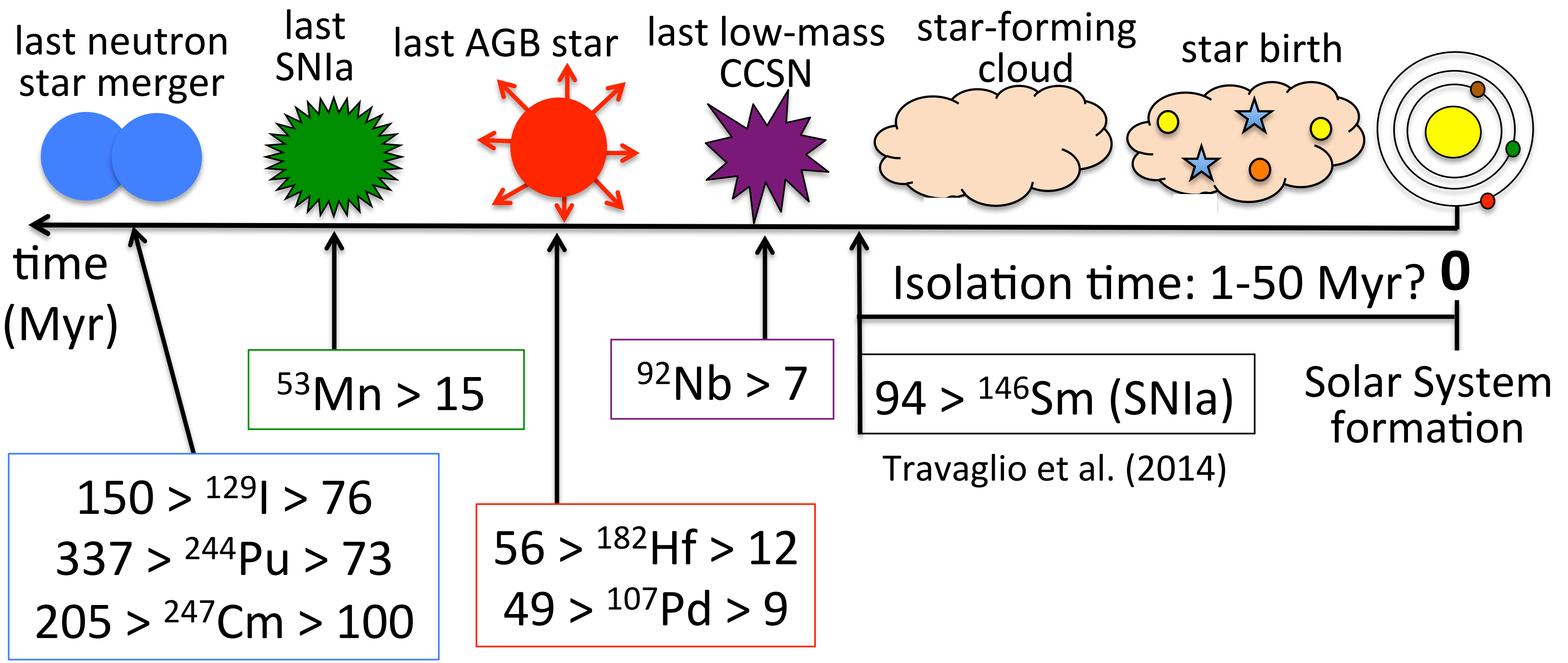


Uncertainties from:

- the ^{148}Gd(γ,α)^{144}Sm reaction rate;
- the ^{146}Sm decay rate (68 Myr: Kinoshita et al. 2012, 103 Myr: Marks et al. 2014)

The prehistory of the Solar System

updated from Lugaro et al. (2014, Science); Lugaro et al. (2016, PNAS)

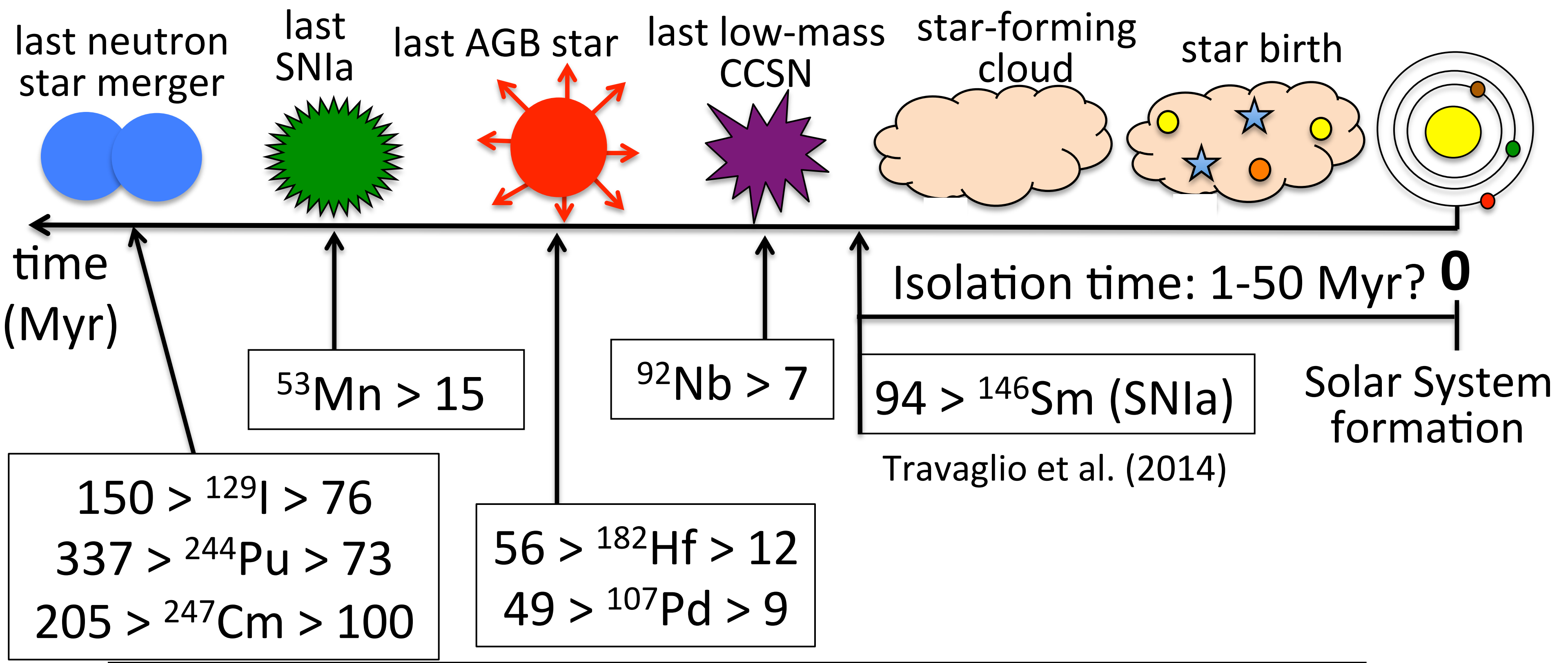


Uncertainties from:

- missing galactic chemical evolution predictions
- core-collapse supernova models

The prehistory of the Solar System

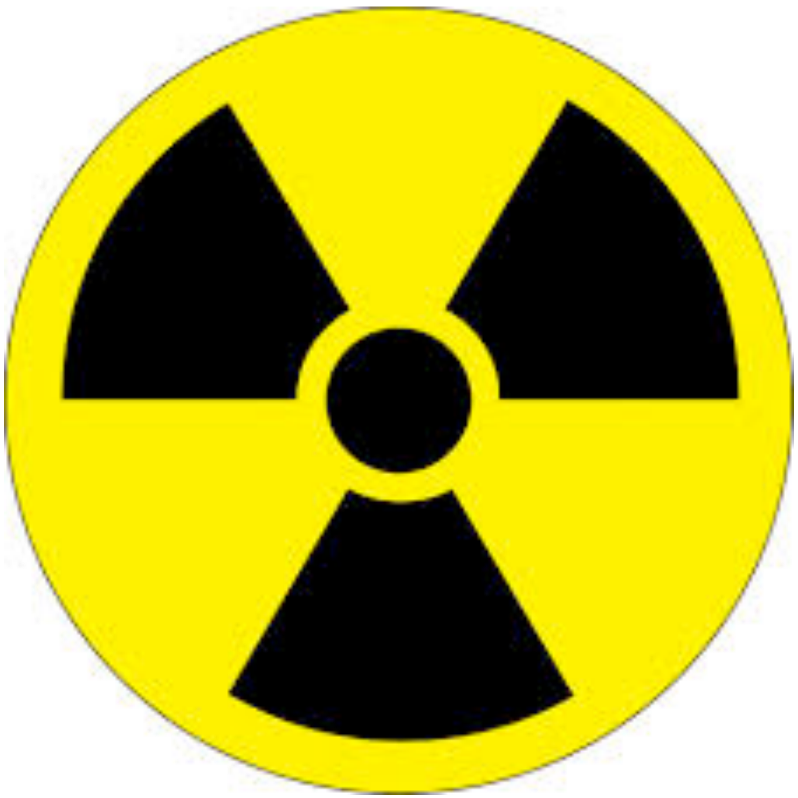
updated from Lugaro et al. (2014, Science); Lugaro et al. (2016, PNAS)



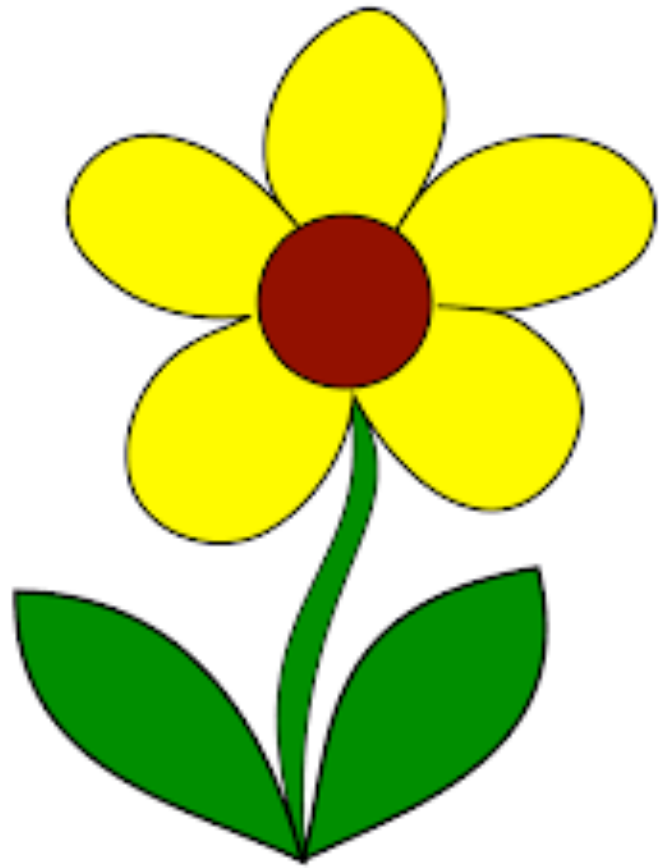
Need to improve:

- the nuclear and stellar physics inputs
- the description of galactic chemical evolution
- the accuracy and precision of meteoritic data

Why are radioactive nuclei of interest for **habitability**?

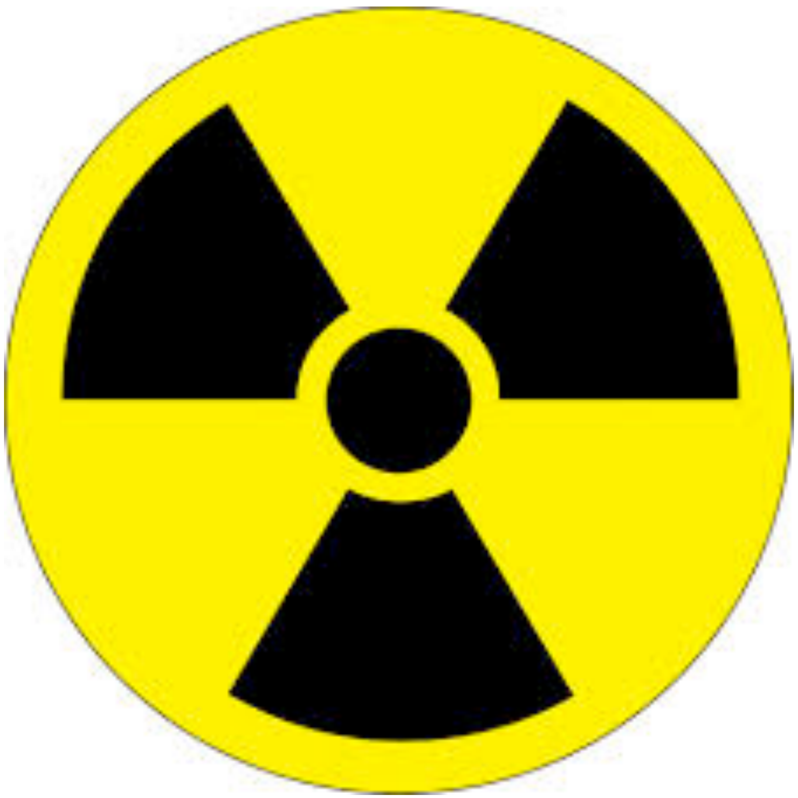


$\stackrel{?}{=}$



Why are radioactive nuclei of interest for **habitability**?

Because their decay can generate heat



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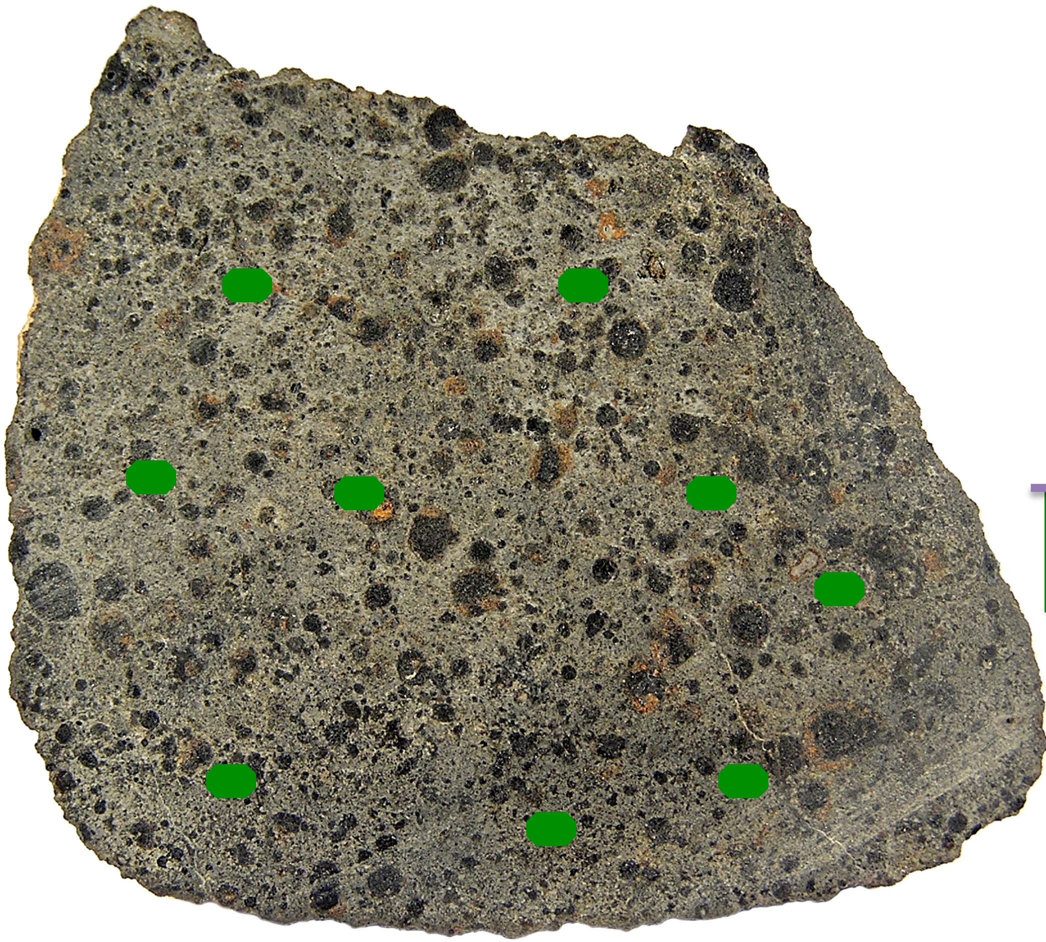

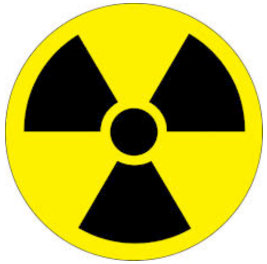

=

$J = 5$

^{26}Al

0.7 Myr

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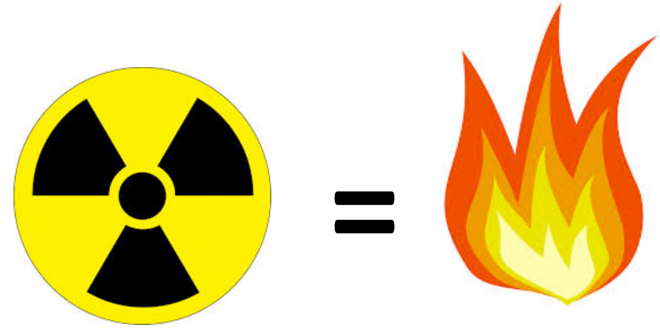

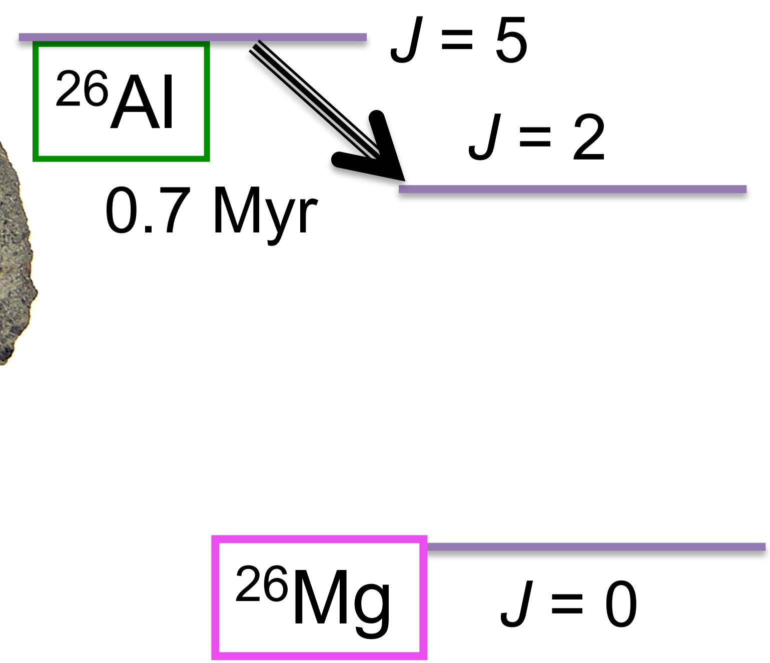

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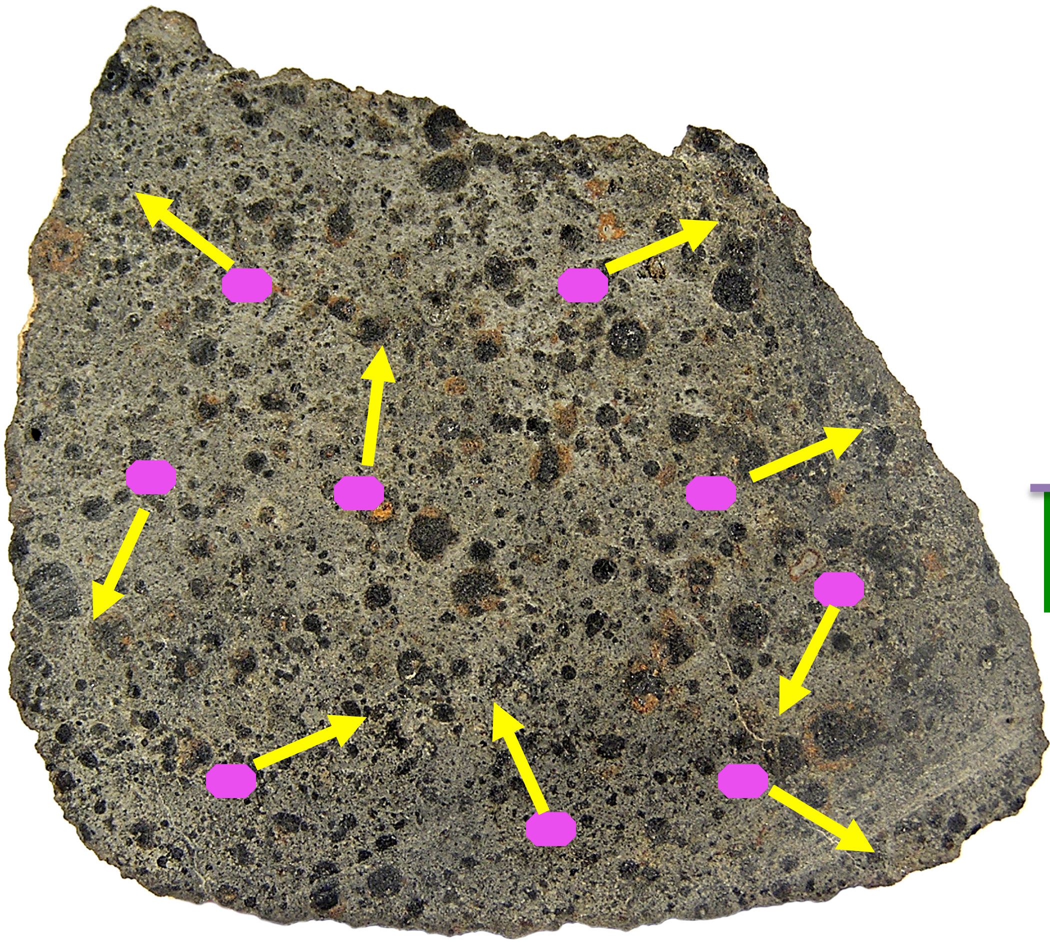
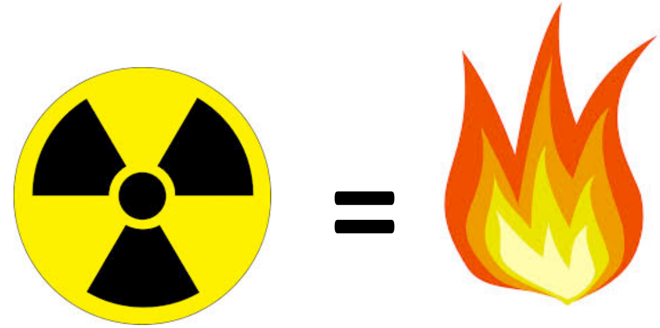
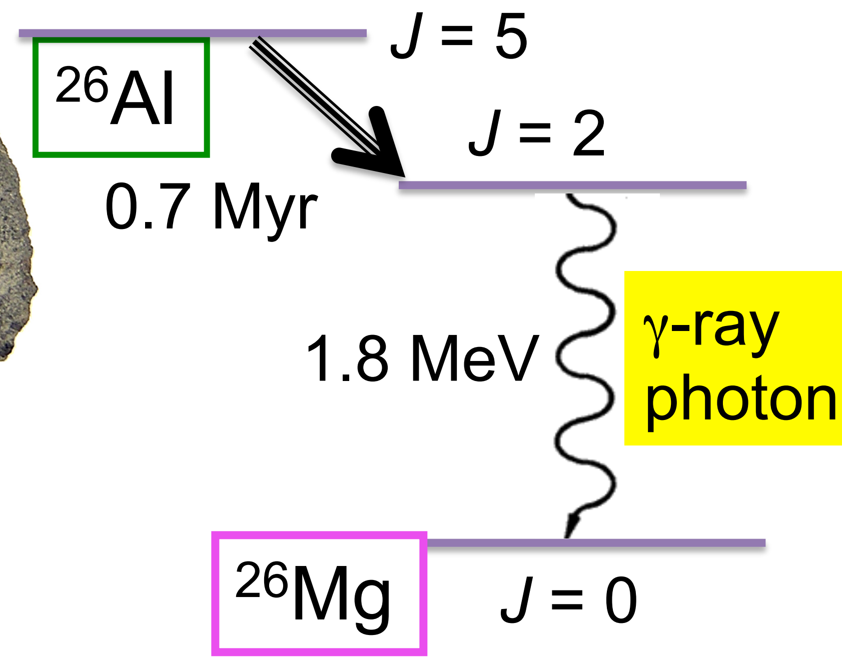
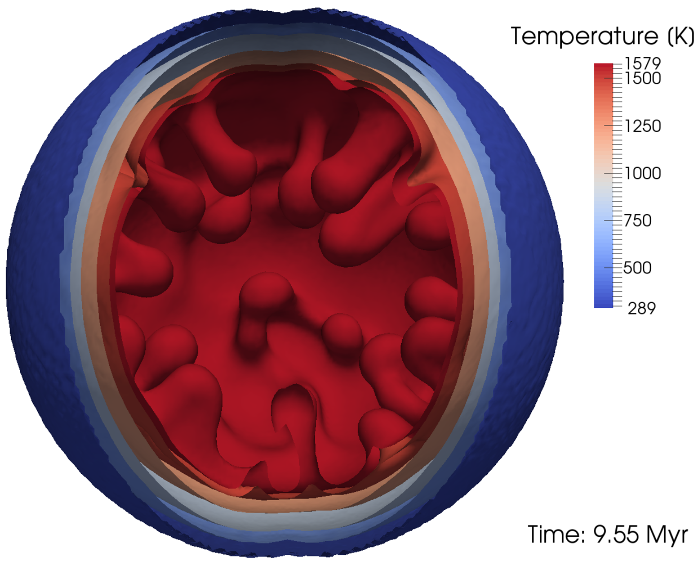






The implications



Lichtenberg et al. 2016 (Icarus)

The radioactive decay of ^{26}Al (0.7 Myr) in the early Solar System was a main **source of heat in planetesimals**, altering their thermo-mechanical evolution and outgassing volatiles.

Are other planetary systems born rich in ^{26}Al?

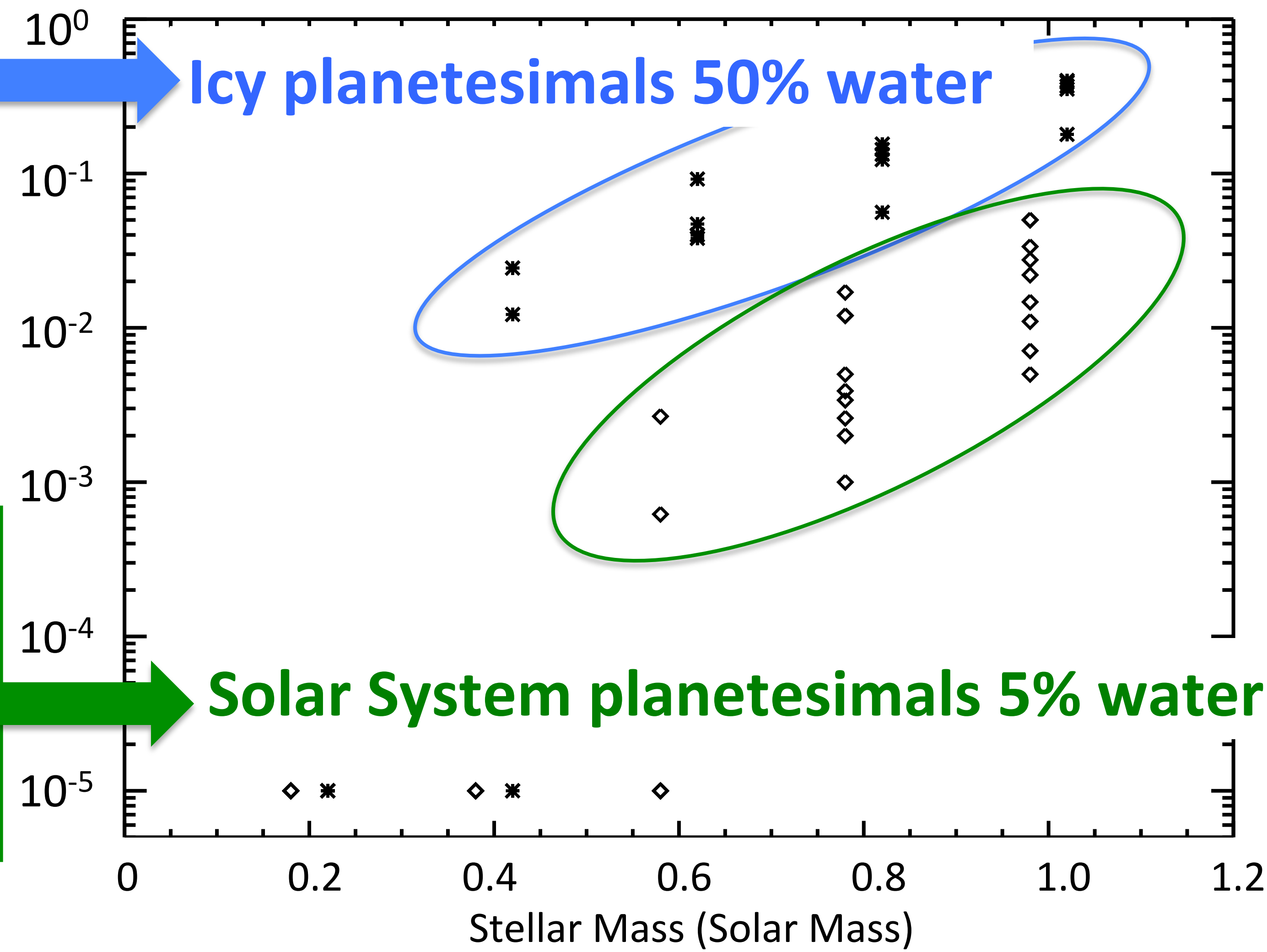
Extrasolar planetesimals **without ^{26}Al** would have more ice, and **deliver more water** to extrasolar terrestrial planets, with implications on their habitability.

Ciesla et al. (2015, ApJ) calculated the effect of different ice content in the planet building blocks beyond the snow line:

Water mass fraction for planets in the Habitable Zone

much less ^{26}Al than in the Solar System

as much ^{26}Al as in the Solar System



The hypotheses

"LOCAL": A nearby star or supernova injected ^{26}Al into the protosolar nebula or disk

Cameron & Truran 1977 … Hester et al. 2004 … Wasserburg et al. 2006 … Lugaro et al. 2012 … Pan et al. 2012 … Gounelle 2015

"GLOBAL": The molecular cloud lived long enough that stellar winds and supernovae polluted with ^{26}Al the gas from which new stars formed

Gaidos et al. 2009 … Vasileiadis et al. 2013 … Young 2014, 2016

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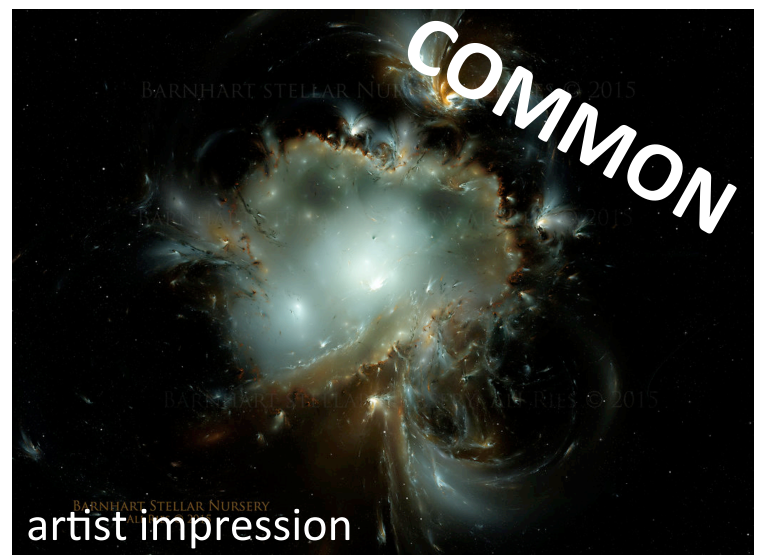

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Pan et al.

No consensus on a 40 year old question

“GLOBAL”: The molecular cloud lived long enough that stellar winds and supernovae polluted with ^{26}Al the gas from which new stars formed

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^{232}**Th** (14 Gyr) and ^{238}**U** (4.5 Gyr)

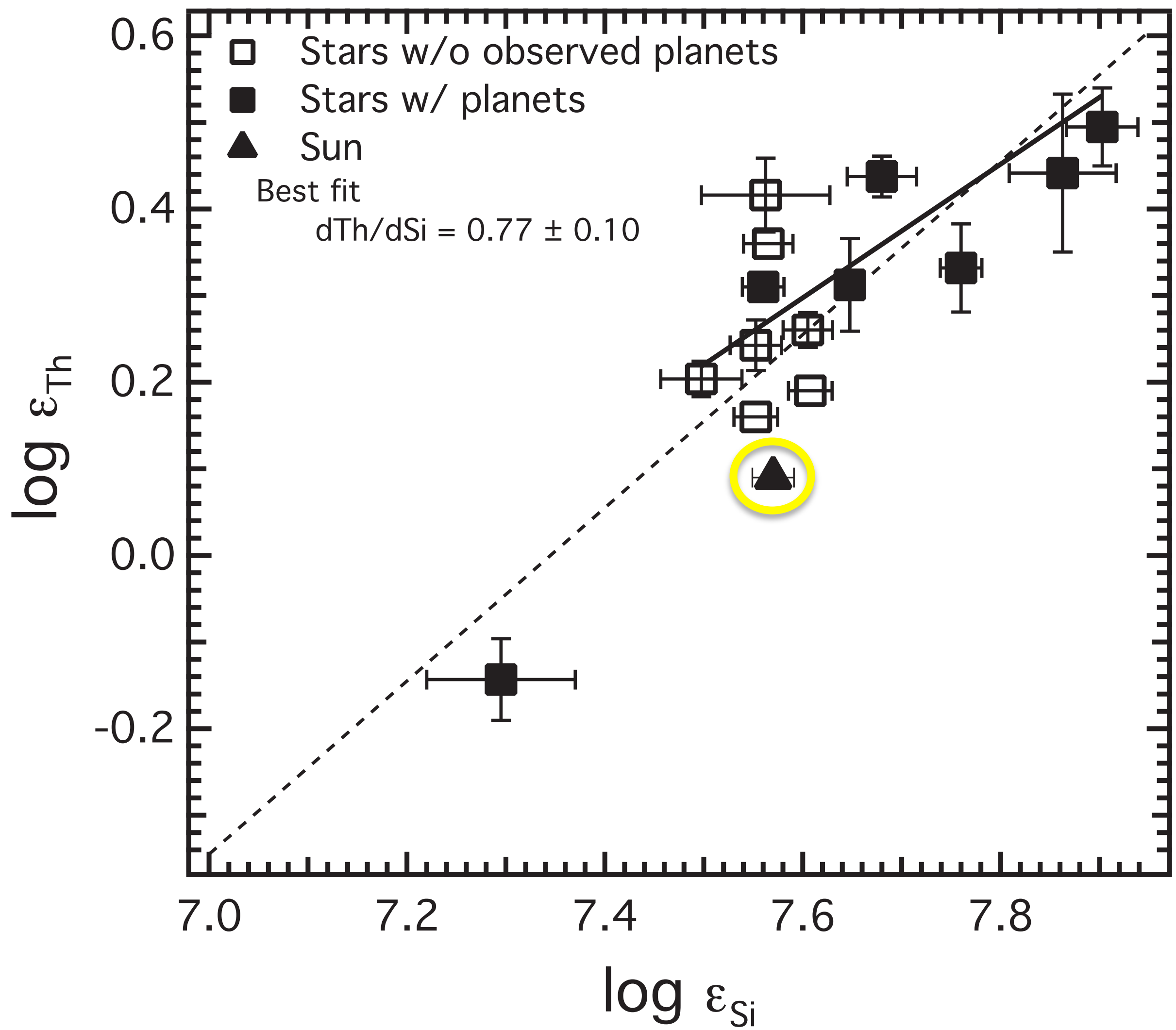
make up 30%–50% of the Earth's energy budget.

Would this be similar in extrasolar terrestrial planets?

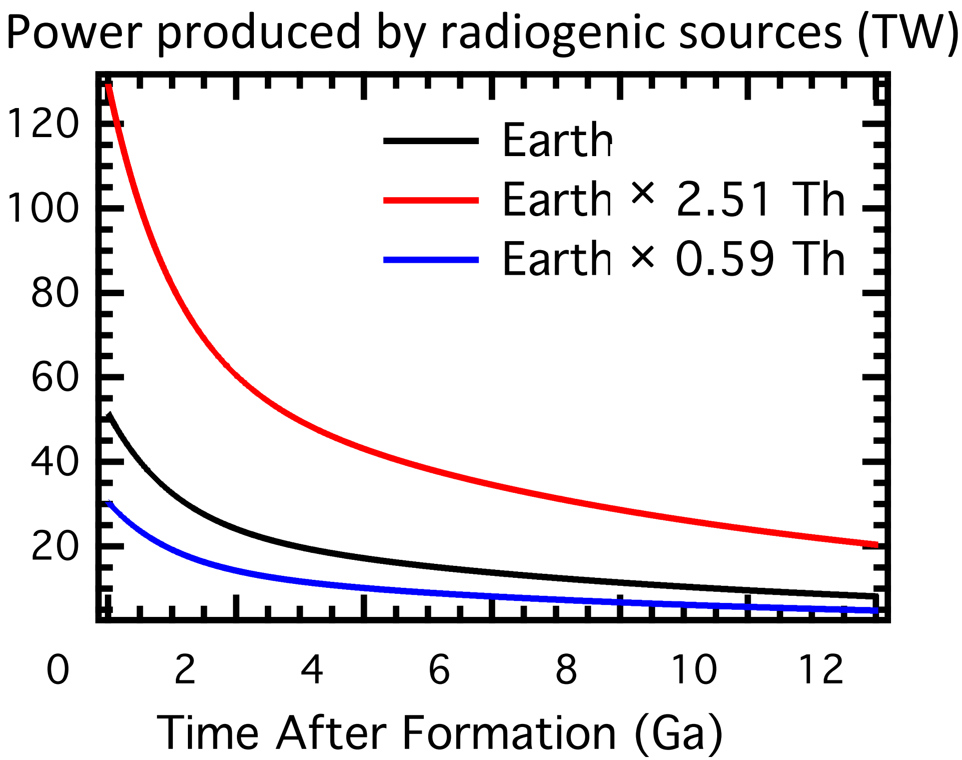
^{232}Th (14 Gyr) and ^{238}U (4.5 Gyr) make up 30%–50% of the Earth's energy budget.

Would this be similar in extrasolar terrestrial planets?

First observations of Th abundances in solar twins: **up to 2.5 times higher than in the Sun** (Unterborn et al. 2015, ApJ)



Unterborn et al. (2015) also presented a thermal model to evaluate the effect of different amounts of Th in extrasolar terrestrial planets.



Planets with higher Th possess larger energy budgets.

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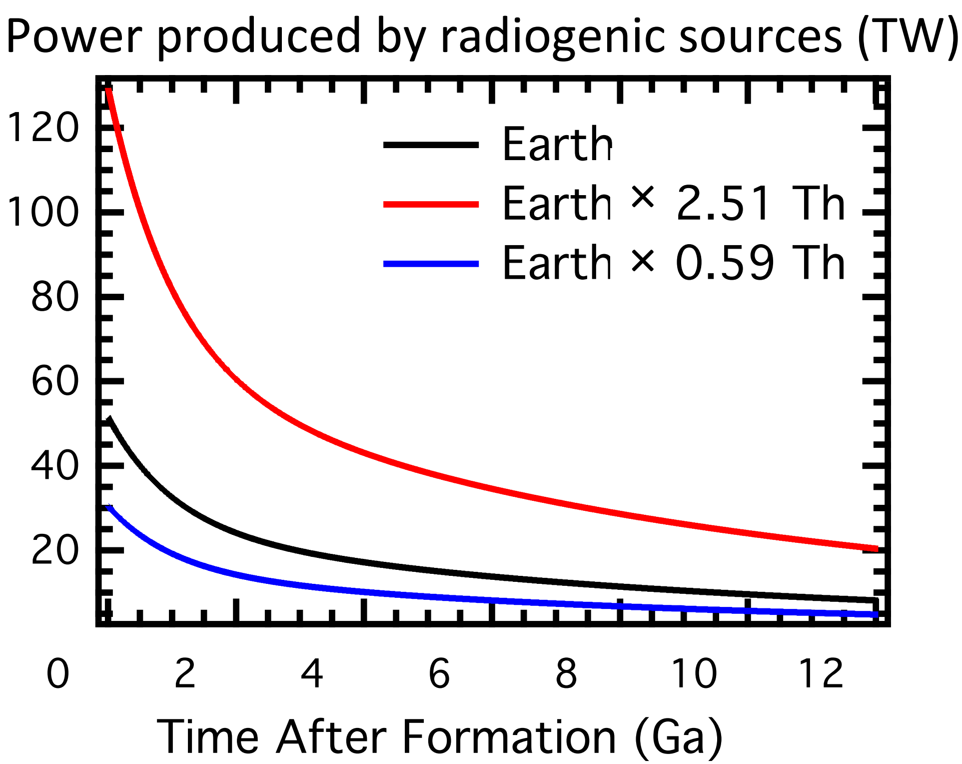
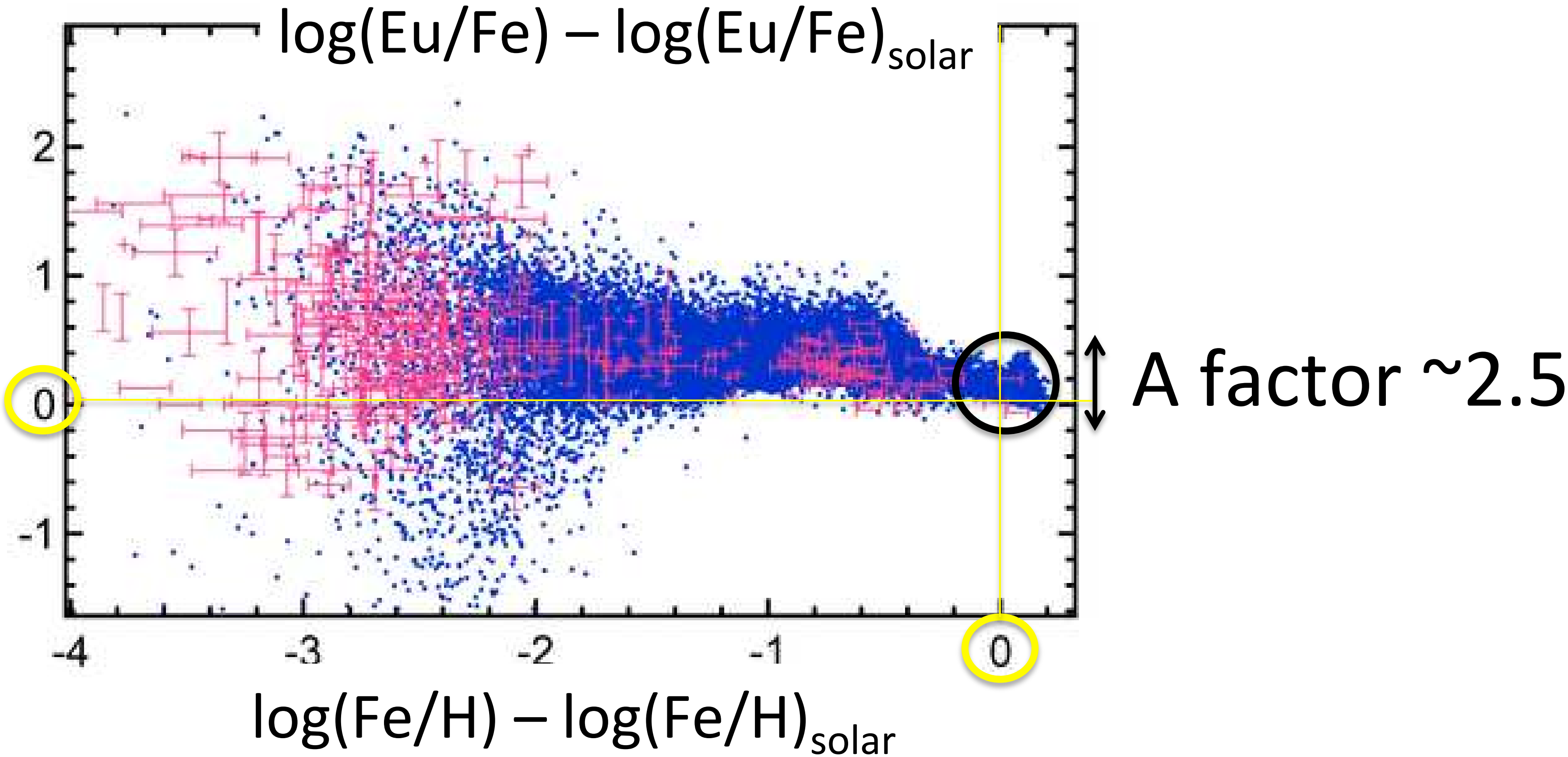


Planets with higher Th possess larger energy budgets.

1. Mantle convection starts earlier
2. Increased likelihood for carbon and water cycling between the surface crust and planetary interior
3. Broader range of planets which may support habitable surfaces

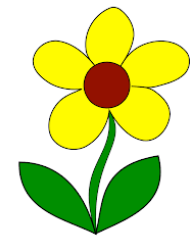
Why such a spread in Th?

Th and U are produced by the *r* process: use Eu as a proxy



Evolution of Eu abundances in an **inhomogeneous** model of galactic enrichment including both *Jet_Supernovae* and neutron star mergers as r-process sites (Wehmeyer et al. 2015)

Conclusions

- Opportunities are growing to use radionuclides to investigate
  - **the origin of the Solar System** 
  - **the properties of extrasolar planetary systems** 
- **Stellar nucleosynthesis** is the core knowledge on which all these applications are based
- **Nuclear physics inputs are needed** for accurate model predictions: from half lives (e.g.,^{146}Sm) to n-captures (e.g., ^{107}Pd, ^{108}Pd, ^{26}Al), p-captures (e.g., ^{25}Mg and ^{26}Al), etc. etc.