Nuclear burning recorded in meteorites as a tracer of the birth of the Sun and its planets

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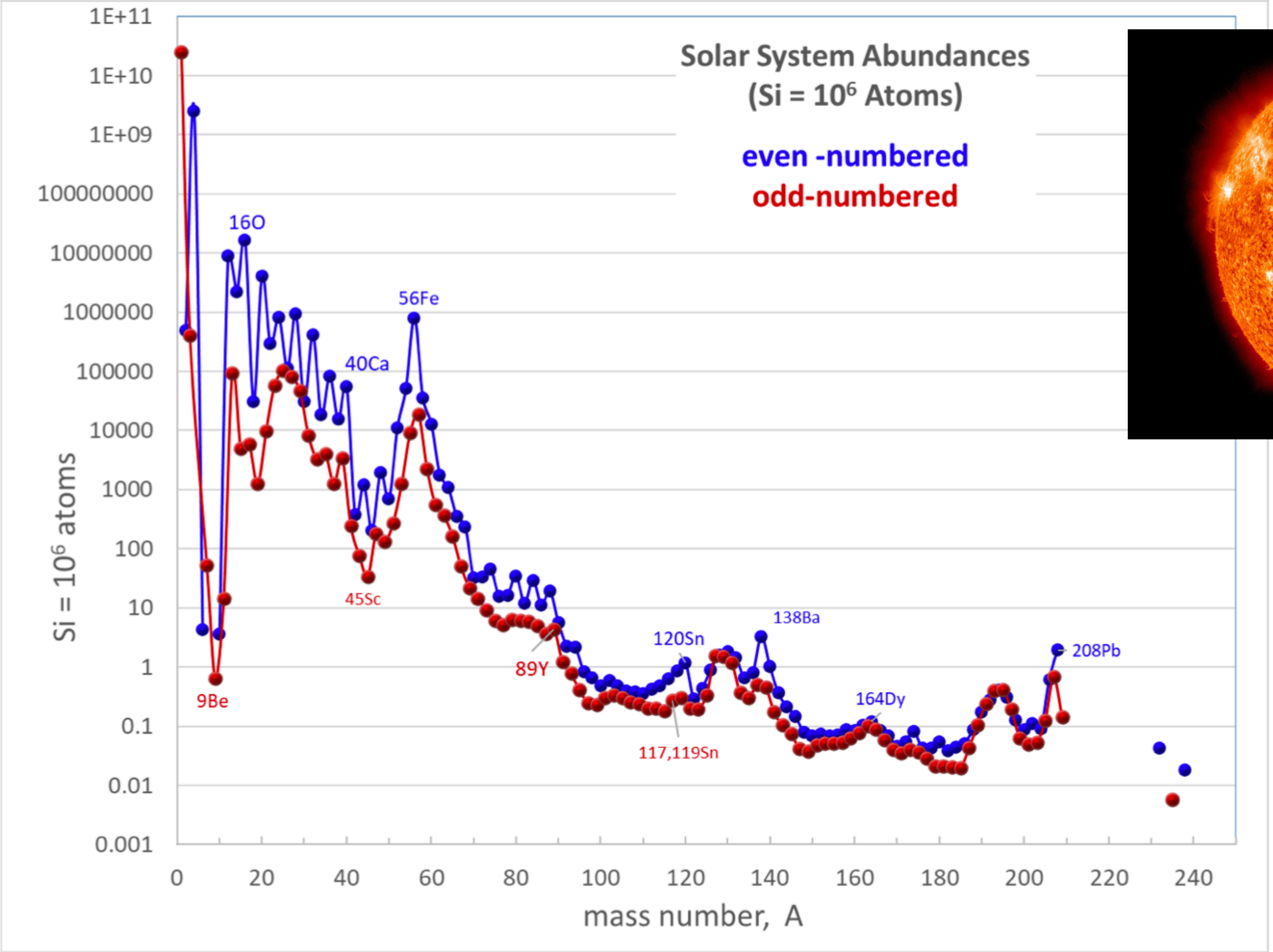
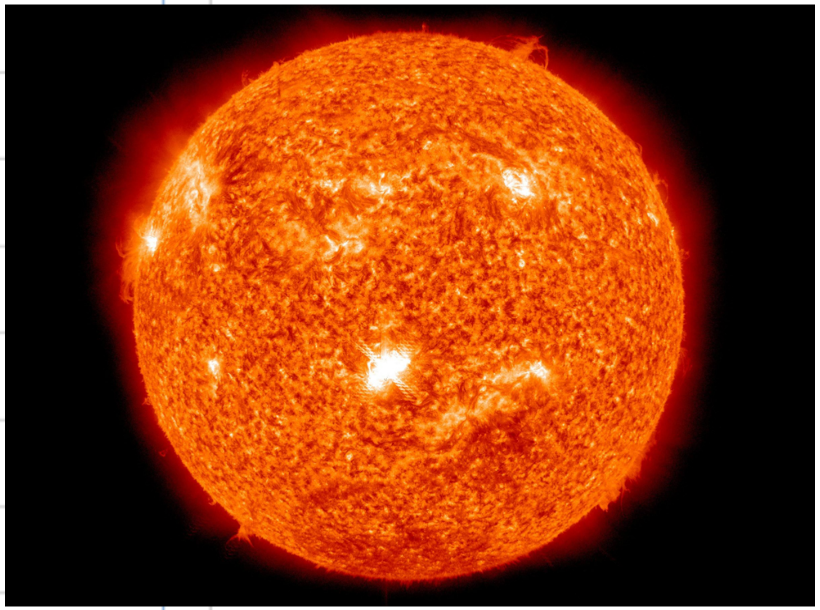
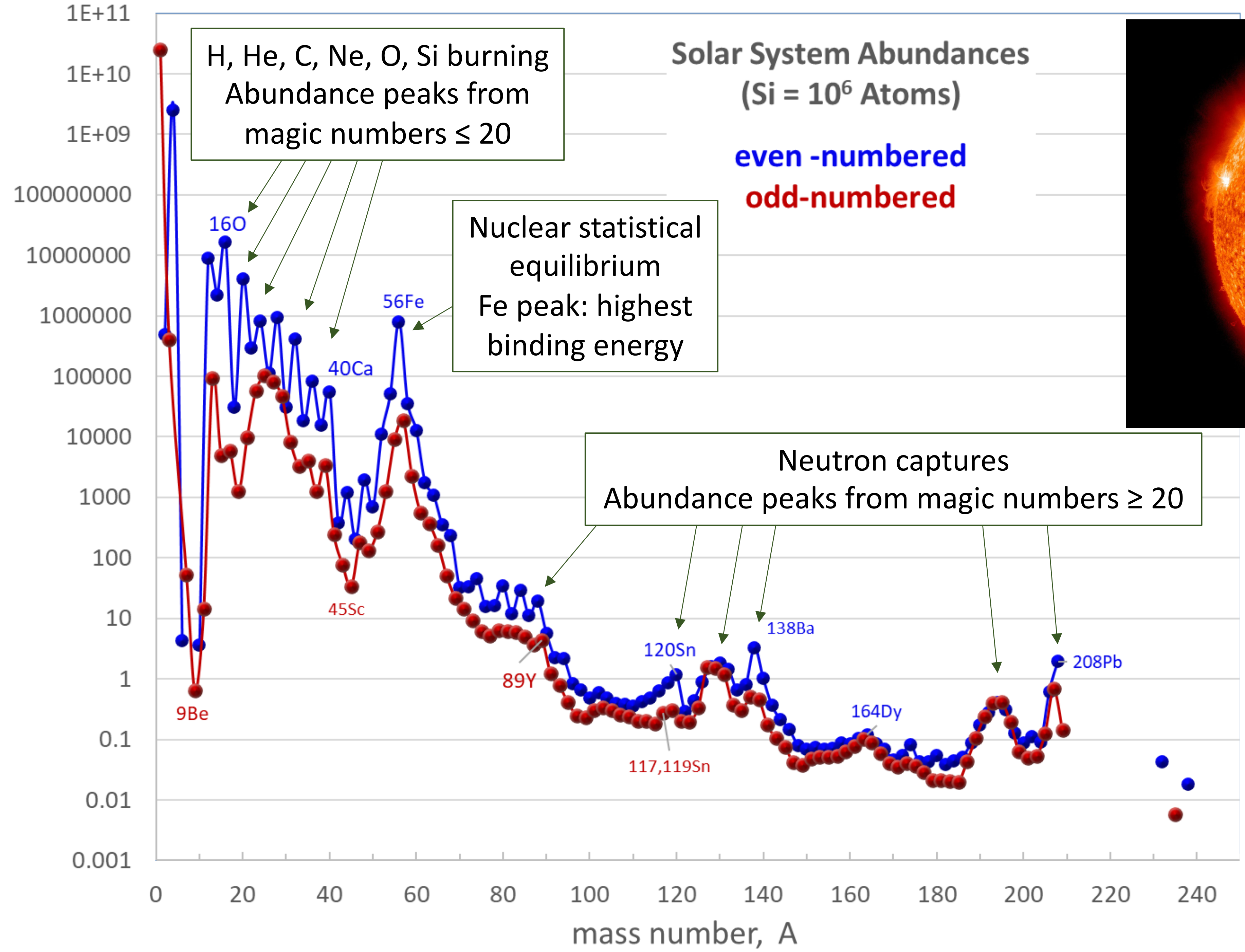
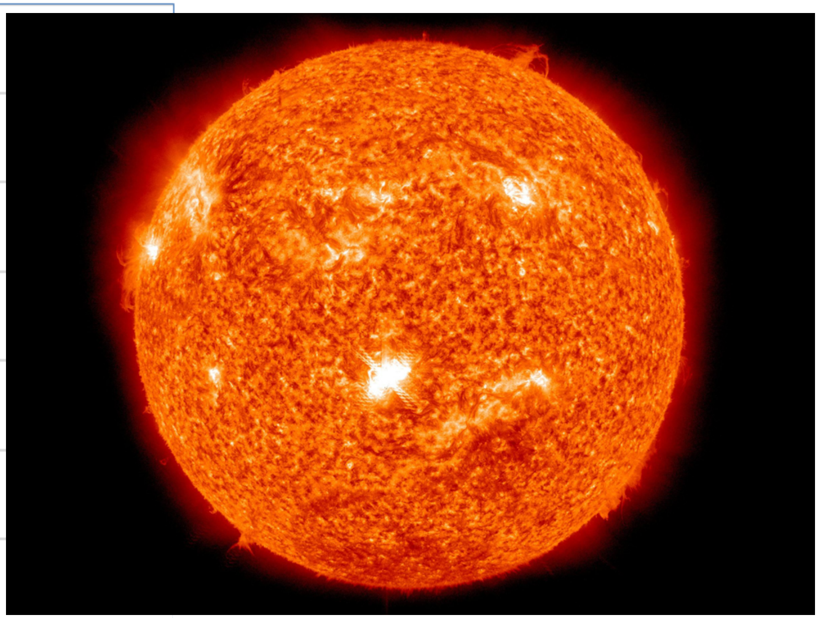




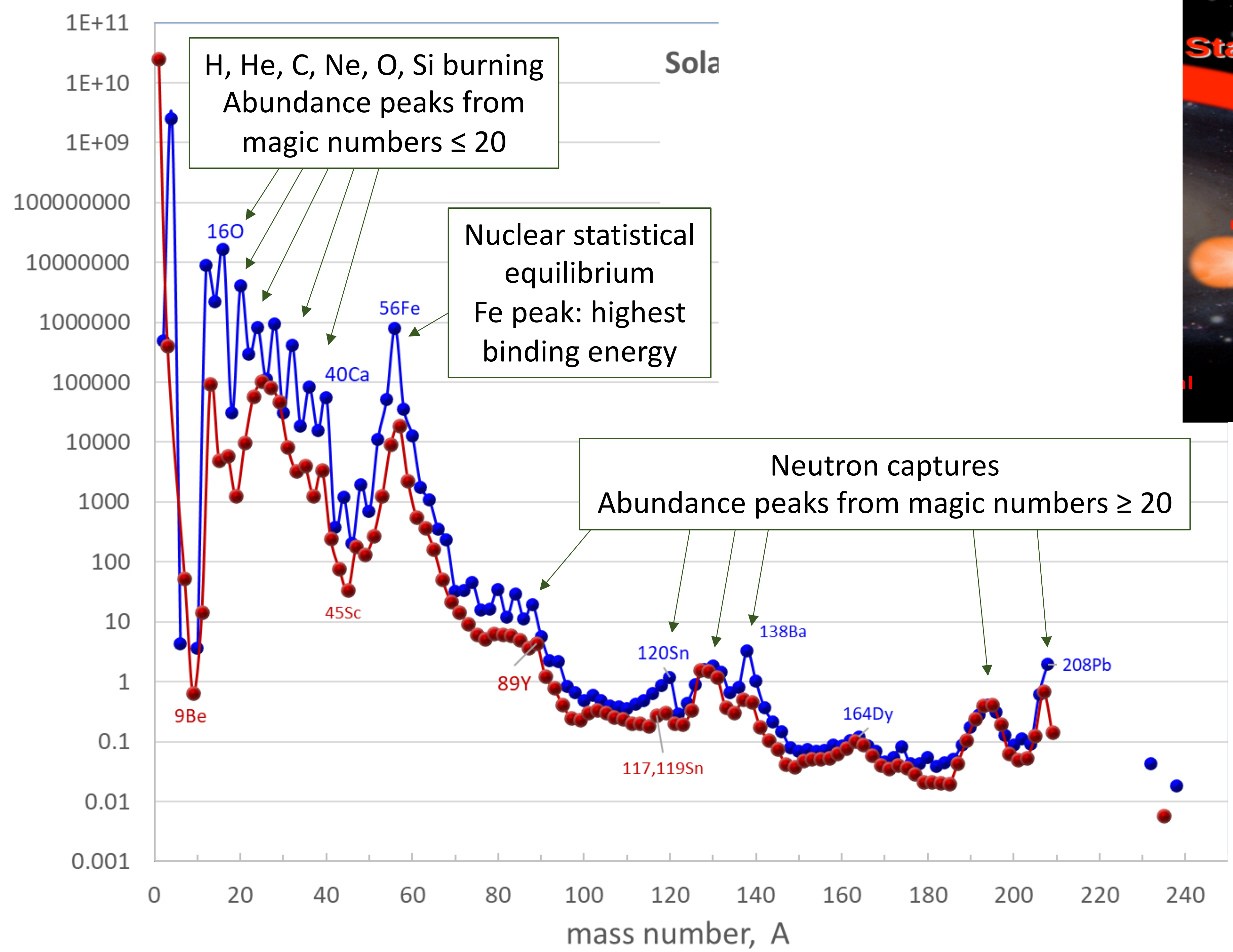
Lodders 2020

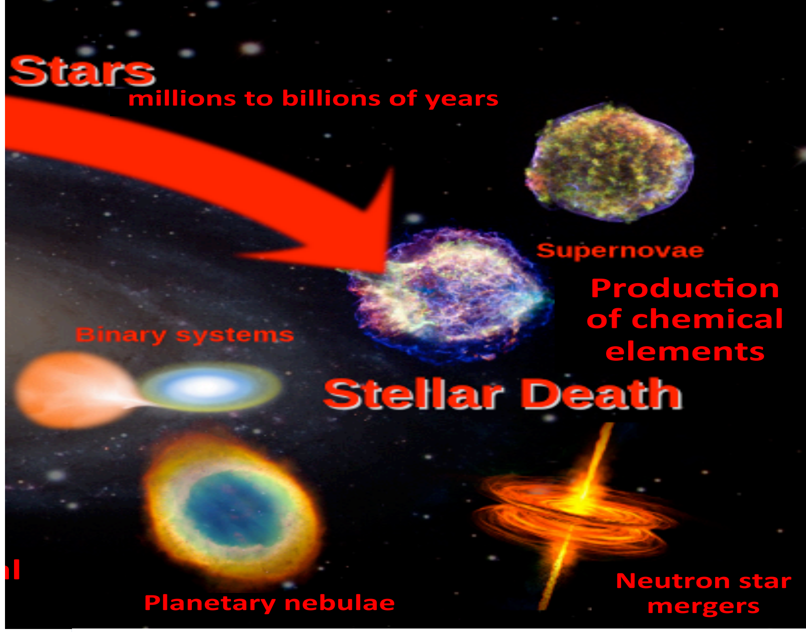




These abundances are at the basis of nuclear astrophysics

Lodders 2020
Modified Lugaro et al. 2023





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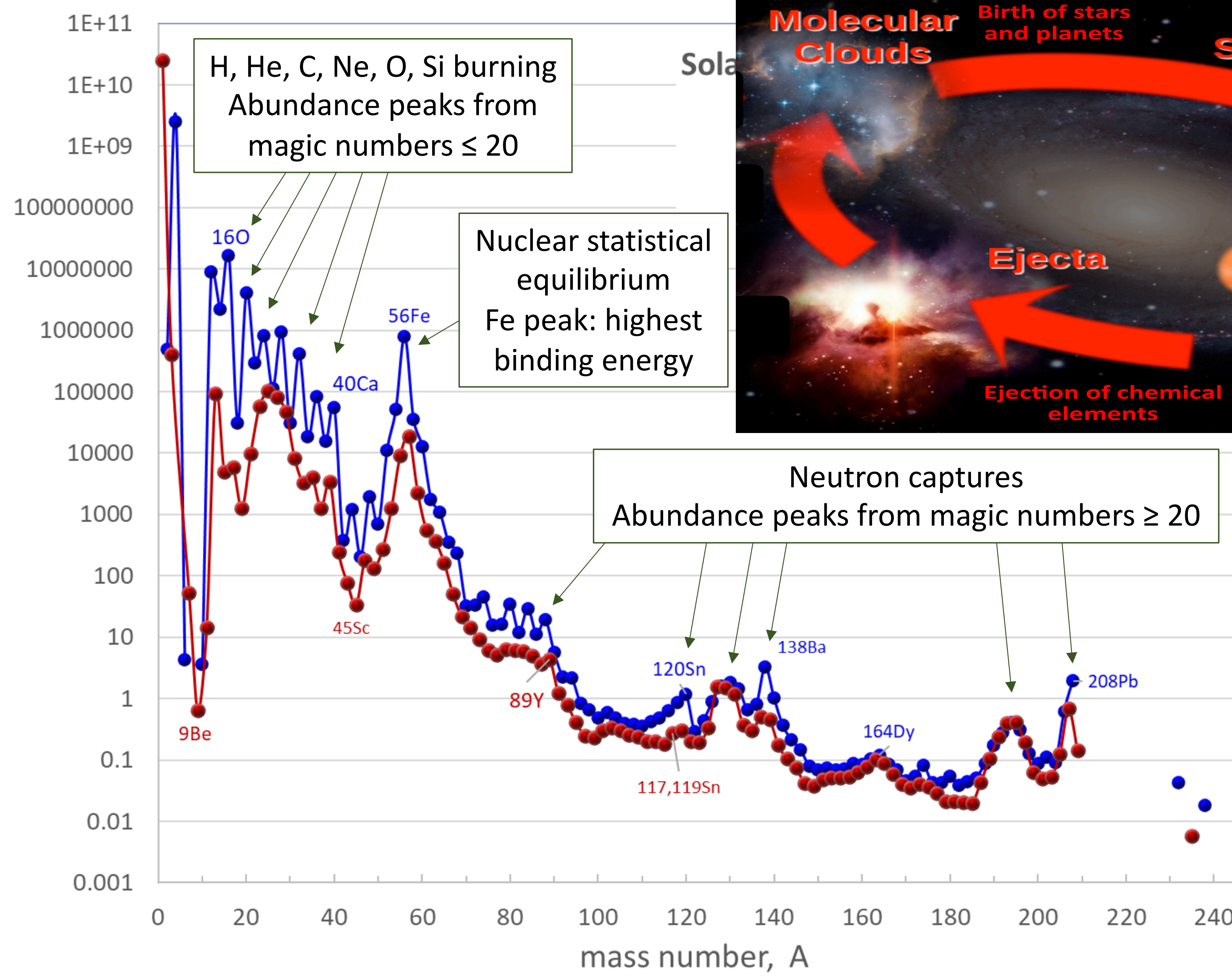

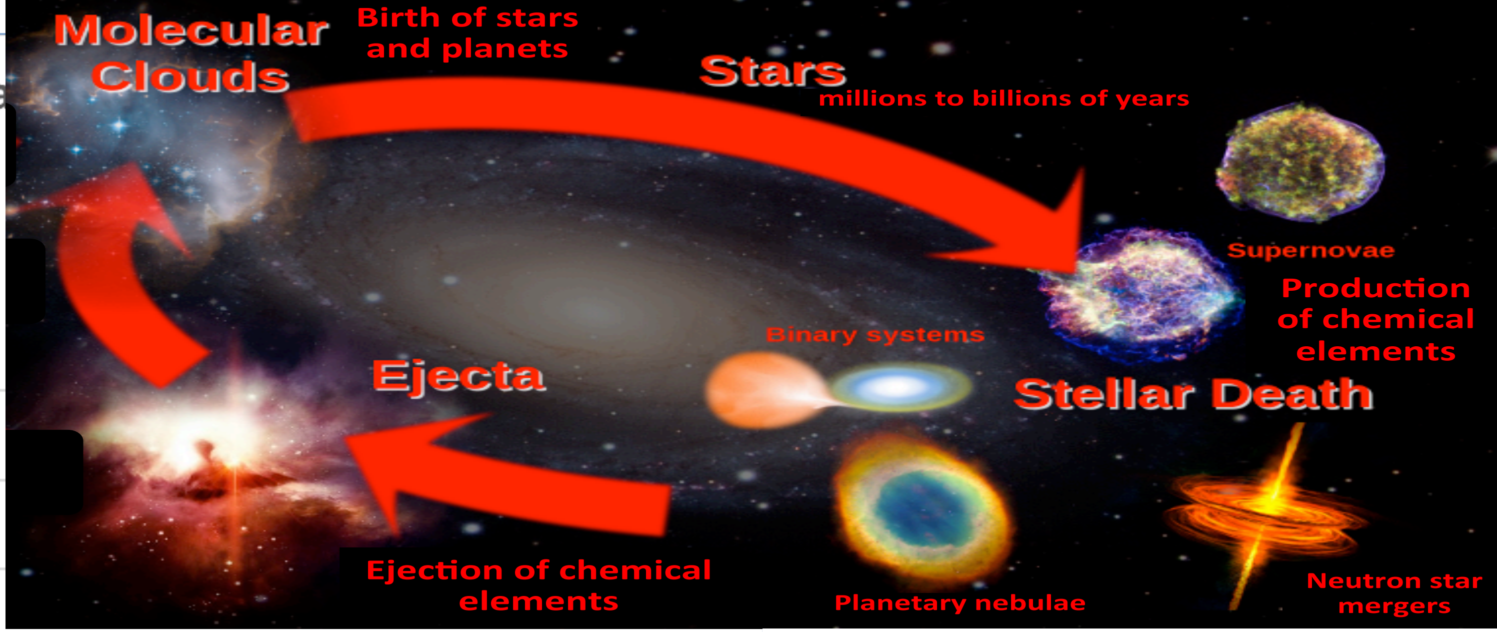

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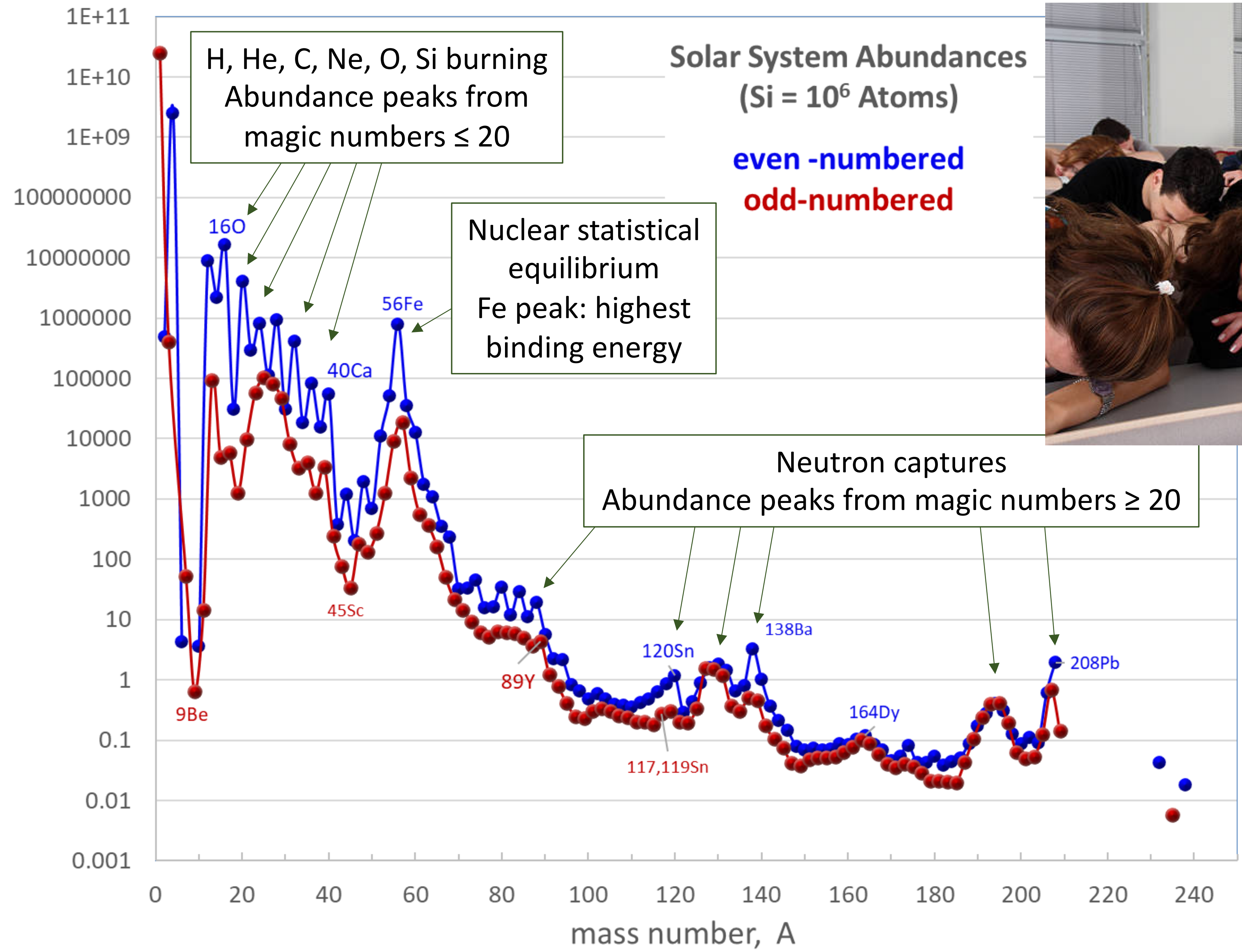

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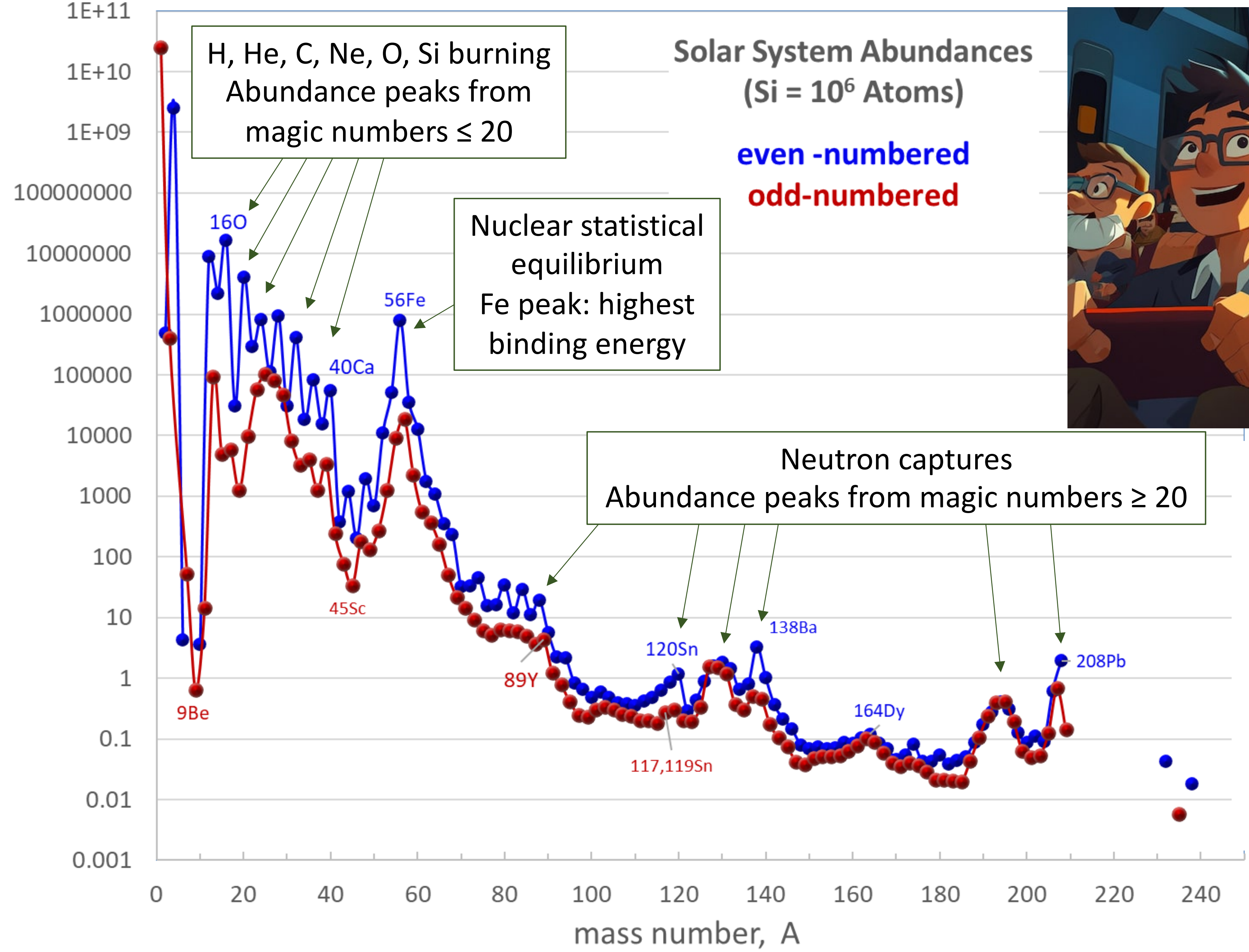


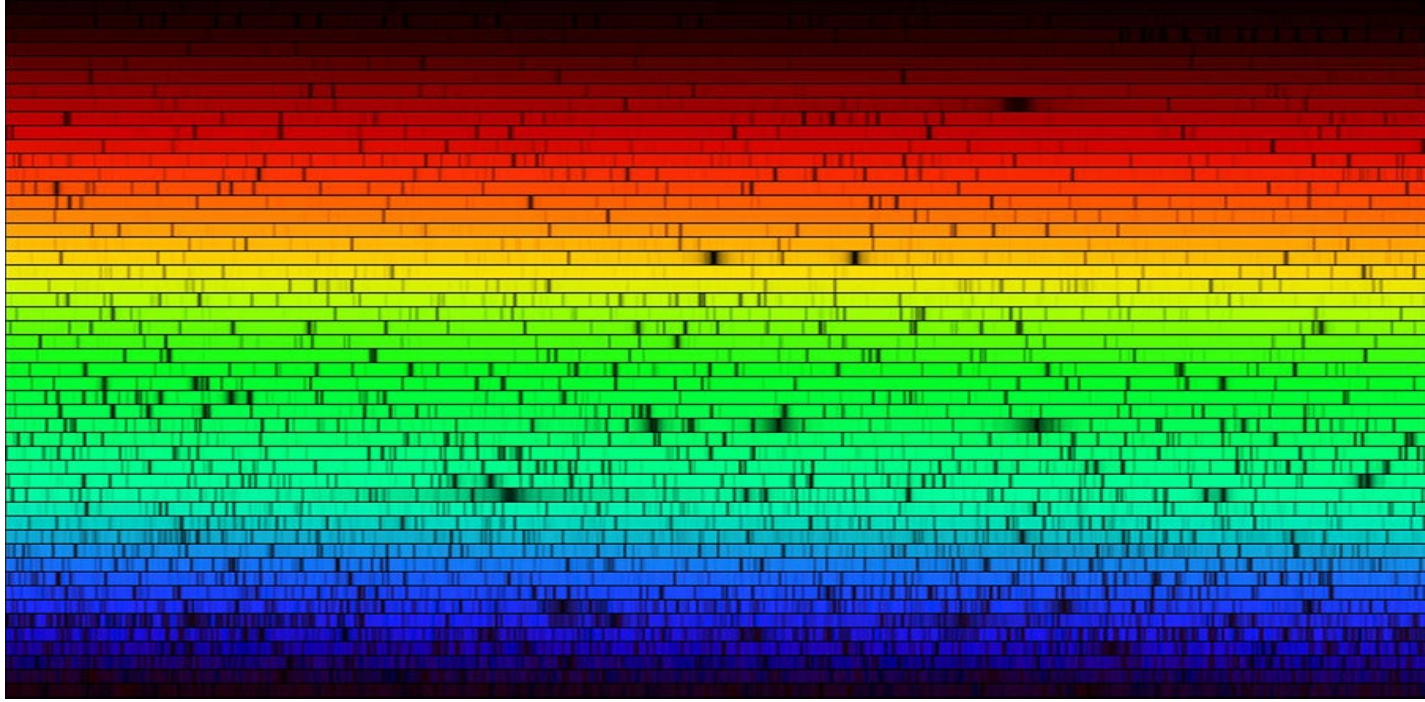
Where do these numbers come from?

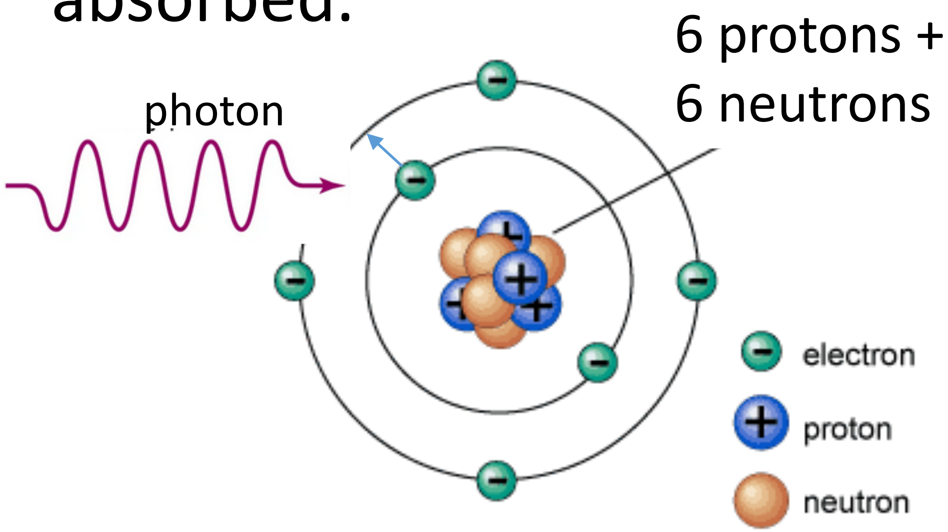
Lodders 2020

Modified Lugaro et al. 2023

The solar spectrum: black lines appear because

- photons pass through the gas.
- photons with energies matching the energy levels of the atoms are absorbed.





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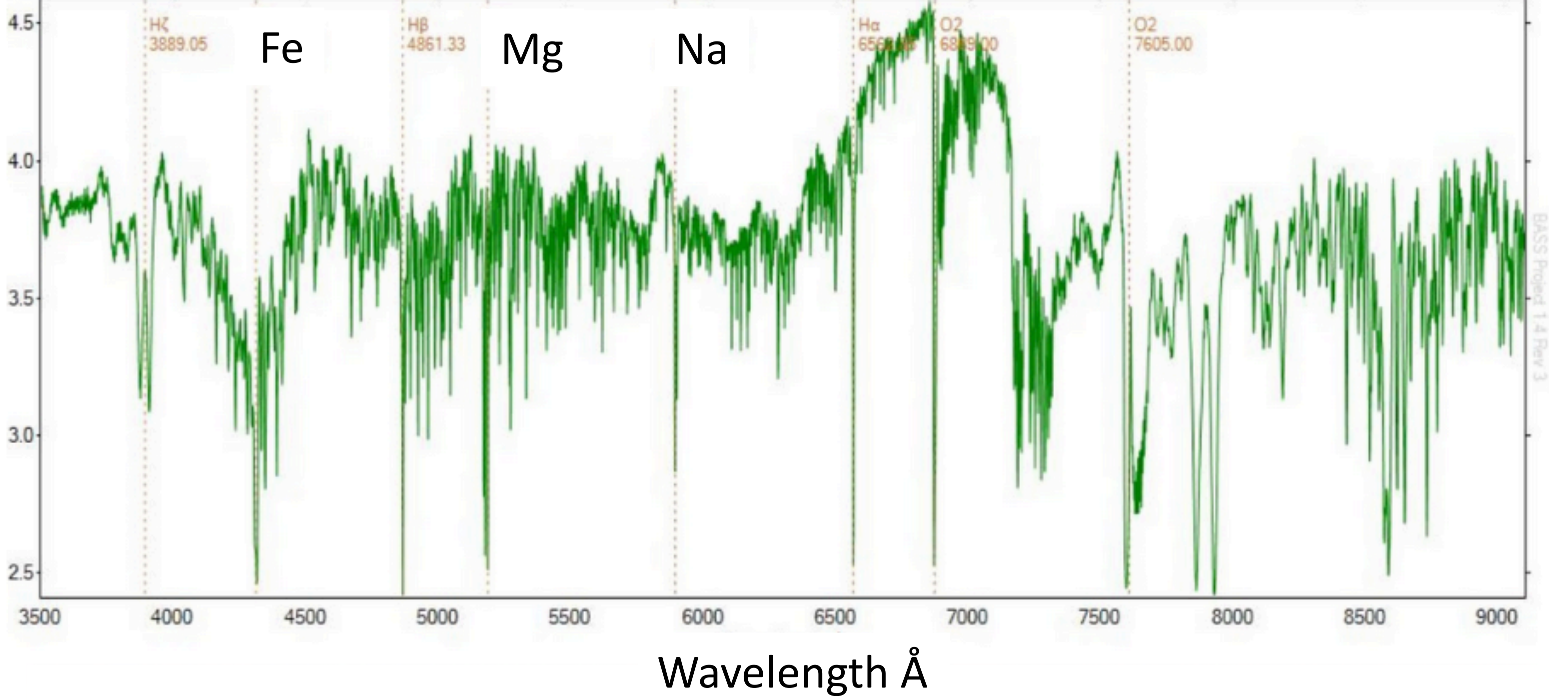

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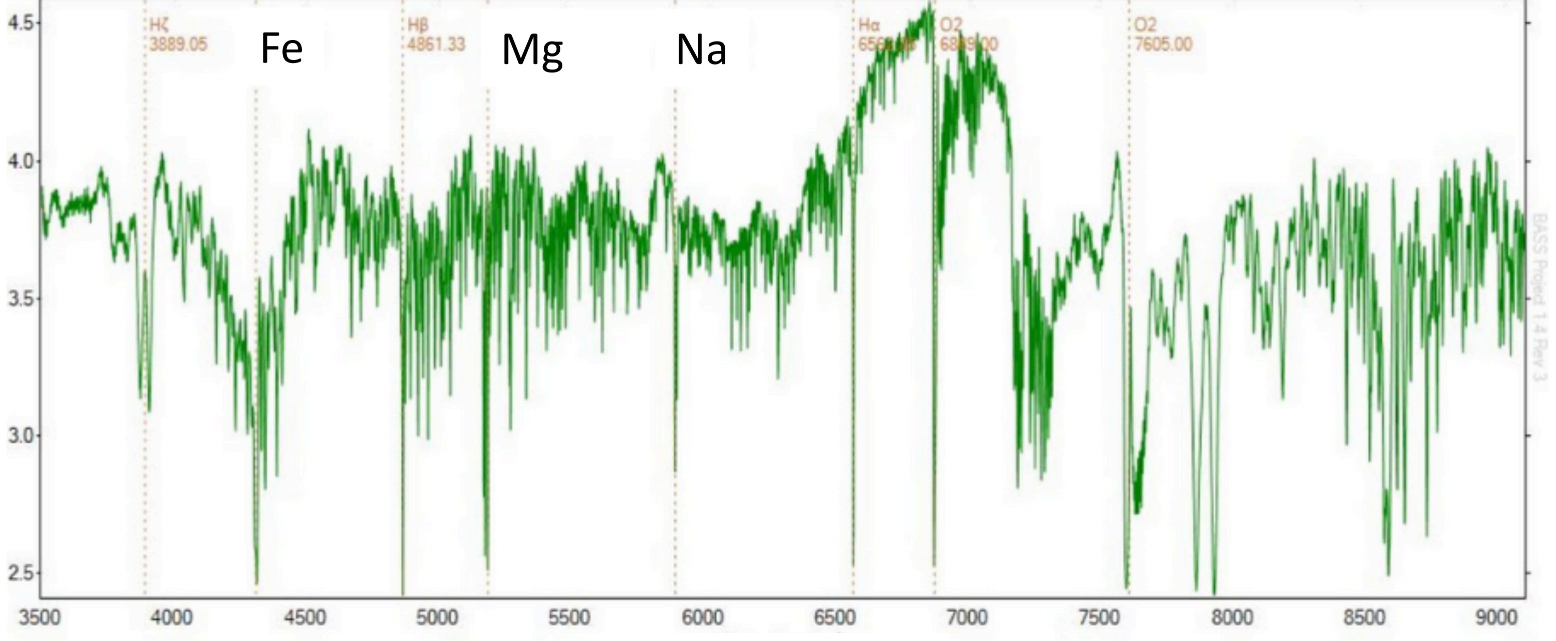
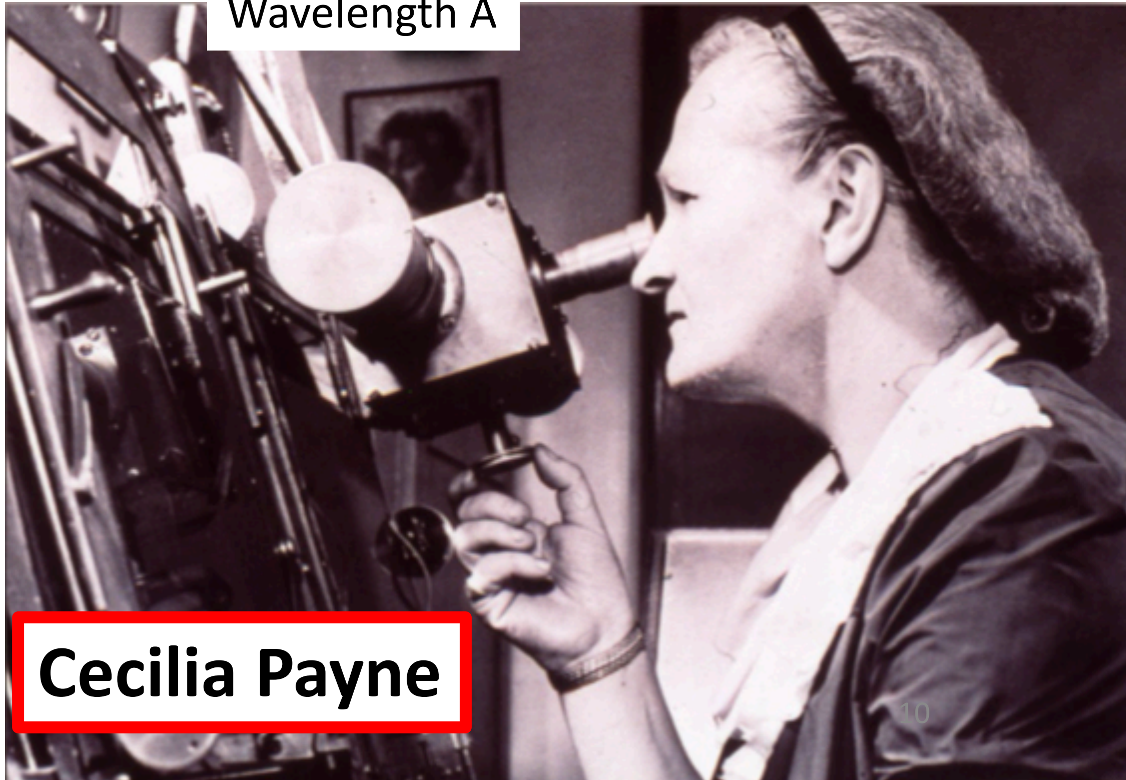
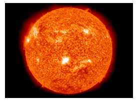


1925

- Hydrogen is the main component of the Sun!
- H and He are found in much greater quantities in the Sun than Si, C, etc.

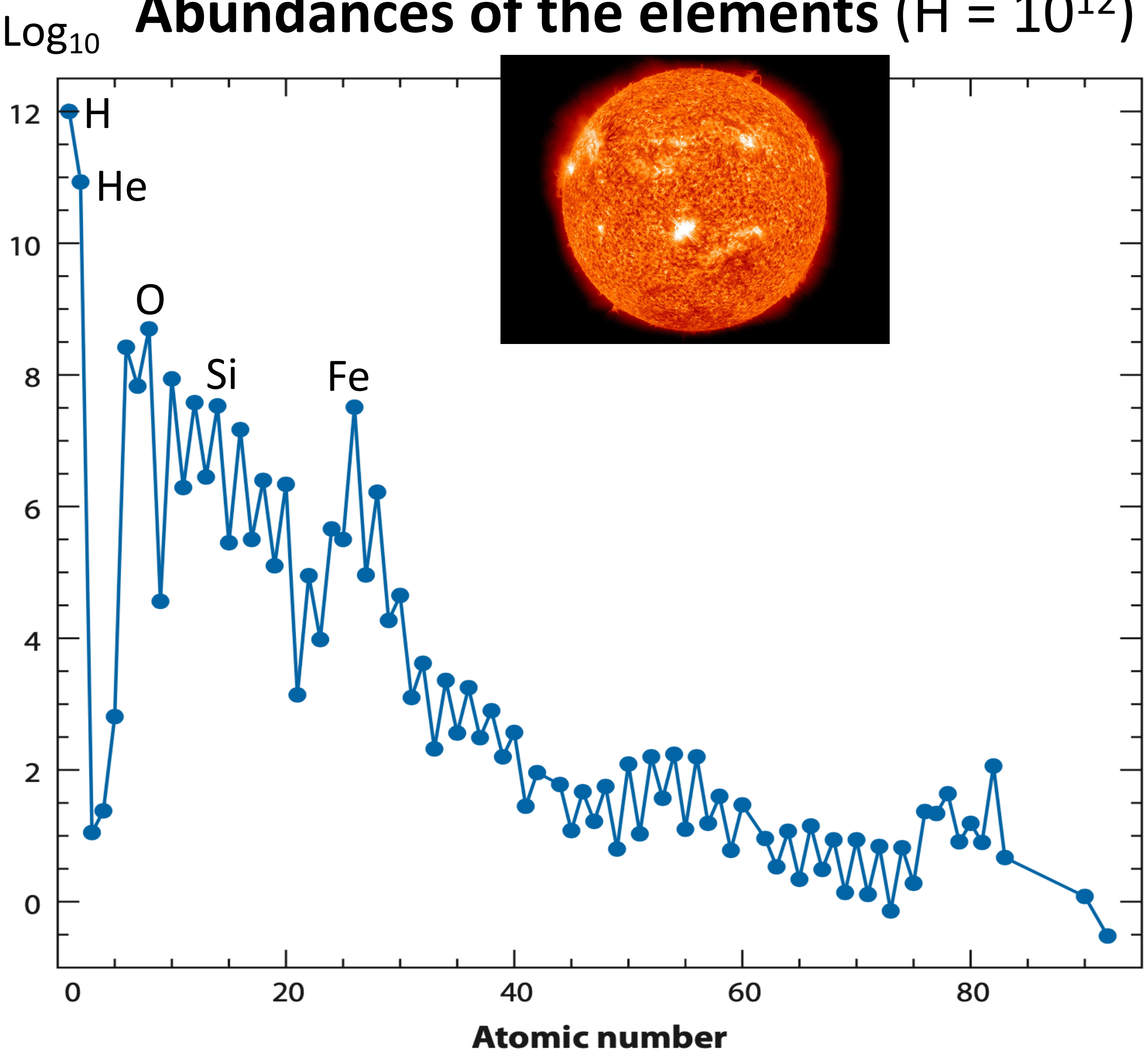


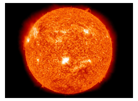
Cecilia Payne



The Sun is 98% H and He

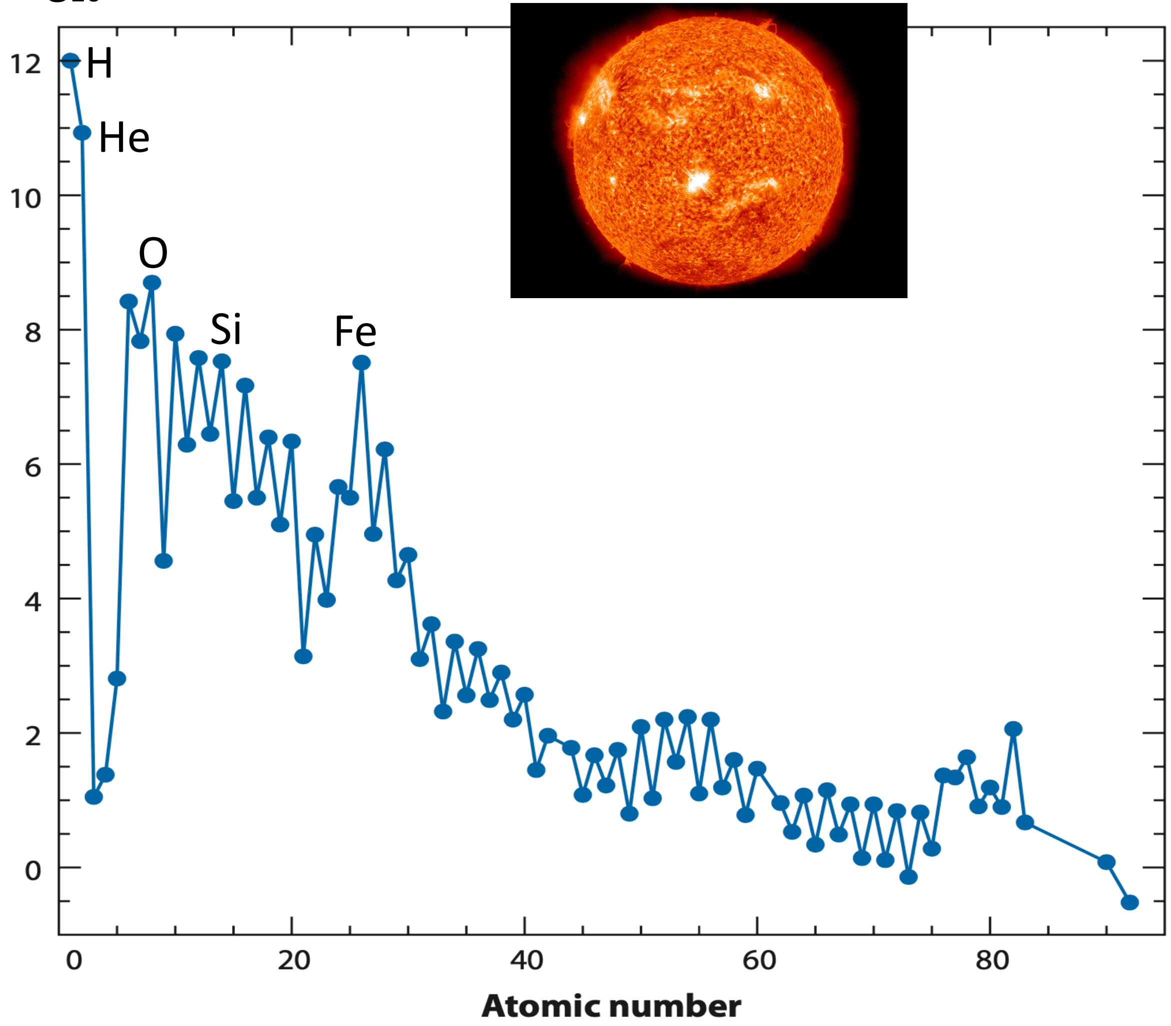
Abundances of the elements (H = 10^{12})



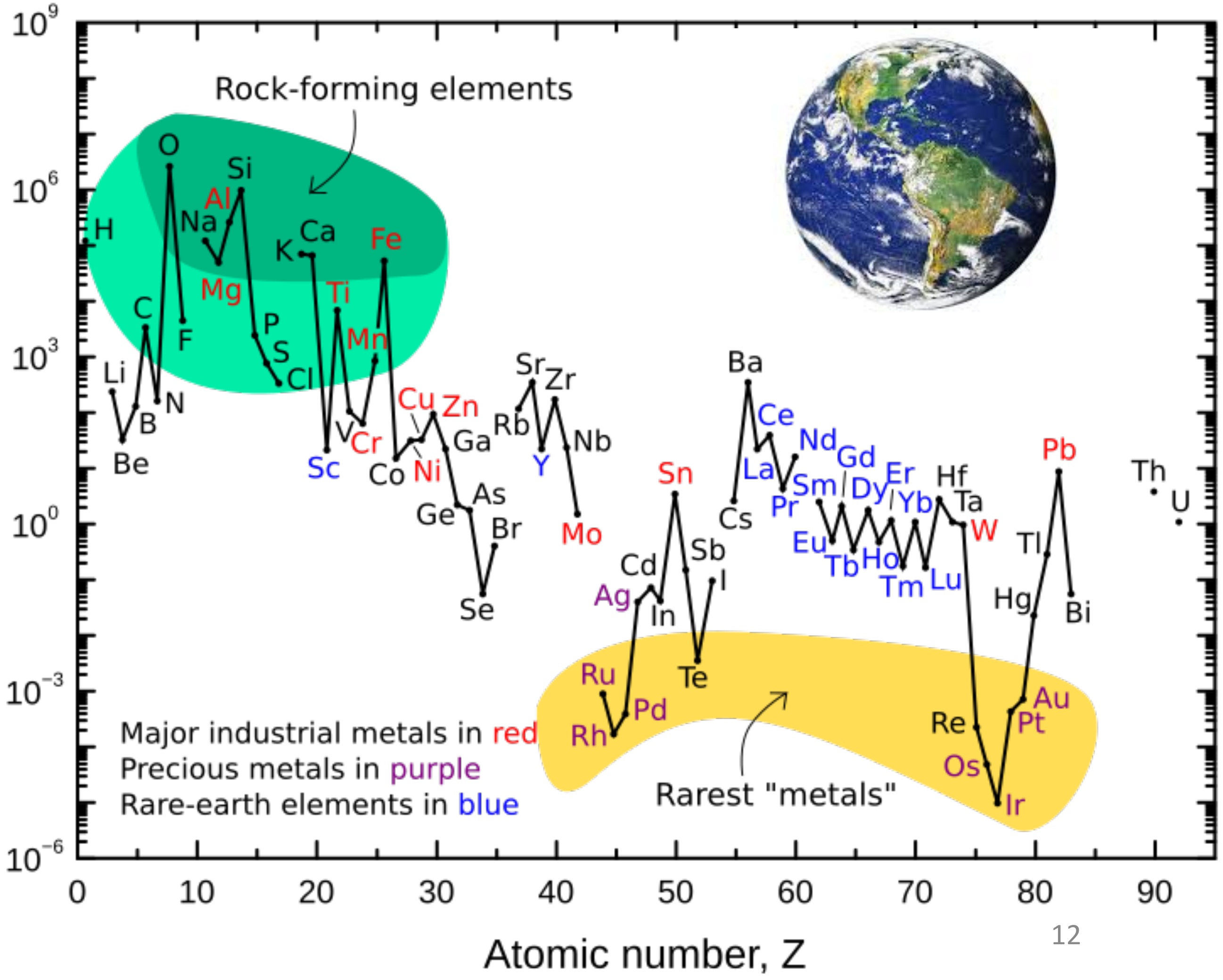
 The Sun is 98% H and He

 More than 90% of the Earth's crust is O, Si, Al, Fe, Mg, Ca

Log$_{10}$ **Abundances of the elements** (H = 10^{12})



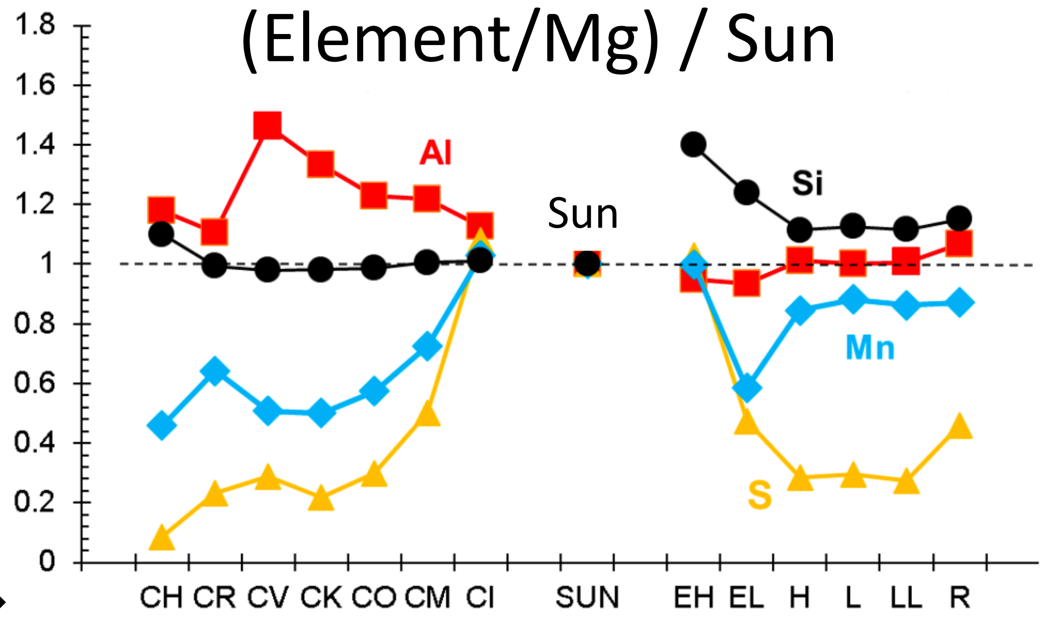
Abundances of the elements (Si = 10^6)



Abundances of the elements from meteorites

Lodders et al. (2025)

Meteorite type→



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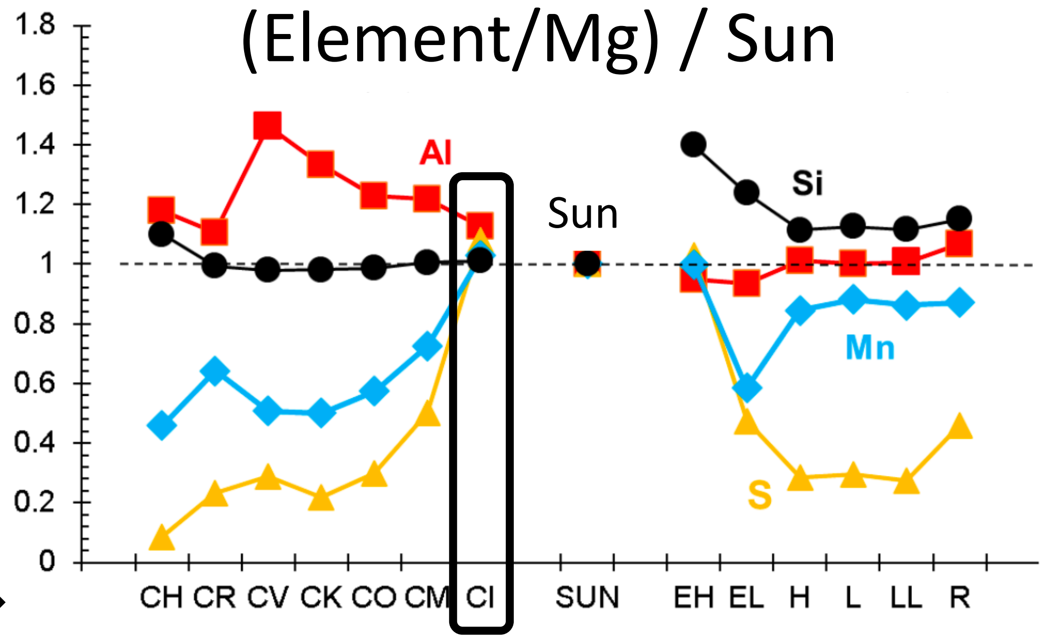

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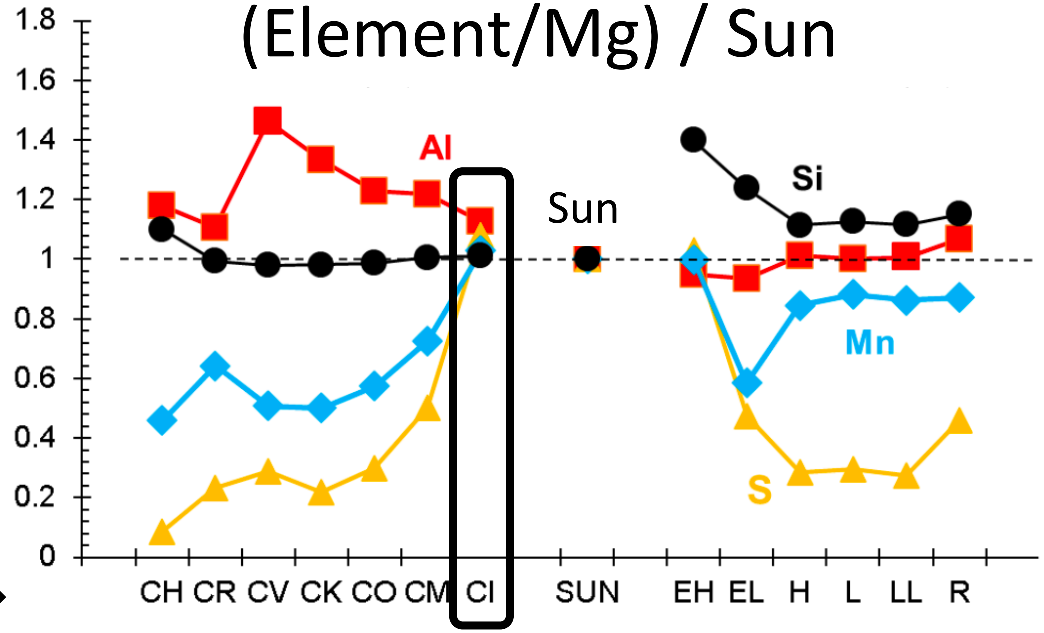

There are only 5 confirmed CI type meteorites, e.g. Orgueil (discovered in 1864, 14 kg).

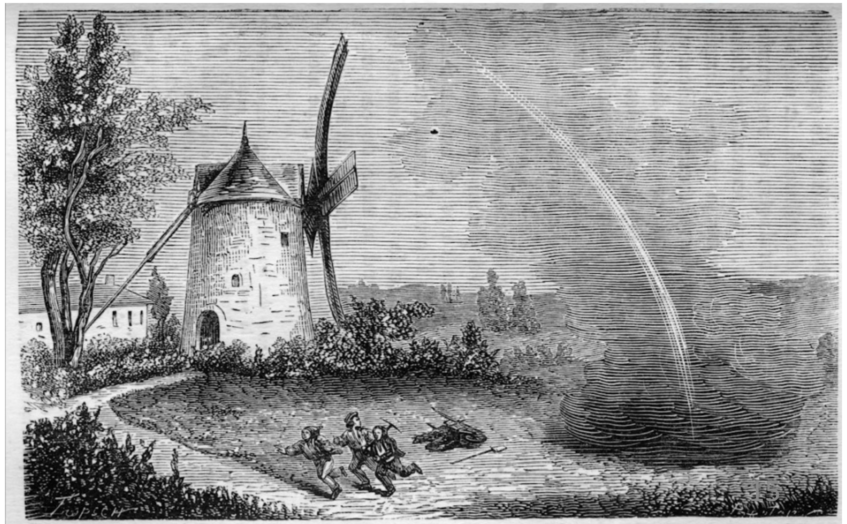

Fig. 3. Chute du bolide du 14 mai 1864.

Abundances of the elements from meteorites

Lodders et al. (2025)

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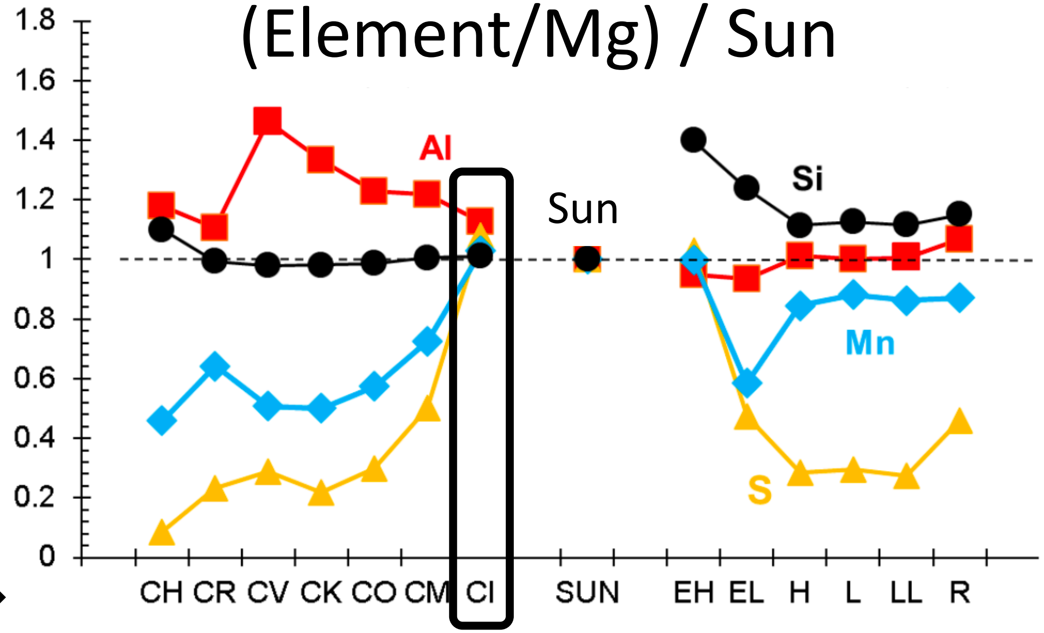

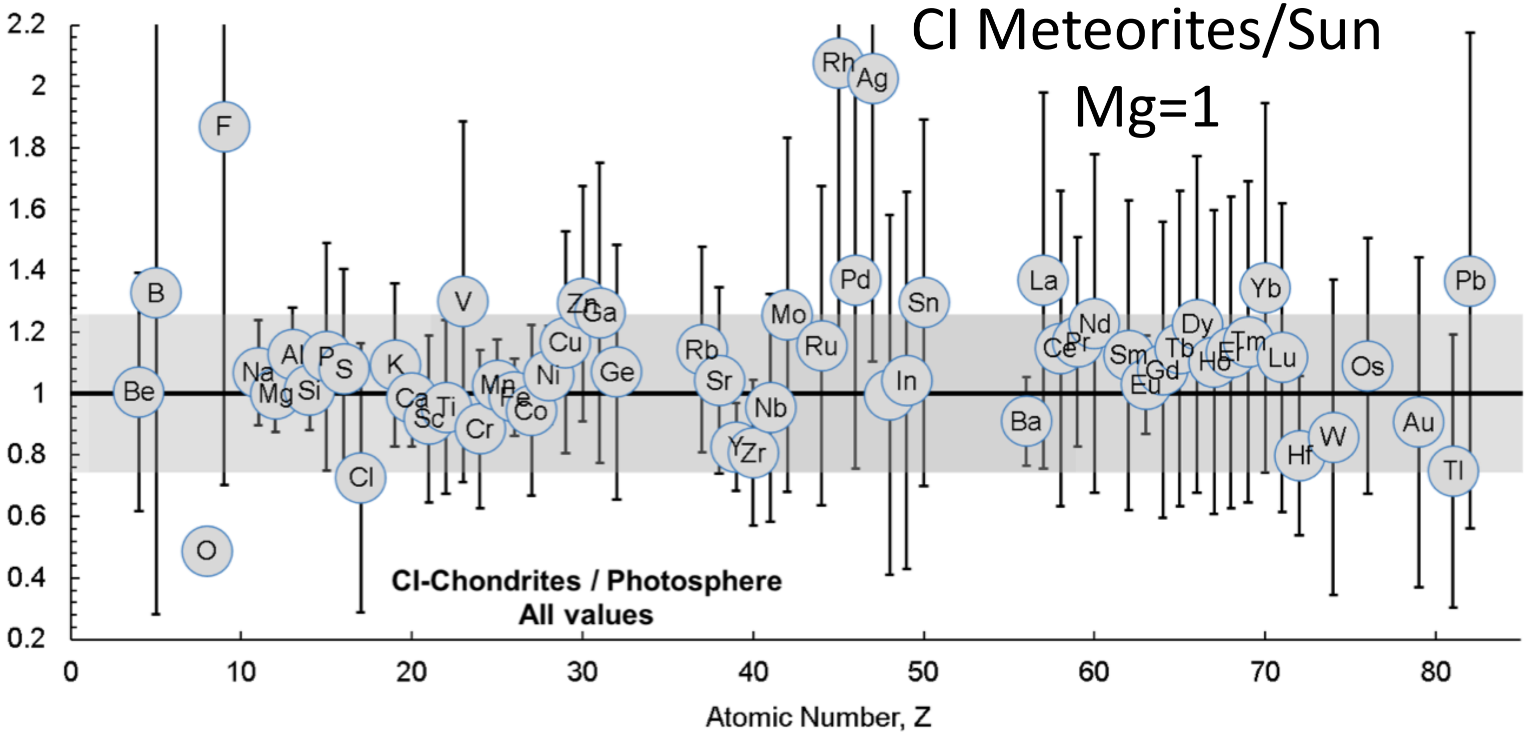

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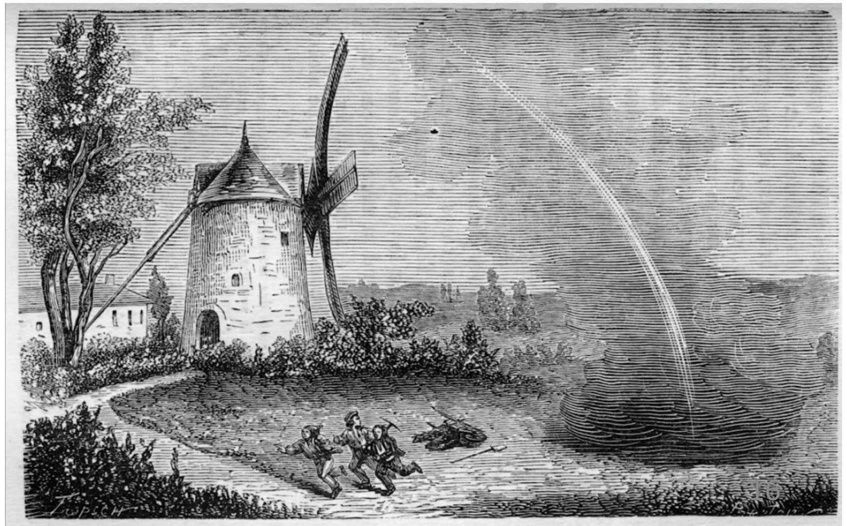

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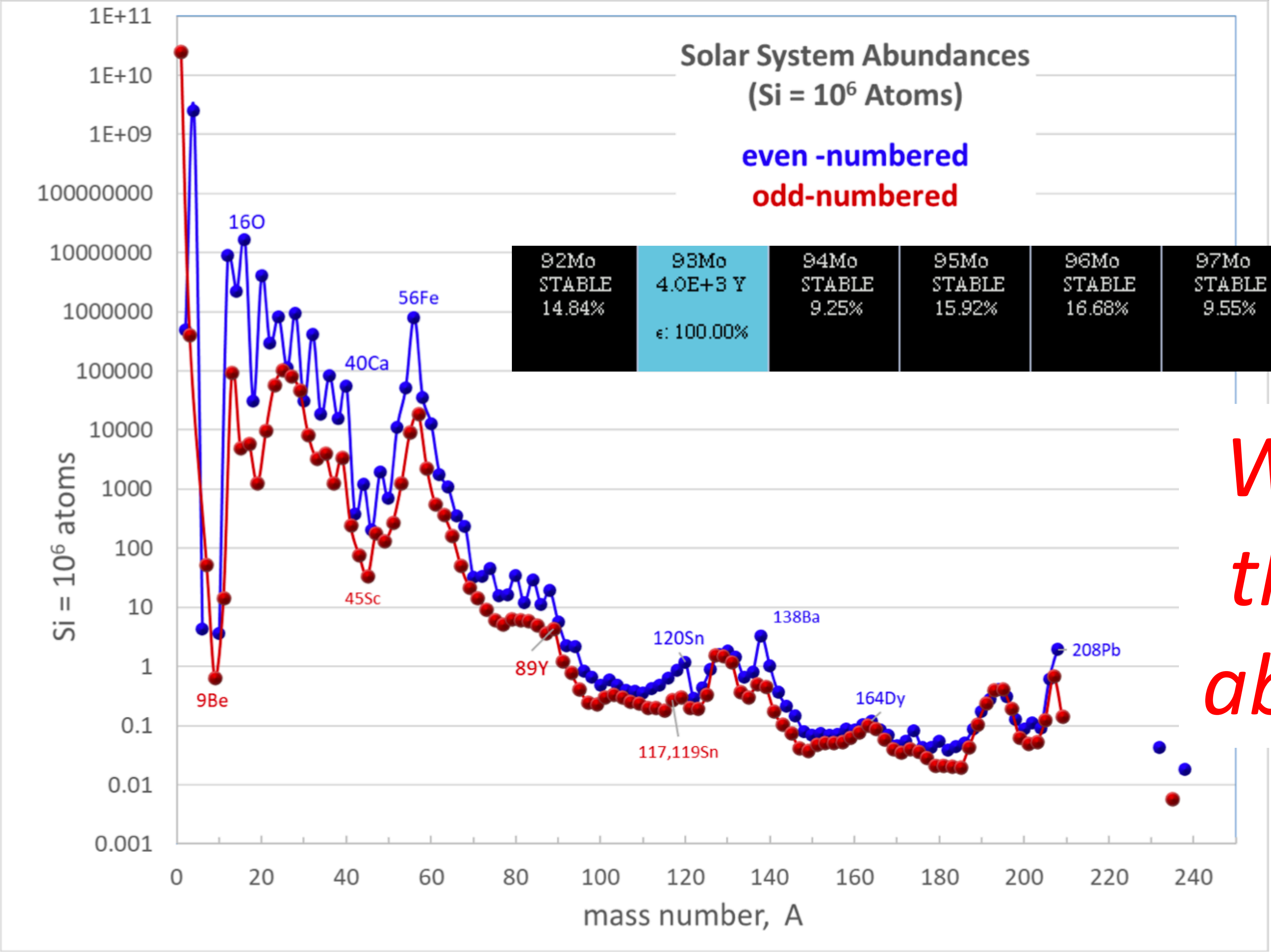

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STABLE	4.0E+3 Y	STABLE	STABLE	STABLE	STABLE	STABLE	2.7489 D	STABLE
14.84%		9.25%	15.92%	16.68%	9.55%	24.13%		9.63%
	ϵ: 100.00%						β-: 100.00%	

*What about the **isotopic** abundances?*

Lodders 2020

DE GRUYTER Pure Appl. Chem. 2016; 88(3): 293–306

IUPAC Technical Report

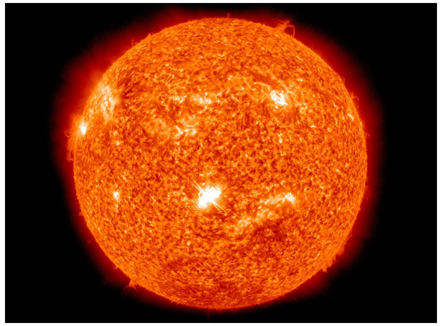
Juris Meija*, Tyler B. Coplen, Michael Berglund, Willi A. Brand, Paul De Bièvre, Manfred Gröning, Norman E. Holden, Johanna Irrgeher, Robert D. Loss, Thomas Walczyk and Thomas Prohaska

Isotopic compositions of the elements 2013 (IUPAC Technical Report)

DOI 10.1515/pac-2015-0503
Received May 29, 2015; accepted December 8, 2015

Abstract: The Commission on Isotopic Abundances and Atomic Weights (ciaaw.org) of the International Union of Pure and Applied Chemistry (iupac.org) has revised the Table of Isotopic Compositions of the Elements (TICE). The update involved a critical evaluation of the recent published literature. The new TICE 2013 includes evaluated data from the "best measurement" of the isotopic abundances in a single sample, along with a set of representative isotopic abundances and uncertainties that accommodate known variations in normal terrestrial materials.

Keywords: atomic weight; ciaaw.org; critical evaluation; elements; isotopes; isotopic abundance; IUPAC Technical Report; periodic table.



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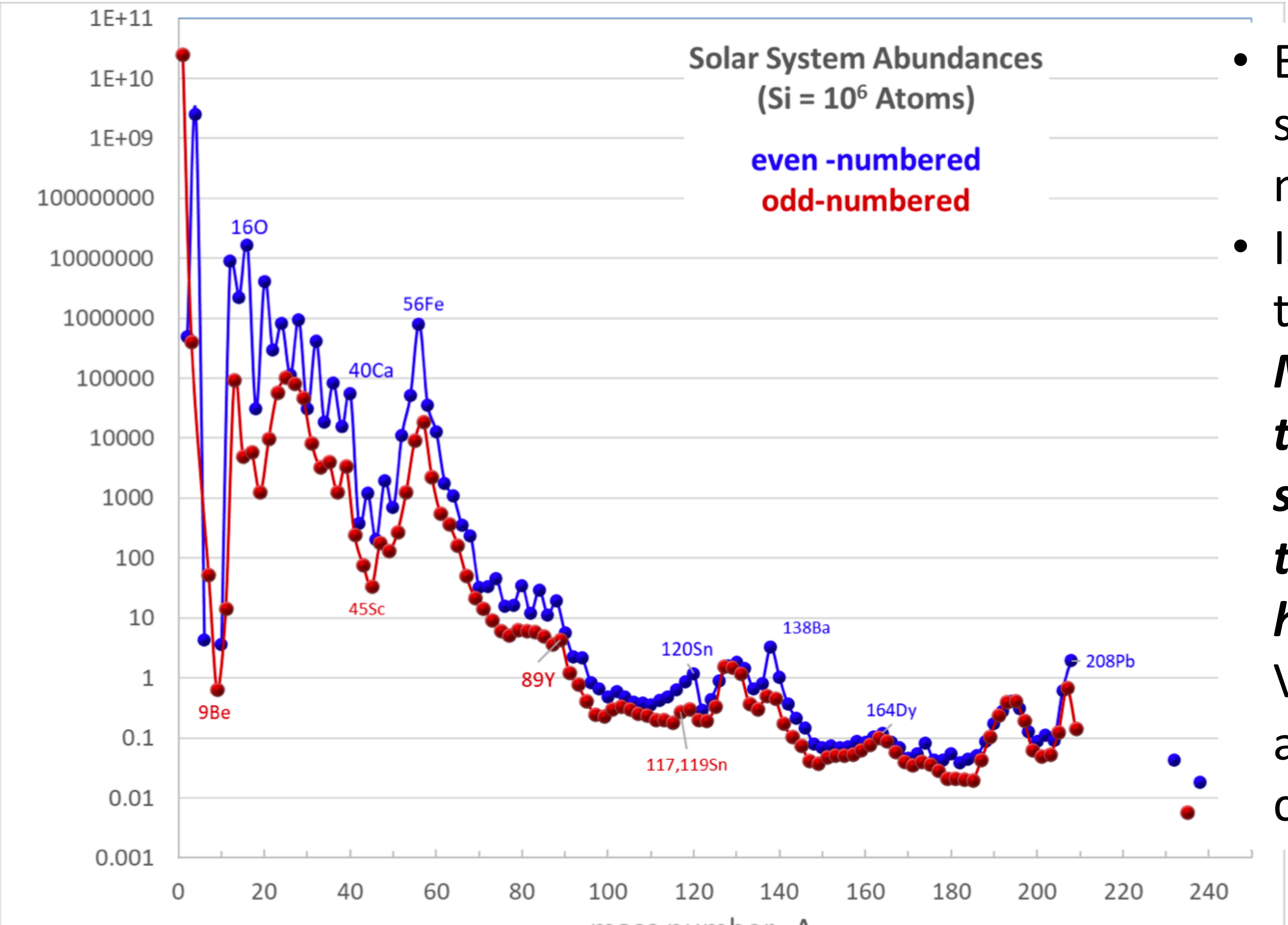
*What about the **isotopic** abundances?*

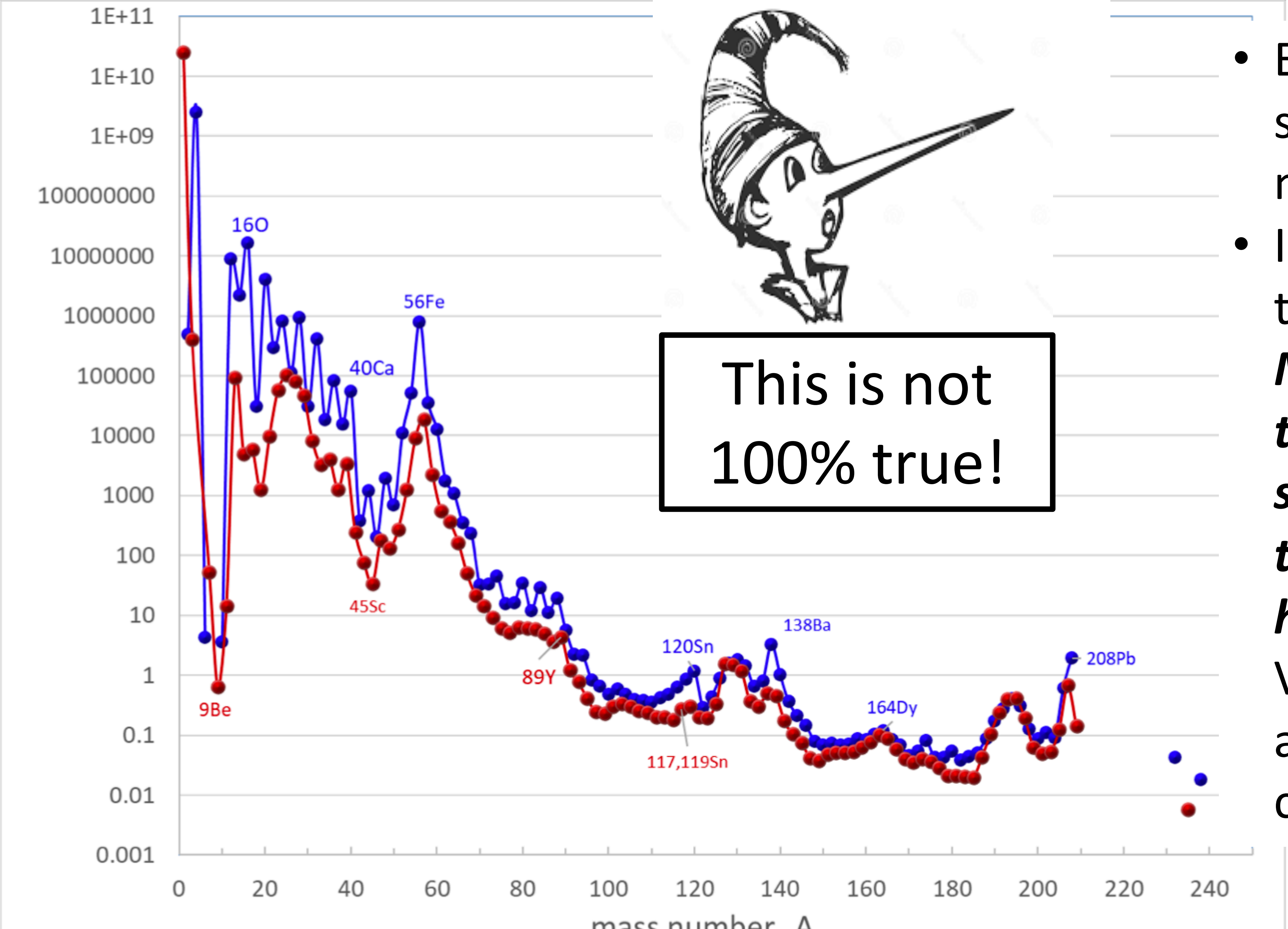
Most are the same throughout the Solar System, from the Sun to Jupiter to the human body!

Variations can be attributed to known chemical processes



Lodders 2020

- Elemental ratios from solar spectra and meteorites
- Isotope ratios from terrestrial samples: ***Most are the same throughout the solar system, from the Sun to Jupiter to the human body!*** Variations can be attributed to known chemical processes



This is not 100% true!

Lodders 2020

- Elemental ratios from solar spectra and meteorites
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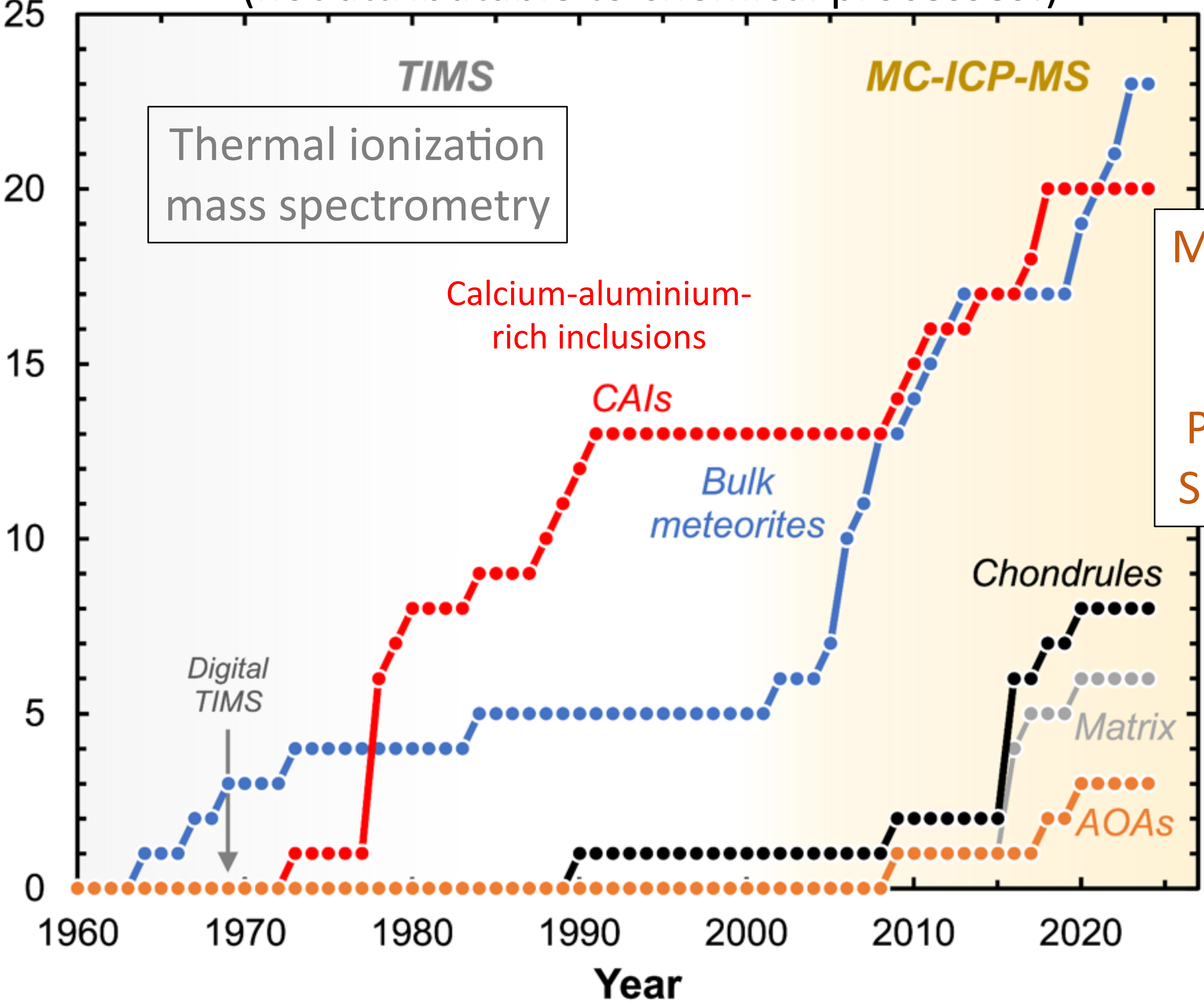
Number of elements showing isotopic variability in meteorites

(not attributable to chemical processes!)

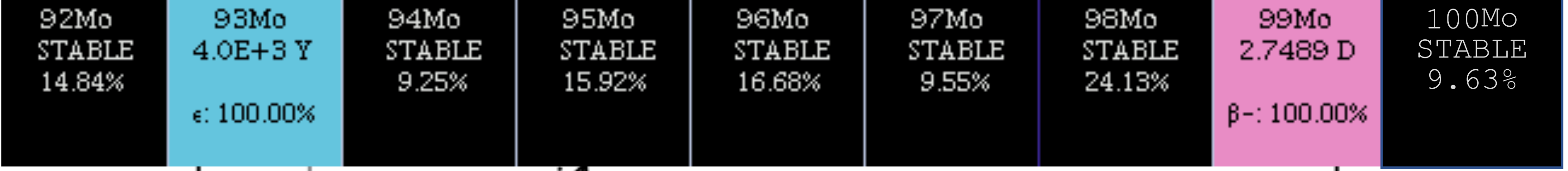
Tissot et al. (2025)

Chondritic meteorite

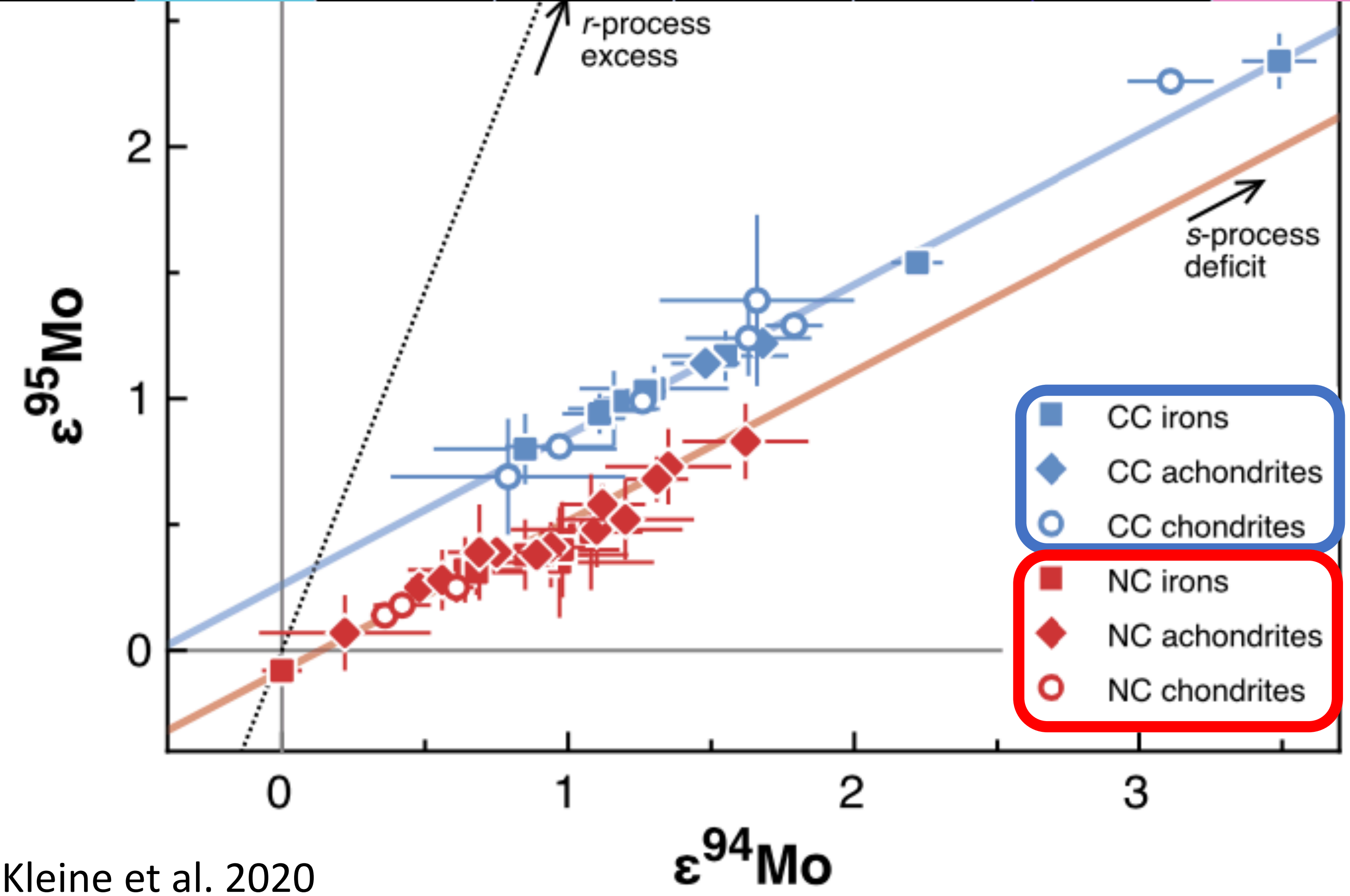


MultiCollector Inductively Coupled Plasma Mass Spectrometry

Amoeboid olivine aggregates



Molybdenum isotopic composition of meteorites: ***large scale*** variability



CC = Outer Solar System

NC = Inner Solar System

Kleine et al. 2020

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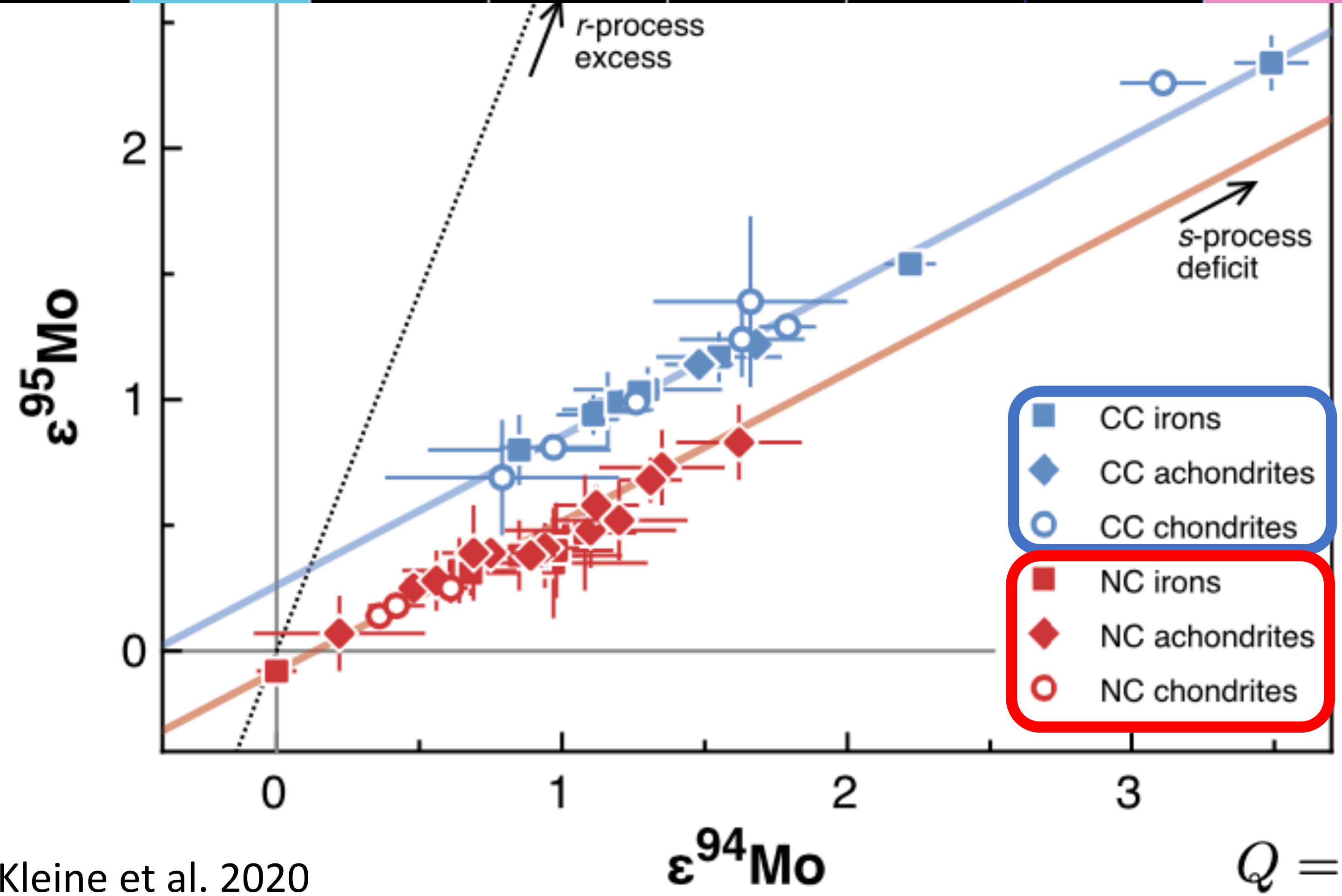

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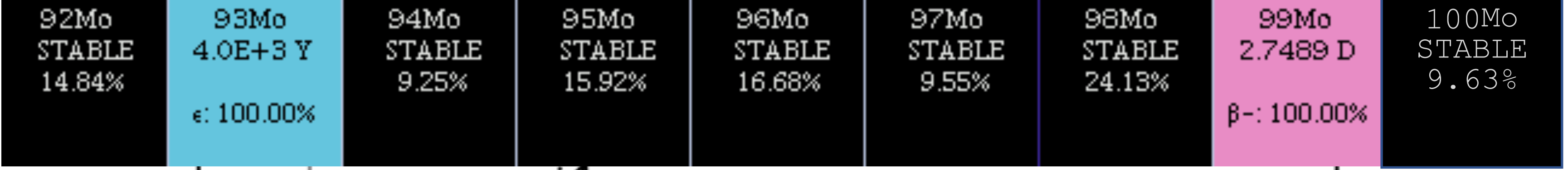
Kleine et al. 2020

$$Q = \frac{\ln(94) - \ln(96)}{\ln(98) - \ln(96)}$$

1 ε = 0.001%

higher than the laboratory standard

$$\varepsilon^{94}\text{Mo} = \left[\left(\frac{(^{94}\text{Mo}/^{96}\text{Mo})_{SMP}}{(^{94}\text{Mo}/^{96}\text{Mo})_{STD}}\right)\left(\frac{(^{98}\text{Mo}/^{96}\text{Mo})_{SMP}}{(^{98}\text{Mo}/^{96}\text{Mo})_{REF}}\right)^{-Q} - 1\right] \times 10^4$$



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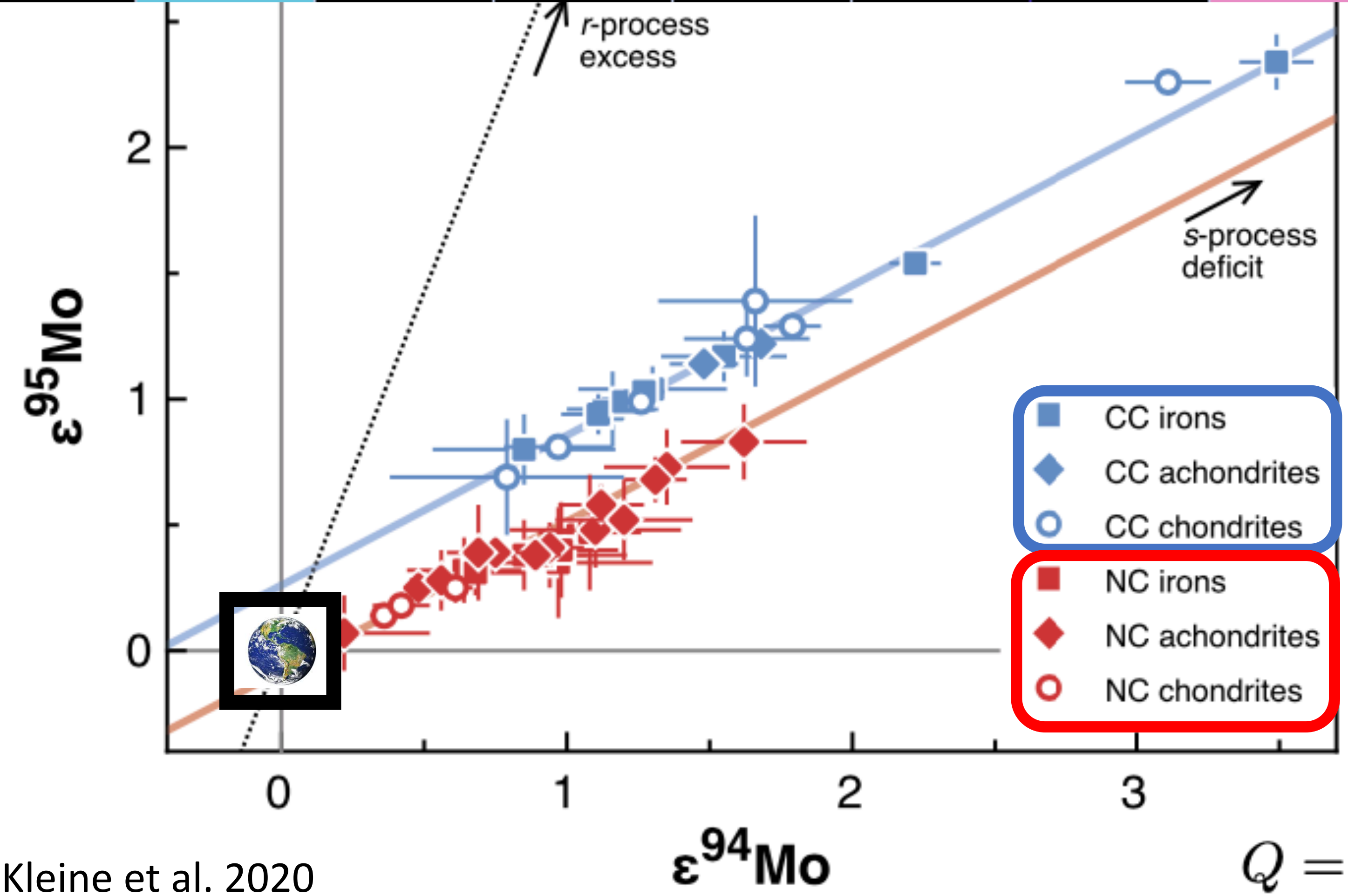

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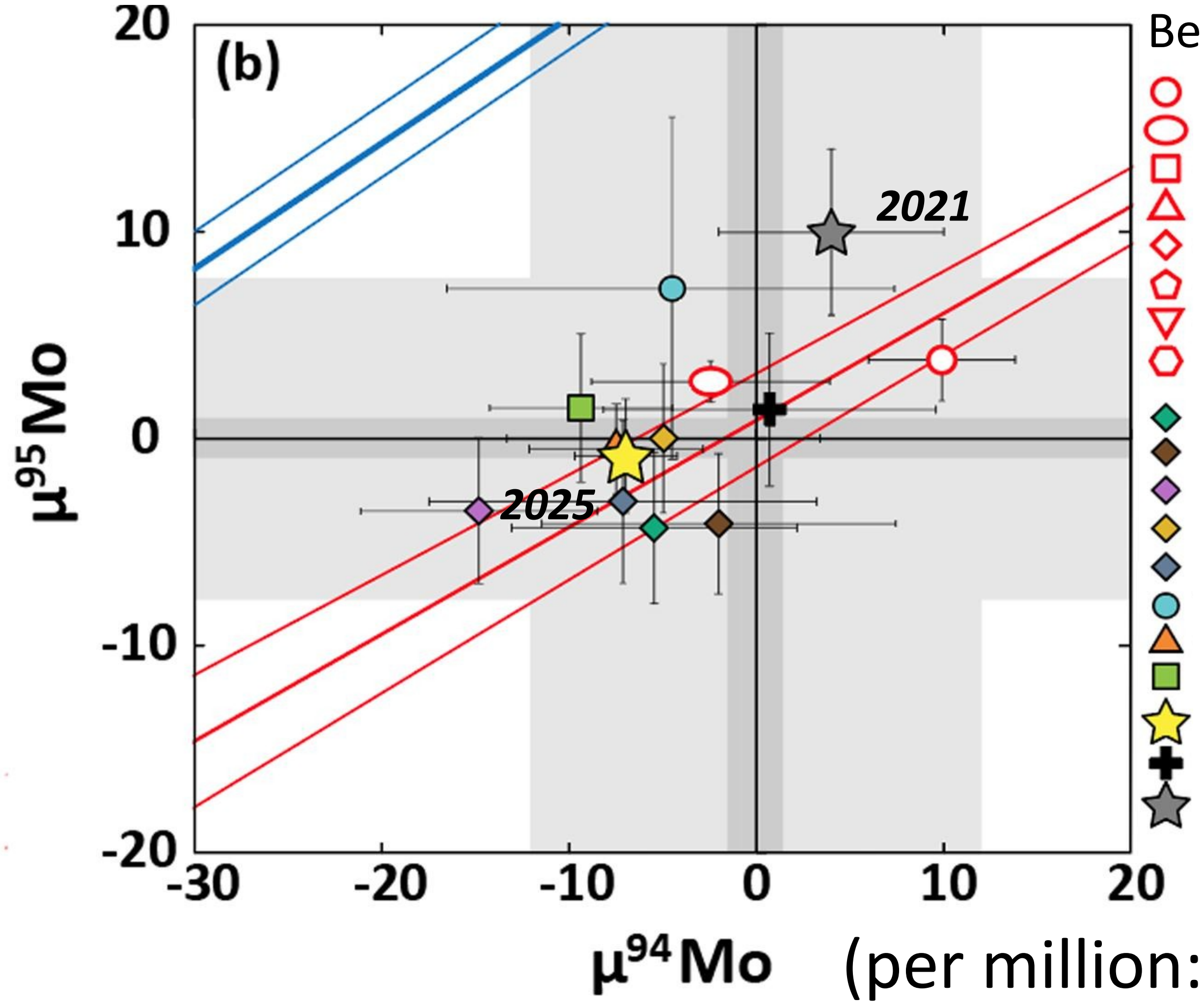
Molybdenum composition of the Earth

Bermingham et al. (2025)



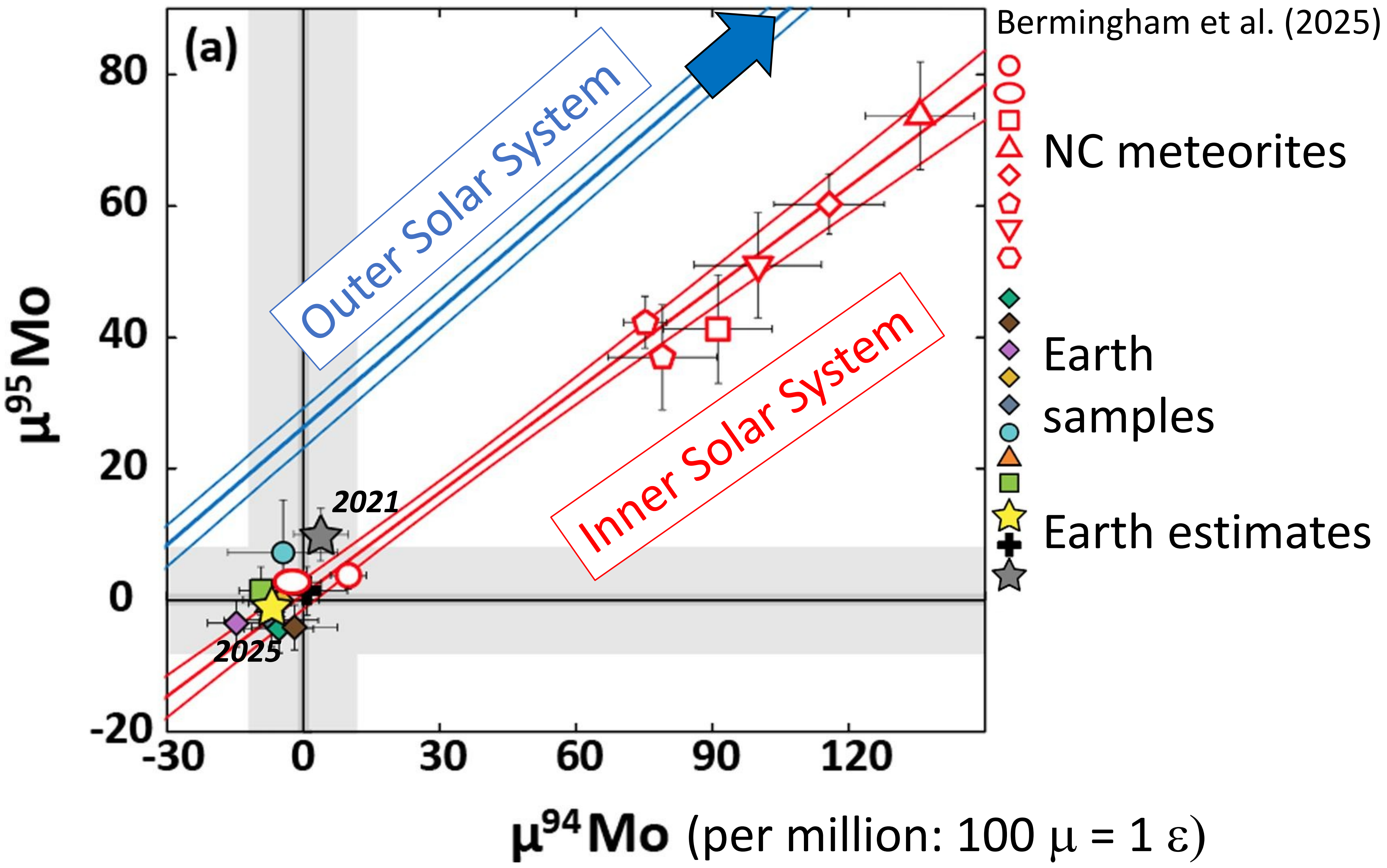
NC meteorites

Earth samples

Earth estimates

(per million: 100 μ = 1 ε)

1. The isotopic composition of the Earth tells us what its building blocks were → formation of the terrestrial planets



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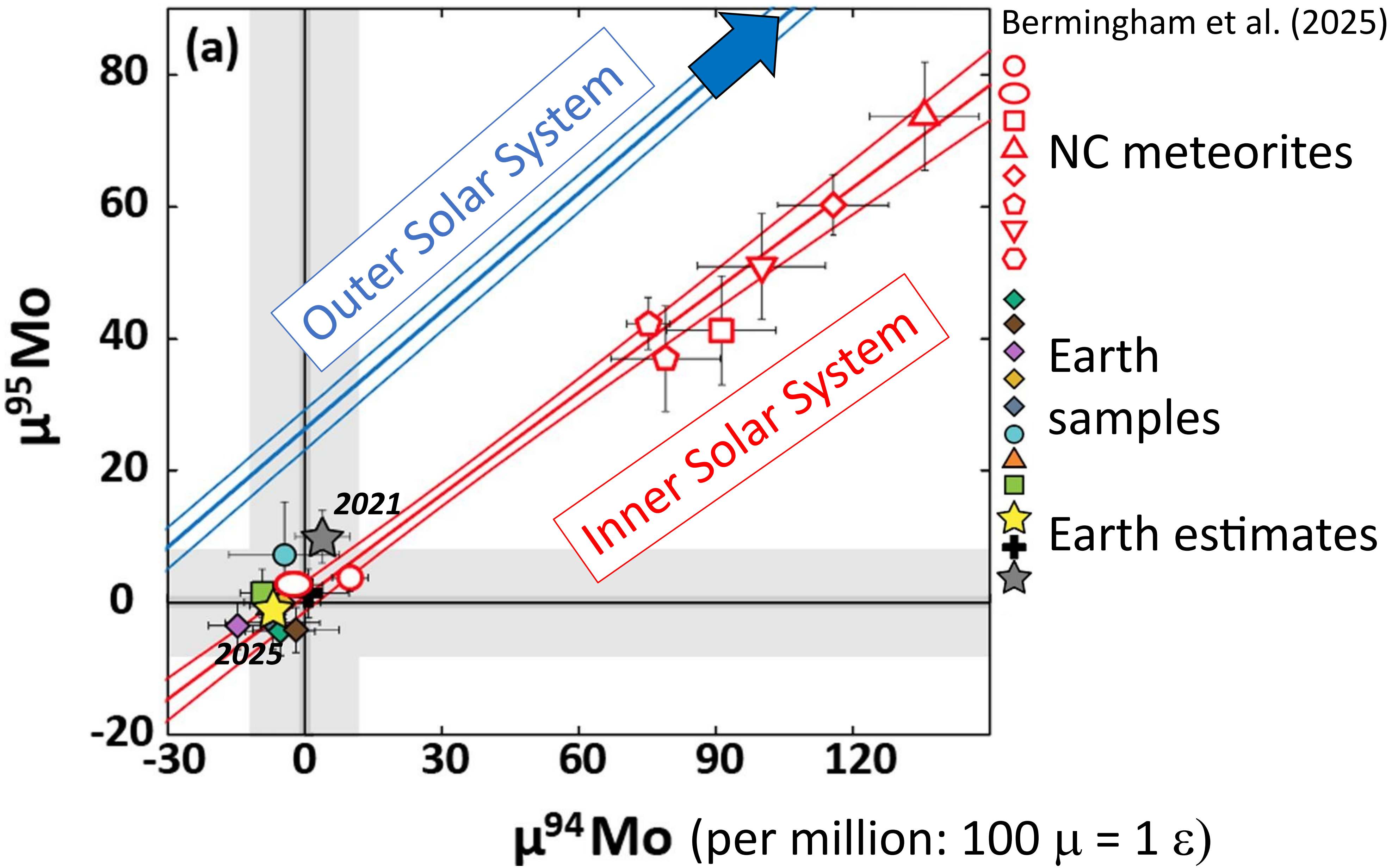


2. The isotopic variability is due to original stellar material distributed heterogeneously at large scale in the early Solar System

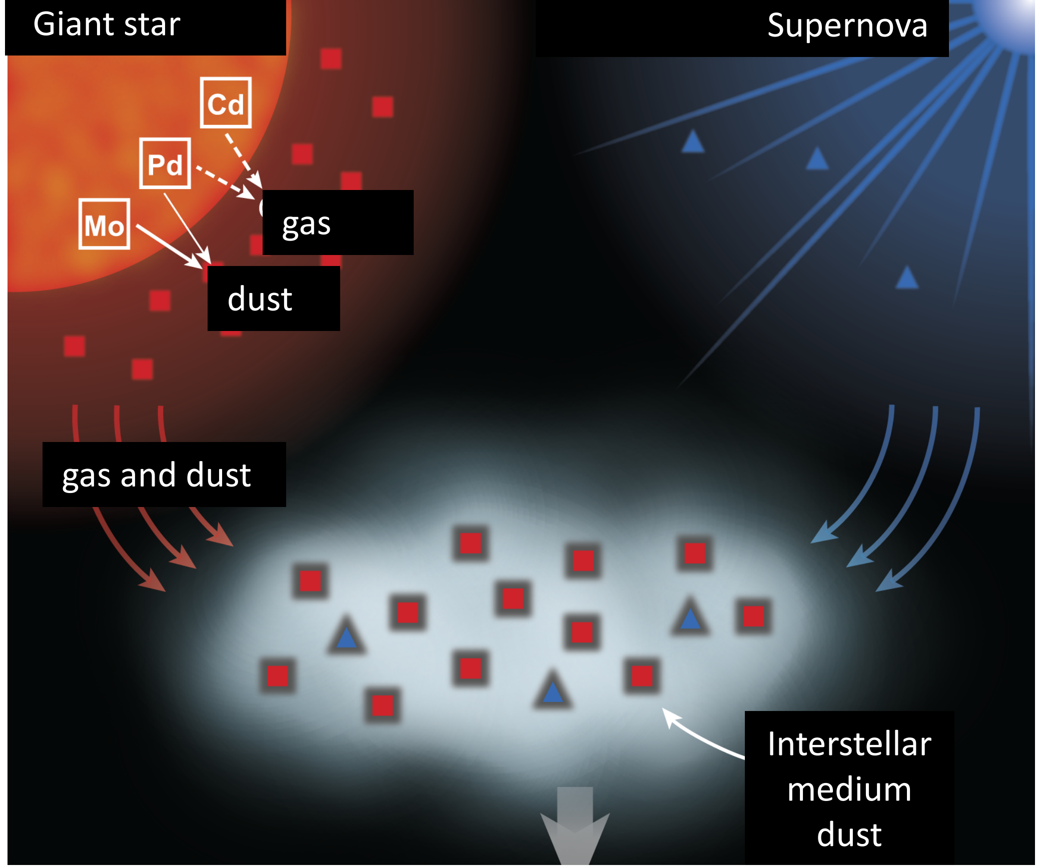
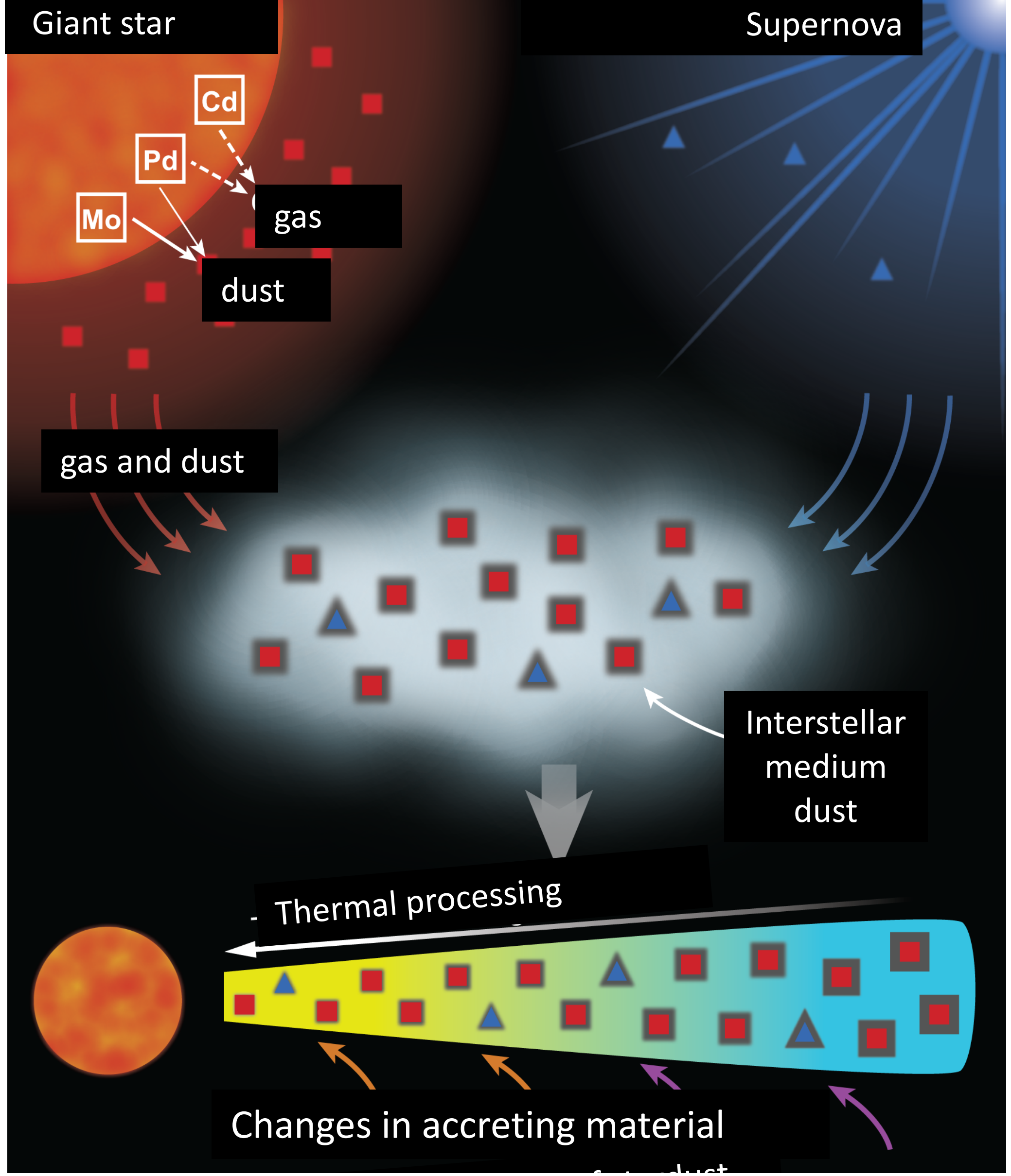


Figure from: Ek, Hunt, Lugaro, Schönbächler (2020, Nature Astronomy)

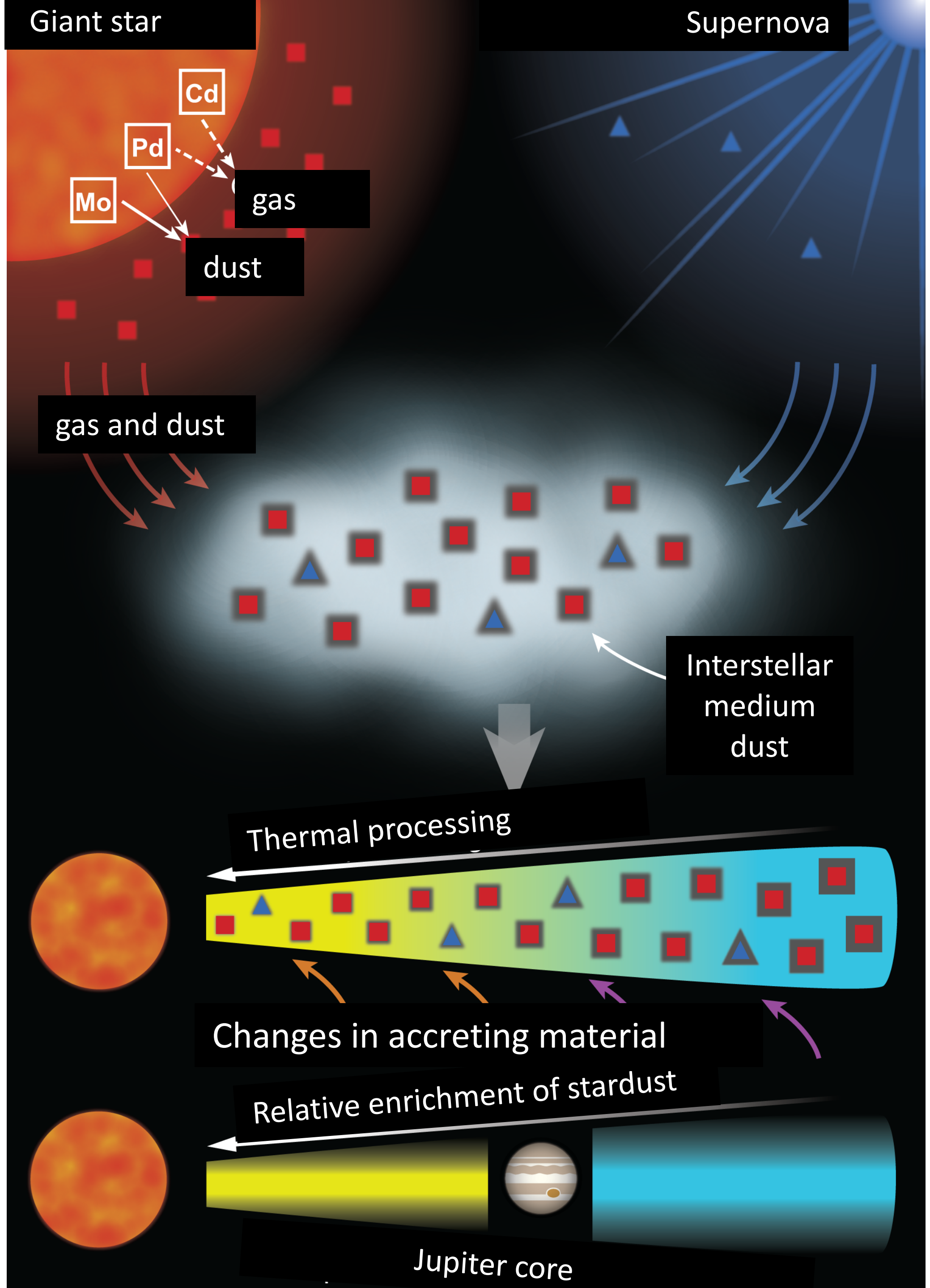


Why wasn't the stellar material mixed well?

1. **Dust processing**: heat, size, mineralogy, …?
2. **Changes in the accreting material** (from a local source?)

Figure from: Ek, Hunt, Lugaro, Schönbächler (2020, Nature Astronomy)

Why is there a gap between the inner and outer Solar System? A spatial barrier in the disk? For example, the very rapid (< 1 million year) formation of Jupiter's core (Kruijer et al. 2017)



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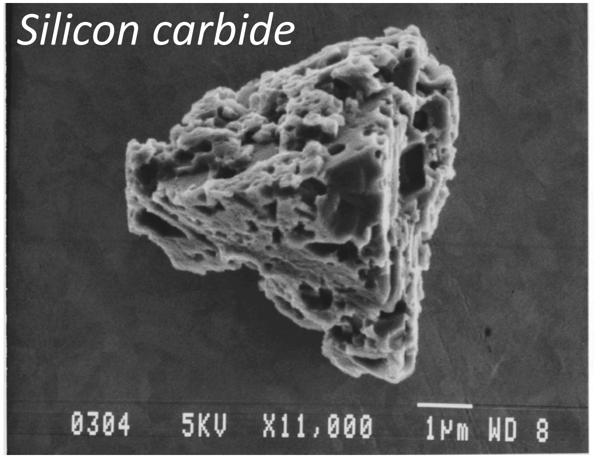
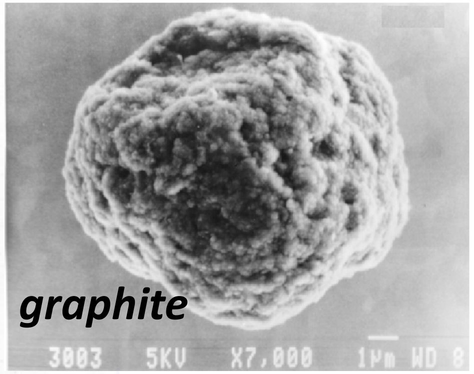
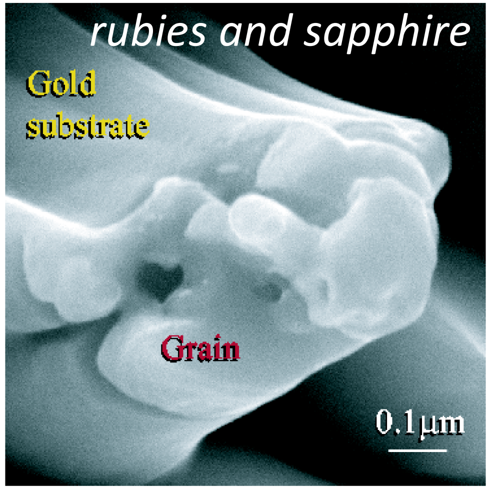
Solid stellar material is found in meteorites: tiny pieces of microscopic dust

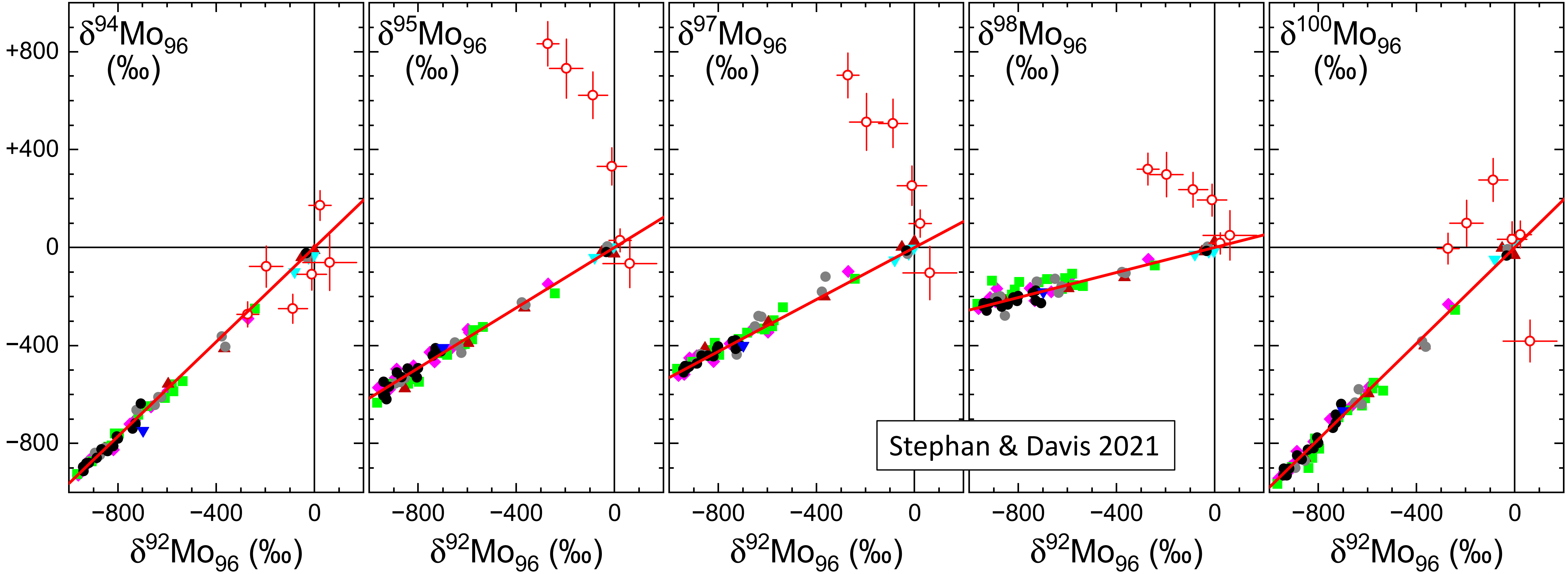






Physical pieces of giant stars and supernovae!

Each dot is a separate grain of stardust



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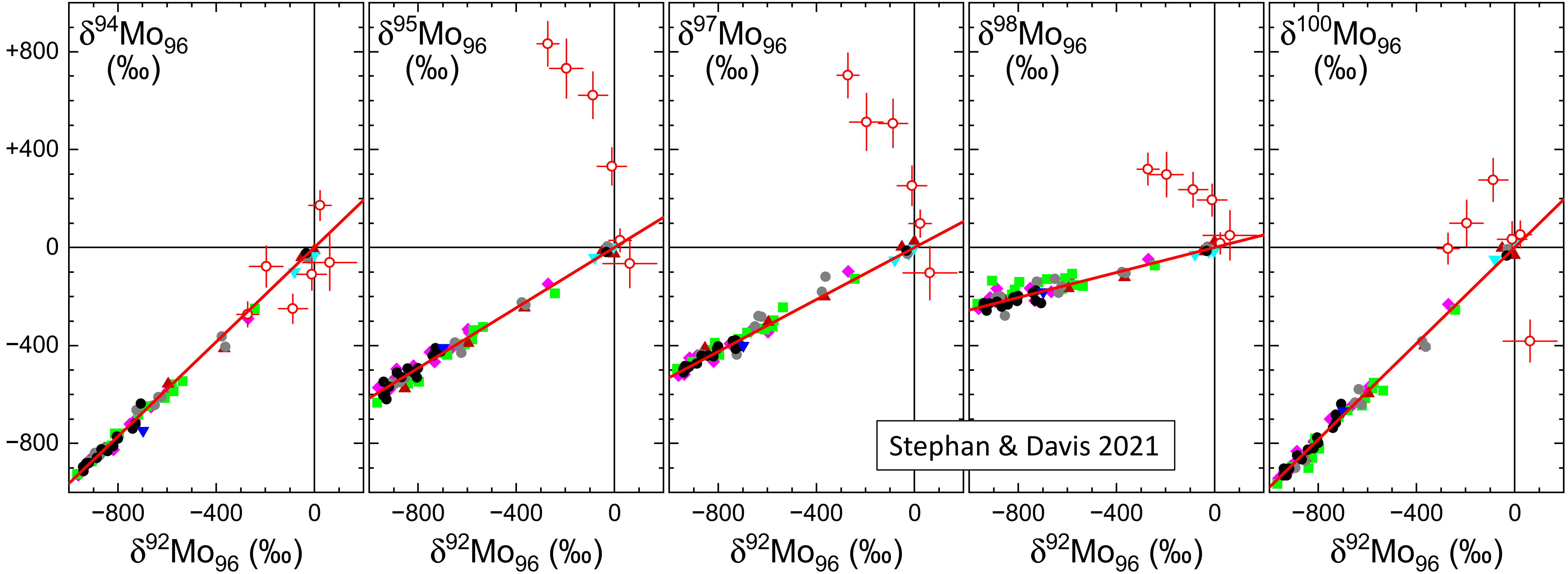
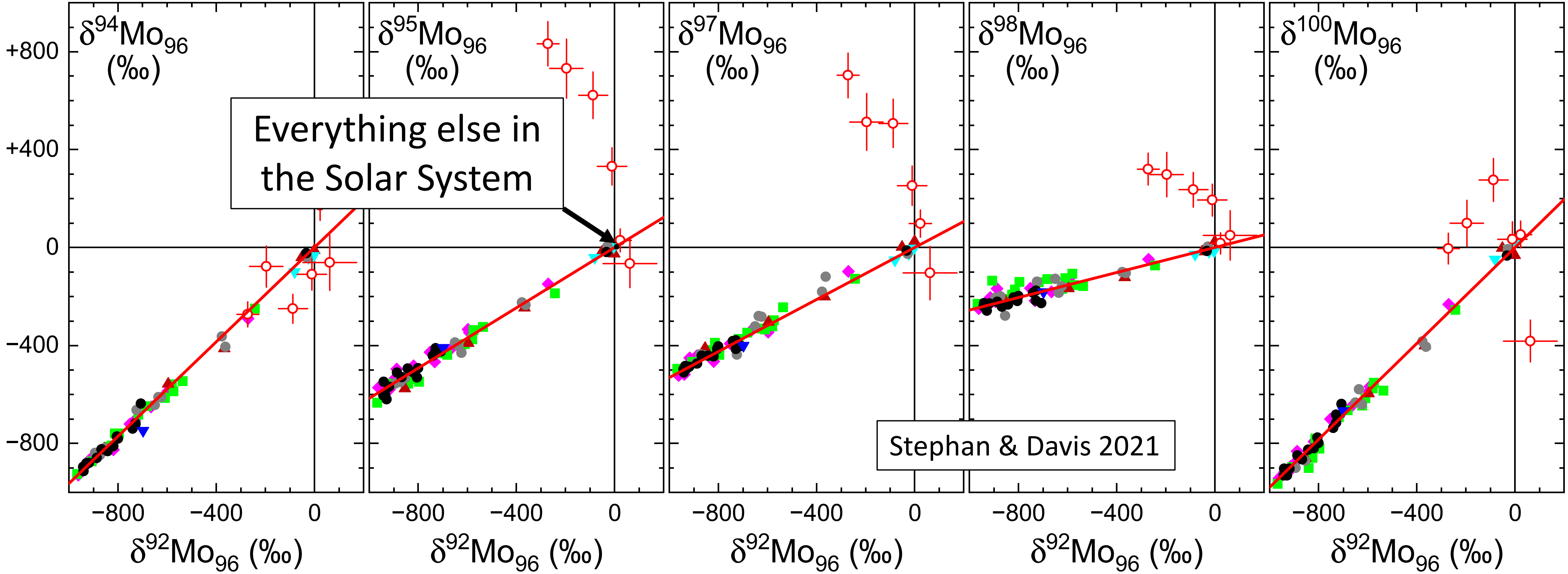
Red lines: stardust from giant stars → effect of ***slow*** **neutron captures**



Red lines: stardust from giant stars → effect of ***slow* neutron captures**

δ = permil variation; μ = per million variation → 1000 μ = 1 δ



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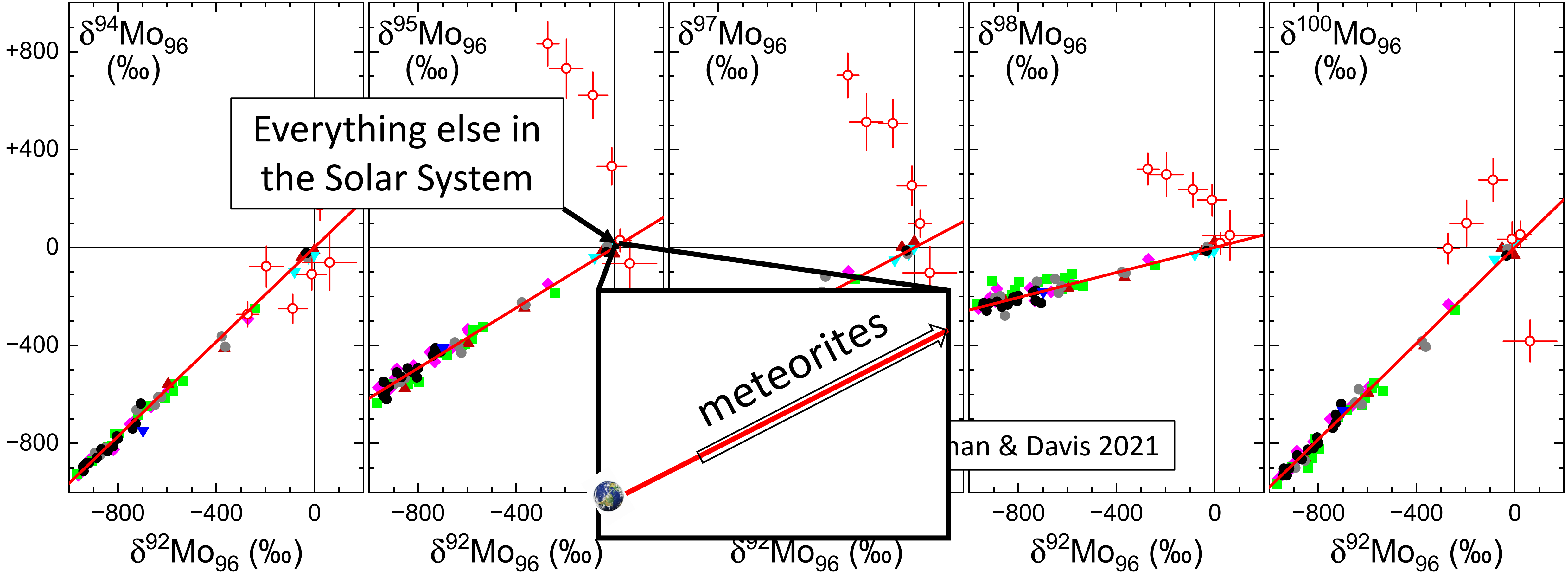
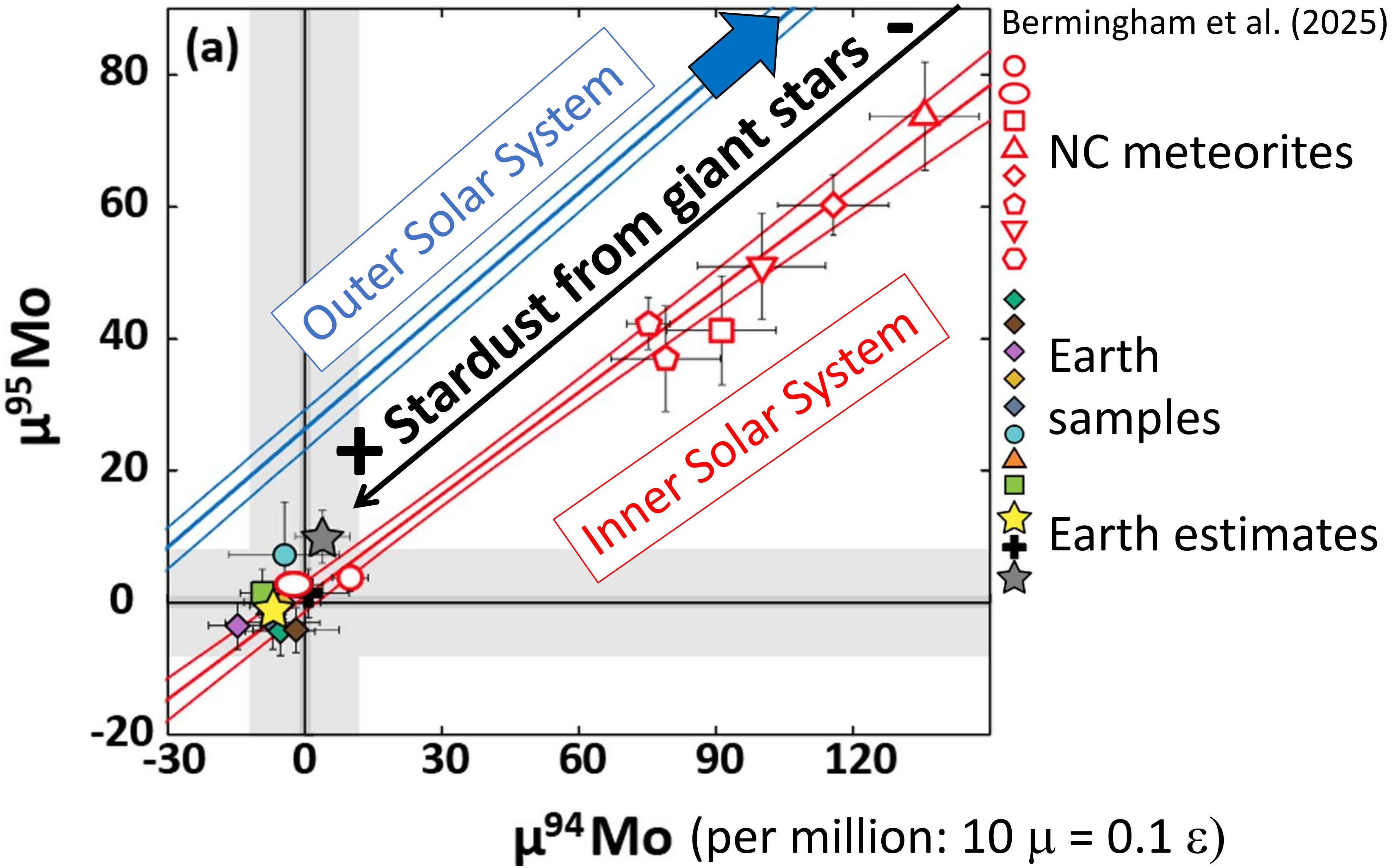
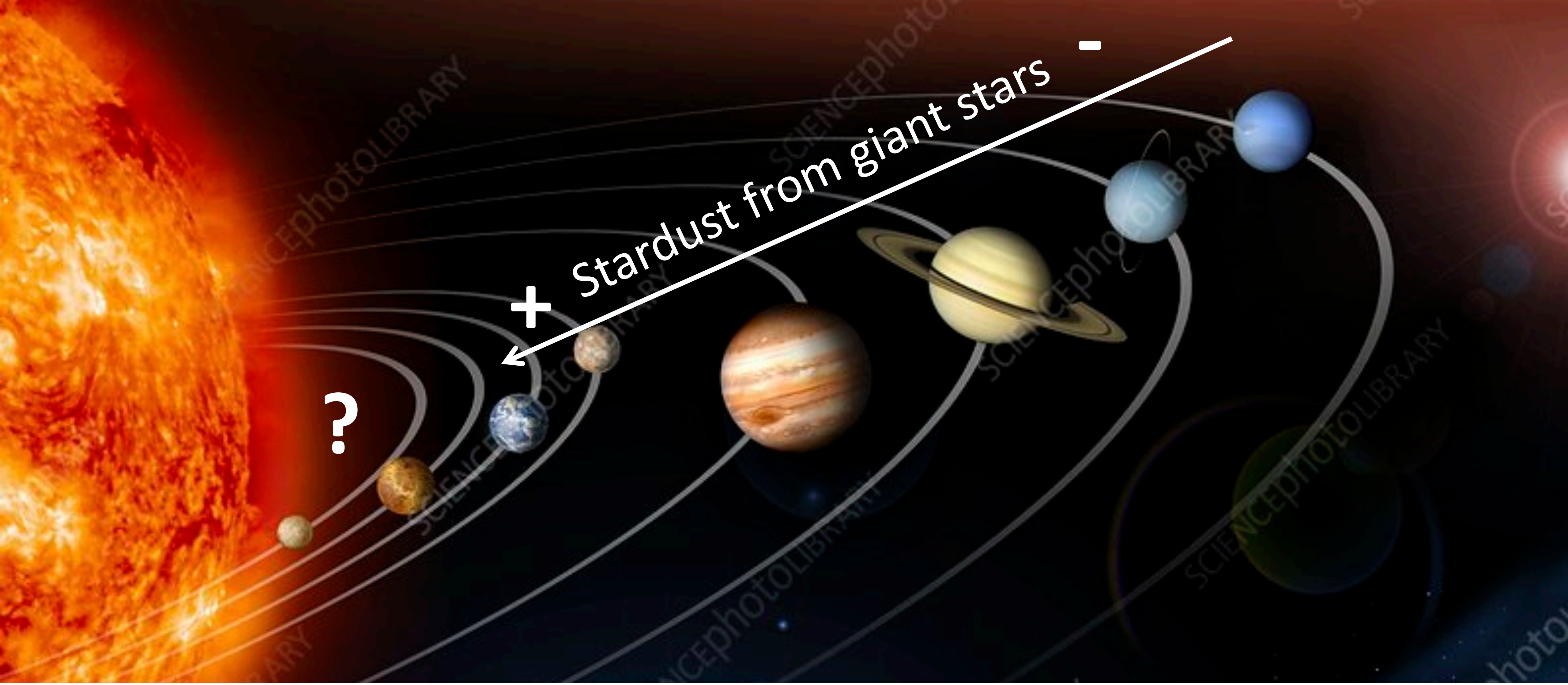
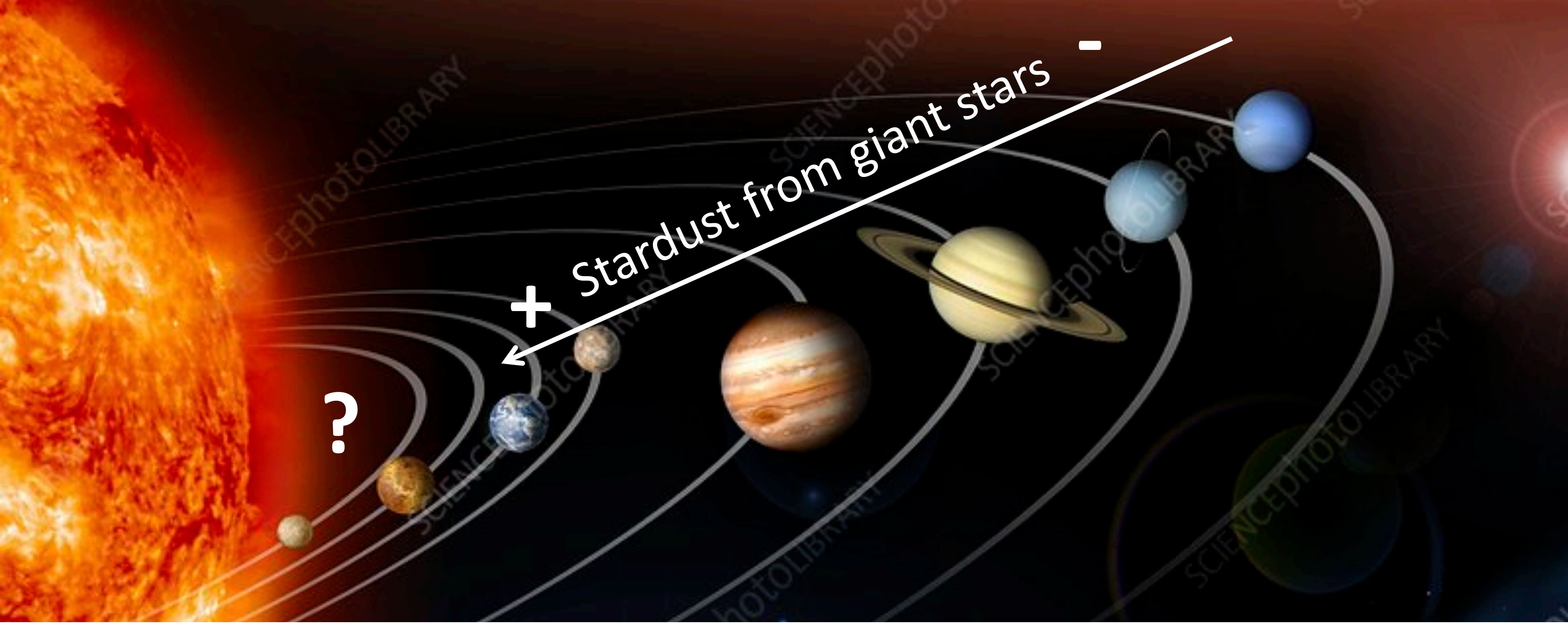


Black line: Conversion of the red lines from the previous figure (δ) onto this figure (μ)

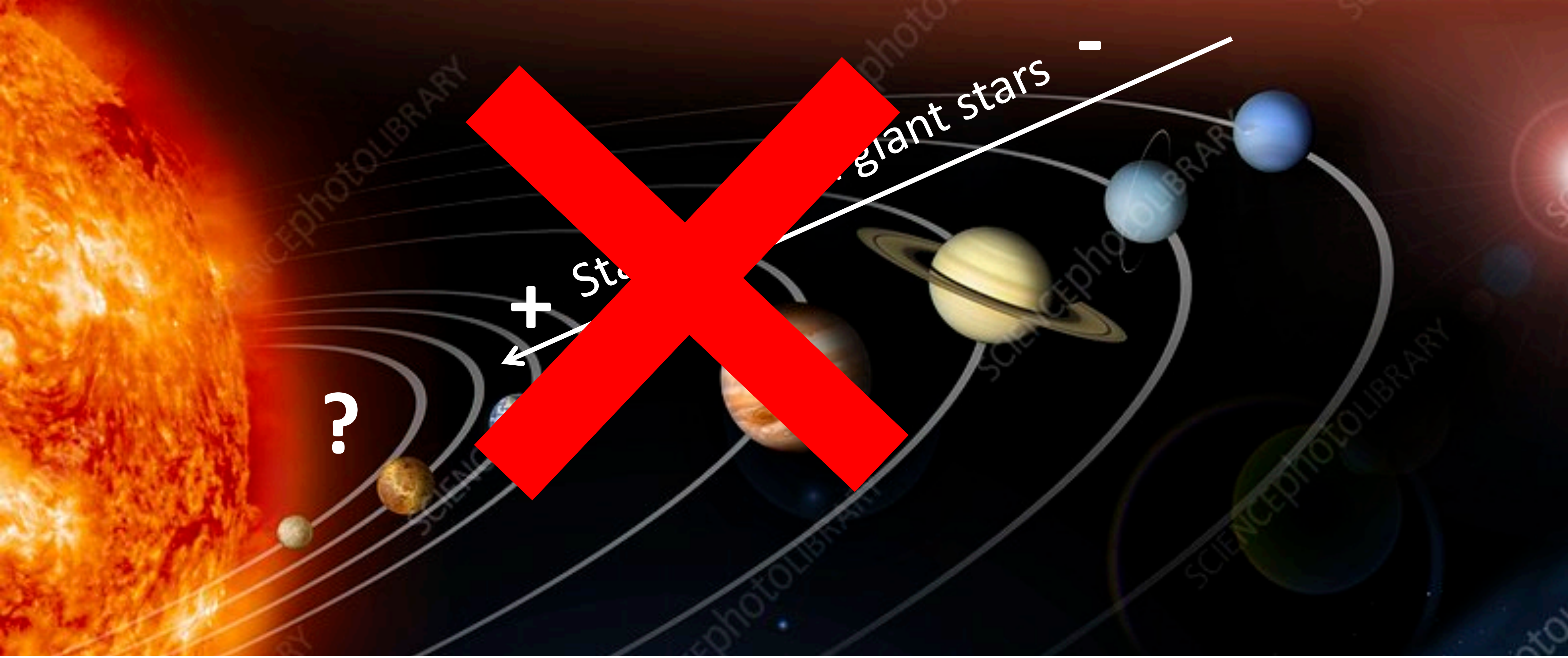




The Earth is the richest in stardust from red giant stars in the Solar System! This is a problem because the Earth should have formed from a mixture of material, how can it be an end member?



1) The even richer material fell into the Sun. *Prediction*: Venus and Mercury should be even richer, but we do not know their Mo isotopic composition (Mezger et al. 2020, Space Sci Rev)

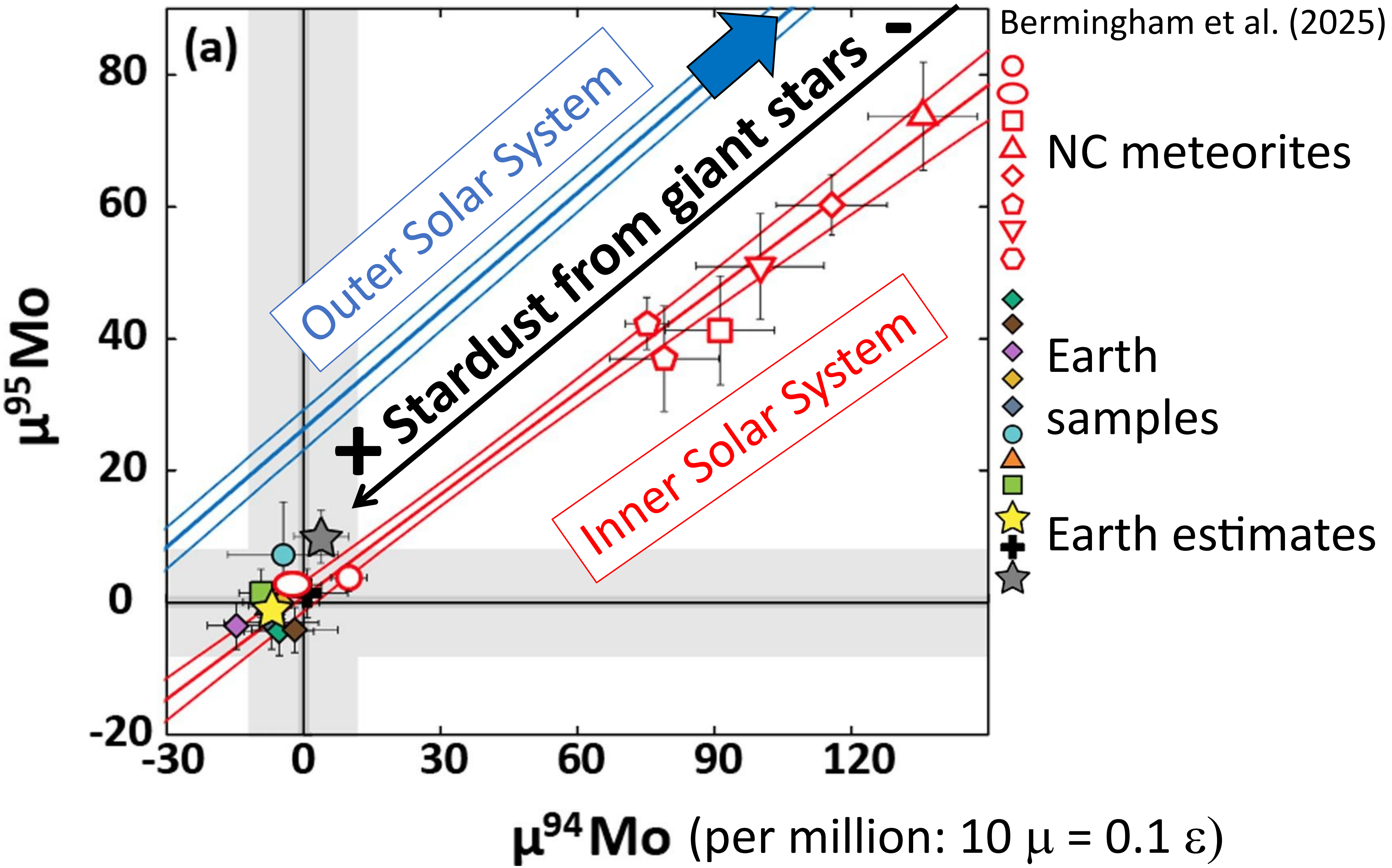


2) Or, the AGB stardust enrichment did not happen in the protosolar disk, but during the formation of the Earth, assuming pebble accretion (Oneytt et al. 2023)

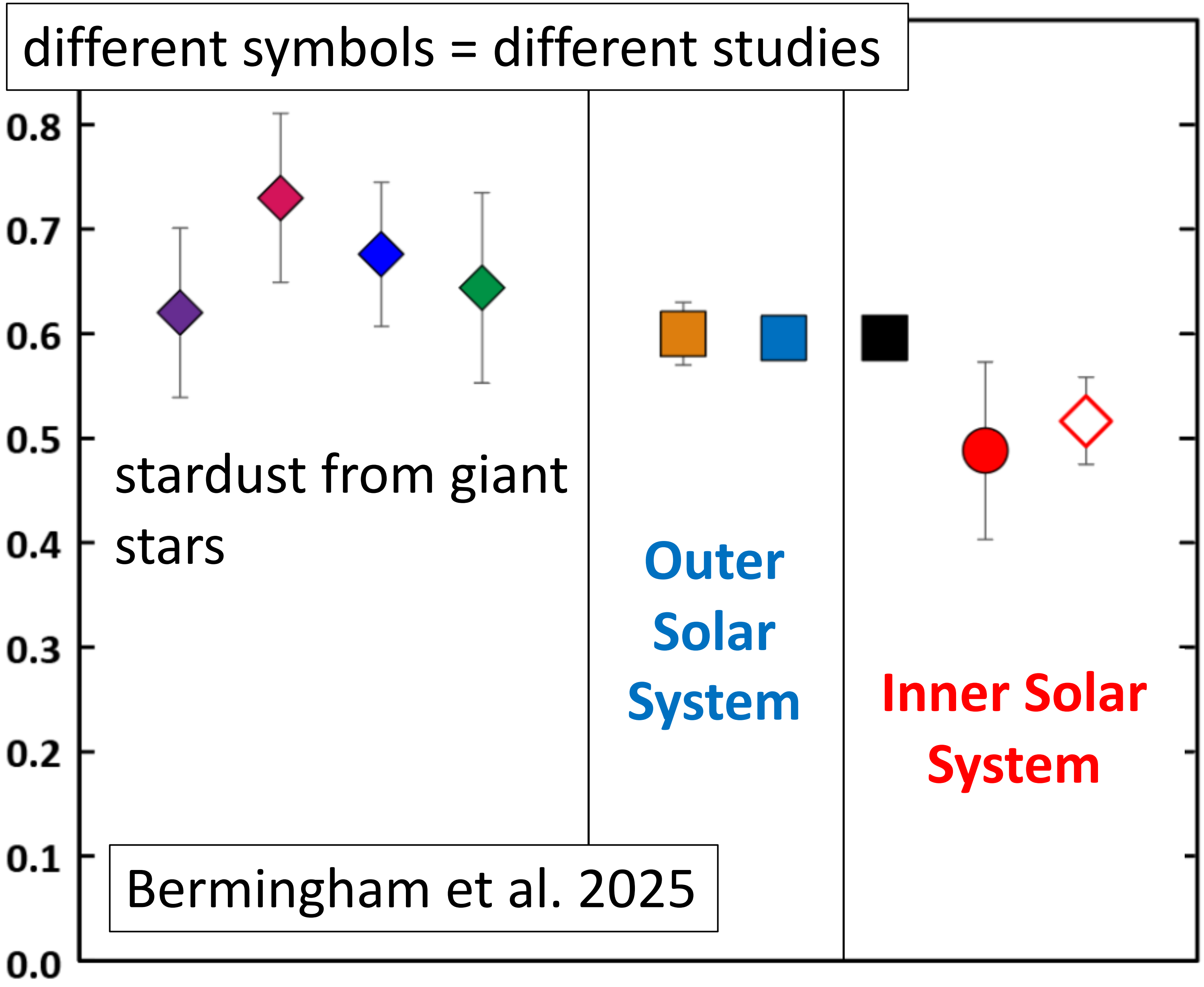
What about the slope of the three lines:

1. **Stardust**,
2. Outer Solar System,
3. Inner Solar System

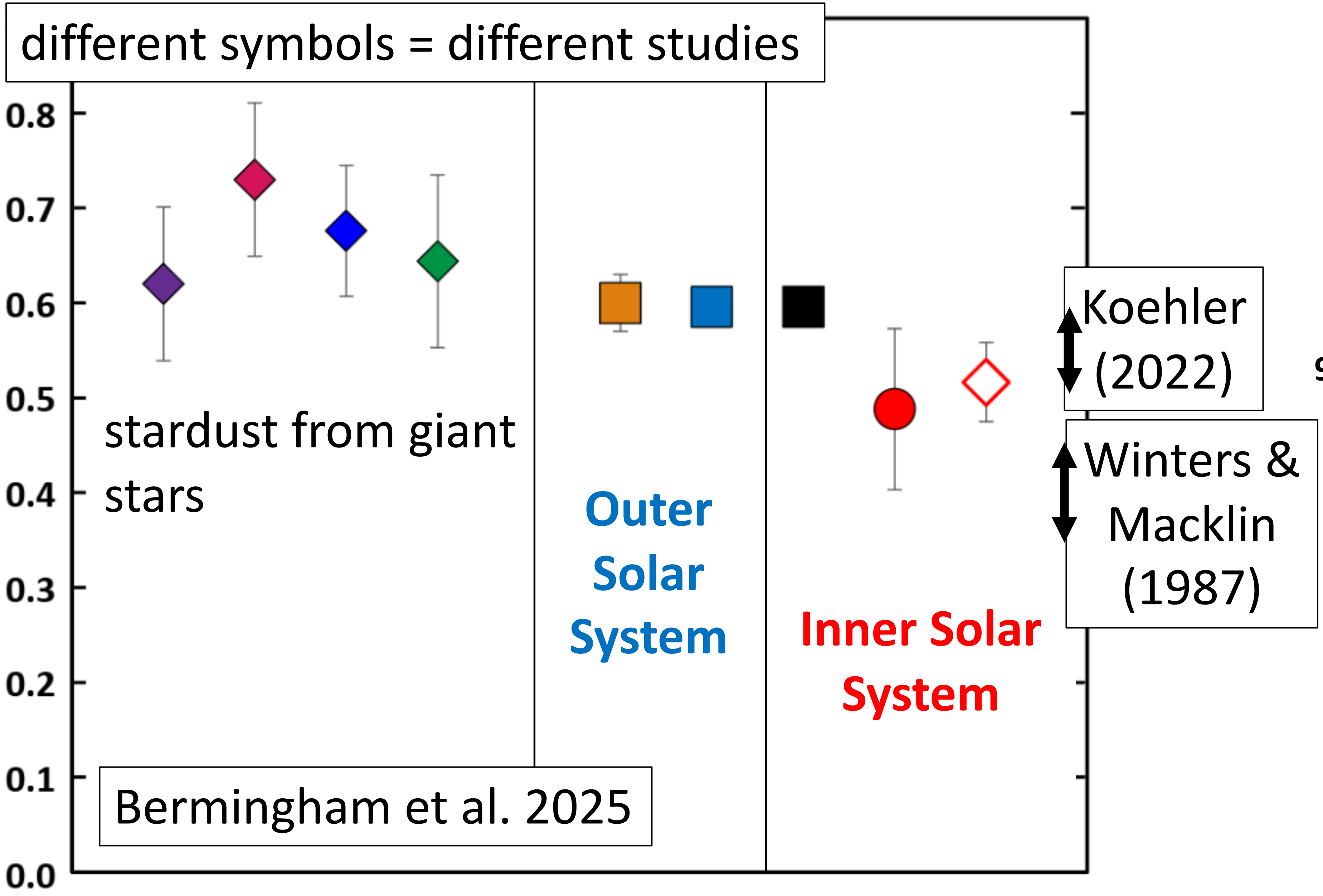
Is it exactly the same?



Slope from neutron captures μ^{95}Mo vs. μ^{94}Mo



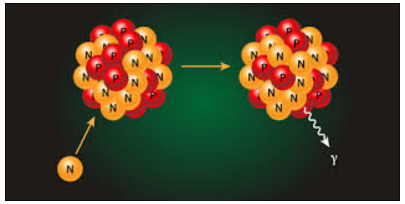
Slope from neutron captures μ^{95}Mo vs. μ^{94}Mo



The predicted slope is a function of the Mo neutron capture cross sections, e.g.,

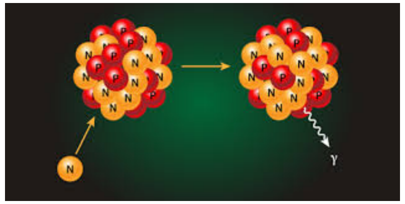
^{95}Mo + n → ^{96}Mo + γ

(Lugaro et al. 2023, The European Physical Journal A)



$^{i}Mo + n \rightarrow {}^{i}Mo + \gamma$: Currently measured at CERN n_TOF and GELINA JRV-Geel

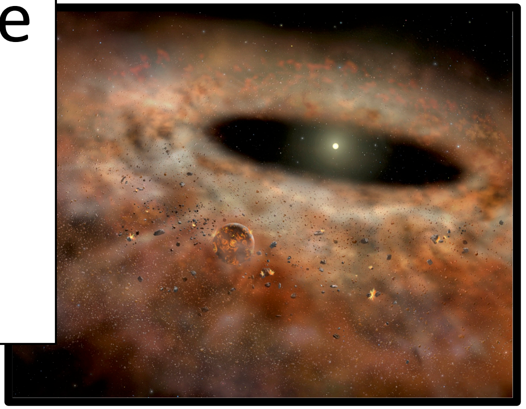
^{i}Mo + n → ^{i}Mo + γ : Currently measured at CERN n_TOF and GELINA JRV-Geel

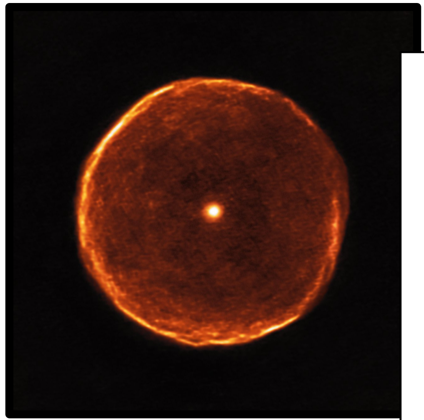


Prediction of the neutron capture signal in giant stars

Future tasks

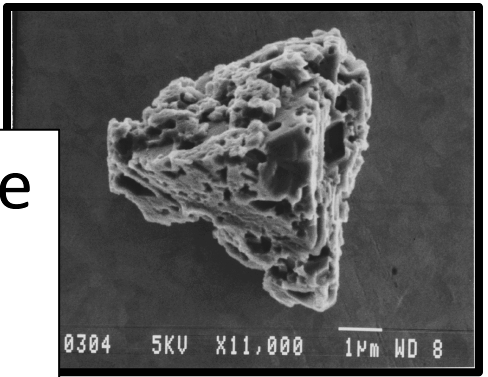
Understanding the evolution of the protoplanetary disk





Identification of the giant stars from where the signal originated

Determination of the type of stardust in the outer and inner early Solar System



Summary and conclusions

- The isotopic composition of meteorites is not 100% the same as terrestrial, which shows that large-scale variation were present in the protoplanetary disk due to variability of various stellar materials (e.g., stardust)
- Isotopic variations can be used to understand the environment of the Sun's birth, the evolution of the protoplanetary disk, and the formation of the planets
- Identification of their stellar origin is the new research direction needed to test these theories