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

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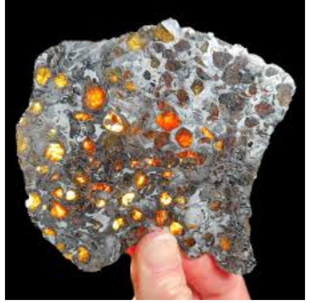
Outline

- Brief Introduction on meteorites
- **Three** examples of meteoritic studies with impact from nuclear physics, one for each the three main types of signatures of stellar material in meteorites

1. Stardust
2. Radioactive nuclei
3. Bulk meteoritic data

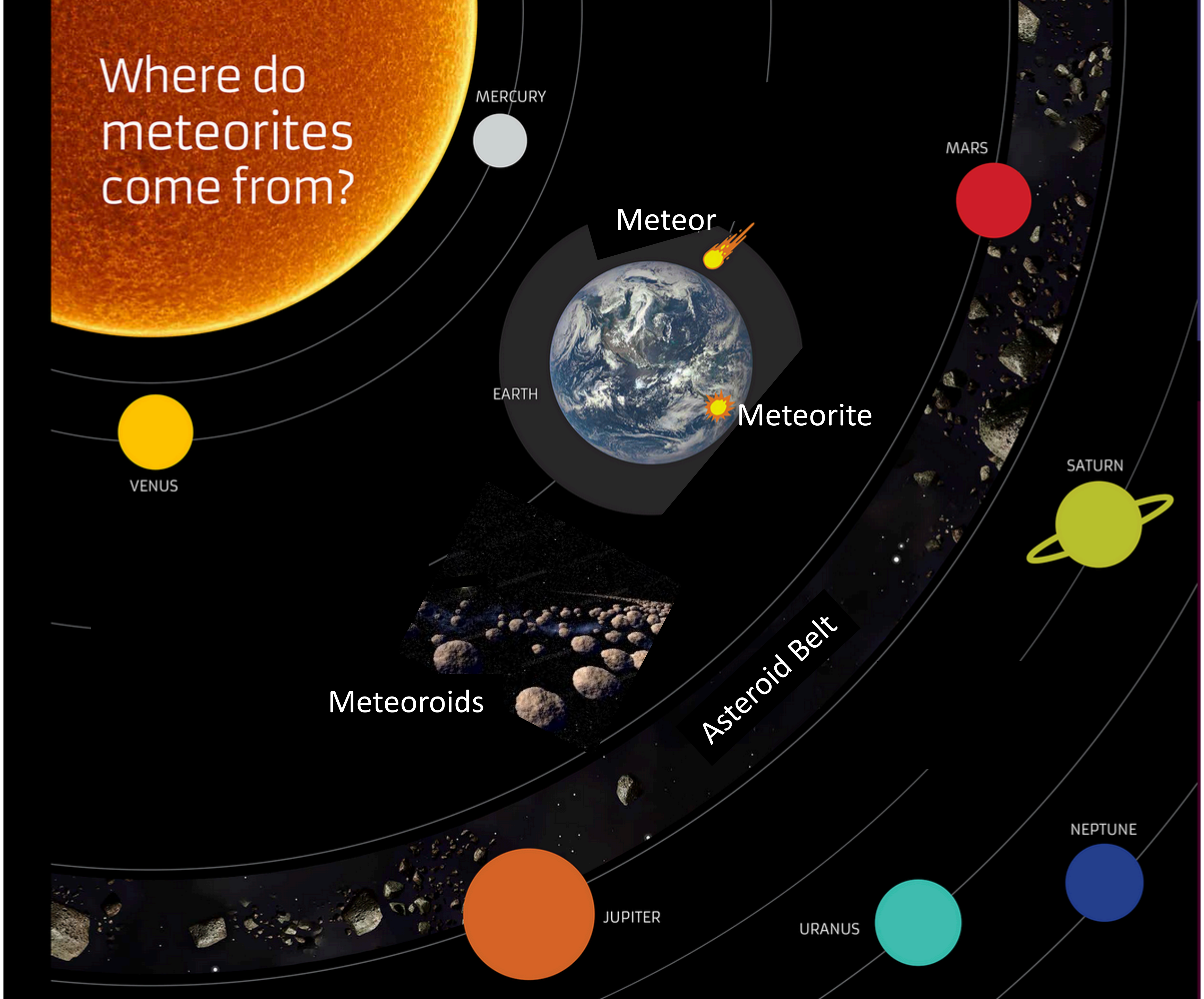


Meteorite

Meteor

Meteoroid

Asteroid
parent body



Asteroids formed in different region of the protosolar disk. They were then scattered into the Asteroid Belt.

Meteorite types

Chondrites (86%)
Chondrules: mm-size roundish droplets
Calcium-aluminium-rich inclusions (CAIs): whitish, the oldest solids ever found
Darker *Matrix*: also contains stardust grains.

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Achondrites (8%): the rocky silicate-dominated crust

Iron meteorites (6%): the iron-dominated core

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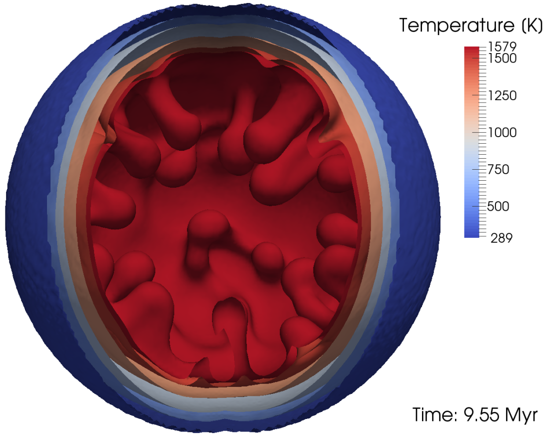
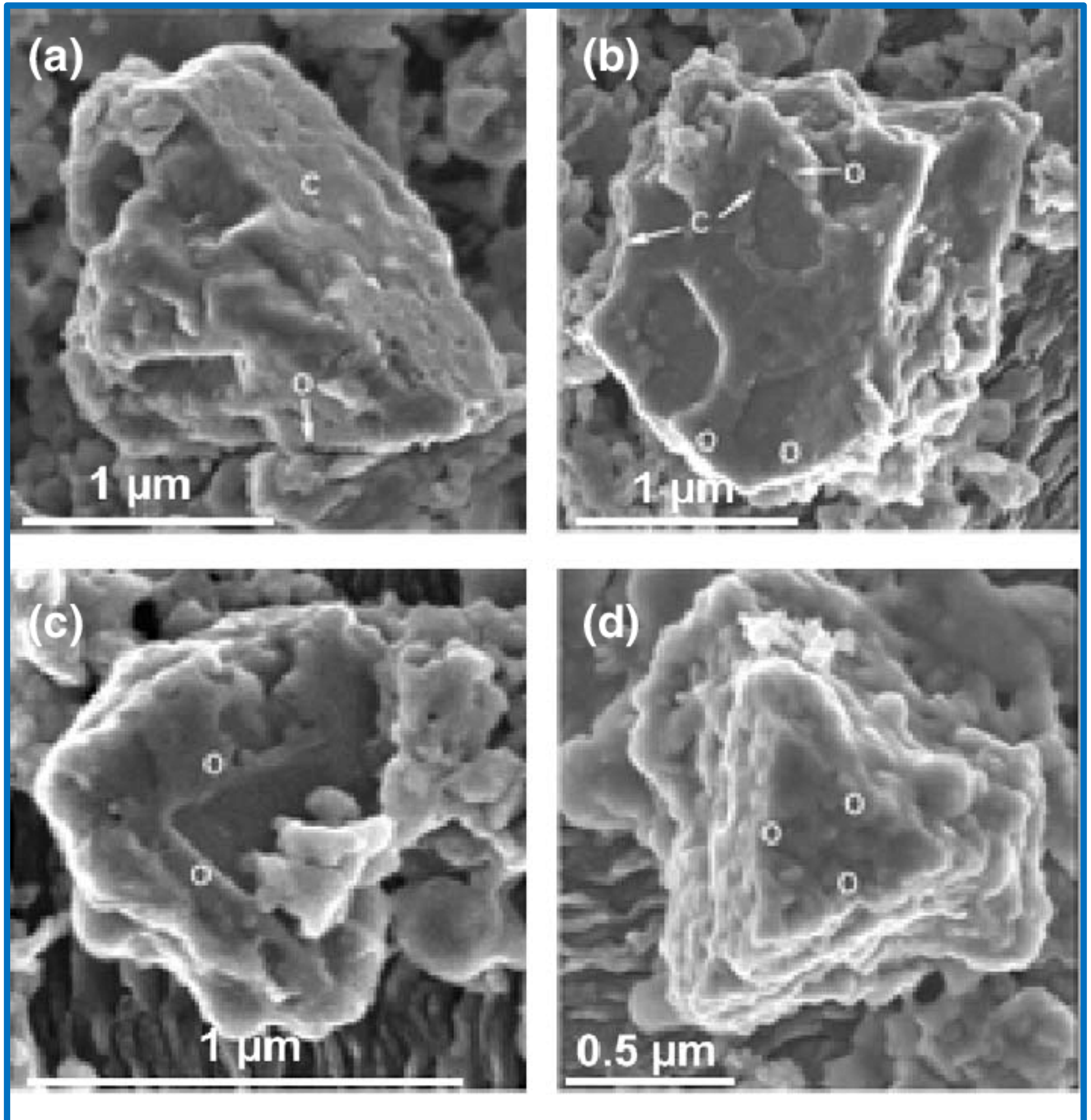


Lichtenberg et al. 2016 (Icarus)

Iron meteorites (6%): the iron-dominated core

of asteroids that melted and differentiated in the early Solar System via **the decay of ^{26}Al, 0.7 Myr.**

Electron microscope images (Tyrone Daulton)



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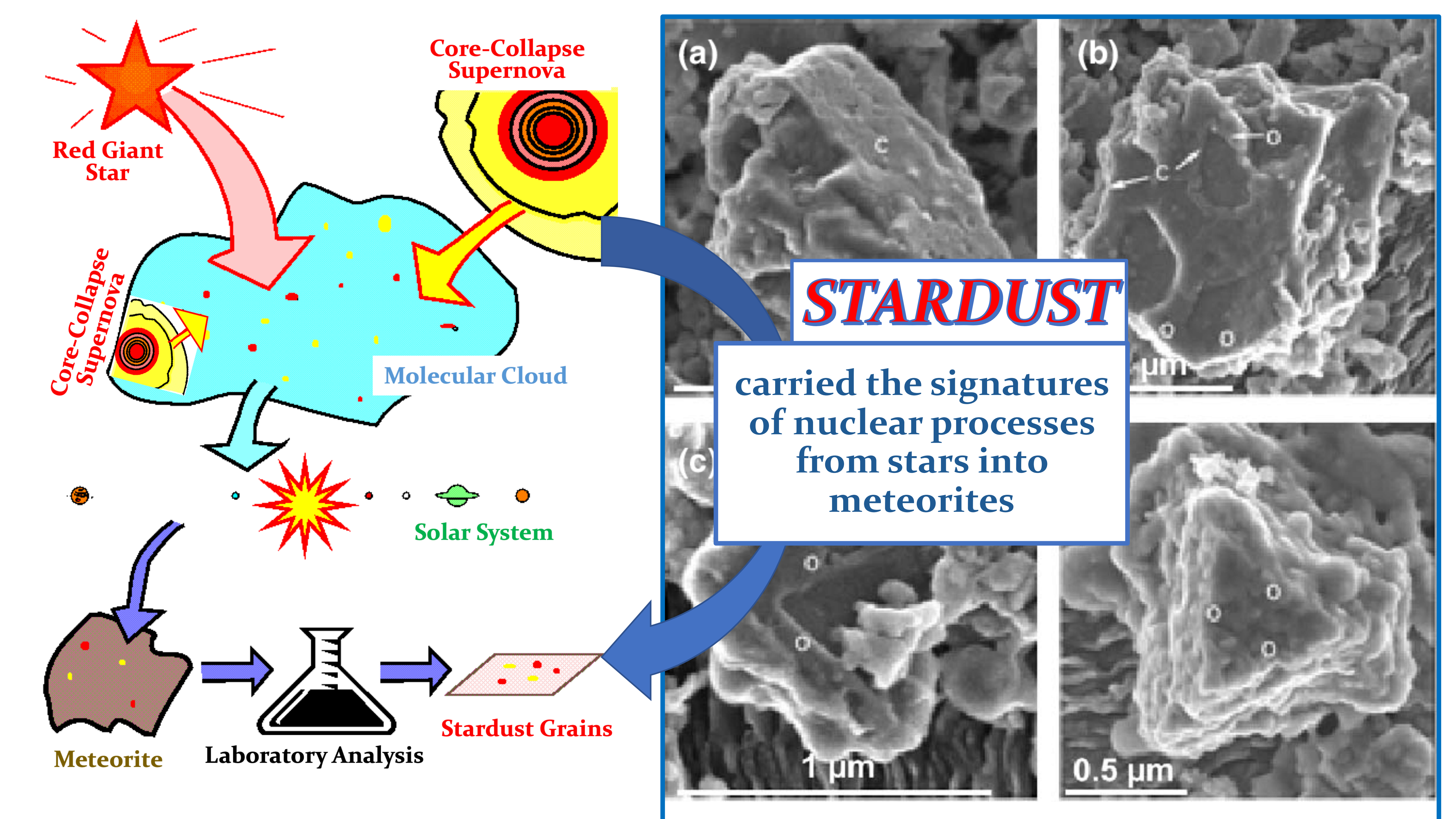
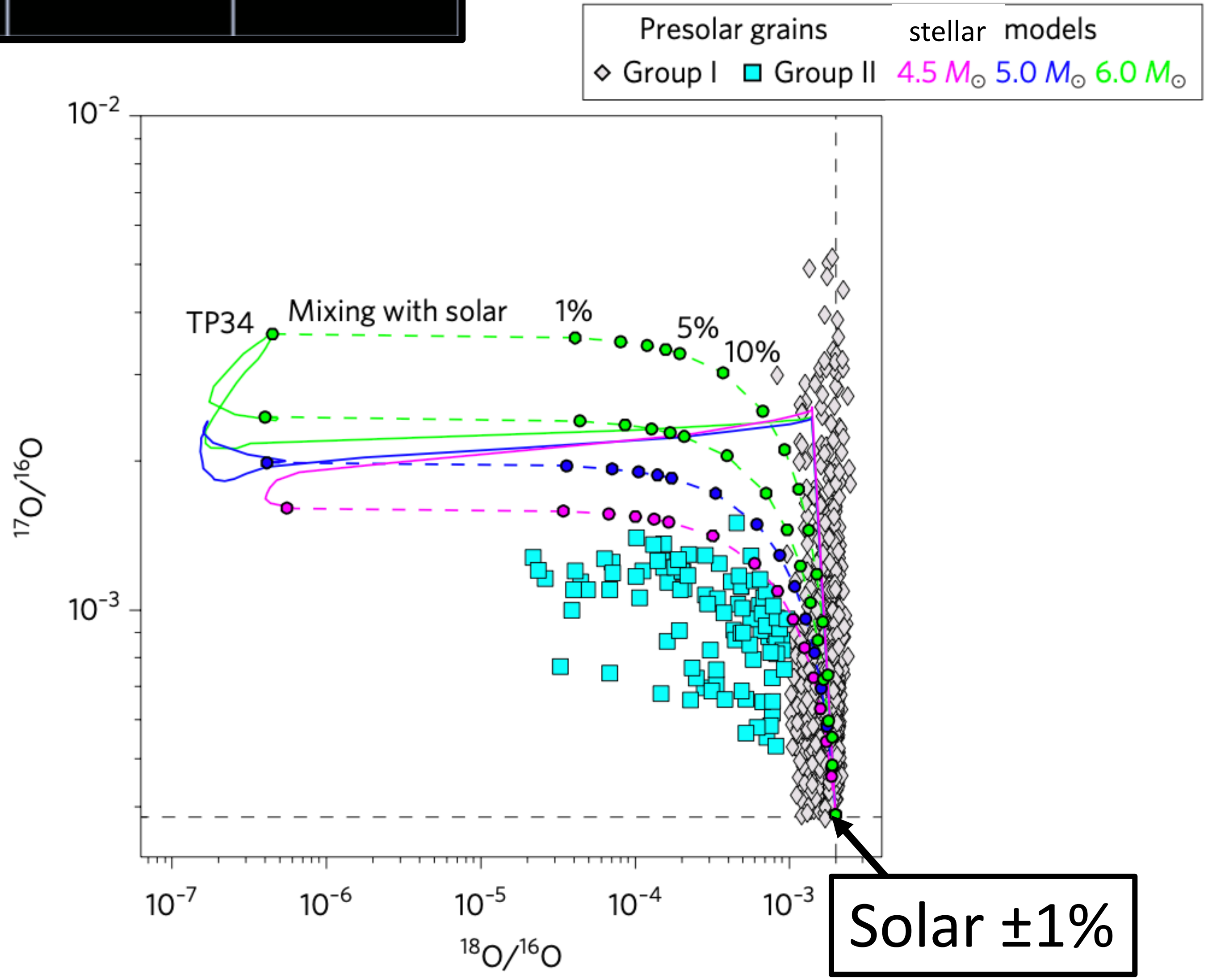

Core-Collapse Supernova
Red Giant Star
Core-Collapse Supernova
Molecular Cloud
Solar System
Meteorite
Laboratory Analysis
Stardust Grains
(a)
(b)
(c)
C
C
O
O
O
O
O
O
O
O
O
1 μm
0.5 μm
STARDUST
carried the signatures of nuclear processes from stars into meteorites

O isotopic composition of **stardust oxide grains**…

…produced in giant stars where H burning happened



O isotopic composition of **stardust oxide grains**…

16O	17O	18O
STABLE	STABLE	STABLE
99.762%	0.038%	0.200%

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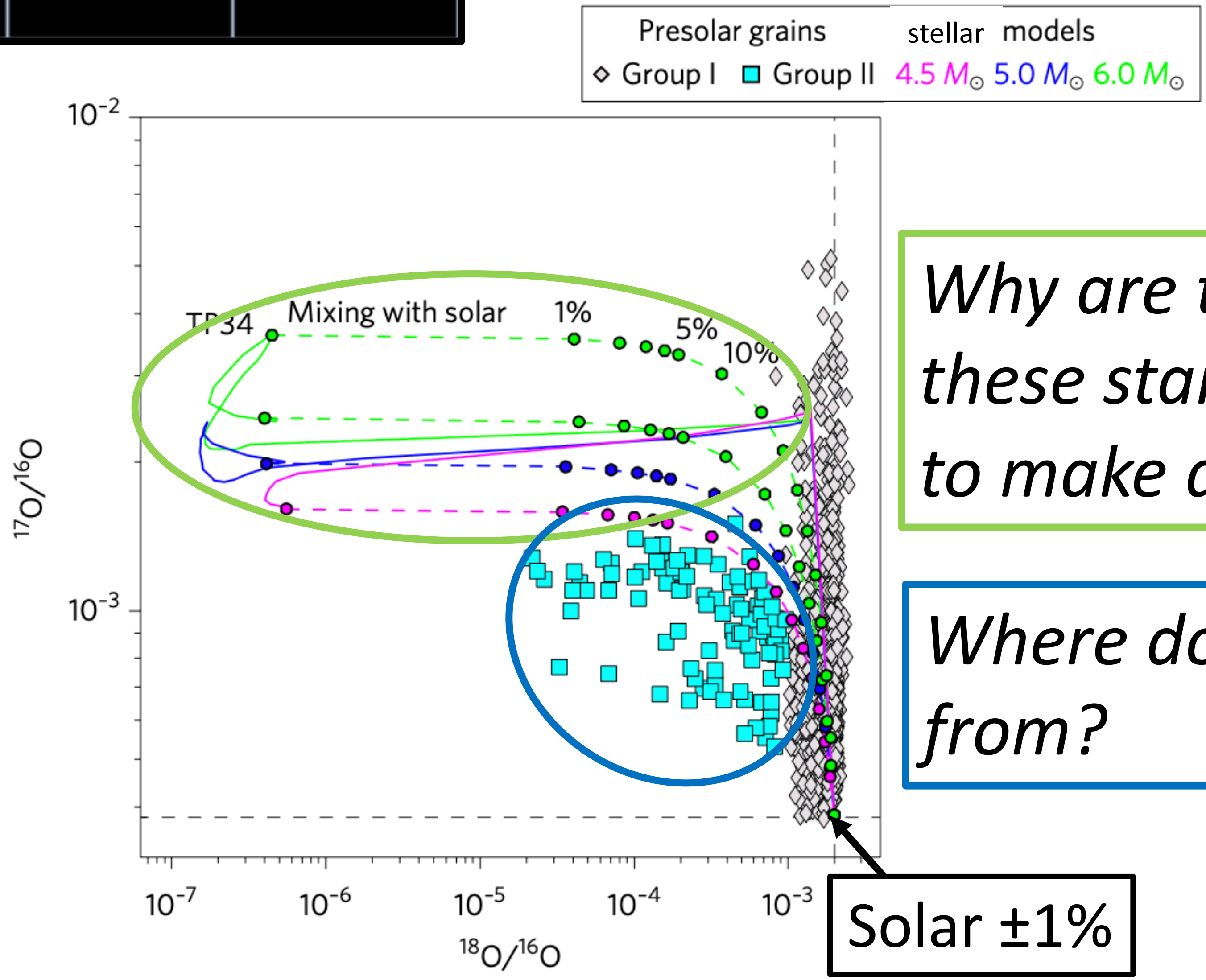

Why are there no grains from these stars, which are observed to make a lot of dust?

Where do these grains come from?

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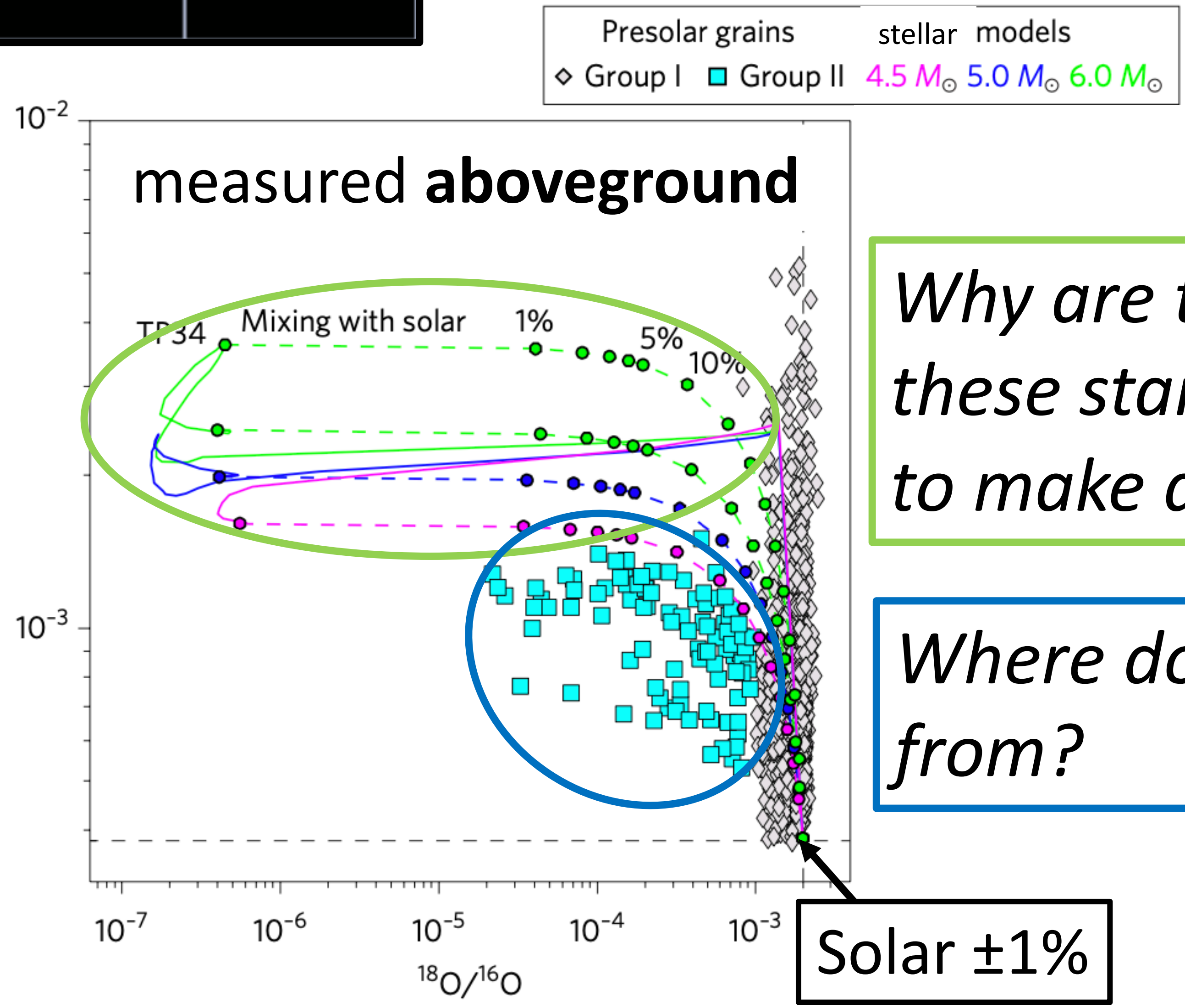

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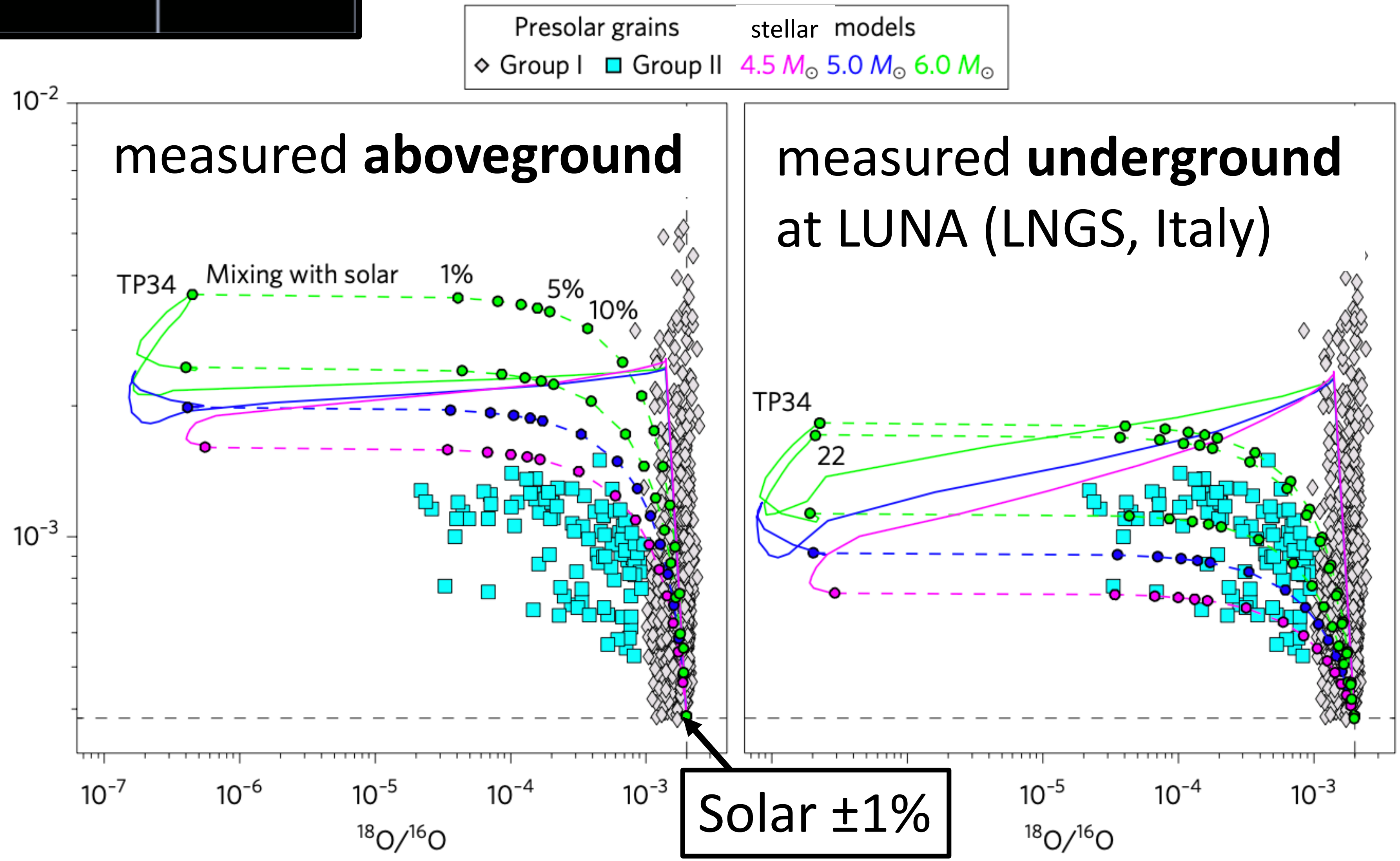
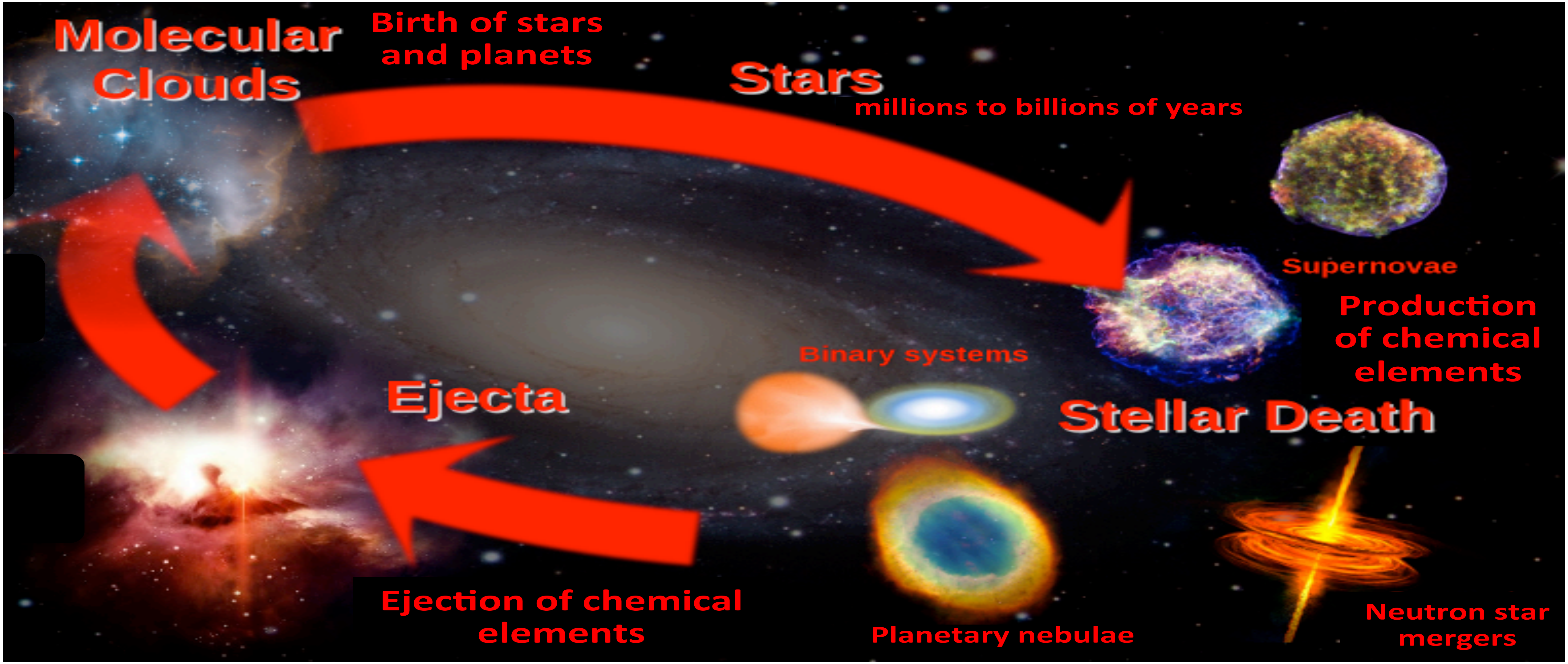
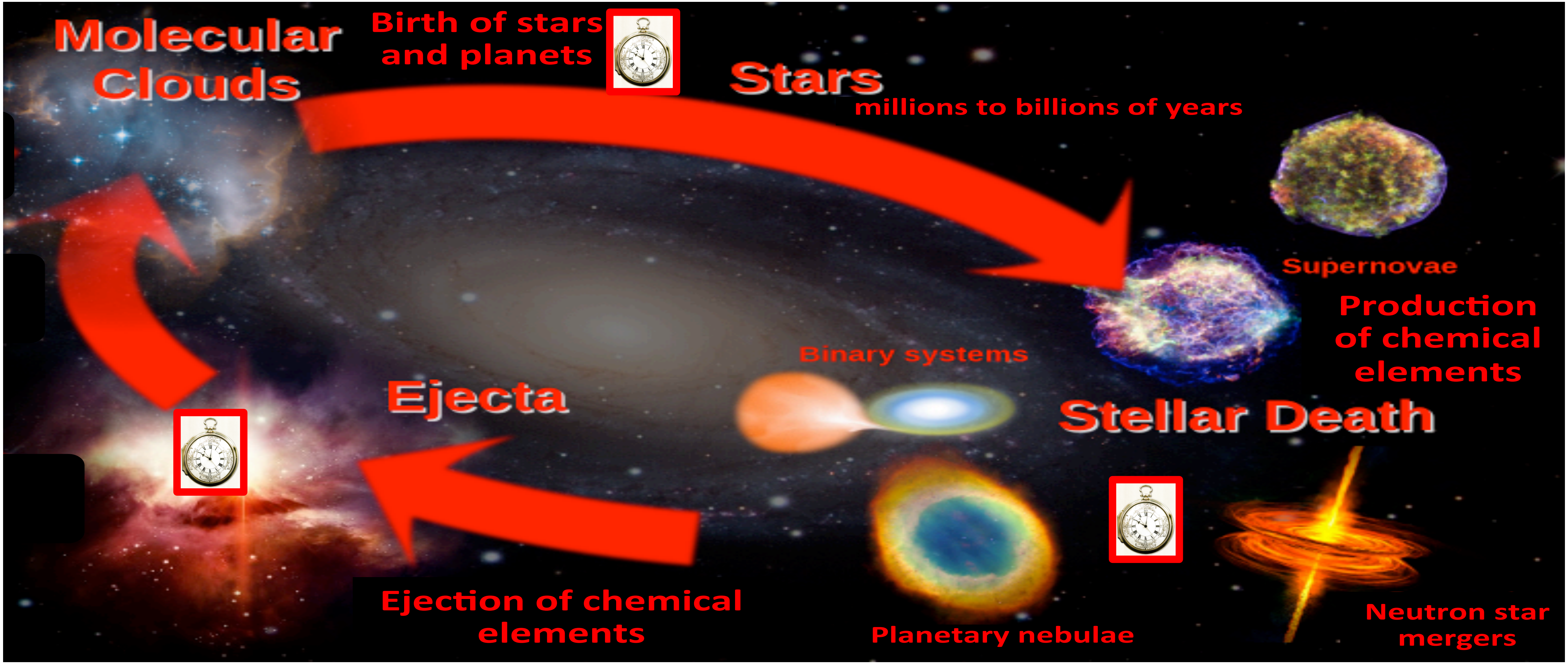


Lugaro et al. (the LUNA collaboration) 2017 Nature Astronomy

The Chemical Evolution of the Milky Way

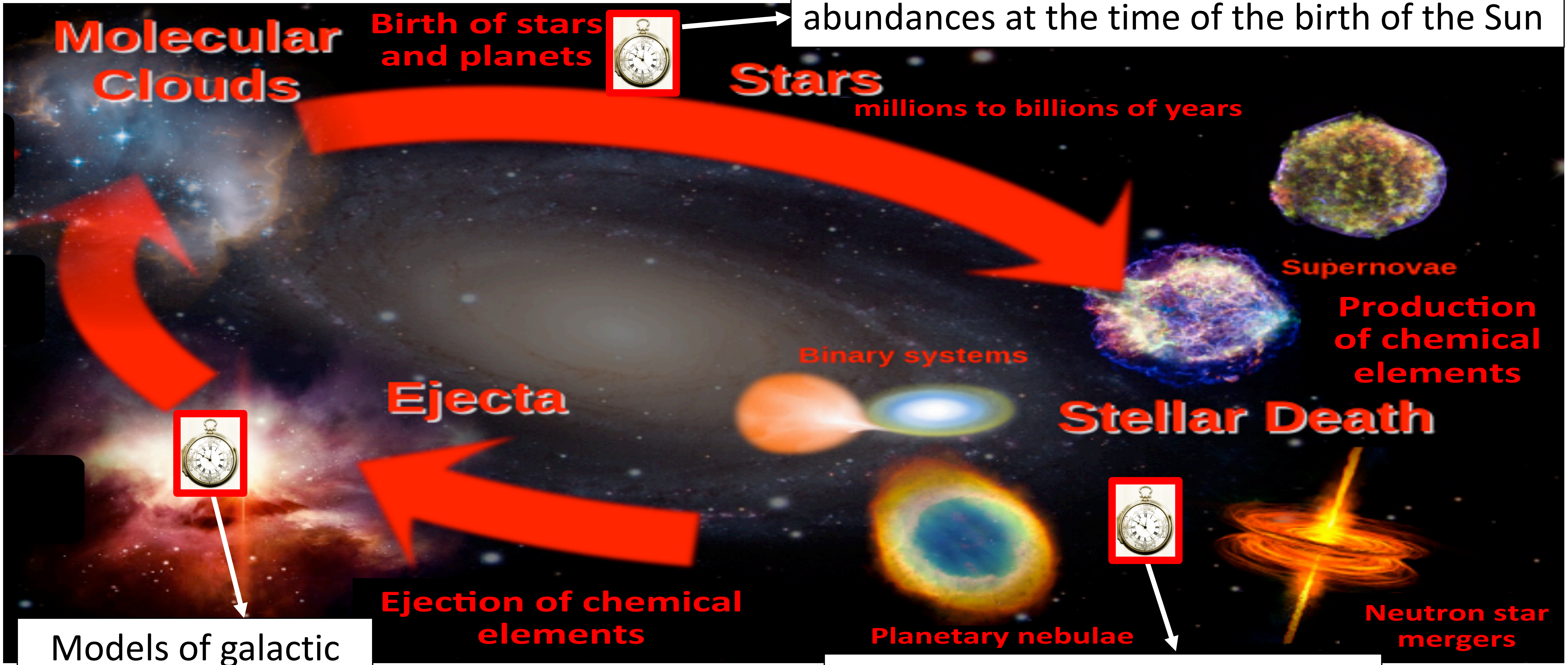


The *Radioactive* Chemical Evolution of the Milky Way



The *Radioactive* Chemical Evolution of the Milky Way

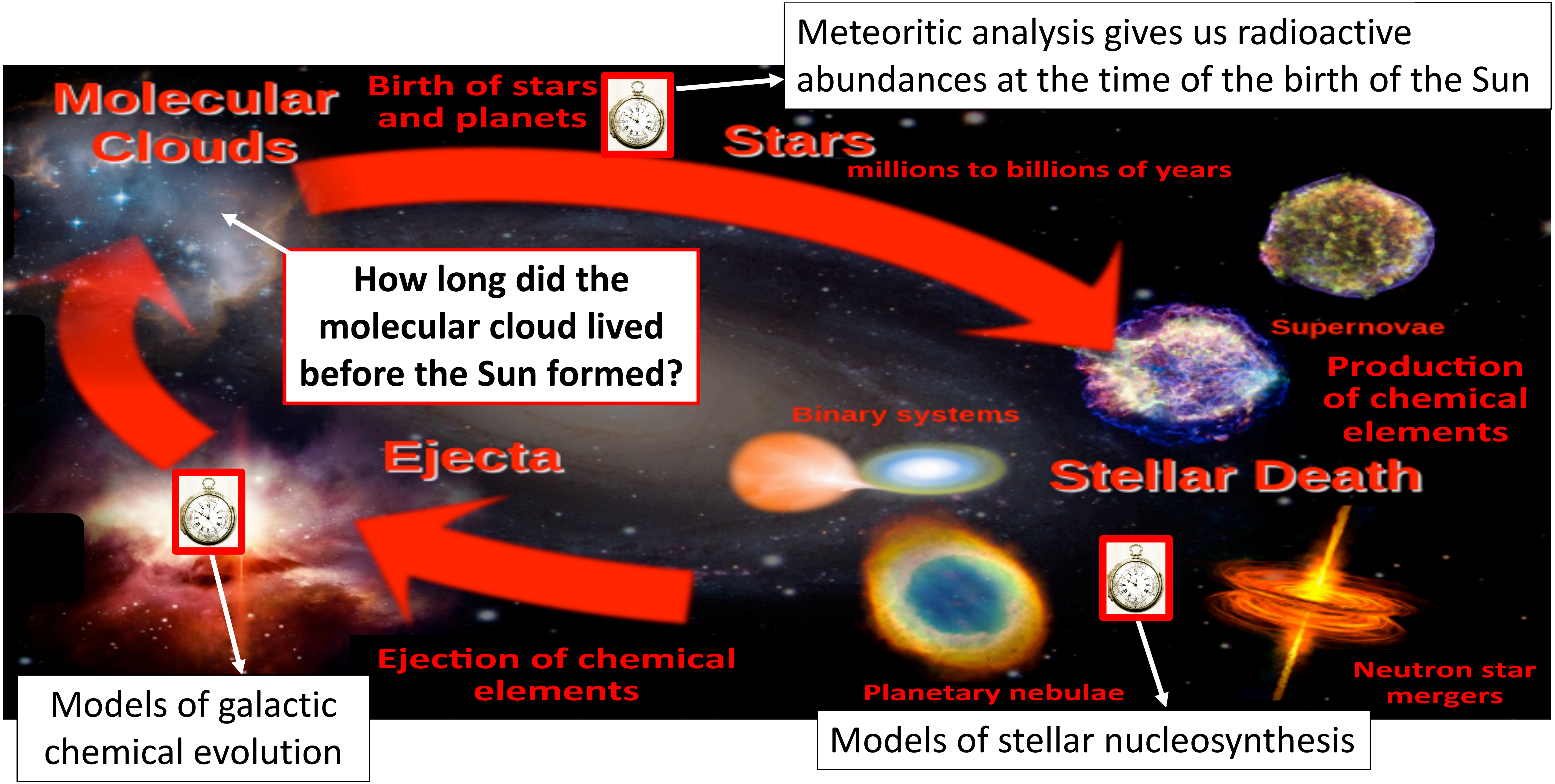
Meteoritic analysis gives us radioactive abundances at the time of the birth of the Sun



Models of galactic chemical evolution

Models of stellar nucleosynthesis

The *Radioactive* Chemical Evolution of the Milky Way



First measurement of the exotic bound-state β^- decay of ^{205}Tl
(Experimental Storage Ring, GSI, Germany)

Leckenby et al.
2024, ***Nature***

204Pb STABLE 1.4%	205Pb 1.73E+7 Y ϵ: 100.00%	206Pb STABLE 24.1%
203Tl STABLE 29.524%	204Tl 3.78 Y β-: 97.10% ϵ: 2.90%	205Tl STABLE 70.476%

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Radioactive ^{205}Pb is produced via *slow* neutron captures in low-mass stars

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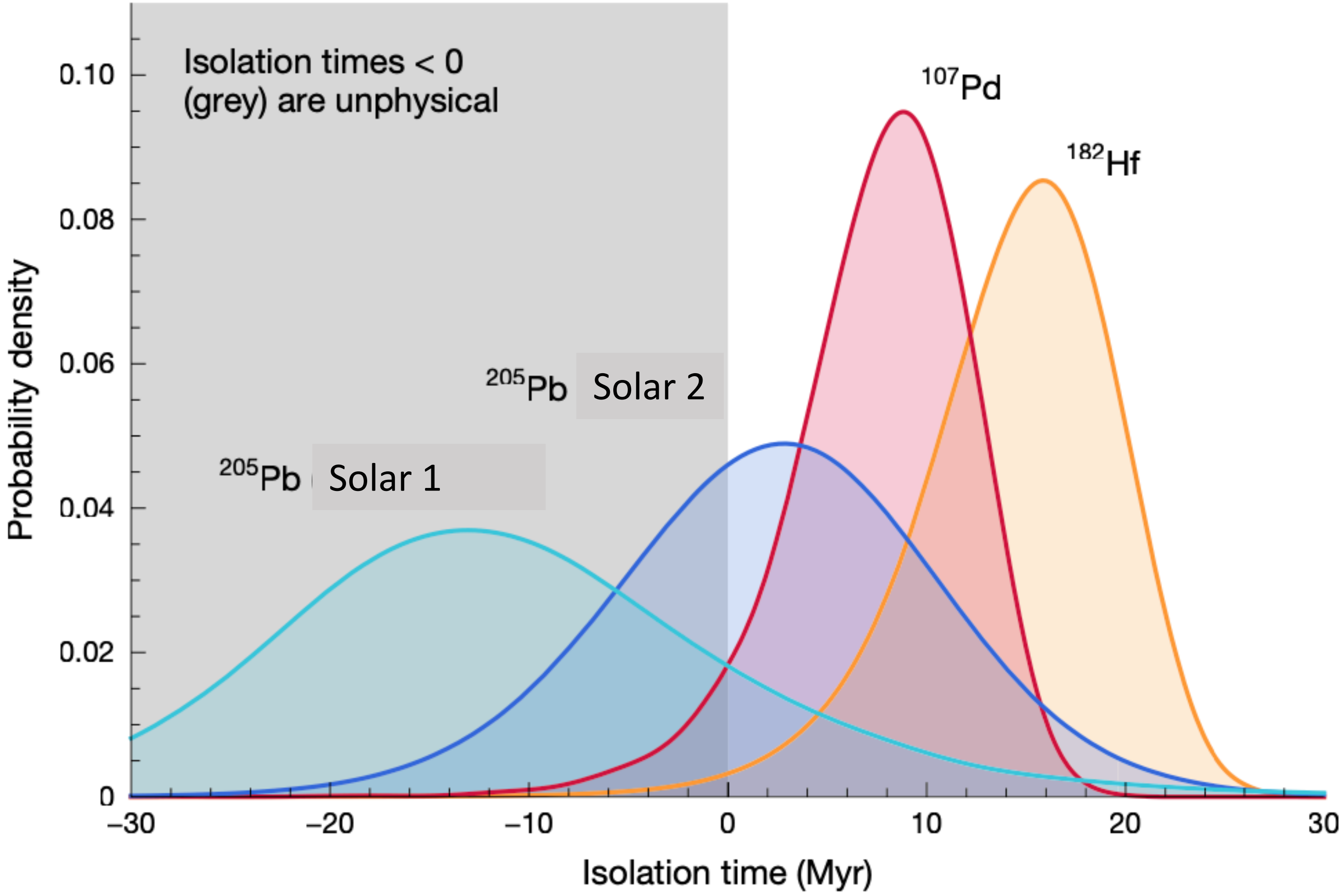
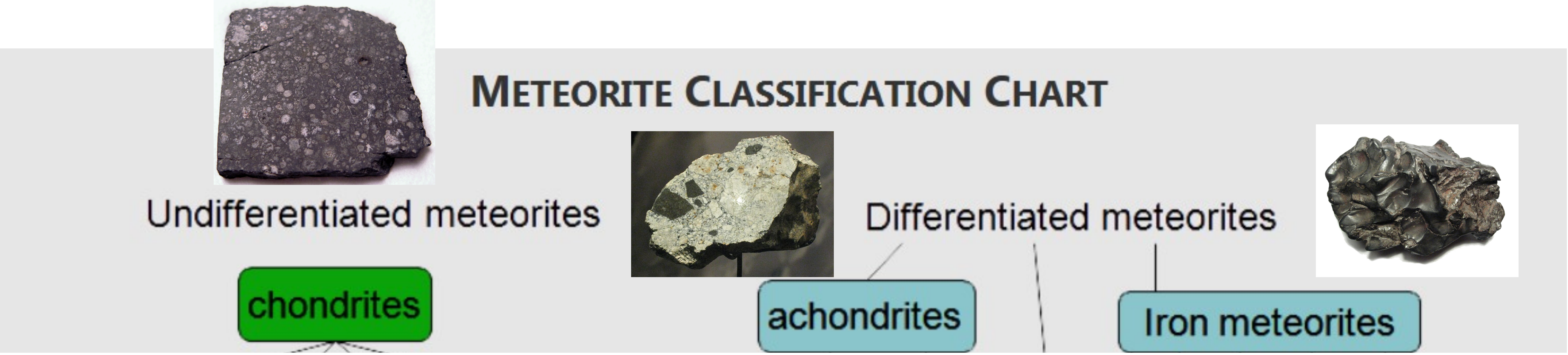
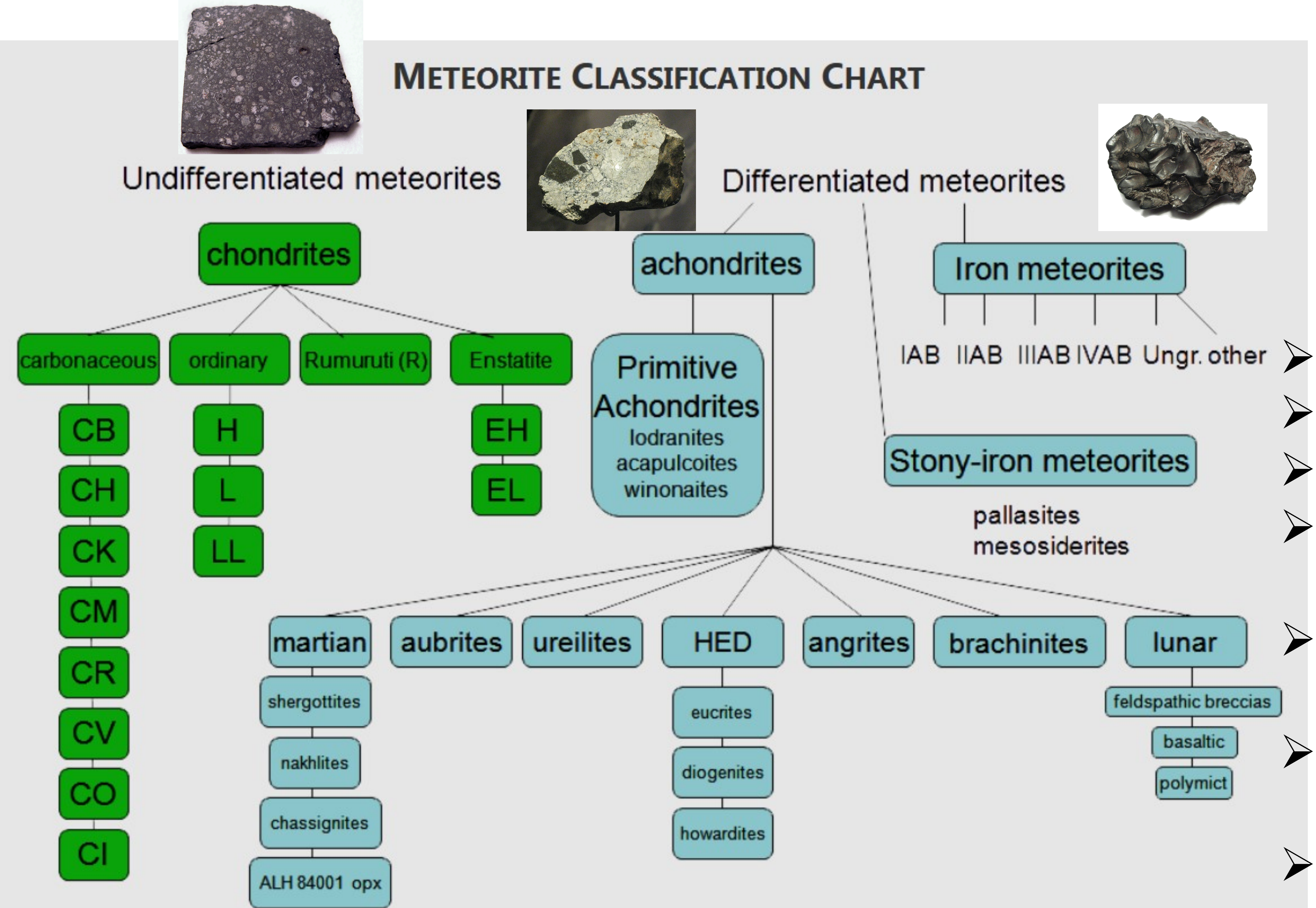


The Sun was born after ~ 10 Myr of the birth of the cloud, therefore, in a relatively long-living and massive molecular cloud, with many stellar siblings.

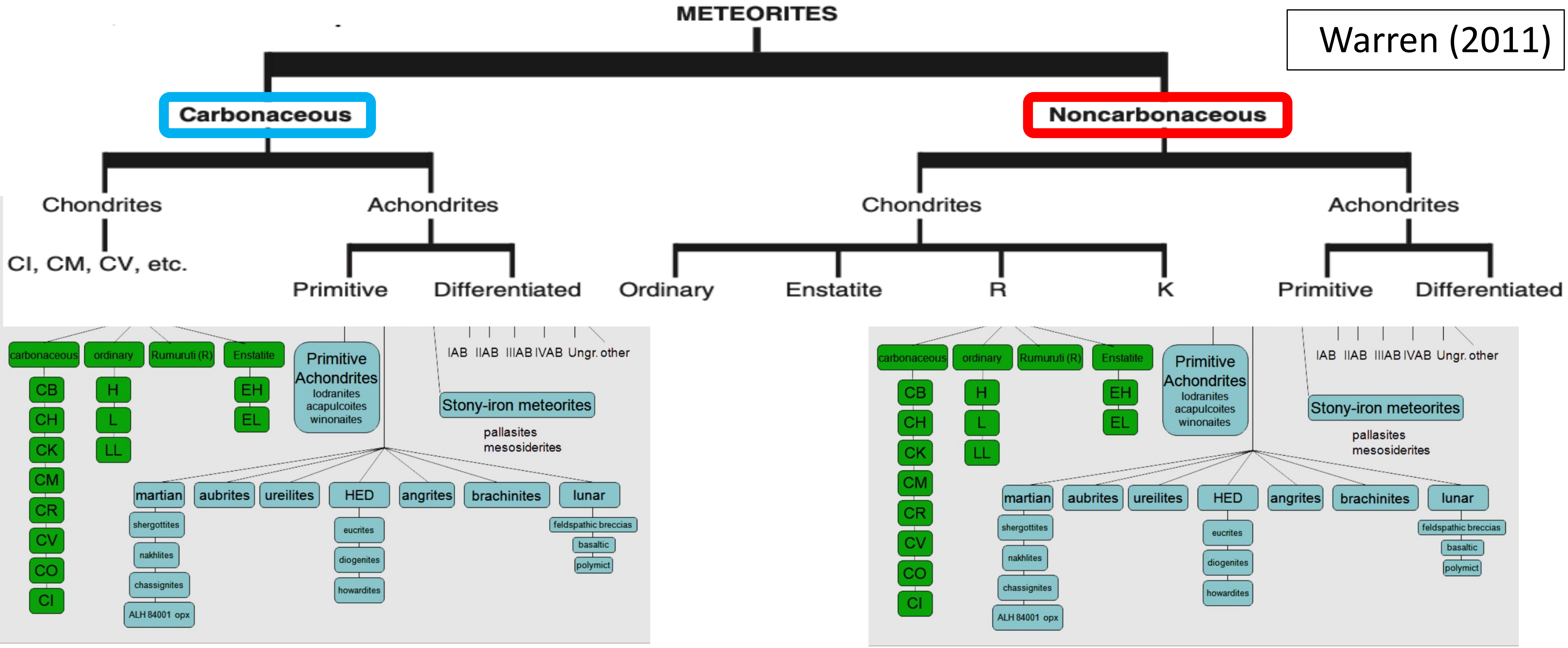

METEORITE CLASSIFICATION CHART
Undifferentiated meteorites
chondrites
Differentiated meteorites
achondrites
Iron meteorites



- Structure
- Mineralogy
- Petrography
- Elemental abundances
- Water content
- Temperature experienced
- ….

NEW, TOP category in the classification of meteorites
based on isotopic anomalies produced by nuclear reactions in stars

Warren (2011)



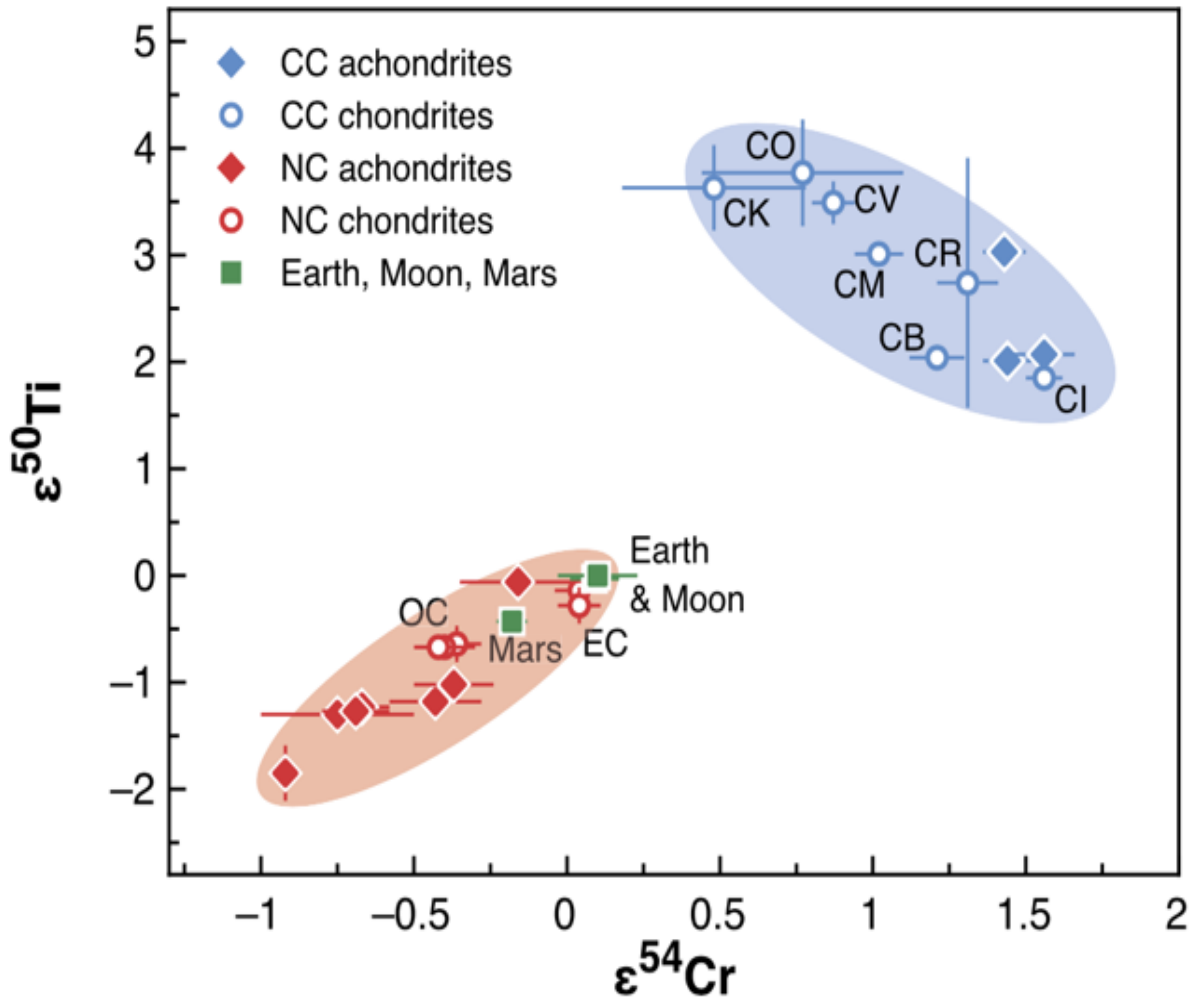


Figure from the review by Kleine et al. 2020

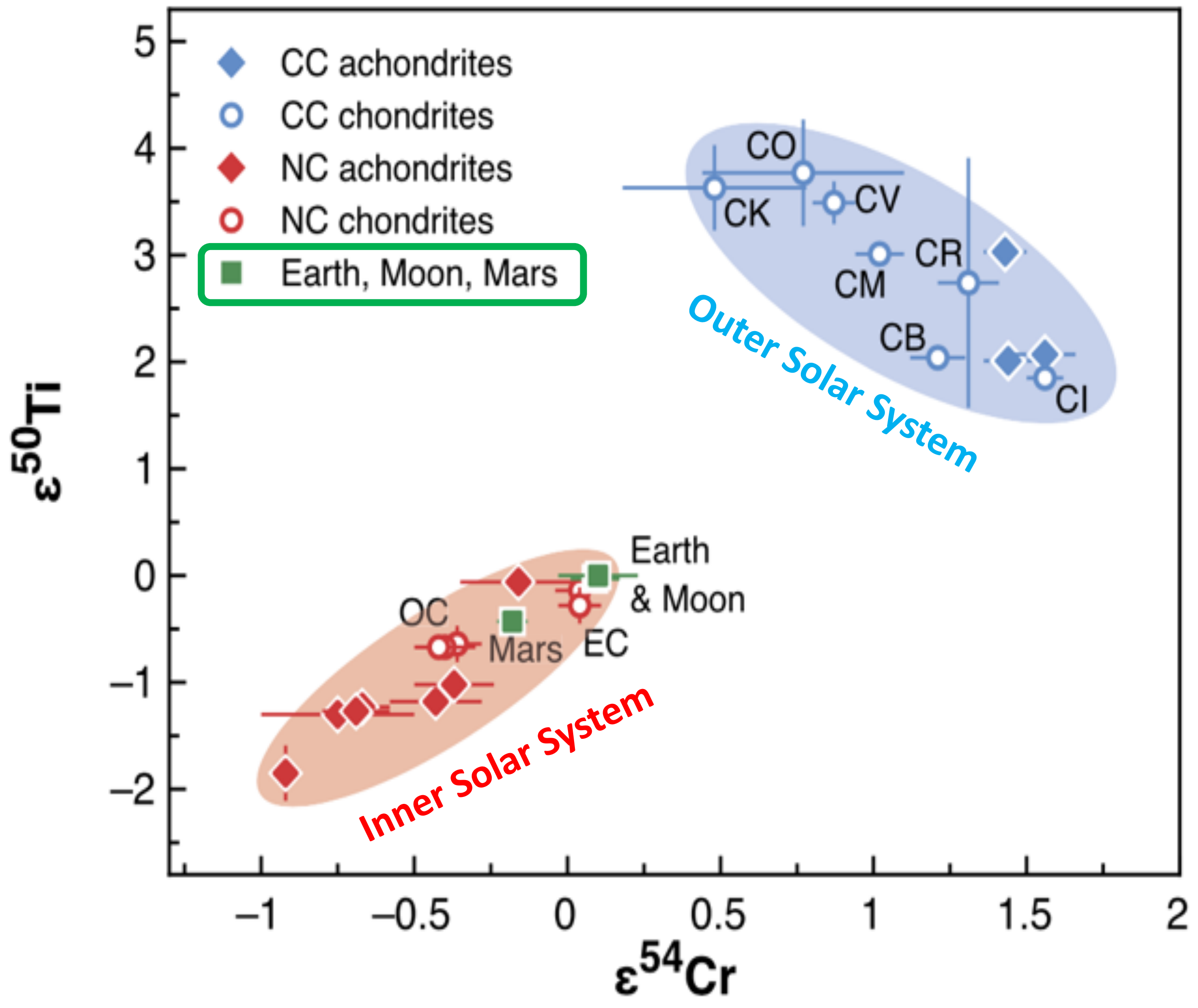
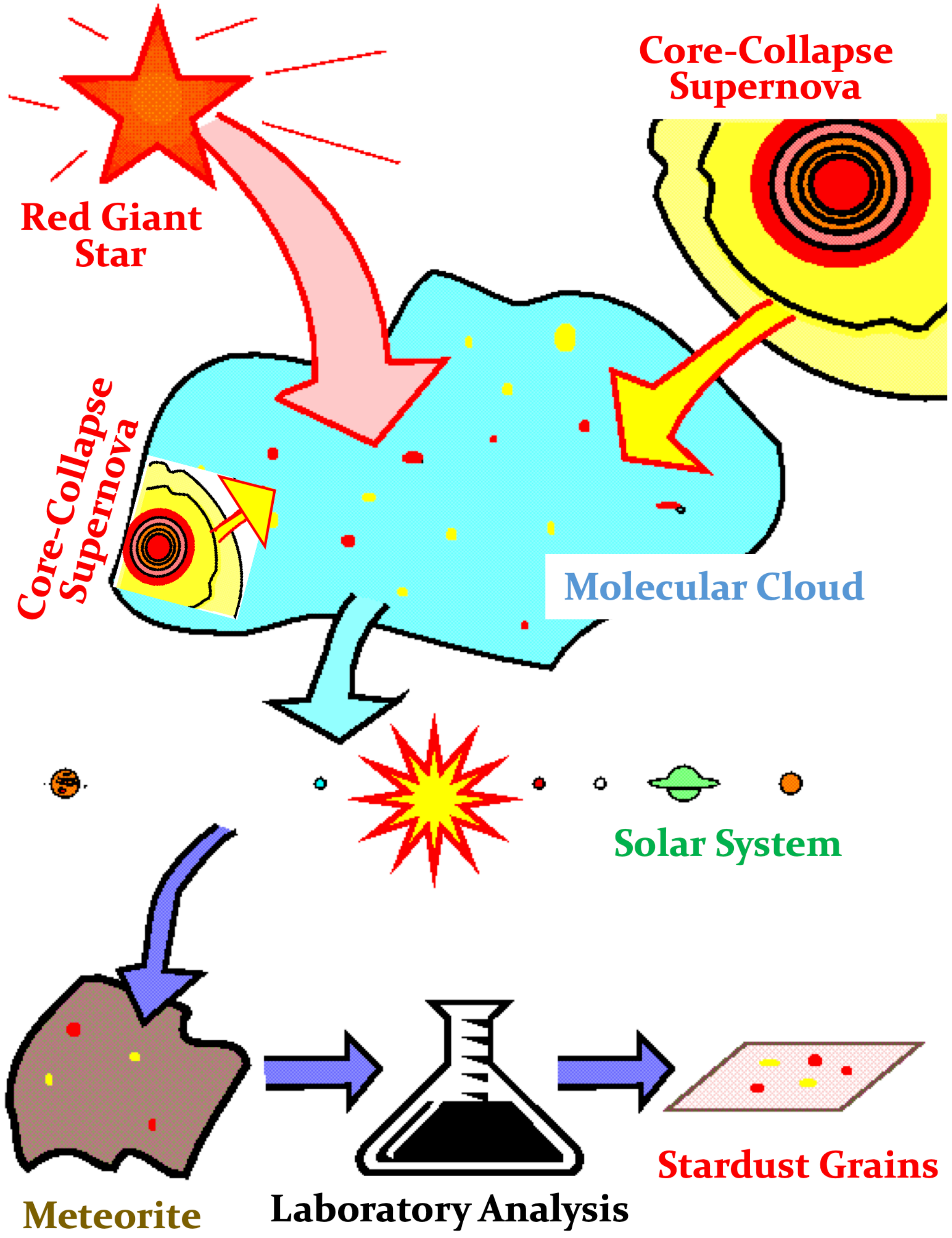


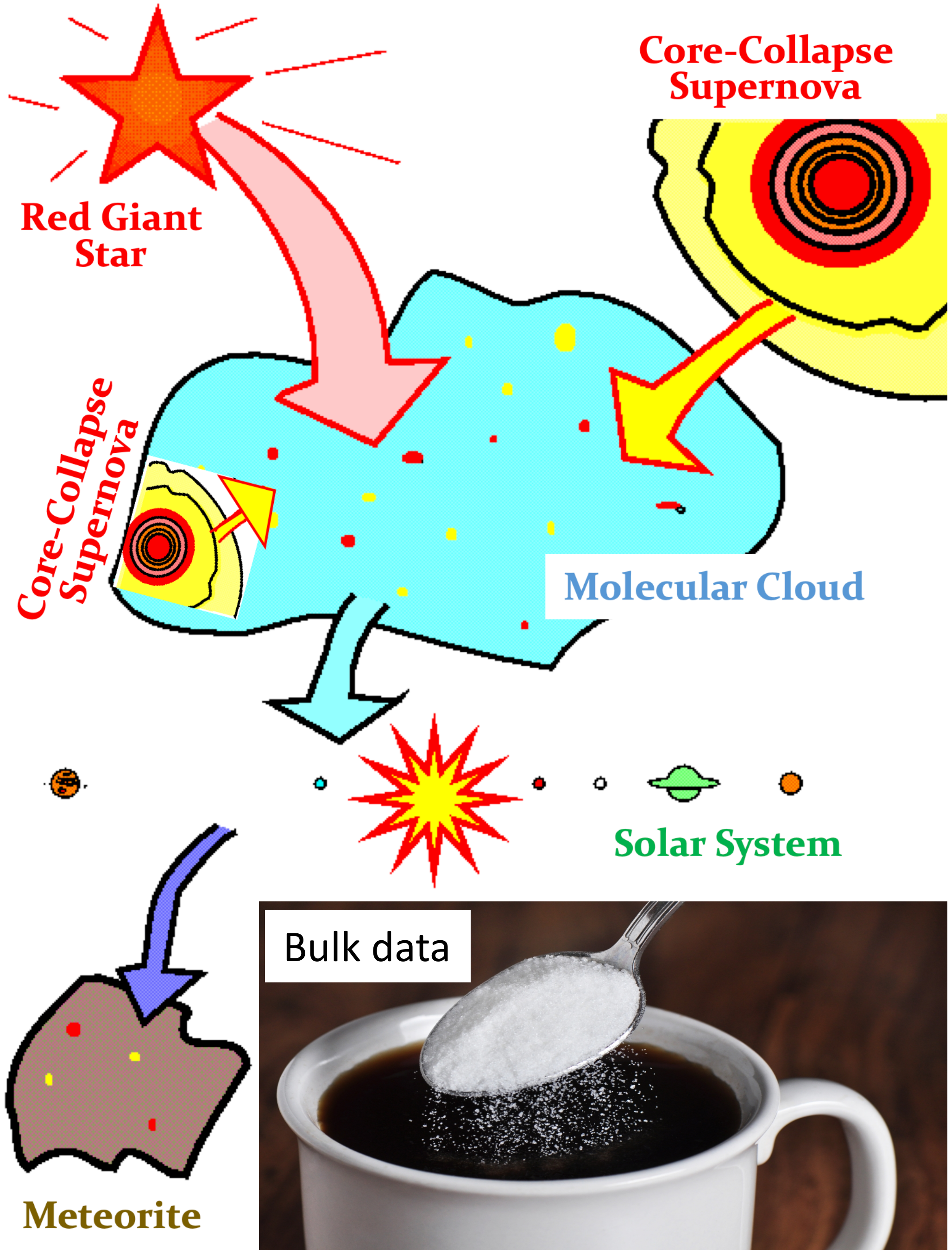
Figure from the review by Kleine et al. 2020

- Understand the **formation and evolution** of different types of meteorites and their various components
- Constrain the **accretion process** from dust to planetesimals in the solar proto-planetary disk
- Use as a ***genetic* link** between meteorites and the Earth and Mars to investigate the formation of terrestrial planets

Qualitative scenarios



Qualitative scenarios



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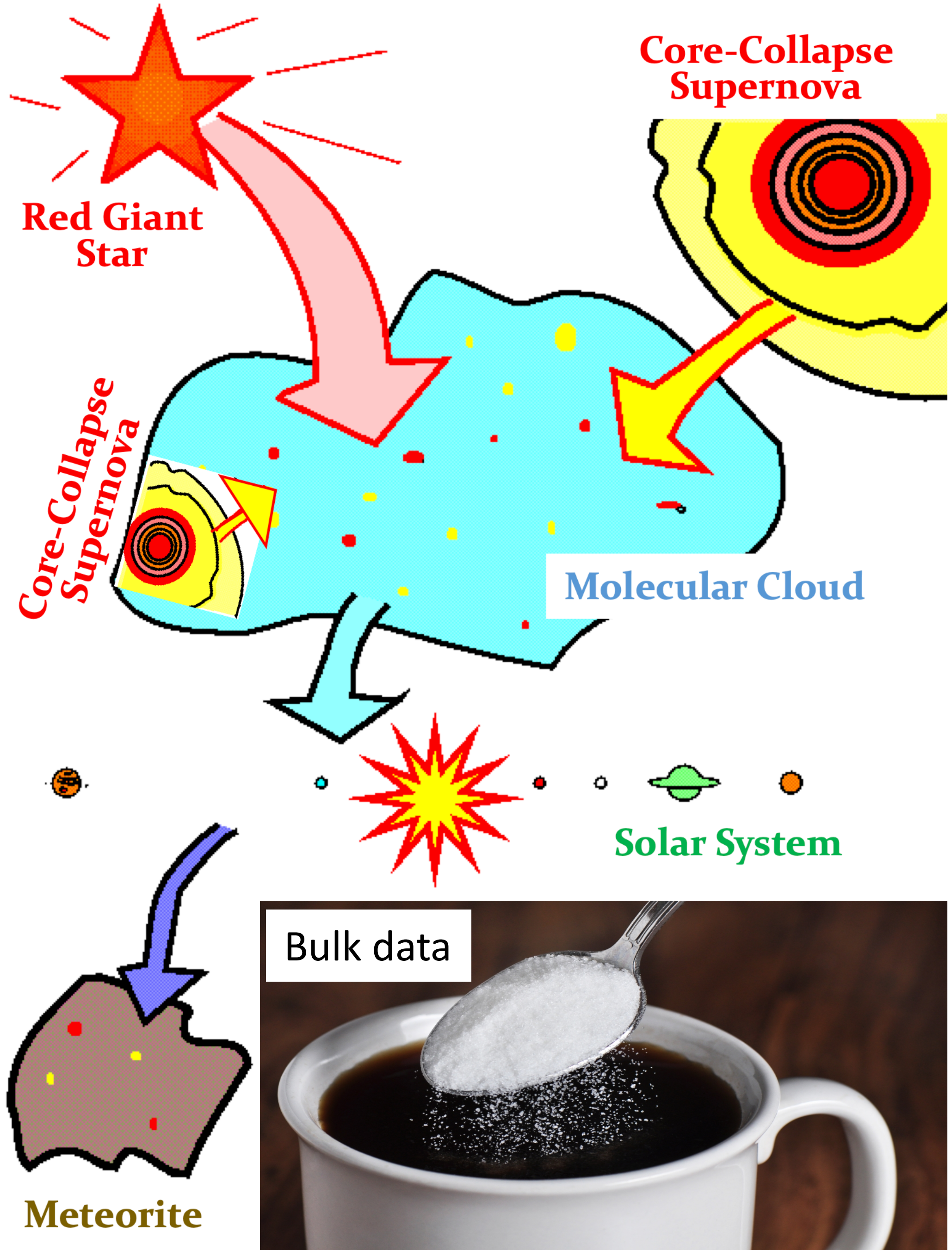
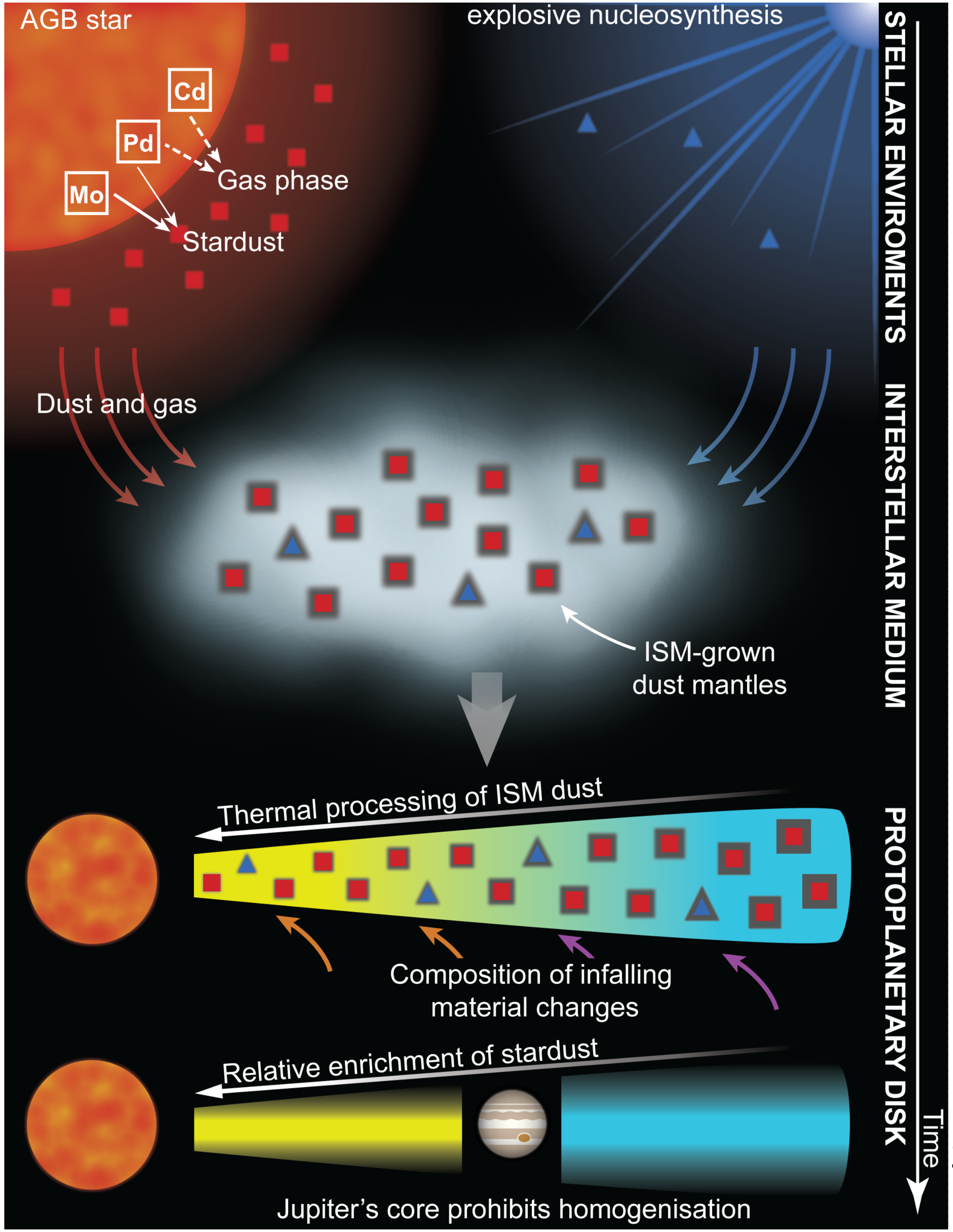
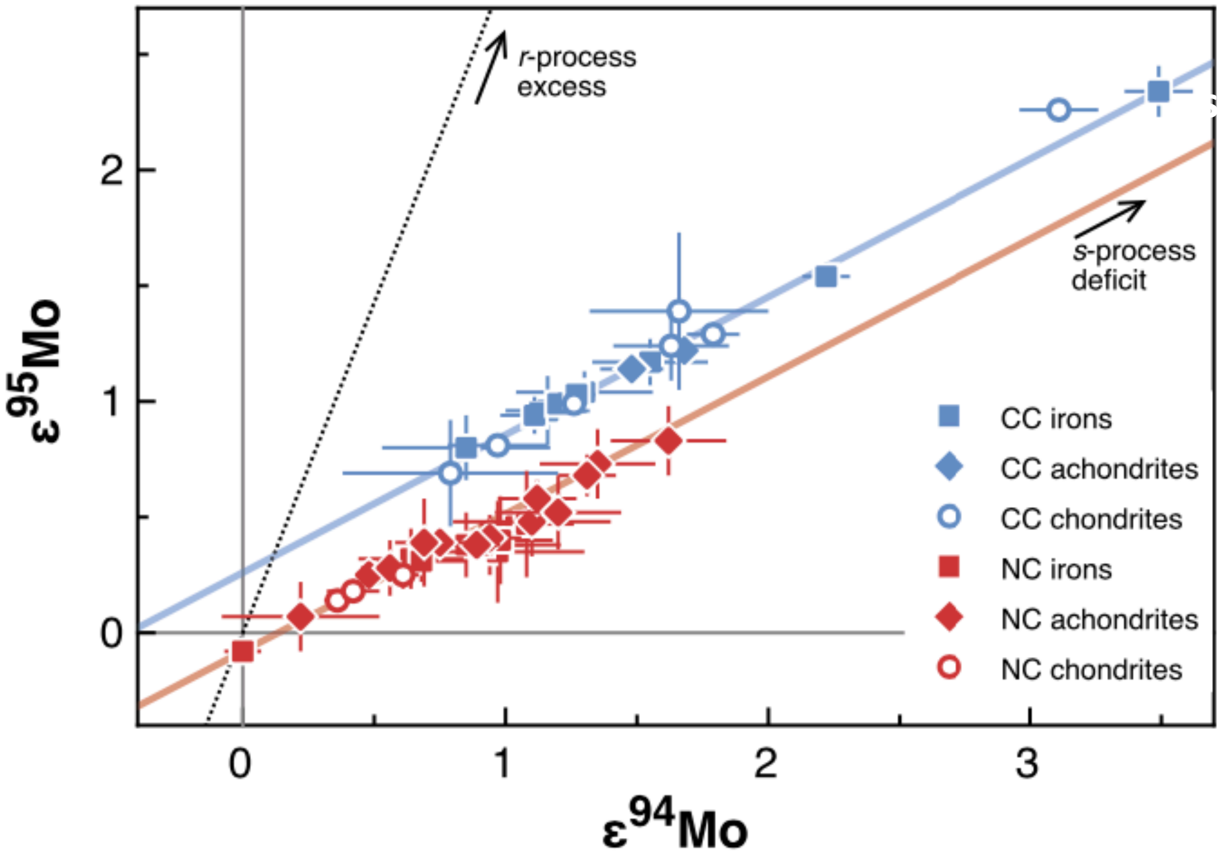




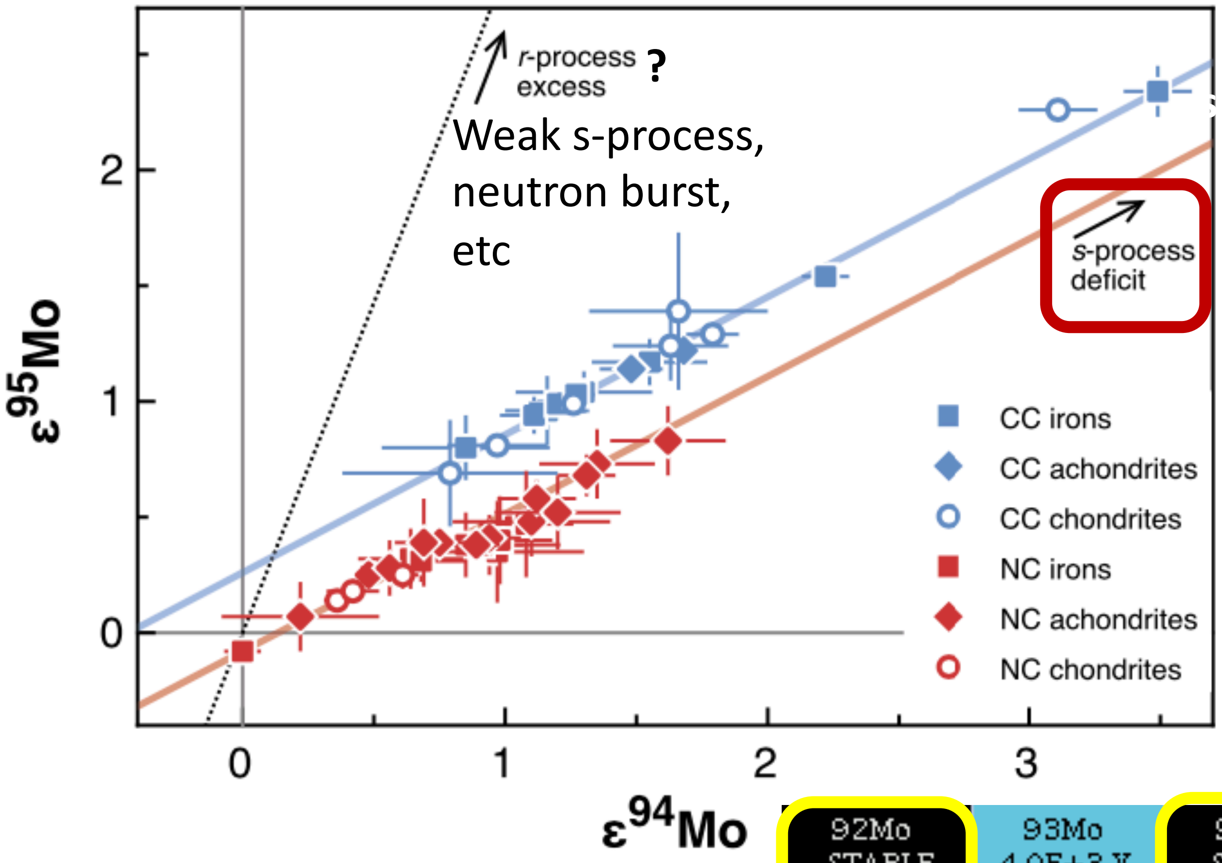
Ek, Hunt, Lugaro, Schönbächler 2020, NA



Variation x 10,000 relative to terrestrial laboratory standard and internally normalised to $^{98}Mo/^{96}Mo$

Measured on the 5th significant digit

Figure from the review by Kleine et al. 2020



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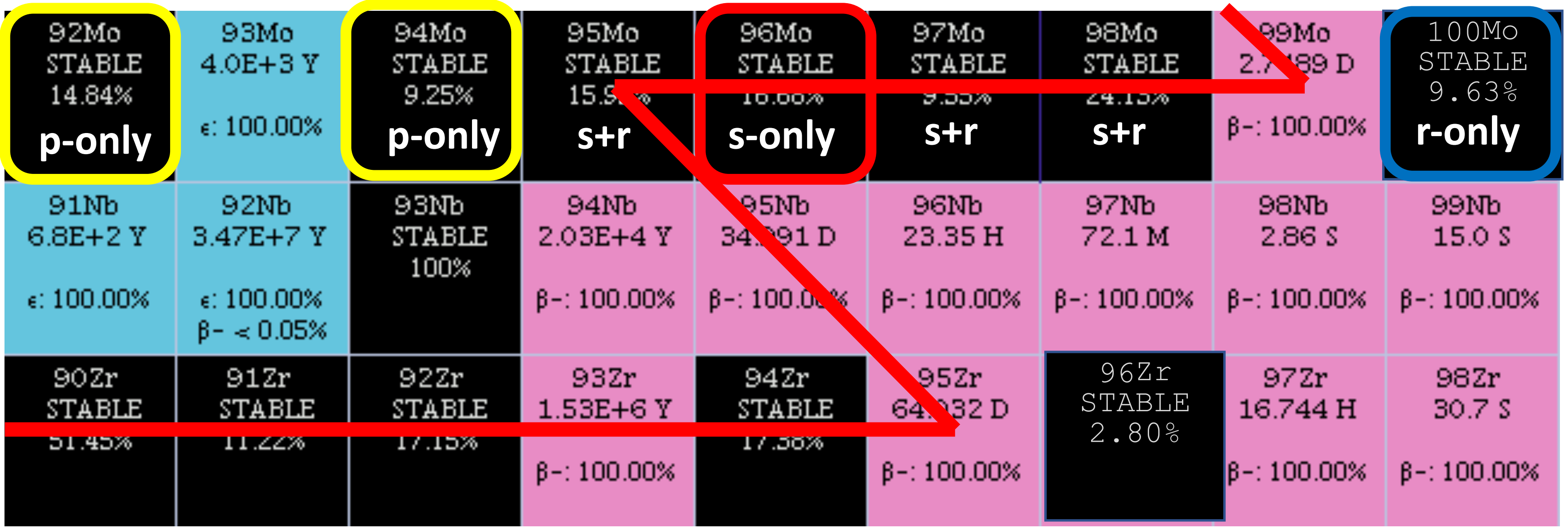
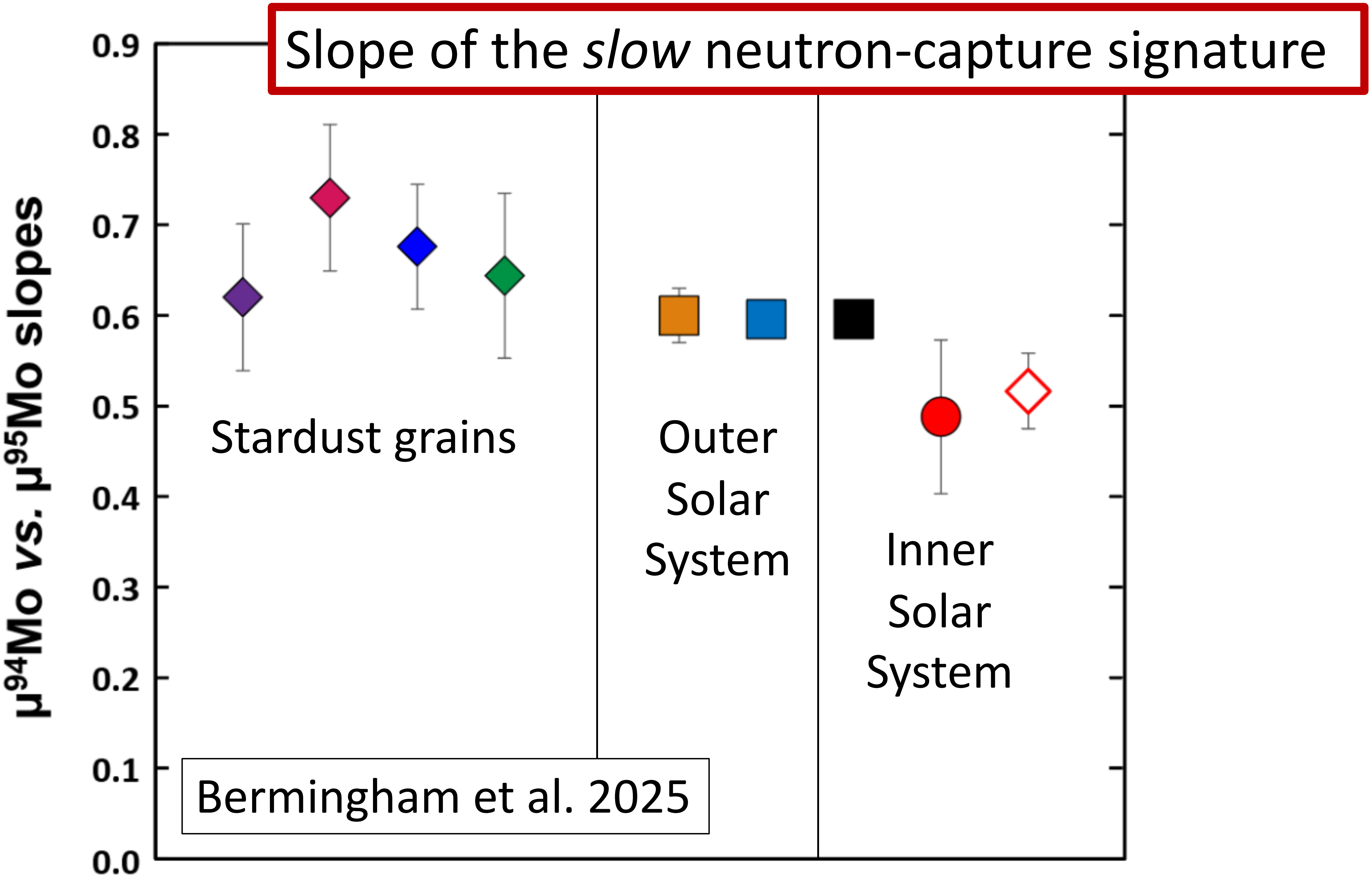
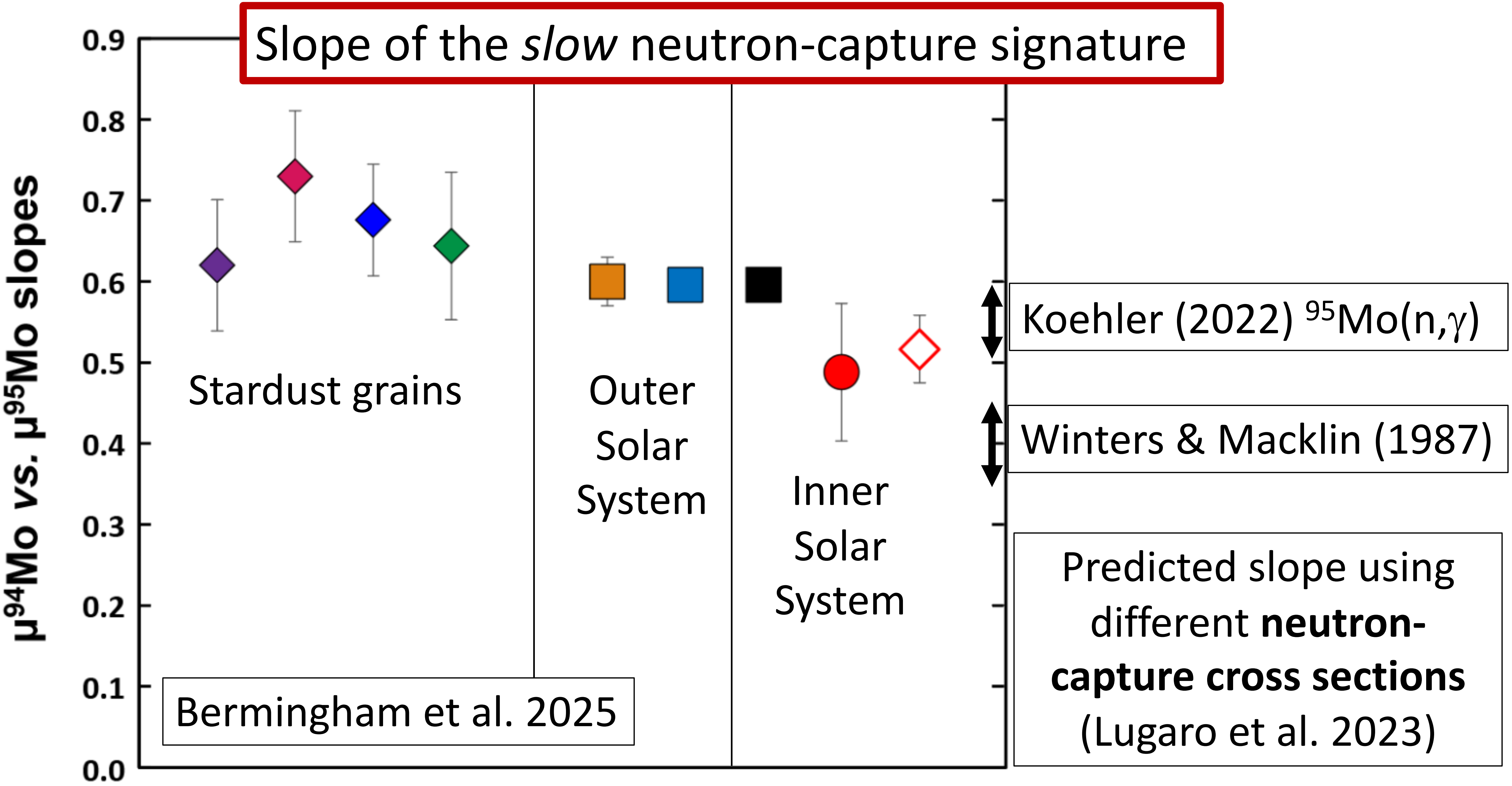
slow neutron captures





Slope of the slow neutron-capture signature
μ94Mo vs. μ95Mo slopes
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Stardust grains
Outer Solar System
Inner Solar System
Bermingham et al. 2025



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Koehler (2022) 95Mo(n,γ)
Winters & Macklin (1987)
Predicted slope using different **neutron-capture cross sections** (Lugaro et al. 2023)

Nuclear physic input are needed to investigate:

- The origin of **meteoritic stardust**, which implication on stellar and galactic evolution
- The presence of **radioactive nuclei** in the early Solar System, to clarify the birth environment of the Sun
- Recent data from **bulk meteorites**, to constrain the accretion process from dust to planetesimals in the proto-planetary disk and understand planet formation

Meteorites

25Al 7.183 S ϵ: 100.00%	26Al 7.17E+5 Y ϵ: 100.00%	27Al STABLE 100%
24Mg STABLE 78.99%	25Mg STABLE 10.00%	26Mg STABLE 11.01%

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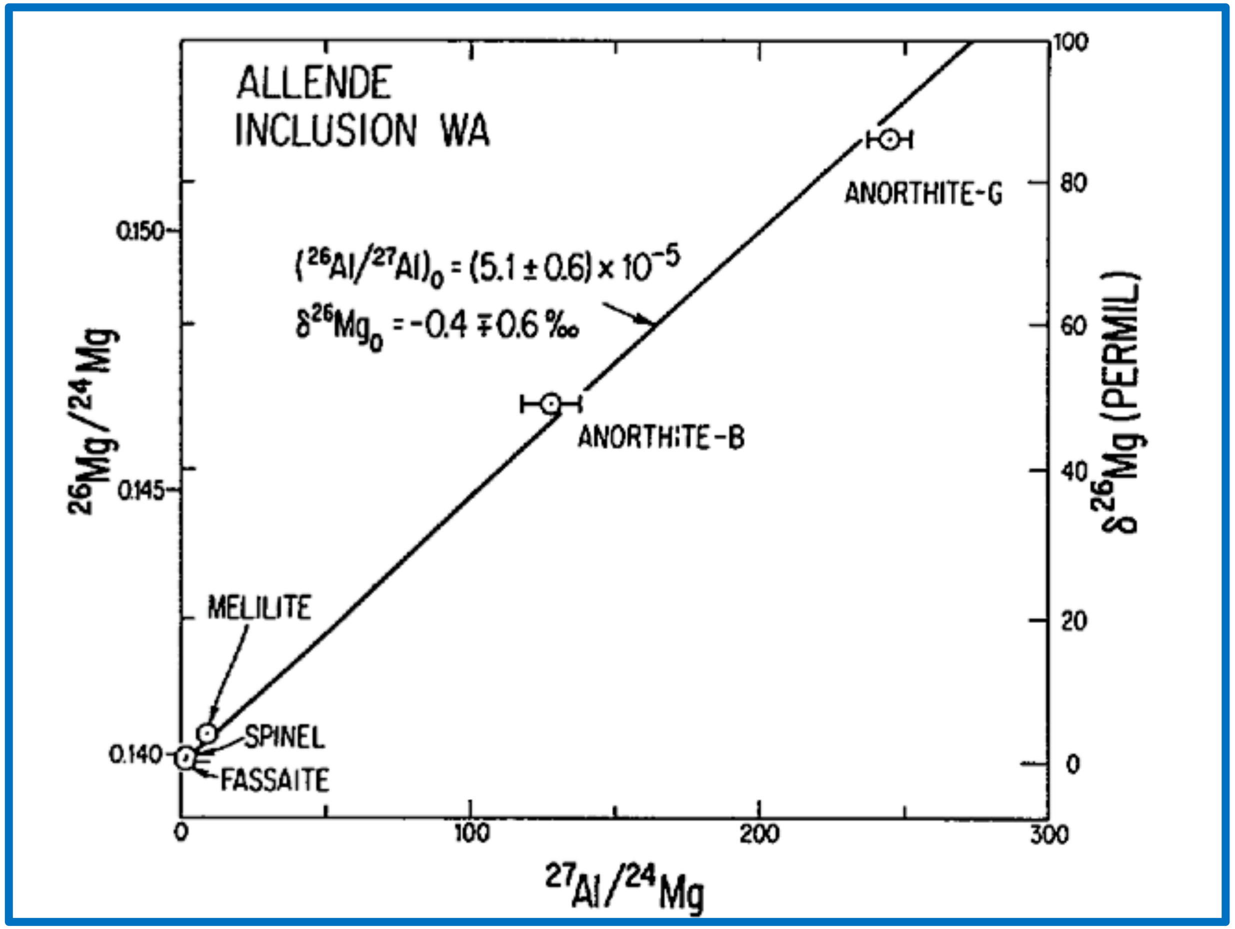

Lee et al. 1977, ApJL