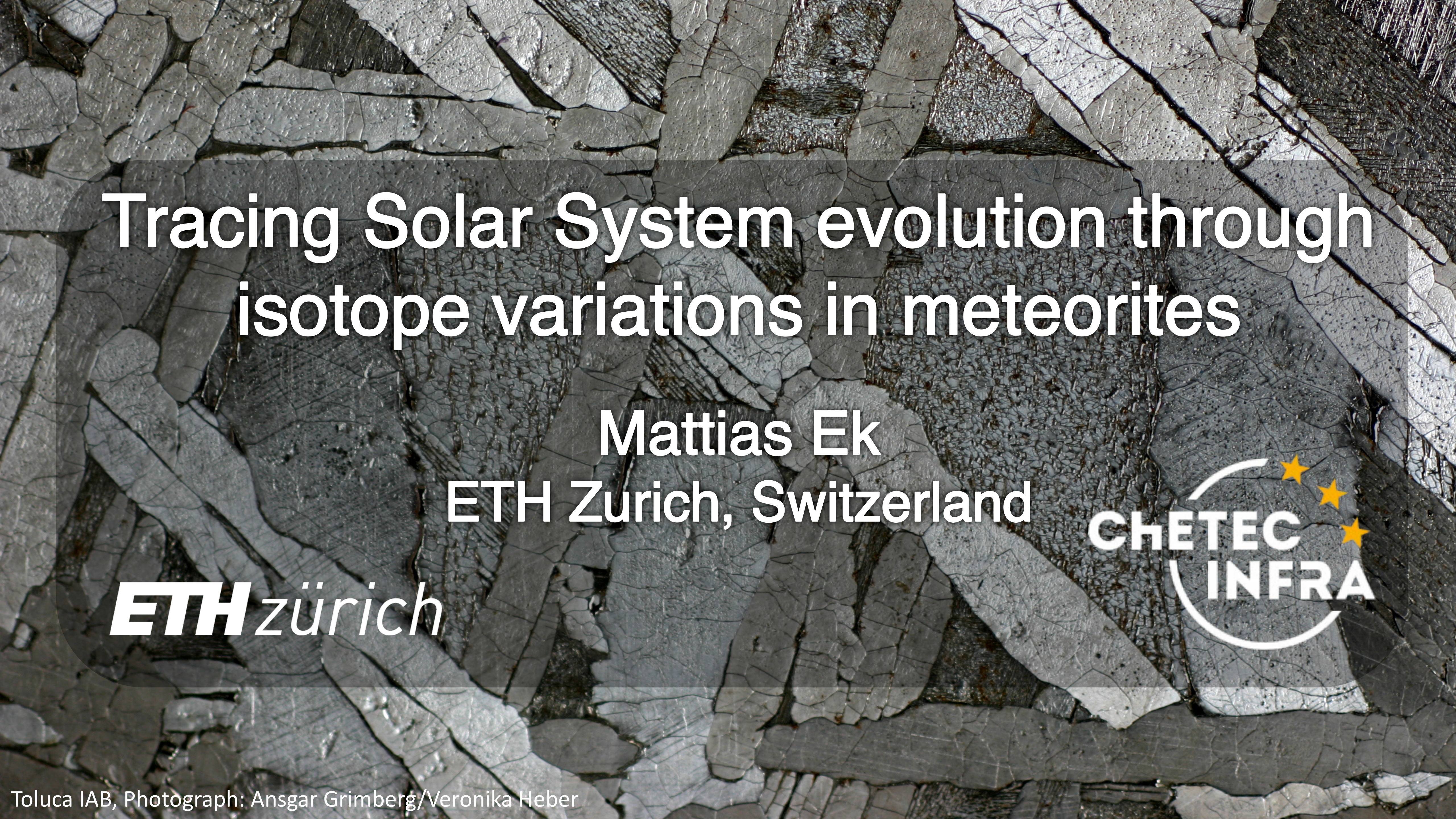


Tracing Solar System evolution through isotope variations in meteorites

Mattias Ek
ETH Zurich, Switzerland

ETH zürich

ChETEC INFRA

Toluca IAB, Photograph: Ansgar Grimberg/Veronika Heber

Glossary

What is a cosmochemist?
Someone who studies the chemical compostion and/or evolution of extraterrestrial rocks/meteorites.

What is an isotope?
Different versions of an element with the same chemical properties.

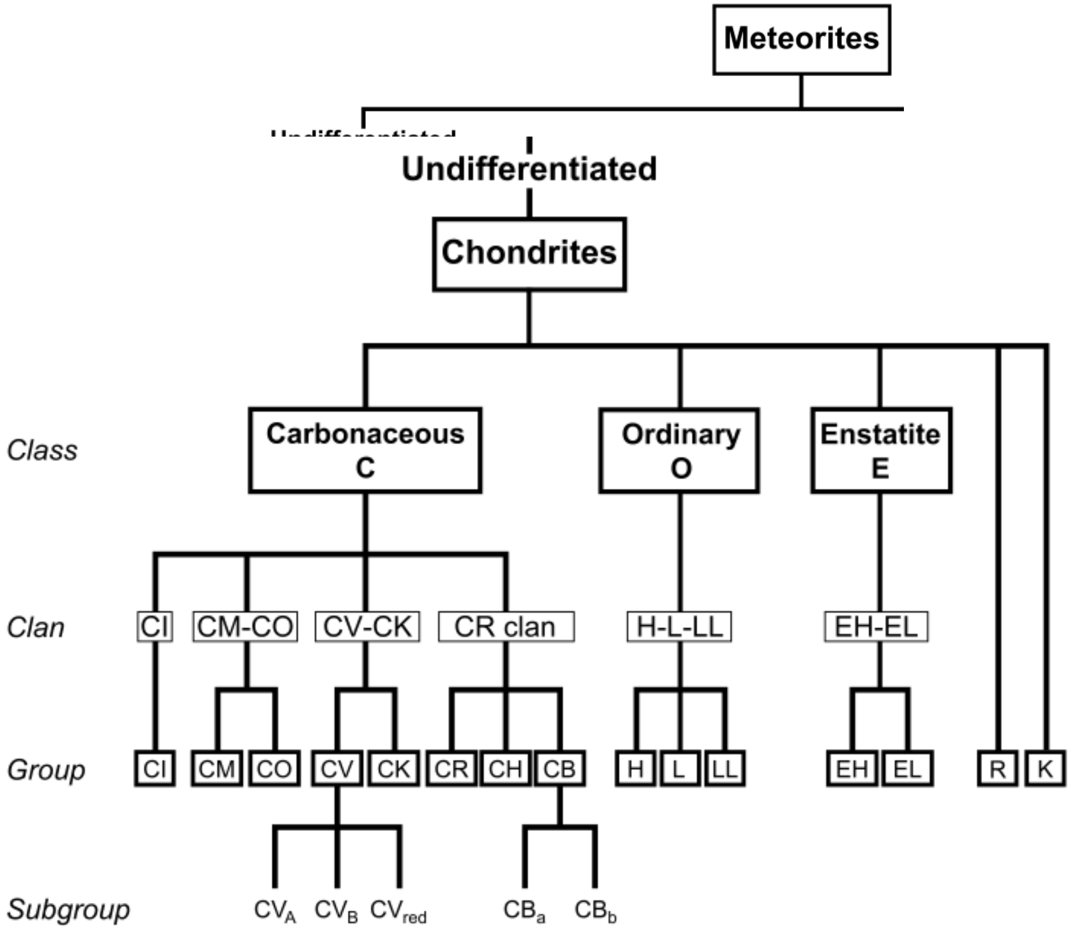
What is a meteorite?
Any rock that has fallen to Earth from space.

Where do we find meteorites?
They fall everythwere on Earth in equal proportion but they can be difficult to distinguish from local rocks.

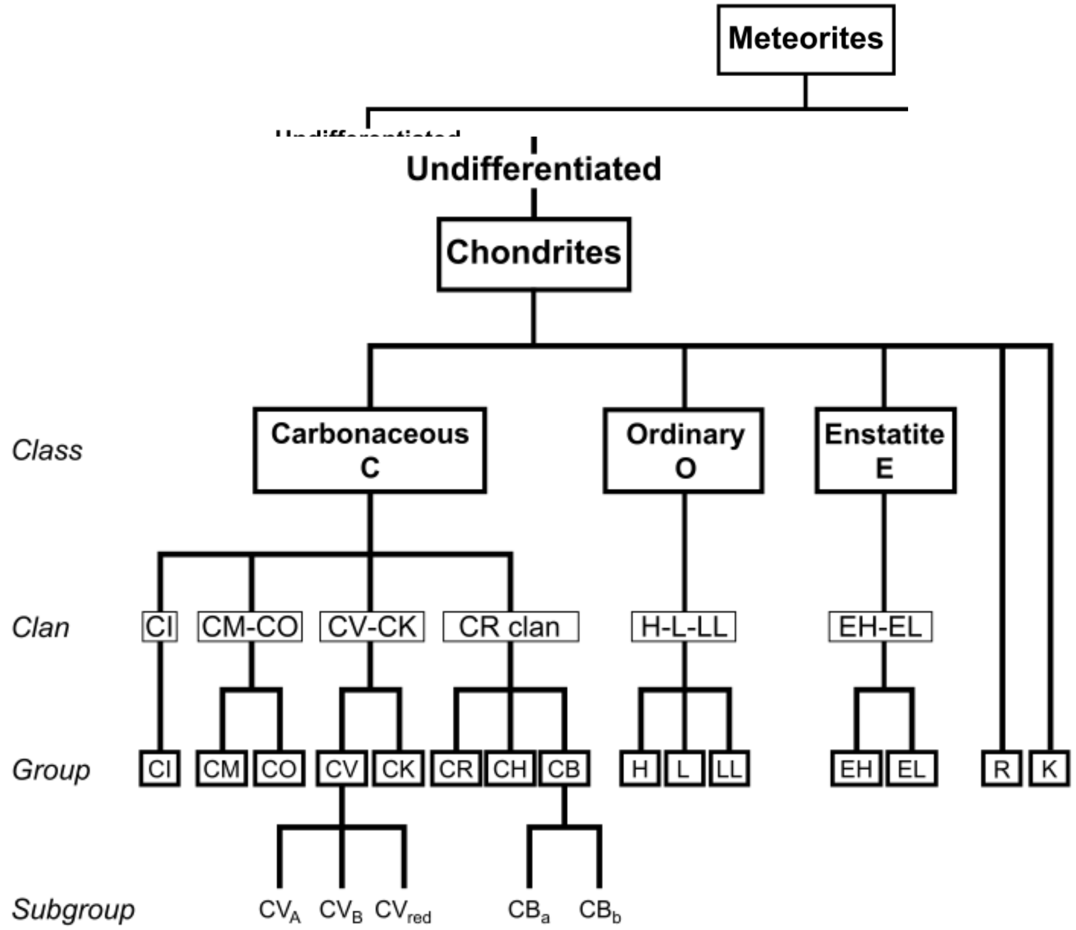
- **Falls:** Observed to fall and typically found shortly thereafter. The freshest meteorites.
- **Finds:** Found out and about. Many are found in desert regions, like the sahara or antartica, due to the lack of local rocks.

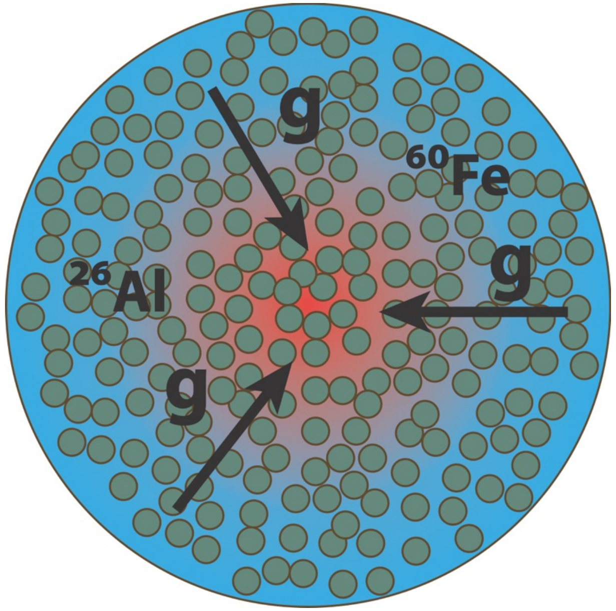
Glossary

Meteorite Classification



Meteorite Classification





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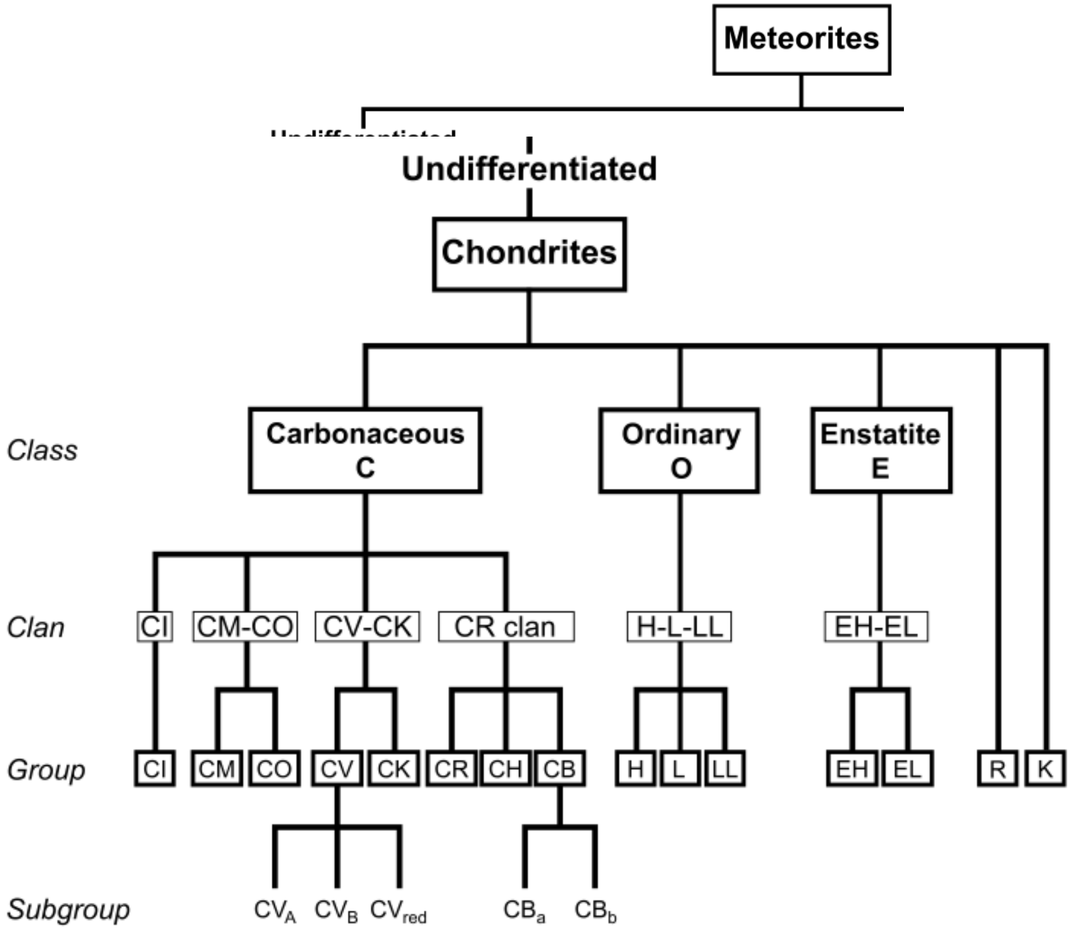

Allende CV3, Photograph: Ansgar Grimberg/Veronika Heber

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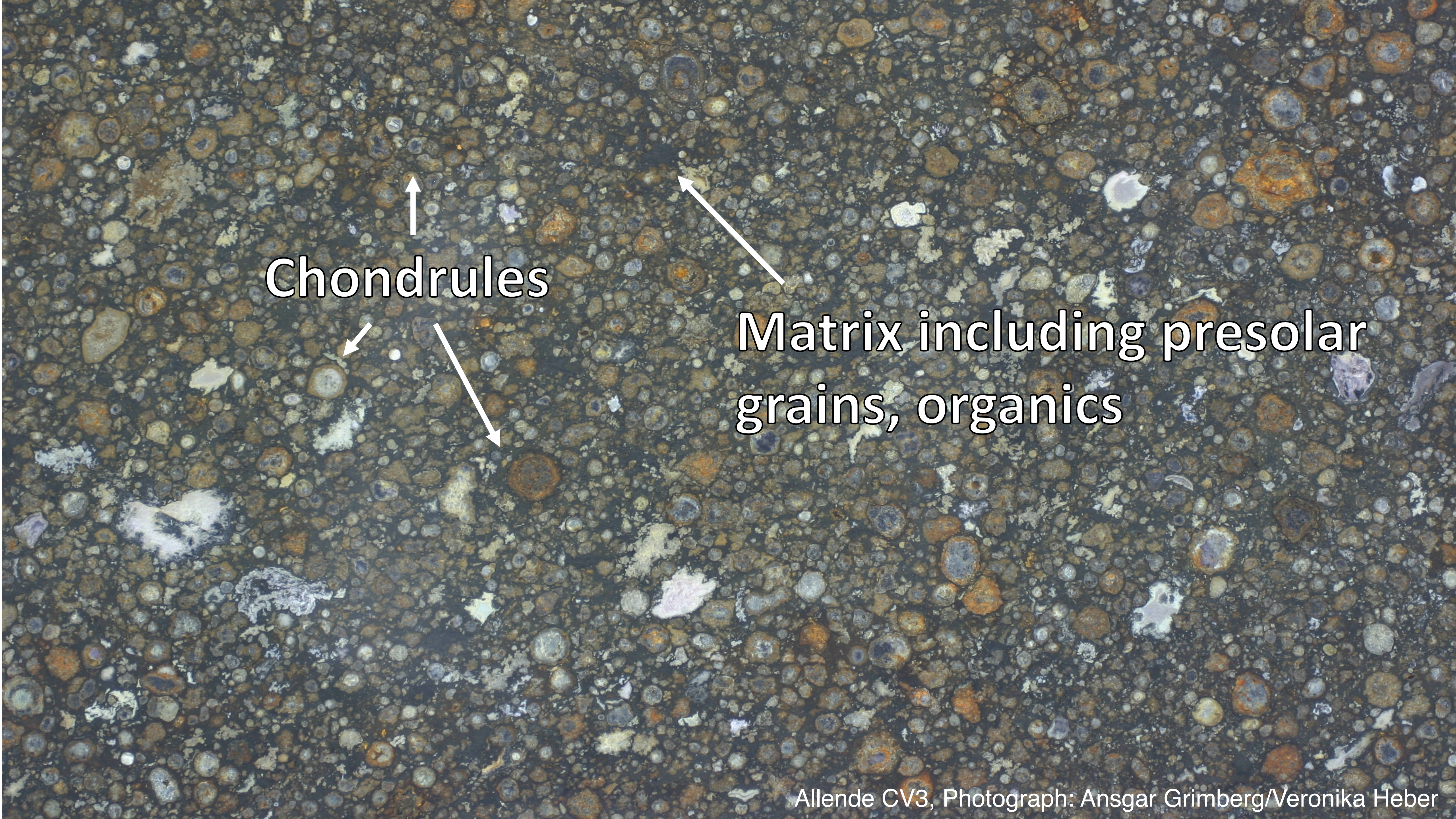
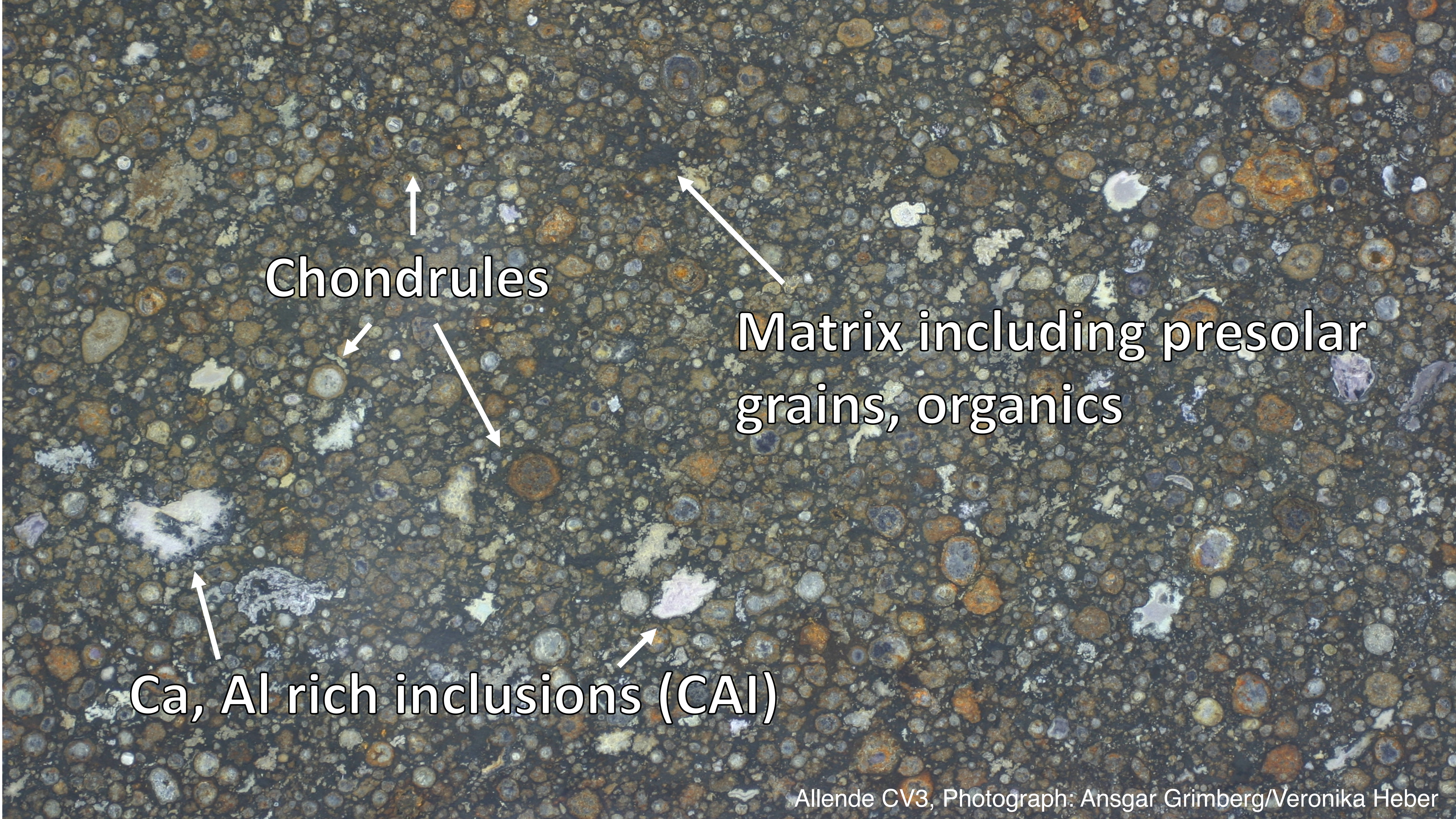
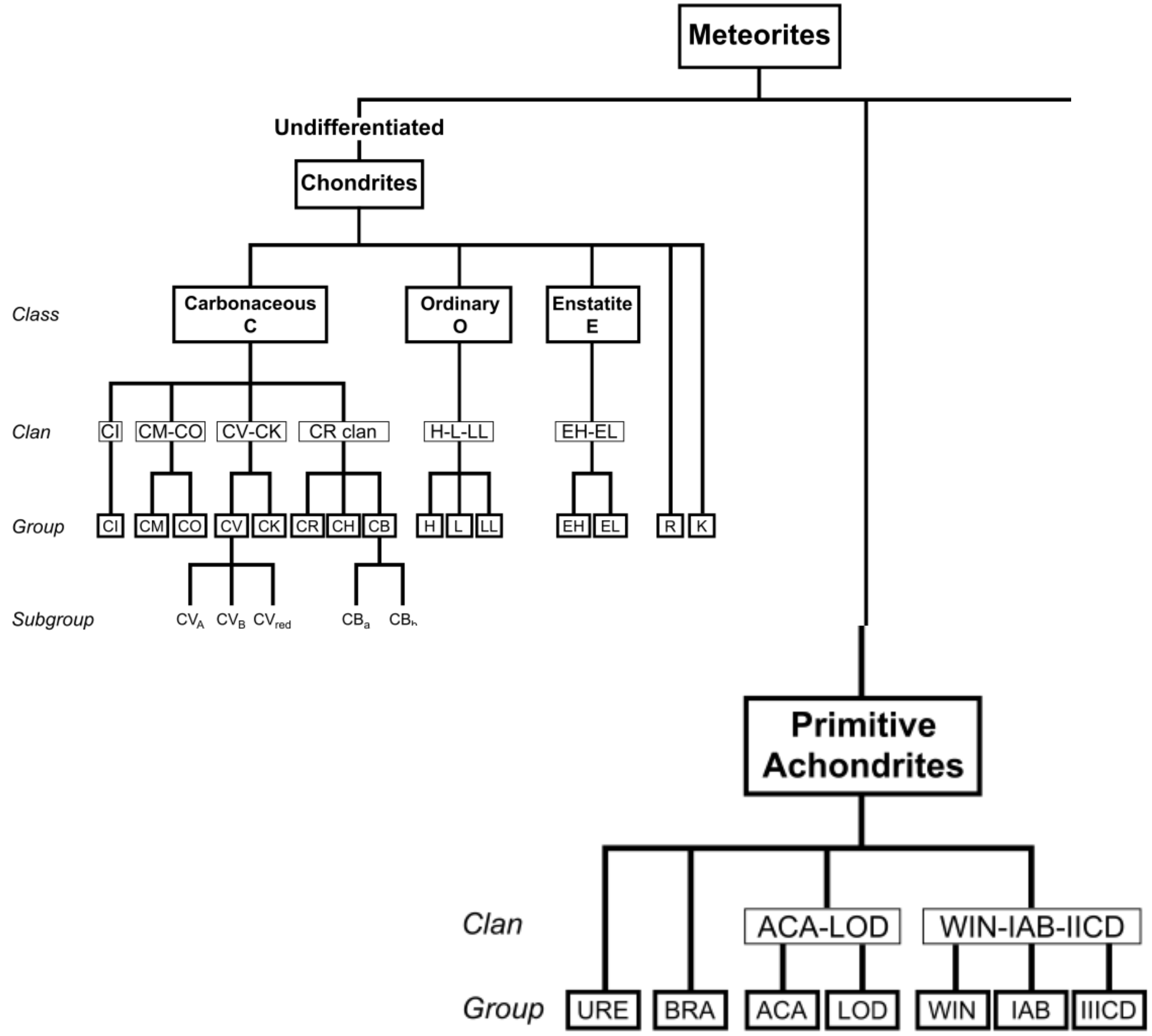


Chondrules
Matrix including presolar grains, organics
Allende CV3, Photograph: Ansgar Grimberg/Veronika Heber


Chondrules
Matrix including presolar grains, organics
Ca, Al rich inclusions (CAI)
Allende CV3, Photograph: Ansgar Grimberg/Veronika Heber

Meteorite Classification



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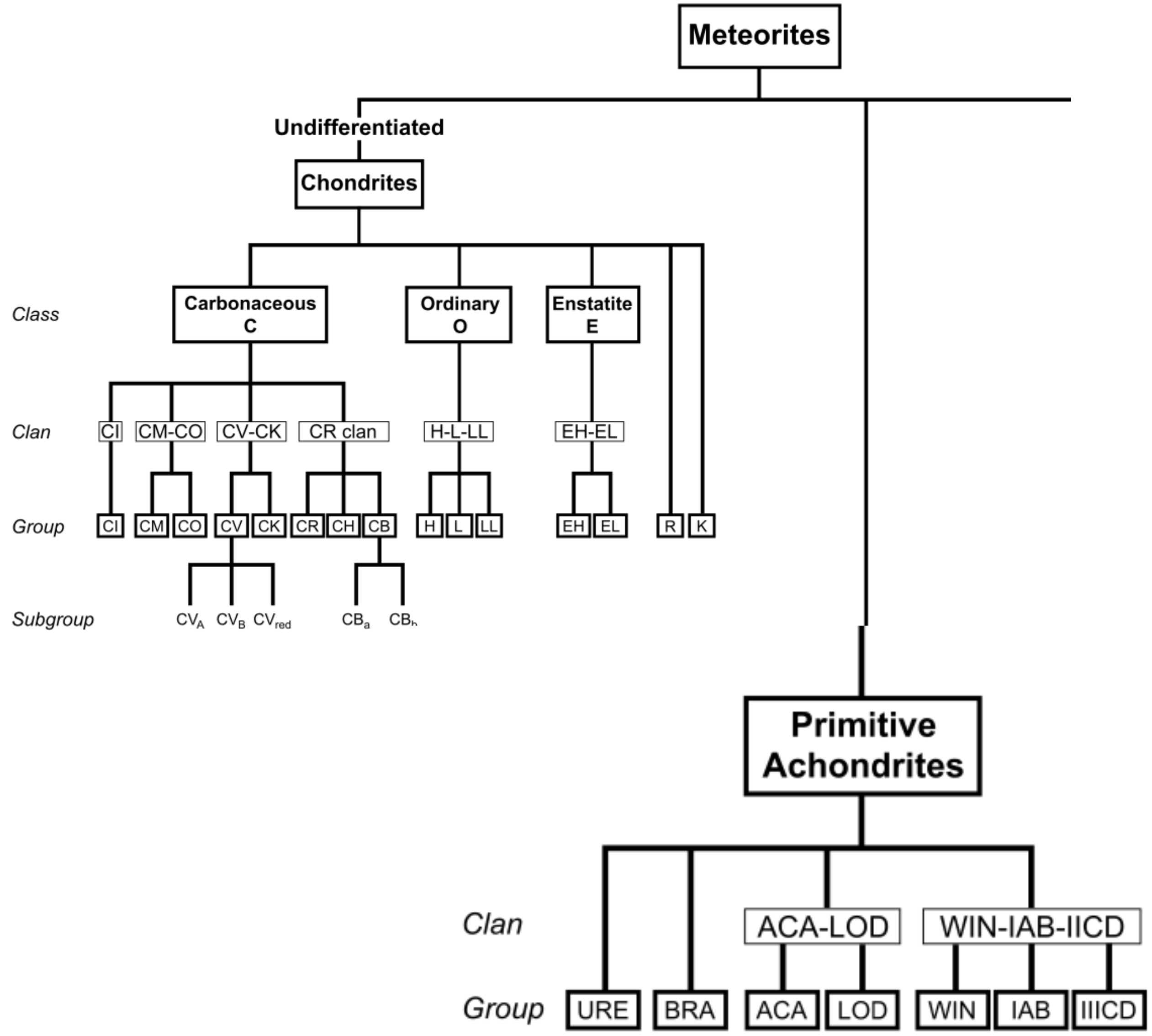

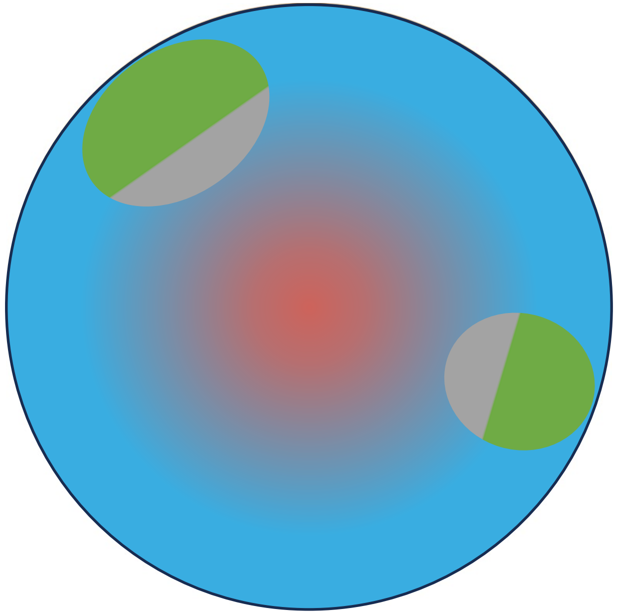

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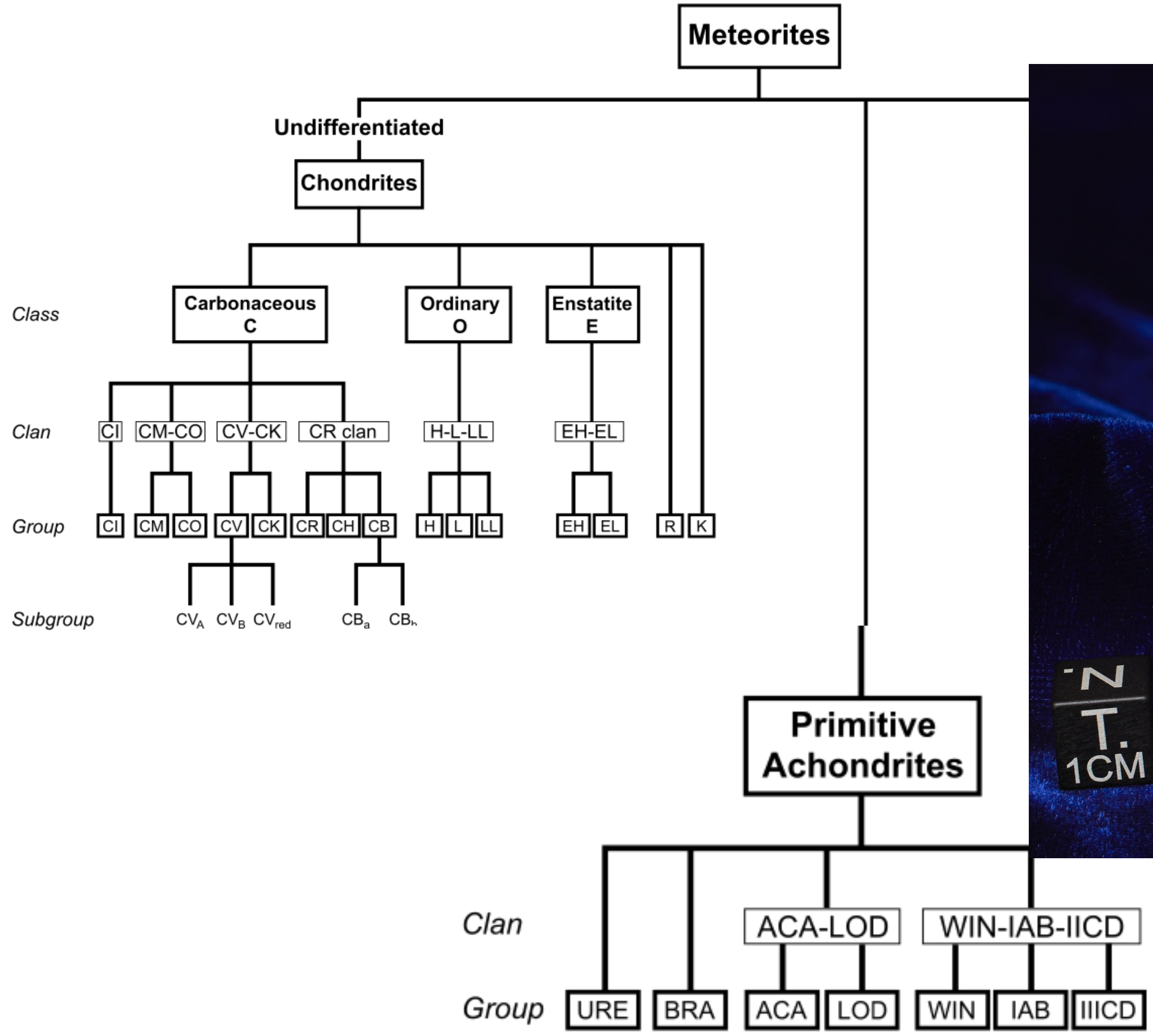
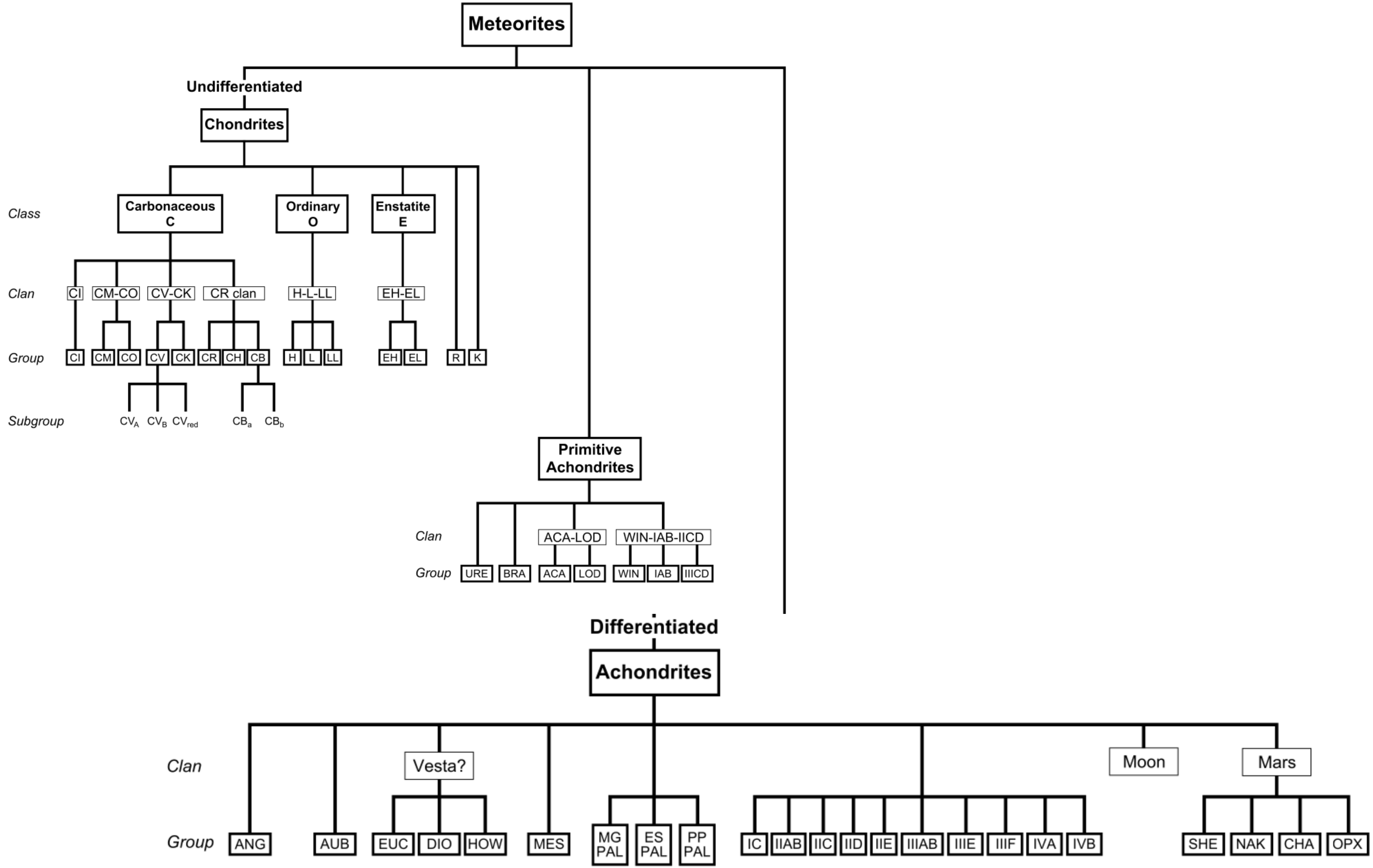


NWA13679 Win, Photo: Aurelia Meister

Meteorite Classification



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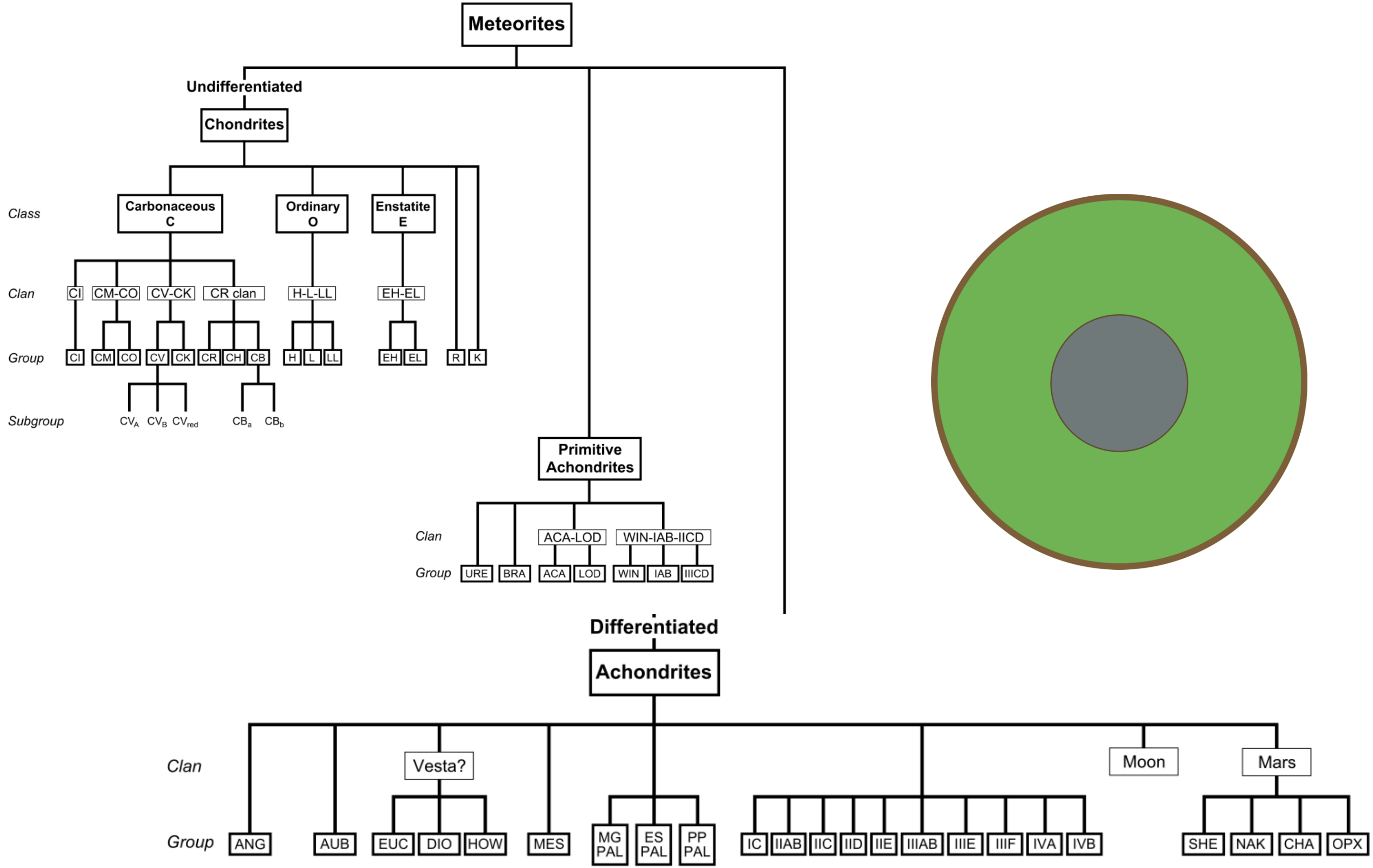

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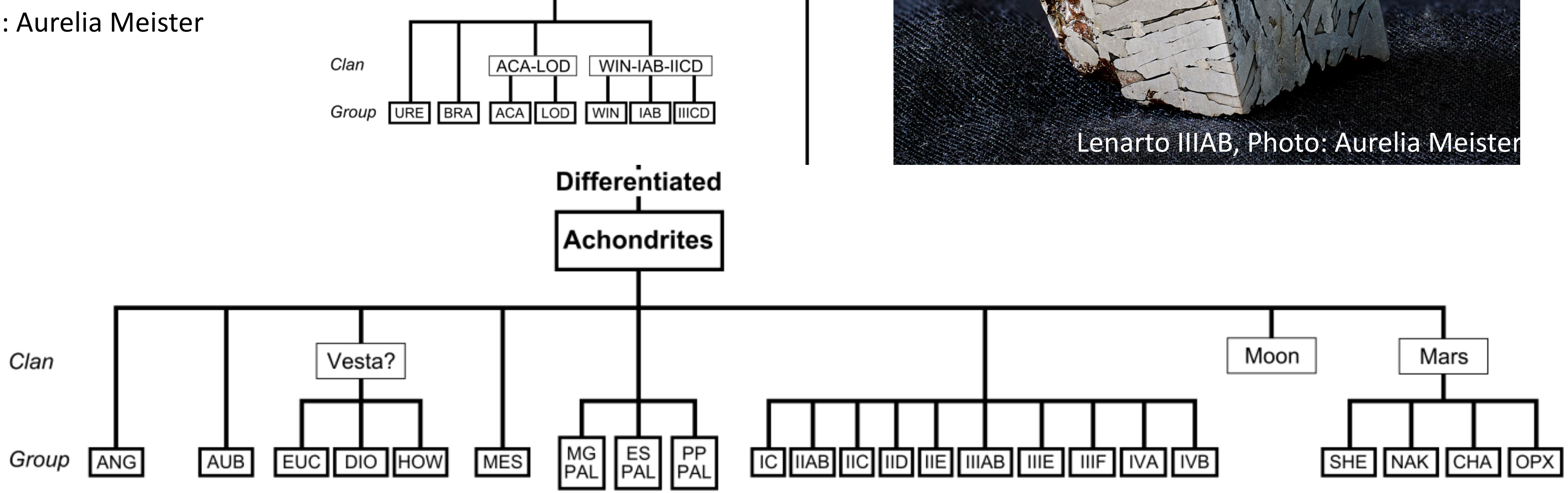


NWA 14685, Photo: Aurelia Meister

Lenarto IIIAB, Photo: Aurelia Meister

Marjalahti (Pallasite), Photograph: Aurelia Meister

Isotope Measurements

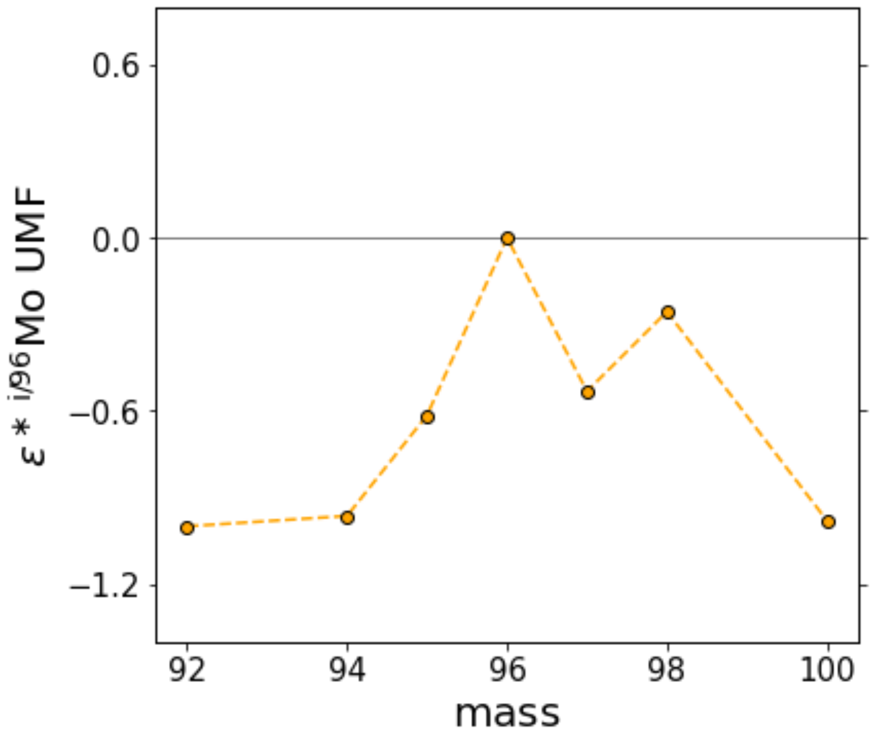
High preision requires measuring isotope ratios to the 5th or 6th decimal point.

To achive this we have to cleanly separate the element of interest from the matrix and any isobaric interferences.

Isotope Measurements

Mass independent isotope variations can be generated by

- Heterogenous distribution of nucleosynthetic material
- Radioactive decay
- Exposure to galactic cosmic rays



s-process anomaly

$$\varepsilon R_{ij} = \left(\frac{R_{ij}^{SMP}}{R_{ij}^{STD}} - 1 \right) \times 10^4$$

Isotope Measurements

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- Heterogenous distribution of nucleosynthetic material
- Radioactive decay
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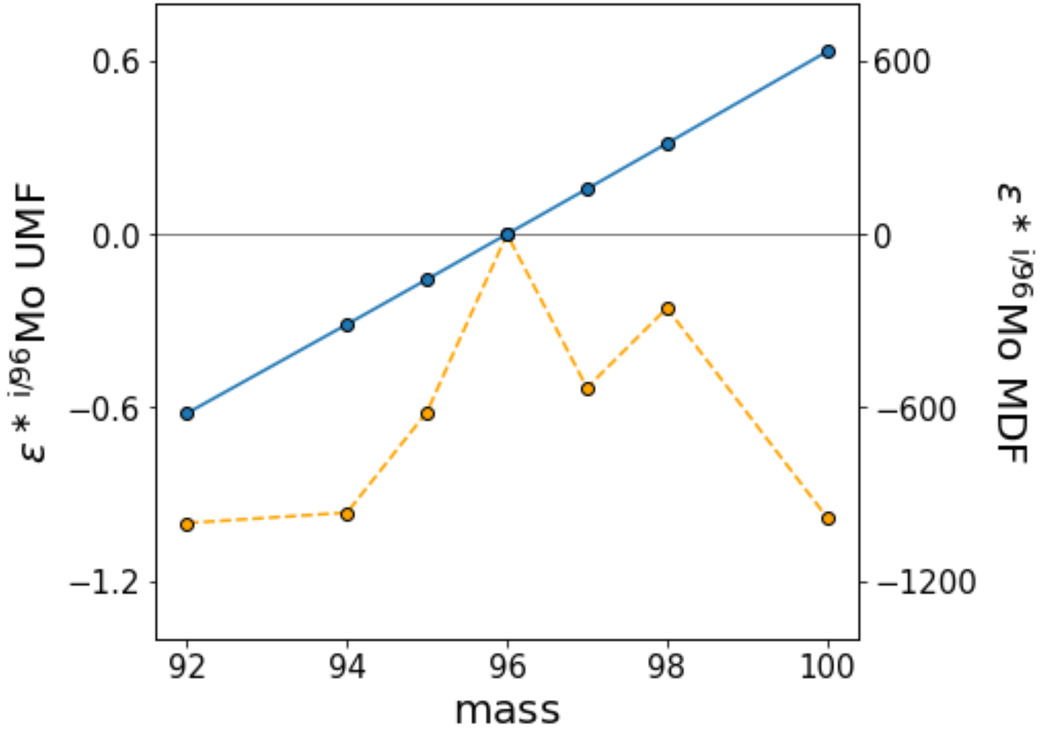
Mass dependent isotope variations can arise from

- Geological/biological processes
- Chemical seperation of elements
- Isotopic analysis

$$r_{i/d} = R_{i/d} * \left(m_{i/d}\right)^{\alpha}$$

$$\varepsilon R_{ij} = \left(\frac{R_{ij}^{SMP}}{R_{ij}^{STD}} - 1\right) \times 10^{4}$$



s-process anomaly

s-process anomaly + MDF

Isotope Measurements

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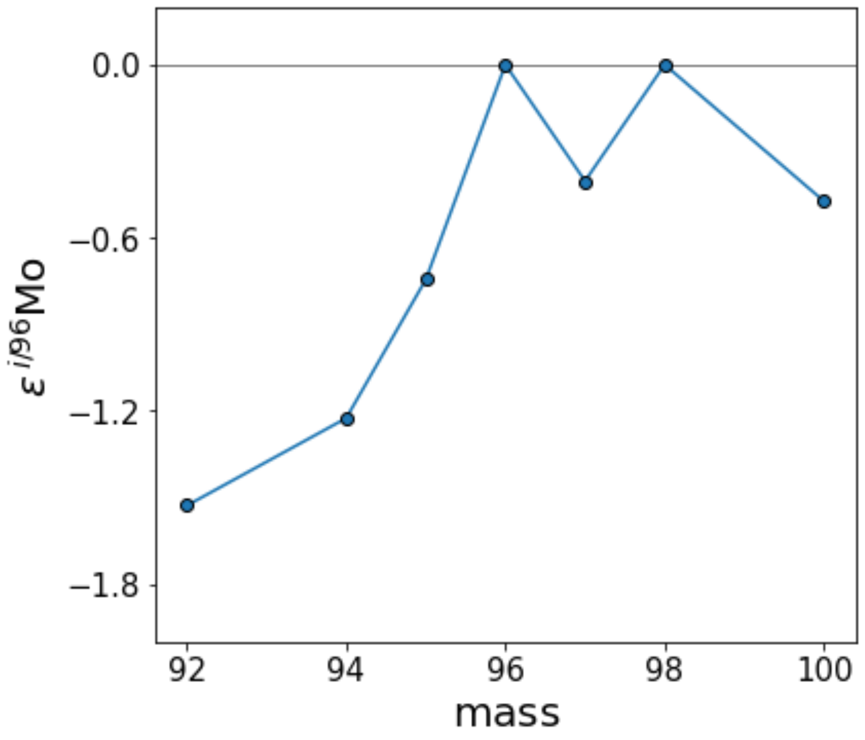

s-process anomaly after internal normalisation procedure

$$\varepsilon R_{ij} = \left(\frac{R_{ij}^{SMP}}{R_{ij}^{STD}} - 1\right) \times 10^4$$

Eur. Phys. J. A (2023) 59:53
https://doi.org/10.1140/epja/s10050-023-00968-y

THE EUROPEAN PHYSICAL JOURNAL A

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Regular Article - Theoretical Physics

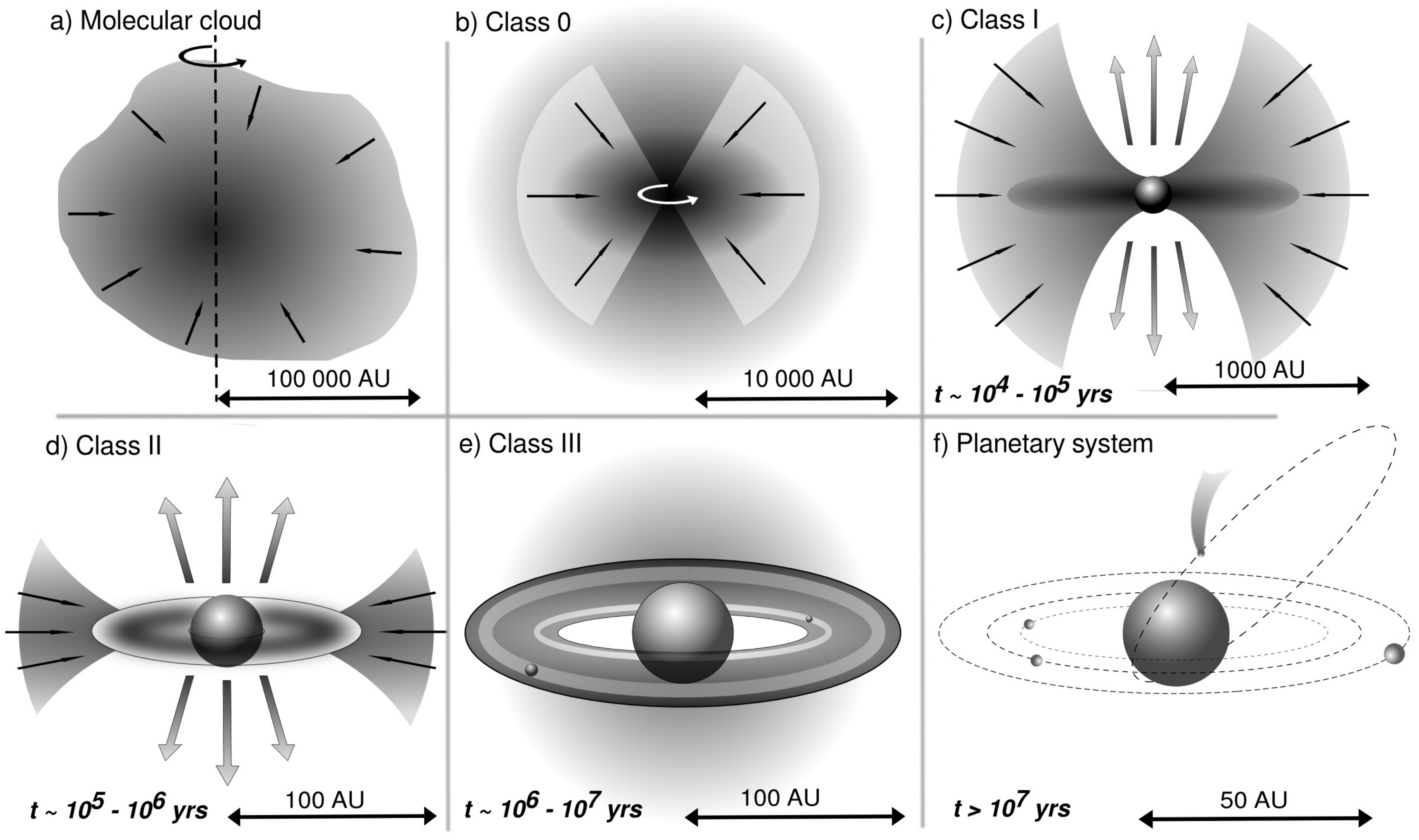
Representation of *s*-process abundances for comparison to data from bulk meteorites

Maria Lugaro[1,2,3,4,a], Mattias Ek[5], Mária Pető[1,2], Marco Pignatari[1,2,6], Georgy V. Makhatadze[7], Isaac J. Onyett[7], Maria Schönbächler[5]

[1] Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Eötvös Loránd Research Network (ELKH), Konkoly Thege M. út 15-17, Budapest 1121, Hungary
[2] CSFK, MTA Centre of Excellence, Konkoly Thege Miklós út 15-17, Budapest 1121, Hungary
[3] Institute of Physics, ELTE Eötvös Loránd University, Pázmány Péter sétány 1/A, Budapest 1117, Hungary
[4] School of Physics and Astronomy, Monash University, Clayton, VIC 3800, Australia
[5] Institute for Geochemistry and Petrology, ETH Zürich, Zurich, Switzerland
[6] E. A. Milne Centre for Astrophysics, University of Hull, Cottingham Road, Kingston upon Hull, HU6 7RX, UK
[7] Centre for Star and Planet Formation (StarPlan), Globe Institute, Faculty of Health and Medical Sciences, University of Copenhagen, Øster Voldgade 5-7, 1350 Copenhagen K, Denmark

There is a ongoing project working on supernovae models

Molecular Cloud to planets



Credit: Drazkowska, https://k-poster.kuoni-congress.info/eas2021/poster/8d42d420-c000-412d-9a75-2a7ce80be1fe

Earliest Solids

Chondrites represent the building blocks of planetary bodies in the solar system.

CAI’s are the first solids to form in the solar system. Chondrules formed ~1-5 My later.

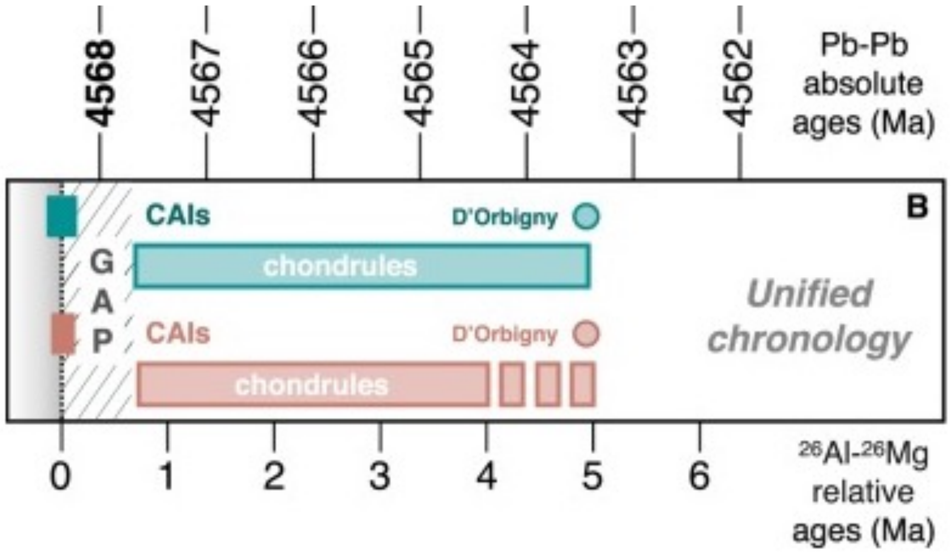
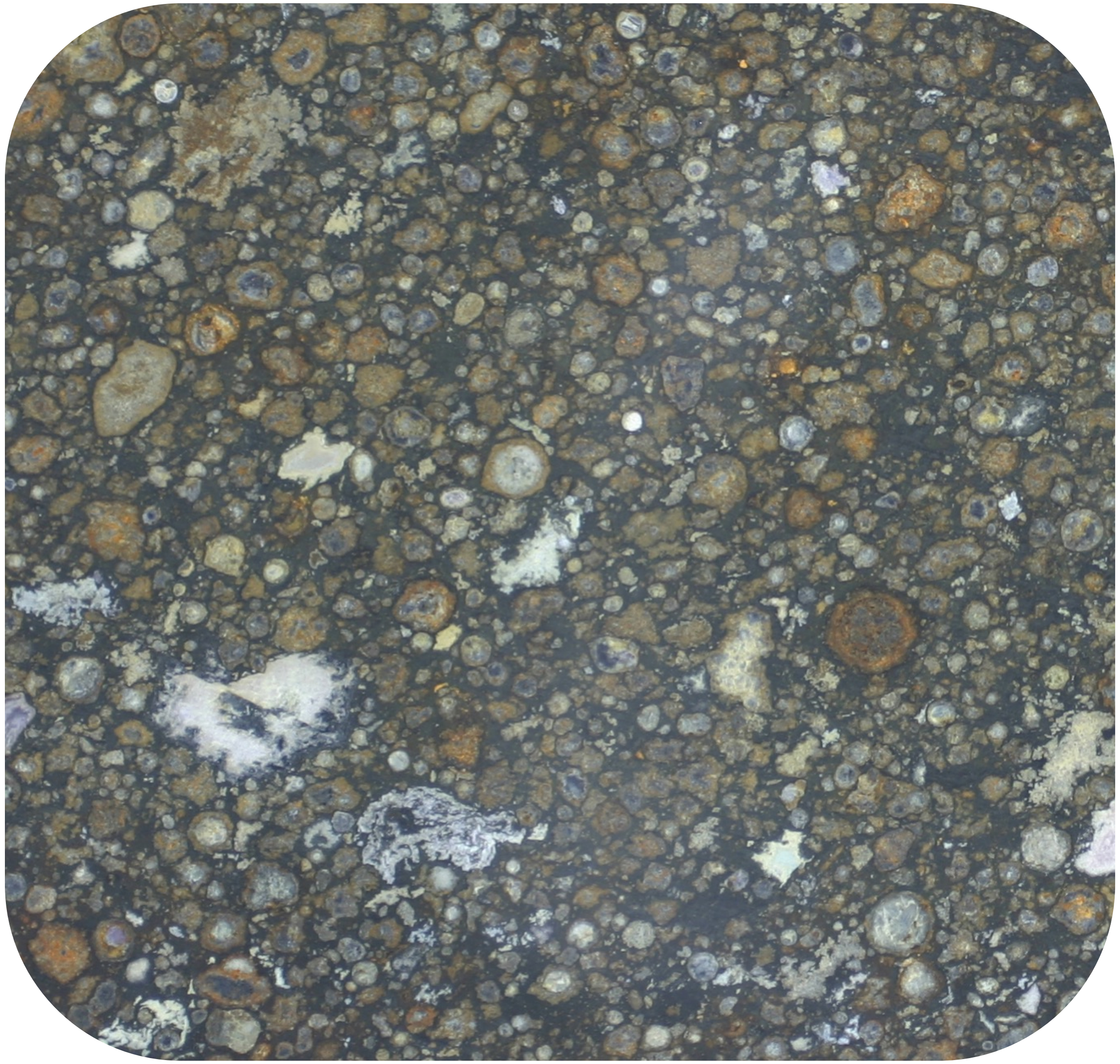


Figure from Piralla *et al.*, Icarus **394**, 2023



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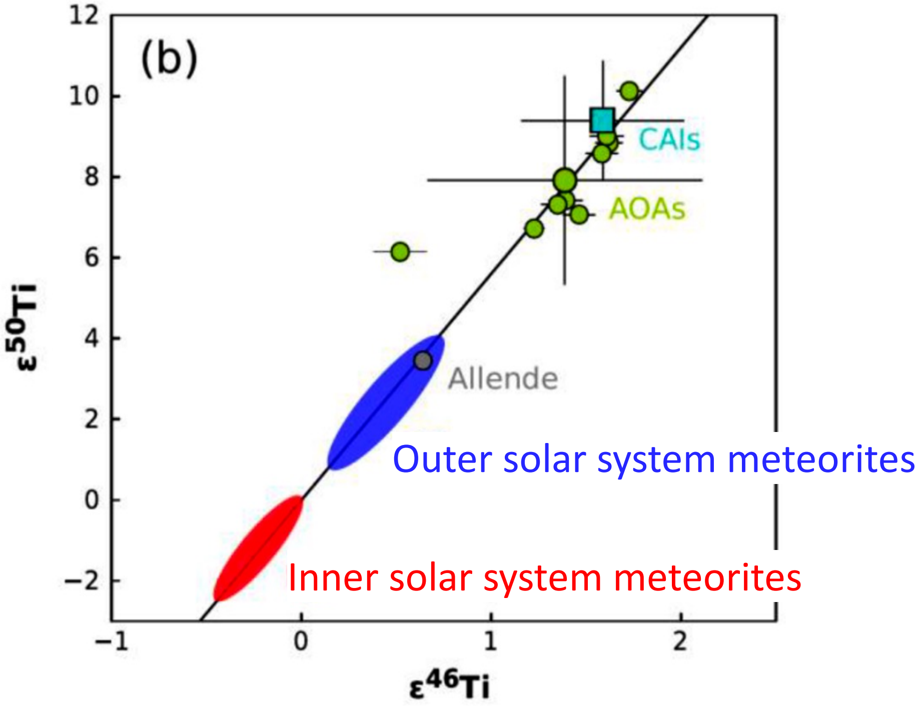
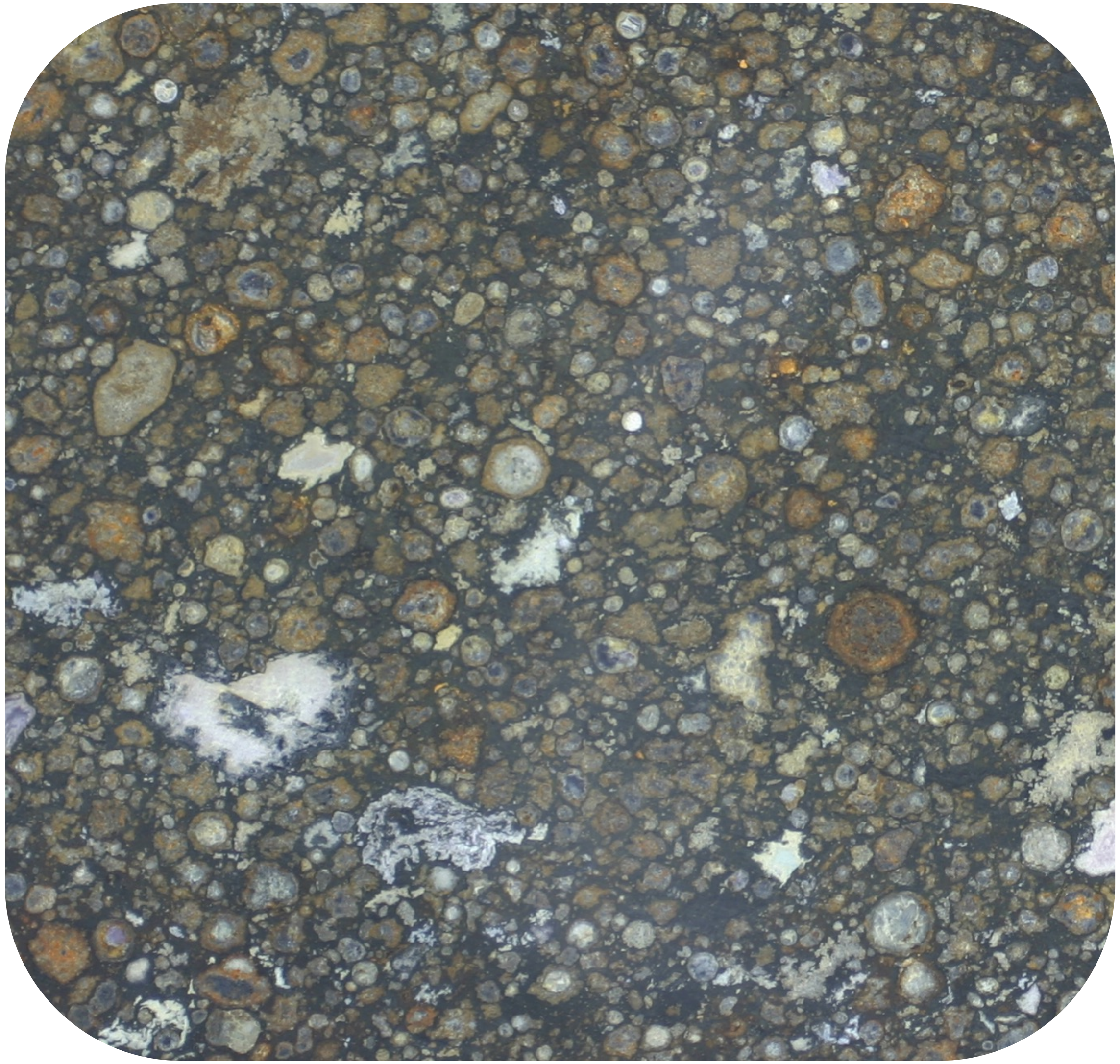


Figure from Jansen *et al.*, Earth Planet. Sci. Lett. **627**, 2024



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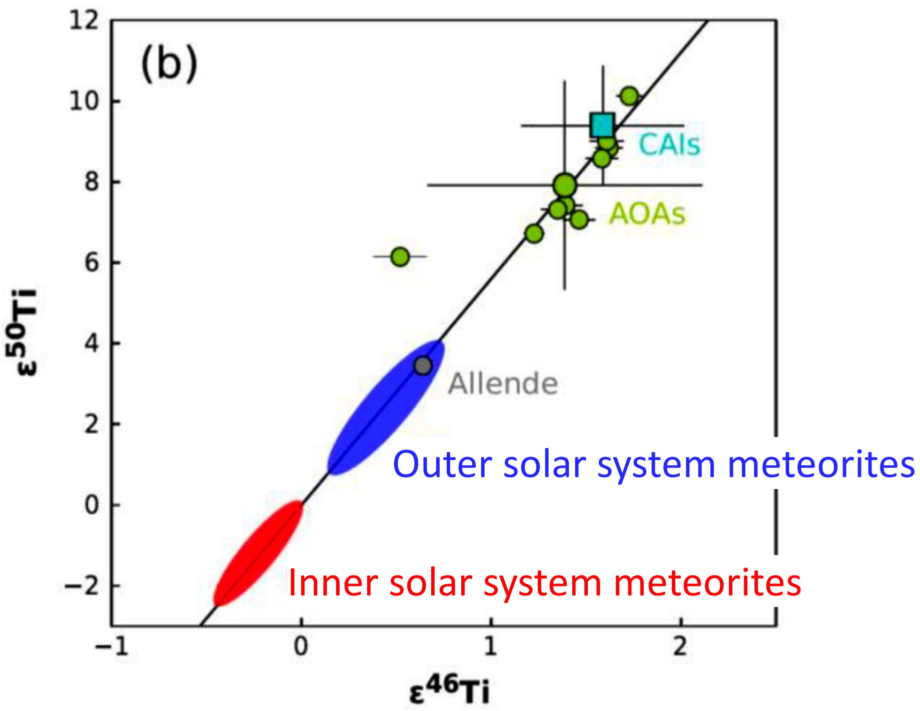

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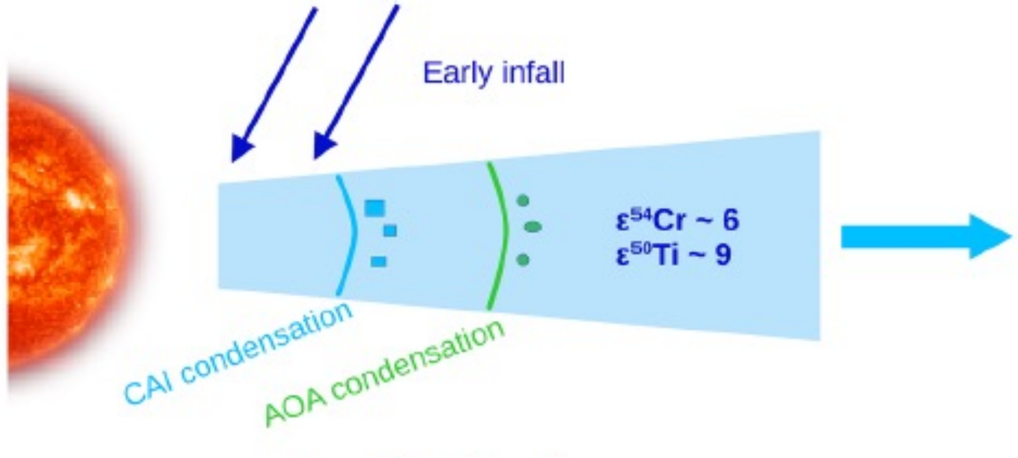

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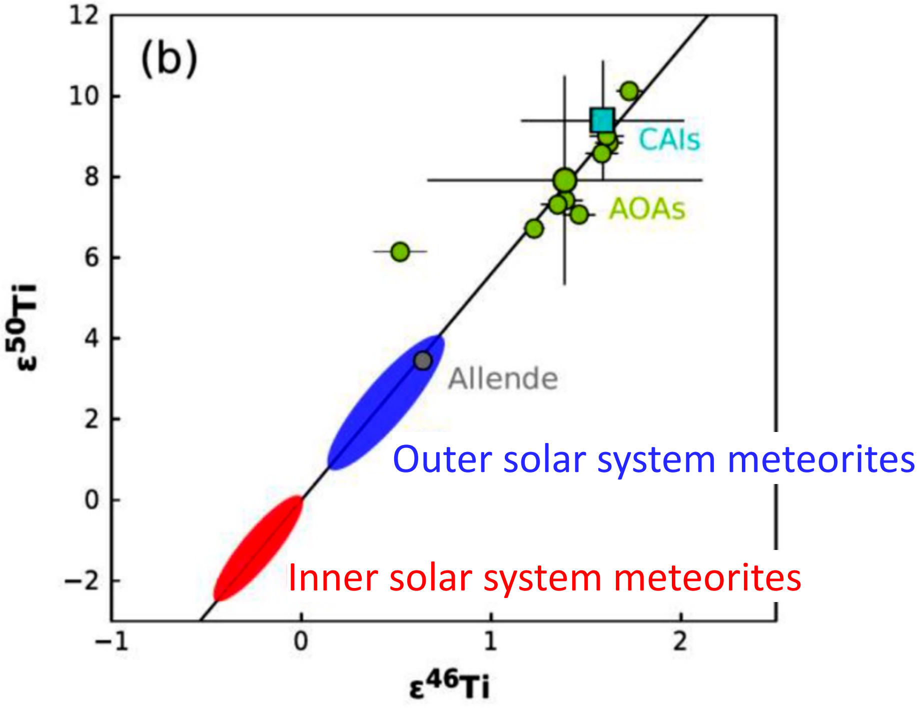

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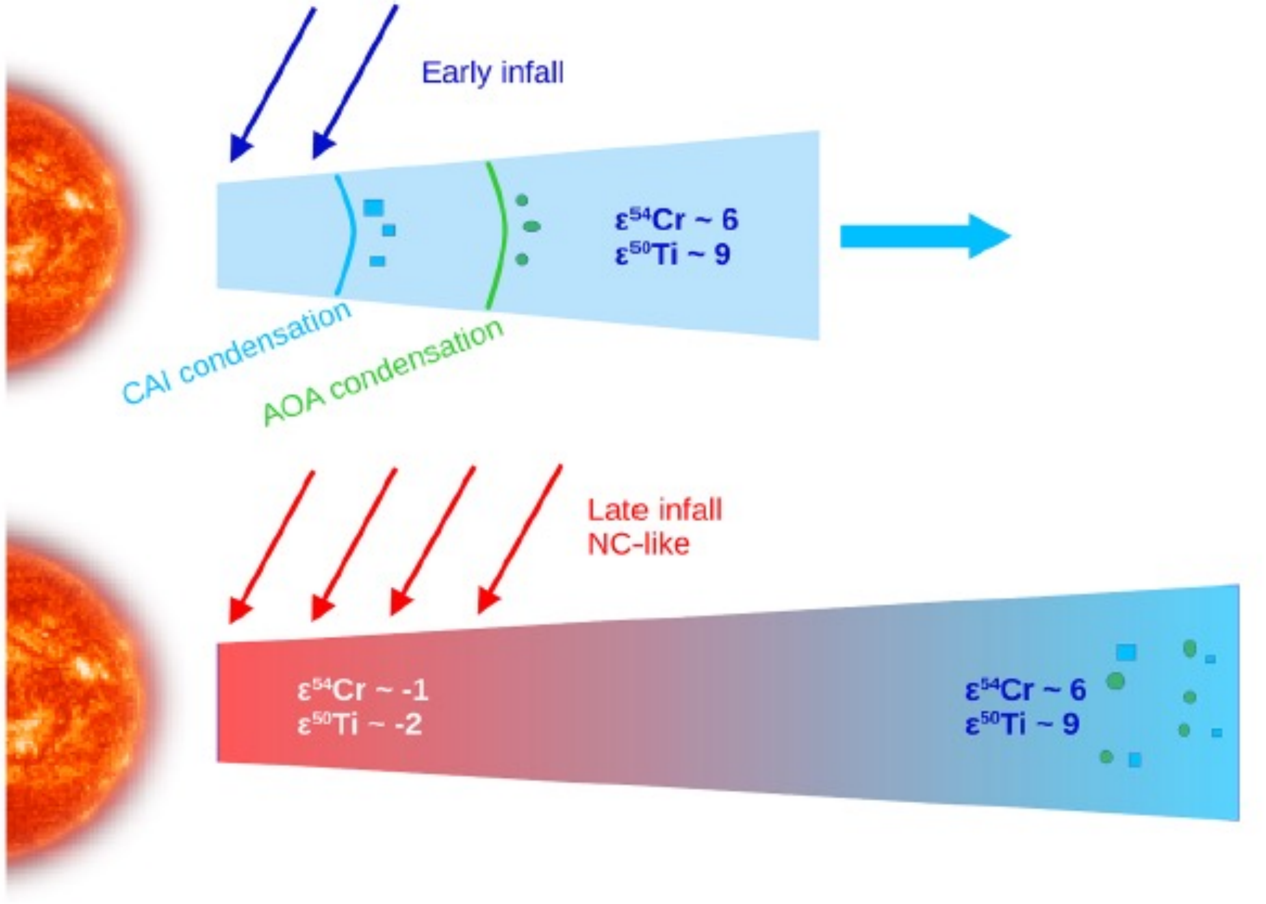

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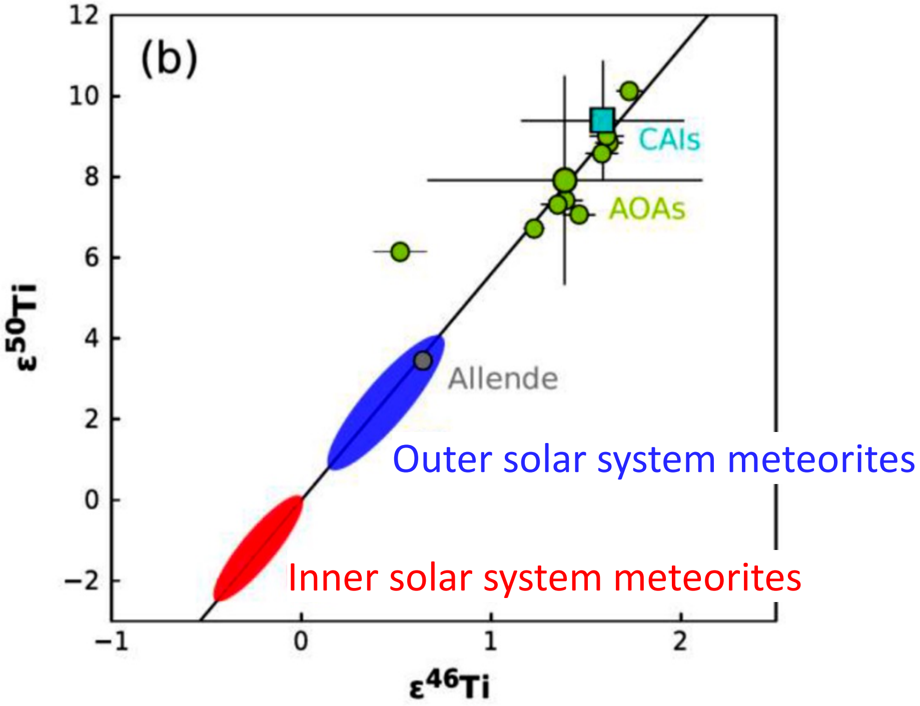

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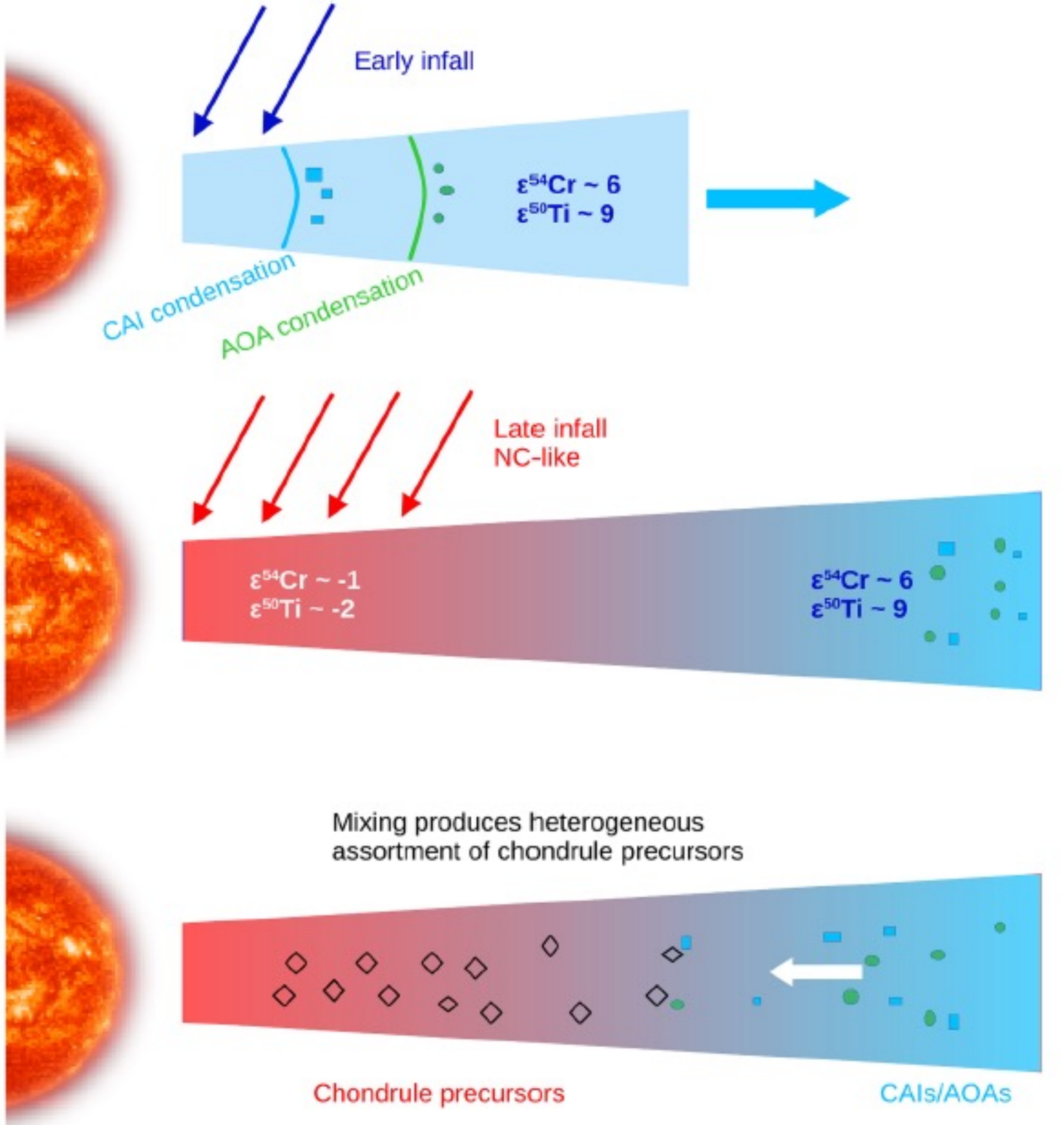


Figure from Jansen *et al.*, Earth Planet. Sci. Lett. **627**, 2024

Protoplanetary disk evolution

There is a compositional gap between the inner (NC) and outer (CC) Solar System materials.

- Rapid formation of Jupiter[1]
- Migration of the snow line[2]
- Pressure maximima in the disk[3]

Rufenacht et al. (2023) reports secondary gaps within the inner Solar System.

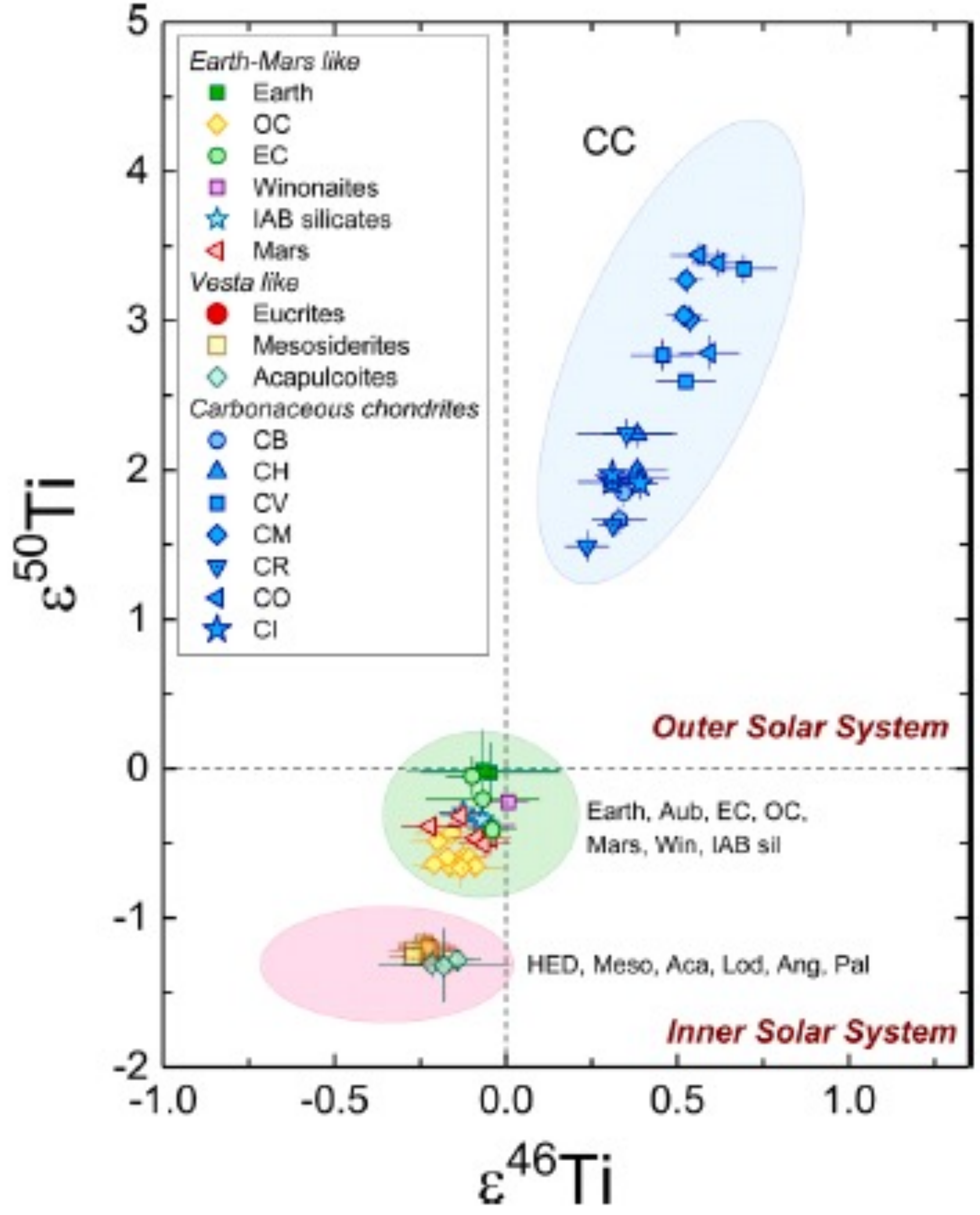
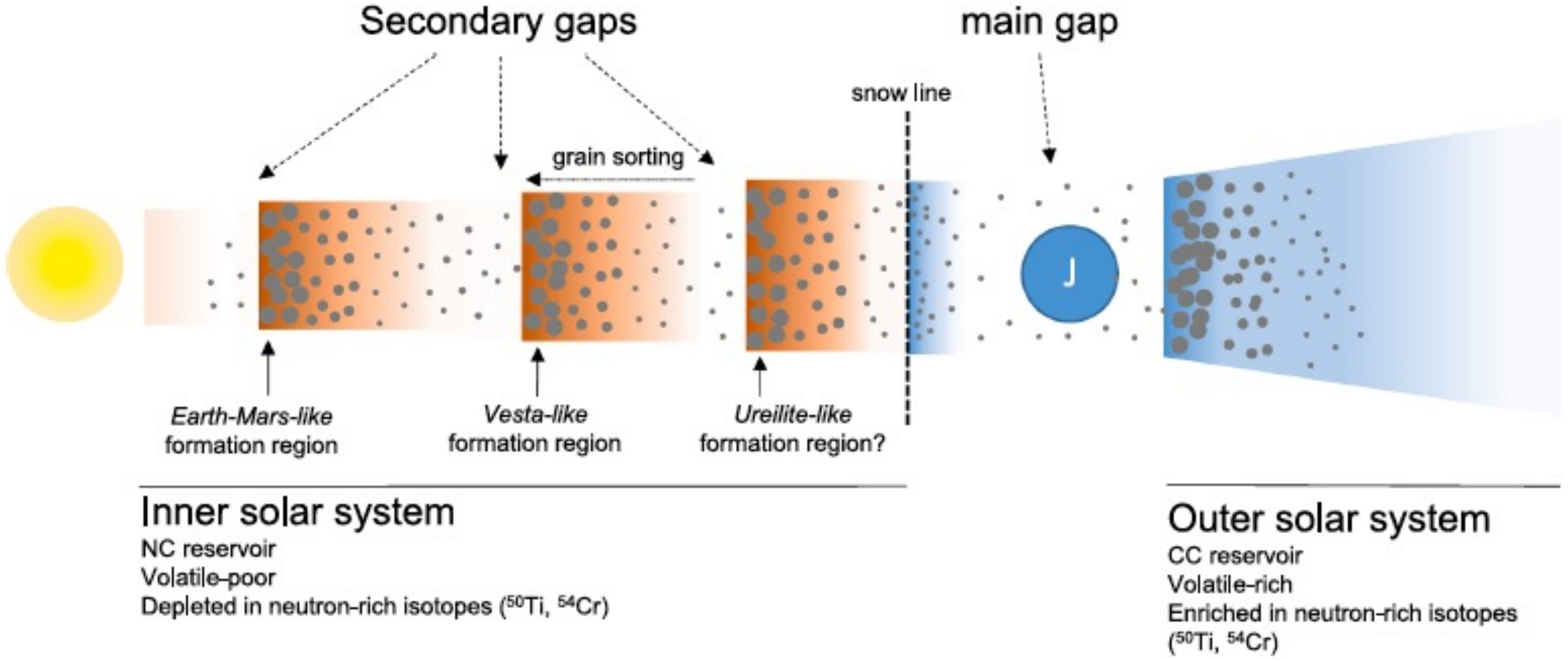


Figure from Rüfenacht *et al.*, Geochim. Cosmochim. Acta **335**, 2023

[1] Kruijer *et al.,* PNAS **114** 2017
[2] Lichtenberg *et al.,* Science **371** 2021
[3] Brasser & Mojzsis, Nature Astron. **4** 2020

Protoplanetary disk evolution

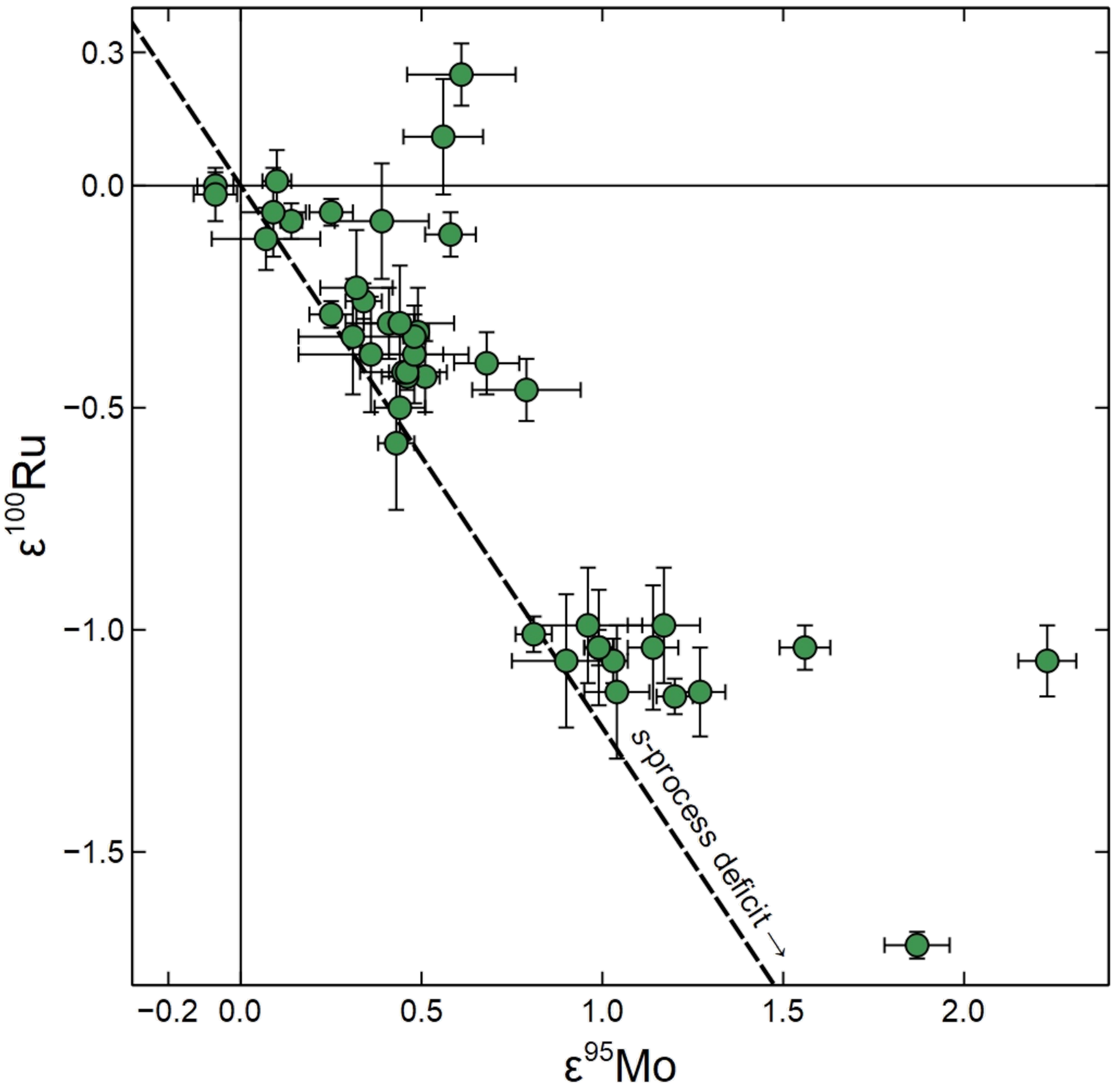


Jupiter forming in the primary gap created spiral arms, which lead to the generation of multiple pressure maxima and gaps interior and exterior to its orbit[1].

[1] Bae & Zhu, Astrophys. J. **859** 2018

Figure from Rüfenacht *et al.*, Geochim. Cosmochim. Acta **335**, 2023

Protoplanetary disk evolution



Dataset from Hopp *et al.*, Earth Planet. Sci. Lett. **312**, 2020

This linear correlation between different meteorite groups has been reported for many refractory s-process elements.

These are typically in good agreement with a mixing line with the modelled Solar System *s*-process component.

The slope of the Ru-Mo correlation is in good agreement with a mixing line with the **bulk** Solar System *s*-process composition.

Protoplanetary disk evolution

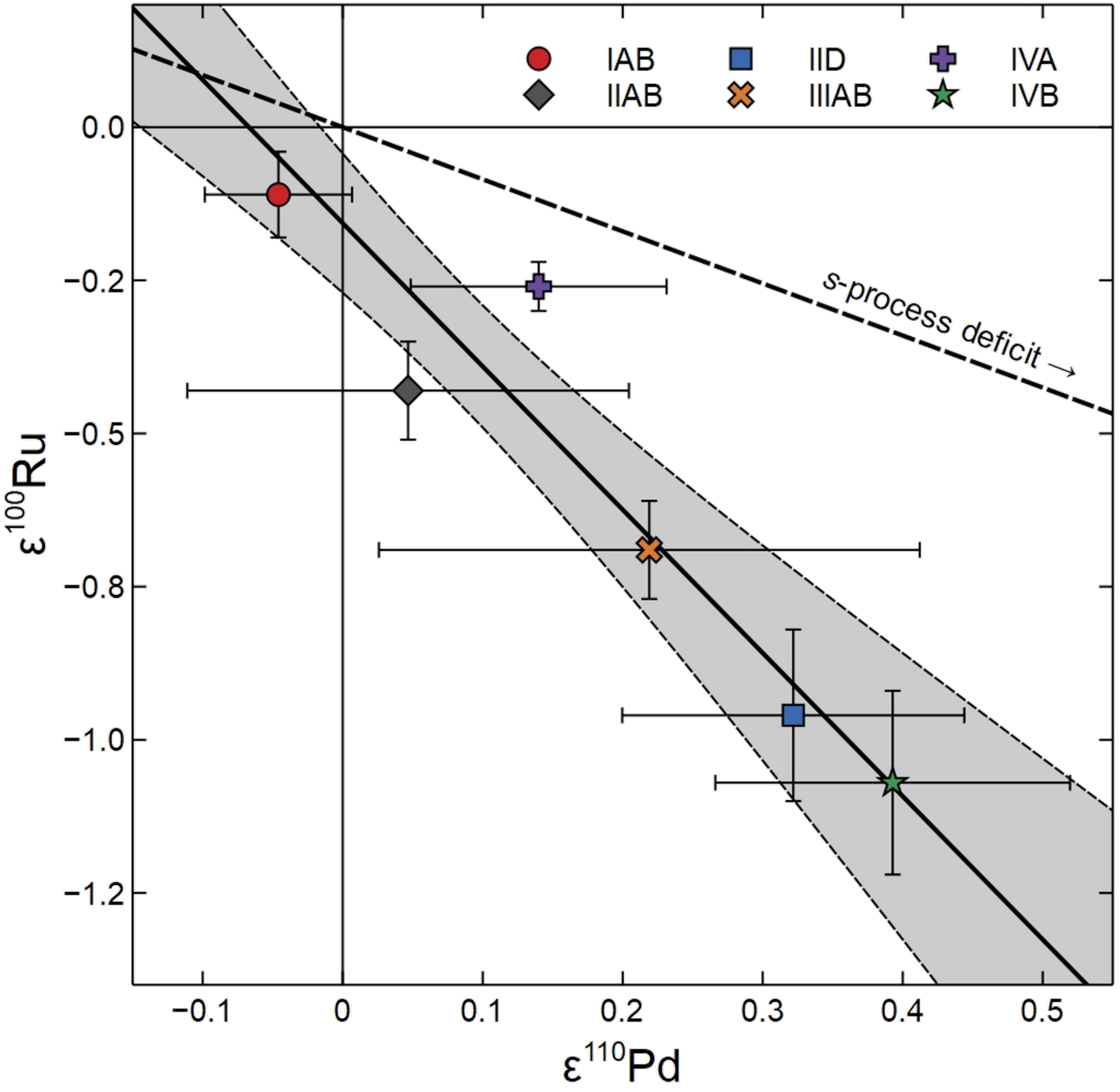


Figure from Ek *et al.*, Nature Astron. **4**, 2020

We find a linear correlation between Mo-Ru and Pd that suggest a common origin of the s-process nucleosynthetic variation in the Solar System.

However, the offsets in Pd are only a third of that predicted by variable mixing of the **bulk** Solar System *s*-process endmember based on the Mo-Ru offsets.

Therefore, the composition of stardust was not the same as the bulk solar system *s*-process component.

Protoplanetary disk evolution

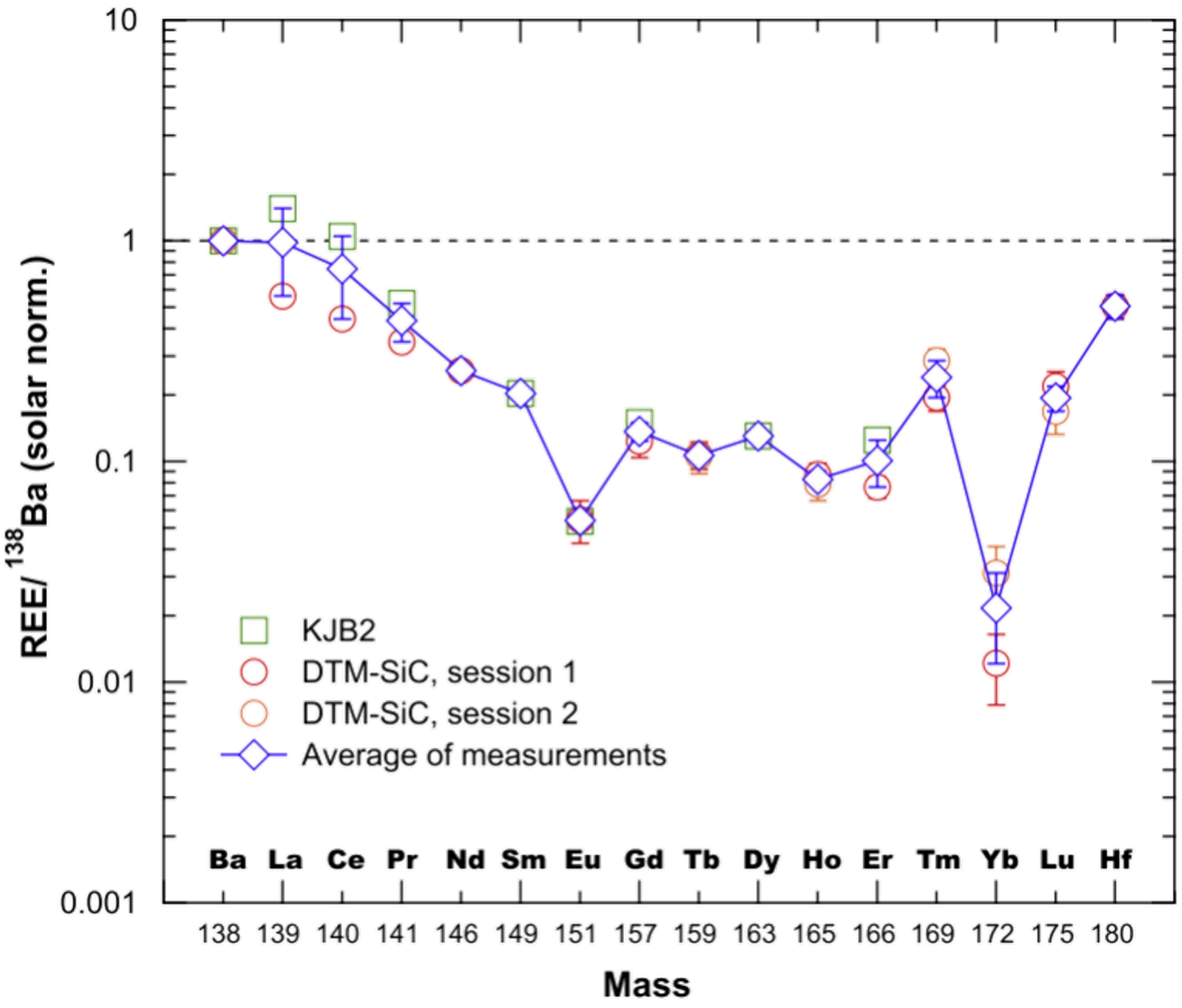


Figure from Ireland *et al.*, Geochim. Cosmochim. Acta **221**, 2018

We attribute the smaller Pd offsets to incomplete condensation of elements into stardust as a function of the elemental condensation temperature.

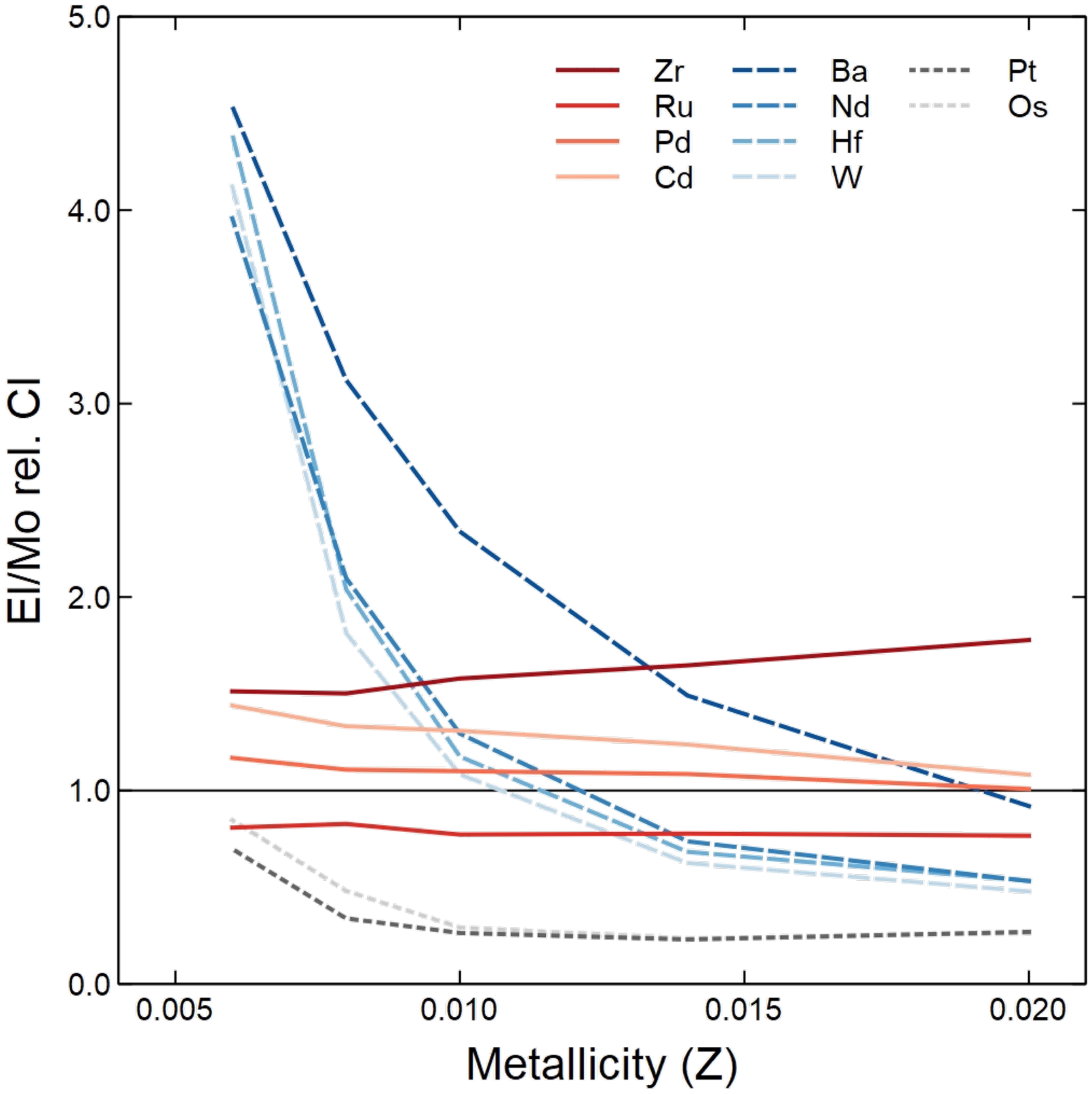
It has been shown that stardust is depleted in elements with lower condensation temperatures.

Palladium is less refractory than Mo and Ru and therefore did not as readily condense into stardust.

This can also explain the lack on nucleosynthetic offsets in elements even more volatile than Pd such as Te[1] and Cd[2].

[1] Fehr *et al.*, Geochim. Cosmochim. Acta **69**, 2005
[2] Toth *et al.*, Geochim. Cosmochim. Acta **274**, 2020

Protoplanetary disk evolution



Data for a 3 $M_{\odot}$ AGB star from the FRUITY database[3]

Figure from Ek *et al.*, Nature Astron. **4**, 2020

Heavy refractory elements ($Z \geq 56$) also show smaller than expected nucleosynthetic offsets[1].

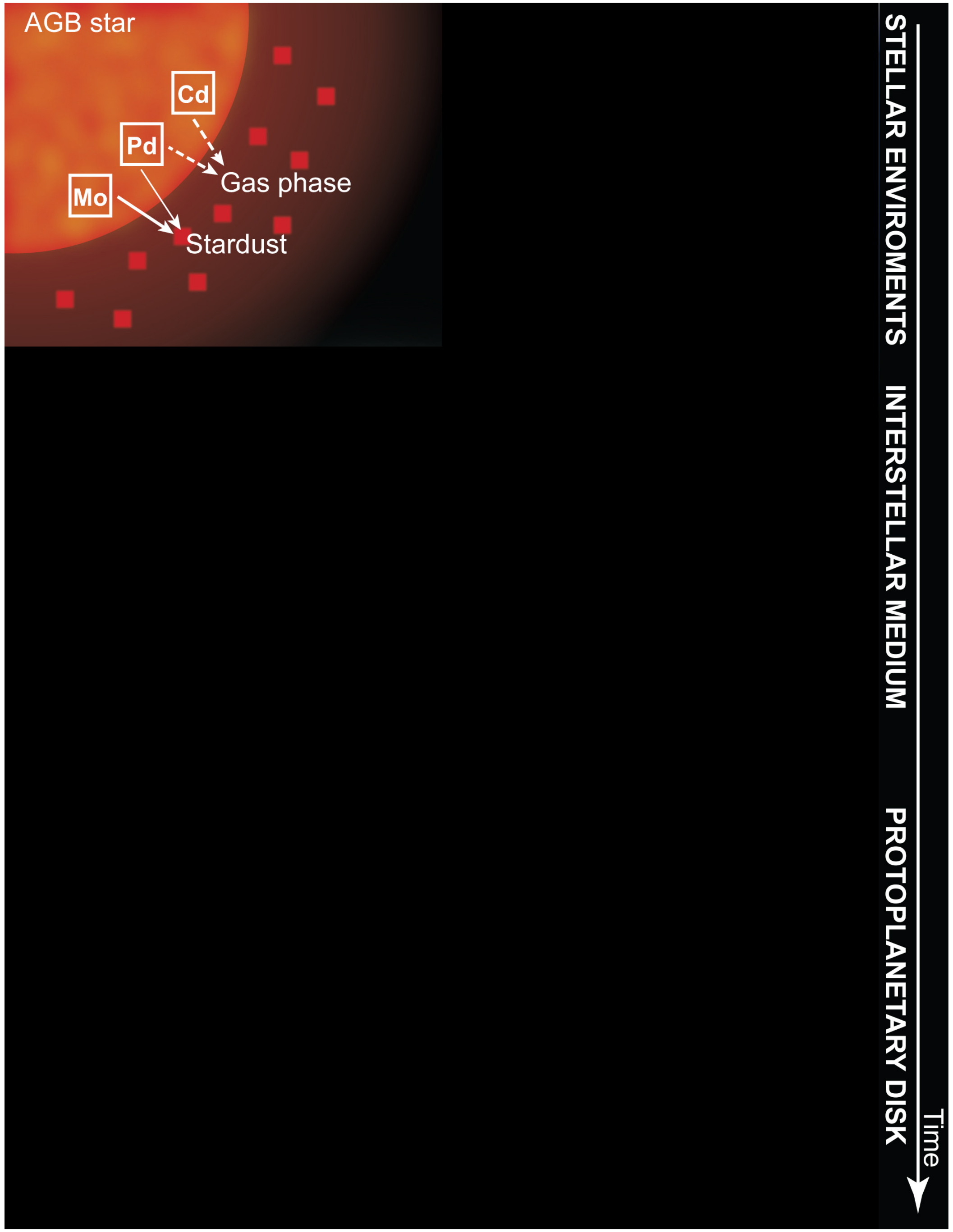
The production of heavy elements ($Z \geq 56$) in AGB stars decreases as the metallicity increases.

It has been suggested that a large fraction of SiC grain originated from high metallicity AGB stars[2].

Therefore, if a large fraction of stardust originated from high metallicity AGB stars this could explain the smaller than expected nucleosynthetic offsets reported for heavy ($Z \geq 56$) refractory elements.

[1] Qin & Carlson, Geochem. J. **50**, 2016
[2] Lugaro *et al.*, Geochim. Cosmochim. Acta **221**, 2018
[3] Cristallo *et al.*, J. Phys. Conf. Ser. **665**, 2016

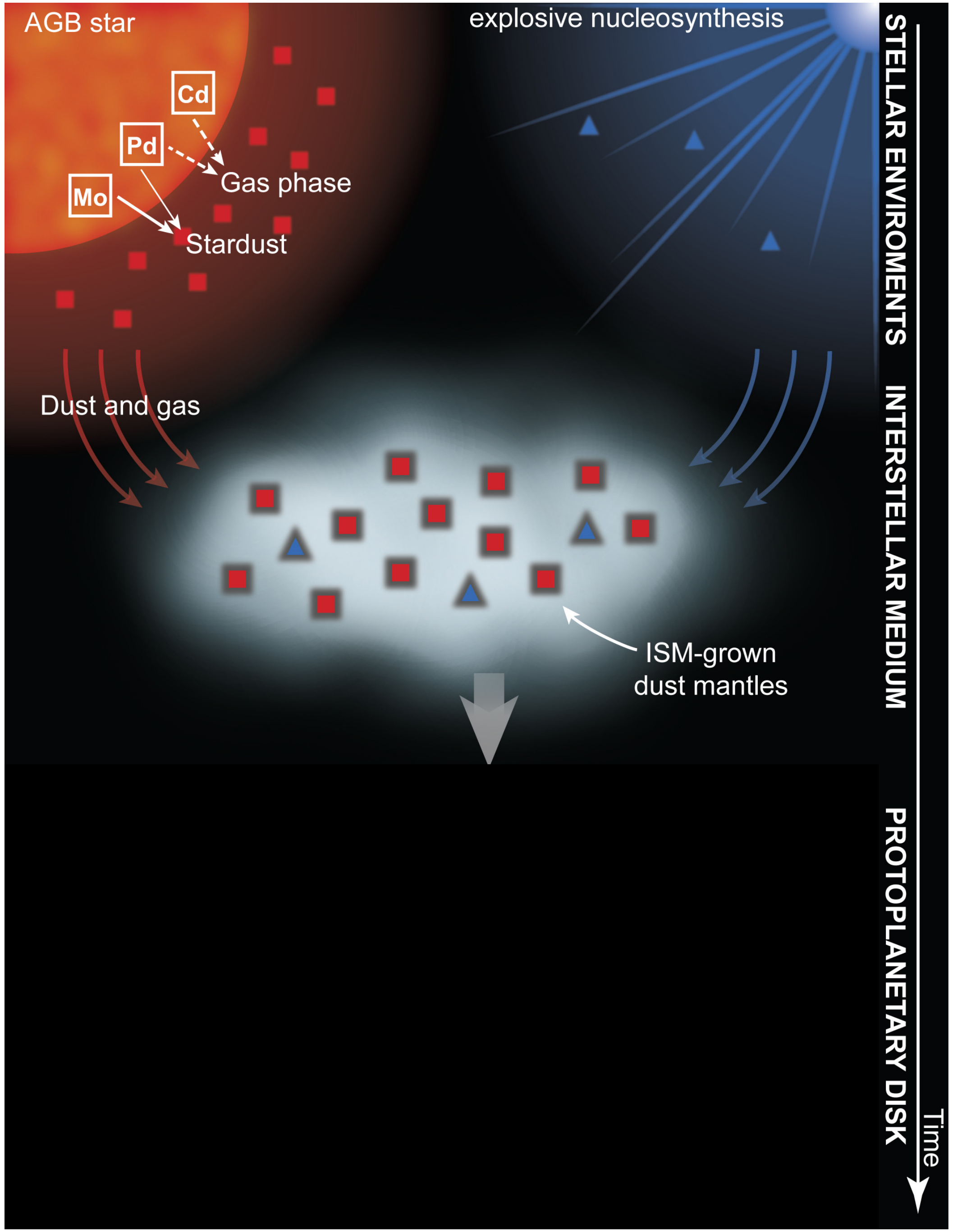
Protoplanetary disk evolution



Incomplete condensation of elements around high metallicity AGB stars results in dust grains depleted in more volatile elements and the heavy refractory elements.

Figure from Ek *et al.*, Nature Astron. **4**, 2020

Protoplanetary disk evolution



Incomplete condensation of elements around high metallicity AGB stars results in dust grains depleted in more volatile elements and the heavy refractory elements.

Dust mantles grow around stardust in the interstellar medium from an isotopically homogenised gas phase.

Stardust (presolar gains) accounts for a few percent of the total dust fraction[1] and was predominately made up of *s*-process material[2].

[1] Hoppe *et al.*, Nat. Astron. **1**, 2017
[2] Zhukovska *et al.*, Astron. Astrophys. **479**, 2008

Figure from Ek *et al.*, Nature Astron. **4**, 2020

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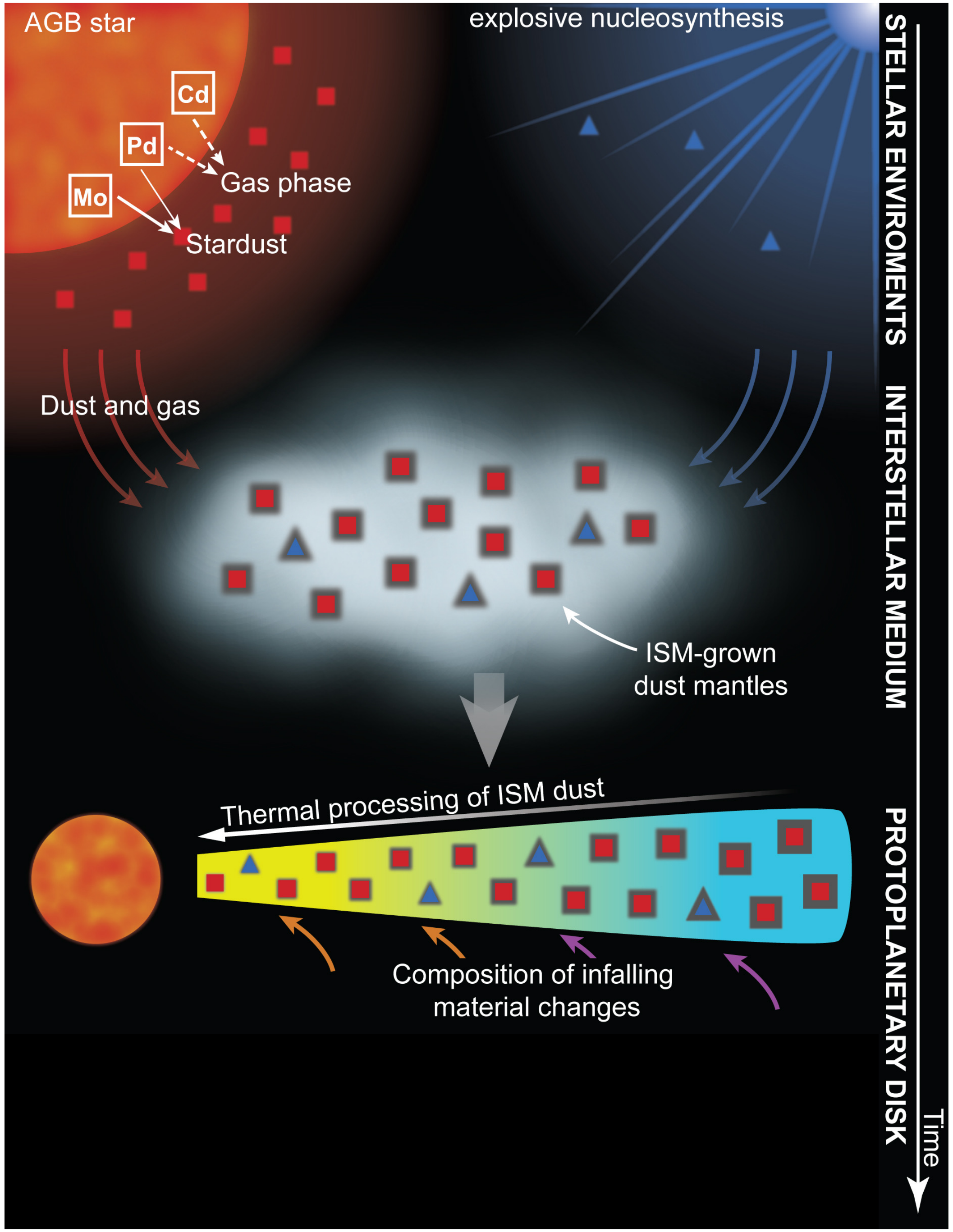

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[3] Jacquard *et al.*, Astrophys. J. **884**, 2019

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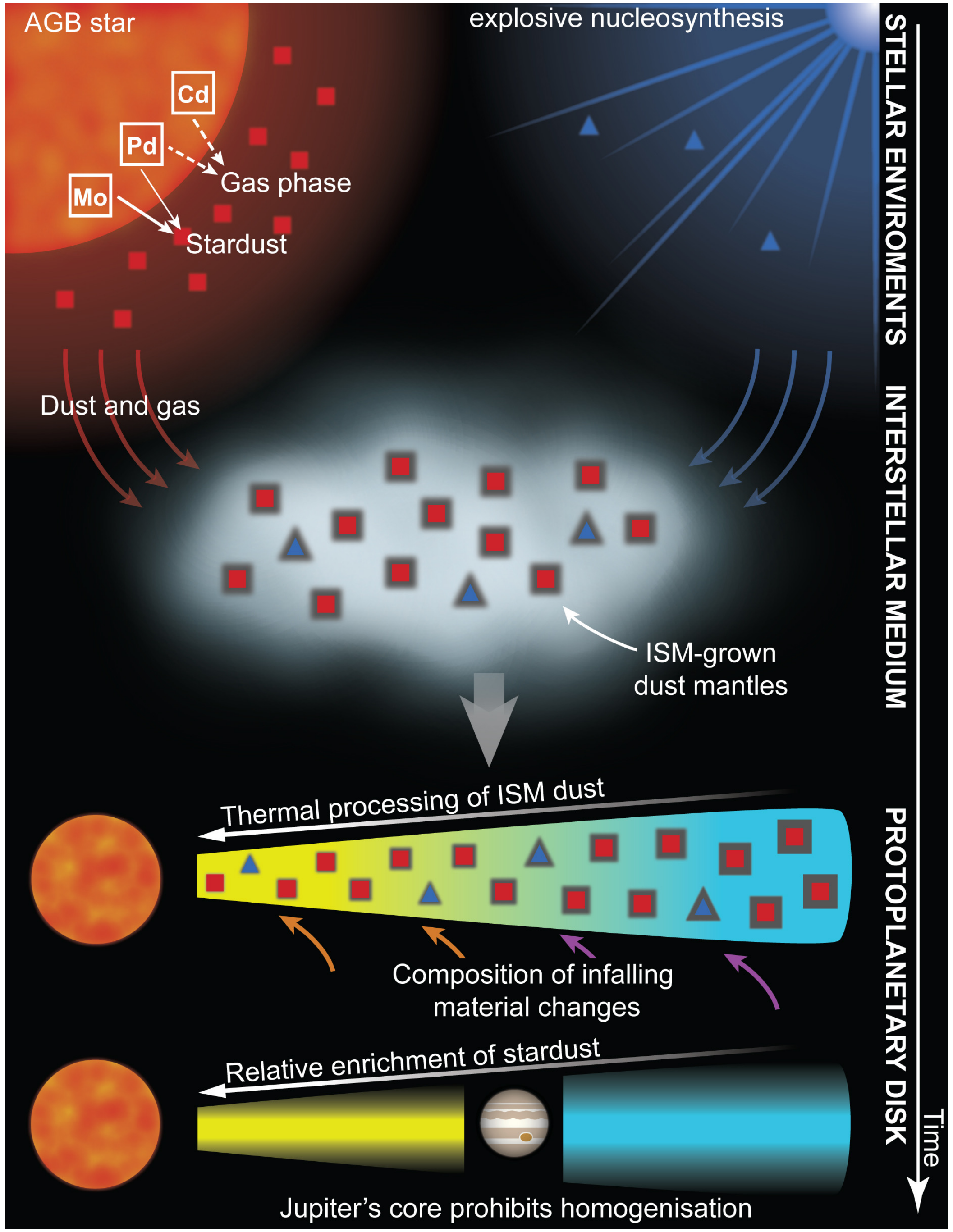

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The formation of Jupiter core [4]/migration of the snow line[5] prohibits homogenisation between the inner and outer disk.

[1] Hoppe *et al.*, Nat. Astron. **1**, 2017
[2] Zhukovska *et al.*, Astron. Astrophys. **479**, 2008
[3] Jacquard *et al.*, Astrophys. J. **884**, 2019
[4] Kruijer *et al.*, Proc. Natl Acad. Sci. USA **114**, 2017
[5] Lichtenberg *et al.*, Science **371**, 2021

Figure from Ek *et al.*, Nature Astron. **4**, 2020

Planetary Building Blocks

There are no chondritic meteorites that matches the Earth composition.

Earth is primarily an isotopic mixture of ~92% E , 6% CI, and < 2% CO-CV+O.

Note This cannot explain the elemental composition of Earth!

The accretion of CI material in the latter stages can be explained by scattering of carbonacous material inwards by the giant planets.

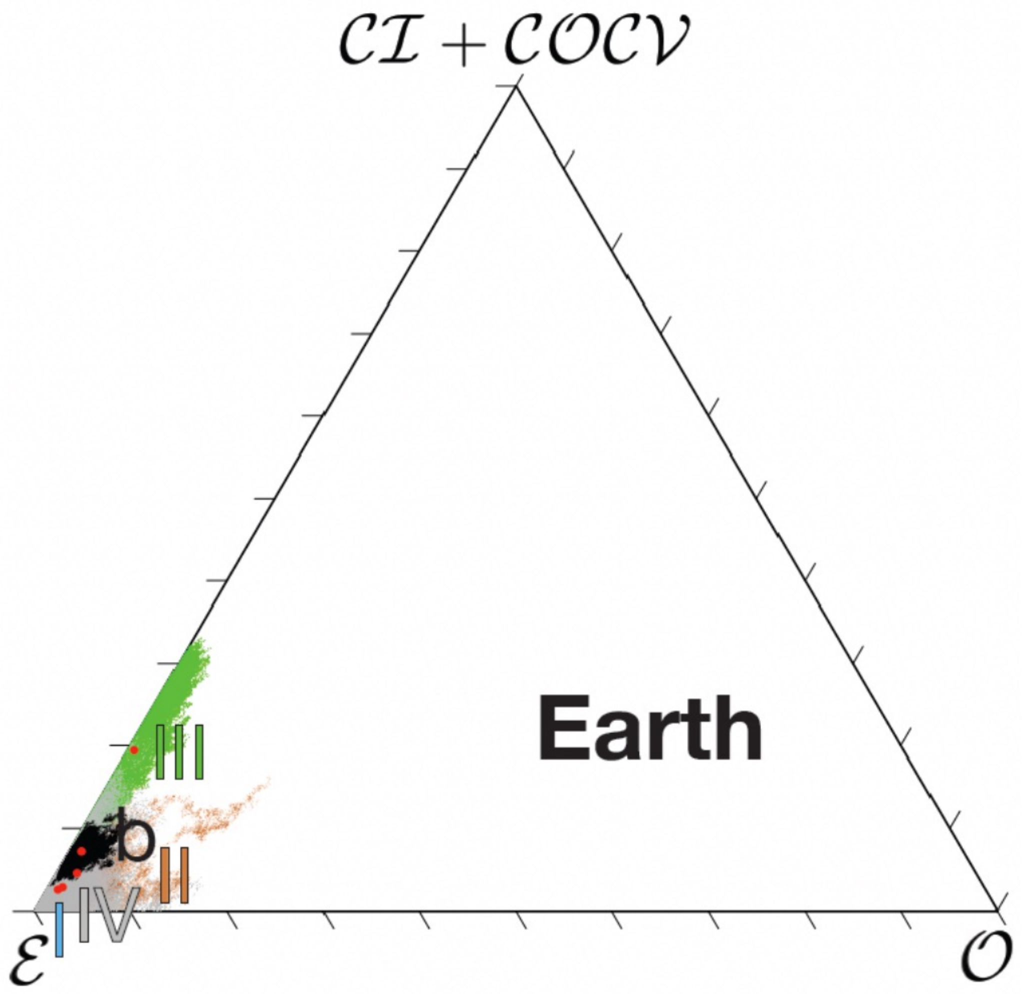

Figure from Dauphas *et al.*, Icarus **408**, 2024

Planetary Building Blocks

^{146}Sm decays to ^{142}Nd with a half life of 103 My.

Earth has a higher ^{142}Nd composition than the inner Solar System building blocks.

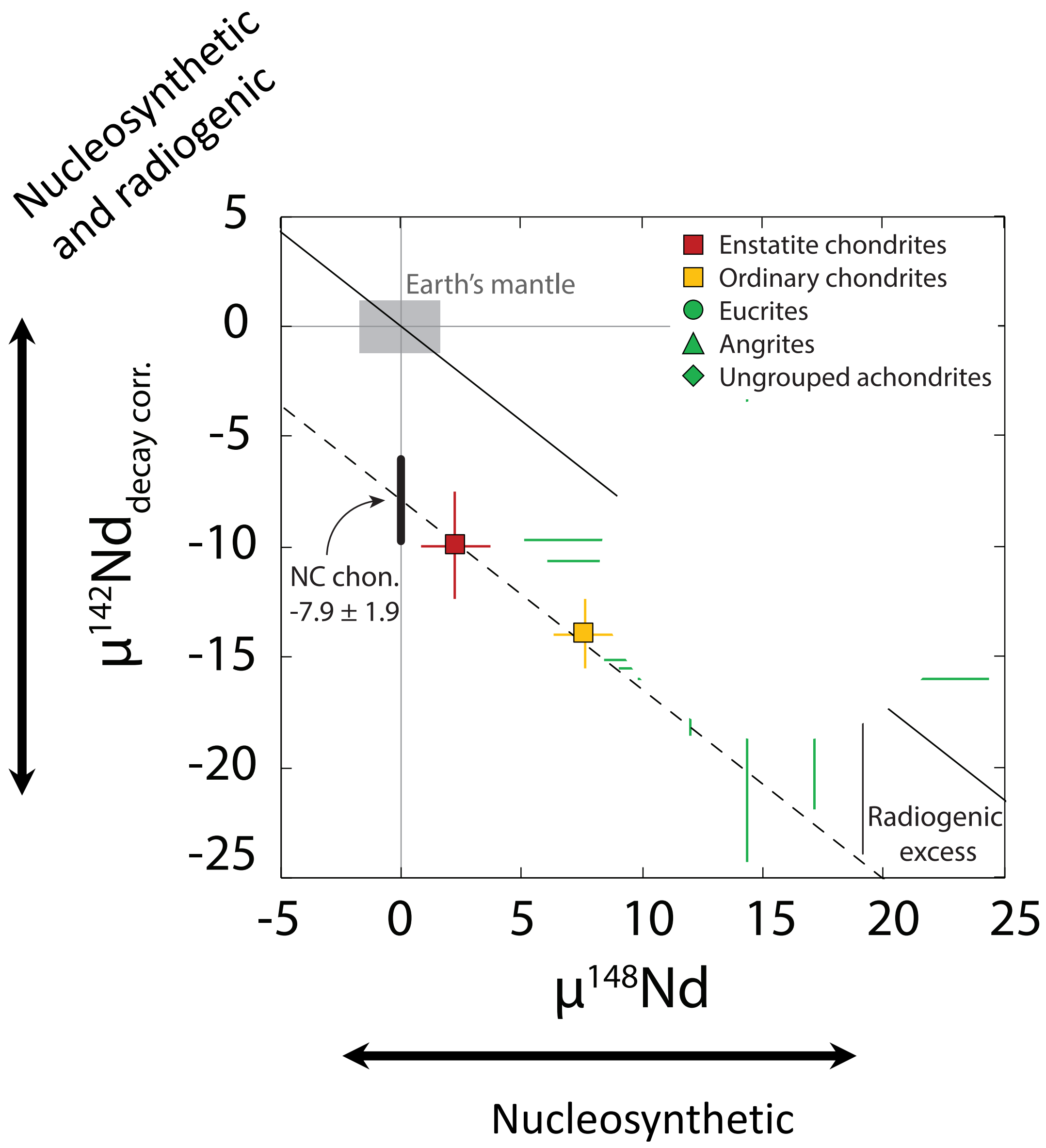

Figure from Frossard *et al.*, Science **377**, 2022

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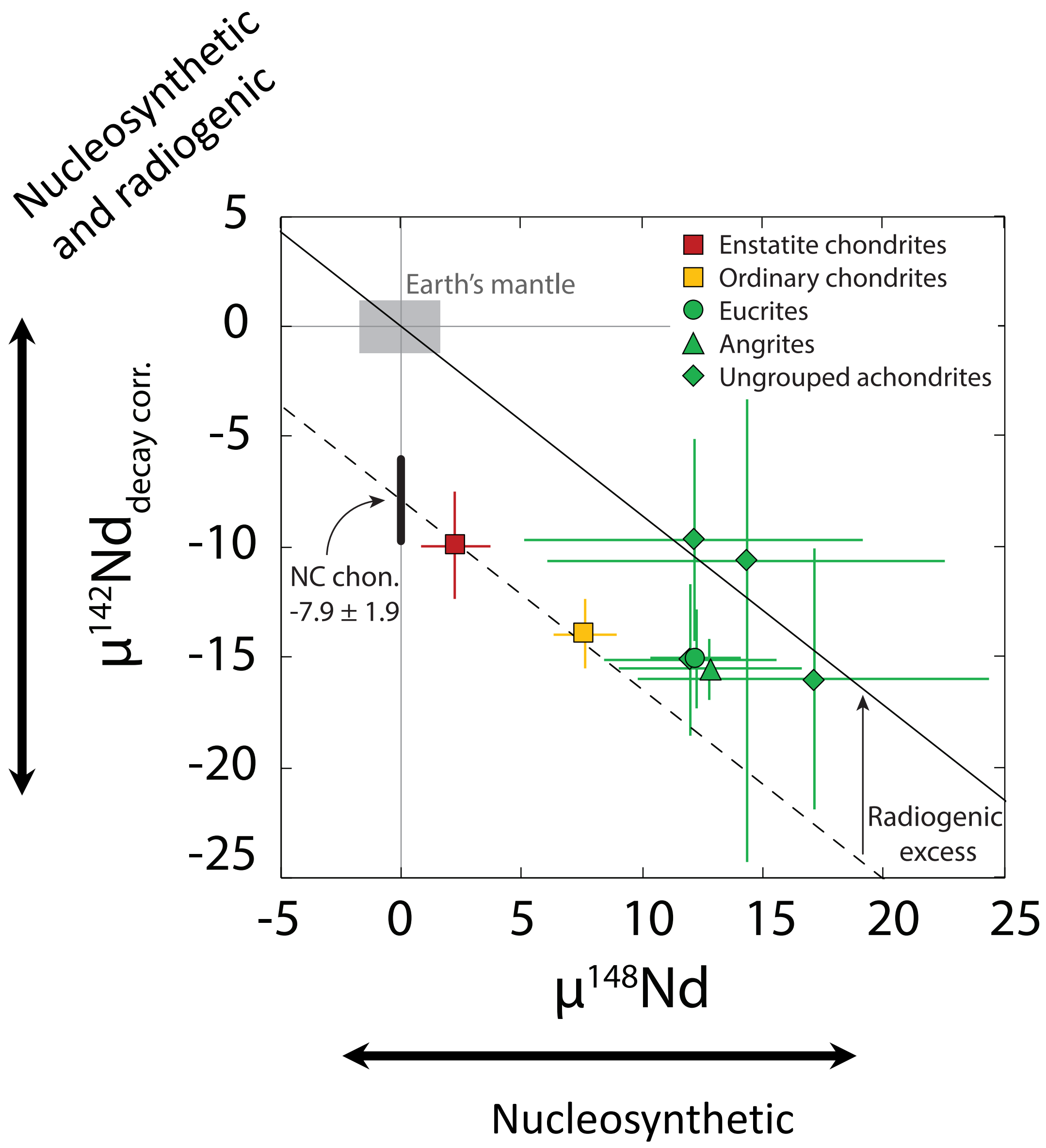

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Earth has a higher ^{142}Nd composition than the inner Solar System building blocks.

As do differentitated inner solar system planetisimals.

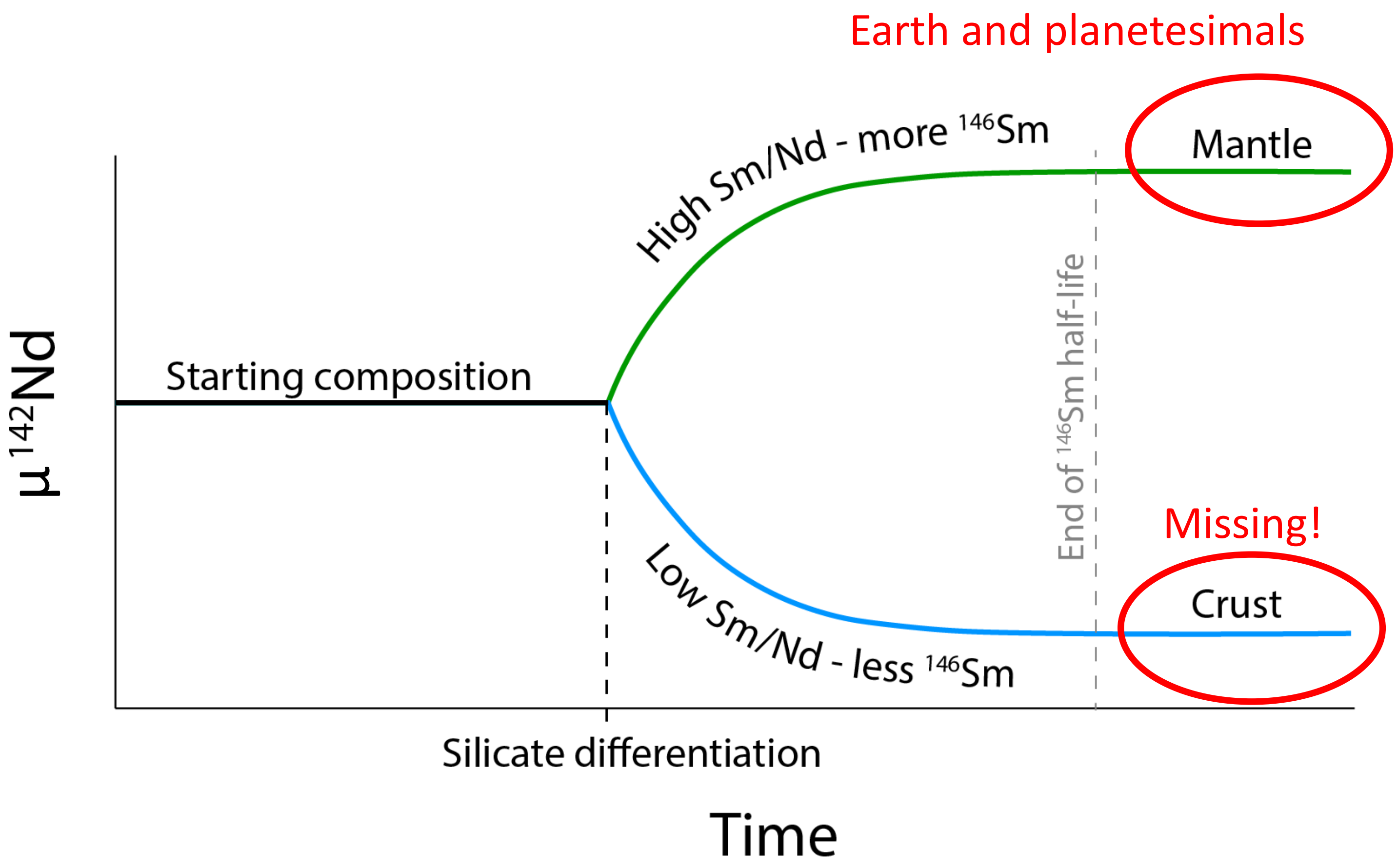


Figure from Frossard *et al.*, Science **377**, 2022

Several hypotheses:

- Primordial crust is buried in the mantle
- Planetesimals and Earth did not accrete from a chondritic composition
- **Primordial crust is lost during accretion**

Earth and planetesimals

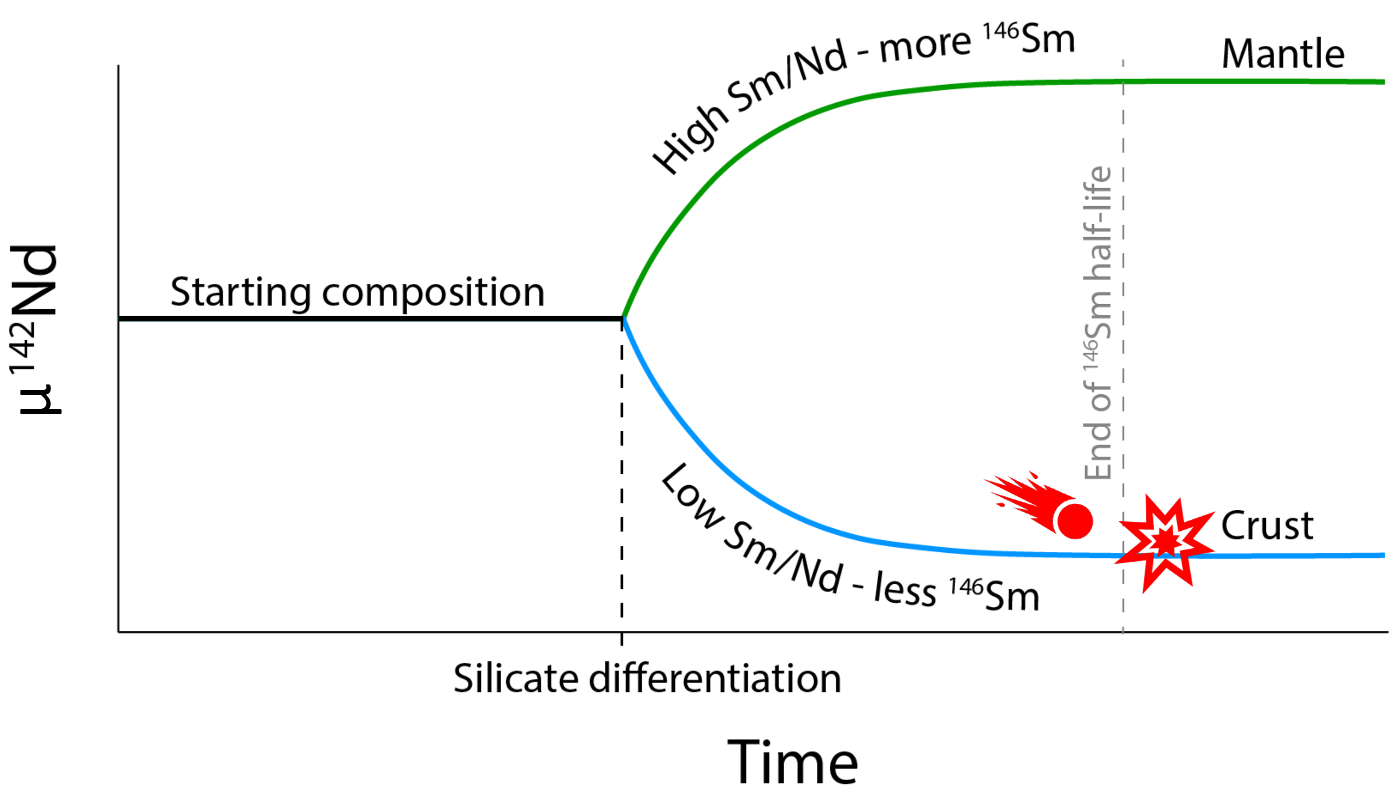


Figure from Frossard *et al.*, Science **377**, 2022

Planetary Building Blocks

Most likely model considers a crust similar to volcanic rocks called basalt
→ 5 to 20 % lost

Results are consistent with numerical modelling of collisional erosion (e.g. Bonsor et al., 2015, Icarus; Carter et al., 2018, EPSL; Allibert et al., 2021, Icarus)

The composition of the Earth is not what we think it is!

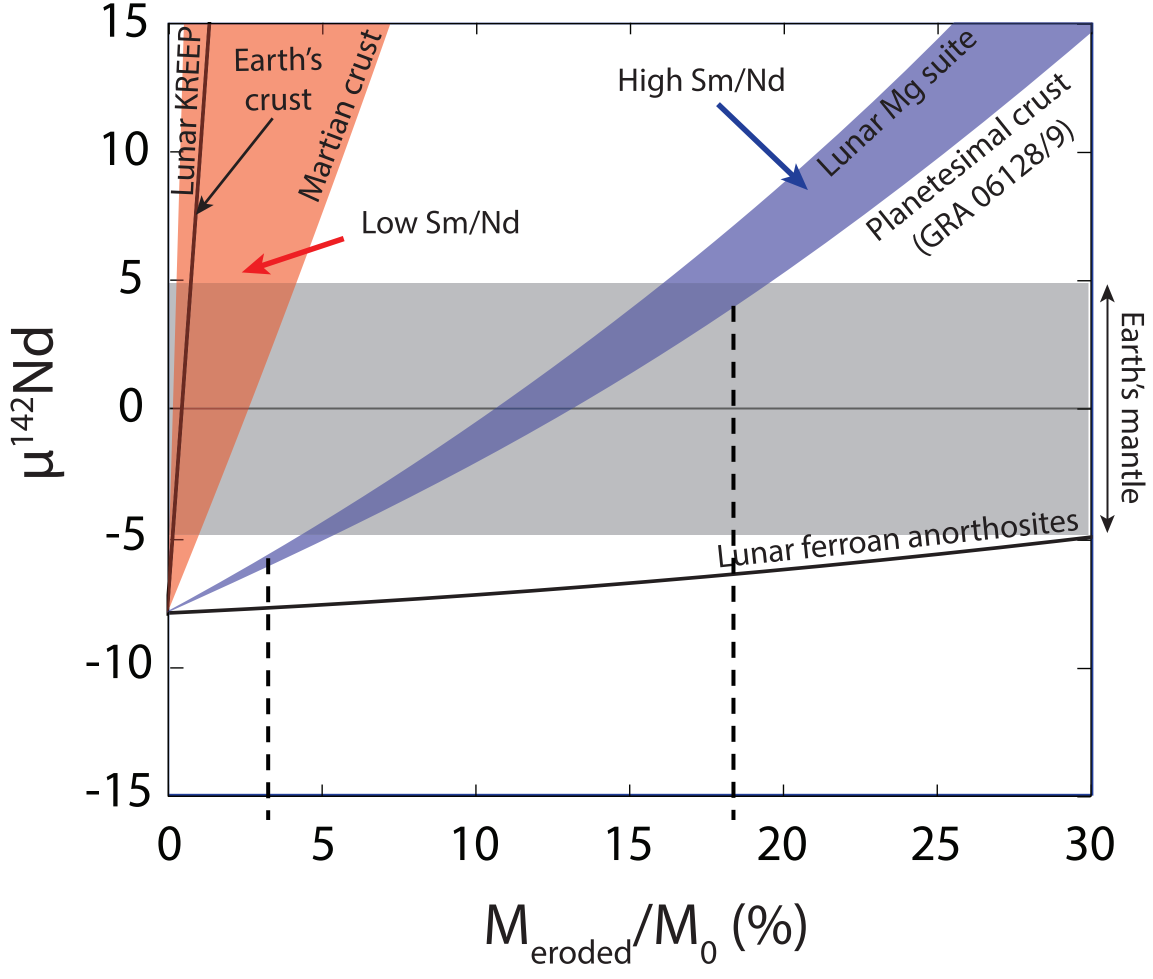


Figure from Frossard *et al.*, Science **377**, 2022

- **Evidence for ubiquitous collisional erosion of primordial crusts of planetesimals**

- **The process of accretion profoundly modifies the composition of planets**

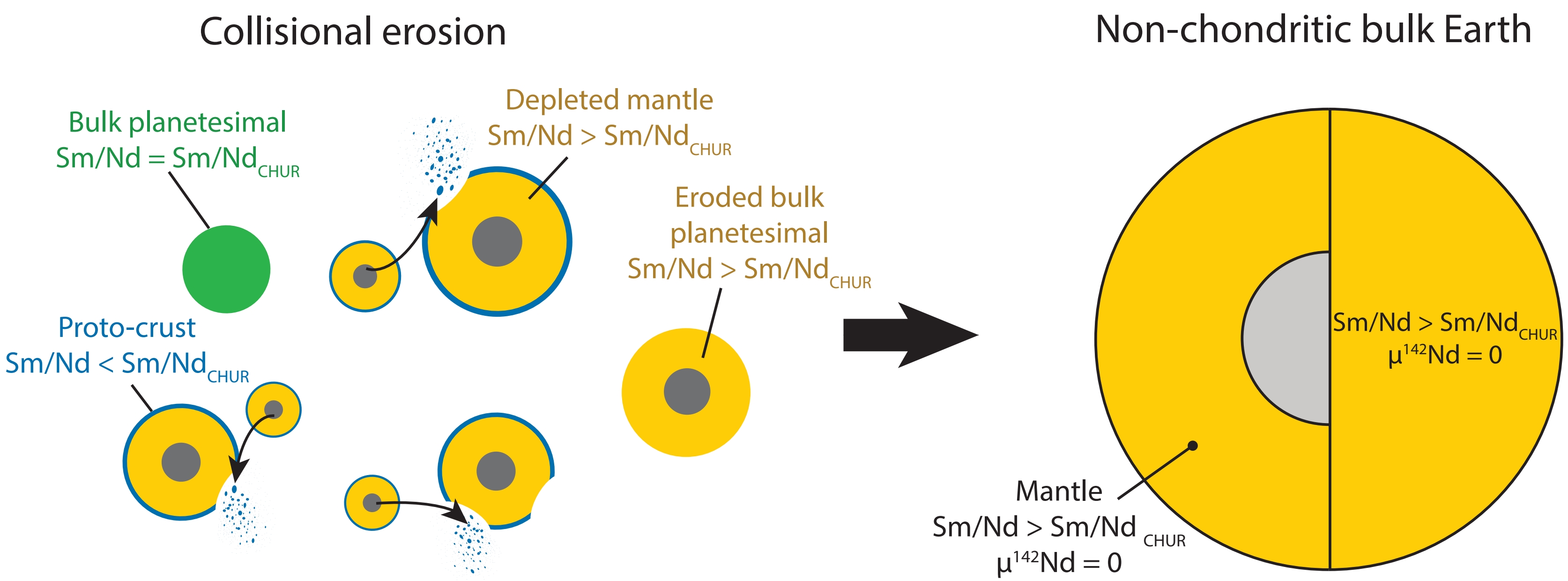
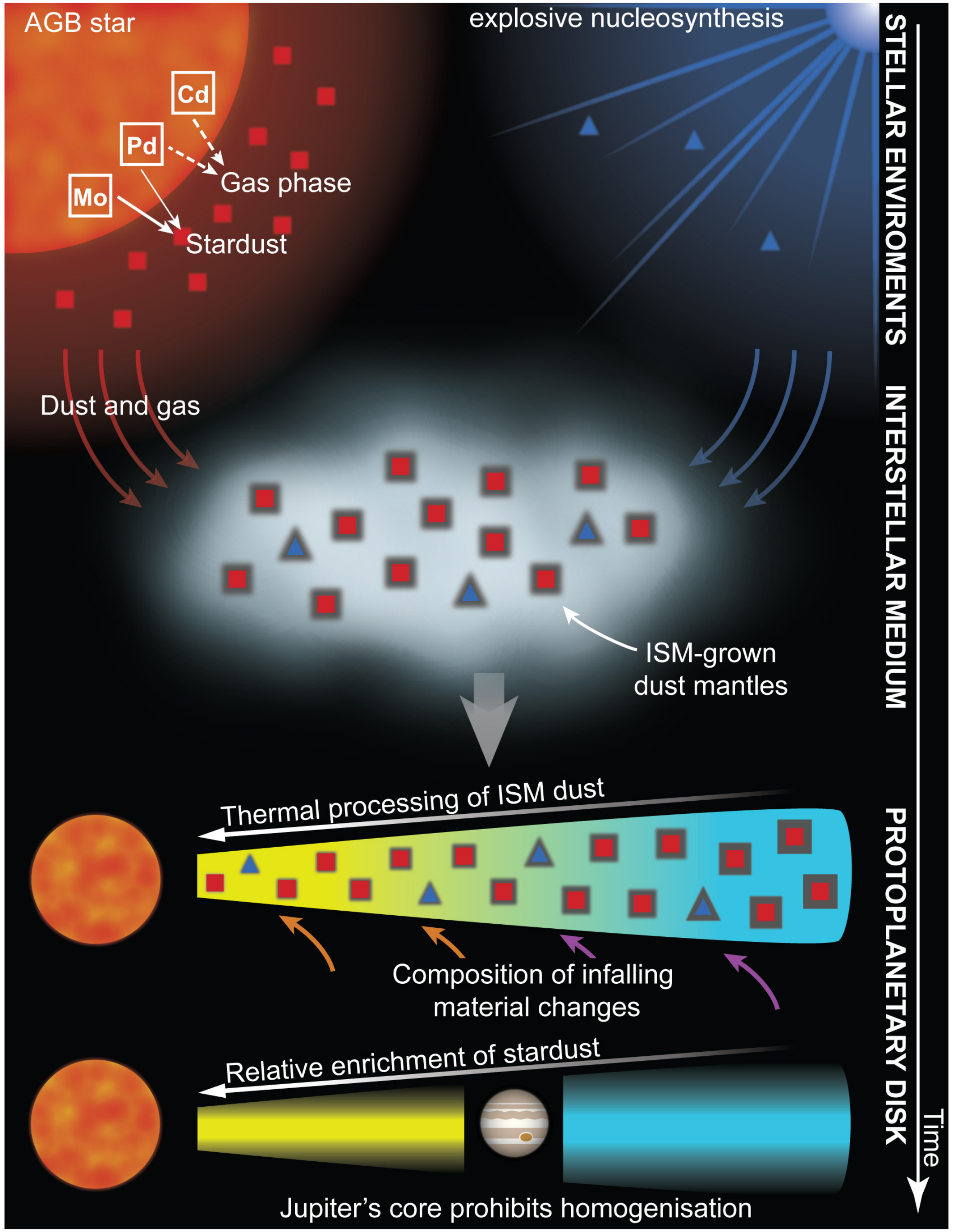


Figure from Frossard *et al.*, Science **377**, 2022

The End

Conclusions



To understand the evolution of the protoplanetary disk we need to understand:

- Where isotopes are produced
- How stellar material is preserved in the ISM and then delivered to the disk.