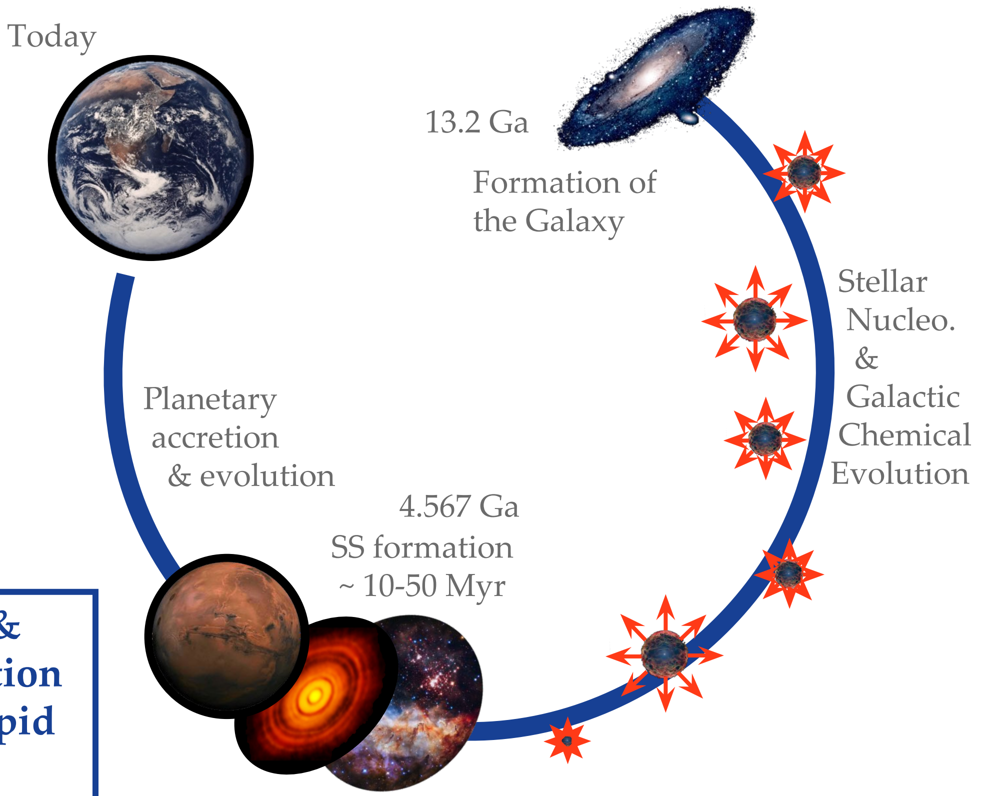
Linking the protosolar disk with the inner Solar System

Sample Return from across the Solar System – KISS Workshop
Short Course – Talk 2

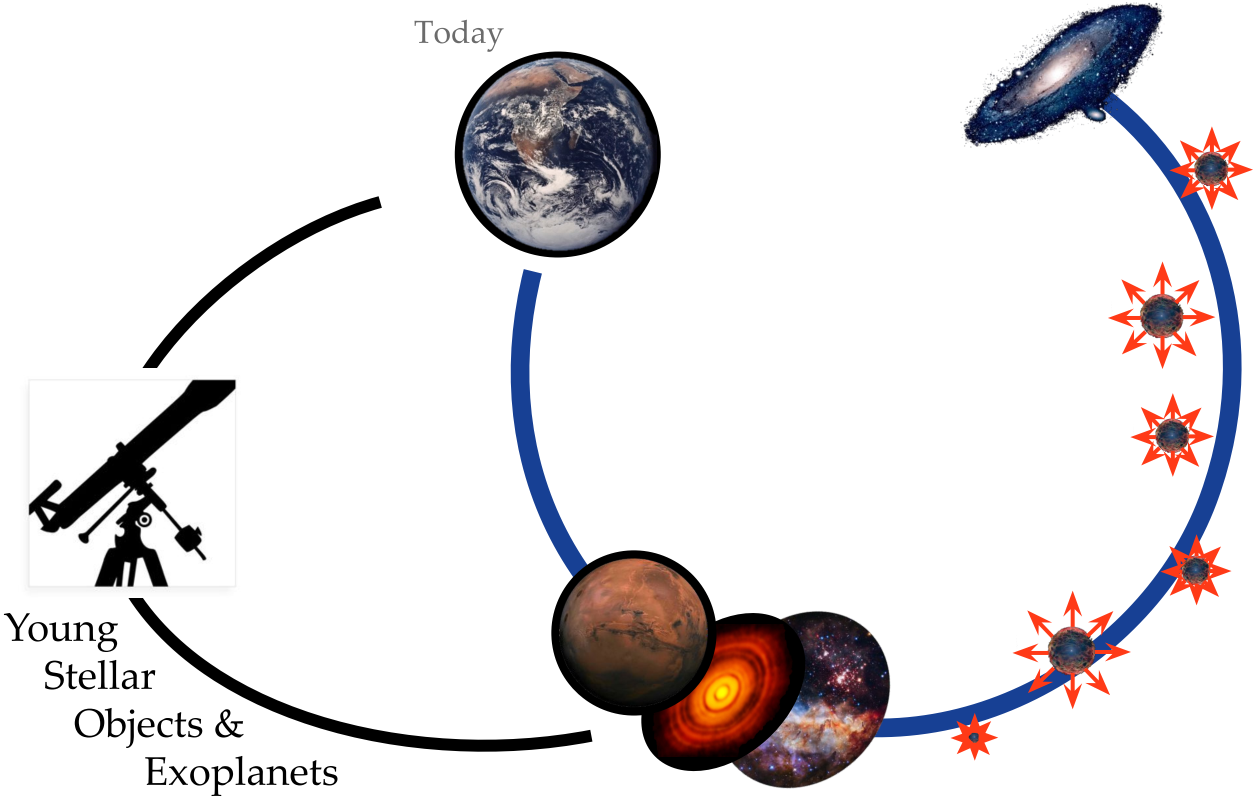
François L.H. Tissot
The Isotoparium, Caltech

A short history of everything

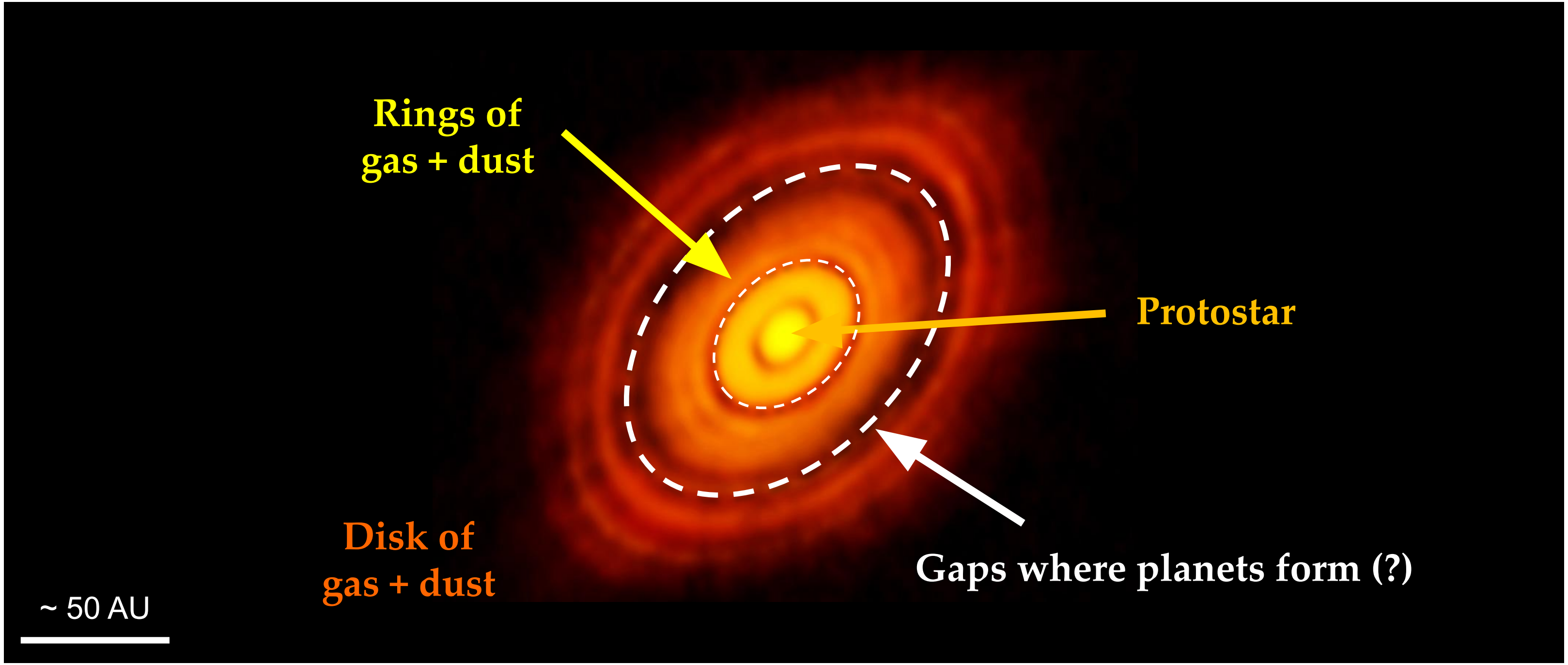


Solar System & planetary formation is a relatively rapid process!

A short history of everything



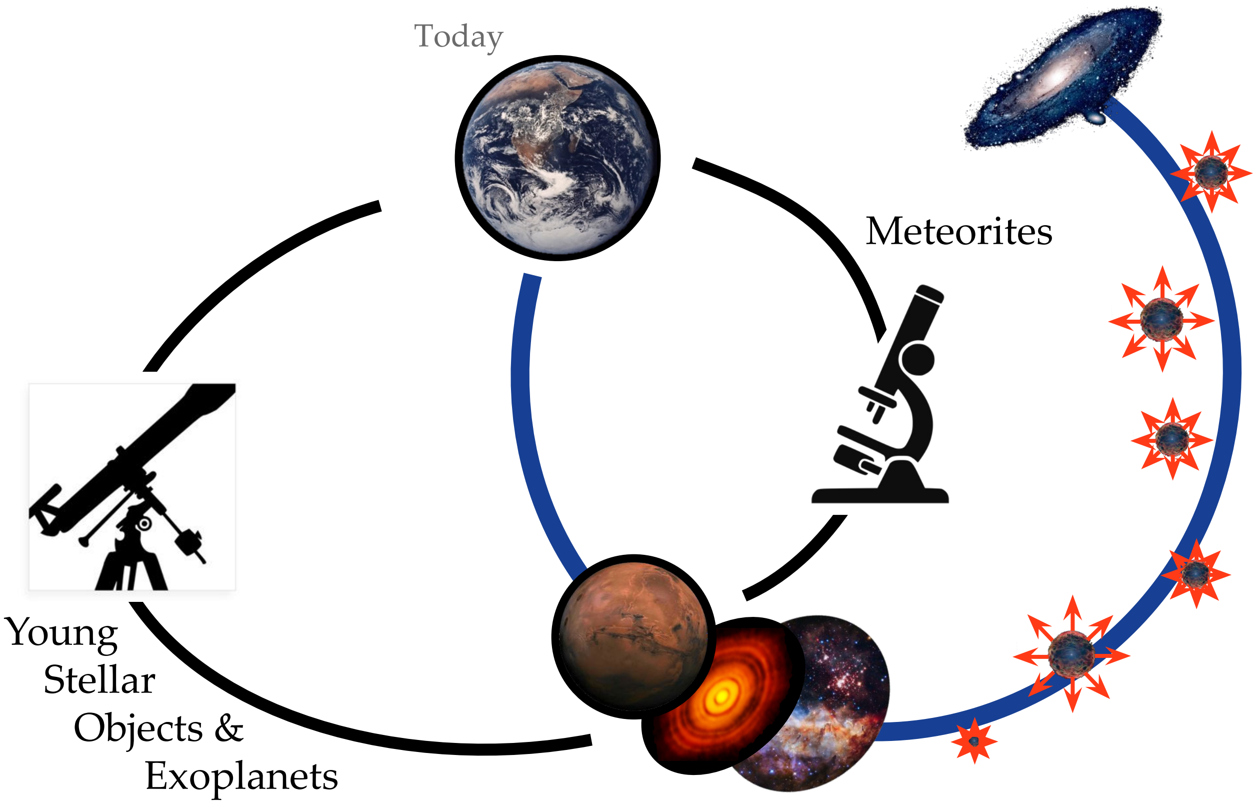
Insights into exoplanetary system formation



Actual image of a planetary system being formed
□ Is this how *our* Solar System formed?

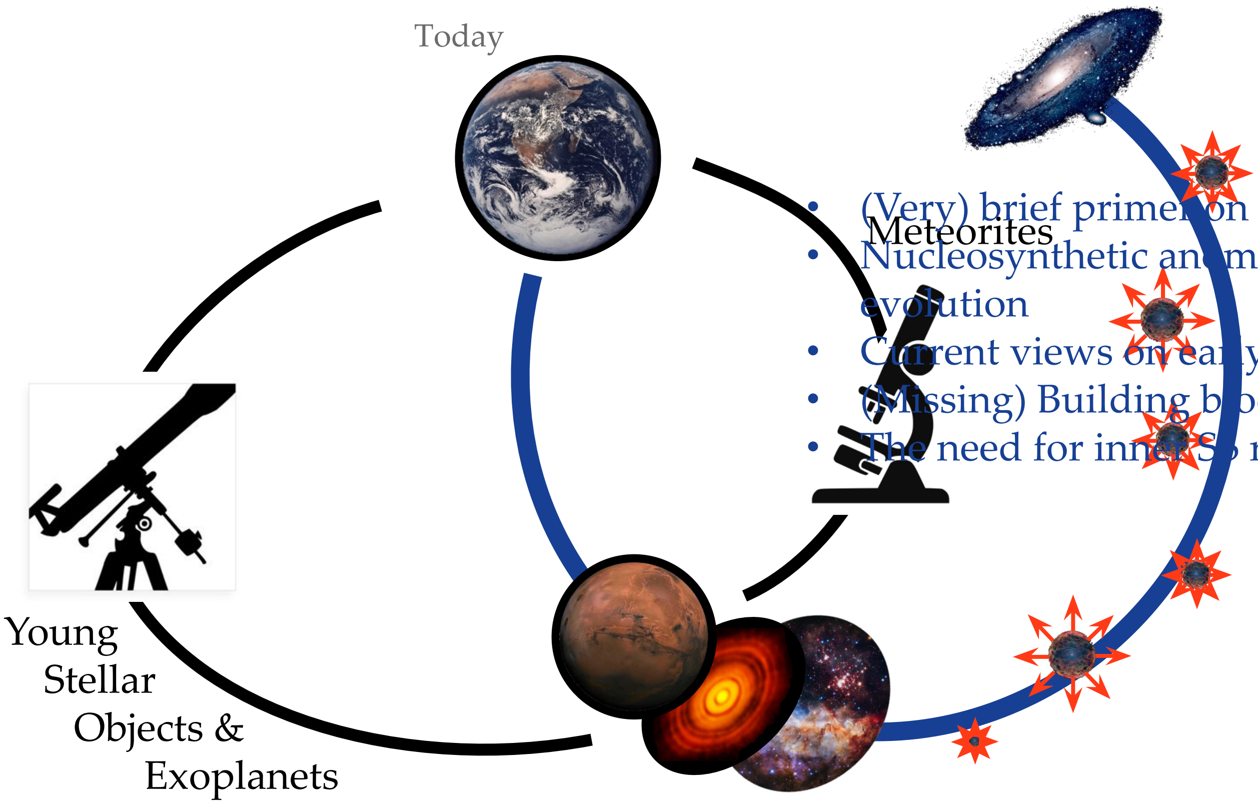
HL Tauri, ALMA

Studying Solar System formation

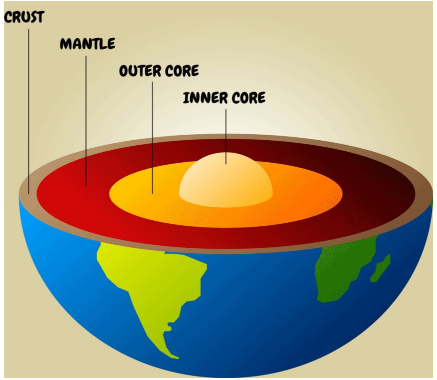


Focus and outline

- (Very) brief primer on meteorites
- Nucleosynthetic anomalies as tracers of early SS evolution
- Current views on early SS architecture
- (Missing) Building blocks of terrestrial planets
- The need for inner SS return sample missions



Part I. Meteorites: archives of planetary evolution

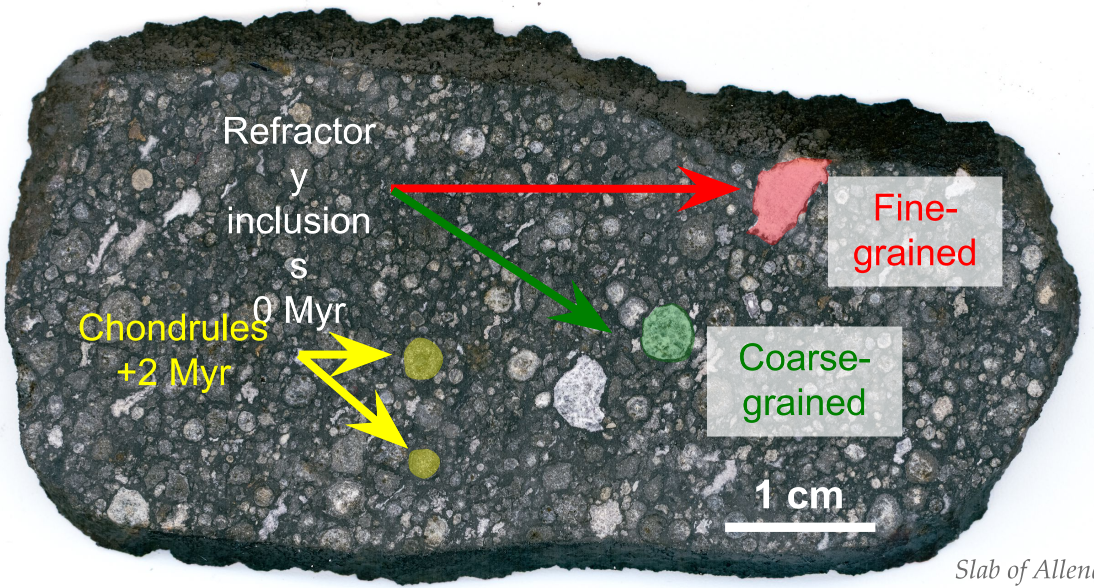


Stony meteorites
Crusts/Mantles

Stony-iron meteorites
Core-Mantle boundaries

Iron meteorites
Cores

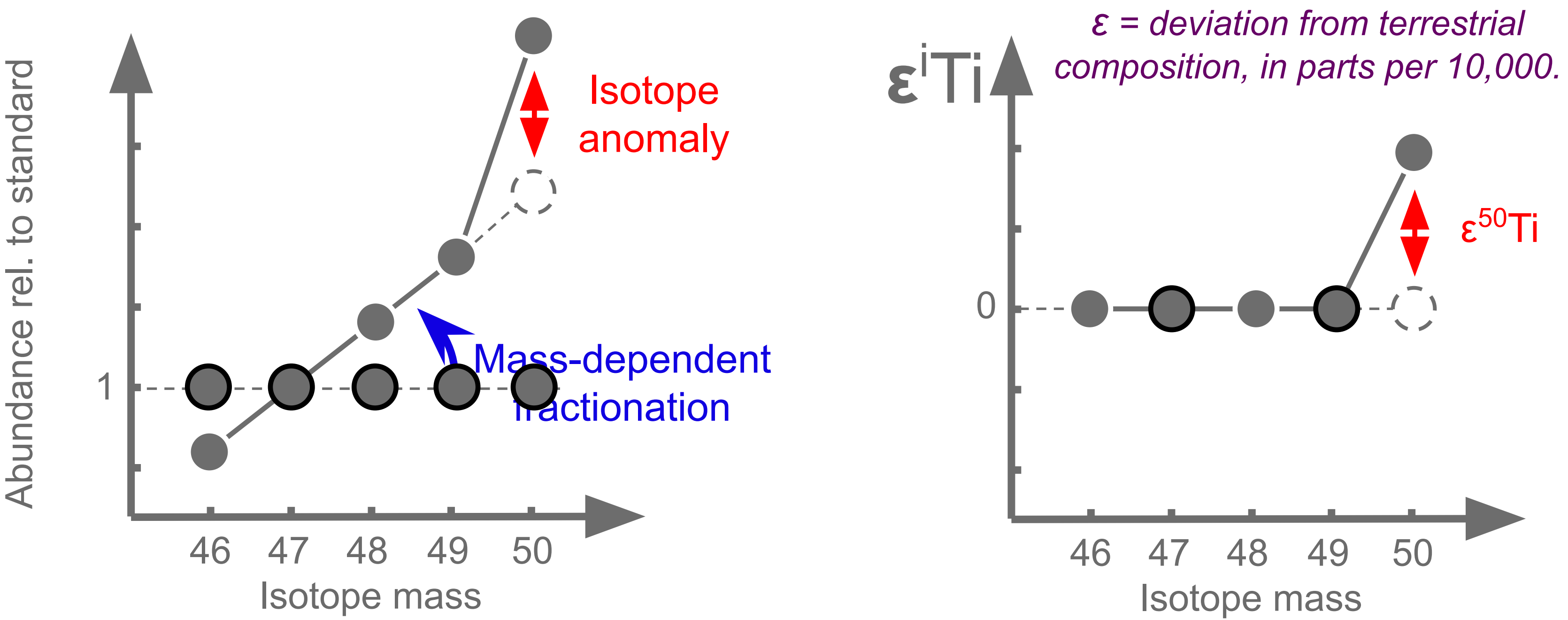
Meteorites: archives of Solar System evolution



Slab of Allende
(carbonaceous meteorite)

Chondrites = **Space sediments containing snapshots of the early Solar System composition**

Part II: Nucleosynthetic anomalies



Anomalies can be radiogenic (radioactive decay), cosmogenic (cosmic ray exposure), nucleogenic (particle capture), or…

…nucleosynthetic: reflecting difference in nucleosynthetic heritage.

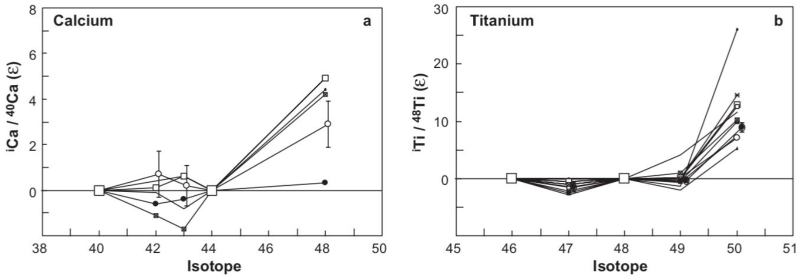
A timeline of anomalies

Early 60s: **Uniform isotopic composition of Solar System material**

□ hypothesis of homogeneization in a hot solar nebula (Cameron, 1962)

Late 60s: **Anomalies in Xe and Ne in chondrites**

70s & 80s: Anomalies in Ca, Ti, Sr, Ba, Nd, Sm **in refractory inclusions**.



Birck (2004)

Late 80s: In an attempt to dissolve the carrier of anomalous Xe...

Residue left!

Nano diamonds

(Lewis et al. 1987)

□ **Discovery of presolar grains**

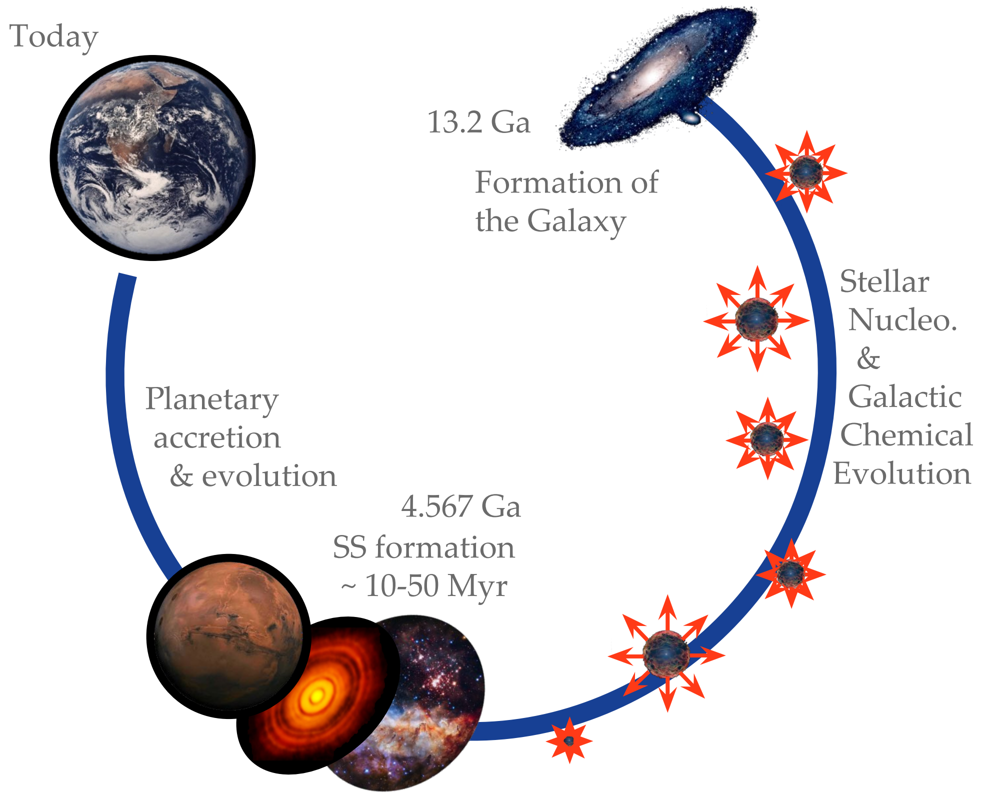
Early 00s and on: Nucleosynthetic anomalies in bulk undifferentiated and iron meteorites

□ **Isotopic heterogeneity from micron-scale to planetary-scale**

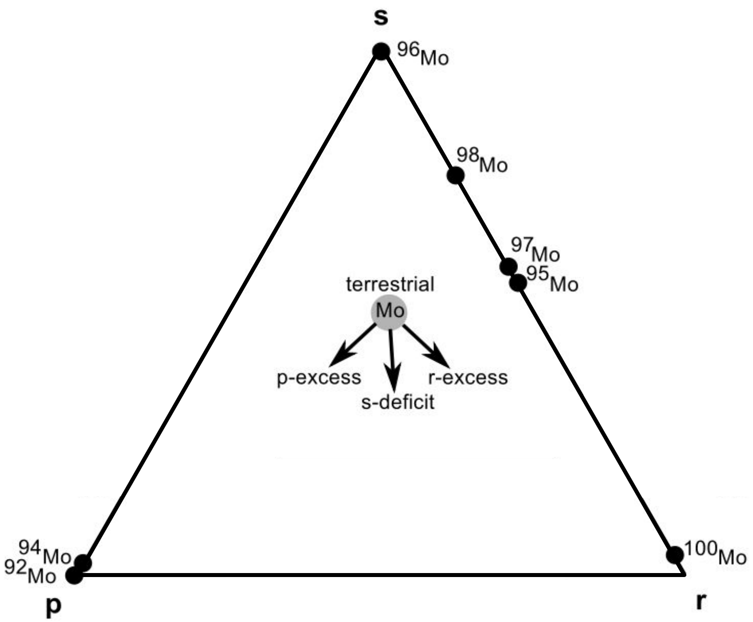
Powerful cosmic tracers

Nucleosynthetic anomalies inform us on:

- Stellar sources to the SS
- Early Solar System architecture
- Genetic links between planetary bodies
- Material mixing/transport in the disk



Nucleosynthetic anomalies track stellar processes

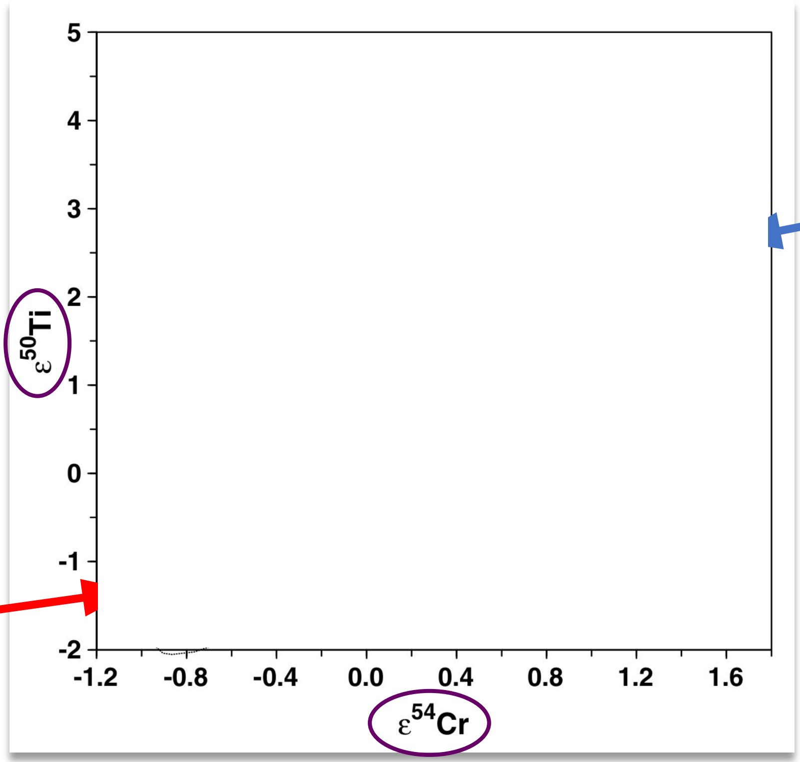


Patterns diagnostic of nucleosynthetic processes

Burkhardt et al. (2011)

Part III. Isotope anomalies and the SS architecture

ε = deviation from terrestrial composition, in parts per 10,000.



Rich in water and volatiles.
Lower T material

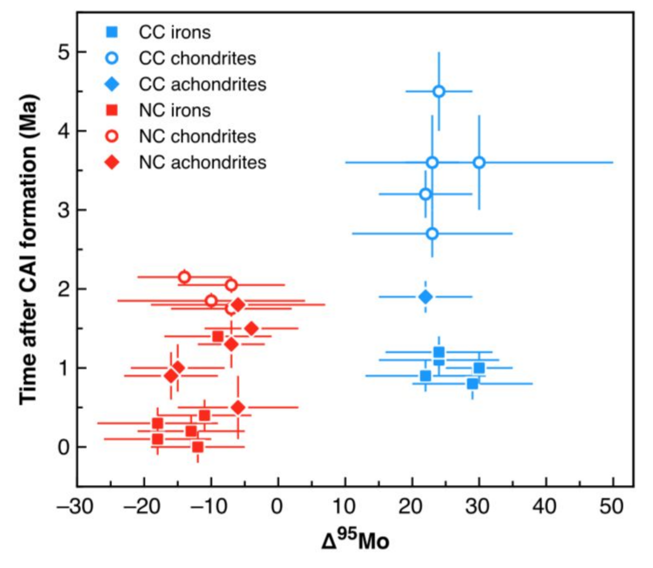
Extremely water and volatile poor.
High T material

**Two main reservoirs kept separate.
In time? In space? Both?**

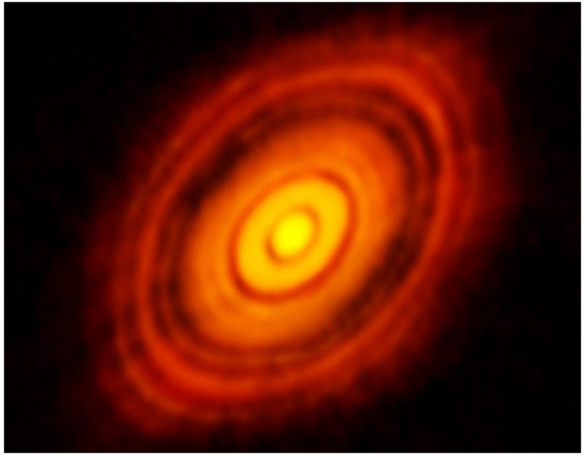
Separated by what?

Warren (2011)

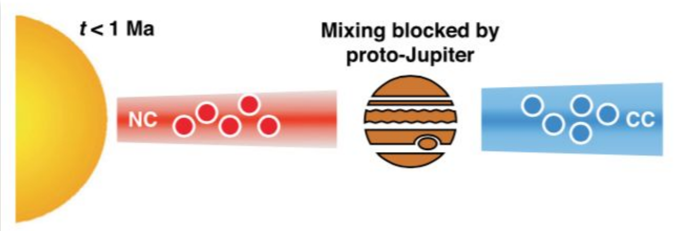
Long-term preservation of disk heterogeneity



Kleine et al (2020)



HL Tauri, ALMA



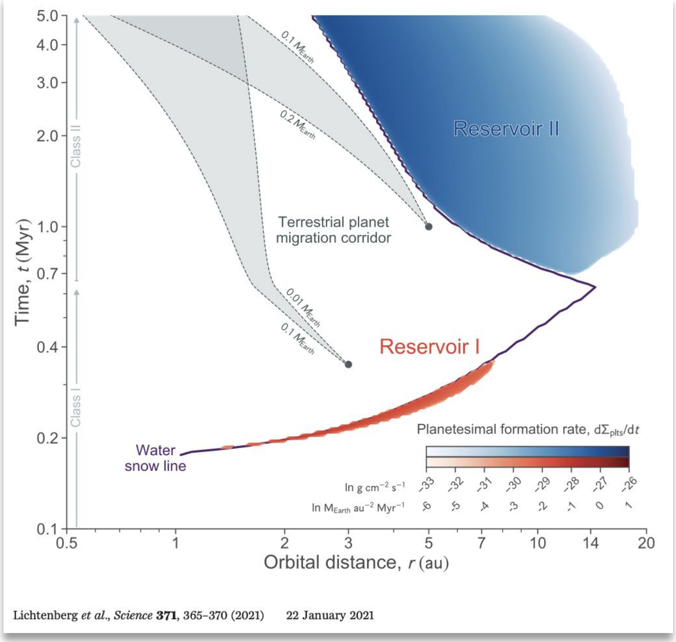
Kleine et al (2020)

NC and CC reservoir co-existed!

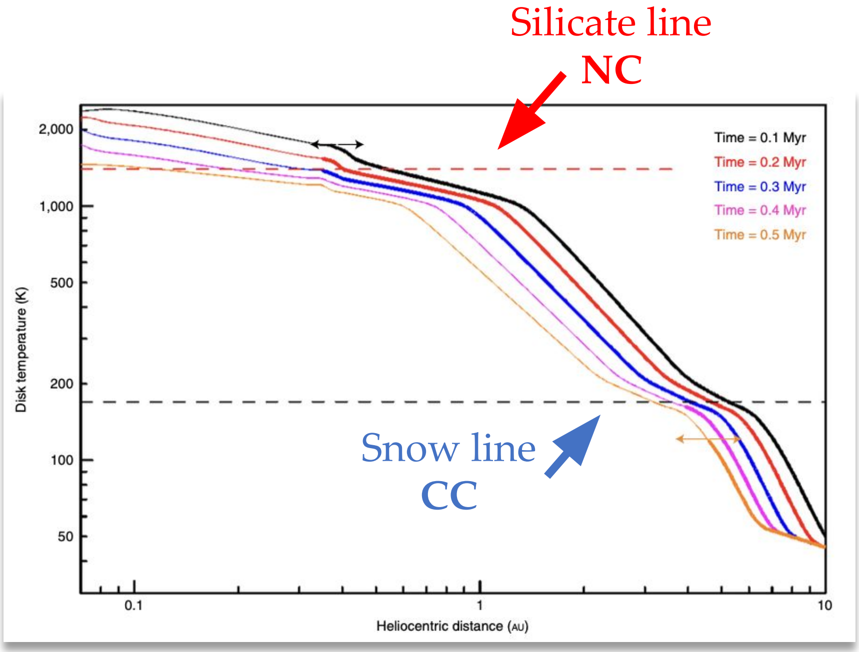
How can we separate and preserve 2 major reservoirs formed within 1 Myr of SS formation?

Rapid formation of Jupiter's core?

Long-term preservation of disk heterogeneity



Lichtenberg et al (2021)

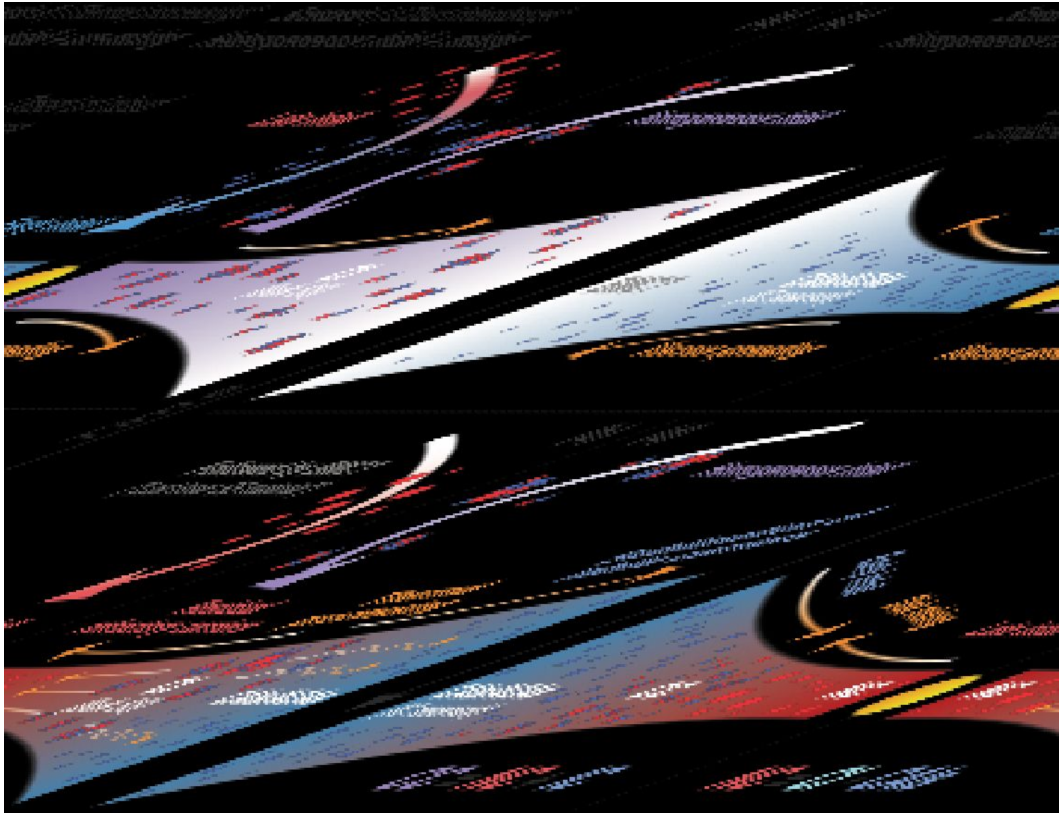


Morbidelli et al (2022)

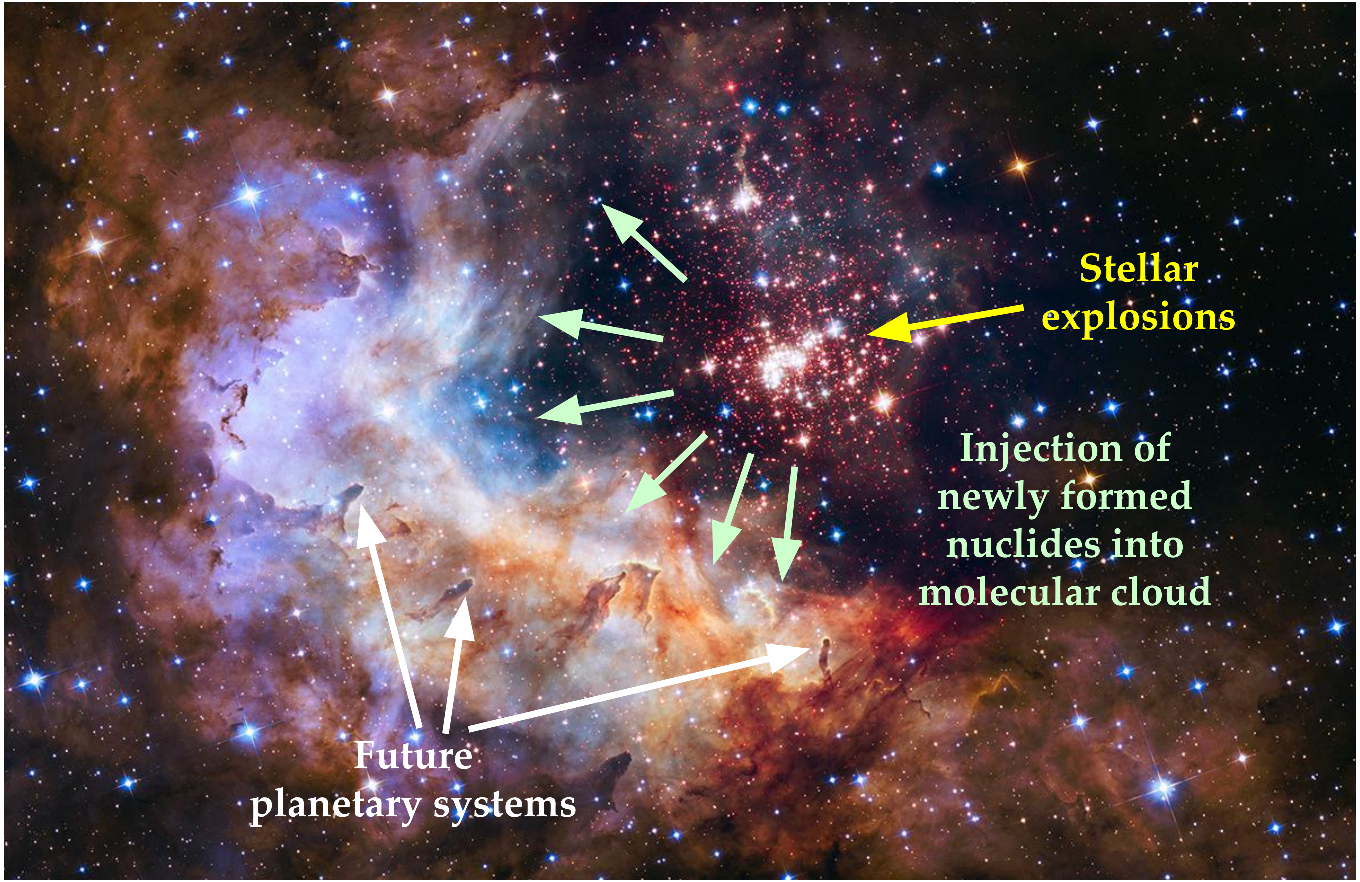
Migration of snow line

Formation at different T: silicate lines *vs* snow lines

Origin of disk heterogeneity: current debate

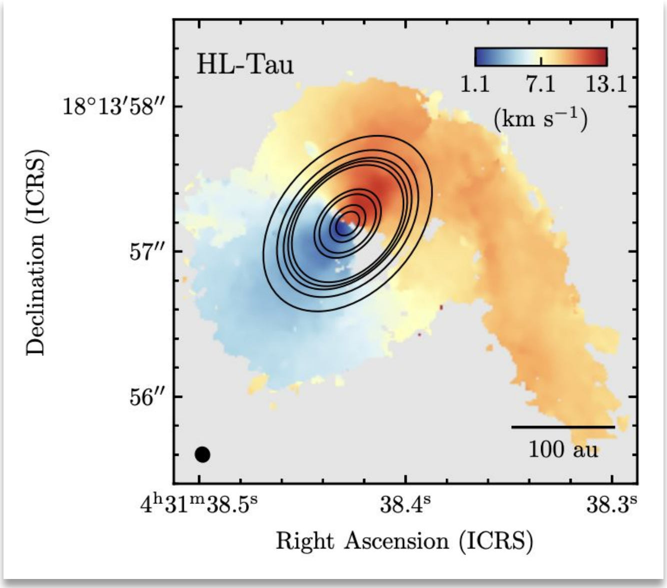


Origin of disk heterogeneity



Westerlund 2 star cluster

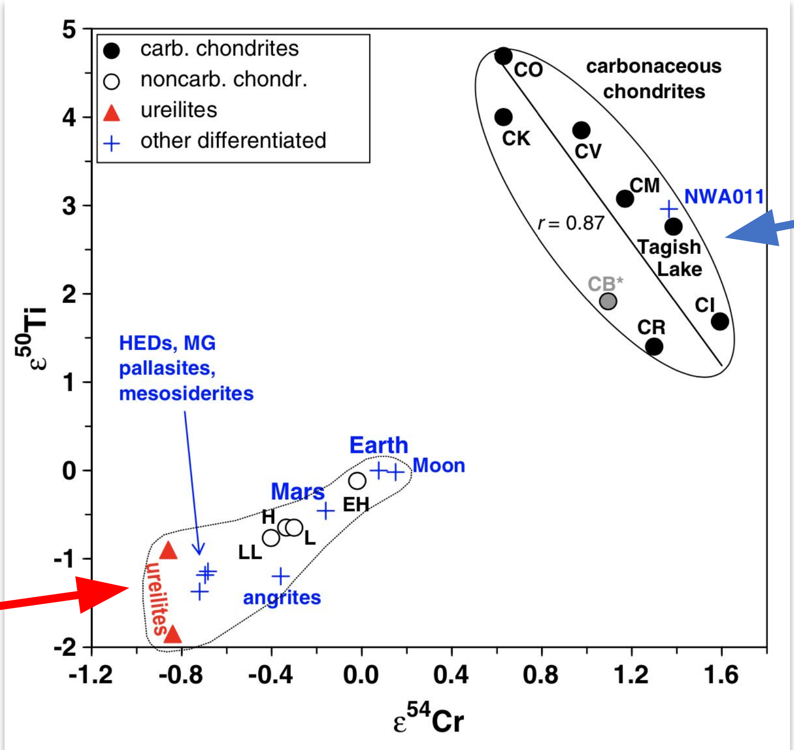
Origin of disk heterogeneity: streamers?



Streamers are ubiquitous and can deliver isotopically distinct materials to protoplanetary disks

Pineda et al. (2023)

IV. Building blocks of terrestrial planets



Rich in water and volatiles.
Lower T material

Earth's water source?

Extremely water and volatile poor.
High T material

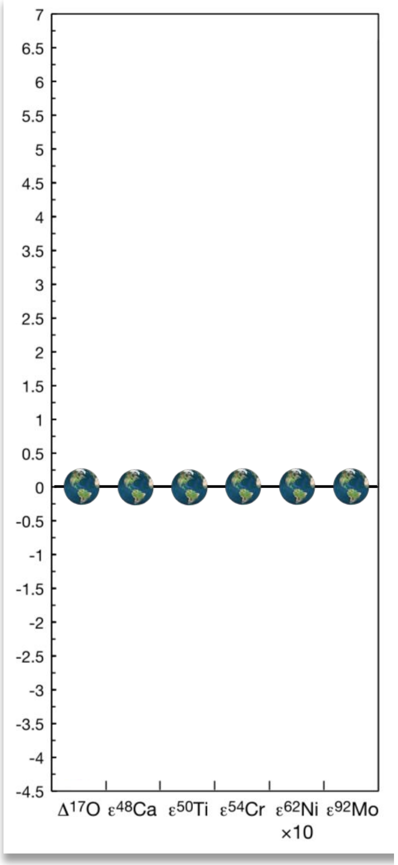
Earth's main building blocks?

Earth = x% NC + (1-x)% CC

(e.g., 90% EC + 10 % CI or 60% Ureilites + 40% CI)

Warren et al (2011)

The building block of planets?



Similar minimization exercises since the 1990s, using:
- Elemental ratios
- O, Ti, Cr, Ni, Mo, Ca, Sr isotopes
- Chondrites and differentiated meteorites

(e.g., Lodders & Fegley 1997; Sanloup+ 1999, Fitoussi+ 2016; Brasser+ 2018;... and many more!)

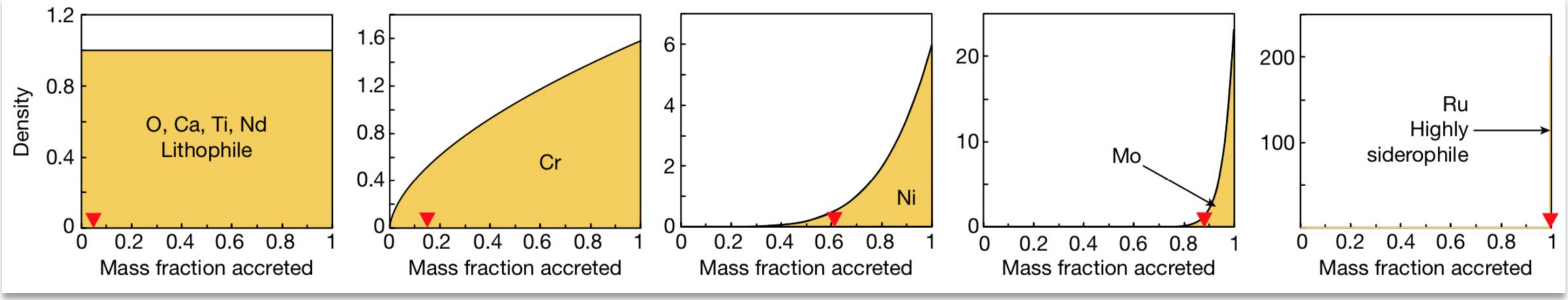
Main limitations:

□ **Answer = f(input parameters)**
- # of element/isotope systems considered
- Sampling bias (all possible building blocks?)

Chondrites only: Earth is enstatite-like (~90%)
Chondrites & achondrites: Earth & Mars >50% angrite.

□ **Latter is consistent with recent model of planetary formation via accretion of differentiated planetesimals.**

The building block of planets: Accretion history

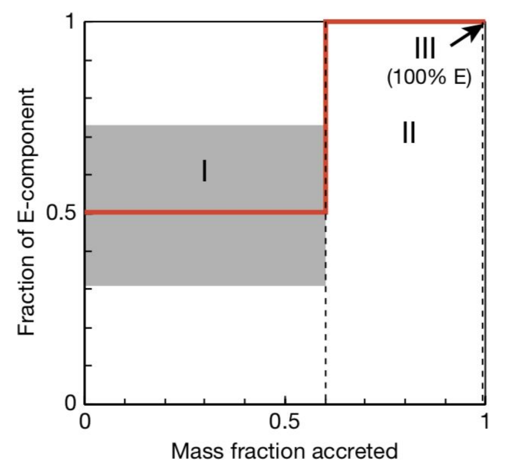


Metal/silicate partitioning needs to be considered to compare Earth vs potential building blocks

 Elements record different periods in a planet's accretion

Assuming an exhaustive collection of potential building blocks, could reconstruct the accretion history of a planet!

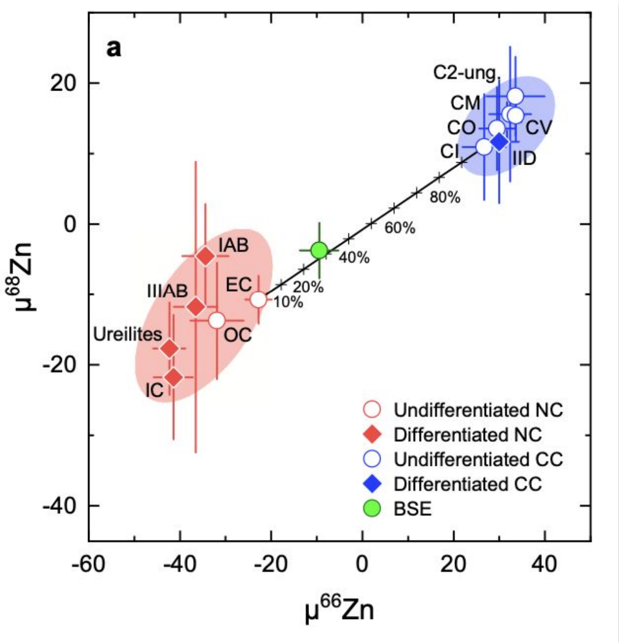
(Here Earth mainly accreted from enstatite-like material)



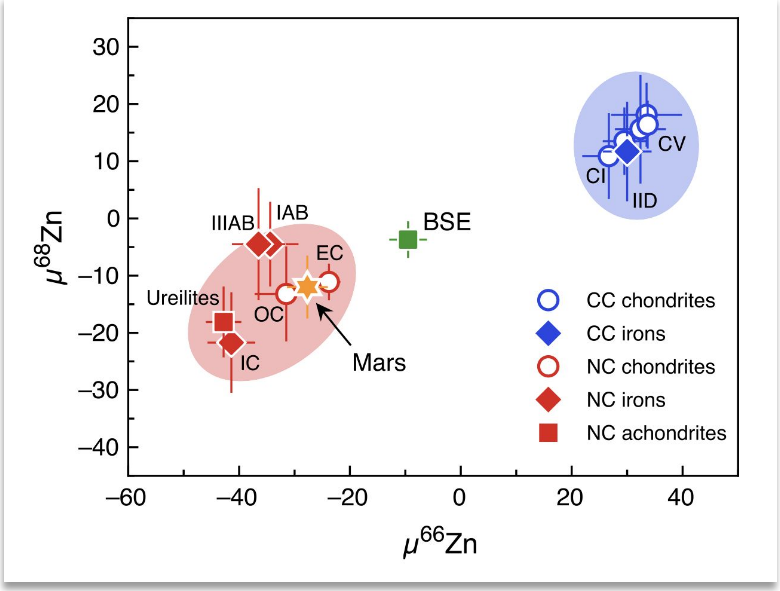
Dauphas (2017)

 Do we have an exhaustive collection of potential building blocks?

Source of (moderately) volatiles in terrestrial planets



Steller et al. (2022)



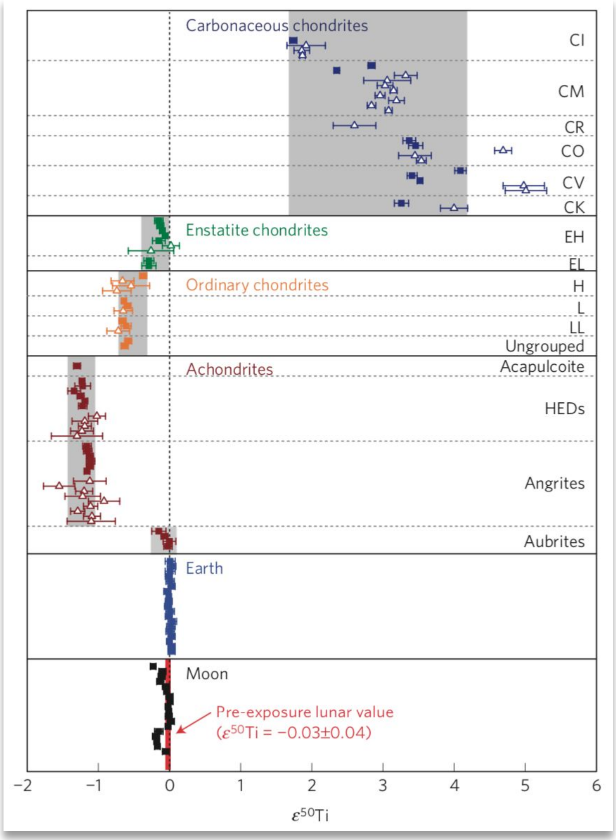
Kleine et al. (2023)

30% of Earth's Zn is of CC origin

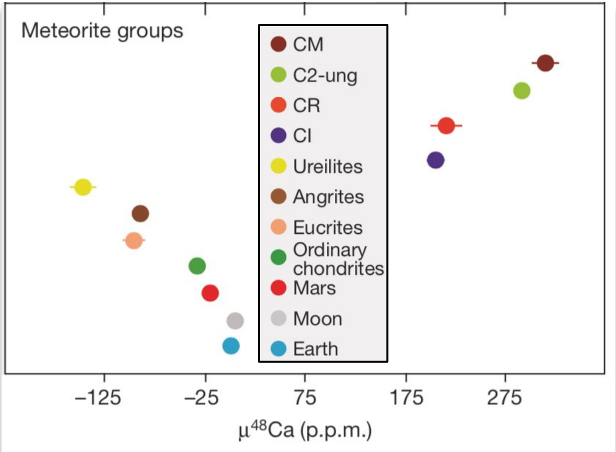
~0% of Mars' Zn is of CC origin

Clear differences in accretion history,
□ what about Venus and Mercury?

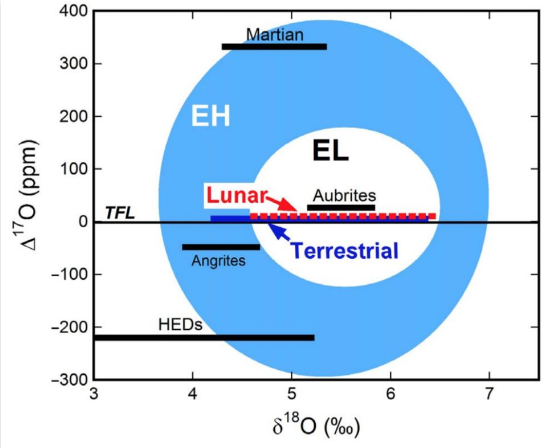
The Earth-Moon isotopic kinship



Zhang et al. (2012)



Schiller et al. (2018)



Greenwood et al. (2018)

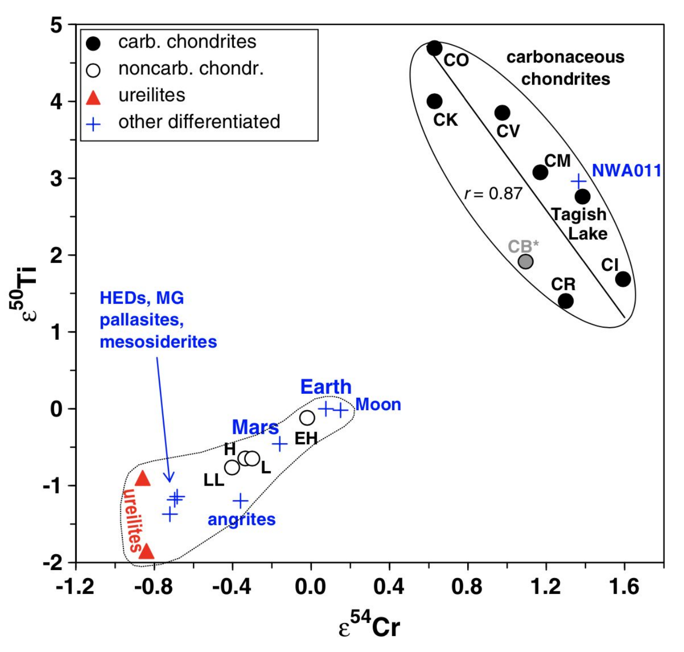
- Earth-Moon isotopically identical, incl. for refractory elements.

Either Theia is isotopically Earth-like

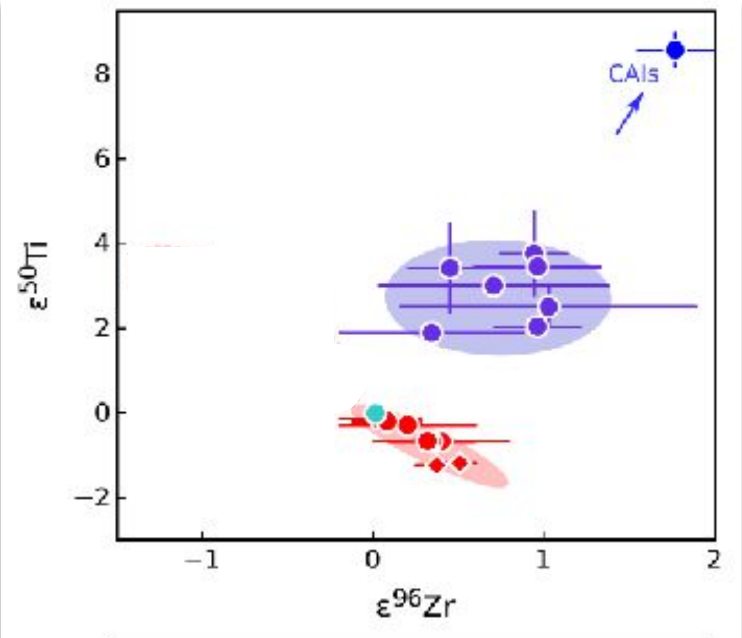
or

Earth and Theia completely equilibrated upon impact (synestia)

Missing building blocks of terrestrial planets



Warren (2011)



Burkhardt (2021)

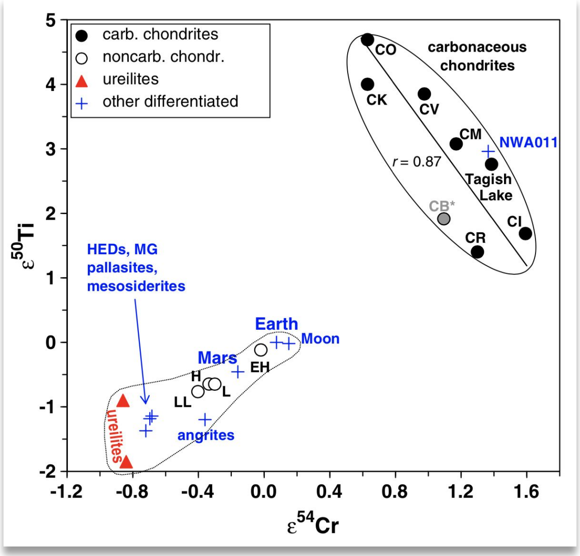
Earth = x% NC + y % CC

(e.g., 90% EC + 10 % CI
or 60% Ureilites + 40% CI)

Problem as Earth is an end-member

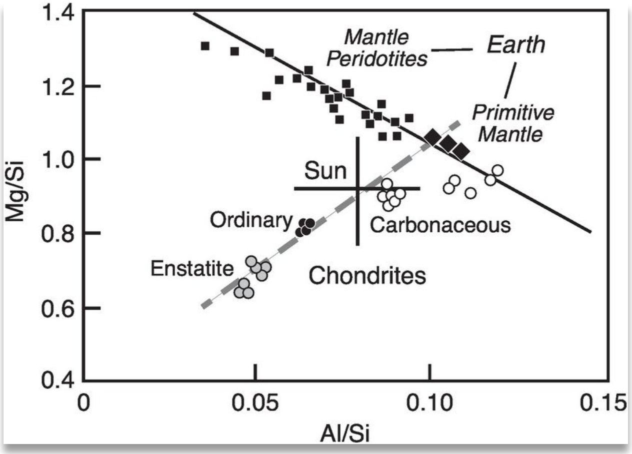
Earth = … 100% Earth? *(or 100% EC)*

Earth = EC ?



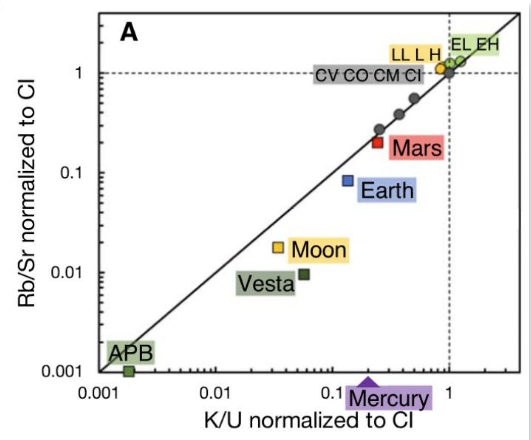
Warren (2011)

Major elements



McSween & Huss (2022)

Moderately volatile elements

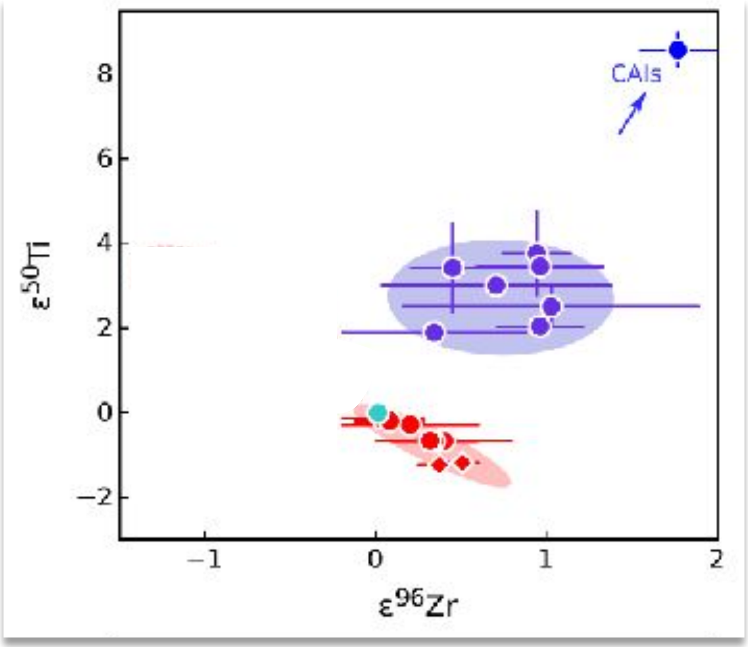


Dauphas et al. (2022)

Isotopically, Earth closest to enstatite chondrites

Chemically, Earth is furthest from enstatite chondrites

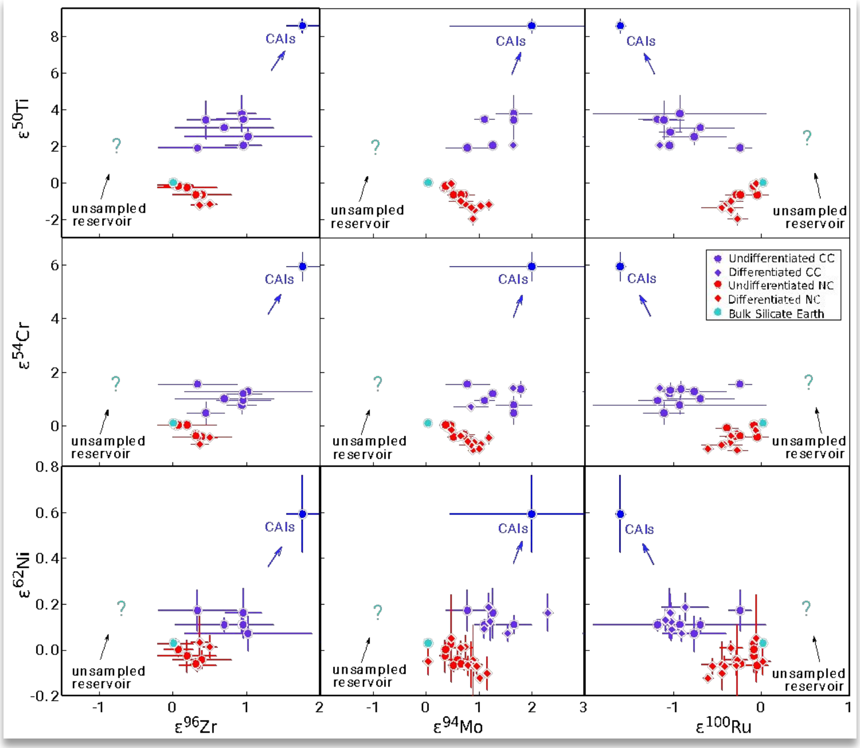
Unsampled reservoir?



 Are we missing a major building block of the Earth?

Unsampled reservoir?

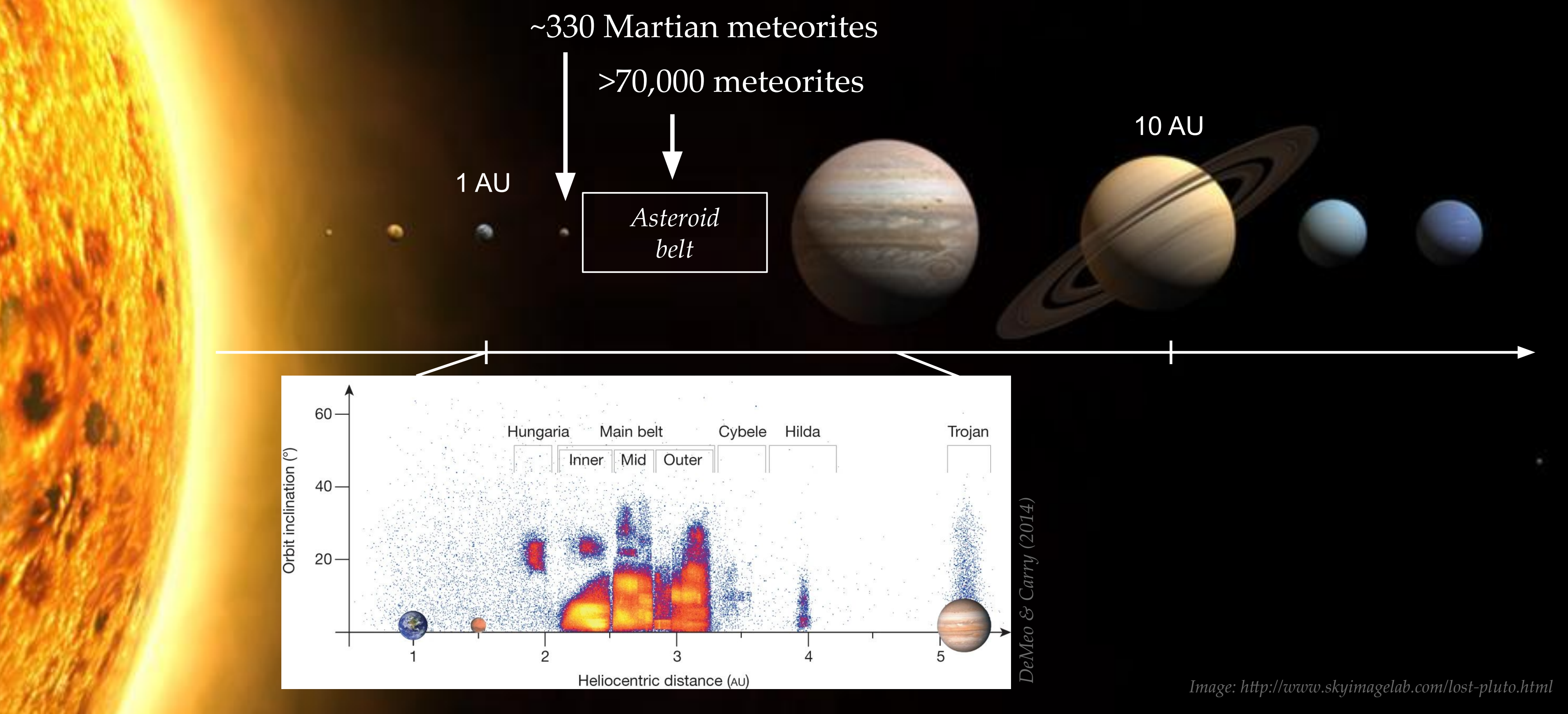
Observation in numerous isotope-isotope spaces.



Correlations even for elements with different geochemical behaviors (lithophile/ siderophile) *(e.g., Ti, Mo, Zr).*

 Was this unsampled reservoir the inner SS material?

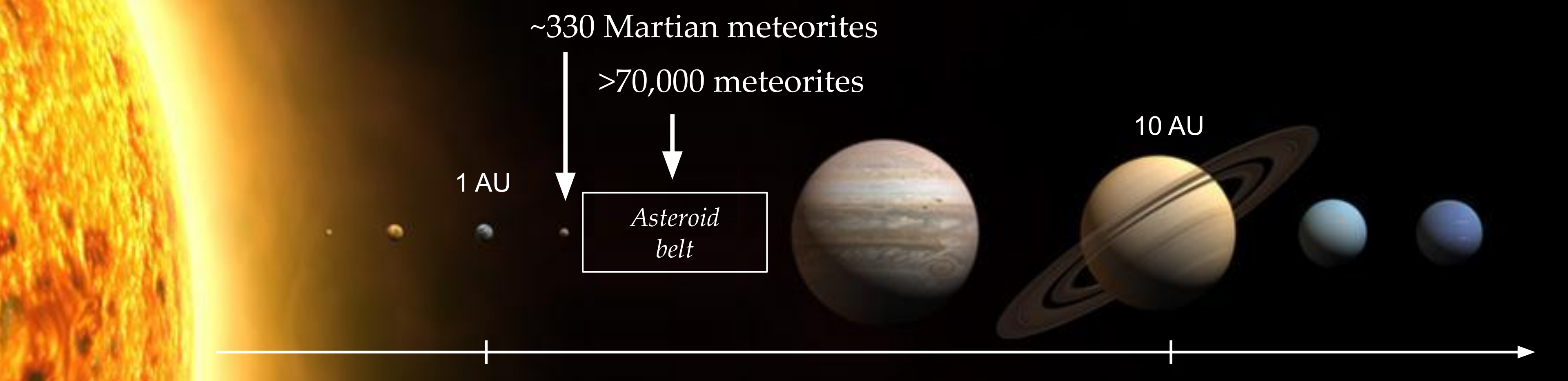
The need for return samples: a biased collection



DeMeo & Carry (2014)

Image: http://www.skyimagelab.com/lost-pluto.html

The need for return samples: a biased collection



1) Unlikely that **<u>all SS materials</u>** are stored in the asteroid belt.

2) Even more unlikely that **<u>a fragment of each</u>** is in our museum collections.

Image: http://www.skyimagelab.com/lost-pluto.html

Inner SS return sample: key questions

1) What is the composition of the inner SS?

- Is it homogeneous/uniform?
  - Would readily Earth and Moon isotopic kinship
- Is there a missing end-member currently lacking from our collections?
  - Most readily addressed by return mission

2) What was the volatile accretion history of terrestrial planets?

- Did Earth and Venus form with the same volatile budget?
  - Venus return mission is needed.

3) Is the chondritic model of composition of the Earth adequate?

- Are terrestrial planet building blocks chondritic?
- If not, why are most of the building blocks of the Earth lacking from our meteorite collections?

Conclusions

Nucleosynthetic anomalies **testify to the incomplete homogenization of presolar materials** during solar system formation.

They have become **invaluable tracers** of: (i) genetic relationships, (ii) early SS architecture, and (iii) mixing and transport in the early SS.

1st order dichotomy between carbonaceous and non-carbonaceous SS materials.

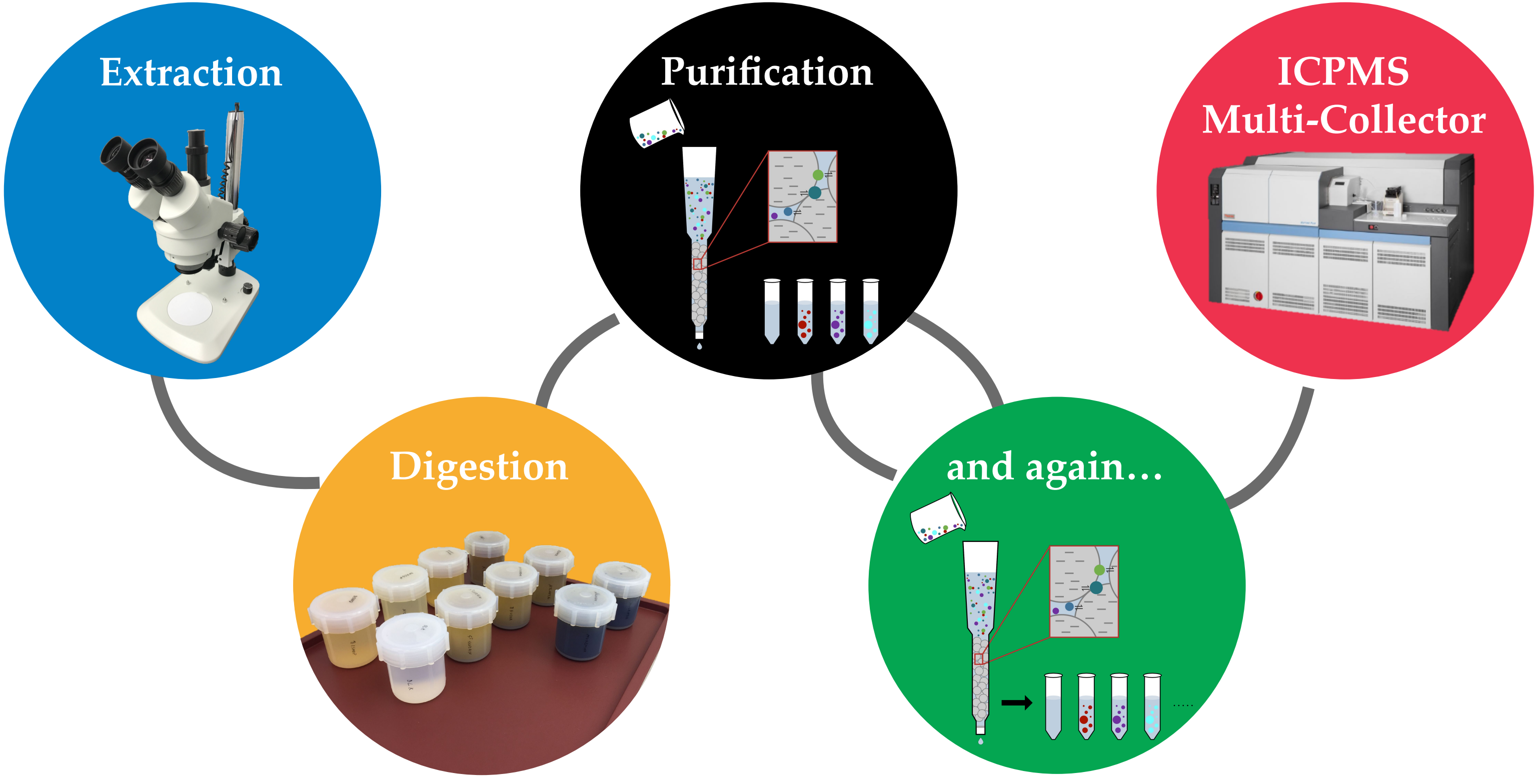
Origin of the dichotomy is a major topic of research:
(i) Early formation of Jupiter? (ii) Snow line migration?
or (iii) Condensation at distinct locations?

Origin of isotopic heterogeneity is also debated: **inheritance vs unmixing.**

Inner SS sample return will be key understanding:
(i) Inner SS chemistry, (ii) Bulk composition of the Earth,
and (iii) Accretion history of terrestrial planets (including volatiles)


Thank you for your attention!
Image credit: JPL/Nasa

Isotope cosmochemistry workflow



The Isotoparium

Sample preparation in a dust-free, metal-free, acid-resistant environment.