Dynamical Modeling of Early Solar System Formation.
Current Understanding and Open Questions I

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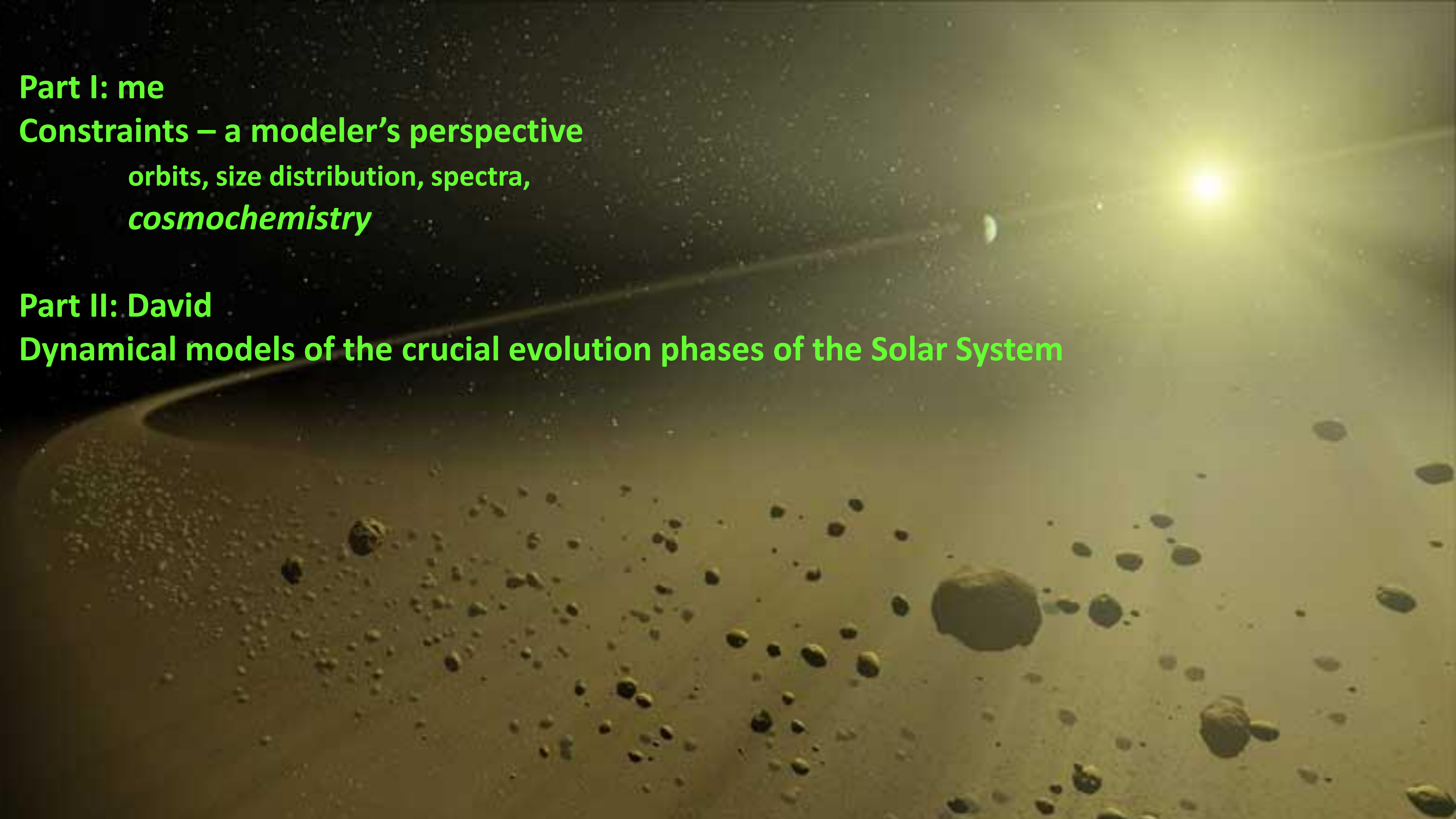
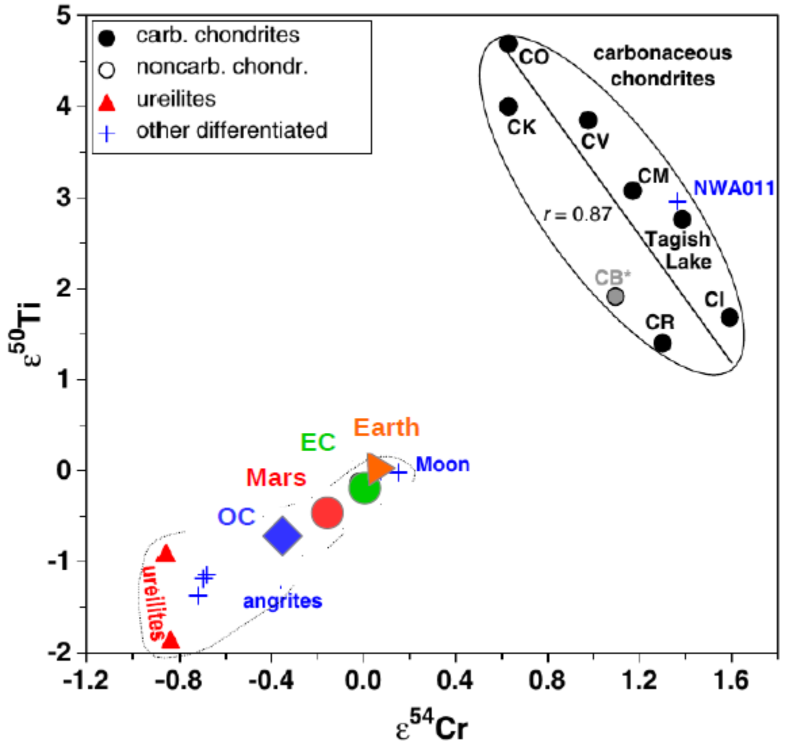
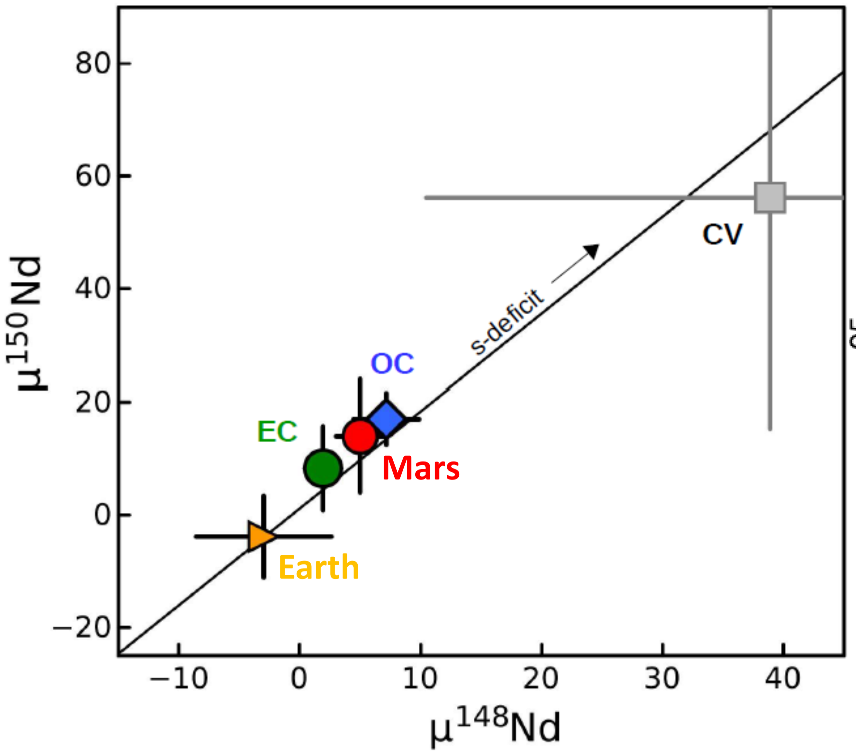


Part I: me
Constraints – a modeler’s perspective
orbits, size distribution, spectra,
cosmochemistry
Part II: David
Dynamical models of the crucial evolution phases of the Solar System

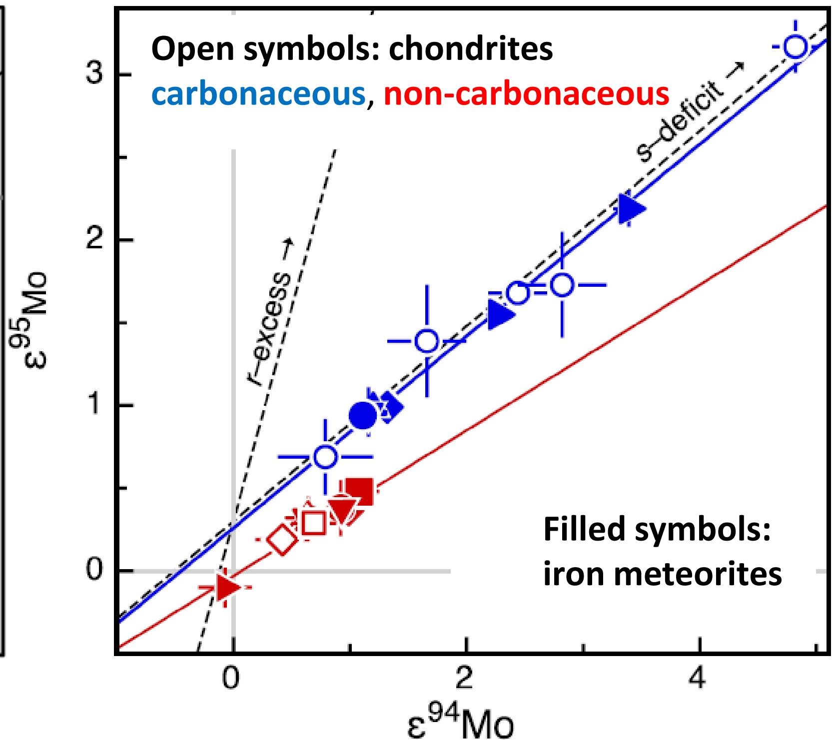
The isotopic dichotomy



Warren, 2011



Burhardt et al., 2016



Kruijer et al., 2017

Why is it important?

Two options to explain the dichotomy: either NC and CC accreted at different times in a disk that was changing of composition or they accreted at different places in a heterogenous disk.

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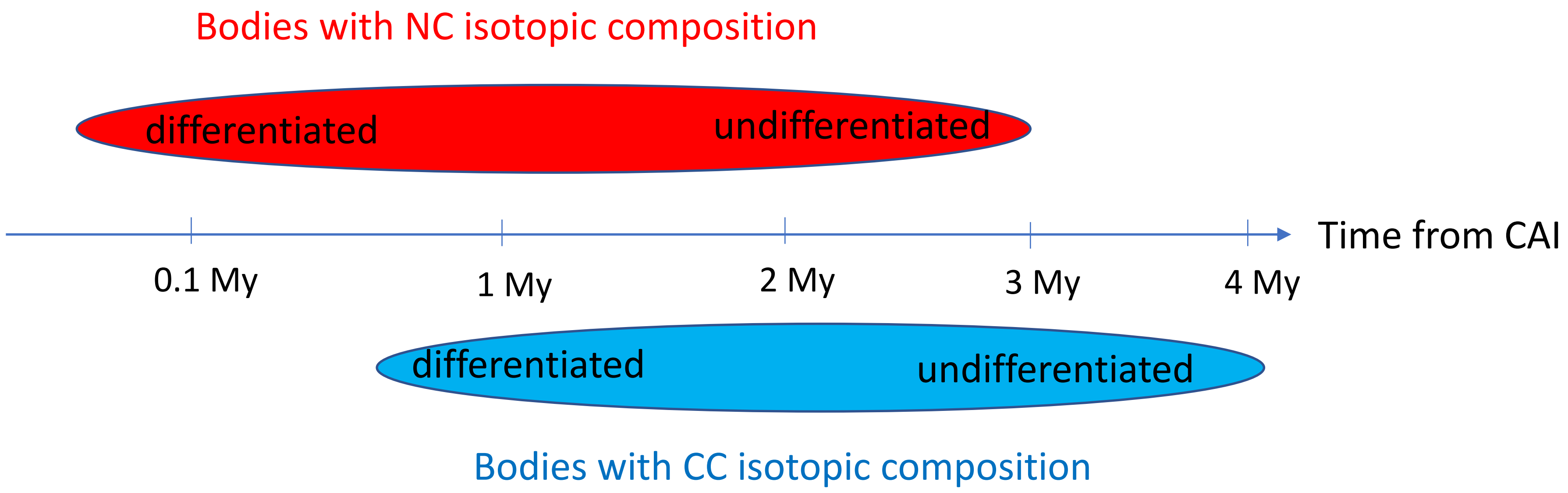

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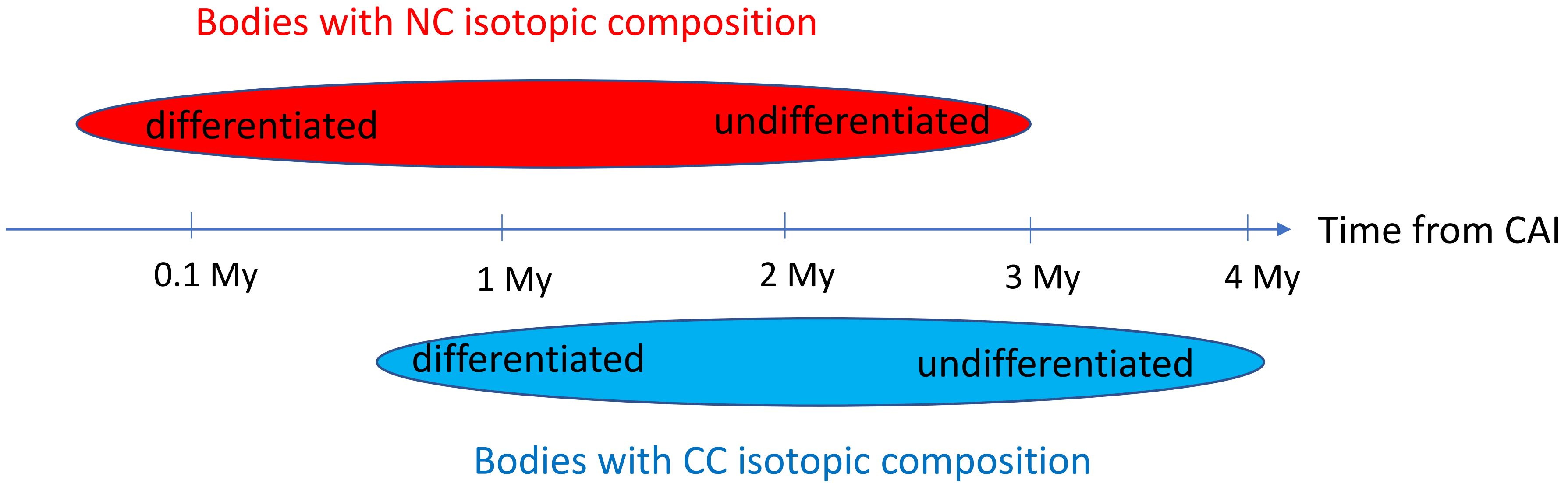
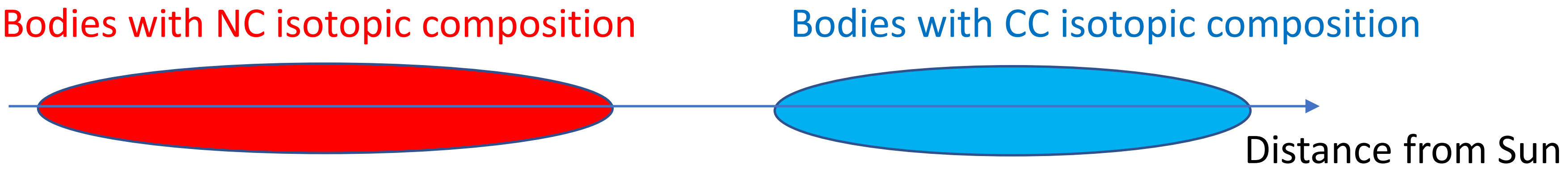
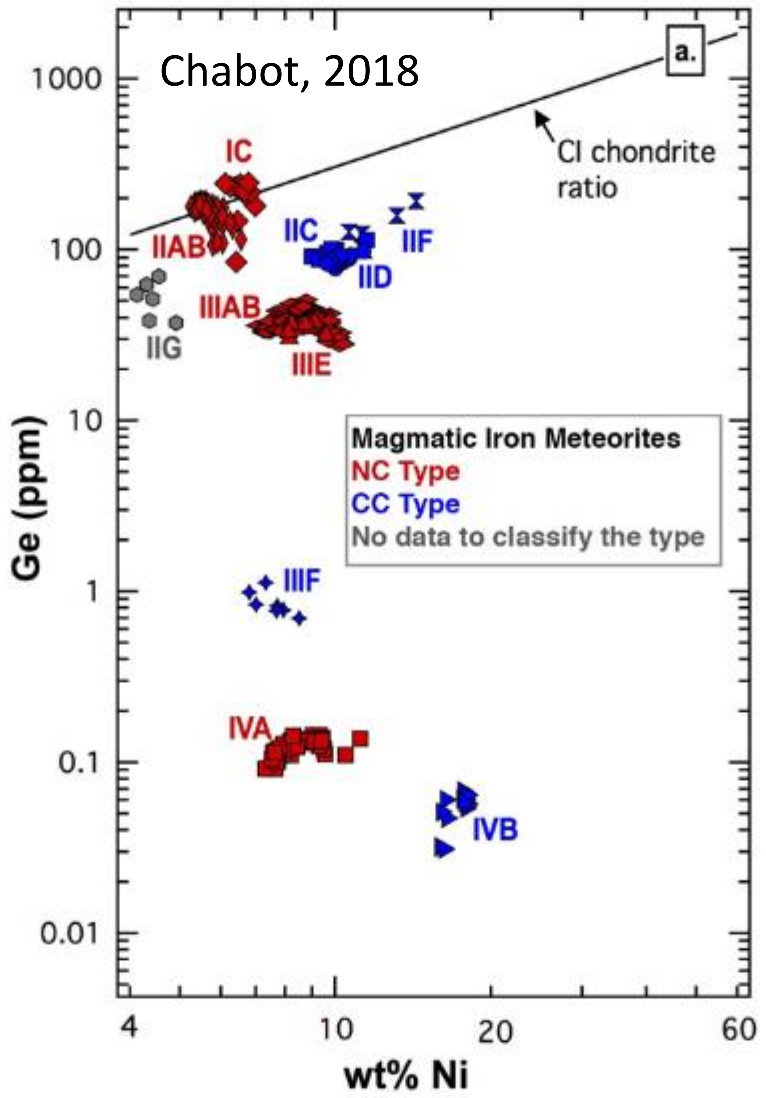
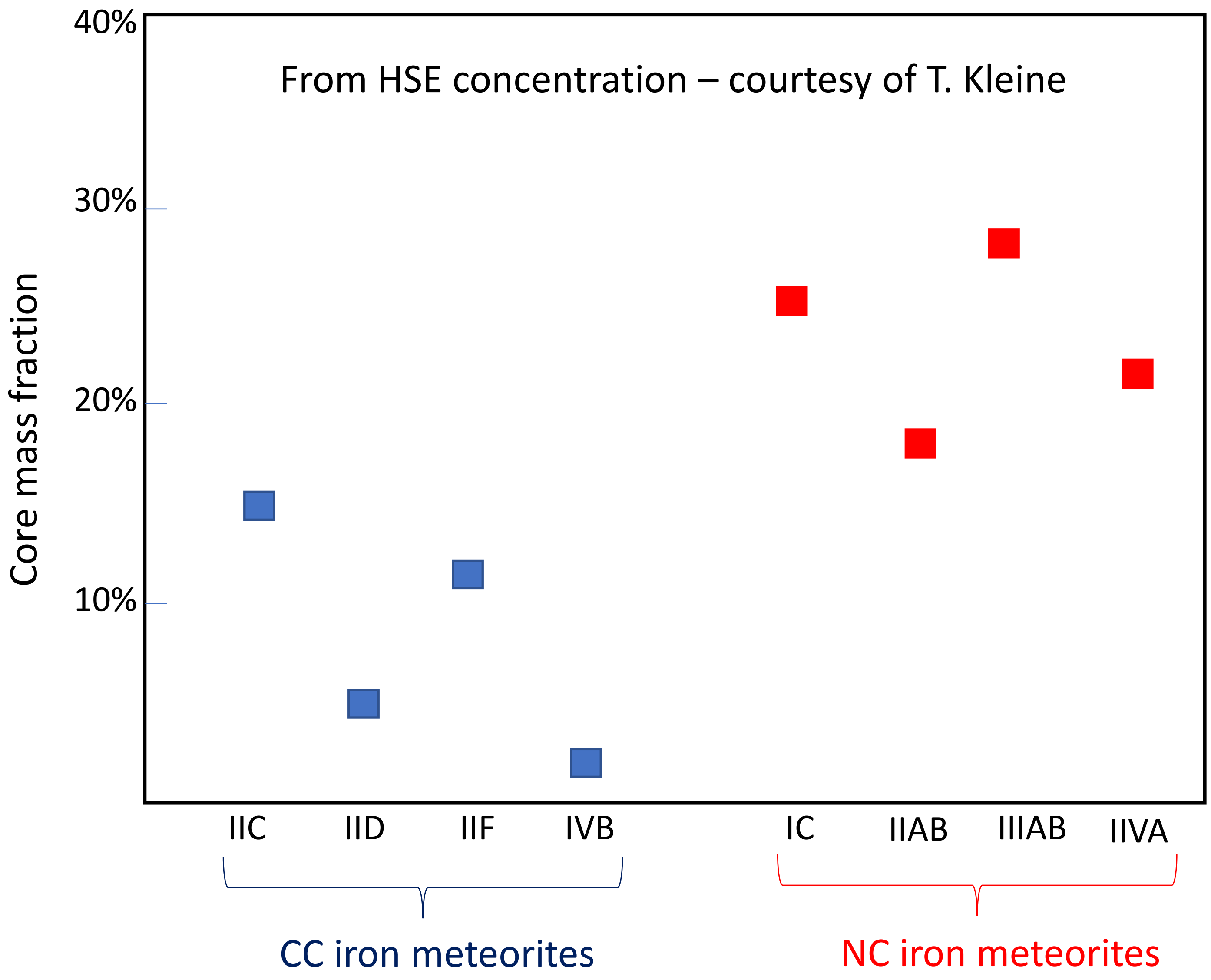


Hence, they must have been separated in space, with a dynamical barrier precluding CC dust to reach the NC reservoir **(Kruijer et al., PNAS, 2017):**



CC iron meteorites formed from more oxidized parent bodies than NC iron meteorites

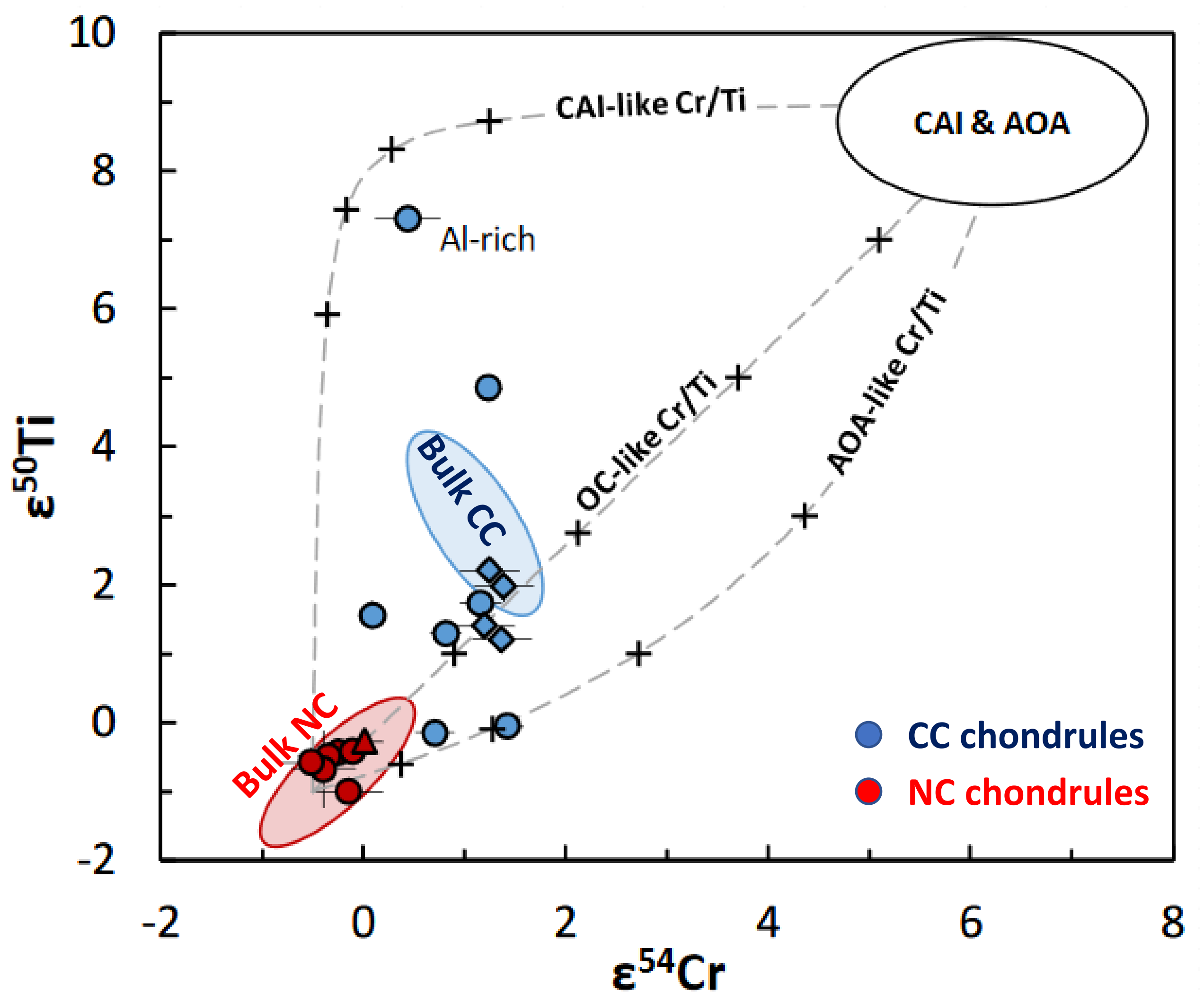




CC irons have larger Ni and HSE abundances, suggesting that a smaller fraction of the p.b. bulk iron went into the core

Origin of the isotopic dichotomy

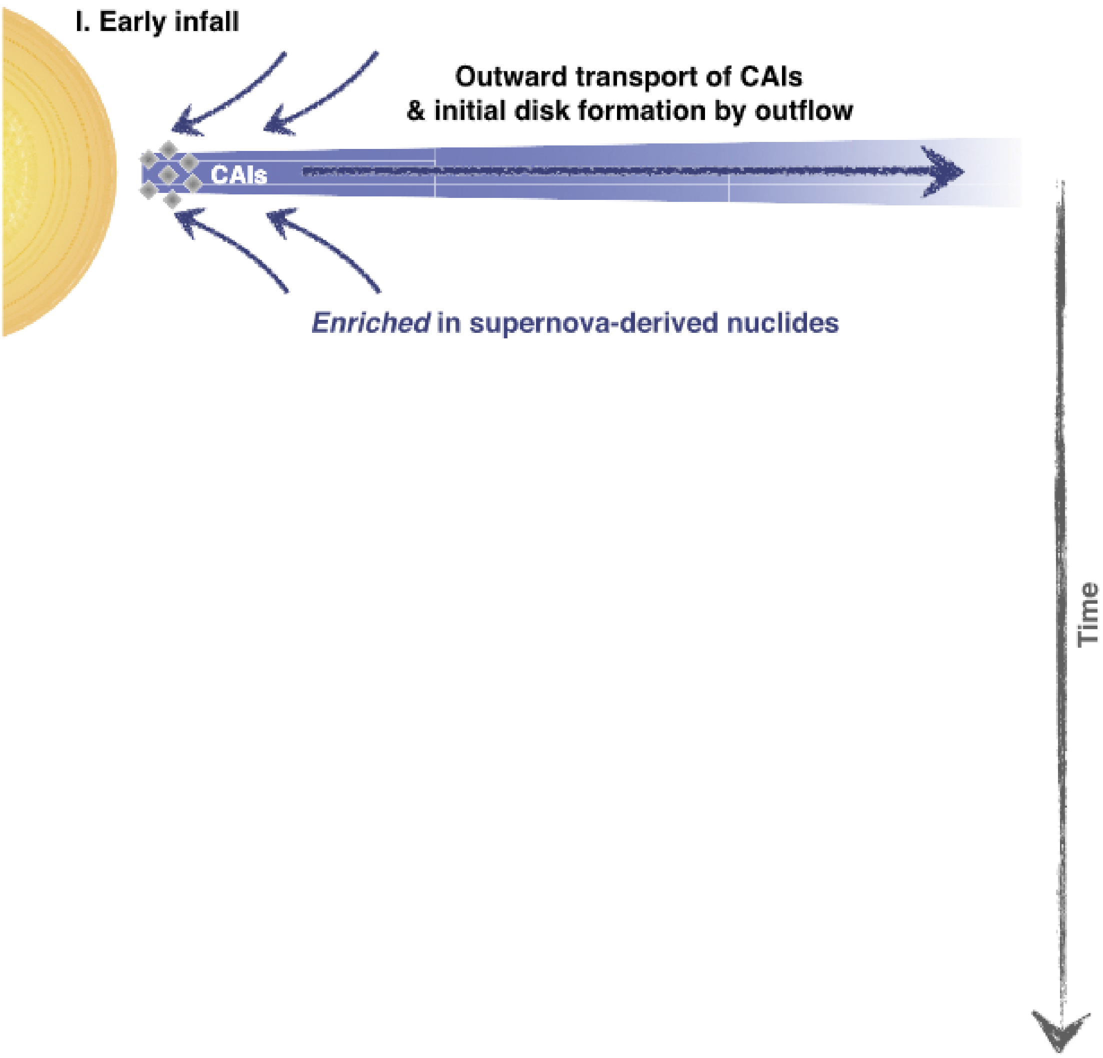
An important observation: the CC isotope composition can be interpreted as the result of a mixture between the NC composition and that of calcium-aluminum inclusions (CAIs) and amoeboid olivine aggregates (AOAs)



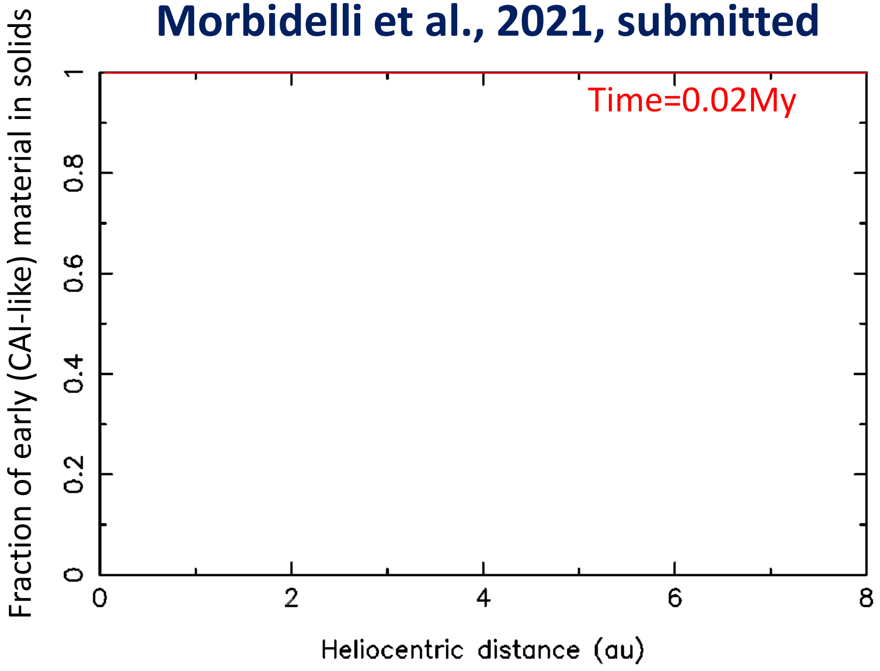
Schneider et al. (2020)

Origin of the isotopic dichotomy

Nanne et al., 2019



Morbidelli et al., 2021, submitted



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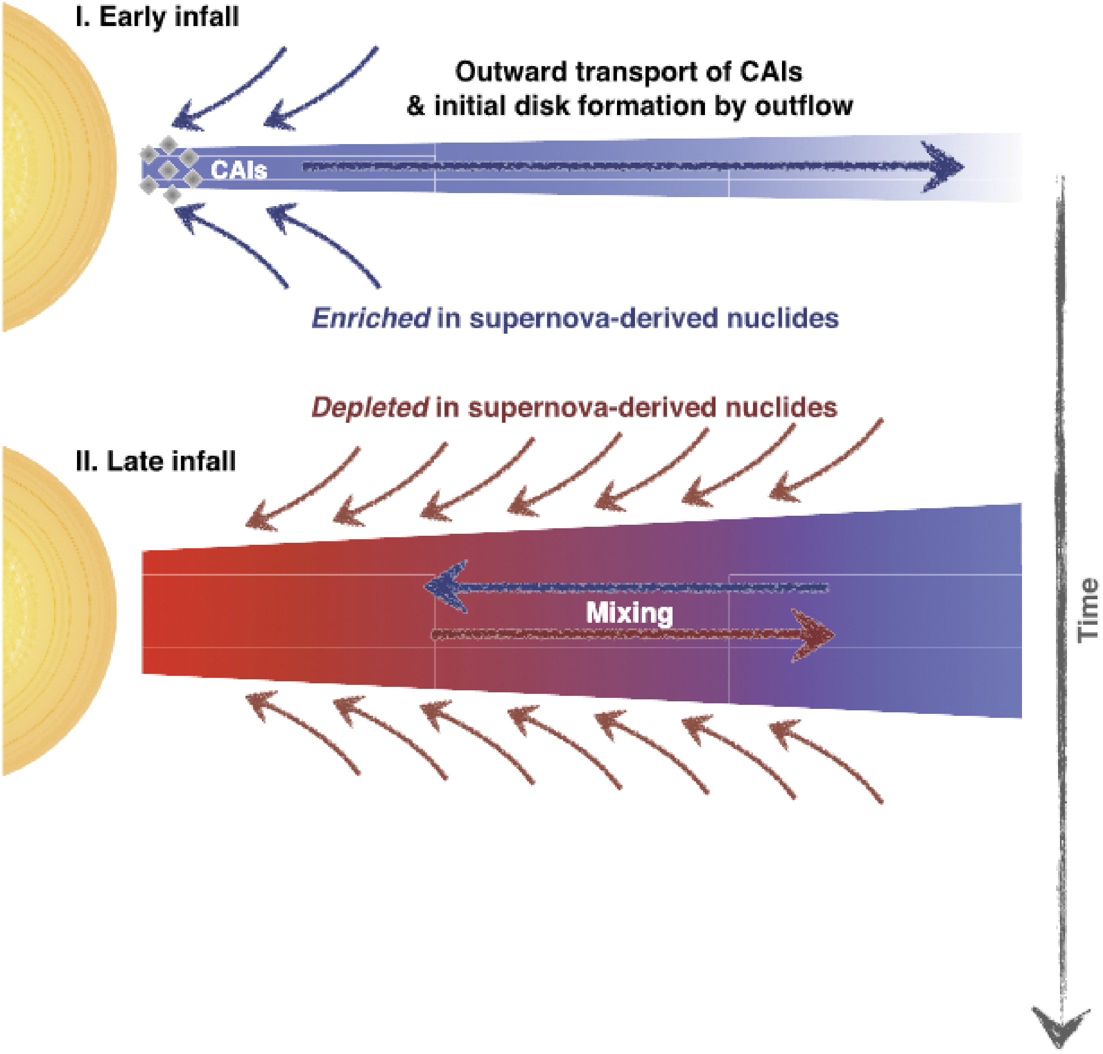

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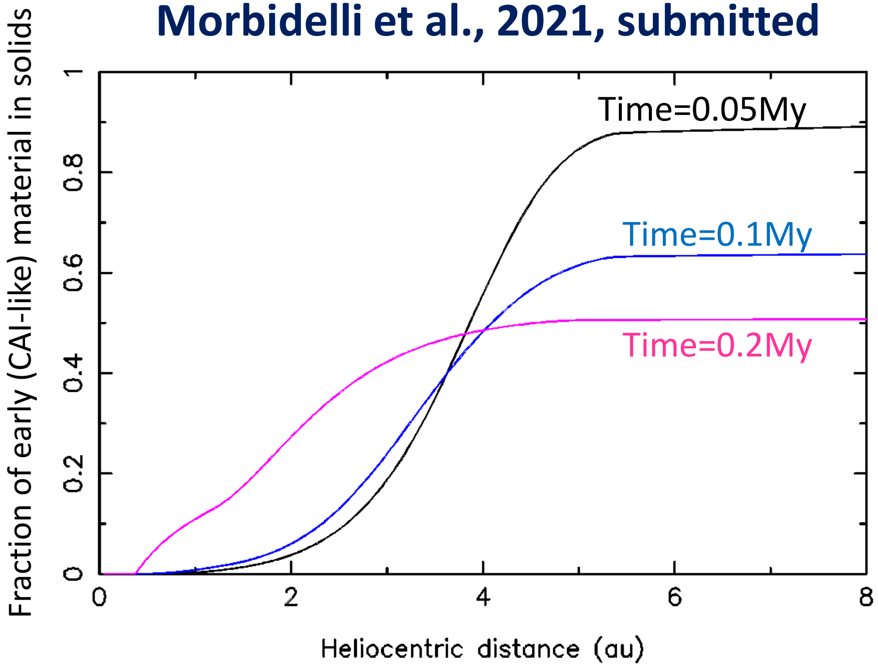

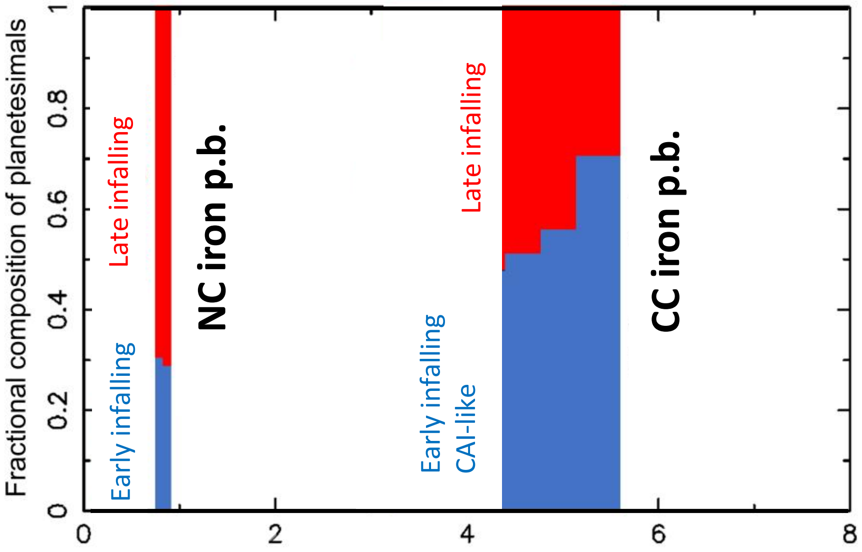

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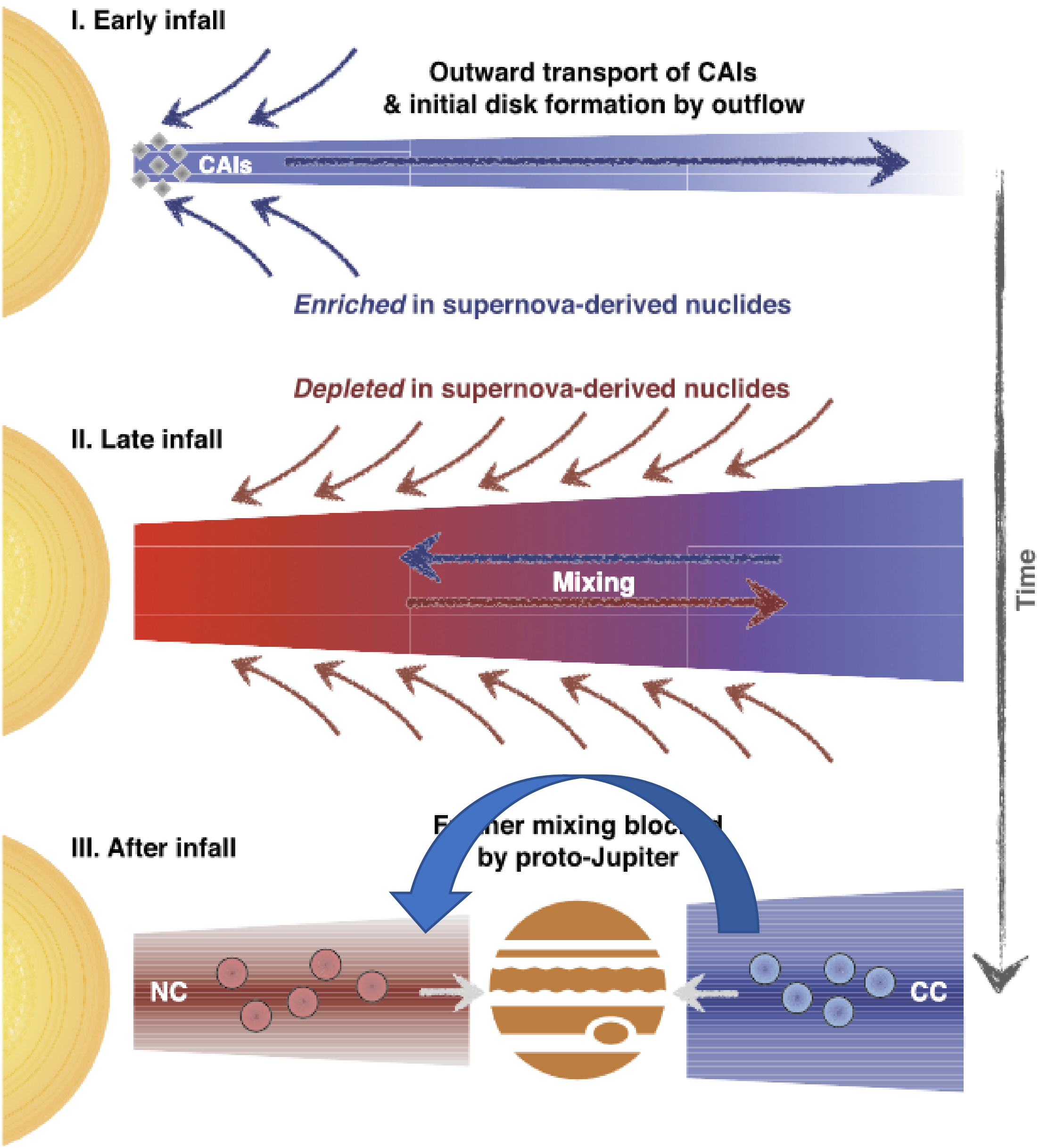

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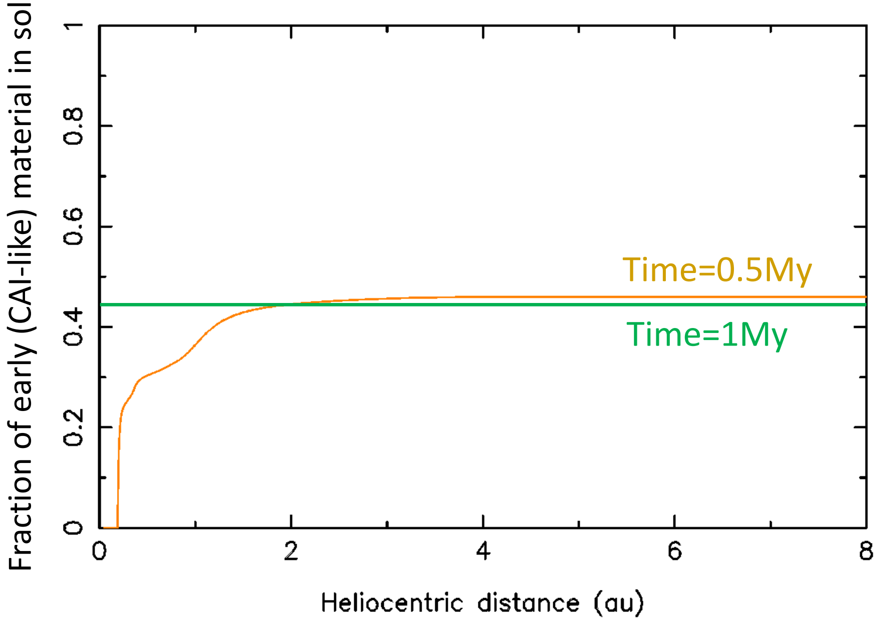
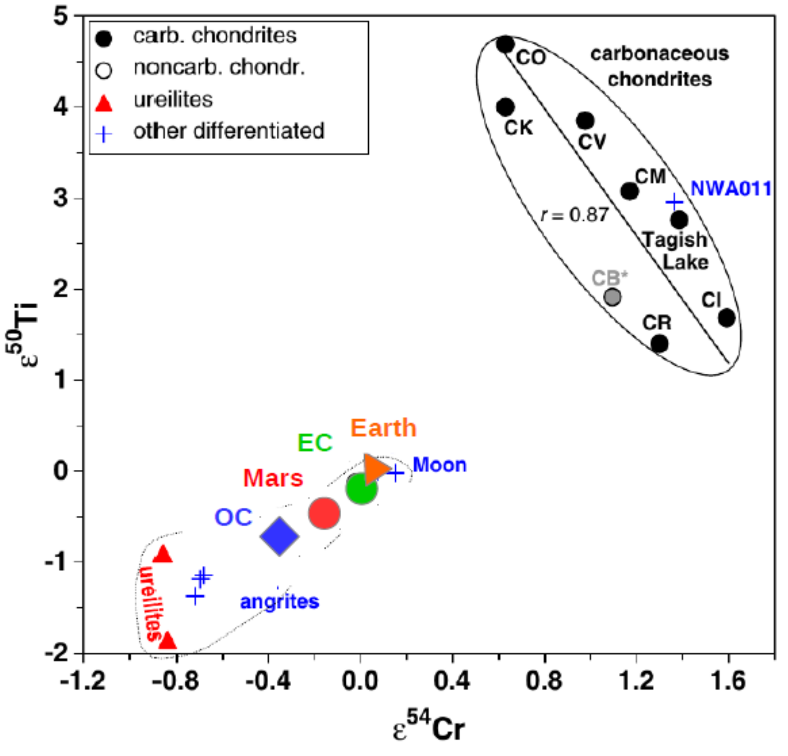


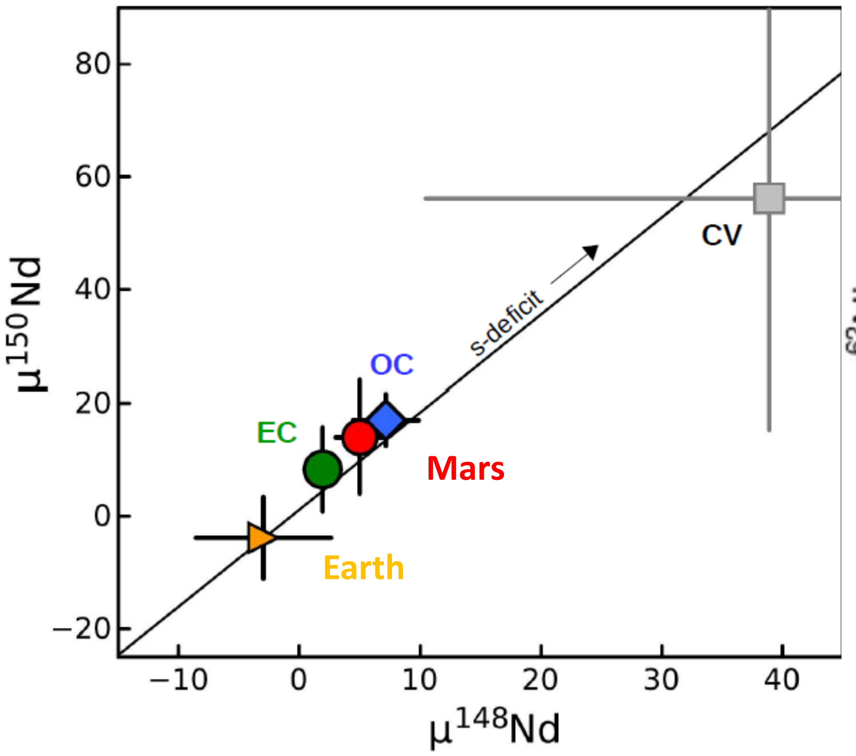
Jupiter's barrier:

- Morbidelli and Nesvorny, 2012
- Lambrechts et al., 2014
- Morbidelli et al. 2015
- Kruijer et al., 2017
- Weber et al. 2018
- Haugbølle et al., 2019

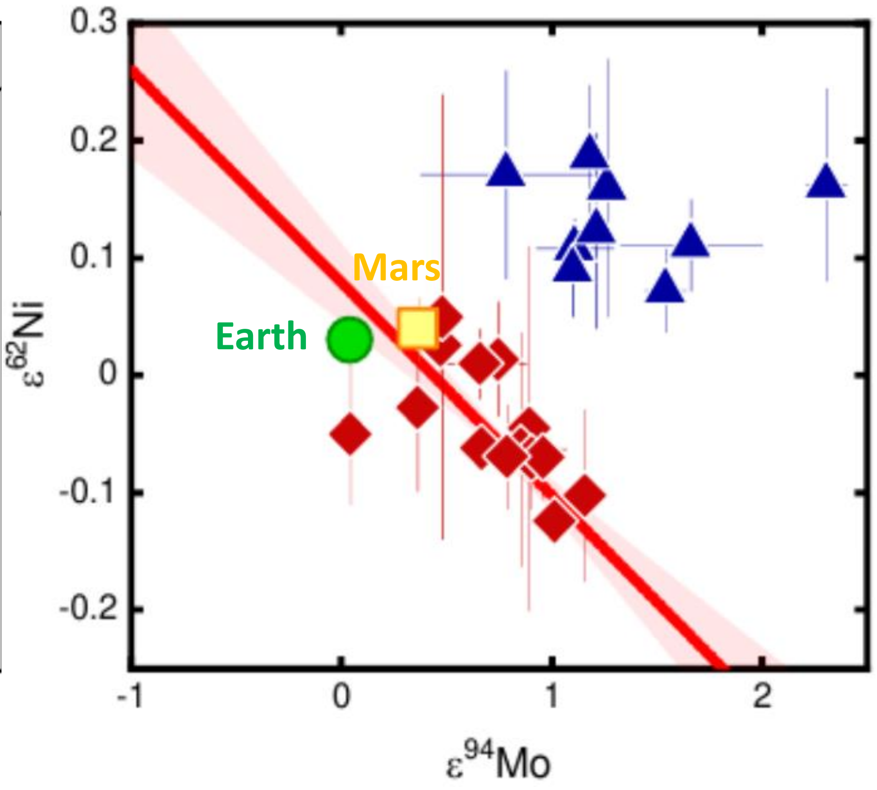
The formation of the terrestrial planets within the isotopic dichotomy



Warren, 2011



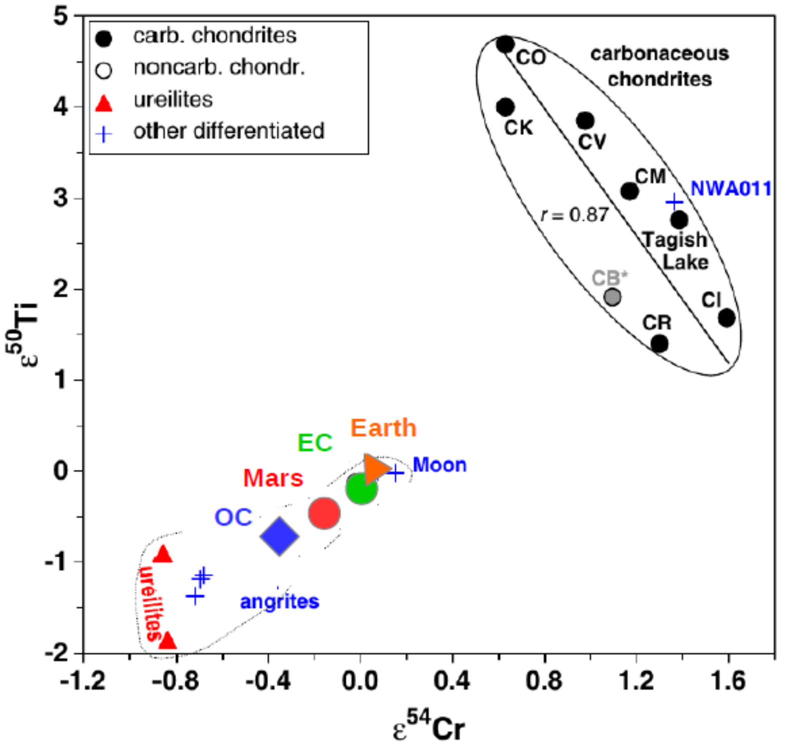
Burhardt et al., 2016



Burkhardt et al., 2021, subm.

- **No evidence for preferential accretion of CC material by the terrestrial planets relative to NC**

The formation of the terrestrial planets within the isotopic dichotomy



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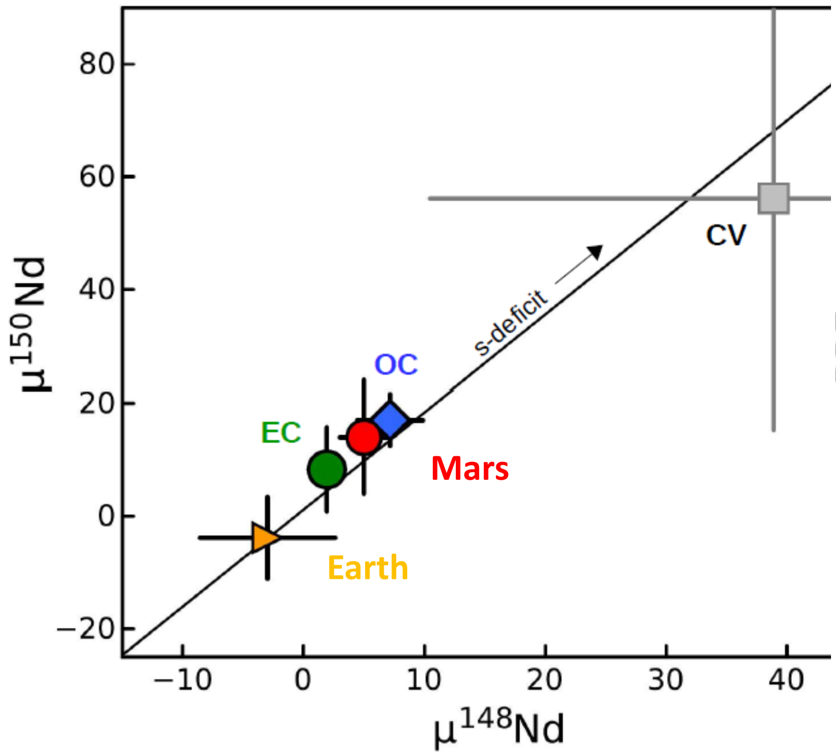

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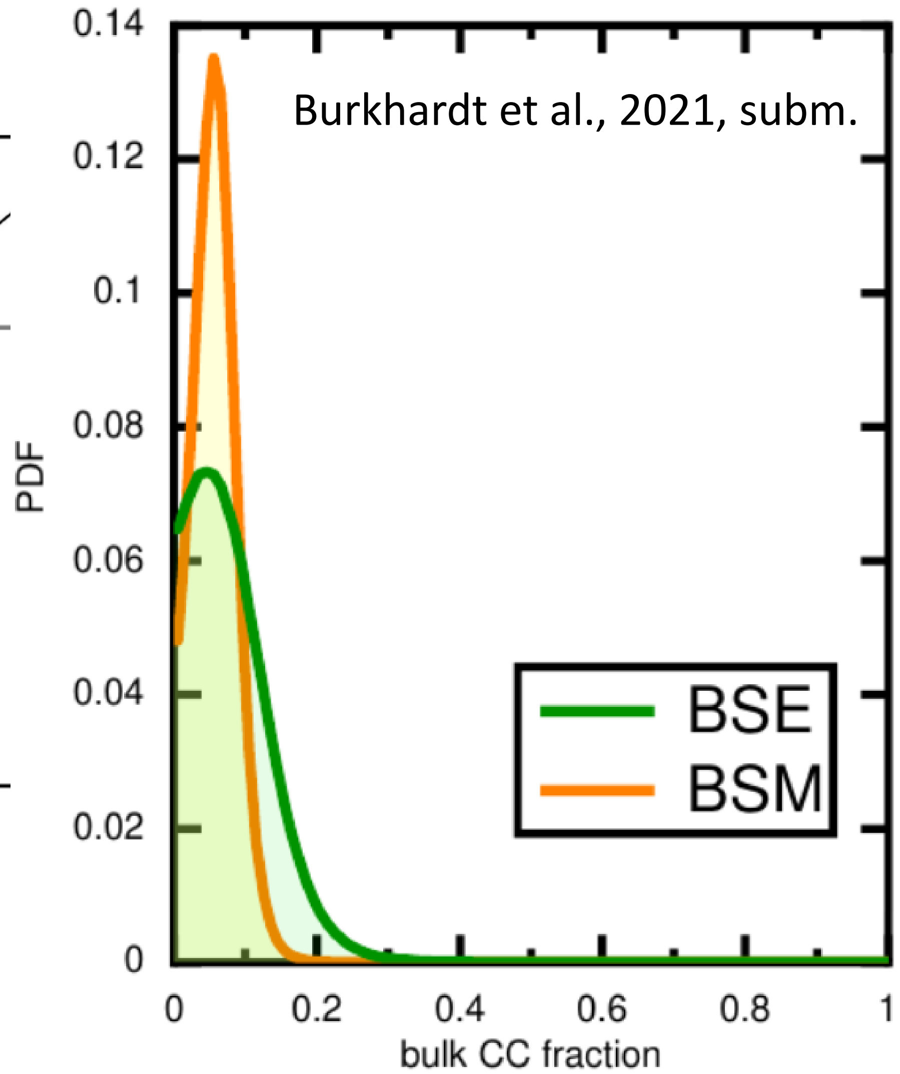
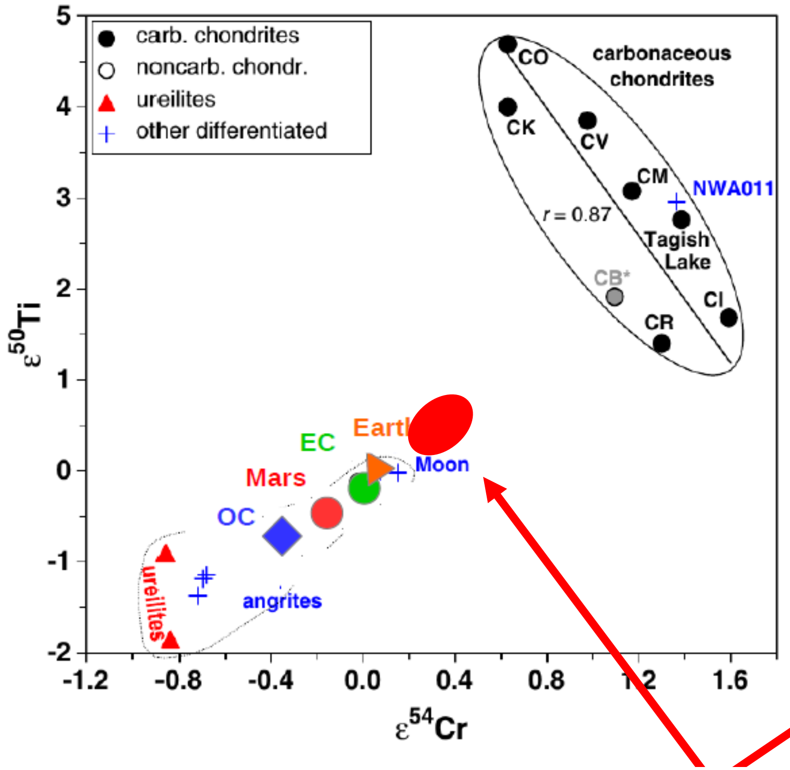
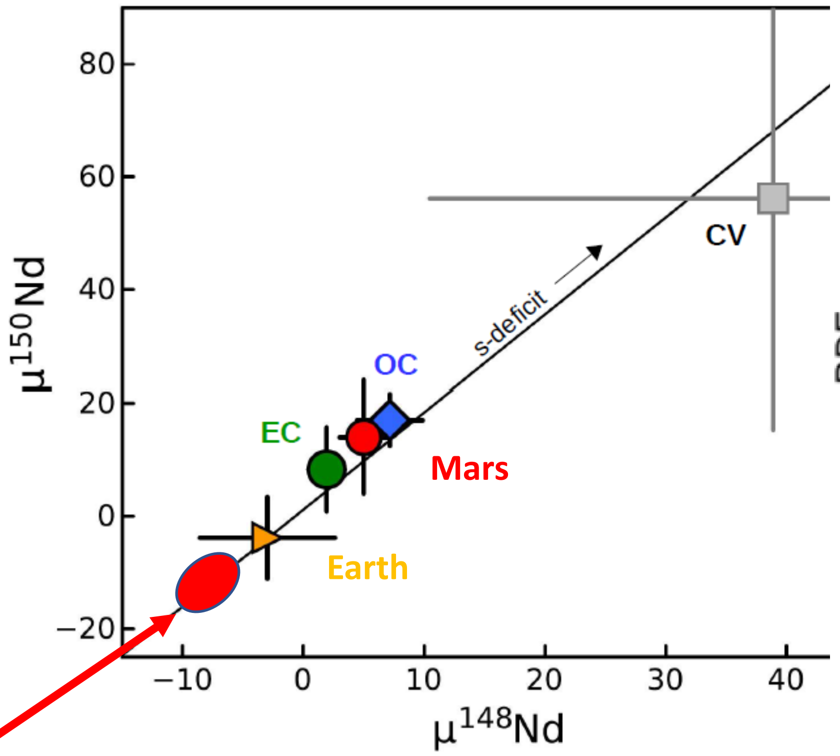
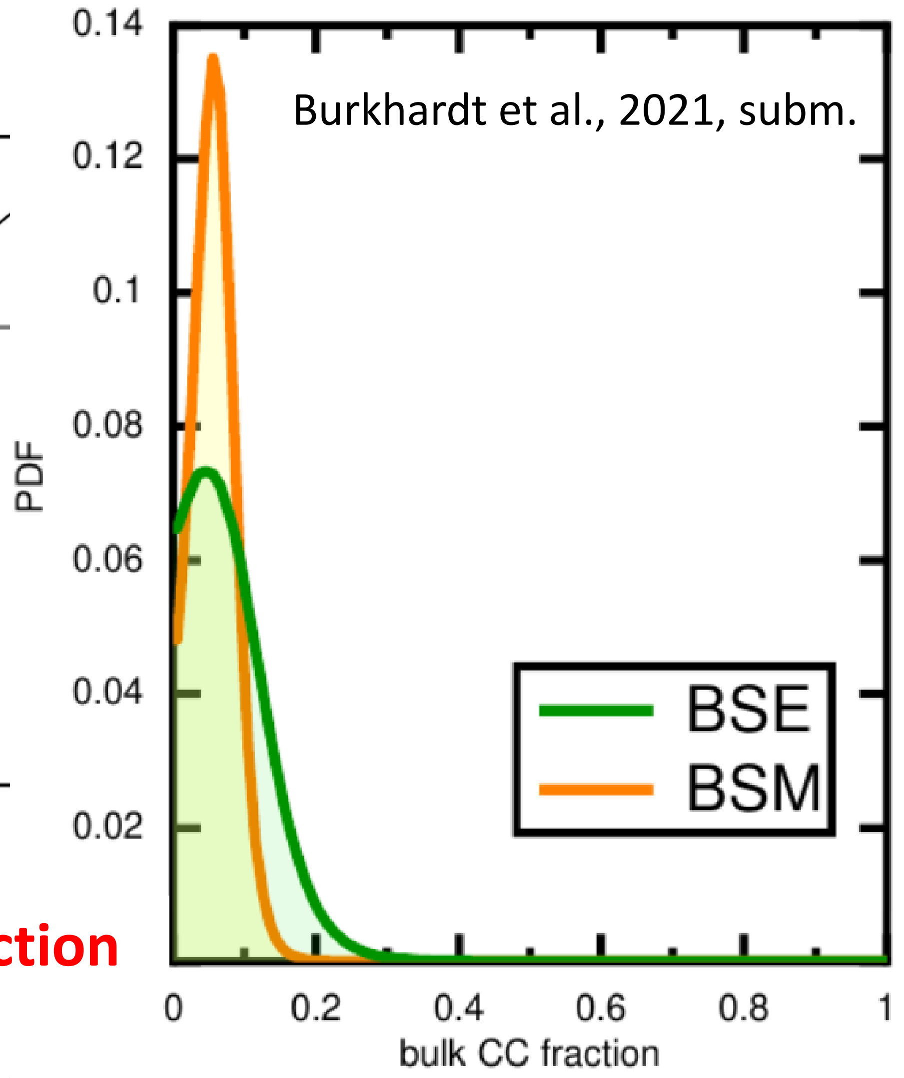


- **No evidence for preferential accretion of CC material in the terrestrial planets relative to NC meteorites -> pebble accretion was NOT a relevant process in the growth of the terrestrial planets**

The formation of the terrestrial planets within the isotopic dichotomy





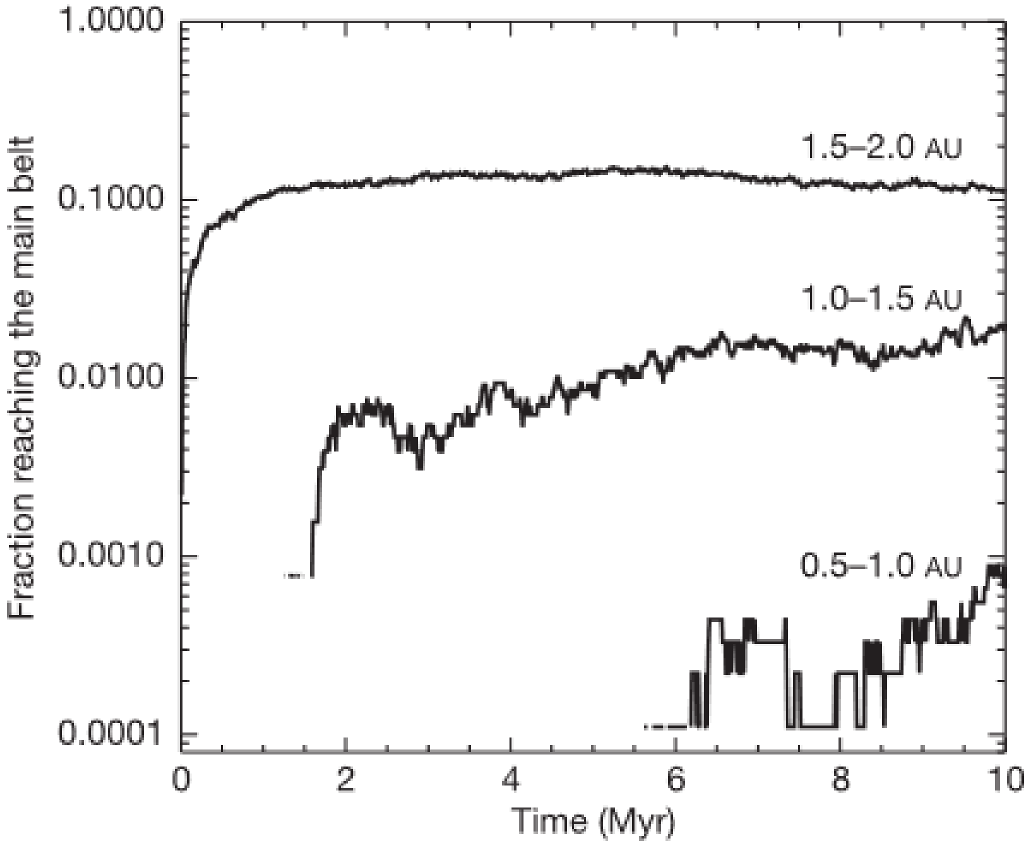


Original NC planetesimals unsampled in the meteorite collection

- No evidence for preferential accretion of CC material by the terrestrial planets relative to NC meteorites -> pebble accretion was NOT a relevant process in the growth of the terrestrial planets
- The Earth is an end-member of the NC distribution

Most likely, these unsampled planetesimals formed closer to the Sun than the Earth, so that their probability to be captured into the asteroid belt was very small

Bottke et al., 2006



CONCLUSIONS

- The identification of the NC-CC isotopic dichotomy is (one of) the most exciting new result(s)
- Revolutionizes our understanding of the early evolution of the solar system
  - The disk accreted materials from the GMC with different isotopic signatures at different times
  - Early planetesimal formation occurred at two distinct sites in the disk
  - Jupiter formed early (less 1My) providing an effective barrier to dust-drift into the inner solar system
  - Pebble accretion was ineffective for the terrestrial planets
    - This is probably why they accreted slowly, were small during the disk-lifetime and avoided migration
    - Vigorous pebble accretion would have led to the formation of close-in super-Earth (Lambrechts et al., 2019)
  - The NC planetesimal population had a range of isotopic properties that extends beyond that sampled by meteorites
  - Presumably the unsampled planetesimals were closer to the Sun than the Earth
  - Carbonaceous asteroids formed beyond Jupiter's position and have been implanted into the asteroid belt.

OPEN QUESTIONS

- What is the origin of the isotopic spread within the NC group? Was it correlated with radial distance, accretion time..?
- What is the origin of the NC material that formed later planetesimals (i.e. NC chondrites)? Was it preserved for Mys in the inner disk or regenerated as collisional debris of the early NC planetesimals?