Sampling Disk Heterogeneity and Collisional Erosion in the Building of the Terrestrial Planets

CARNEGIE INSTITUTION OF WASHINGTON · 1902 ·

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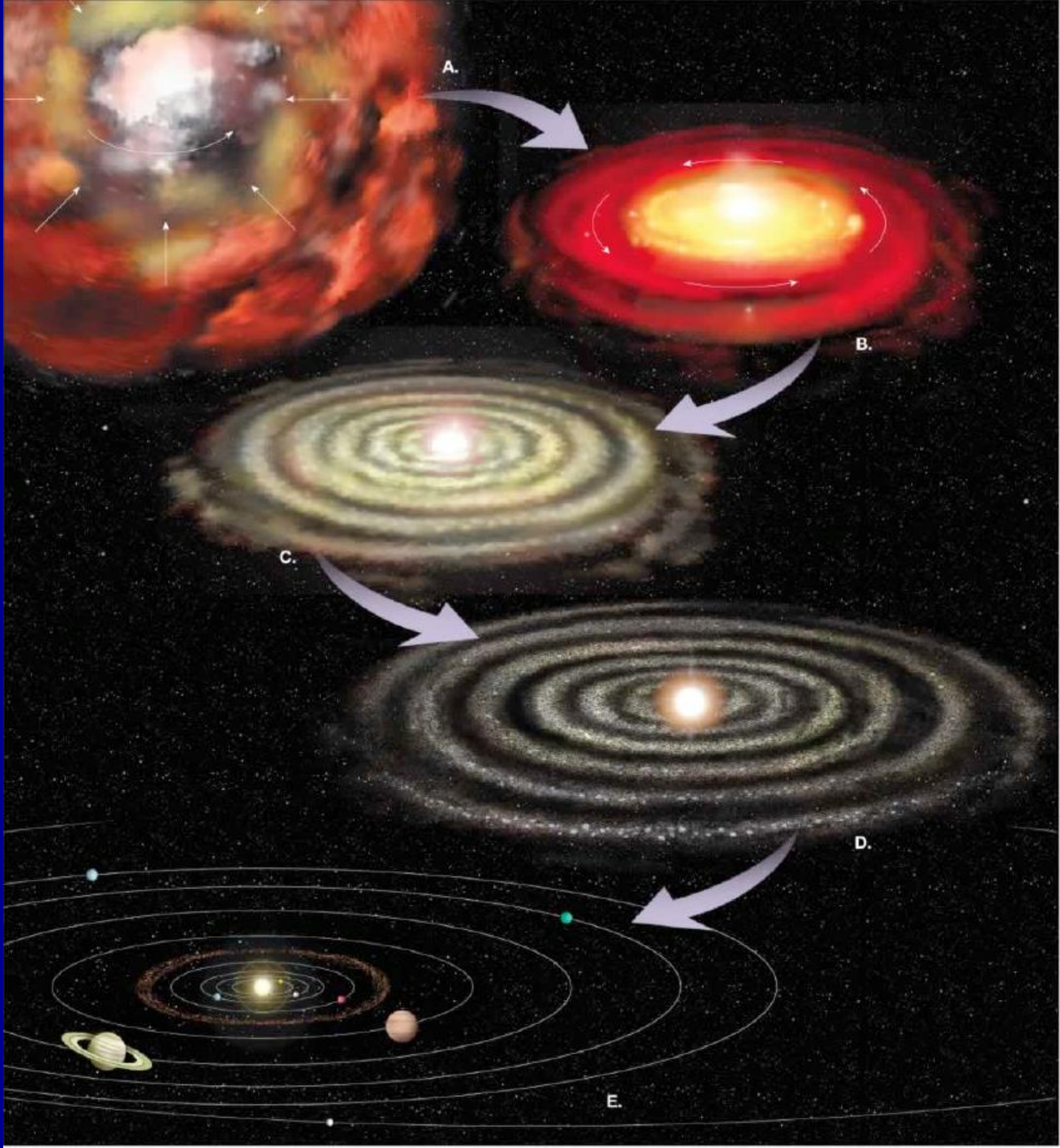
Circumstellar Disks & Planet Formation

University of Michigan, October 14, 2014

DEPARTMENT OF TERRESTRIAL MAGNETISM 1904 - 2004

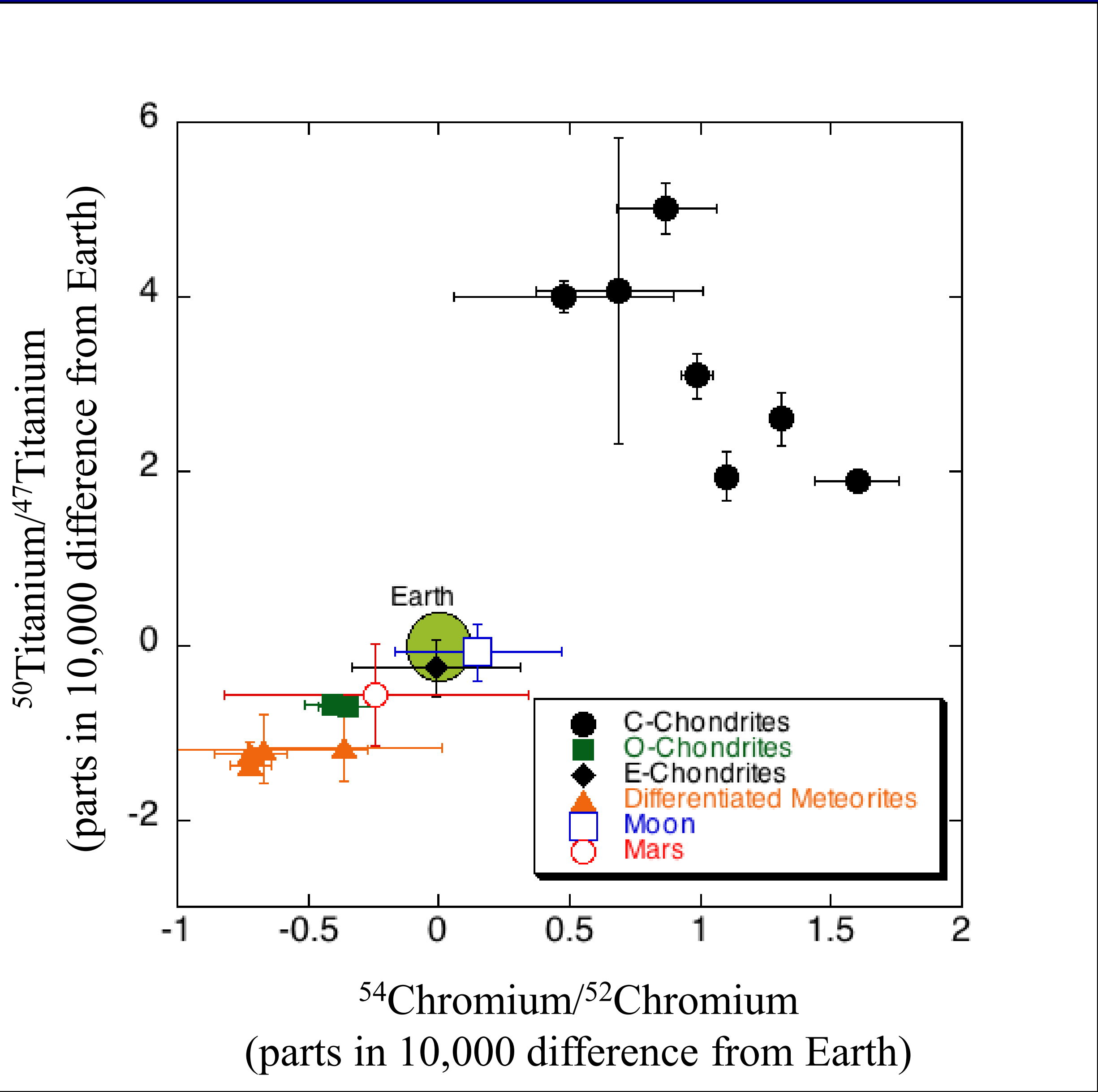
Examine the End Result of the Planet-Forming Process in our Solar System to Infer the Conditions in the Disk at the Start of Planet Formation



Isotopic Variability in Meteorites

Distinct Nucleosynthetic Components in an Inhomogeneous Nebula?

Neutron-rich isotopes (^{50}Ti, ^{54}Cr) reflect supernova nucleosynthesis

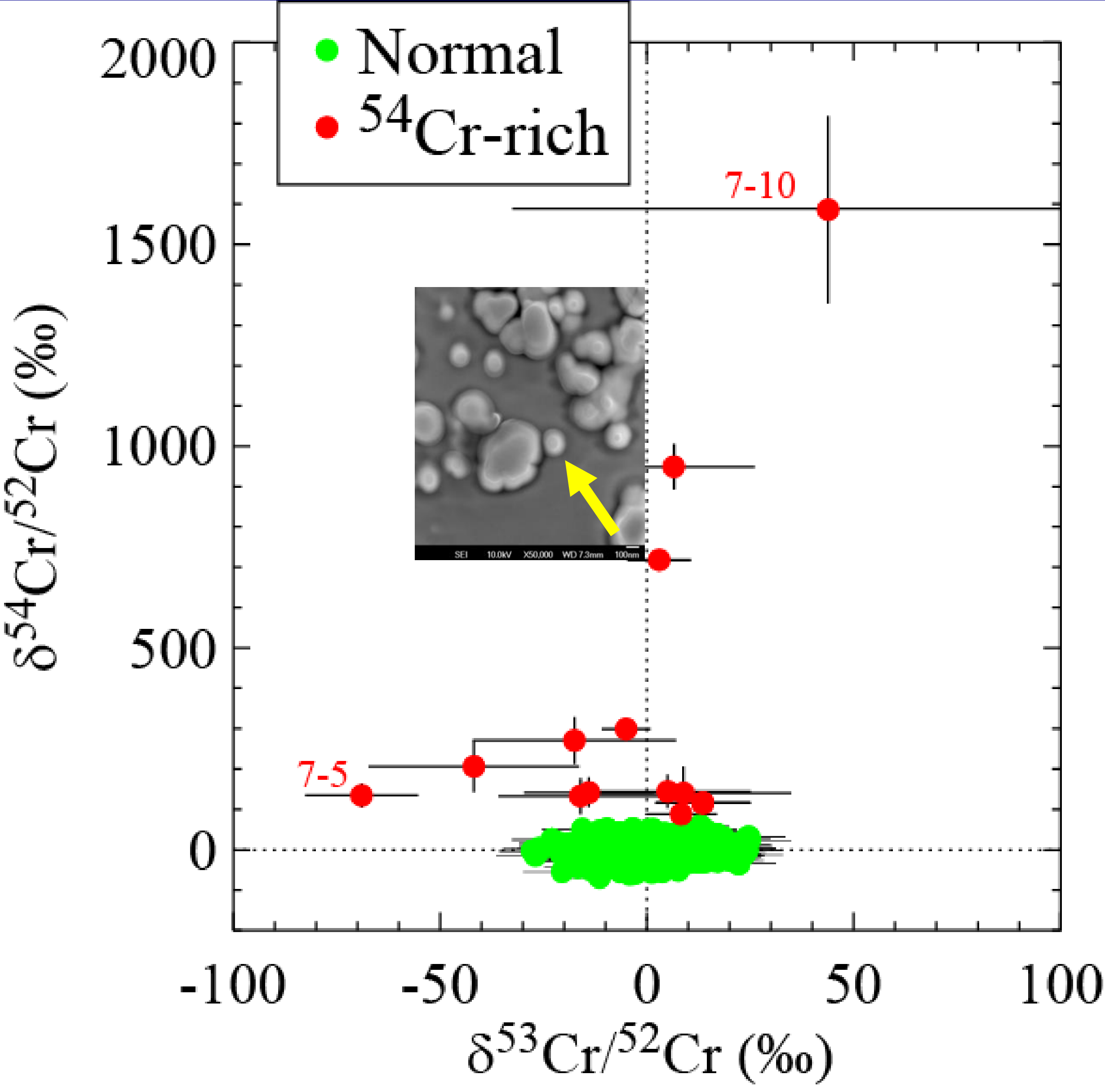


Data from Trinquier et al., 2008, 2009), Qin et al., 2010)

Cause of Chromium Isotopic Variation?

Variable abundance of presolar grains from type II supernova

Cr-Al oxide grains found in C-chondrite dissolution residues have extreme ^{54}Cr enrichment. Likely grains condensed from the outflow of a type II supernova



Data from Qin et al., GCA 2011

A Clear Carrier of Pure s-Process Barium Presolar Silicon Carbide

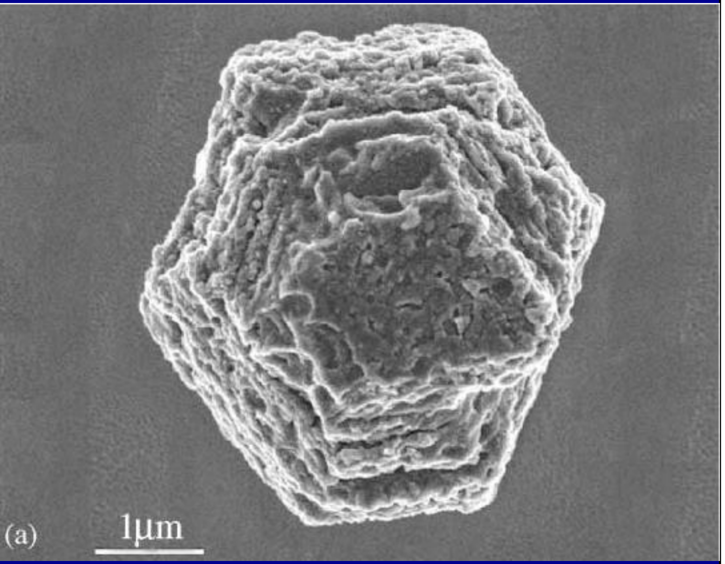
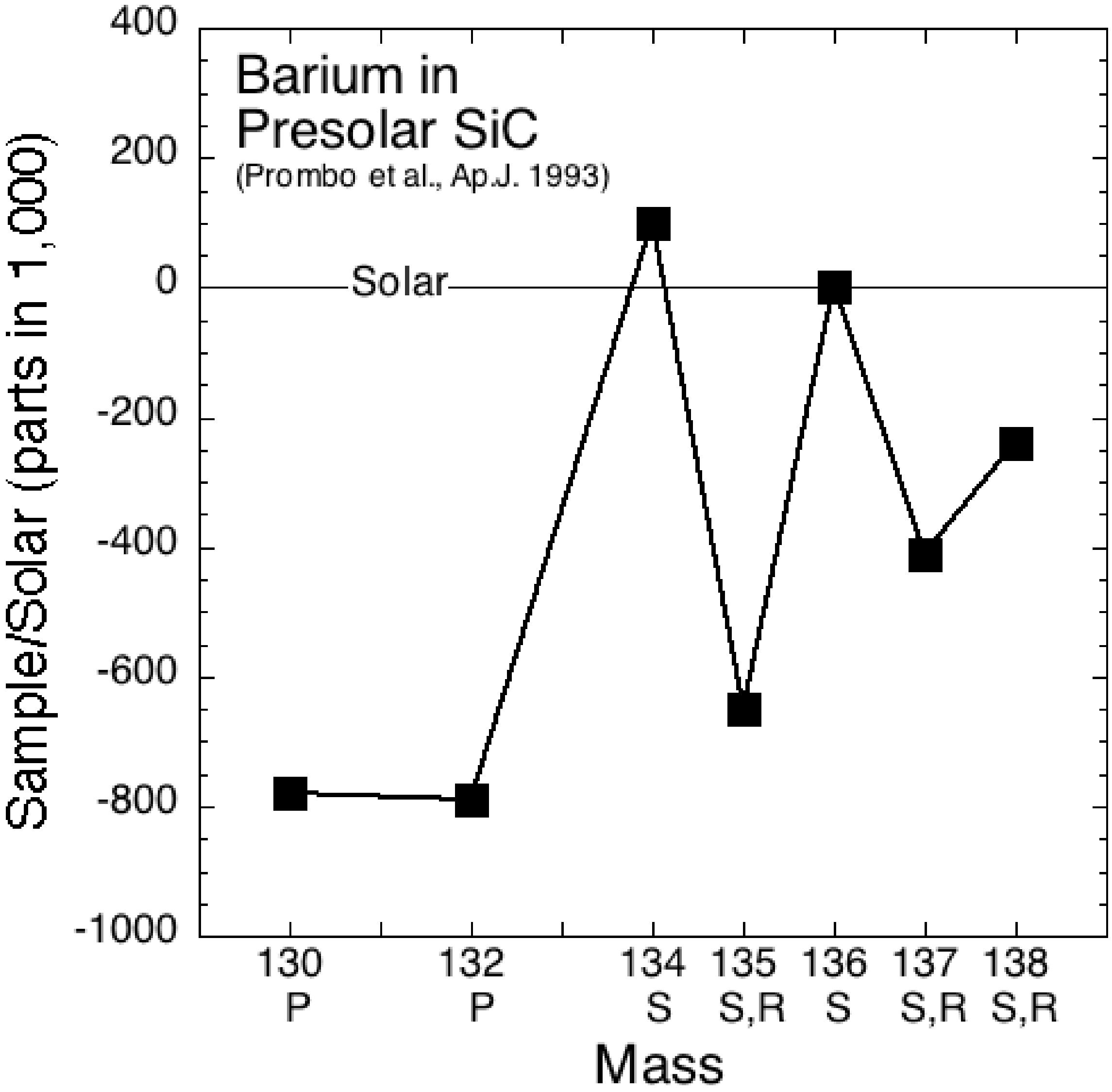
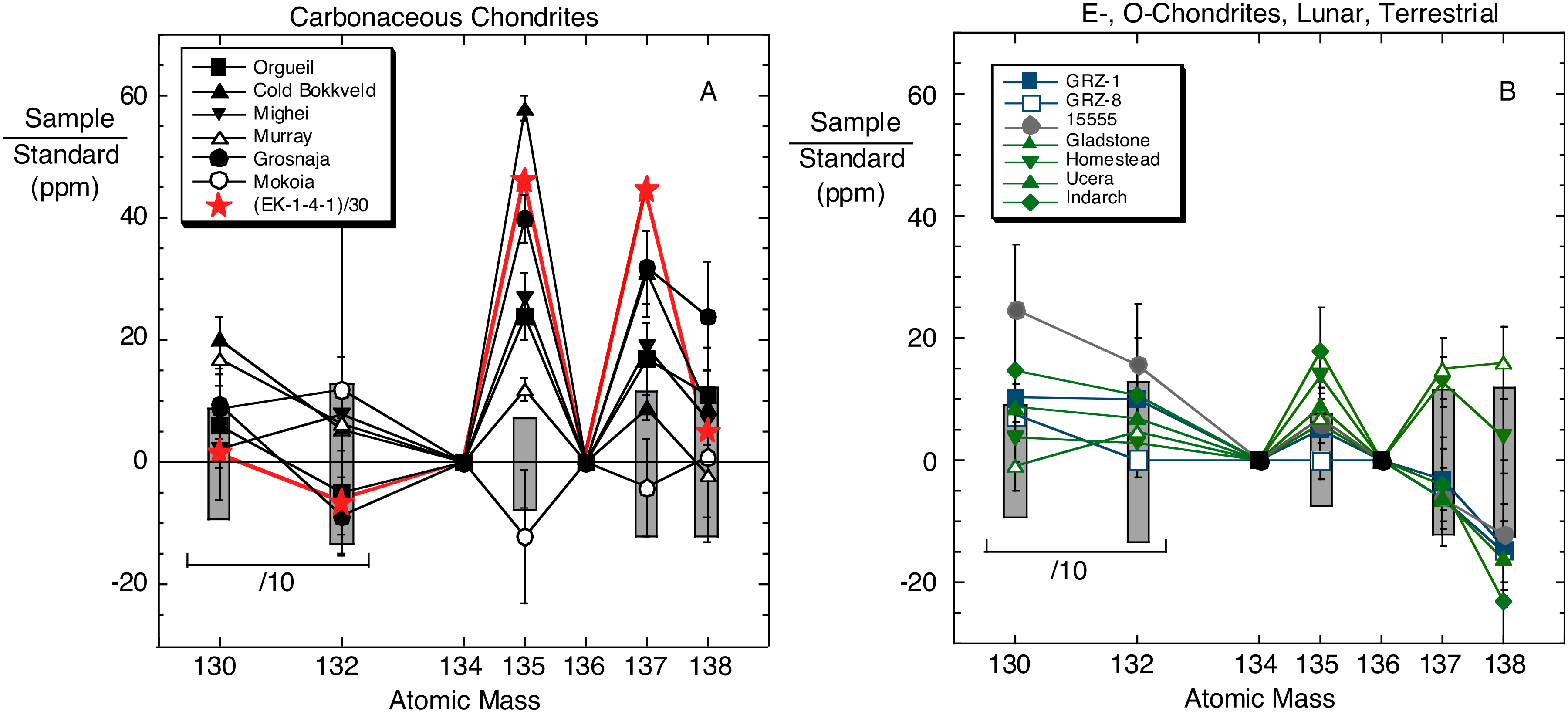


Photo of presolar SiC grain from Zinner, Treatise on Geochemistry, 2003



Isotopic Anomalies in Barium in Carbonaceous-Chondrites at the “Whole Rock” Scale

r-process enrichment from same source as ^{50}Ti, ^{54}Cr enrichment?



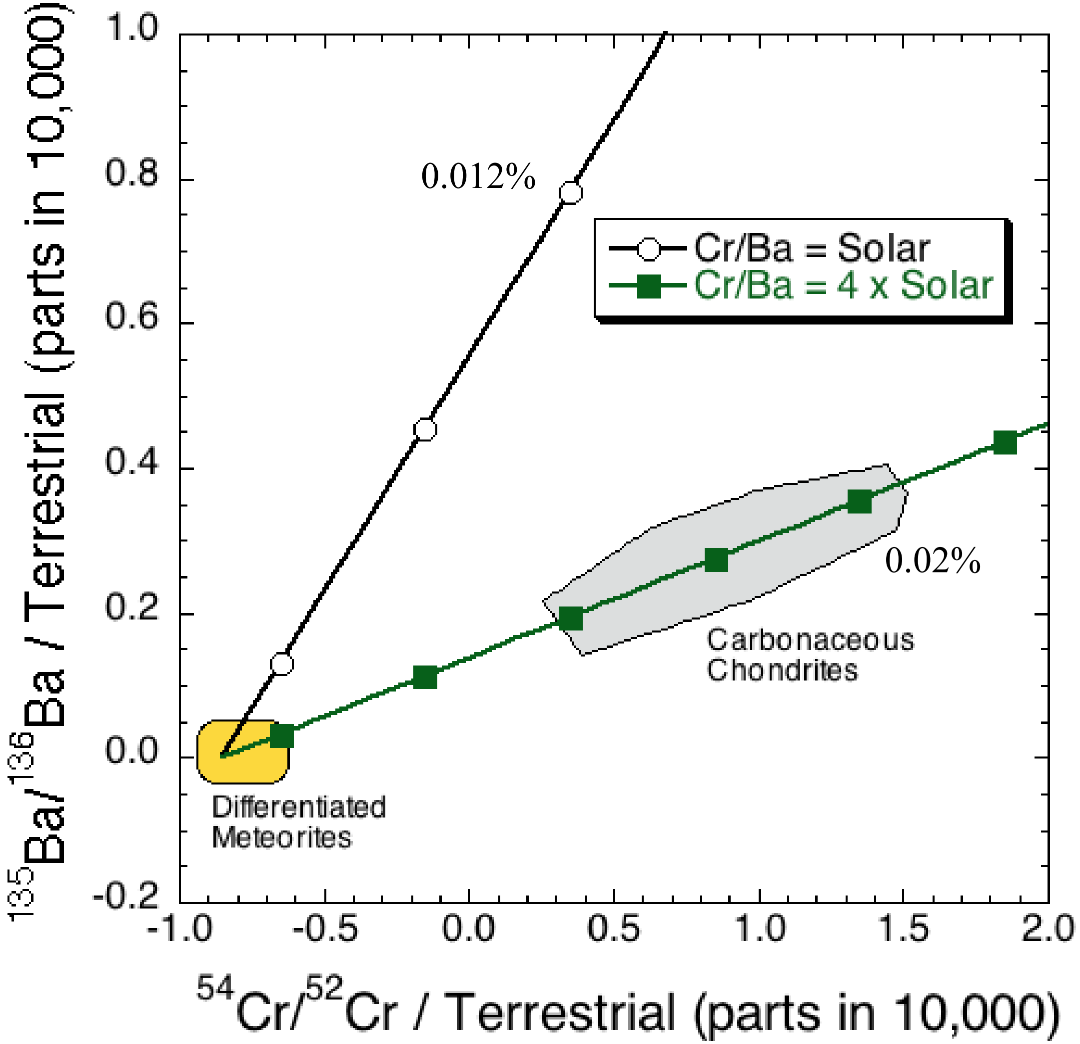
Carlson et al., Science, 2007

Cr Isotope Variation Larger than for Ba. Why?

1) High ^{54}Cr component has Cr/Ba ratio 4 times the Solar value. Low metalicity supernova?

2) s, r-process carriers (e.g., SiC) well mixed into protosolar molecular cloud. Neutron-rich Cr, Ti grains injected by supernova that induced cloud collapse. Time of collapse too short to allow adequate mixing into nebula.

Mixing of Solar Cr and Ba with presolar carrier Cr and Ba

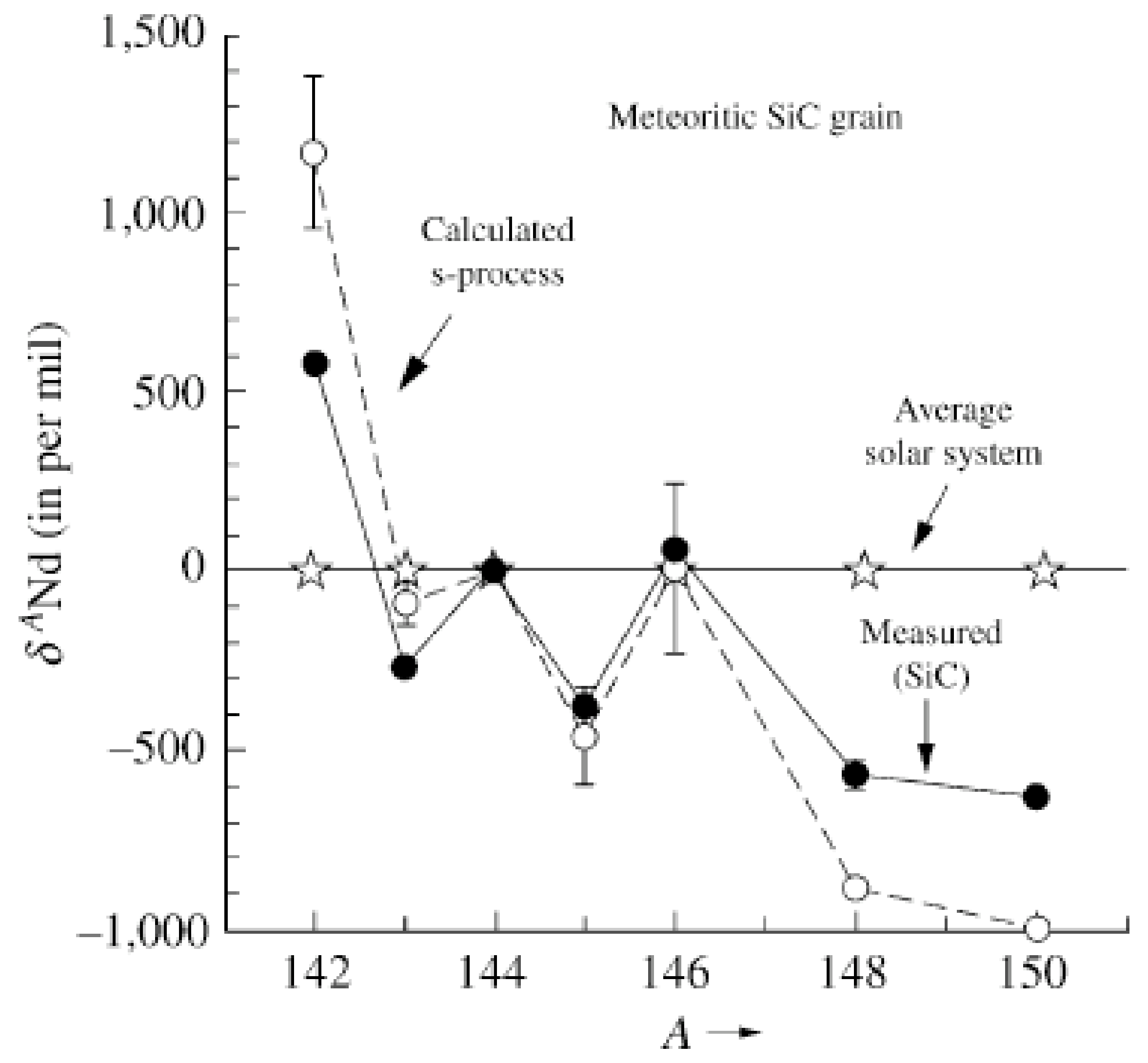


^{142}Neodymium: Distinguishing Radiogenic from Nucleosynthetic Variation

Importance for estimating planetary composition

s-process enriched presolar grains in meteorites preserve massive neodymium isotope anomalies including huge enrichments in ^{142}Nd.

^{142}Nd also is produced by the 103 Myr half-life decay of ^{146}Samarium and so will vary depending on the Sm/Nd ratio of the planet/planetesimal



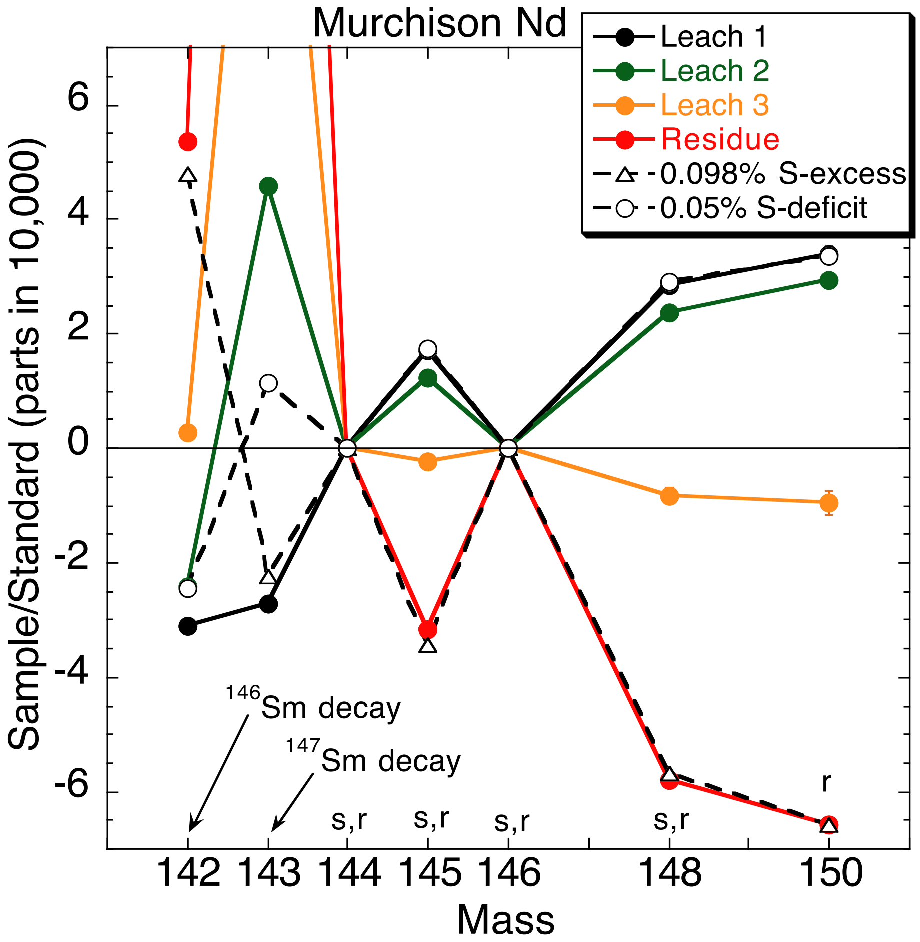
Data from Richter et al., 1992

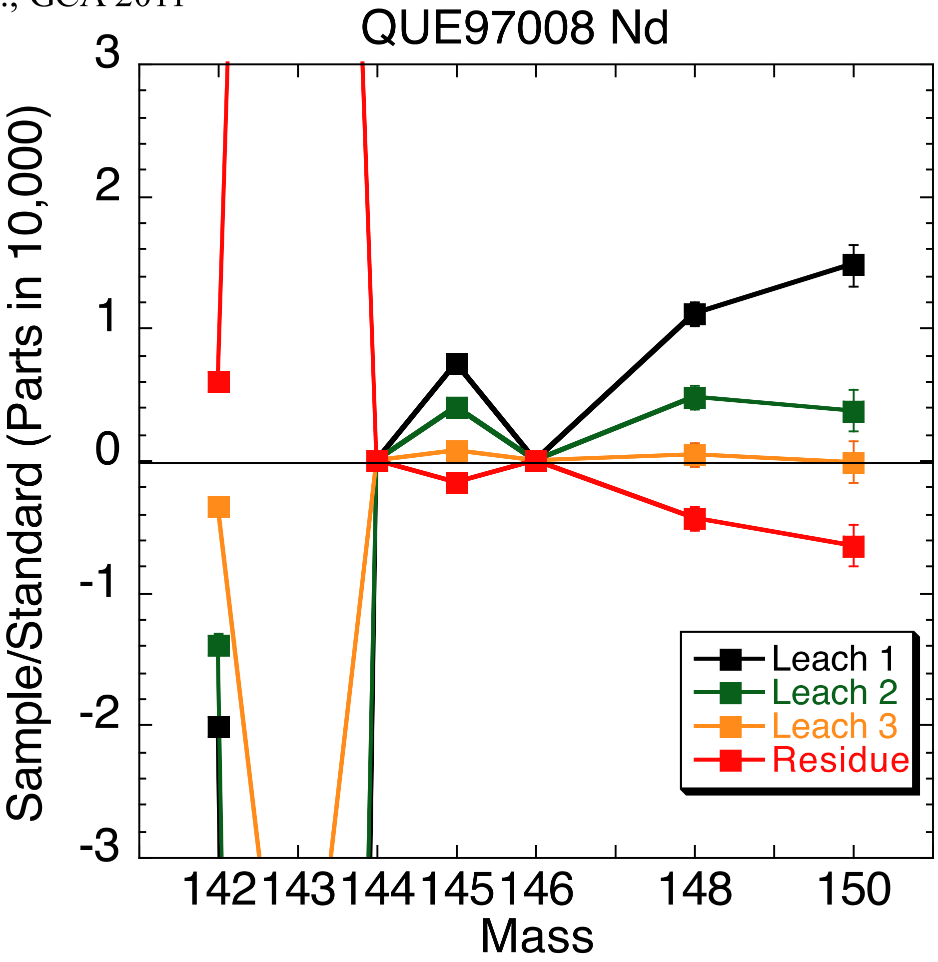
Nd Isotope Variation in Leaches of Primitive C (Murchison) and O (QUE97008) Chondrites

Murchison: Anomaly magnitude similar to Ba leaches. S-, r-process variability dominates (except for ^{143}Nd) and well matches isotopic variation.

QUE97008: Nucleosynthetic variation smaller than in Murchison. Radiogenic contributions to ^{142}Nd and ^{143}Nd significant.

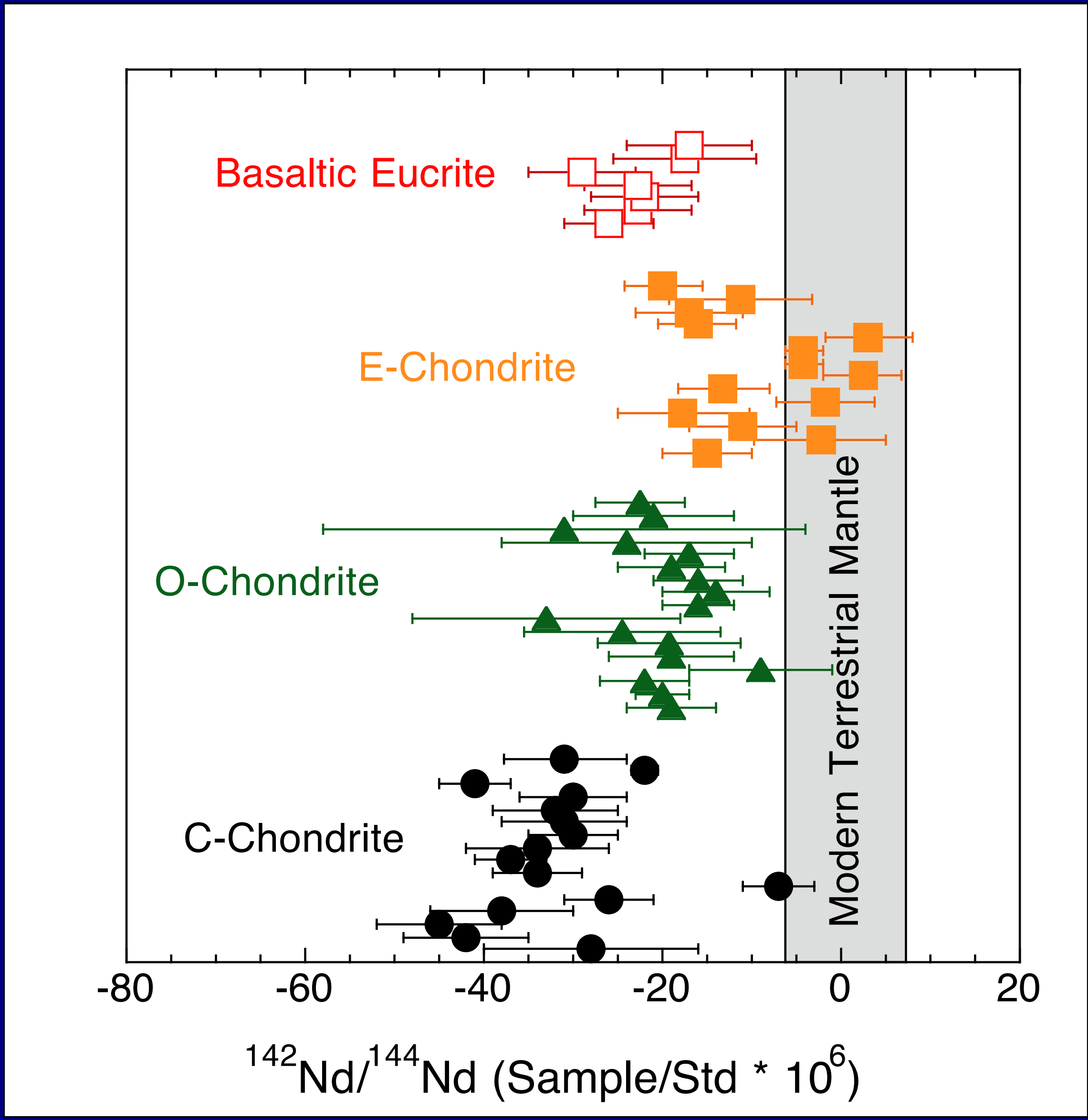
Qin et al., GCA 2011





^{142}Nd/^{144}Nd ratios measured in most meteorite groups, are 10 to 45 ppm lower than terrestrial

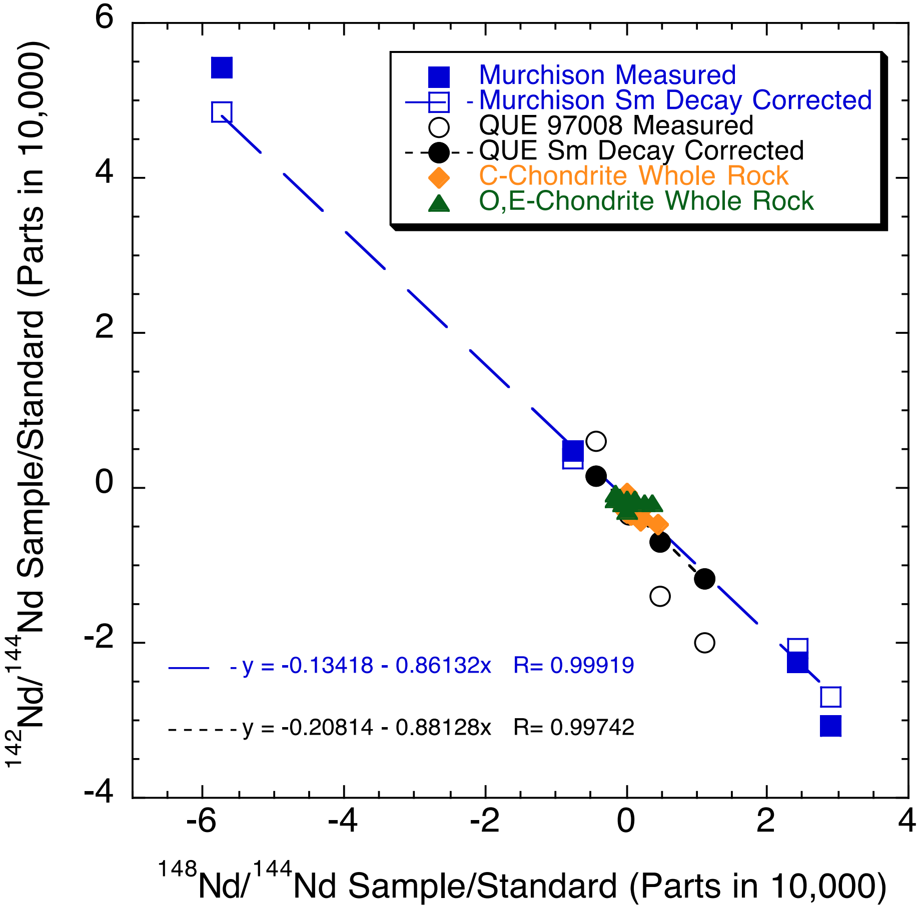
Is this isotopic offset due to ^{146}Sm decay or to a slightly different mixture of r-, s-process contributions to Nd?

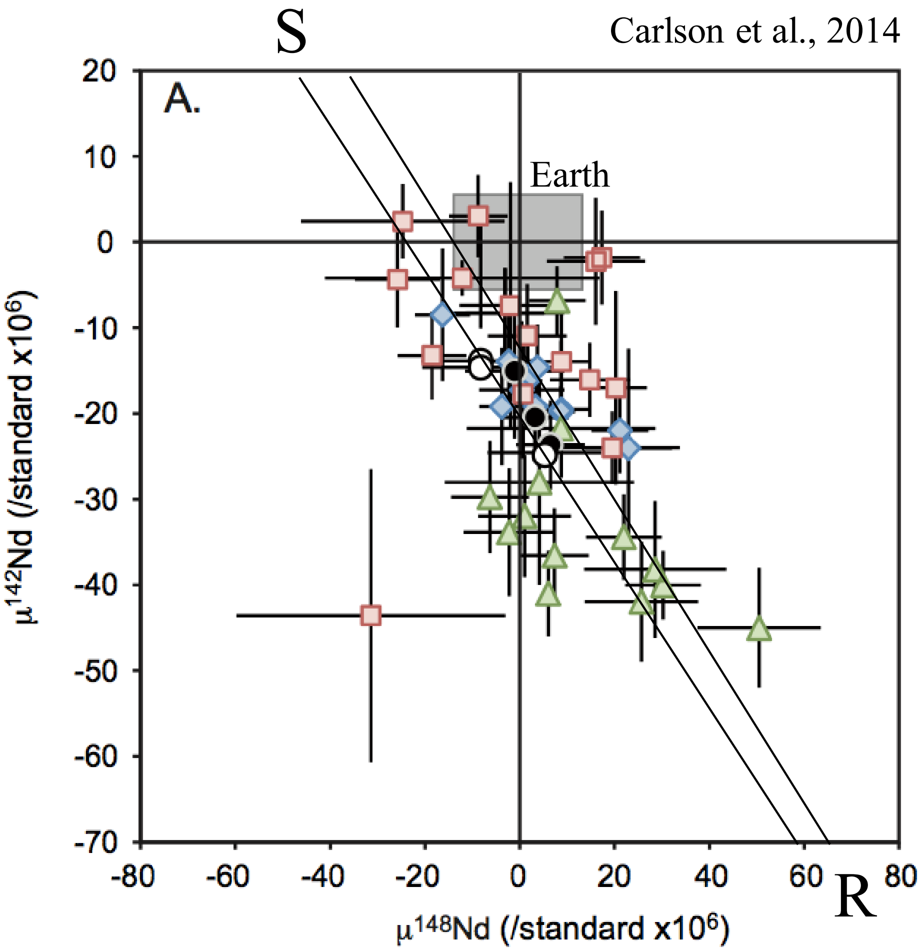


Data from: Nyquist et al., 1995; Andreasen and Sharma, 2006; Rankenburg et al., 2006, Boyet and Carlson, 2005; Carlson et al., 2007).

Correcting for Nucleosynthetic Contributions to Nd

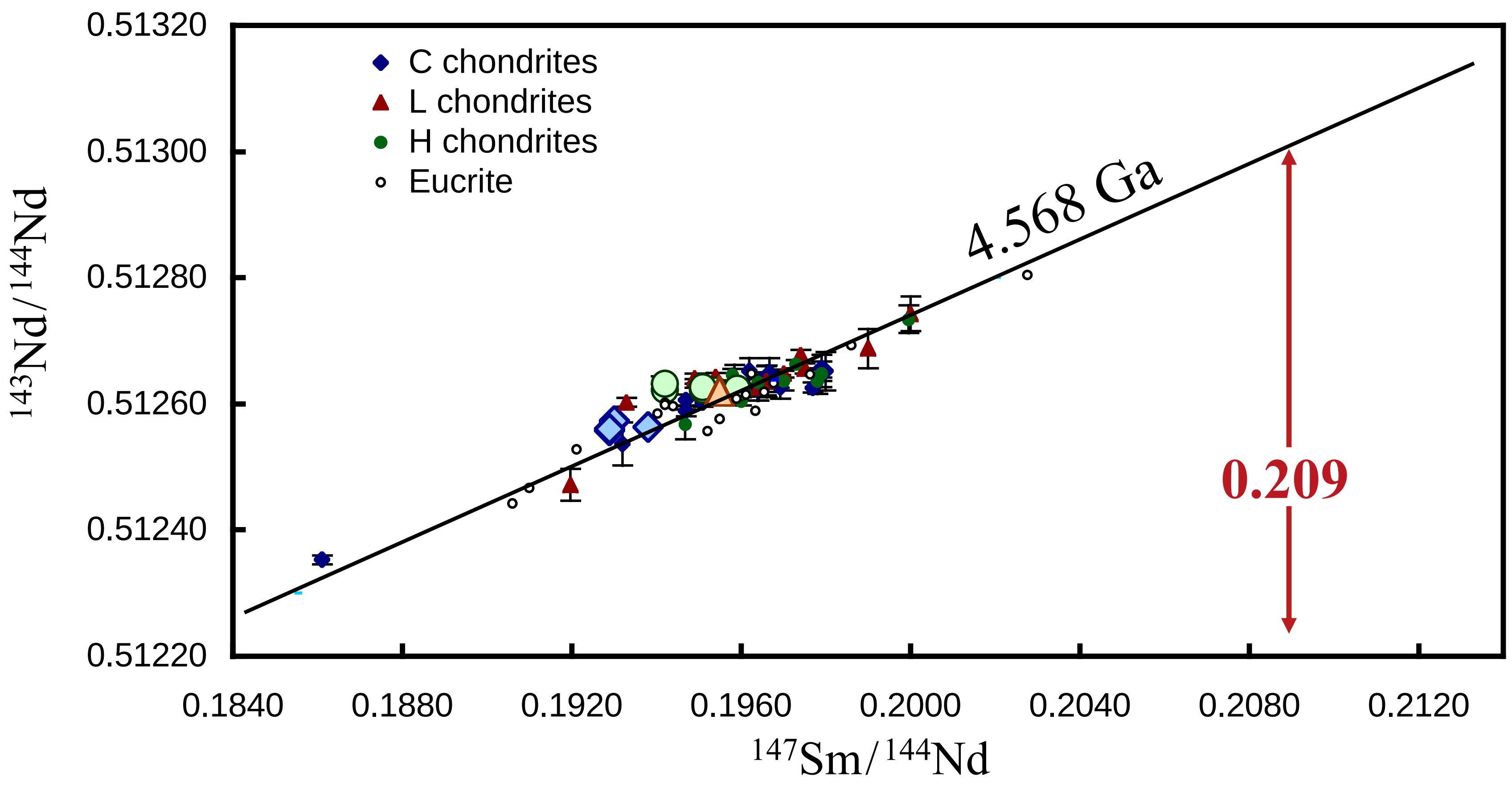
Leaves Earth with a 10-20 ppm excess in ^{142}Nd.
From ^{146}Sm decay at superchondritic Sm/Nd ratio?


Qin et al., GCA 2011

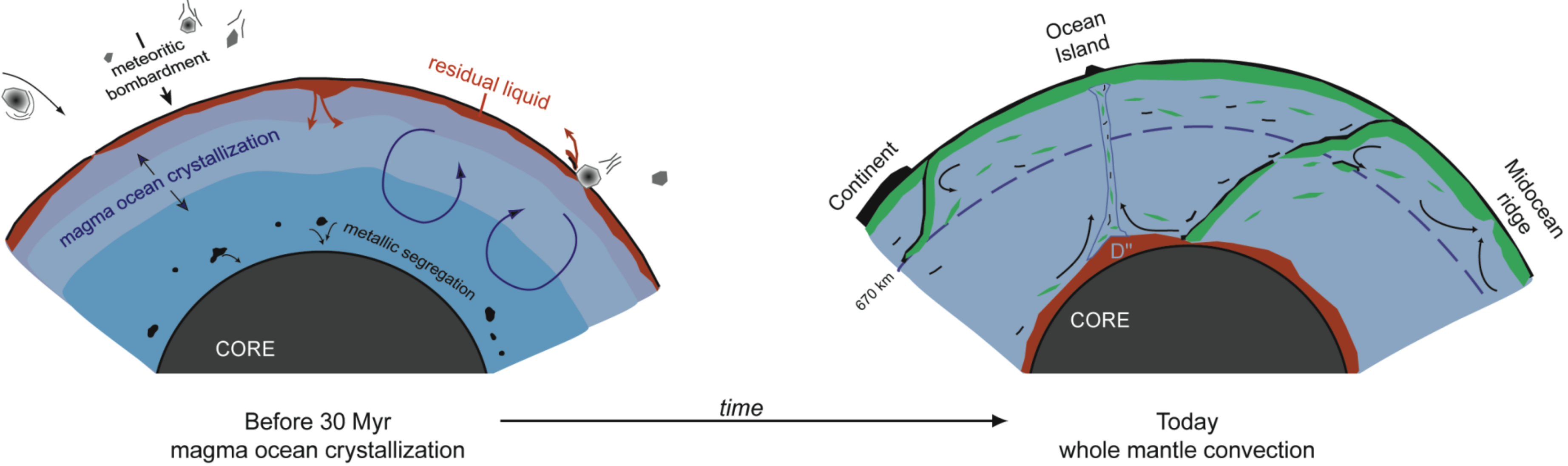

Carlson et al., 2014

Is the Composition of the Bulk Earth Different from Solar?

- Sm and Nd are both refractory lithophile (silicate-soluble) elements
- Very small range of Sm/Nd ratio among chondrites (~3%) and basaltic eucrites
- 20 ppm excess ^{142}Nd/^{144}Nd of terrestrial rocks, if not due to nucleosynthetic causes, requires a Sm/Nd ratio 6.6% higher than chondritic



Could Reflect Initial Igneous Differentiation of Earth

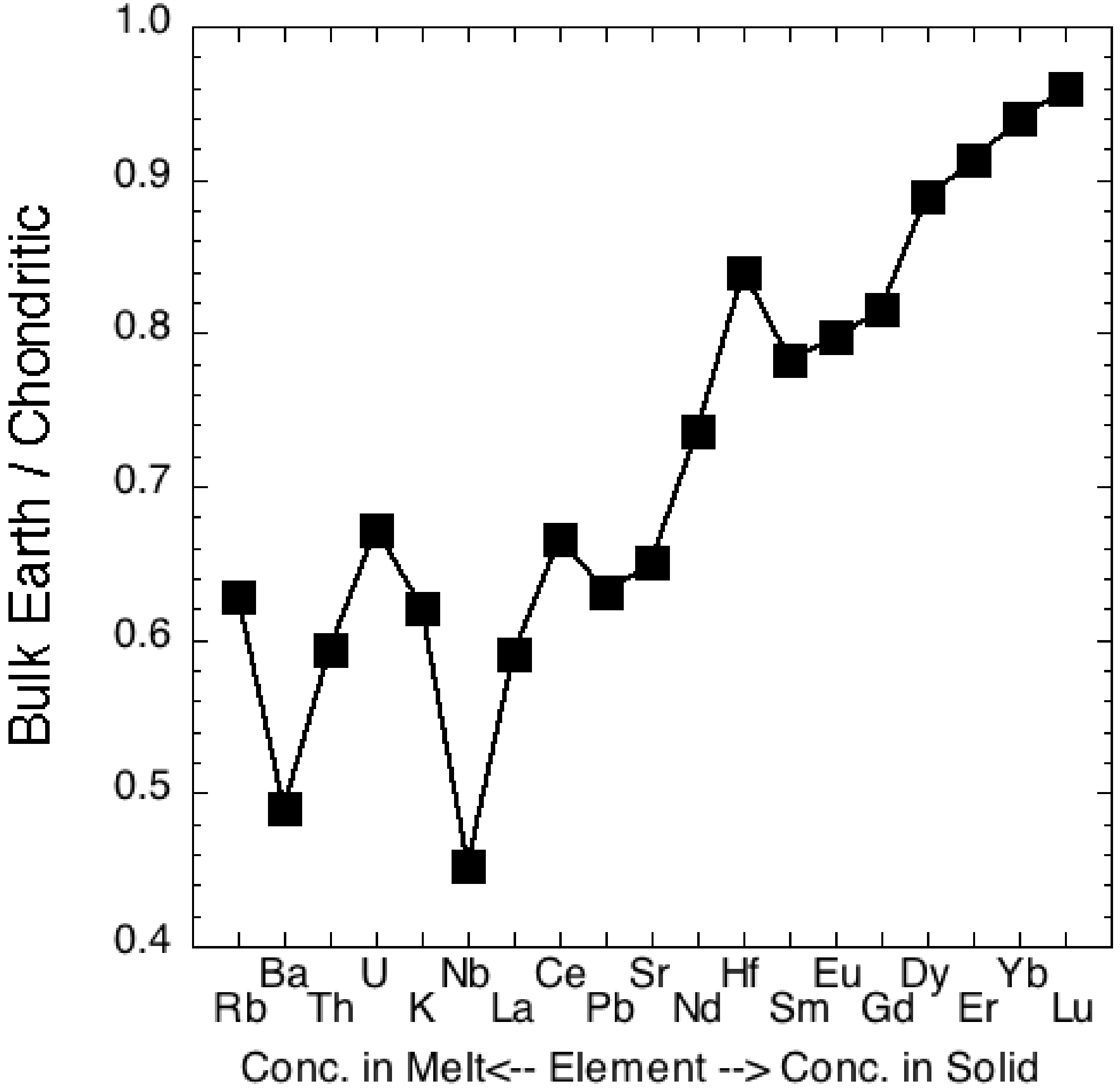


Magma Ocean Overturn

Nd prefers the melt more than Sm, so crystallization of a magma ocean produces a solid with high Sm/Nd ratio, and a residual liquid with low Sm/Nd ratio. The low Sm/Nd ratio source is not seen on Earth, but it could be buried deep enough to escape contributing to surface volcanism throughout Earth history

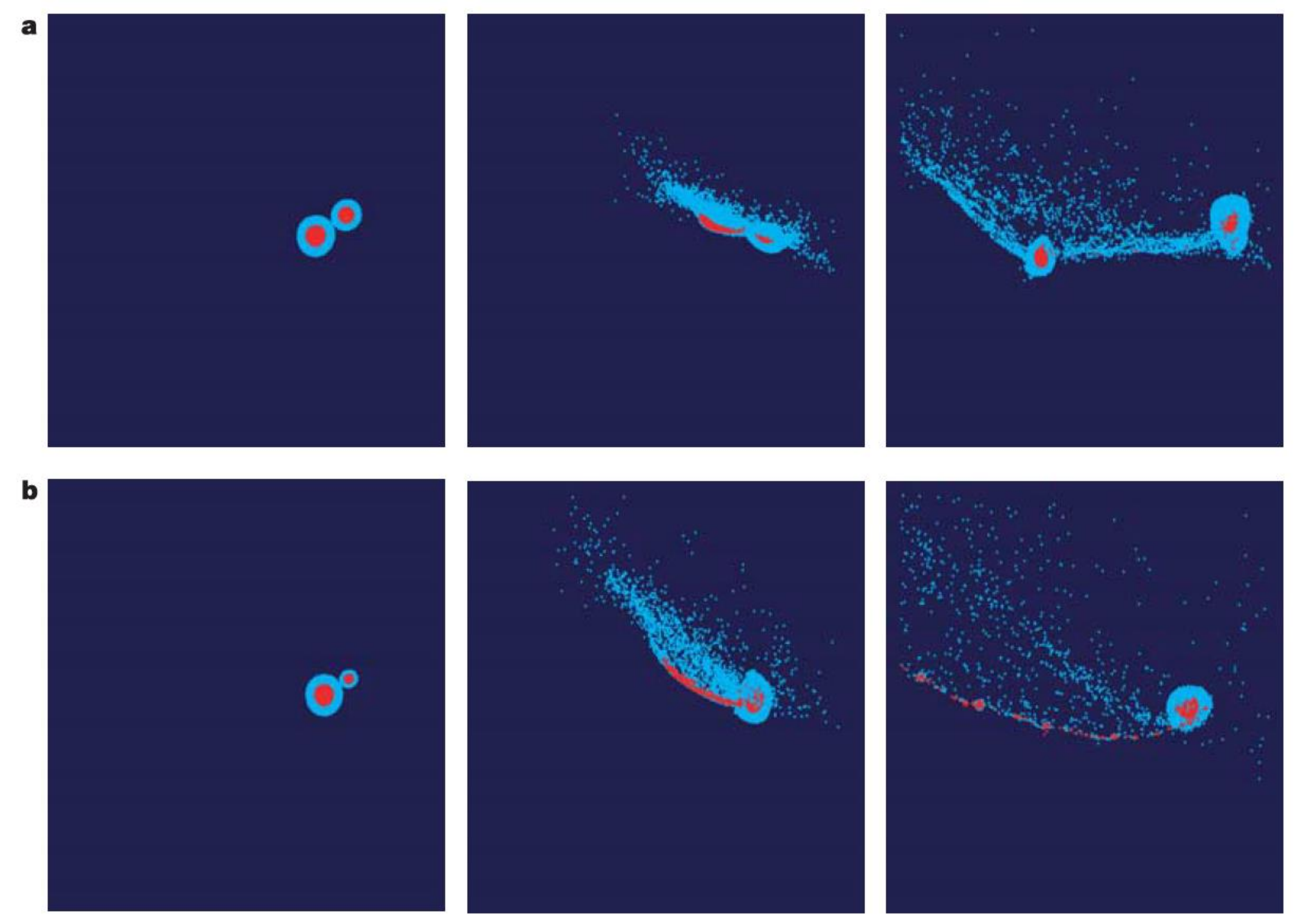
Elevated terrestrial ^{142}Nd, if explained by superchondritic Sm/Nd ratio, translates into a trace element pattern for Earth that is most consistent with low pressure crystal-liquid differentiation, not that expected for a 1000+km deep terrestrial magma ocean

Silicate soluble trace element pattern for bulk-Earth calculated from modern rocks on the assumption that terrestrial Sm/Nd ratio is 6% higher than chondritic

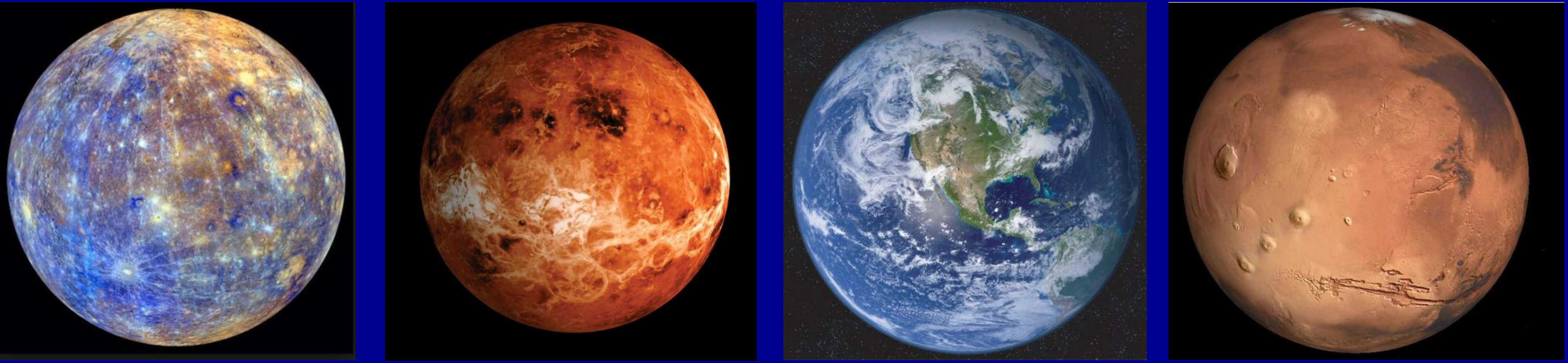


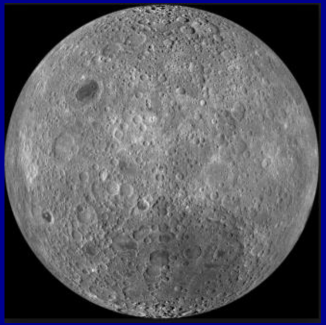
The Physics of Planetary Accretion

Imperfect accretion during “hit and run” collisions,
e.g. Asphaug et al., 2006



The Lesson from Comparative Planetology





Five Examples, Five Different Outcomes

Mars – rapid accretion, mostly ancient crust, oxidized

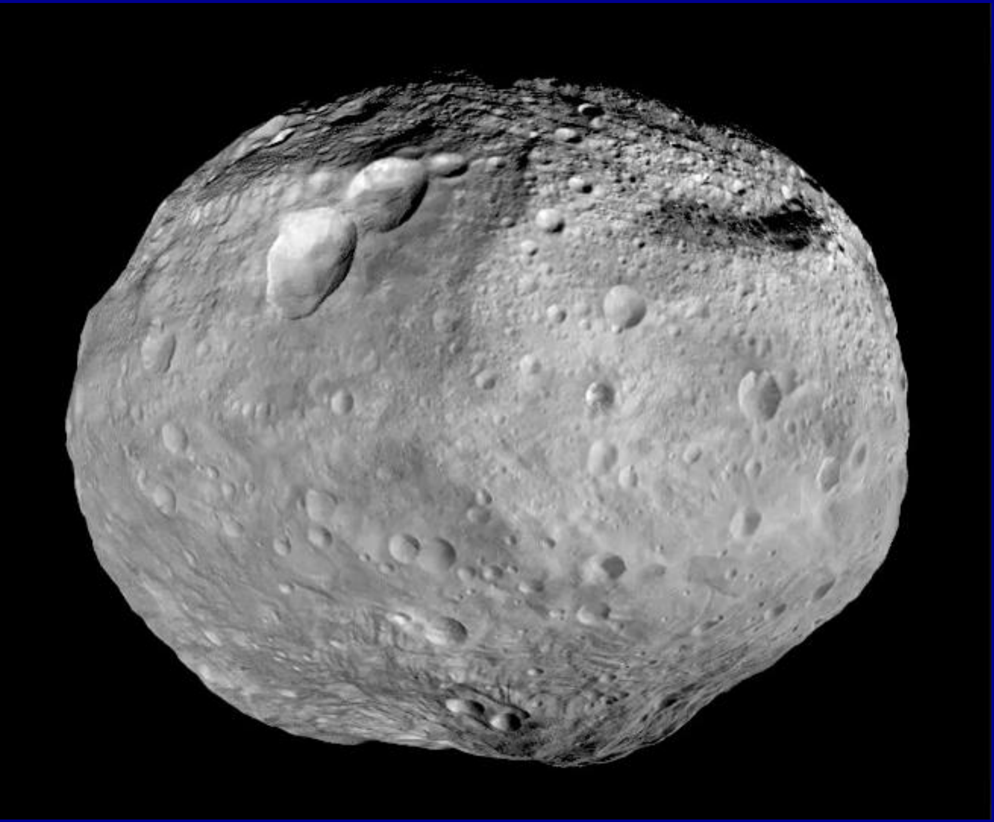
Mercury – ancient crust, very high metal to silicate ratio

Moon – mostly ancient crust, very low metal to silicate ratio

Earth, Venus – young surfaces, probably for very different reasons. One with a magnetic field, one without. One with a massive atmosphere, one without.

A Major Fraction of Earth’s Mass Likely Came from:

This: Vesta, a highly differentiated planetesimal that lost its atmosphere and segregated core, mantle, and crust as the result of a global magma ocean at 4565 Ma (Solar system is 4568 Ma old)



Instead of this: A primitive chondrite with Solar composition in all but the most volatile elements

Orgueil, CI Carbonaceous Chondrite

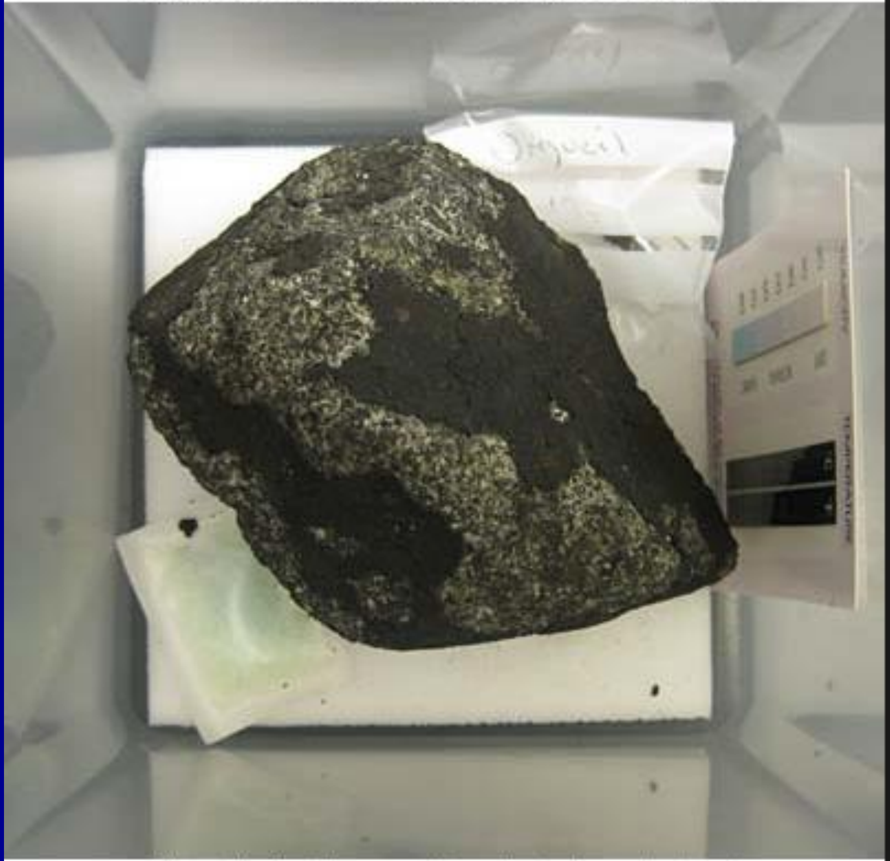


Photo by L. Martel, www.psrd.hawaii.edu with permission of Natural History Museum, London.

Conclusions

1) The Solar nebula may not have been perfectly homogenized before planet formation began
   - Remnants of various stellar contributions survive as presolar grains whose abundance in different meteorites, in particular C-chondrites, is sufficiently variable to cause measureable variation at the "whole rock" scale in an increasingly large number of elements
   - Magnitude of isotope variation largest for supernova produced isotopes. Is this a sign of a late supernova injection with imperfect mixing of the newly arrived extra-solar grains with the proto-Solar molecular cloud?

2) Collisional erosion may be a key process in determining the bulk composition of a planet
   - Is the Earth-Moon system anomalous in its implication of impacts between proto-planets over 100 Myr after the start of planet formation?

When Was the Moon-Forming Impact?

Various approaches to estimate the earliest differentiation events on the Earth and Moon point more towards 4.40 to 4.45 Gyr than 4.568 Gyr.

Consequences of late giant impacts for dust creation in accretionary disks?