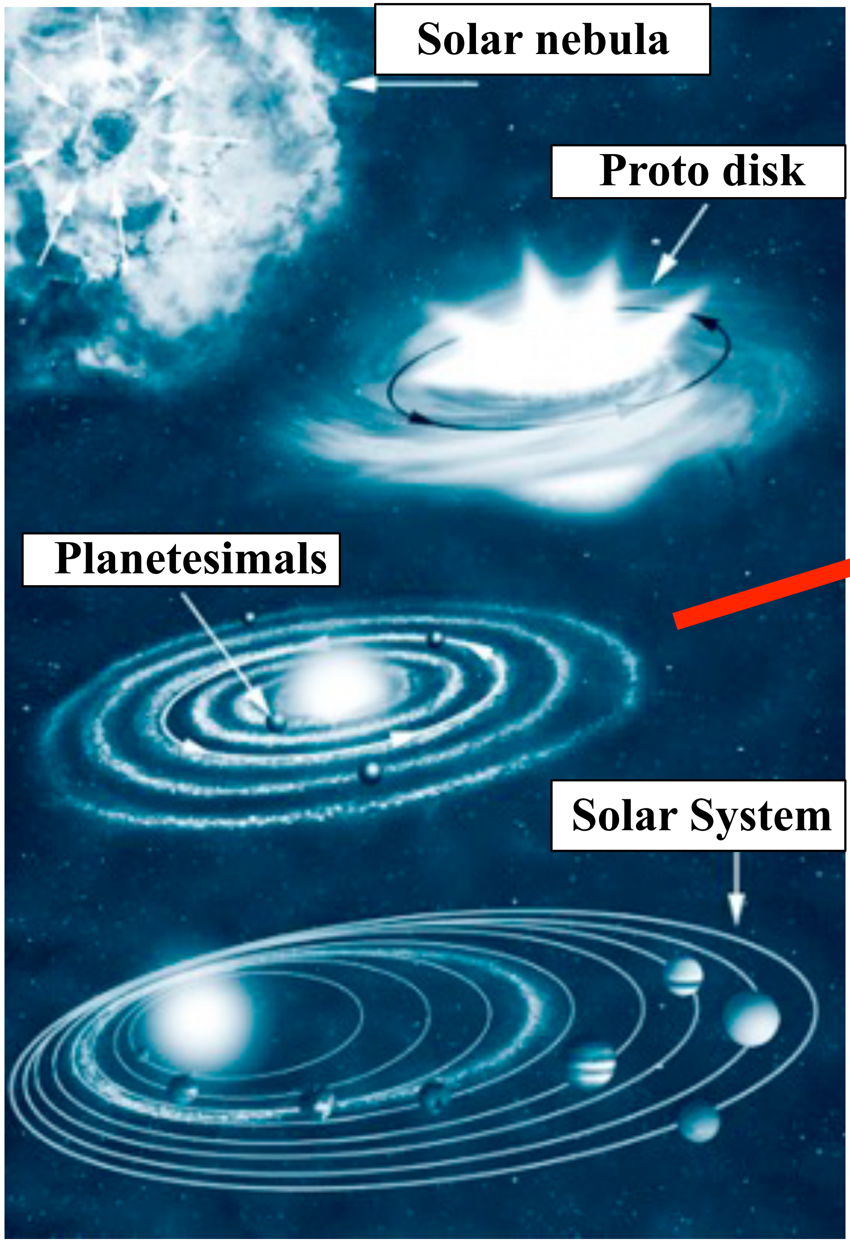
SAMPLE RETURN
OF PRIMITIVE MATTER
FROM THE OUTER SOLAR SYSTEM

Pierre Vernazza & Pierre Beck

Deciphering the History of the Solar System



Planetesimals:
asteroids
comets
TNOs

tell us about:

The chronology of the early Solar System

The primordial chemical composition from which planets once accreted

The dynamical evolution of the Solar System

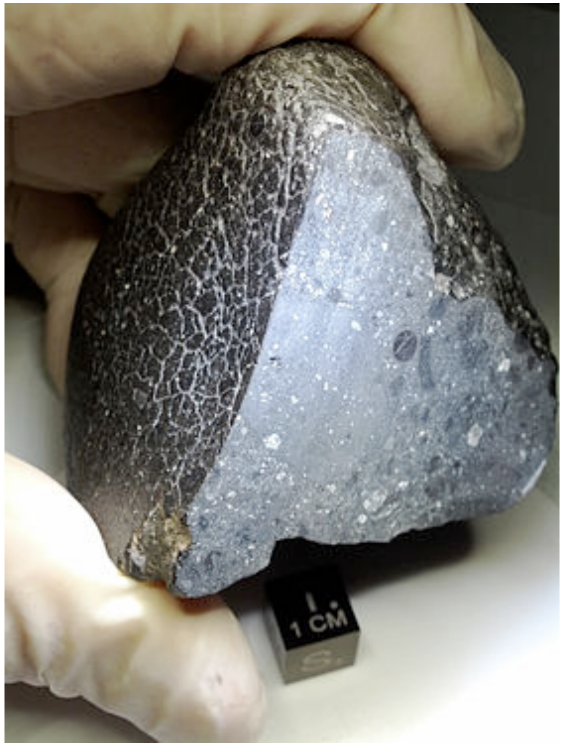
Deciphering the History of the Solar System: What has been learned from the study of extra-terrestrial samples (selection)

- The Age of the Solar system
- The existence of chondrules and CAIs, major “dust” reservoirs at least in the inner solar system.
- The bulk composition of the Earth
- Earth-Moon impact theory based on Lunar samples
- The “motor” of planetesimal differentiation, ^{26}Al
- Early formation of Mars from Martian meteorites (<2 Myrs) and an early formation of Jupiter’s core from chondritic meteorites.

This is today’s knowledge; limited by what we can measure in the laboratory as a function of

1) present-day technology
2) what sample we have

How cosmochemistry relies on samples: example of the “black beauty” Martian meteorite



« black beauty » meteorite: a new type of Martian meteorites identified in 2013

The oldest Martian rock:
Agee et al., *Science* 2013

An early formation of the continental crust:
Humayun et al., *Nature* 2013

Trace of an ancient hydrosphere:
Nemchin et al., *Nature Geo.* 2014

An early crust and magma ocean:
Bouvier et al., *Nature* 2018

The lack of giant impacts after 4.48 Ma on Mars:
Moser, *Nature Geo.*, 2018

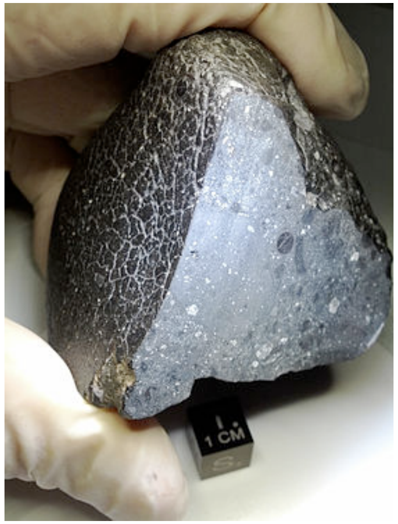
An early formation of the crustal dichotomy:
Cassata et al., *Science Adv*. 2019

and more to come….

The suite of extra-terrestrial materials

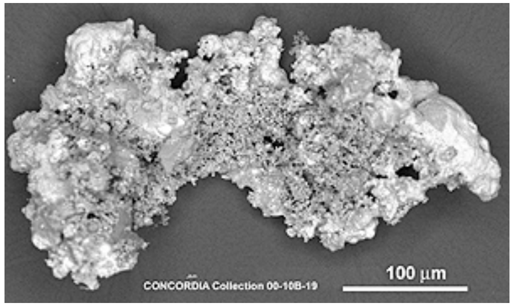
ROCKS

Meteorites

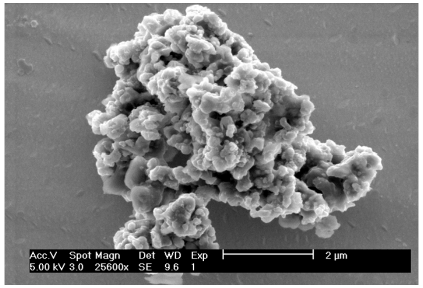


DUST

Micrometeorites



IDPs



Planetary

Mars & Moon

Asteroidal

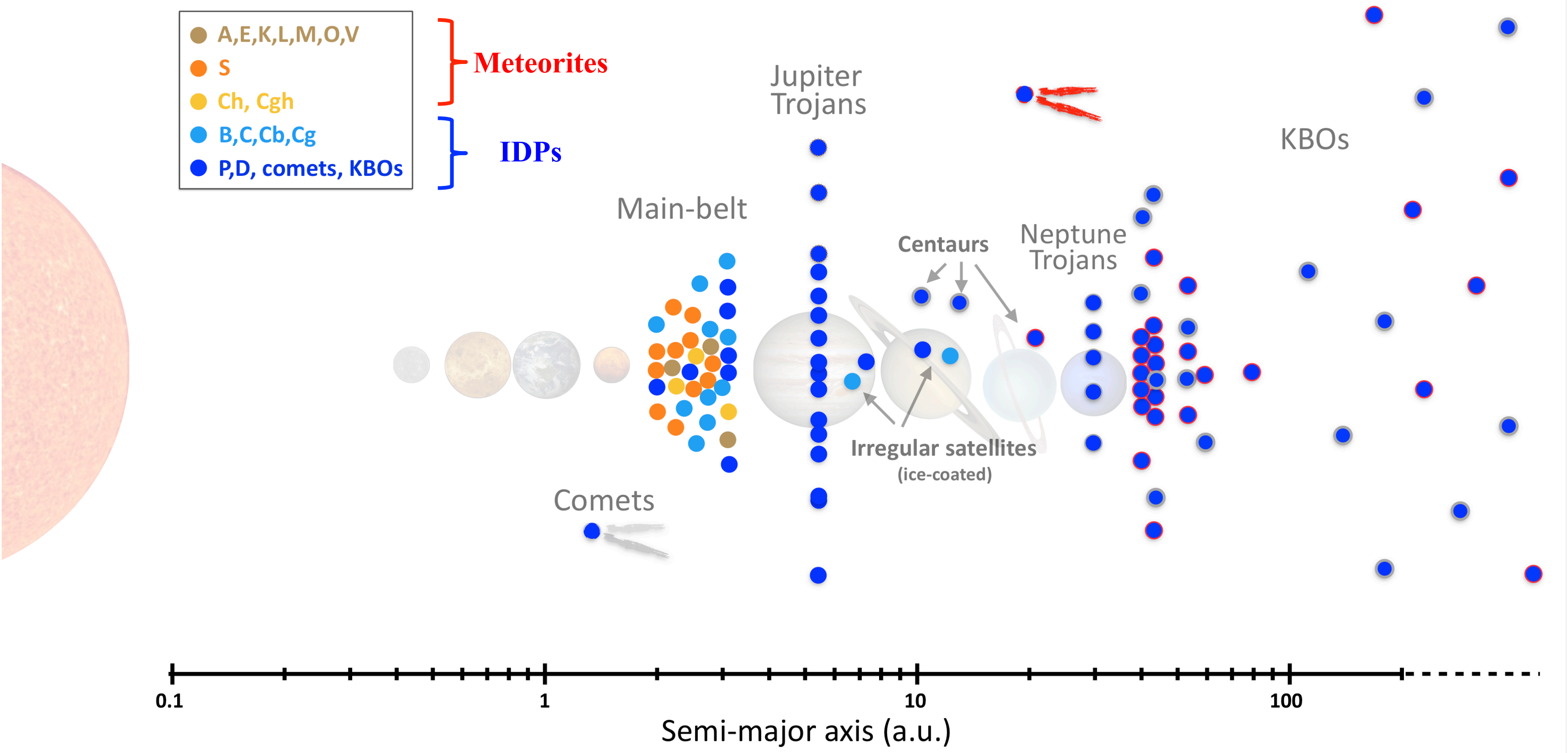
Comets

10^5 kg in the collection

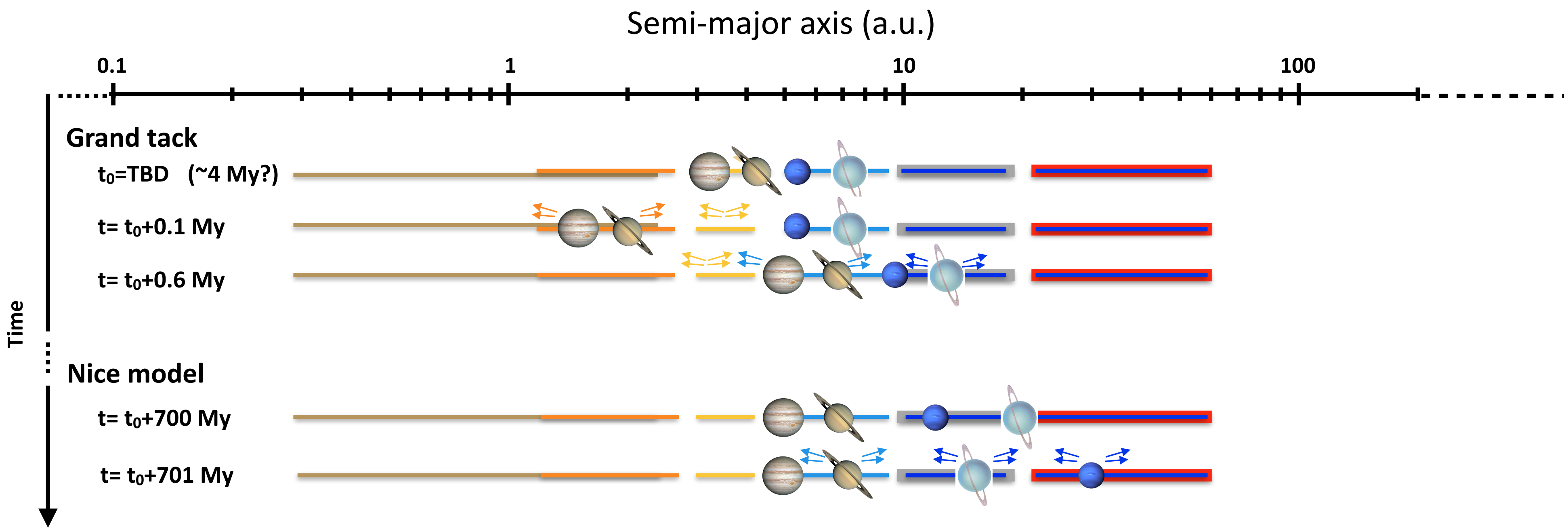
10^{-7} kg in the collection

Compositional distribution across the solar system: Current knowledge

From Vernazza & Beck (2017)

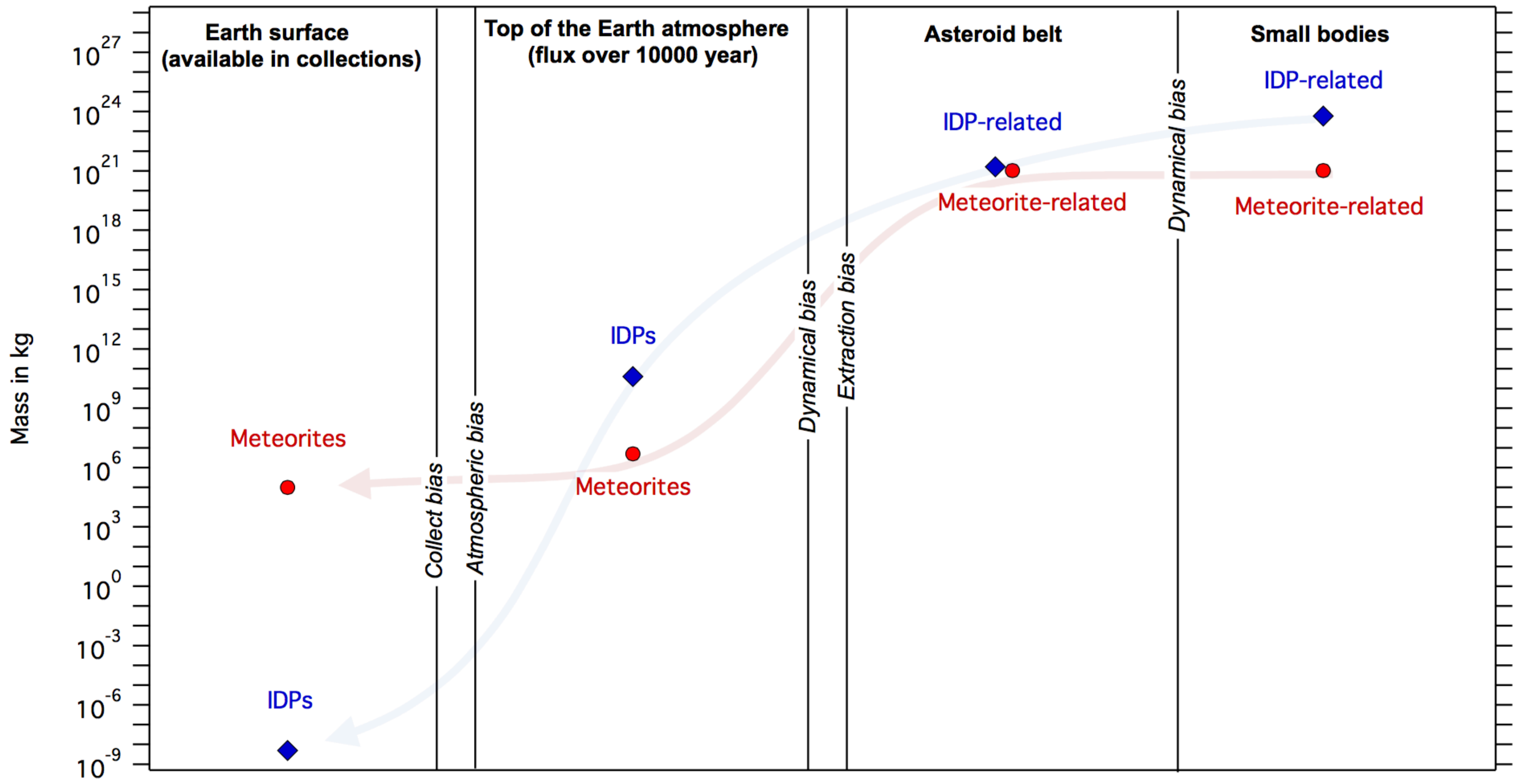


Current dynamical scenarios

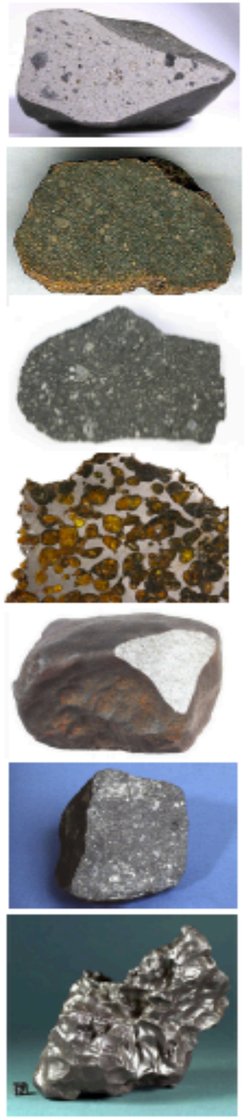


From Vernazza & Beck (2017)

Extra-terrestrial samples of small bodies:
What we miss !



Meteorites: any “very” primitive samples? No !



- Meteorites are classified into chondrites (from undifferentiated bodies) and achondrites (from differentiated parent bodies).

- The least-altered meteorites (some chondrites) contain only **traces** of the starting materials (including interstellar dust grains and molecular cloud material).

- Even the most primitive meteorites are comprised almost entirely of secondary materials, the most notable of these secondary materials being chondrules (mm-sized molten silicate spherules).

- Finally, even the most “primitive” meteorites (CI, CM) have experienced extensive aqueous alteration !

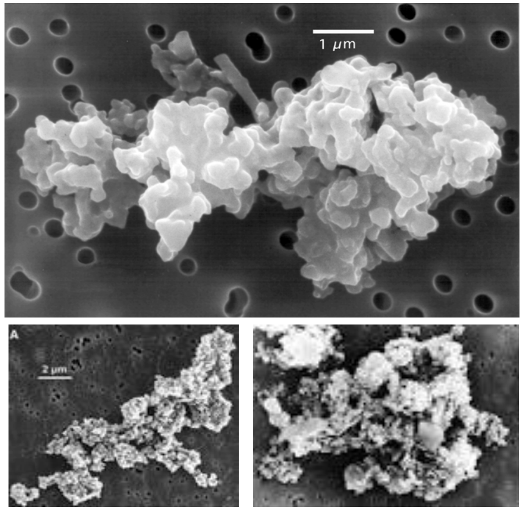
IDPs: any “very” primitive samples? Yes !

- Chondritic porous IDPs (CP IDPs) are currently recognized among the available extra-terrestrial materials as the closest to the starting ones.

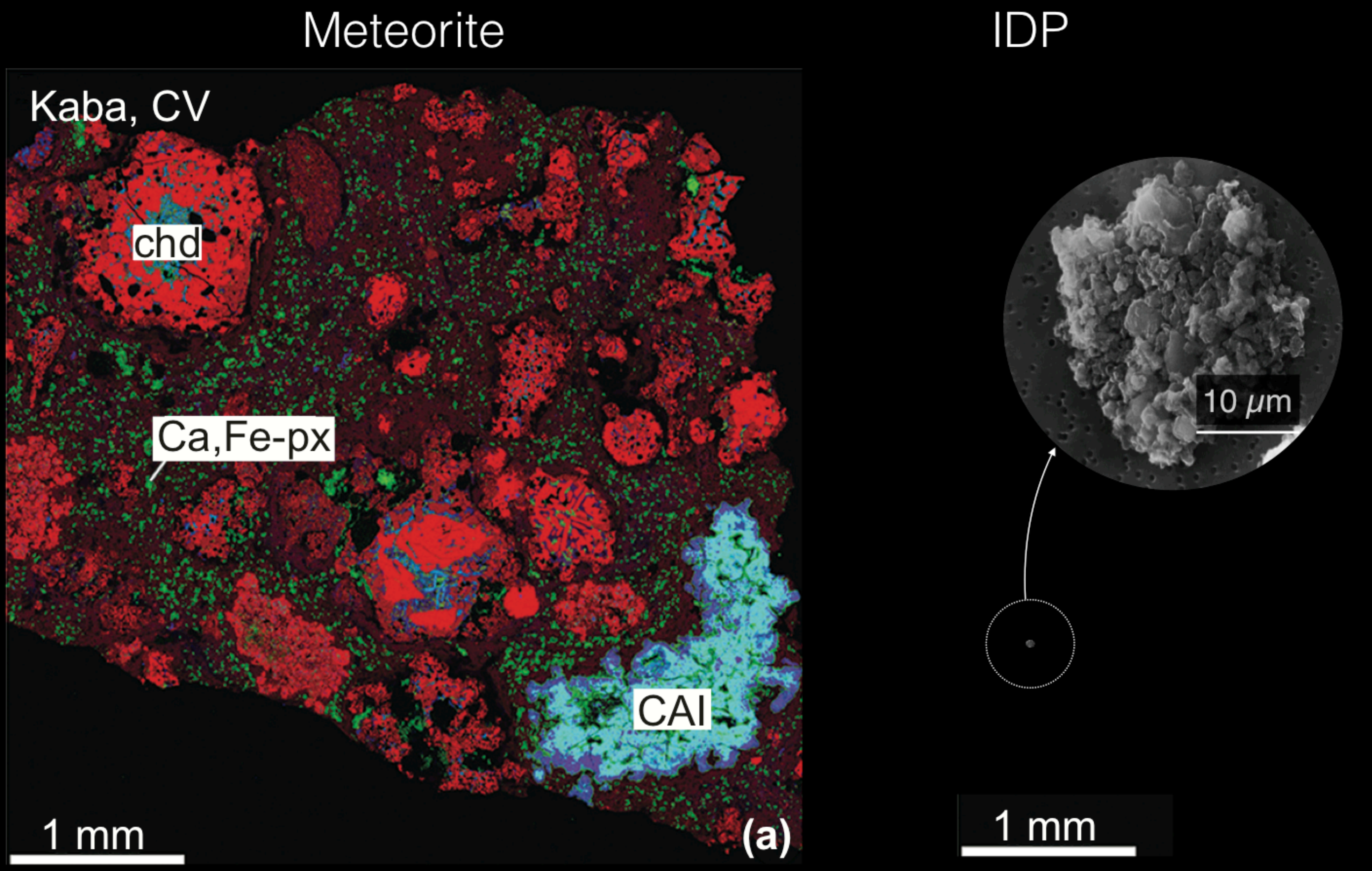
- CP IDPs are structurally similar to cometary materials in being extremely fine-grained (subgrains <0.5 µm in diameter), porous, and fragile which explains why they are unable to survive atmospheric entry.

- CP IDPs contain a mix of submicrometer glass with embedded metal and sulfides (GEMS) (Bradley 1999), organic materials, olivine, pyroxene, pyrrhotite, and less-well-defined materials .

- Notably, CP IDPs are highly enriched in C [2–3× CI] and volatile trace elements relative to CI carbonaceous chondrites.



Are IDPs fully representative of the bulk composition of their parent bodies? (1)



Are IDPs fully representative of the bulk composition of their parent bodies? (2)

- The volatiles phases are lost ! Yet, volatiles should represent at least 50% of the volume of their parent bodies !

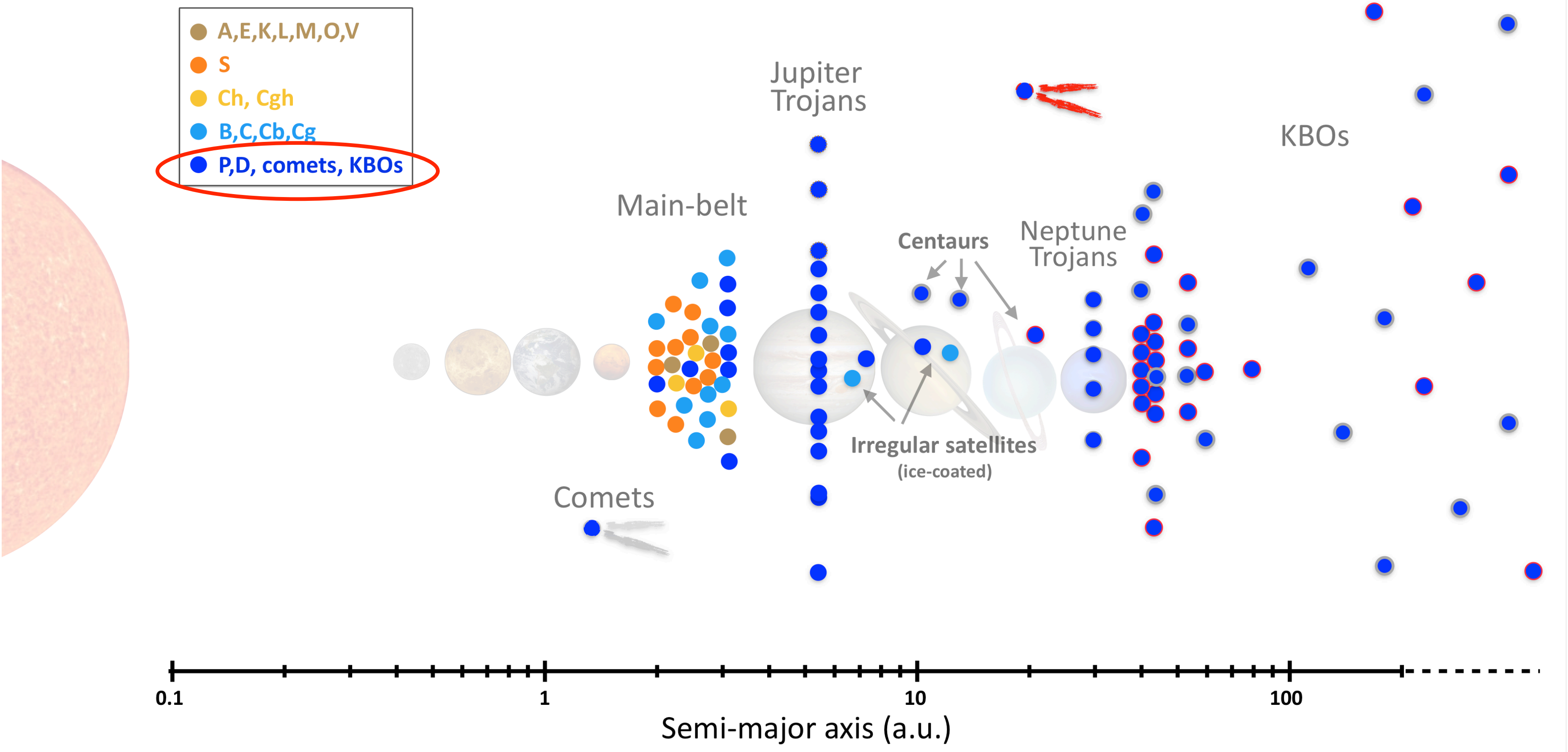
- IDPs may have been altered during atmospheric entry

- IDPs are rich in C; but not as rich as some comets !

Top level science questions that justify a sample return mission of a primitive small body

- **What is the path to an inhabited planetary system?**
- What were the initial ingredients of the Solar System and how were these ingredients distributed around the young Sun?
- What is the fraction of presolar material that survived until today in outer Solar System bodies?
- How diverse was the origin of the starting materials and what was the environment of the pre-solar cloud core?
- What is the pathway of life-forming elements (C,H,N,O) from the interstellar medium to the Solar System?
- How and when did planetesimals accrete in the outer Solar System?

Objects that satisfy our science objectives



Mission profile and orbiter payload

Mission profile: L-class mission

- Sample return mission (Rendez vous with a P/D asteroid or a comet, multiple sampling, Earth re-entry)
- Either a single spacecraft or a configuration with a mother spacecraft and a landing/hopping platform could be envisaged
- Possibility of a lander/rover should be studied

Orbiter payload

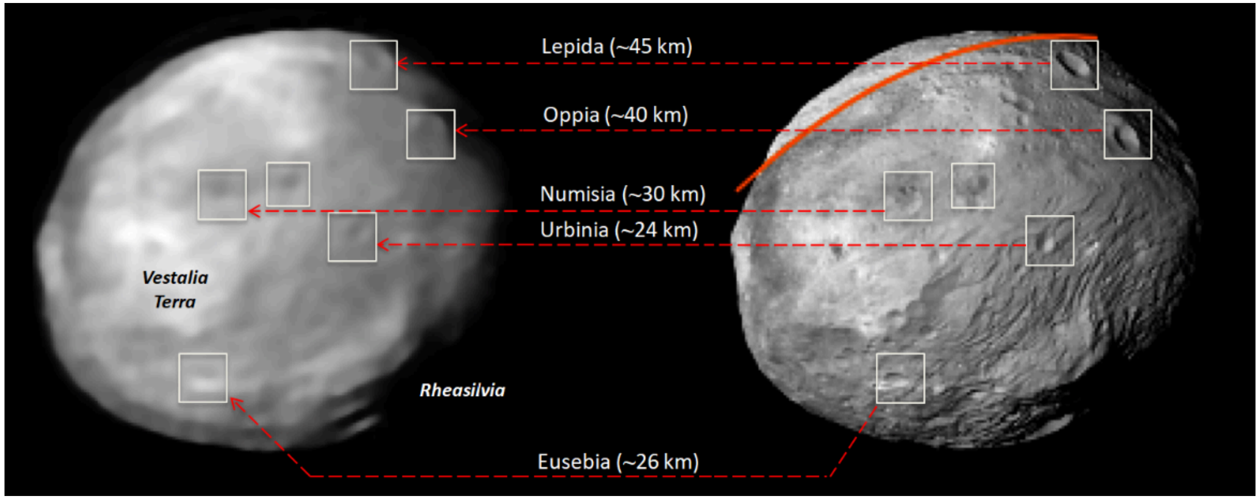
1) Camera (NAC)
2) Near and thermal infrared imaging spectrometers
3) Mass spectrometer

Sample return key capability

- Sample, preserve and return material at cryogenic temperatures in order to keep volatiles species, i.e., water ice in their solid form.
- The temperature of liquid nitrogen (77K) is sufficient to preserve both crystalline and amorphous ice.
- To keep other volatiles such as CO and CO2 and to retain heavy noble gases, a lower temperature (down to 10K) would be required.

The era of sample return (1)

- Recent observations of asteroid (4) Vesta with VLT/SPHERE and of Neptune with VLT/MUSE have revealed in a striking fashion to what extent the gap between interplanetary missions and ground-based observations is getting narrower.



- With the advent of very large telescopes (ELT, GMT, TMT), the science objectives of future interplanetary missions have to be carefully thought out so that these missions will complement – not duplicate – what will be achieved via Earth-based telescopic observations in the next decades.

The era of sample return (2)

- Future ELT adaptive-optics imaging observations of main belt asteroids will allow to resolve craters down to ~2-5 km in size !

- ELT observations of Jupiter with the near-IR integral field spectrograph HARMONI will have a higher spatial resolution (at least a factor of 3) than those performed in-situ by the ESA JUICE mission with MAJIS !

- In the field of Solar System small bodies, this propels missions performing cosmochemistry, namely sample return missions and to a lesser extent landing missions, at the forefront of space exploration

- Apart from ESA, all major space agencies (NASA, JAXA, Roscosmos, CNSA) have already launched or plan to launch in the very near future a sample return mission.

From a laboratory perspective

- A sample return mission would allow to maintain the currently high scientific level of the community working on extra-terrestrial samples in European laboratories while at the same time providing new challenges and exciting perspectives for developing new state of the art instruments and curation facilities.

- At present there are no official European sample curation facilities of extra-terrestrial samples. This has to be built, and such a facility would need to be able to host cryogenic samples.

The end