FROM THE OUTER SOLAR SYSTEM
OF PRIMITIVE MATTER
SAMPLE RETURN
Deciphering the History of the Solar System

- The dynamical evolution of the Solar System
- The primordial chemical composition from which planets once accreted
- The chronology of the early Solar System

Planetary objects:
- Planets
- Asteroids
- Comets
- TNOs

Tell us about:
- Planets
- Asteroids
- Comets
- TNOs

Image of a solar nebula, proto disk, and planetimals.
Deciphering the History of the Solar System: What has been learned from the study of extra-terrestrial samples (selection)
How cosmochemistry relies on samples:

- Example of the "black beauty" Martian meteorite:

  - "Black beauty" Martian meteorite: a new type of Martian meteorites identified in 2013.

  - The oldest Martian rock: The oldest Martian rock:

- Early formation of the crustal dichotomy:
- The lack of giant impacts after 4.48 Ma on Mars:
- An early crust and magma ocean:
- Trace of an ancient hydrosphere:
  - Nemchin et al., Nature Geo. 2014.
- An early formation of the continental crust:
  - Agee et al., Science 2013.
- An early formation of the crustal dichotomy:


- More to come...
The suite of extra-terrestrial materials

- Comets
- Asteroidal Rocks
- Micrometeorites
- IDPs
- Mars & Moon

10^7 kg in the collection
10^5 kg in the collection

Dust

The suite of extra-terrestrial materials
Compositional distribution across the solar system: Current knowledge from Vernazza & Beck (2017)
Current dynamical scenarios

From Vernazza & Beck (2017)
What we miss!

Extra-terrestrial samples of small bodies:
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 molecular cloud material.
- Even the most primitive meteorites are comprised almost entirely of secondary materials (some chondrites) containing only traces of the starting materials (including interstellar dust grains and chondrules).
- Finally, even the most „primitive“ meteorites (CI, CM) have experienced extensive aqueous alteration.

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IDPs: any "very" primitive samples? Yes!

Notably, CP IDPs are highly enriched in C [2–3 × CI] and volatile olivine, pyroxene, pyrrhotite, and less-well-defined materials. CP IDPs contain a mix of submicrometer glass with embedded metal and sulfides (GEMS) (Bradley 1999), organic materials, and extremely fine-grained (subgrains <0.5 µm in diameter) porous ones. CP IDPs are structurally similar to cometary materials in being the available extra-terrestrial materials as the closest to the starting CHON-rich porous IDPs (CP IDPs) are currently recognized among

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

- IDPs may have been altered during atmospheric entry

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

- The volatiles phases are lost; yet, volatiles should represent at least 50% of the volume of their parent bodies!
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 and when did planetesimals accrete in the outer Solar System?
- 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?
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. 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 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)

Observations in the next decades will be achieved via Earth-based telescopic, what will be duplicated – what will be achieved via Earth-based telescopic, 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 – ground-based observations. Recent observations of asteroid (4) Vesta with VLT/SPHERE and of Neptune with VLT/MUSE have revealed in a striking fashion to the gap between interplanetary missions and ground-based observations is getting narrower.
The era of sample return missions have already launched or plan to launch in the very near future a

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

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

Future ELTs and 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 MAIS.

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.

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From a laboratory perspective, a sample return mission would allow to host cryogenic samples at very high scientific level of the community working in European laboratories while at the same time providing new challenges and exciting perspectives for developing new state of the art instruments and sample 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