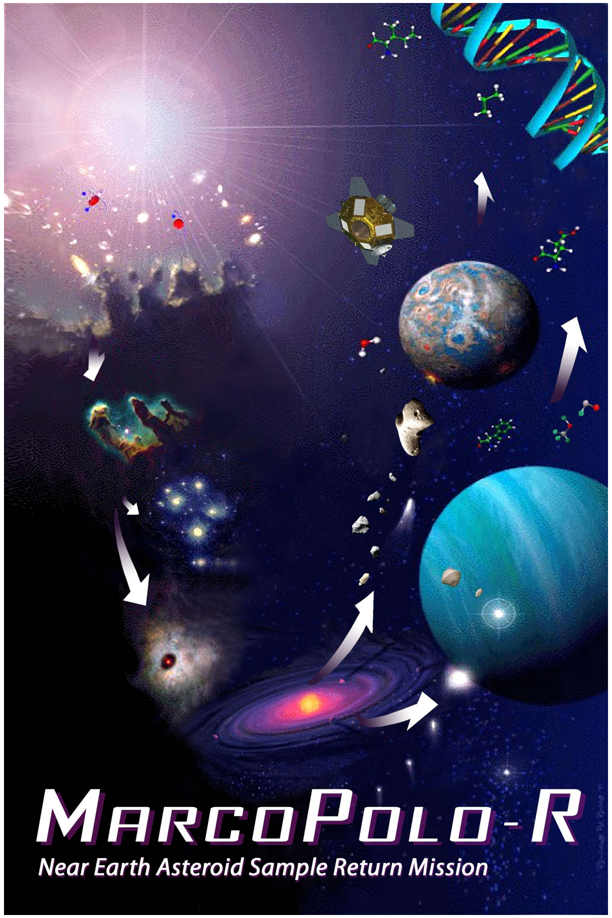
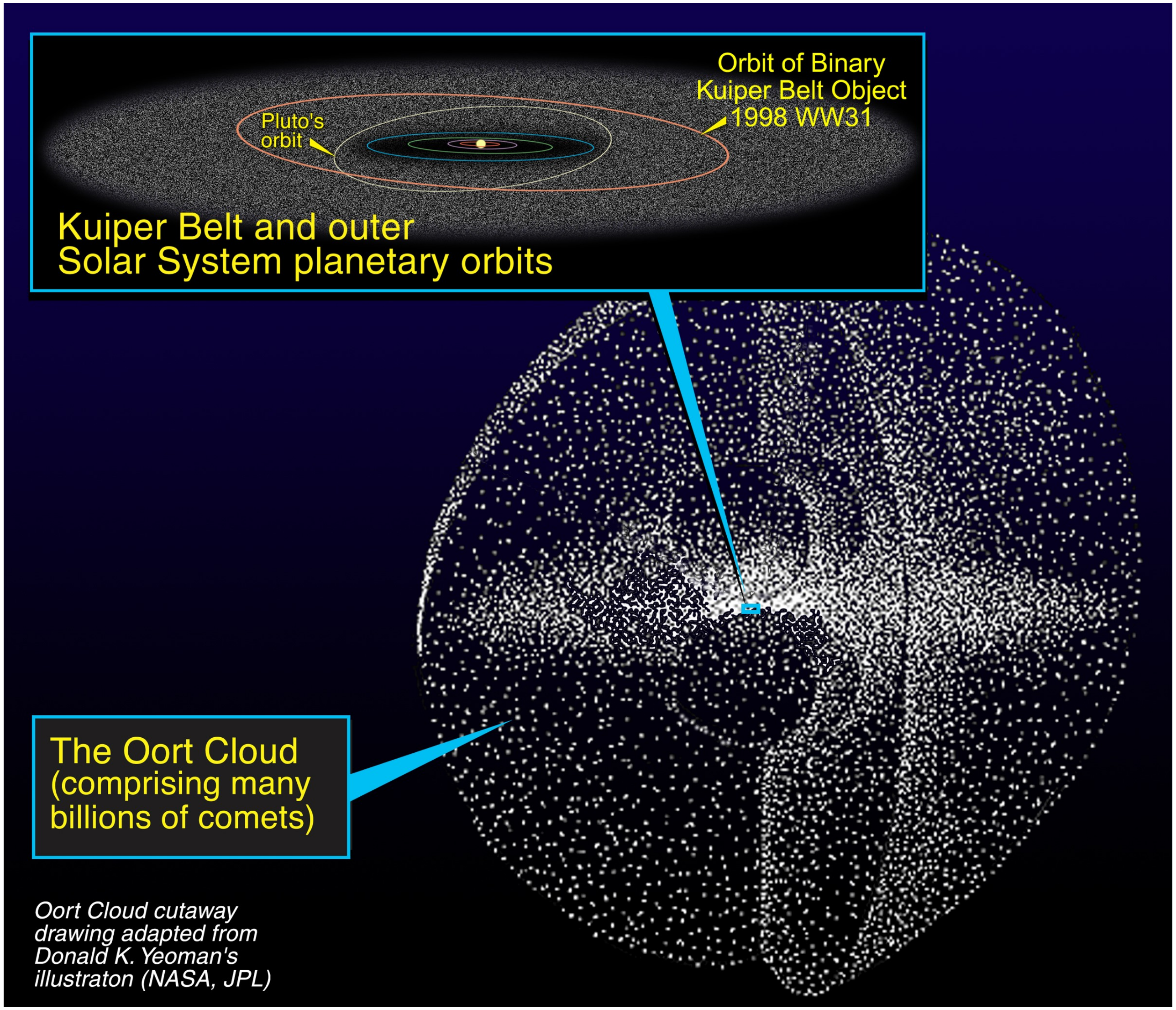
A sample return mission to a primitive Near Earth Asteroid: the ESA Cosmic Vision M3 mission MarcoPolo-R

Elisabetta Dotto
(INAF-Osservatorio Astronomico di Roma)

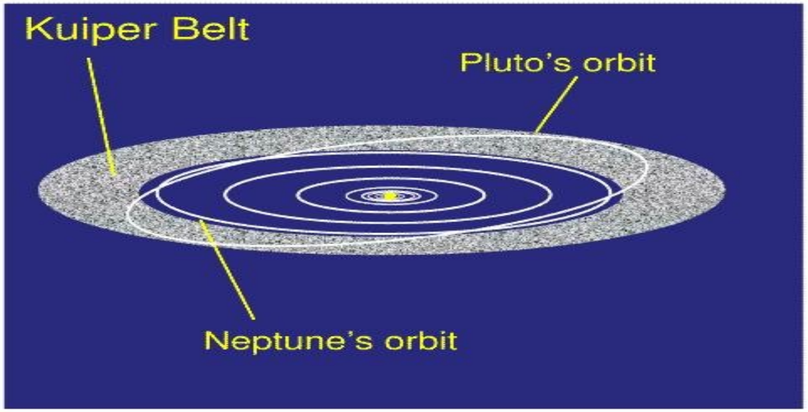


The Solar System

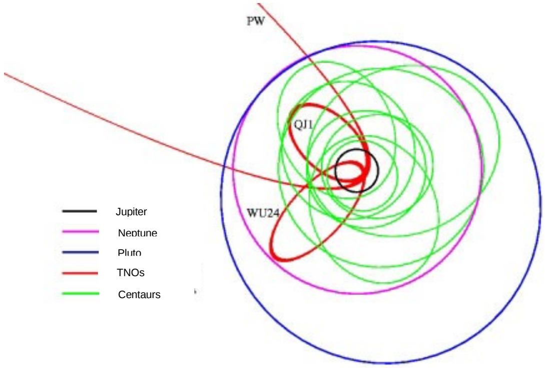


Small bodies of the Solar System

- Trans-Nettunian Objects
- Centaurs
- Jupiter Troians
- Main Belt Asteroids
- Near Earth Objects

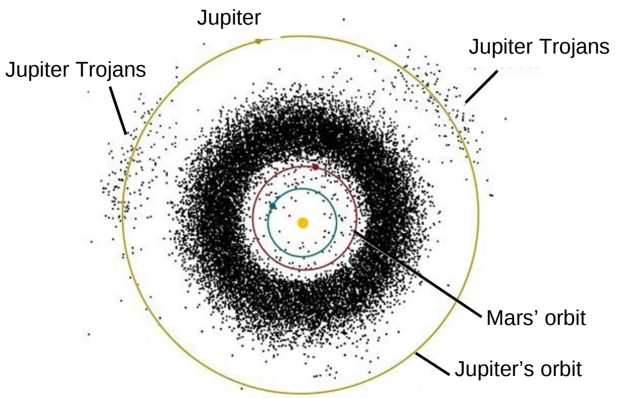


➢ they are the less evolved bodies of the Solar System



➢ they are remnants of the planetary building blocks (planetesimals)

➢ their composition changes accordingly to the solar distance where they formed



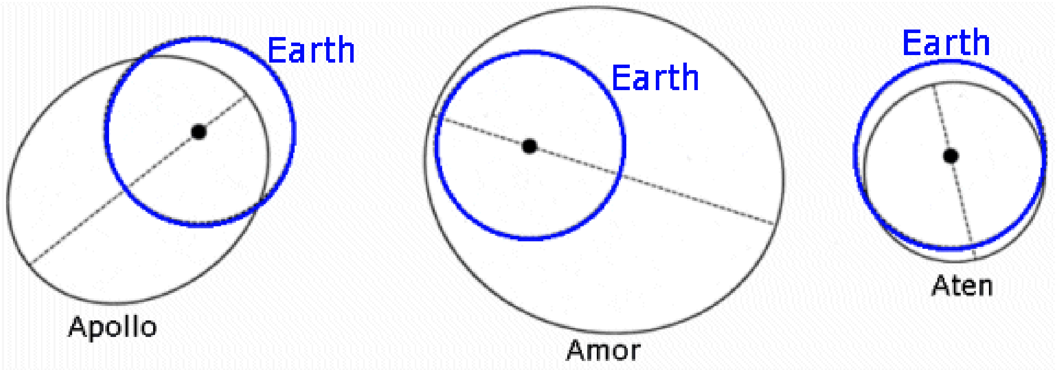
Small bodies of the inner Solar System: the Near Earth Objects

So far we know more than 7800 NEOs.

Apollo: $a > 1$ UA
$q < 1.017$ UA

Amor: 1.017 UA $< q < 1.3$ UA

Atens: $a < 1$ UA
$Q > 0.983$ UA



- are the final stage of asteroids and comets orbiting around the Sun in the inner Solar System
- they formed in other regions of the Solar System
- they moved in their present orbits (dynamical mechanisms, lifetime million years)
- they collide with Sun or inner planets

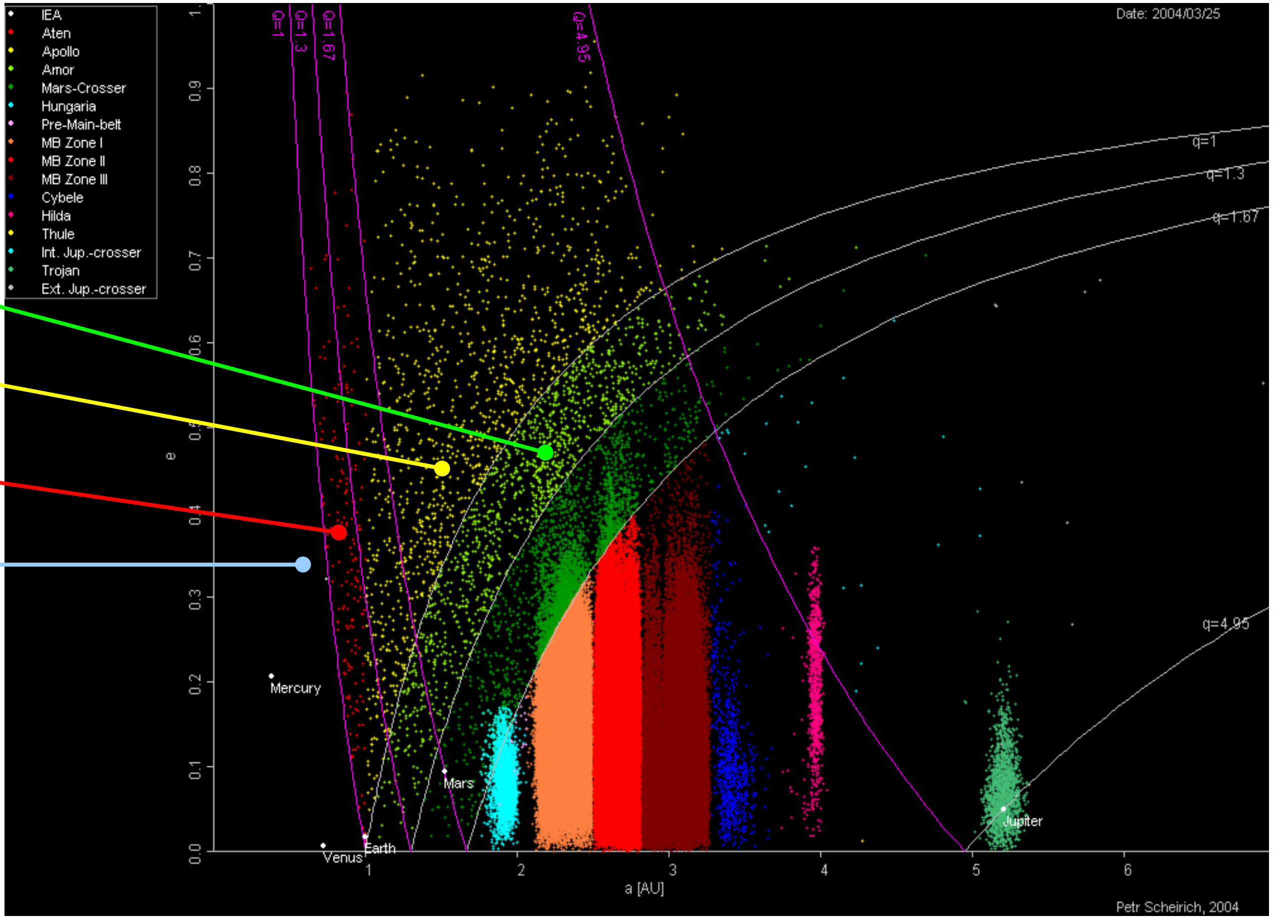
The Near Earth Asteroids

Amor (1<q<1.3)

Apollo (q<1, a>1)

Aten (Q>1, a<1)

IEO (Q<1)



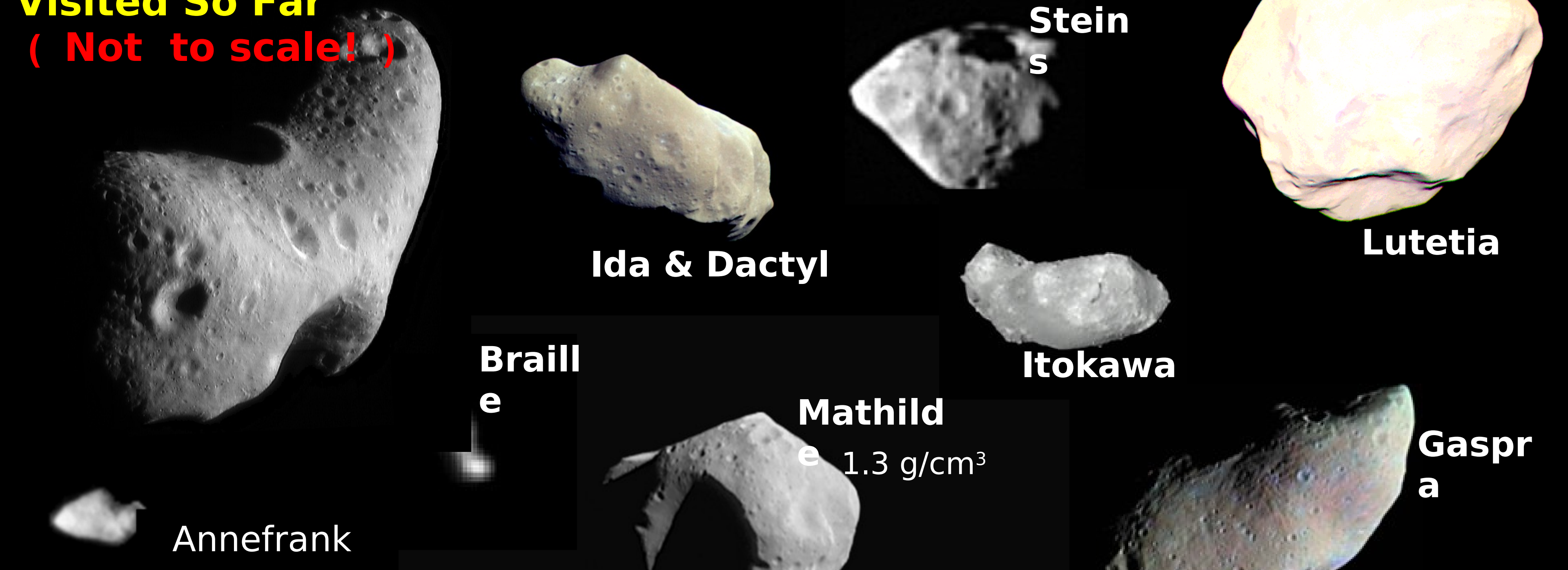
Why an asteroid?

Asteroids, as primitive building blocks of the solar system formation process, offer clues to the chemical mixture from which the terrestrial planets formed some 4.6 billion years ago.


Look different, but common origin

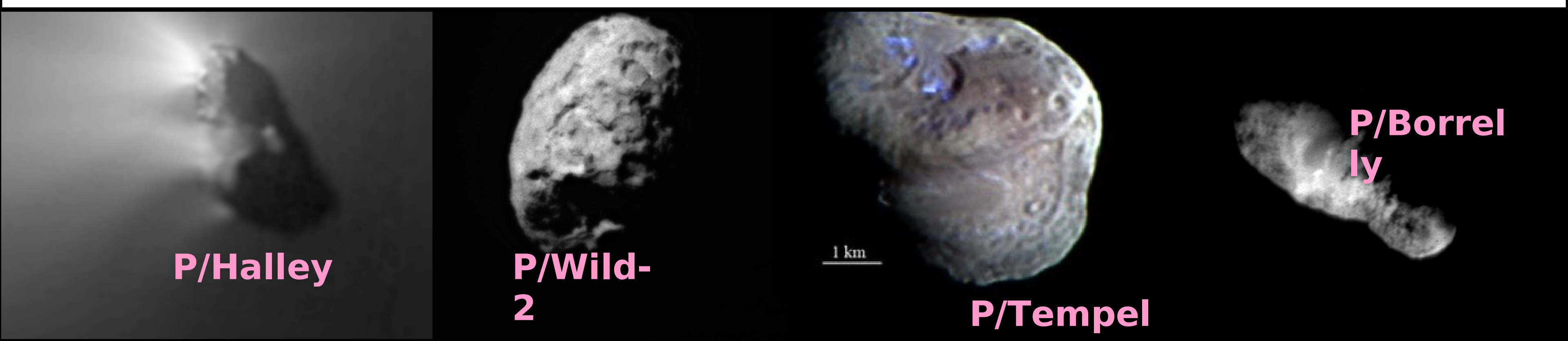
Minor Bodies: Asteroids and Comets Visited So Far

(Not to scale!)



Look different, but common origin.

Only primitive types retain a memory of the origin.

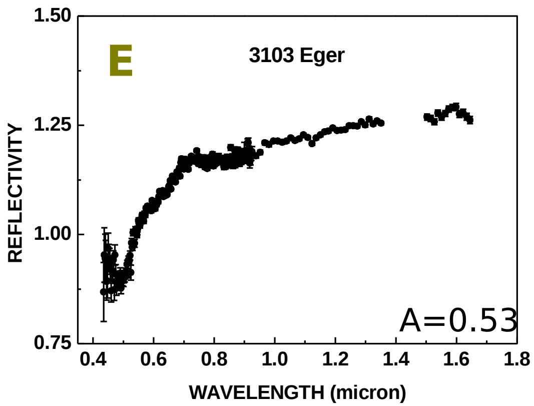


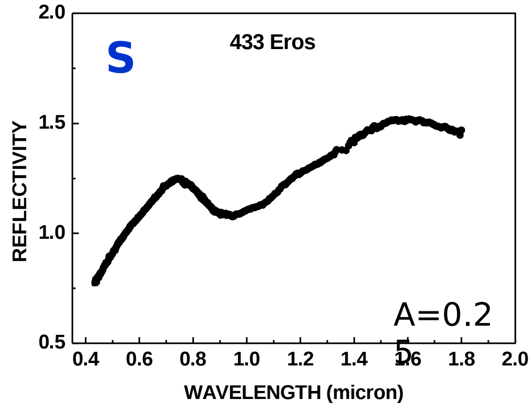
Taxonomy of Asteroids: Surface Composition

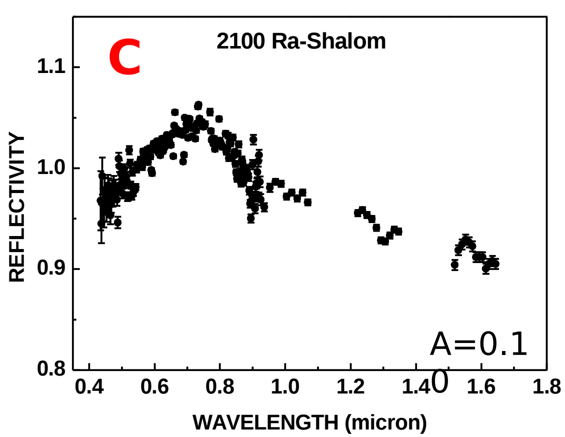
<u>**Tax.Type**</u>	<u>Minerals</u>	<u>Possible Meteorite Analogous</u>
A	Olivine ± FeNi metal	Olivine Achondrites Pallasites Olivine-metal partial melt residues
V	Pyroxene ± Feldspar	Eucrites, Howardites, Diogenites
E	Enstatite	Enstatite achondrites (aubrites) Iron-bearing Enstatites Fe-bearing Aubrites
M	Metal ± Enstatite Hydrates Silicates + Organics?	Iron Meteorites Enstatite Chondrites
S	Metal ± Olivine ± Pyroxene	Pallasites with accessory py. Olivine-dominated Stony-Iron Urelites and primitive achondrites Ordinary Chondrites
O	Olivine+Pyroxene	L6-LL6 Ordinary chondrites
Q	Olivine+Pyroxene (+metal)	Ordinary Chondrites
R	Olivine+Orthoyroxene	Olivine-pyroxene cumulates Olivine-pyroxene partial melt residues
C	Iron-bearing hydrated Silicates	CI1 and CM2 Chondrites Dehydrated CI1 and CM2 assemblages
P	Anhydrous silicates + organics	Olivine-organic cosmic dust particles
D	Organics+Anhydrous silicates	Organic-olivine cosmic dust particles

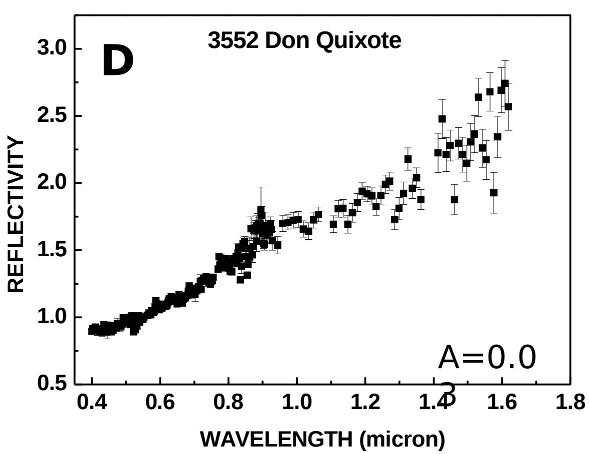
Asteroids taxonomic classes

The asteroid taxonomic classes are indicative of different mineralogies.





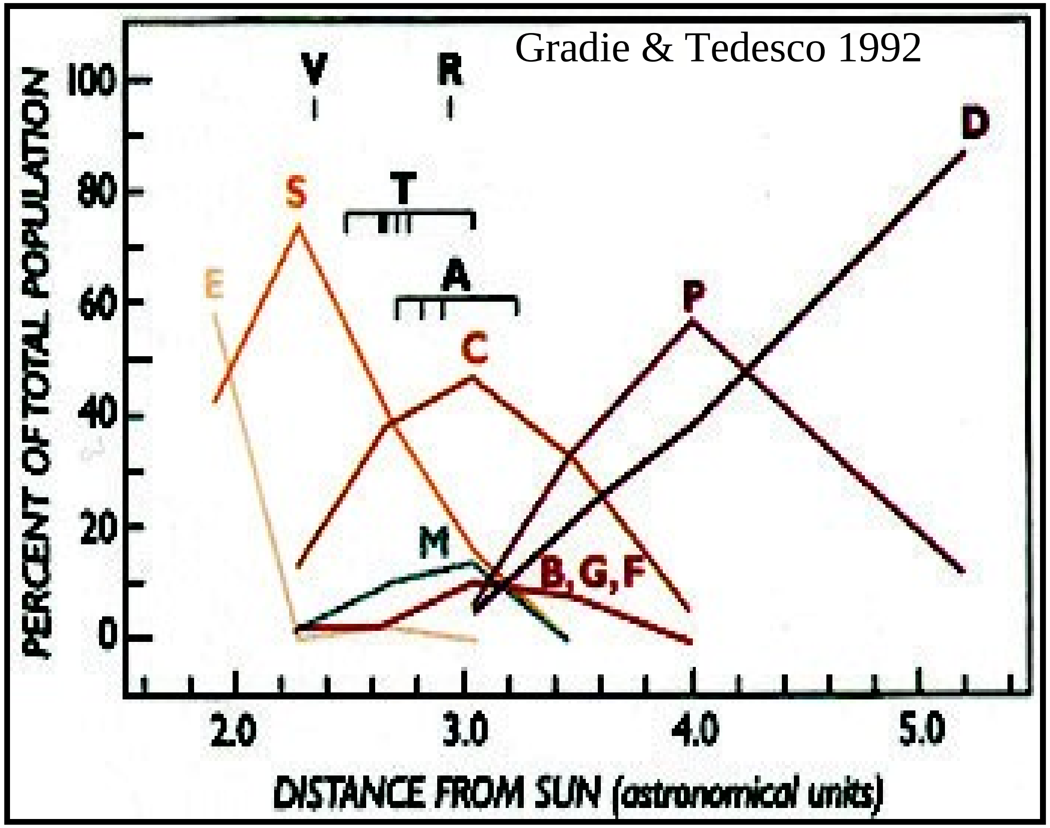




Asteroids taxonomic classes

The asteroid taxonomic classes are indicative of different mineralogies.

Their distribution varies with the heliocentric distances:



•a < 2.5 AU : S type

S (silicates) : evolved

•2.5<a<3.5AU: C type

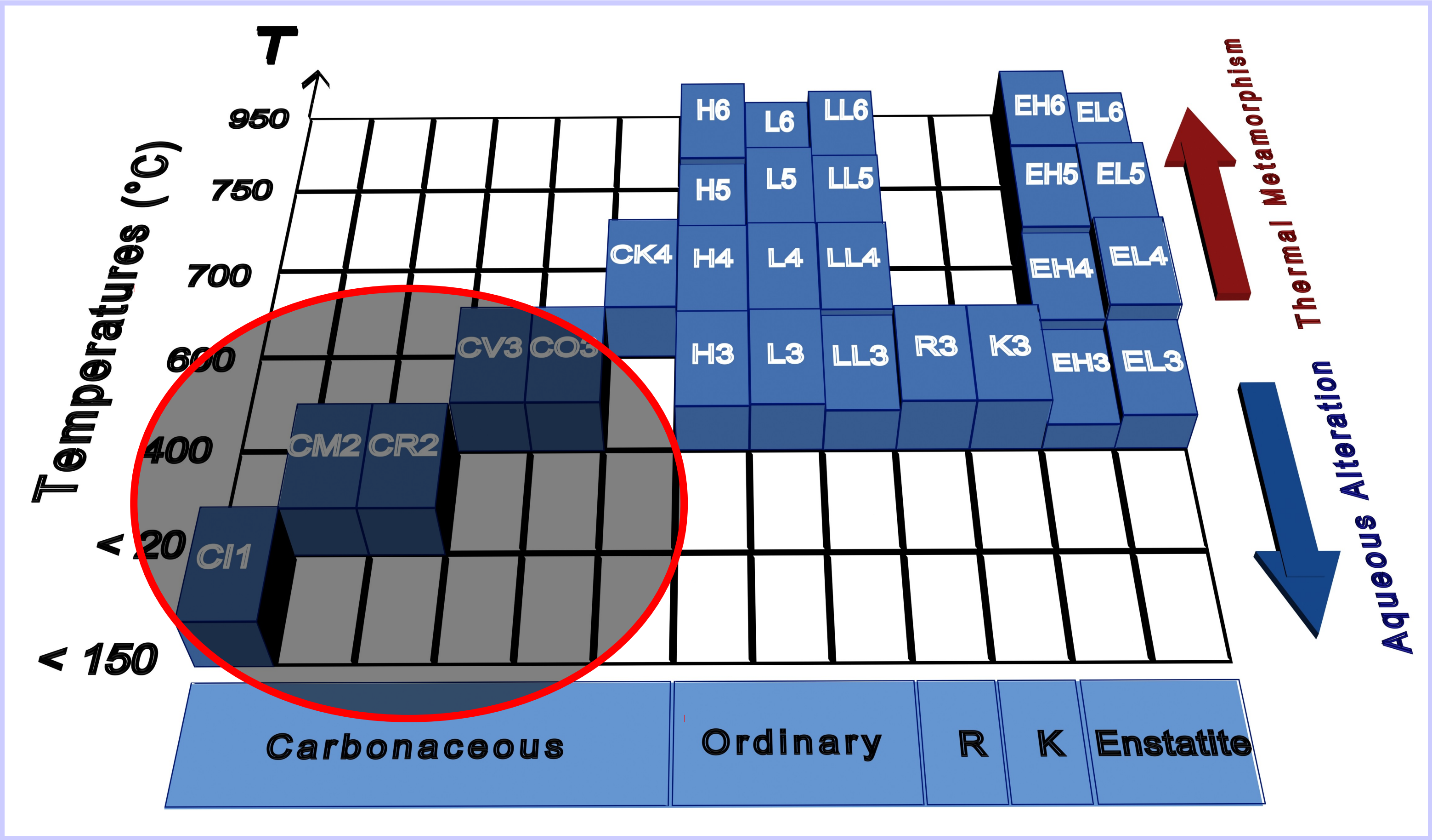
C (carbonaceous): less processed, quite primordial

• a>3.5 AU : D type

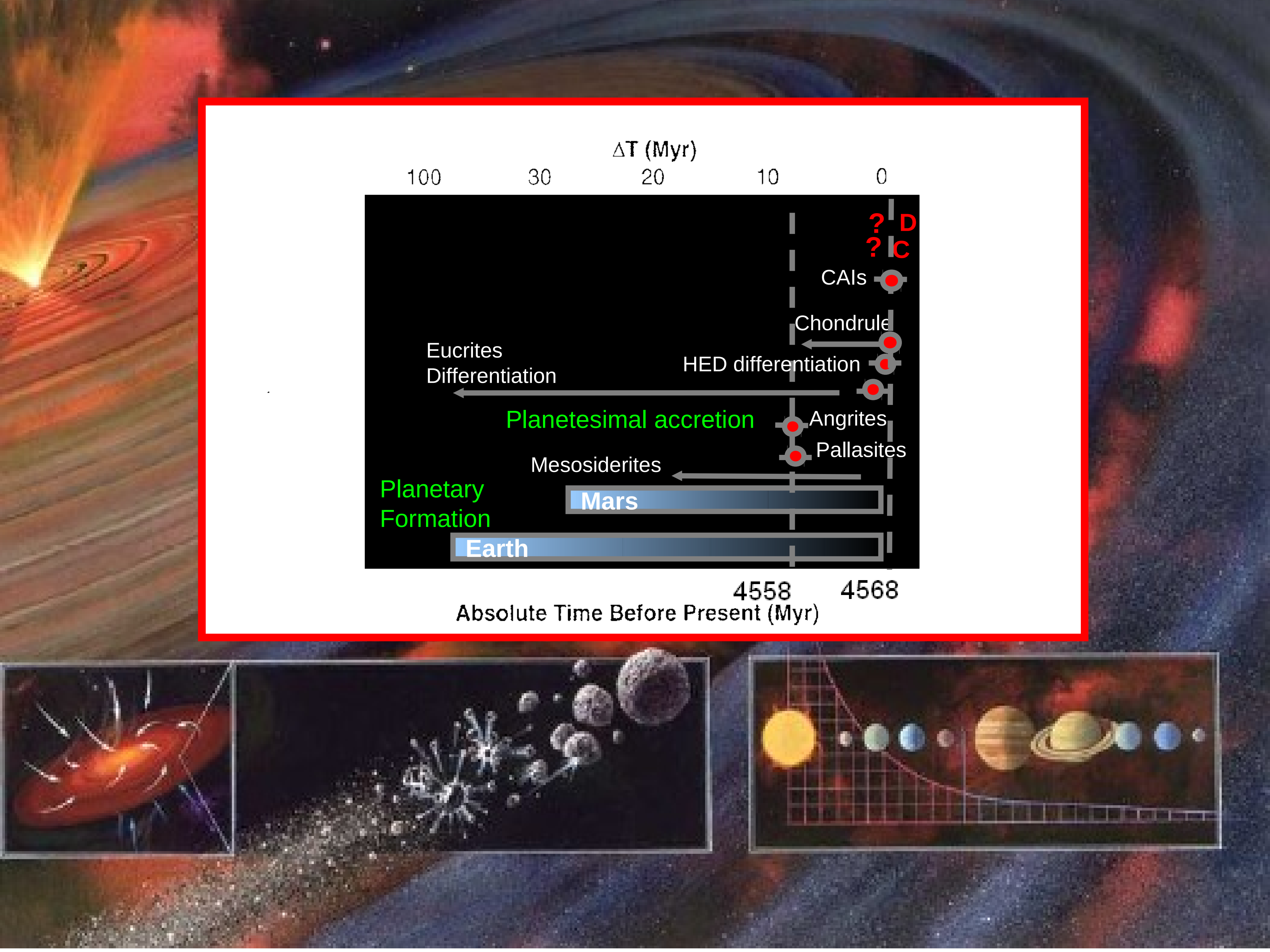
D: primordial

The asteroids classes distribution reflects the presence of a temperature gradient in the Solar System

Chondritic meteorites: temperatures and evolution

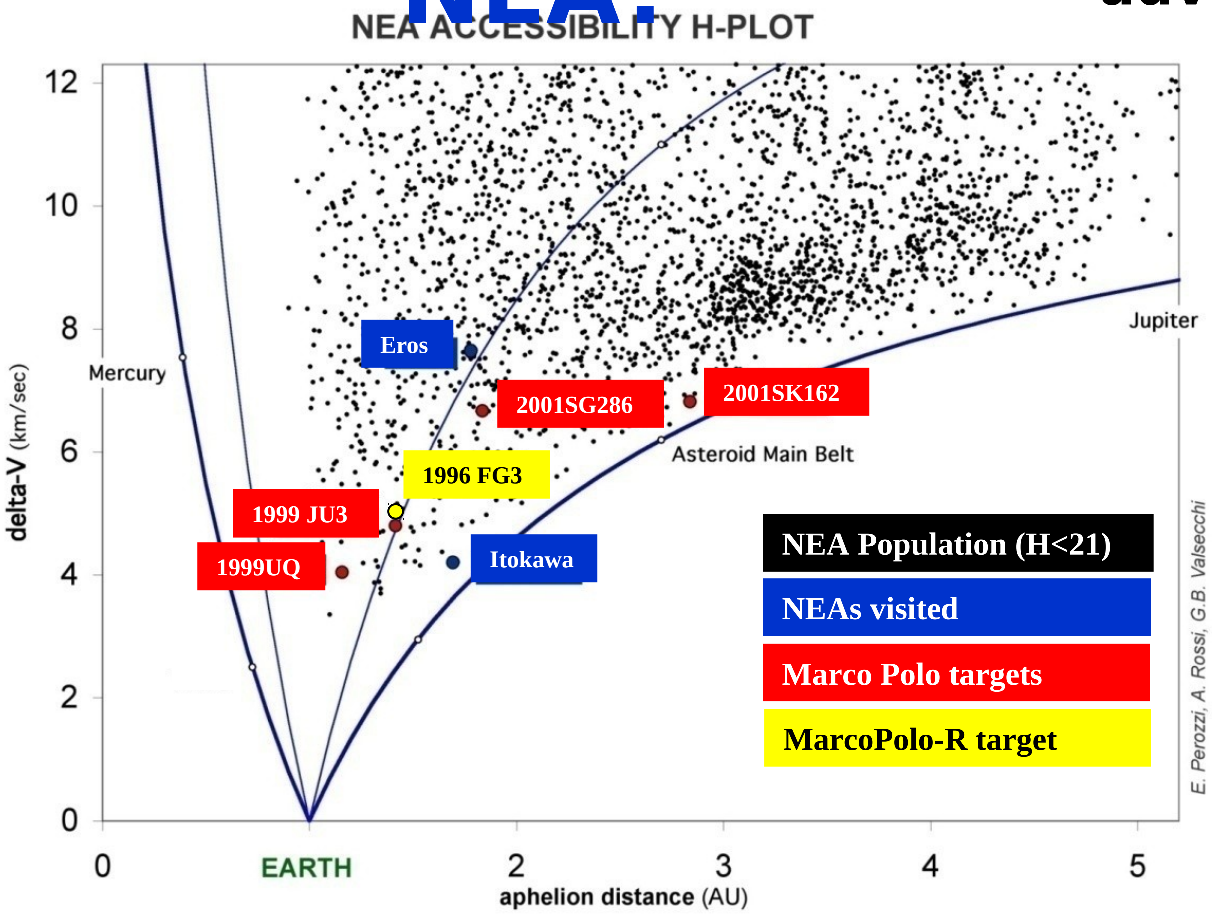


Primitive Objects


ΔT (Myr)
100
30
20
10
0
? D
? C
CAIs
Chondrule
Eucrites
Differentiation
HED differentiation
Planetesimal accretion
Angrites
Pallasites
Mesosiderites
Planetary
Formation
Mars
Earth
4558
4568
Absolute Time Before Present (Myr)


"Why a Near Earth Asteroid?"

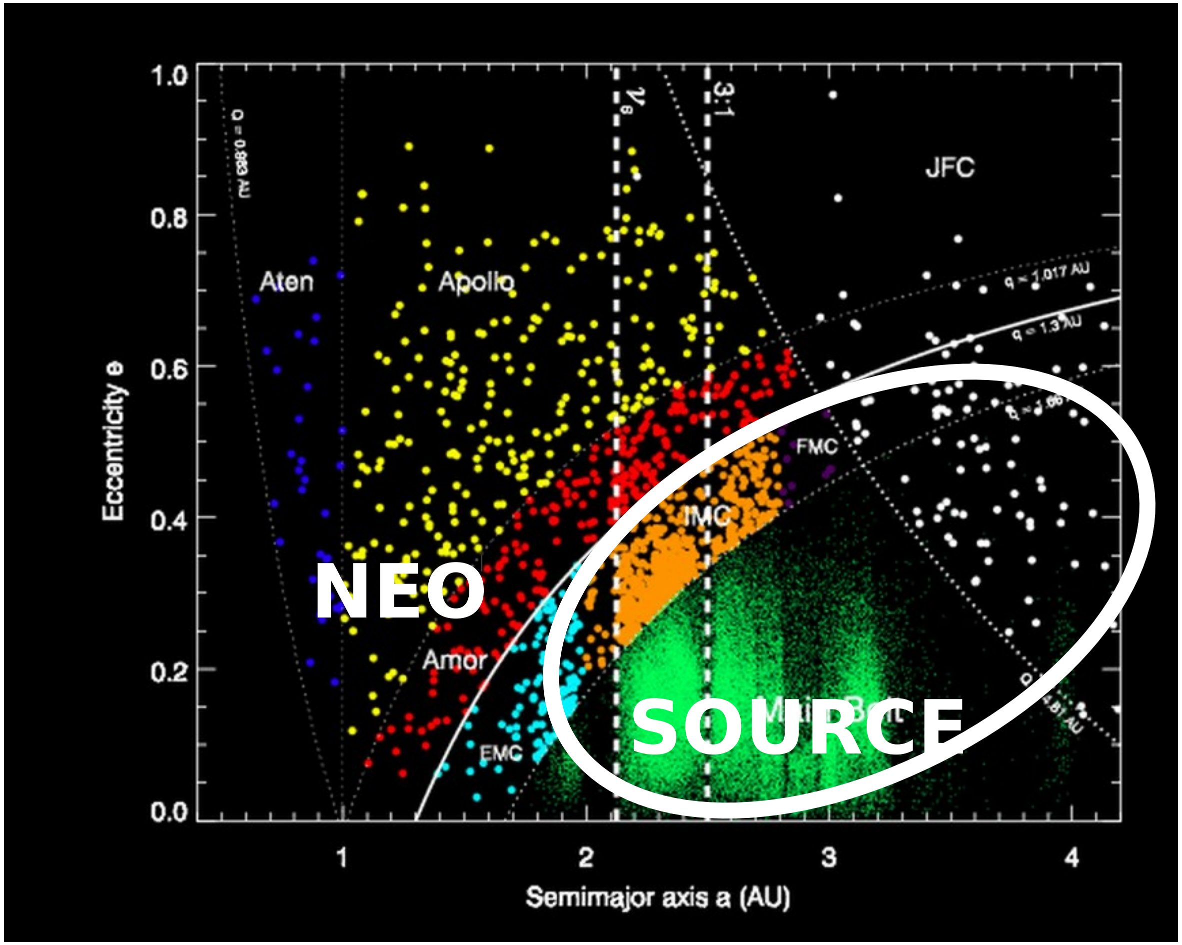
Why an NEA?



NEAs offer many advantages:

- **Accessibility**
- **Great diversity of physical properties composition**
- **Identified links to the origin population**

More than 7800 known NEOs



Fast resonances: Main Belt Asteroids become rapidly NEAs by dynamical transport from a source region (in a few million years)

MarcoPolo-R

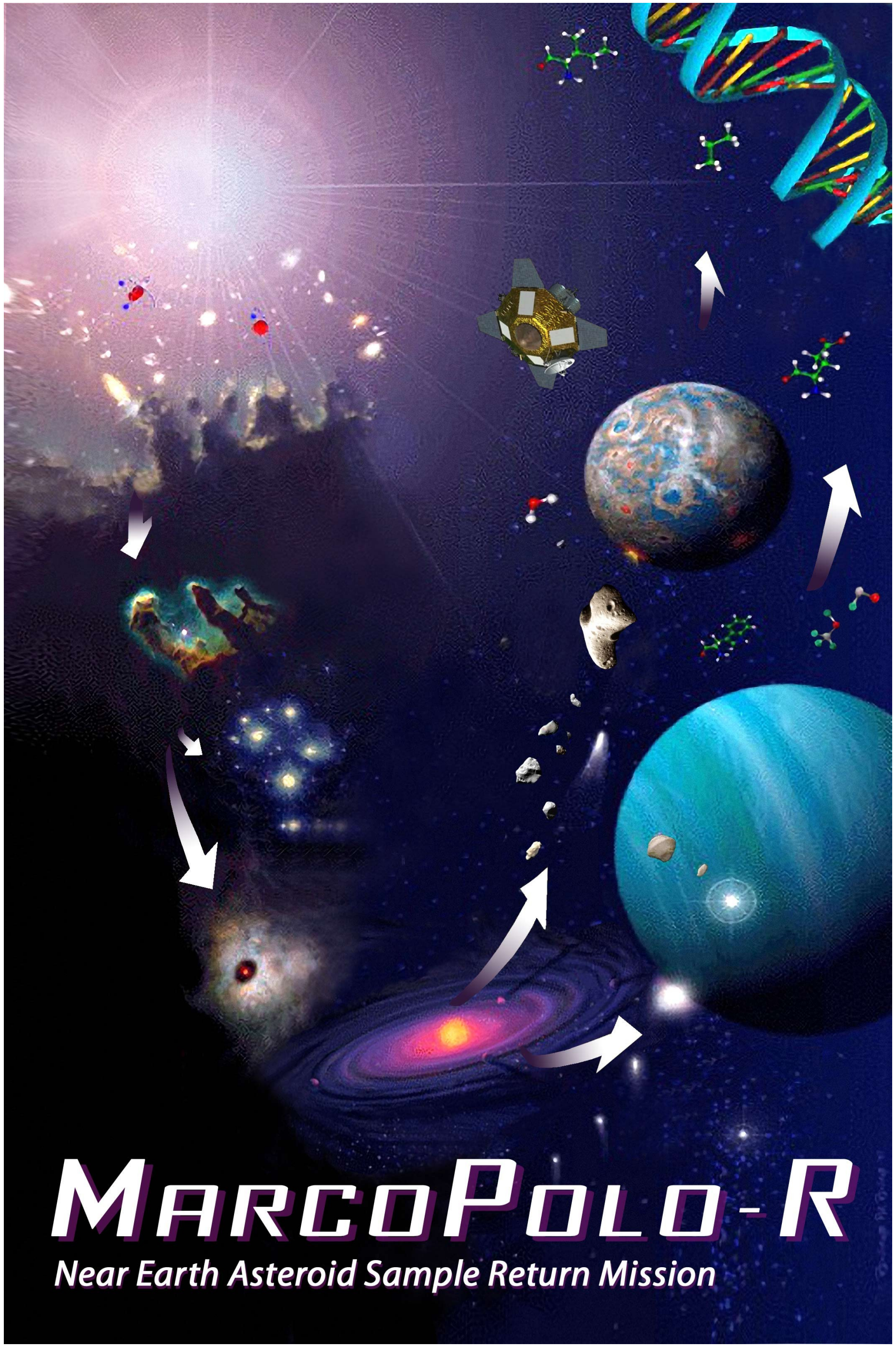
will rendez-vous with a primitive NEA,

will scientifically characterize it at multiple scale (global characterization, local characterization, context measurements),

will return a sample to Earth

Core team:

M.A. Barucci, P. Michel, P.A. Bland, H. Boehnhardt, J. R. Brucato, A. Campo Bagatin, P. Cerroni, E. Dotto, A. Fitzsimmons, I.A. Franchi, S.F. Green, L.M. Lara, J. Licandro, B. Marty, K. Muinonen, A. Nathues, J. Oberst, R. Saladino, J. TrigoRodriguez, S. Ulamec, A. Cheng, L. Benner, R. Binzel, A. Rivkin, M. Zolensky



The Cosmic Vision Plan

Major scientific questions:

1. What are the conditions for planet formation and the emergence of life?

2. How does the Solar System Work?

3. What are the fundamental physical laws of the Universe?

4. How did the Universe originate and what is it made of?

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The Cosmic Vision Plan

2. How does the Solar System Work?

2.1. From the Sun to the edge of the Solar System

Study the plasma and magnetic field environment around the Earth and around Jupiter, over the Sun's poles, and out the heliopause where the solar wind meets the interstellar medium

2.2. The giant planets and their environments

In situ studies of Jupiter, its atmosphere, internal structure and satellites

2.3. Asteroids and other small bodies

Obtain direct laboratory information by analysis samples from
a
Near-Earth Object

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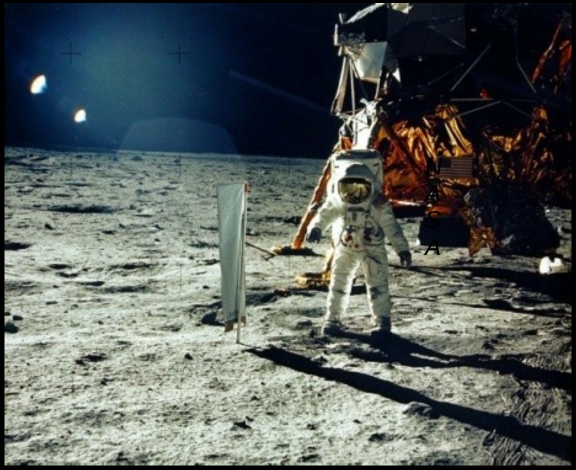
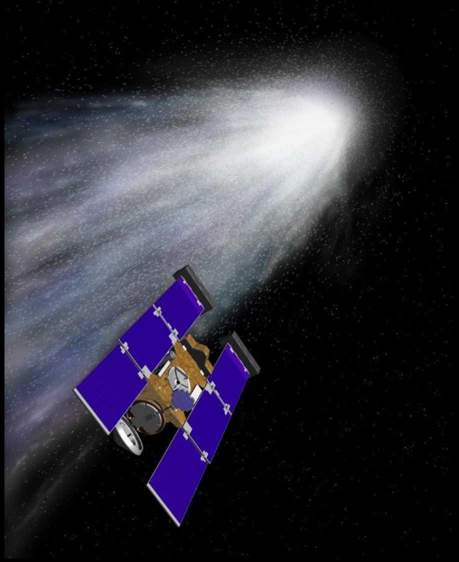
We need to return samples from space

Original material
Formation processes
Chronology

Genesi
s



Apollo & Luna



Stardu
st

A pristine sample from a primitive asteroid is required to study the precursors of terrestrial planets

The Cosmic Vision Plan

Major scientific questions:

1. What are the conditions for planet formation and the emergence of life?

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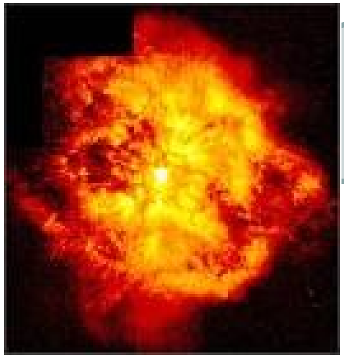
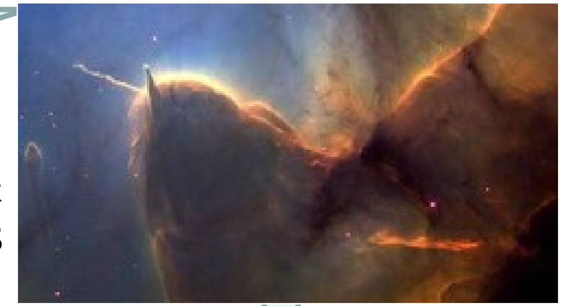
A mission to a primitive Near Earth Asteroid



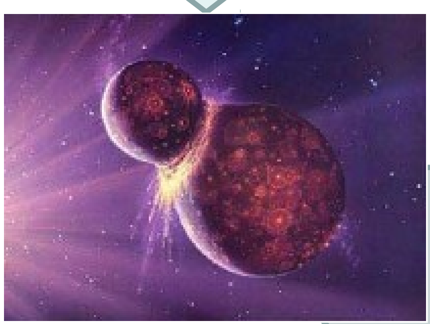
Stars
Stellar nucleosynthesis
Nature of stellar condensate grains



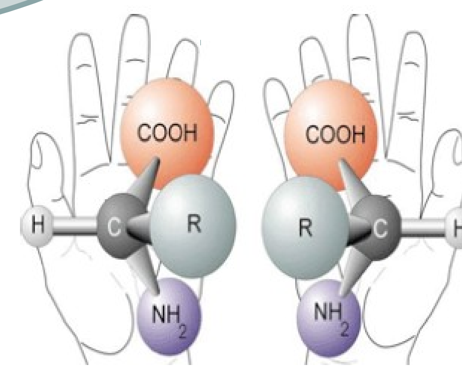
The Interstellar Medium
IS grains, mantles & organics

The proto-solar nebula
Accretion disk environment, processes and timescales

Planetary formation
Inner Solar System Disk & planetesimal properties at the time of planet formation



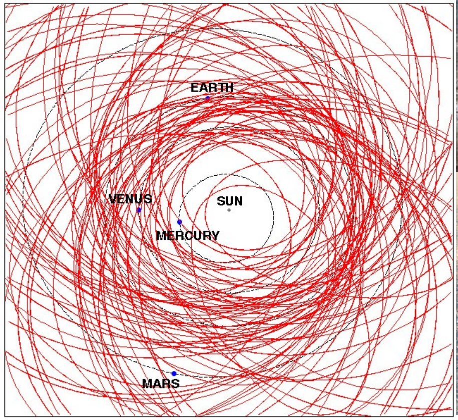
Accretion history,
alteration processes, impact ev
regolith



Life
Nature of organics in NEAs

The Earth
Impact hazard
Evolution of life on Earth

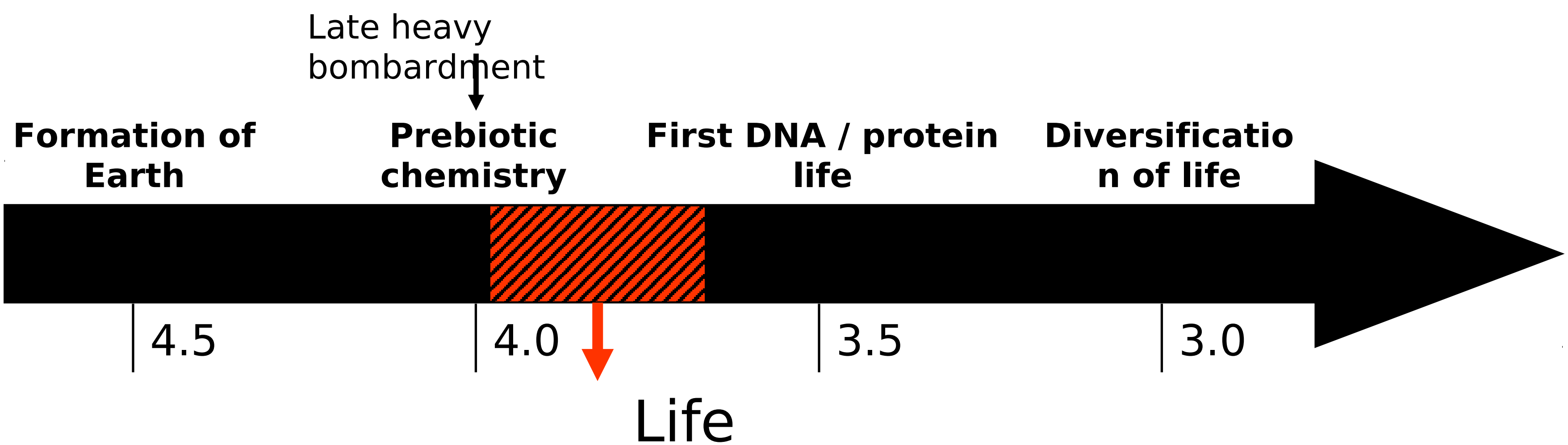
)11



Origin of Life:

The planets of the inner Solar System experienced an intense influx of cometary and asteroidal material for several hundred million years after they formed.

The earliest evidence for life on Earth coincides with the decline of this enhanced bombardment. The fact that the influx contained vast amounts of complex organic material offers a tantalising possibility that it may be related to the origin of life.



MarcoPolo-R Mission

MarcoPolo-R will rendezvous with a primitive NEA:

- scientifically characterize it at multiple scales, and

- return a sample to Earth unaffected by the atmospheric entry process or terrestrial contamination.

- ❑ it is the first sample return mission to a primitive low albedo asteroid
- ❑ it will return a sample (few 10s of grams) for laboratory analyses of organic-rich material
- ❑ it will determine the geological context of the returned sample

Community supporters:

556 scientists, 16 countries, ~130 Italians

Web page: www.oca.eu/MarcoPolo-R/

[redacted]

MarcoPolo-R will provide crucial elements to answer the following key questions:

1) What were the processes occurring in the primitive solar system and accompanying planet formation?

2) What are the physical properties and evolution of the building blocks of terrestrial planets?

3) Do NEAs of primitive classes contain pre-solar material yet unknown in meteoritic samples?

4) What are the nature and the origin of the organics in primitive asteroids and how can they shed light on the origin of molecules necessary for life?

What were the processes occurring in the early solar system and accompanying planet formation?

A. Characterise the chemical and physical environments in the early solar nebula

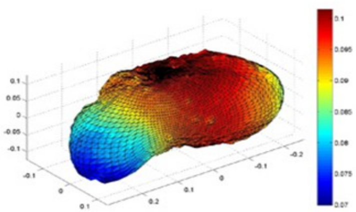
B. Define the processes affecting the gas and the dust in the solar nebula

C. Determine the timescales of solar nebula processes

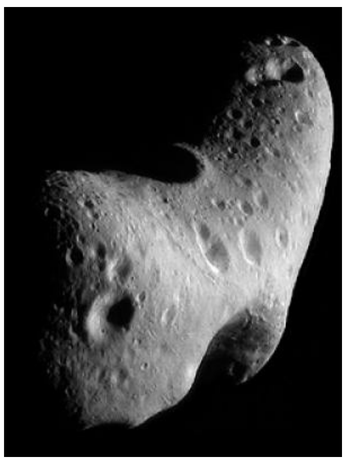
Measurements

Bulk chemistry.
Mineralogy,
Petrology.
Isotopic chemistry in inclusions, matrix, presolar grains and volatiles, water.

What are the physical properties and evolution of the building blocks of terrestrial planets?



Gravity Map (Modell-A)



D. Determine the global physical properties of an NEA

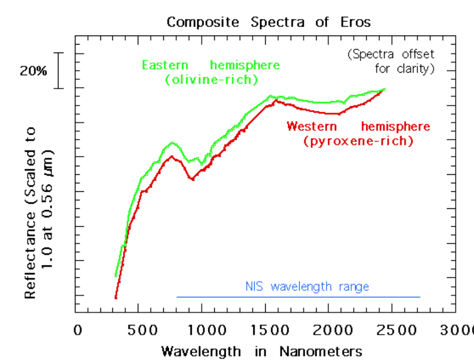
E. Determine the physical processes, and their chronology, that shaped the surface structure

F. Characterise the chemical processes that shaped the NEA composition (*e.g.* volatiles, water)

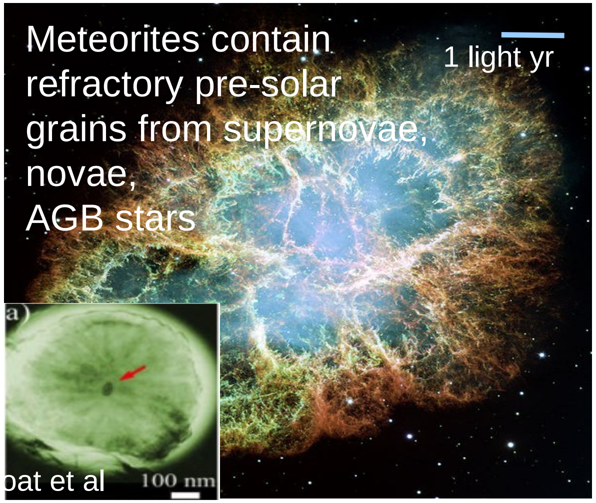
G. Link the detailed orbital and laboratory characterisation to meteorites and IDPs and provide ground truth for the astronomical database

Measurements

Volume, shape, mass.
Surface morphology and geology.
Mineralogy & Petrology.
Isotope geochemistry & chronology
Weathering effects.
Thermal properties.



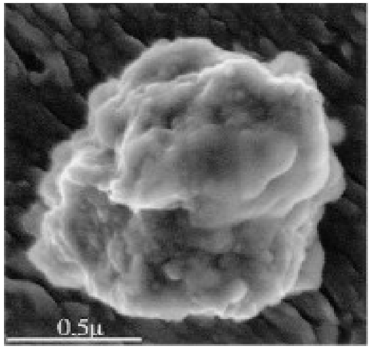
Do NEAs of primitive classes contain pre-solar material yet unknown in meteoritic samples?

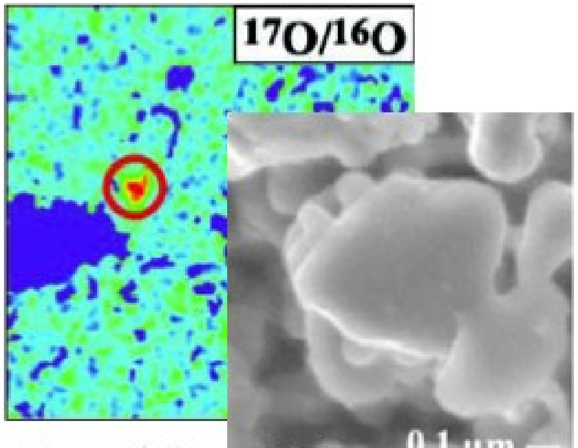


H. Determine the interstellar grain inventory

I. Determine the stellar environment in which the grains formed

J. Define the interstellar processes that have affected the grains





Nguyen & Zinner 2004

Measurements

Bulk chemistry.
Grain mineralogy and composition,
Isotope chemistry of grains.

What are the nature and the origin of the organics in primitive asteroids and how can they shed light on the origin of molecules necessary for life?

Current exobiological scenarios for the origin of life invoke the exogenous delivery of organic matter to the early Earth

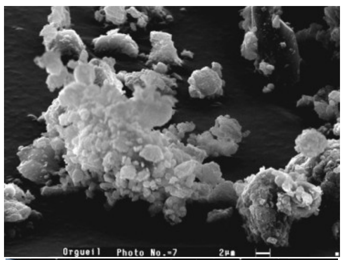
oma

The planets of the inner solar system experienced an intense influx of organic-rich material for several hundred million years after they formed.

The earliest evidence for life on Earth coincides with the decline of this bombardment.

Many biologically important molecules are present in the organic materials.

What are the nature and the origin of the organics in primitive asteroids and how can they shed light on the origin of molecules necessary for life?



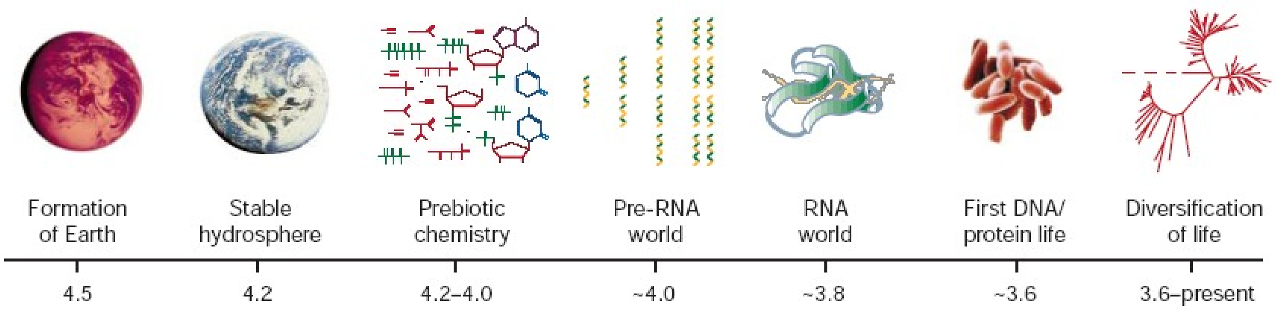
K. Determine the diversity and complexity of organic species in a primitive asteroid

L. Understand the origin of organic species

M. Provide insight into the role of organics in life formation

Measurements

Abundances and distribution of insoluble organic species.
Soluble organics.
Global surface distribution and identification of organics



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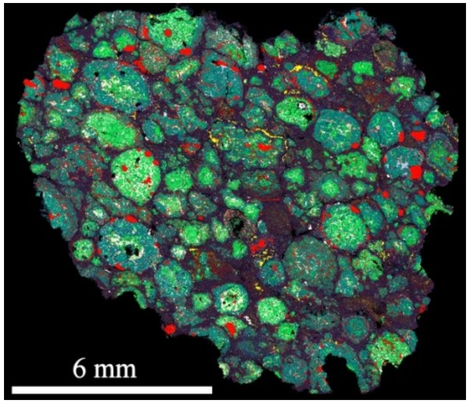
Near Earth Asteroid Sample Return
"Why do you need to *return* samples?"

Laboratory investigation:

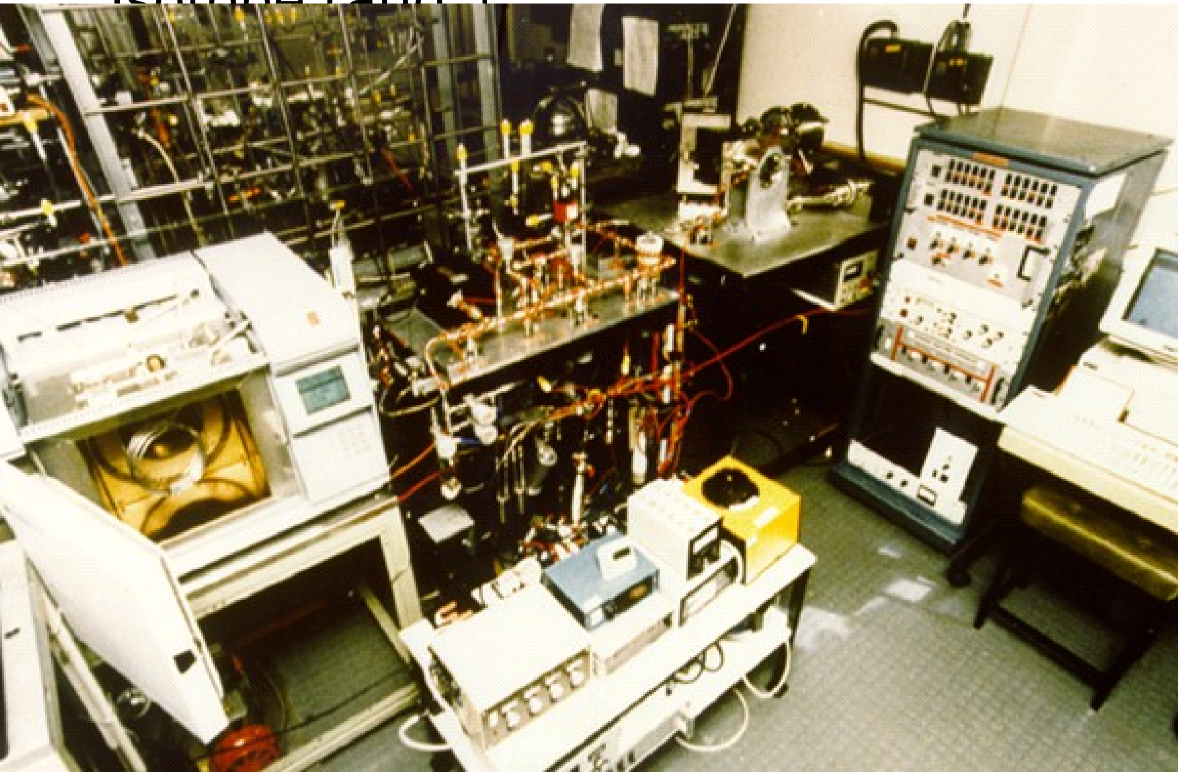
High spatial resolution and analytical precision are needed:

- High precision analyses - including trace element abundances to ppb levels and isotopic ratios approaching ppm levels of precision
- High spatial resolution - a few microns or less
- Requires very specific sample selection and preparation.
- Requires large, complex instruments – e.g. high mass resolution instruments (large magnets, high voltage), bright sources (e.g. Synchrotron) and usually requires multi-approach studies



Superior instruments...

“Miranda” GC-IRMS
Laboratory
Isotope ratio ±

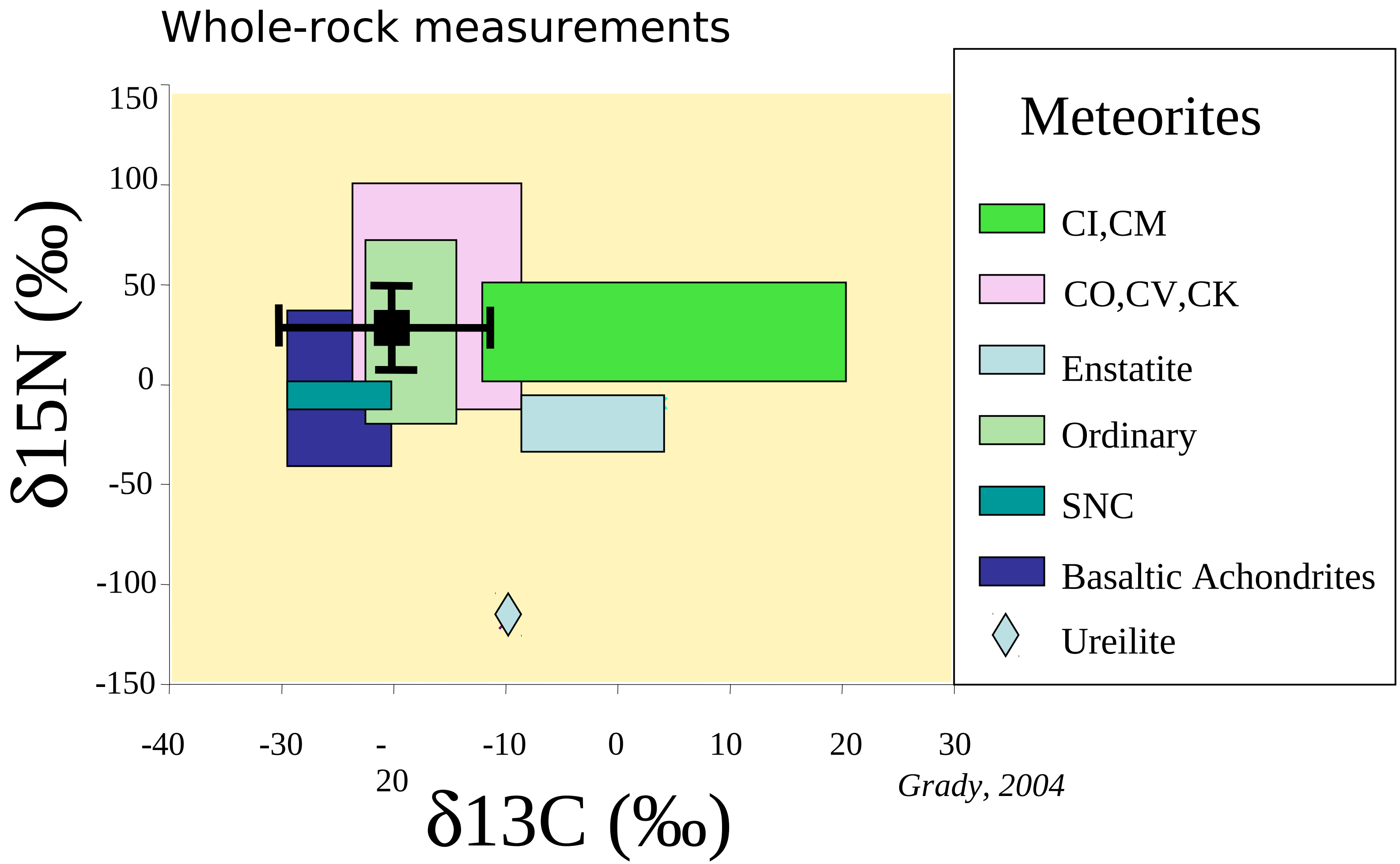


Rosetta
Ptolemy
In situ
Isotope ratio ±
1%

In-situ instruments limited (mass/volume/power/reliability)

Superior instruments…

In-situ measurements provide insufficient precision

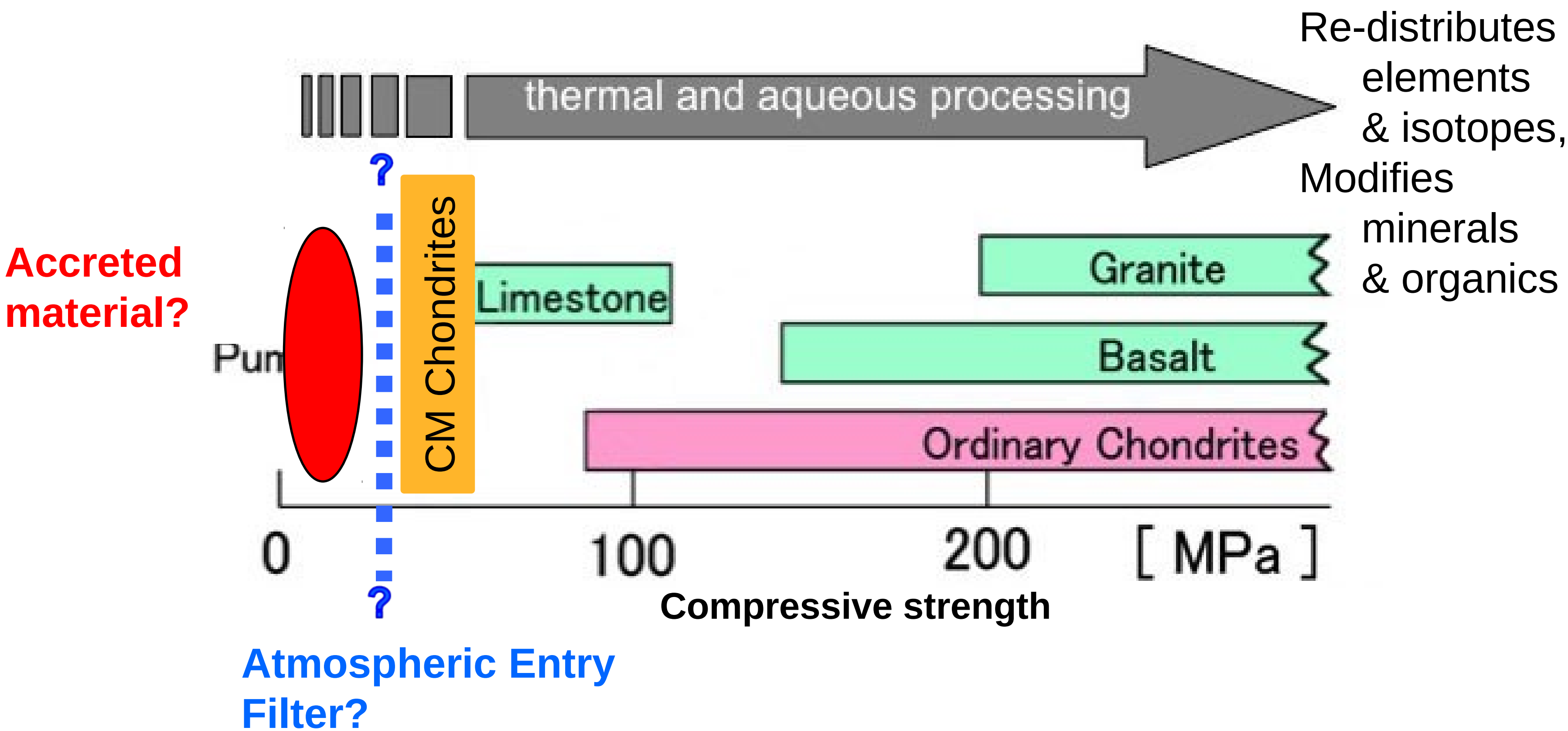


Grady, 2004

Near Earth Asteroid Sample Return

"Why do you need to return samples when we have meteorites?"

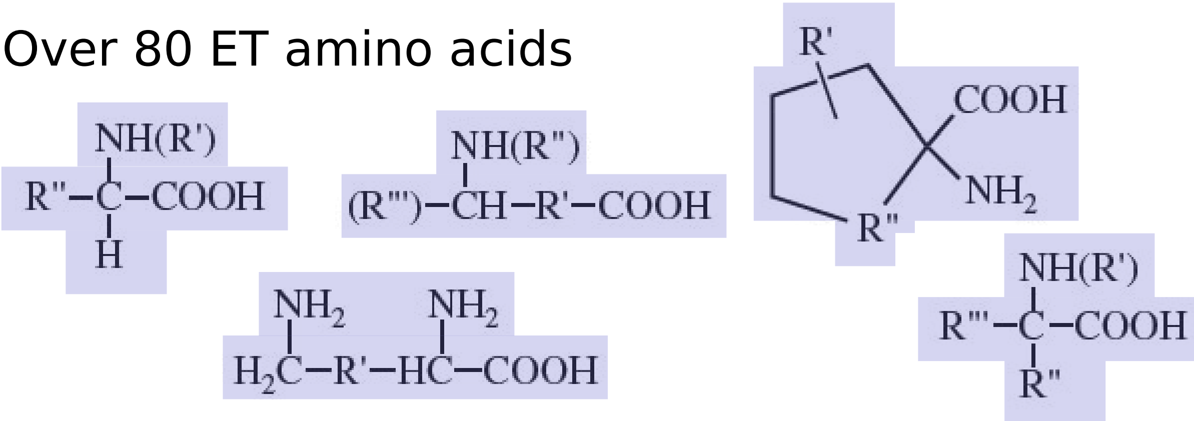
Going beyond meteorites



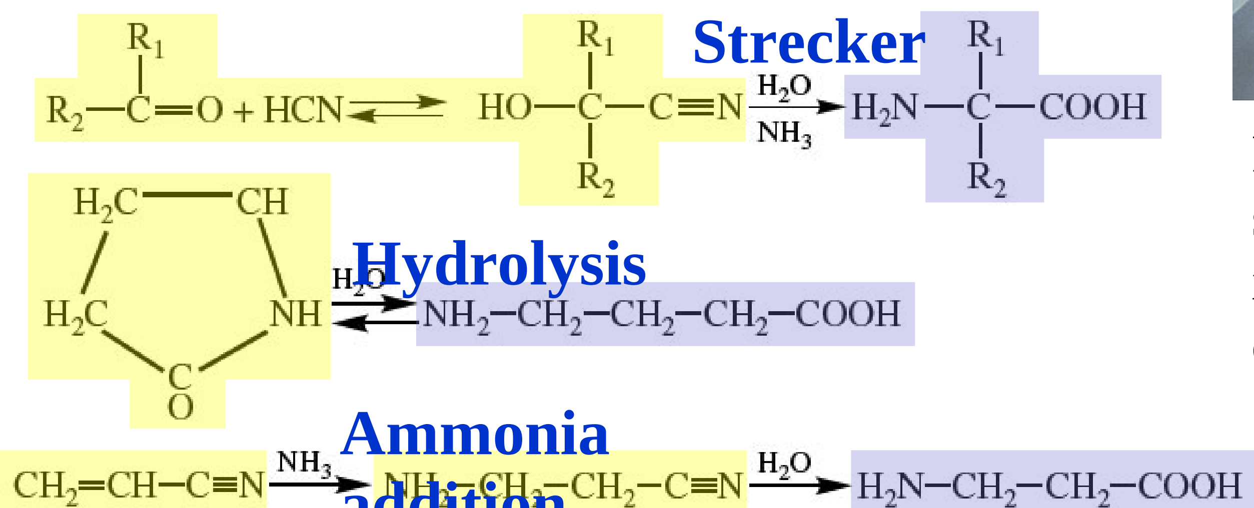
To survive atmospheric entry *requires* major processing

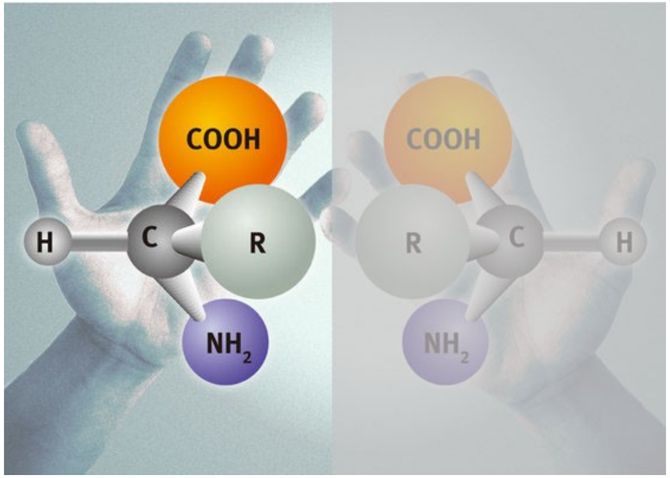
Organics

Over 80 ET amino acids



Many different synthesis mechanisms



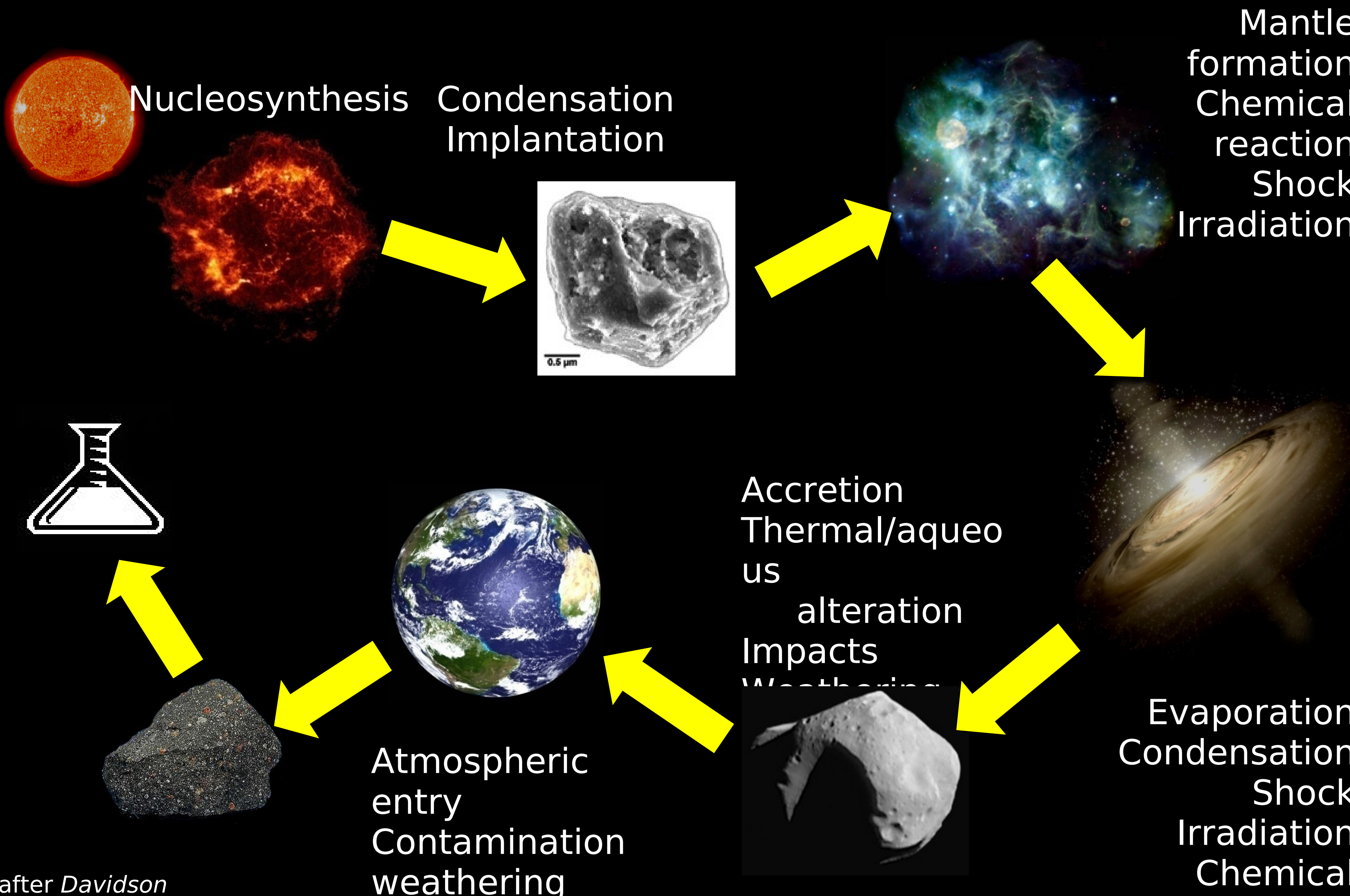


Preponderance of left handed structures in a few meteorites: is it a result of terrestrial contamination?

Precise abundances of molecules and precursors are required to understand the origin of these molecules.

A sample return from a primitive Near Earth Asteroid

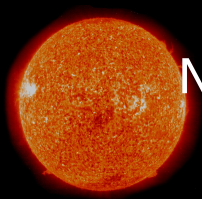
From stars to meteorites



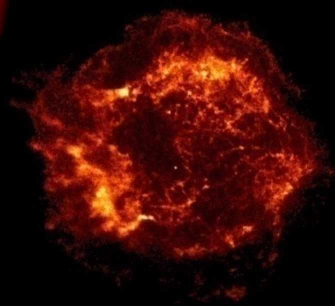
after *Davidson*

A sample return from a primitive Near Earth Asteroid

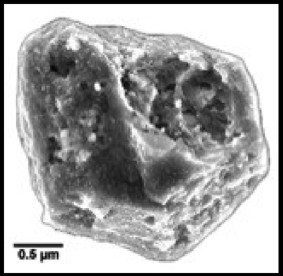
From stars to asteroid sample



Nucleosynthesis



Condensation
Implantation



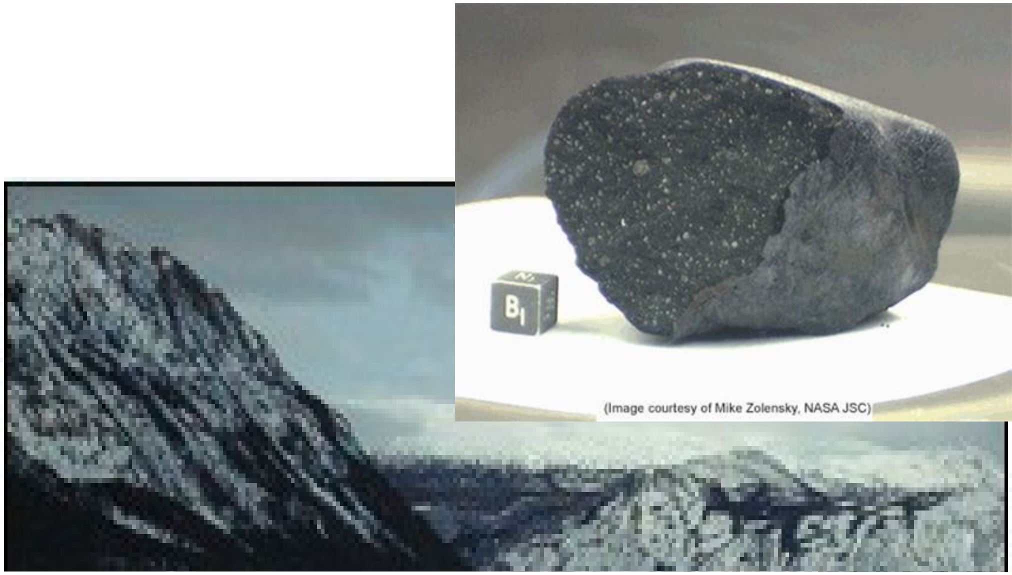
Mantle formation
Chemical reaction
Shock
Irradiation

Evaporation
Condensation
Shock
Irradiation
Chemical

Accretion
Thermal/aqueous alteration
Impacts

after *Davidson*

Avoid contamination…

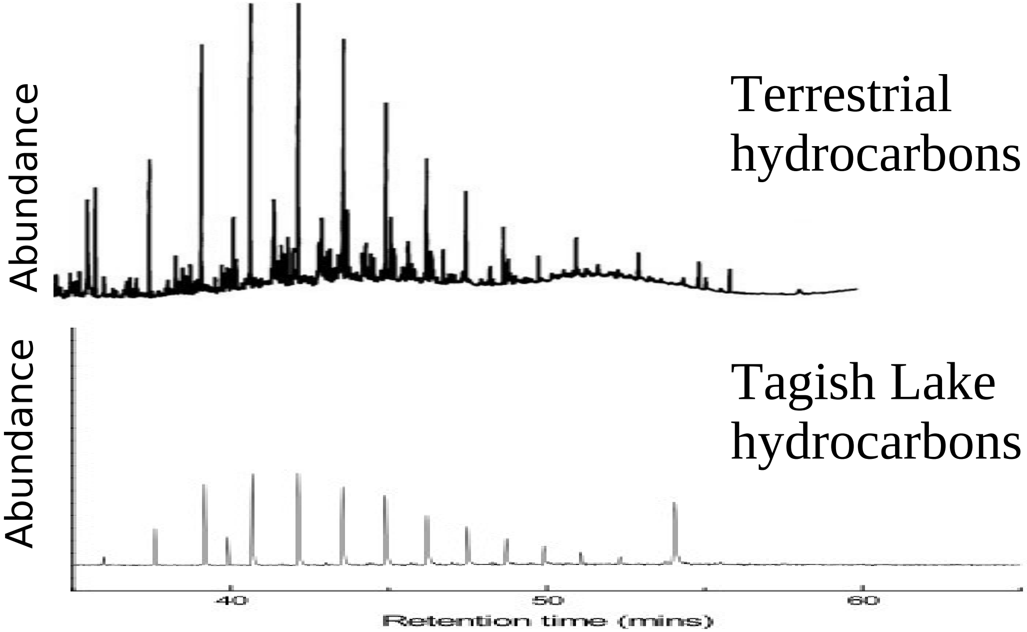


Tagish Lake
Most perfectly collected sample?

Collected within 5 days from frozen lake and kept at -20°C

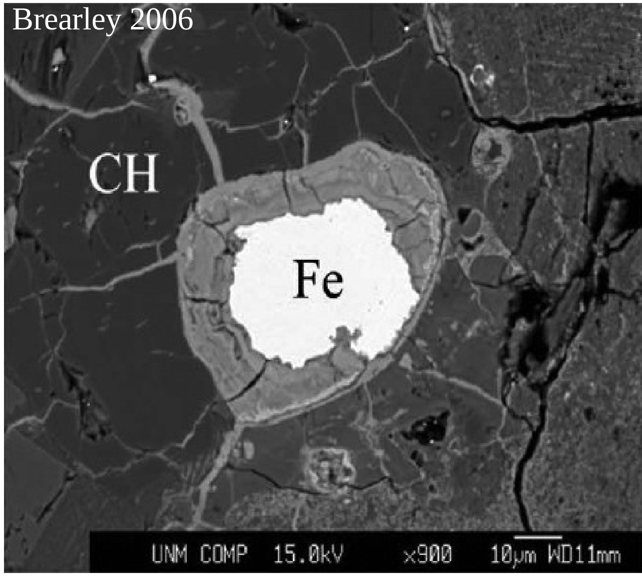
 terrestrial contamination

… any result obtained for organics in meteorites may be questioned



Aqueous alteration

Mixed regolith provides range of alteration
Free of terrestrial contamination
□ find low alteration materials
□ study alteration process

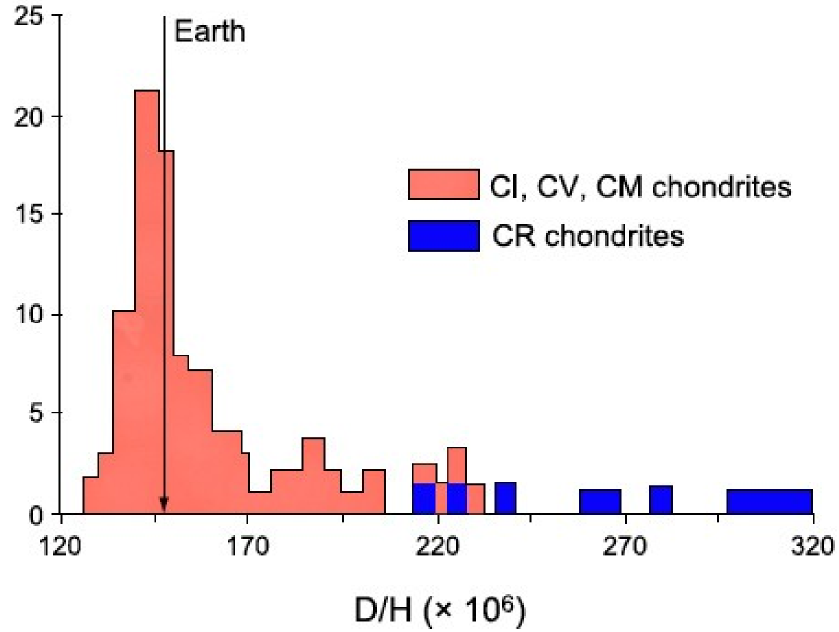


Water

Carbonaceous chondrites

exhibit aqueous alteration

- How much water was there nitially?
- What was the fate of the water?
- Implications for terrestrial planets



Is D/H in primitive asteroids similar to that on Earth?

MarcoPolo-R Mission

MarcoPolo-R will rendezvous with a primitive NEA:

- scientifically characterize it at multiple scales, and

- return a sample to Earth unaffected by the atmospheric entry process or terrestrial contamination.

- ❑ it is thefirst sample return mission to a primitive low albedo asteroid
- ❑ it will return a sample (few 10s of grams) for laboratory analyses of organic-rich material
- ❑ it will determine the geological context of the returned sample

MarcoPolo-R Mission

Cosmic Vision M3 cost = 470 ME

The present proposal is based on the previous Marco Polo mission study, which was selected for the Assessment Phase of the first round of Cosmic Vision.

Its scientific rationale was highly ranked by ESA committees and it was not selected only because the estimated cost was higher than the allotted amount for an M class mission.

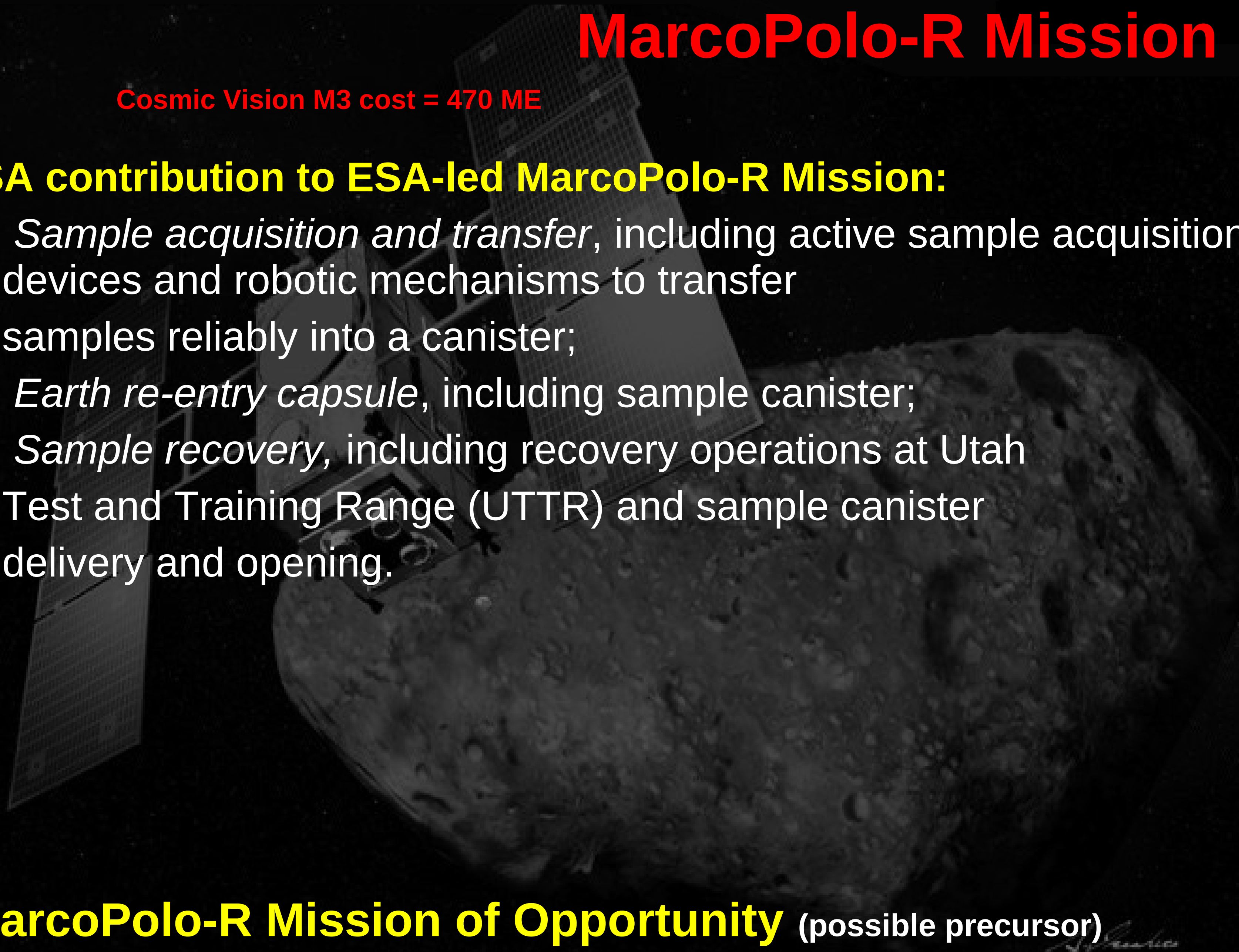
The cost of MarcoPolo-R will be reduced to within the ESA medium mission budget by collaboration with APL and JPL in the NASA program for coordination with ESA's Cosmic Vision Call for Proposal.

MarcoPolo-R Mission

Cosmic Vision M3 cost = 470 ME

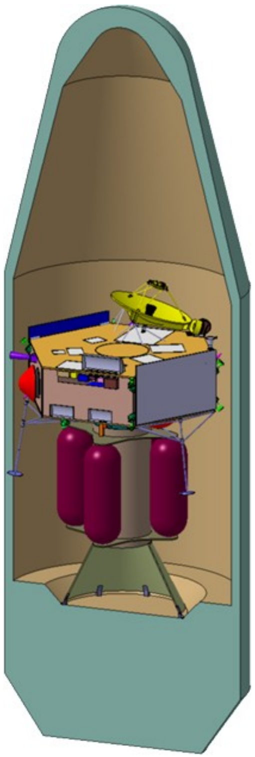
NASA contribution to ESA-led MarcoPolo-R Mission:

- *Sample acquisition and transfer*, including active sample acquisition devices and robotic mechanisms to transfer samples reliably into a canister;
- *Earth re-entry capsule*, including sample canister;
- *Sample recovery,* including recovery operations at Utah Test and Training Range (UTTR) and sample canister delivery and opening.

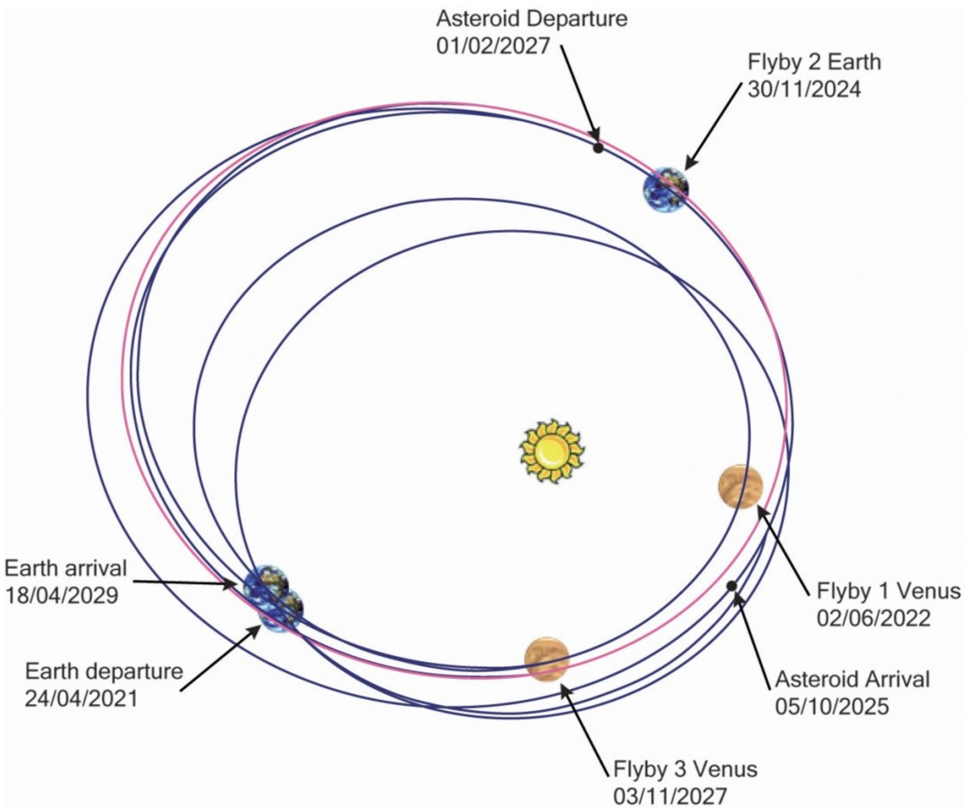


MarcoPolo-R Mission of Opportunity **(possible precursor)**

MarcoPolo-R mission baseline



Launch	Mission duration (yrs)	Stay time (months)	Δv (km.s^{-1})	Entry v (km.s^{-1})
10.03.2020*	6.98	10.5	2.07	12.0
10.03.2020*	4.70	3.5	1.9	15.0
23.02.2021*	9.09	13.7	2.93	12.0
24.04.2021	**7.99**	**16.1**	**2.81**	**13.6**
09.01.2022	**7.28**	**9.3**	**2.88**	**13.6**

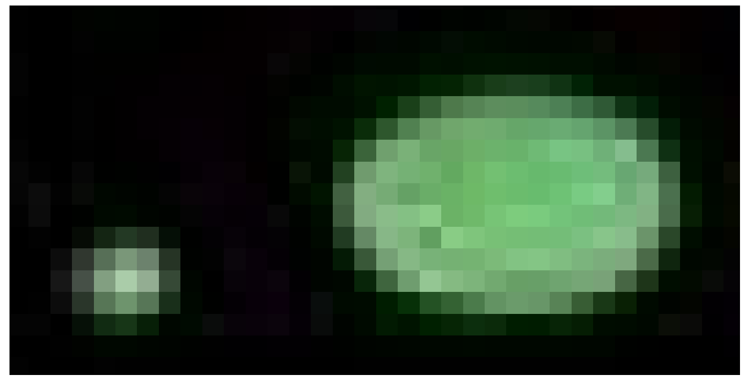


ASTEROID TARGET: 1996 FG3

1996 FG3 is a binary object and it is probably a rubble pile

D_p=1.4 km P_p= 3.5942 ± 0.0002h

D_s = 430 m   P = 16.135 ± 0.005h



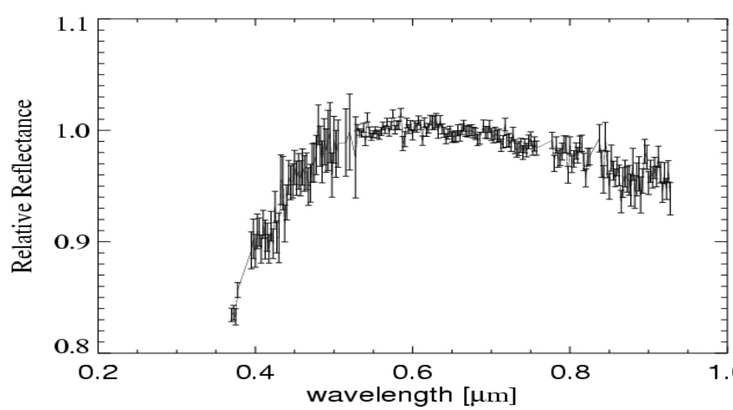
Dist. = 2.4 km

$a_p:b_p:c_p$ 1.05:0.95:0.70

$a_s:b_s:c_s$ 0.32:0.23:0.23

mass: 2.1 x 1012 kg

density: 1.4 ± 0.3 g/cm^3



Classified as belonging to the C class.

Sample requirements

Small (sub-mm) particles?

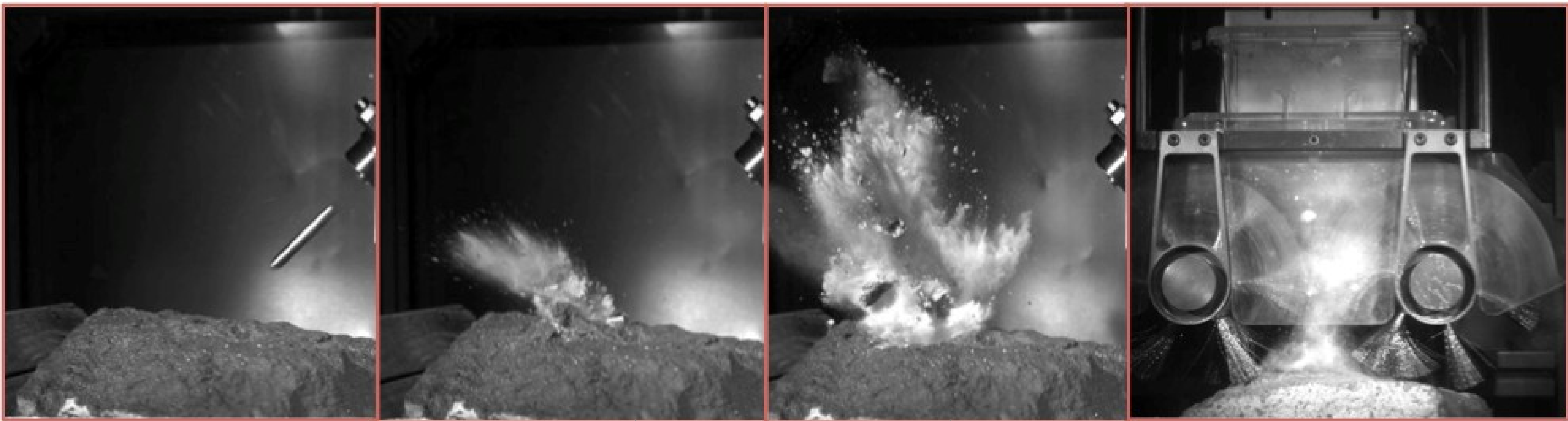
- Large numbers collected
- Sample multiple lithologies
- Range of weathering

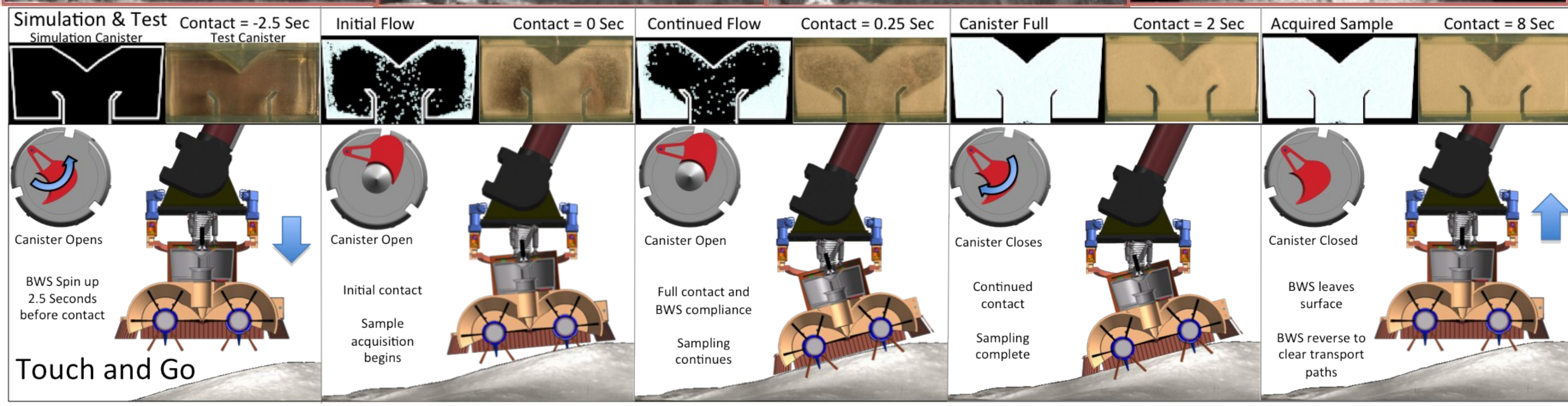
Large (~cm) particles?

- Interiors protected
- Trace organic species
- Weathering gradients

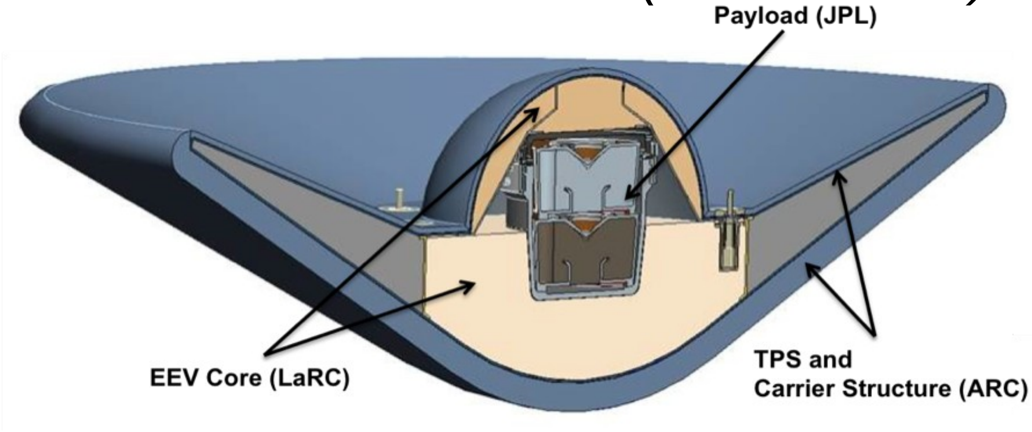
A few 10s of grams of sample will guarantee the scientific success of MarcoPolo-R.

Test with Brush Wheel Sampler and tuff rocks
BWS collecting lunar regolith simulant

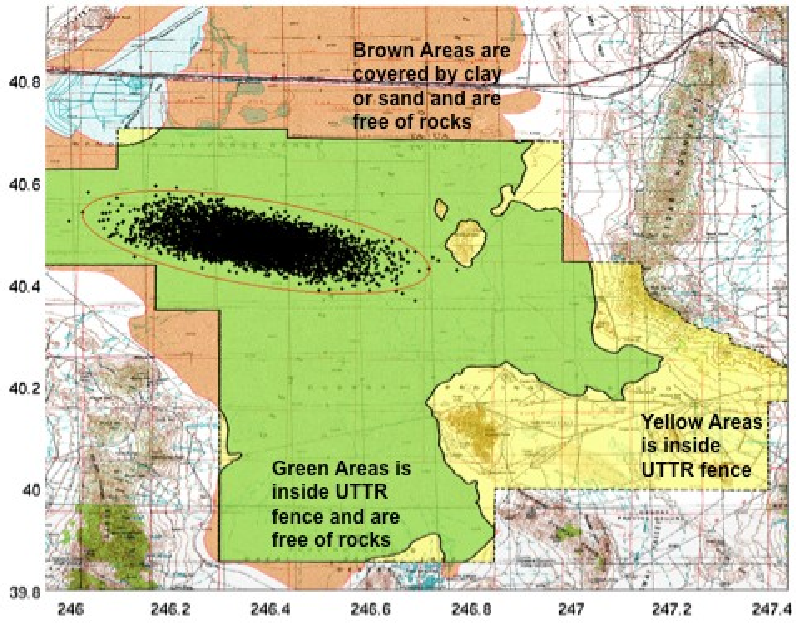




The MarcoPolo-R ERC (cross section)

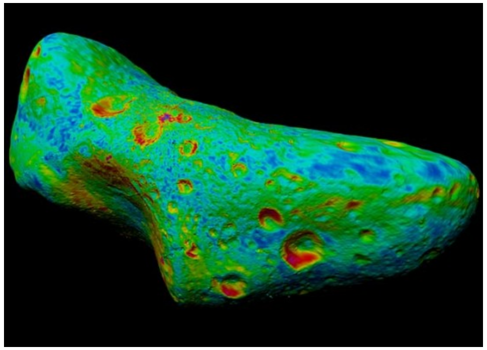


The MarcoPolo-R ERC Landing Footprint at UTTR



Baseline payload

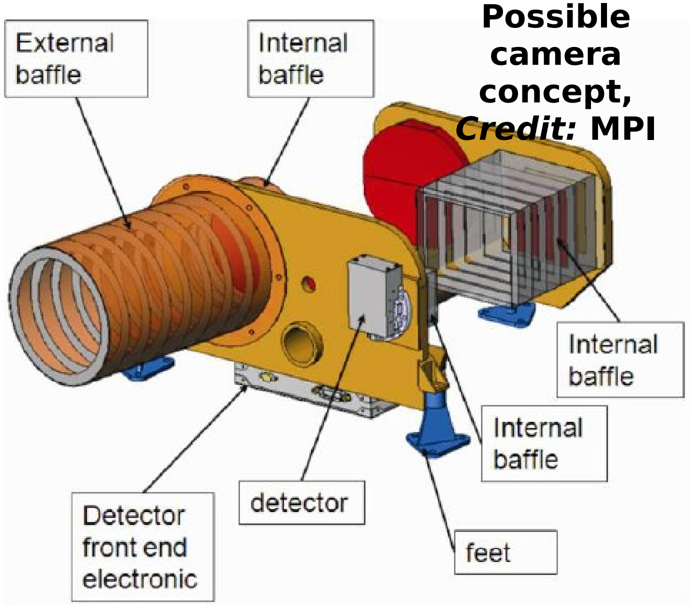
Wide angle camera
Narrow angle camera
Close-up camera
Vis/NIR imaging spectrometer
MIR spectrometer
Radio science
Laser altimeter
Neutral particle analyser
Complementary instruments/lander possible


Coloured image of Eros, *Credit:* NASA

	Total
Mass [kg]	30
Power [W]	90
Data volume [Gbit]	280

Development compatible with overall schedule

Possible camera concept, *Credit:* MPI



Sample Return mission opens new perspectives

Analyses of organic compounds that could be responsible for the origin of life on Earth;

Discovery primitive materials preserved during Solar System formation;

Understanding evolutionary processes occurred during the Solar System lifetime.

Development of Sample Return technologies suitable for future exploration: *Sampling mechanism, Earth return vehicle, re-entry capsule*.

Development of robotic systems able to make use of SR resources for human exploration.

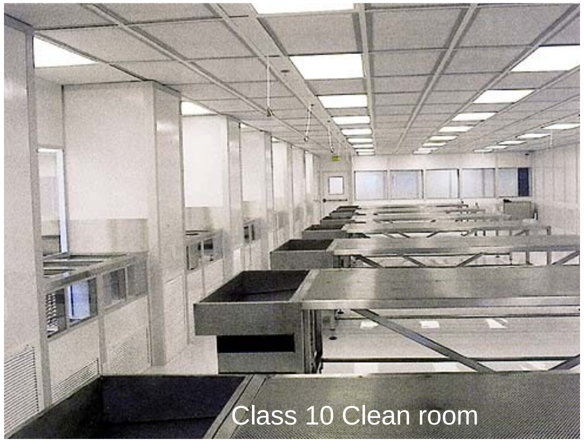
Development of Curation Centers for analyses, delivery and storage of ET samples.

Educational
&
Public-Outreach

Curation basic equipments

A dedicated sample return storage and curation facility will be equipped with the following characteristics:

- Clean room environment of class 10;
- Maintenance of ambient temperature in the laboratory;
- Containment cabinets with positive-pressure in controlled atmosphere (e.g. GN2, Ar);
- Humidity control;
- Dedicated processing cabinets (e.g stainless steel gloved cabinet);
- Combination of human and robotic processing;

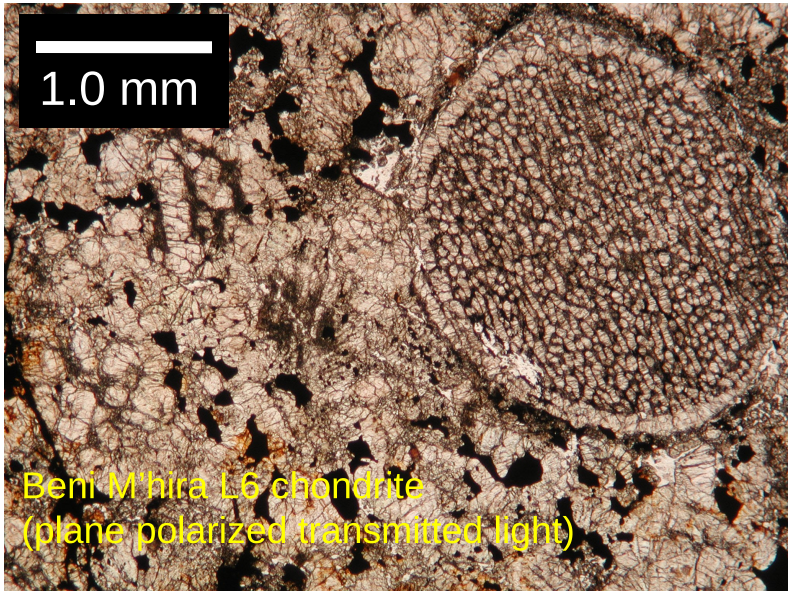


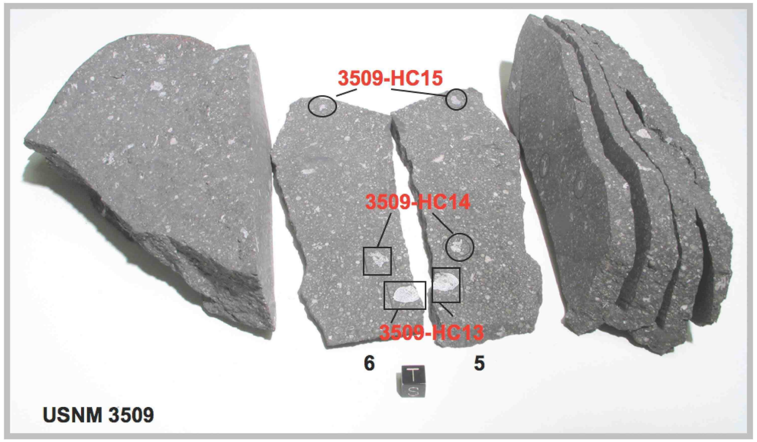
Class 10 Clean room

The Stardust Curation class 100 cleanroom at JSC

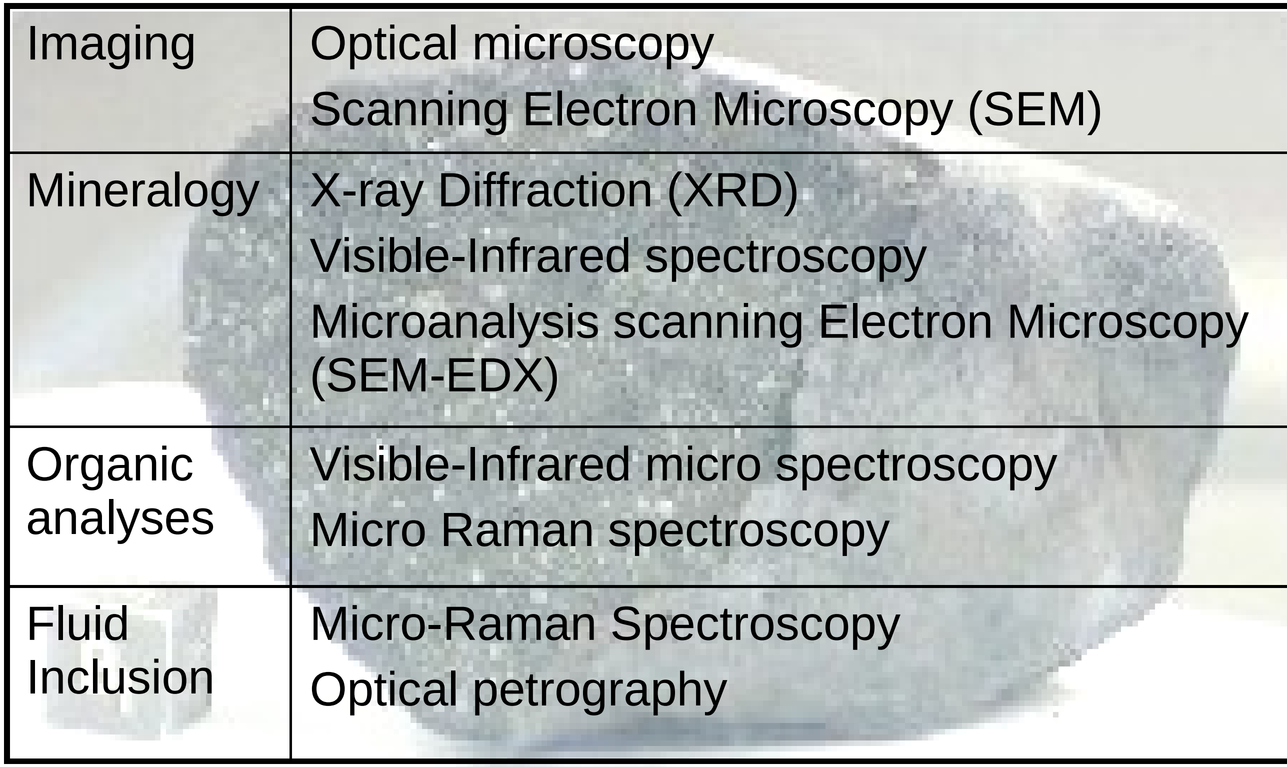
Sample Preparation

- Separation of pebbles and dust;
- Sample preliminary examination;
- Sample classification;
- Polished sections of pebbles and dust;
- Separation of samples to be delivered to laboratory for studies and those stored indefinitely in the facility;
- Sample allocation in special holders for delivering to worldwide laboratories.





Preliminary Characterization



Imaging	Optical microscopy Scanning Electron Microscopy (SEM)
Mineralogy	X-ray Diffraction (XRD) Visible-Infrared spectroscopy Microanalysis scanning Electron Microscopy (SEM-EDX)
Organic analyses	Visible-Infrared micro spectroscopy Micro Raman spectroscopy
Fluid Inclusion	Micro-Raman Spectroscopy Optical petrography

Preliminary Curation Database

Samples will be catalogued in order to set up a series of self-consistent describing elements according to:

- Specimen description: name, physical properties, preliminary investigation data set, classification.
- Sample description: name, type (e.g. rock, pebbles, dust), form (e.g., single chip, cube, plate, fragments, many grains, powder, etc.).
- Sampling site (e.g., outer part, inner part, central, etc.).
- Sample allocation.

General activities of storage and curation facility

- To prevent mineralogical, chemical and physical alteration of samples;
- To protect samples from chemical (inorganic and organic) and particulate contamination;
- To catalogue and archive the samples;
- To document sample handling history;
- To perform and document the sample preliminary examinations;

- To separate and section samples;
- To distribute samples to scientists around the world for detailed study;
- To preserve a portion of each sample collection for future study;
- To secure the samples;
- To spread information of scientific results to the public.

Collaboration and personnel sharing among curation facilities are envisaged.

MarcoPolo-R will use a combination of in situ and laboratory measurements to

- ✓ Provide a window into the distant past
- ✓ Allow scientists to unravel mysteries surrounding the birth and evolution of the solar system
- ✓ Involve large community, in a wide range of disciplines

Planetology	Astrobiology
Nucleosynthesis	Cosmochemistry

- ✓ Retain samples for future advances

  through a **Curation and Distribution Facility**

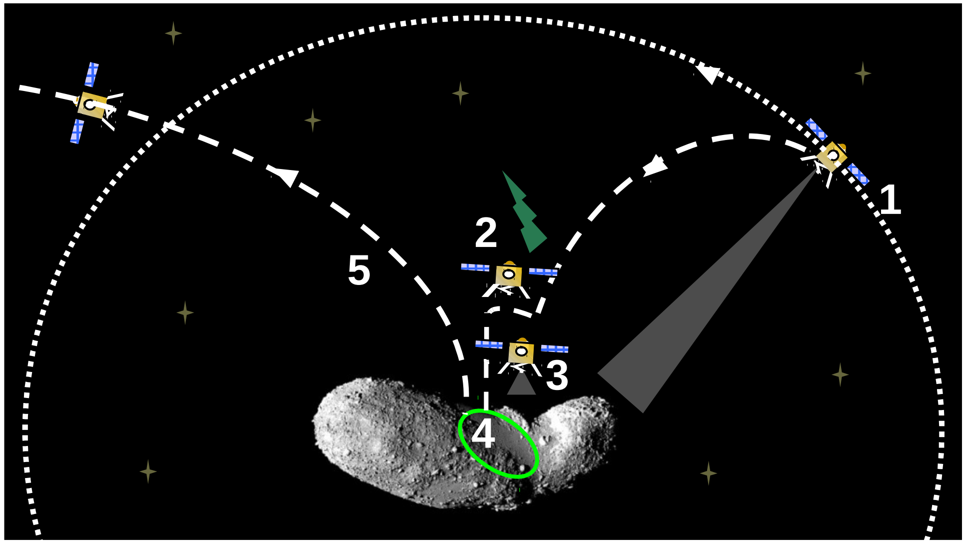
- ✓ Demonstrate key capabilities for any sample return mission
- ✓ Generate public interest

David Hardy

Descent/Sampling

Landing/touchdown
- ❑ 3 sampling attempt capability
- ❑ Clearance: ~ 50 cm hazards
- ❑ Landing accuracy ~ 5 m

Sampling
- ❑ Dust to cm-sized fragments
- ❑ Contamination-avoidance strategy

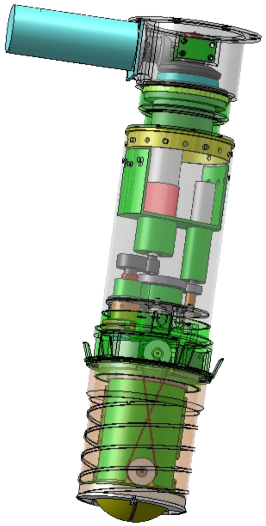


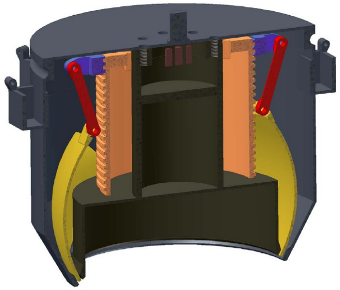
Asteroid descent and sampling sequence

1. Asteroid characterization
2. Hovering at 200 – 400 m altitude, “go-decision”
3. Autonomous terrain-relative descent
   - Navigation camera + multi-beam laser/radar altimeter
4. Touchdown/sampling
5. Ascent to safe position

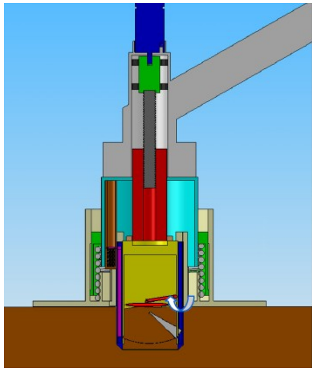
Descent/Sampling

- **Sampling option 1:** Short-term landing (~ 10 min.), "energy-absorbing" landing legs, down-thrust, rotating corer (sample canister)
- **Sampling option 2:** Touch & go (< 3 sec.), "elastic" legs, fast sampler (sample canister)





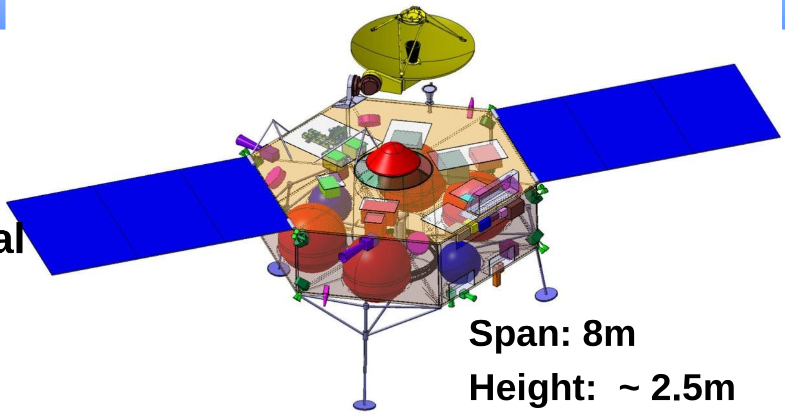
Rotating corer designs

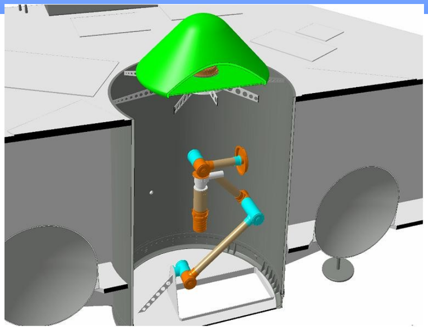


Fast sampler

Main spacecraft

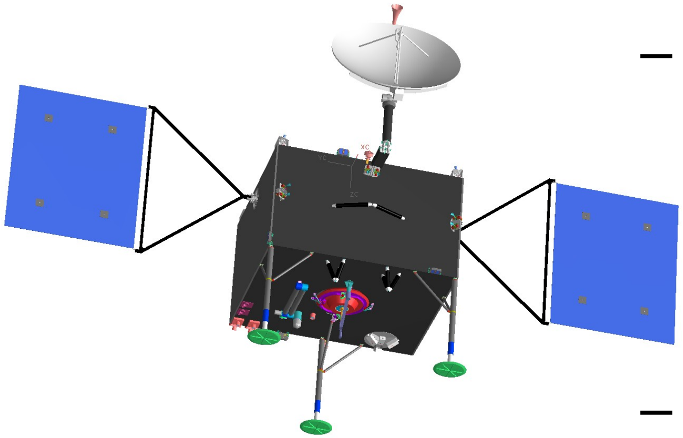
Concept 1**: Corer, top-mounted capsule, one articulated arm inside central cylinder**

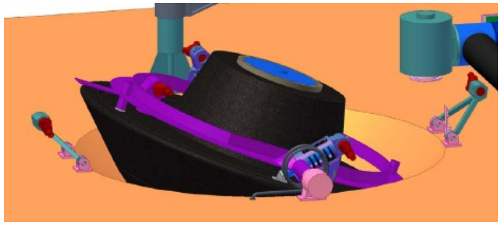




Span: 8m

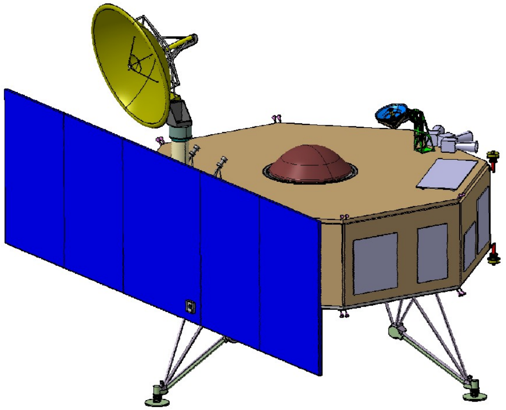
Height: ~ 2.5m

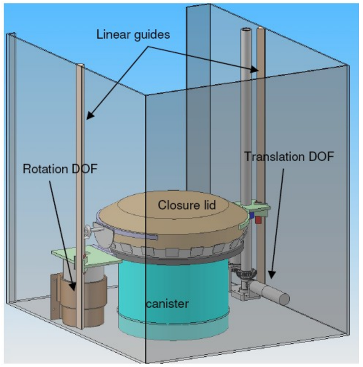




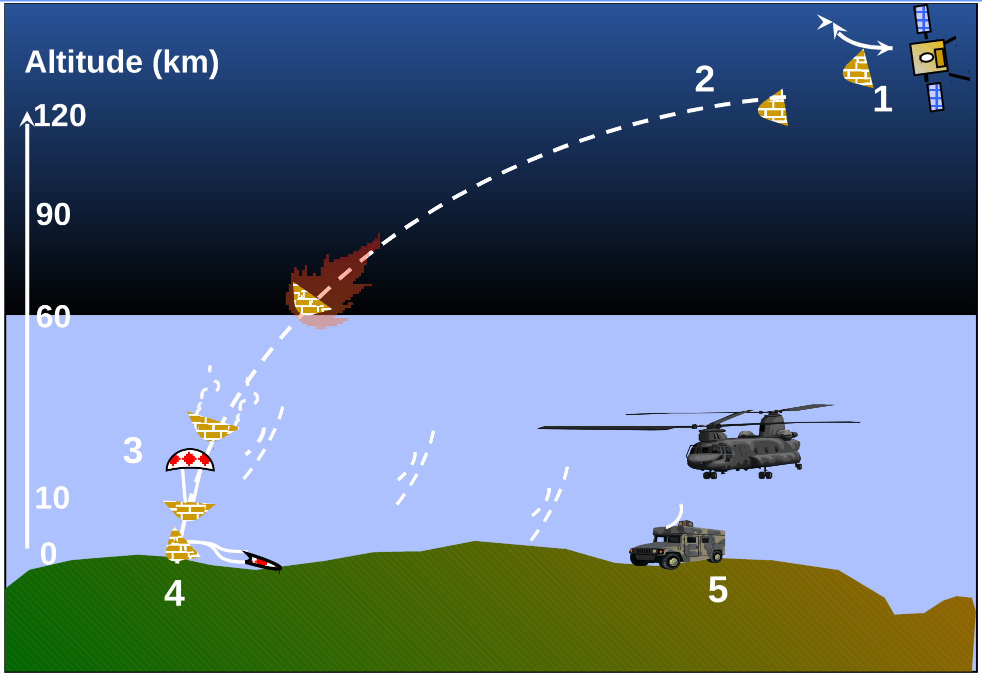
Concept 2: Corer, bottom-mounted capsule, two articulated arms

Concept 3: Fast sampler, top-mounted capsule, transfer via landing pads/legs + elevator in central cone





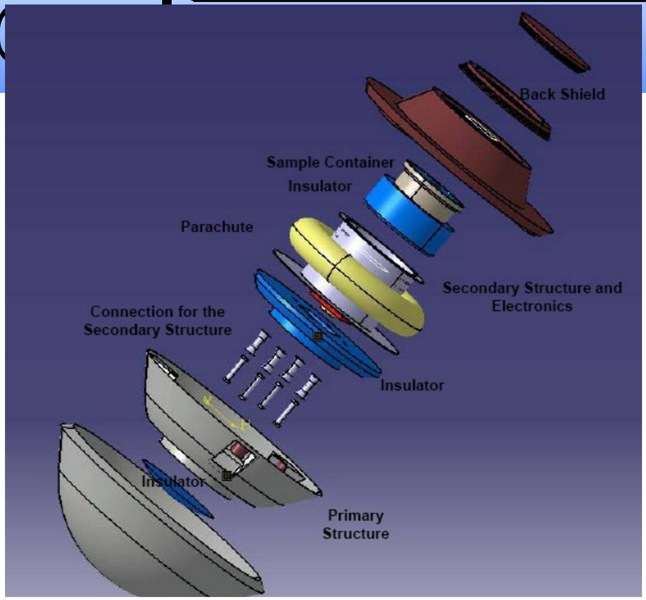
Earth re-entry



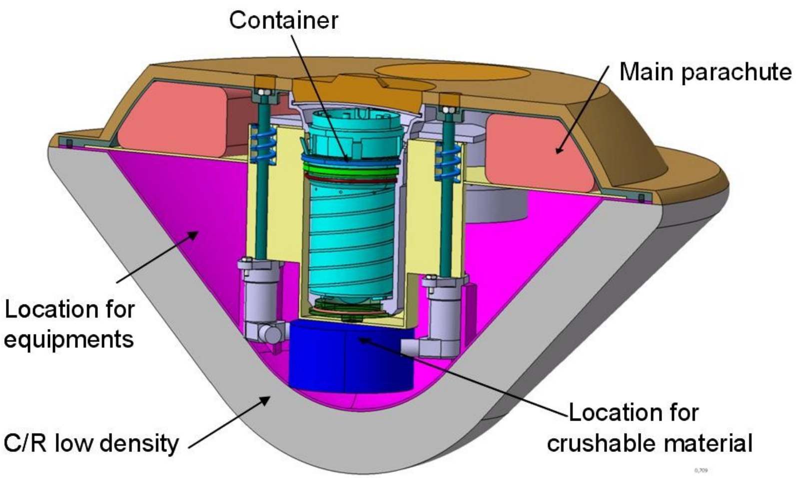
Stardust capsule recovery operations, *Credit:* NASA

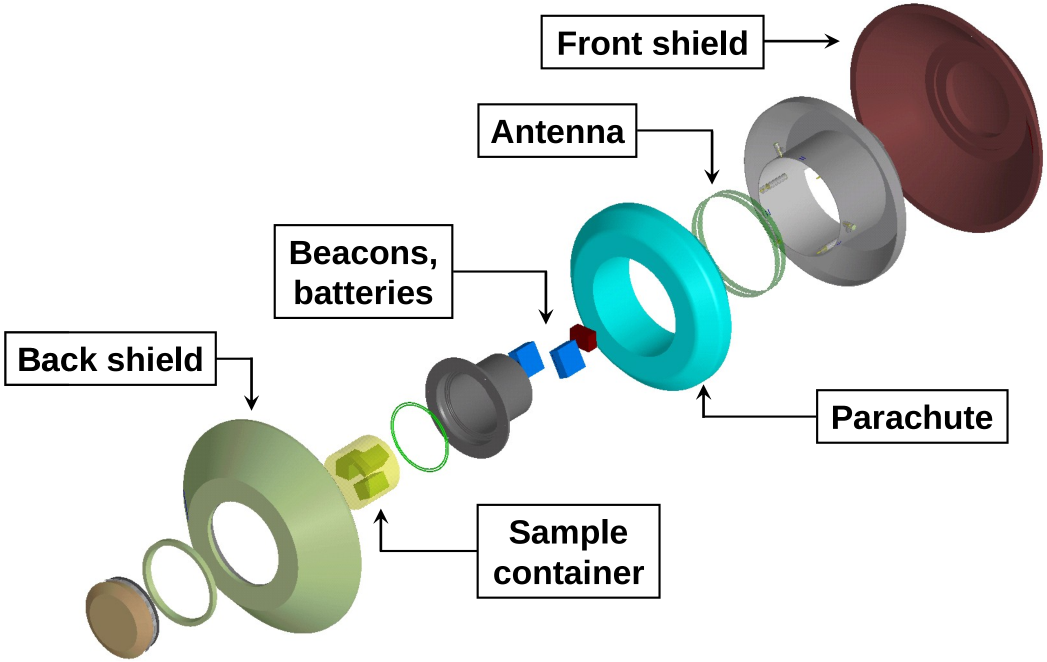
1. T_0 – 4 hours: Separation with main spacecraft
2. T_0: Re-entry (heat flux ~ 15 $MW{\cdot}m^{-2}$)
3. T_0 + 200 s: Parachute opening (~ 10 km, subsonic)
4. T_0 + 1800 s: Soft landing in Woomera, Australia
5. Landing + few min/hrs: Search & Recovery

Earth re-entry cap



- **45º half-cone angle front shield**
- **In-development lightweight ablative material or classical carbon phenolic**
- **Capsule mass: 25 – 69 kg**

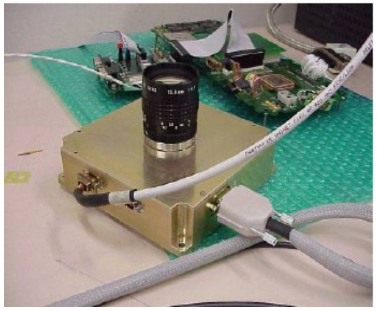




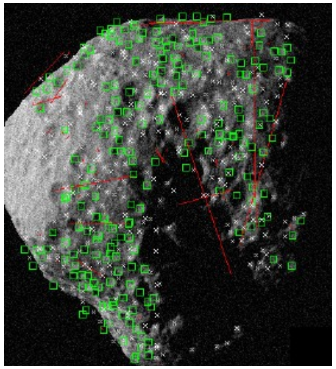
Development

- Proto-Flight Model + dedicated qualification models
- No specific planetary protection measures required
- Pre-development

Enabling and enhancing technology activities	Heritage (or activities ongoing for future missions: *e.g.* ExoMars, MoonNEXT)
Sample acquisition, transfer and containment system	Exomars, Philae, MSR activities
Low-gravity and high-clearance landing/touchdown system	Philae, Moon NEXT activities
Parachute system: canopy, packaging and deployment device	Huygens, Exomars
Autonomous GNC technology for proximity operations	MSR/MoonNEXT activities (VisNav, etc.), NEA GNC TRP activity
FDIR, altimetry and attitude measurement sensor *(need to be confirmed in future phases)*	ExoMars, ongoing Aurora activities
Delta-development of high-flux ablative TPS material	Ongoing TRP and previous ESA activities
Contamination assessment of bi/mono-propellant thrusters	Classical thrusters firing tests
Capsule dynamic stability	Huygens, ExoMars



Navigation camera *Astrium*

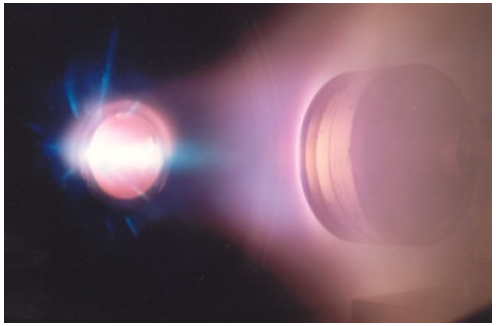


Navigation landmarks *TAS*

- All testing facilities available

Sampling test results *SENER*

Sampling test results *SELEX Galileo*



High heat flux test of heat shield material, *IRS*

A technically feasible mission

	Contractor 1	Contractor 2	Contractor 3
Total dry mass	745	744	812
Launch mass	1448	1462	1557
Launch vehicle performance	1629	1719	1629
Launch mass margins (%)	11	15	4

Marco Polo spacecraft mass budget (kg)

Maximal use of ongoing/past activities allows an effective and robust development plan

- ✓ Safe landing/touchdown (including “relaxed” GNC)
- ✓ Sample collection, transfer and sealing
- ✓ Earth re-entry

High heritage and no pre-development needed for:

- ✓ Mission and science operations
- ✓ “Standard” platform equipment (e.g. power, thermal, propulsion)

Programmatics

Option 1 – A NASA led sample return mission with ESA participation in the framework of a Mission of Opportunity in OSIRIS-REx mission.

Option 2 – An ESA led sample return mission with major components provided by a partner, namely the Earth re-entry capsule and a sample mechanism both provided by APL and JPL and based on the GALAHAD proposal.