

Dwarf planets

Comets

Small planetary satellites

Near Earth asteroids

Kuiper belt objects

Main belt asteroids

Rocks in Space

The science, danger and profits of small bodies

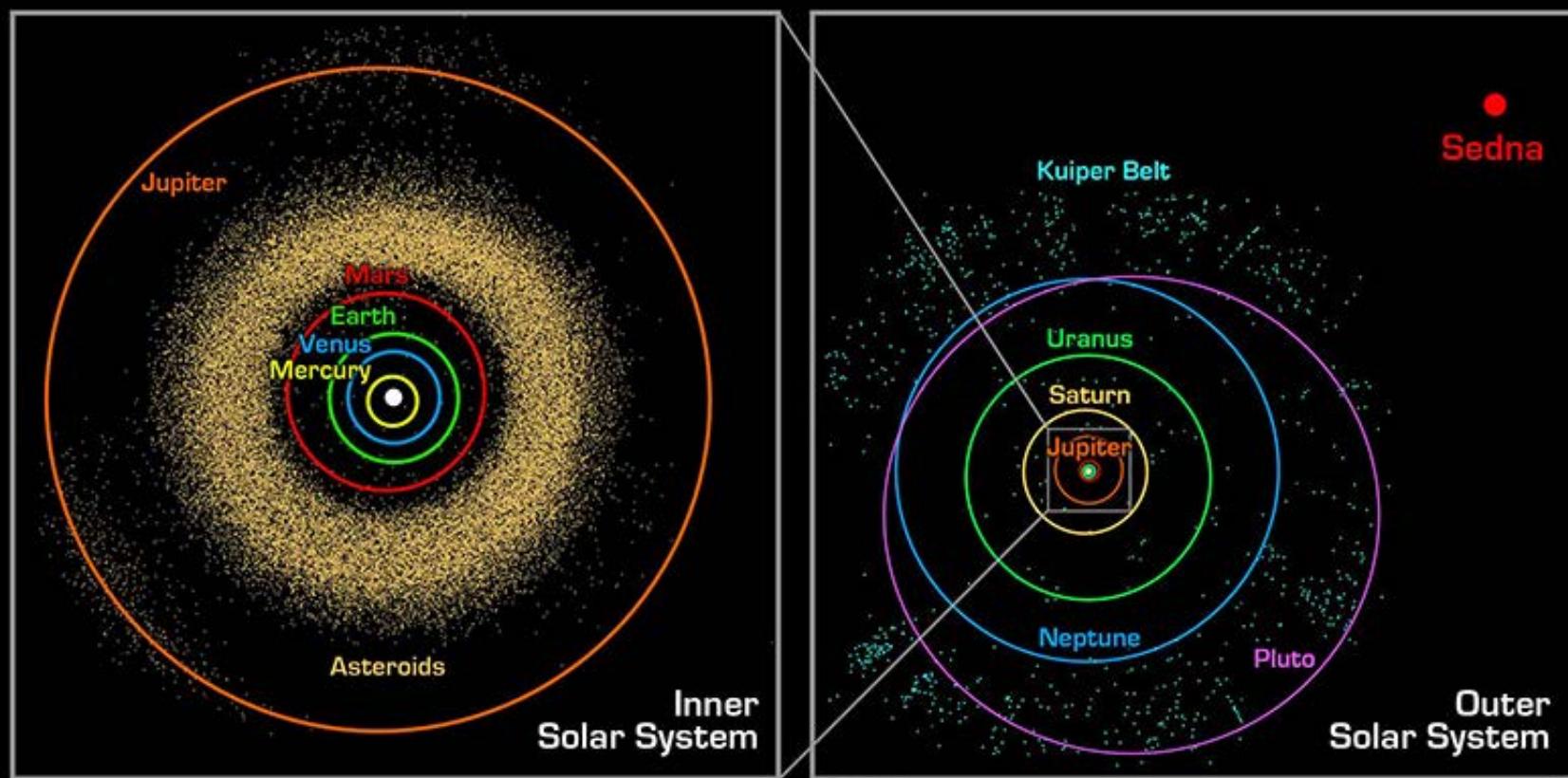
Bin Cheng & Hexi Baoyin

School of Aerospace Engineering
Tsinghua University

What are small bodies?

■ Small solar system bodies

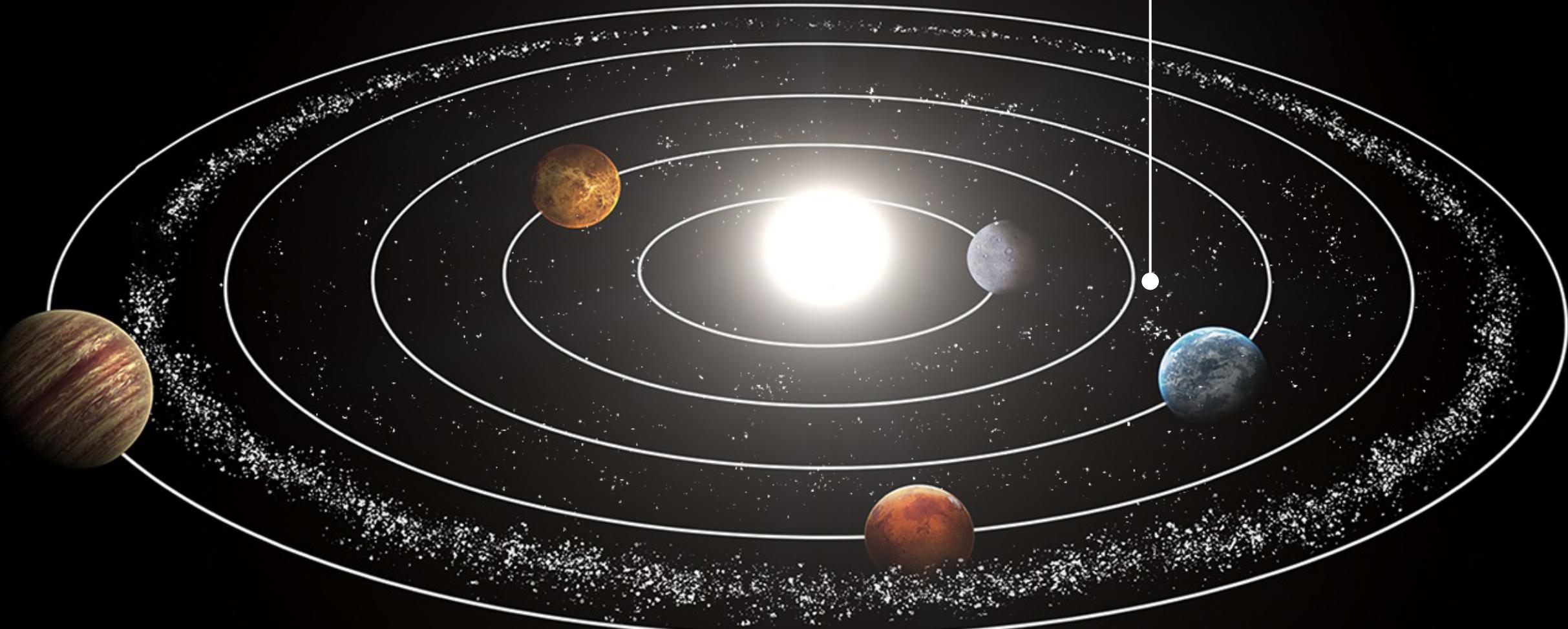
- Asteroids, comets, the objects in the Kuiper Belt and the Oort cloud, small planetary satellites, interplanetary dust and so on.
- Largest one is Ceres (a dwarf planet), almost 1000 km across.
- Smallest is ... as tiny as grains of sand.
- Diverse collection of bodies with differing compositions, shapes, sizes, history, locations...



SMALL OBJECTS IN THE SOLAR SYSTEM

Near-Earth Objects

Perihelion less than 1.3 AU



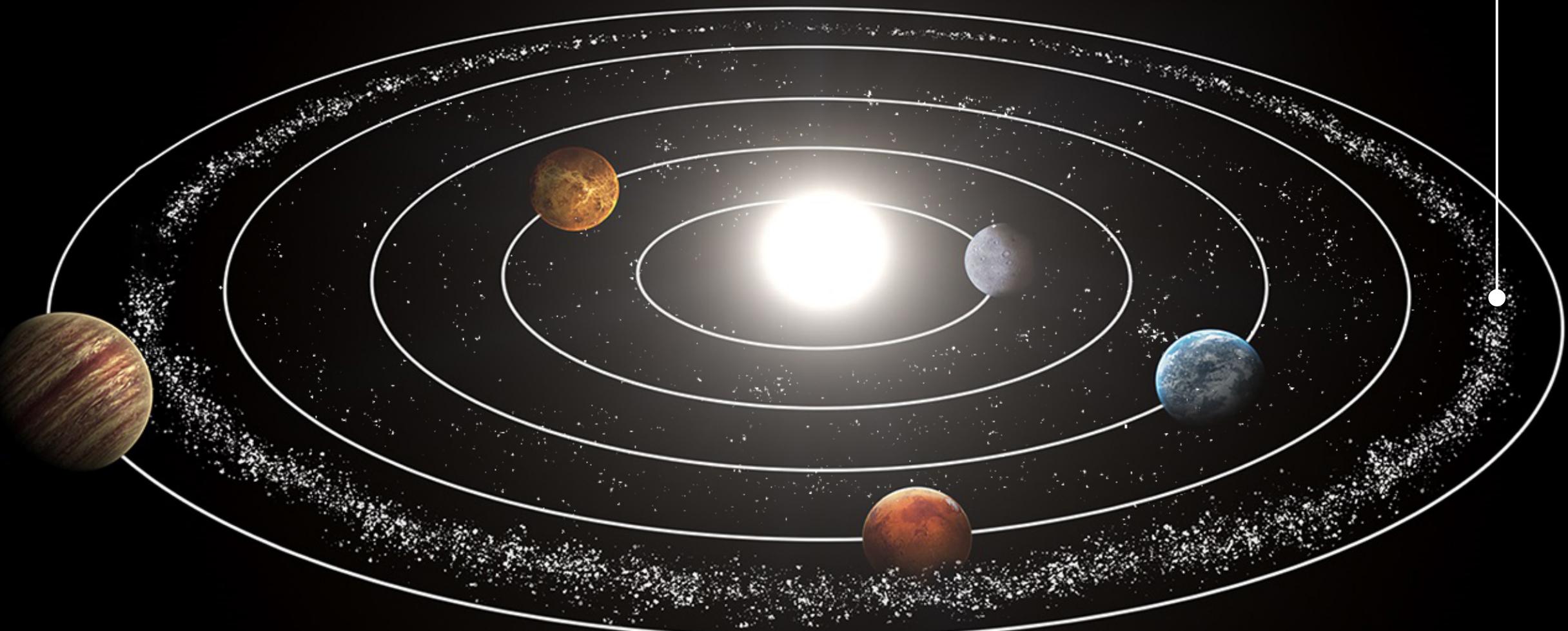
1 AU = Earth-Sun distance ~150 million km

This infographic is representative and not to scale.

SMALL OBJECTS IN THE SOLAR SYSTEM

Main Asteroid Belt

Distance from sun: 2.1-3.3 AU



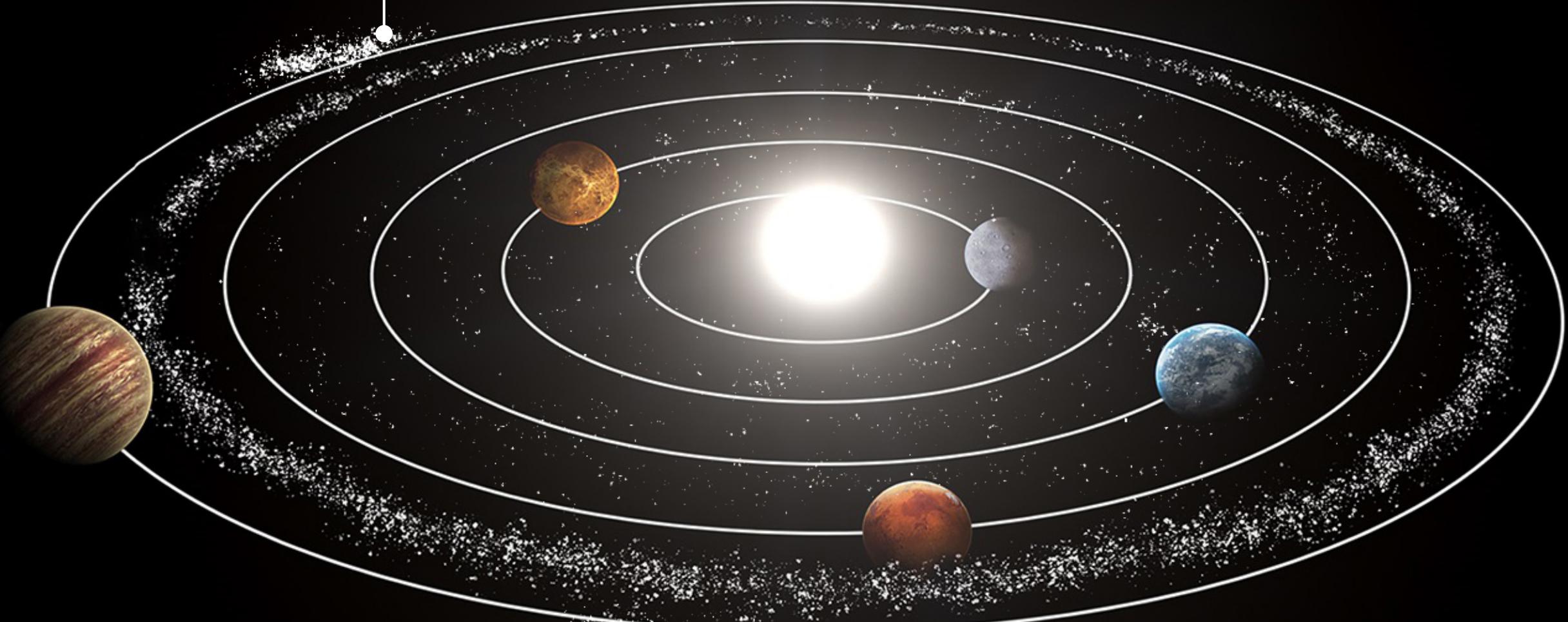
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SMALL OBJECTS IN THE SOLAR SYSTEM

Jupiter Trojans

Librate around the L4 and L5 points of Jupiter



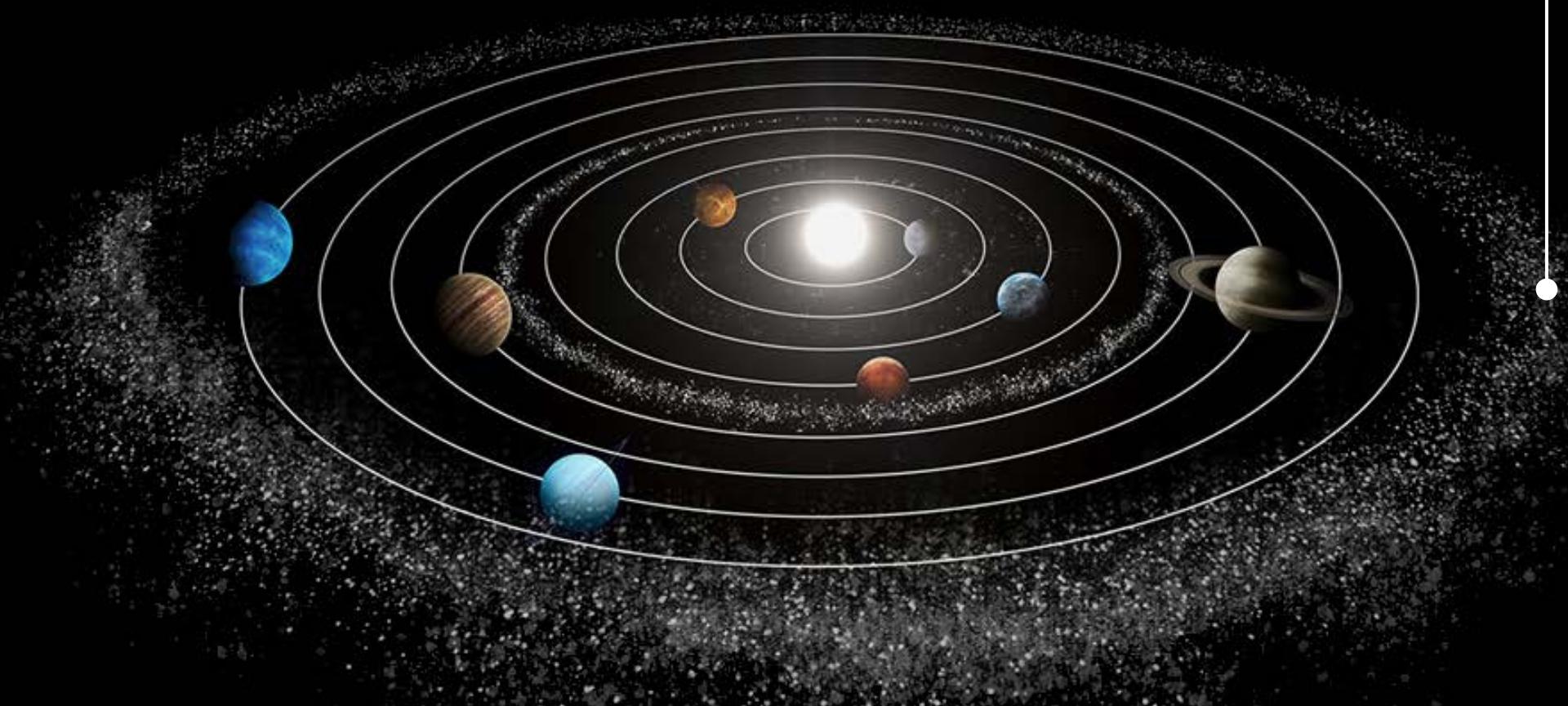
1 AU = Earth-Sun distance ~150 million km

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SMALL OBJECTS IN THE SOLAR SYSTEM

Kuiper Belt

Distance from Sun: 30-50 AU



1 AU = Earth-Sun distance ~150 million km

This infographic is representative and not to scale.

SMALL OBJECTS IN THE SOLAR SYSTEM

Oort Cloud

Distance from Sun: 2000-200000 AU



1 AU = Earth-Sun distance ~150 million km

This infographic is representative and not to scale.

Small but diverse worlds



The Moon

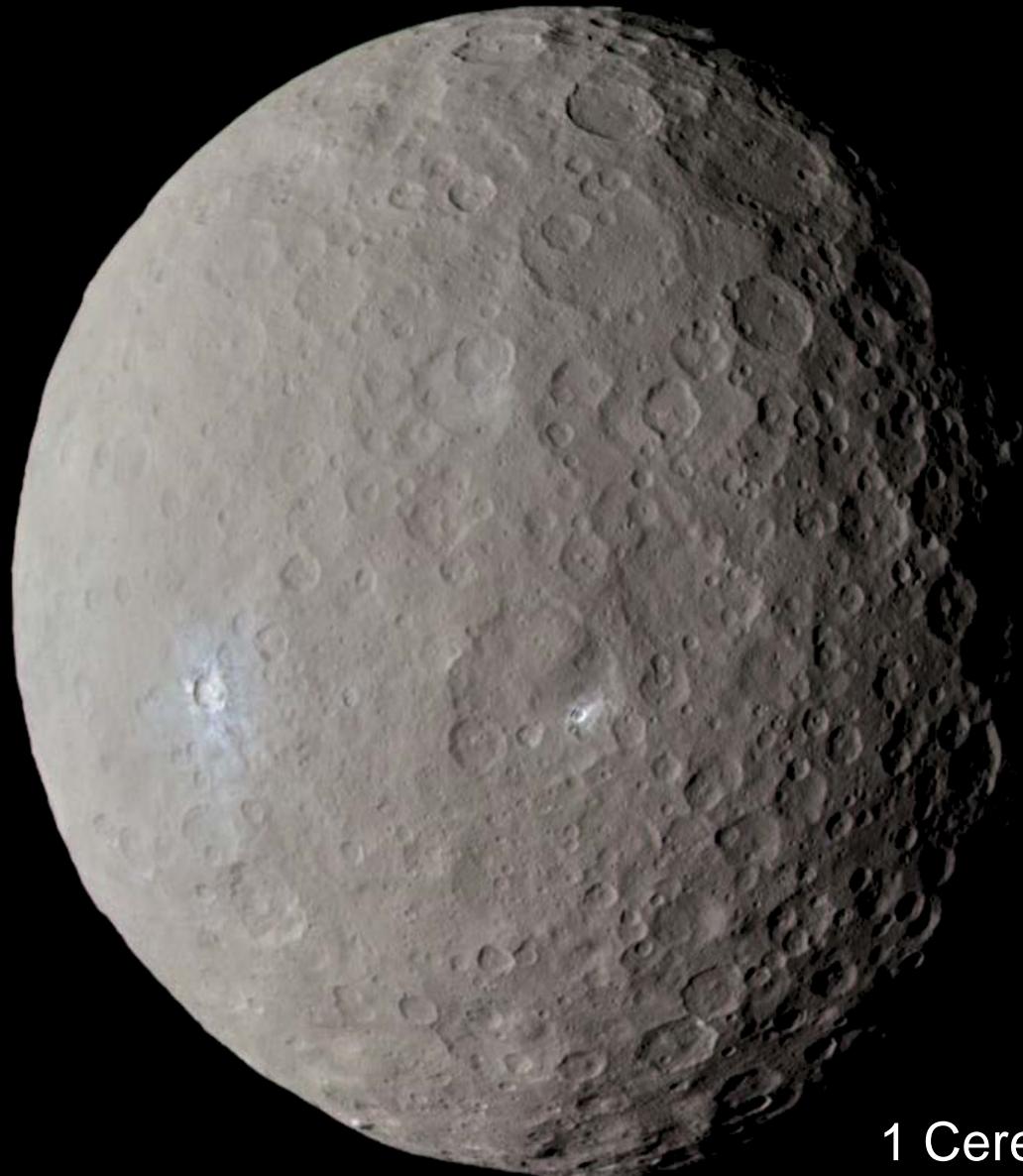


Ceres



Earth

Small but diverse worlds



1 Ceres



4 Vesta



21 Lutetia



253 Mathilde



243 Ida



433 Eros



951 Gaspra



2867 Šteins

5535 Annefrank

— 25143 Itokawa

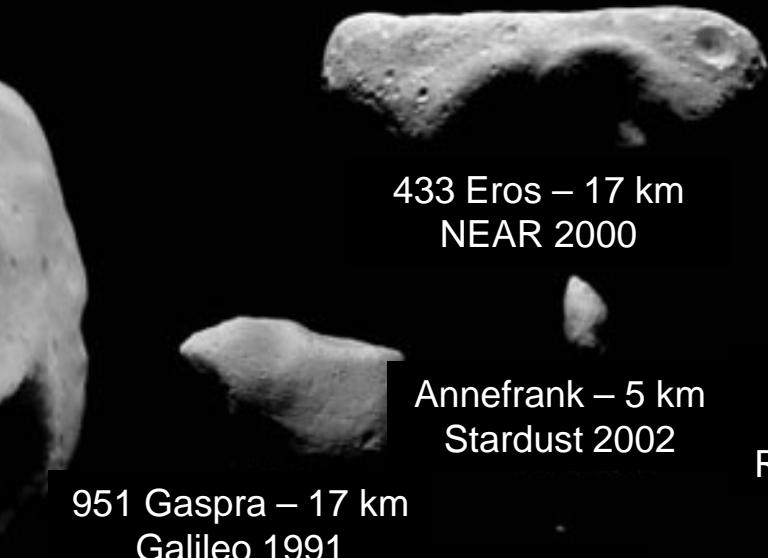
Small but diverse worlds



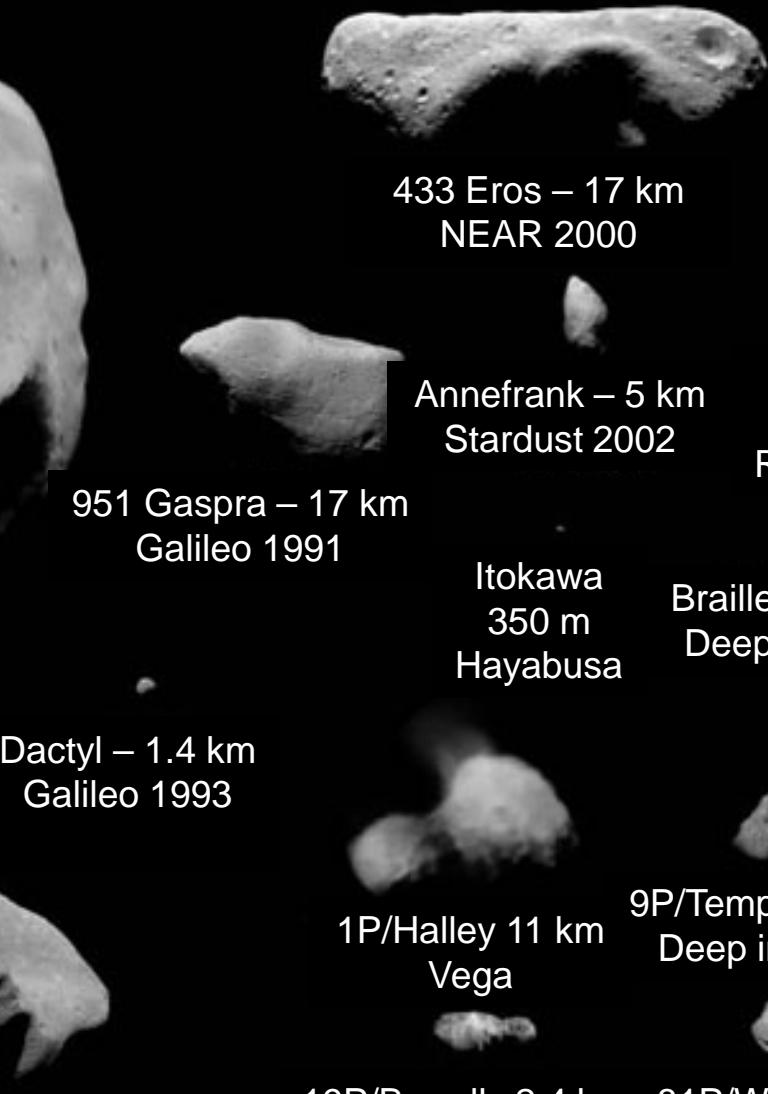
21 Lutetia – 130 km
Rosetta 2010



243 Ida – 31 km
Galileo 1993



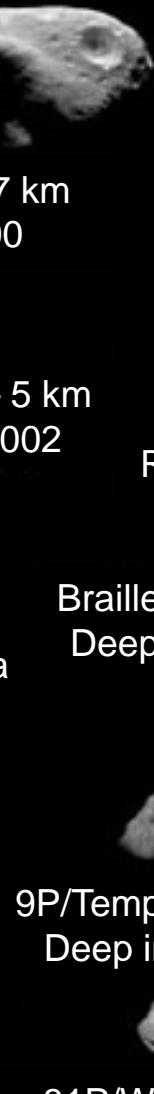
951 Gaspra – 17 km
Galileo 1991



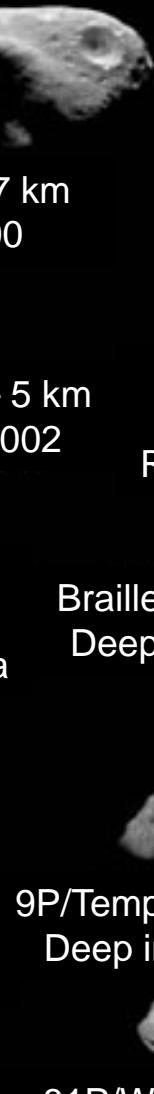
Dactyl – 1.4 km
Galileo 1993



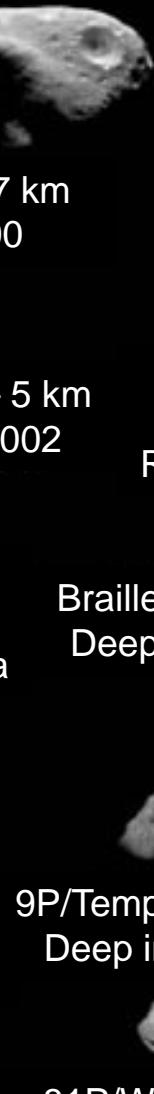
1P/Halley 11 km
Vega



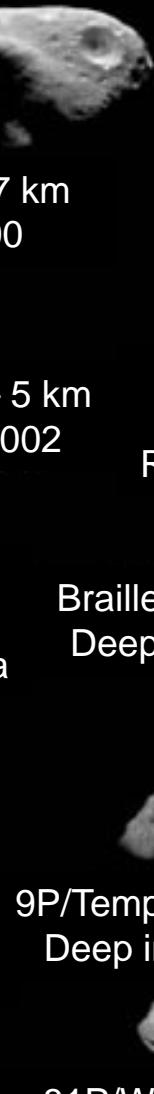
433 Eros – 17 km
NEAR 2000



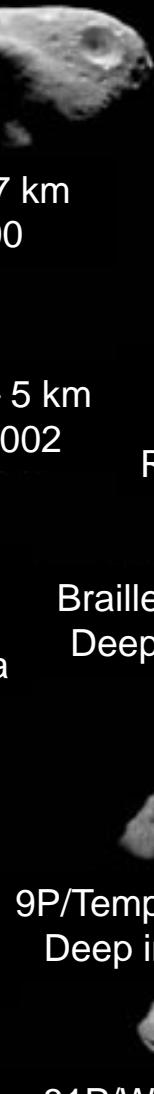
Annefrank – 5 km
Stardust 2002



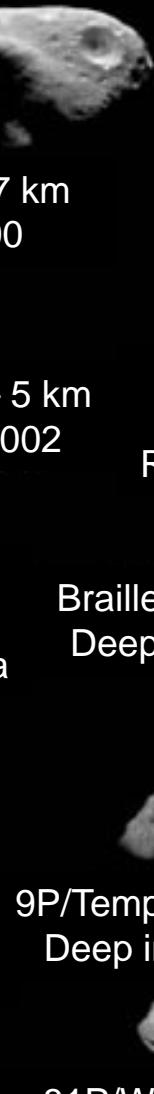
Steins
5 km
Rosetta



Itokawa
350 m
Hayabusa



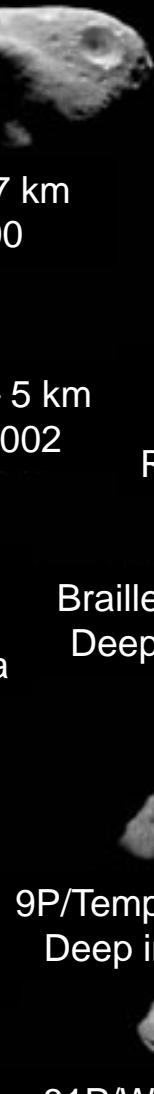
Braille 1.6 km
Deep space



9P/Tempel 6 km
Deep impact



19P/Borrelly 2.4 km
Deep space 1



81P/Wild 4 km
Stardust

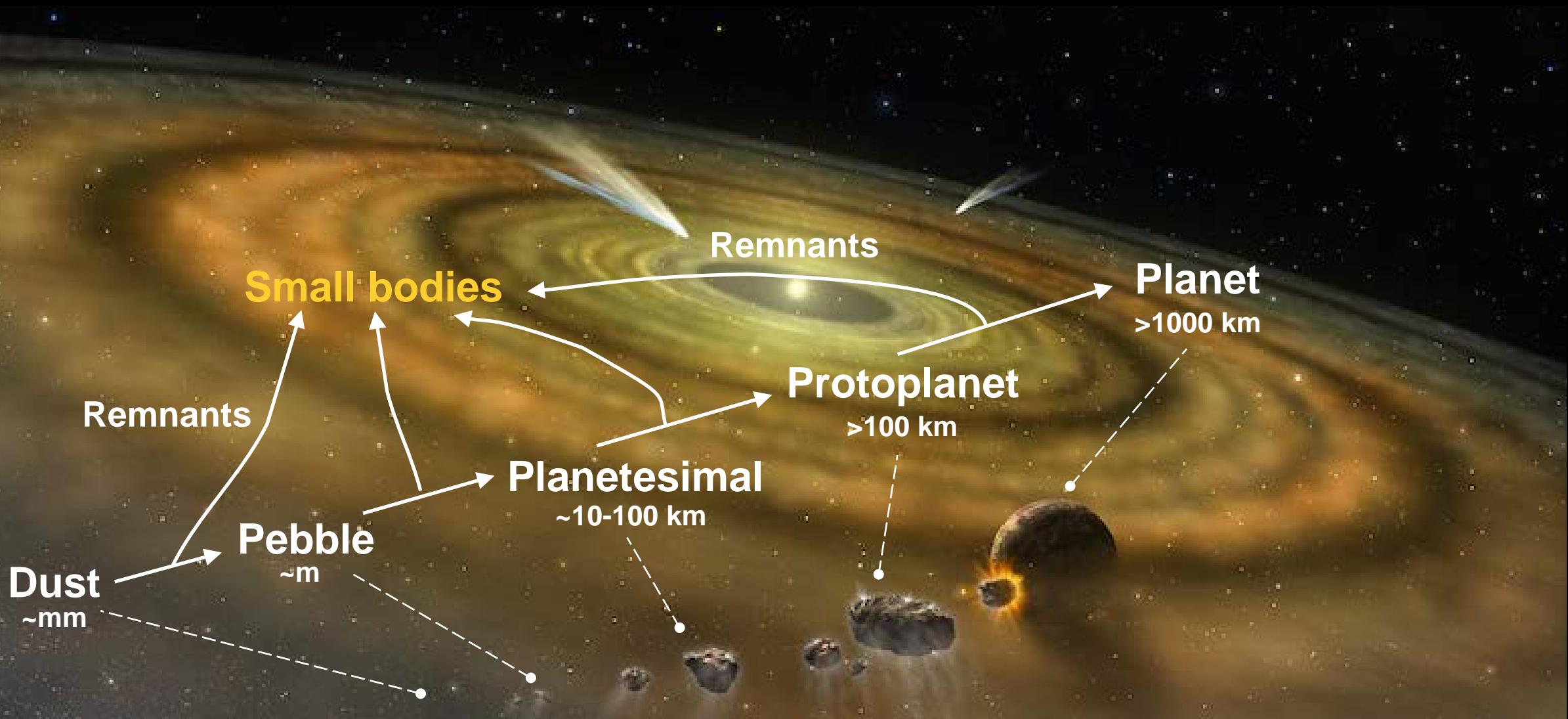
Credit: NASA/ESA/JAXA

Why are we interested?

Why are we interested?

■ Time capsules from the early solar system

- “Leftovers” that record the birth, growth and death of the planets.



Dust ----> Planetesimal ----> Protoplanet ----> Planets ----> Disruption

~mm

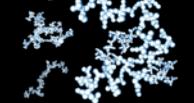
~10-100 km

>100 km

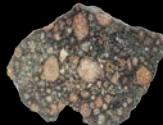
>1000 km

-> fragments

Small bodies with different sizes record the birth, growth and death of the planets.



Chondrite



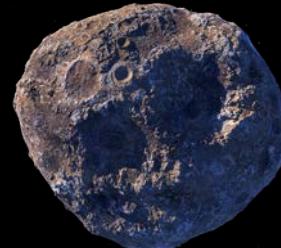
Mathilde



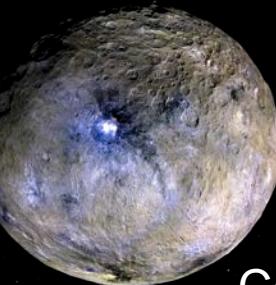
Lutetia



Psyche



Vesta



Ceres



Mars



Mercury



Ryugu



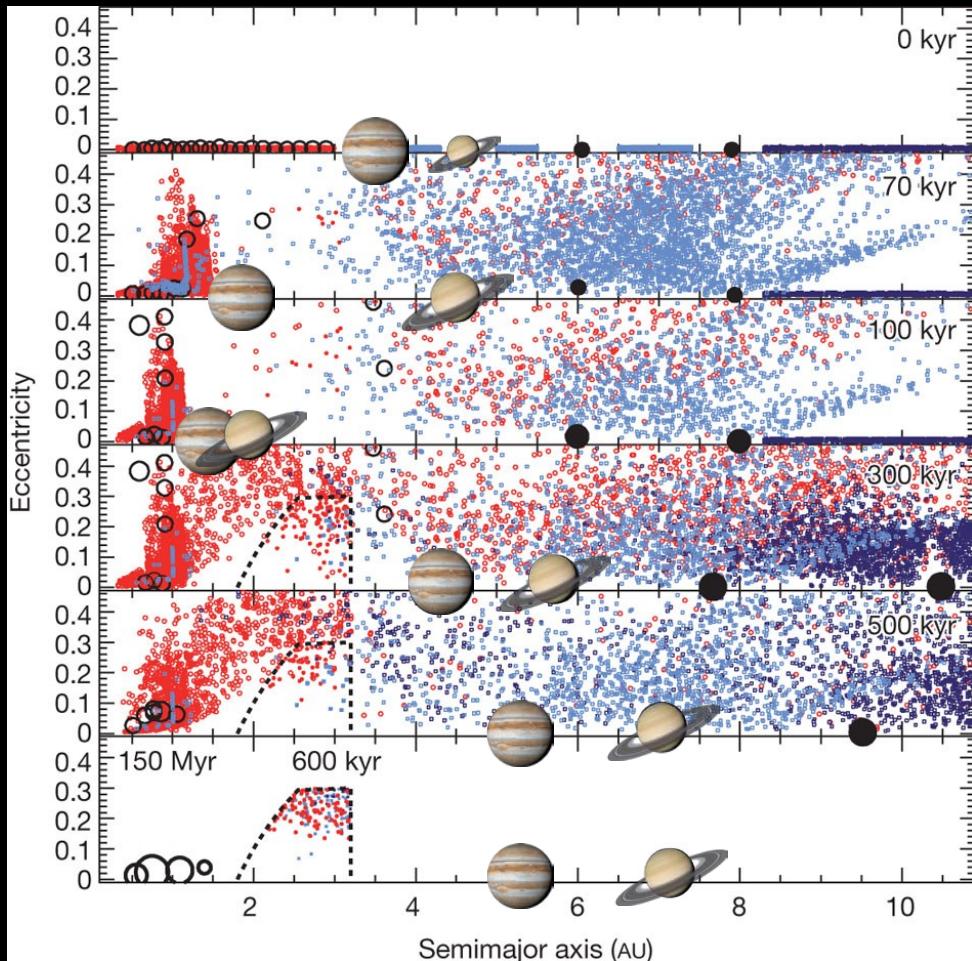
Itokawa



Why are we interested?

■ Time capsules from the early solar system

- “Leftovers” that record the birth, growth and death of the planets.
- “Tracer particles” that record how the major planets move over time.



Quite similar with \Rightarrow

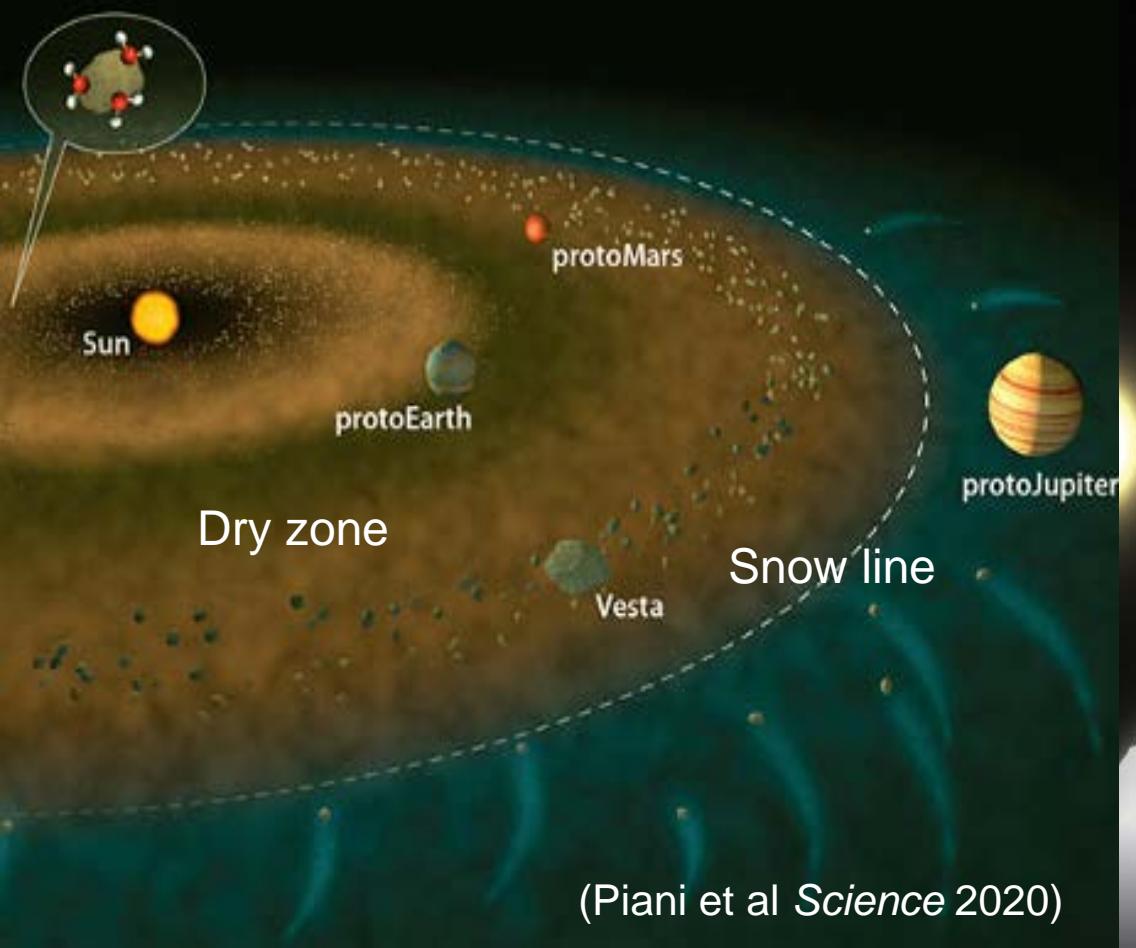


Fluid dynamics experiment

Why are we interested?

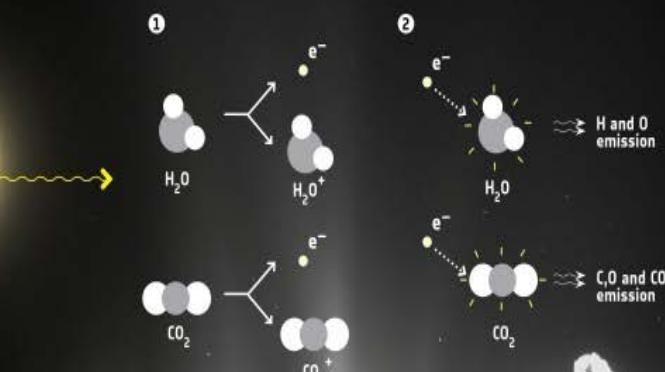
■ They have shaped life on Earth

- “Life-starters” that seed water and organic compounds to ancient Earth.

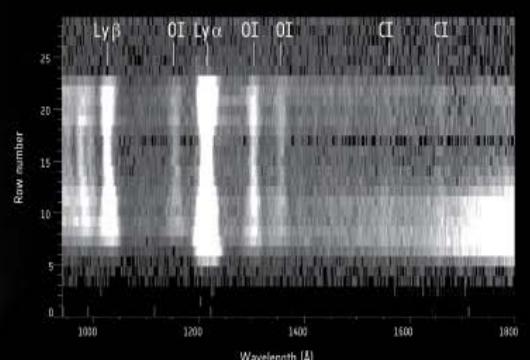


Comparing volatile-rich small bodies with Earth water

Rosetta's close study of Comet 67P/Churyumov–Gerasimenko at ultraviolet wavelengths has revealed that electrons and not photons are responsible for the rapid breakup of water and carbon dioxide molecules erupting from the surface.



Example of a spectral image (below) obtained by Alice for positions in the comet's coma indicated in the NavCam image (above). The emission by oxygen (OI) and carbon (CI) in the coma are indicated. The bright bands labelled Ly α and Ly β are due to electron impact on H_2O .



- 1 Solar photons ionise comet water and carbon dioxide molecules, producing electrons
- 2 Electrons impact other water and carbon dioxide molecules, creating emission detected by Alice

Why are we interested?

■ They have shaped life on Earth

- “Life-starters” that seed water and organic compound to ancient Earth.
- “Life-enders” that caused extinction event 66 Mya, and maybe in the future?!



A 10 km size asteroid impacted Earth and ended the age of dinosaurs 66 Mya.

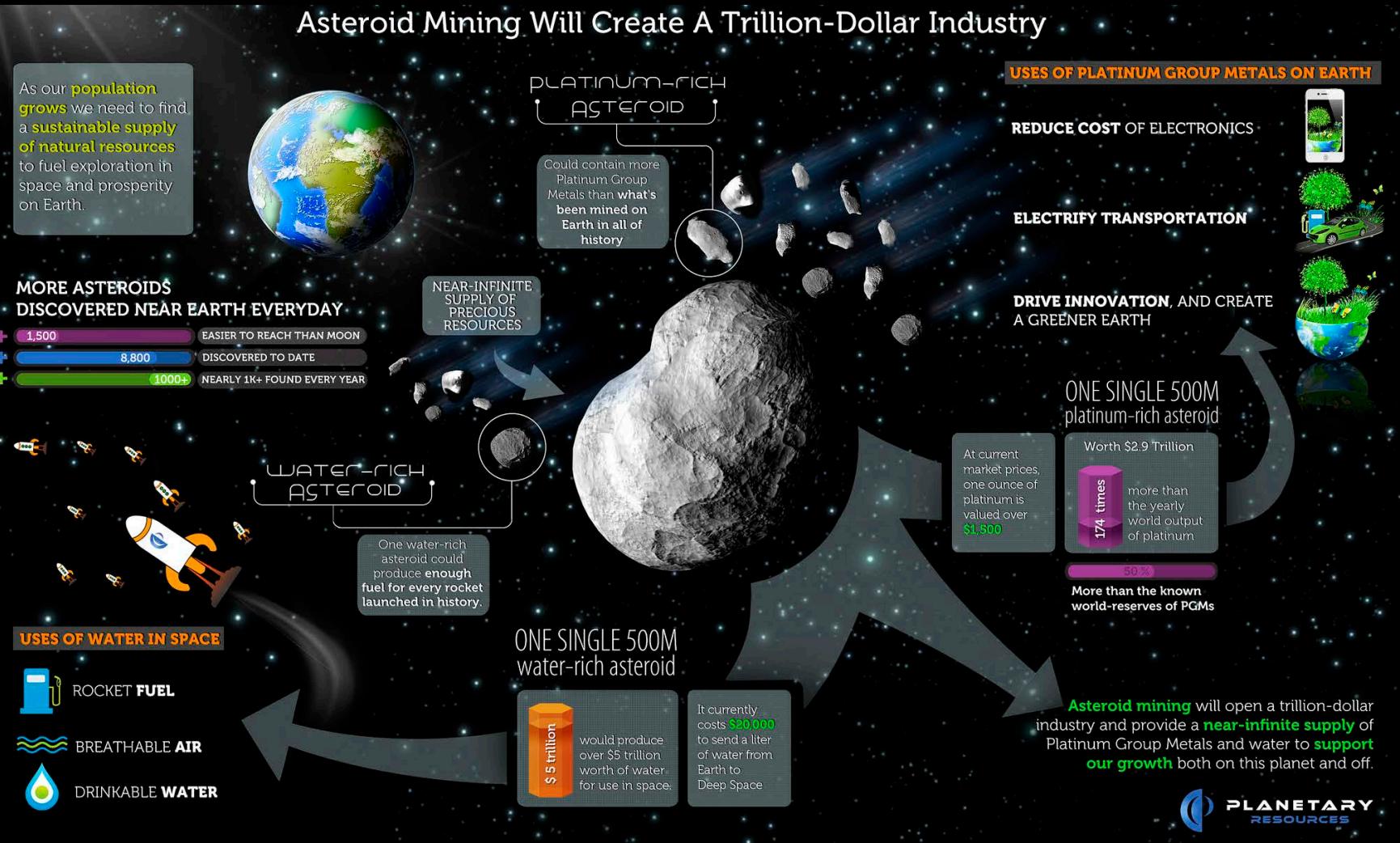
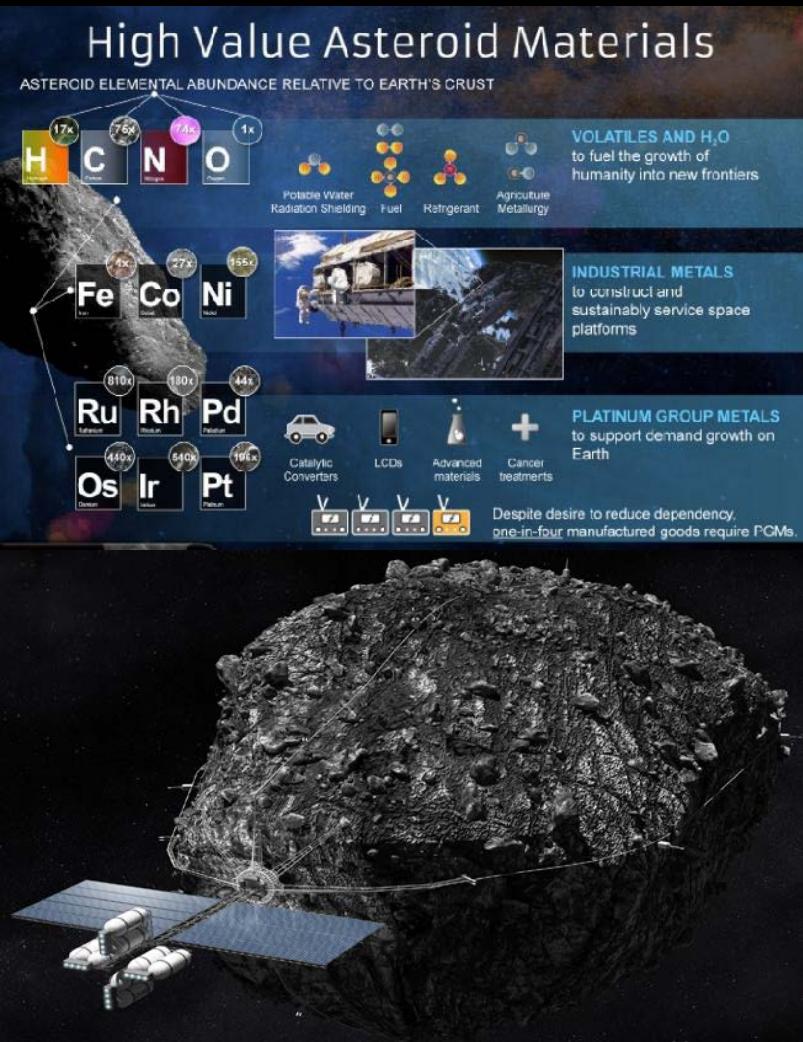
(Hand et al *Science* 2016)



Why are we interested?

Asteroid mining: A modern day gold rush

- Sound like Sci-Fi for years... but has recently spawned new interest.



What small body missions have we done?

What small body missions have we done?

Flyby missions: 14

Rendezvous missions: 4

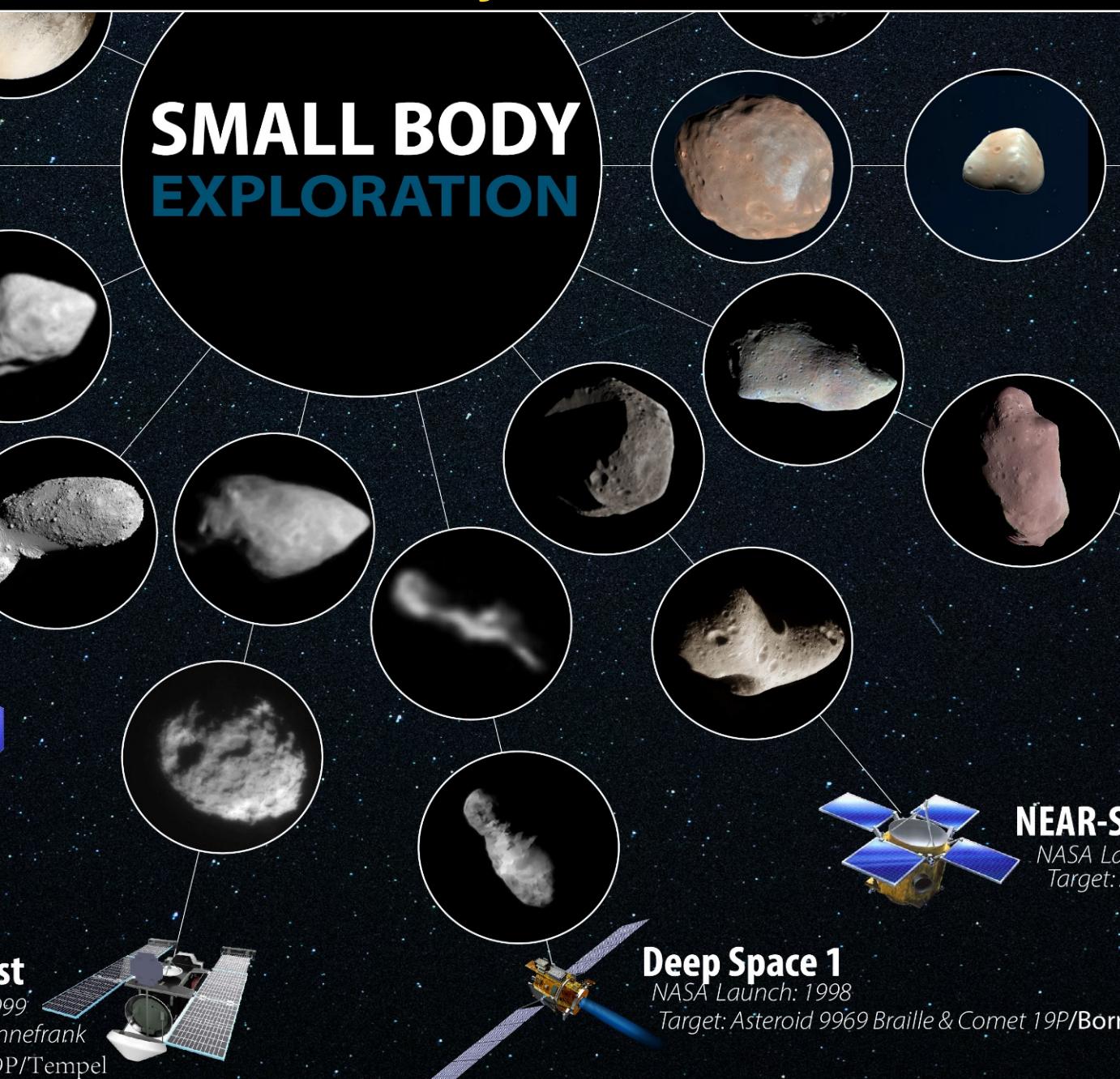
Sample-return missions: 4

Impact missions: 2



What small body missions have we done?

SMALL BODY EXPLORATION



First spacecraft to orbit an asteroid.

NEAR-Shoemaker

NASA Launch: 1996
Target: Asteroid 253 Mathilde & 433 Eros

Deep Space 1

NASA Launch: 1998
Target: Asteroid 9969 Braille & Comet 19P/Borrelly

Mariner 9

NASA Launch: 1971

Target: Martian Moon Phobos & Deimos

Viking 1

NASA Launch: 1975

Target: Martian Moon Phobos



First images of small bodies.

Galileo

NASA Launch: 1989

Target: Asteroid 951 Gaspra & 243 Ida



What small body missions have we done?

SMALL BODY EXPLORATION



Deep Impact

NASA Launch: 2005
Target: Comet 9P/Tempel

First impact on small bodies.



First landing on comets.

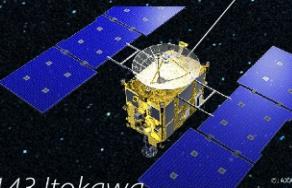
Rosetta

ESA Launch: 2004
Target: Asteroid 2867 Šteins & 21 Lutetia & Comet 67P/C-G



Hayabusa

JAXA Launch: 2003
Target: Asteroid 25143 Itokawa

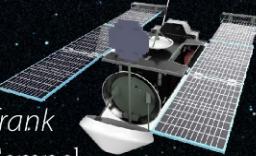


First sample from an asteroid.

First sample from a comet.

Stardust

NASA Launch: 1999
Target: Asteroid 5535 Annefrank & Comet 81P/Wild & 9P/Tempel



Data compiled as of October 2023

Credit: Bin Cheng, Tsinghua University

Deep Impact
NASA Launch: 2005
Target: Comet 9P/Tempel

What small body missions have we done?

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New Horizon
NASA Launch: 2006
Target: Pluto & KBO 486958 Arrokoth
First flyby to KBOs.



First impact on small bodies.

Dawn
NASA Launch: 2007
Target: Asteroid 4 Vesta & 1 Ceres



China's first asteroid mission.

Chang'e 2
CNSA Launch: 2010
Target: Asteroid 4179 Toutatis



Hayabusa2
JAXA Launch: 2014
Target: Asteroid 162173 Ryugu

SMALL BODY EXPLORATION

What small body missions have we done?

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Hayabusa2

JAXA Launch: 2014

Target: Asteroid 162173 Ryugu

OSIRIS-REx

NASA Launch: 2016

Target: Asteroid 101955 Bennu



DART

NASA Launch: 2021

Target: Asteroid 65803 Didymos

First test of changing the orbit of an asteroid.

SMALL BODY EXPLORATION



Mariner 9

NASA Launch: 1971

Target: Martian Moon Phobos & Deimos

Viking 1

NASA Launch: 1975

Target: Martian Moon Phobos

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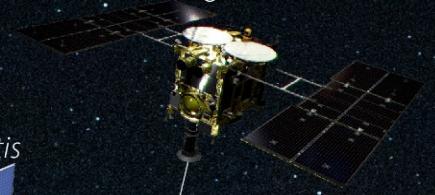
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SMALL BODY EXPLORATION

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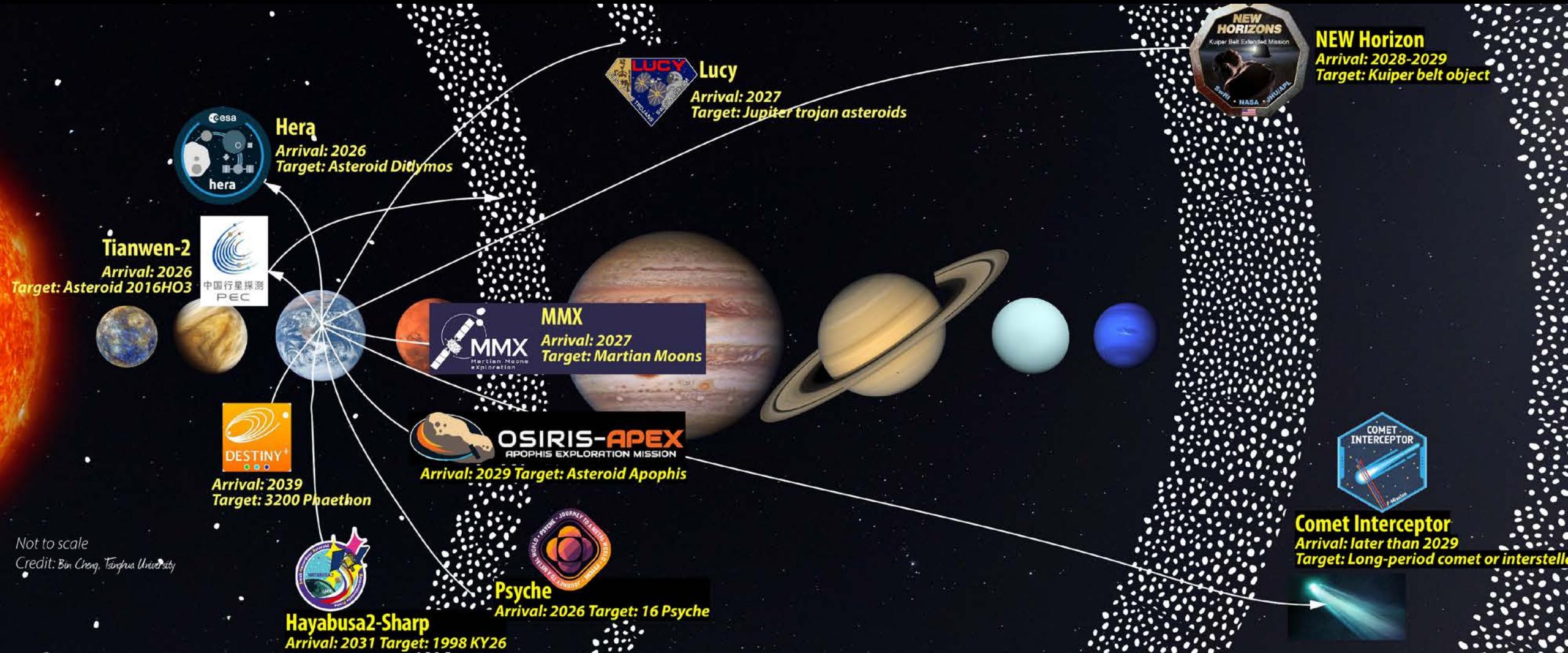
What about the future?

What about the future?

■ Go farther

- At least 10 missions in next 5 years!

Near Earth→Main Asteroid Belt→Jupiter Trojan→Kuiper Belt→Oort cloud



What about the future?

■ Go farther

- Near Earth→Main Asteroid Belt→Jupiter Trojan→Kuiper Belt

■ Diverse targets

- Asteroid C-type ✓ S-type ✓ M-type ✗ (NASA's Psyche mission)
- Short-period comets ✓ Long-period comets ✗ Interstellar Object ✗ (ESA's Comet Interceptor mission)
- Martian Moons ✗ (JAXA's MMX mission)
- KBOs ✓
- Size: 100 m – 100 km ✓ <100 m ✗ (most dangerous asteroids: China's Tianwen-2 mission)

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■ Advanced missions

- Flyby→Rendezvous→Sample-return→Impact deflection→?
- Manipulate asteroid trajectories (for mining or planetary defense)?
- In-Situ Resource Utilization?

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■ Advanced missions

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- In-Situ Resource Utilization?

■ More material back to Earth

- Stardust: 1 mg (1999) → Hayabusa: <1 g (2003) → Hayabusa2: 5.4 g (2014)
→ OSIRIS-REx: ~249 g (2016) → ?
- Still far from the scale required for asteroid mining... How to significantly increase it?

Rocks in Space: The Science, Danger and profits of small bodies

- We are living in a “golden age” of small body exploration!
- For science, for Human beings, and ... for Money!

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