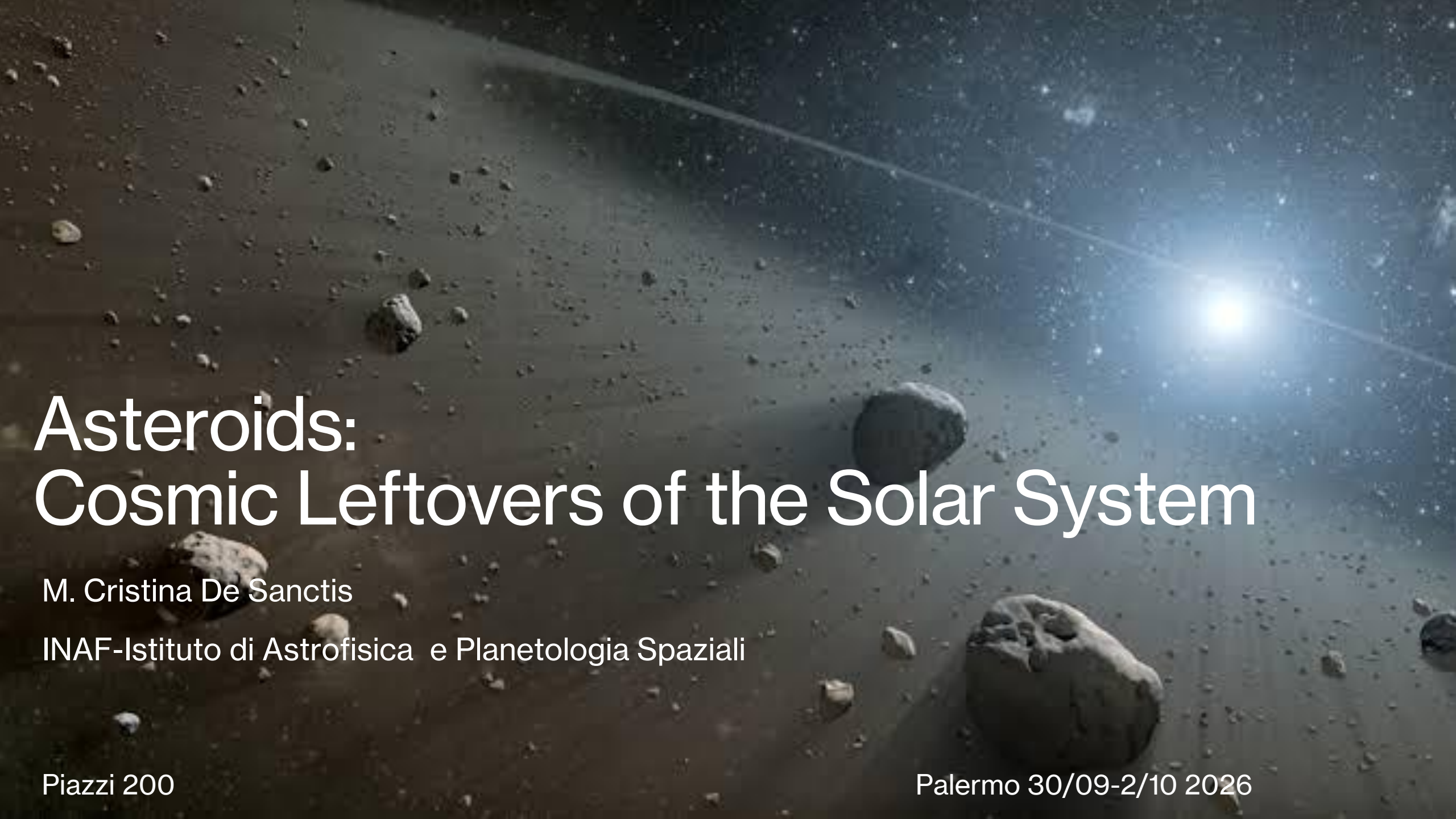




Asteroids: Cosmic Leftovers of the Solar System

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Piazzì 200

Palermo 30/09-2/10 2026

Outline

Infos:

- The Asteroid Belt and Other Regions – Dynamic
- Mass, size and shapes
- Classification and Types

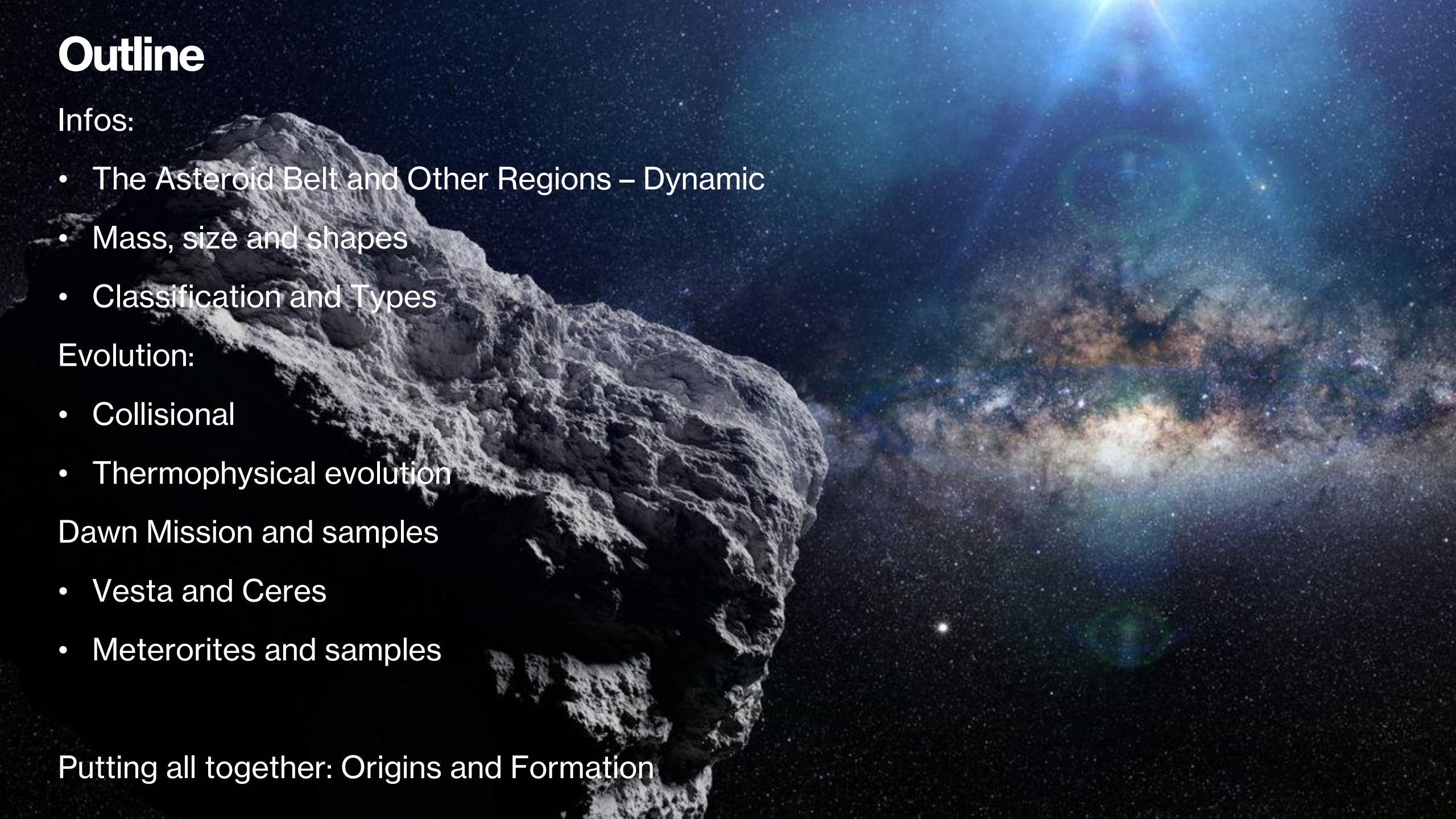
Evolution:

- Collisional
- Thermophysical evolution

Dawn Mission and samples

- Vesta and Ceres
- Meteorites and samples

Putting all together: Origins and Formation



What is an Asteroid?

Herschel

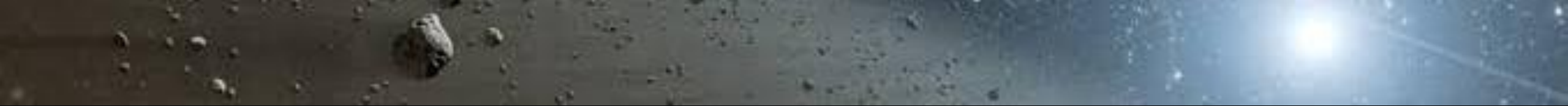
coined the word "**asteroid**" (meaning "starlike") because these objects only appear as points of light in a telescope

Piazzi

preferred the term «**planetoid**» over asteroid because these bodies resemble planets more than stars!

Our Community

No clear definition !!!



What is an Asteroid?

Based on

RESOLUTION B5

IAU we know what is
a Planet and a Dwarf
planet

A **planet** is a celestial body that : (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) **has cleared the neighbourhood** around its orbit.

A "**dwarf planet**" is a celestial body that: (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, (c) has **not cleared the neighbourhood** around its orbit, and (d) is not a satellite.

All other objects, except satellites, orbiting the Sun shall be referred to collectively as "**Small Solar System Bodies**"

These currently include most of the Solar System **asteroids**, most Trans-Neptunian Objects, comets, and other small bodies.

Asteroids fall in the generic definition of Small Solar System Bodies

What we «usually» consider Asteroids

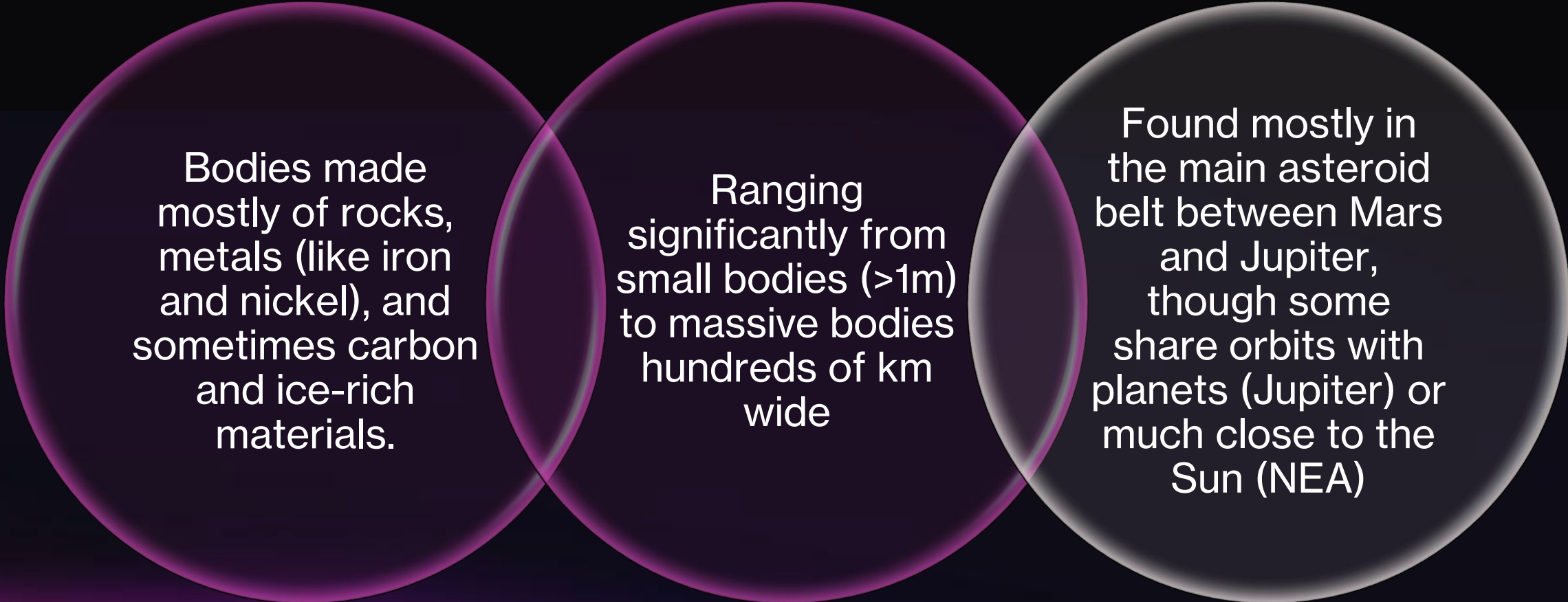


Bodies made mostly of rocks, metals (like iron and nickel), and sometimes carbon and ice-rich materials.

Ranging significantly from small bodies (>1m) to massive bodies hundreds of km wide

Found mostly in the main asteroid belt between Mars and Jupiter, though some share orbits with planets (Jupiter) or much close to the Sun (NEA)

What we «usually» consider Asteroids



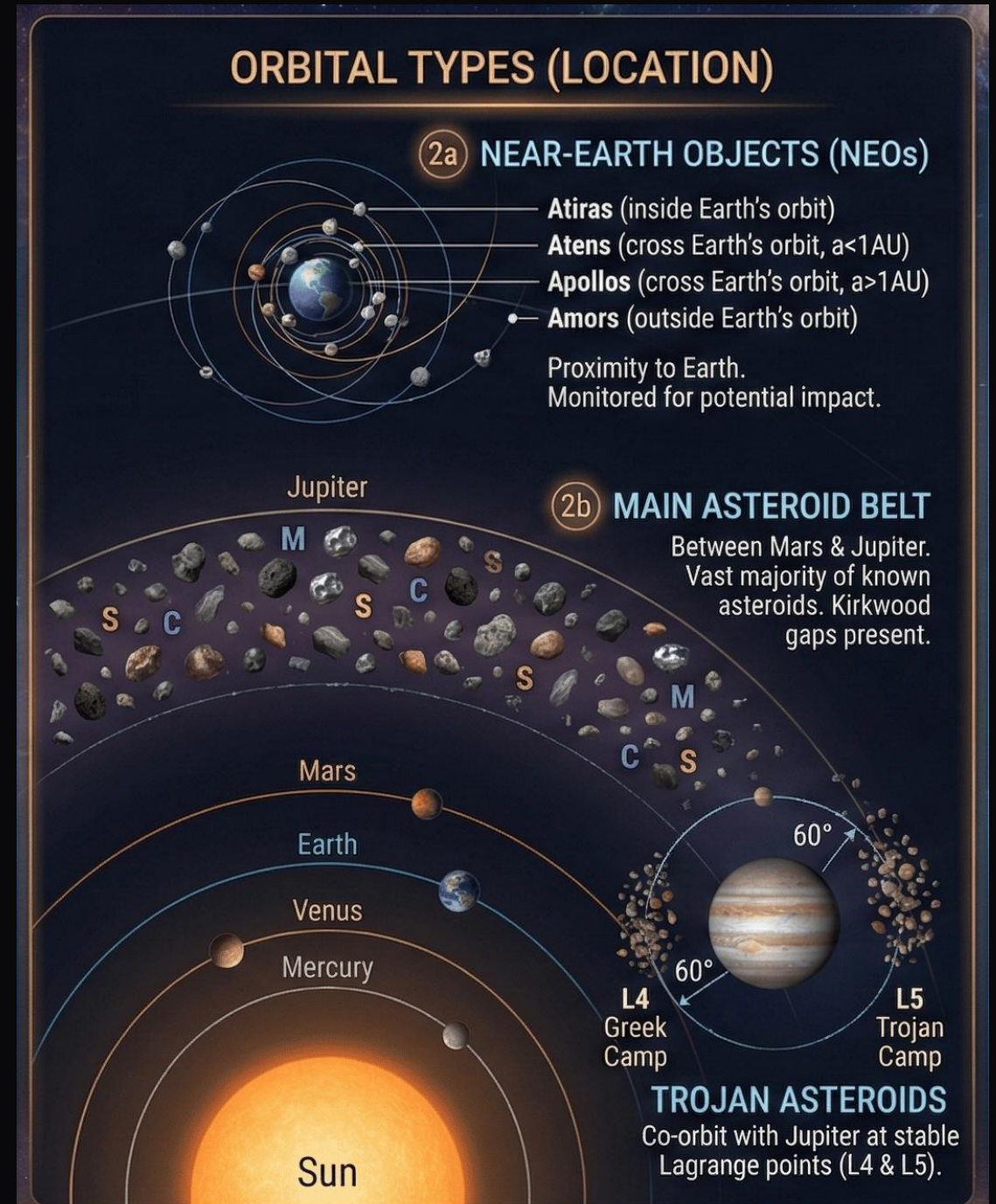
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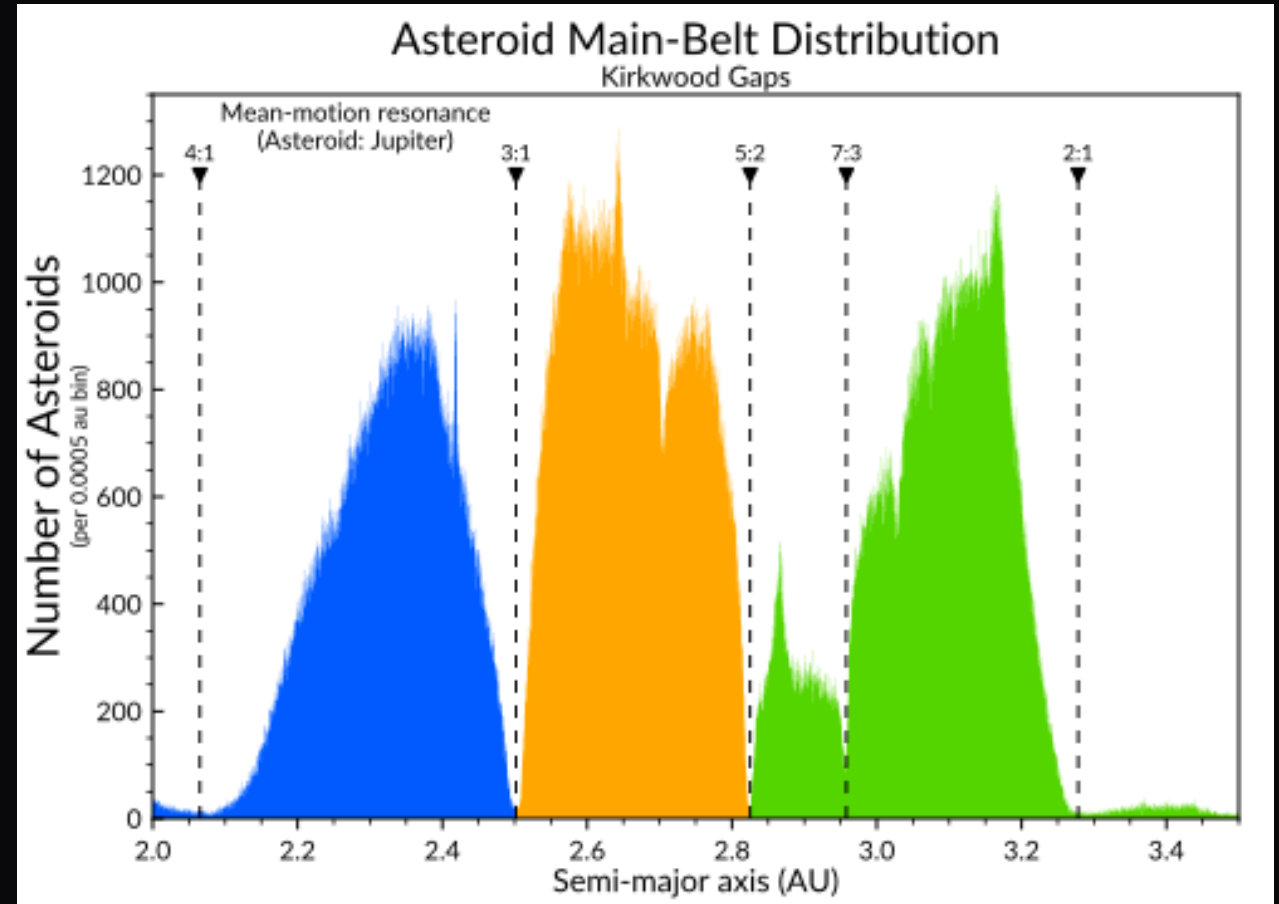
Where Do They Live?

- **The Main Asteroid Belt:** The vast majority orbit the Sun between **Mars and Jupiter**.
- **Trojans:** Asteroids that share an orbit with a larger planet (mostly Jupiter) but don't collide because they sit in stable gravitational points (Lagrange points).
- **Near-Earth Asteroids (NEAs):** Asteroids whose orbits bring them close to Earth's orbit
- **Vulcanoids:** A theoretical group of asteroids hypothesized to stable-orbit inside Mercury's orbit, though none have been definitively found yet

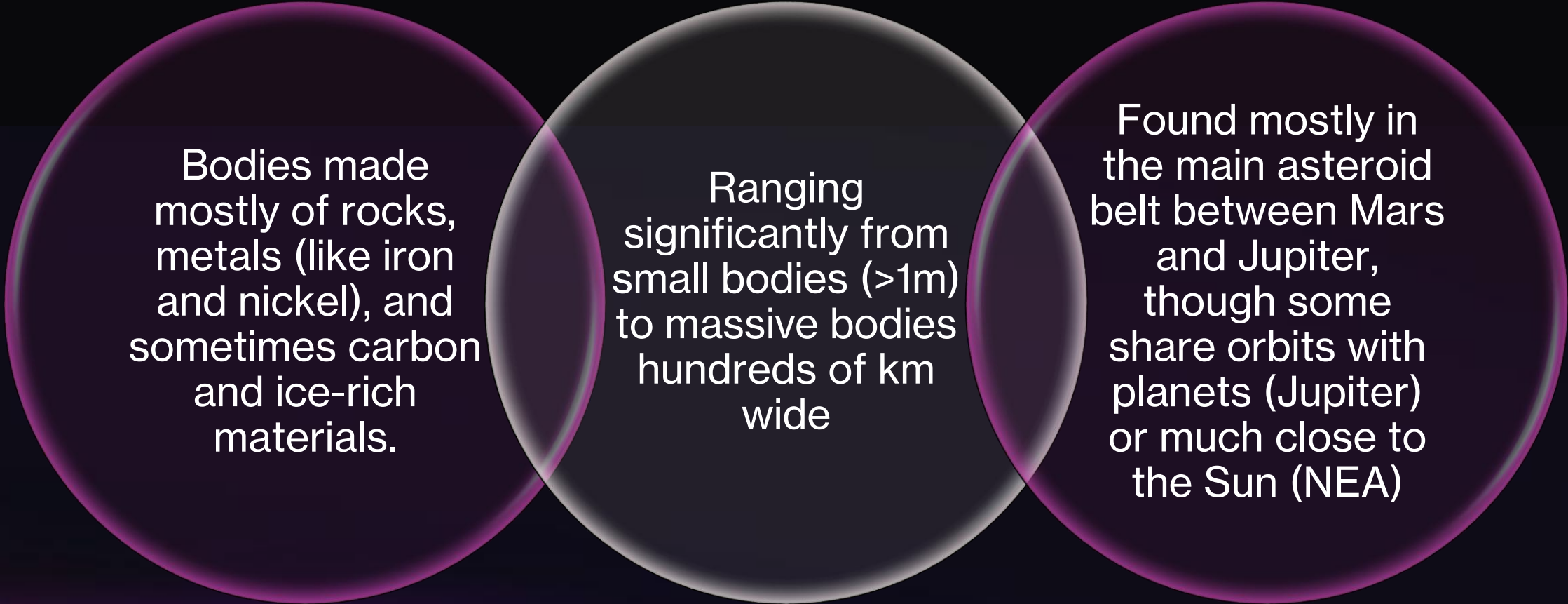


Structure of the main belt with the Kirkwood gaps

- **Orbital Resonance:** The gaps match locations where an asteroid's orbital period forms a simple integer fraction of Jupiter's orbit.
- **Gravitational Tugs:** In a resonance, an asteroid orbits the Sun several times for every single orbit of Jupiter.
- **Destabilized Orbits:** Because they meet at the same point repeatedly, Jupiter's gravity gives these asteroids regular tugs. This process changes their paths and clears them out of those resonant orbits.
- **Source of Near-Earth Objects:** Gravitational shifts near the gaps can push asteroids into new paths, making these zones major contributors to near-Earth asteroids.



What we «usually» consider Asteroids



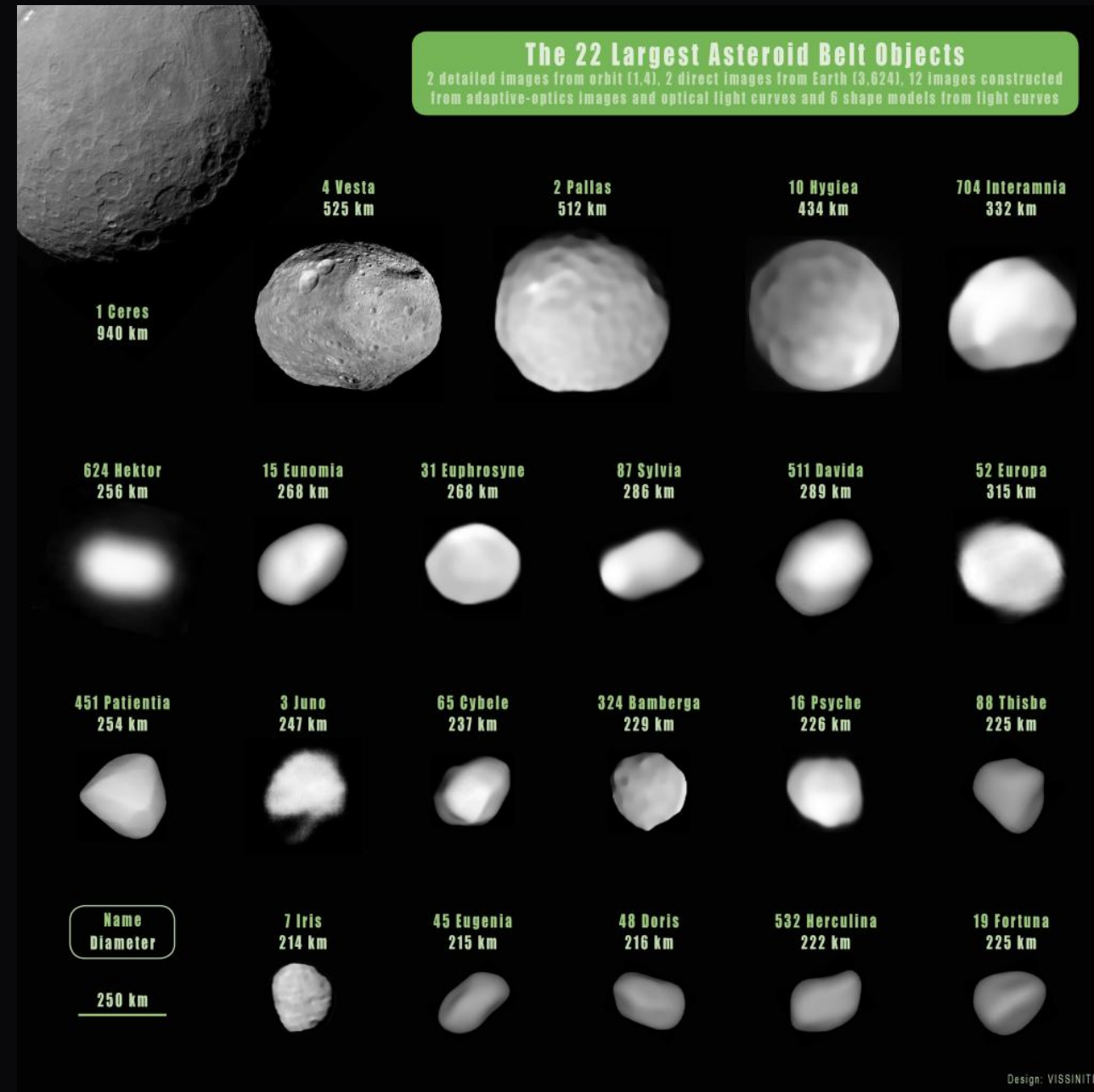
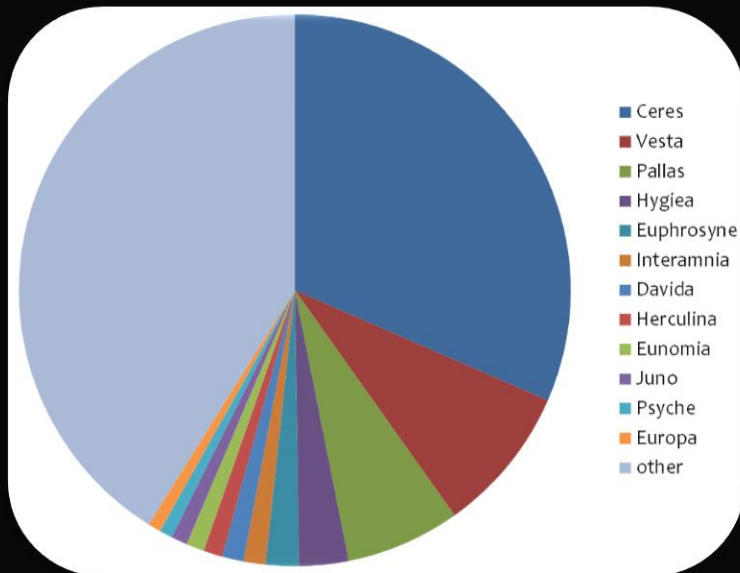
Bodies made mostly of rocks, metals (like iron and nickel), and sometimes carbon and ice-rich materials.

Ranging significantly from small bodies (>1m) to massive bodies hundreds of km wide

Found mostly in the main asteroid belt between Mars and Jupiter, though some share orbits with planets (Jupiter) or much close to the Sun (NEA)

Size

- Main Belt total mass is estimated to be 3% that of the Moon
- Few asteroids have diameter >200 km
- Most have much smaller sizes
- Most of the main belt mass is in few bodies , with about 60% contained in the four largest asteroids: Ceres, Vesta, Pallas, and Hygiea



Asteroids Visited by Spacecraft

Official Name
Spectral Type Diameter Period Semi-Major Axis
Mission, Year Visited & Space Agency

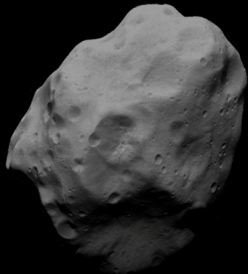
243 Ida & Dactyl
S | 31 km, 1.4 km | 4.84 y | 2.86 AU
Galileo 1993, NASA



253 Mathilde
Cb | 53 km | 4.31 y | 2.65 AU
NEAR Shoemaker 1997, NASA



21 Lutetia
M | 98 km | 3.80 y | 2.44 AU
Rosetta 2010, ESA ★



5535 Annefrank
S | 4.5 km | 3.29 y | 2.21 AU
Stardust 2002, NASA



2867 Šteins
E | 5.1 km | 3.63 y | 2.36 AU
Rosetta 2008, ESA



152830 Dinkinesh & Selam
Sq | 0.79 km | 3.24 y | 2.19 AU
Lucy 2023, NASA



25143 Itokawa
Sqw | 0.32 km | 1.52 y | 1.32 AU
Hayabusa 2005-2007, JAXA



1 Ceres
Cgh | 945 km | 4.61 y | 2.78 AU
Dawn 2015-2018, ESA ★



4179 Toutatis
Sq | 2.5 km | 4.03 y | 2.53 AU
Chang'e 2 2012, CNSA



9969 Braille
Q | 1.6 km | 3.58 y | 2.34 AU
Deep Space 1 1999, NASA



65803 Didymos & Dimorphos
Sq/Xk | 0.87 km, 0.16 km | 2.11 y | 1.64 AU
DART 2022, NASA



162173 Ryugu
Cg | 0.89 km | 1.30 y | 1.19 AU
Hayabusa2 2018-2019, JAXA



951 Gaspra
Sa | 12 km | 3.29 y | 2.21 AU
Galileo 1991, NASA ★



4 Vesta
V | 525 km | 3.63 y | 2.36 AU
Dawn 2011-2012, ESA ★



433 Eros
Sqw | 17km | 1.76 y | 1.46 AU
NEAR Shoemaker 1998-2001, NASA



101955 Bennu
B | 0.53 km | 1.20 y | 1.13 AU
OSIRIS-REx 2019-2021, NASA



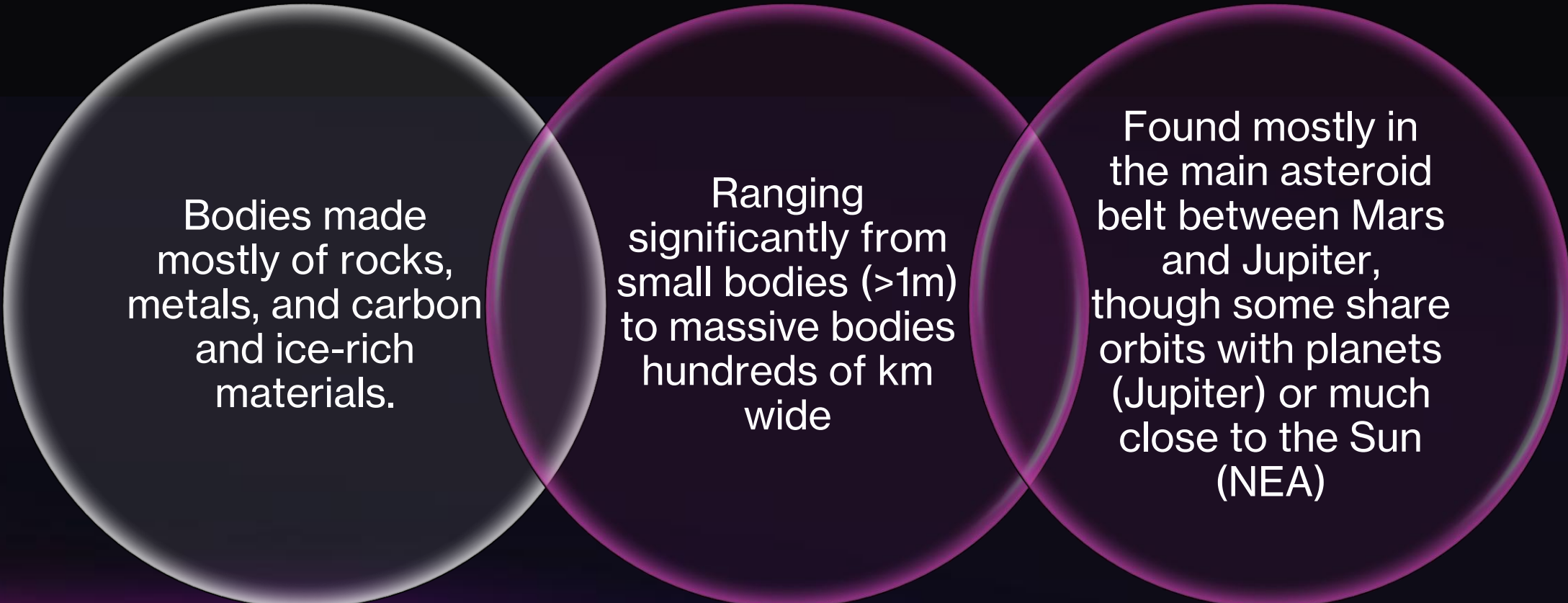
Shapes and size

- Asteroids exhibit a wide range of shapes, from nearly spherical to highly irregular.
- Only few have shape of homogeneous hydrostatic equilibria (Maclaurin and Jacobi ellipsoids)
- Most of them deviate from figures of equilibrium and have been largely affected by the evolution of the solar system in different ways:
 - Irregular shape
 - Diamond-like
 - Binary asteroids and satellites
 - Rubble-pile



VERY FEW have homogeneous hydrostatic equilibria shapes and large size. They are those less affected by the evolution after their formation

What we «usually» consider Asteroids



Bodies made
mostly of rocks,
metals, and carbon
and ice-rich
materials.

Ranging
significantly from
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to massive bodies
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wide

Found mostly in
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belt between Mars
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Main Types of Asteroids

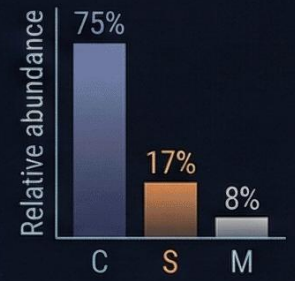
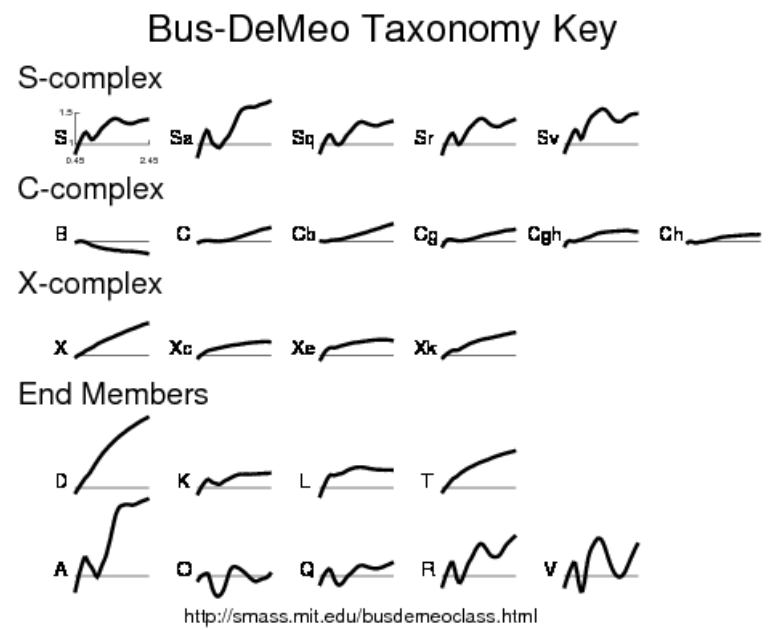
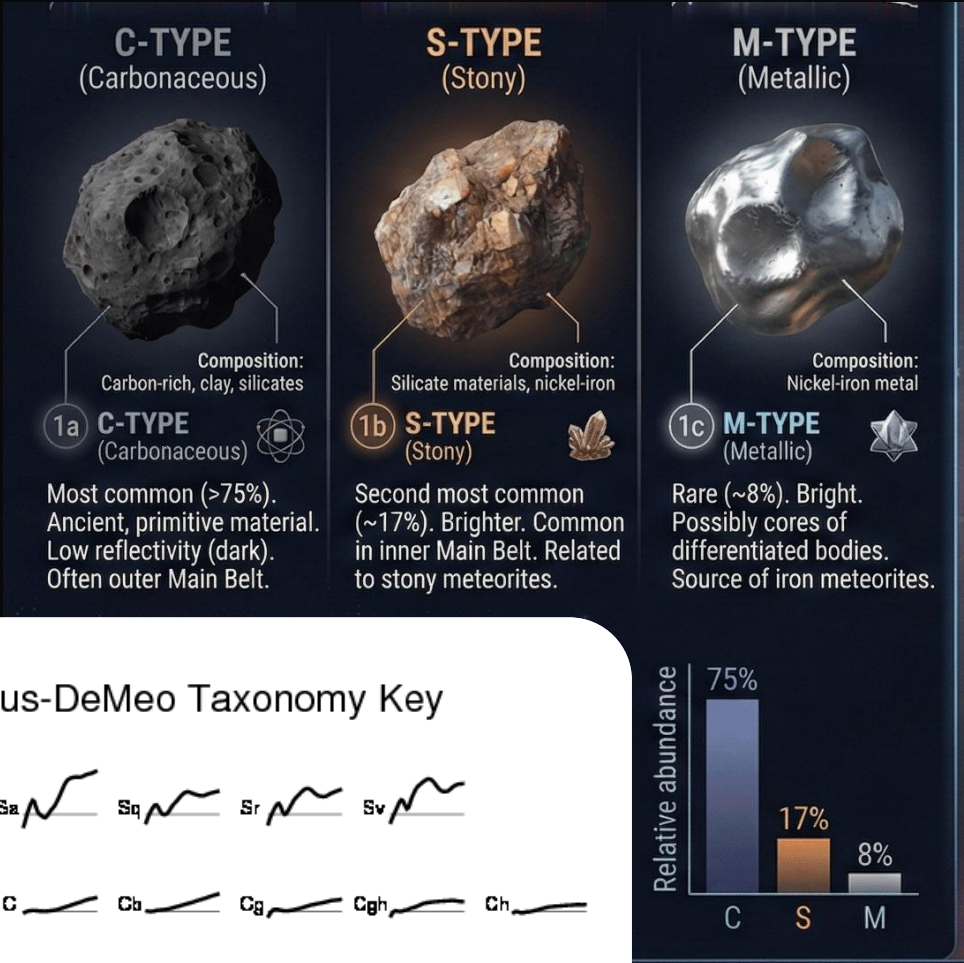
Asteroids are broadly classified into three composition groups:

C-type (Carbonaceous): Greyish in color, most common type, rich in carbon, organic molecules, and water.

S-type (Stony/Silicate): Greenish to reddish, made of silicate materials and nickel-iron; dominate the inner asteroid belt.

M-type or X (Metallic or ???): Reddish, mostly made of pure nickel-iron; could be the shattered cores of ancient proto-planets or ???

The classification is based on the spectra of the bodies and the association with meteorites and terrestrial analogs



Meteorites Groups and Class

Dyar et al, <https://doi.org/10.1016/j.icarus.2023.115718> Received 19 April 2023; Received in revised form



HED & CC

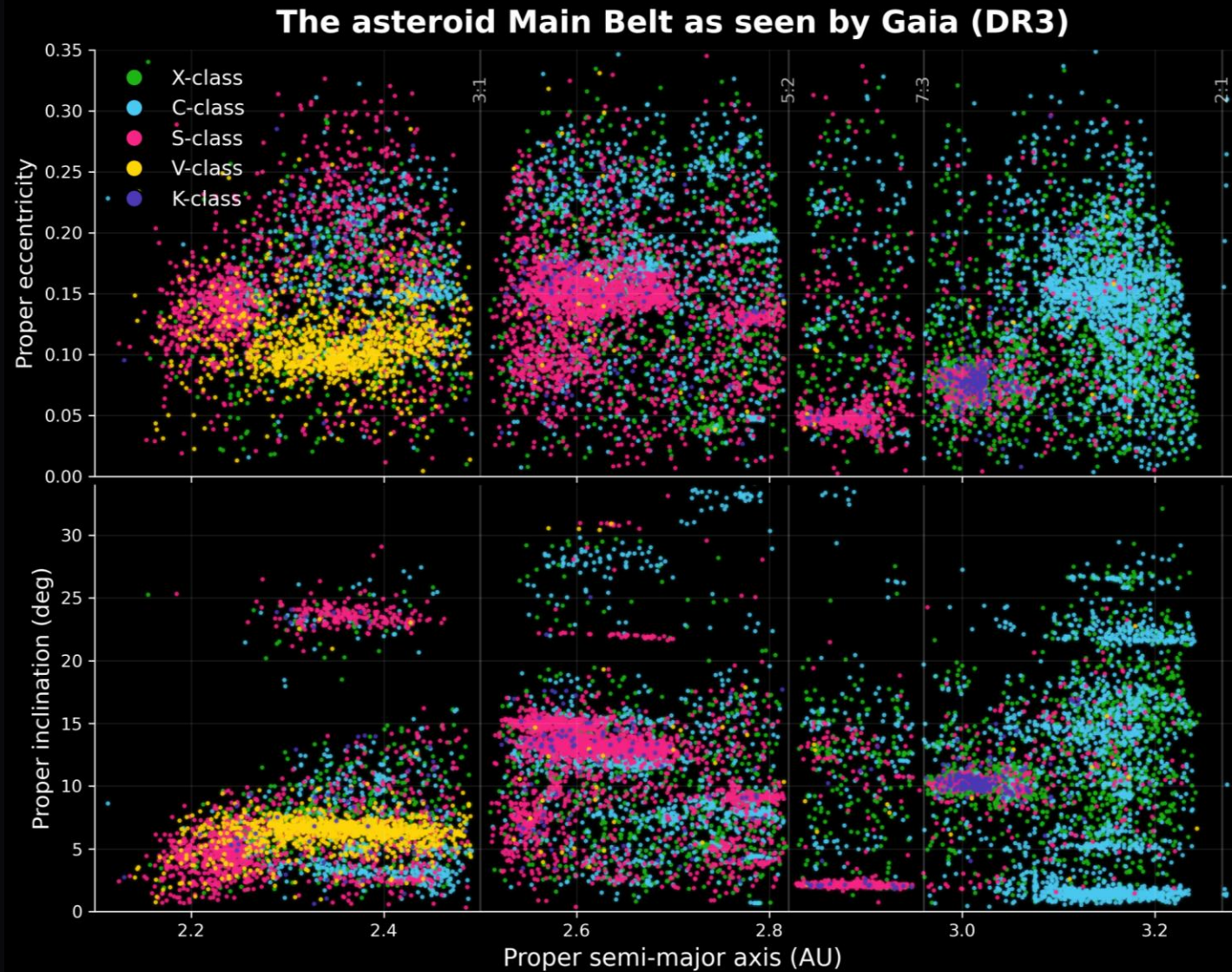
Table 1

Derived classes based on meteorite spectra used to predict asteroid spectra.

Group name	Meteorite class	Major mineral components	Spectral similarity
CM/C2/CR	CM	Fe-Mg serpentines, clumps of tochilinite/cronstedtite, sulfides, magnetite. Chondrules contain olivine, low-Ca clinopyroxene, and isotropic glassy mesostases. Abundant hydrated minerals and abundant fine-grained matrix; chondrules are present; sulfides are Ni-bearing	Relatively featureless spectra lacking major olivine and pyroxene features
	C2	Olivine, low-Ca pyroxene, metallic FeNi, troilite, FeNi sulfides, Fe—Mg serpentines, and magnetite.	
	CR	Olivine, low-Ca pyroxene and pigeonite, feldspathic glass, metallic FeNi, and minor sulfides, and CAIs*	
CO/CV	CO	Olivine, low-Ca pyroxene, glass, metallic FeNi, troilite, anorthite, and CAIs*	Relatively weak absorption features due to olivine and pyroxene
	CV	Olivine, low-Ca pyroxene, anorthite, diopside, fassaite, magnetite, pentlandite, and CAIs*	
	CK	Olivine, low-Ca pyroxene, anorthite, diopside, fassaite, magnetite, pentlandite, and CAIs*	
CK/R/brachinites	R	Abundant olivine, less abundant in low-Ca pyroxene. Can also contain pigeonite, augite, diopside, albite or oligoclase, and spinel.	Olivine-dominated absorption features
	Brachinites	Olivine-dominated, Ca-pyroxene, chromite, plagioclase, Fe-sulfides	
	H	olivine, low-Ca pyroxene, pigeonite, FeNi metal, troilite. Approximately equal abundances of olivine and pyroxene. Less Fe-rich olivine and low-Ca pyroxene than L chondrites.	
H/L/LL/URE	L	olivine, low-Ca pyroxene, pigeonite, FeNi metal, troilite. Less Fe-rich olivine and low-Ca pyroxene than LL chondrites. Olivine more abundant than pyroxenes. FeNi metal less abundant than H chondrites.	Absorption features due to olivine and pyroxene representing a continuum between varying amounts of olivine and pyroxene
	LL	olivine, low-Ca pyroxene, pigeonite, FeNi metal, troilite. Olivine much more abundant than pyroxenes. FeNi metal less abundant than L chondrites.	
	Ureillite	Carbon-bearing, olivine-pyroxene achondrites. Typically olivine is more abundant than pyroxene.	
EH/EL/AUB	EH	Low-Ca pyroxene, forsterite, calcic pyroxene, plagioclase, FeNi metal, sulfides	Featureless spectra due to being dominated by enstatite and FeNi metal
	EL	Low-Ca pyroxene, forsterite, calcic pyroxene, plagioclase, FeNi metal, sulfides	
	Aubrites	Enstatite-dominated, albite, diopside, forsterite, sulfides	
ACA/LOD	Acapulcoites	Orthopyroxene, olivine, Cr-diopside, sodic plagioclase, FeNi metal, troilite.	Orthopyroxene-dominated spectra
	Lodranites	Orthopyroxene, olivine, Cr-diopside, sodic plagioclase, FeNi metal, troilite. Coarser grained than acapulcoites.	
	IAB	FeNi metal, tetrataenite, troilite, daubréelite, schreibersite	
IAB/IIAB	IIAB	FeNi metal, kamacite, martensite, taenite, tetrataenite, troilite, daubréelite, schreibersite, cohenite, haxonite, edscottite, graphite, diamond, carlsbergite, chromite, fusion-crust magnetite, merrillite, chlorapatite	Featureless, slightly red spectra due to the abundance of FeNi and absence of silicates
		Igneous volcanic monomict rocks rich in pyroxene (pigeonite) and calcic plagioclase	
	Eucrites	Orthopyroxenite monomict rocks with <10% plagioclase and minor chromite, olivine, silica, pigeonite, and augite.	
EUC/DIO/HOW	Diogenites	Polymict breccias composed predominantly of eucritic and diogenitic clasts.	Continuous range of absorption features due to varying amounts of pyroxene
	Howardites		

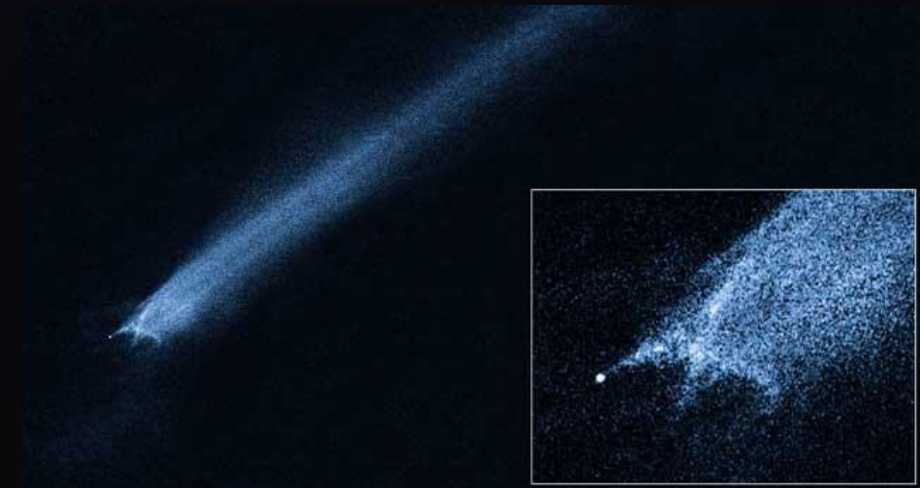
The asteroids classification is based on the spectra of the bodies and the association with meteorites and terrestrial analogs

Distribution of the types in the main belt based on Gaia data



Main belt comets/active asteroids

- Main-belt comets are icy objects found in the asteroid belt, with asteroid-like orbits – rather than cometary orbits.
- They show comet-like features, like tails extending away from the Sun.
- Main-belt comets belong to a larger group of objects known as active asteroids. This larger group includes objects whose clouds and tails are made of ejected dust produced after an impact or as they quickly rotate, rather than just those that eject dust due to vaporized ice.



Evolution

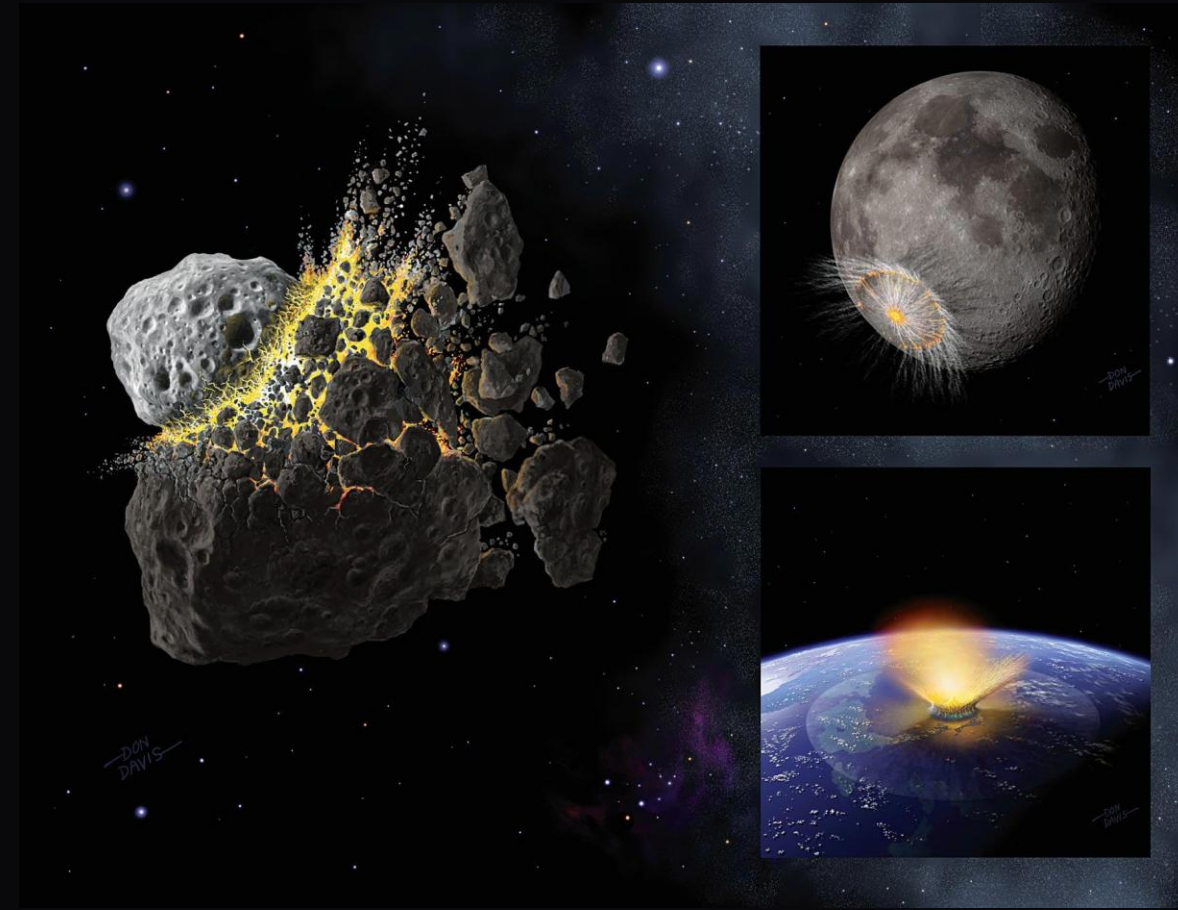
Thermophysical/geochemical

Collisional

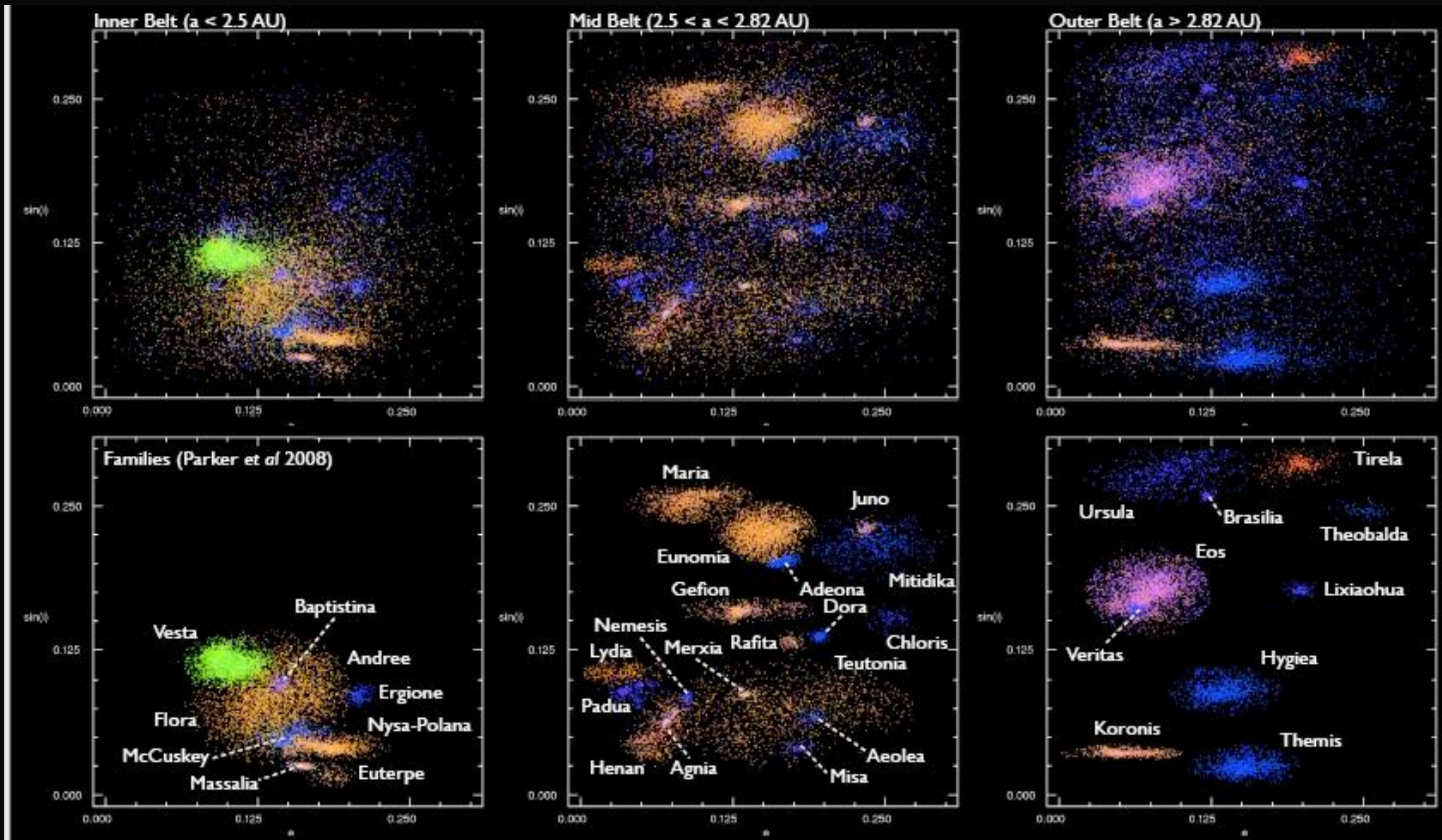
Collisional evolution

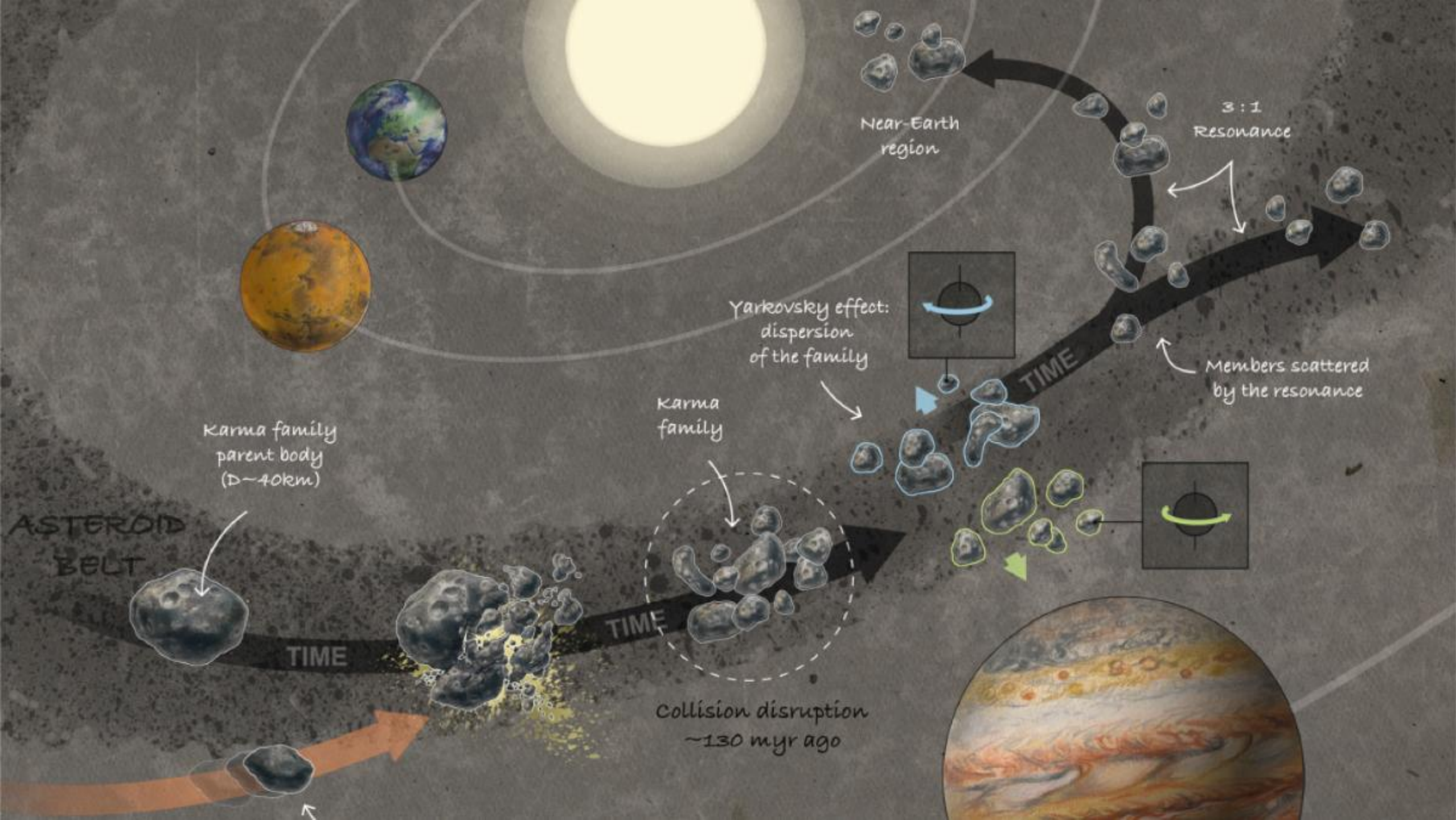
The collisional evolution is likely the most strong process that affected the bodies in the belt. The effects can be seen on:

- Shapes
- Mass
- Surface (craters, boulders, regolith, **exogenic materials**)
- Internal structure
- Asteroidal families



Asteroid families





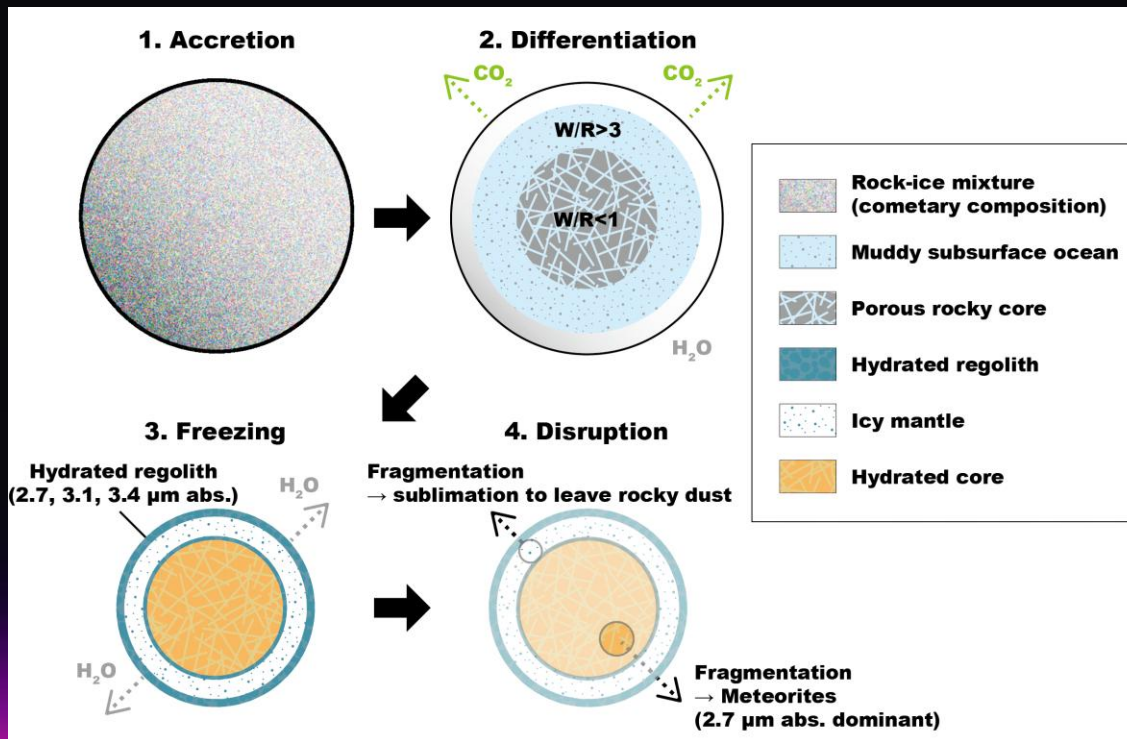
How families formed ?

- Created when a catastrophic collision shatters a larger parent body into smaller fragments that continue traveling along similar paths (fragments form clusters in proper elements)
- Families can be very old or quite recent and are constantly undergoing dynamical orbital evolution from thermal (Yarkovsky) forces and spin vector evolution from thermal (YORP) torques
- Almost all the large asteroids have families with the **exception of Ceres**
- **Vesta has two families**

Most of the asteroids are fragments and only very few remained almost intact from their formation: the clearest examples are Ceres and Vesta

Thermal evolution

Schematic views of the internal evolution of an asteroidal body



Different Asteroid & Meteorite Types

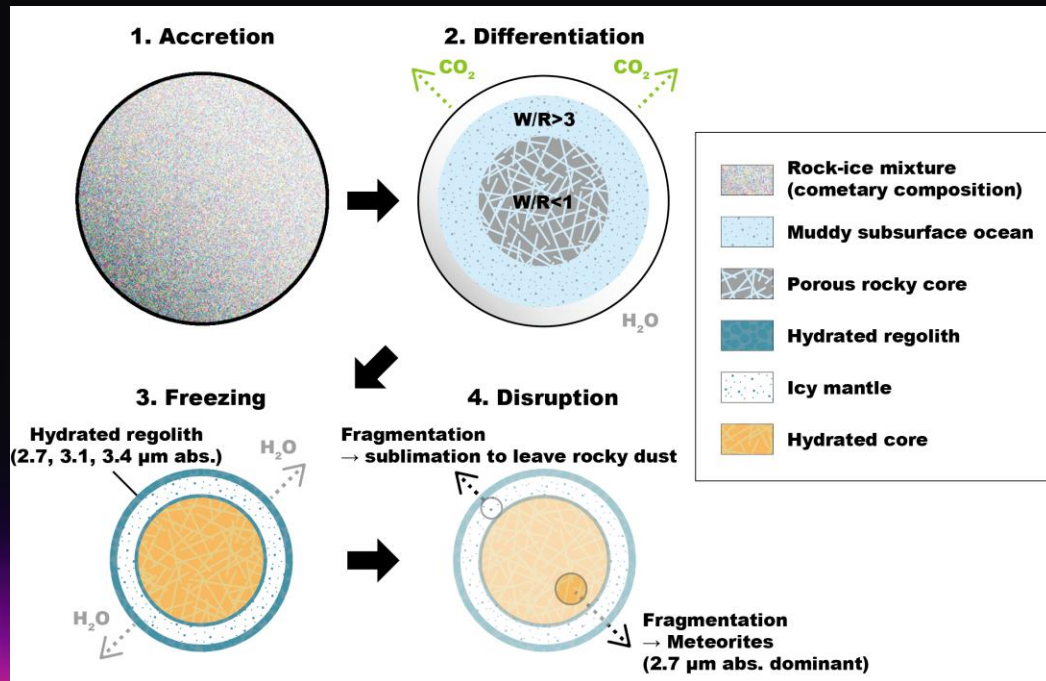
Source: Smithsonian Museum of Natural History http://www.mnh.si.edu/earth/text/5_1_4_0.html



Thermal evolution

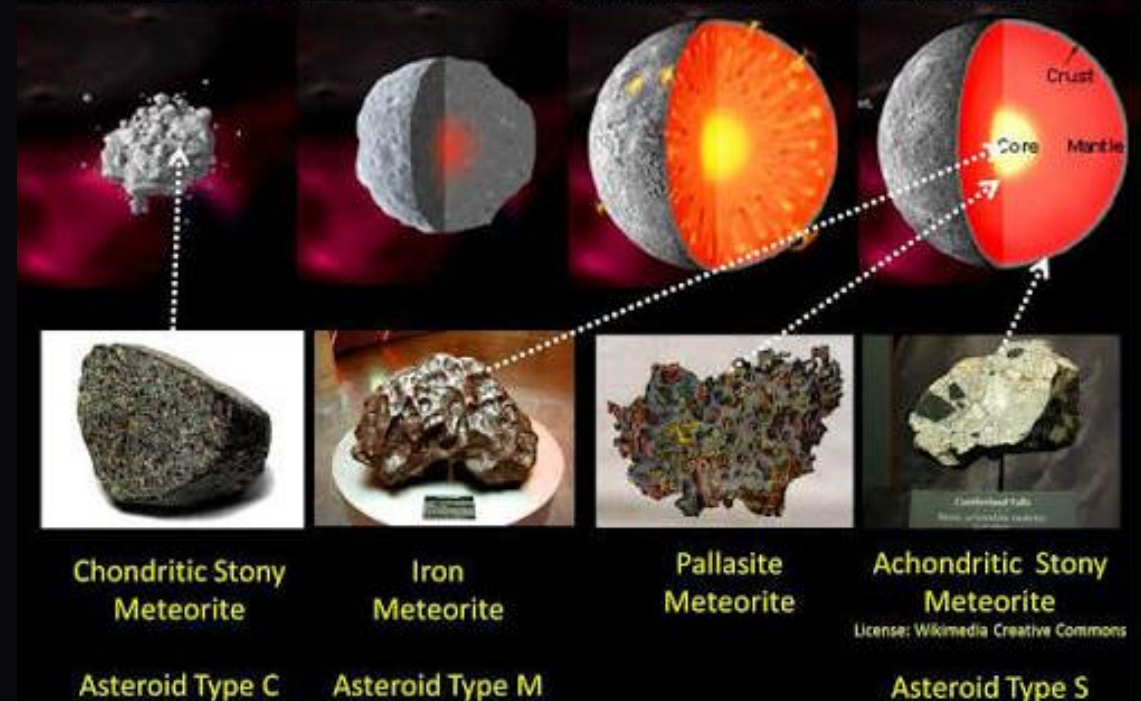
Schematic views of the internal evolution of an asteroidal body

CERES



Different Asteroid & Meteorite Types

Source: Smithsonian Museum of Natural History http://www.mnh.si.edu/earth/text/5_1_4_0.html



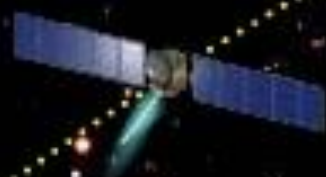
VESTA

Dawn mission at Vesta and Ceres



DAWN

Mars flyby



2007 Dawn
mission launch



Journey to the beginning of the Solar System with the Dawn mission. Travel with the Dawn spacecraft as it explores Vesta and Ceres:

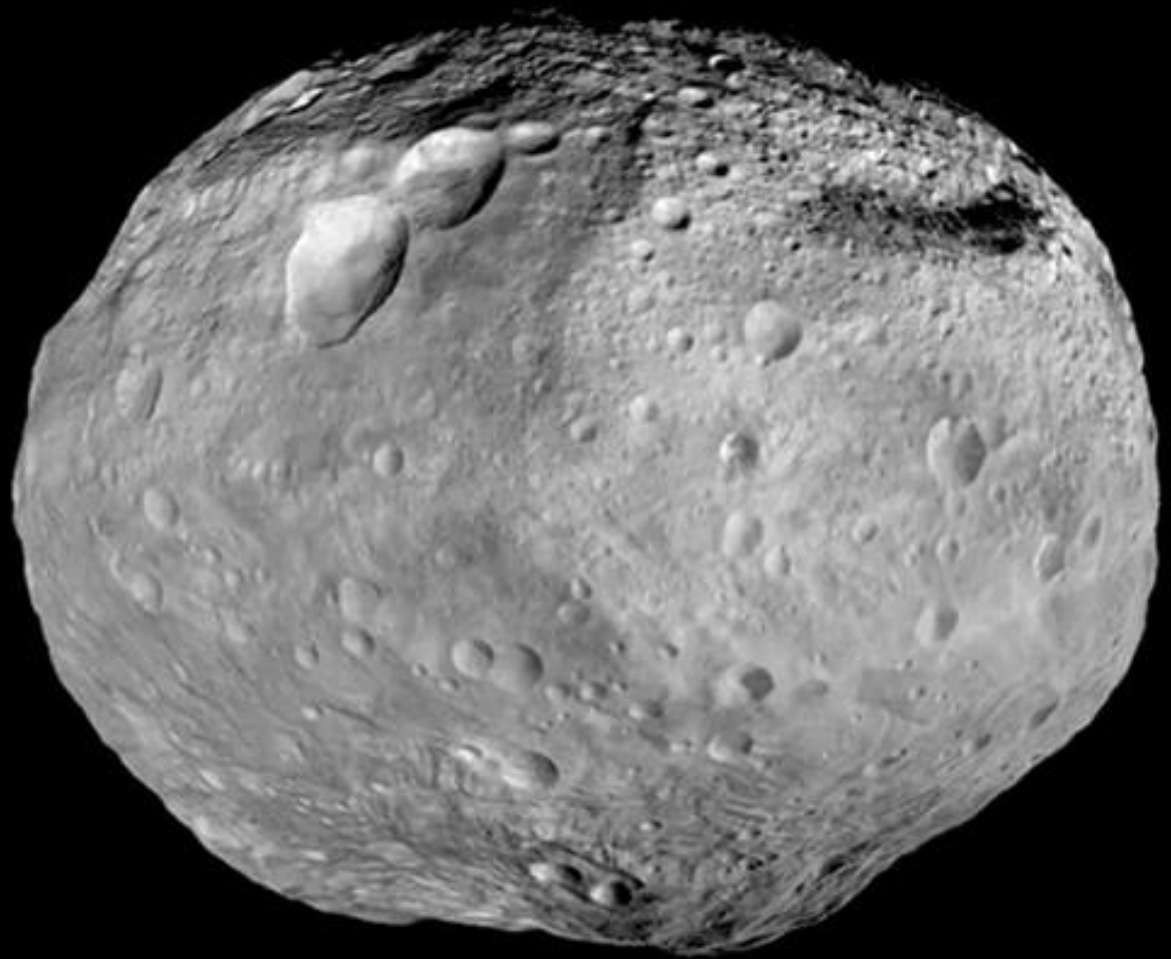
2011 Dawn
orbits Vesta



2015 Dawn
orbits Ceres



VESTA



Vesta

Vesta is a small planet formed at the dawn of the solar system

Vesta size about 500km -too small for gravitational differentiation

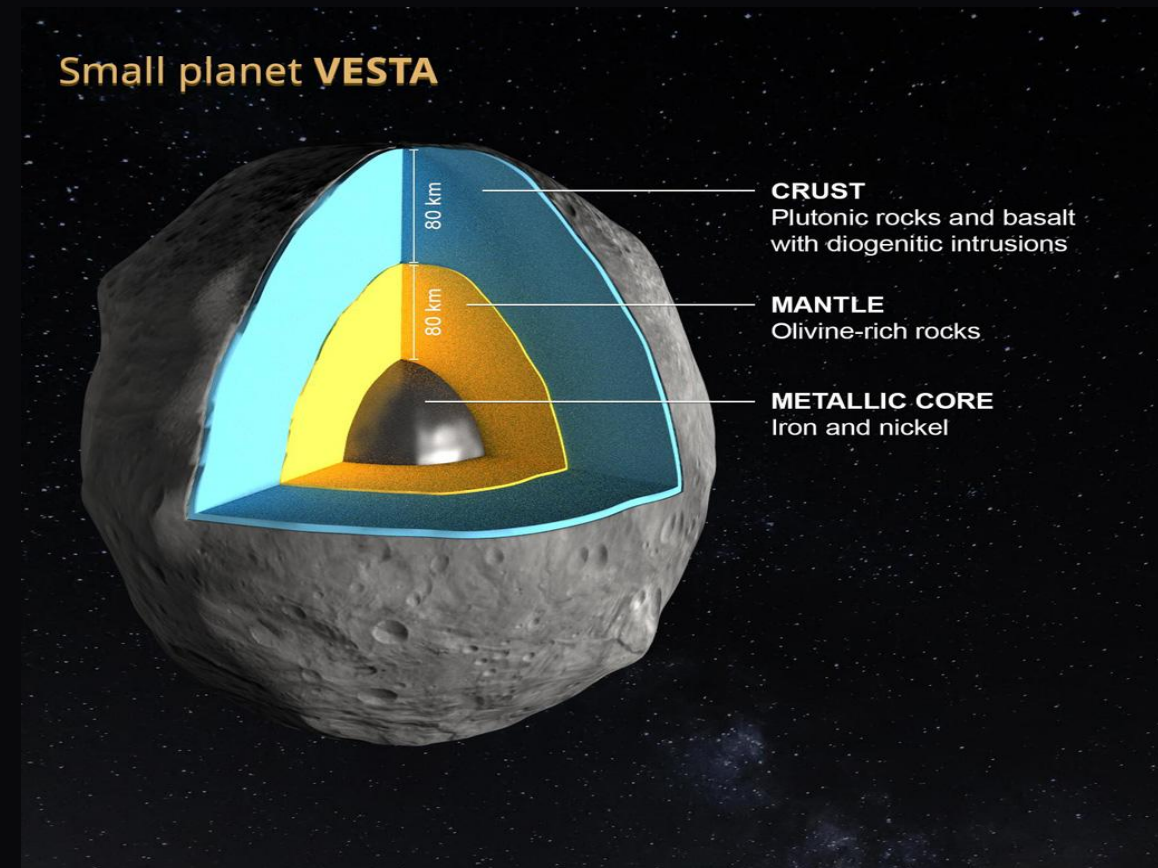
Radiogenic heating necessary to differentiate the body

Al^{26} is the main active element: energetic and short lived

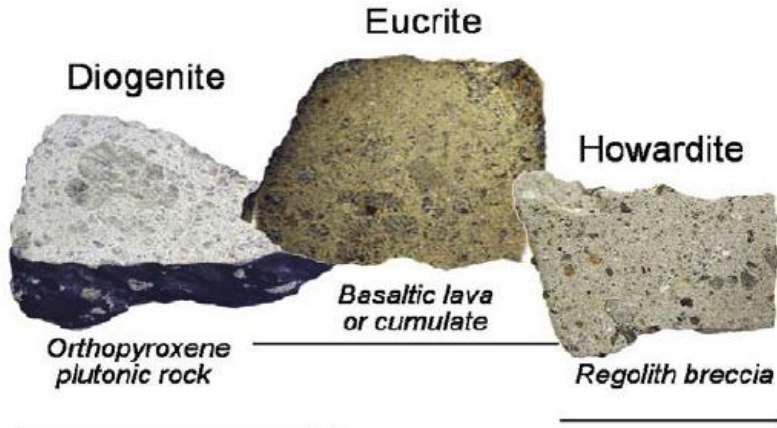
Differentiation very early during the primordial phases when the Al^{26} was abundant –supernova explosion

Russell et al., Science, Vol. 336, 6082, pp. 684- (2012).

Jaumann et al., Science, Vol. 336, 6082, pp. 687- (2012).



HED meteorites = Vesta samples



Chronology of the early Solar System from the radiometric ages of meteorites (Scott, 2007)

- CAls (the most ancient) appeared 4.568 Ga ago
- **HEDs appear to have formed about 2.5 Myr later when the AL26 was abundant**
- Meteorites associated with other parent bodies date to even more recent times

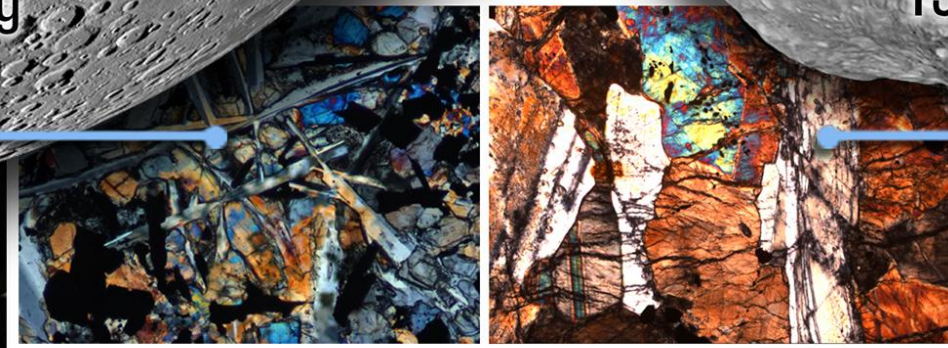
Dawn: sample return mission

The Moon

Lunar rocks:
448 kg

Vesta

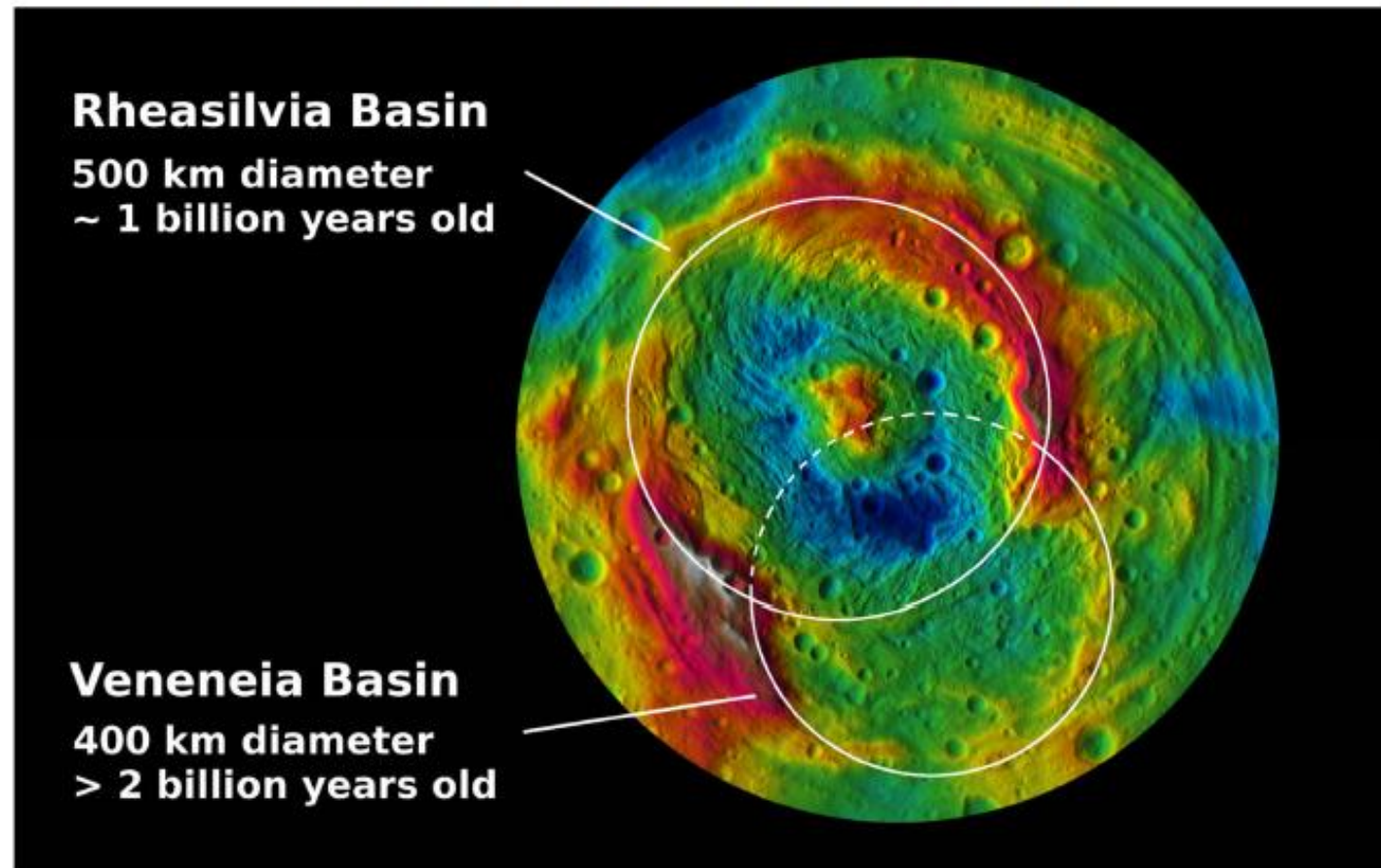
HED meteorites:
1332 kg



Vesta violent past

The basins are the impacts that formed the V-type asteroids, Vesta families and HED meteorites

The Ancient Basins

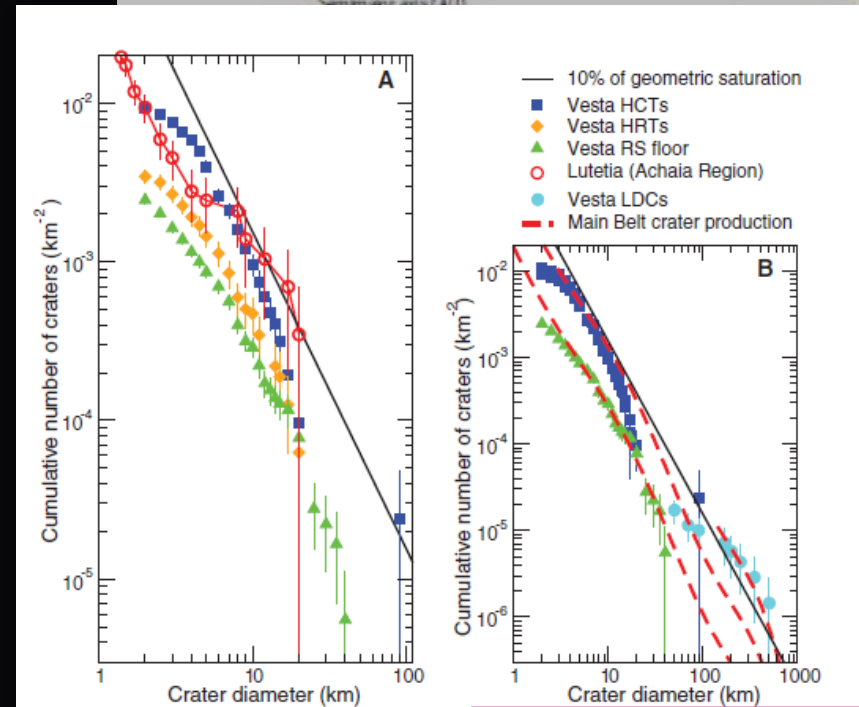
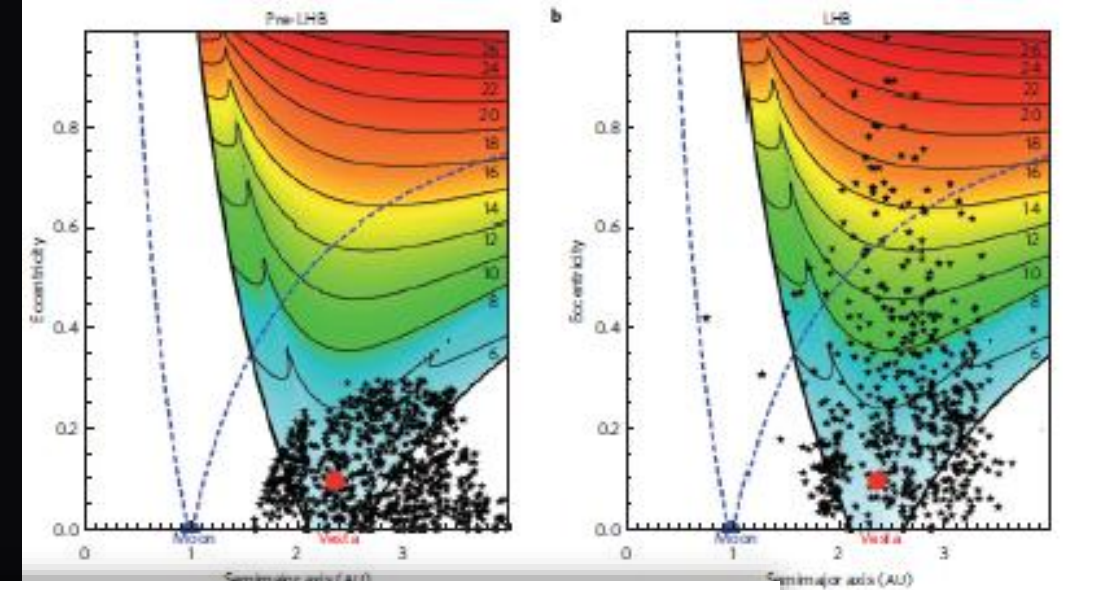


- A large surprise was the second large ancient basin Veneneia.

Collisional history of the solar system

Vesta surface talks about its past but not only: it is cratered with large basins (large as Vesta diameter) and smoothed regions.

The craters age, with the HED isotopic age, indicates that the «late heavy bombardment (LHB)» spanned all the internal solar system from the asteroid belt to terrestrial planets. LHB well fits the crater ages, dynamical models and HED ages.

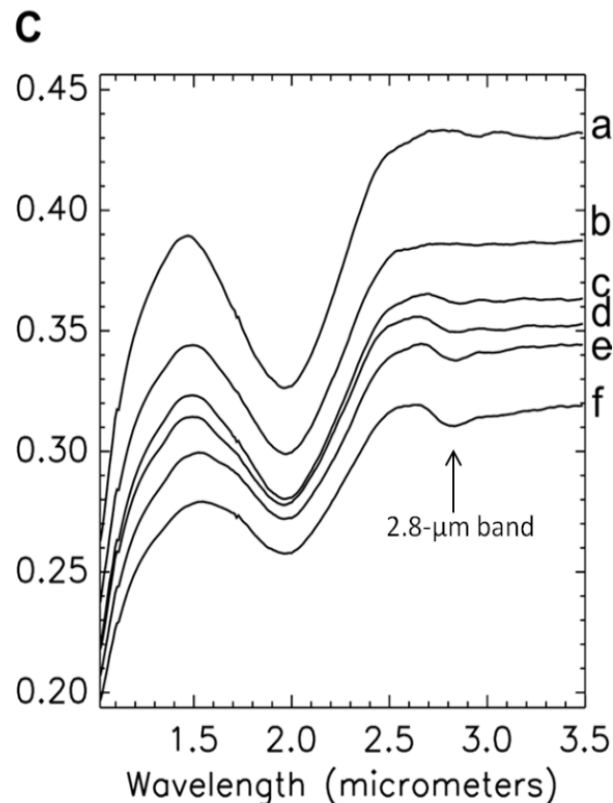


Exogenic hydrous infall on Vesta

OH band detected by VIR on Vesta

THE ASTROPHYSICAL JOURNAL LETTERS, 758:L36 (5pp), 2012 October 20
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DETECTION OF WIDESPREAD HYDRATED MATERIALS ON VESTA BY THE
VIR IMAGING SPECTROMETER ON BOARD THE DAWN MISSION



LETTER

doi:10.1038/nature11561

Dark material on Vesta from the infall of carbonaceous volatile-rich material

T. B. McCord¹, J.-Y. Li², J.-P. Combe¹, H. Y. McSween³, R. Jaumann⁴, V. Reddy^{5,6}, F. Tosi⁷, D. A. Williams⁸, D. T. Blewett⁹,
D. Turrini⁷, E. Palomba⁷, C. M. Pieters¹⁰, M. C. De Sanctis⁷, E. Ammannito⁷, M. T. Capria⁷, L. Le Corre⁵, A. Longobardo⁷, ...

The distribution of OH on Vesta indicates a primordial process different from that on the Moon.

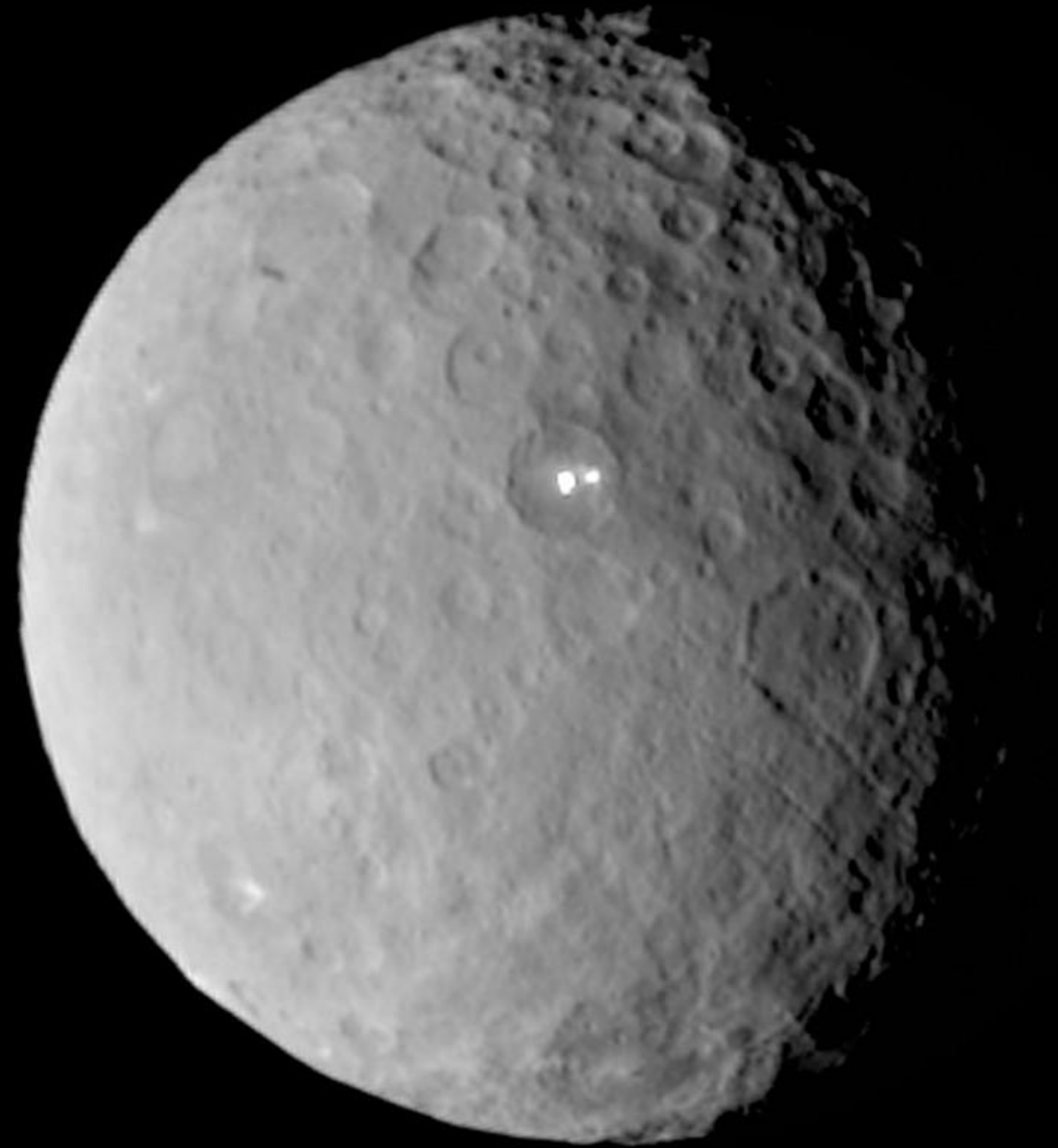
This same process may be responsible for the transport of water and organic materials both in the main belt and on the terrestrial planets.

VIR/Dawn data provided key observations for understanding the process of water transport on Earth.

De Sanctis et al., ApJ Lett., 758, L36, 2012
McCord et al., Nature, Vol. 491, 7422, pp. 83-86 (2012)

Ceres

The innermost dwarf
planet



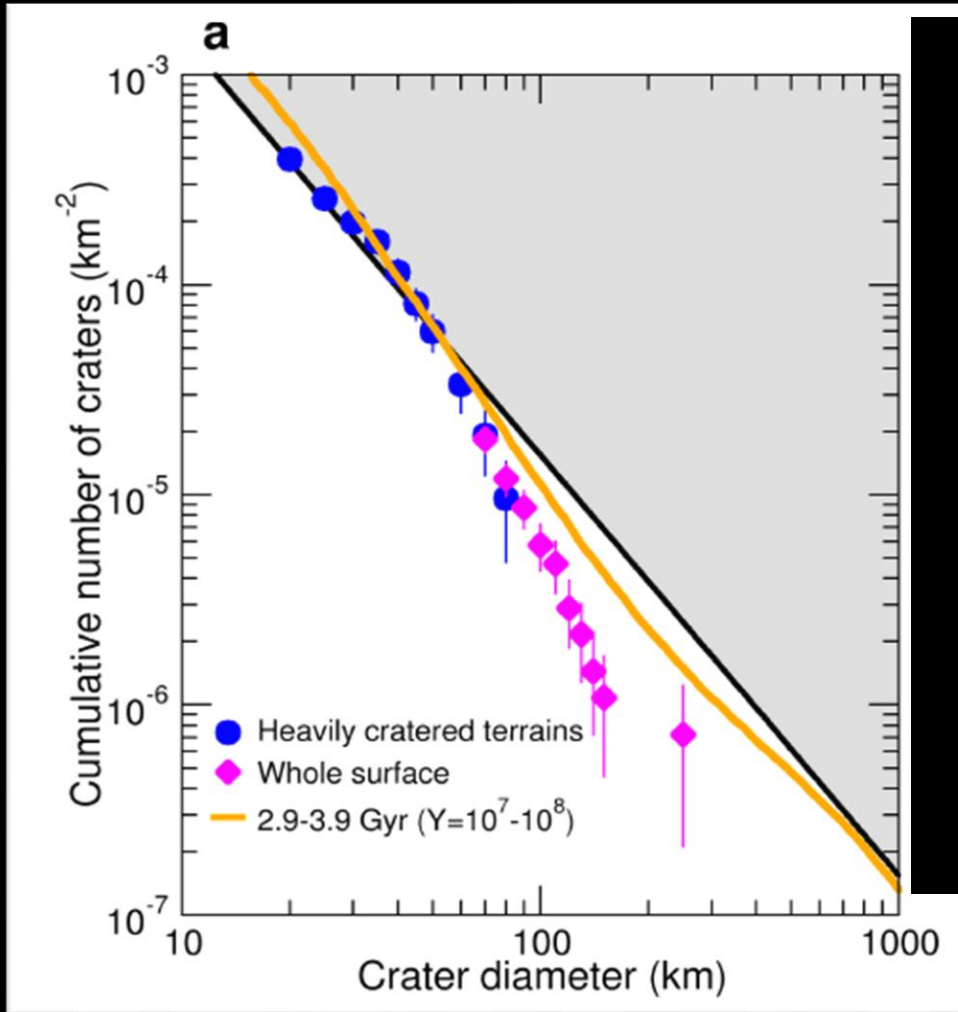
Ceres

A few striking features of Ceres



A highly cratered surface and 'bright spots' (Occator crater)

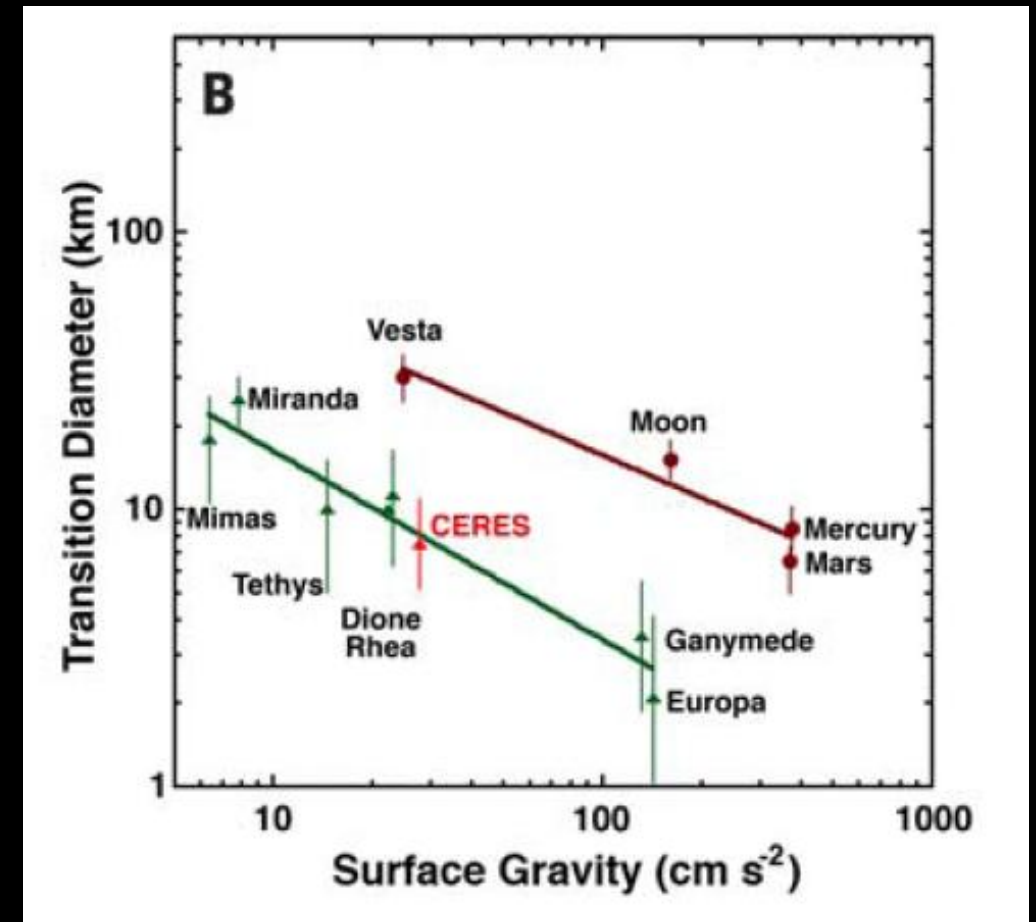
Rheology of the outer shell



(Marchi et al., *Nature Comm.*, 2016)

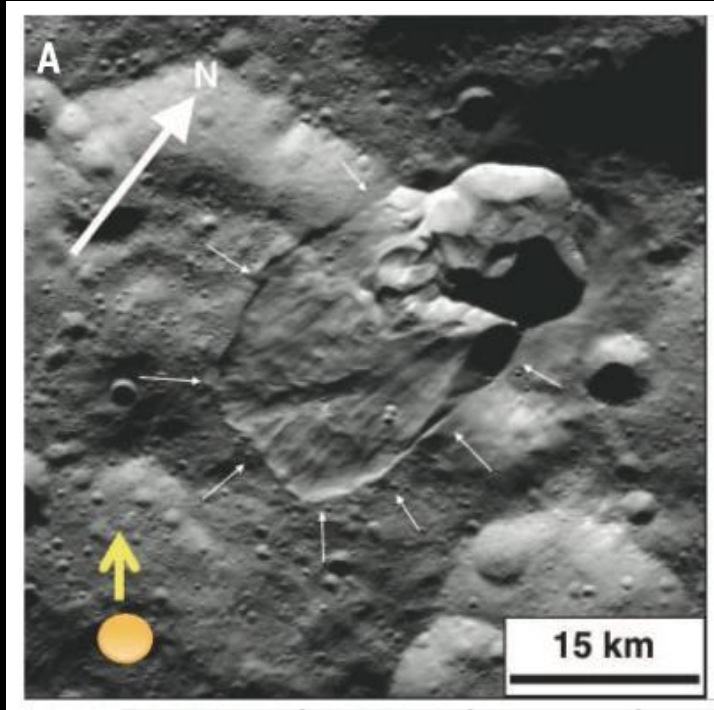
Largest craters are 'missing'

Transition compatible with those observed on « icy » bodies

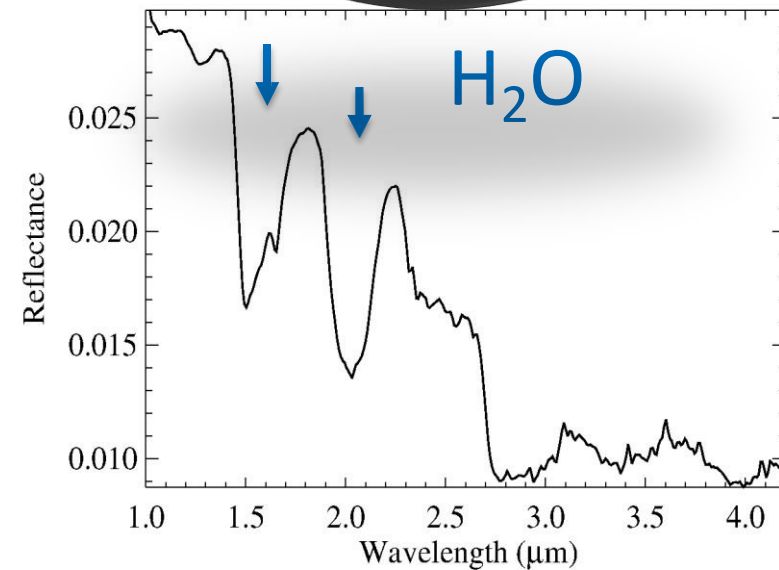
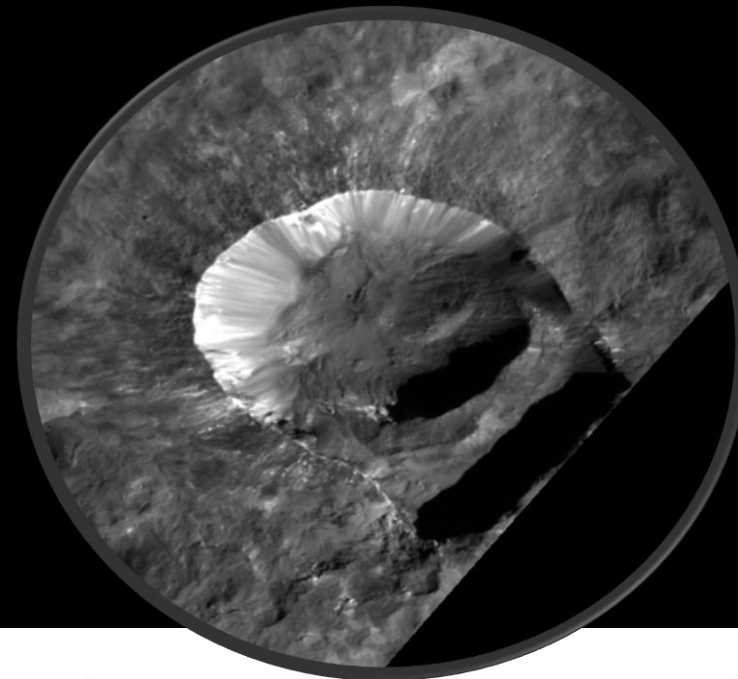


(Hiesinger et al., *Science*, 2016)

Evidence of water ice on the surface and subsurface

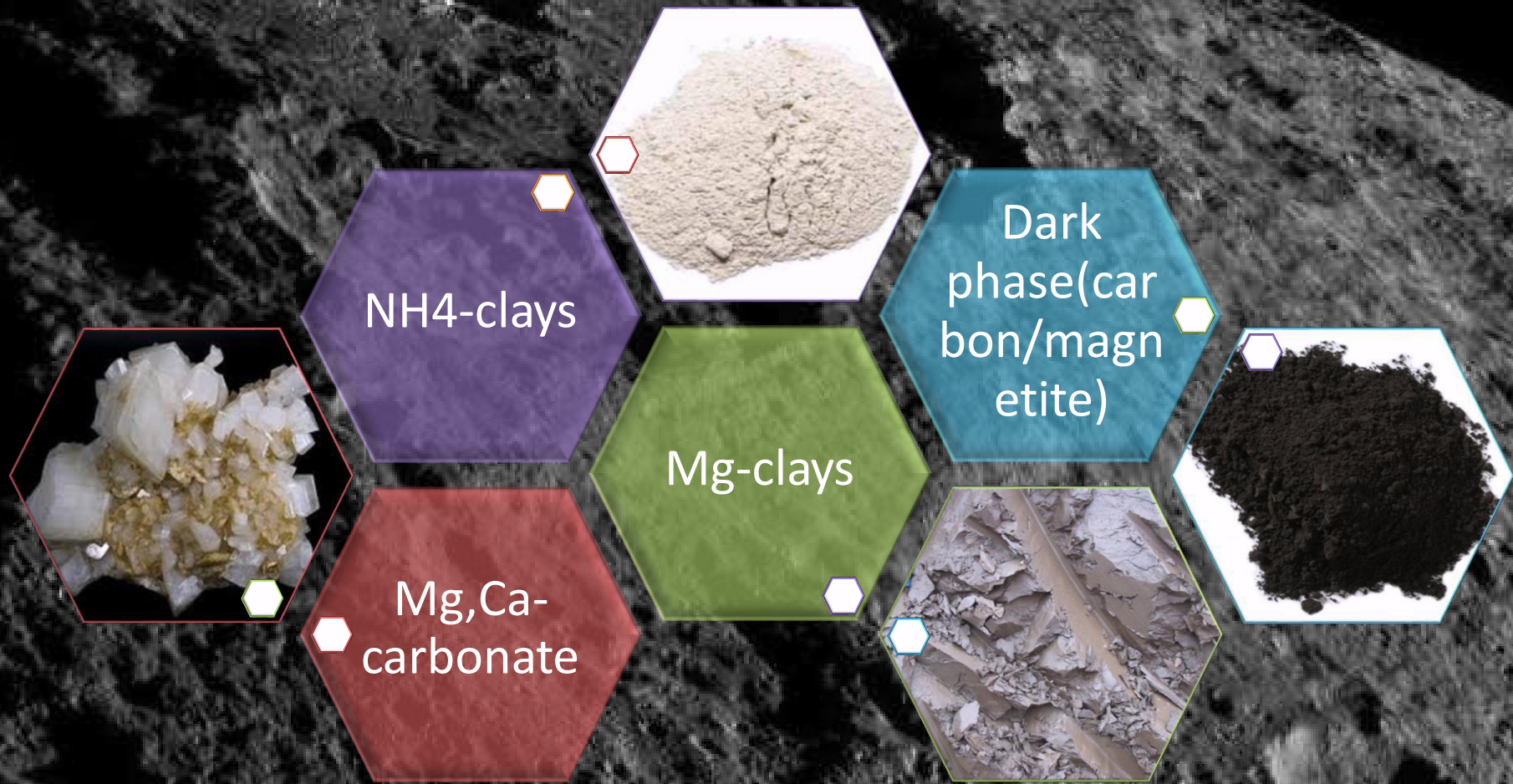


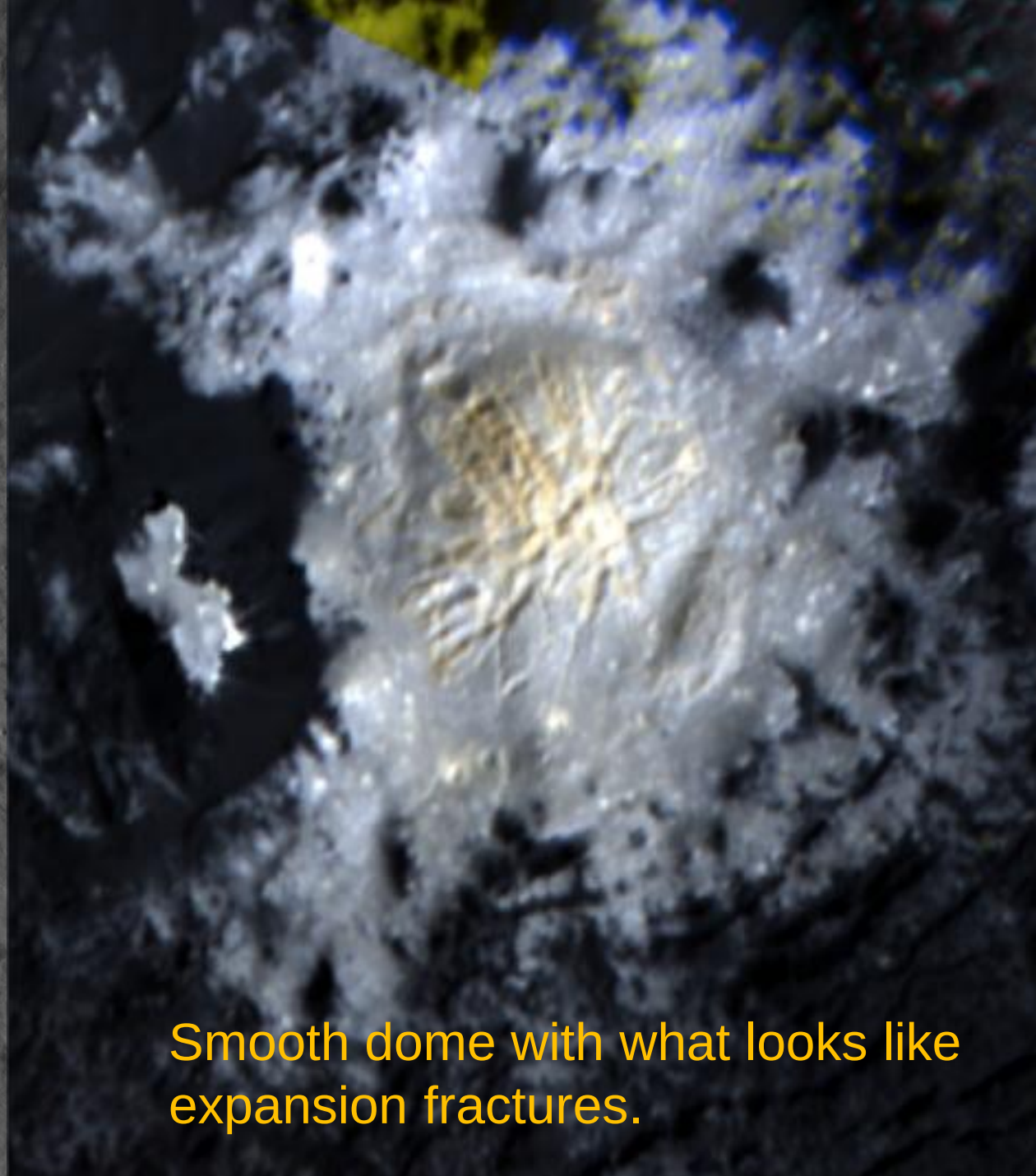
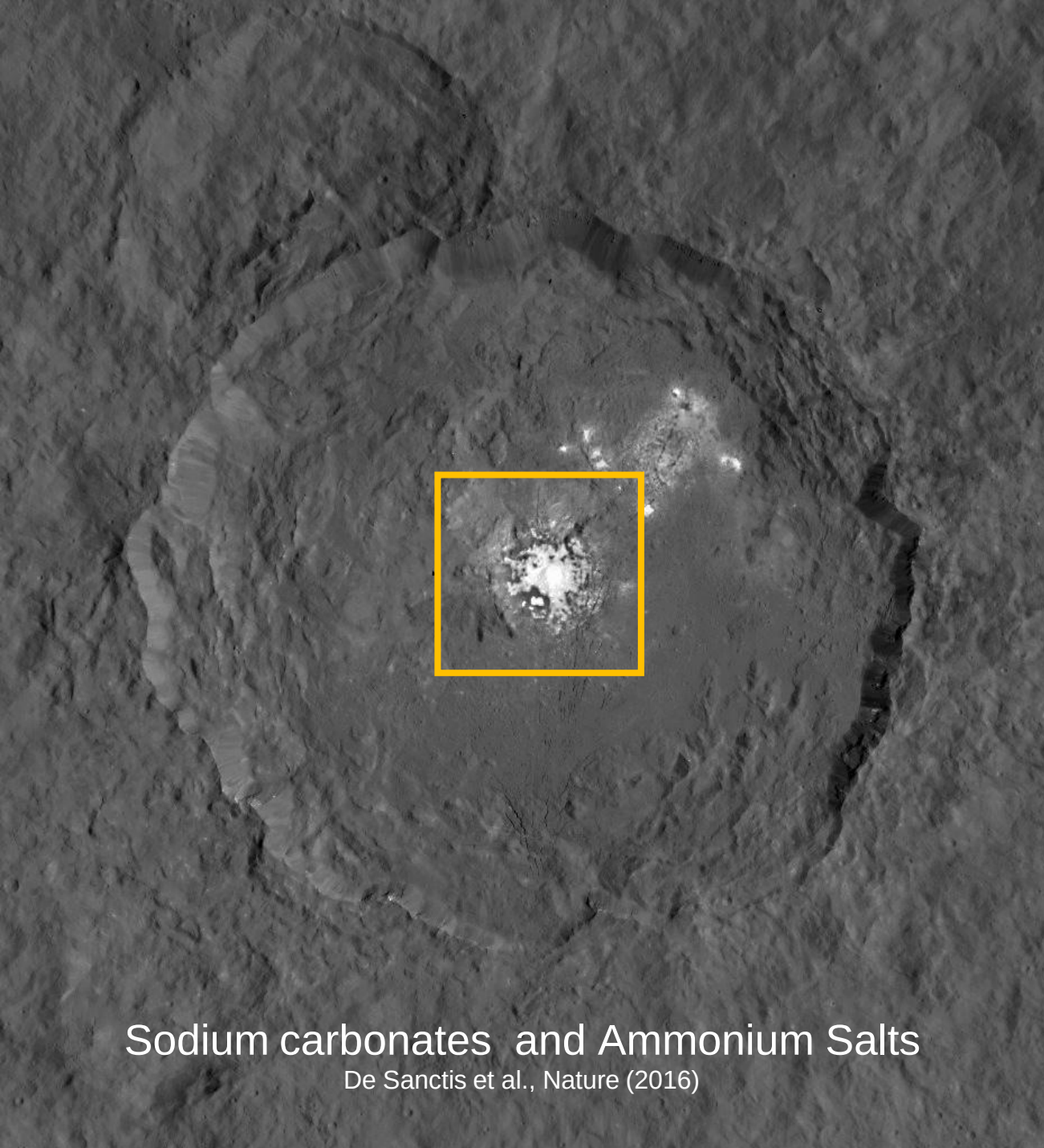
Buczkowski et al., Science, 2016;
Schmidt et al., Nature Geo., 2017



Combe et al., Science, 2016,
Raponi et al., Science Adv., 2018

Average mineralogy of the surface: aqueous alteration products





Ahuna Mons: cryo-volcano

The emplacement of 4-km high Ahuna Mons requires a molten material

PLANETARY SCIENCE

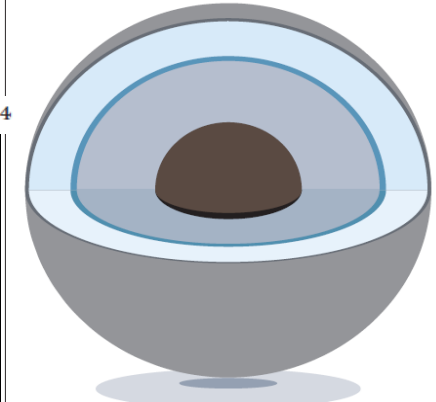
Dawn probe to look for a habitable ocean on Ceres

Asteroid belt's largest body to yield its icy secrets to NASA orbiter, due to arrive next month

20 FEBRUARY 2015 • VOL 347 ISSUE 6224

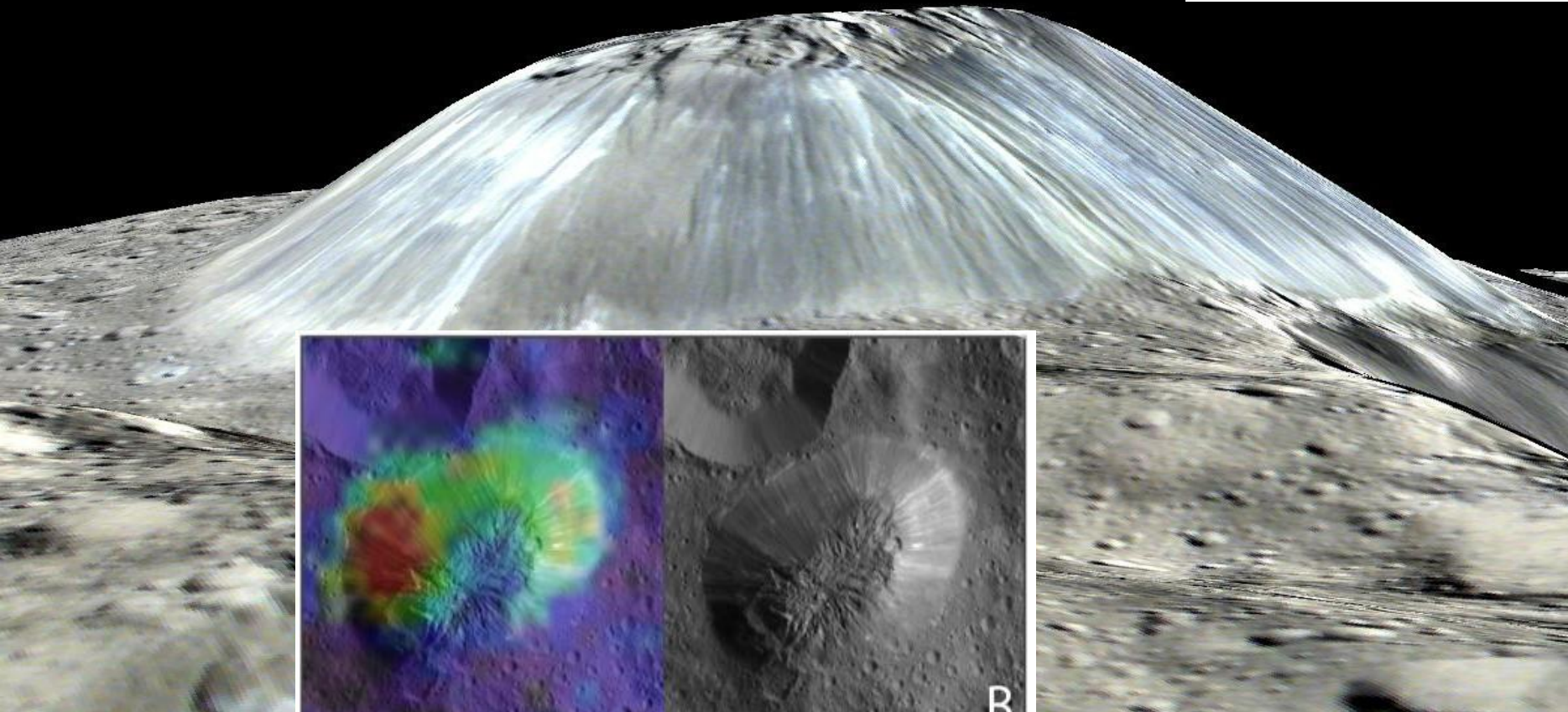
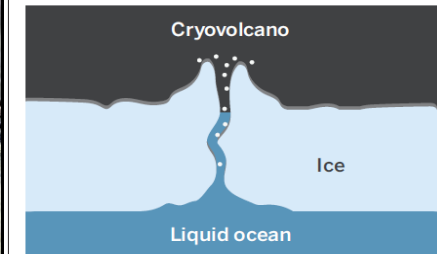
Iced over

Under an icy mantle, Ceres may harbor a thin ocean of liquid water, some of which could spew to the surface in cryovolcanoes.

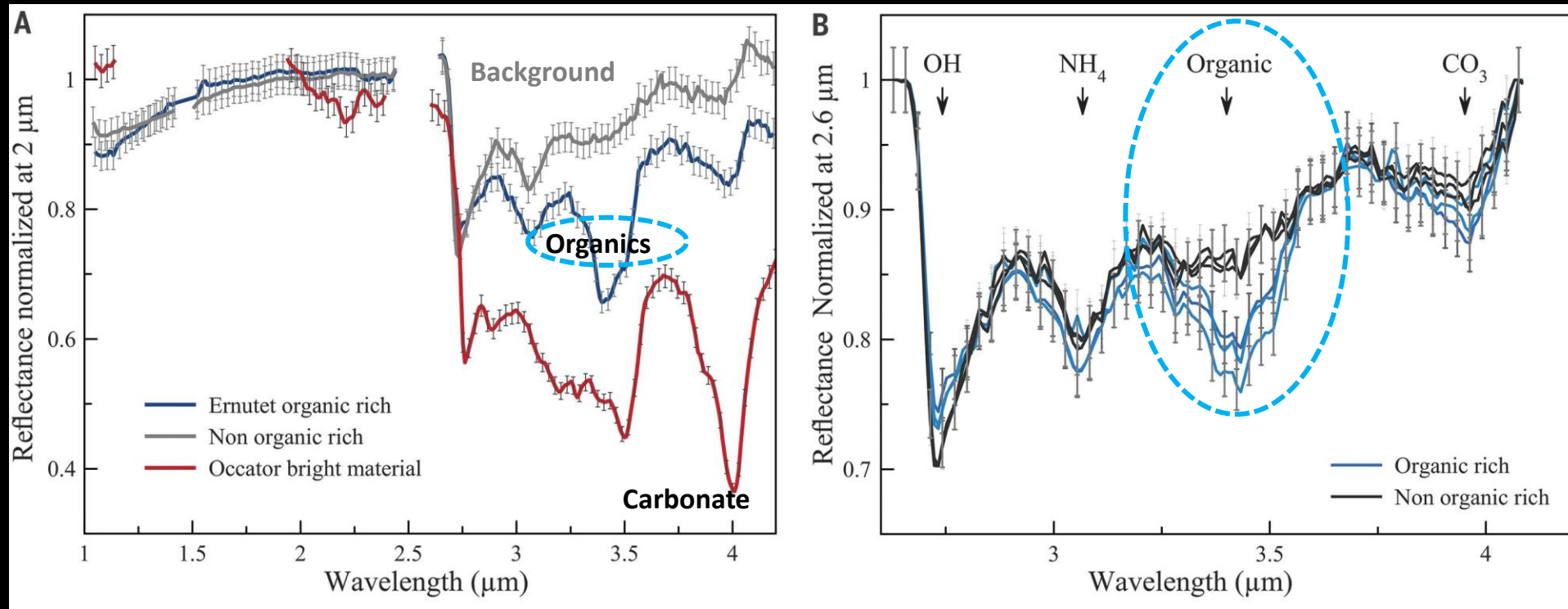


950 km

- Thin dirty crust
- Liquid ocean
- Ice mantle
- Hydrated silicates
- Rocky core



Ceres Organics



De Sanctis et al., (2015) Nature, 528, 241-244, doi: 10.1038/nature16172. OH & NH₄ everywhere

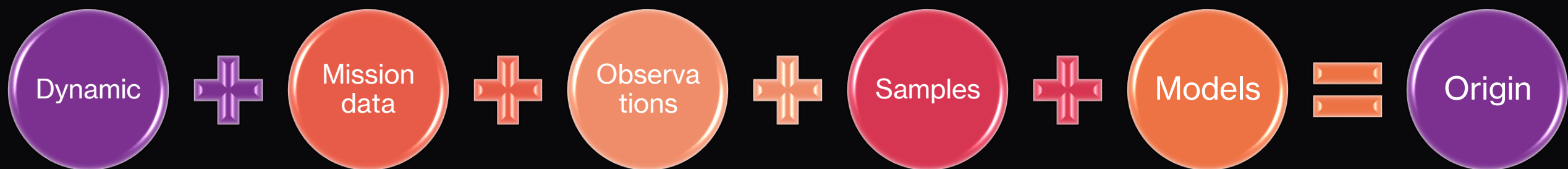
De Sanctis et al., (2016) Nature, 536, 54-57, doi: 10.1038/nature18290. Carbonate @ Occator (bright areas)

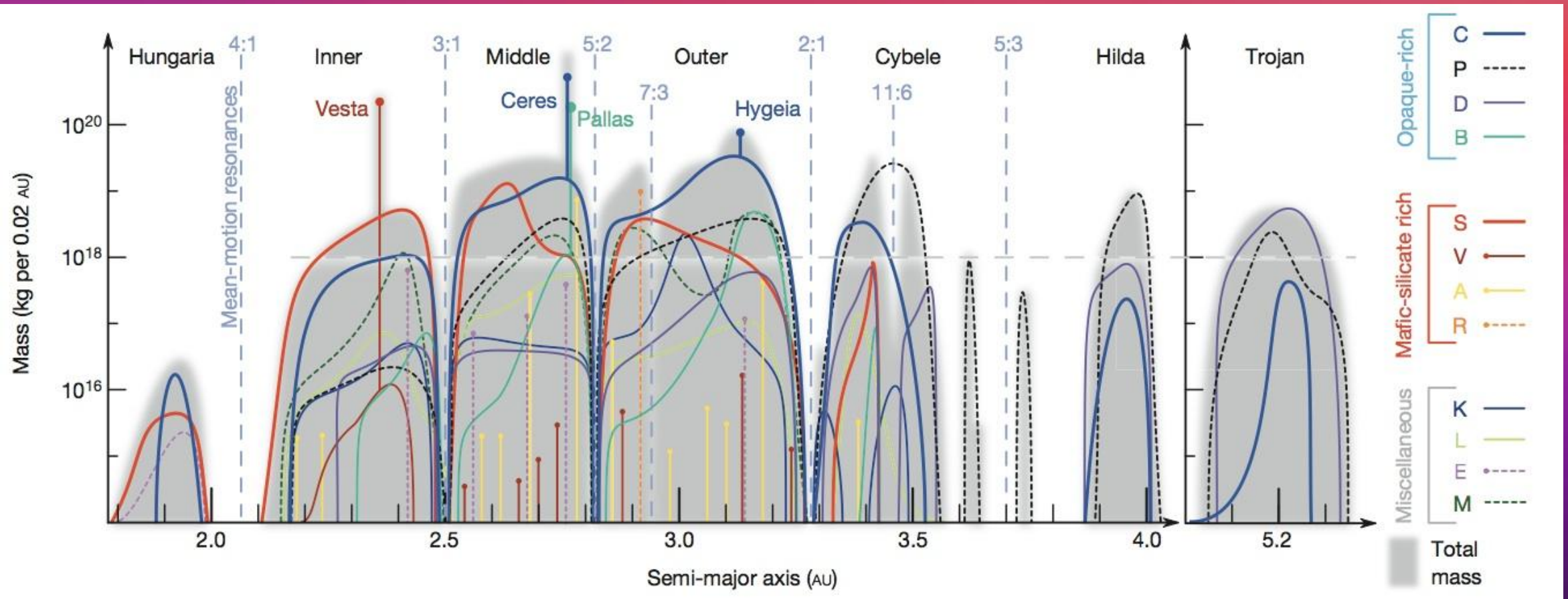
De Sanctis et al., (2017) Science 355, 719-722 **Aliphatic Organics**

What the Ceres composition tell us

- Ammoniated clays and Mg phyllosilicates are ubiquitous. The widespread presence of these two types of minerals is a strong indication of a global and extensive aqueous alteration.
 - Carbonates are also aqueous alteration products !
 - NH_4Cl , NH_4CO_3 detected- Presence of salts that lower the eutectic: possible fluids at lower temperature
 - Cryo-volcanism and faculae compositio indicates brines at depth
 - Sodium carbonates and salts identified also on Enceladus plume
- 
- Past global ocean
 - Formation region
 - Possible liquid water in the subsurface

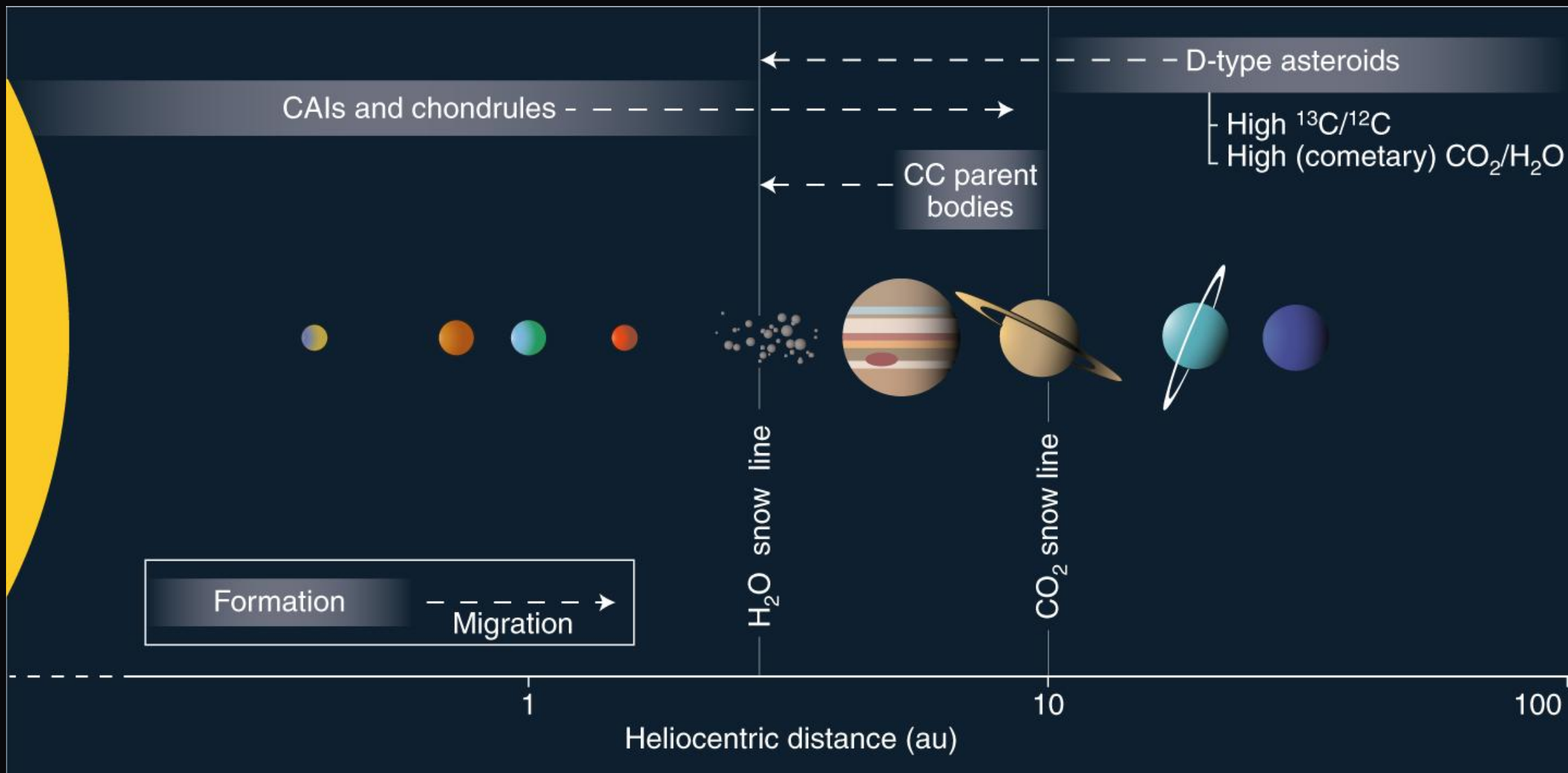
Solar system and asteroid formation





Observations:
Distribution of the asteroids
types and orbits

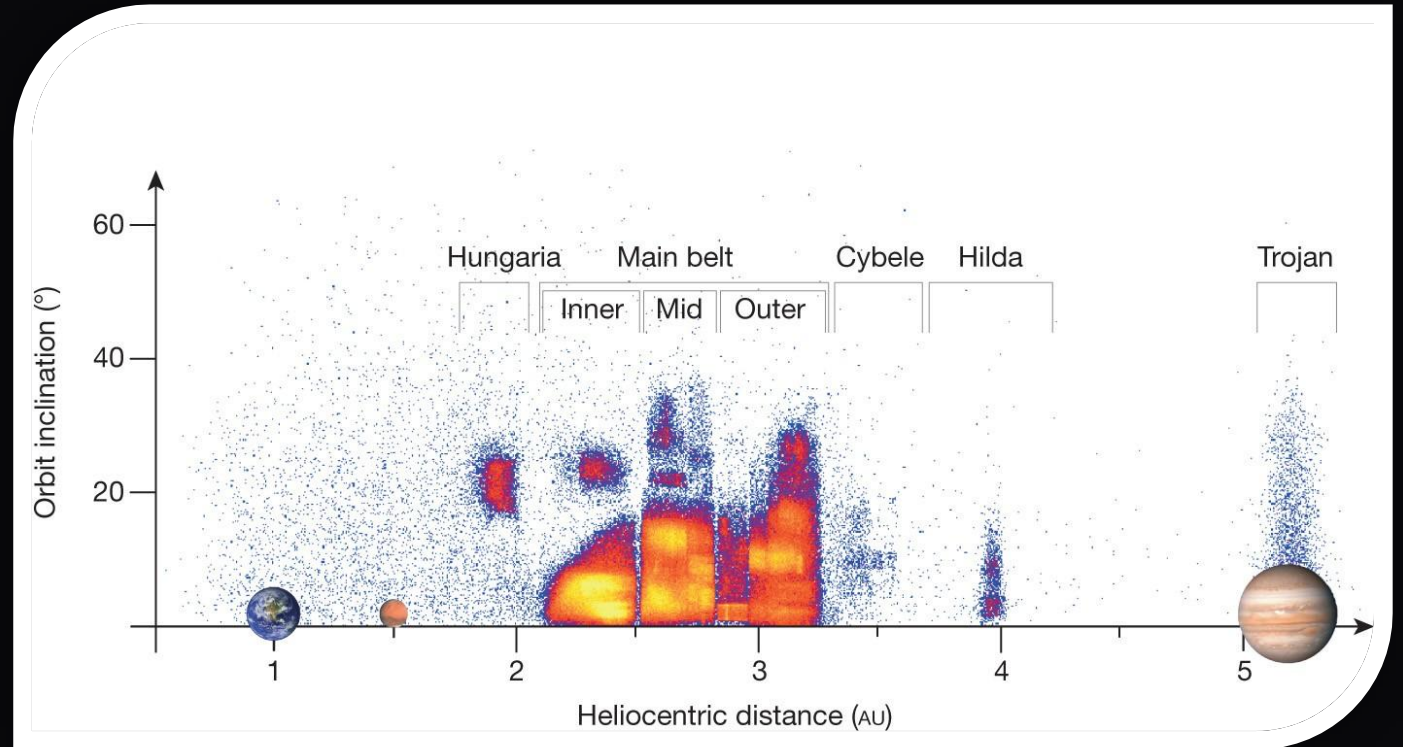
The stratification of the main belt intuitive as a general view that protoplanetary disks should have temperatures decreasing with increasing distance from the central star.



Orbital excitation

A key major characteristic of the asteroid belt population is the orbital excitation, i.e., the fact that the eccentricities and inclinations of many asteroidal orbits are quite large (e.g, *Petit et al., 2002*).

The values of eccentricities and inclinations of the largest asteroids are considerably dispersed, with the former ranging between 0 and 0.30, while the latter ranges between 0° and 33°



Planetesimals are expected to have formed on circular and coplanar orbits.

one or more dynamical excitation mechanism(s) within the primordial asteroid belt were needed to stir up eccentricities and inclinations to randomly dispersed values.

Missions: Dawn, Haybusa, Osirix Rex, Dart and others-Key findings

- Main belt: mixture of different bodies dry and wet
- Differentiation: few bodies (Vesta), only those formed very early thanks to short lived radioisotopes
- LHB: process affecting the main belt region and not only the terrestrial region
- Exogenic material on asteroid surface: basaltic material on Bennu/hydrous material on Vesta
- Bennu (carbonaceous) samples contain an abundance of carbon-bearing organic material, nitrogen-rich compounds, ammonia, and formaldehyde (Osiris-REX)
- **Delivery Mechanism:** The missions findings strongly support the theory that carbonaceous asteroids delivered crucial water and prebiotic organic molecules to early Earth
- **Ancient Water History:** The presence of hydrated clay minerals (phyllosilicates) and traces of evaporite salts (such as trona and calcite) indicates that Bennu's ancient parent body possessed pockets of subsurface liquid water and a hydrothermal saltwater system.
- Water rich bodies are quite common: **Ceres** is the most clear example

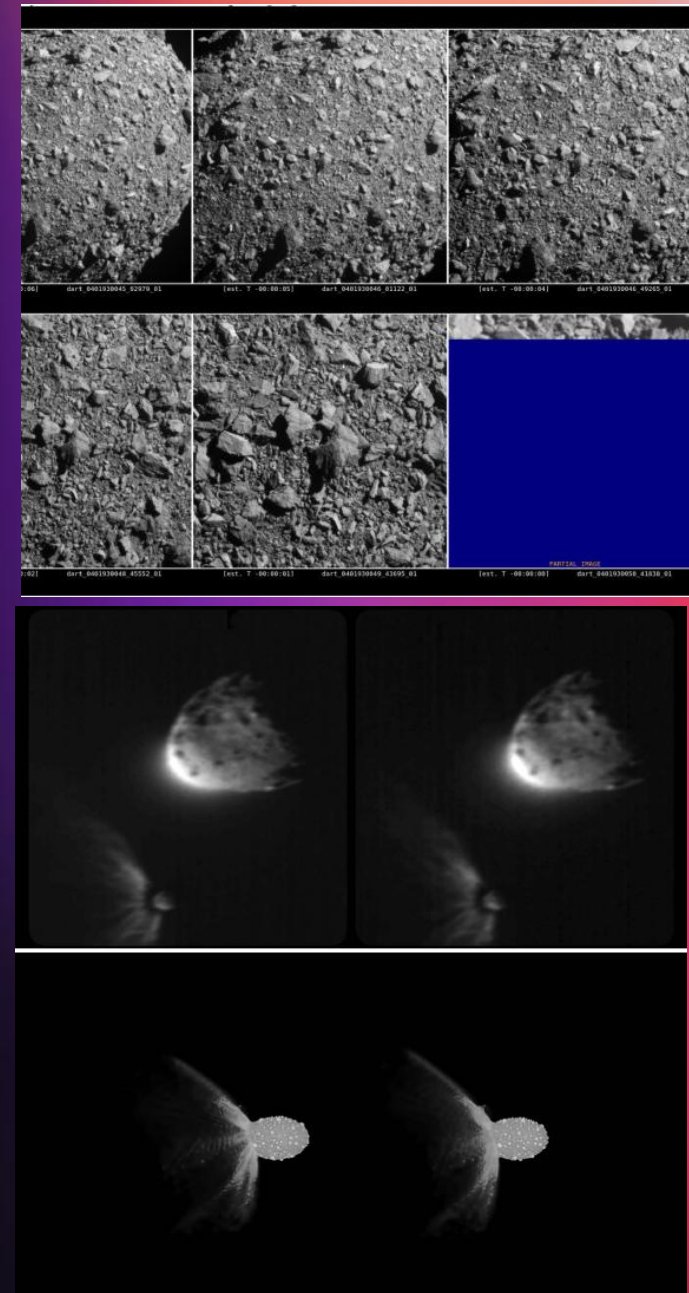
DART Mission

Dimorphos is the smallest asteroid ever investigated by a spacecraft.

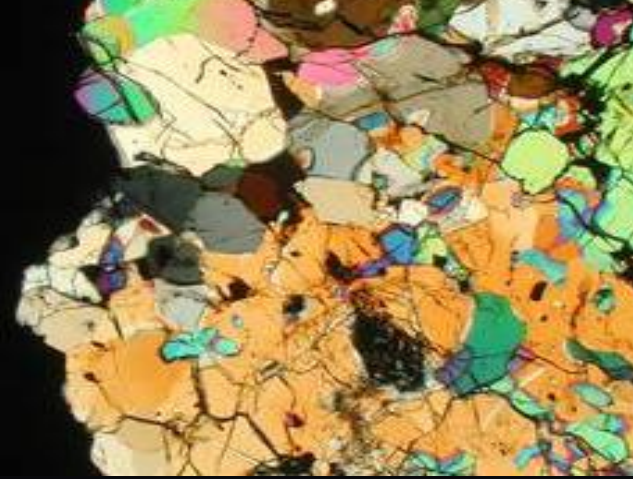
The surface geology of Dimorphos is suggestive of a loosely consolidated rubble pile, though the possibility of some larger, stronger aggregates in its interior cannot be ruled out currently,

The size-frequency distribution of boulders on Dimorphos suggests that the boulders might have originated from impacts but were also later modified by other processes, such as repeated impacts, thermal fragmentation, or re-accumulation processes. Individual cracks seen on boulders also suggests that thermal-driven stresses are affecting the boulders on Dimorphos.

→ COLLISIONAL EVOLUTION DOMINATES THE SMALL ASTEROIDS



Raducan et al. *Nat Astron* **8**, 445–455 (2024).
<https://doi.org/10.1038/s41550-024-02200-3>



Meteorites and samples:

composition and ages

Meteorites contain various solids born in the disc of gas and dust, known as the protoplanetary disc, which surrounded the young Sun before the planets were formed.

Time Zero: Primitive meteorites (called chondrites) contain microscopic white inclusions (CAIs) that formed **4,567 million years ago**, marking the exact start of solid material condensation in our solar system.

“Classical” models generally consider an isolated protoplanetary disc. However, the CAIs formed in such a short time (~200,000 years) that the protoplanetary disc must still have been in the process of forming, from a contracting interstellar cloud. In this primordial phase, the disc in formation was anything but isolated: it was sprinkled over its entire surface by cold material from the cloud.

Chronology

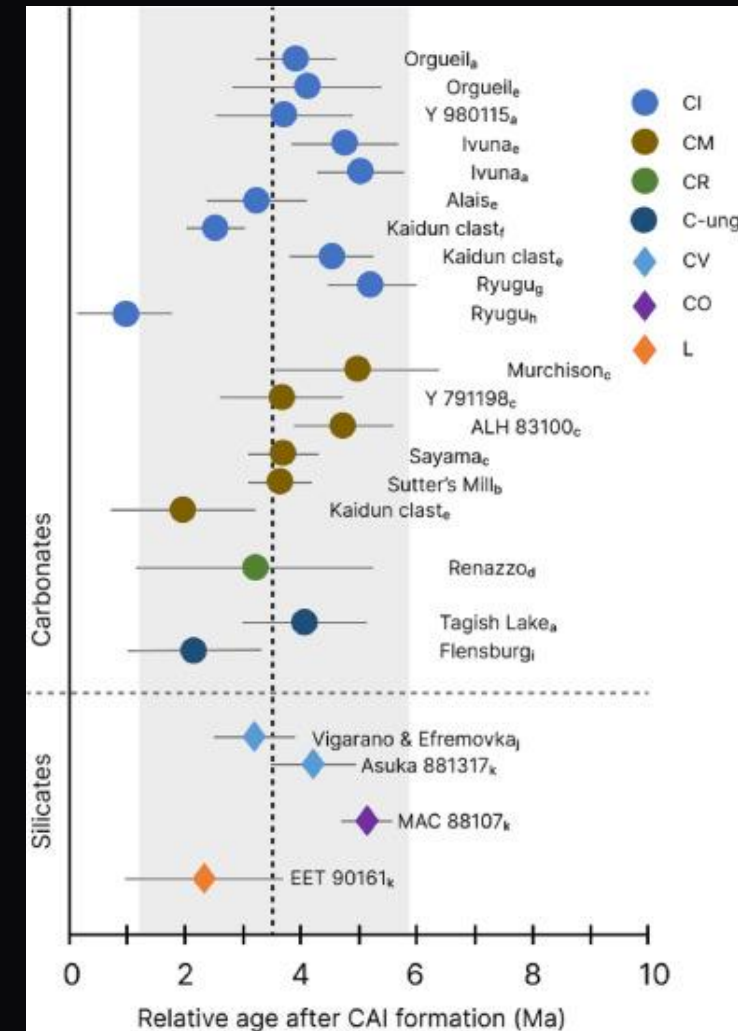
Time zero: chondrites contain microscopic inclusions (CAIs) that formed **4,567 million years ago**, marking the exact start of solid material condensation in our solar system

Formation of Ca-Al-rich inclusions was restricted to the inner solar system and to a short time interval of $\ll 1$ Ma, and marks the “**beginning of the solar system**”.

These chronometers provide highly resolved time constrains for the formation of the **first solids (Ca-Al-rich inclusions or CAIs), chondrules, planetary cores**, for the accretion and differentiation of planetesimals and hydrous/thermal alteration.

The oldest planetesimals accreted within a few 10^5 a after the formation of CAIs. The accretion of early formed planetesimals and their subsequent differentiation into a metallic core and a silicate mantle was a continuous process that occurred at different times in different locations of the solar nebula and extended over a time interval of at least ~ 4 Ma.

During this time interval the accretion process may have changed from planetesimal formation via streaming instability to pebble accretion.



Dynamical evolution

In the last decade our view of the solar system evolution changed dramatically, thanks to new models and observational constraints.

Different global models for Solar System formation imply contrasting dynamical histories of the asteroid belt.

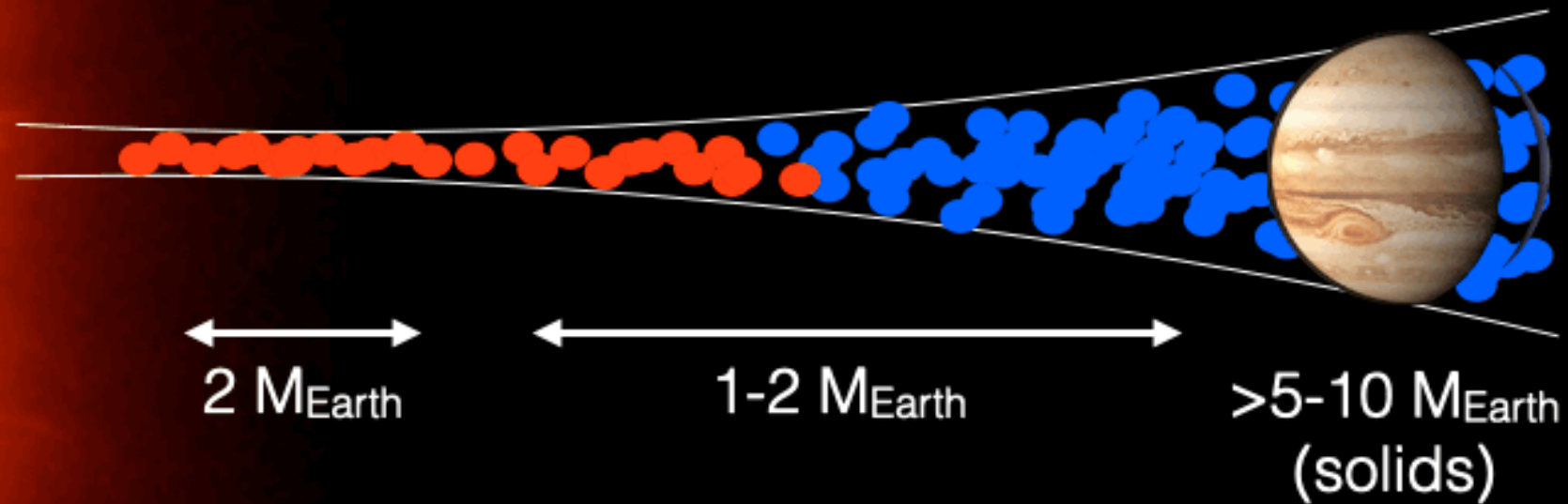
- Classical
- Alternative



Classical view

- Initial planetesimal orbits should have been quasicircular and almost coplanar.
 - The total mass now contained in the asteroid population is a small fraction of that existing primordially.
 - Asteroids with different chemical/mineralogical properties are not ranked in an orderly manner with mean heliocentric distance (orbital semimajor axis) as one might expect from the existence of a radial gradient of the temperature in the protoplanetary disk, but they are partially mixed
-
- **The classical view is that the belt was born with several Earth masses in planetesimals, then strongly depleted.**

The “classical model”



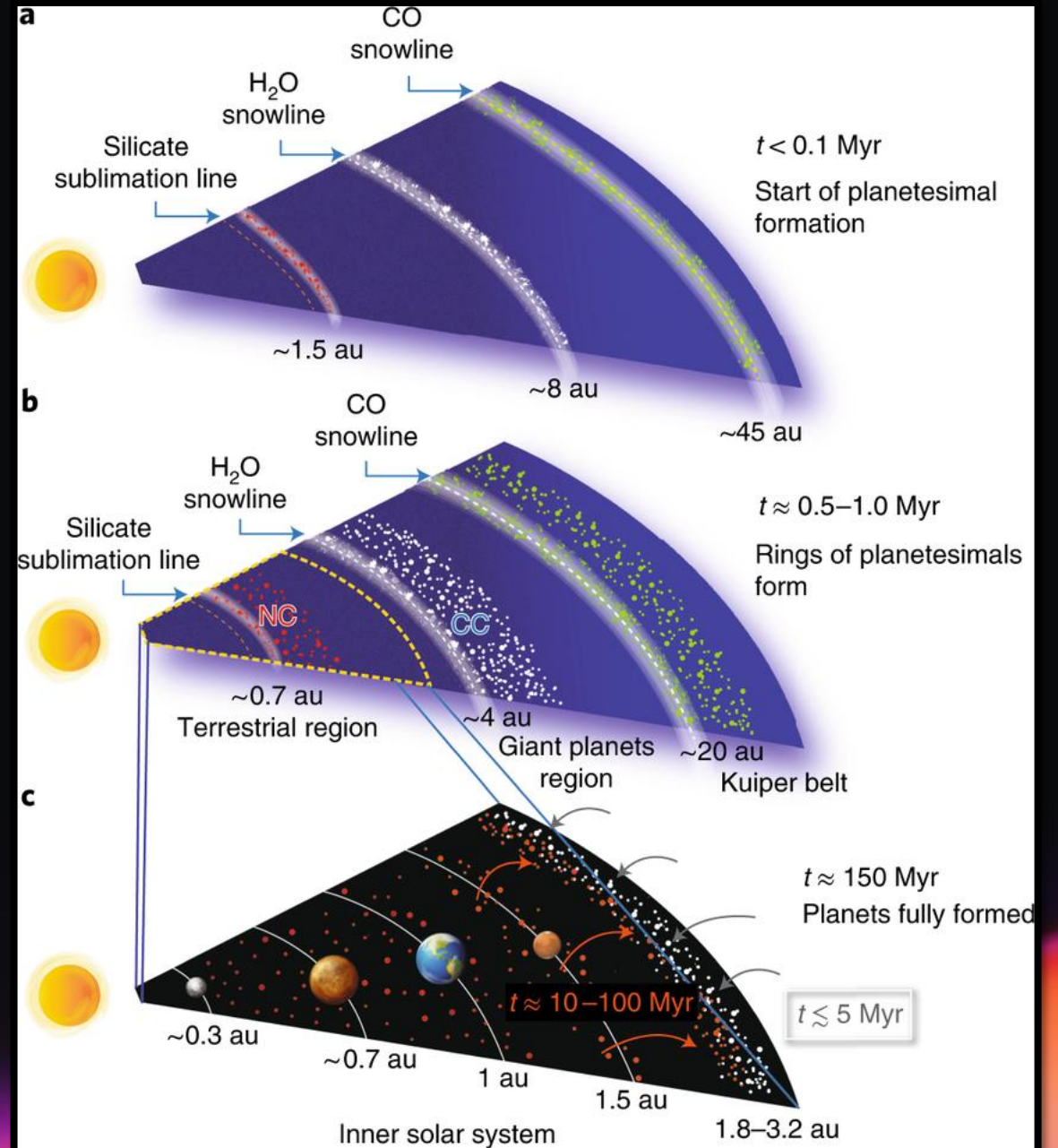
Wetherill (1980, 1994, 1996); Chambers (2001); Raymond et al (2006, 2009, 2014); O'Brien et al (2006)



Alternative view

- Very few planetesimals ever formed in the asteroid region and the belt's story is one of **implantation rather than depletion**.
- Many processes may have implanted asteroids from different regions of the Solar System, dynamically removed them, and excited their orbits.
- During the gaseous disk phase these include the effects of giant planet growth, migration, and sweeping secular resonances. After this phase these include scattering from resident planetary embryos, chaos in the giant planets' orbits, giant planet instability, and long-term dynamical evolution.
- In this view, **Vesta and Ceres may have been implanted from opposite regions of the Solar System** – Ceres from the Jupiter–Saturn region and Vesta from the terrestrial planet region – and could therefore represent very different formation conditions.

Alternative view



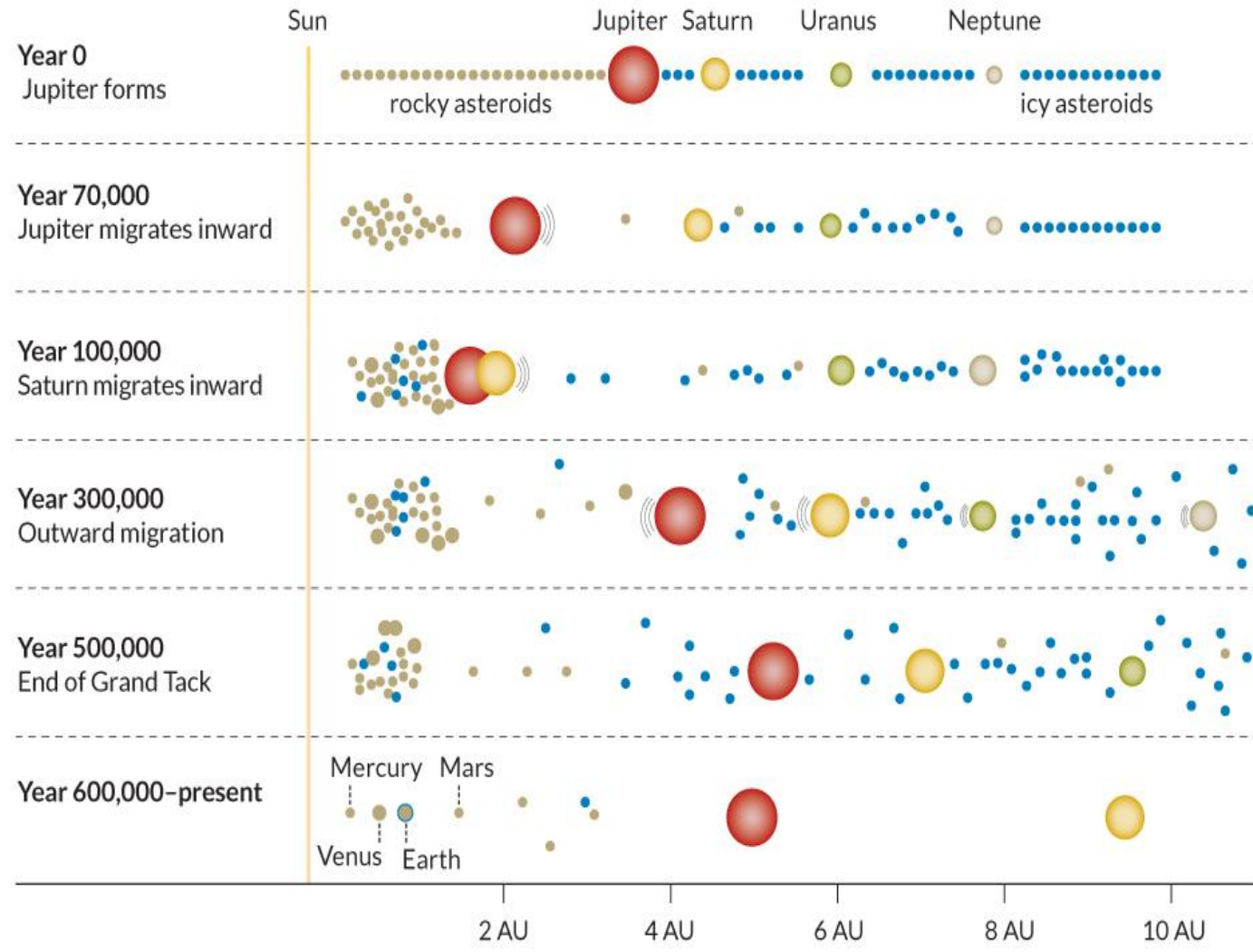
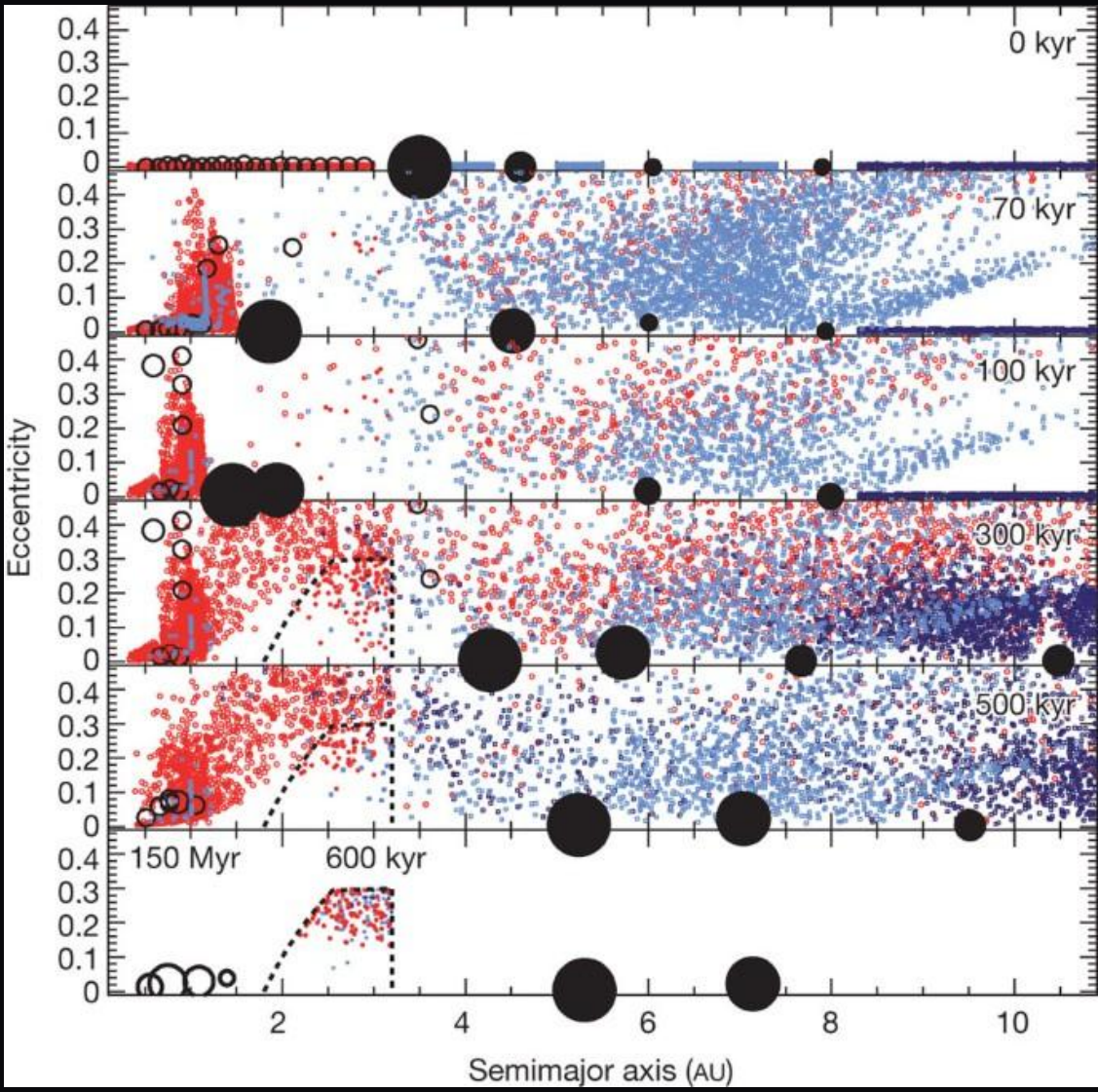
Models of the asteroid population evolution

- Classical first model, which linked the evolution of the asteroid belt with the process of terrestrial planet formation, was that proposed by *Wetherill* (1992)
- In this model, **at the time gas was removed from the system**, the protoplanetary disk interior to Jupiter consisted of a bimodal population of planetesimals and planetary embryos, the latter with masses comparable to those of the Moon or Mars.
- Numerical simulations show that, under the effect of the mutual perturbations among the embryos and the resonant perturbations from Jupiter, embryos are generally cleared from the asteroid belt region, whereas embryos collide with each other and build terrestrial planets inside 2 AU. While they are still crossing the asteroid belt, the **embryos also excite and eject most of the original resident planetesimals**.
- Only a minority of the planetesimals (and often no embryos) remain in the belt at the end of the terrestrial planet formation process, which explains the mass depletion of the current asteroid population.

Gran tack model

The Grand Tack scenario is built on results from hydrodynamics simulations finding that Jupiter migrates toward the Sun if it is alone in the gas disk, while it migrates outward if paired with Saturn (*Masset and Snellgrove, 2001; Morbidelli and Crida, 2007, etc*).

1. The scenario postulates that Jupiter formed first. As long as the planet was basically alone, Saturn being too small to influence its dynamics, Jupiter migrated inward from its initial position (poorly constrained but estimated at ~3.5 AU) down to 1.5 AU.
2. Then, when Saturn reached a mass close to its current one and an orbit close to that of Jupiter, Jupiter reversed migration direction (i.e., it “**tacked**,” hence the name of the model) and the pair of planets started to move outward.
3. This outward migration continued until the final removal of gas in the disk, which the model assumes happened when Jupiter reached a distance of ~5.5 AU. The migration of the cores of giant planets is still not fully understood
4. Thus, the Grand Tack model comes in two “flavors.”
 - In one, Saturn, while growing, migrates inward with Jupiter.
 - In another, Saturn is stranded at a no-migration orbital radius until its mass exceeds $50 M_{\oplus}$ then it starts migrating inward and it catches Jupiter in resonance because it migrates faster. Both versions exist with and without Uranus and Neptune.



Pebble Accretion models

Pebble accretion is a modern model of planet formation where growing planetary embryos rapidly accumulate millimeter- to centimeter-sized particles (pebbles) drifting inward through the protoplanetary disk via aerodynamic gas drag.

Aerodynamic Drag: Gas in the protoplanetary disk orbits slightly slower than solid particles, creating a headwind that causes small (cm-sized) pebbles to spiral inward toward the star.

Gravitational Capture: As these pebbles drift past larger planetary seeds (protoplanets), the seeds' gravity – assisted by the gas drag slowing the pebbles down relative to the body – efficiently pulls them into the growing core

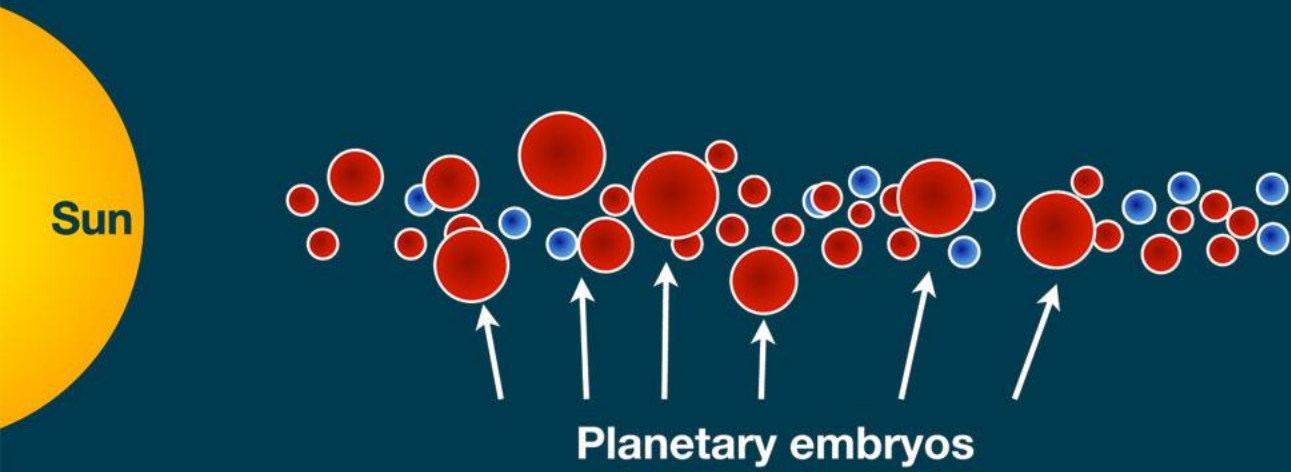
Pebble Isolation Mass: Growth continues rapidly until the planet reaches a critical size (the pebble isolation mass), where it alters the local pressure profile of the gas disk, creates a partial gap, and halts further inward pebble drift onto that specific body.

Isotopic Signatures: Accreting different "generations" of pebbles over time helps explain the distinct non-carbonaceous and carbonaceous isotopic reservoirs found on Earth and Mars.

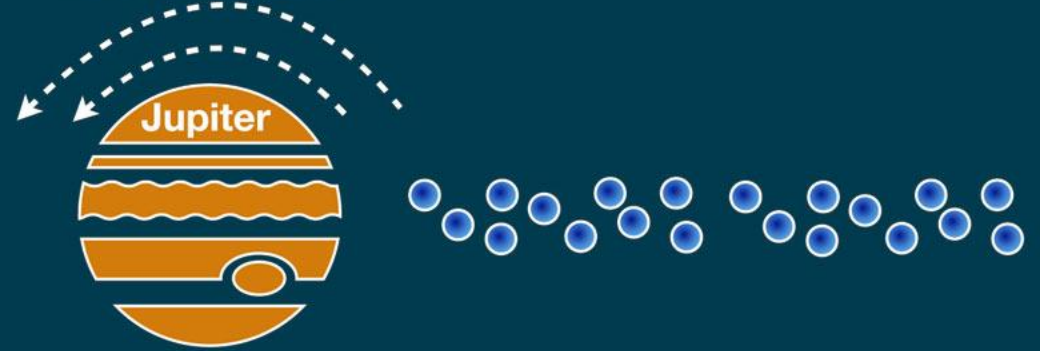
Volatile Delivery: Water, carbon, and other volatiles may have been delivered to Earth by early-generation icy pebbles before planetary gas envelopes heated up enough to vaporize them.

Outer Solar System: In the outer disk, rapid pebble accretion explains the runaway growth of giant planet cores (Jupiter and Saturn) before the gaseous disk dispersed.

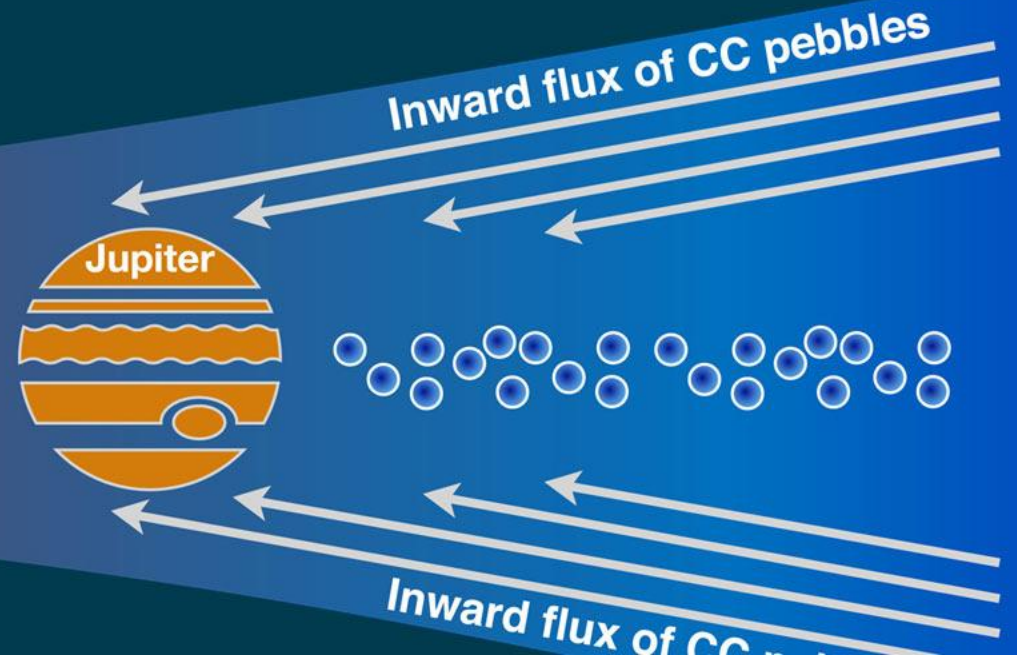
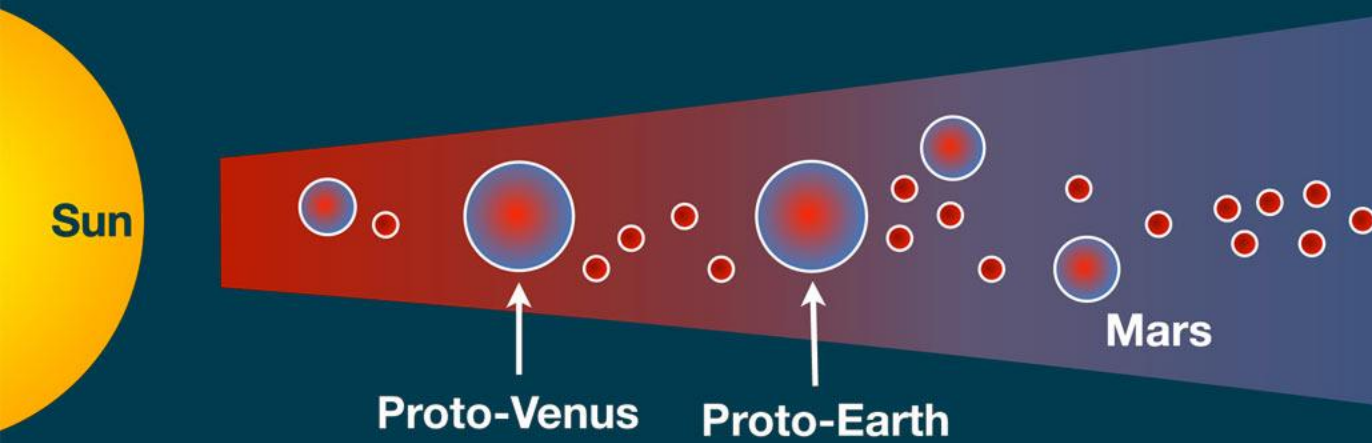
I. Wetherill-type accretion



Inward scattering
of CC bodies



II. Pebble accretion





Conclusion

- **Summary:** Asteroids are more than just dangerous rocks; they are ancient clues to our origin and potential stepping stones for our future in space.
- **Questions?** Open the floor to the audience.