Caelus

A Tour through the Main Asteroid Belt

Summer School Alpbach 2025 – **Team Green**

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Science Case and Objectives

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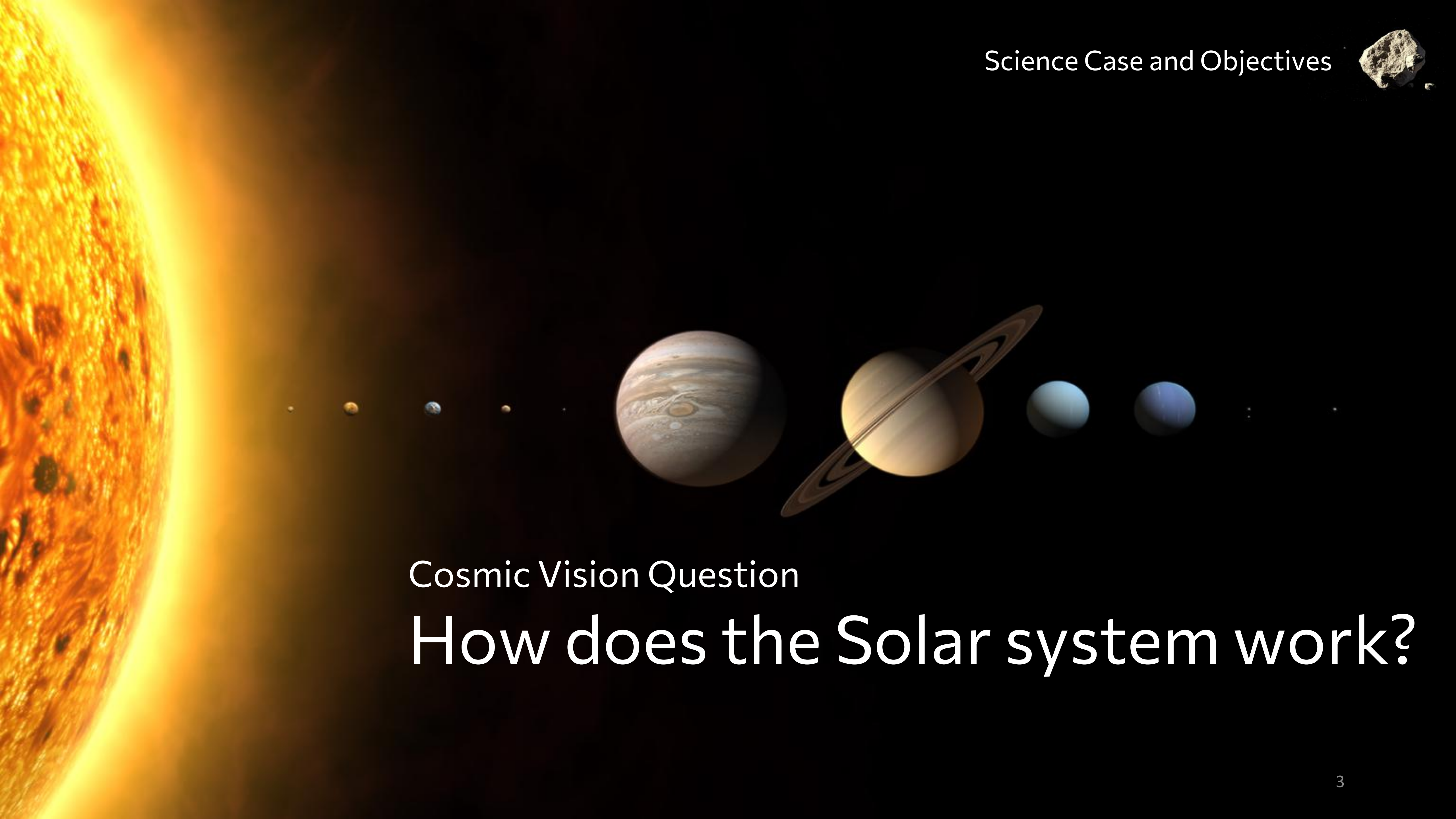
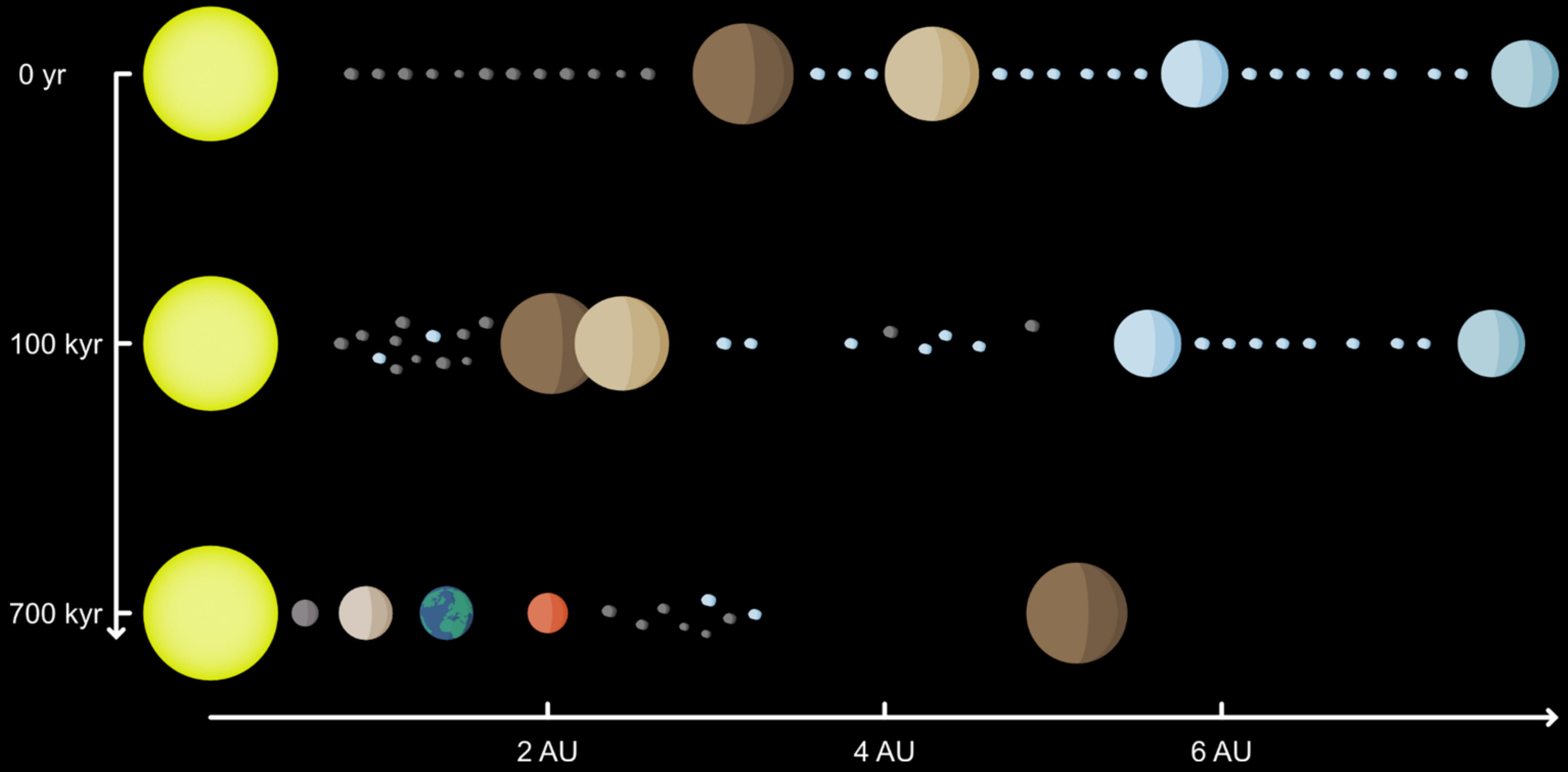


Cosmic Vision Question

How does the Solar system work?

Current Knowledge - Asteroids

What we know and why it is important



Current Knowledge - Asteroids

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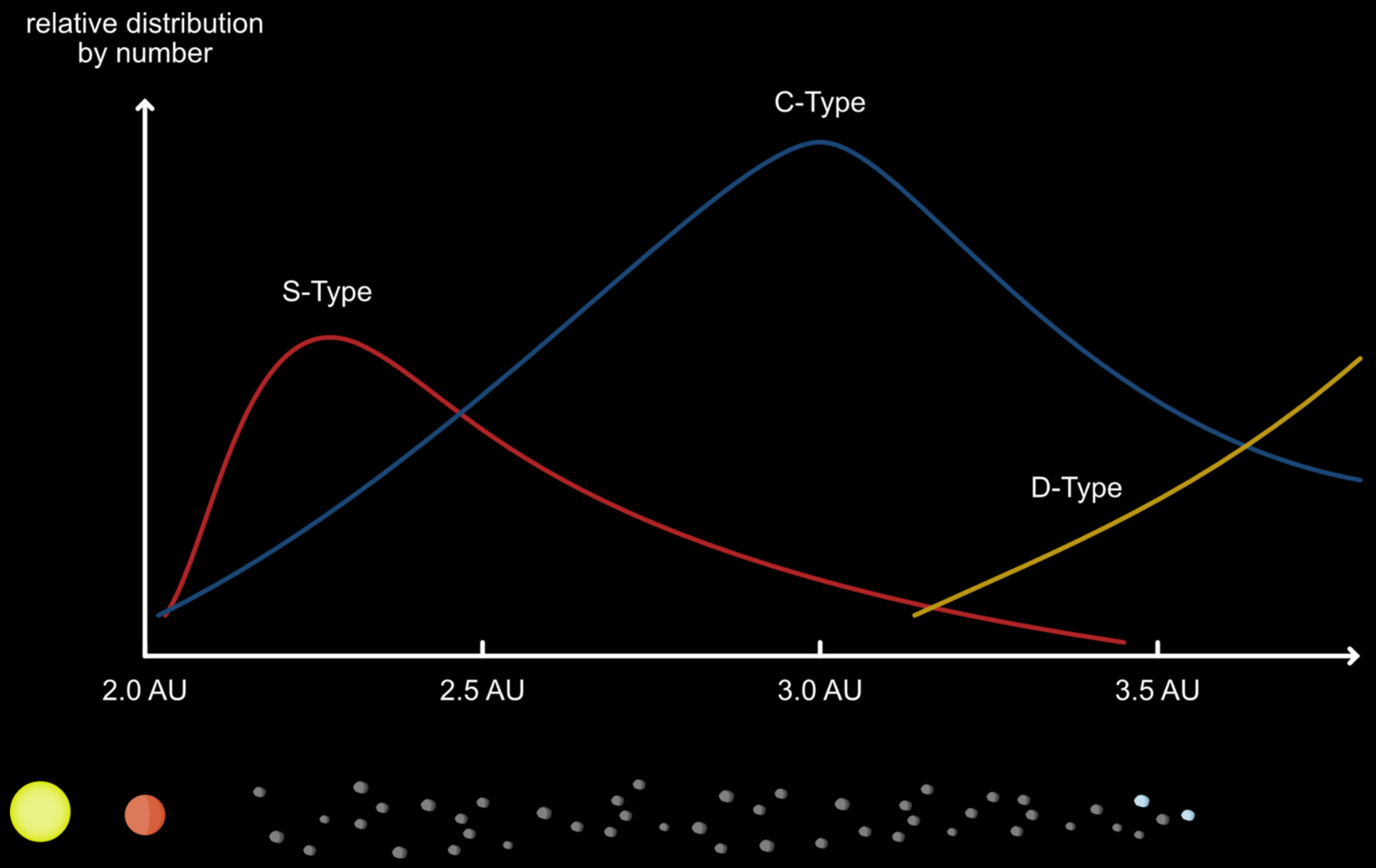
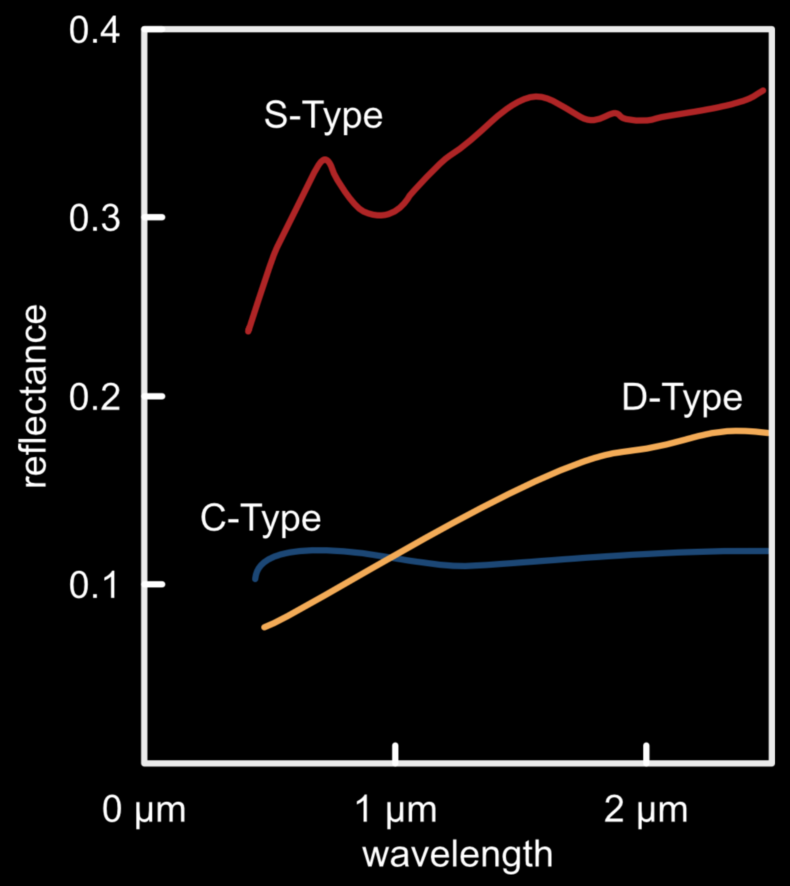




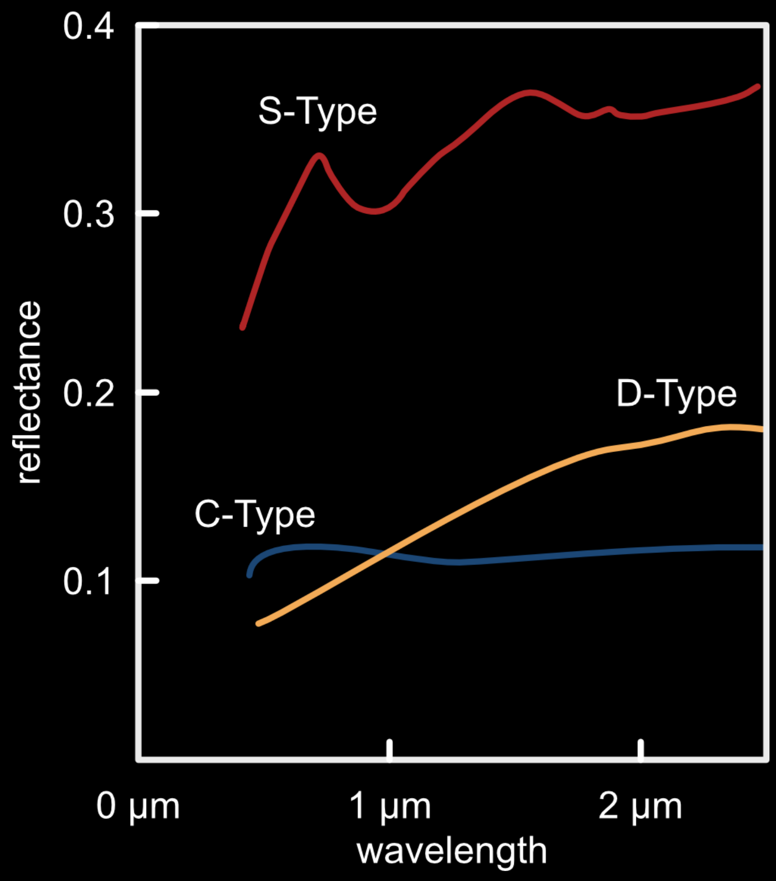
Data from Gradie and Tedesco 1982

Data from Burbine et al. 2024

Current Knowledge - Asteroids

What we know and why it is important

Global Spectral Properties



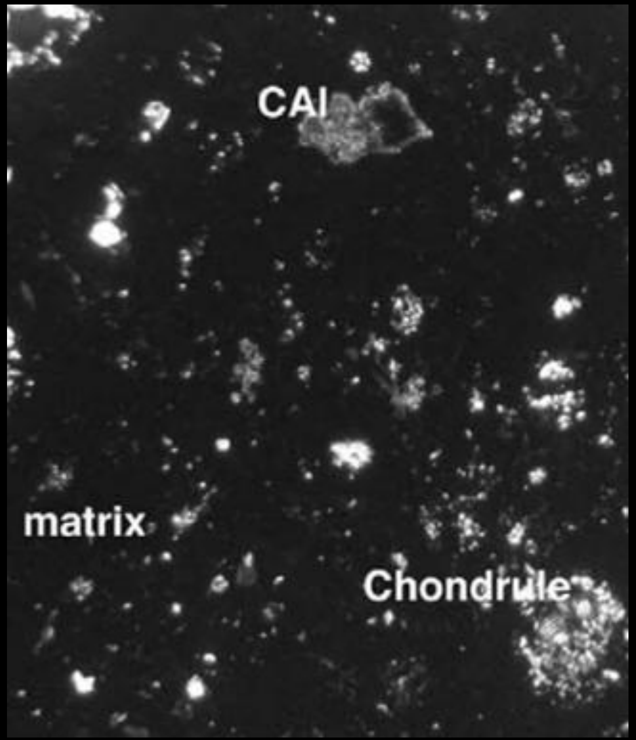
Silicate-rich

Low albedo, reddish spectrum

Carbon-rich

Data from Burbine et al. 2024

Meteorite samples

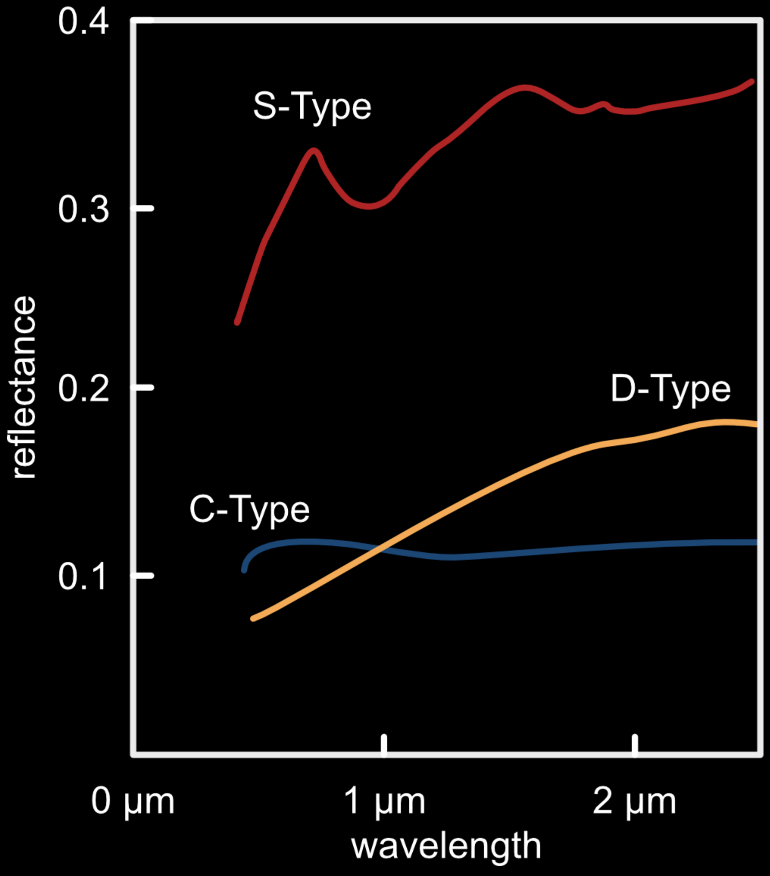


Weisberg, McCoy and Krot 2006

Current Knowledge - Asteroids

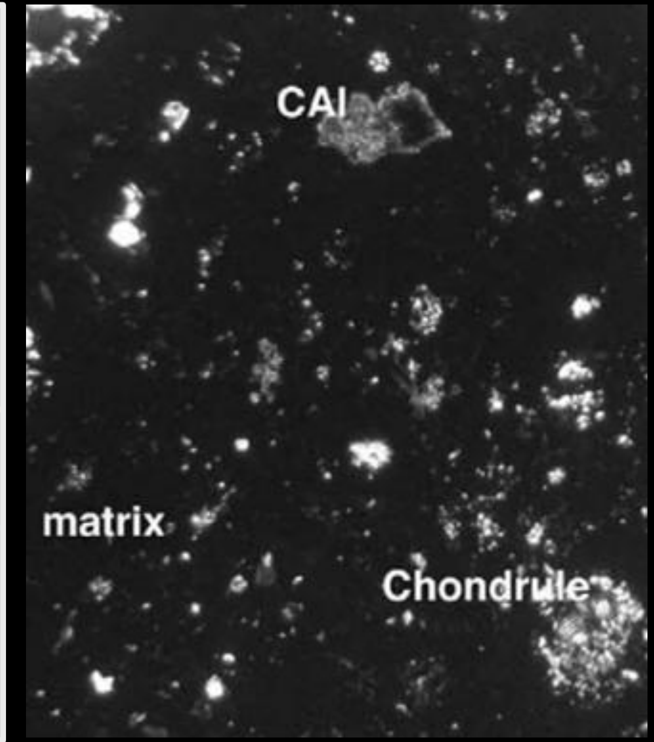
What we know and why it is important

Global Spectral Properties



Data from Burbine et al. 2024

Meteorite samples



Weisberg, McCoy and Krot 2006

?

Local Physical and Morphological Properties

Size: ~1 m to ~100 km

Locations: NEOs, Main Belt, Trojans

Shape: Irregular, elongated, binary

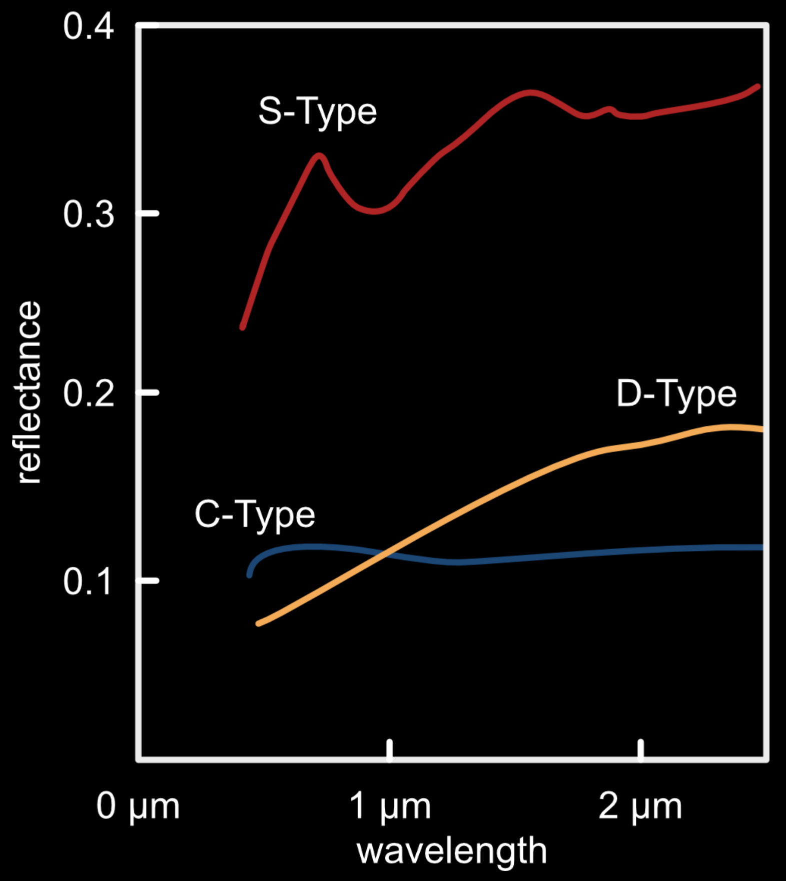
Surface: Ridges, grooves, regolith

Composition: Metals, silicates, organics, ices

Rotation: Different periods

Caelus Science Case

What we know and why it is important



Data from Burbine et al. 2024

Science Goal

- What causes the spectral diversity across the asteroids of the main belt?

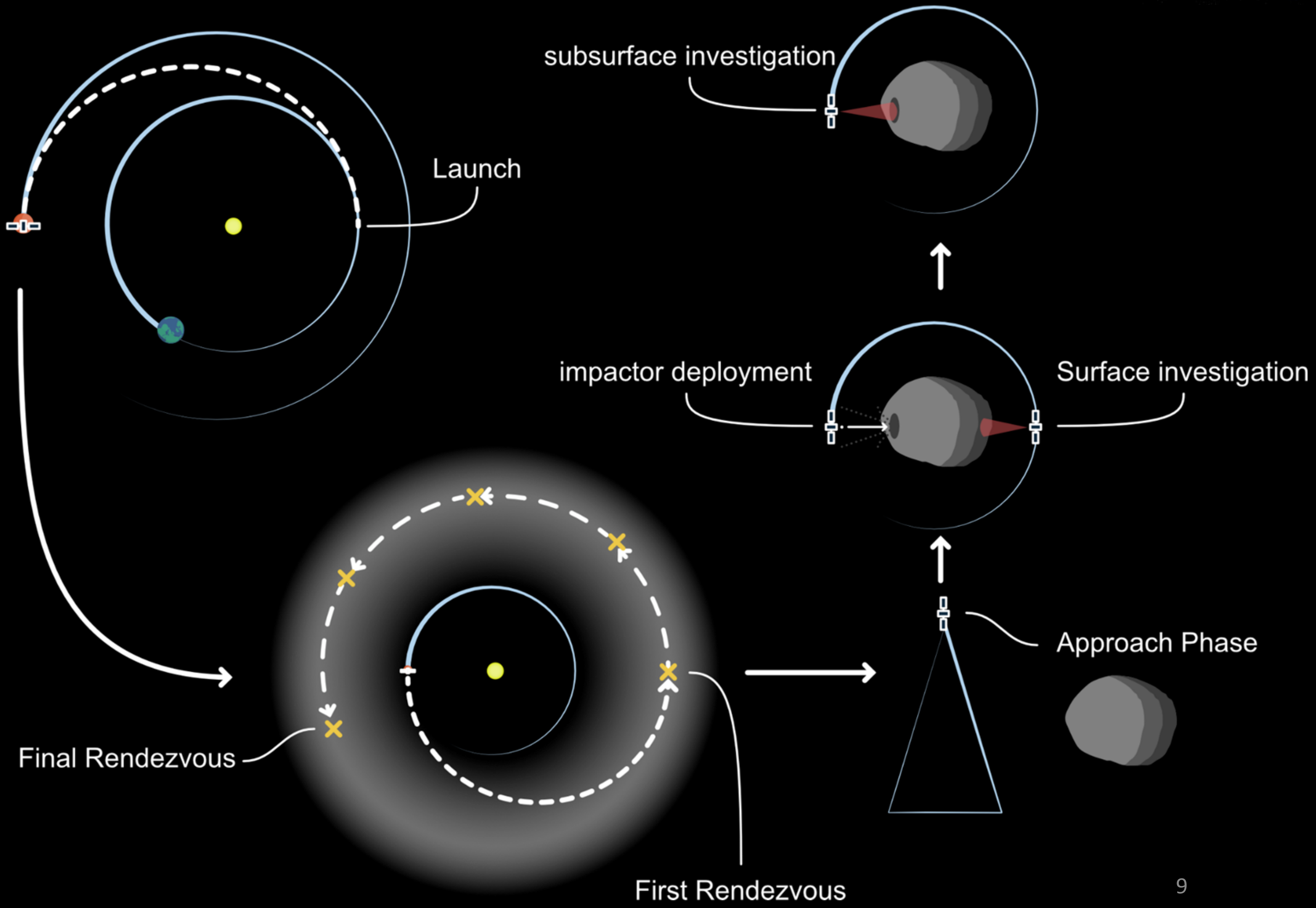
Mission Objectives

- Using measurements of the **surface** and **subsurface** morphology and composition of at least 5 MBAs, we investigate their **formation** and **evolutionary history** and link our findings to meteorite samples.

Mission Overview

Simple overview

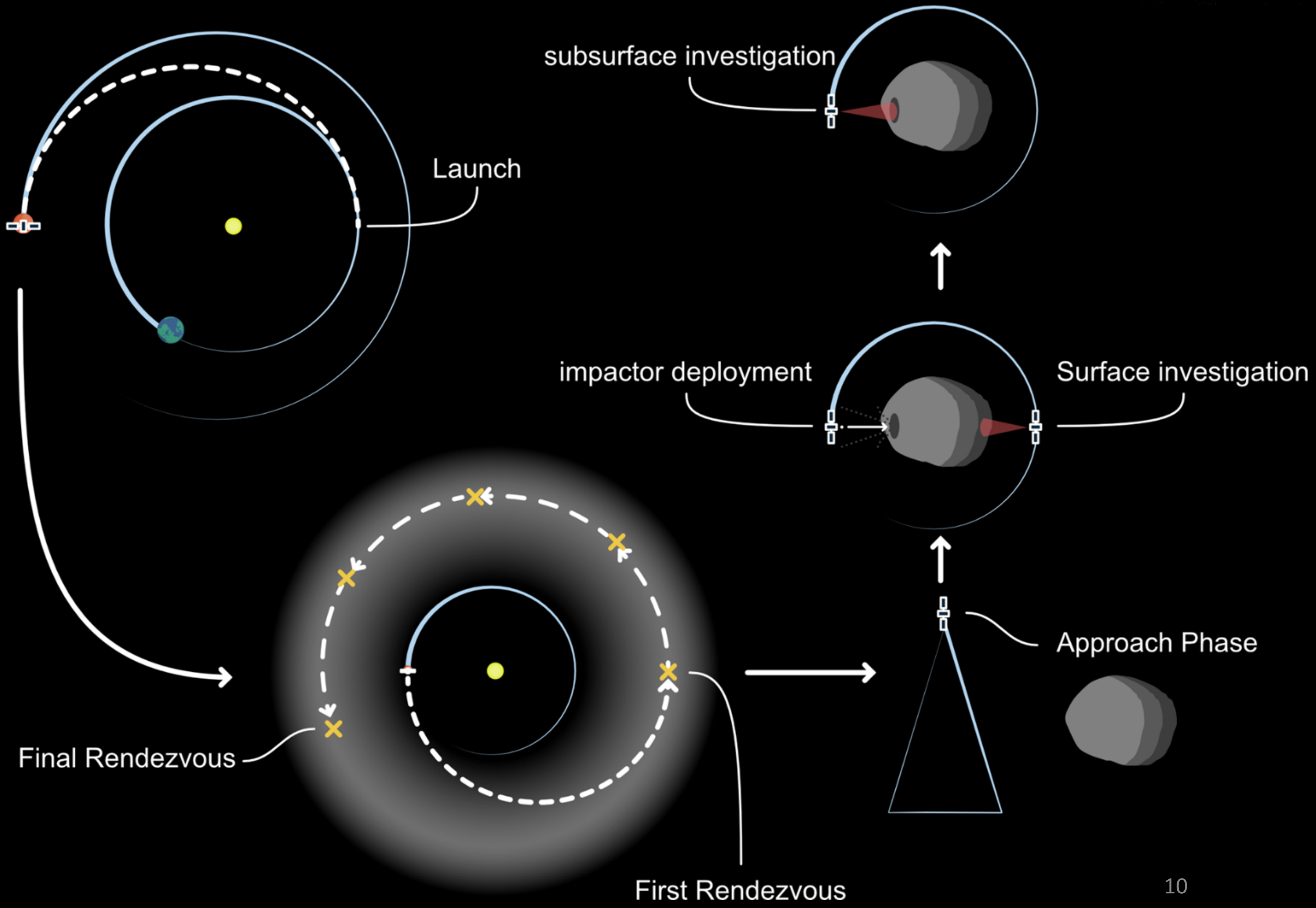
Using a **single spacecraft**, we will investigate multiple bodies in the Main Asteroid Belt



Mission Overview

Simple overview

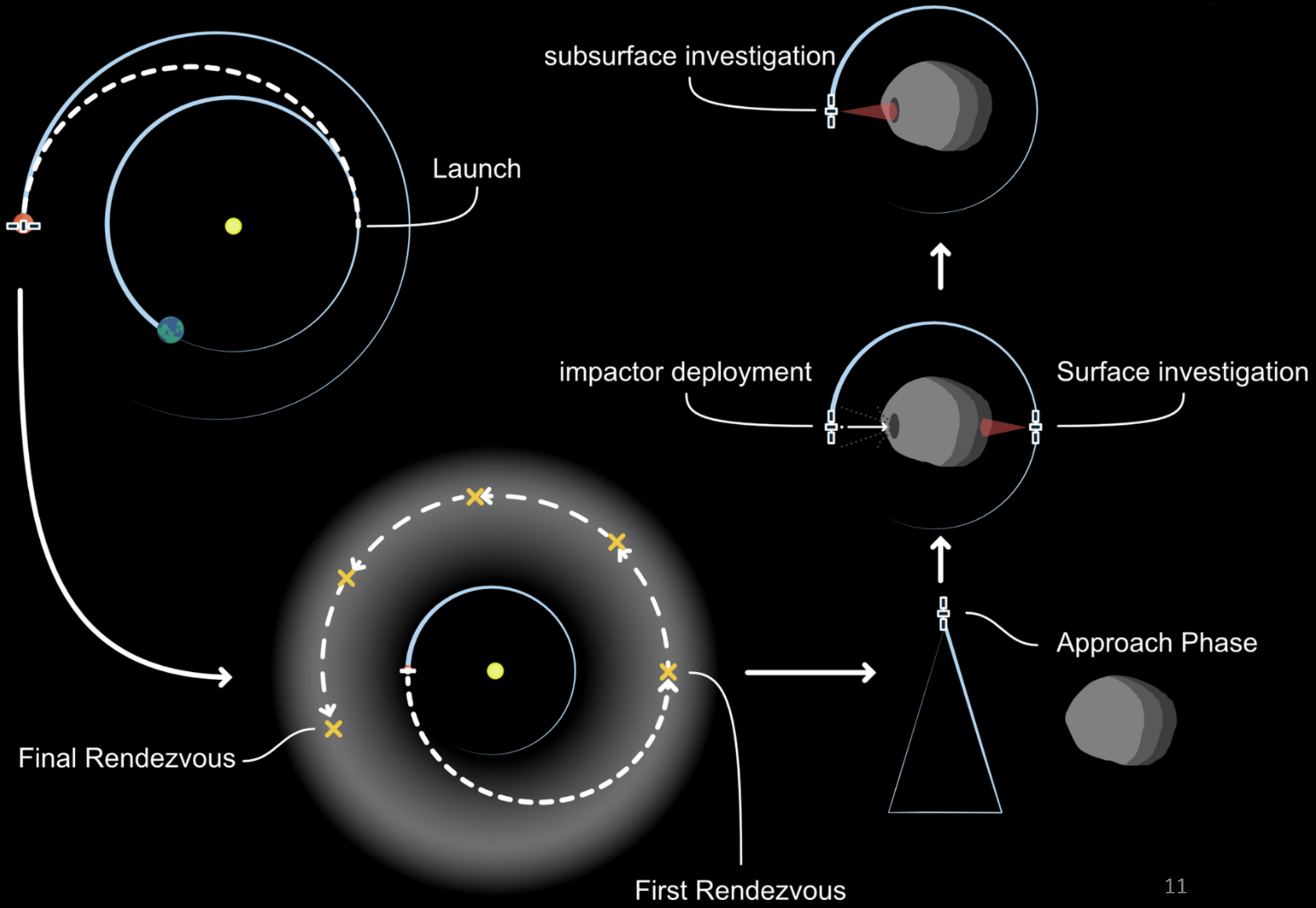
We will investigate a **minimum of 5 bodies**, maximizing the number of different spectral classes, visiting **at least 3 asteroids classes**



Mission Overview

Simple overview

In **Rendezvous**, we will investigate the surface and subsurface composition, morphology and internal structure of each body.

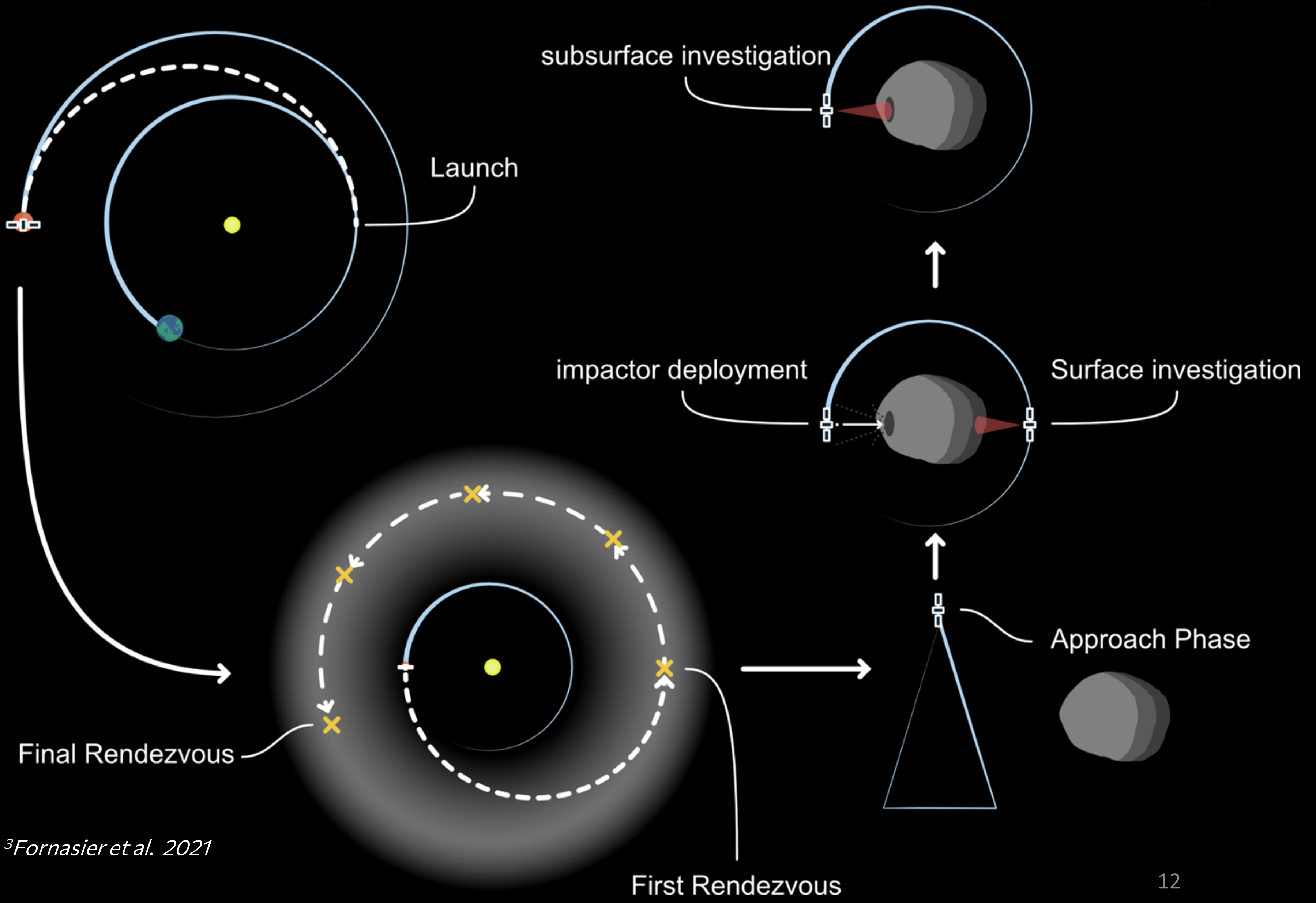


Mission Overview

Simple overview

Targets of interest are

- **P/D-type** spectral similar to comets[1]
- **M-type** potentially cores of differentiated bodies[2]
- **E/M/P-type** similar spectra, probably distinct composition[3]



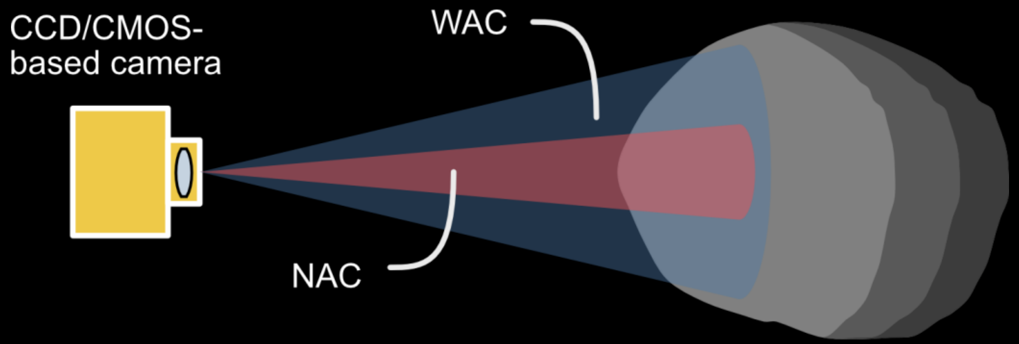
[1]*Vernazza et al. 2021* [2]*Margot and Brown 2003* [3]*Fornasier et al. 2021*

Science Question

What causes the spectral diversity across the asteroids of the main belt?

Science Objectives

Scientific Objective	Scientific Requirement	Observable	Instrument
SO 1: Subsurface composition and structure	Bulk density	Asteroid shape	VIS Camera (WAC)
			TIR Imager
		Asteroid mass	HGA
	Boulder microporosity	Boulder size	VIS Camera (NAC)
		Boulder thermal inertia	TIR Imager
	Subsurface mineral composition	Fresh material excavation	Impactor
		Mineral components	Hyperspectral Camera
	Subsurface elemental composition	Elemental composition	γ-ray and Neutron Detector



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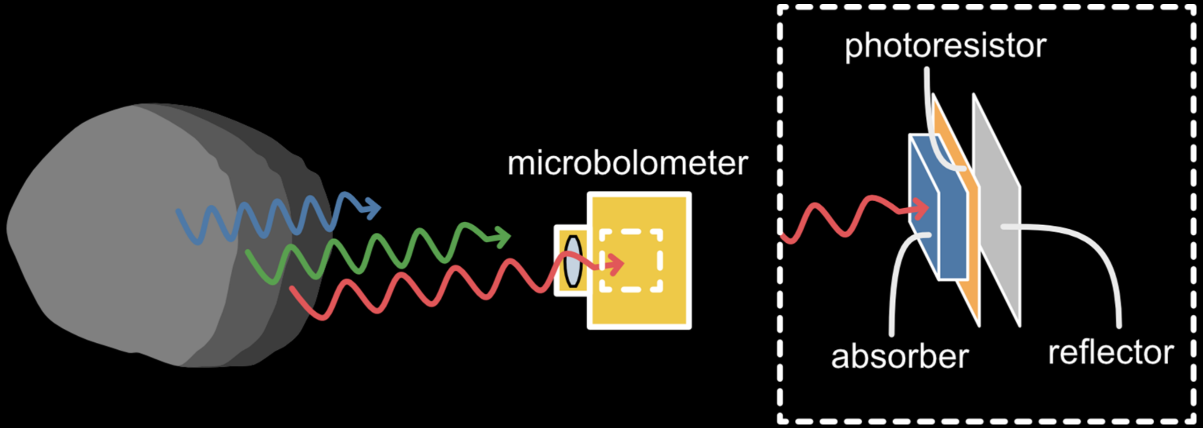

Requirements document

ID	Short Descriptor	Requirement Text	Justification	Parent
L1-010-OR	Asteroid shape	The volume shall be measured with an accuracy sufficient to reach density accuracy < 10% together with mass accuracy	Low-density bodies may vary in their density on the order of ~10%, which shall be resolved (Carry 2012)	**L0-010-MO**
L2-010-PR	Shape model computation method	The shape model shall be computed using a combination stereo and photoclinometry	This method was employed successfully by multiple mission, resulting in high-accuracy shape models (Al Asad 2021)	**L1-010-MI**
L2-020-OR	Imaging data for high-resolution shape model	For the high-resolution shape model, imaging data covering the entire asteroid shall be used with a resolution of 0.75 m/px. The high-resolution shape model shall be generated using the medium-resolution imaging data, whereas the high-resolution imaging data will be used for investigation of surface features on cm scale	This resolution is expected to be sufficient to determine the asteroid volume to within less than 5 % (Al Asad 2021)	**L1-010-MI**

Requirements document

ID	Short Descriptor	Requirement Text	Justification	Parent
L3-010-IR	Shape model camera spatial resolution	To achieve a spatial resolution of 0.75 m/px on the asteroid surface, the camera requires an iFoV of 0.75 mrad at an orbital altitude of 1 km. For higher higher orbits, a smaller iFoV is required.	The spatial resolution of an optical system is defined by the working distance and the iFoV (instantaneous field of view) (Valenzuela et al. 2024)	**L2-020-OR**
L3-020-IR	Shape model camera spectral range	To collect sufficient spectral radiance reflected from the asteroid surface for an accurate mapping of the surface morphology, a panchromatic camera with QE >= 0.7 at a spectral range of 500 to 800 nm shall be used	The spectral range of 500 to 800 nm covers about 95% of the reflected photons from solar radiation using a typical albedos of 4.5 % observed for Ryugu (Sugita et al.2019)	**L2-020-OR**
L3-021-IR	Shape model camera SNR	The camera shall make use of at least 90 % of the available dynamic range at the expected largest heliocentric distance of ~3 AU (TBC)	High dynamic range is needed to differentiate between surface features.	**L2-020-OR**
L4-010-PR	Data reduction redundancies high-resolution shape model	The acquired medium-resolution images from which the high-resolution shape model will be generated shall be filtered on-board to remove redundant information.	This step reduced requirements to GSE and thus operational mission cost	**L3-040-PR**
L4-020-PR	Data reduction pixel binning high-resolution shape model	The acquired medium-resolution images from which the high-resolution shape model will be generated shall be binned on-board to a spatial resolution of 0.75 m/px to reduce the data volume that needs to be transmitted	This step reduced requirements to GSE and thus operational mission cost	**L3-040-PR**

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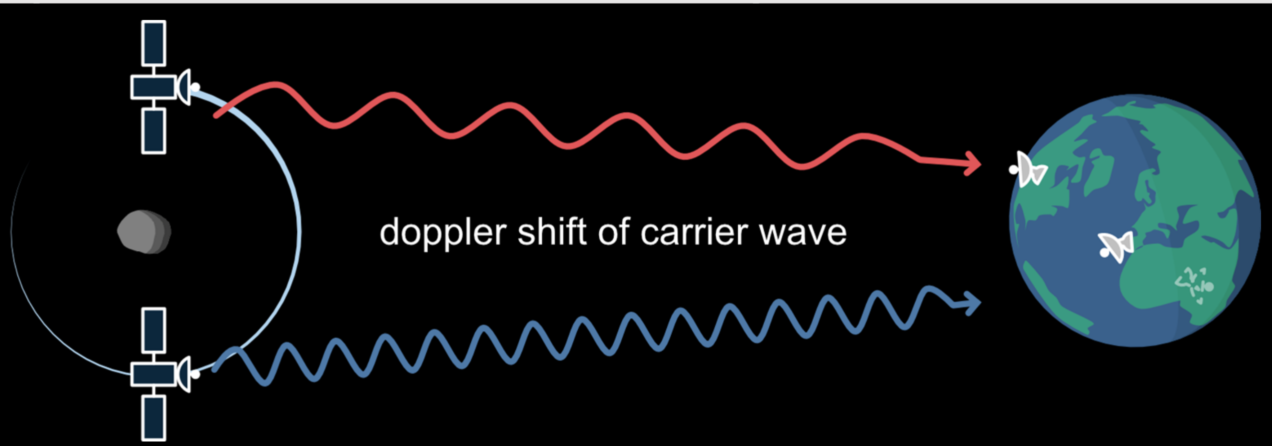

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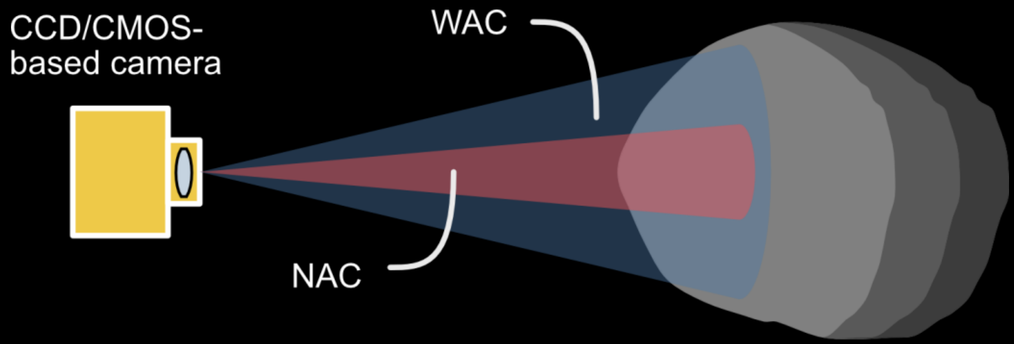

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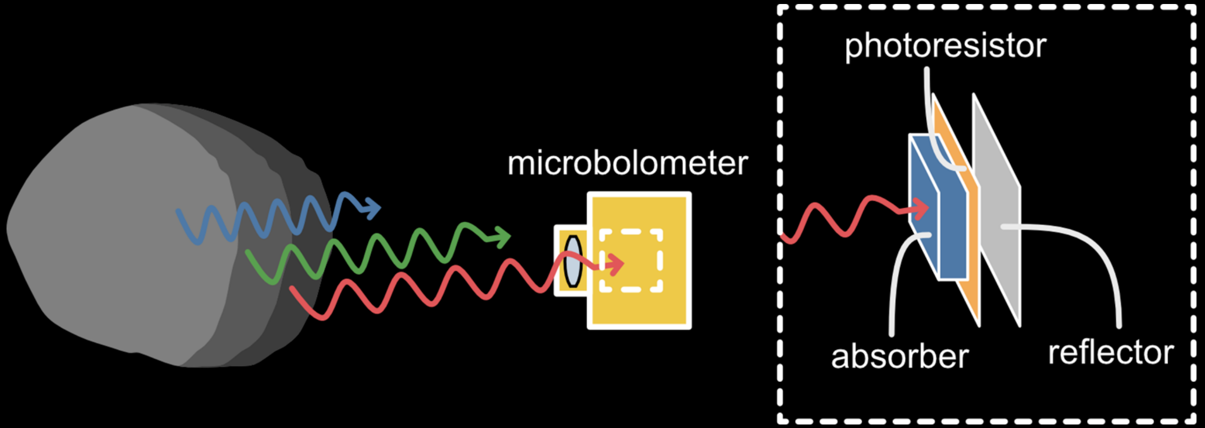

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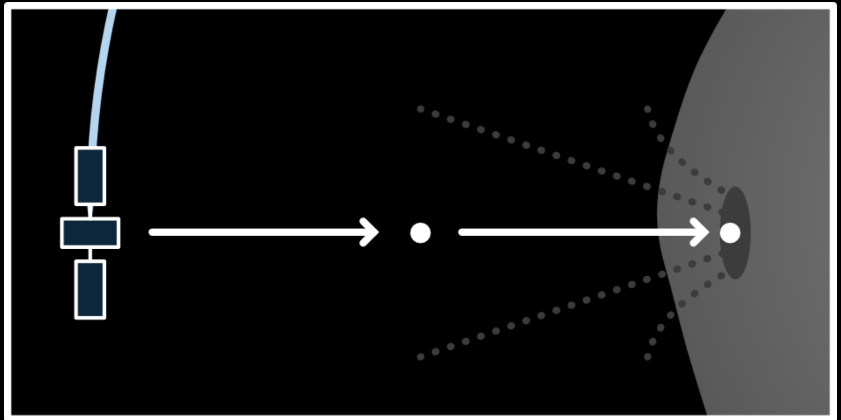

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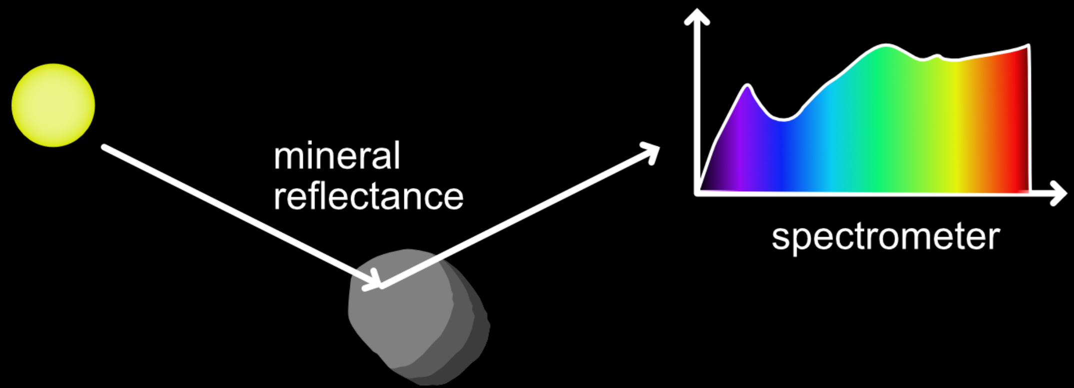

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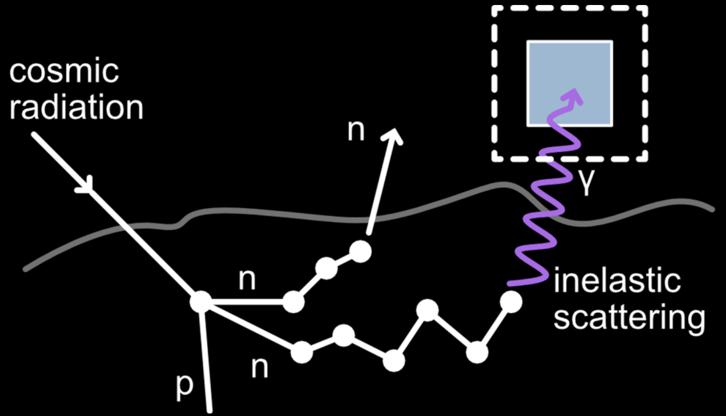
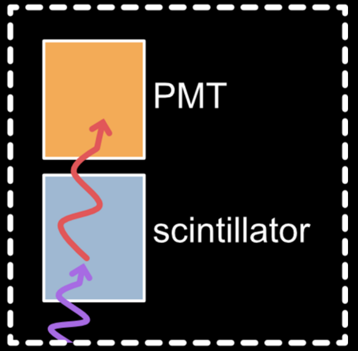
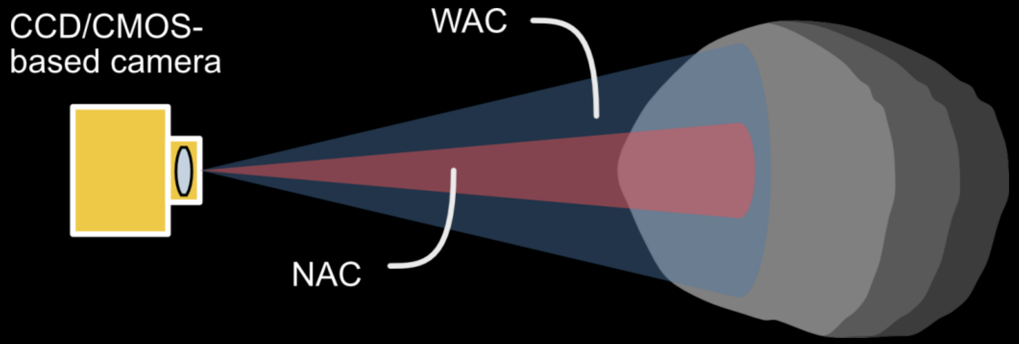




Science Objectives

Scientific Objective	Scientific Requirement	Instrument
SO 2: Evolutionary changes of composition and structure	Surface mineral composition	Hyperspectral Camera
	Surface mineral distribution	Hyperspectral Camera
	Crater size distribution	VIS Camera (WAC)
	Crater spatial density	VIS Camera (WAC)
	Surface regolith size distribution	VIS Camera (NAC)
	Surface features linked to, e.g. weathering, and erosion	VIS Camera (NAC)
		TIR imager
	Surface reddening	Hyperspectral Camera



Instrument selection

Simple overview 

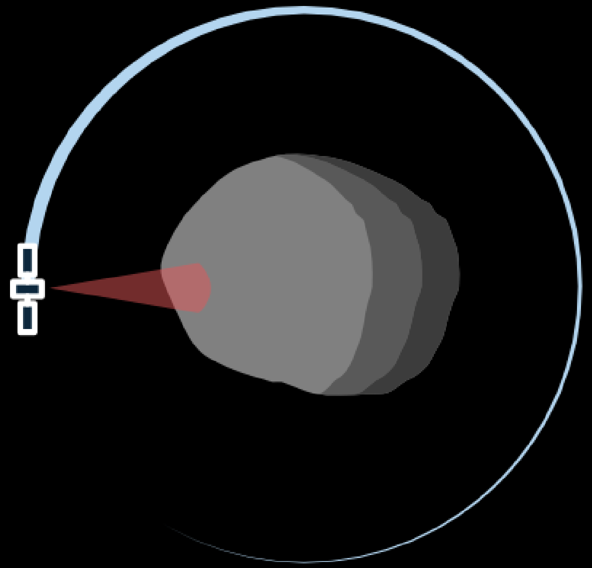
Instrument	Number of related scientific requirements
Hyperspectral camera	4
Wide angle camera	3
Narrow angle camera	3
Thermal infrared imager	3
Radio science antenna	1
Impactor	1
Gamma-ray and Neutron detector	1

Minimum mission success criteria:
Receiving hyperspectral data, shape model and mass of at least three asteroids of different classes

Target selection - target size

Diameter < 5 km

- Higher chance of dust free boulder impacting **boulder temperature** measurement
- Larger crater size increases chance of reaching **primordial composition**
- Faster surface mapping decreases required **operations time**
- Less data volume decreases **downlink time**



Target selection

Simple overview 

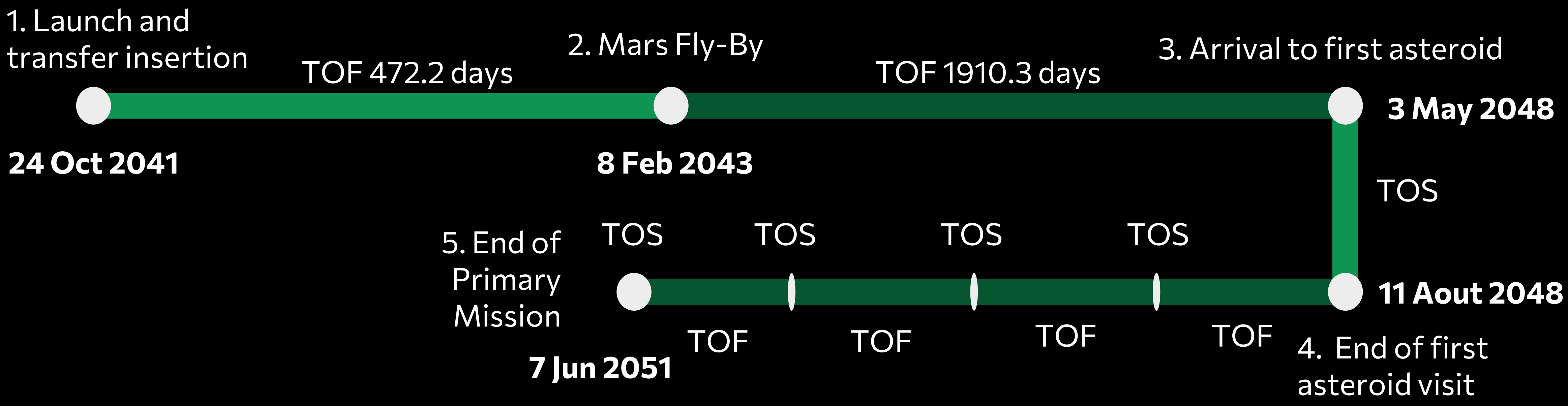
- Plan A
  - Survey to **spectrally characterize** larger number of known bodies < 5 km
  - Target **selection during mission development** phases
- Plan B
  - Start with **target of list** below
  - Search for further reachable **targets of desired classes**

Asteroid name	Spectral class (Tholen)	Diameter [km]
2048 Dwornik (1973 QA)	E	2.6
1920 Sarmiento (1971 VO)	X *	2.9
2491 Tvashtri (1977 CB)	X *	3.3
96177 (1984 BC)	D	3.4
2001 Einstein (1973 EB)	X *	4.0
1355 Magoeba (1935 HE)	X *	4.3

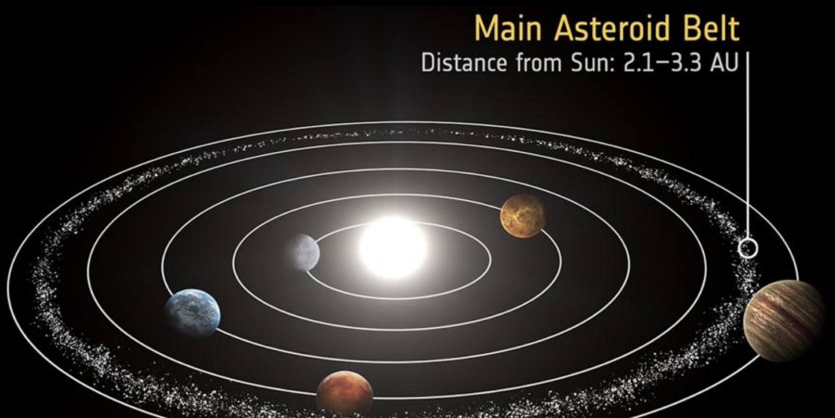
*Currently without known albedo

Mission Design

Mission Design - Timeline



Time of Flight (TOF) - days	Time of Science (TOS) - days
150	100



ESA

Mission Design - DV Budget

Mission Sequence	Wet Mass S/C [kg]	Prop Mass used [kg]	delta-V produced [m/s]	Type of Propulsion
Interplanetary Transfer				
Earth - Mars	4812	315.4	2660	Electric
Mars - Einstein	4496.6	1261.6	12921	Electric
Asteroid Hopping				
Transfer (all 4)	3235	1000	10569	Electric
Asteroid Visit				
Approach Phase (all 5)	2235	12	12	Chemical
Orbital Phase (all 5)	2223	160	260	Chemical
Total				
End of Primary Mission	2063	2749	26422	

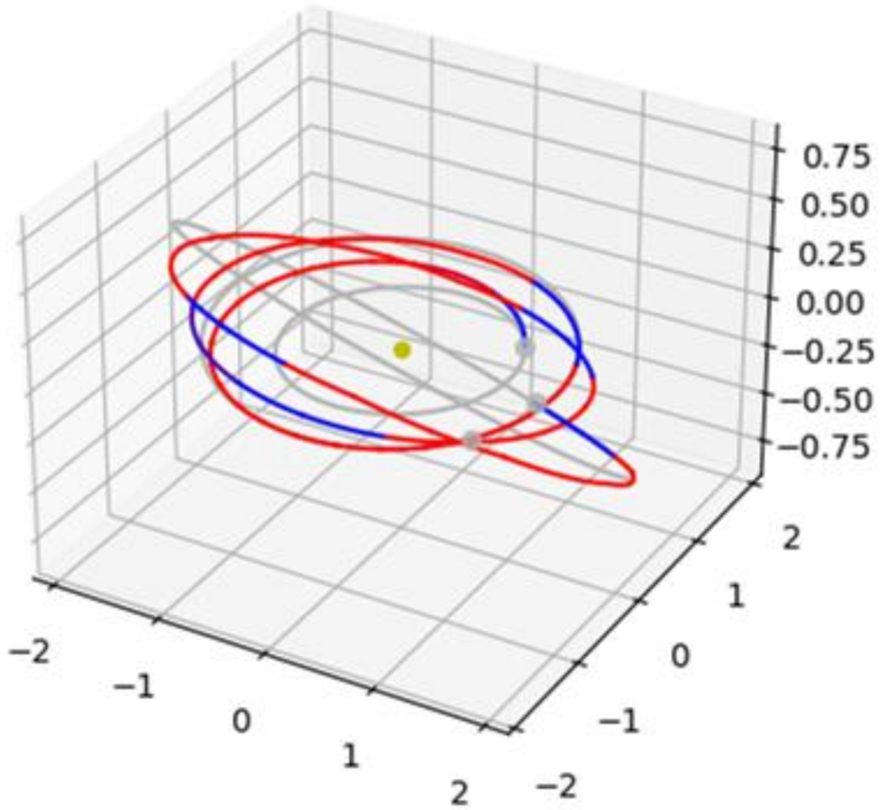
$$\Delta V = \ln\left(\frac{m_0}{m_f}\right) g_0 Isp$$

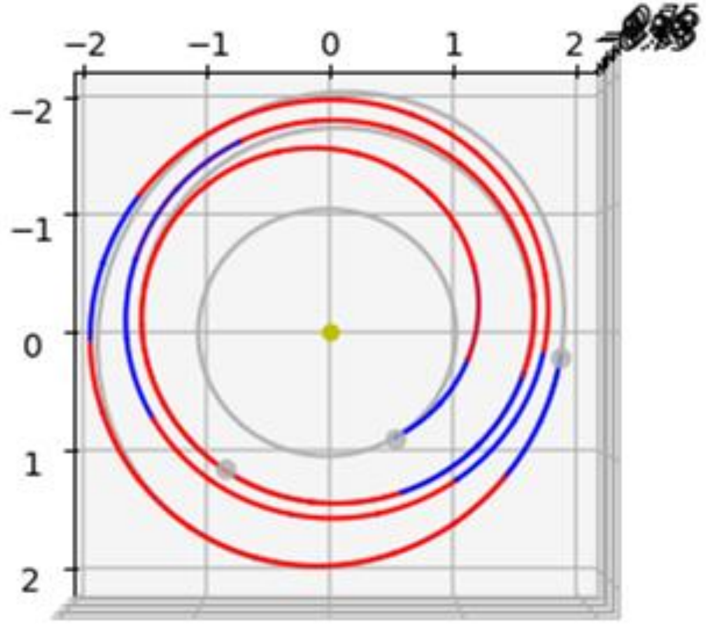
Dry mass: 1493 kg

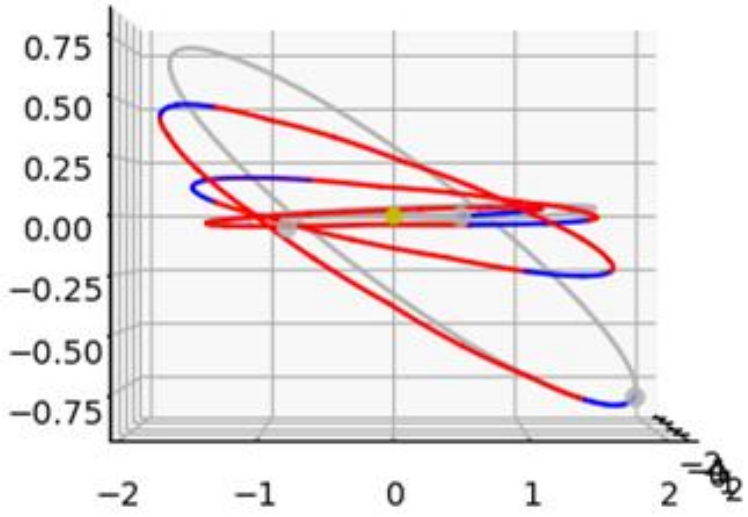
$V_\infty = 3582$ m/s

→ **Margin for the launch window**

Mission Design - Interplanetary Transfer







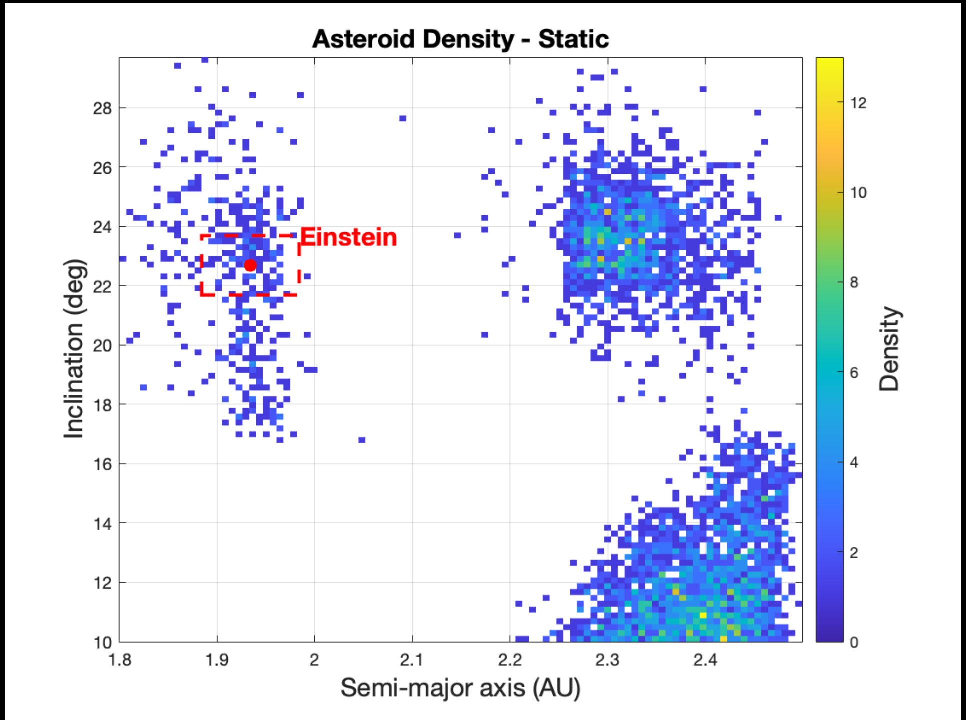
- Units are in AU
- The red trajectory segments are when the thrusters are used

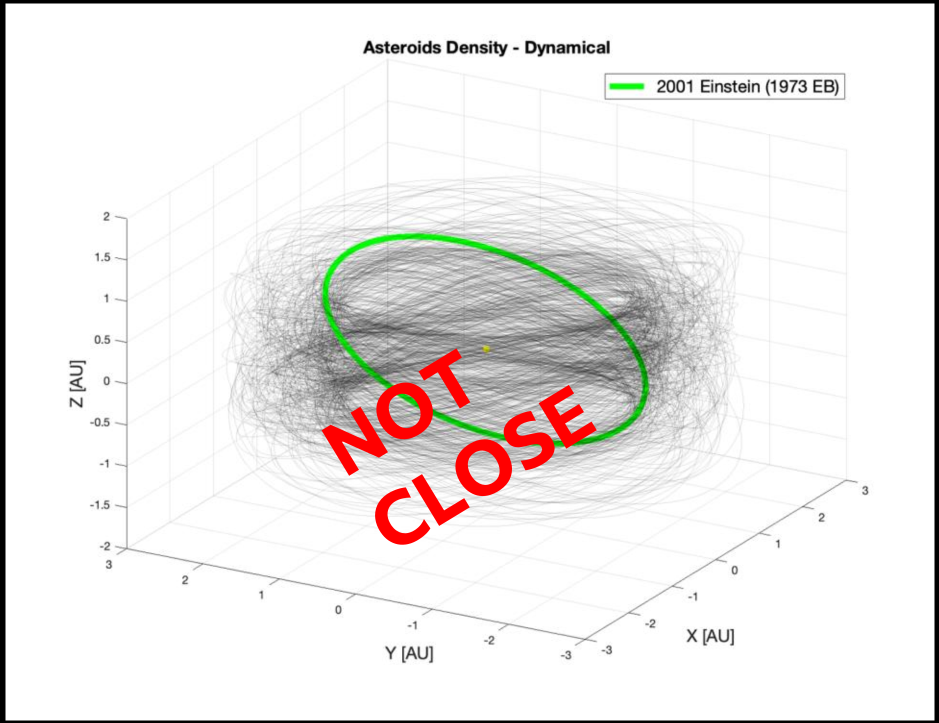
Mission Design - Asteroid Hopping

Asteroid Sequence Generation:

- First Target: Einstein
- Sequence: TBD

Static Analysis





Potential targets ≈ 4000

Mission Design - Asteroid Hopping

Asteroid Sequence Generation:

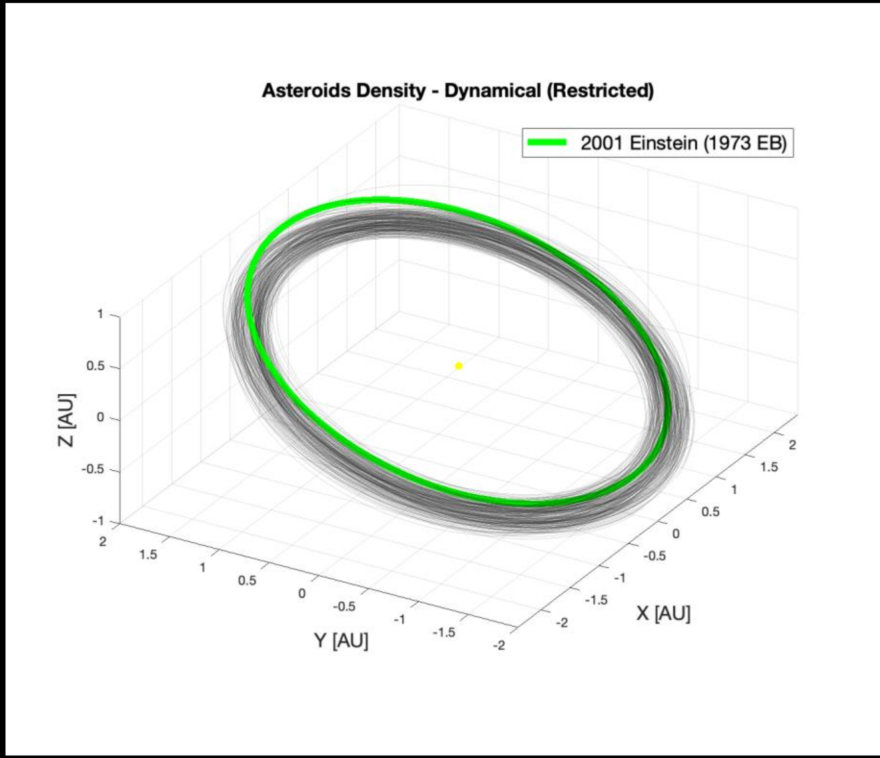
- First Target: Einstein
- Sequence: TBD

- Angular momentum based Searched

$$\vec{H} = \vec{r} \times \vec{v}$$

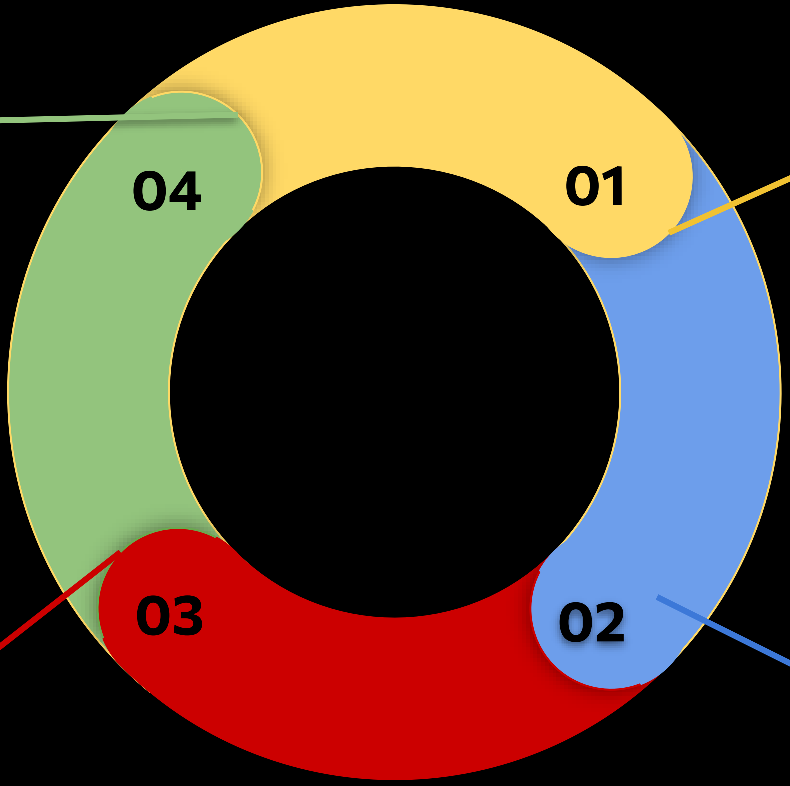
- Potential targets ≈ 200

Dynamical Analysis



BETTER

Mission Design - Asteroid Visit



Departure Phase

Once all the scientific objectives are met (or other critical reason). Leaving the target to the next one

Arrival Phase

Inbound trajectory to the target. Need to slow down and enter the proximity operations mode.

Orbital Phase

Stable orbit and scientific operations during proximity operations. Duration of ~100 days

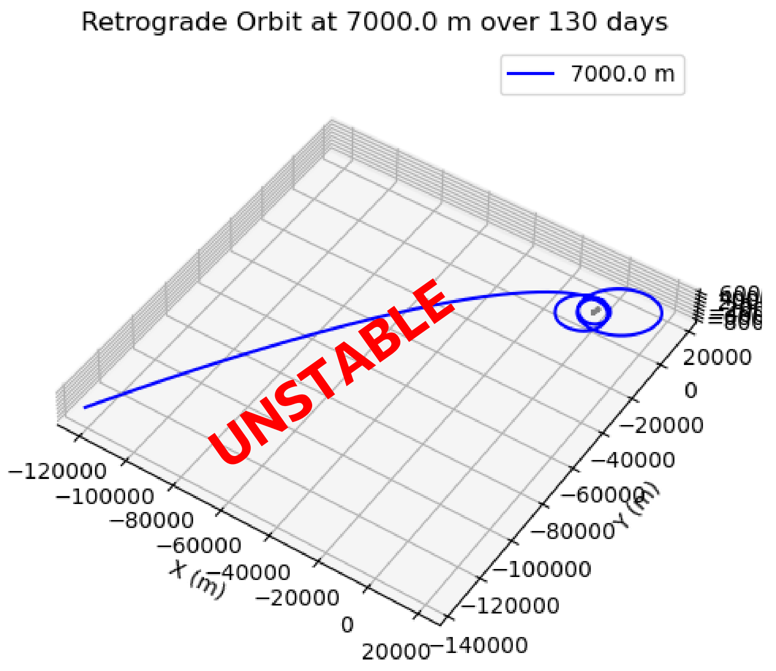
Approach Phase

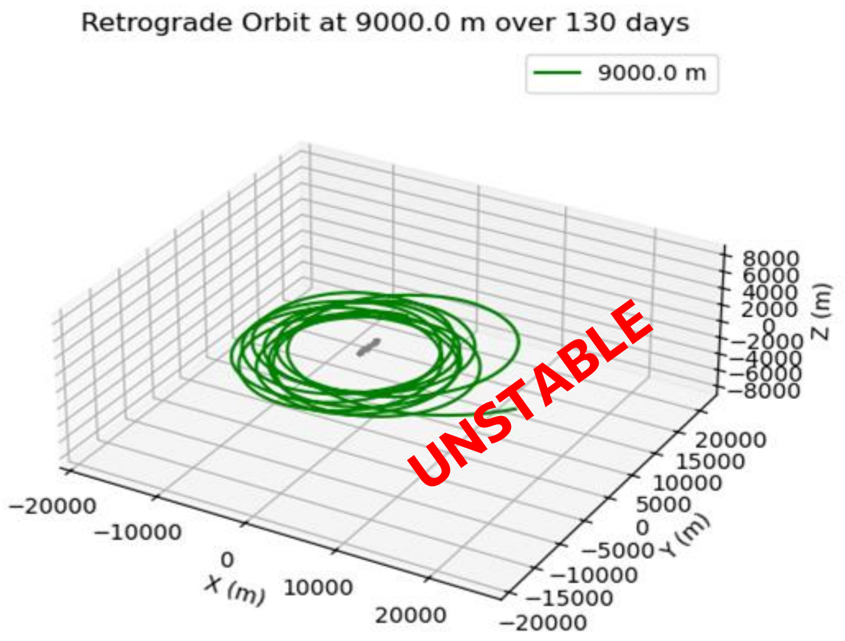
Hyperbolic arcs to characterize the shape of the objects using the cameras and compute the gravity field of the asteroids

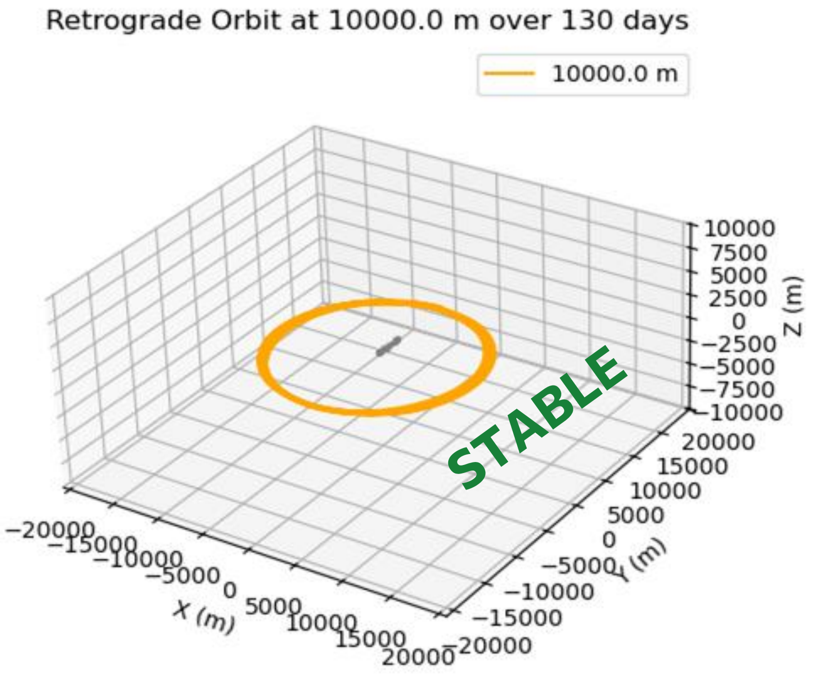
Mission Design - Orbital Phase Analysis

Einstein Asteroid

- D = 3.975 km
- X class
- Revolution period: 5.49 hrs







Mission Design - End Of Life Analysis

- Safe disposal orbit (DRO) vs Impact trajectory compliant with *(SD-OP-03)*
- Passivation Phase *(SD-DE-08)*
  - **Eject remaining** propellant and pressurants
  - **Drain the spacecraft's batteries** completely and ensure lowest internal energy.

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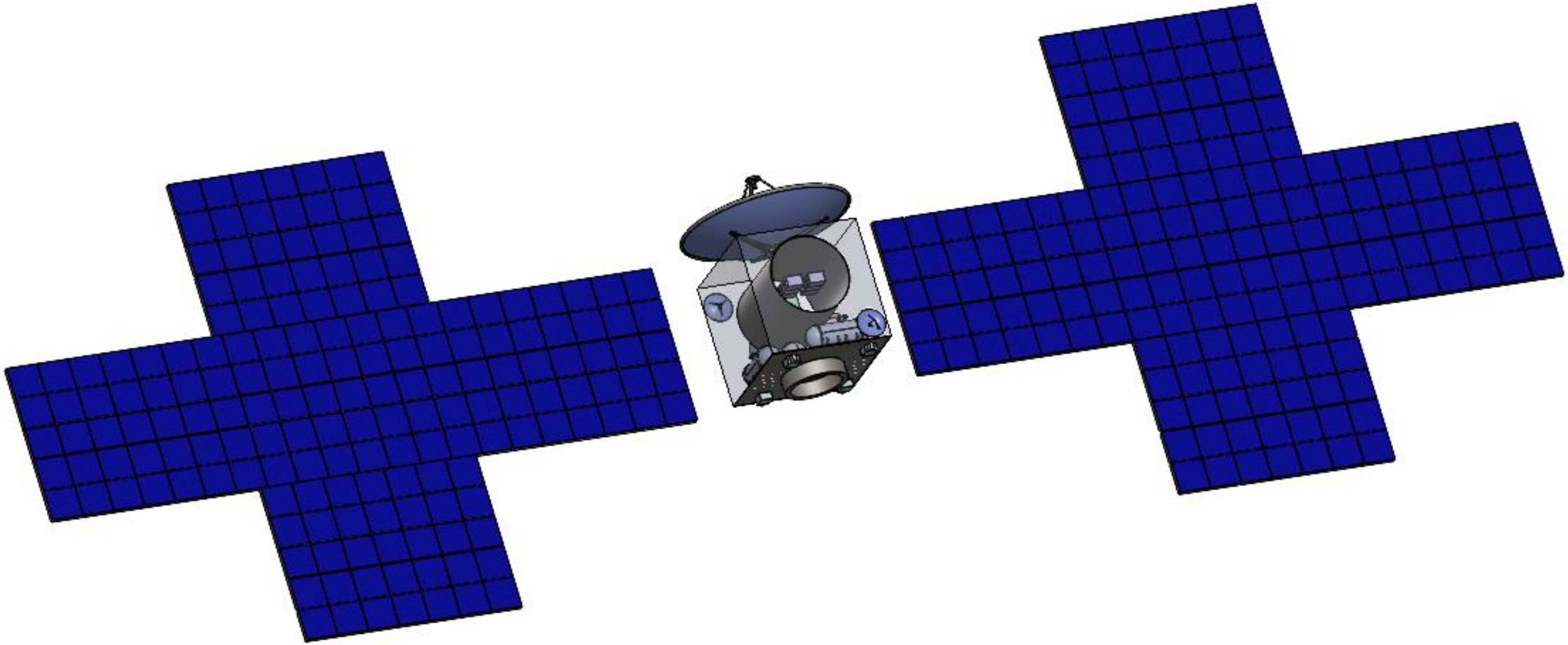
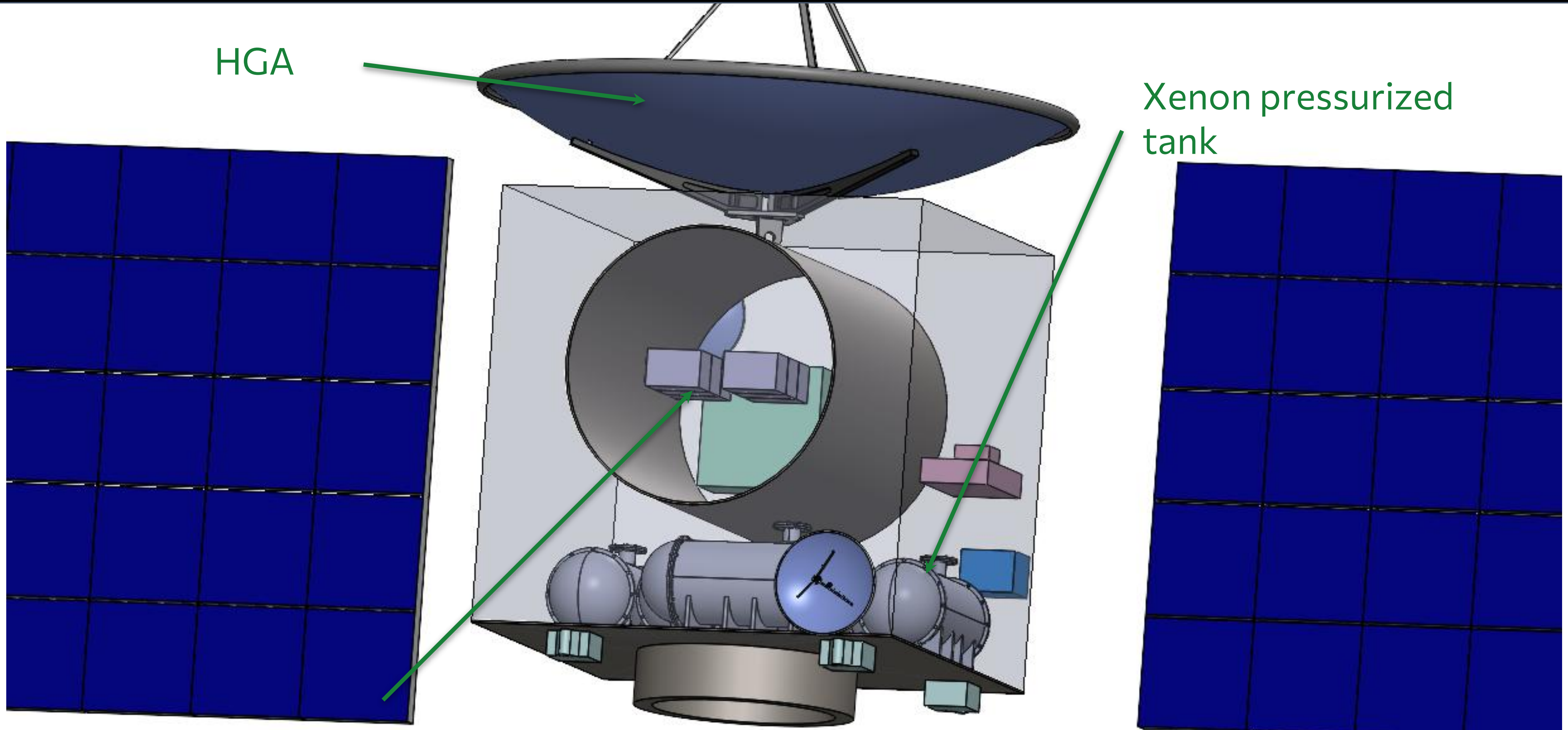
Eurocode Space Debris

Spacecraft

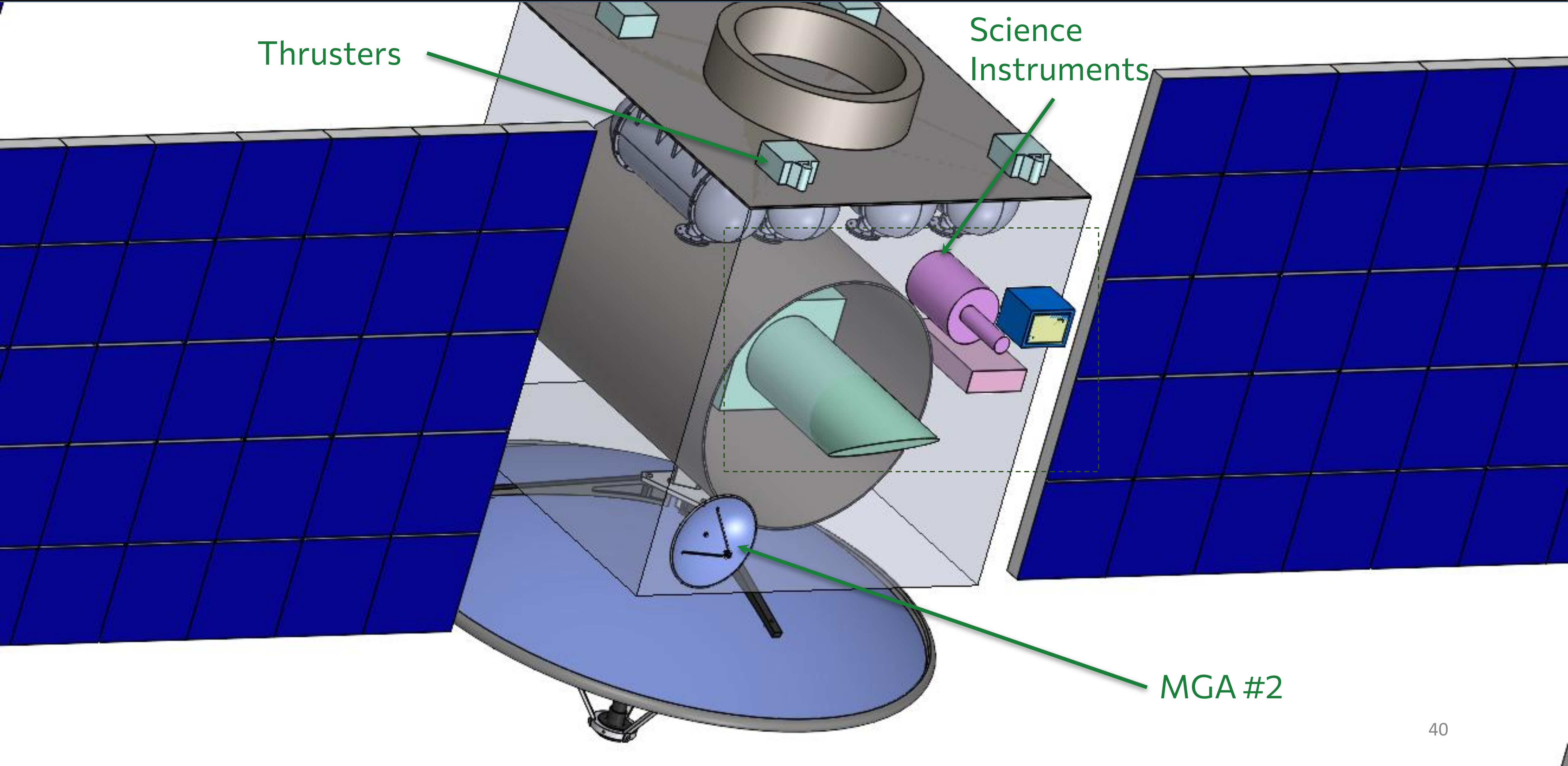
Spacecraft Model



Spacecraft Model



Spacecraft Model

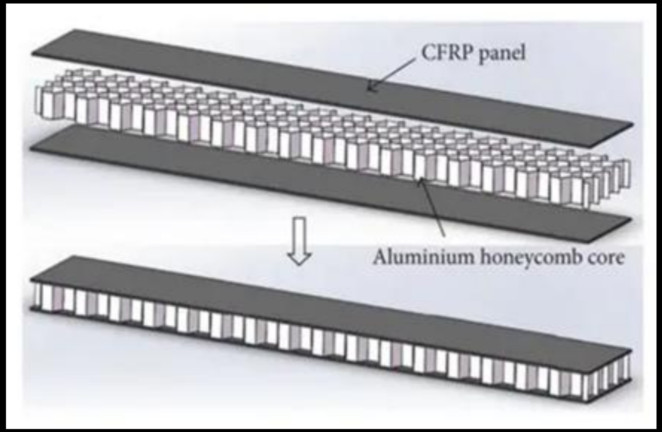


Structure

Primary Structure:
Cube-shaped 2 x 2 x 2 m with a central load-bearing 0.55 m diameter tube.

Bus:

- 6 panels of sandwich structure material (CFRP facesheets + 20 mm Al5052-H39 honeycomb core)
- **High stiffness-to-mass ratio, proper load transfer, thermal and radiation compatibility**



Sandwich panels with aluminium honeycomb core and CFRP skins used in vehicles' body

Central Tube:

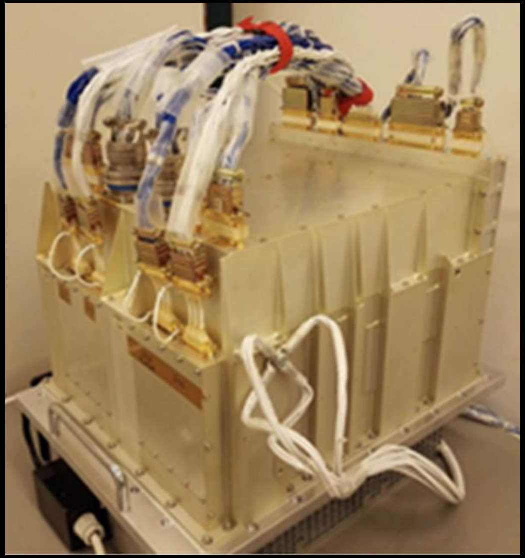
- CFRP 3.5 mm thickness central tube (M55J + cyanite ester resin; 30 orientated plies)
- **Carries axial loads and serves as interface between faces (stability)**

Hera asteroid spacecraft assembled (2023)

Propulsion System

Characteristics	RIT-2X Radio-frequency thruster
Nominal power per unit	4650 W
Nominal thrust per unit	168 mN
Nominal specific impulse	4000 s
Manufacturer	ArianeGroup
Power Processing Unit (PPU)	2x Thales PPU Mk3 cross-strapped
Mass of 4 thrusters + 2 PPUs	~35 kg + ~37 kg = ~72 kg
Propellant	Xenon in five 60L tanks

PPU Mk3



Bourguignon and Fraselle (2019)

RIT-2X

GIESEPP

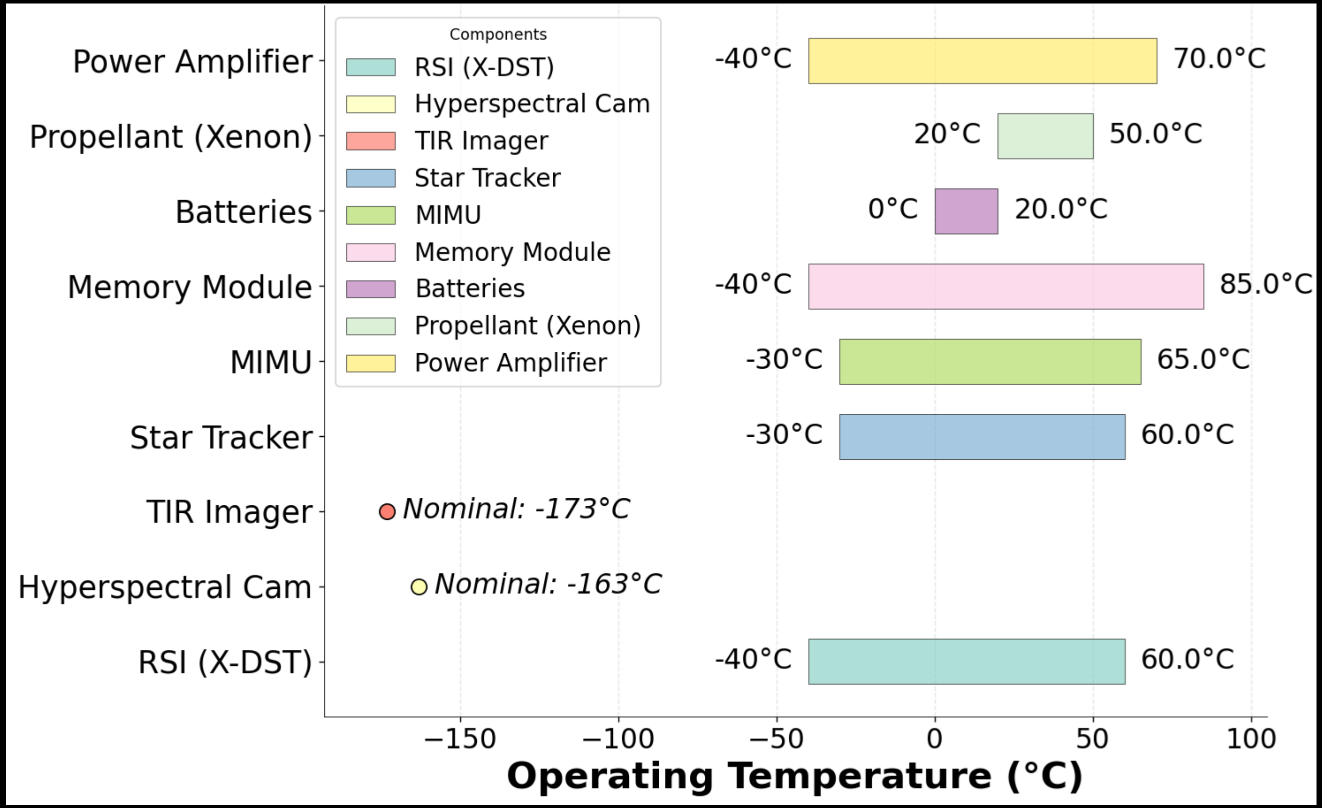
Thermal Control System

Active Thermal Control

- Heaters used for:
  - Batteries (included in the COTS batteries)
  - Electronics
  - Payload instrumentation (WAC, NAC)

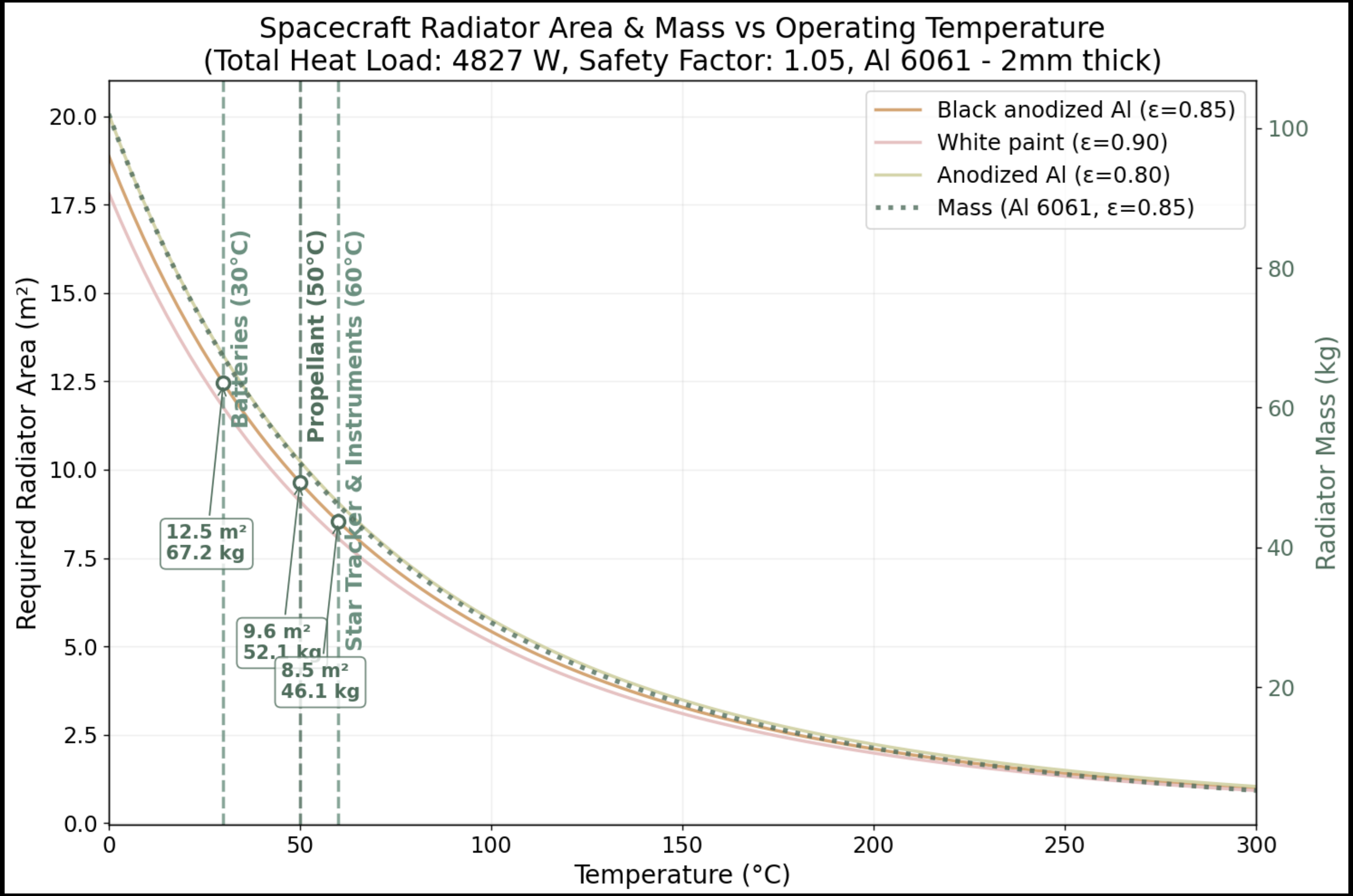
Passive Thermal Control

- MLI
- Passive radiators
- Louvers



Hot case: Radiators in Transfer Mode

Spacecraft



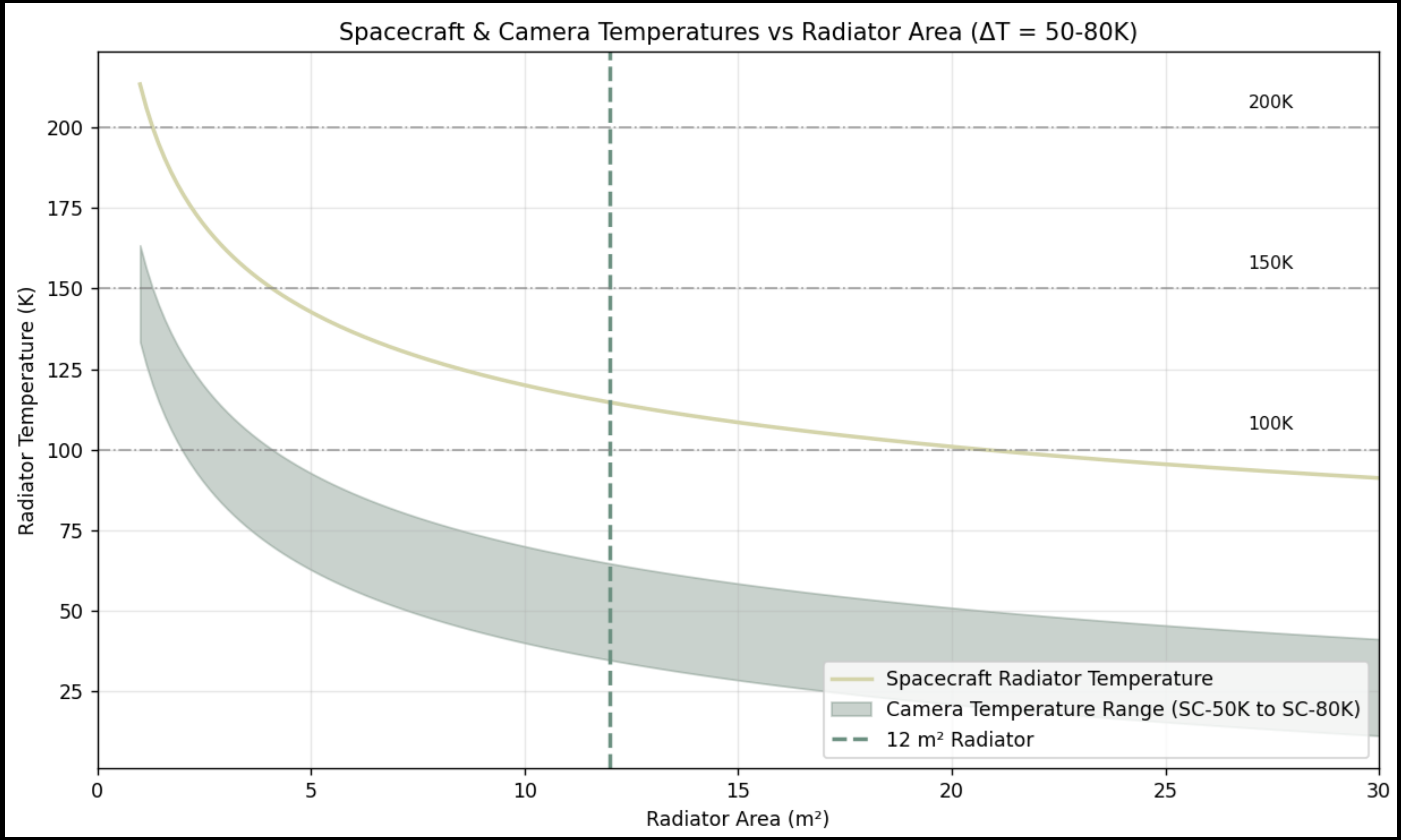
Surface: 12.5 m^2 for black anodized Al

Mass: 67.2 kg

Transfer mode (highest power consumption)

Hot case: Radiators in orbit

Spacecraft



Spacecraft - Instruments ΔT assumption: 50-80 K

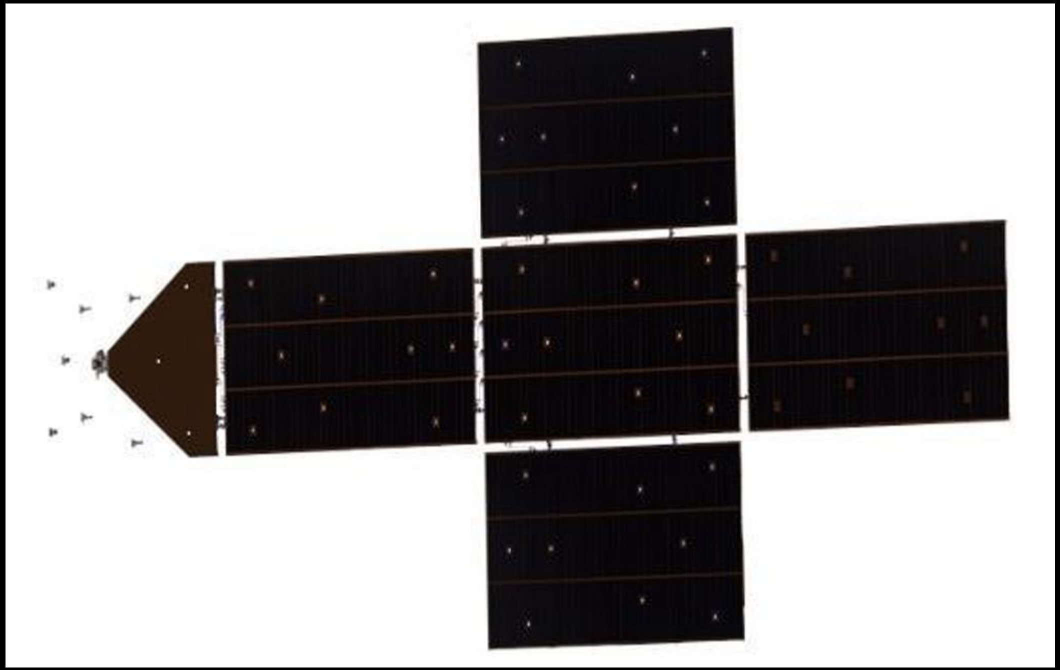
1. **Separate radiator on the instruments and extra MLI and isolation for 100K operational temperature**

1. **Louver: compensation for the different environments**

Science mode in orbit: instruments low temperature restrictions

EPS: Solar Array Design

Heritage	JUICE / Europa Clipper
Solar array area (2 wings)	90 m^2
Total weight	~350 kg
Panel dimensions	~3.5 x ~2.5 m
Deployed wing length	~12.4 m
Solar cells	Azure 3G28
Efficiency BOL/EOL	28% / ~17%
Power BOL/EOL @ 1 AU	34 kW / 23 kW
Power BOL/EOL @ 2.1 AU	7.7 kW / 5.2 kW
Power BOL/EOL @ 2.8 AU	4.3 kW / 2.9 kW
Power BOL/EOL @ 3.3 AU	3.1 kW / 2.1 kW

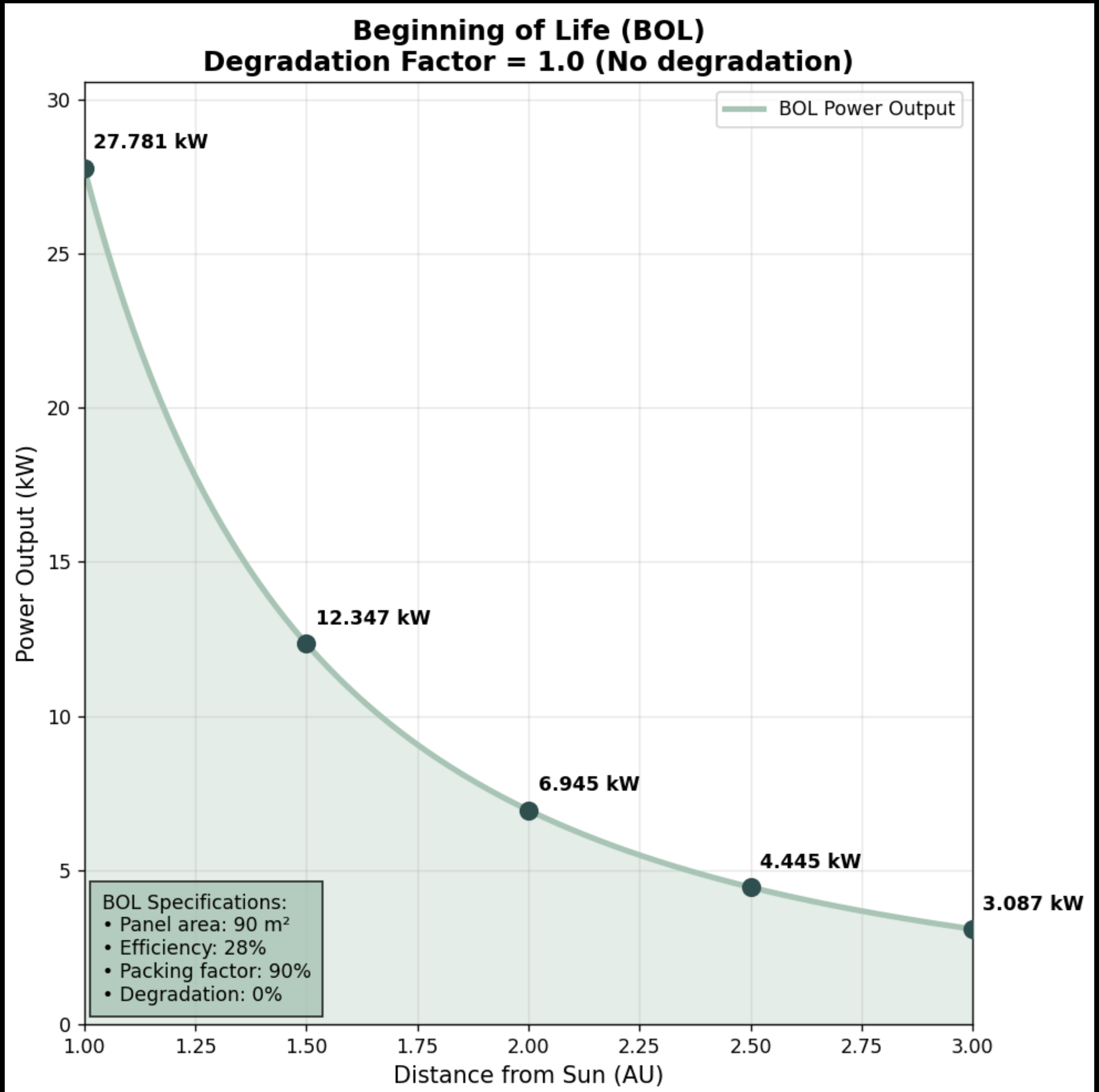


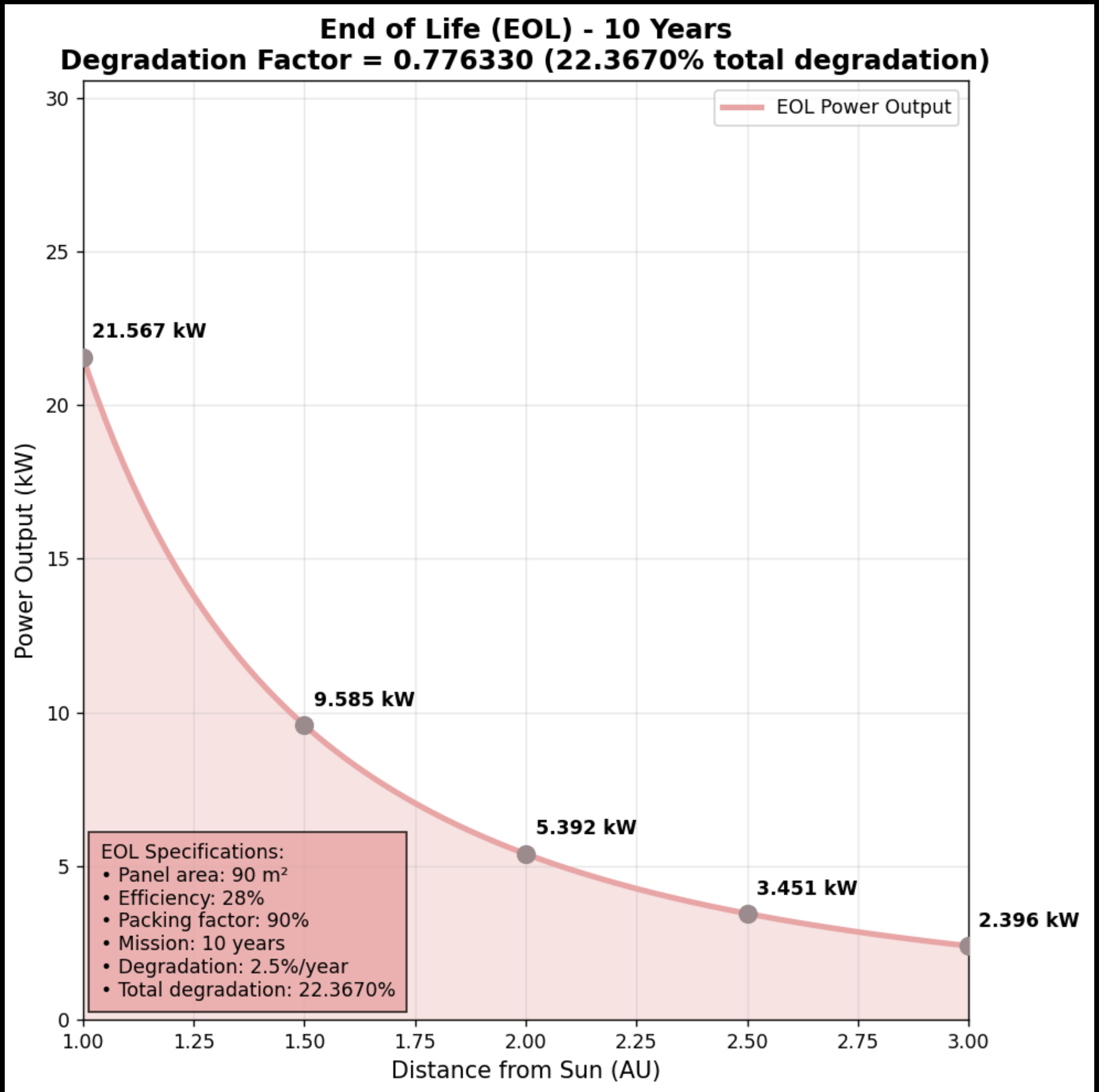
AIRBUS

PCDU: AIRBUS PSR 100V MKII with a power capability of 11 kW.
Battery pack: 2 x Li-ion with 144Ah (=9 kWh @ 48 V) each.

EPS: Solar Array Degradation

Spacecraft





Attitude Determination and Control System

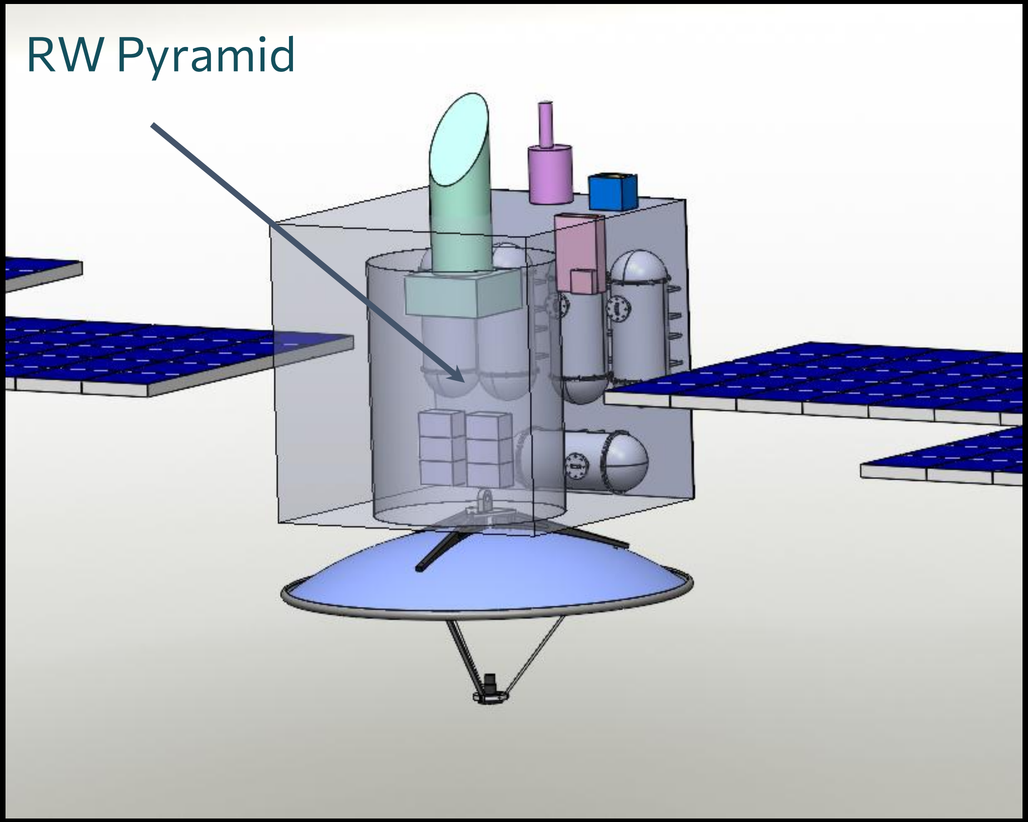
3-axis control is achieved with:

Actuators

- 4x **Reaction Wheels**
- 12x **Thrusters** for desaturation

Sensors

- 2x **Star Trackers**
- 6x **Sun Sensors**
- 1x **MIMU** (Miniature Inertial Measurement Unit, RLG)



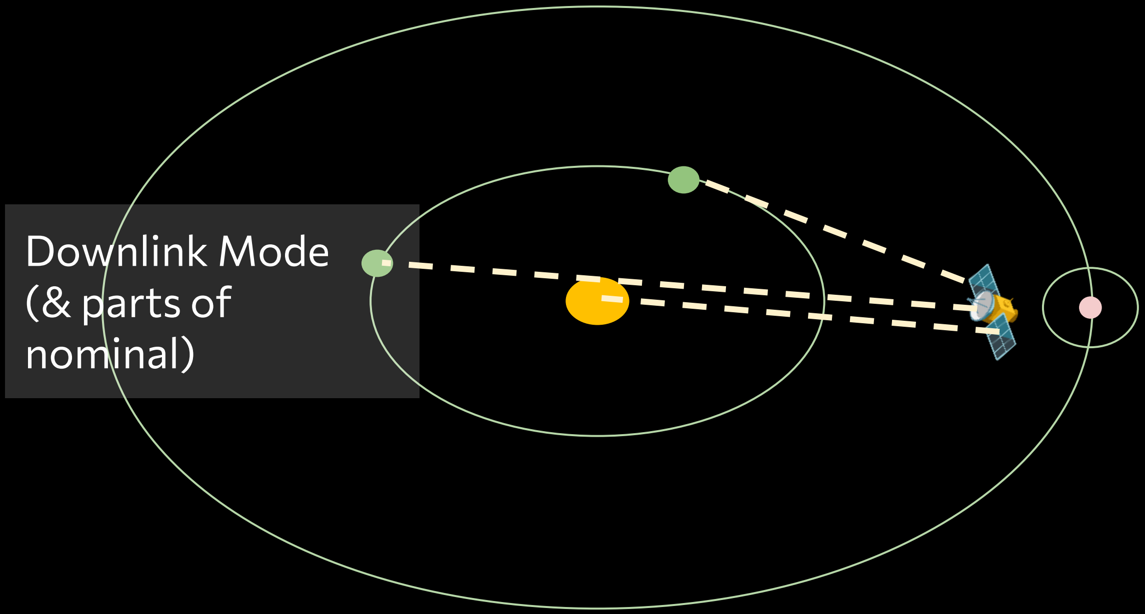
Pointing

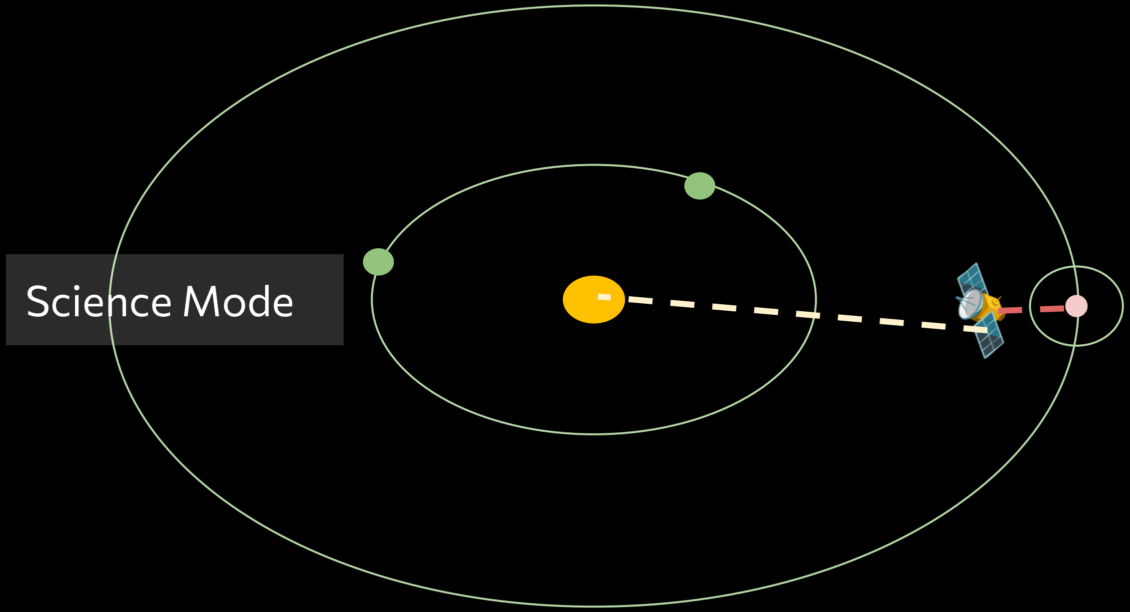
Spacecraft

Solar panels: pointing mechanism

HGA: gimbaled (to be used during Downlink Mode)

MGA: pointing mechanism (to be used for housekeeping during Science Mode, Transfer Mode)





Scientific Instruments: All instruments point to the surface of the asteroid with 3-axis control

On-board computer (OBC)

Processor

- (Based on) GR-SBC-GR740 board by Frontgrade
- Radiation-hardened
- 200 Mbps links
- GR740 processor is on European Preferred Parts List, flown in missions
- 1-out-of-2 redundancy

Mass storage

- 10x UT81NDQ512G8T SSDs = 40 TB
- Radiation-hardened
- Enough to keep all data before computer chooses what to downlink
- Drive failure redundancy

Main SW requirement: steer autonomously for >1.5 hours (back and forth communication time)

GR-SBC-GR740, in development, Frontgrade

UT81NDQ512G8T SSD, Frontgrade

Communication

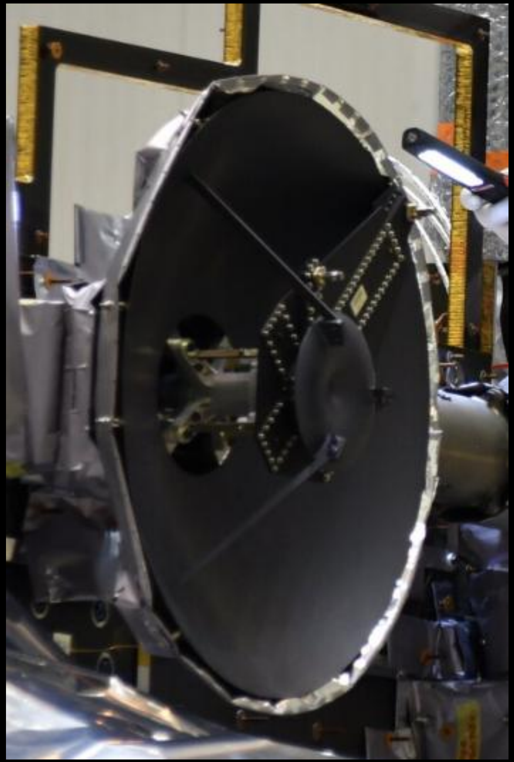
HGA (gimbaled)

- Diameter: 3 m
- Band: X and Ka
- Gain: ~58 dB
- Use: **Downlink Mode and radio science**
- Heritage: Mars Reconnaissance Orbiter

MGA * 2 (steerable)

- Diameter: 0.5 m
- Band: X and Ka
- Gain: ~50 dB
- Use: **Safe mode, Transfer Mode, housekeeping during Science Mode**
- Heritage: JUICE

Mars Reconnaissance Orbiter



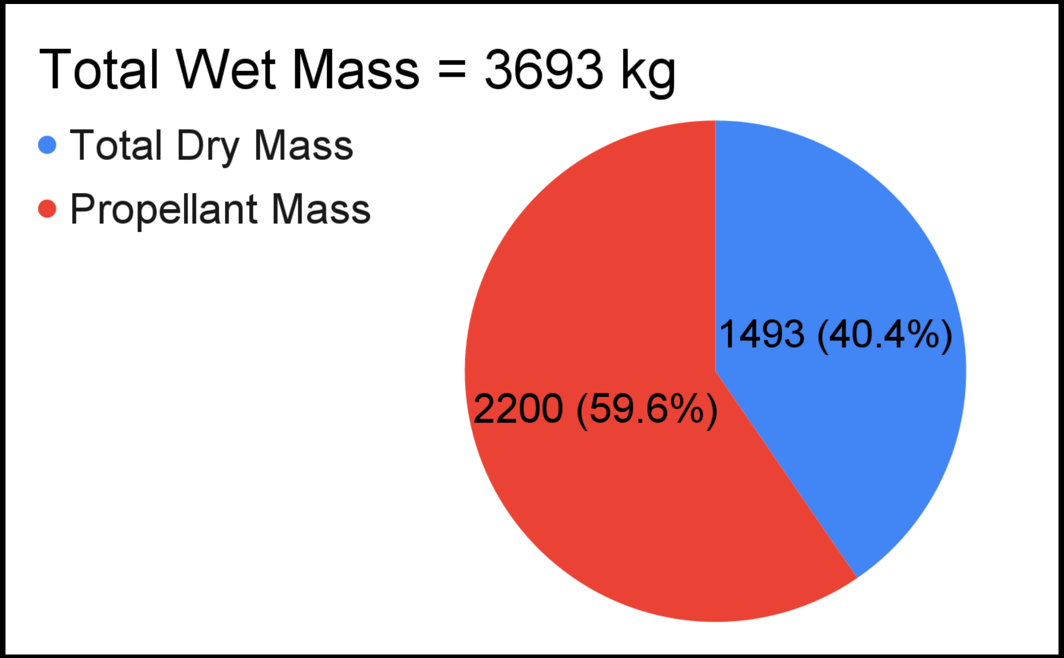
JUICE's Medium Gain Antenna Subsystem (MGAMA)

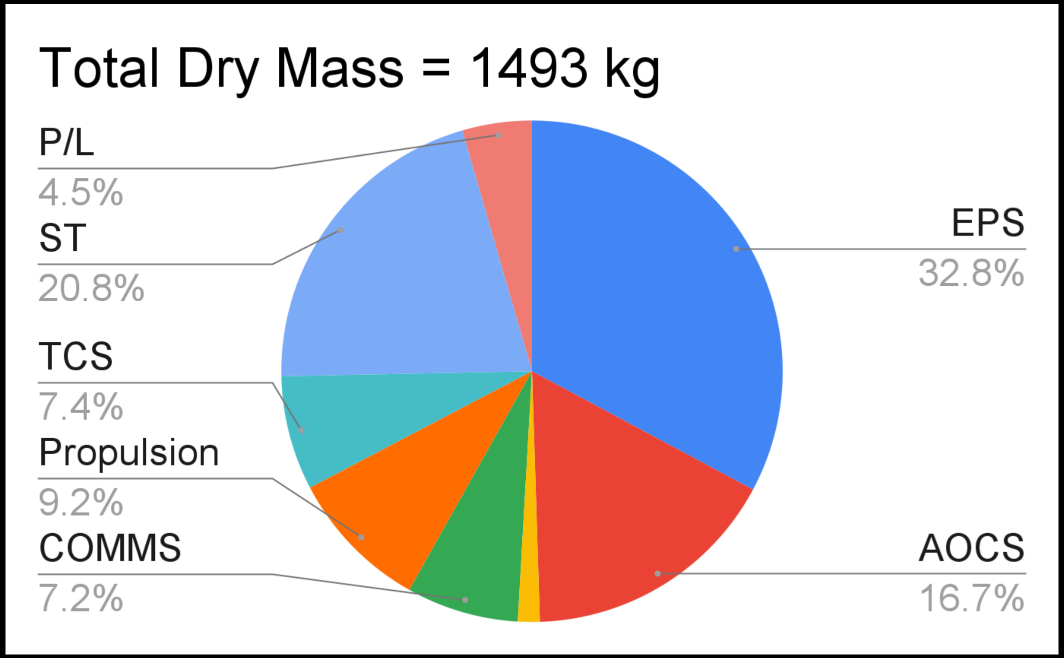
Budgets

Mass Budget

Subsystem	EPS	AOCS	OBC	COMMS	Propulsion	TCS	ST	P/L	Total Dry Mass
Mass [kg]	490	249	21	108	137	110	311	67	**1493**

EPS: Electric propulsion system | AOCS: Altitude and orbit control system | OBC: On-board computer | COMMS: Communication system | Propulsion: Thrusters + PPU | TCS: Thermal control system | ST: Structure | P/L: Payload





Power Budget

Subsystem	Nominal power per mode (W)						
	TM	**IM**	**ScM**	**SM**	**DM**	**CM**	**AM**
EPS	80	80	80	32	80	32	80
AOCS	95.4	173.4	147.4	43.7	169	0.72	169
OBC	19.5	19.5	19.5	7.8	19.5	7.8	19.5
COMMS	87.6	87.6	75.6	24	292	0	120
Propulsion	9320	0	0	0	0	0	0
STC	10	10	10	5	10	6	10
TCS	100.7	100.7	100.7	60.4	100.7	0	100.7
P/L	0	0	96.3	0	0	0	18.515
Total Power (W)	**11656**	565.4	635.4	207.5	805.4	55.8	621.2

Legend	
TM	Transfer Mode
IM	Idle Mode
ScM	Science Mode
SM	Safe Mode
DM	Downlink Mode
CM	Commissioning Mode
AM	Approach Mode

Data Budget

- *Downlink is limiting, storage is not*
- Estimate = Surface area · proportion imaged · required bits per cm^2 / compression
- 3 levels
  - quick low res model for decisions
  - medium res global model
  - high res interesting features
- Assumptions
  - asteroid diameter = 7 km
  - downlink speed 1.3 GB/h at 8 h/day
  - lossless compression with 2.5 : 1 ratio

Model type	Instruments	Ratio of surface	Data created [GB]	Compressed data [GB]	Downlink time [days]
preliminary	WAC, HS cam	1	52.88	21.15	2.03
global	WAC, HS cam, TIR imager, spectrometer, RS antenna	1	170.95	68.38	36.92
local	NAC, HS cam hi-res	0.2	394.47	157.79	
post-impact	NAC, HS cam hi-res	0.2	394.47	157.79	

39 days to downlink, 100+ days between asteroids ✓

Link Budget

Distance: 1.2 au to 4 au

Transmission loss
≈ -280 dB (X-band)
≈ -292 dB (Ka-band)

Antennas	Frequency band	Data rate (GB/h)	Data rate (GB/h)
HGA	X-band	0.18	0.036
MGA	X-band	0.0058	0.0009
		Standard	**Worst case**

Uplink

Antennas	Frequency band	Data rate (GB/h)	Data rate (GB/h)
HGA	Ka-band	1.3	0.225
MGA	X-band	0.006	0.0011
		Standard	**Worst case**

Downlink

Data Budget

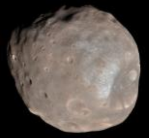
Downlink of low resolution data (**21.15 GB**) and **GS intervention** (2 days)

Impact

Collected Data	**68.38 GB**	**157.79 GB**	**157.79 GB**
Collection Time	**20-25 days**	**5-8 days**	**5-8 days**
	Detailed mapping of the full surface (WAC, TIR, Hyperspectral Camera)	Areas of interest (10-20%) with NAC, TIR, Hyperspectral Camera	Impact Area observation (NAC, TIR, Hyperspectral)

High resolution Data Downlink (36.92 days in total)

Instruments - Payload



Summary

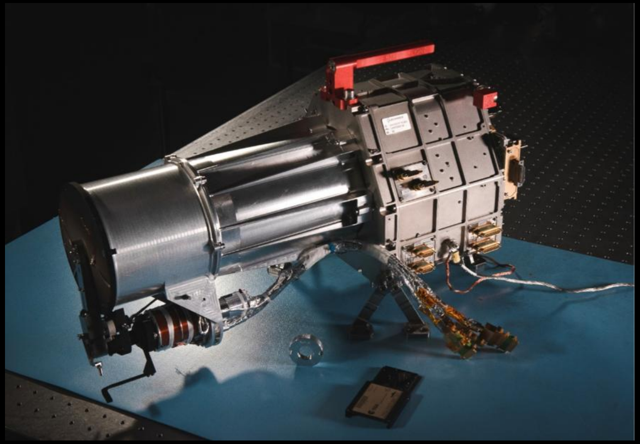
Instrument	Mass [kg]	Power [W]	Data Rate [kbps]	TRL	Heritage
Hyperspectral Cam	10.2	17	53’000	7	MIRS (MMX)
TIR Imager	3.9	16	12’600	7	TIRI (Hera)
RSI (X-DST)	3.2	12.5-19.5	4	7	X-DST (Hera)
Gamma Ray and Neutron Spectrometer	10.5	12	3.1	6	GRaND (Dawn)
WAC	5.5	17	16’000	6	FC (Dawn)
NAC	2.89	5	56’000	6	JANUS (JUICE)
Impactor	20.2	8	-	3	Hayabusa 2

Instruments - examples

- *Payload instruments will be better defined during phase B* of the mission, following our instrument requirements
- There are instruments in literature which show that the requirements can be fulfilled:

Narrow Angle Camera (NAC)

- **VIS mapping** (regolith size and distribution, boulder surface)
- Spatial resolution: 2.5 cm/px at 1 km distance
- *JANUS (JUICE)*



The JANUS (Jovis Amorum ac Natorum Undique Scrutator) VIS-NIR Multi-Band Imager for the JUICE Mission

Wide Angle Camera (WAC)

- **Asteroid surface mapping**
- Spatial resolution: 9.3 cm/px at 1 km distance
- *FC (Dawn)*

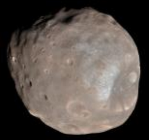
The Dawn Framing Camera

Small Deep-Space Transponder SDST)

- **Determine the asteroid mass**
- The instrument shall be able to detect velocity changes smaller or equal to 3 μm/s over 1000 s
- *X-DST (Hera)*

Small Deep-Space Transponder (SDST) Reliable X-Band and Ka-Band Deep Space Transmission

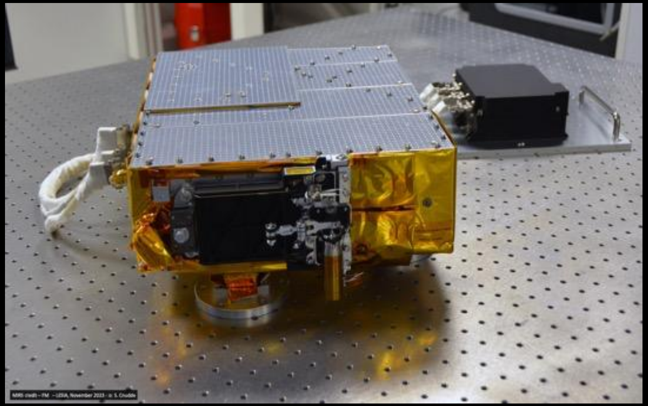
Instruments - examples



- *Payload instruments will be better defined during phase B* of the mission, following our instrument requirements
- There are instruments in literature which show that the requirements can be fulfilled:

Hyperspectral Camera

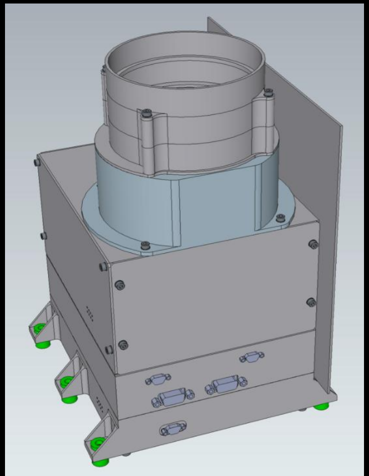
- Determine **surface and subsurface composition, and distribution, surface reddening**
- Spectral range 0.9-3.4 μm, spectral resolution 20 nm, spatial resolution 12.8 cm/px
- *MIRS (MMX)*



Design and performance of MIRS infrared imaging spectrometer onboard MMX mission

Thermal InfraRed Imager (TIRI)

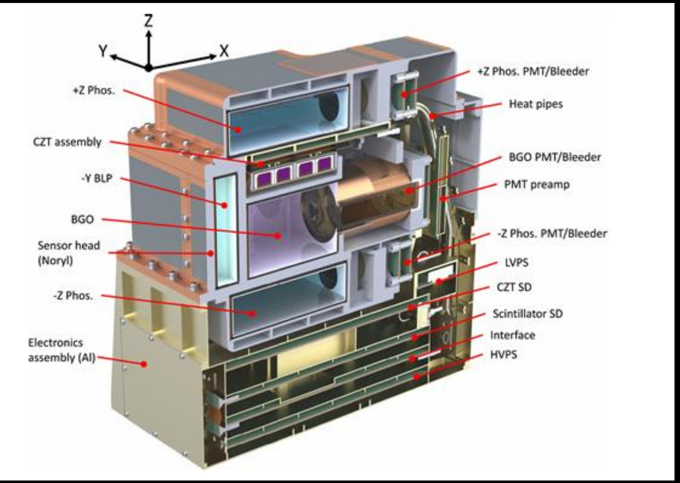
- **VIS mapping** (regolith size and distribution, boulder surface)
- Temperature range 80-350 K, temperature resolution <1 K, spatial resolution of 12.8 cm/px
- *TIRI (Hera)*



Thermal InfraRed multiband Imager TIRI for ESA Hera, mission to Didymos binary asteroid

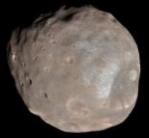
Gamma ray and neutron emission detector

- Detect important **major rock-forming and volatile forming elements** (including H, K, Si, O, Mg, Al, Ca, Fe, C, Cl)
- Resolution of 1.5 times the orbital height
- *GRaND (Dawn)*



Dawn's Gamma Ray and Neutron Detector

Impactor

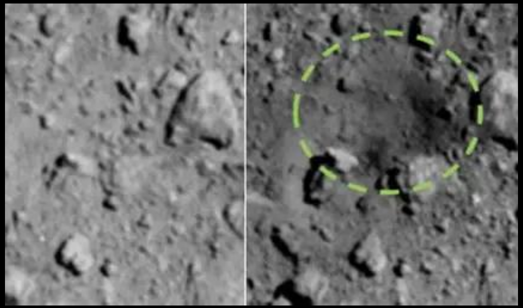


Requirements:

- **5 kinetic impacts** that generate a 20 cm depth crater with a radius affectance of 0.75 m from a 1 km distance.
- **No destabilization** of the spacecraft
- **No interference** with the scientific instruments
- ESA-qualified components
  (mainly the explosive)

Projectile:

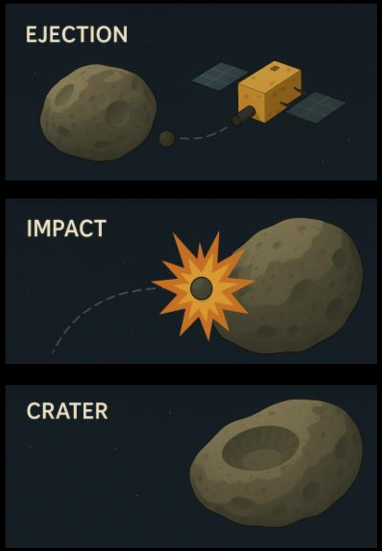
- 6 hollow marbles (redundancy) of zirconium
- 0.04 m radius
- 2.5 mm thickness
- 270 g mass
- 450 m/s impact velocity

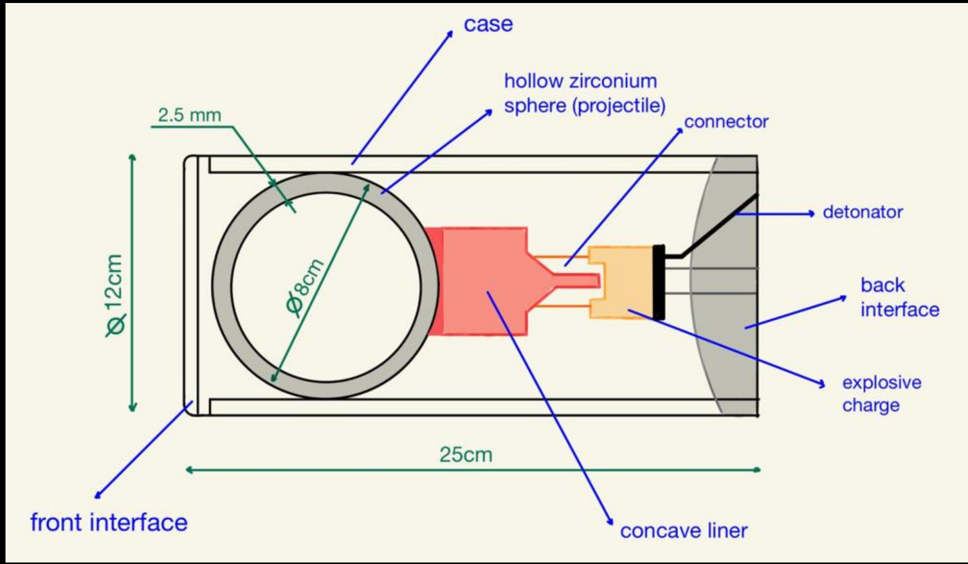


Pictures confirm Hayabusa2 made a crater in asteroid Ryugu

Mechanism:

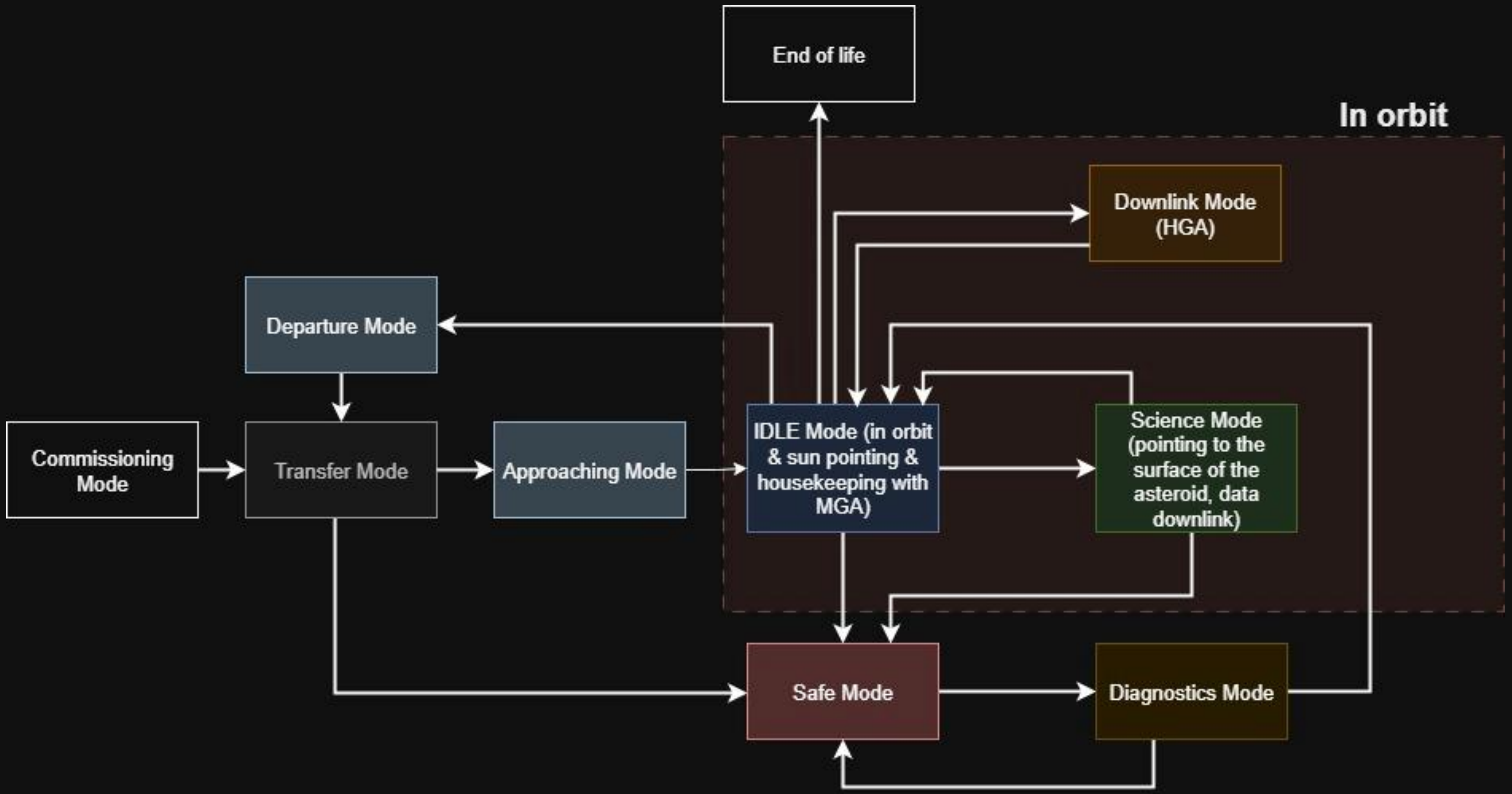
- SCI-type (Hayabusa2)
- 6 ejectors: ejection plate, conical liner, internal electronics.
  15.7g of HMX per impact
- Blast shielding, electrical safe device, thermal and pressure-resistant casing





Operations

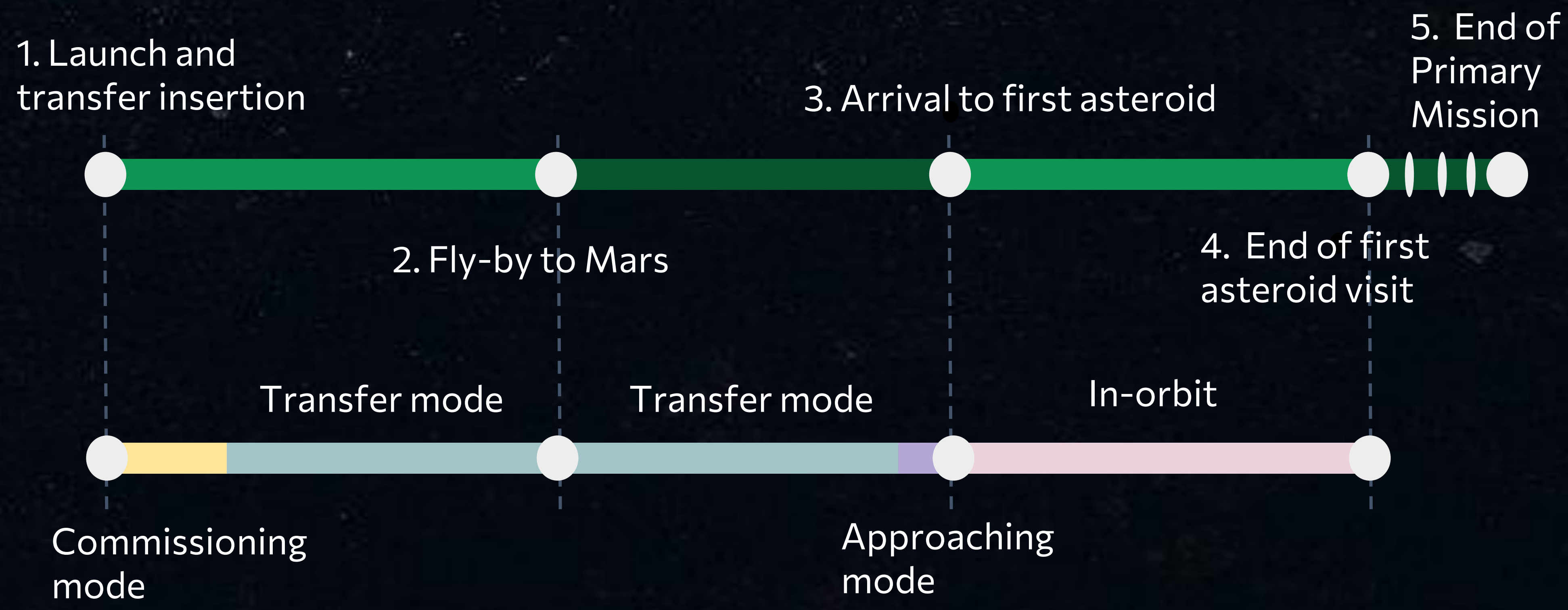
CONOPS


End of life
In orbit
Downlink Mode (HGA)
Departure Mode
Commissioning Mode
Transfer Mode
Approaching Mode
IDLE Mode (in orbit & sun pointing & housekeeping with MGA)
Science Mode (pointing to the surface of the asteroid, data downlink)
Safe Mode
Diagnostics Mode

Mission Timeline

CONOPS

Operations



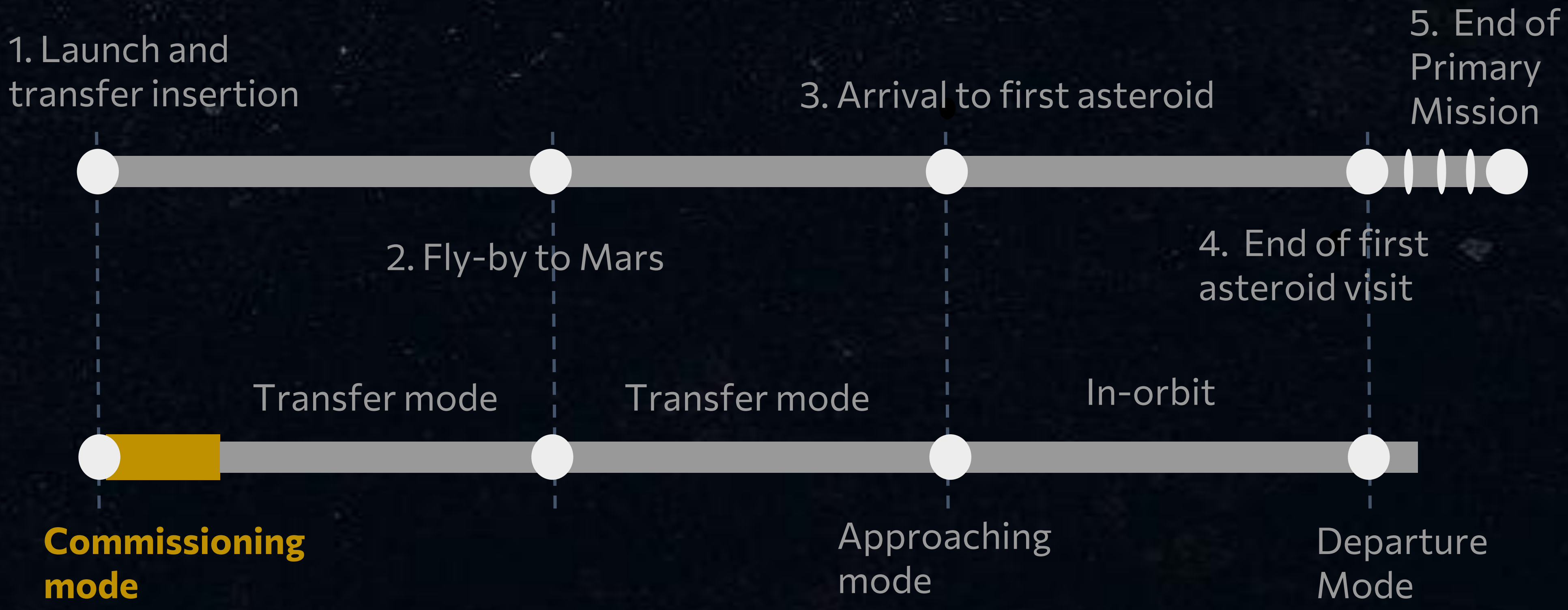
Commissioning mode

CONOPS

Operations

Solar Panels Deployment

Housekeeping



Transfer mode

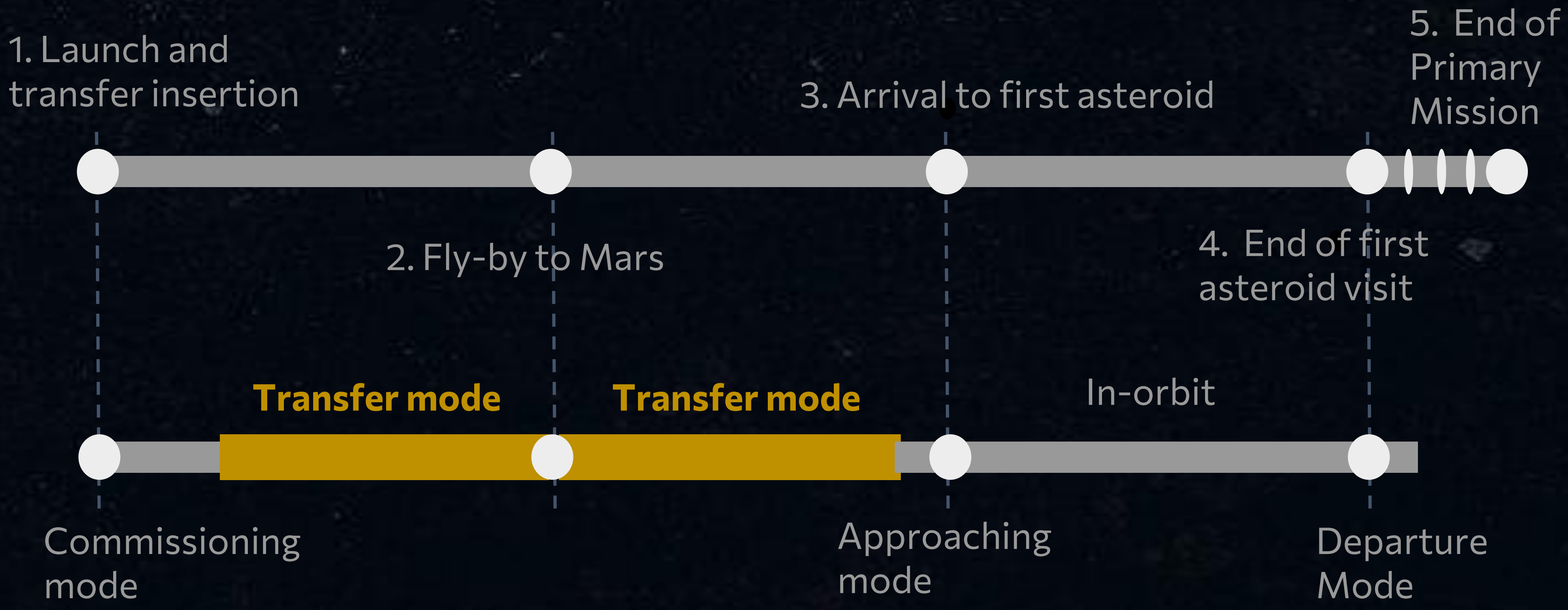
Thrusters open

Housekeeping (MGA)

Sun Pointing

CONOPS

Operations

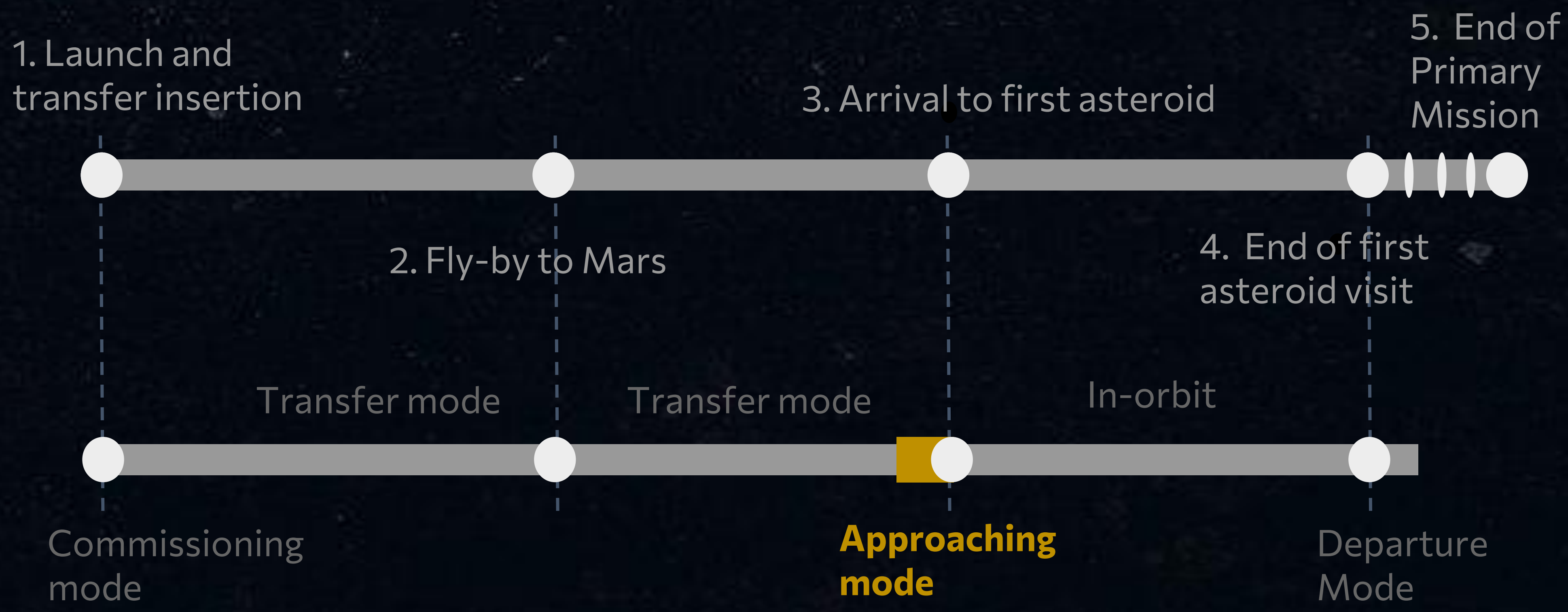


Approaching mode

CONOPS

Operations

Initial mapping of the asteroid.

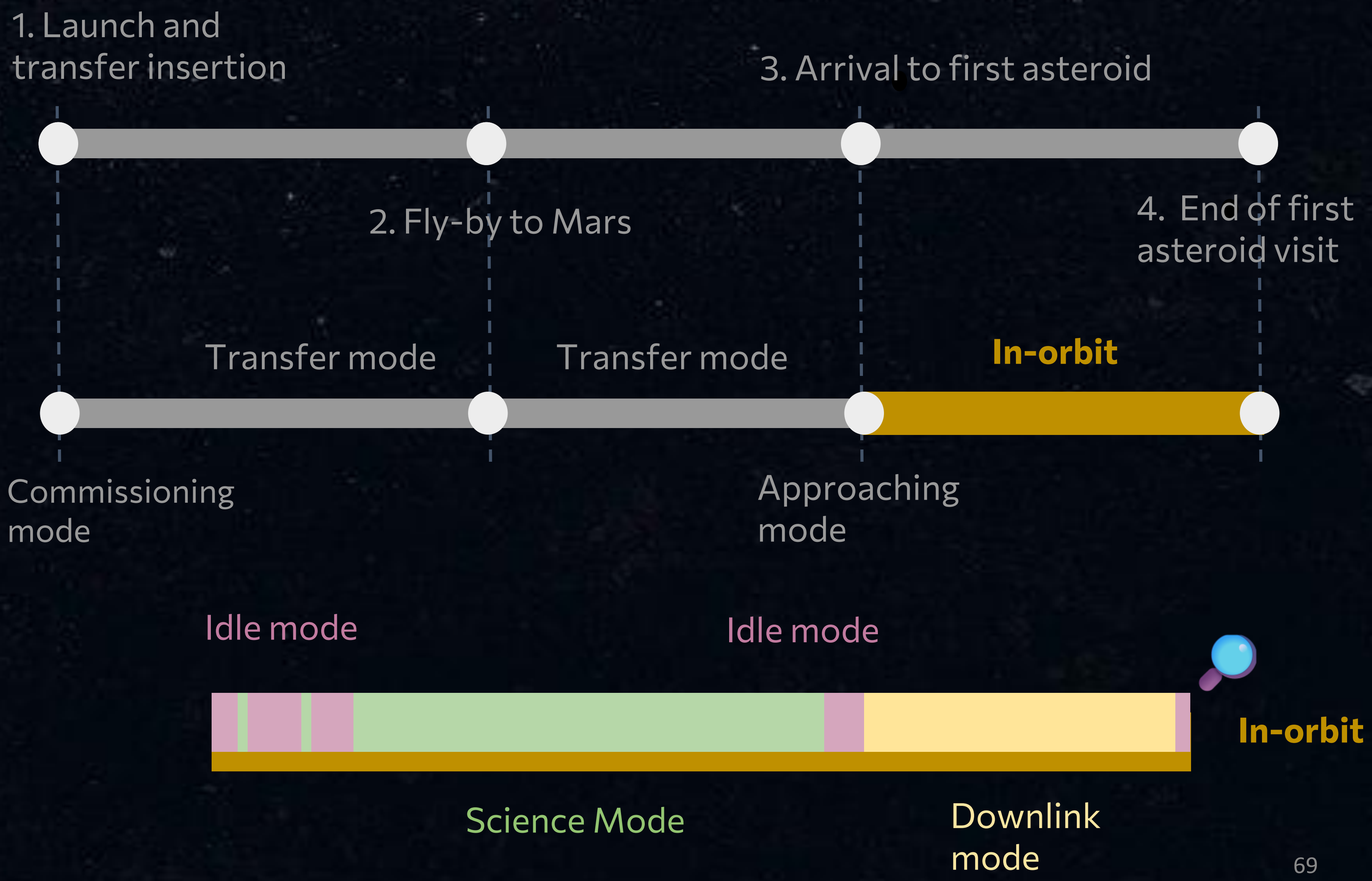


In orbit

Main modes: Science mode and Idle mode.

CONOPS

Operations

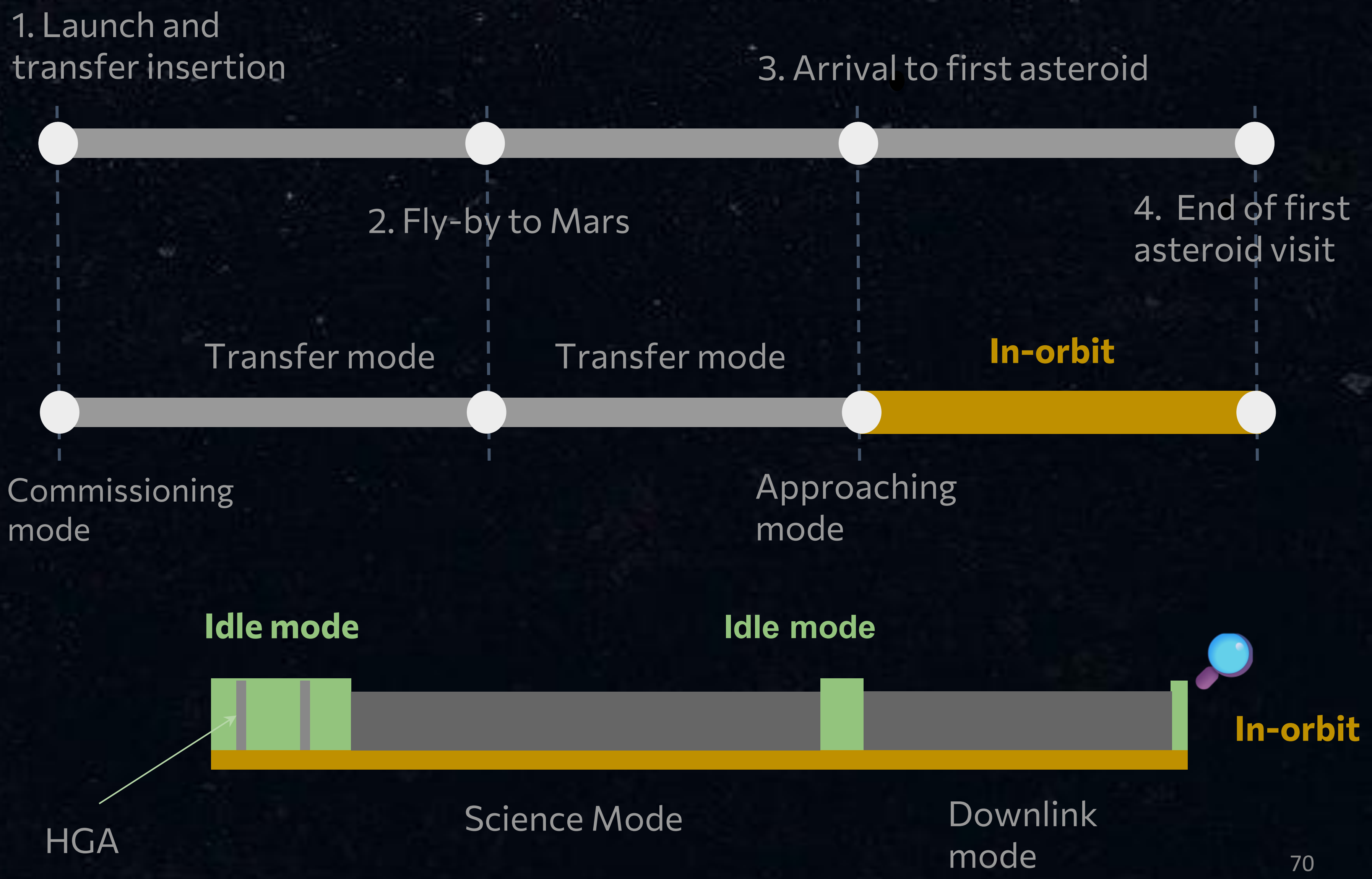


In orbit

Mass calculation (**HGA**)

CONOPS

Operations



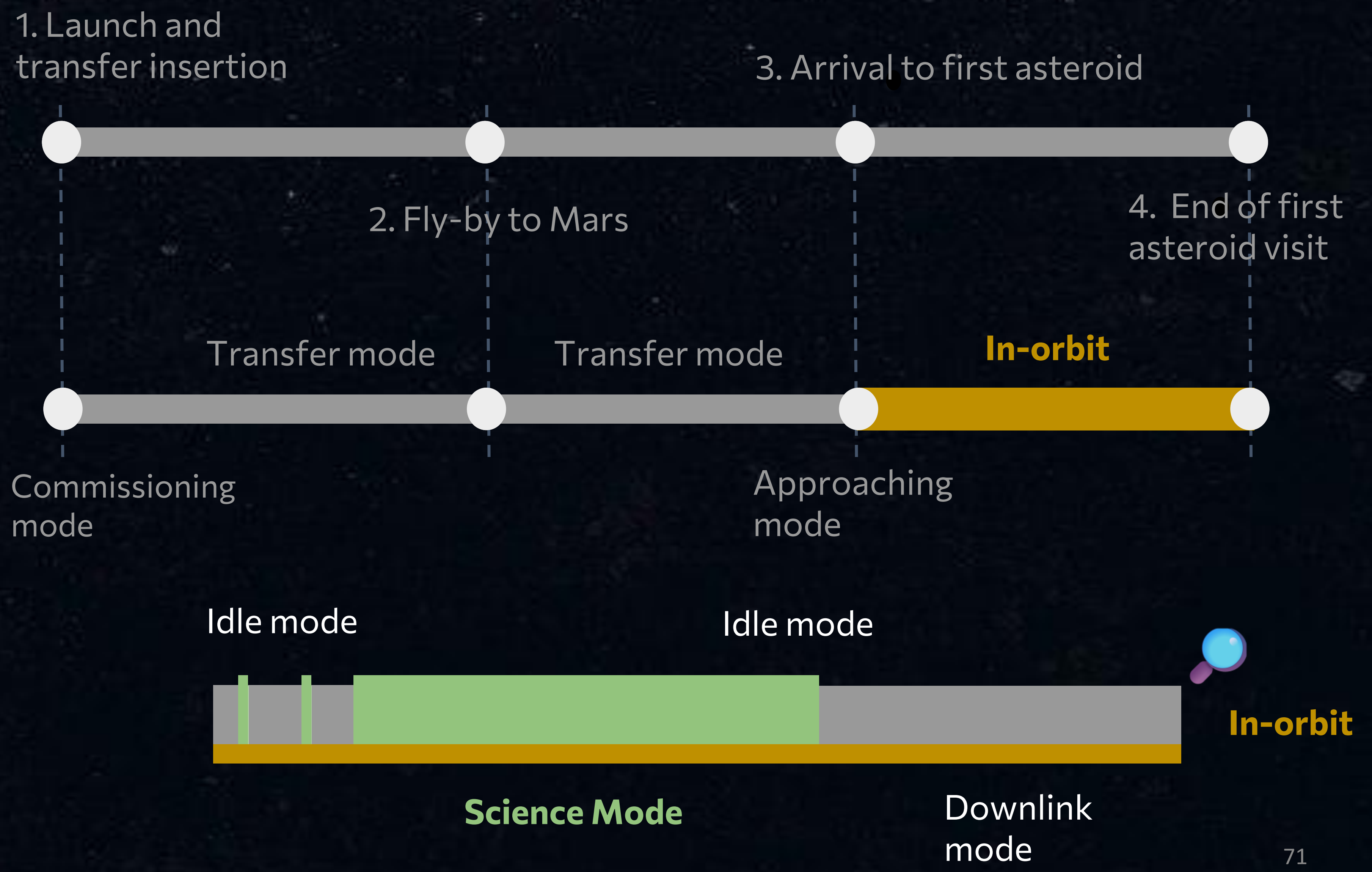
In orbit

Primary experiment

Instruments usage

CONOPS

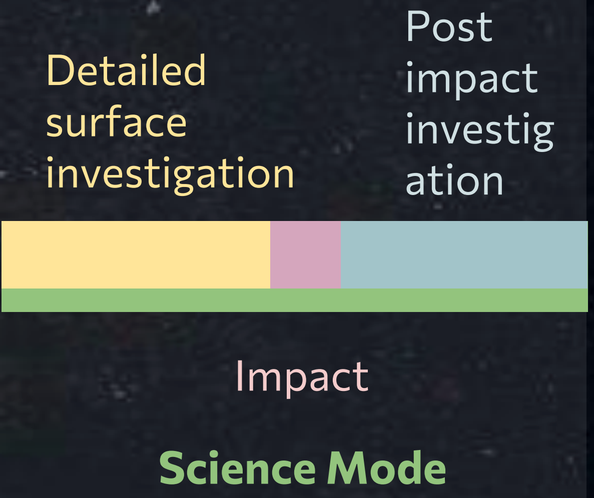
Operations

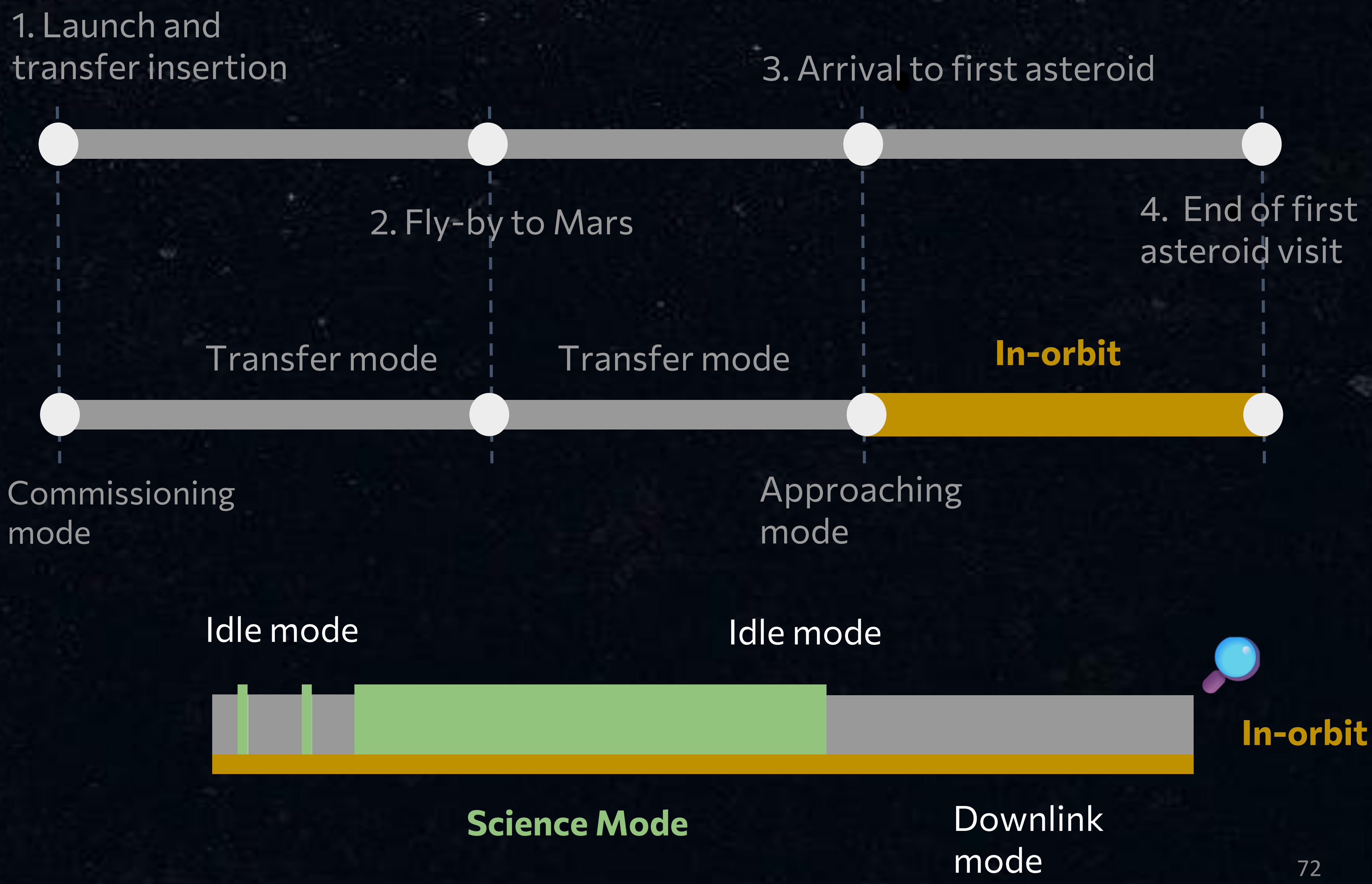


CONOPS

Operations

In orbit





CONOPS

Operations

In orbit

During the detailed surface investigation, NAC, WAC, Hyperspectral Camera and TIR will be used.

Detailed surface investigation

Post impact investigation

Impact

Science Mode

1. Launch and transfer insertion

2. Fly-by to Mars

3. Arrival to first asteroid

4. End of first asteroid visit

Transfer mode

Transfer mode

In-orbit

Commissioning mode

Approaching mode

Idle mode

Idle mode

In-orbit

Science Mode

Downlink mode

In orbit

During the impact phase, the following actions will take place:

Impact

Detailed surface investigation

Post impact investig ation

Impact

Science Mode

CONOPS

Operations

1. Launch and transfer insertion

2. Fly-by to Mars

3. Arrival to first asteroid

4. End of first asteroid visit

Transfer mode

Transfer mode

In-orbit

Commissioning mode

Approaching mode

Idle mode

Idle mode

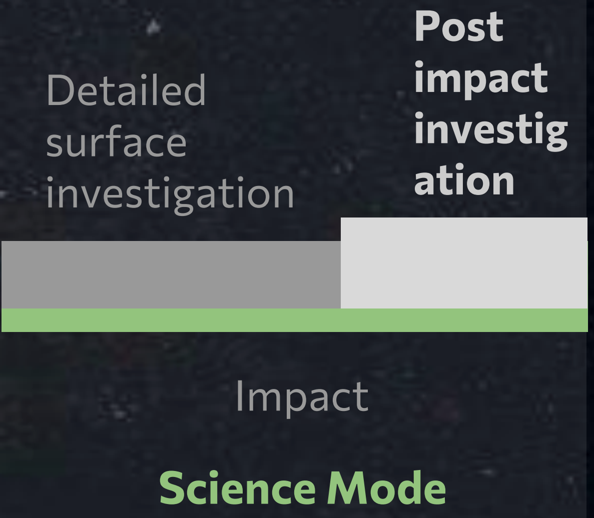
In-orbit

Science Mode

Downlink mode

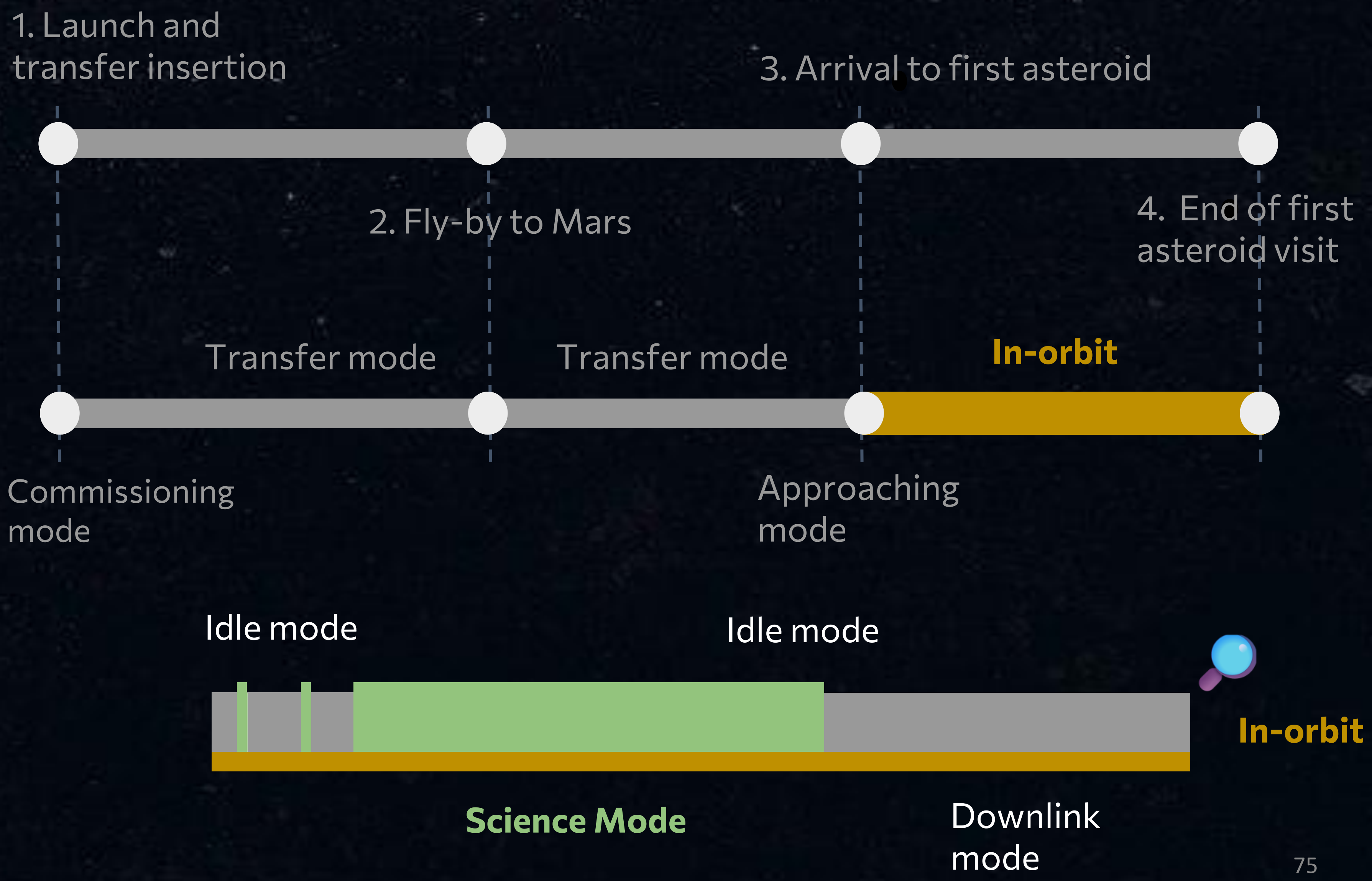
In orbit

NAC, Hyperspectral, TIR will be used during this phase.



CONOPS

Operations



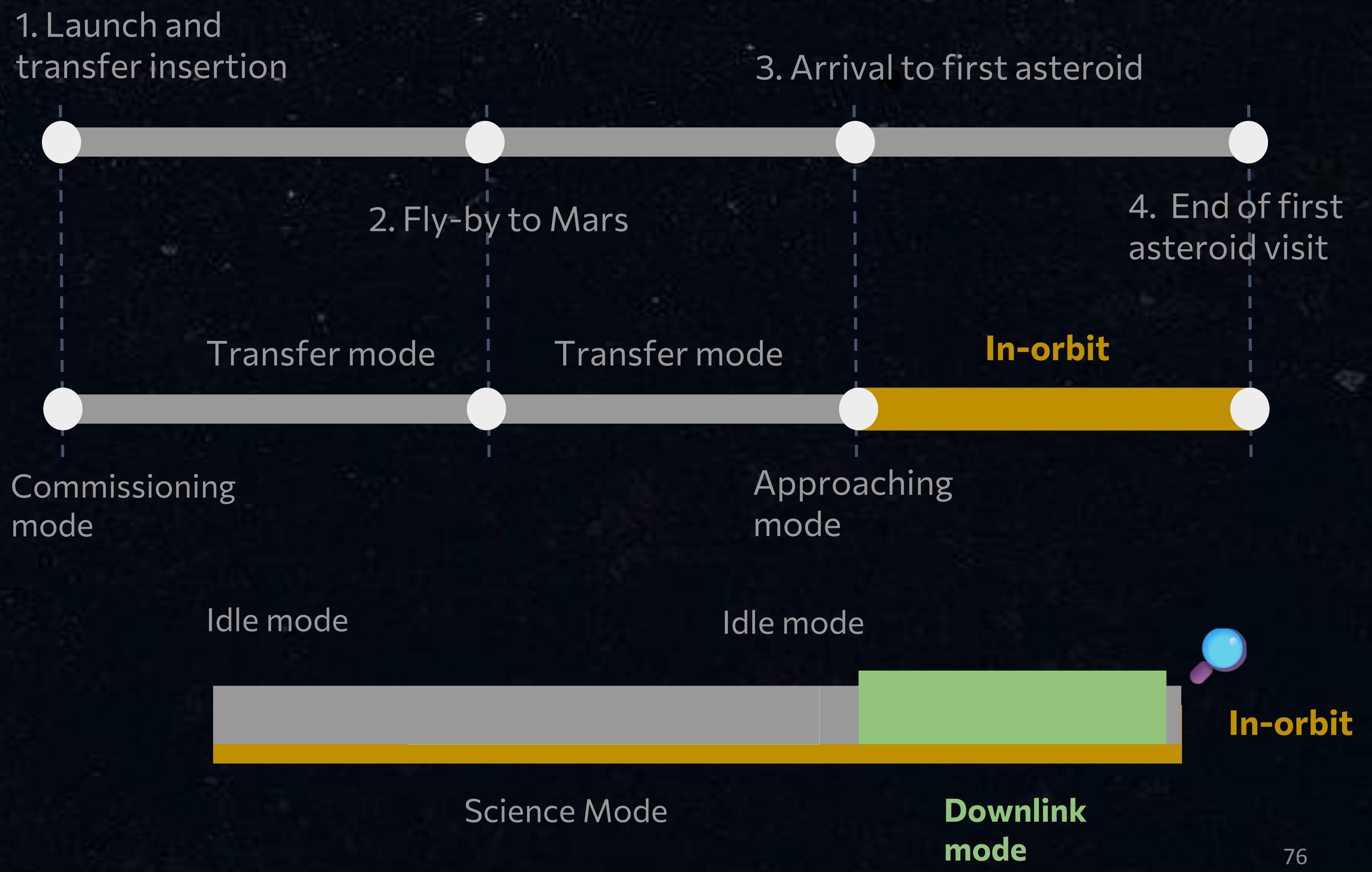
Downlink mode

During downlink mode, the data that were stored in Science Mode are downlinked using the HGA (which is pointed to earth).

The rest of the data will be downlinked during transfer.

CONOPS

Operations

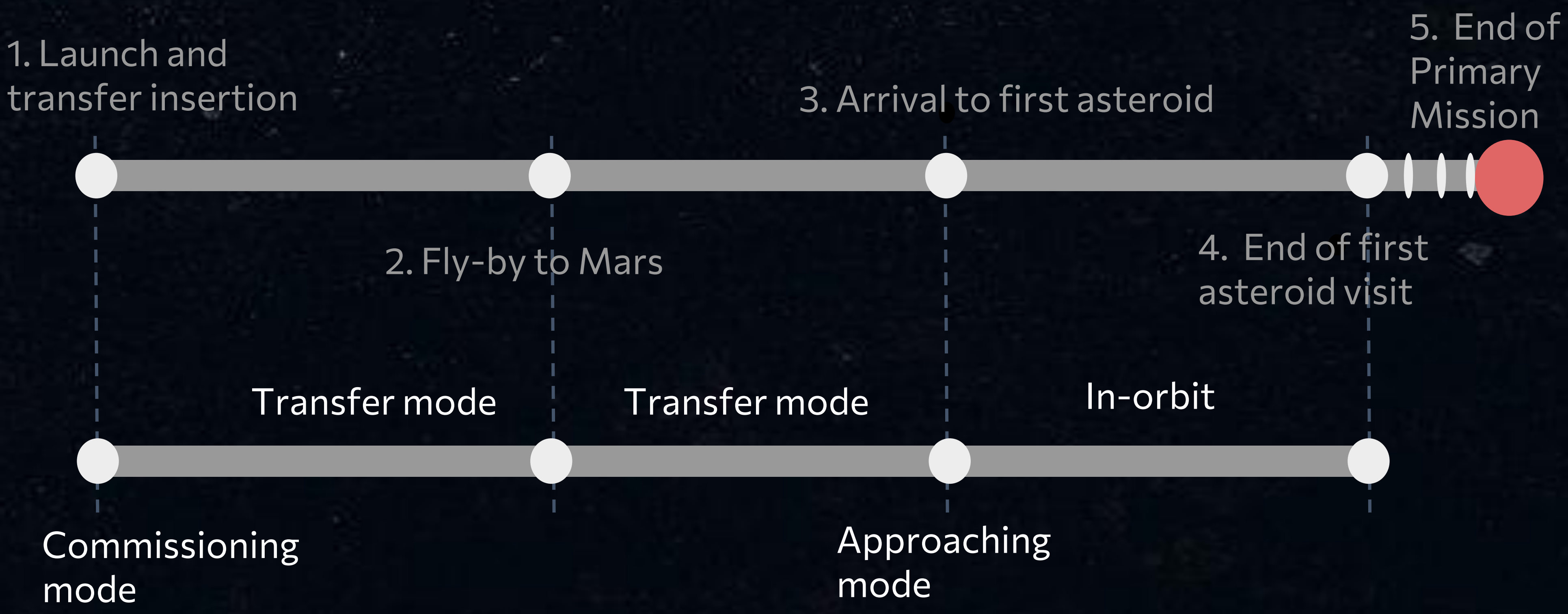


CONOPS

Operations

End of Life

Once the last asteroid is observed, the disposal will be based on the ESA Space Debris Regulations.



Safe Mode & Engineering Mode

CONOPS

Operations

Critical triggers
- Voltage failure (above / below threshold)
- Thermal failure (above / below threshold)
- Tumbling
- ETC

→

Safe Mode
- Stabilization
- Sun Pointing
- COMMS

→

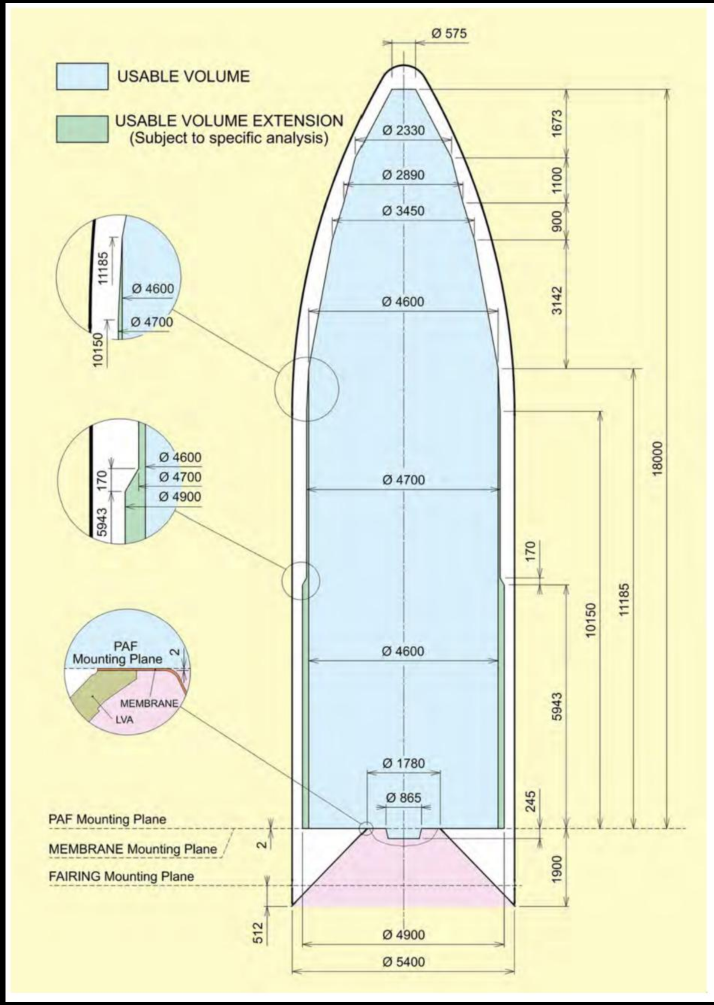
Engineering Diagnostics Mode
- Subsystem diagnostics
- Instruments healthcheck & calibration

Launcher

- Caelus' dimensions:
  3 m diameter + 4 m height
  (Ariane 64's usable space: 4.6 m diameter × 19 m height)

- Caelus' launch:
  3693 kg with $V_{\infty} = 3.6$ km/s

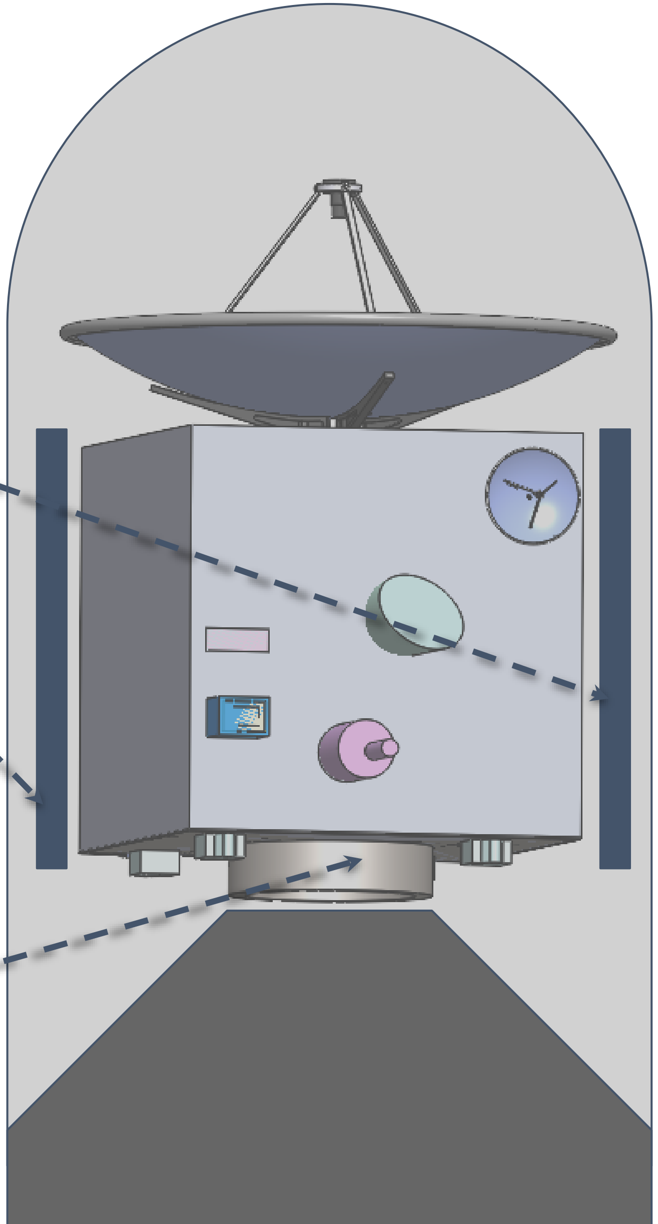
The mission is compatible with **Ariane 64**'s performance range and usable volume.



Payload usable volume definition, Ariane 6 user's manual (2021)

Launcher Adapter

Solar Panels (not deployed)



Adapter Ring

PLA6 1194 adapter was chosen due to:

- medium size of available ones for stability
- does not block thrusters

Ground Segment

ESA's tracking station network:

Diameter	35 m
Communication length per day	8 h
Transmission of the telemetry data (per minute)	0.11 seconds (1500 bps)
Transmission of the science data (per asteroid)	308 hours ≈ 38,5 days (400 GB)
X-band	transmission and reception
Ka-band	reception
Science operations	ESAC
Mission operations	ESOC

Deep Space stations:

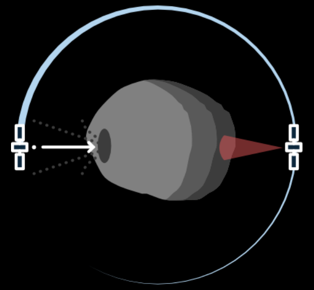
- Cebreros (Spain)
- New Norcia (Australia)
- Malargüe (Argentina)

Mission Drivers

The key mission drivers for the Caelus Mission are:

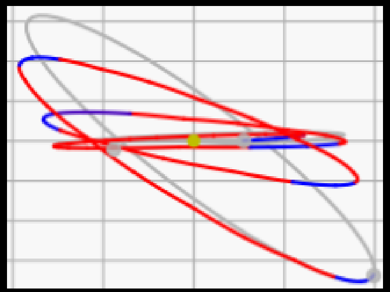
Asteroid classification pre-survey

Impactor development, test and verification plan

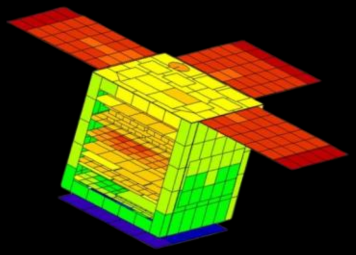


Successful downlink of the data

Detailed **trajectory analysis**

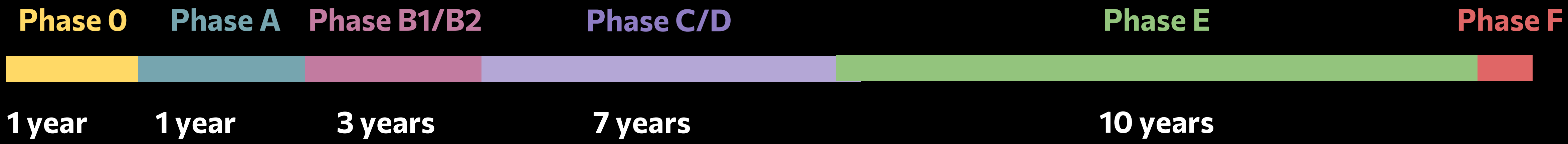


Detailed **thermal profile** for the whole mission duration



Refinement of **in-orbit operations**

Development Plan



Phase	Contents
Phase 0	Proposal
Phase A	Feasibility Analysis
Phase B1/B2	Preliminary Design
Phase C/D	Design & Development activities, MAIT/MAIV
Phase E	Launch Campaign & Launch Window, Operations
Phase F	Disposal

Scientific Risks

Risk	Mitigation
Asteroid surface is covered by dust - P1/S3	Relax science requirements related L0-020-MO (5/10)
Asteroid shape doesn't allow for safe operations at 1 km - P2/S2	Detailed science observations at ground distances > 1 km
Impactor fails to excavate a sufficient amount of unaltered material - P2/S1	Redundant impactor projectile

Probability ↑

P3/S1	P3/S2	P3/S3
P2/S1	P2/S2	P2/S3
P1/S1	P1/S2	P1/S3

Severity →

Technical Risks

Risk	Mitigation
Construction delay - missed launch window - P2/S2	Flexible targets
Unexpected costs / low budget - P2/S2	Descope to Ariane 62
Insufficient downlink speed- P2/S1	1. Less data transmitted but still partial success 2. Possibility of utilization of a 2nd GS antenna
Impact-generated debris affects performances - P1/S3	1. Instruments do not face the impact direction 2. Solar panels can be rotated
Thruster failure - P1/S3	Redundant 3rd & 4th thrusters
OBC radiation damage - P1/S2	OBC resists 500 Gy total dose and single event latchup

Extended mission options

After the end of the nominal mission, depending on the state of the spacecraft and its payload, the remaining fuel and the downlink available, **the mission could continue** with:

- Which would lead to increased scientific output. **More rendezvous** to 1 or more possible **new targets** (one with impactor)
- **Increased in-orbit time** around the last asteroid, more **detailed surface investigation**
- **More flybys** to different objects

De-scoping options

To achieve adaptation and mission agility, a scaled mission **for Ariane 62** is presented.

- Ariane 62 requires up to 2600kg for Earth-escaping orbits ($V_{infinity}$ of 2.5 km/) and no resizing.
- Reduction in the number of targets **from 5 to 3**: partial fulfillment of the current science objectives.

De-scoped element	Reduction of mass
Payload (GRaND, impacts)	20 kg
Solar arrays	90 kg
Propellant & propulsion system	950 kg
Battery	10 kg
Margin reduction	(35, 80) kg
TOTAL	**(1105, 1150) kg**

The scientific return enabled by Ariane 64 significantly outweighs the cost and risk savings of switching to Ariane 62

Approximated achievable total wet mass: 2540 kg

Open points (to be defined past phase 0)

- **ORBITS**:
  - **Finalizing the sequence of asteroid** using angular momentum based tree search method and NN (nearest neighbor) schemecoupled with a nonlinear optimization algorithm
  - Choose the **EoL option**

- **IMPACTOR**:
  - Ground tests could **push the TRL level** from 3 to 5
  - **3-axis pointing accuracy and barrel's alignment precision** will be studied in order to ensure a successful ejection and impact
  - **Recoil effects on spacecraft dynamics** need to be modeled, recoil compensation strategies will be studied (gas vents, AOCS)
  - **Crater ejecta dynamics** need more accurate estimation

- **INERTIA TENSOR:**
  - Verify that the **positioning of the thrusters** is sufficient taking into account the asymmetries due to the fuel decrease

Costs

Costs numbers are a rough order of magnitude (ROM) estimate based on ESA experts' experience and knowledge.

Payload costs are considered to be about 30% of the total costs and are a **contribution by ESA member states**.

Caelus fits within the frame of an ESA L-Mission!

Item	Percent	Costs
Project Team	9%	70M €
Industrial costs	40-50%	350M €
MOC	5-10%	80M €
SOC	5-10%	70M €
Contingency	20%	114M €
Cost at completion	100%	**684M €**
Launcher (Ariane 64)		131M €
ESA COST		**815M €**
Payload		250M €
TOTAL (with payload)		**1065M €**

Team Green

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Alina Vassiljeva

Engineer Tutor:
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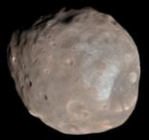
Thank you!

Summer School Alpbach 2025 – Team Green

Annex

Instruments - Specifications



Narrow Angle Camera (NAC)

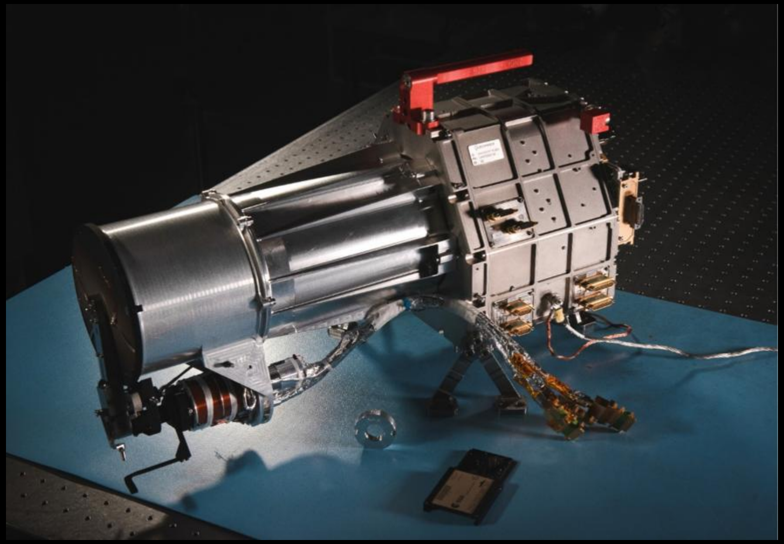
Scientific Requirement: VIS mapping (regolith size and distribution, boulder surface)

Instrument Requirement: 2.5 cm/px at 1 km distance

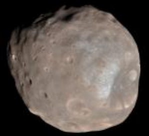
Heritage: JANUS (JUICE)

JANUS parameters:

- Modified Ritchey-Chrétien telescope
- Aperture: 100 mm
- Focal length: 467 mm
- Spatial resolution: ~2 cm/px at 1 km distance
- Spectral range: 340-1080 nm
- FoV: 1.72° × 1.29°
- Detector size: 2000 × 1504 px (CMOS)
- Pixel size: 7 μm
- Mass: 2.89 kg
- Power consumption: 5 W



The JANUS (Jovis Amorum ac Natorum Undique Scrutator) VIS-NIR Multi-Band Imager for the JUICE Mission

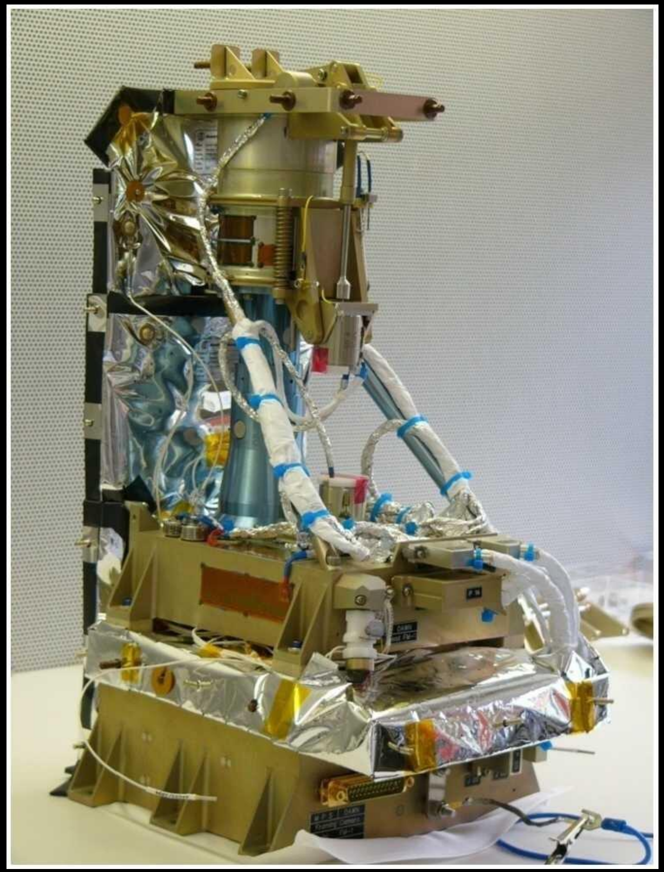


Wide Angle Camera (WAC)

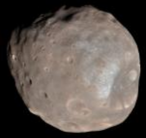
Scientific Requirement: asteroid surface mapping
Instrument Requirement: 2.5 m/px at 1 km distance
Heritage: Framing Camera (Dawn)

FC parameters:

- Optical system comprising four lenses and a selectable band-pass filter
- Aperture: 20 mm
- Focal length: 150 mm
- Spatial resolution: 9.3 cm/px at 1 km distance, can be improved by optimizing the optic configuration
- Spectral range: 400-1050 nm
- FoV: 5.5° × 5.5°
- Detector size: 1024 × 1024 px
- Pixel size: 14 μm
- Mass: 5.5 kg
- Power consumption: 17 W



The Dawn Framing Camera



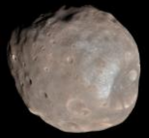
RSI

Scientific Requirement: determine the asteroid mass
Instrument Requirement: The instrument shall be able to detect velocity changes smaller or equal to 3 μm/s over 1000 s
Heritage: X-DST (Hera)

Parameters:

- Deep-Space Network Compatible
- Radio Science Mode (using USO Input)
- Low Phase Noise and Allan Deviation
- Carrier delay variation ≤ 0.5 ns; ranging delay variation ≤ 6 ns
- 1’000’000 in-flight operational hours
- Operating Temperature: -40°C to +60° C
- Mass: 3.2 kg
- Power consumption: 19 W

Small Deep-Space Transponder (SDST) Reliable X-Band and Ka-Band Deep Space Transmission



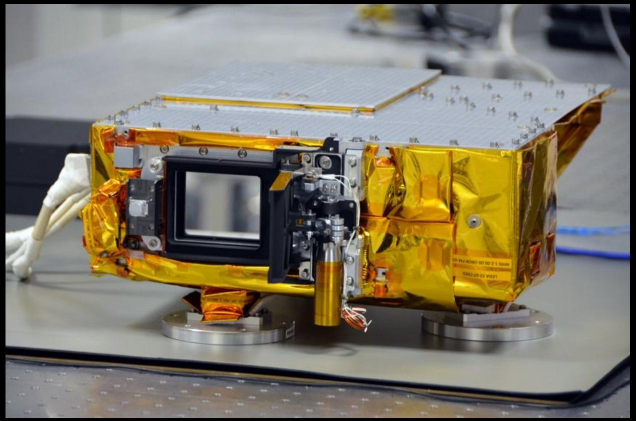
HyperSpectral Camera

Scientific Requirement: determine the subsurface composition, surface mineral composition and distribution, surface reddening
Instrument Requirement: spectral range 0.9-3.6 μm, spectral resolution 20 nm, spatial resolution 12.8 cm/px
Heritage: MIRS (MMX)

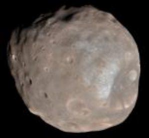
MIRS parameters:

- Based on a push-broom imaging spectrometer, composed of an optical (OBOX) and an electronic (EBOX) box
- Aperture: 23.4 mm
- Focal length: 93.5 mm
- Spatial resolution: 22.5 cm/px at 1 km distance, can be improved by optimizing the optic configuration
- Spectral range: 900-3600 nm
- FoV: 3.3°
- Detector size: 256 × 500 px
- Pixel size: 30 μm
- Mass: 10.24 kg
- Power consumption: 17 W

Design and performance of MIRS infrared imaging spectrometer onboard MMX mission



Design and performance of MIRS infrared imaging spectrometer onboard MMX mission

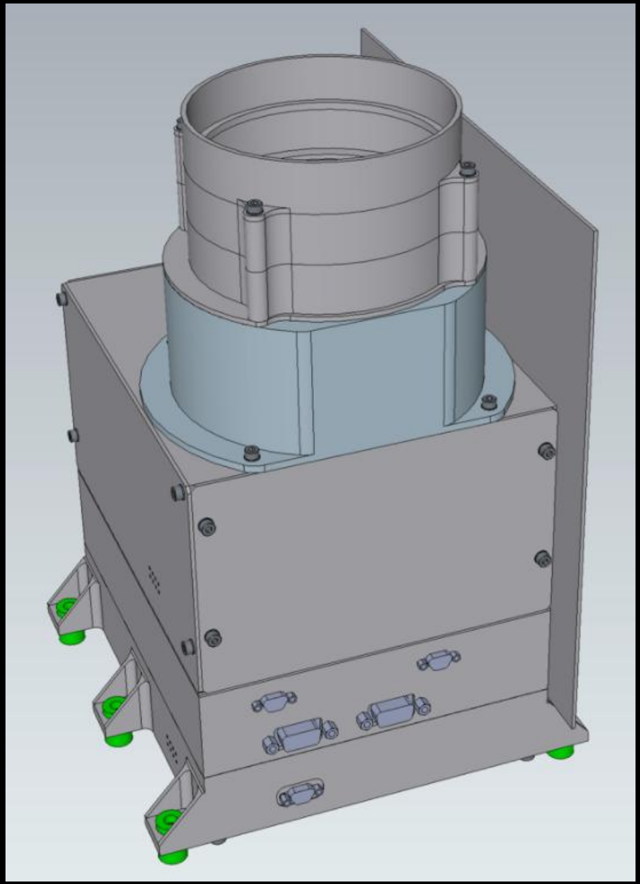


Thermal InfraRed Imager (TIRI)

Scientific Requirement: determine the asteroid shape, and the boulder thermal inertia and cycling
Instrument Requirement: temperature range 80-350 K, temperature resolution <1 K, spatial resolution of 12.8 cm/px
Heritage: TIRI (Hera)

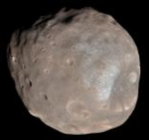
TIRI parameters:

- Uncooled microbolometer array
- Spatial resolution: 22.7 cm/px, can be improved by optimizing the optic configuration
- Spectral range: 800-1400 nm
- FoV: 13.3° × 10.0°
- Detector size: 1024 × 768 px
- Pixel size: 17 μm
- Mass: 3.9 kg
- Power consumption: 16 W



Design and performance of MIRS infrared imaging spectrometer onboard MMX mission

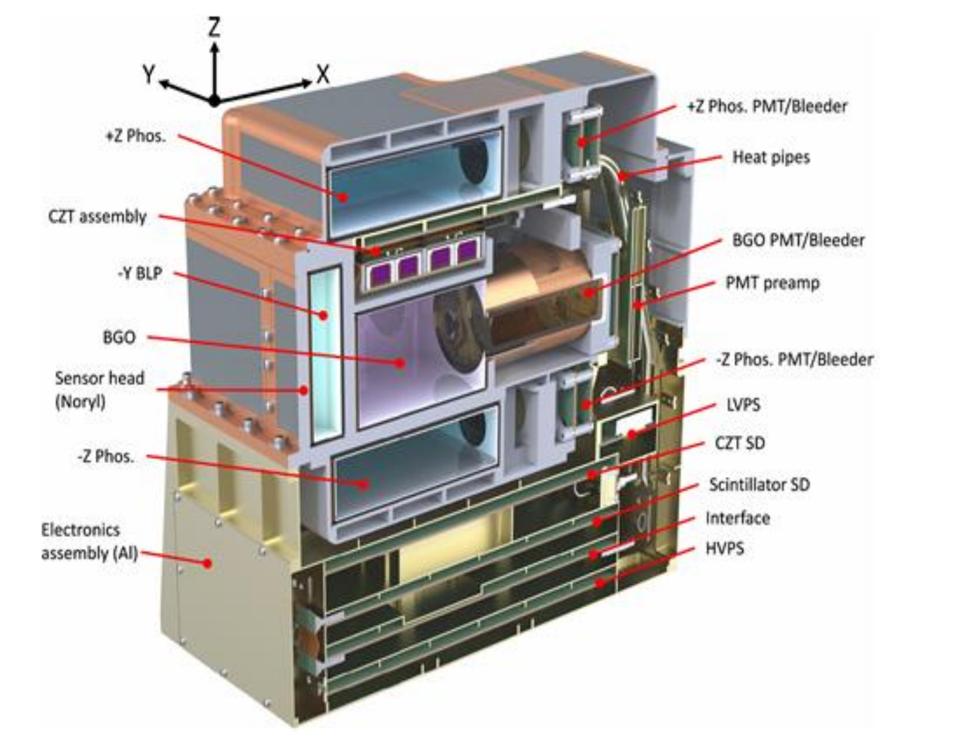
Gamma ray and neutron emission detector



Scientific Requirement: Detect important major rock-forming and volatile forming elements (including H, K, Si, O, Mg, Al, Ca, Fe, C, Cl).
Heritage: GRaND (Dawn)

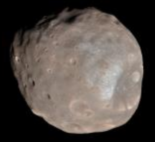
GRaND parameters:

- CdZnTe sensor fully resolves gamma rays from most elements of interest.
- Pulse-height resolution: better than 3% FWHM at 662 keV at 20°.
- 478 keV gamma ray from 7Li* used as gain calibration.
- Measures epithermal neutrons (0.2 eV - 0.5 MeV)
- Thermal neutrons from the asteroid are measured using the 6Li loaded glass.
- Detects epithermal neutrons having 0.2 eV - 0.5 MeV energy.
- Detects fast neutrons having 0.5 MeV - 8 MeV energy.
- Data transfer: 3.1 kb/s data string with an accumulation time of 60s.
- FoV: 2π sr^{-1}
- Mass: 10.5 kg
- Power consumption: 12 W



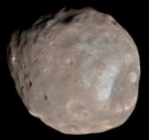
Dawn's Gamma Ray and Neutron Detector

Subsystem Requirements



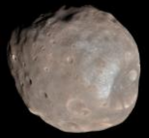
Subsystem Requirements

Electrical Power Subsystem	Requirement
EPS-010	The thrusters shall be able to provide a voltage channel of 300-400 V
EPS-020	The peak power that can be reached by the EPS shall be of 6 kW
EPS-030	The spacecraft batteries shall be able to provide power for 4h in science mode
EPS-040	The energy generated shall be higher than 20 MWh before the spacecraft reaches the Main Asteroid Belt
EPS-050	The solar cells efficiency shall be higher than 25%
EPS-060	The solar arrays shall be configured in parallel



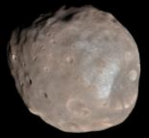
Subsystem Requirements

Structural Subsystem	Requirement
STR-010	The primary structure shall withstand an acceleration between -20g and 20 g during launch, and of 3000 g in shock loads
STR-020	The first axial frequency of the structure shall be higher than 50 Hz
STR-030	The first lateral frequency of the structure shall be higher than 35 Hz
STR-040	The entire spacecraft shall fit in a volume of 4.5 m diameter and 19.5 m height
STR-050	The structure shall assure a clear field of view for the instrumentation
STR-060	A refurbishment procedure shall be defined for the MAIV phase



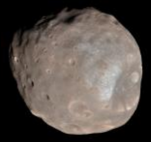
Subsystem Requirements

Thermal Subsystem	Requirement
THE-010	Panels and primary structure shall tolerate a range of temperature between -100°C and 120°C
THE-020	The thermal expansion coefficients of contacting surfaces shall not surpass 2%
THE-030	Batteries shall operate between 0°C to 25°C
THE-040	All mechanism should operate between 10°C and 40°C
THE-050	Power Processing Unit shall operate between 10°C and 40°C
THE-060	All payload instruments shall operate within their operational limits



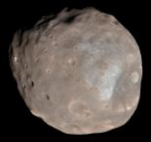
Subsystem Requirements

Attitude Determination and Control Subsystem	Requirement
ADCS-010	The solar arrays shall be pointing to the Sun with an error smaller than 1° during nominal mode
ADCS-020	The instruments shall point to the target with a pointing error of maximum 1° during science mode
ADCS-030	The High Gain Antenna shall point to Earth with pointing error TBD during telemetry mode
ADCS-040	The spacecraft shall turn 90° until the impactor points to the target per On Board Computer instruction during science mode
ADCS-050	The spacecraft shall remain pointing the impactor's face to the asteroid for half of an orbit
ADCS-060	The spacecraft shall recover its attitude after the impact in a time window smaller than 2 minutes, using the thrusters
ADCS-070	The spacecraft shall be 3-axis stabilization with a pointing error less than 1%



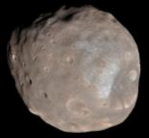
Subsystem Requirements

On Board Computer Subsystem	Requirement
OBC-010	The OBC shall process 100 Mbits/s
OBC-020	the OBC shall store 4 TB of payload data
OBC-030	The OBC processor shall have the capacity to run (near) lossless compression algorithms such as CCSDS or JPEG-LS with projected compression ratio 2.9
OBC-040	The OBC shall be capable of autonomously steering the spacecraft for 1.5 hours
OBC-050	The OBC and other electronics shall withstand a total radiation dose of 500 Gy and shall be resistant to SEU (single event upsets)
OBC-060	The OBC shall command every subsystem and initiate the operational modes
OBC-070	The OBC processor shall have 1-out-of-2 warm redundancy (the redundant processor is always powered up)



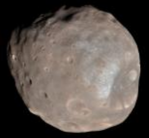
Subsystem Requirements

Communications Subsystem	Requirement
COMMS-010	The High Gain Antenna shall be able to send data of 1 GB/h in the Main Asteroid Belt
COMMS-020	The Medium Gain Antenna shall be able to send data of 0.008 GB/h in the Main Asteroid Belt
COMMS-030	The recover amplifier shall be of 50 dB
COMMS-040	The antenna shall be omnidirectional



Subsystem Requirements

System	Requirement
SYS-010	The mass of the spacecraft shall be below 5 tons
SYS-020	The Reaction Wheels vibrations shall not interfere with the instruments
SYS-030	All the subsystems shall be able to communicate with the spacecraft bus
SYS-040	All failure triggers shall result to safe mode



Subsystem Requirements

Propulsion Subsystem	Requirement
PRO-010	The thruster shall provide a thrust above 150 mN
PRO-020	The thruster shall have a specific impulse above 1600 s
PRO-030	The propulsion system shall operate with an electrical efficiency above 60%
PRO-040	The propulsion system shall be able to operate continuously for 10000 hours

Development Plan

Phase 0
Proposal

Phase A
Feasibility Analysis

Phase B1/B2
Preliminary Design

Phase C
Design & Development activities

Phase D
D1: Subsystem Level Testing, Procurements, Manufacturing, System AIV

D2: System Environmental Testing

Phase E
E1: Launch Campaign & Launch Window

E2: Operations