- CIRCE -

Centaurs Investigation, Reconnaissance and Compositional Exploration

Centaurs:

A window into the building blocks of the Solar System

Team Gold (Yellow)

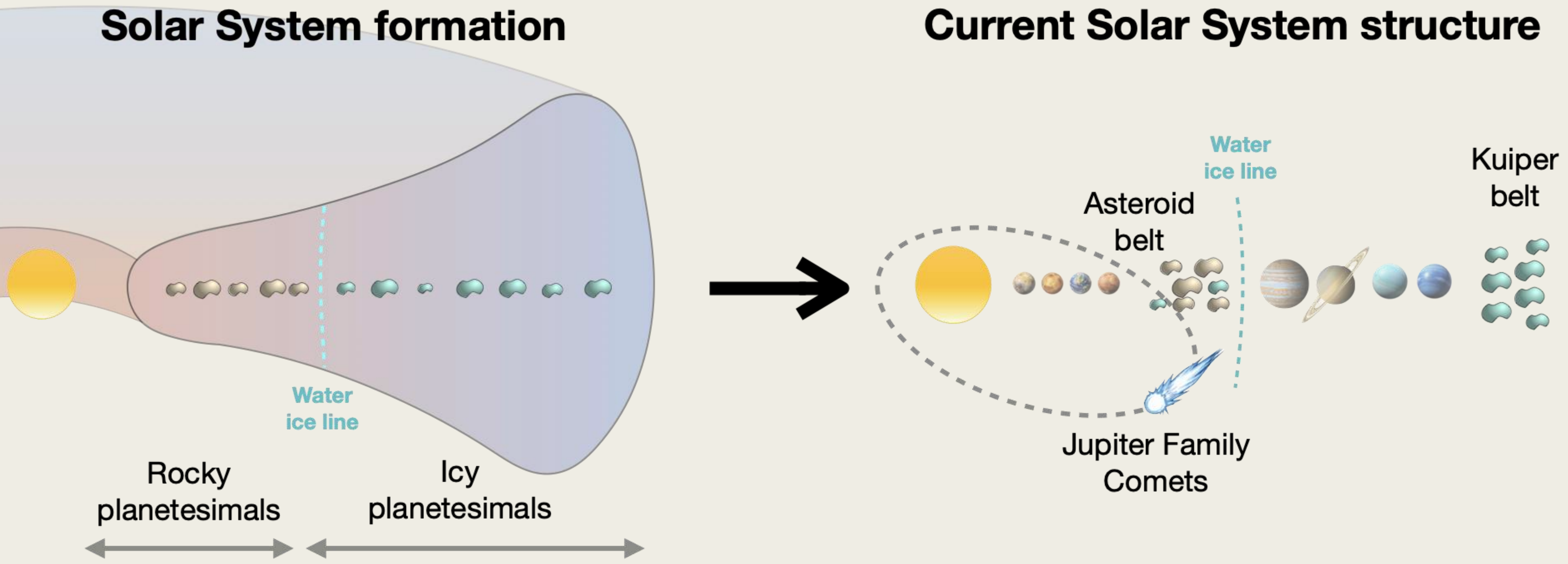
Agenda

- Science Case
- Mission Profile
- Programmatics

Motivation
Science Objectives
Target Selection
Requirements
Instruments
Mission Success Criteria

SCIENCE CASE

Minor bodies are the building blocks of the Solar System



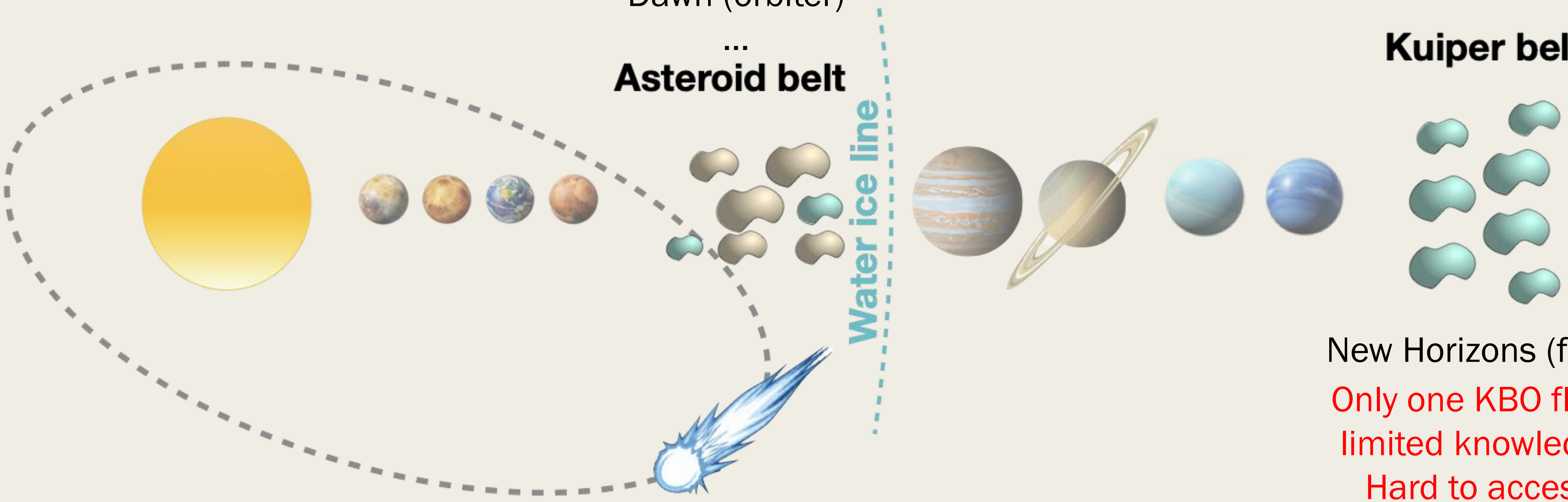
Formation location ≠ Current location

(Some of the) **Previous exploration to minor bodies**

Some water lost
Several collisions

Dawn (orbiter)

...



New Horizons (flyby)

Only one KBO flyby, limited knowledge
Hard to access

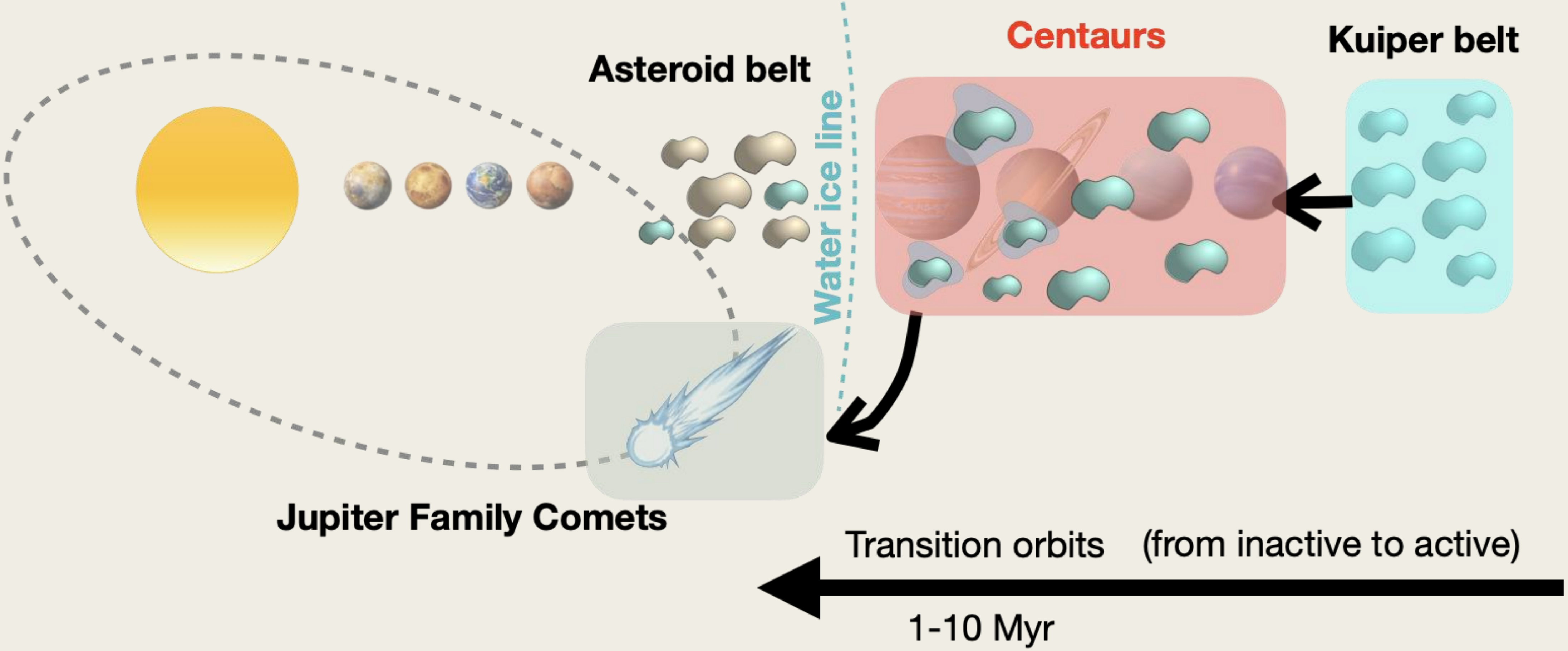
Surface highly processed
How were they before crossing the water ice line?

Jupiter Family Comets

Stardust (sample return)
Rosetta (orbiter/lander)
...

We know very little about the outer Solar system and the origin of JFC

Centaurs: an unique window into the more pristine outer Solar System



Scientific objectives

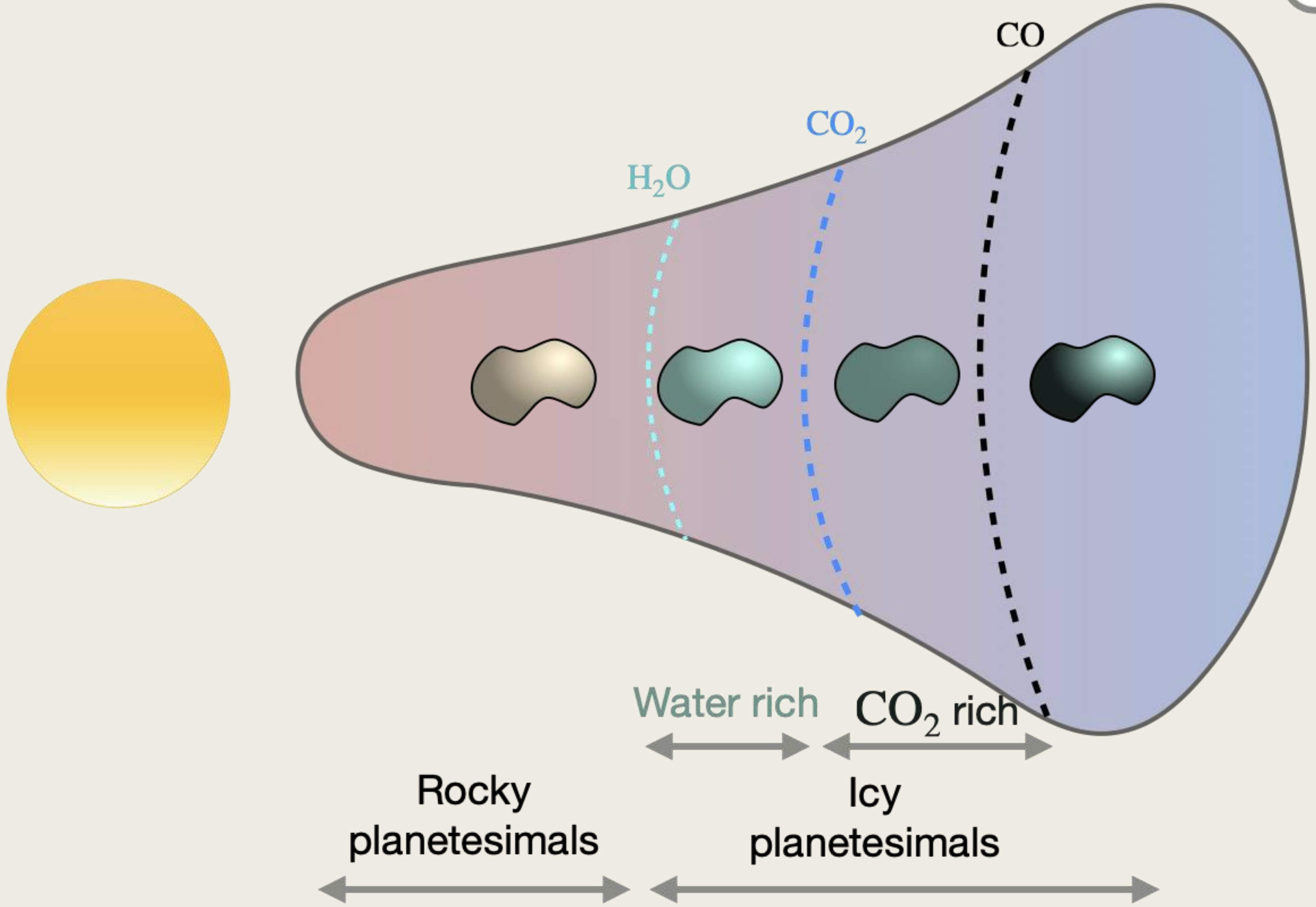
SO1. How did the icy planetesimals form and evolve?

SO2. Which processes drive the activity of Centaurs?

SO1.

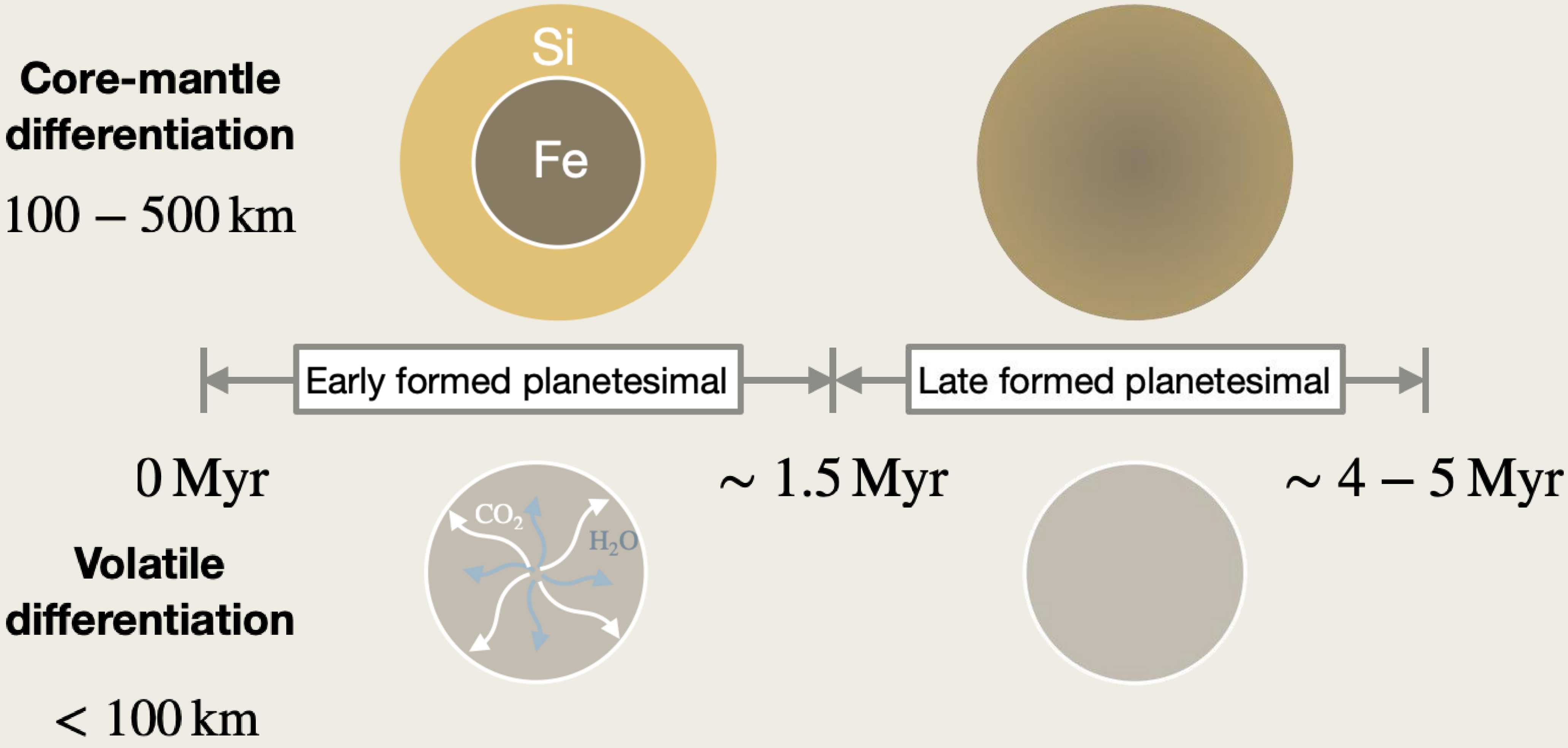
Formation location

Ice lines determine the planetesimal composition



SO1. Formation time

Formation time influences internal structure



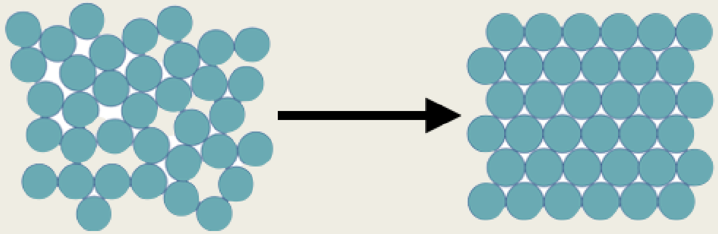
Potential heat source: decay of ^{26}Al with halftime of 0.7 Myr

SO2.

Potential driver of activity in Centaurs

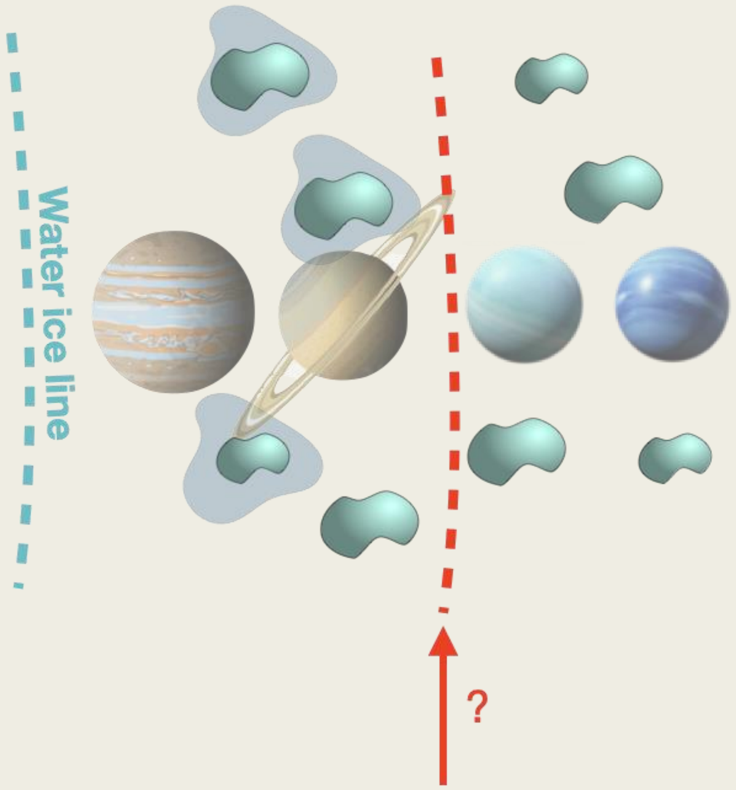
Active centaurs are beyond the water ice line, up to around 10 AU

- Transition from amorphous to crystalline water ice?



- Sublimation of more volatile components such as CO_2

(Lisse et al. 2022)



Another phase change

SO2.

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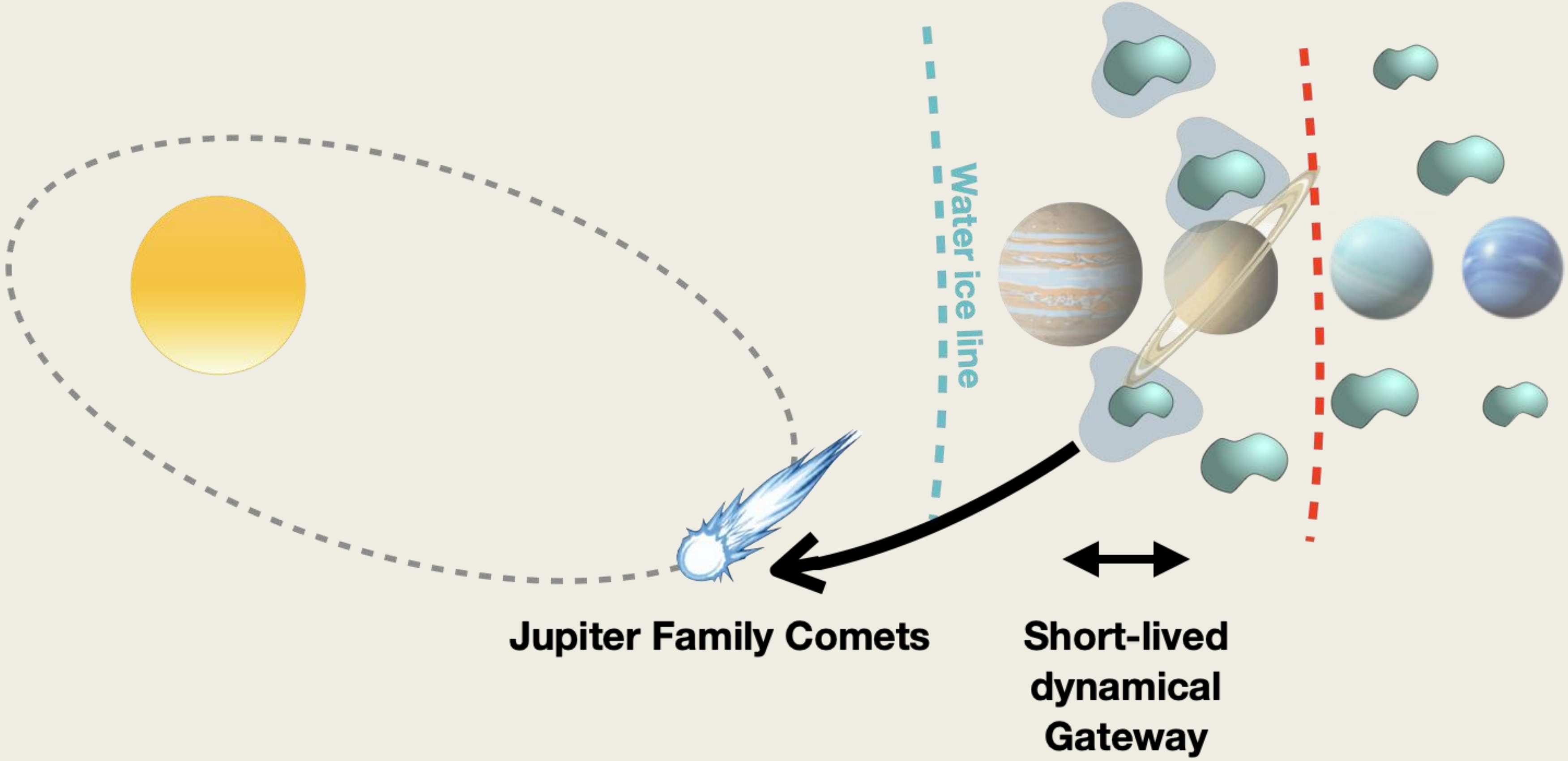


Sarid et al. 2019

Target options

Criteria

Primordial object

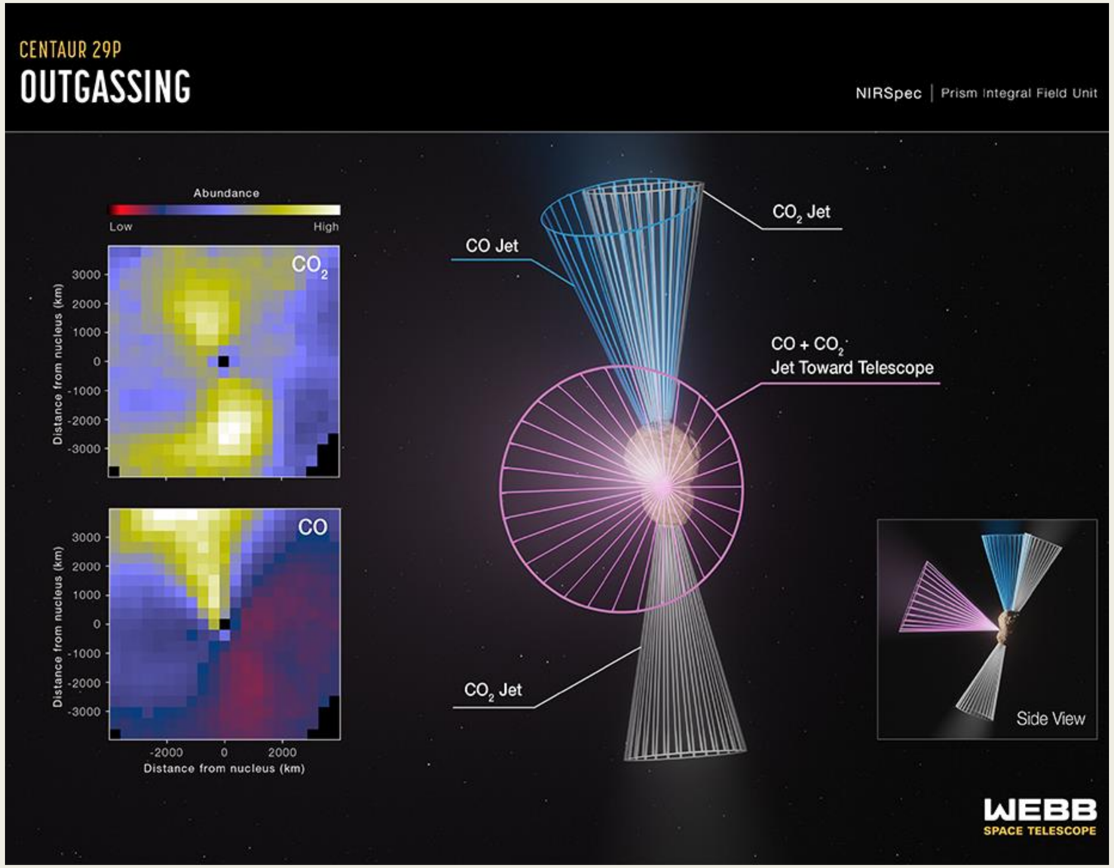
Active object

Score Scale
0-3
4-7
8-10

Name	Scientific Interest (60%)	Size (20%)	Accessibillity (20%)	Total Score
29P/Schwassmann -Wachmann	„Gateway“ Region, study transition Centaurs, most active	~60 km	Hard	8.6
2060 Chiron	Study remnants of KBOs, more pristine surface, ring system	~200 km	Very hard	7.8
P/2019 LD2	Very young comet, will become JFC in 2063	<2.4 km	Easy	4.2
174P/Echeclus	Show unusually low CO levels	~60 km	Hard	5.2

29P/Schwassmann–Wachmann

- a potential contact binary of 60 km in diameter



Source: NASA, ESA, CSA, Leah Hustak (STScI), Sara Faggi (NASA-GSFC, American University)

Arrokoth – 36 km diameter
Contact binary – Prediction of planetesimal formation

Mission Statement

- Explore the evolution from KBOs to JFCs
  Implications for Solar System formation and evolution
- Constraint pristine planetesimals formation and differentiation
  Implications for planet formation
- Investigate comet activity beyond the water ice line
  Implications for evolution of small bodies

Science Requirements – Themes (1)

Composition and Chemistry ***[surface, subsurface, coma]***

SR-010*. The bulk composition of the surface and shallow sub-surface of a Centaur shall be assessed.*

SR-020*. The chemical composition of the coma/exosphere of a Centaur shall be identified.*

SR-021*. Isotopic reservoir of key elements shall be identified.*

Physical Geology, Topography, and Thermal State ***[terrain, mapping, fine-scale features]***

SR-030*. Physical characteristics on the surface of a Centaur shall be mapped.*

SR-090*. The thermal state of a Centaur shall be characterised.*

Activity, Outgassing, and Spin Evolution ***[coma dynamics, outbursts, mass loss]***

SR-031. *Outgassing patterns, outburst events and their temporal evolution shall be investigated.*

SR-040*. The dynamic state of a Centaur and its evolution due to outgassing events shall be analysed.*

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Science Requirements – Themes (2)

Interior Structure and Gravity Field ***[bulk density, mass concentrations]***

***SR-050**. The interior mass distribution of a Centaur shall be investigated.*

Electromagnetic and Plasma Environment ***[remnant magnetism, plasma interactions]***

***SR-060**. The magnetic state of a Centaur shall be explored.*

***SR-070**. The interaction with the interplanetary magnetic field shall be investigated.*

***SR-080**. Interactions of a Centaur's magnetic field with the solar wind shall be investigated.*

Dust and Particulate Environment ***[grain velocity, embedded volatiles]***

***SR-100**. The dust in the coma/ring of a Centaur shall be characterised.*

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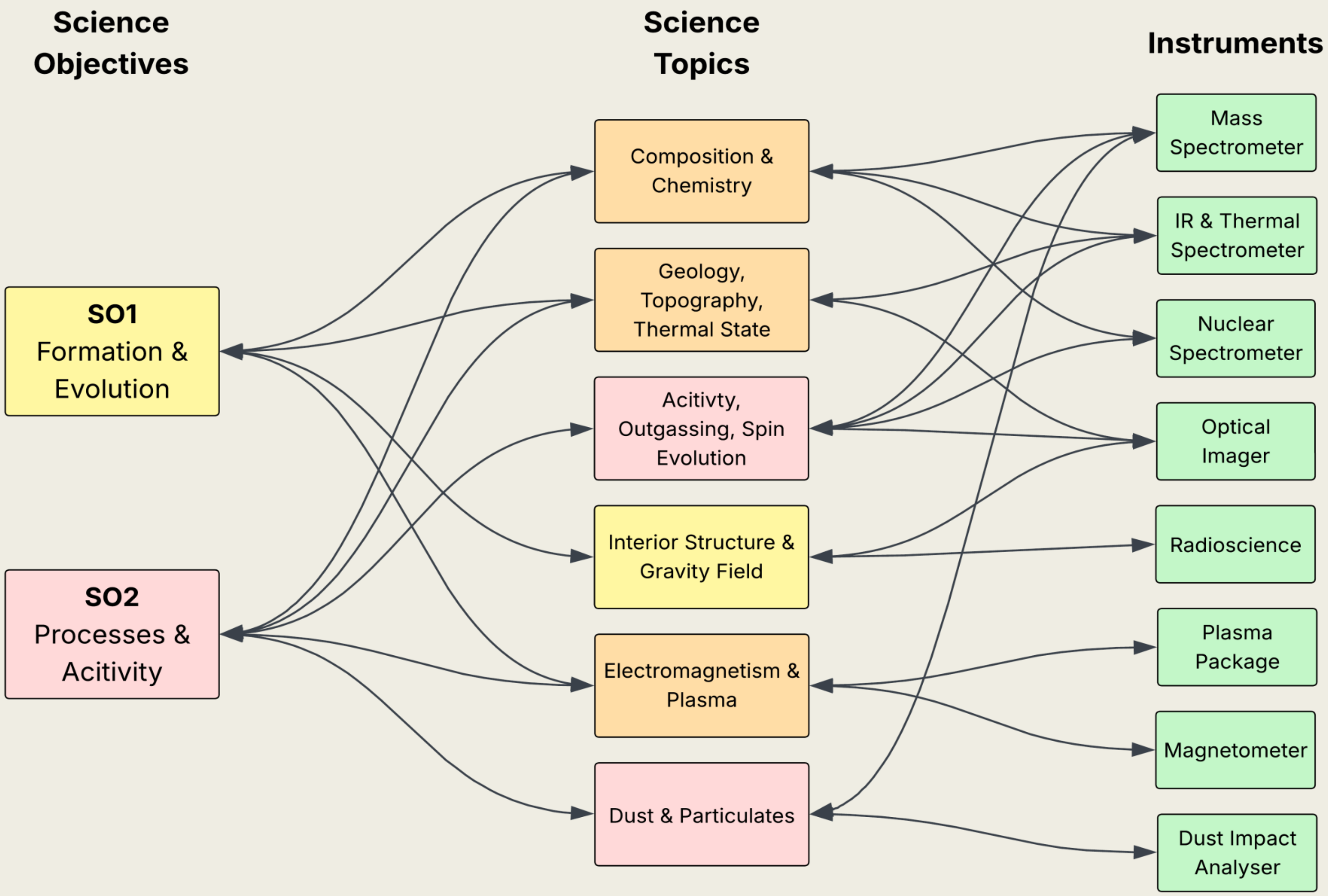

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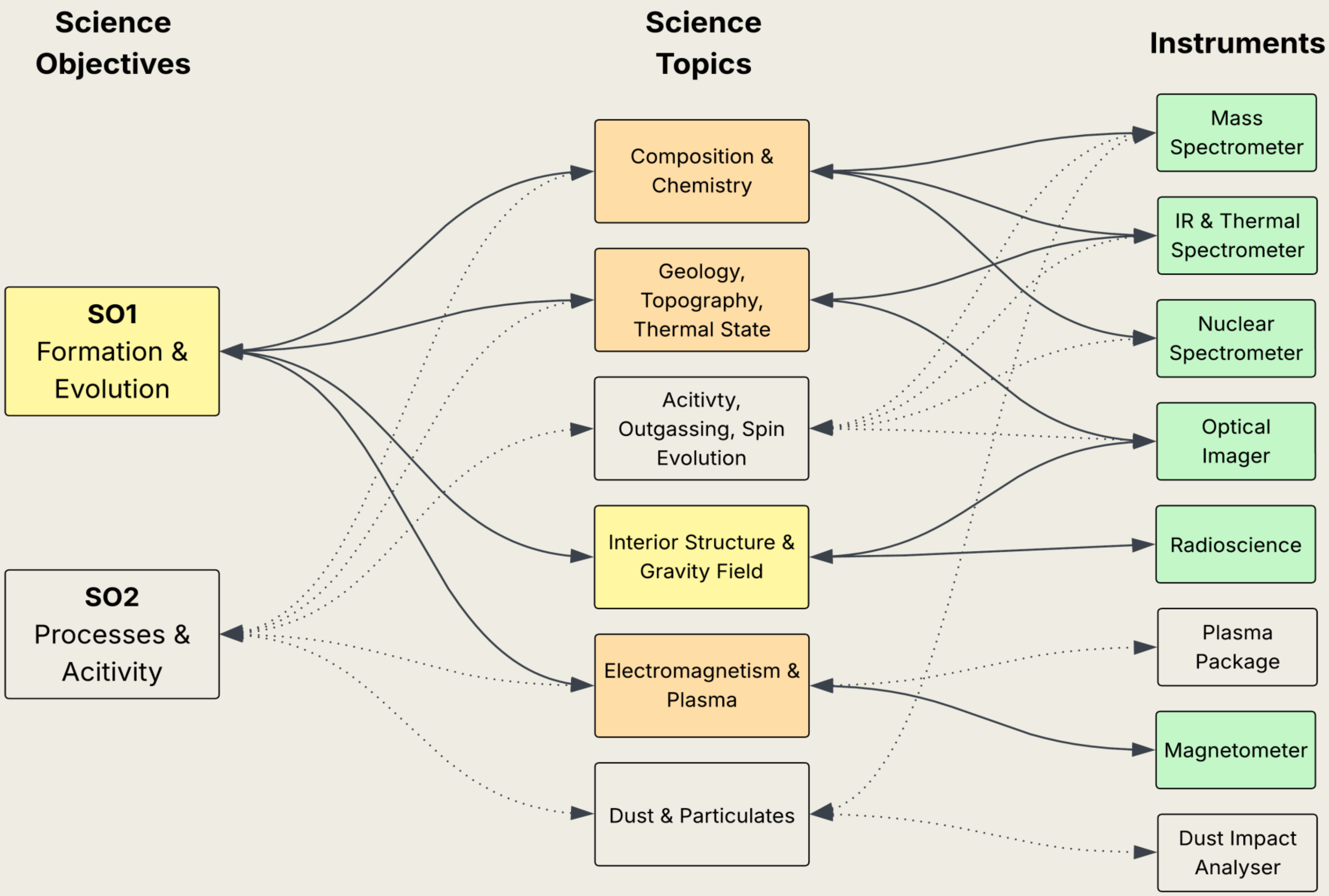
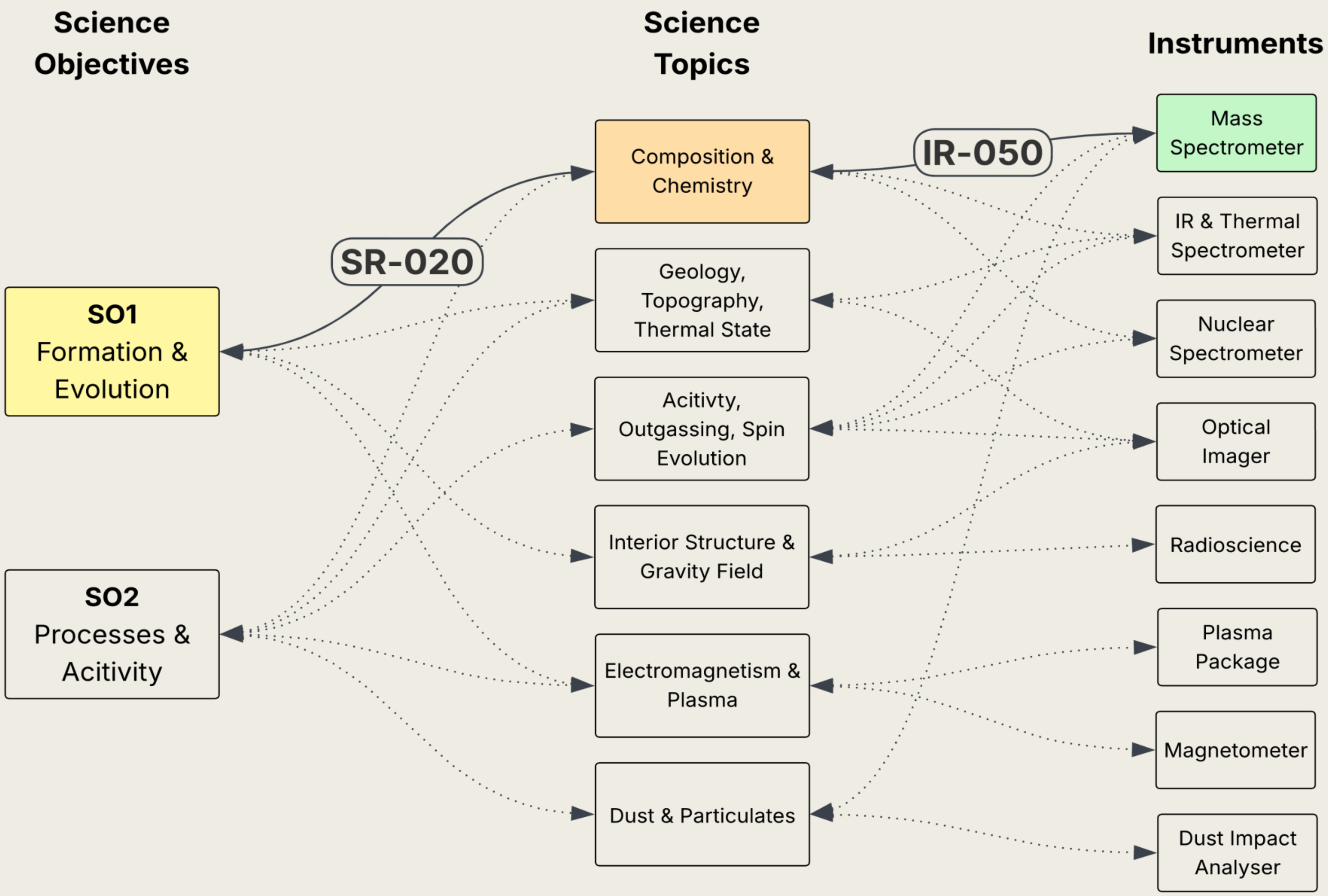


Science Requirements – Traceability Example 1



Science Objectives – Traceability Example 1

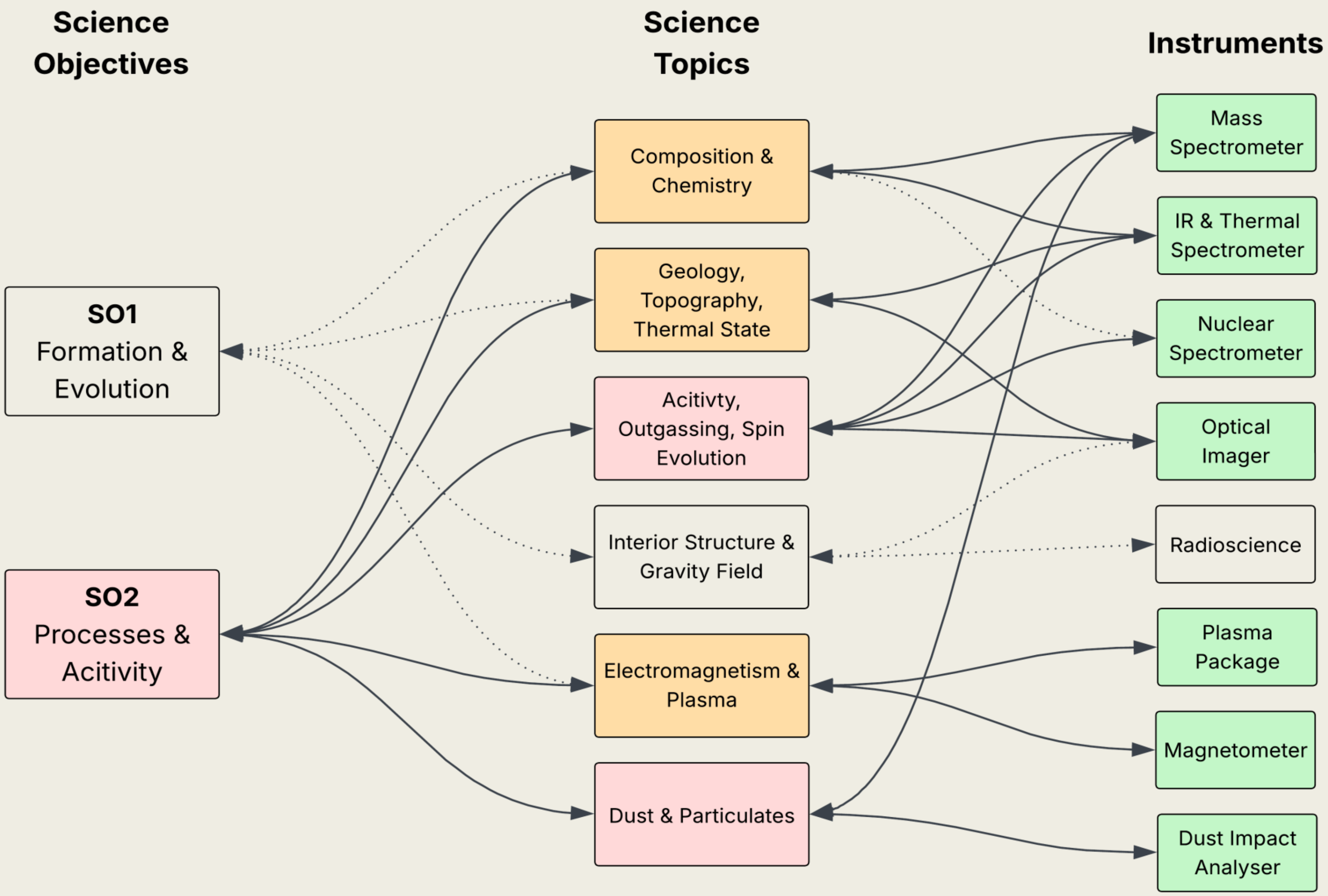
S01

How did the icy planetesimals form and evolve?

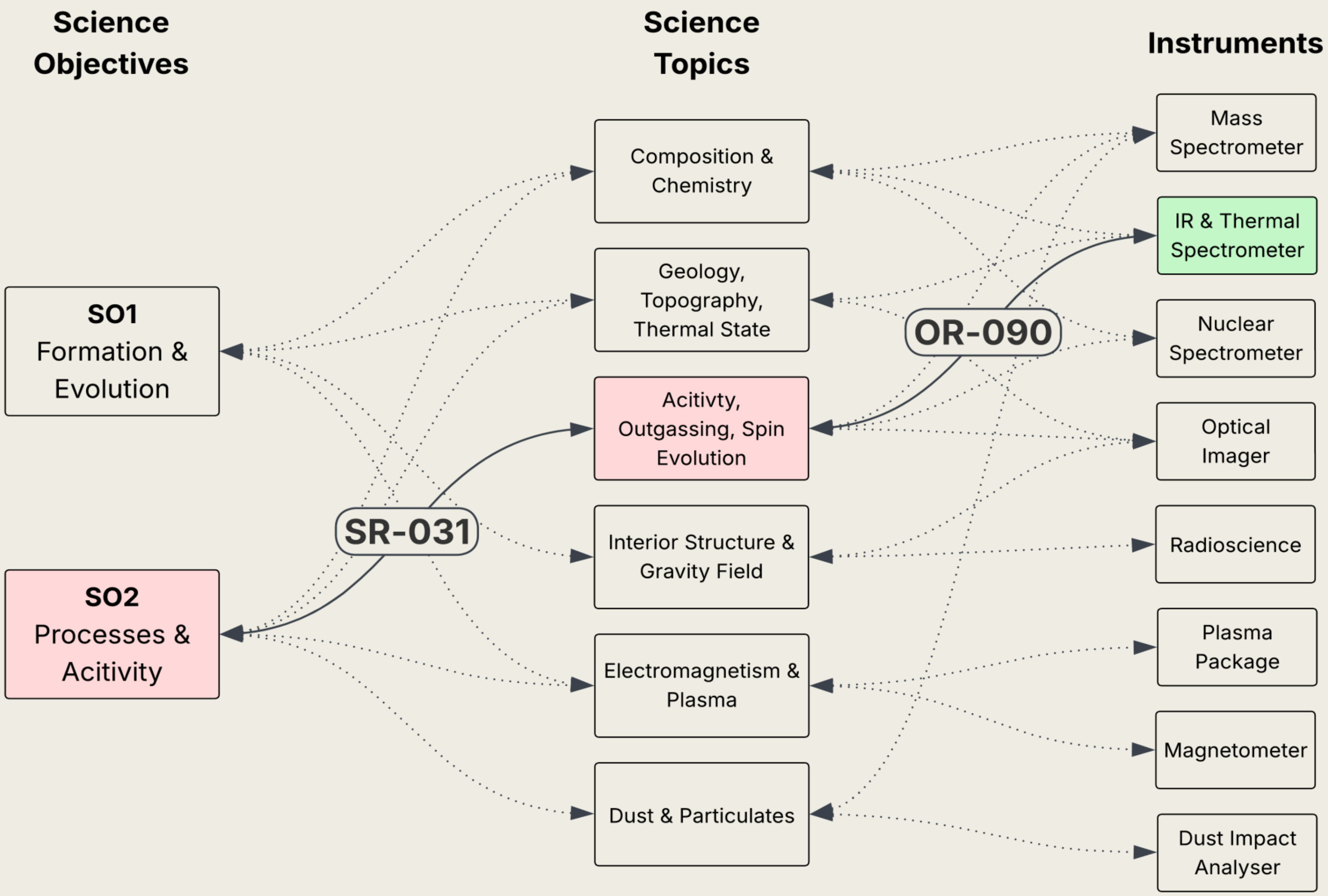
- SR-020: Composition and Chemistry
  The chemical composition of the coma/exosphere of a Centaur shall be identified.
  - OR-050
    Volatiles and hyper-volatiles (CO, CO_2, CH_4, N_2, O_2, HCN) in the coma shall be distinguished and quantified by the spacecraft.
  - IR-050: Mass Spectrometer
    High-cadence mass spectrometric measurements with resolving power greater than 1'000 over a mass range from 5 to 100 amu down to an ambient pressure of 10^{-17} mbar.

⇒ High resolution time-of-flight mass spectrometer

Science Requirements



Science Requirements – Traceability Example 2



Science Objectives – Traceability Example 2

S02

Which processes drive the activity of Centaurs?

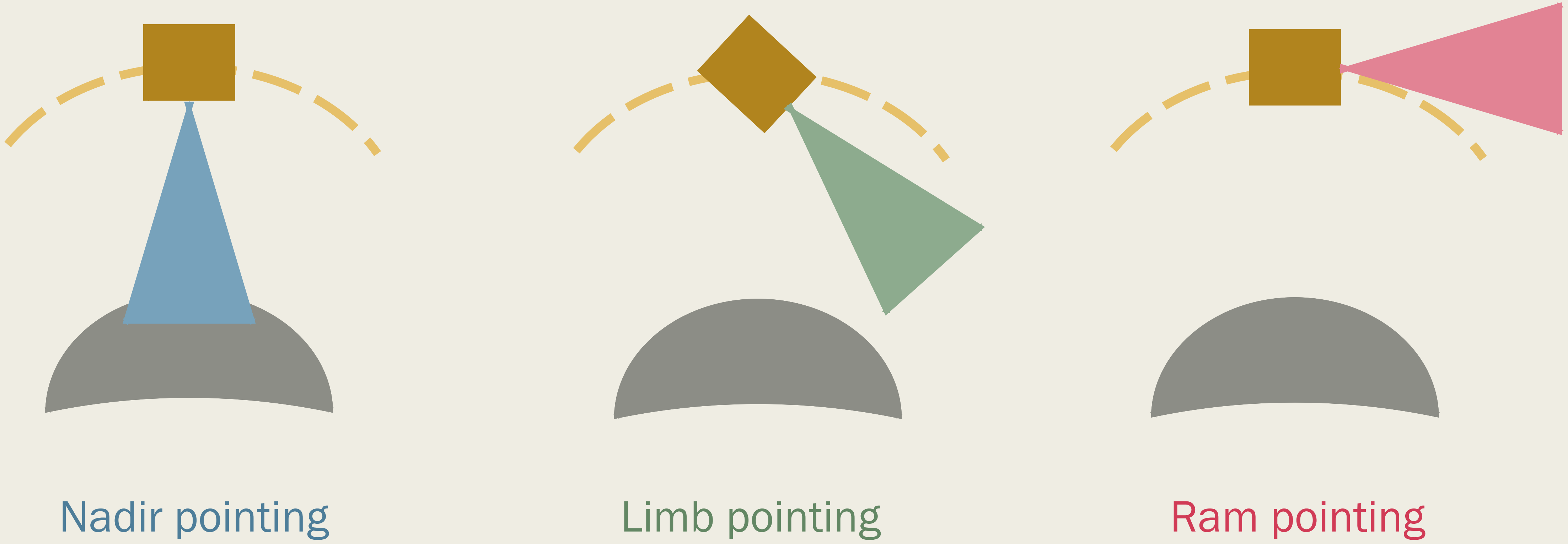
- **SR-031: Activity, Outgassing, and Spin Evolution**
  Outgassing patterns, outburst events and their temporal evolution shall be investigated.
  - OR-090
    The optical thickness of the coma and its temporal variation shall be monitored during active outburst events (days to weeks)
  - ***IR-090: Infrared Spectrometer***
    Limb pointing for transmission measurement during stellar occultation by the coma in the CO (5 μm), CH_4 (1.65 μm), and CO_2 (4.27 μm) spectral bands.

⇒ ***Mid-IR spectrometer***

Instrument Overview

- **Mass Spectrometer [MS]** Ram pointing
- **Infrared and Thermal Spectrometer [NIR + MIR + TIR]**
- **Nuclear Spectrometer [GND]**
  - *Gamma and Neutron Spectrometers*
- **Optical Imager [NAC]**
  - *Narrow Angle Camera*
- **Dust Impact Analyser [DIA]** Nadir pointing
- **RadioScience [RS]**
- **Plasma Package [PP]**
  - *3-axis Magnetometer [MAG]*
  - *Langmuir Probe [LAP] & Ion and Electron Sensor [IES]* No pointing

Science Pointing Modes



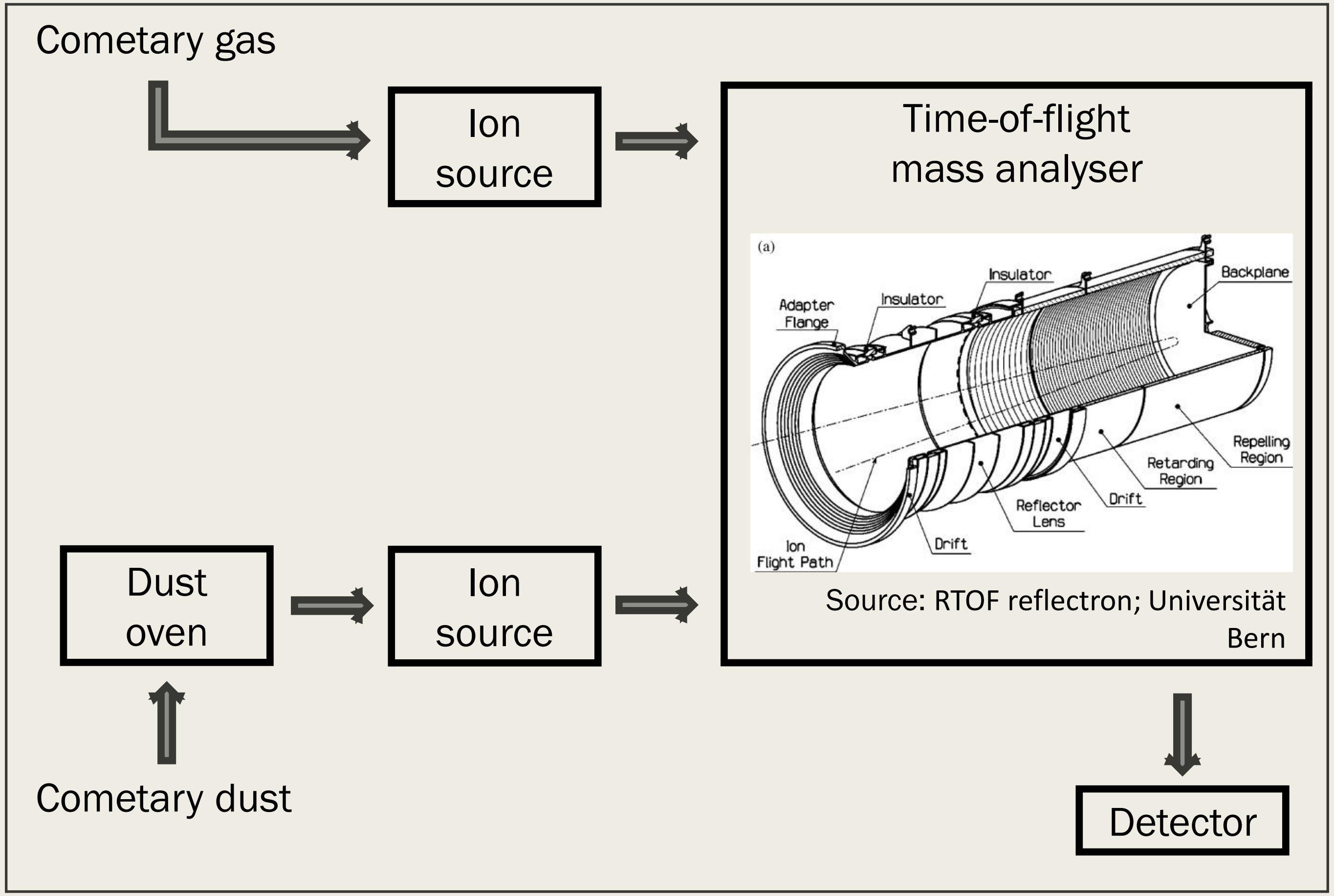
TRL 4, SR-020, SR-021, SR-031

Time-of-flight Mass Spectrometer [MS]

Heritage:
Rosetta/ROSINA &
Rosetta/COSAC

- Ram pointing
  - *Gas measurements*
  - *Dust volatile measurements*
- Any pointing
  - *Reference ambient pressure measurement*

Mass range	1 – 300 amu
Resolving power	> 10 000 FWHM
Dynamic range	10^8
Pressure range	10^{-6} – 10^{-17} mbar



Source: RTOF reflectron; Universität Bern

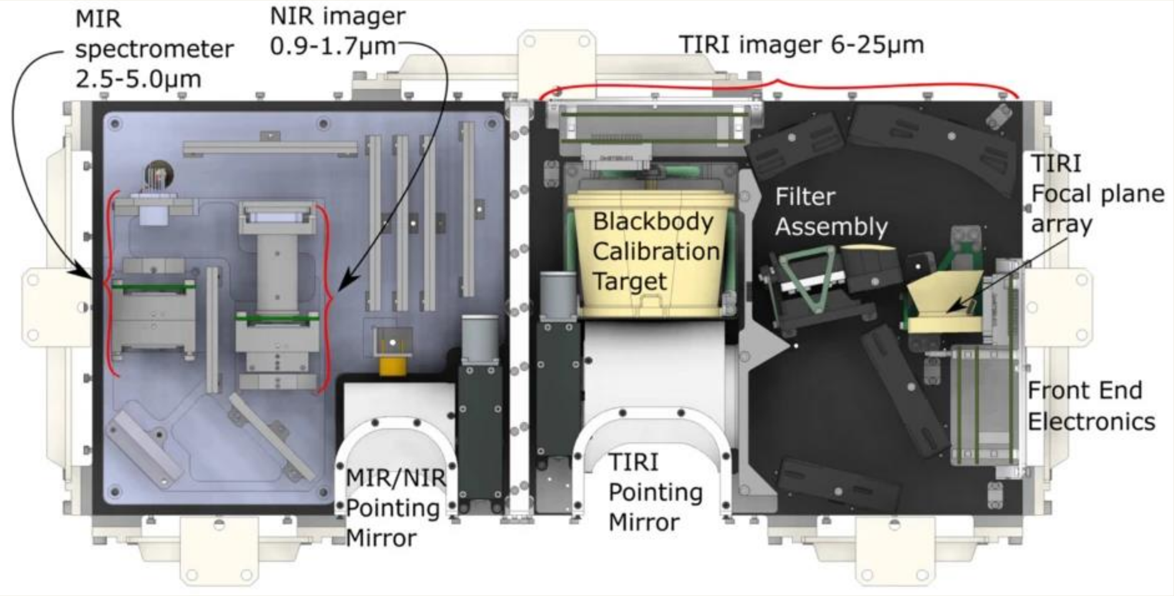
TRL 5, SR-010, SR-031, SR-090

Infrared and Thermal Spectrometer [NIR + MIR + TIR]

Heritage:
Comet Interceptor /MIRMIS

- **Nadir pointing**
  - *Detection of surface ices, mineralogy, organics by NIR/MIR spectroscopy*
  - *Temperature mapping by TIR emission*
- **Limb pointing**
  - *Coma thickness measurement by stellar occultation*

Spectral range	0.6 – 25 µm
Spectral resolution	< 30 nm FWHM
FOV NIR	6.7° x 5.4°
FOV MIR	0.286° (circular)
FOV TIR	9°x 7°



Source: MIRMIS

Components

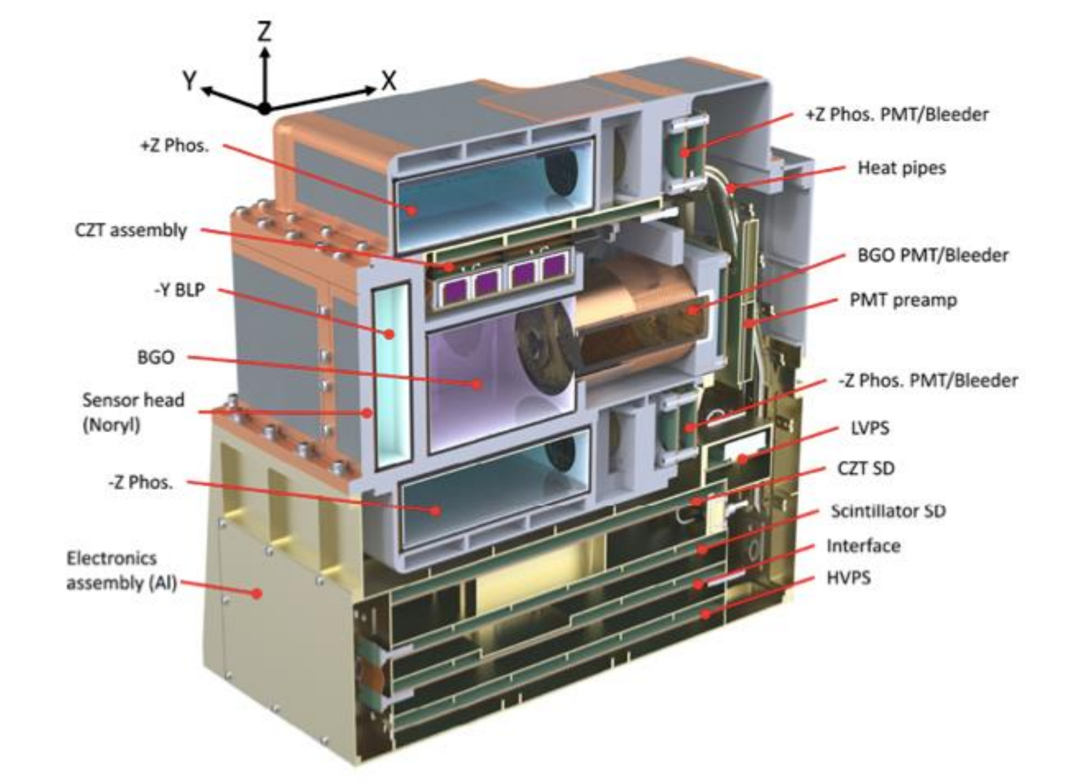
- *NIR* *Imaging spectrometer*
- *MIR* *Point spectrometer*
- *TIR* *Thermal imager with filters*

TRL 7, SR-010, SR-031

Heritage: DAWN/GRAND

Gamma and Neutron Detectors [GND]

- Nadir pointing
  - *Remote mapping of specific elements in the shallow subsurface by spectroscopy of nuclear interactions with galactic cosmic rays (GCRs)*



Source: Prettyman 2021

Energy range	0.1 – 10 MeV
Temperature range	-20 to 30 °C

Element(s)	O, Si, Fe, Ca, Al, Mg, Ti	C	H
Approximate sensitivity (ppm)	1000–10 000	~1000–5000	~100–200

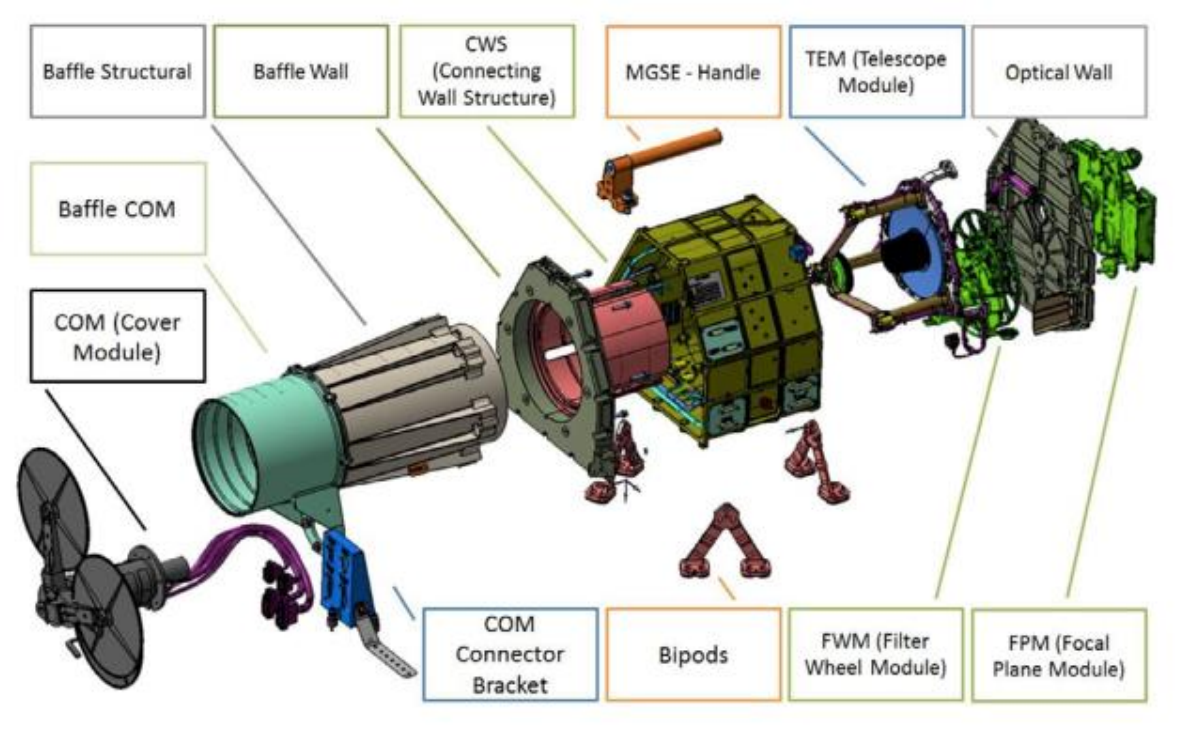
TRL 4, SR-030, SR-040, SR-050

Heritage:
JUICE/JANUS

Optical Imager [NAC]

- Nadir pointing
  - *Mapping of shape, surface features, rotation state*
- Limb pointing
  - *Side-looking imaging for stereoscopic measurements and increased ground coverage*

Source: JANUS/JUICE



Required developments

- *Increase of optical aperture size to adapt to low albedo (~3%) object*

Spectral range	VIS (380 – 740 nm)
Spectral resolution	Down to 10 nm
FoV	1.72° x 1.29°

TRL 7, SR-100

Heritage: Rosetta/GIADA

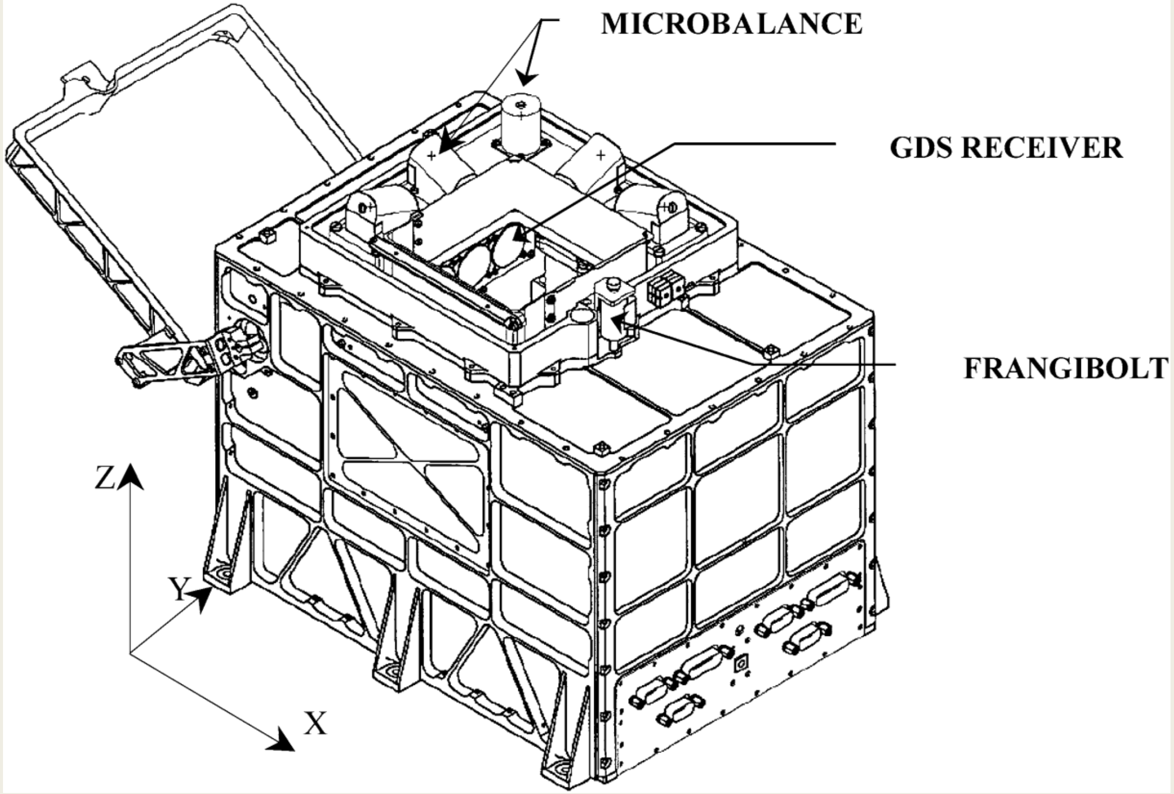
Dust Impact Analyser [DIA]

- Nadir pointing
  - *Characterisation of dust flux evolution and grain dynamic properties*

Components

- *Grain detection system*
- *Impact sensor*
- *Microbalances*

Particle size	> 10 µm
Particle velocity	< 300 m/s
Particle momentum	6.5×10^{-10} – 4.0×10^{-4} (kg m)/s



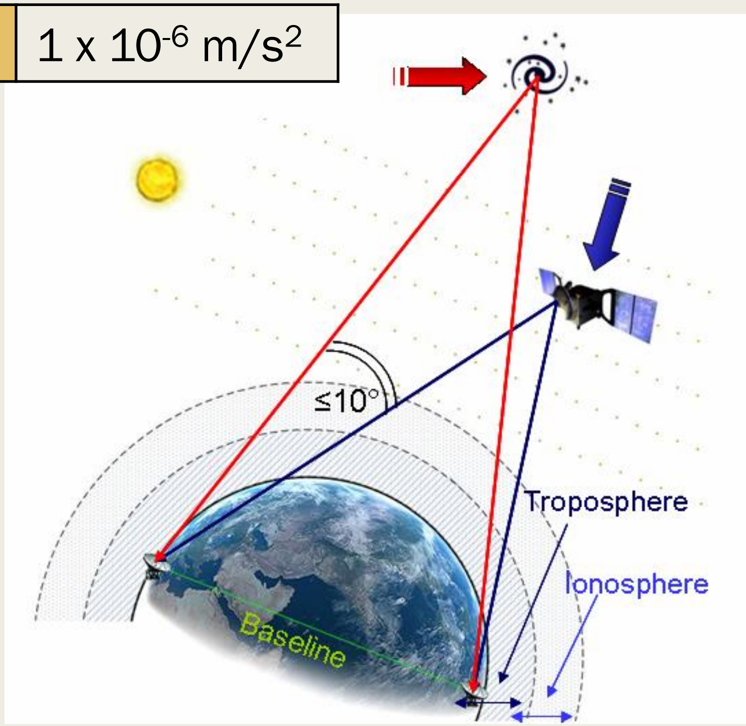
Source: Colangeli 2006

SR-050

Δ-DOR Radioscience [RS]

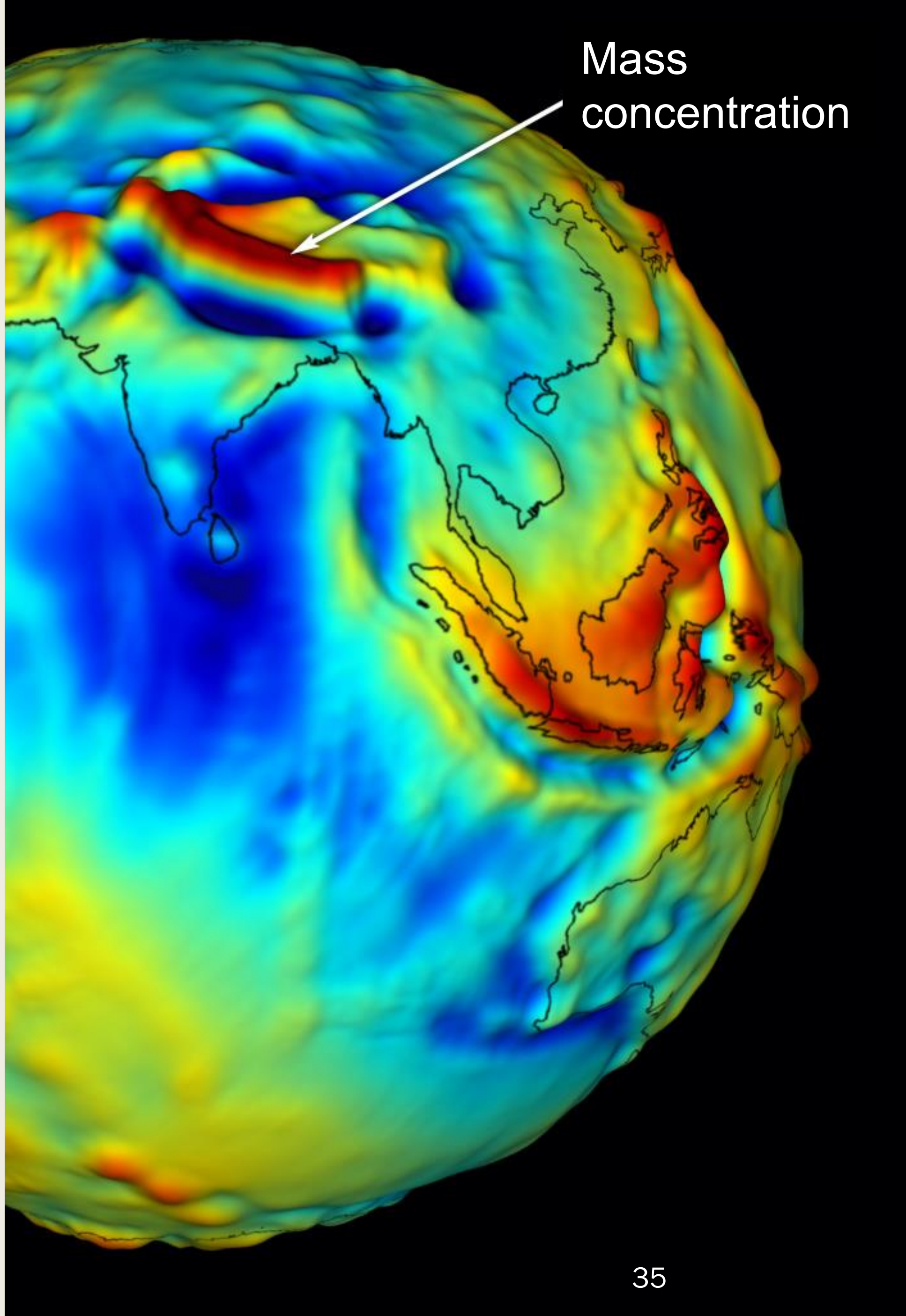
- Any pointing
  - *Determining mass distribution by establishing a gravity field measurement via Doppler and differential time-of-flight measurements*

Resolution	1×10^{-6} m/s^2



Source: Barbaglio et al. 2012

Credit: NASA's Goddard Space Flight Center: Mapping Earth's Gravity

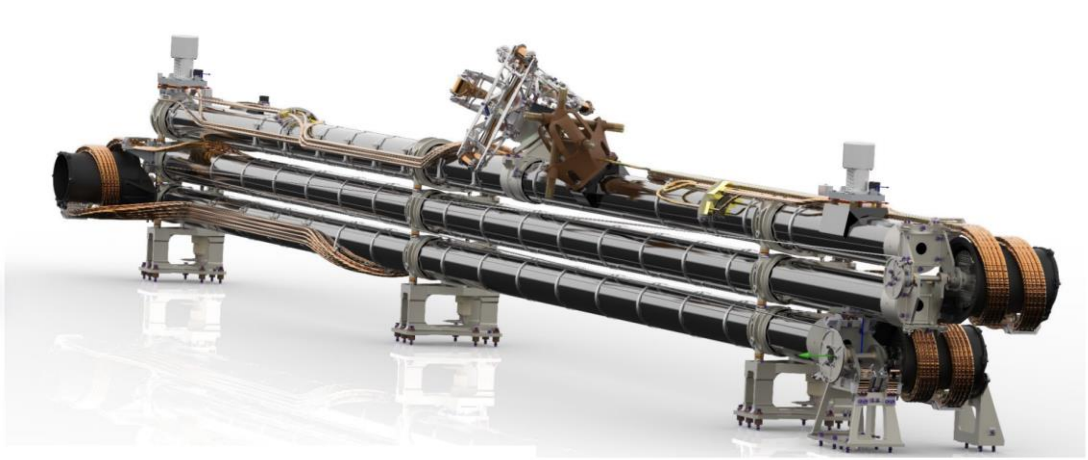


TRL 7, SR-080

Heritage: Rosetta/RPC

Plasma Package [PP] – (1)
2x 3-Axis Magnetometer [MAG]

Source: ESA, SENER



- Any pointing
  - *Detection of a potential remnant magnetic field*
  - *Detection of a potential induced magnetic field and interaction with the interplanetary magnetic field*
  - *Detection of a potential bow shock and magnetic bubble*

Resolution	Magnitude	Range ±1000 nT with resolution 0.015 nT
	Direction	1 vec/s in nominal mode, 50 vec/s in max. mode

TRL 7, SR-080

Heritage: Rosetta/RPC

Plasma Package [PP] – (2)

2x Langmuir Probes [LAP]

- *Measurement of plasma density variations and flow velocity*

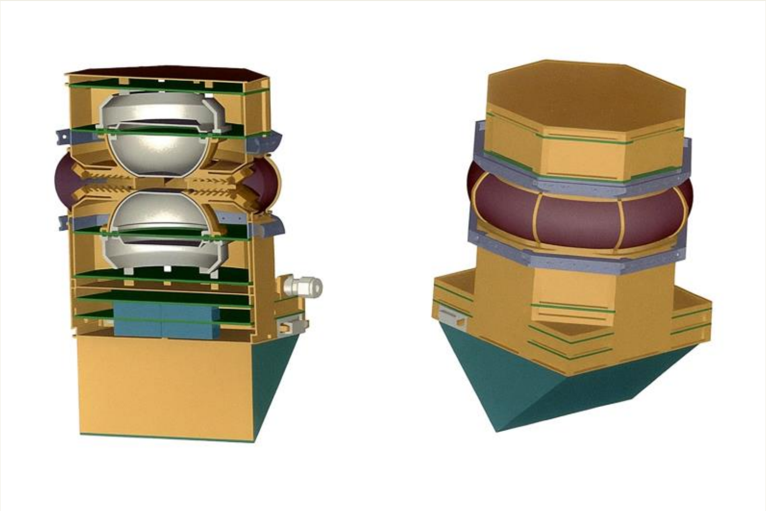
Performance parameters	Electric field	Up to 8 kHz
	Plasma density	$(1 - 10^6)\ cm^{-3}$
	Plasma drift	Up to 10 km/s

Sources: Rosetta

Ion and Electron Sensor [IES]

- *Measurement of particle energies and directions*

Energy range	3 eV/e – 30 keV/e	
FoV	90° x 360°	
Angular resolution	Electrons: 5° x 22.5°	
	Ions: 5° x 45°	
	Solar wind ions: 5° x 5°	

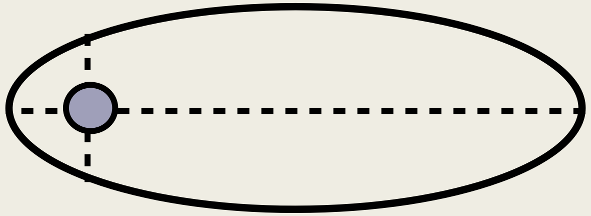


Mission Success Criteria

Observational requirement	Linked objectives	Instrument	Min. Performance for success
OR-020: Map surface distribution of volatile ices	SO 1 / 2	Mapping spectrograph (NIR, MIR)	50% surface coverage detect at least 3 species
OR-090: Coma optical thickness + temporal variations	SO 2	Mapping spectrograph (MIR)	10 occultations over whole mission
OR-100: Coma optical thickness + spatial variations	SO 2	Mapping spectrograph (MIR)	50% outbursts events measured
OR-050: Quantify coma volatiles	SO 1 / 2	Mass spectrometer	Measure and separate heavy hydrocarbons up to mass 300 amu
OR-210: Measure embedded volatiles in the dust	SO 2	Mass spectrometer	

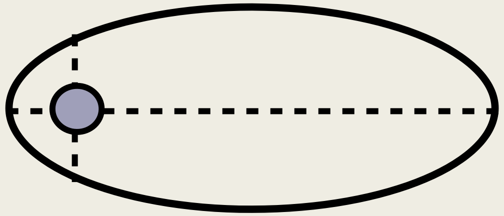
- *Failure to meet any of these five observational requirements means the mission does not achieve its baseline science objectives.*

Orbital Requirements



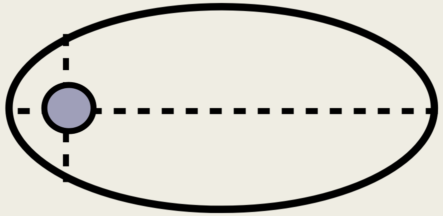
Capture orbit

- *Low-res imaging*
- *Plasma environment*
- *Activity tracking*



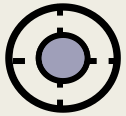
Survey orbit

- *Low-res mapping*
- *Establishing safety for lower orbits*



High/low orbits

- *Nuclear spectrometry*
- *Gravity field*



Circular orbit

- *High-res mapping*
- *Gravity field*
- *Magnetic surface interactions*

Mission Overview
Launcher & Transfer
Spacecraft Description
Subsystems
Budgets
Ground Segment
Critical Technology

MISSION PROFILE

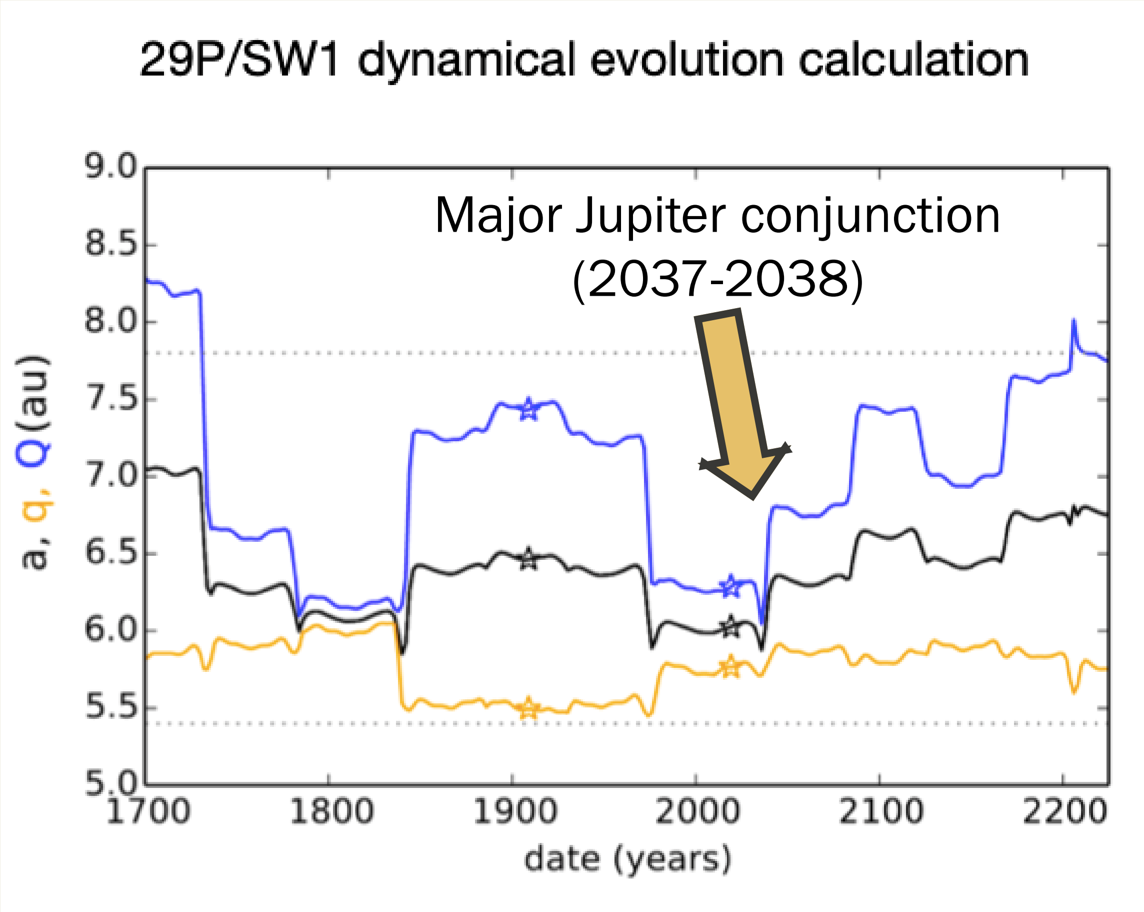
Mission Requirements

1. The system shall be able to rendez-vous with 29P.
2. The system shall be able to maintain a distance from 29P between 800 and 50 km for at least 2 years.
3. The spacecraft shall be compatible with a launch of Ariane 64 from French Guiana.
4. The mission shall be designed for a lifetime of 15 years.
5. The system shall have a pointing accuracy of 0.1 degrees.
6. The system shall keep an attitude with maximum accuracy for at least 600 minutes.
7. Optical measurements shall be made at a maximum solar phase angle of 30 degrees.
8. At least 50% of the surface of 29P shall be observed on the illuminated side.
9. Spacing of subsequent ground tracks of science orbits shall be at least 1 km.

Key Mission Drivers

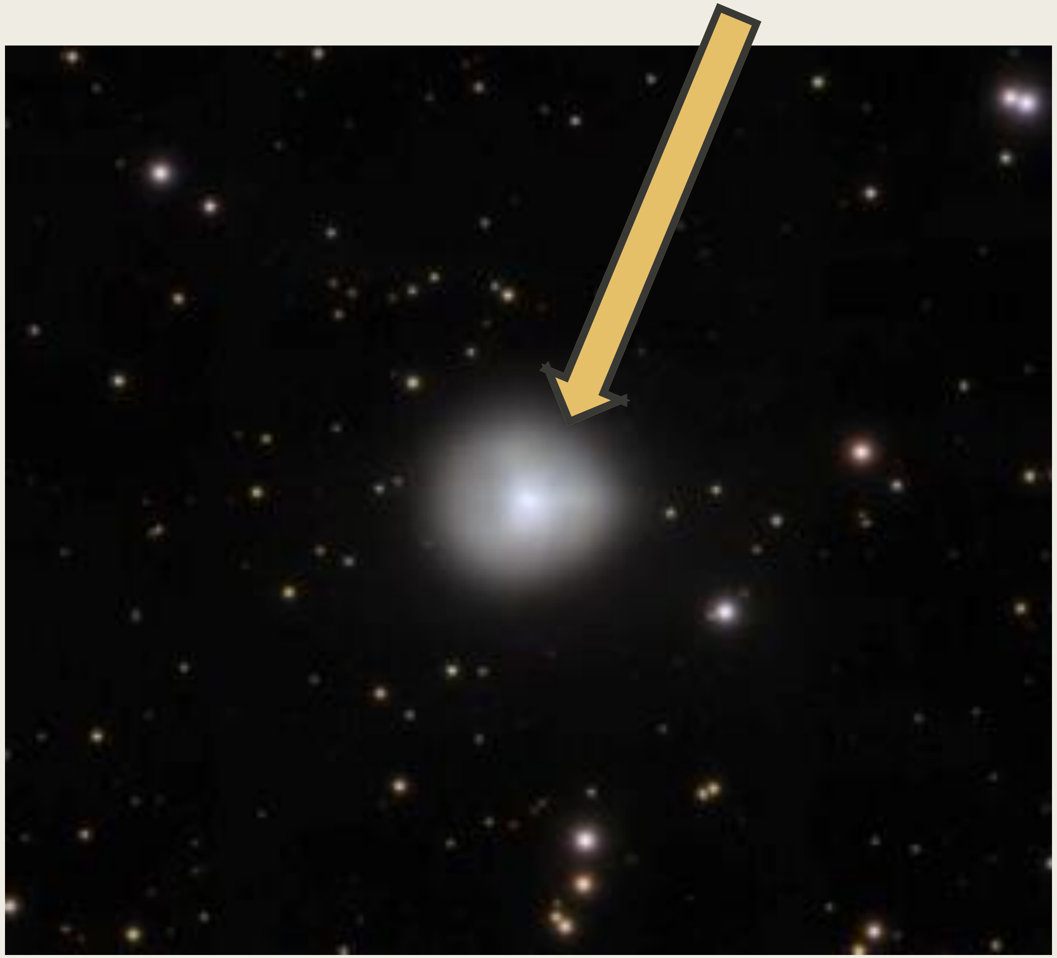
Operational Uncertainties	• Unknown rotational dynamics of 29P • Unknown gravitational field of 29P
Data Generation and Communication Complexity	• Large data production during scientific modes • Low data link due to large distance from Earth
Long Total Mission Duration (Transfer + Operations)	• Degradation of spacecraft components • Reliability of spacecraft components
Limited Power Availability	• Limited power generation at 6 AU

29P – Orbit Dynamics – (1)



Source: Sarid et al. 2019

Activity on 29P



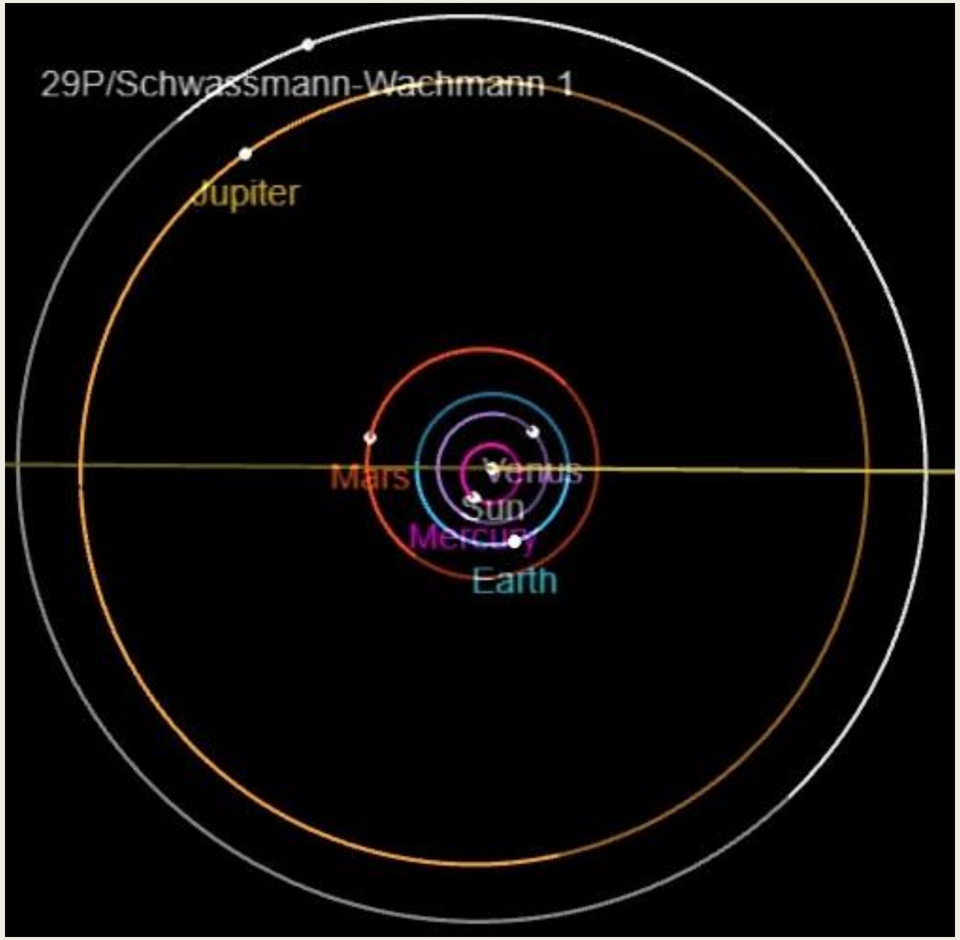
Source: International Gemini Observatory

29P – Orbit Dynamics – (2)

Element	Value	Uncertainty (1σ)	Units
e	0.045	1.8471E-8	-
a	6.046	9.4891E-8	au
i	9.365	9.6252E-7	degree

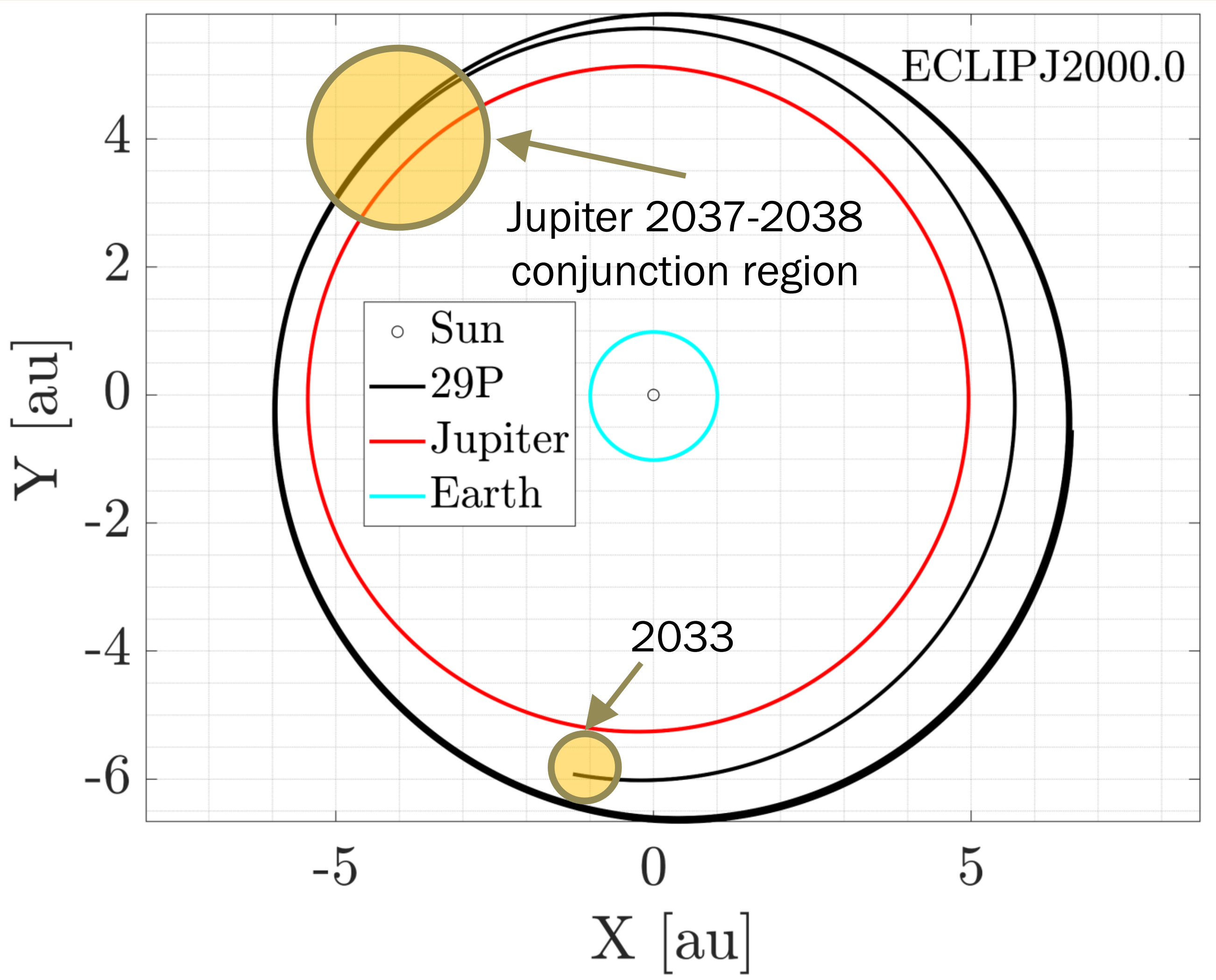
Next **Jupiter conjunction:**

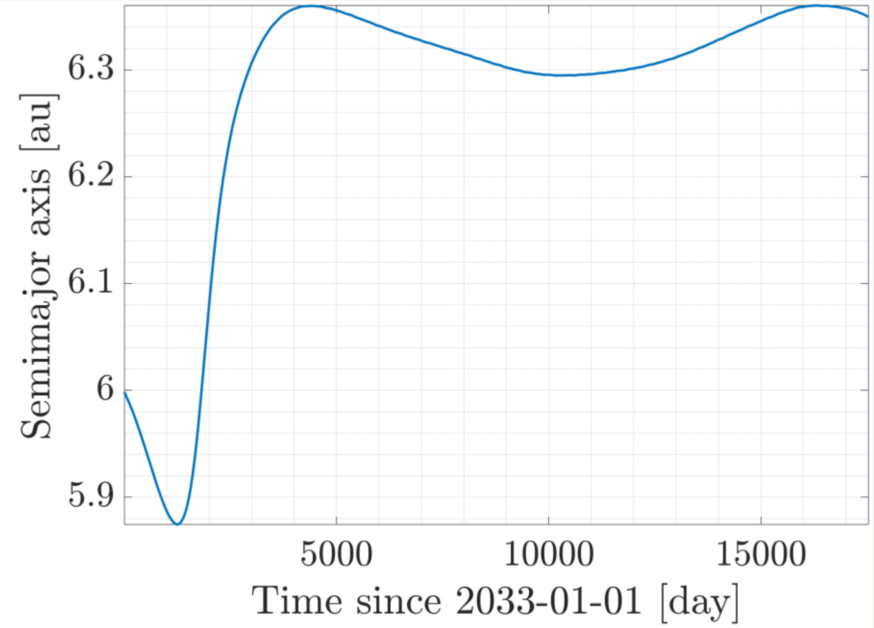
- Date: **2037-Oct-11**
- Minimum Distance: **0.9 au**
- Relative speed: **2.53 km/s**

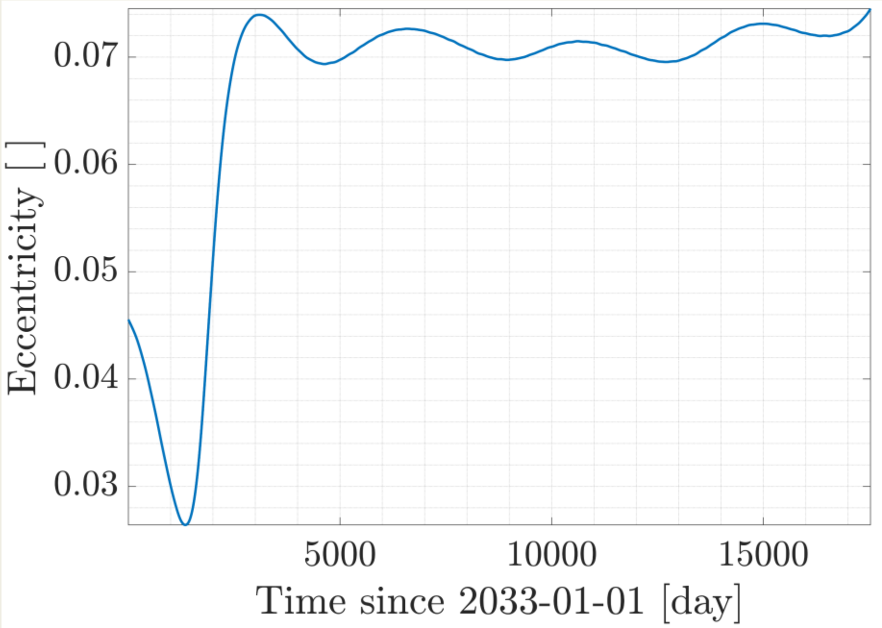


Source: NASA JPL Small-Body Database Lookup

29P – Orbit Dynamics – (3)





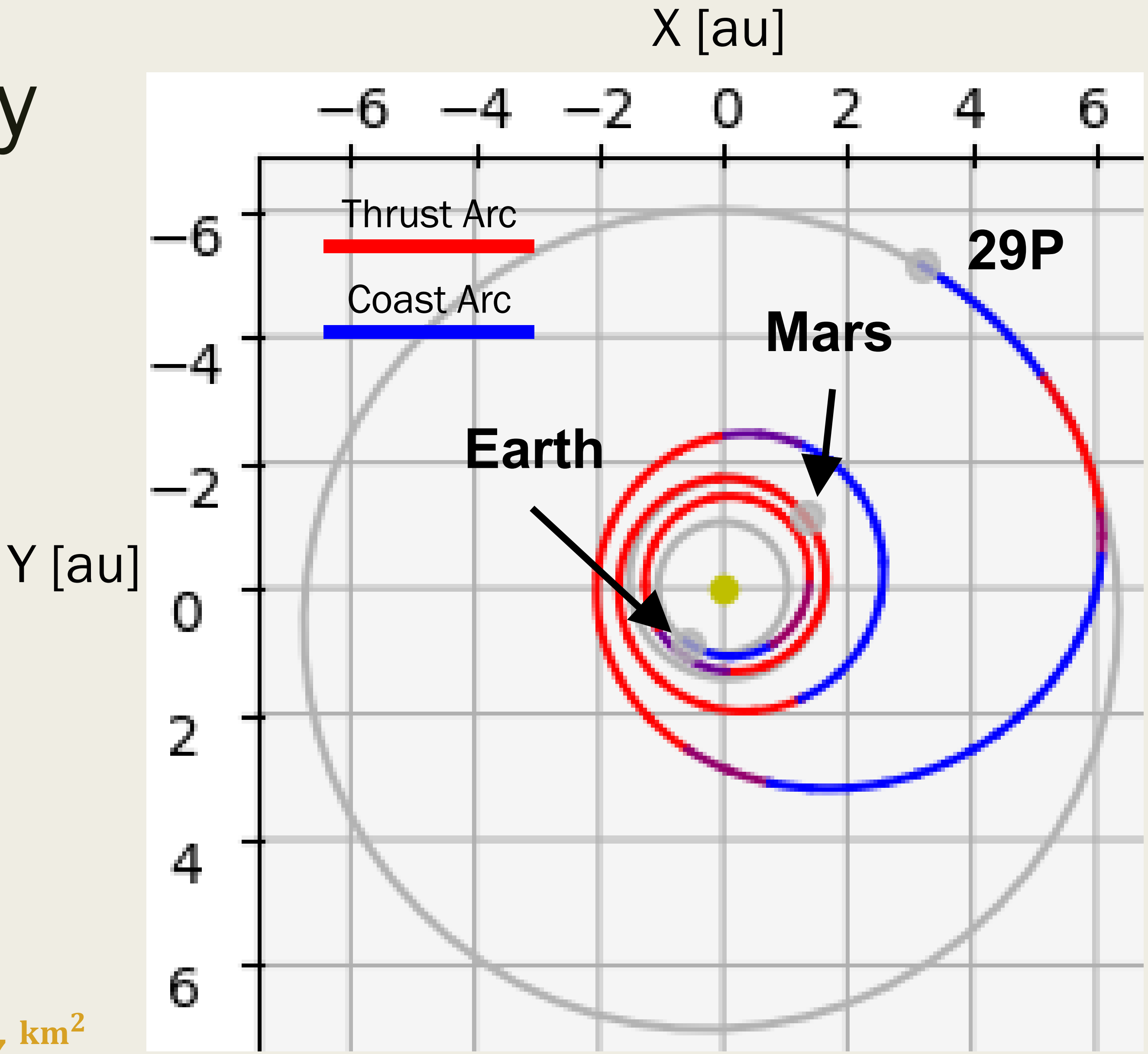


Mission Timeline

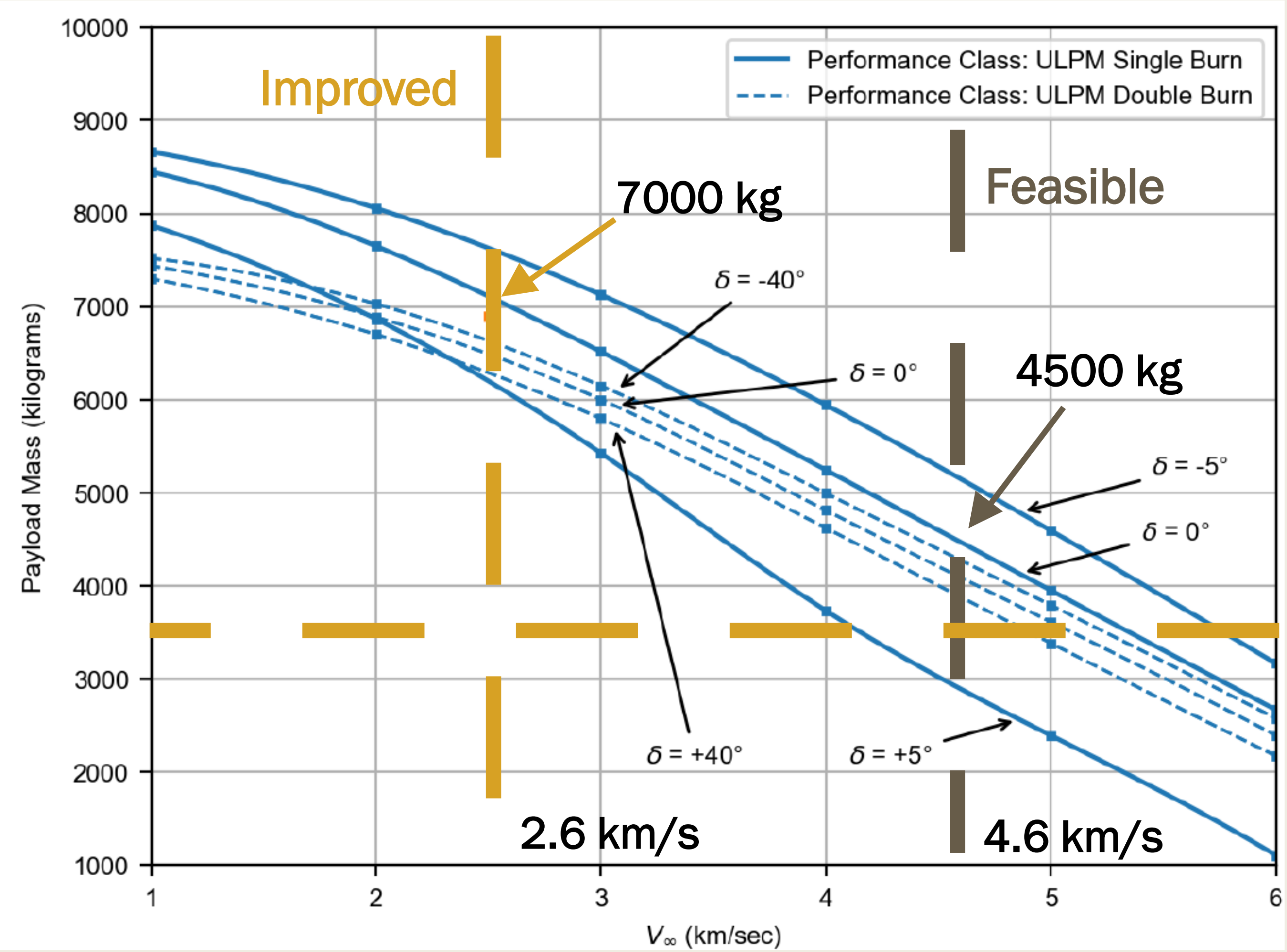
0	Pre-Launch Phase (Launch Campaign)		August 2043
1	Launch and Early Operations Phase (LEOP)		3-4 weeks
2	Commissioning Phase		
	2.1	Spacecraft Operational Commissioning Phase	4 months
	2.2	Spacecraft Science Commissioning Phase	2 weeks
3	Cruise Phase		2 years
4	Mars Flyby		~
5	Cruise Phase		10 years
6	Commissioning Phase		1 month
7	Nominal Phase (starting ~2055)		2-3 years
8	Extended Mission Phase		TBD years
9	Decommissioning Phase		TBD months

Transfer Trajectory

- Mass at 29P: 1640 kg
- Launch Mass: 3613 kg
- Thrust: 0.200 N
- Specific Impulse: 2000 s
- Transfer $\Delta v \simeq \mathbf{15} \frac{\mathbf{km}}{\mathbf{s}}$
- Launch Date: **19-August-2043**
- Earth to Mars: **800 day**
- Mars to 29P: **3653.7 day**
- Total TOF: **4363.7 day** ≃ 12 year
- Escape Speed: **2588.9 m/s** → $C_3 \simeq 6.7 \frac{km^2}{s^2}$



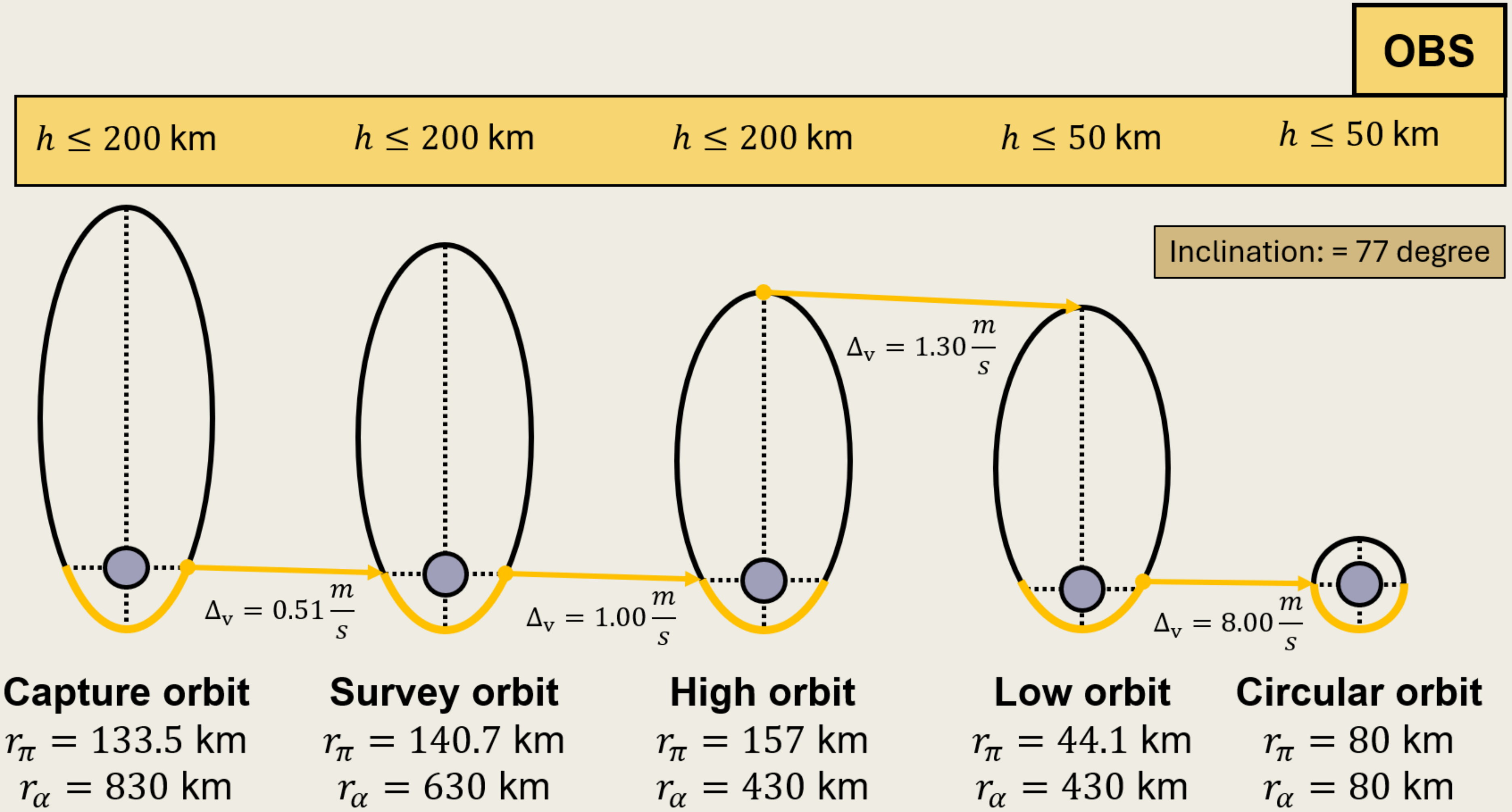
Launcher – Ariane 64



Source: ESA, Future Mission Department (SCI-F), 2025

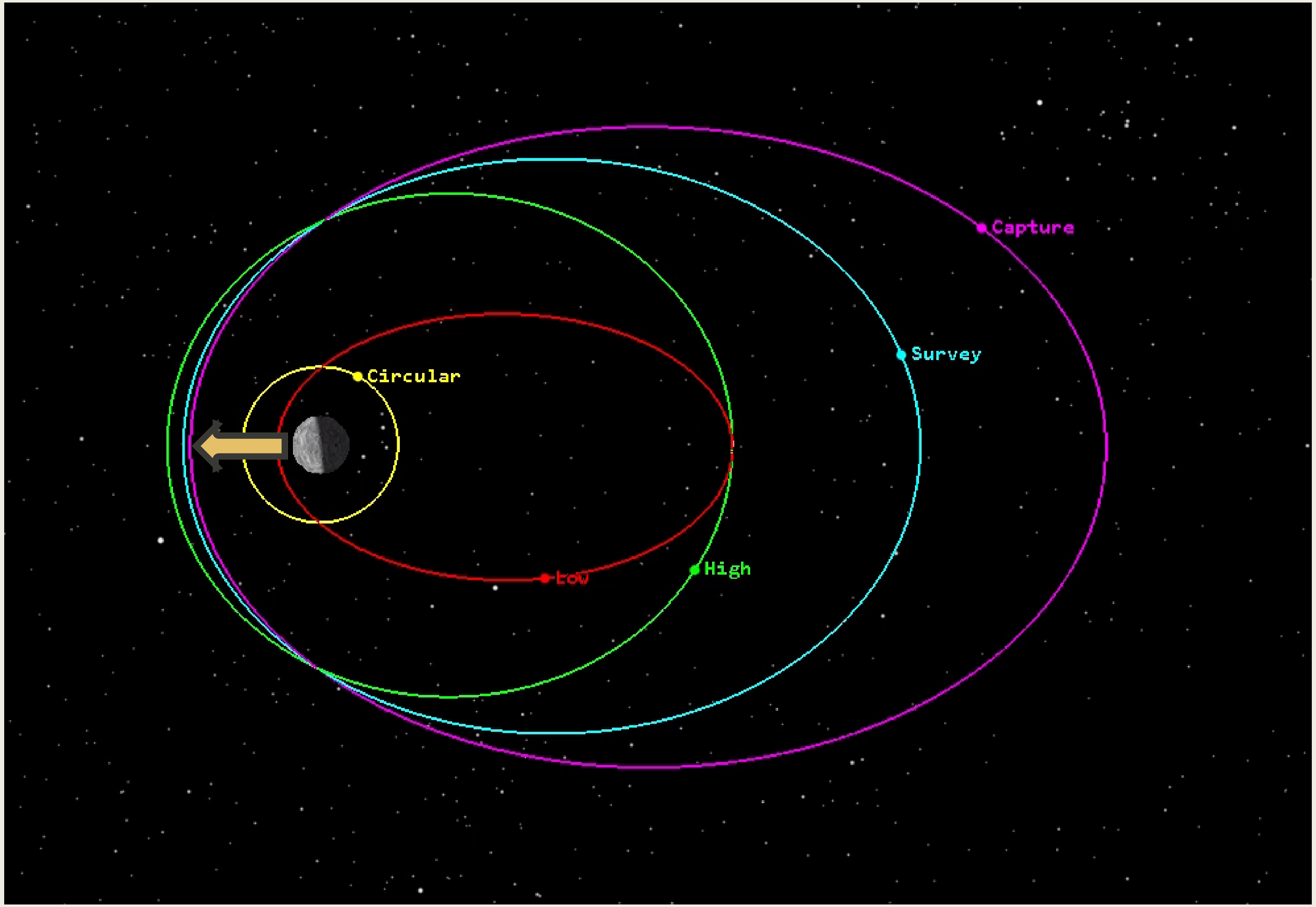
- **Launch window width:** ≃ 2 month
- **Launch window frequency:** ≃ 2.2 year (Earth-Mars synodic period and ≃ circular orbit of 29P)

Target Orbits – (1)



Target Orbits – (2)

- Max eclipse duration: 10 h



Target Orbits – (3)

Delta-v budget and propellant mass

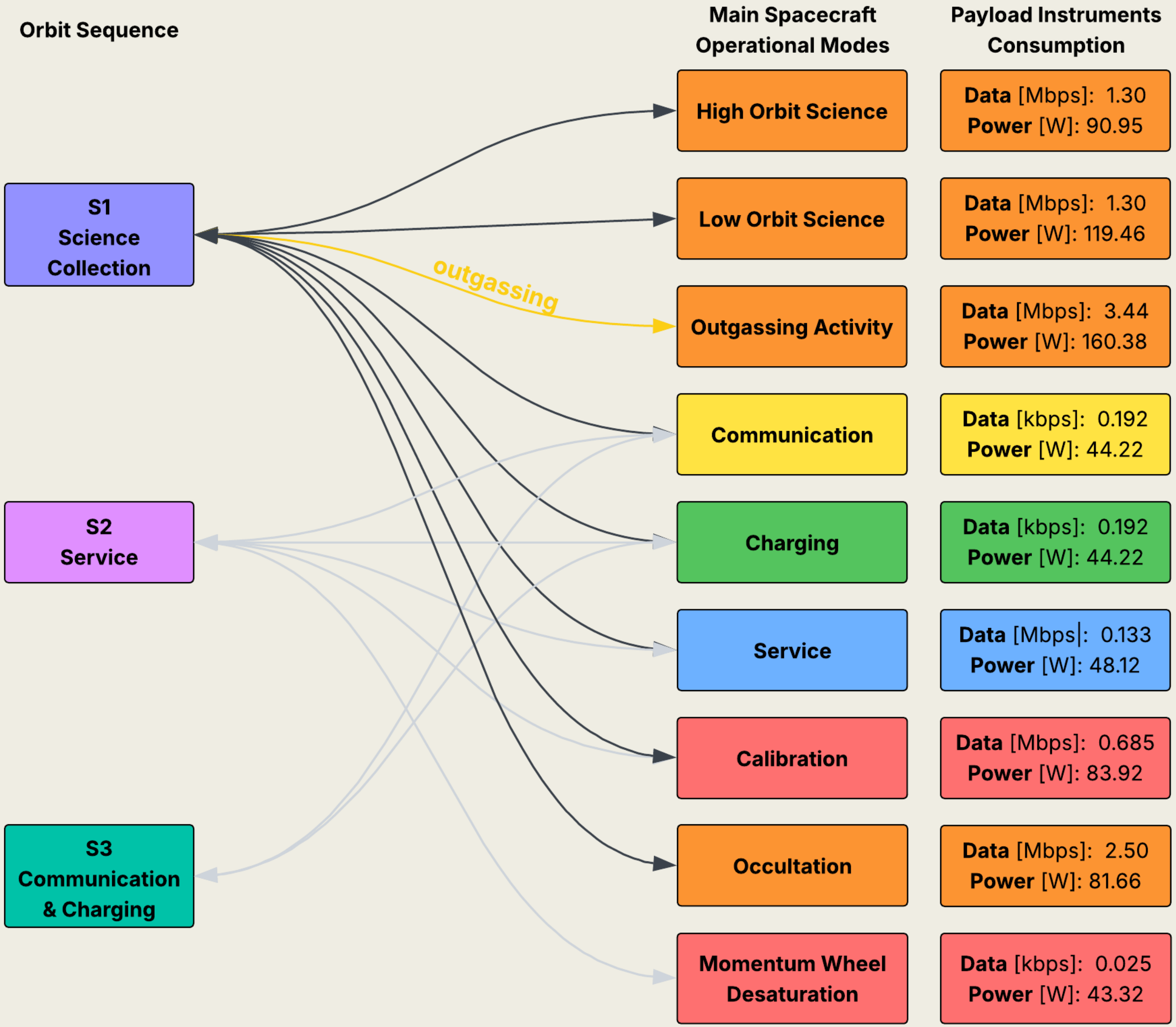
Total	Delta-v [m/s]	Propellant mass [kg]
w/o inc change	10.80	1.83
w inc change	28.19	4.8
w inc change (+100% margin)	**56.38**	**9.6**

CONOPS: Operational Modes – (1)

In High Orbit:
→ Science collection takes **memory space** and **energy** from battery
→ Have to downlink and recharge the battery: **Communication and Charging**

Service for occasional internal and ground-directed maintenance tasks.

HIGH ORBIT – One Orbit	Data Compressed ± Total [Gbits]	Data % Change -	Energy ± [Wh]	Energy % Change
SCIENCE COLLECTION	84.16	**4.55%**	-222.47	**-2.11%**
COMMS AND CHARGING	-41.2	**-2.06%**	118.6	**1.12%**
SERVICE	15.17	**0.76%**	17.73	**0.17%**

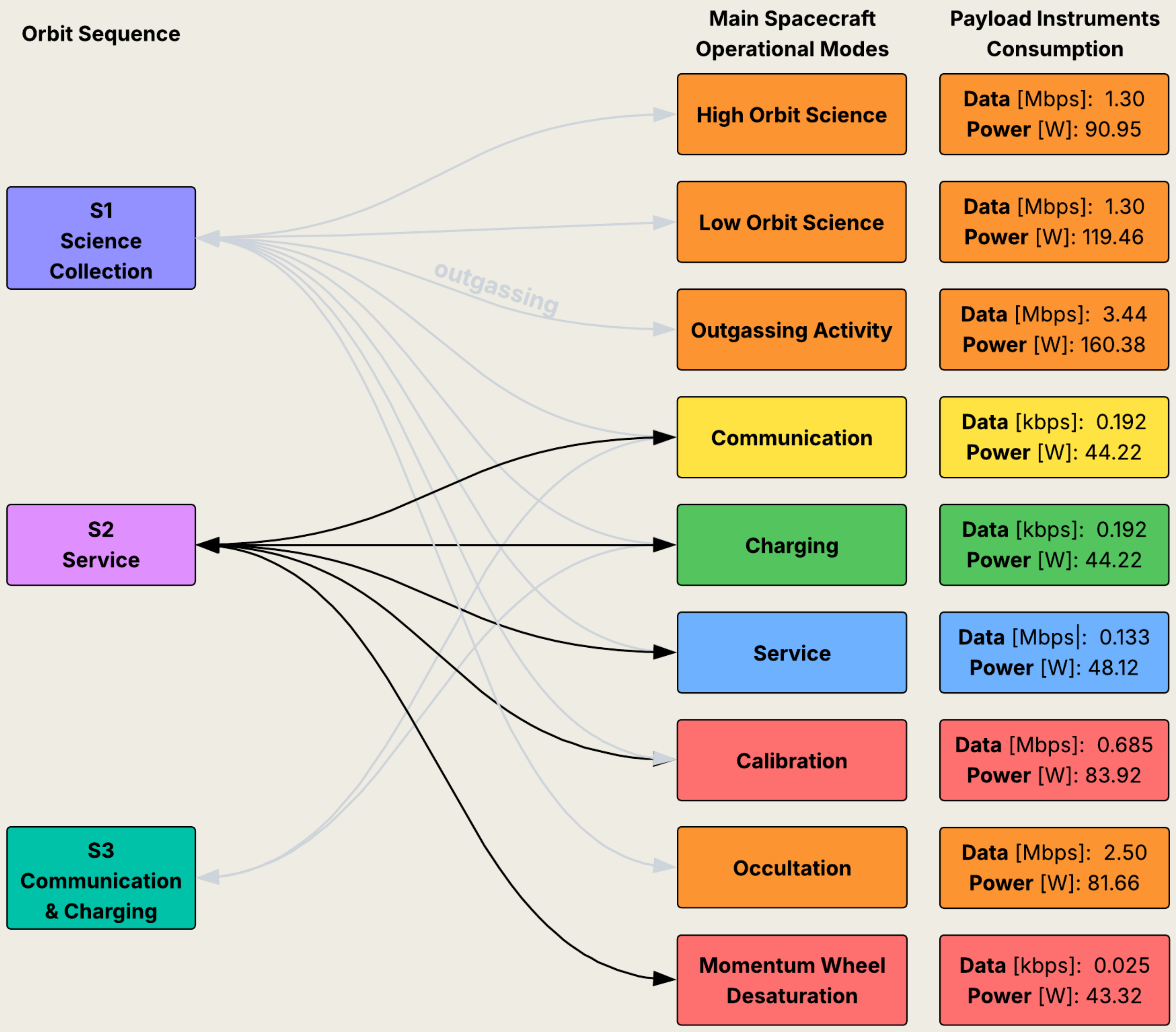


CONOPS: Operational Modes – (2)

Each orbit → **3 different sequences** (S) of satellite operating modes.

Each **operating modes correspond to different payload instruments being on/off** → different Power and Data consumption

CONOPS: Operational Modes – (2)



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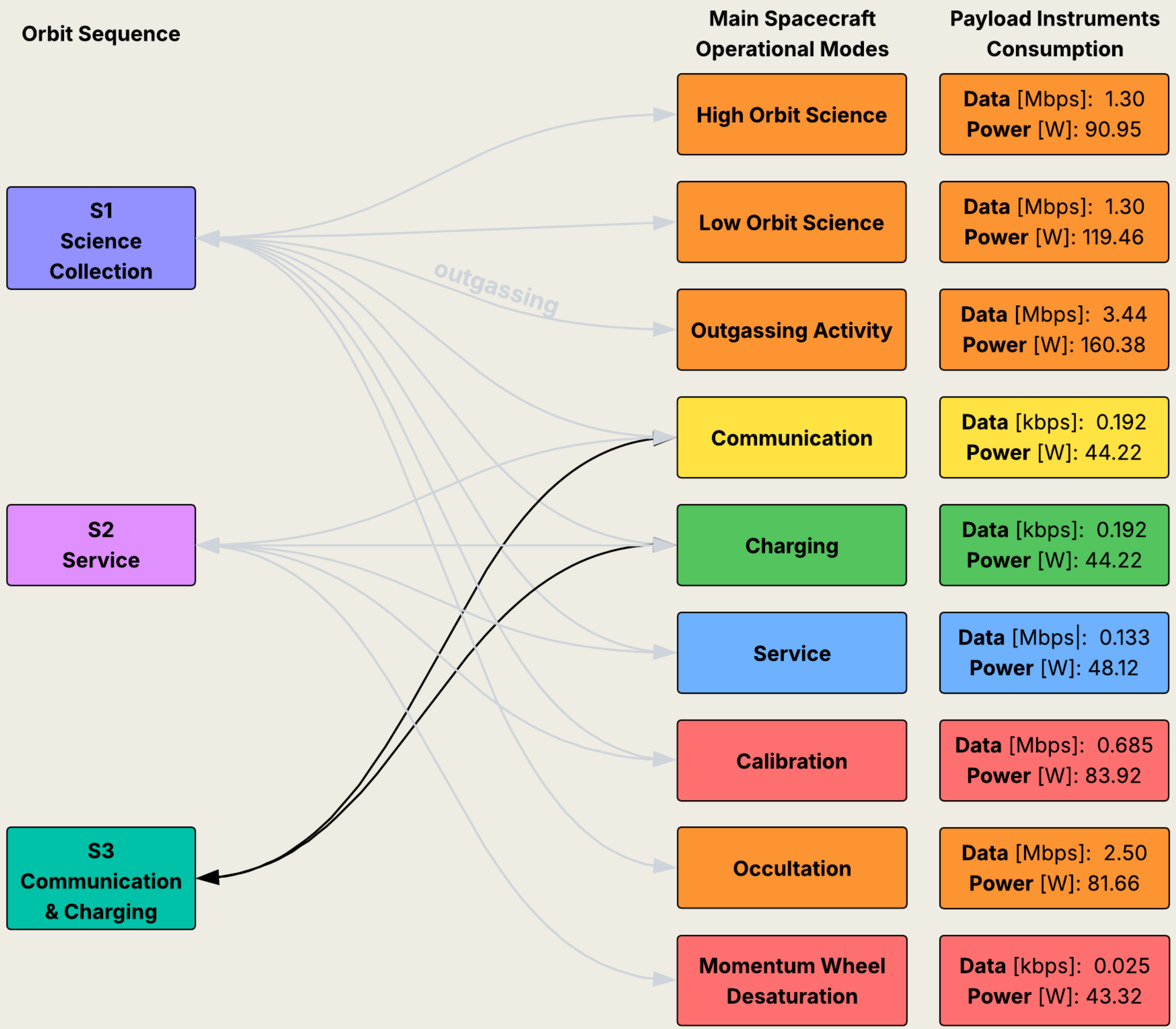
CONOPS: Operational Modes – (2)



Each orbit → **3 different sequences** (S) of satellite operating modes.

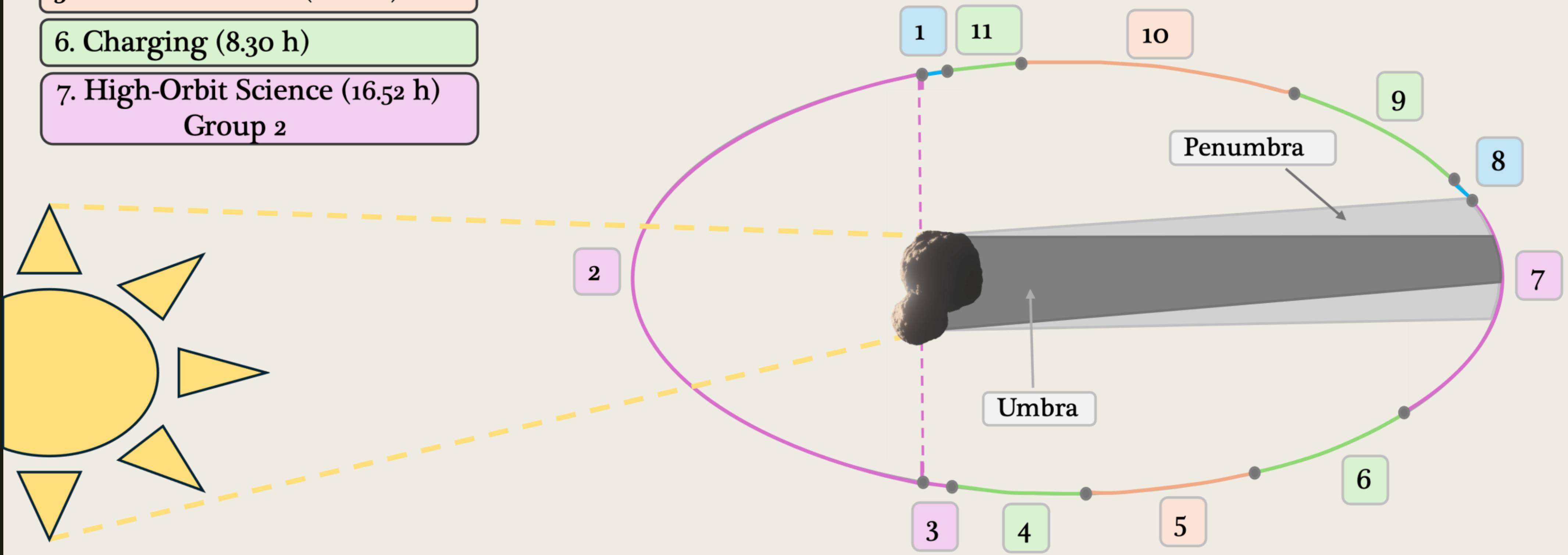
Each **operating modes correspond to different payload instruments being on/off** → different Power and Data consumption

CONOPS: Science Collection Sequence – (3)

1. Calibration (2.00 h)
2. High-Orbit Science (18.66 h) Group 1
3. Occultation (0.50 h)
4. Charging (7.40 h)
5. Communication (8.00 h)
6. Charging (8.30 h)
7. High-Orbit Science (16.52 h) Group 2
8. Service (2.00 h)
9. Charging (6.80 h)
10. Communication (7.50 h)
11. Charging (9.10 h)

Orbit Operational Modes: Science Observation Sequence

HIGH ORBIT
Periapsis : 156.99 km
Apoapsis: 430 km

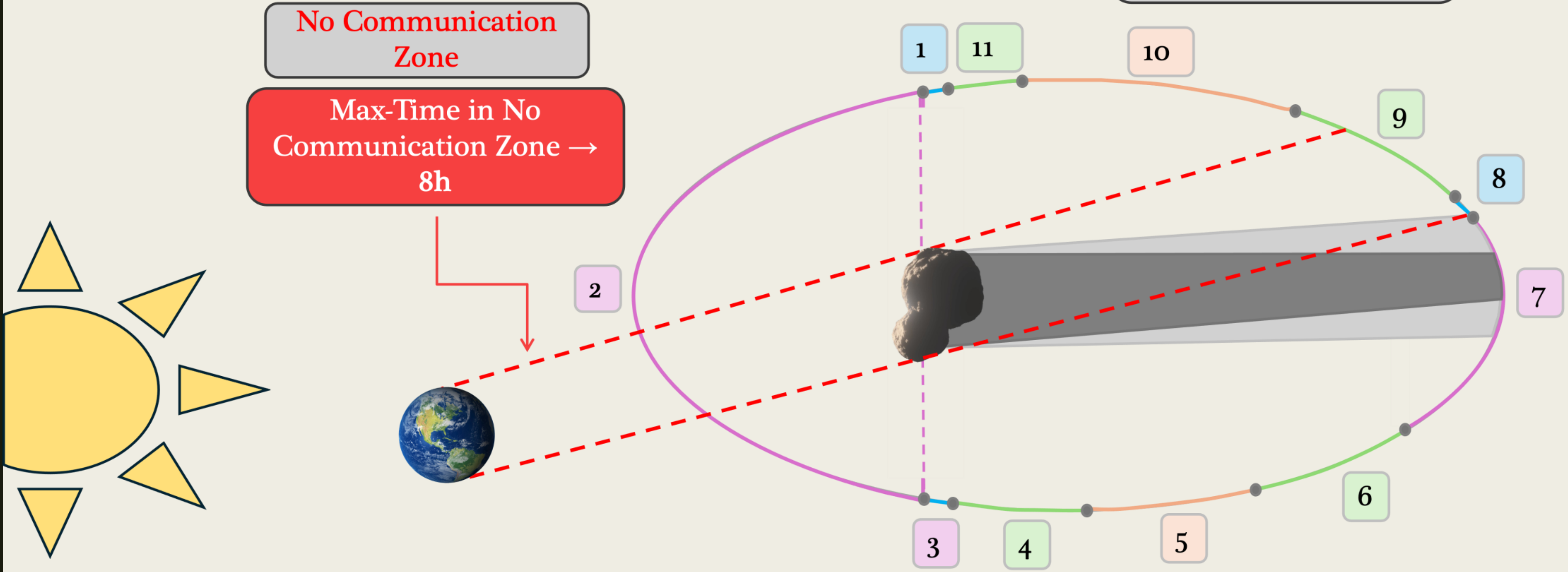


CONOPS: Science Collection Sequence – (4)

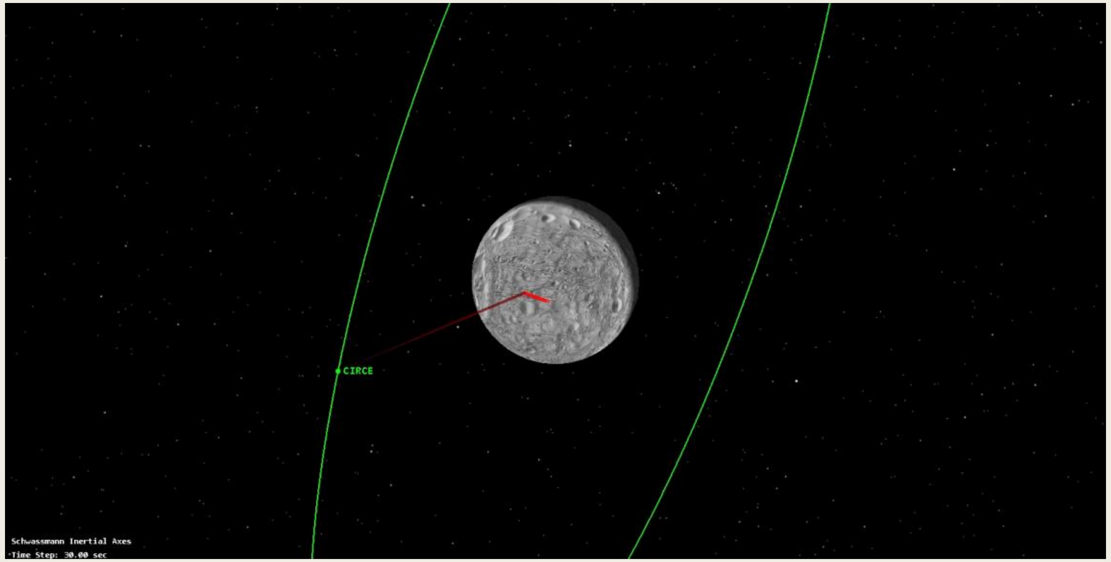
Service – 4.61% of Orbit Period	Charging - 36.41% of Orbit Period
Scientific Observation – 41.11% of Orbit Period	Communication - 17.86% of Orbit Period

Orbit Operational Modes: Science Observation Sequence

HIGH ORBIT
Periapsis : 156.99 km
Apoapsis: 430 km



CONOPS: Science Measurement – High Orbit (5)

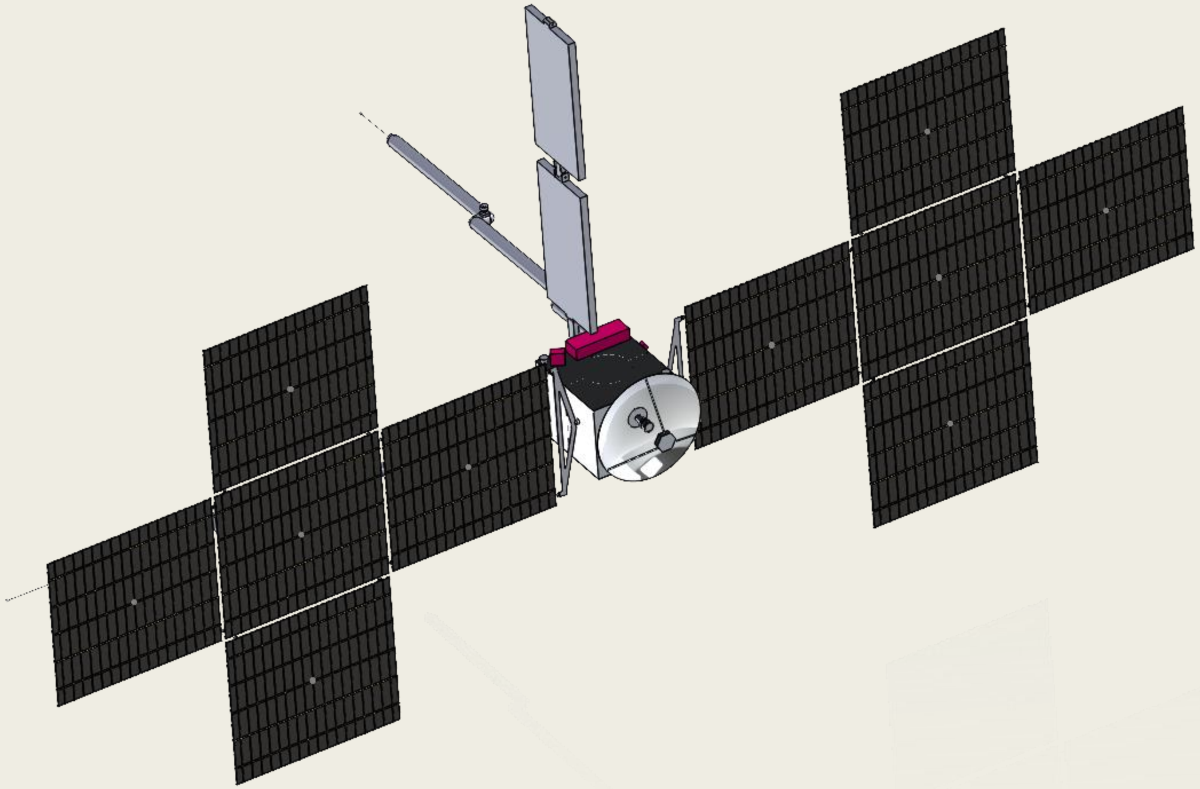


Need 39 Science Collection Orbits	Time (days)	Data Storage	Battery
Start Config	0.0	5.00%	70.00%
Science Collection	43.4	59.66%	44.72%
Communication	90.4	8.09%	72.80%
Science Collection	39.8	58.19%	49.62%
Communication	72.3	16.94%	72.08%
Service	3.6	16.94%	72.25%
Science Collection	32.5	57.93%	53.29%
Communication	83.2	10.49%	79.12%
Science Collection	25.3	42.37%	64.37%
Total	**390.5**		

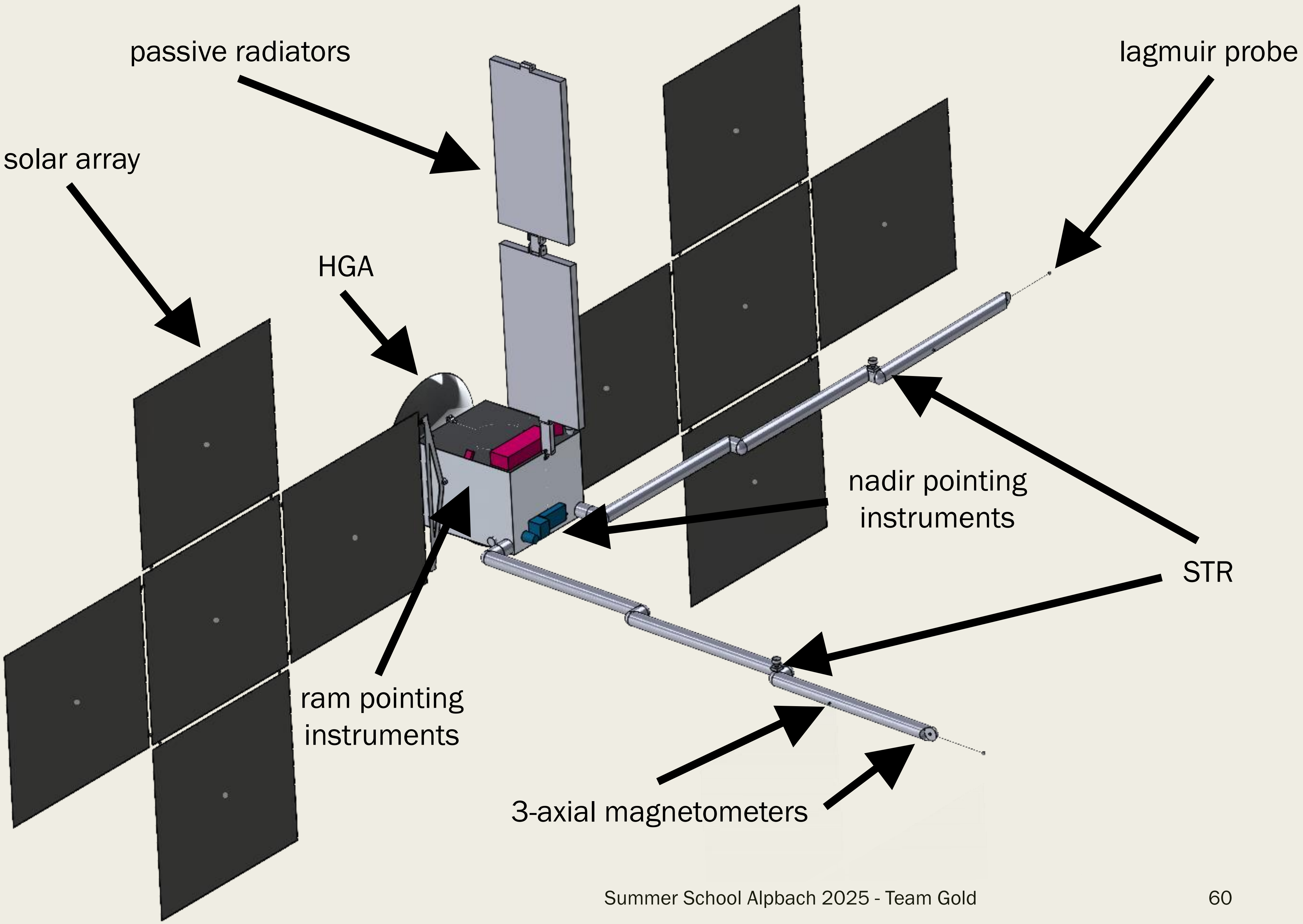
Limiting Case: IR Spectrometer need the equivalent of 30 days of observation in our High Orbit for 98% coverage of 29P.

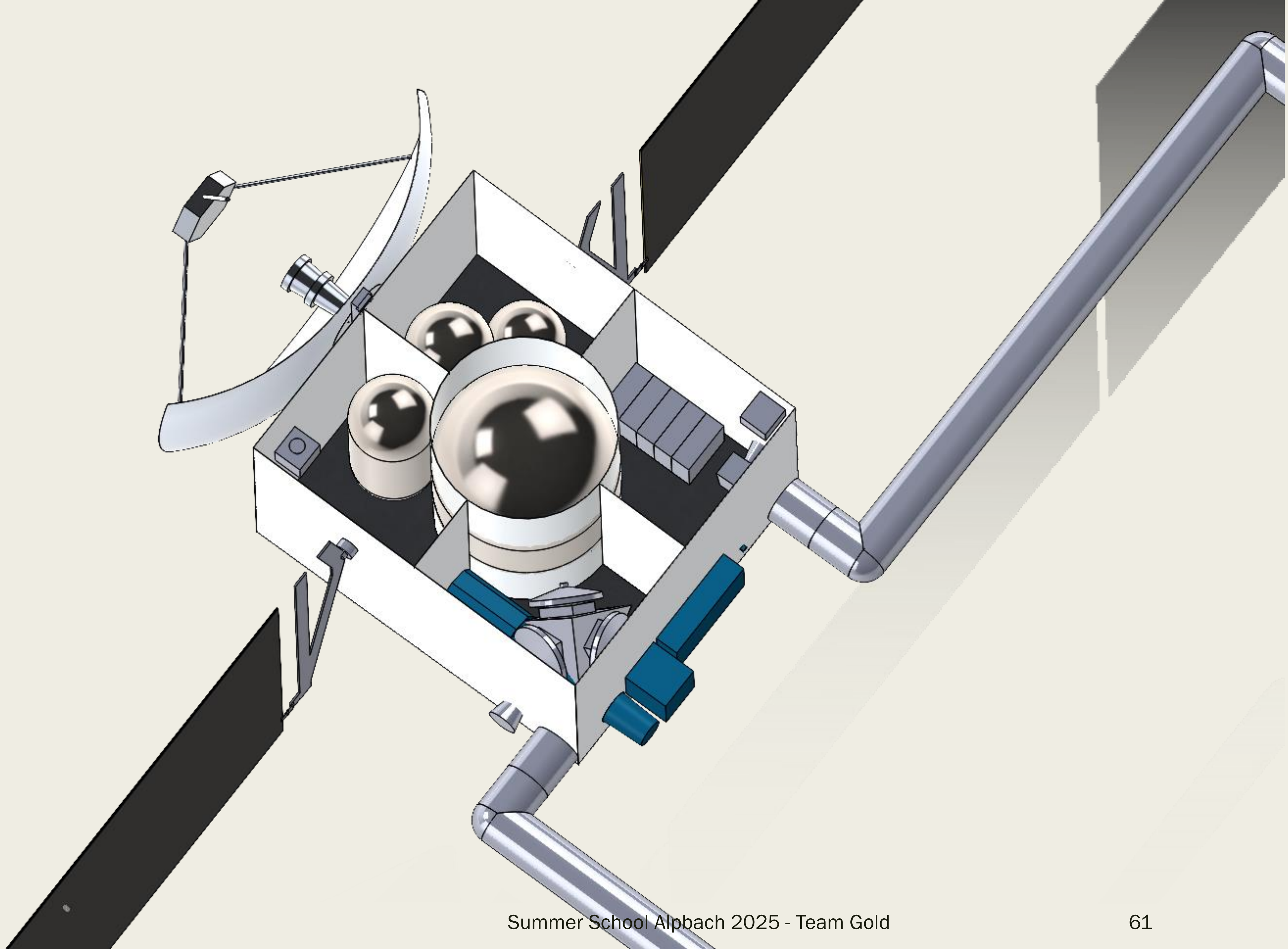
→ Example of sequence of 108 orbits with orbital period 86.78h ~ **1.07 years** for full coverage.

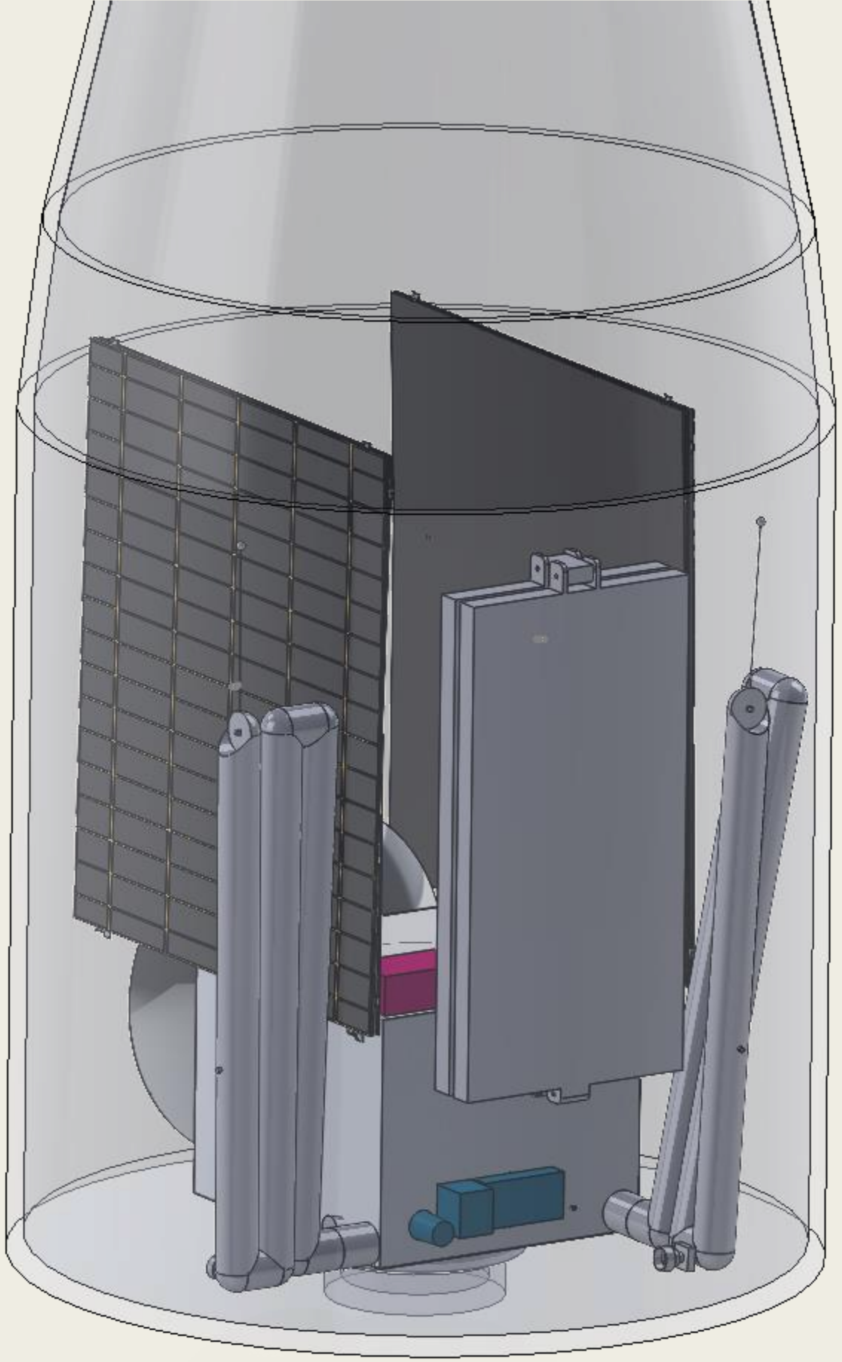
Expect **~3 years** of scientific operation before decommissioning.



SPACECRAFT DESCRIPTION


passive radiators
lagmuir probe
solar array
HGA
nadir pointing
instruments
STR
ram pointing
instruments
3-axial magnetometers





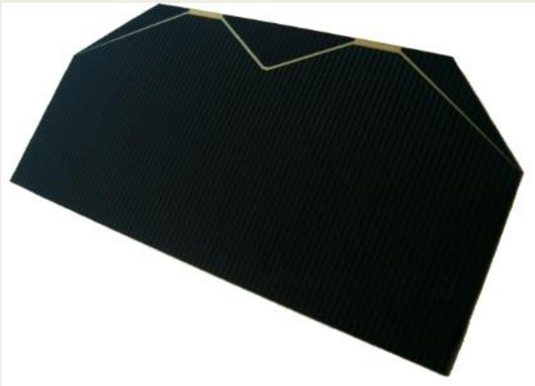
Power Budget

Power consumption with margin [W]			
Item	**Propulsion mode**	**Outgassing Activity**	**Communication**
Payloads	43	143	0
AOCS	3247	126	126
EPS	11	11	11
TCS	0	263	105
Comms	9	3	301
Avionics	10	10	10
TOTAL	3320	**556**	553
TOTAL w/ System Margin (30%)	4316	**723**	719

Electrical Power Systems

	Propulsion at 3 AU	Propulsion at 6 AU	Outgassing activity
Solar Constant [W/m²]	1367	1367	1367
Distance AU	3	6	6
Efficiency [%]	25 degradation →	20 degradation →	18
Power Consumption [W]	4315	800	721
Required solar cell area $[\mathbf{m^2}]$	**114**	**105**	**105**

- Batteries have a usable capacity of **6.3 kWh.**
- Solar cells: AZUR SPACE Solar Power **Triple Junction**



Source: AZUR SPACE

Attitude, Guidance and Orbit Control System

4x Reaction Wheels
(Honeywell HR14)

16x RCS thrusters
(Ariane 20N Hydrazine)

3x Star Trackers
(Leonardo AA-STR)

3x main thrusters
(BUSEK BHT-1500)

3x LASER Gyroscopes
(AN/WSN-7)

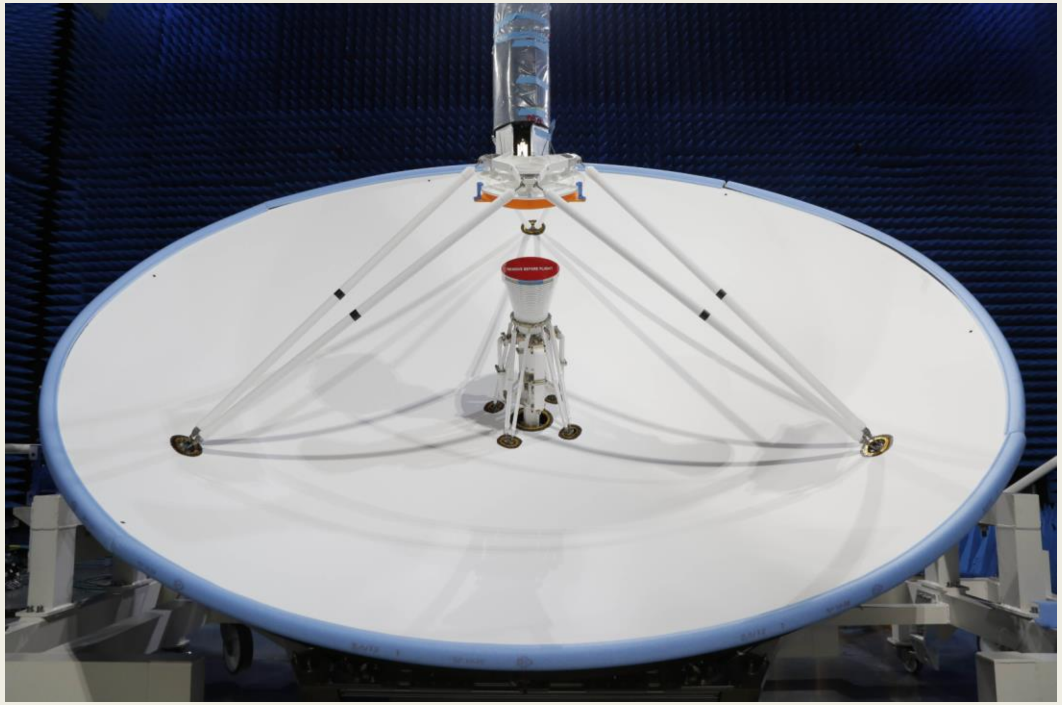
4x Sun Sensors
(Redwire Sun Sensors)

Communications

- 2.5 m diameter High Gain Antenna
  - 55.87 dB Antenna Gain
  - Science data link
  - Maximum downlink: 7.48 Gbit/day
  - Maximum uplink: 34.56 Gbit/day

- 0.5 m diameter Medium Gain Antenna
  - From JUICE mission
  - 39.25 dB Antenna Gain
  - Telemetry and housekeeping
  - Maximum downlink: 0.268 Gbit/day
  - Maximum uplink: 1.61 Gbit/day

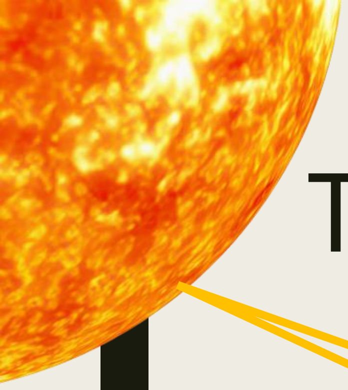
Design based on the JUICE mission

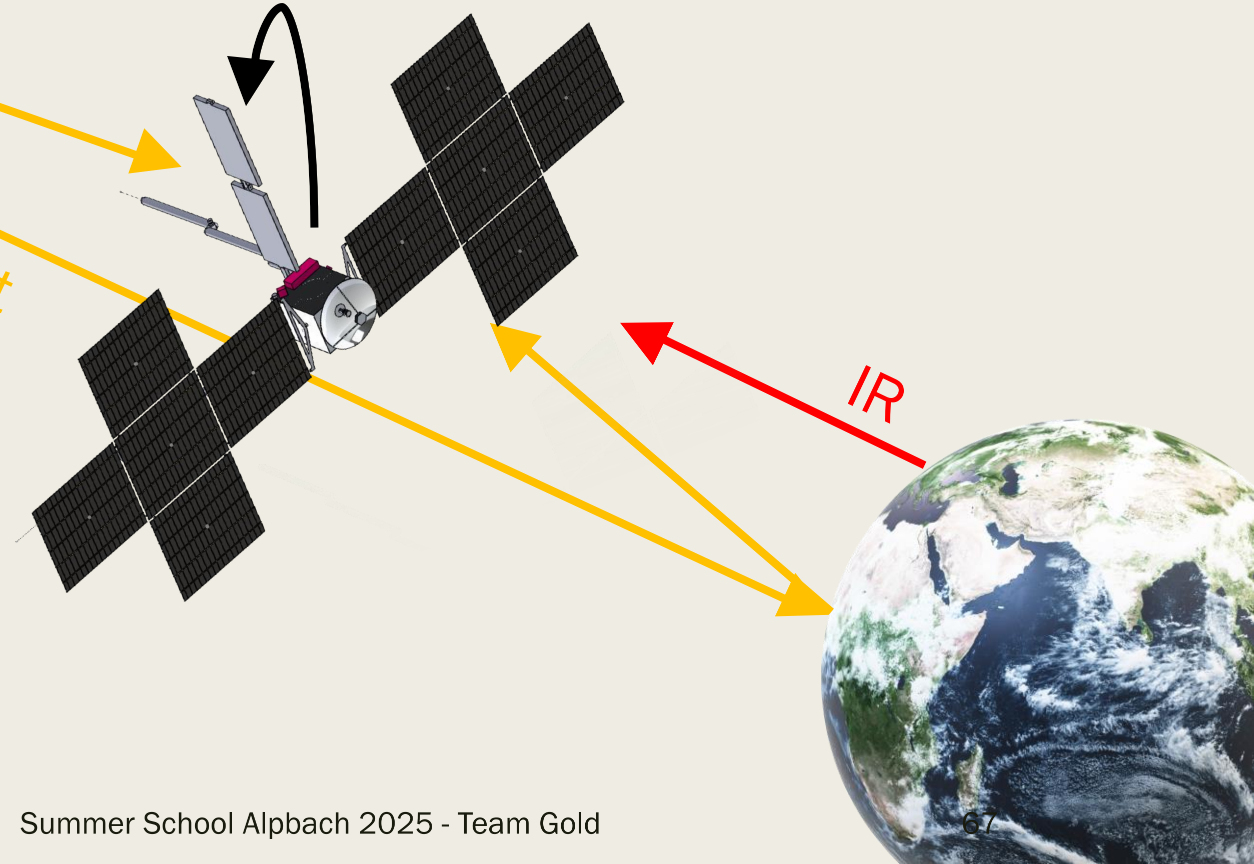


Source: High Gain Antenna THALES ALENIA

Thermal Control System

Instrument	Operating Temperature
NIR+MIR+TIR	100 - 140 K (radiator included)
NAC	233 - 243 K
MAG	243 – 333 K
GND	253 – 303 K





Hot case

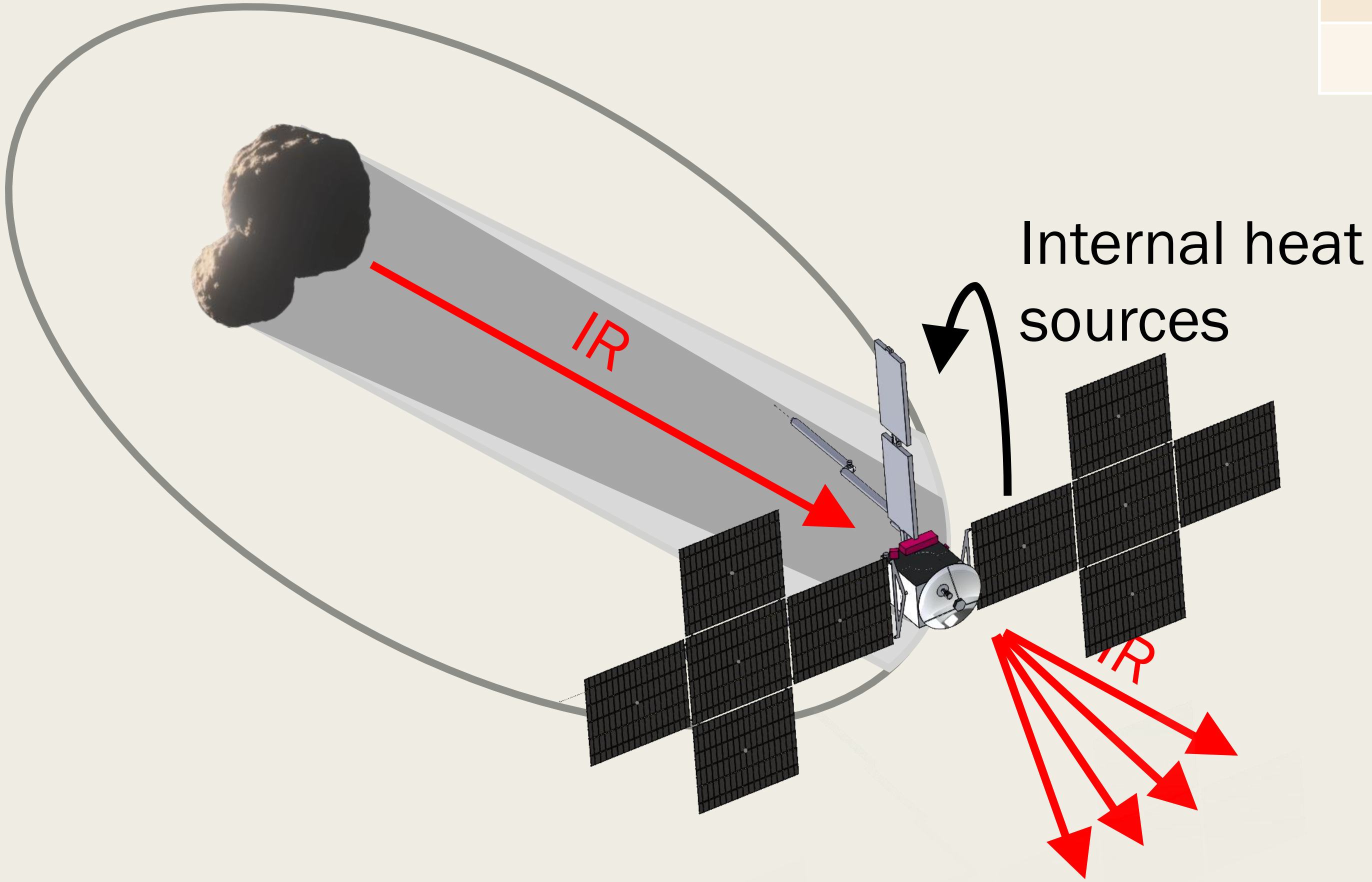
Closest to the sun

~ 9 m^2 deployable passive radiators

20 layer aluminised Kapton (2 mil) MLI

Thermal Control System

Instrument	Operating Temperature
NIR+MIR+TIR	100 - 140 K (radiator included)
NAC	233 - 243 K
MAG	243 – 333 K
GND	253 – 303 K



Cold case
Eclipse

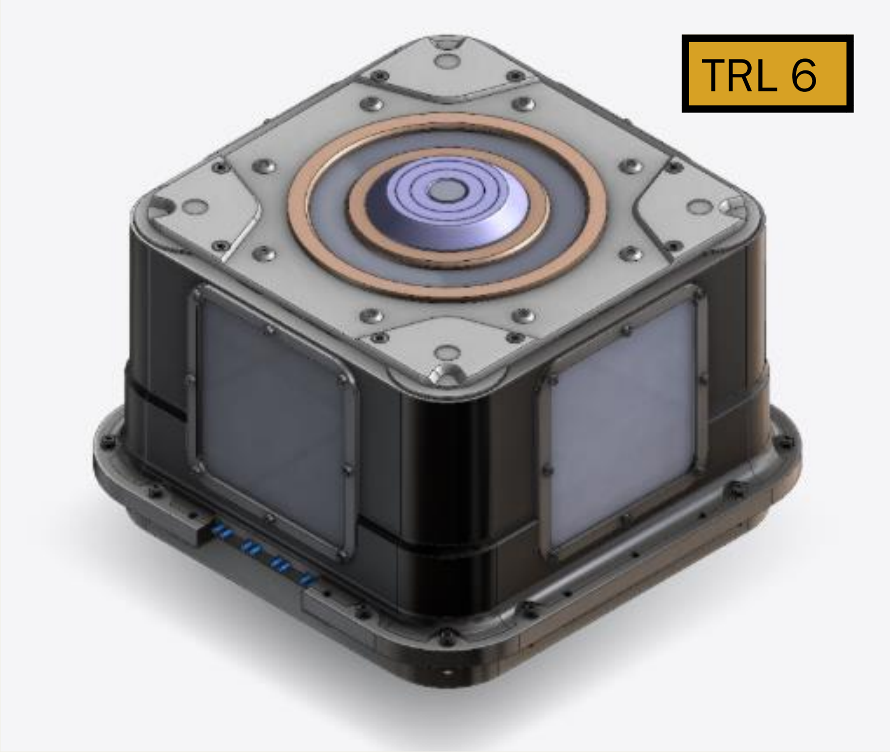
~500 W heaters

20 layer aluminised Kapton (2 mil) MLI

Propulsion

Operating two thrusters at different modes with respect to the available power

Power	High Thrust Mode	
	Thrust (mN)	Total I_{sp} (s)
1000	68	1615
1500	101	1710
1800	120	1740
2000	134	1700
2400	158	1735
2700	179	1865



Source: BUSEK

TRL 6

Mass Budget

Biggest Contributors:

- Xe propellant
- Electrical Power System
- Structures

Max. mass at arrival:

- 1650 kg

Max launch mass:

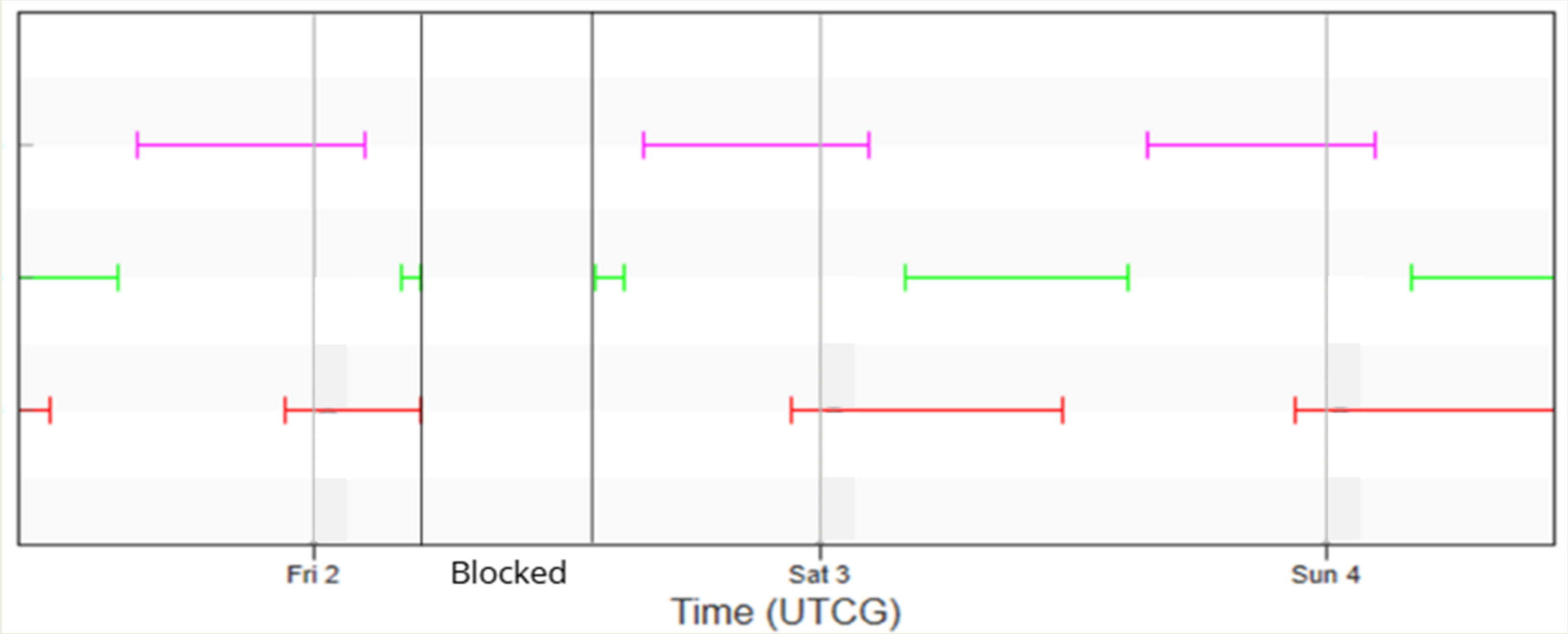
- 7000 kg

Mass budget			
System	**Mass [kg]**	**Margin [%]**	**Mass w/ margin [kg]**
Payloads	98	(5-20%)	110
AOCS	88	5%	92
EPS	539	5%	566
TCS	57	5%	60
Structures	363	(5-20%)	429
Communication	35	5%	37
Avionics	64	5%	71
Total dry mass	**1365**	**20%**	**1638**
Xe propellant	1495	20% + 10% early stage + 2% res	1973
N_2H_4 propellant	5	100%	10
Launch mass with 20% margin			**4341**
Wet mass at arrival with 20% margin			**1645**

Operations and Ground Segment

- **Comms window average (sharing with other missions) → ~ 8h / day**
- Longest blackout window (worst case) → ~ 8h

3x ESTRACK Deep Space Antennae (DSA):



Critical Technology

Mass Spectrometer

- *Necessary development (TRL 4)*
- *Critical for mission success*

Optical Imager

- *Necessary development (TRL 4)*
- *Critical for mission success*

Solar Panel Configuration

- *Very big solar panel area required for power generation*
- *Requires development of adequate mechanisms for sun-tracking and ensuring structural integrity*

Schedule

Risks

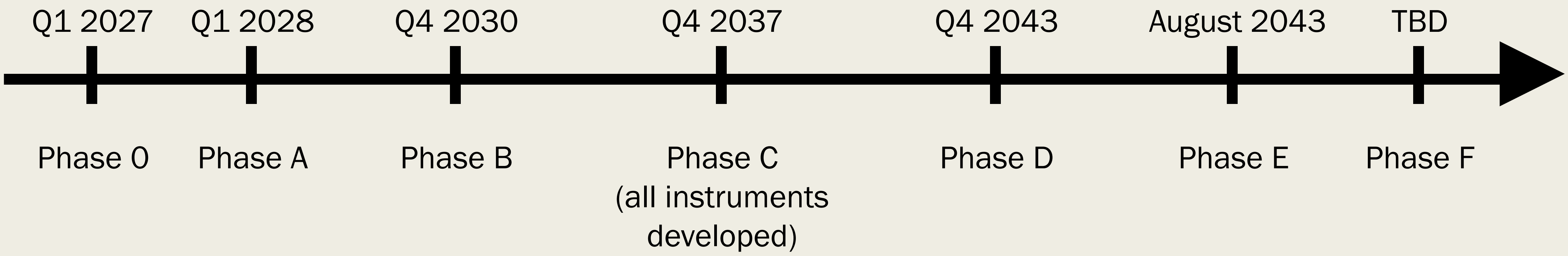
Descoping

Costs

Outreach

PROGRAMMATICS

Development Schedule



Risk Heat Map

Likelyhood

Near certain		R2			
Highly likely	R1				
Likely					
Unlikely		R3, R4			
Remote					
	1	2	3	4	5

Impact

Risks

Mission Risks	Name	Justification	Mitigation
R1 (highly likely)	Unstable dynamics of 29P incompatible with stable orbit	Orbiting 29P may be unfeasible if its rotation state is unstable.	Characterise the object's dynamics through a stepwise approach (e.g. a survey orbit). Update the mission plan before initiating proximity operations. If a stable orbit is not possible, conduct multiple hyperbolic arcs to provide high resolution observations of selected areas with slower coverage.
R2 (near certain)	Unpredictable outburst activity	Unexpected outgassing and dust release during low orbits may disrupt navigation, contaminate instruments or damage the spacecraft.	Monitor activity and outbursts from a distance (e.g., during survey orbit). Approach only regions with low outburst activity. Increase distance if significant outbursts occur.
R3 (unlikely)	Missing the launch window	Possible delays due to e.g. bad weather or development setbacks.	Include schedule margins, large launch windows and a plan for backup launch windows.
R4 (unlikely)	Cost overrun	Potential cost increases due to delays, e.g., missing the launch window or extended spacecraft integration and testing phases.	Request additional funds at the earliest sign of cost overruns to prevent project delays or compromise.

Descope Candidates: Scientific Impact Assessment

Instrument	Linked objectives	Priority level	Science covered elsewhere?
Plasma Package	OR-170	2 (low)	❌ No
Dust Impact Analyser	OR-200	3 (medium)	✅ Partially by the spectrometry and imaging instruments

Cost category

Source: Voyage 2050 (ESA)

Comet type	Fly-by	Rendezvous	Landing	Sample return	Cryogenic SR
Centaur	M	M/**L**	L+		
Jupiter Family	DI, DS1, EPOXI etc.	Rosetta	Philae	Stardust	L++
Extinct JFC	F/M	M/L	L	L	
Returning OCC	Giotto etc.	L+	L++		
Dynamically new	Comet Interceptor				
Main Belt Comet	M	ZhengHe-A	L	M (Stardust-like) L (surface)	
Interstellar comet	M				

Rendezvous with orbits → L-class

Cost Analysis

Segment	TOTAL (M €)
Total platform hardware & software	113
Total spacecraft system level activities	185
Total payload instruments -S/C	196
ESA project management	62
Launch	130
Operations	192
TOTAL EXCLUDING MARGINS	878
Risk margin (20 %)	176
TOTALS + RISK MARGIN	**1,054**

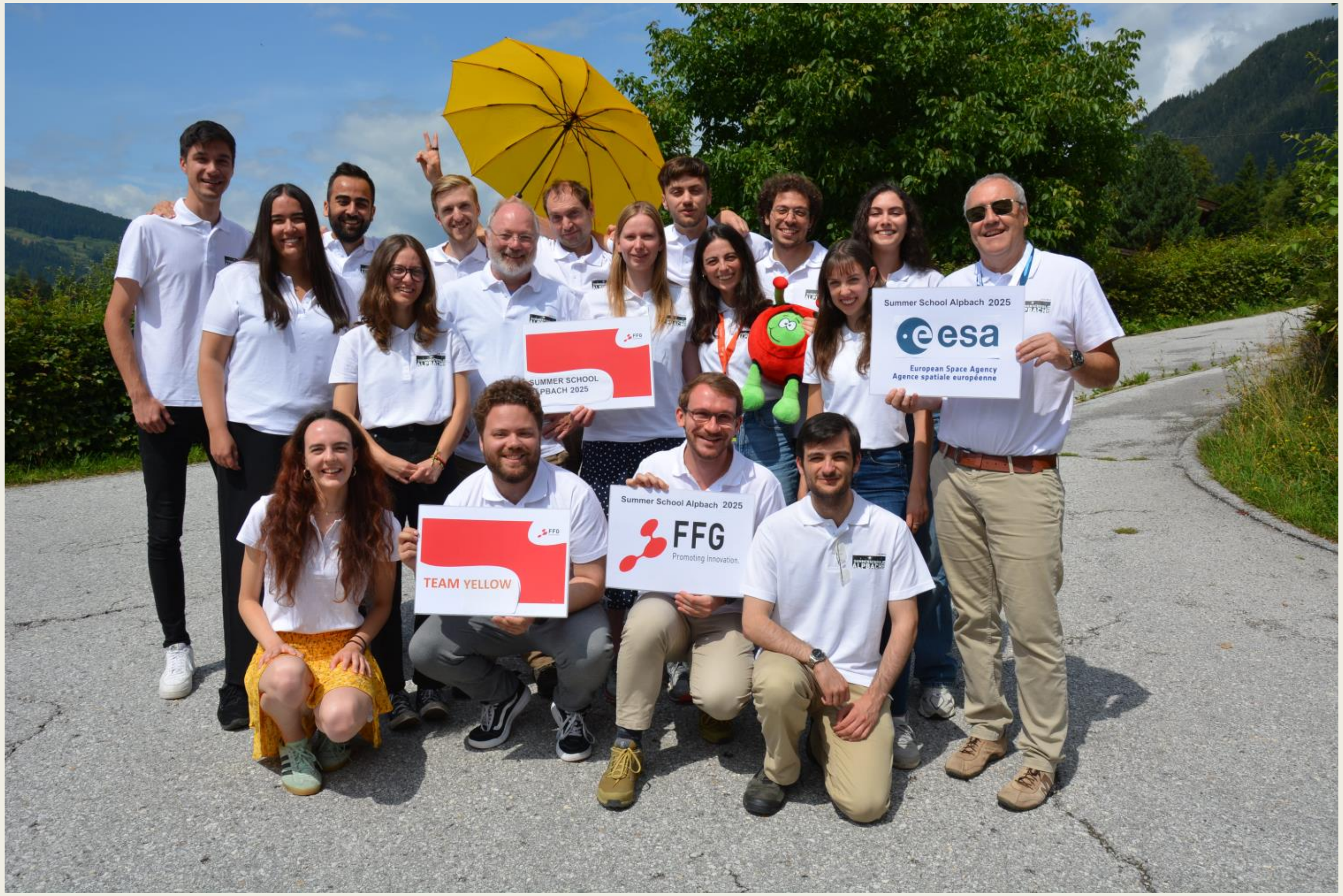
Segment	TOTAL (M €)
Total costs for ESA without margins	682
Total costs for ESA + margins (20 %)	819

Outreach: Projects

- ESRO
  - *Model kit for schools*
  - *Small bodies astronomy observation events*
- ESA Kids
  - *Cartoon series*
  - *Games*
- ESA Academy
  - *Orienteering competitions organised on university campuses, with prominent small bodies research to shine a light on recent developments*
  - *Centaur experts can serve as mentors*
  - *Open-source data for students*

Outreach – Social Media

- Social media presence for general public with emphasis on citizen science



Thank You!

Team Gold (Yellow)

S. Amberg, A. Beolchi, R.F. Bonny, A.F. Retselis, J. González de Regàs, E. Gmeiner, N. Gurrutxaga, E. Blond Hanten, C. Herrmann, M. Hubert, C. Vejby Larsen, D. Práznovský, M. Reis, F. Saveriano, V. Schulz

Tutors: G. Kargl, T. Kohout

Why Go to Centaurs?

Centaurs are Time Capsules

Centaurs Tell the Origin of the Solar System

Never Been Studied Before

29P is Very Active

In Gateway Region

BACKUP SLIDES

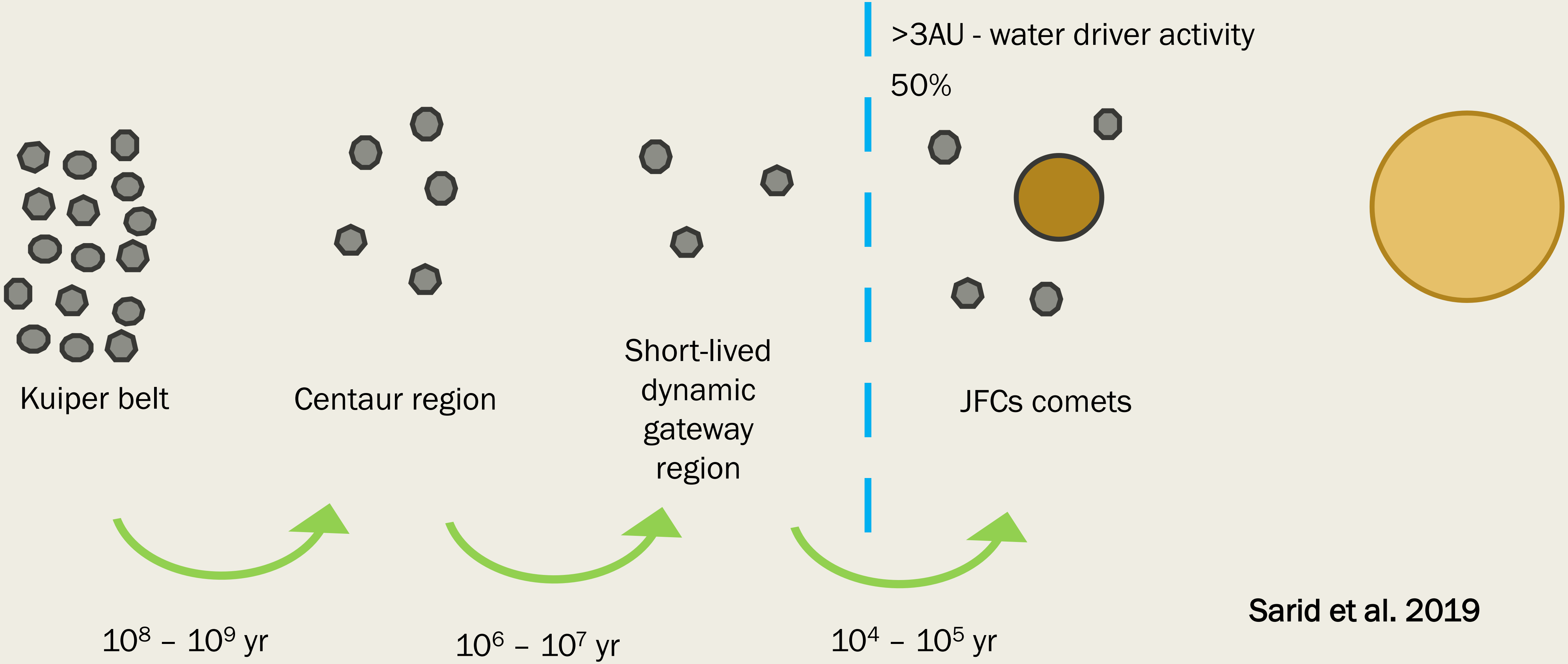
Summary: Main Scientific Goals

Surface and coma bulk composition	• Volatiles • Organics
Physical characteristics	• Surface morphology • 3D shape
Coma behaviour during outbursts	• Spatial and temporal variations • Composition
Chemical dust composition in-situ	• Embedded volatile species

Cost Analysis

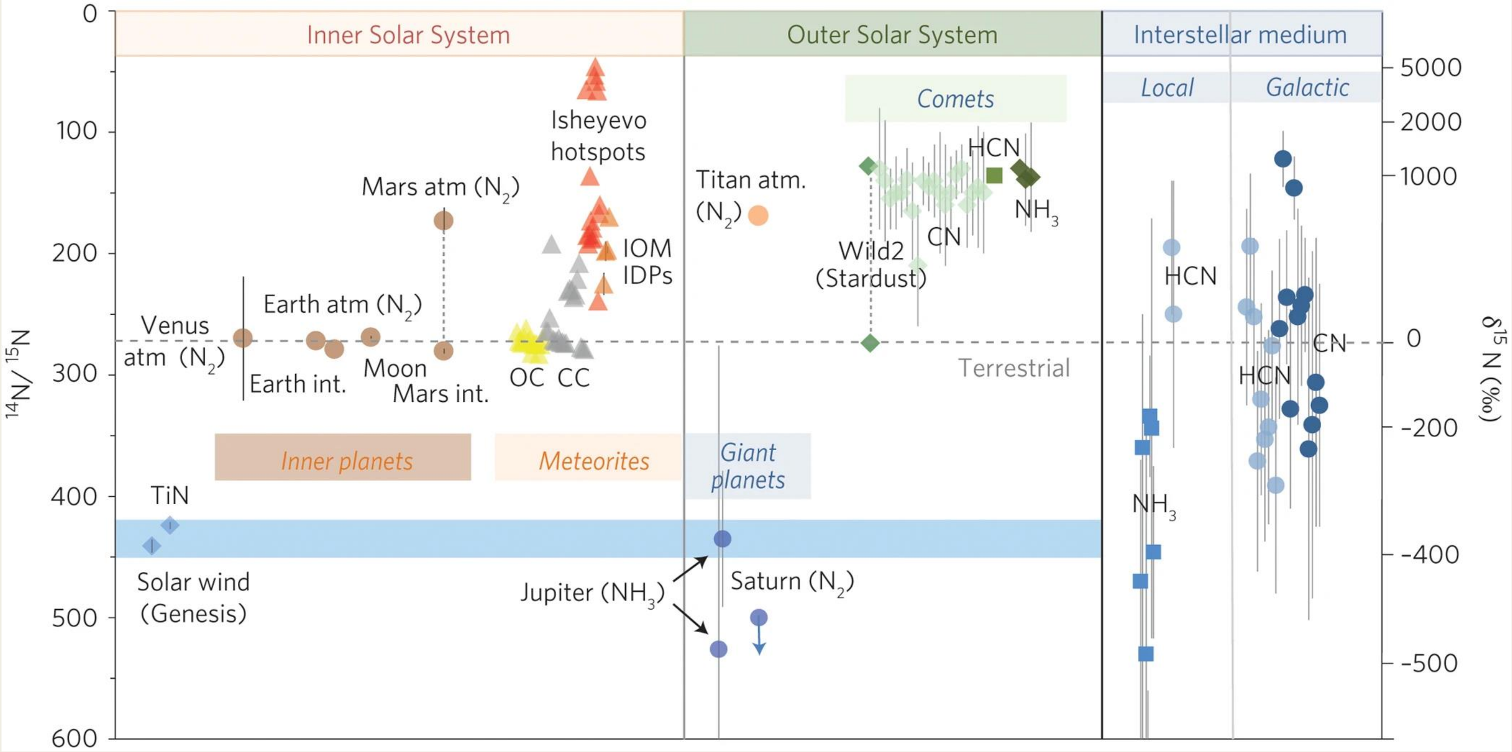
All values in k€	Phase B2	Phase C/D	Phase E/F	TOTAL
Spacecraft Platform				
AOCS/GNC	70	8,930	0	9,000
Propulsion	140	11,410	0	11,550
Power	0	42,400	0	42,400
Harness	0	970	0	970
Communications Data & Onboard Software	260	16,720	0	16,980
Structure	0	4,800	0	4,800
Thermal	0	1,480	0	1,480
Mechanisms	0	12,260	0	12,260
Planetary Protection impacts		0	0	0
Total Platform Hardware & Software	**600**	**112,240**	**0**	**112,840**
Spacecraft System Level Activities				
Management	8,100	23,900	1,200	33,200
Management - Planetary Protection add-on		0		0
Product Assurance	3,400	10,100	510	14,010
Product Assurance - Planetary Protection add-on		0		0
Engineering	17,200	50,700	2,540	70,440
Engineering - Planetary Protection add-on		0		0
Assembly, Integration and Verification/Test (AIV/T)	1,220	24,300	12,300	37,820
AIV/T - Planetary Protection add-on		0		0
AIV/T Facilities	0	9,500	2,600	12,100
Ground Support Equipment	0	17,100	0	17,100
Total Spacecraft System Level Activities	29,920	135,600	19,150	184,670
ESA Project Management				61,713
Payload Instruments				
TOF mass spectrometer	1,400.0	36,085.0	0	37,485
Optical Imager	1,050.0	35,002.5	0	36,053
IR and thermal spectrograph	700.0	18,042.5	0	18,743
3-axial magnetometer	350.0	9,021.3	0	9,371
Plasma suite	350.0	9,935.0	0	10,285
Gamma and Neutron Detectors	1,400.0	46,480.0	0	47,880
Dust Impact Analyzer	1,050.0	34,860.0	0	35,910
Total Payload Instruments - S/C	6,300.0	189,426.0	0	195,726
Launch		113,100	16,900	130,000
Mission Operations Centre (MOC)	2,000	38,700	68,400	109,100
Science Operations Centre (SOC)	1,200	23,200	58,600	83,00T0
Total Operations	3,200	61,900	127,000	192,100
TOTALS EXCLUDING MARGINS	46,620	655,566	163,050	877,050
Risk Margin (20 %)	9,324	131,113	32,610	175,409
TOTALS + RISK MARGIN	55,944	786,680	195,660	1,052,459

From dynamical study



Sarid et al. 2019

Nitrogen isotope variations in Solar System objects and reservoirs



SR-010 – Bulk composition of the surface

D. Britt 2019

justification for the chosen wavelength range for the spectrograph (NIR + MIR + TIR)

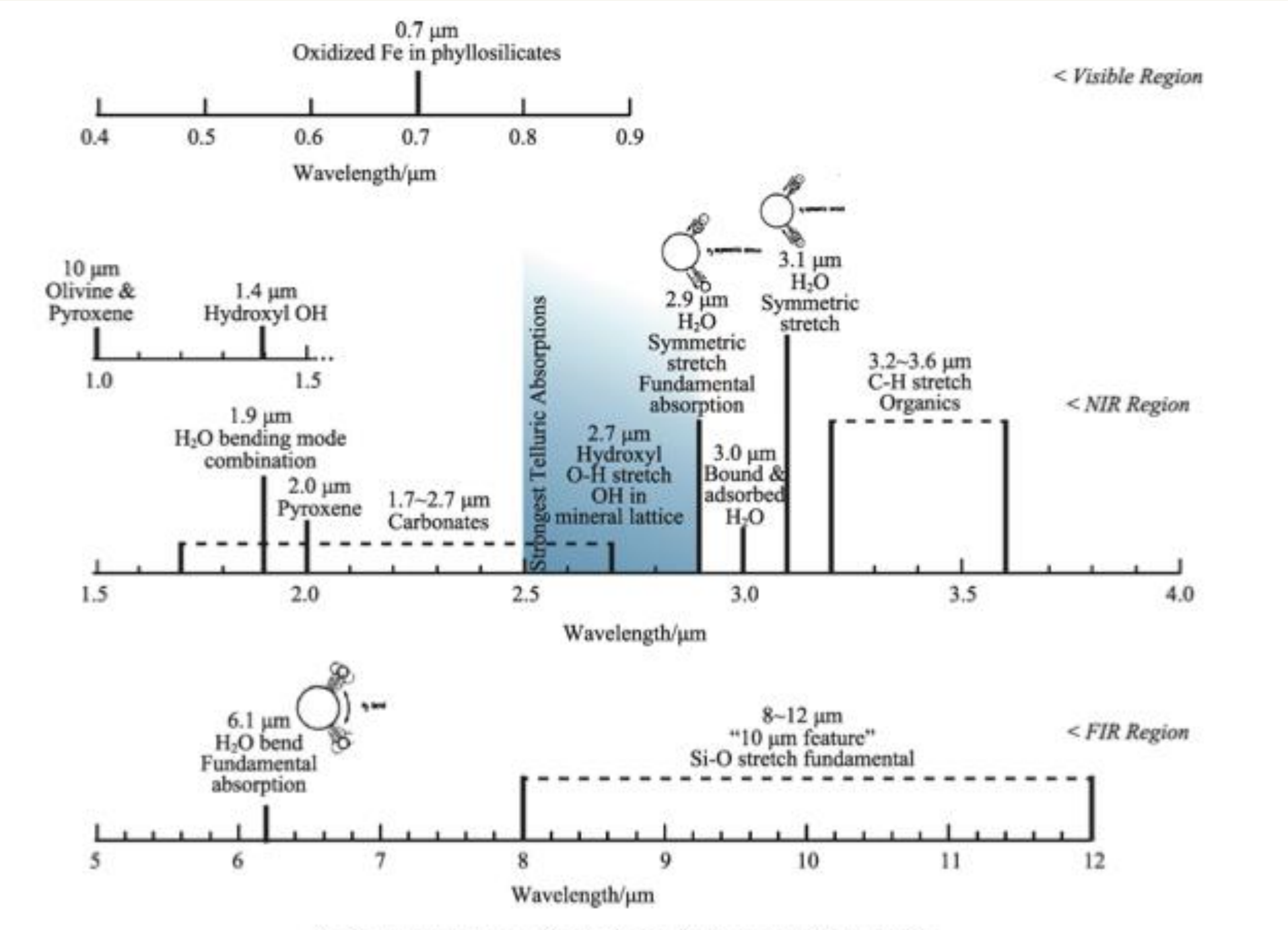
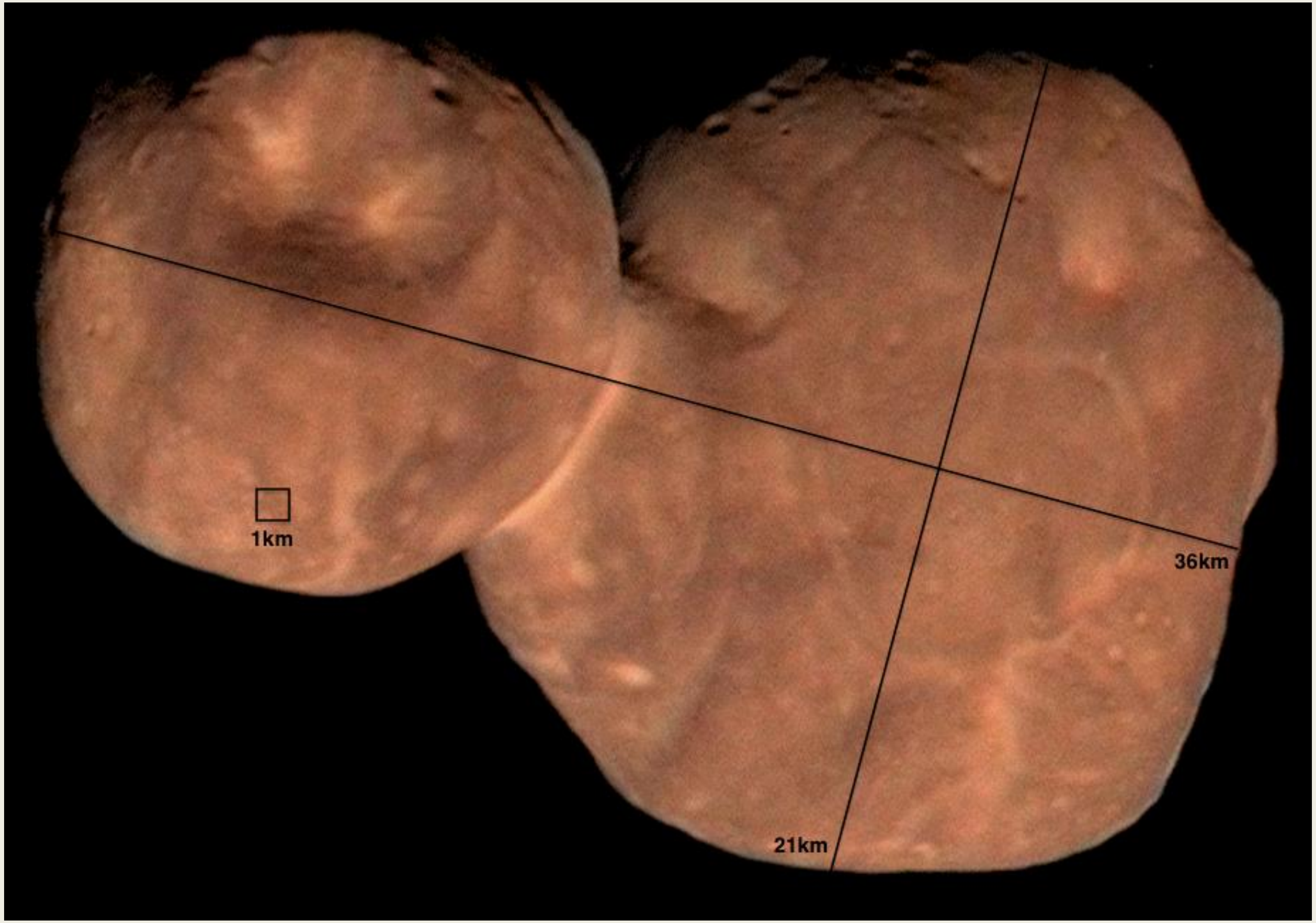


Fig. 3 Spectral absorption features of major asteroidal minerals

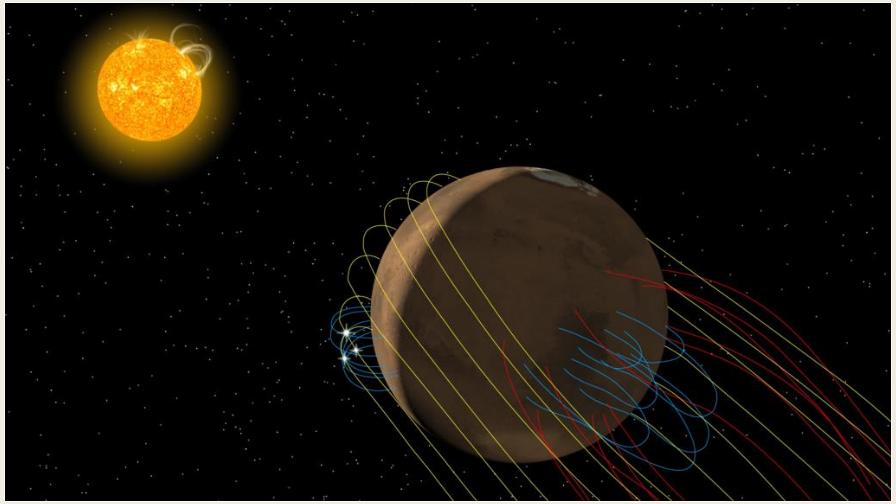
Arrokoth (New Horizons)

justification for the spatial resolution of the spectrograph (MIR)

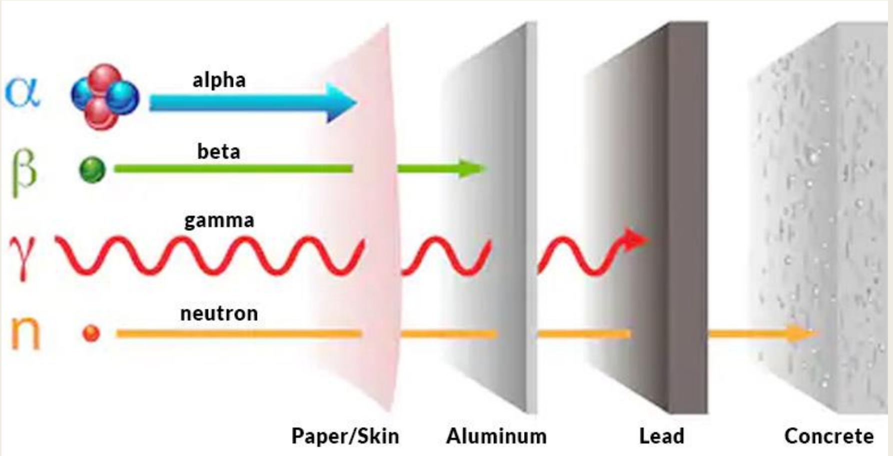


Radiation Shielding

Radiation	• Mars has no strong magnetic field • not exposed to Jupiter's intense magnetic field • gravity assist flyby dominated by GCRs and SPEs
Shielding	• Traditional aluminium shielding (~20 mm) is considered sufficient



Frame taken from: Mars' Magnetic Tail NASA



Frame taken from: Radiation Shielding Marshield

Feasibility of a Hybrid Rocket for the Transfer

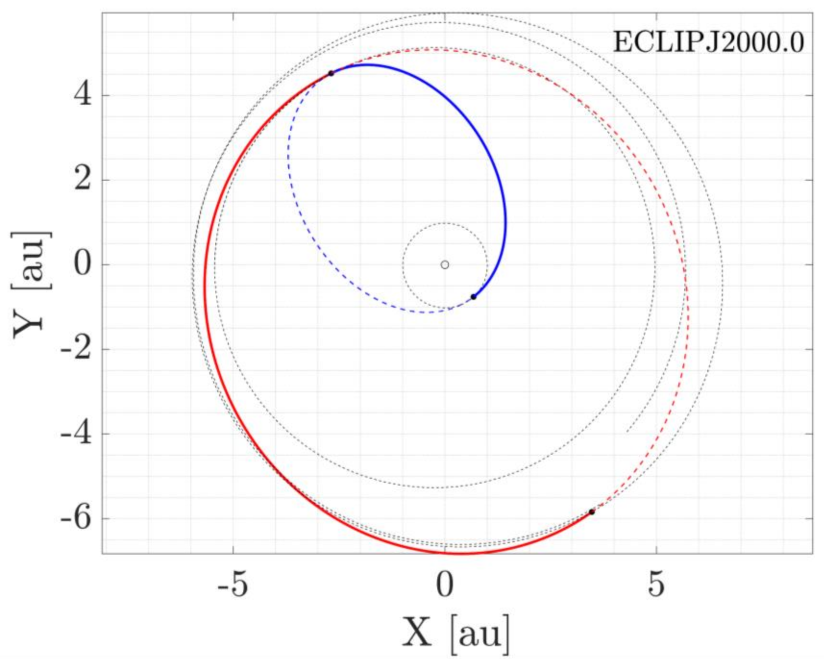
Using a chemical thruster for the transfer beyond Mars would relax solar power requirements.

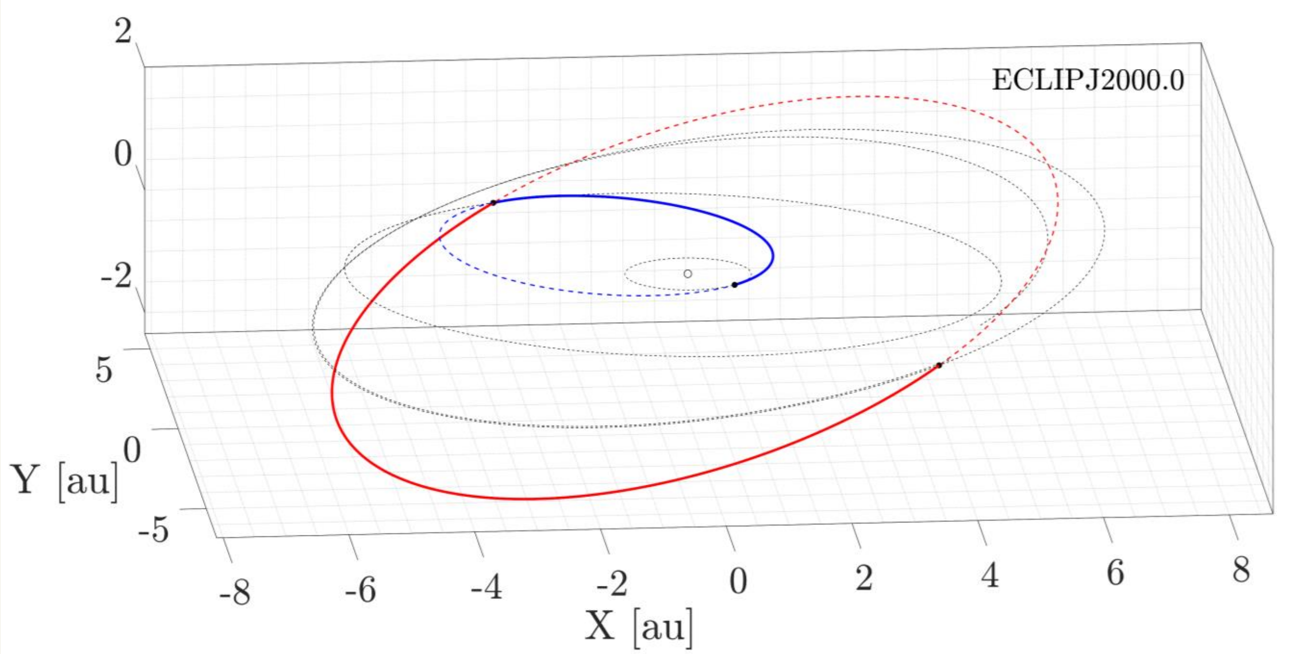
This is infeasible for this mission because:

- The Δv for the burn between Mars and the target would be 3 km/s.
- Using a chemical thruster with $\mathrm{m}_0 < 3000\ \mathrm{kg}$ requires $I_{sp} > 430$ s.
- At these ranges only LH_2/LOX rockets would be available.
- These require large fuel cells and strict thermal control.
- The Δv at capture would be too large for a chemical thruster.

Transfer

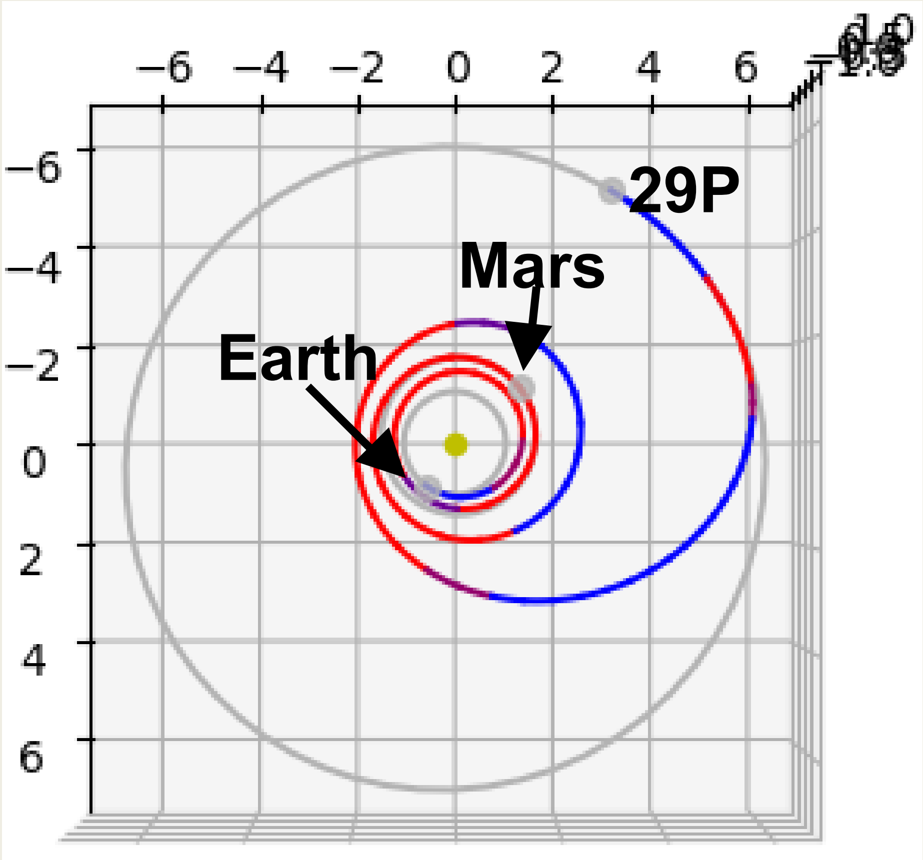
Earth-Jupiter leg → Jupiter gravity assist → Jupiter-29P leg





$c_3 = 88\ \mathrm{km^2/s^2}$
$\Delta v_1 = 0.53$ km/s
$\Delta v_2 = 2.4$ km/s
t_0 = August 2035, t_1 = April 2038, t_2 = June 2046

Thruster operations/Breaking up the last propulsion leg



- Duration of last leg: **2 years**
- Thrusters reliability demonstrated for **7200 on/off cycles**
  (S.H. Yeo et al., 2021)
- Thruster reliability is adequate to increase the last leg to 4 years:
  - *50% charging*
  - *50% maneuvering*

Transfer Feasibility

Final Mass: **1542 Kg**

Thrust: **0.200 N**

Specific Impulse: **4000 s**

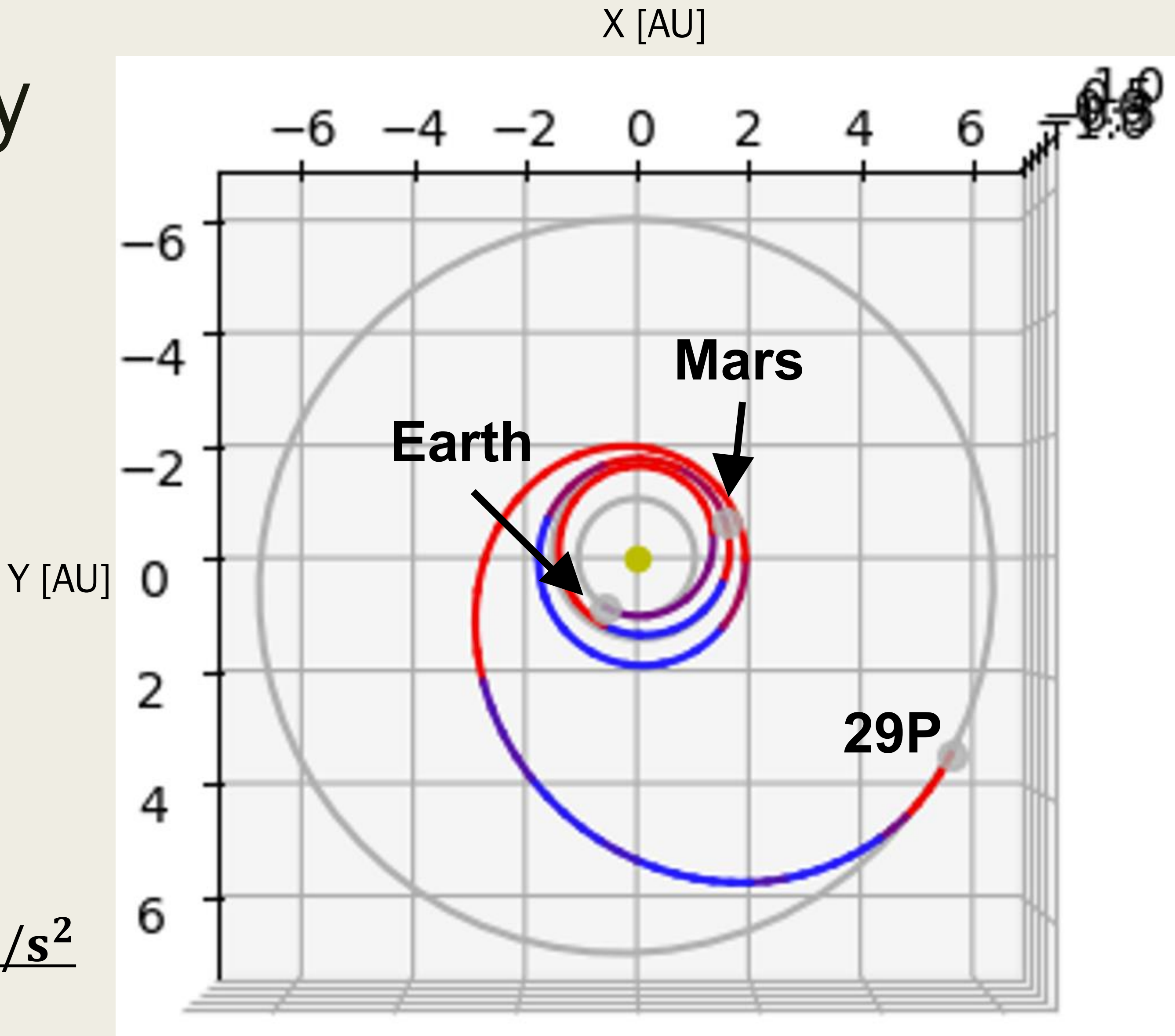
Launch Date: 20-August-2041

Earth to Mars: 800 day

Mars to 29P: 2988.8 day

Total TOF: 3788.8 day ~ **10,4 years**

Escape Speed: 4627.9 m/s ~ $\mathbf{21.4\ km^2/s^2}$



CONOPS: Operational Modes

SATELLITE MODES	WHAT IT DOES	Data compressed with margins [Mbps]	Power Consumption/Prod with 20% Margin
HIGH ORBIT SCIENCE - GROUP 1	Spacecraft nadir pointing; performs science observations of surface from high altitude, Sun facing.	1.3003	90.95
HIGH ORBIT SCIENCE - GROUP 2	Spacecraft nadir pointing; performs science observations of surface from high altitude, not Sun facing	0.0003	76.91
LOW ORBIT SURFACE	Spacecraft nadir pointing; high-resolution observations or detailed imaging of the surface.	1.3005	119.46
OUTGAS ACTIVITY	Spacecraft source pointing; focuses instruments on areas of volatile release or venting.	3.4439	160.38
OCCULTATION	Spacecraft star pointing; observes starlight through atmosphere or other body to analyze composition.	2.5003	81.66
CALIBRATION	Individual for instruments; adjusts, validates, and calibrates sensors or instruments.	0.6852	83.92
CHARGING	No science operation; satellite recharges batteries, typically in sunlight, instruments off.	0.0002	44.22
COMMUNICATION	High gain antenna Earth pointing; used for data downlink and receiving commands.	0.0002	44.22
SAFE/HOLD	Re-acquire sun pointing (for solar panels) and high gain antenna Earth pointing; minimal activity to protect spacecraft.	0.0000	45.12
SERVICE	Ground-directed or internal maintenance tasks, may include diagnostics or software updates.	0.1334	48.12
PROPULSION	Executes orbital adjustments or attitude maneuvers using thrusters; science instruments off	0.0000	43.32
CRUISE SCIENCE	Spacecraft nadir pointing; conducts limited science while transiting between destinations.	0.0002	62.94
FLYBY	Spacecraft nadir pointing; gathers high-priority data during a close approach to a target body.	0.3687	50.46
LEOP (Launch and Early Orbit Phase)	Initial operations after launch; includes system checkouts, solar array deployment, and establishing stable orientation.	0.6834	57.64
SURVEY	Survey the Centaur's surface at low resolution, determine the rotation rate and axis before approaching closer for the science measurement orbits.	0.1336	72.30

Target Orbit

Delta-v budget and propellant mass

Type of Orbit:
1. Arrival → Survey
2. Survey → Mid Orbit (without inclination change)
3. Mid Orbit → Low Mapping Orbit Transfer
4. Survey → Mid Orbit (with 90º inclination change)
5. Low Mapping Orbit → Disposal

	Delta-v [m/s]	Propellant mass [kg]
Total	15.05	2.57
Total (+100% margin)	30.1	5.14
Total inclination change	28.19	4.8
Total inclination change (+100% margin)	**56.38**	**9.6**

Category	Type of orbit	Delta-v [m/s]	Propellant mass [kg]
Maneuver	1.	0.21	0.04
	2.	0.37	0.06
	3.	0.84	0.14
	4.	13.51	2.29
	5.	8.53	1.45
Stationkeeping (6 months/orbit type)	Arrival	0.8	0.14
	Mid Orbit	1.5	0.26
	Survey	0.5	0.09
	Low mapping	2.3	0.39

Power budget (1)

Item	Power consumption [W]	Duty cycle	Margin [%]	Power consumption w/ margin [W]
	Propulsion mode			
	Payloads			
All payloads	36.1	1	20	43.32
	Attitude and Orbit Control Subsystem			
Main thruster	3000	1	5	3150
3x Star Trackers	16.8	1	5	17.64
4x Reaction Wheels	88	0.75	5	69.3
24x RCS thrusters	5	0	5	0
3x Sun Sensors	5	1	5	5.25
3x Laser Gyros	5	1	5	5.25
	Electrical Power Subsystem			
Power conditioning and Misc electronics	10	1	5	10.5
	Thermal Control System			
Heaters	10	0	5	0
	Communications			
X/Ka-band TWTA (100 W RF out)	250	0.03	5	7.875
Baseband + Modulation	20	0.03	10	0.66
RF Switches, OBC interface	10	0.03	10	0.33
Antenna tracking/switching	5	0.03	10	0.165
	Avionics			
Generic Avionics	10	0.8	20	9.6
			Total	**3319.89**
			Total w/ Syst	**4315.857**

Power budget (2)

Item	Power consumption [W]	Duty cycle	Margin [%]	Power consumption w/ margin [W]
	Outgass Activity			
	Payloads			
All payloads	119.25	1	20	143.1
	Attitude and Orbit Control Subsystem			
Main thruster	600	0	5	0
3x Star Trackers	16.8	1	5	17.64
4x Reaction Wheels	88	1	5	92.4
24x RCS thrusters	5	1	5	5.25
3x Sun Sensors	5	1	5	5.25
3x Laser Gyros	5	1	5	5.25
	Electrical Power Subsystem			
Power conditioning and Misc electronics	10	1	5	10.5
	Thermal Control System			
Heaters	500	0.5	5	262.5
	Communications			
X/Ka-band TWTA (100 W RF out)	250	0.01	5	2.625
Baseband + Modulation	20	0.01	10	0.22
RF Switches, OBC interface	10	0.01	10	0.11
Antenna tracking/switching	5	0.01	10	0.055
	Avionics			
Generic Avionics	10	0.8	20	9.6
			Total	**554.5**
			Total w/ System	**720.85**

Power budget (3)

Item	Power consumption [W]	Duty cycle	Margin [%]	Power consumption w/ margin [W]
	Communication			
	Payloads			
All payloads	36.1	1	20	0
	Attitude and Orbit Control Subsystem			
Main thruster	0	0	5	0
3x Star Trackers	16.8	1	5	17.64
4x Reaction Wheels	88	1	5	92.4
24x RCS thrusters	5	1	5	5.25
3x Sun Sensors	5	1	5	5.25
3x Laser Gyros	5	1	5	5.25
Electrical Power Subsystem				
Power conditioning and Misc electronics	10	1	5	10.5
Thermal Control System				
Heaters	500	0.2	5	105
Communications				
X/Ka-band TWTA (100 W RF out)	250	1	5	262.5
Baseband + Modulation	20	1	10	22
RF Switches, OBC interface	10	1	10	11
Antenna tracking/switching	5	1	10	5.5
Avionics				
Generic Avionics	10	0.8	20	9.6
			Total	**551.89**
			Total w/ System	**717.457**

Mass budget (1)

Item	mass [kg]	Margin [%]	Mass w/ margin [kg]
Payloads			
Time-of-flight mass spectrometer	18	20	21.6
Ambient pressure sensor	1.6	5	1.68
Infrared and Thermal Spectrograph	7.4	20	8.88
3-axial magnetometer	17.607	5	18.48735
Langmuir Probe (Plasma)	0.454	20	0.5448
Ion and Electron Sensor (Plasma)	0.989	20	1.1868
Optical imager	36.5	10	40.15
Gamma and Neutron detectors	9.4	10	10.34
Dust impact analyzer	6.25	20	7.5
Attitude, Guidance and Orbit Control System			
3x Main thruster	19.8	5	20.79
3x Star Trackers	7.8	5	8.19
4x Reaction Wheels	40	5	42
16x RCS thrusters	10.4	5	10.92
4x Sun Sensors	8	5	8.4
3x Laser Gyros	2	5	2.1

Mass budget (2)

Item	mass [kg]	Margin [%]	Mass w/ margin [kg]
Electrical Power System			
Solar panels	528.8	5	555.24
5x Batteries (M)	49	5	51.45
Power conditioning and Misc electronics	20	5	21
Thermal Control System			
Thermal Insulation	20	5	21
Heaters	5	5	5.25
Radiators	32.4	5	34.02
Structures			
Satellite frame and structures	200	20	240
3x Optical benches (Imagers and Star Trackers)	36	5	37.8
Xe Propellant tank (900 L)	85	20	102
2x Xe Propellant tank (120 L)	33.6	20	40.32
RCS Propellant tank	8.5	5	8.925
Communications			
High Gain Antenna	31	5	32.55
Communication system	4	5	4.2
Avionics			
Harness	67.8261975	5	71.21750738

Mass budget (3)

Total Spacecraft Dry mass w/o Harness nor margin	**1356.52395**	**kg**
Total Spacecraft Dry mass w/o margin	**1427.741457**	**kg**
System margin	**20**	**%**
Total Spacecraft Dry mass with margin	**1713.289749**	**kg**
Xe propellant mass (w margin)	**1973**	**kg**
N2H4 propellant mass (w margin)	**9.6**	**kg**
Launch adapter	71	kg
Spacecraft mass at arrival (no margin)	1435.741457	
Spacecraft mass at arrival	**1722.889749**	**kg**
Spacecraft launch mass (no margin)	3766.889749	**kg**
Spacecraft launch mass (with 20% margin)	**4435.067699**	**kg**

Data Budget

Biggest Contributors:

- Optical Imager
- Infrared and Thermal Spectrometer

Total data rate			
Propulsion mode		Outgass Activity	
Total [bit/s]	**Total w/ System margin [bit/s]**	Total [bit/s]	**Total w/ System margin [bit/s]**
10,178.52	**13,232.076**	247,954,119.1	**322,340,354.9**

Summary

- **Mission Purpose:** By studying these Centaurs, the mission will **unravel the origin and evolution of planetesimal**s and gain insights into the **formation and evolution of our solar system**.
- **Our Destination:** The mission's primary target is **29P/Schwassmann-Wachmann**, a highly active Centaur located in the "Gateway" Region.
- The mission will provide **crucial and never before seen data**. It will offer hints about the formation location and time of planetesimals and reveal the processes driving Centaur activity.
- By expanding our fundamental knowledge of the universe and our solar system's origins, the mission **contributes** to humanity's ongoing quest for discovery and understanding.
- The mission will carry a comprehensive suite of instruments, including a Mass Spectrometer, various spectrometers (Infrared, Thermal), Gamma and Neutron Detectors, an Optical Imager, a Dust Impact Analyser, and a Plasma Package, among others.
- The launch is scheduled for **August 2043**, with a total flight time of approximately 12 years. The nominal science operations phase is expected to begin around 2052 and last for 2-3 years.

Power sources

For an assumed total power of 750 W

DATA	Total Mass [kg]	Power per Mass [W/kg]	Cost [€]
Solar Panels	565	1.33	50 M
American RTGs	360	2.08	500 M
European RTGs	570	1.32	350 M

TRADE-OFF SCORES	Total Mass (30%)	Power per Mass (40%)	Cost (30%)	Total Score	Ranking
Solar Panels	6	7	8	7	1.
American RTGs	7	8	4	6.5	2.
European RTGs	5	6	6	5.7	3.

Science Requirements

SR-010 *The bulk composition of the surface and shallow sub-surface of a Centaur shall be assessed.*

SR-020*. The chemical composition of the coma/exosphere of a Centaur shall be identified.*

SR-021*. Isotopic reservoir of key elements shall be identified.*

SR-030*. Physical characteristics on the surface of a Centaur shall be mapped.*

SR-031. *Outgassing patterns, outburst events and their temporal evolution shall be investigated.*

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SR-060*. The magnetic state of a Centaur shall be explored.*

SR-070*. The interaction with the interplanetary magnetic field shall be investigated.*

SR-080*. Interactions of a Centaur's magnetic field with the solar wind shall be investigated.*

SR-090*. The thermal state of a Centaur shall be characterized.*

SR-100*. The dust in the coma/ring of a Centaur shall be characterised.*

Science Requirements

***SR-010** The bulk composition of the surface and shallow sub-surface of a Centaur shall be assessed.*

- **OR-010**
  The global distribution of water ice phases (amorphous, crystalline) on the surface of the object shall be measured and differentiated from orbit. **[mapping spectrograph (MIR)]**

- **OR-020**
  The global distribution of volatile and hyper-volatile ices (CO, CO2, CH4, N2, O2, HCN) on the surface of a Centaur shall be mapped from orbit. **[mapping spectrograph (NIR, MIR)]**

- **OR-030**
  The surface mineralogy (e.g. pyroxenes, olivines, phyllosilicates) of the object shall be characterised from orbit. **[mapping spectrograph (NIR, MIR)]**

- **OR-031**
  The sub-surface atomic composition (e.g. Ca, Al, O, Si, Fe, Mg, Ti ...) of the Centaur shall be measured from orbit. **[gamma and neutron detector]**

- **OR-040**
  Organic material (e.g. amino acids, lipids, polymers) shall be detected from orbit. **[mapping spectrograph (MIR)]**

***SR-020**. The chemical composition of the coma/exosphere of a Centaur shall be identified.*

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***SR-030**. Physical characteristics on the surface of a Centaur shall be mapped.*

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- **OR-050**
  Volatiles and hyper-volatiles (CO, CO2, CH4, N2, O2, HCN) in the coma shall be distinguised and quantified by the spacecraft. **[mass spectrometer]**

- **OR-051**
  Organic material (e.g. amino acids, lipids, polymers) in the coma shall be detected from orbit. **[mass spectrometer]**

SR-021*. Isotopic reservoir of key elements shall be identified.*

SR-030*. Physical characteristics on the surface of a Centaur shall be mapped.*

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- **OR-060**
  Isotope ratios of the elements C, N, H, O, Xe shall be measured from orbit. **[mass spectrometer]**

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SR-030*. Physical characteristics on the surface of a Centaur shall be mapped.*

- **OR-070**
  The 3D shape of the Centaur shall be characterised by the spacecraft to a minimum accuracy of 1000 m. **[optical imager + radioscience]**
- **OR-080**
  Surface features (terrains) on a Centaur with a size greater than 100 meters shall be mapped by the spacecraft. **[optical imager]**
- **OR-081**
  Surface features (cracks, craters, boulders) on a Centaur with a size greater than 10 meters shall be mapped by the spacecraft. **[optical imager]**

SR-031. *Outgassing patterns, outburst events and their temporal evolution shall be investigated.*

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- **OR-090**
  The optical thickness of the coma and its temporal variation shall be monitored during the outburst event (duration of days to weeks). **[infrared spectrometer]**
- **OR-100**
  The spatial variation of the optical thickness of the coma shall be traced during the outburst event (duration of days to weeks). **[infrared spectrometer]**
- **OR-110**
  The mass loss rate and its variations for different chemical species (CO, CO2, CH4, N2, O2, HCN) shall be quantifed. **[mass spectrometer]**
- **OR-120**
  The sub-surface composition of key atoms (H, C, O, ...) associated with outgassing activity shall be mapped. **[gamma and neutron detector]**

SR-040*. The dynamic state of a Centaur and its evolution due to outgassing events shall be analysed.*

SR-050*. The interior mass distribution of a Centaur shall be investigated.*

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- **OR-130**
  The object's full 3-axis rotation state (including rotation rate, precession, and nutation) shall be measured from orbit to an accuracy of ≤ 0.1 deg/sec. **[optical imager + radioscience]**

SR-050*. The interior mass distribution of a Centaur shall be investigated.*

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- **OR-140**
  A global gravity field with a spatial resolution of 1×10^{-6} m/s² shall be measured from orbit by the spacecraft.
  [radioscience]
- **OR-150**
  The moments of inertia shall be determined to an accuracy of 3% (J2). **[optical imager + radioscience]**

SR-060. *The magnetic state of a Centaur shall be explored.*

SR-070. *The interaction with the interplanetary magnetic field shall be investigated.*

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SR-060*. The magnetic state of a Centaur shall be explored.*

- **OR-151**
  The magnitude of the remnant magnetic field of the Centaur shall be measured on each axis with an accuracy of +- 0.01 nTesla. **[3-axial magnometer]**

SR-070*. The interaction with the interplanetary magnetic field shall be investigated.*

SR-080*. Interactions of a Centaur's magnetic field with the solar wind shall be investigated.*

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Science Requirements

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SR-050*. The interior mass distribution of a Centaur shall be investigated.*

SR-060*. The magnetic state of a Centaur shall be explored.*

SR-070*. The interaction with the interplanetary magnetic field shall be investigated.*

- **OR-160**
  The magnitude of the magnetic field of the Centaur-Solar wind interaction shall be measured on each axis with a minimum range of 1000nT and a resolution of the order +-0.01nT. **[3-axial magnometer]**

SR-080*. Interactions of a Centaur's magnetic field with the solar wind shall be investigated.*

SR-090*. The thermal state of a Centaur shall be characterized.*

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Science Requirements

SR-010. *The bulk composition of the surface and shallow sub-surface of a Centaur shall be assessed.*

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SR-060*. The magnetic state of a Centaur shall be explored.*

SR-070*. The interaction with the interplanetary magnetic field shall be investigated.*

SR-080*. Interactions of a Centaur's magnetic field with the solar wind shall be investigated.*

- **OR-170**
  The plasma environment (ion and electron distributions, density, energy, and flow velocity) in close proximity to the coma/exosphere shall be investigated. **[plasma package]**

SR-090*. The thermal state of a Centaur shall be characterized.*

SR-100*. The dust in the coma/ring of a Centaur shall be characterised.*

Science Requirements

SR-010. *The bulk composition of the surface and shallow sub-surface of a Centaur shall be assessed.*

SR-020*. The chemical composition of the coma/exosphere of a Centaur shall be identified.*

SR-021*. Isotopic reservoir of key elements shall be identified.*

SR-030*. Physical characteristics on the surface of a Centaur shall be mapped.*

SR-031. *Outgassing patterns, outburst events and their temporal evolution shall be investigated.*

SR-040*. The dynamic state of a Centaur and its evolution due to outgassing events shall be analysed.*

SR-050*. The interior mass distribution of a Centaur shall be investigated.*

SR-060*. The magnetic state of a Centaur shall be explored.*

SR-070*. The interaction with the interplanetary magnetic field shall be investigated.*

SR-080*. Interactions of a Centaur's magnetic field with the solar wind shall be investigated.*

SR-090*. The thermal state of a Centaur shall be characterized.*

- **OR-180**
  A global temperature map of the surface of the Centaur at 10 x 10 km resolution shall be established. **[mapping spectrograph (TIR)]**
- **OR-190**
  Thermal inertia measurements over at least 1 full rotation of the nucleus shall be captured by the spacecraft. **[mapping spectrograph (TIR)]**

SR-100*. The dust in the coma/ring of a Centaur shall be characterised.*

Science Requirements

SR-010. *The bulk composition of the surface and shallow sub-surface of a Centaur shall be assessed.*

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SR-090*. The thermal state of a Centaur shall be characterized.*

SR-100*. The dust in the coma/ring of a Centaur shall be characterised.*

- **OR-200**
  The mass and the velocity vector of dust particles in orbit shall be measured. **[dust impact analyser]**
- **OR-210**
  The chemical volatile species (CO, CO2, CH4, N2, O2, HCN) embedded within dust particles in orbit shall be measured. **[mass spectrometer]**