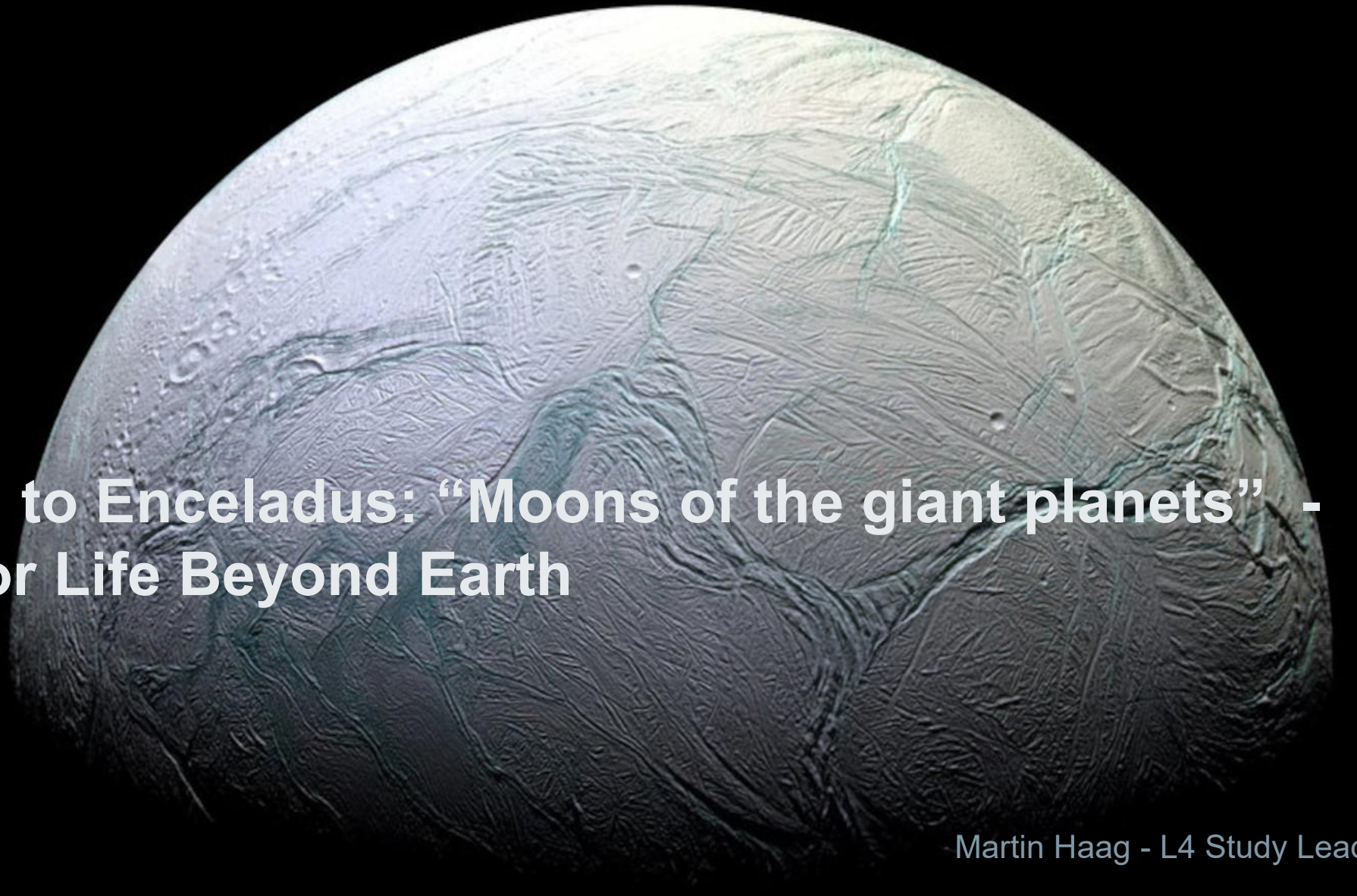


ESA's L4 Mission to Enceladus: "Moons of the giant planets" - and the Search for Life Beyond Earth

Martin Haag - L4 Study Lead

martin.haag@esa.int

ESA science programme – strategic planning



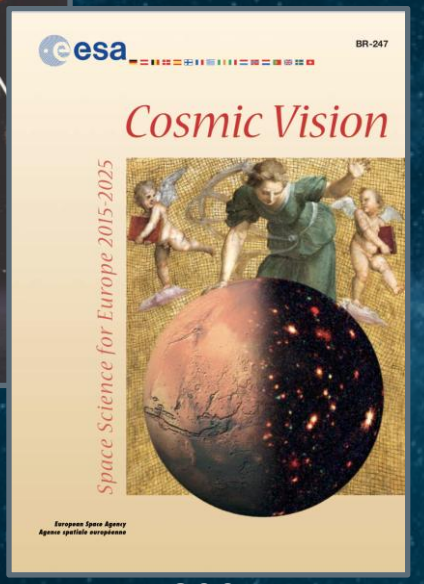
1984

Huygens (Cassini)



1995

Gaia
BepiColombo



2005

JUICE [L1]
Athena [L2]
LISA [L3]



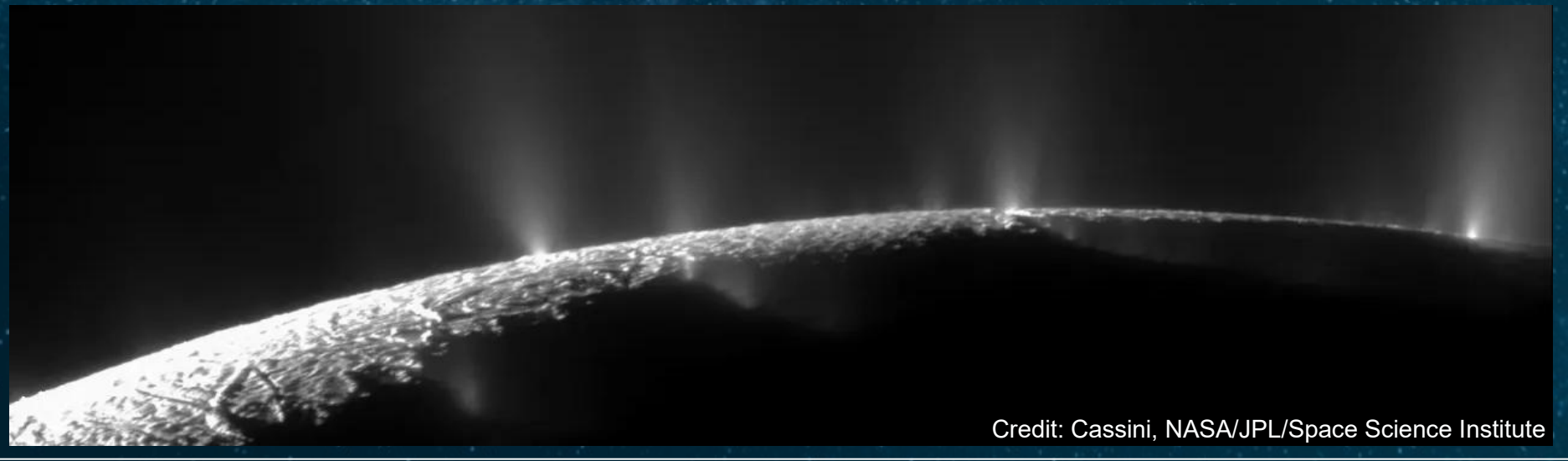
2021

L4: Moons of the giant planets

ESA's Large-class missions are flagship science missions launched every ~7 to 10 years, with budgets exceeding €1 billion.

The origin of Saturn's E–ring & Enceladus

- Early 1980s papers:
  - "The optical depth [of the E-ring] has a pronounced maximum near the orbit of Enceladus, which is therefore widely assumed to be the source of ring material"
  - "This distribution strongly suggests it to be associated with Enceladus and perhaps to be material ejected from Enceladus"
- Cassini, 2004 to 2017 around Saturn:
  - Cassini's magnetometer measured a disturbance in the field around Enceladus in 2005!
  - Flyby over the southern pole of Enceladus revealed the plumes! → It's an ocean world!



Credit: Cassini, NASA/JPL/Space Science Institute

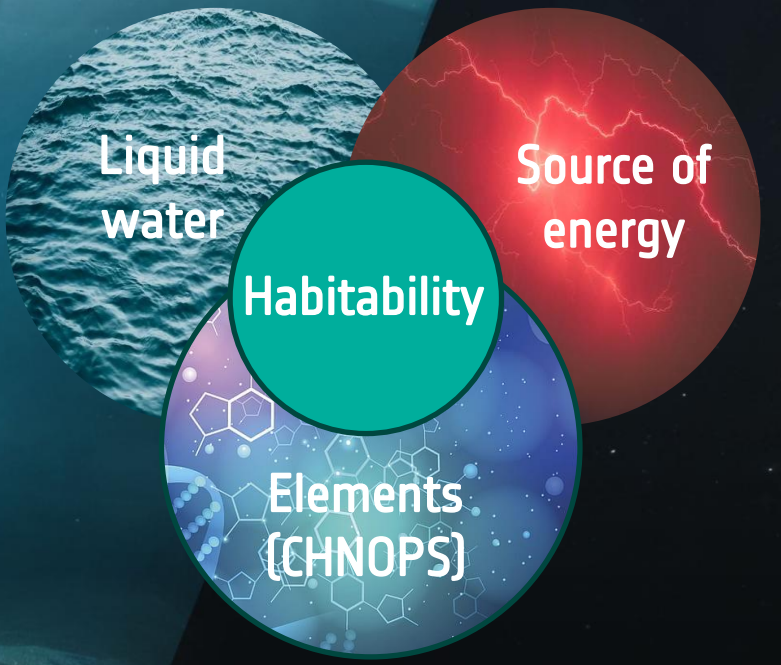
Why Enceladus

ICE SHELL

OCEAN

ROCKY CORE

- 504 km diameter *(6x smaller than Earth's moon)*
- Surface gravity: 0.0116 g *(1% of Earth gravity)*
- Mean surface temperature: -198 °C
- Geologically active, jets observed on south pole
- Subsurface liquid ocean containing the six elements critical for life as we know it!



Main conclusions from ESA's 4 internal CDF studies

- Mass is one of the main design drivers and the launch capability of Ariane 6 is a limiting factor even when considering potential **future evolutions** in the early 2040s.
  - Therefore, the solution identified features two launches and rendezvous/docking in Earth's proximity (HEO, EML2, SEL2).

- We need a very large lander on the south pole of Enceladus!

- The mission is baselined without radioisotope power systems, featuring large solar arrays on the orbiter and a large battery for the lander.

- The use of a solar electric transfer (SEP) stage provides flexibility for the launch date to reach Saturn with a launch window ~every year.


LAUNCH WITH TWO ARIANE 6 ROCKETS
ASSEMBLE IN SPACE
JOURNEY TO SATURN
ORBIT SATURN
esa
TITAN
RHEA
DIONE
TETHYS
ENCELADUS
MIMAS
FLY BY SATURN'S ICY MOONS
SAMPLE PLUMES
ORBIT ENCELADUS
LAND ON THE SOUTH POLE OF ENCELADUS

Pre-phase A industrial activities

- Industrial technical concept studies (2024 - 2025)
  - The industrial activities baselined two separate launches of Ariane 64 **EVO** with the aim to provide a feasibility and cost assessment of the mission.

→ **MISSION IS TECHNICALLY FEASIBLE**

- Recently (re-)started industrial studies (2026 - 2027)
  - After the loss of A64 EVO, industry will (re-)investigate the following mission architectures:
    1. Rendezvous architecture [2x Ariane 6 B2]; baseline European only mission
    2. Single-launch architecture [1x Ariane 6 B2]; new European only baseline, if feasible
    3. International-launcher architecture

- **Preparation for start of Phase A end of 2027**

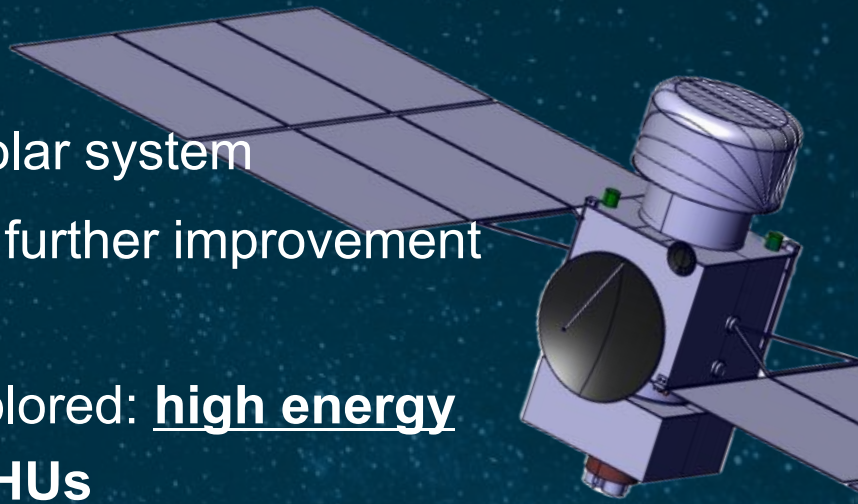
The mission timeline(s):



PRELIMINARY TIMELINES

L4 main design drivers

- Limited solar power available in the outer solar system requires use of large solar arrays and primary batteries:
  - Low solar flux (~14 W/m^2) at Saturn → **~180 m^2 solar arrays** on the orbiter
    - **~700 W generated EOL**
    - Large solar arrays enable electric propulsion in inner solar system
  - **Primary battery for the Enceladus lander** (High TRL, with further improvement being investigated)
    - Low TRL solutions with European equipment being explored: **high energy density fuel cells, deployable solar arrays and/or RHUs**
- The thermal control system is driven by a highly variable thermal environment with extremely low temperatures in the outer solar system and high temperatures generated by the electric propulsion stage at ~0.8 AU
- Telecommunication (orbiter to ground) require a large high-gain antenna (~2.5 m) and arrayed (35 m) ground stations



Enceladus lander design drivers

Preliminary design of an Enceladus lander

14-30 days surface operation

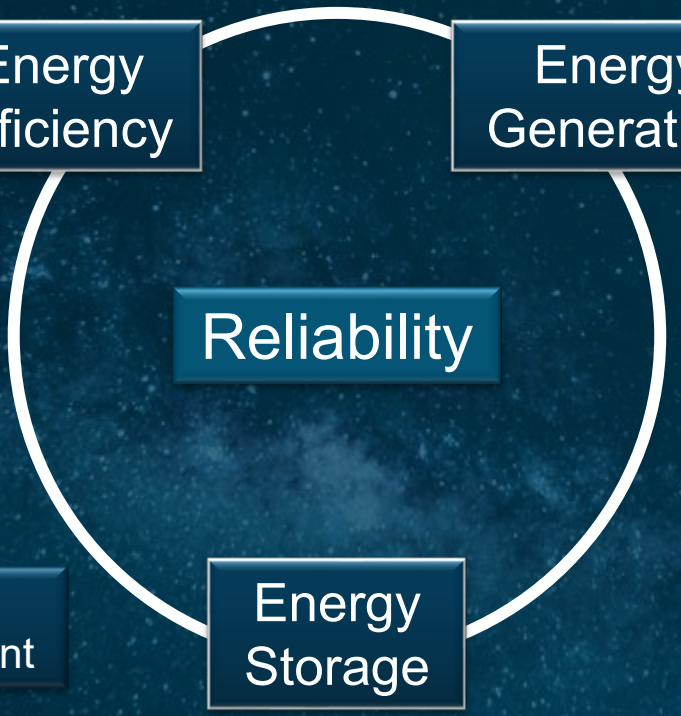
- ~23 h science / day
- 1 h of communication with orbiter / day



System design:

- ~20 kg payload mass + 10 kg sample mechanism
- **Battery mass: ~120 kg!** → 2 weeks on the surface of Enceladus!
- Lander wet mass: ~600 kg (incl. system margins)
- Large crushable structure needed to perform soft landing into unknown terrain with unknown surface properties!

L4: Establishing technology needs and building blocks



Propulsion Systems

Large Solar Arrays

RHU

Coms RF and Optical

Energy Efficiency

Energy Generation

Fuel Cells

Cryogenic Electronics

Astrobiology Instruments

Reliability

Modelling & Tools

Cryogenic sample handling mechanisms

Thermal Management

Energy Storage

Autonomous Landing Technologies

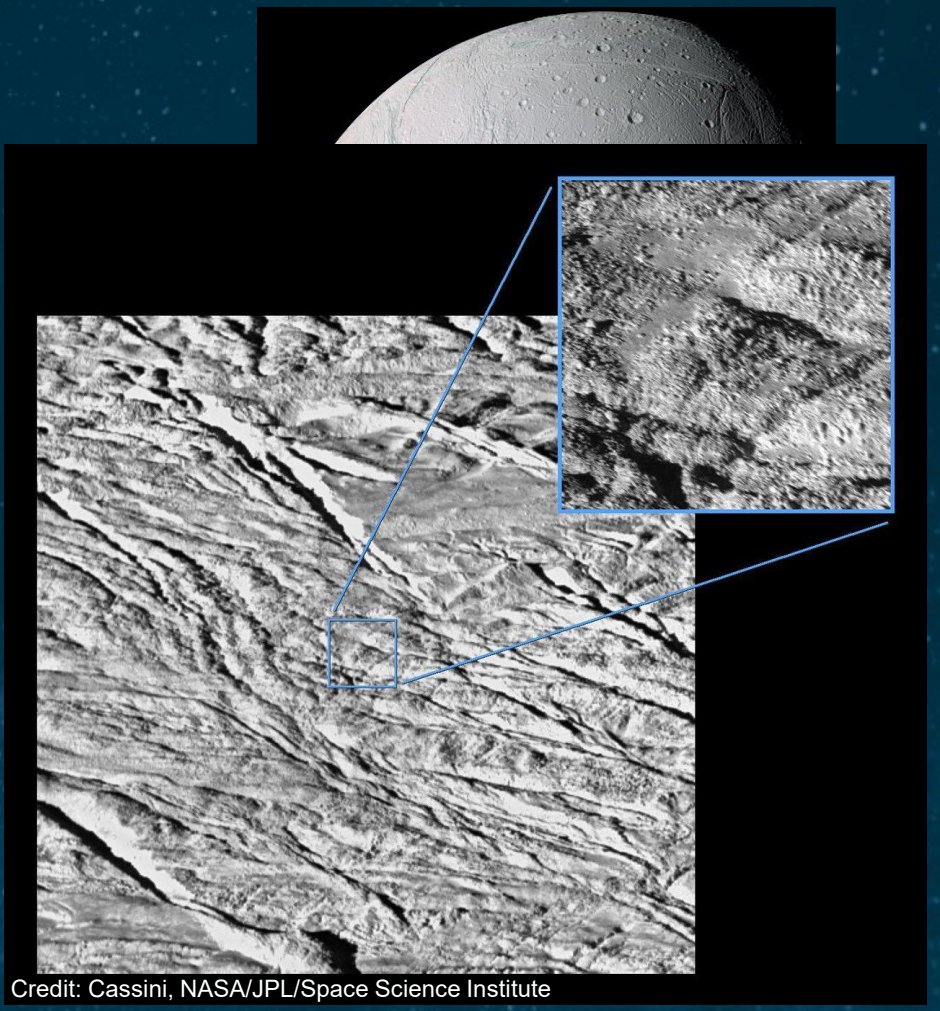
In-Orbit Rendezvous

Primary Battery Systems

Secondary Battery Systems

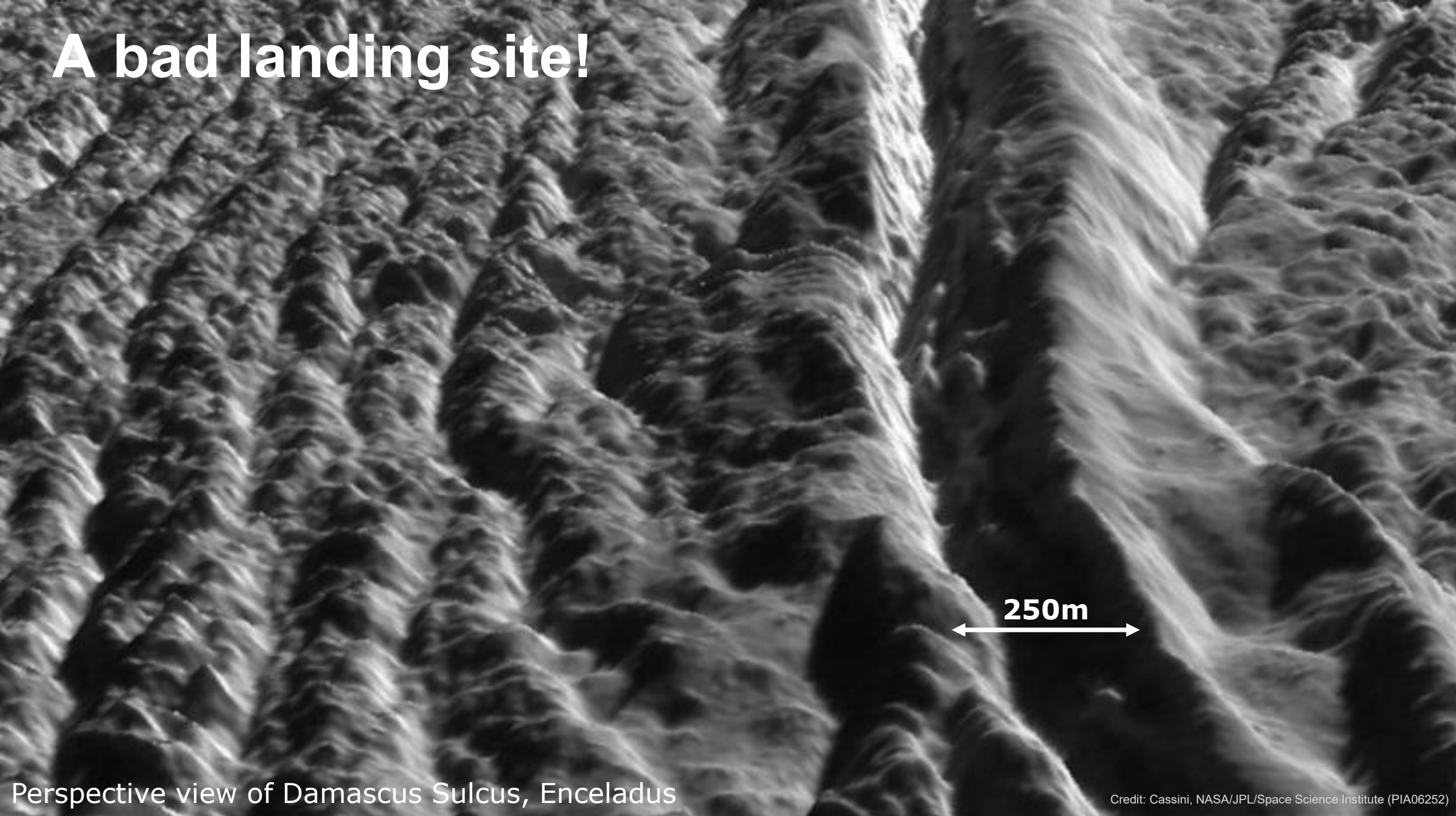
Enceladus – how/where do we land?

- 0.1 - 50 mm/year of “snowfall”, 1 mm/year average
- Icy and rocky surface:
  - “The surface is dominated by ice blocks between 10 and 100 meters across” (camera resolution did not allow to resolve boulders <10 meters)
  - Two ~5x5km areas with low boulder counts have been identified (so far)
  - 50x20km landing ellipse with unguided landing approach
  - ~1km landing ellipse with guided approach



Credit: Cassini, NASA/JPL/Space Science Institute

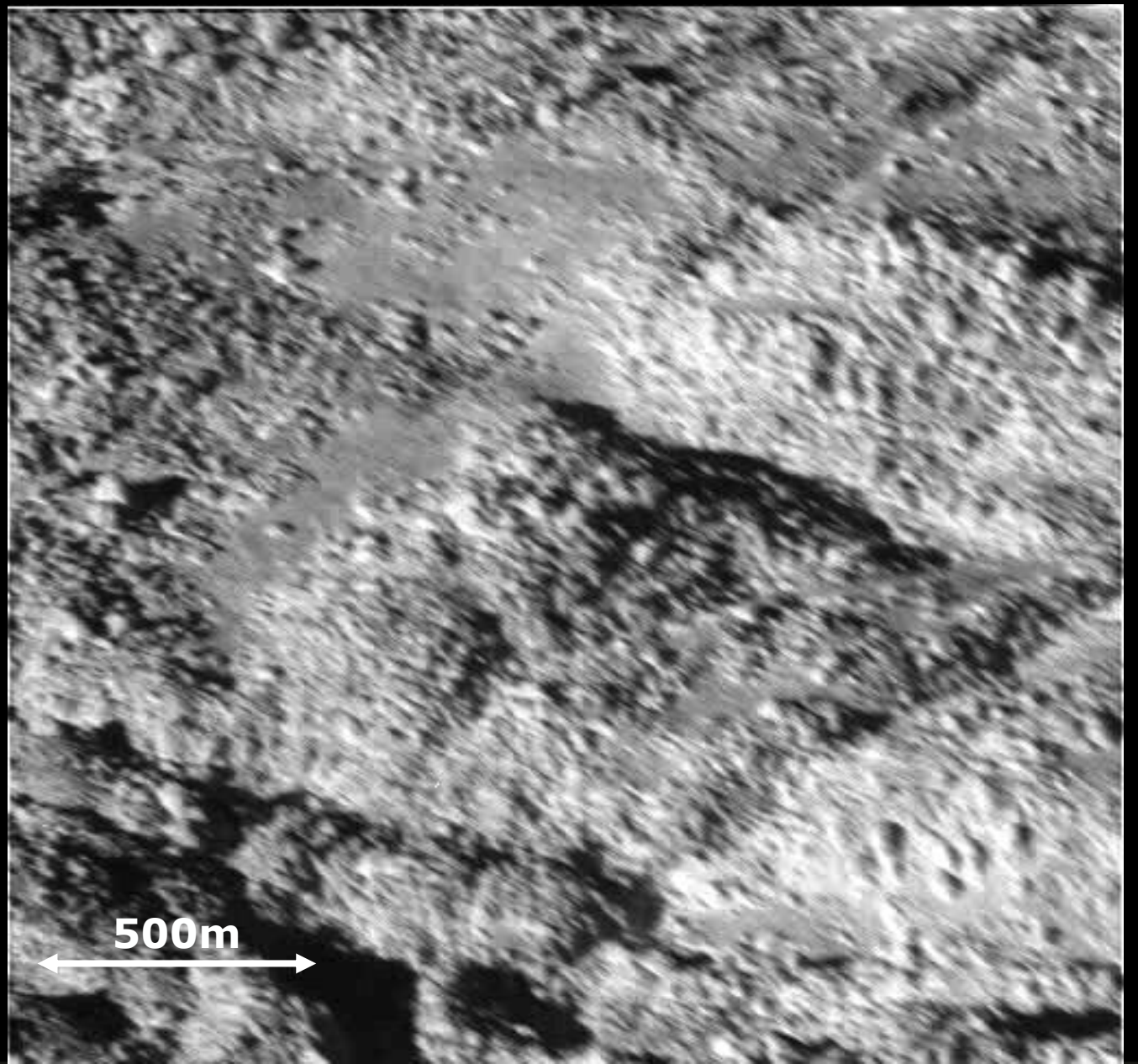
A bad landing site!



Perspective view of Damascus Sulcus, Enceladus

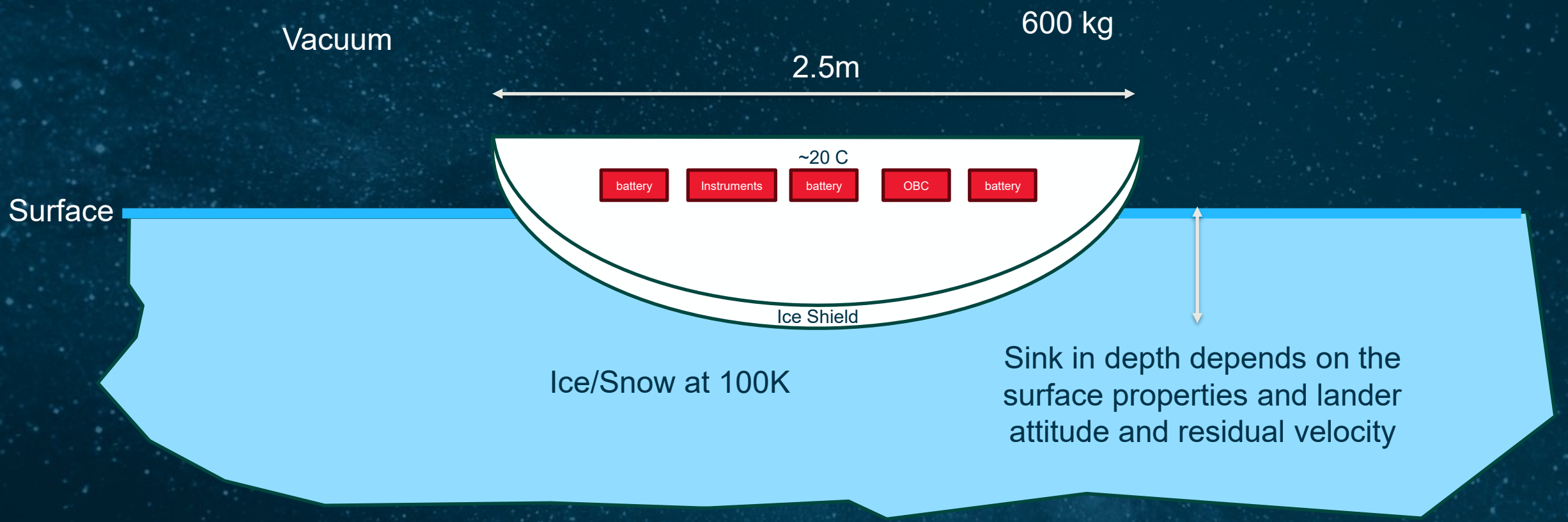
Credit: Cassini, NASA/JPL/Space Science Institute (PIA06252)

A good landing site?



Credit: Cassini, NASA/JPL/Space Science Institute (PIA06252)

Surviving on Enceladus



Need to demonstrate surface survival and operation over the full 2 – 4 weeks in a relevant environment (surface temperature at ~100K)

Finding the balance between too cold and too hot

What are we looking for?

Needed sample size

DNA/RNA

Goal of the L4 mission

Thanks to Cassini we are currently here

RUNG (Roughly, subjectively ordered by (top to bottom): 1. decreasing strength of evidence for life 2. increasing ease of measurement)		FEATURE (Listed in no specific order within a given rung)	MEASUREMENT TARGET		LIKELIHOOD (... that the feature would be a biosignature, given the criteria to the right)	INSTRUMENTAL CRITERIA: Quantifiable (Detectability)	INSTRUMENTAL CRITERIA: Contamination-free (Likelihood of false positive)	INSTRUMENTAL CRITERIA: Repeatable	CONTEXTUAL CRITERIA: Detectable (Detectability)	CONTEXTUAL CRITERIA: Survivable (Likelihood of false negative)	CONTEXTUAL CRITERIA: Reliable (Ambiguity of feature)	CONTEXTUAL CRITERIA: Compatible (Specificity to Earth life)	CONTEXTUAL CRITERIA: Last-resort (Ambiguity of interpretation)
LIFE	Darwinian evolution	Changes in inheritable traits in response to selective pressures	Not practical under mission constraints	• In situ • Sample return	No	-	-	Number of replicates depends on: • Characteristics of the instrument, • Heterogeneity of the sample, • Likelihood of systematic errors, • Required values of the relevant statistical parameters, • Value and cost of information.	-	N/A (extant)	-	-	-
	Growth & Reproduction	Concurrent life stages or identifiable reproductive form, motility	Cell(-like?) structures in multiple stages	• In situ • Sample return	Low	Hard	Low		Med (don't identify stages, timing off, sample size low)	High?	Ambiguous. What is a cell? What morphological differences exist?	Earth	Med / High
	Metabolism	Major element or isotope fractionations indicative of metabolism	Deviation from abiotic fractionation controlled by thermodynamic equilibrium and/or kinetics	• Remote sensing • In situ • Sample return	Low / Med	Easy	High		Medium	High	Hinges on understanding of context	Earth?	Low
		Response to substrate addition	Waste output (compound, heat)	• In situ • Sample return	Low / Med	Easy	Low		High	N/A (extant)	Hinges on understanding of context	Earth	Medium
		Co-located reductant and oxidant	Deviation from abiotic distribution controlled by thermodynamic equilibrium and/or kinetics	• Remote sensing • In situ • Sample return	Med / High	Med (linked to specificity of instrument)	Low / Med		Med / High	High	Mixed reactions, large inventory of chemistries	Generic	Low / Med
SUSPICIOUS BIOMATERIALS	Molecules & Structures Conferring Function	Polymers that support information storage and transfer for terran life (DNA, RNA)	Abundance	• In situ • Sample return	Low	Hard (instrument specificity must be high); RNA hard to measure on Earth	DNA: high; RNA: low (reactive)		Low (technology limited, only terran); RNA highly reactive	Low (hydrolysis in water)	Reliable	Earth	Negligible
		Structural preferences in organic molecules (non-random and enhancing function)	Polymer with repeating charge	• In situ • Sample return	Low / Med	Need a lot of material and overprinting must be discernable	Low		Med / High	Low (hydrolysis in water, diagenesis)	How much preference needed to detect?	Generic	Low
			Enantiomeric excess > 20% in multiple amino acid types	• In situ • Sample return	High	How much excess necessary?	Low		Low	Medium	Mixed sample both processes present	Generic	Low
		Pigments as evidence of non-random chemistries (e.g. specific pathways)	Spectral feature and/ or color, otherwise see "structural preferences"	• Remote sensing • In situ • Sample return	Low / Med	Easy (fluorescence)	Low		Low (limitation of what we are looking for)	Low (diagenesis)	How to define pigment as we don't know it?	Earth (can one abstract?)	Very low
	Potential biomolecule components	Organics not found abiotically (e.g. hopanes, ATP, histidine)	Presence	• In situ • Sample return	Medium	Easy if enough material	Low		High	High	Low	Earth?	High
		Complex organics (e.g. nucleic acid oligomers, peptides, PAH)	Presence	• Remote sensing (PAH) • In situ • Sample return	High	Easy if enough material	Low		High	Medium	Abiotic production known	Generic	Med / High
		Monomeric units of biopolymers (nucleobases, amino acids, lipids for compartmentalization)	Presence	• Remote sensing • In situ • Sample return	Med / High	Limit of detection, need a lot of material	High		High	Med (diagenesis)	Abiotic pathways known	Generic	Medium
	Potential metabolic byproducts	Distribution of metals e.g. V in oil or Fe, Ni, Mo/W, Co, S, Se, P	Presence	• In situ • Sample return	Medium	Easy except background issue	Low		High	High	Background known	Generic	Medium
		Patterns of complexity (organics)	Deviation from equilibrium (P(Poisson distribution of pathway complexity) < 0.01?) or abiotic kinetic distribution	• In situ • Sample return	High	Background issue, material limited	Low		High	Medium?	Limited documentation of abiotic vs. biotic differences	Generic	Medium
	Biofabrics	Textures	Biologically mediated morphologies, preferably with co-located composition	• In situ • Sample return	Medium	Medium	Low		Medium	High?	Highly ambiguous	Earth	High
	Habitability	Liquid water, building blocks, energy source, gradients		Redox, temperature, pH, energy, disequilibria									

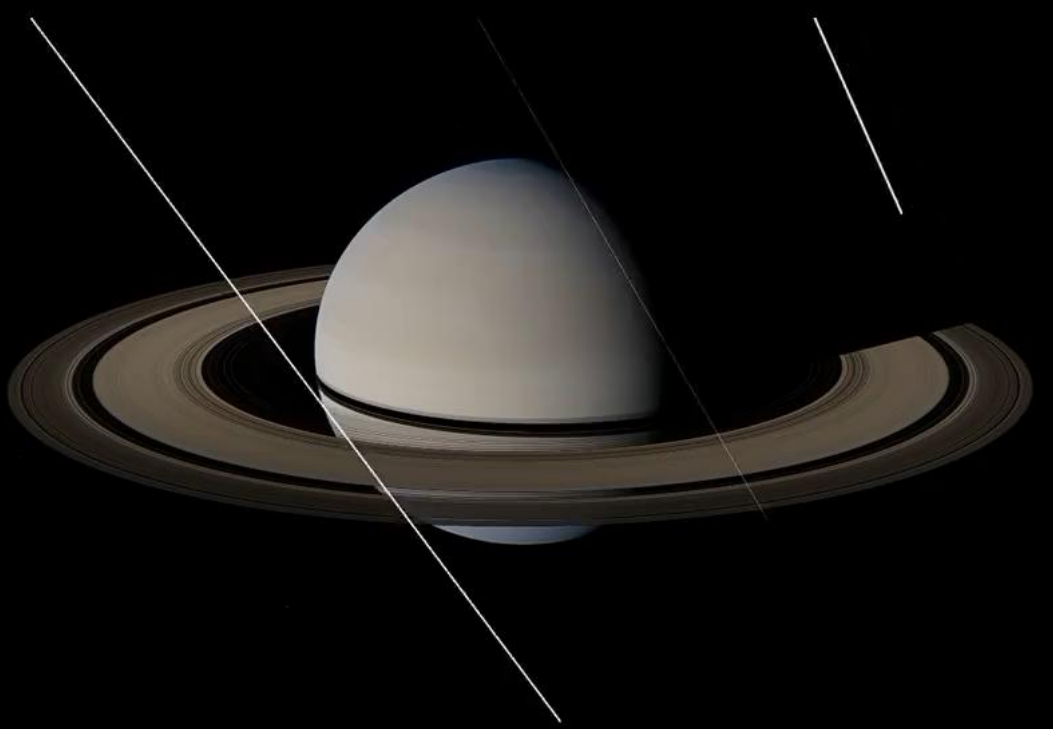
Credit: The Ladder of Life Detection, M. Neveu et al, https://doi.org/10.1089/ast.2017.1773

Two-year outlook

- PLWG payload suite(s) recommendations ready
  - Report due in autumn 2026
- Payload workshop: 8 – 10 December 2026
  - https://www.cosmos.esa.int/web/l4/l4-community-workshop-dec-2026
- Pre-phase A industrial studies: mid 2026 – mid 2027
- Start of Phase A: ~end of 2027

Long term planning

- ~2031: End of Phase A – TRL 4 Needed
- ~2034: Mission Adoption – TRL 6 Needed
- ~2034-2042: Phase B2-C-D
- ~2042: Launch
- ~2053: Arrival at Saturn
- ~2054: High speed Enceladus plume flybys
- ~2055-2058: Saturn Moon Tour
- ~2058: Low-speed Enceladus plume flybys, Enceladus Orbit insertion, lander deployment & operation



Space is huge

Saturn is 1.5 billion km away

Enceladus is 500 km in diameter

We want to land somewhere here →