Jet Propulsion Laboratory
California Institute of Technology

To Boldly Go Where No *Robots* Have Gone Before

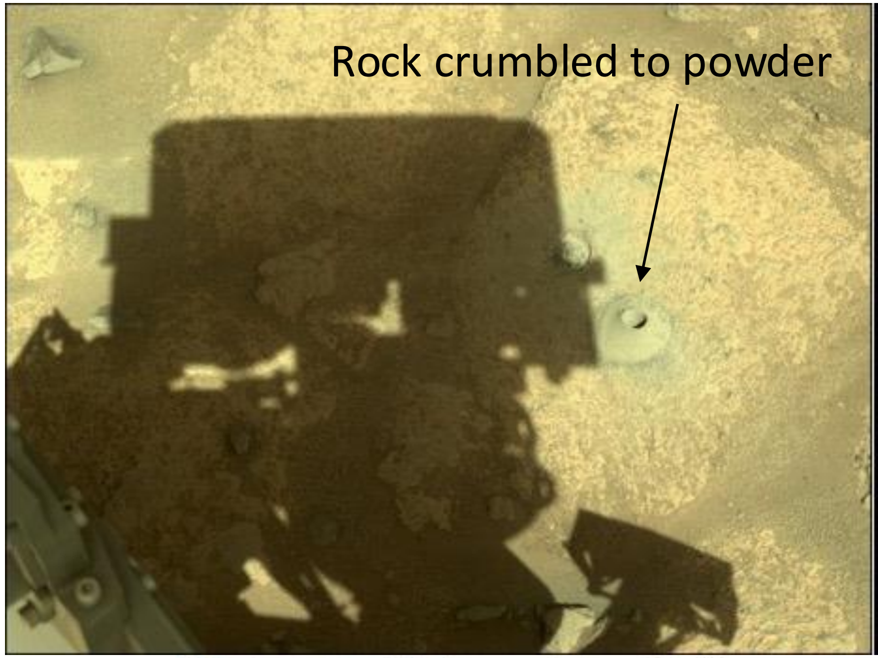
Hiro Ono

Supervisor, Robotic Mobility Group

Jet Propulsion Laboratory, California Institute of Technology


Space is full of unknowns
The reason we explore
The reason it is so hard

Perseverance's First Coring Attempt



- Five rock types were used for Qualification Model Dirty Testing (QMDT), chosen based on experiences from past Mars missions.
- >700 coring tests performed and the Sampling and Caching System met the requirements

Pre-OSIRIS-Rex prediction: Bennu has a smooth surface

Regolith Grain Size and Distribution

There are three independent lines of evidence for the particle sizes and regolith distribution on the surface of Bennu: thermal IR measurements using the Spitzer Space Telescope (Emery et al. 2014), radar circular polarization ratio measurements using the planetary radar systems at Goldstone and Arecibo (Nolan et al. 2013), and geophysical analysis of the asteroid shape, density, and rotation state. All data provide high confidence in the presence of regolith on the surface of Bennu.

Spitzer thermal emission data provide firm constraints on the average regolith grain size (Fig. 7a; Emery et al. 2014). Regolith grains that are comparable in size to the thermal skin depth would behave like bedrock. For grain density (2000 kg m^{-3}) and heat capacity (500 J kg^{-1} K^{-1}) values consistent with carbonaceous chondrites and the derived thermal inertia and rotation period of Bennu, the estimated thermal skin depth is approximately 2 cm. For all reasonable assumptions about the density and heat capacity of surface materials, the thermal skin depth on Bennu is <5 cm. The thermal inertia of Bennu is substantially below the bedrock value of >2000 J m^{-2} $s^{-0.5}$ K^{-1}. This difference implies that regolith grains are significantly smaller than the scale of the skin depth and therefore, average less than a centimeter. The rotational coverage

The Meteoritical Society

Meteoritics & Planetary Science 50, Nr 4, 834–849 (2015)
doi: 10.1111/maps.12353

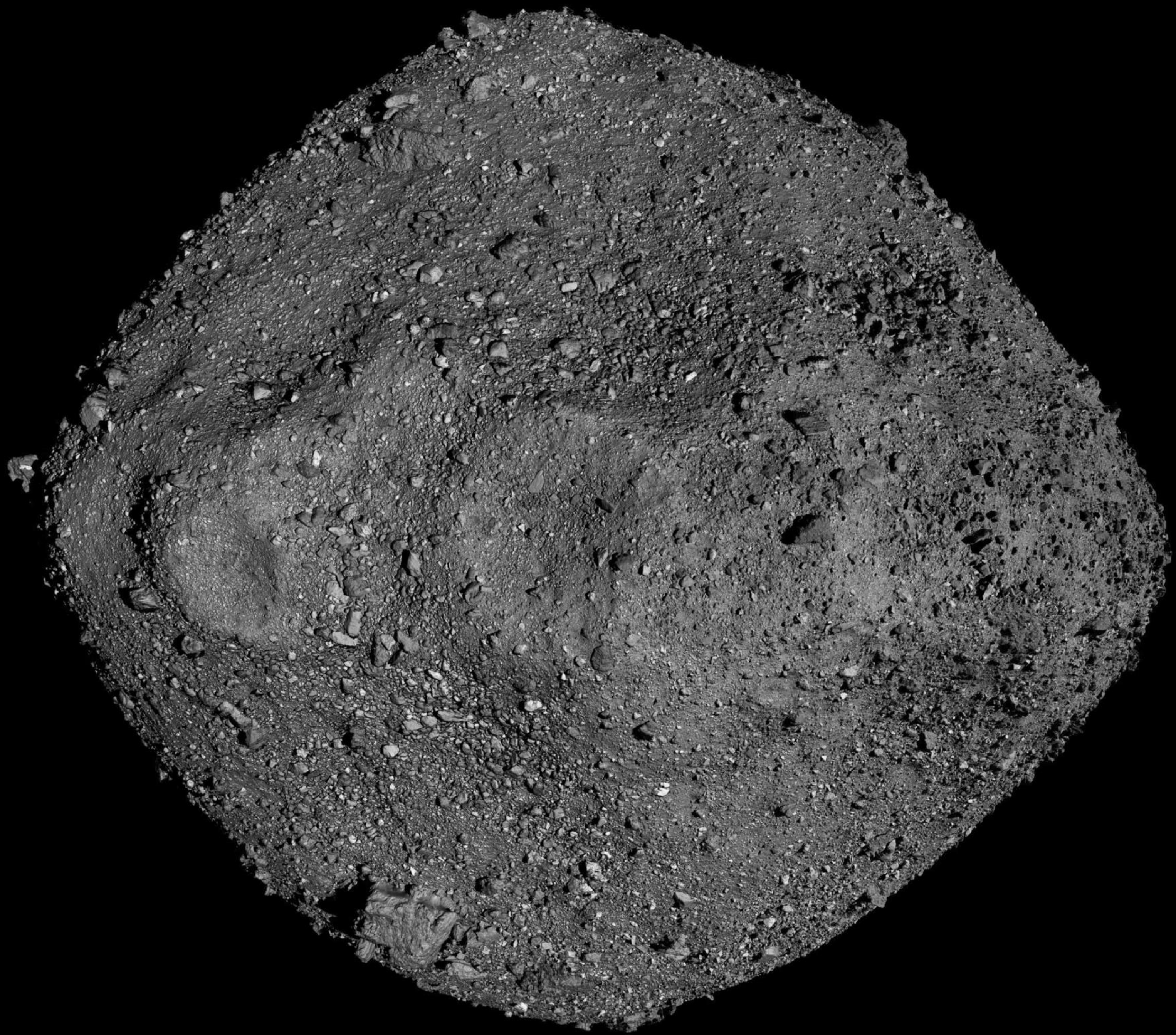
The OSIRIS-REx target asteroid (101955) Bennu: Constraints on its physical, geological, and dynamical nature from astronomical observations

D. S. LAURETTA[1,*], A. E. BARTELS[2], M. A. BARUCCI[3], E. B. BIERHAUS[4], R. P. BINZEL[5], W. F. BOTTKE[6], H. CAMPINS[7], S. R. CHESLEY[8], B. C. CLARK[9], B. E. CLARK[10], E. A. CLOUTIS[11], H. C. CONNOLLY[12,13,14], M. K. CROMBIE[15], M. DELBÓ[16], J. P. DWORKIN[2], J. P. EMERY[17], D. P. GLAVIN[2], V. E. HAMILTON[6], C. W. HERGENROTHER[1], C. L. JOHNSON[18,19], L. P. KELLER[20], P. MICHEL[16], M. C. NOLAN[21], S. A. SANDFORD[22], D. J. SCHEERES[23], A. A. SIMON[2], B. M. SUTTER[4], D. VOKROUHLICKÝ[24], and K. J. WALSH[6]

Analysis of the radar circular polarization ratio for Bennu provides an independent constraint on surface grain size. For Bennu, this ratio is 0.18 ± 0.03 for the 12.6 cm wavelength and 0.19 ± 0.03 at the 3.5 cm wavelength (Nolan et al. 2013). These ratios are substantially lower than that for asteroids Itokawa (0.26 ± 0.04 @ 12.6 cm and 0.47 ± 0.04 @ 3.5 cm) or Eros (0.28 ± 0.06 @ 12.6 cm and 0.33 ± 0.07 @ 3.5 cm), implying that the surface of Bennu is smoother at decimeter spatial scales than either of these two asteroids (Ostro et al. 2004). In addition, the similarity

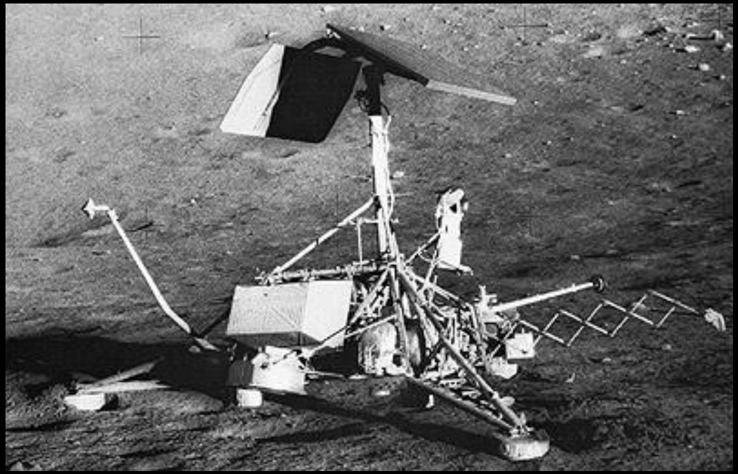
(Miyamoto et al. 2007), compared to Bennu.

Bennu's shape, dynamic state, and geomorphology provide additional evidence for the presence of loose particulate regolith. Combining the asteroid bulk density with the shape model and rotation state allows us to determine the slope distribution (Fig. 8). The average slope is estimated to be 12.6–17.4°, depending on the bulk density of the asteroid. This subdued slope distribution suggests that there is loose material capable of migrating into geopotential lows. Moreover, the most



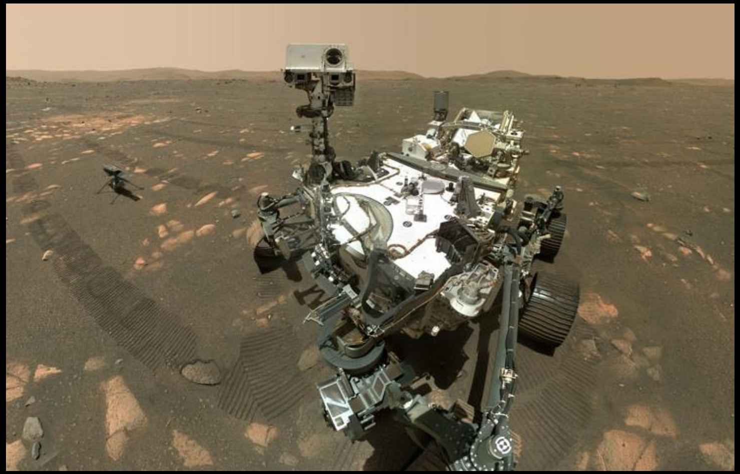
Paradigm Shifts in Robotic Space Exploration (RSE)

RSE 1.0



1960s

RSE 2.0



Current

RSE 3.0

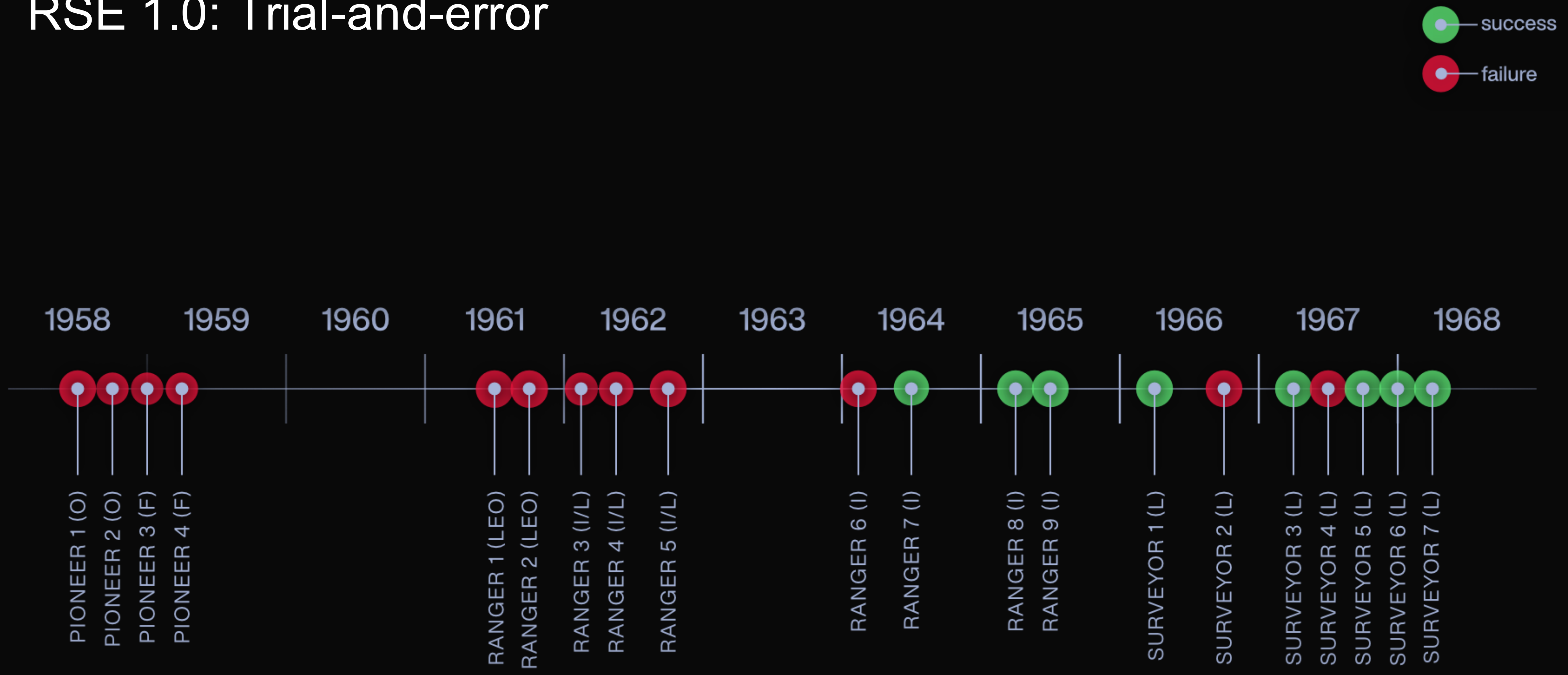
Future

Driver of paradigm shift: *environmental uncertainty of unvisited worlds*

RSE 1.0

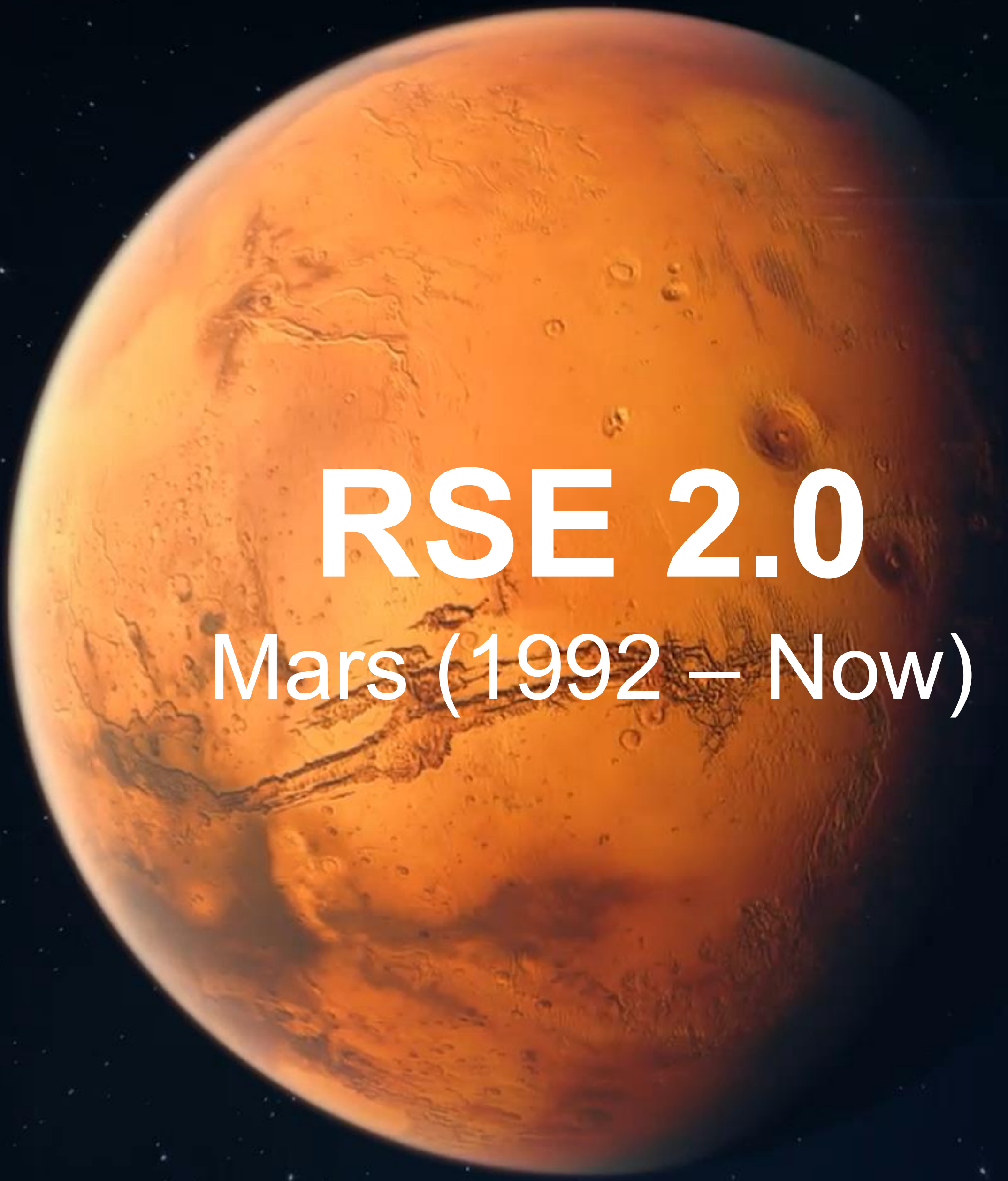
The Moon (1958 – 1968)

RSE 1.0: Trial-and-error



RSE 2.0

Mars (1992 – Now)

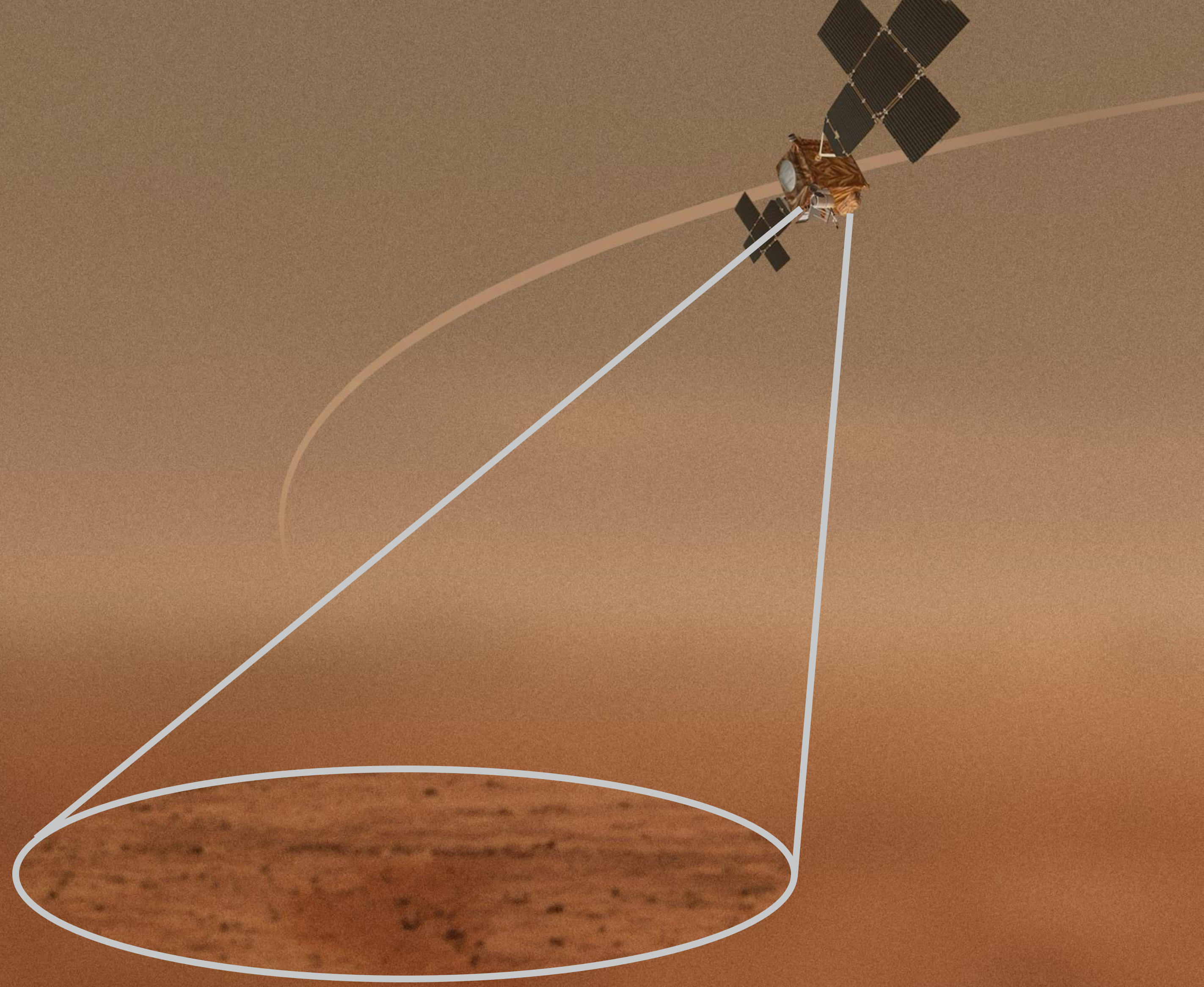


Robotic Space Exploration 2.0

Incremental sophistication through a series of missions

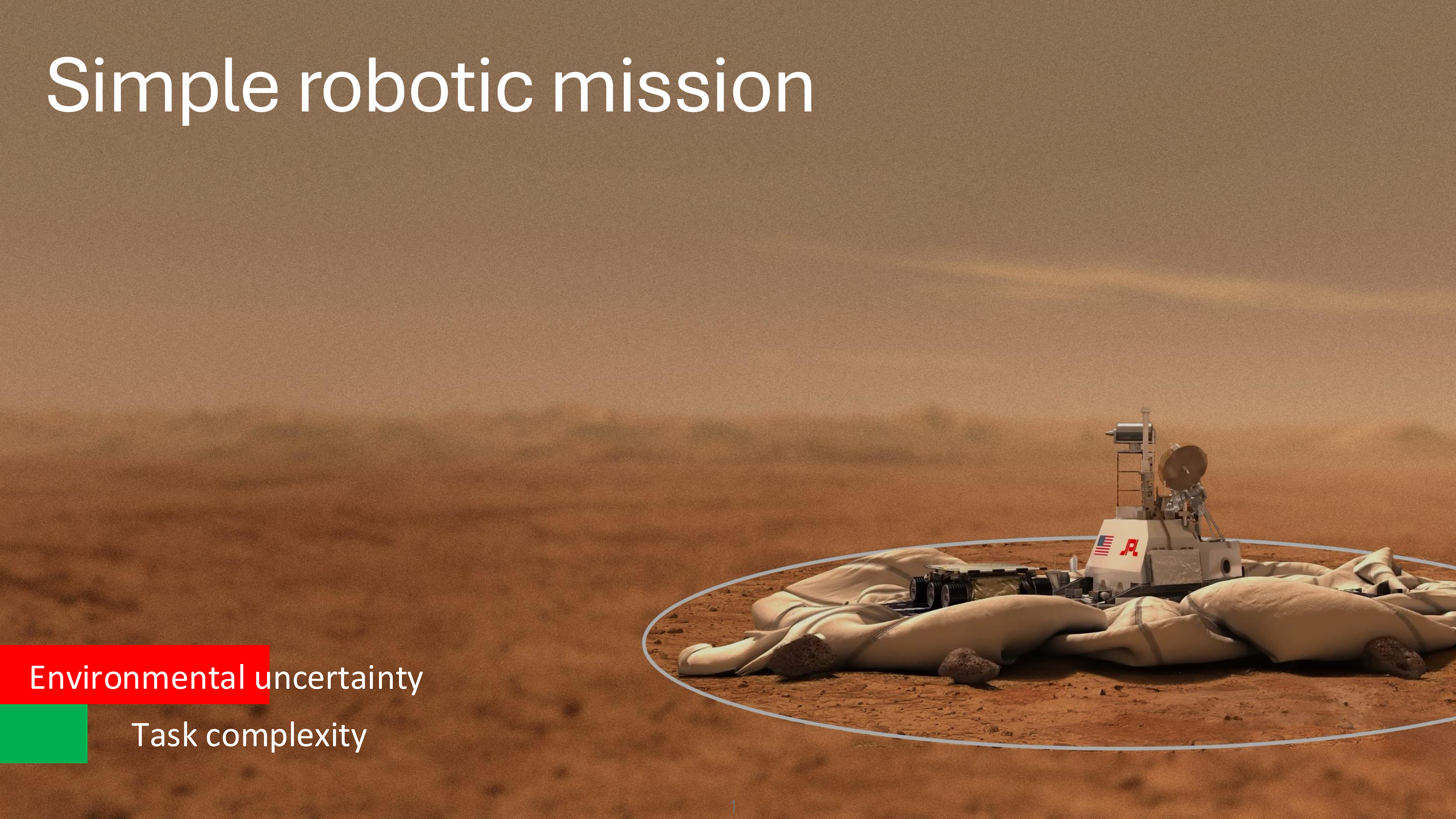
Environmental uncertainty

Orbiter

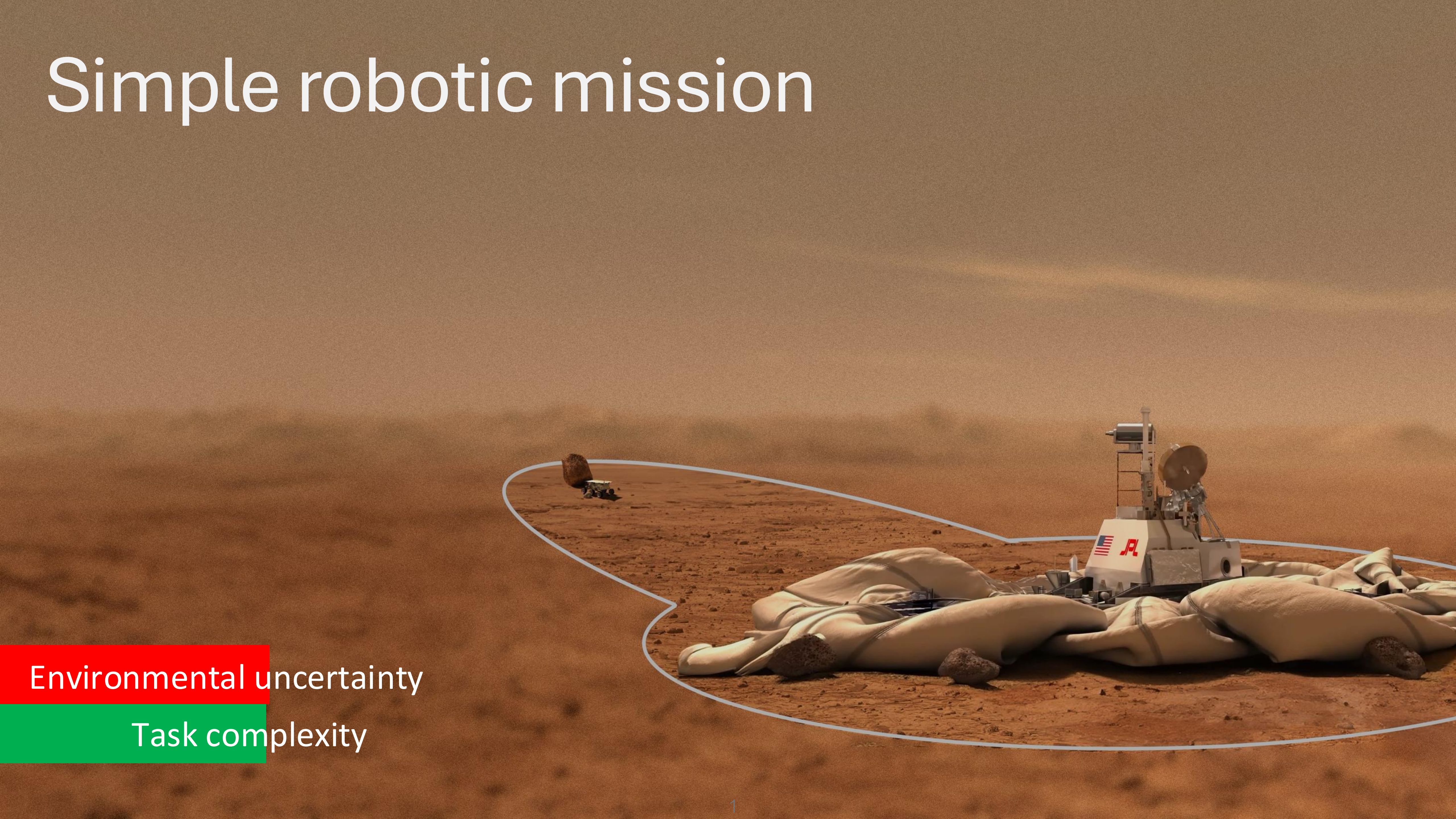


Environmental uncertainty

Task complexity


Simple robotic mission
Environmental uncertainty
Task complexity
1

Simple robotic mission

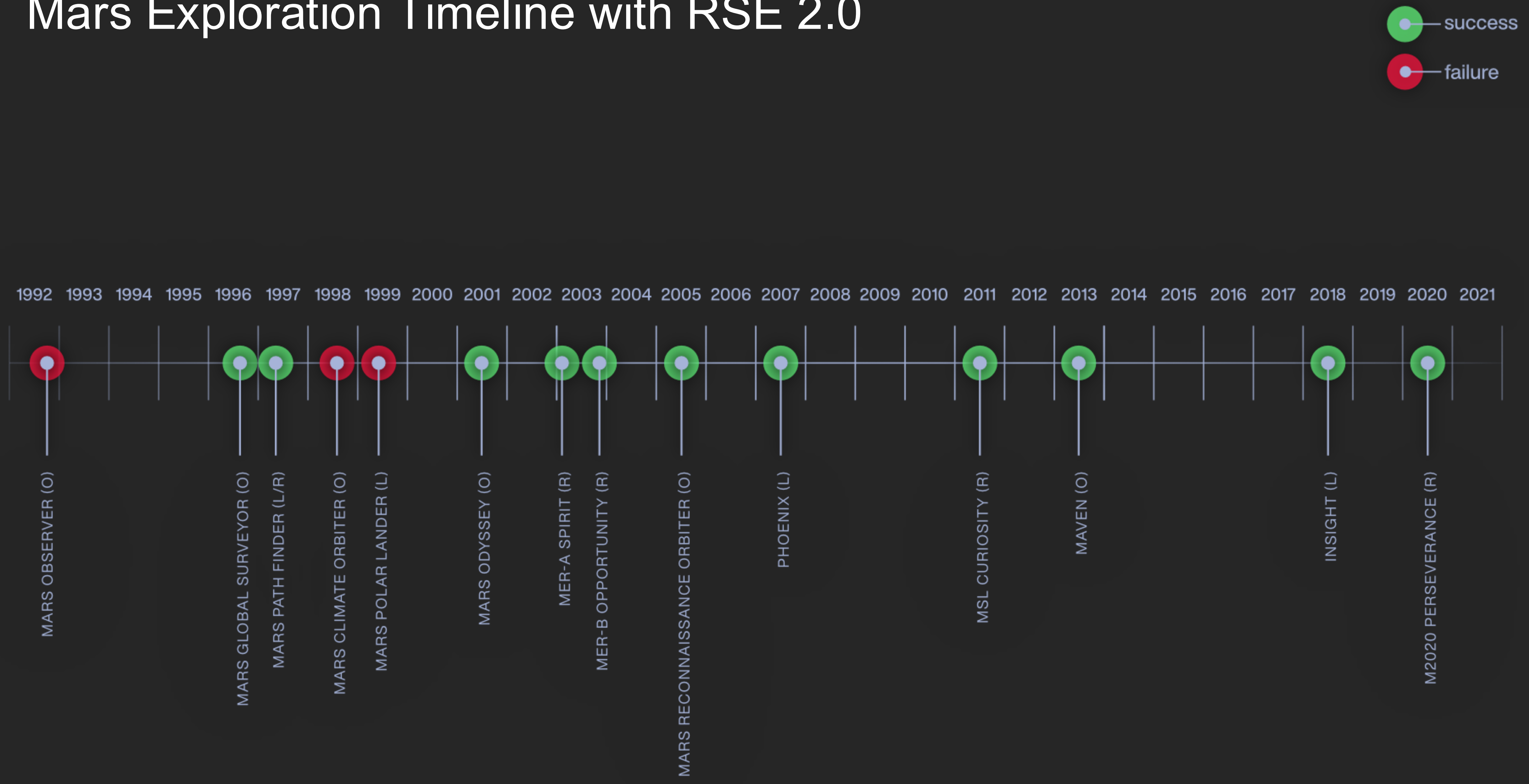


Complex robotic mission

Environmental uncertainty

Task complexity

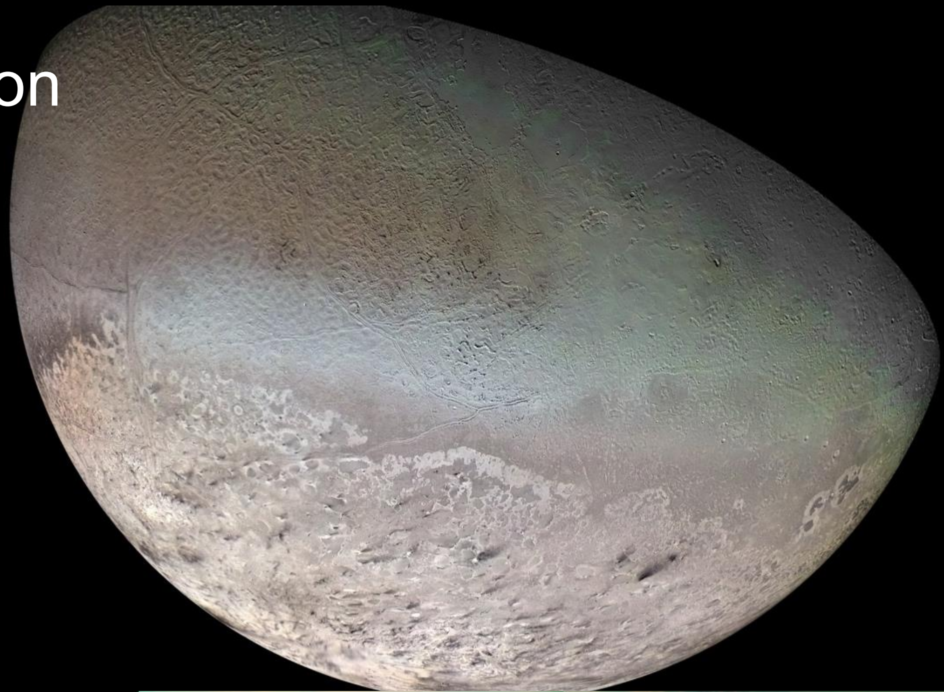
Mars Exploration Timeline with RSE 2.0



Ocean Worlds

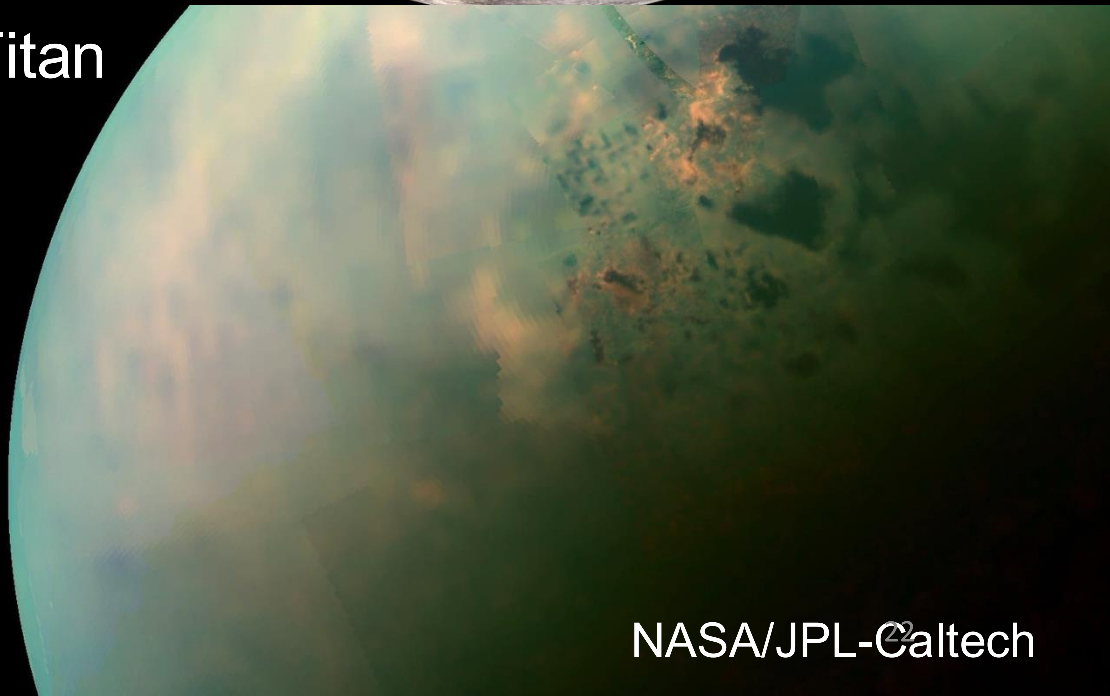
Europa

Triton



Ganymede

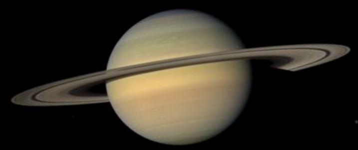
Titan

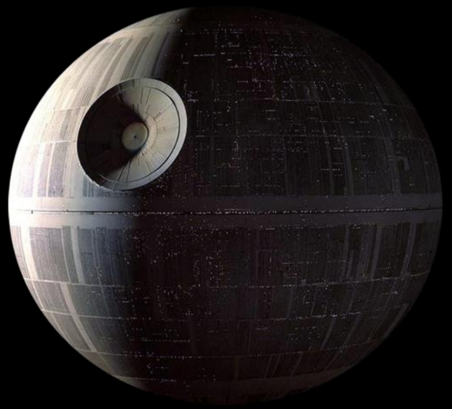


NASA/JPL-Caltech

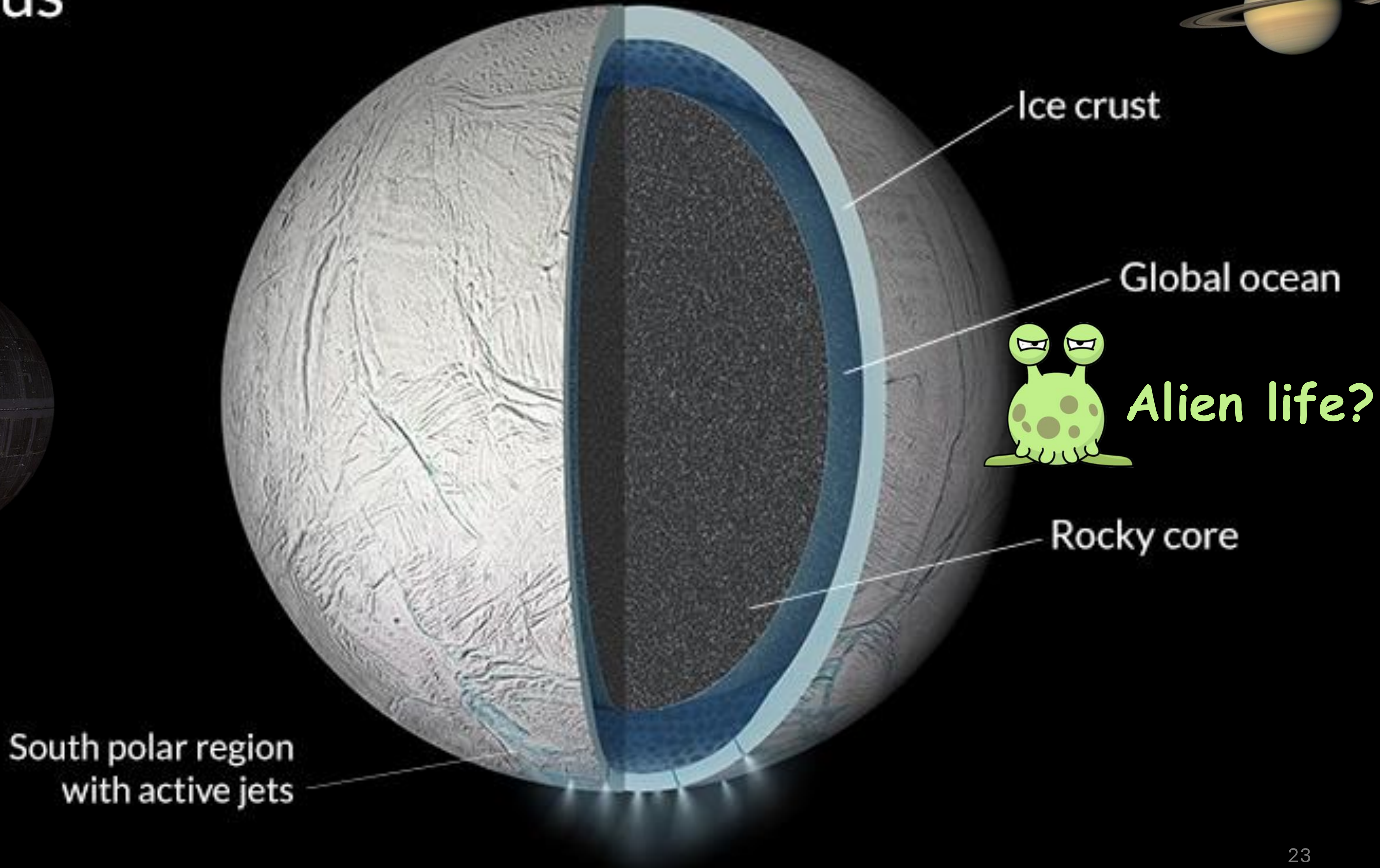
Enceladus

(D = 513 km)





Death Star
(D = 160 km)

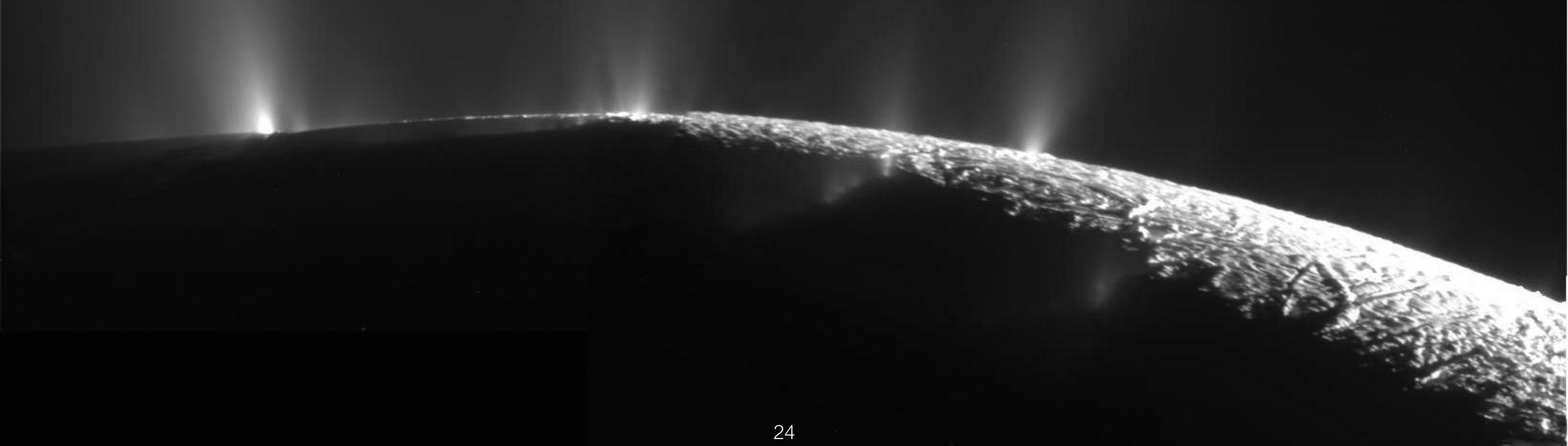


Why RSE 2.0 is not applicable?

Orbital reconnaissance of subsurface environment is not possible

Long cruise time to outer solar system (often >10 yrs)

Multitude of worlds to explore



RSE 3.0

One-shot exploration with an *adaptive* space system

Environmental uncertainty

Land and observe

Environmental uncertainty

Task complexity

Adapt and perform simple tasks

Environmental uncertainty

Task complexity

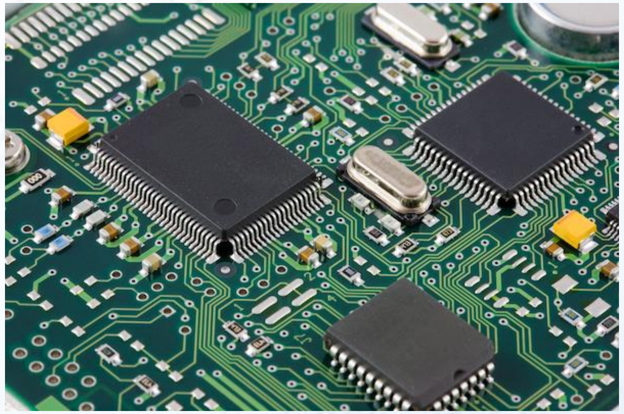
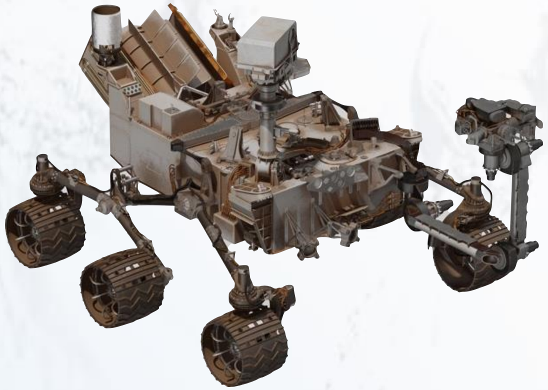
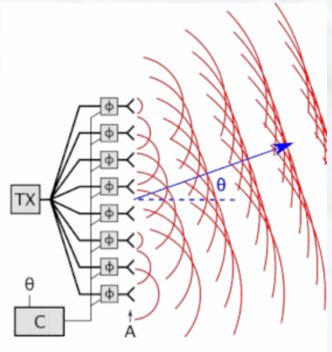
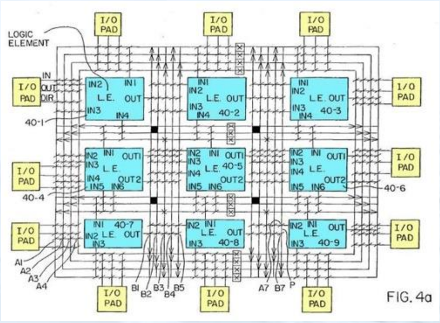
Adapt Complex robotic tasks

EELS (Exobiology Extant Life Surveyor) Mission to Enceladus Vent


EELS Robot Capabilities


LA
STANLEY CUP
CHAMPIONS
1ST PLACE
2021

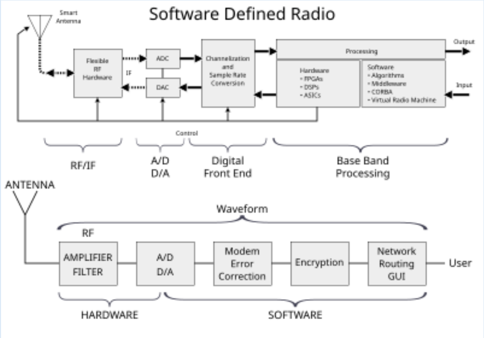
Software-defined Space System

	Antenna	Circuit	Space system
Hardware-defined	  **Antenna pattern is defined by shape**	 **Circuit is defined by electric components**	 **Spacecraft capabilities are (mostly) defined by hardware**
Software-defined	Phased-array antennas   **Antenna pattern is modulated by controller**	  **Circuit is defined by programmable gates**	 **Spacecraft capabilities are (mostly) defined by software**

Programmable, Software-Defined Devices

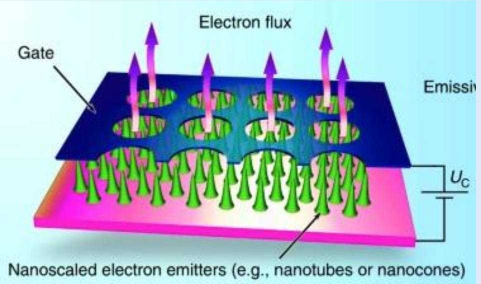
Communication

Software-defined radio



Propulsion

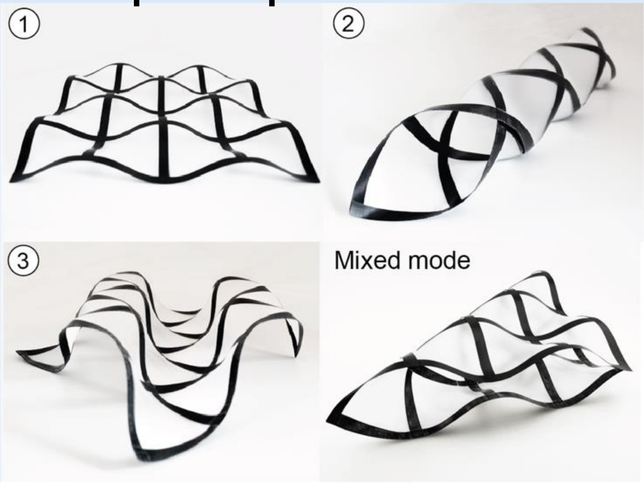
Adaptive ion thrusters



Levchenko et al. Nature Communications 2018

Structure

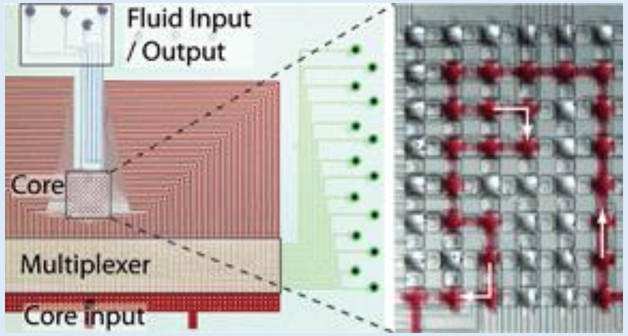
Shape-adaptive materials



Sakovsky at al. *EuCAP* 2024.

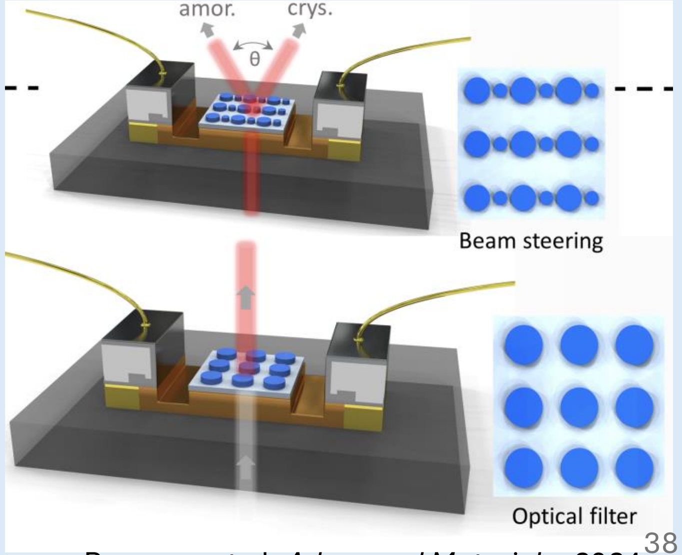
Science Instruments

Programmable microfluidic circuits



Luis & Maerkl. *Lab on a Chip.* 2011

Programmable optical device with metasurface



Popescu et al. *Advanced Materials*, 2024

Mobility

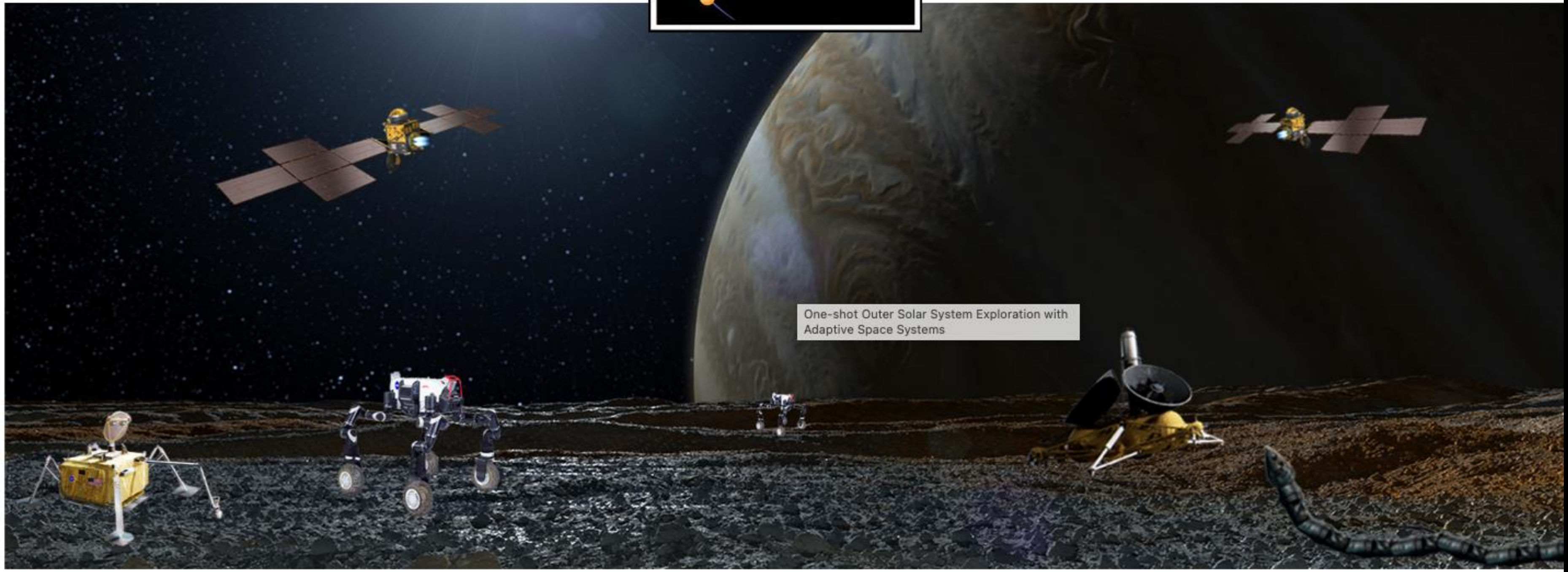
Modular/reconfigurable robots

Lordos et al., *IEEE Aerospace* 2013

Romanishin & Rus *IROS* 2019

Avionics

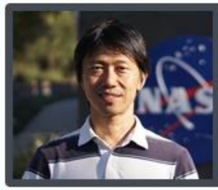
High density FPGAs



Workshop: One-shot Outer Solar System Exploration with Software-defined Space Systems

November 3 - 7, 2025
California Institute of Technology - Pasadena, CA 91125

Team Leads



Hiro Ono

Jet Propulsion Laboratory, California Institute of Technology

Morgan Cable

Jet Propulsion Laboratory, California Institute of Technology

Soon-Jo Chung

California Institute of Technology

Dani Selva

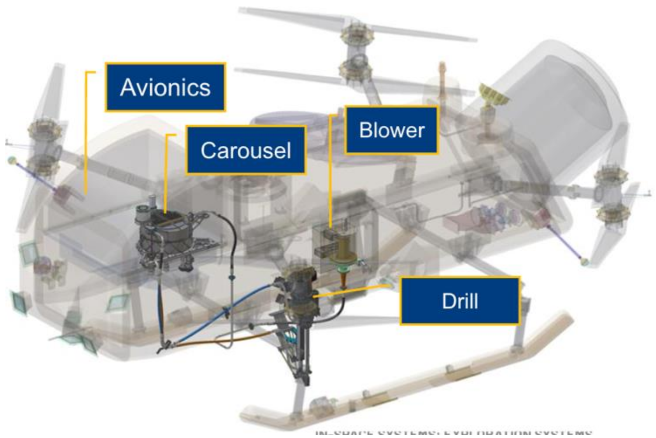
Texas A&M University

Lindy Elkins-Tanton

The Big Questions of Solar System Exploration

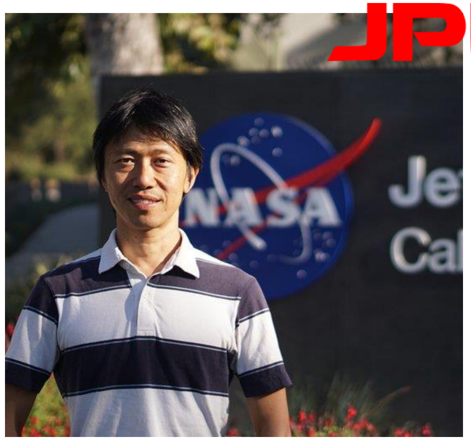
Dean Bergman

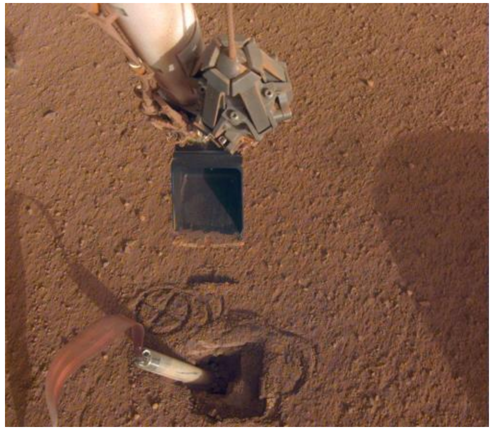
Autonomy for One-Shot Missions



Hiro Ono

Toward Adaptivity by Design: Lessons from Space Mission Operations Beyond the Plan





Annika Rollock

TESSERAE: Robotic Self-Assembly for In-Space Construction