Exploring the Unknown

The EELS Robot as a Steppingstone Towards Evolutionary Spacecraft

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Jet Propulsion Laboratory
California Institute of Technology


What do you pack for exploring?

Magellan

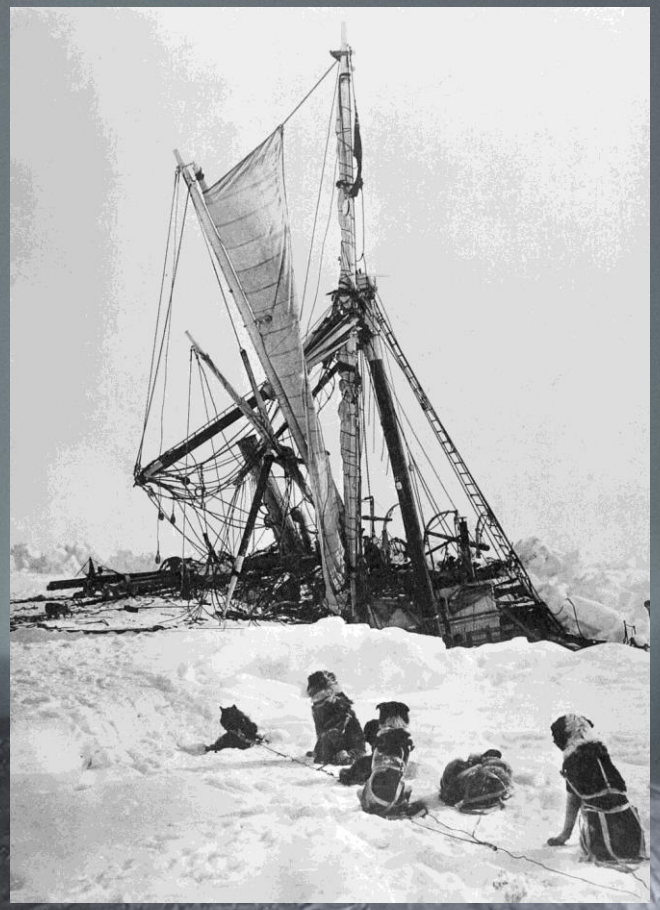
- 5 ships
- 270 men
- 4/5ths of provisions were wine and hardtack
- Flour
- Salted meat
- Livestock: 7 cows and 3 pigs
- Cheese, almonds, mustard, figs.

Lewis and Clark (1804)

- 3 boats
- 193lb of Portable soup
- 130 rolls of Tobacco
- 30 gallons of “strong spirit”
- Medical and surgical supplies
- Oilskin bags
- Native American presents
- Sextant
- Firearms, powder, and shot

Shackelton (1914)

- Woolen hats, under clothes
- Canvas jackets
- Reindeer fur gloves
- Stoves
- Tents
- Dog teams




What if you don’t know what to expect?

JPL Dares Mighty Things

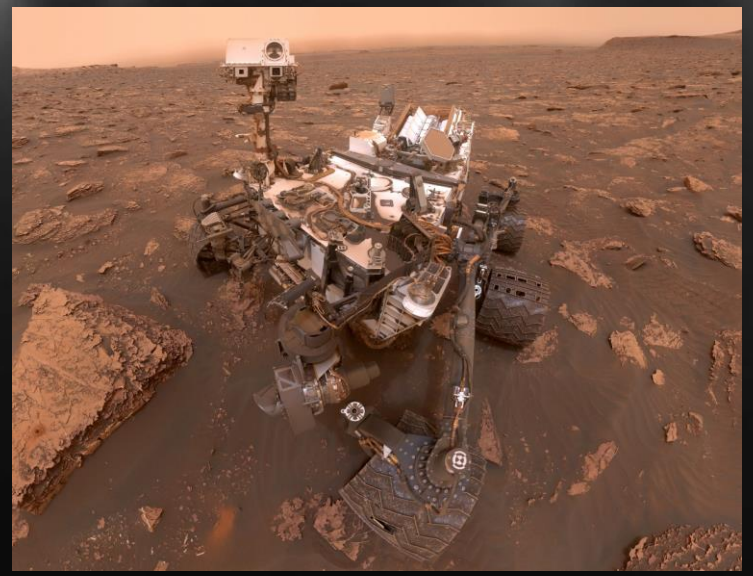
Robotic Exploration 1.0

Pre-Apollo Lunar exploration

High-cadence trial-and-error
e.g. Ranger, Surveyor, and Mariner missions

Robotic Exploration 2.0

Mars



Incremental sophistication in a multi-mission campaign
e.g. Mariner, Viking, Mars Observer, MGS, Pathfinder, Odyssey, MRO

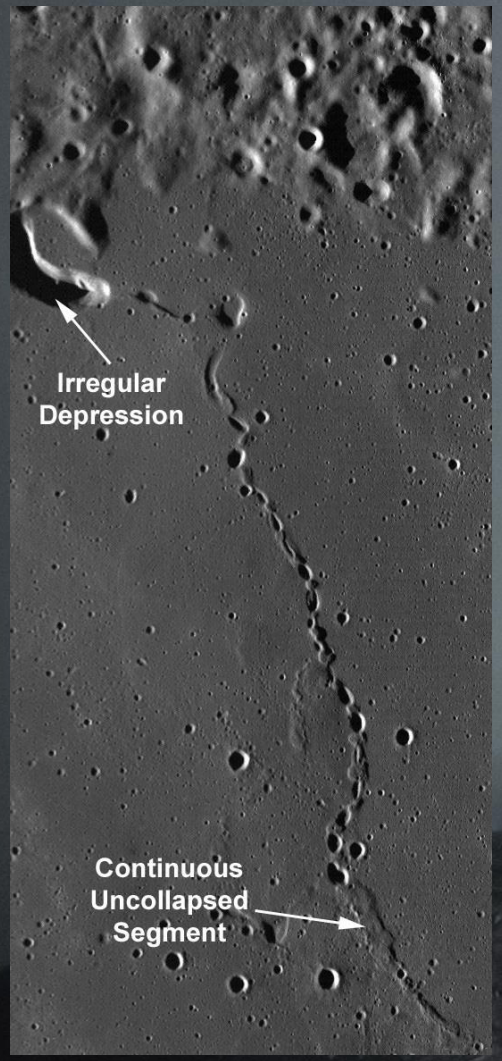
Robotic Exploration 3.0

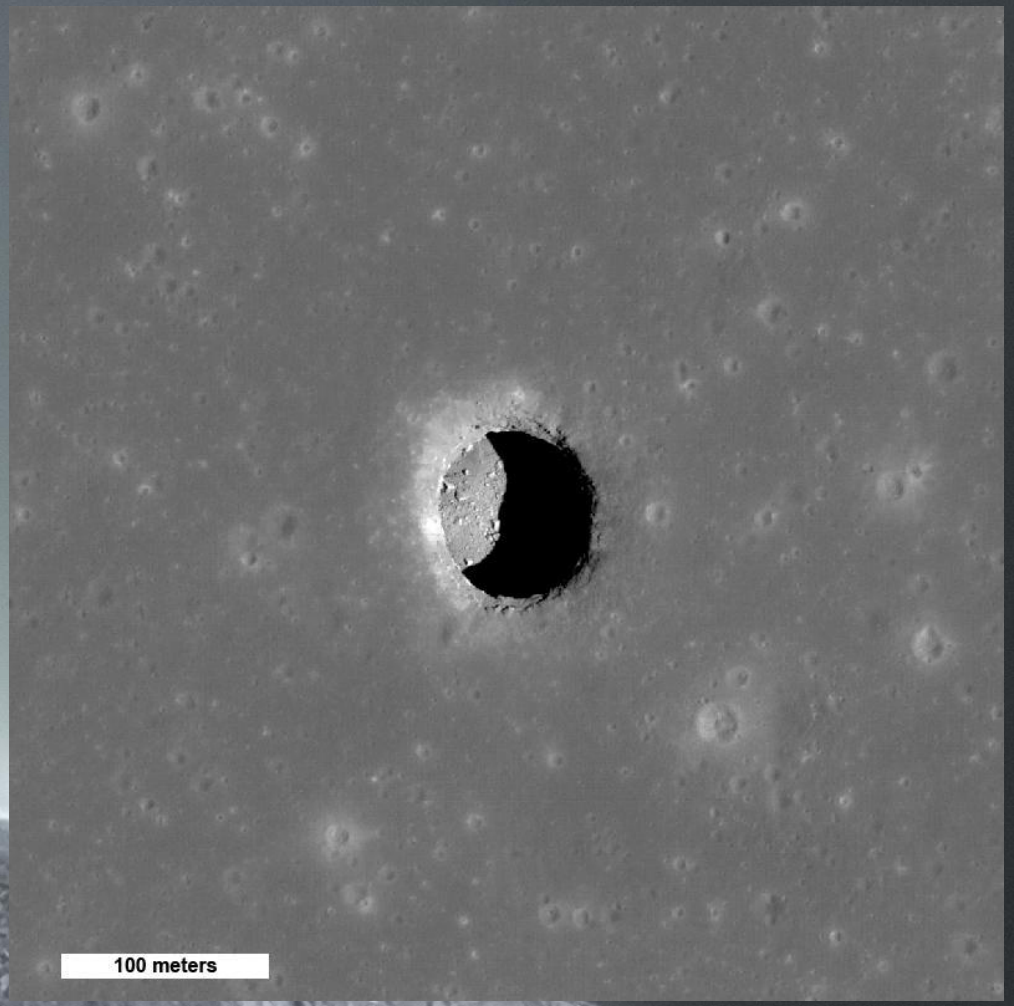
Subsurface, icy moons, & beyond

One-shot mission with adaptive, intelligent robot(s)

Unknown regions of the solar system

Inside Lunar Lava Tubes





Martian Lava Tube

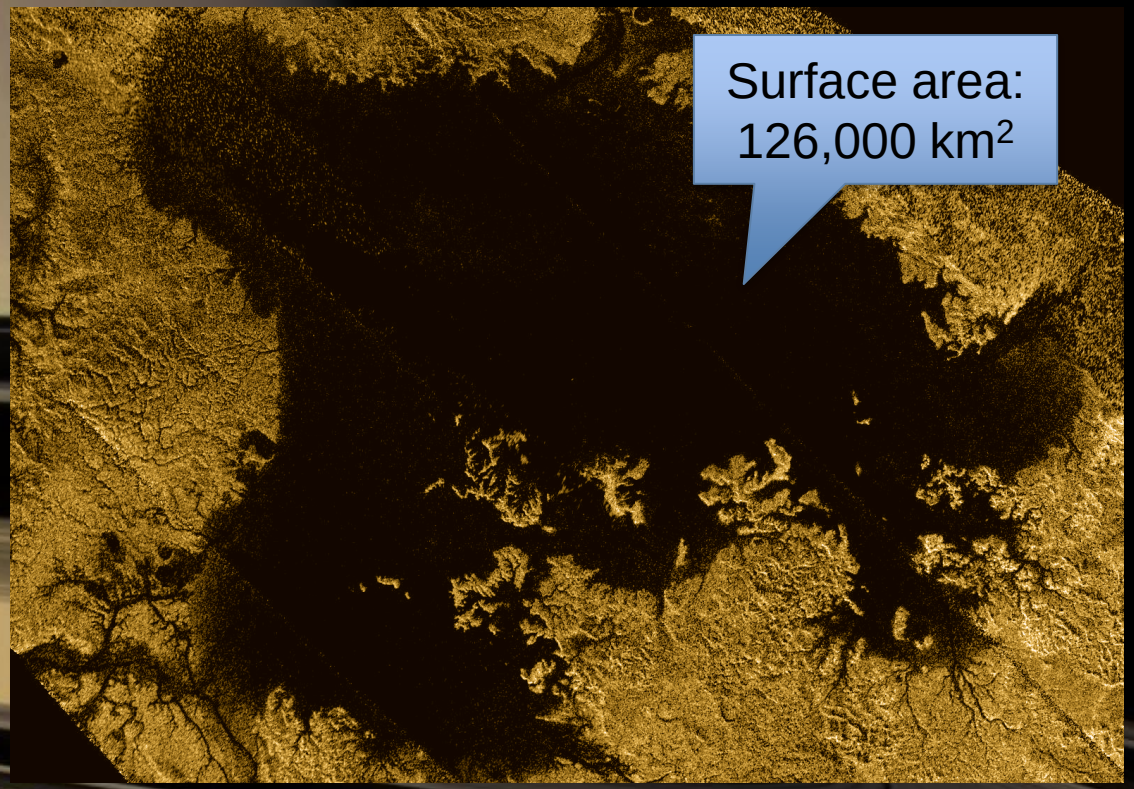
EELS

JPL NEXT
Office of Technology, Infusion, and Strategy

Under the methane lakes on Titan?

Familiar, yet alien

TITAN
Lakes and Seas

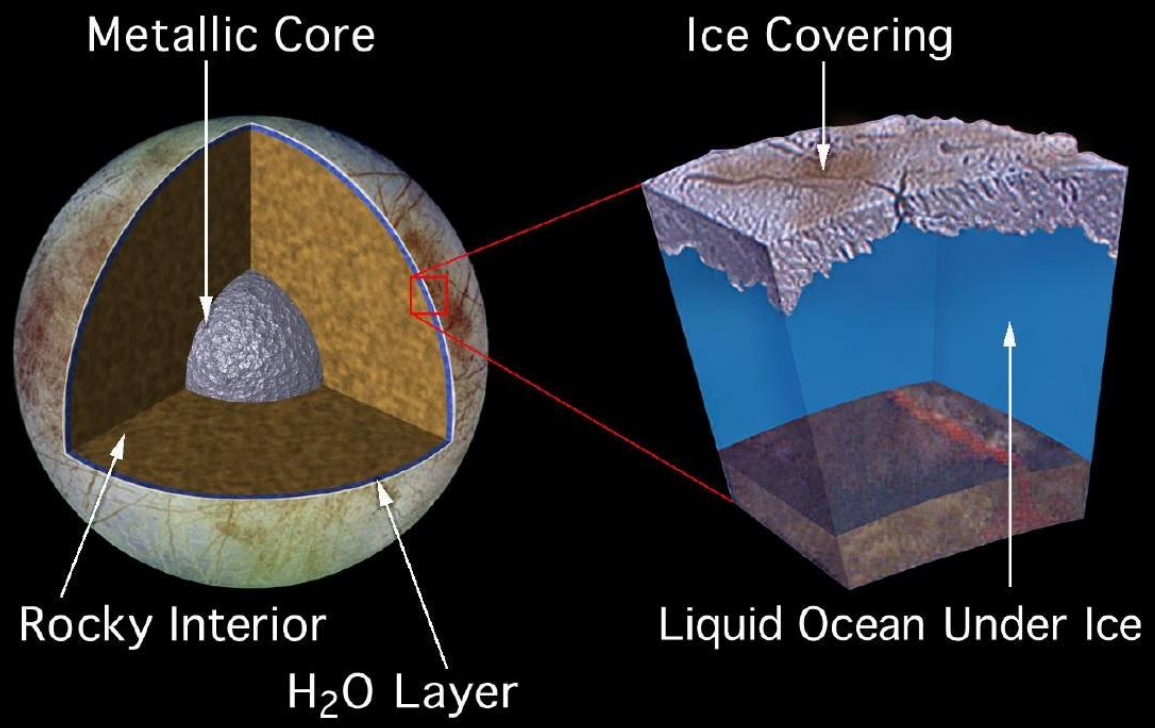


EARTH
Lakes and Seas

Images: NASA/JPL-Caltech/ASI/Cornell; Google Earth

Underwater on Ocean Worlds

What is an Ocean World?

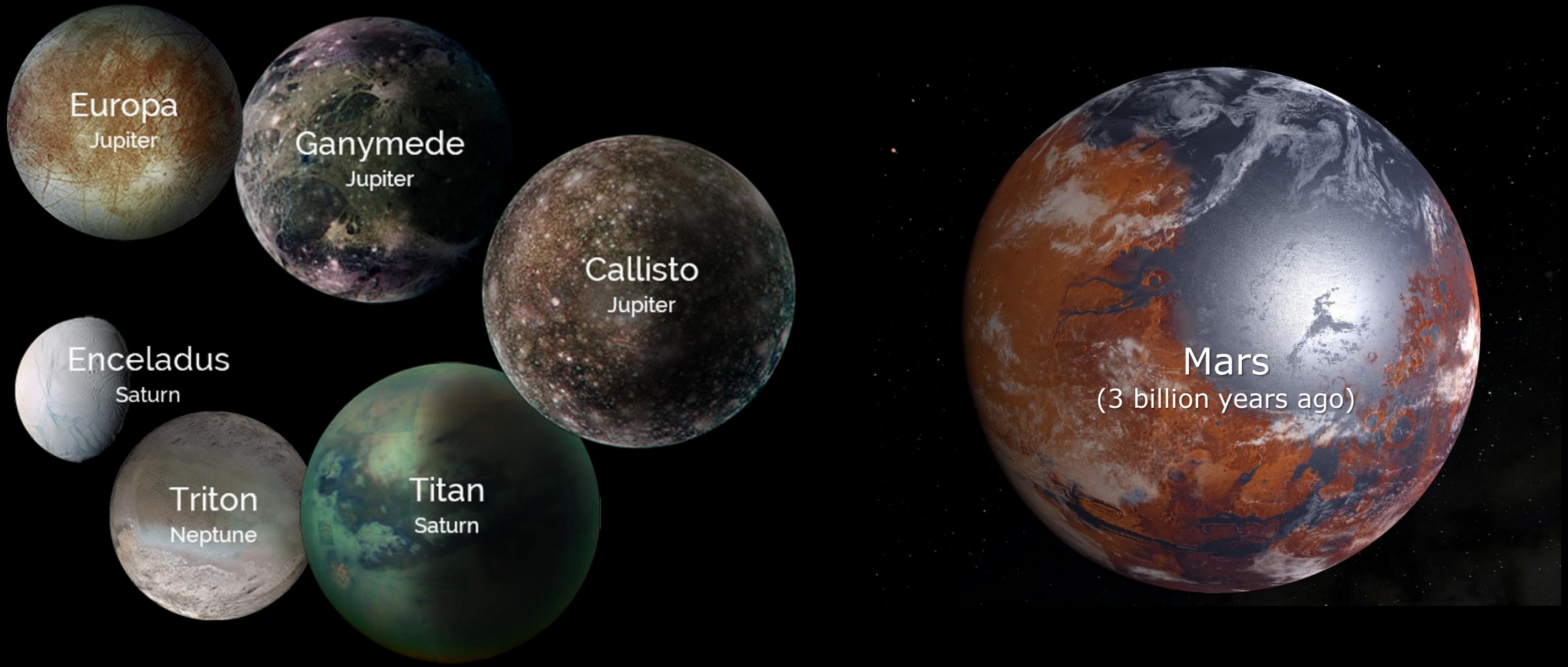


Images: NASA/JPL

What is an Ocean World?

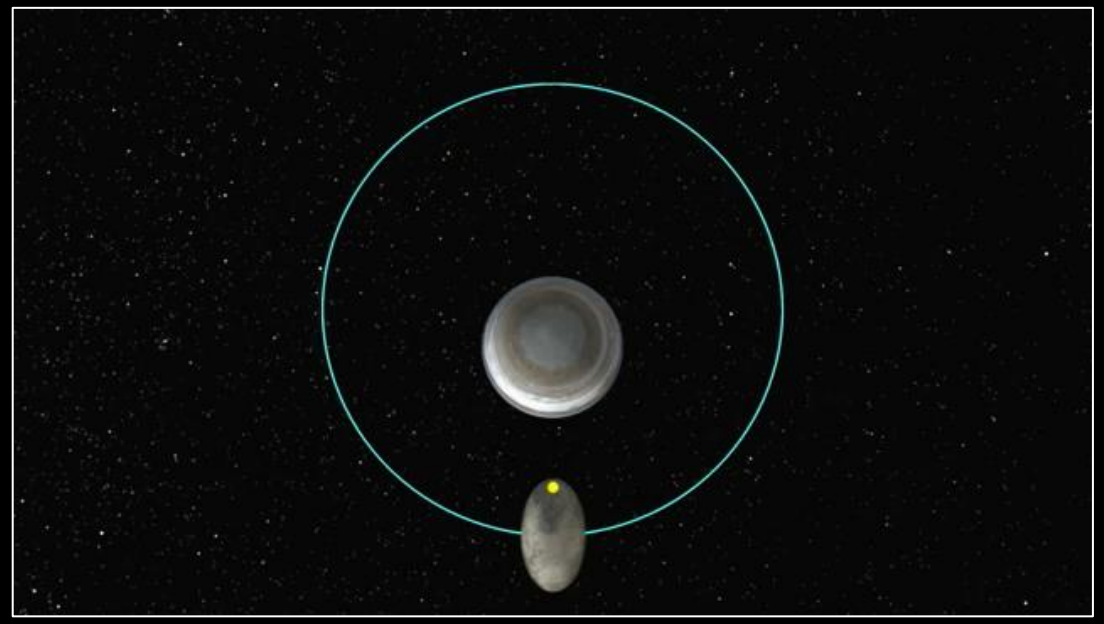
Images: NASA/JPL

What is an Ocean World?

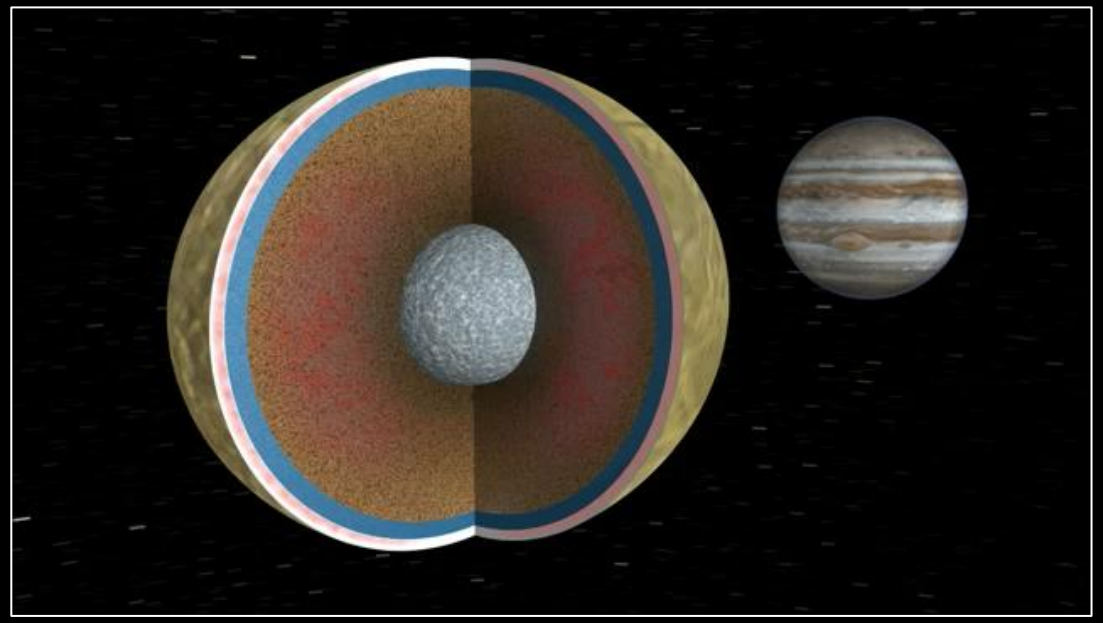


Images: NASA/JPL, NASA/MAVEN/LPI

TIDAL FLEXING → TIDAL HEATING

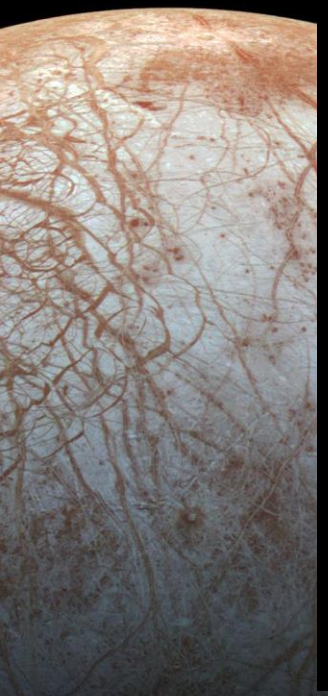


Rotation of Europa around Jupiter from above



Rotation of Europa around Jupiter from horizontal view

HYDROTHERMAL VENTS?



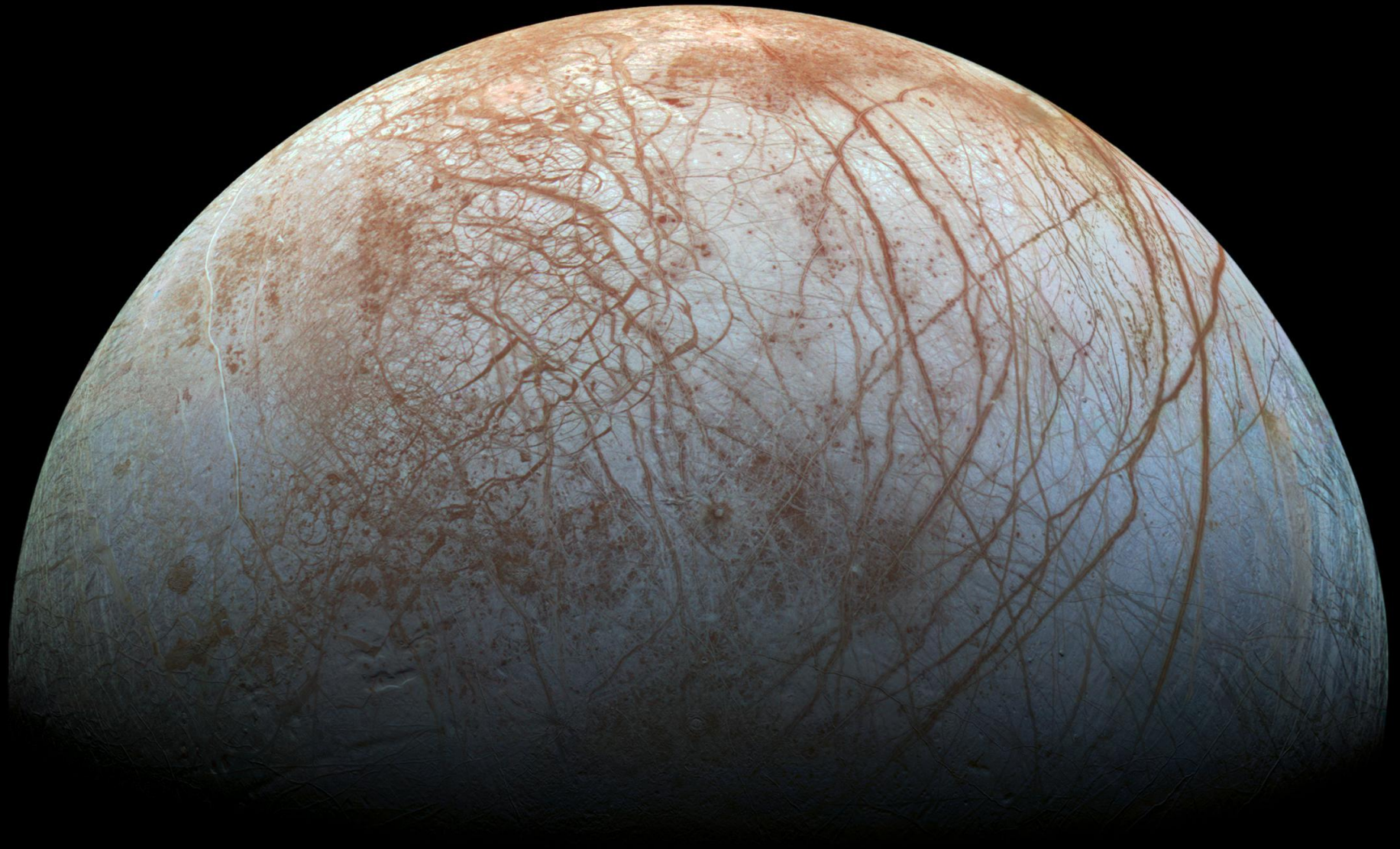
Video: NOAA

National Aeronautics and Space Administration

EUROPA CLIPPER

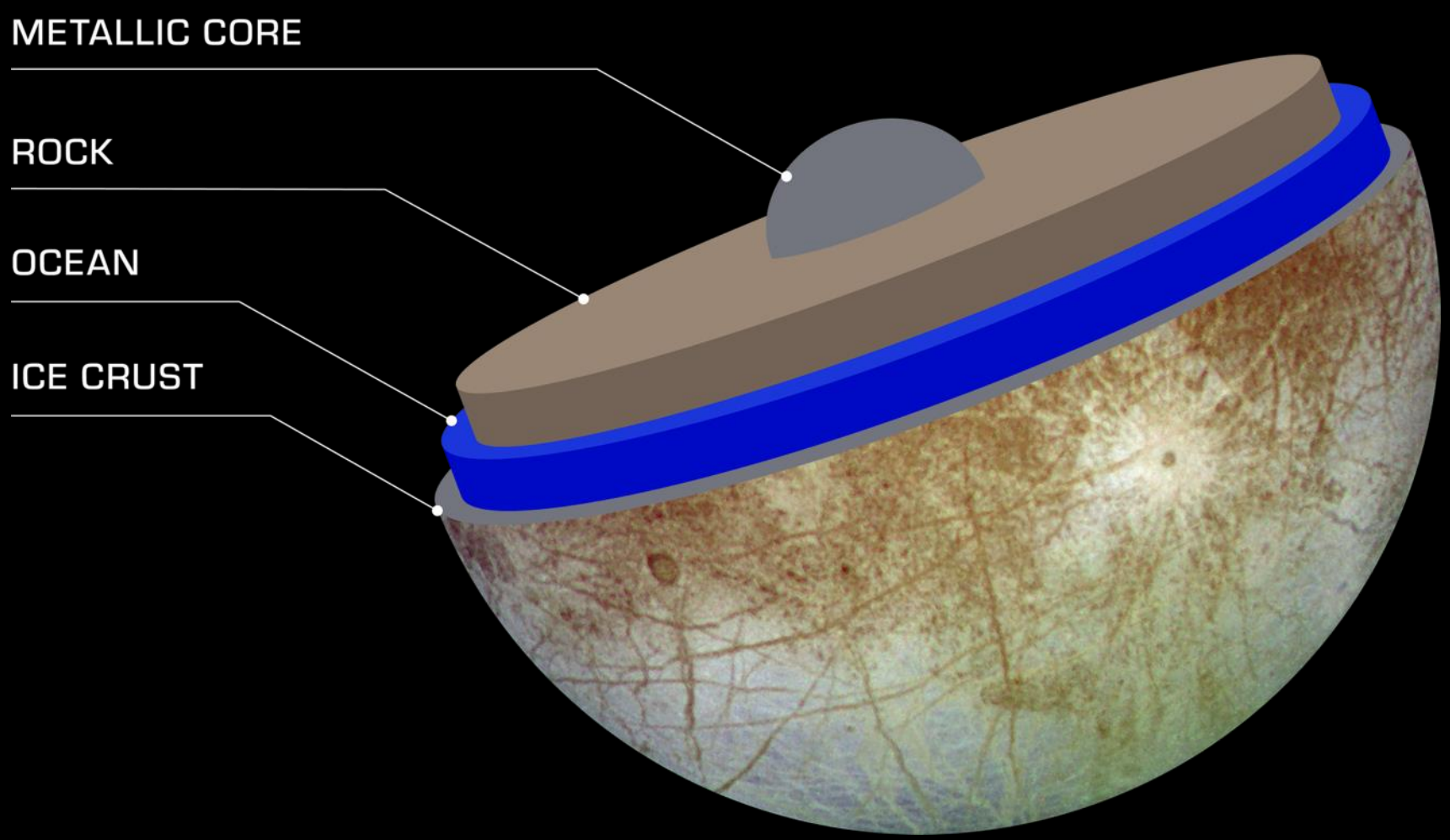
www.nasa.gov

Image: NASA/JPL-Caltech/SwRI/MSSS/Gerald Eichstadt/Sean Doran

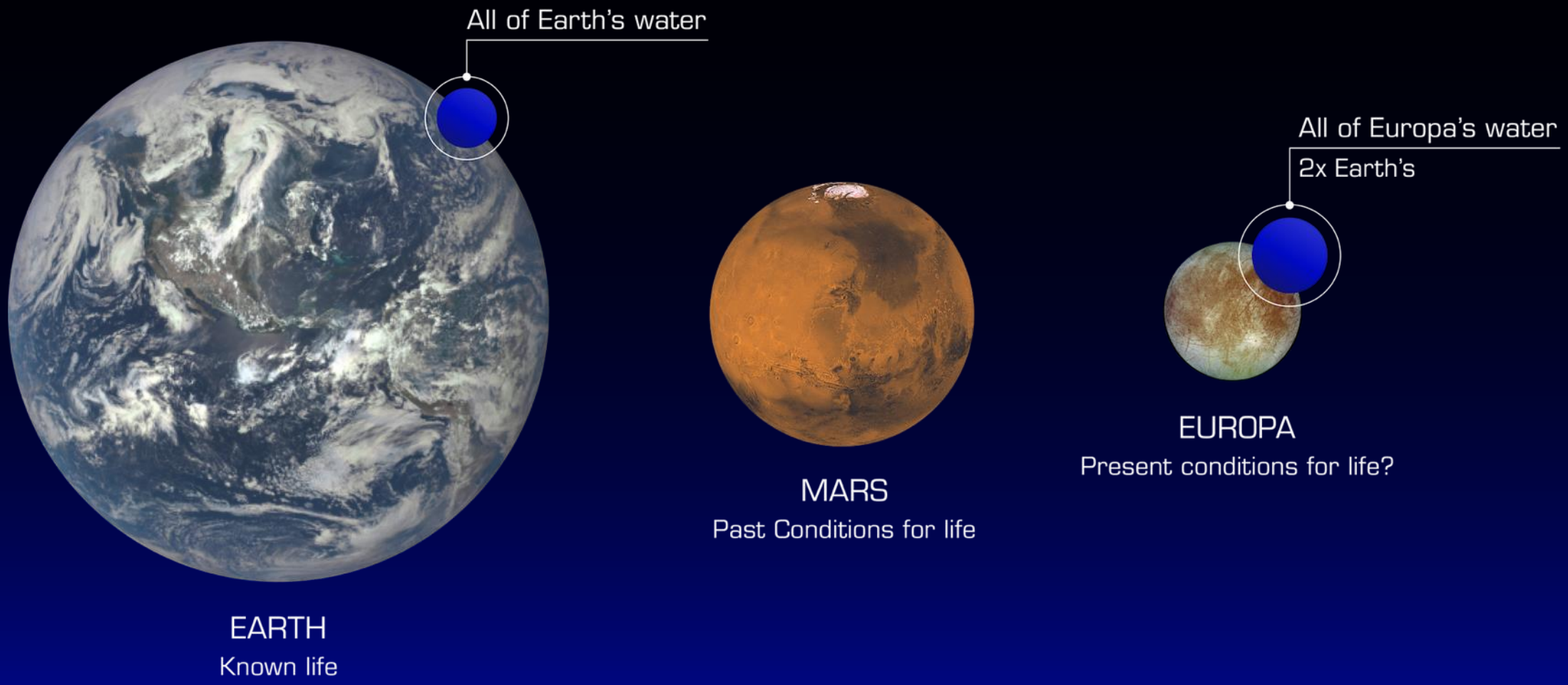


NASA/JPL-Caltech

EUROPA'S INTERIOR



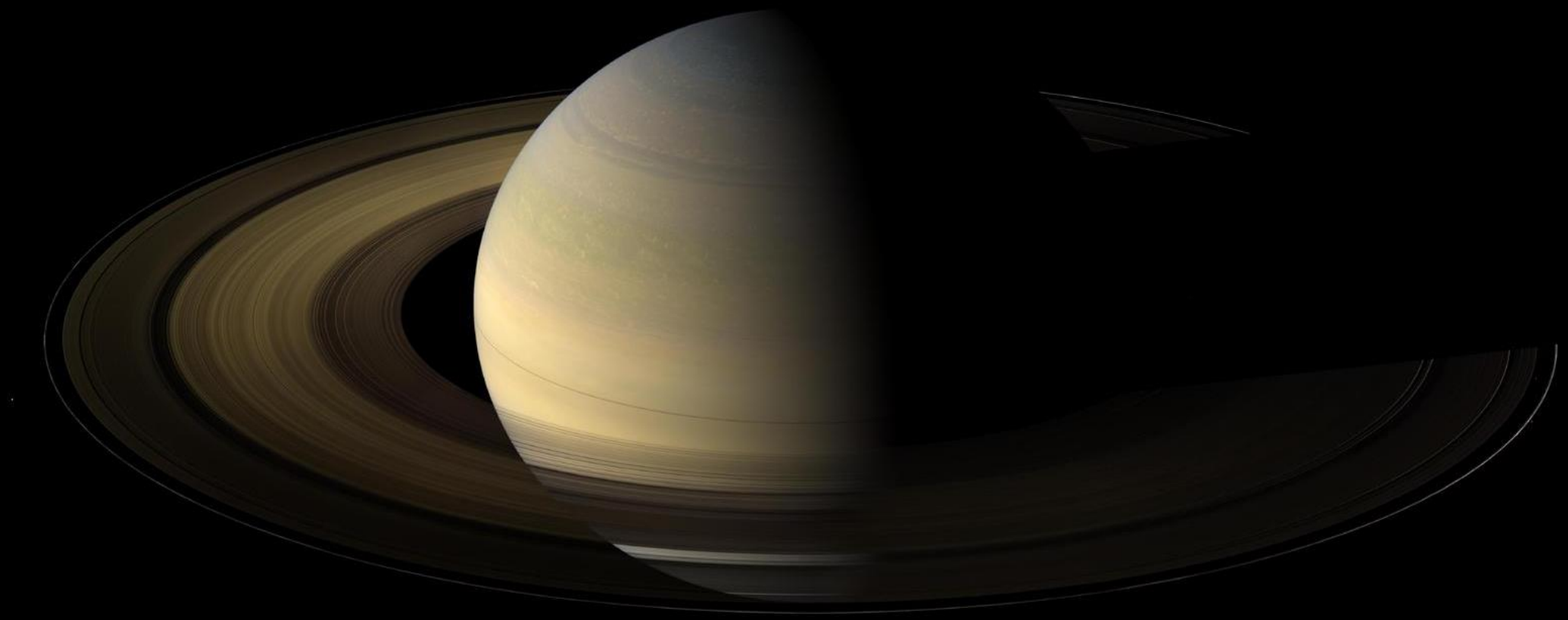
EUROPA: MORE WATER THAN EARTH



INGREDIENTS FOR LIFE?

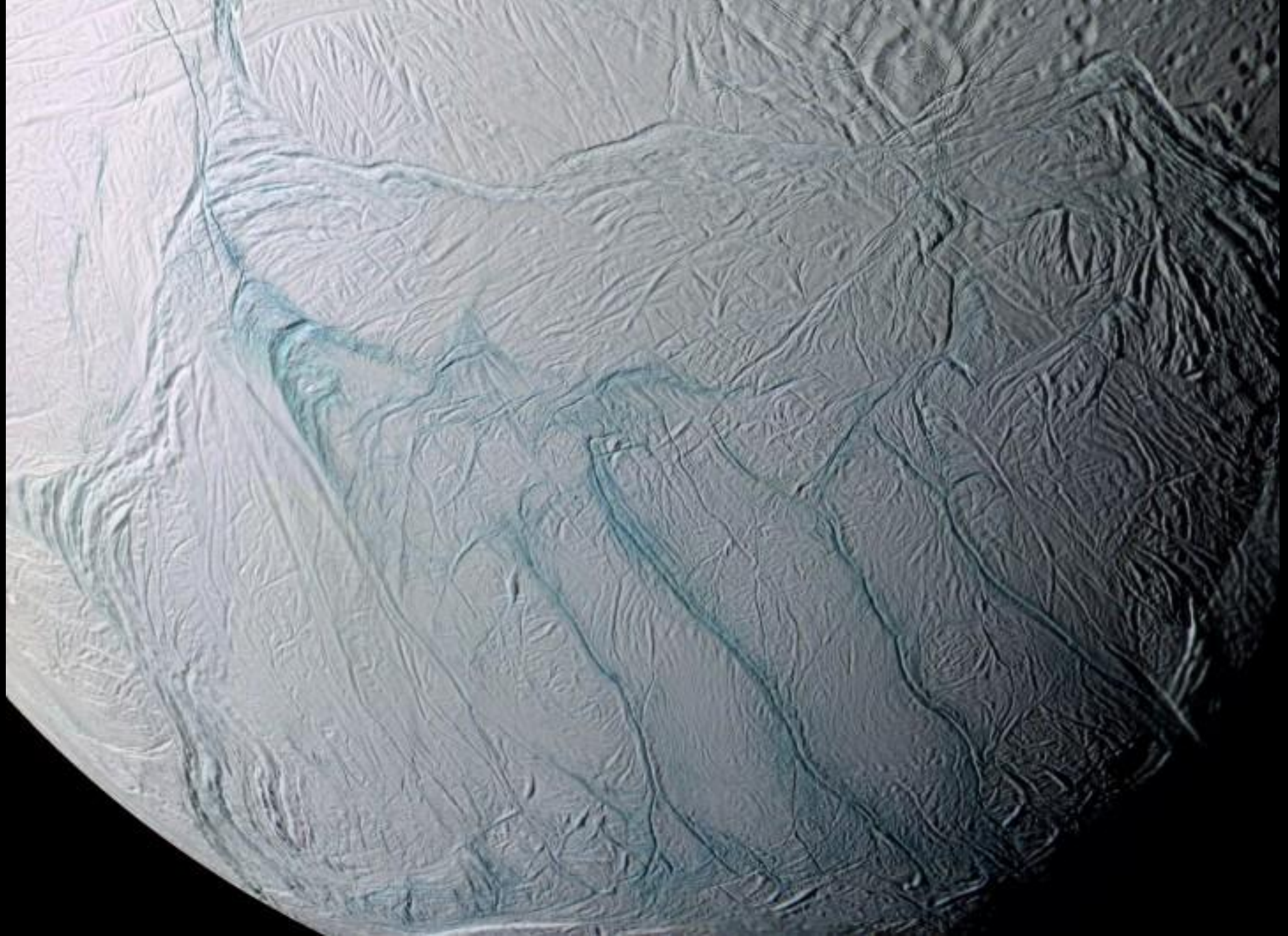
- **WATER:**
  Much more than all of Earth’s oceans
- **ESSENTIAL ELEMENTS:**
  From formation and impacts
- **CHEMICAL ENERGY:**
  From above and below
- **STABILITY:**
  “Simmering” for 4 billion years

NASA/JPL-Caltech

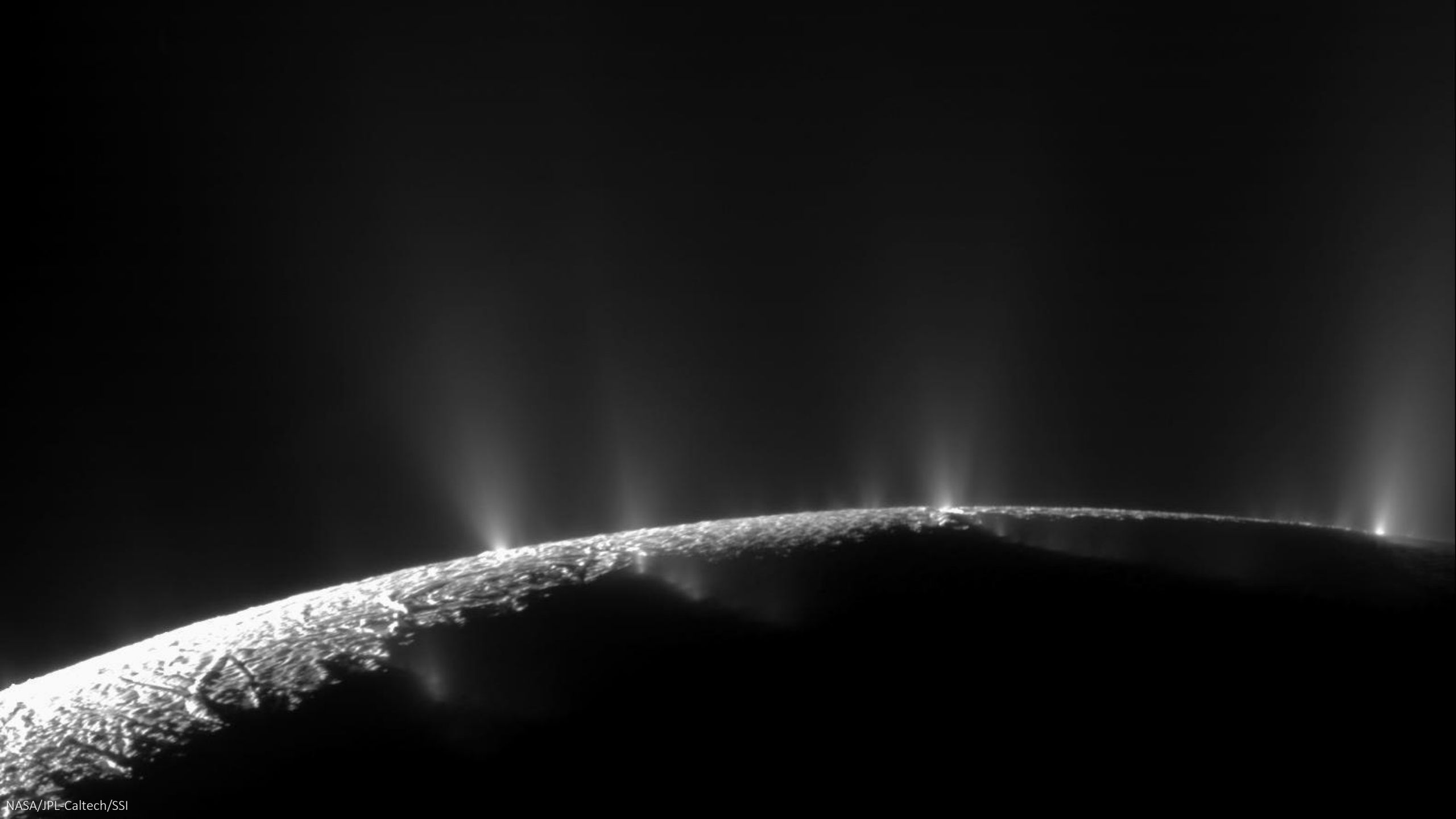


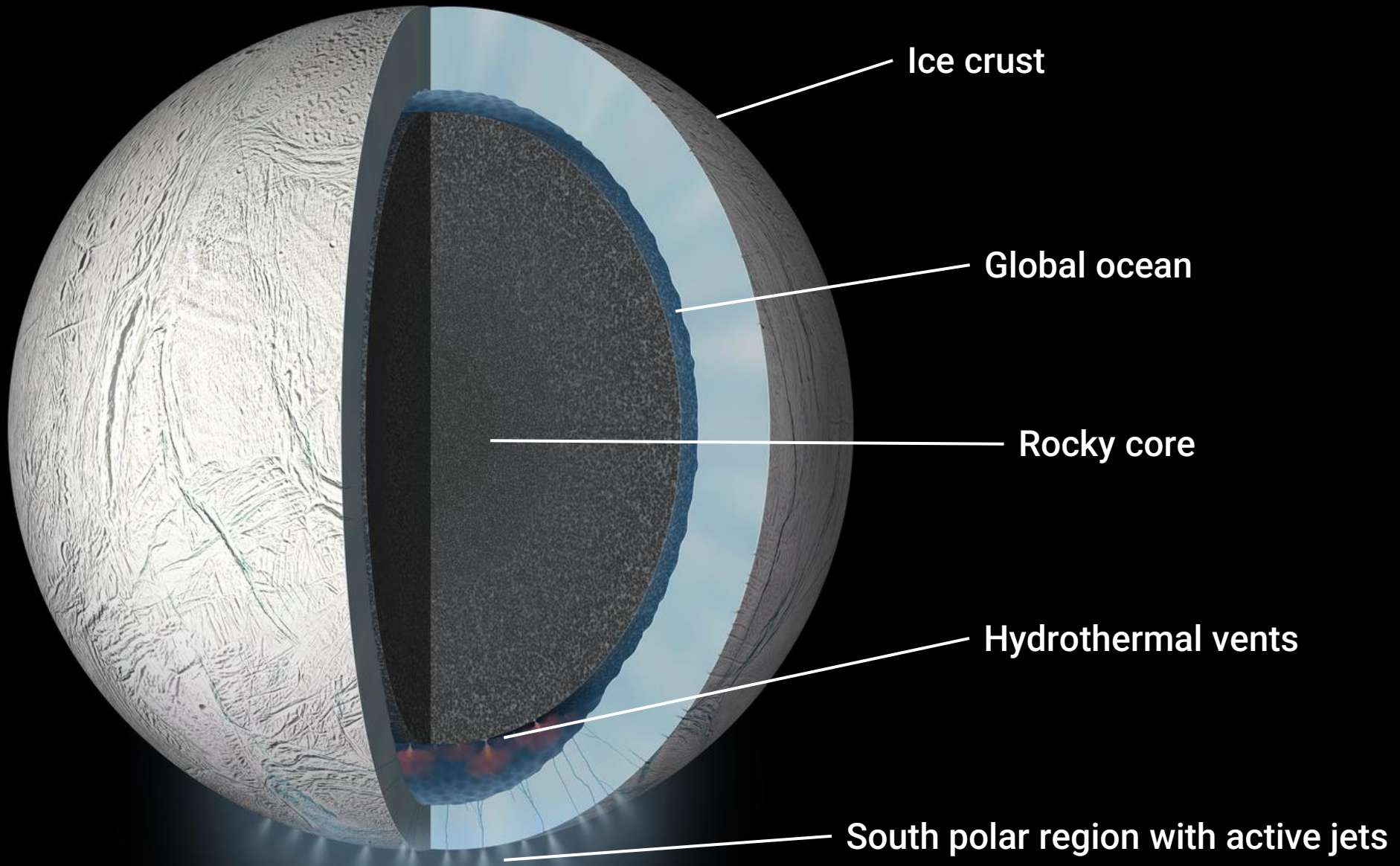
Images: NASA/JPL/SSI

NASA/JPL-Caltech/SSI



NASA/JPL-Caltech/SSI


NASA/JPL-Caltech/SSI



NASA/JPL-Caltech/SSI

Enceladus surface

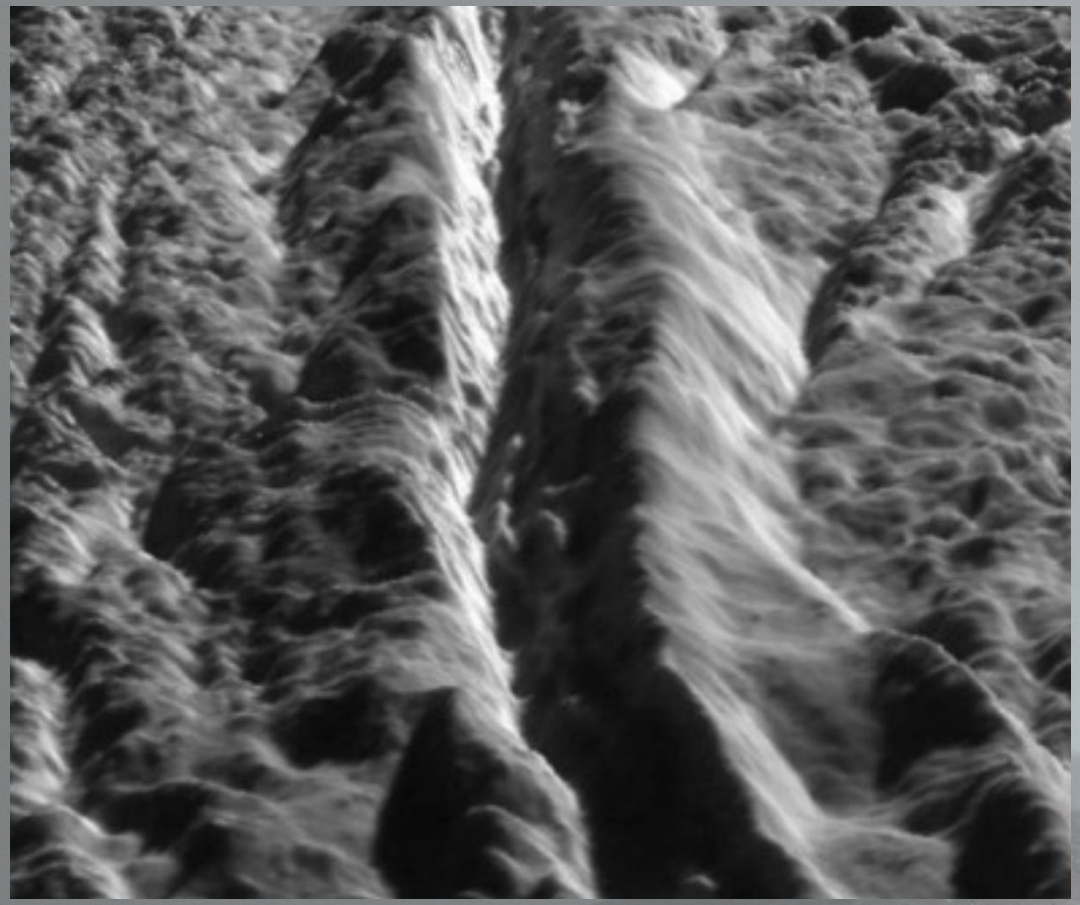


Image: NASA/JPL-Caltech/SSI; Video: P. Schenk

Enceladus vents: Multiple models

Open Conduit Model

Controlled Boiling Model

Cryovolcanic Volatile-Driven Model

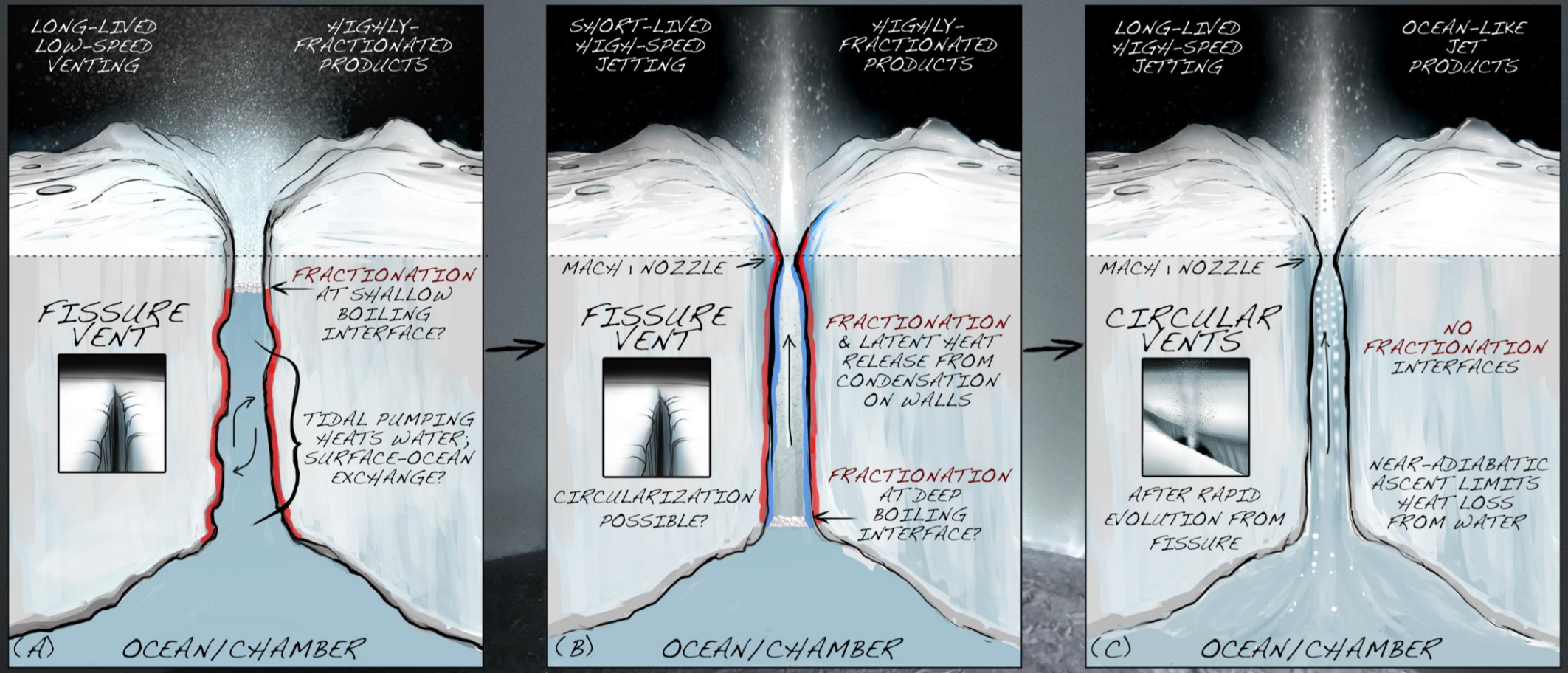
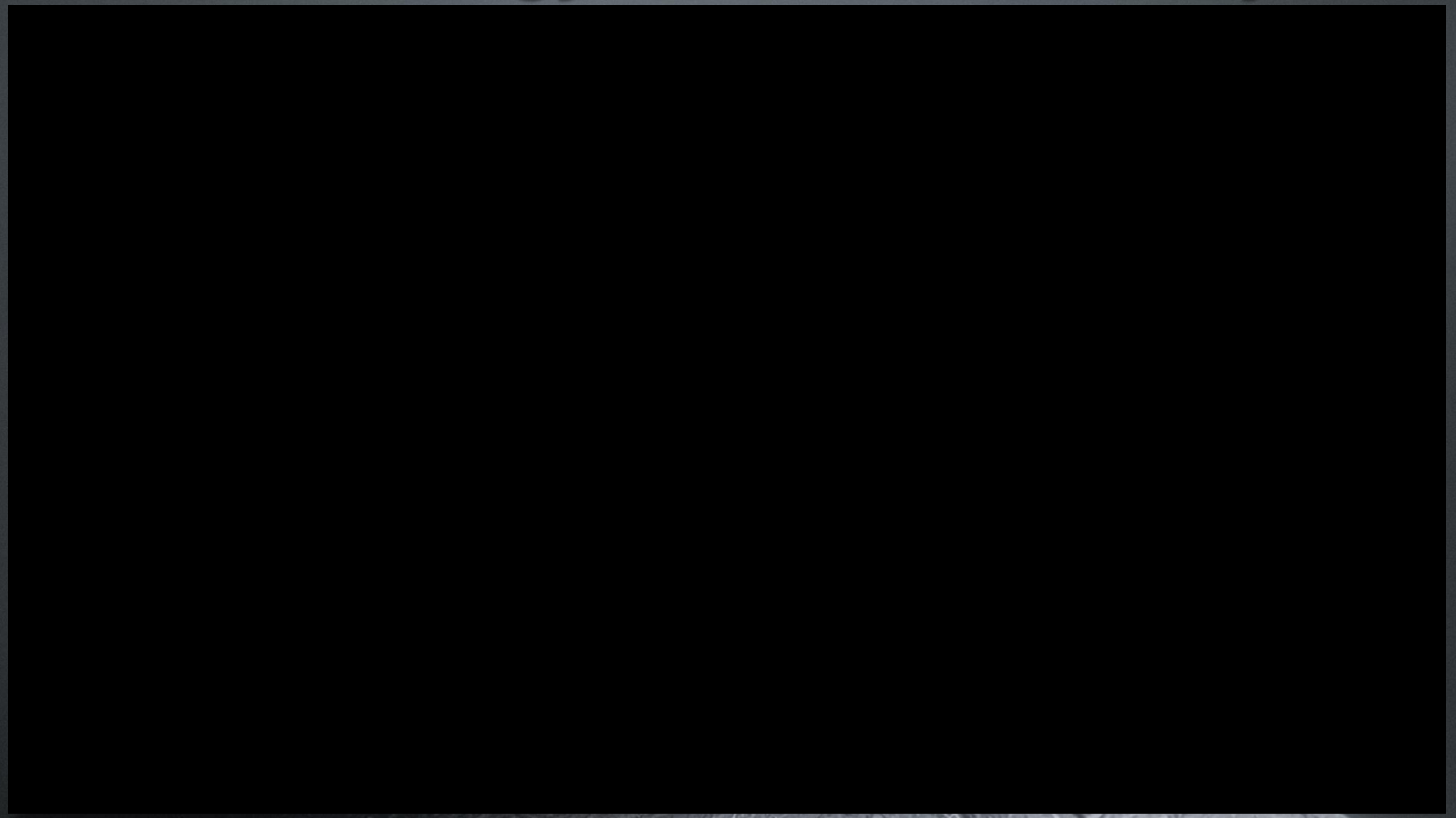


Image: NASA/JPL-Caltech

Kite and Rubin (2016) PNAS; Nakajima & Ingersoll (2016) Icarus; Mitchell & Rabinovitch et al. (2024) JGR Planets.

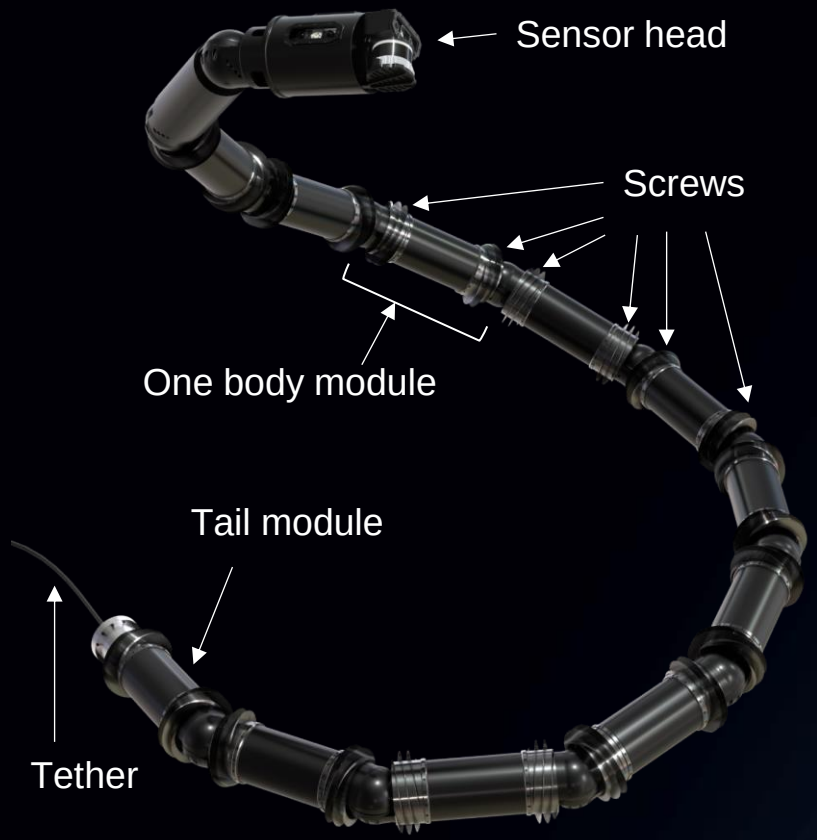
EELS Exobiology Extant Life Surveyor



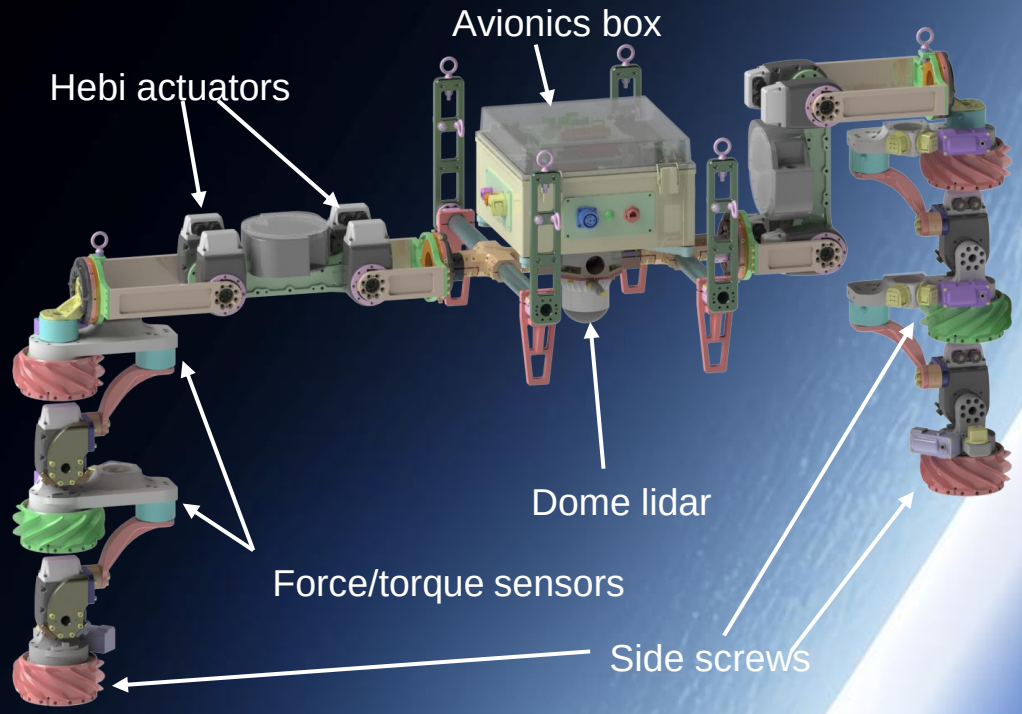
Video: NASA/JPL-Caltech. Pre-decisional – For information and discussion purposes only.

EELS Hardware

EELS 1.0



EELS 1.5



Garden-EELS

EELS 1.0

Science Payload

Proprioceptive perception and control

Tether (50m)

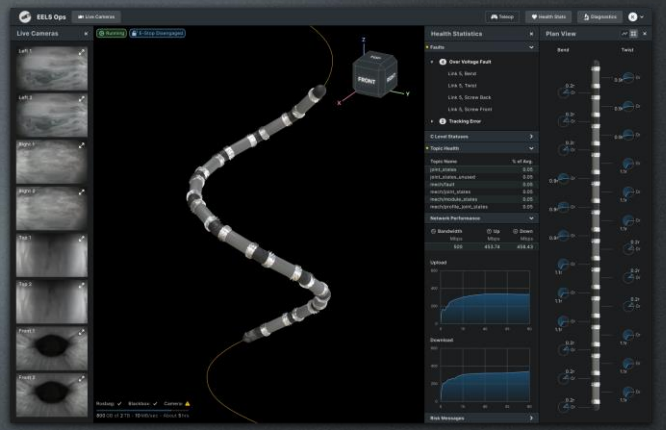
3D situational awareness (LIDAR, IMU, 4 stereo camera pairs)

Active skin locomotion (24 independently-actuated counter-rotating screws)

24 degrees of freedom shape actuation

EELS Ops System

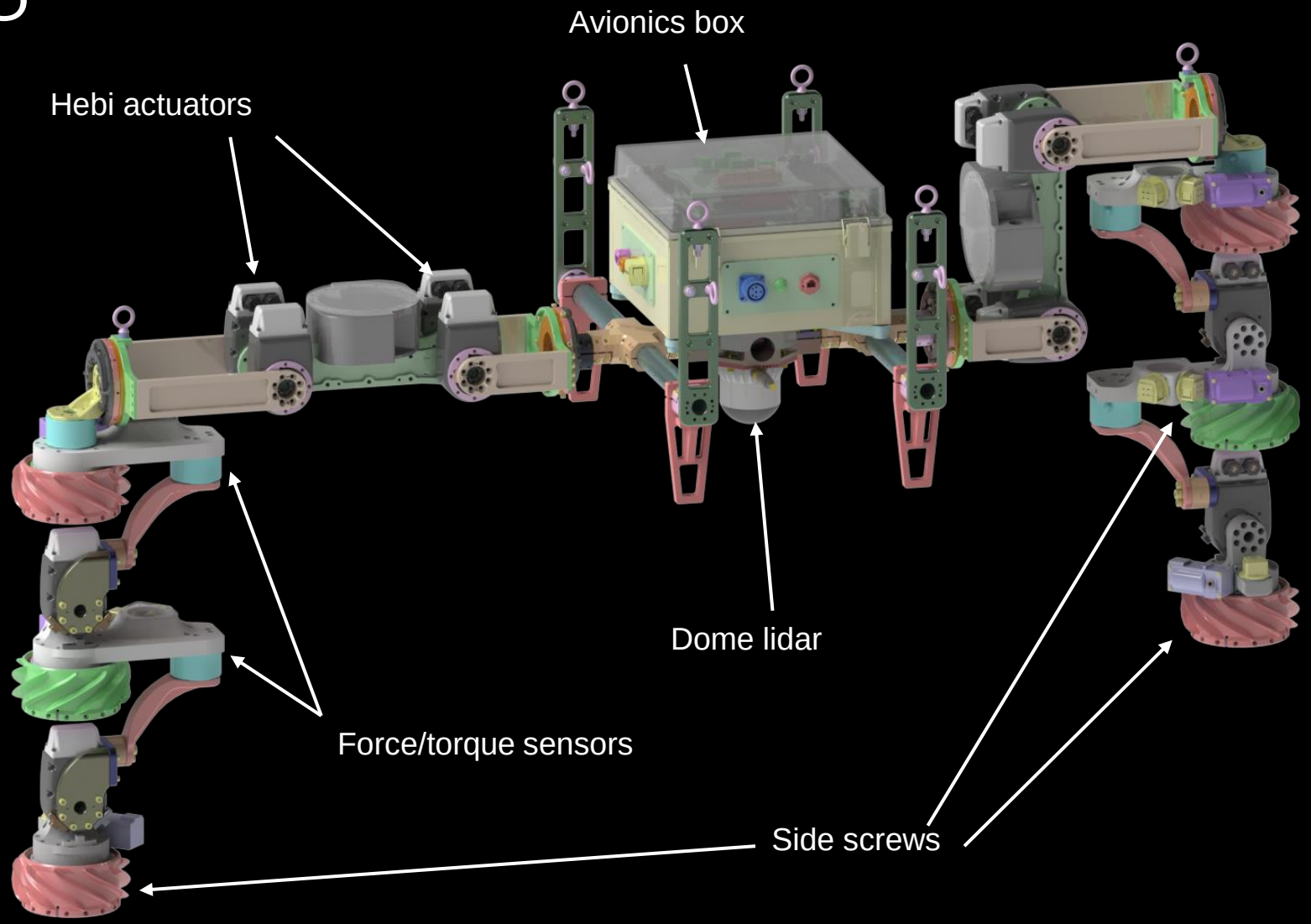
State-of-the-art visualizations are used to monitor and control the robot while the user interface gives the operator situational awareness of the robot's local environment, health, and planned movement.

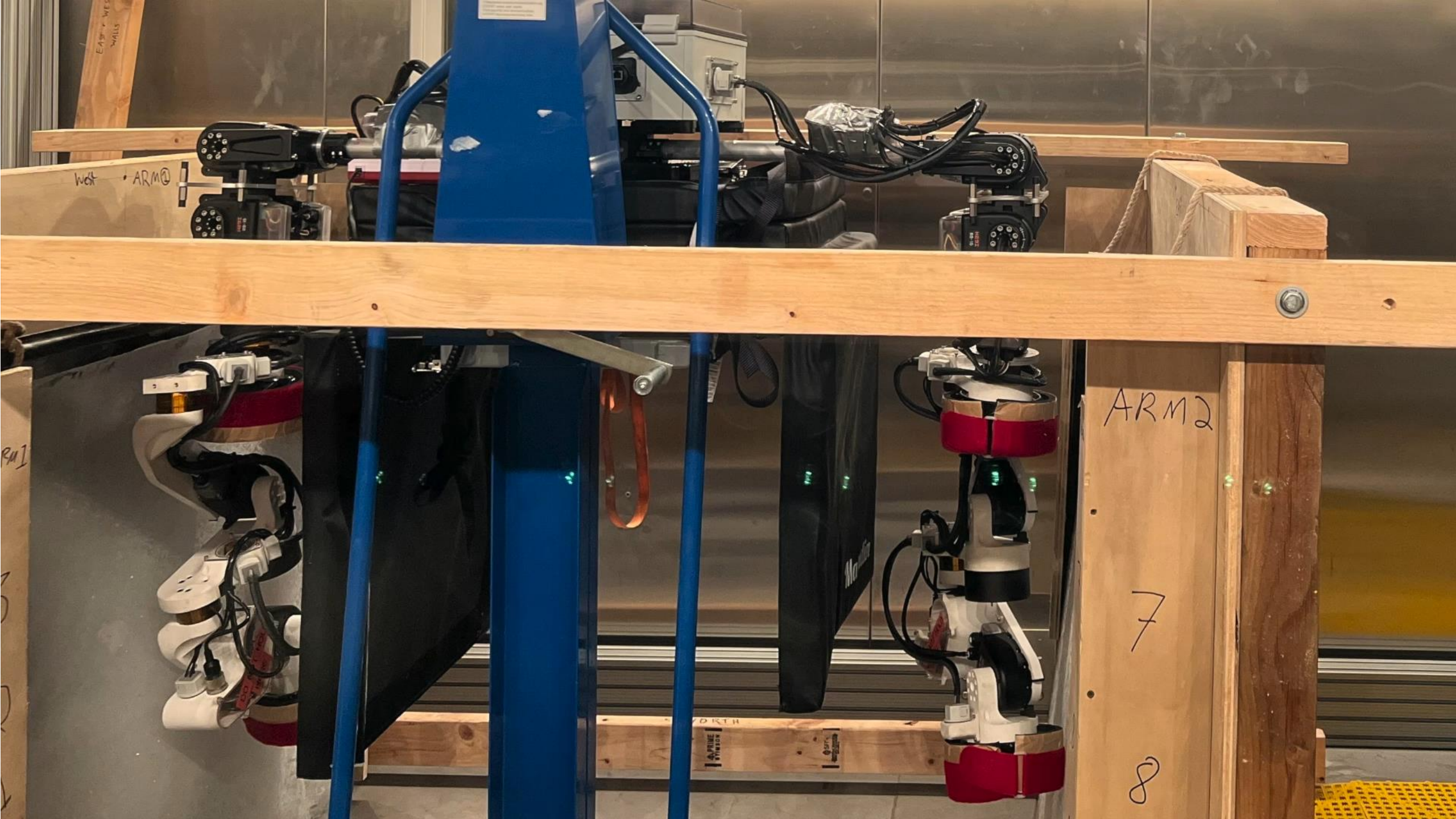


EELS 1.0 mobility testing

Video: NASA/JPL-Caltech. Pre-decisional – For information and discussion purposes only.

EELS 1.5


Avionics box
Hebi actuators
Dome lidar
Force/torque sensors
Side screws


ARM2
7
8

Athabasca Glacier

Athabasca Glacier


Hamber
Provincial
Park
Mt Clemenceau
Mt Columbia
93
93
White Goat
Cummins
Lakes
Provincial
Park
Kinbasket Lake

Athabasca Glacier, Alberta, Canada

Desired Terrestrial Analog Characteristics:

- **Physical terrain types** suitable for horizontal and vertical mobility testing (ridges, cracks, crevasses, moulins)
- Similar **terramechanical properties*** to Ocean Worlds (water-ice with varying salt/regolith contaminants)
- Realistic concentrations of **habitability indicators** for instrument validation (in our case, cations and anions)
- Straightforward **logistical access** for a large team with lots of hardware

*The temperature in the Tiger Stripes near the surface is 200 K (Goguen et al. 2013) and likely reaches 273 K near the ice-ocean interface.

Image: NASA-JPL/Caltech

Athabasca Glacier

Alberta, Canada

The best analog for cryo-vents on icy moons


Base camp

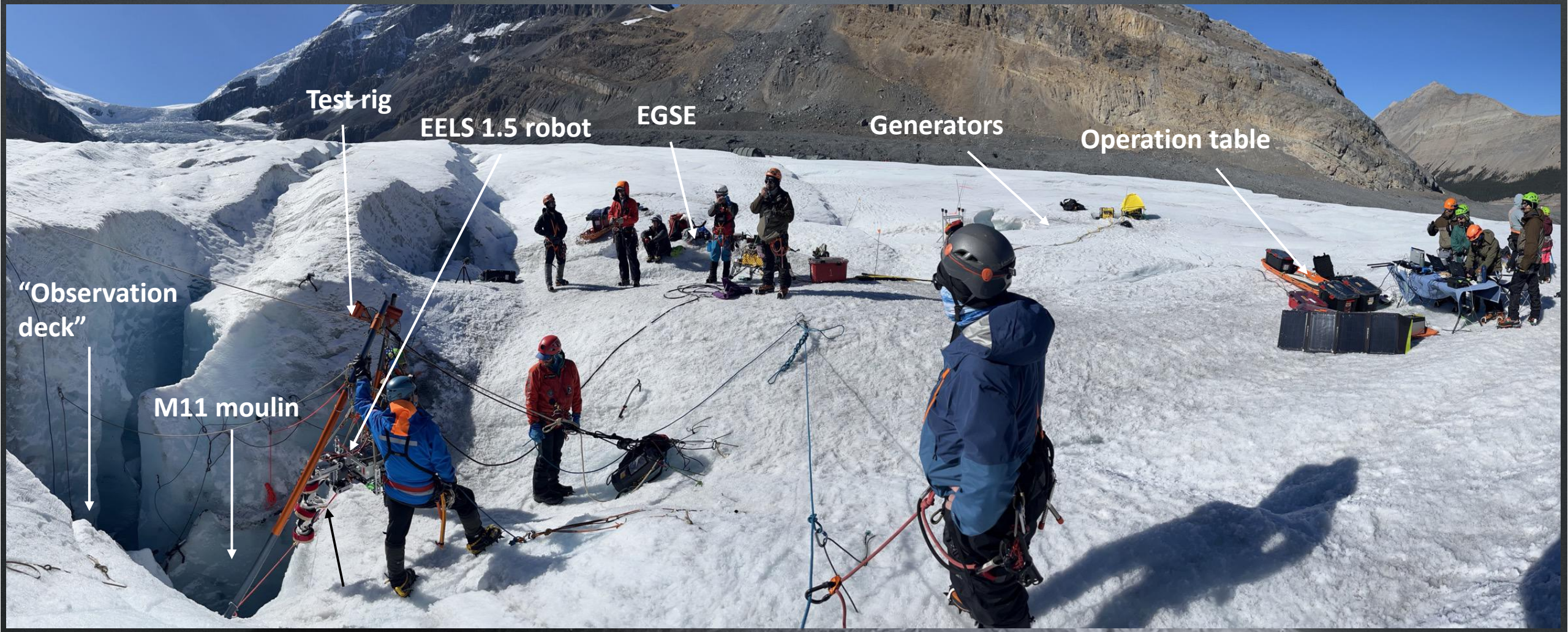
Athabasca englacial features

Video: NASA/JPL-Caltech. Pre-decisional – For information and discussion purposes only.

Horizontal mobility

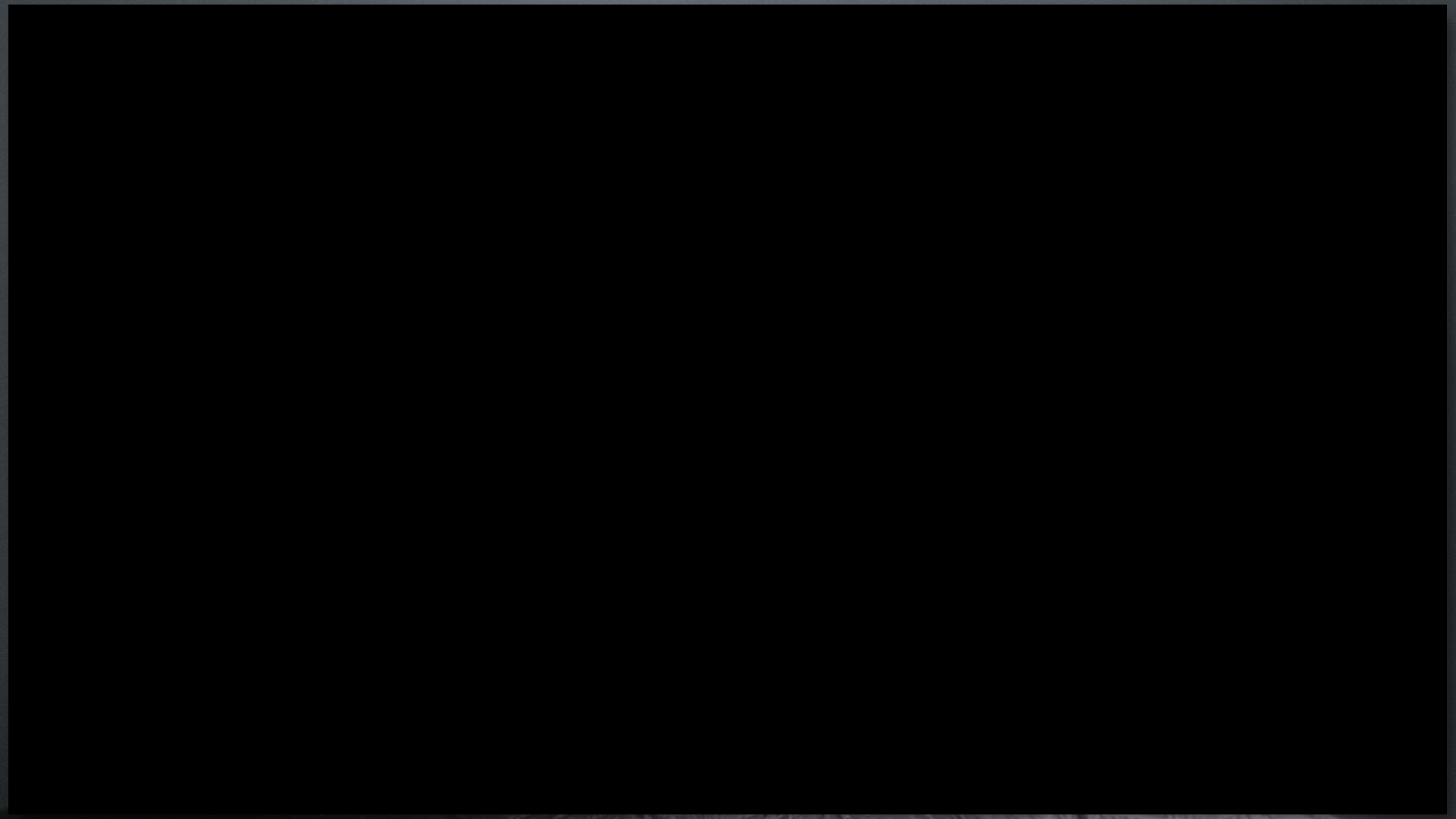
Video: NASA/JPL-Caltech. Pre-decisional – For information and discussion purposes only.

Vertical mobility




DURABOOK

Vertical mobility



Video: NASA/JPL-Caltech. Pre-decisional – For information and discussion purposes only.

What did we learn?

- No matter the terrain shape or the terrain type, EELS overwhelmed the problem space with Degrees of Freedom.
- Operators and software developers could figure out a gait to traverse any terrain type
  - E.g. Sidewinding in sand,
  - Screw-mode on ice, or
  - Cobra-scan for a large viewshed
- **Adaptability** was our superpower


What’s next?

JPL Dares Mighty Things

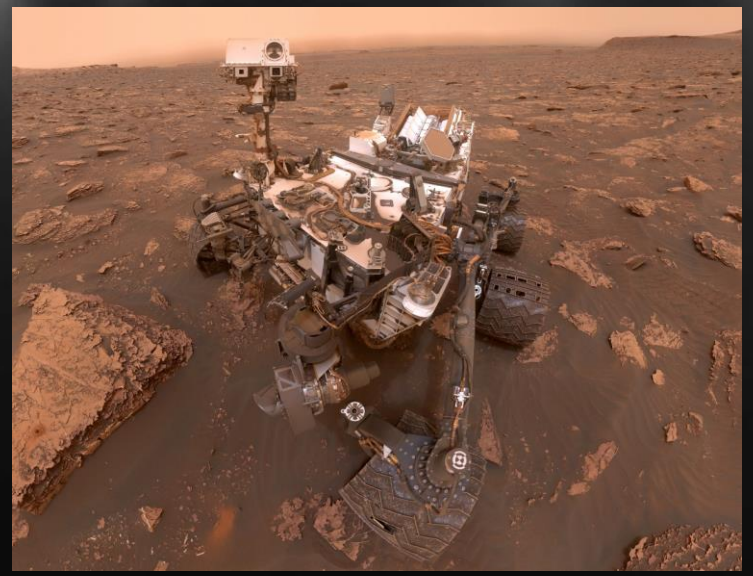
Robotic Exploration 1.0

Pre-Apollo Lunar exploration

High-cadence trial-and-error
e.g. Ranger, Surveyor, and Mariner missions

Robotic Exploration 2.0

Mars



Incremental sophistication in a multi-mission campaign
e.g. Mariner, Viking, Mars Observer, MGS, Pathfinder, Odyssey, MRO

Robotic Exploration 3.0

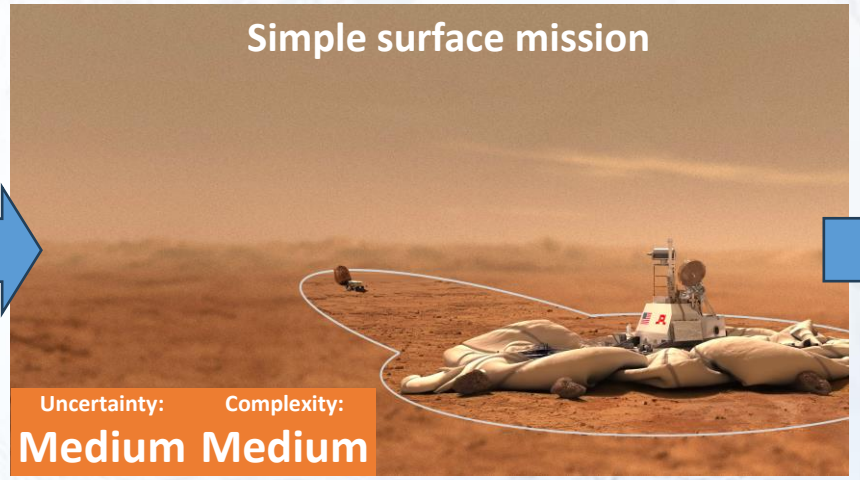
Subsurface, icy moons, & beyond

One-shot mission with adaptive, intelligent robot(s)

Paradigm Change Needed for Future Robotic Exploration

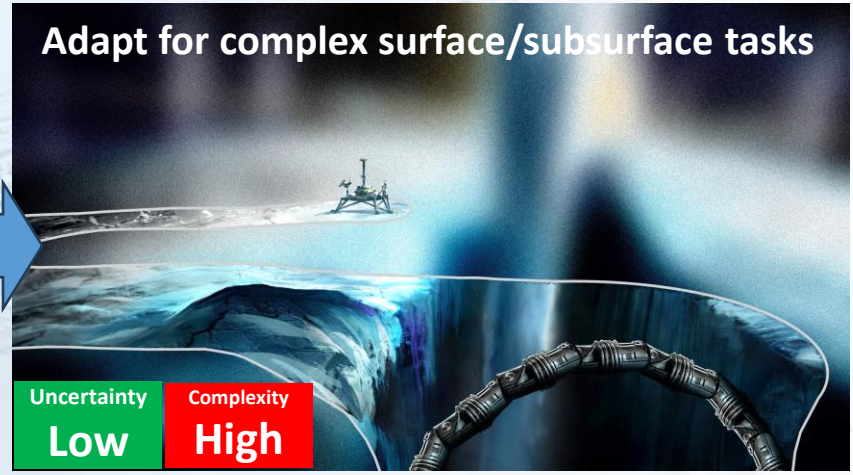
Robotic Space Exploration 2.0 (Current): Incremental sophistication over many missions

- Complex robotic behaviors *pre-designed* based on detailed environmental knowledge brought by prior missions
- Took 3 decades for Mars

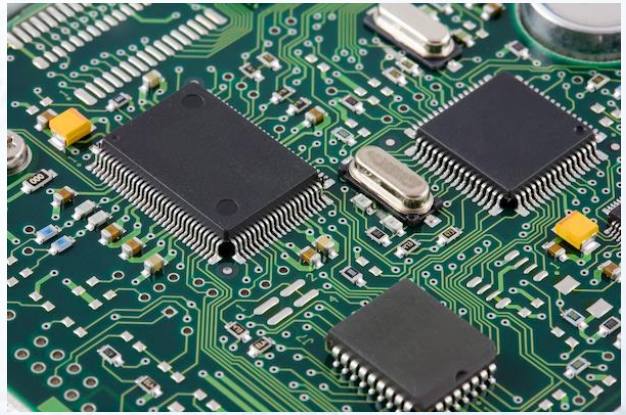
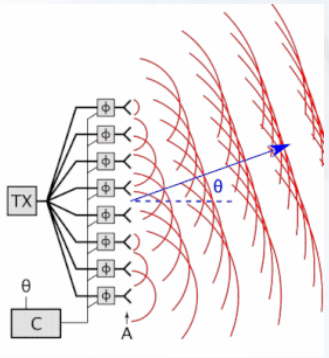
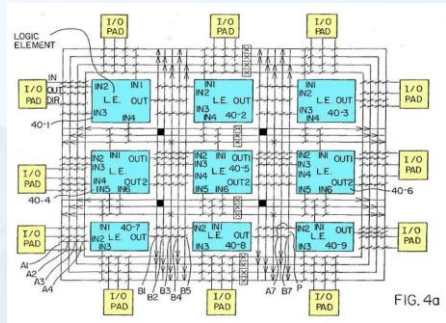


Robotic Space Exploration 3.0 (Future): One-shot exploration with adaptive robot(s)

- A robot (or a team of robots) adapts its behaviors *in-situ* for incrementally complex tasks
- Robotic system designed for adaptation to a wide range of possible environments



Requirement for RSE 3.0 Adaptivity:
Software-defined Space System

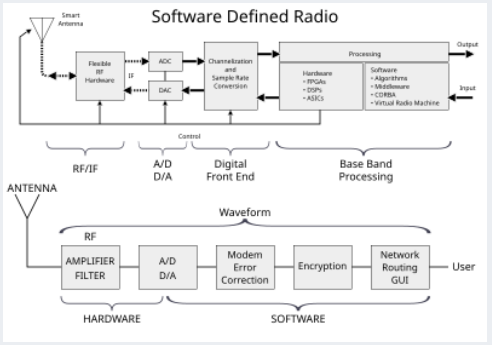
	Antenna	Circuit	Space system
Hardware-defined	  **Antenna pattern is defined by shape**	 **Circuit is defined by electric components**	 **Spacecraft capabilities are (mostly) defined by hardware**
Software-defined	Phased-array antennas   **Antenna pattern is modulated by controller**	  **Circuit is defined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

JPL

Programmable, Software-Defined Devices

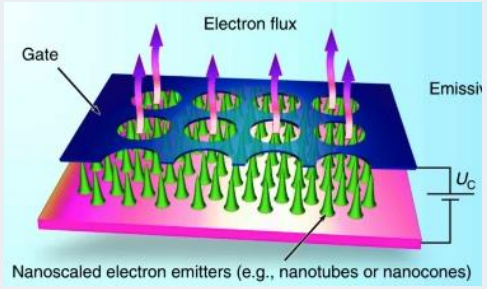
Communication

Software-defined radio



Propulsion

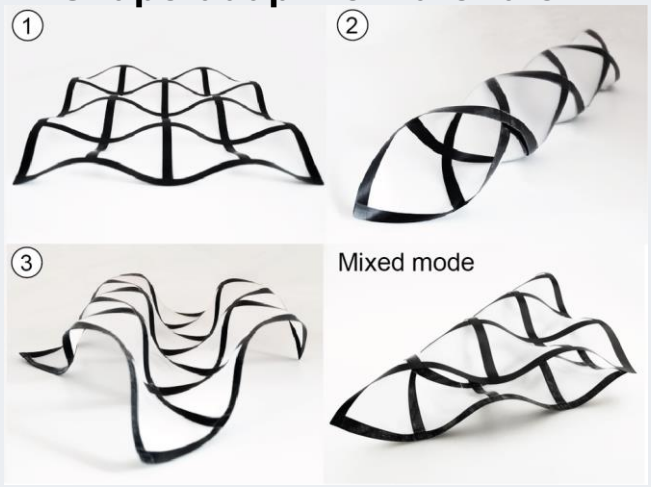
Adaptive ion thrusters



Levchenko et al. Nature Communications 2018

Structure

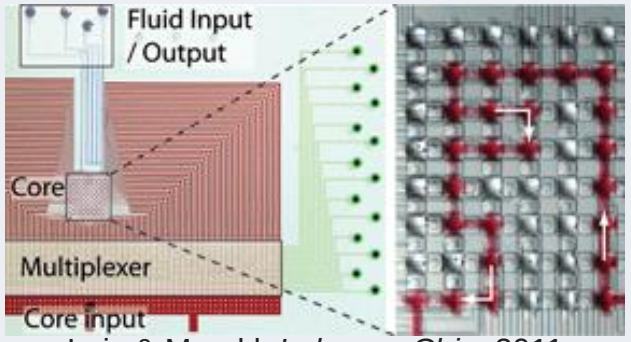
Shape-adaptive materials



Sakovsky at al. *EuCAP* 2024.

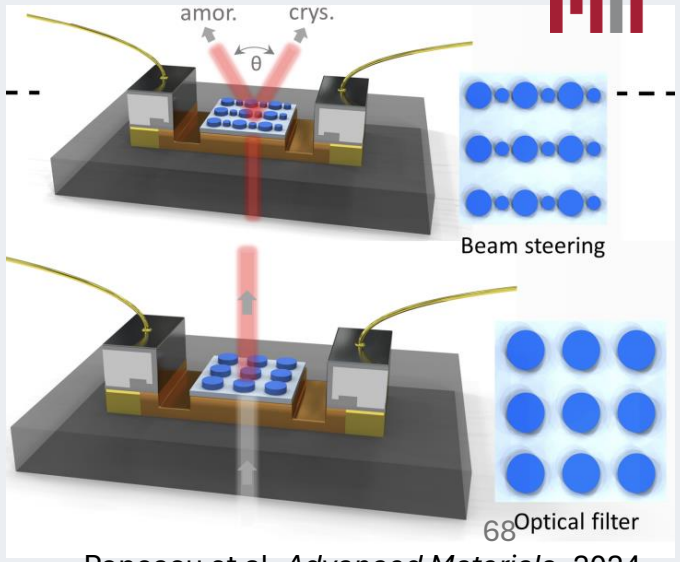
Science Instruments

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

WORMS

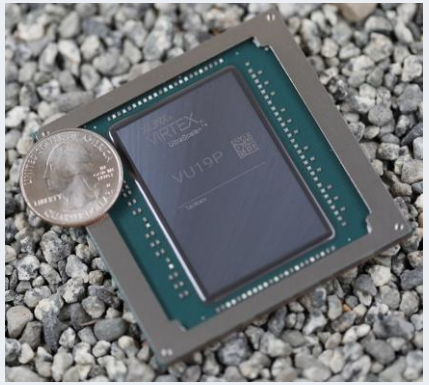
Lordos et al., *IEEE Aerospace* 2013

M-Block

Romanishin & Rus *IROS* 2019

Avionics

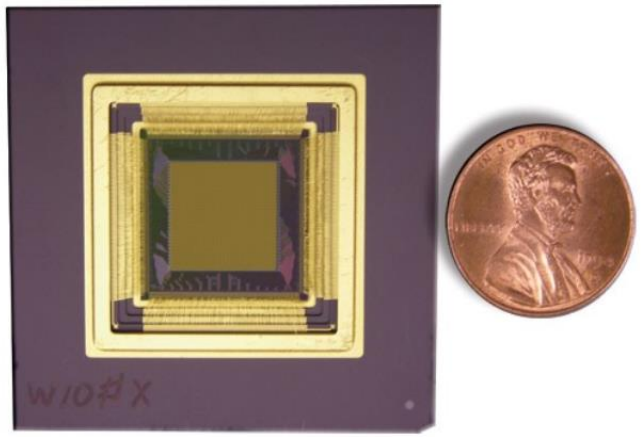
High density FPGAs



What contributions come from optics?

Software-defined Space Systems for Optics - Adaptive Optics

Small electrostatic MEMS mirror (Boston Micromachines, 1024 act)



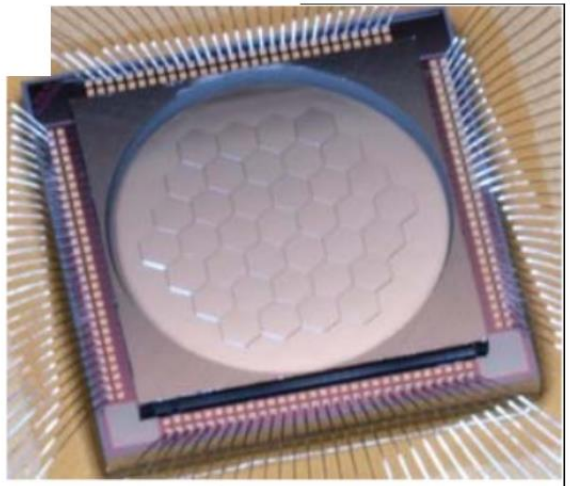
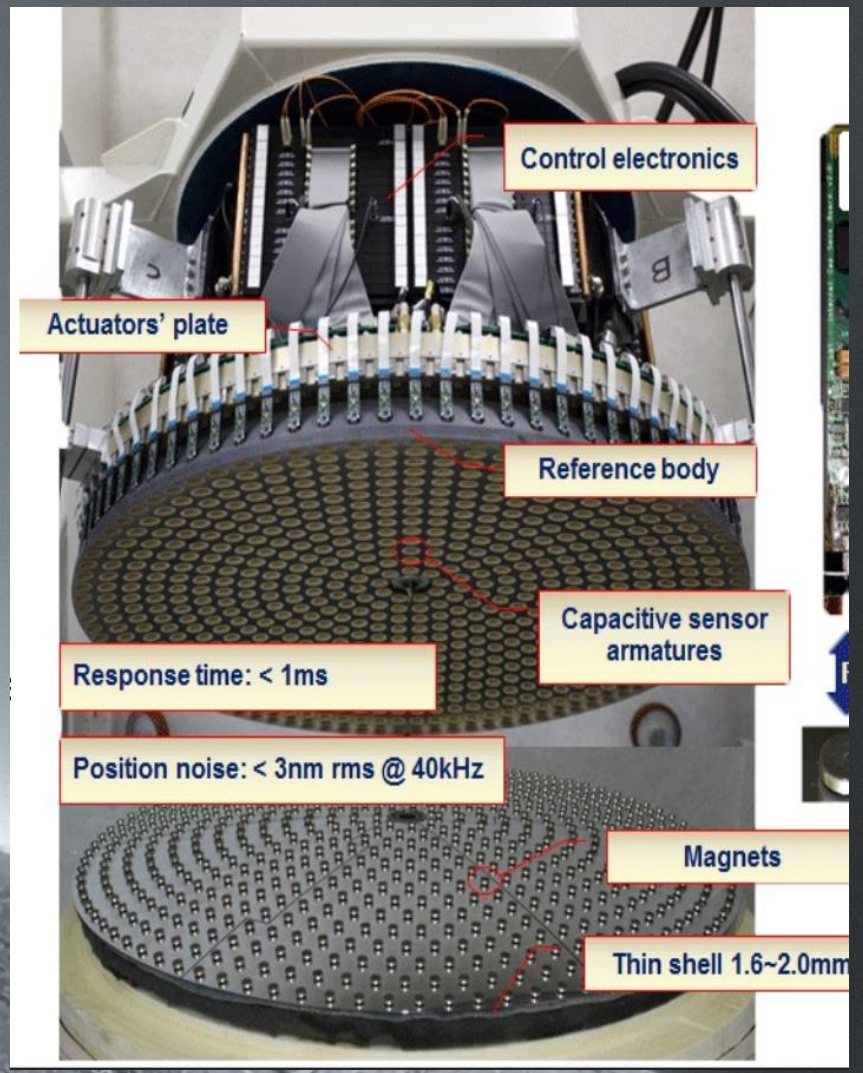
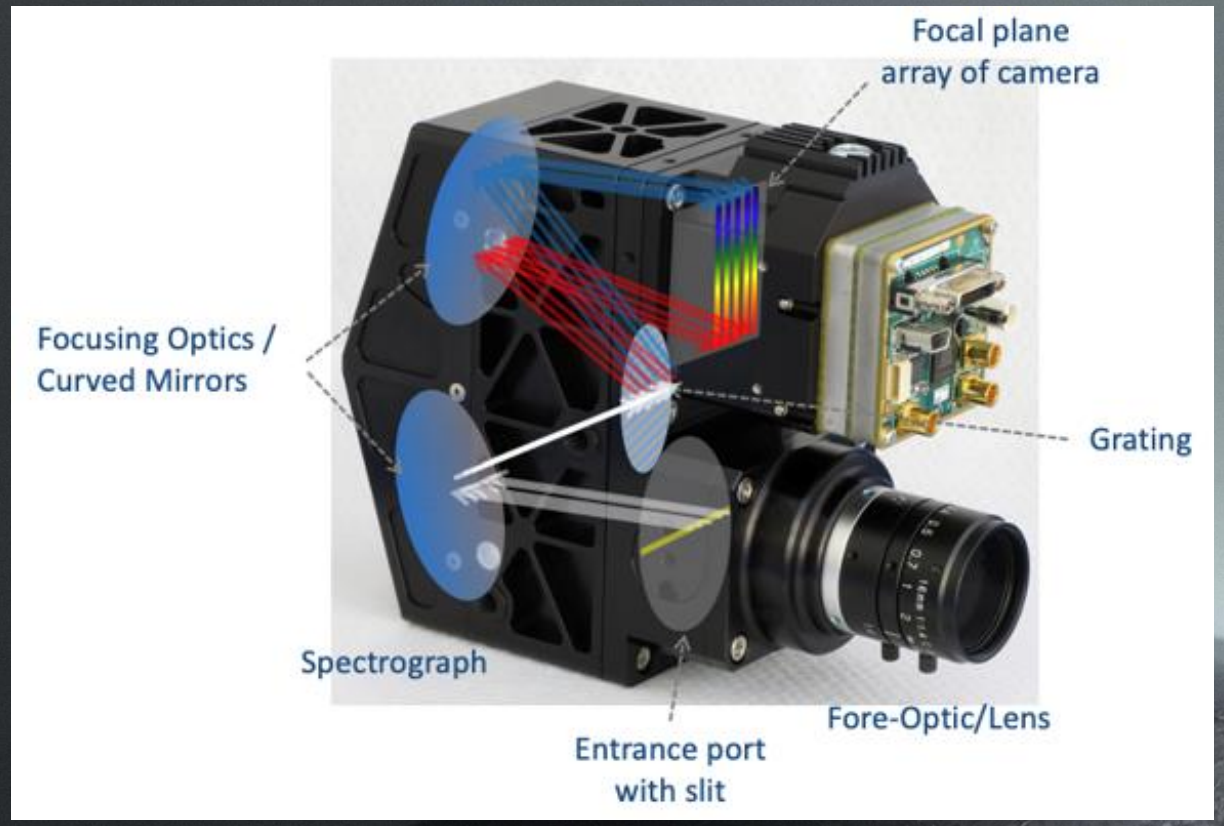


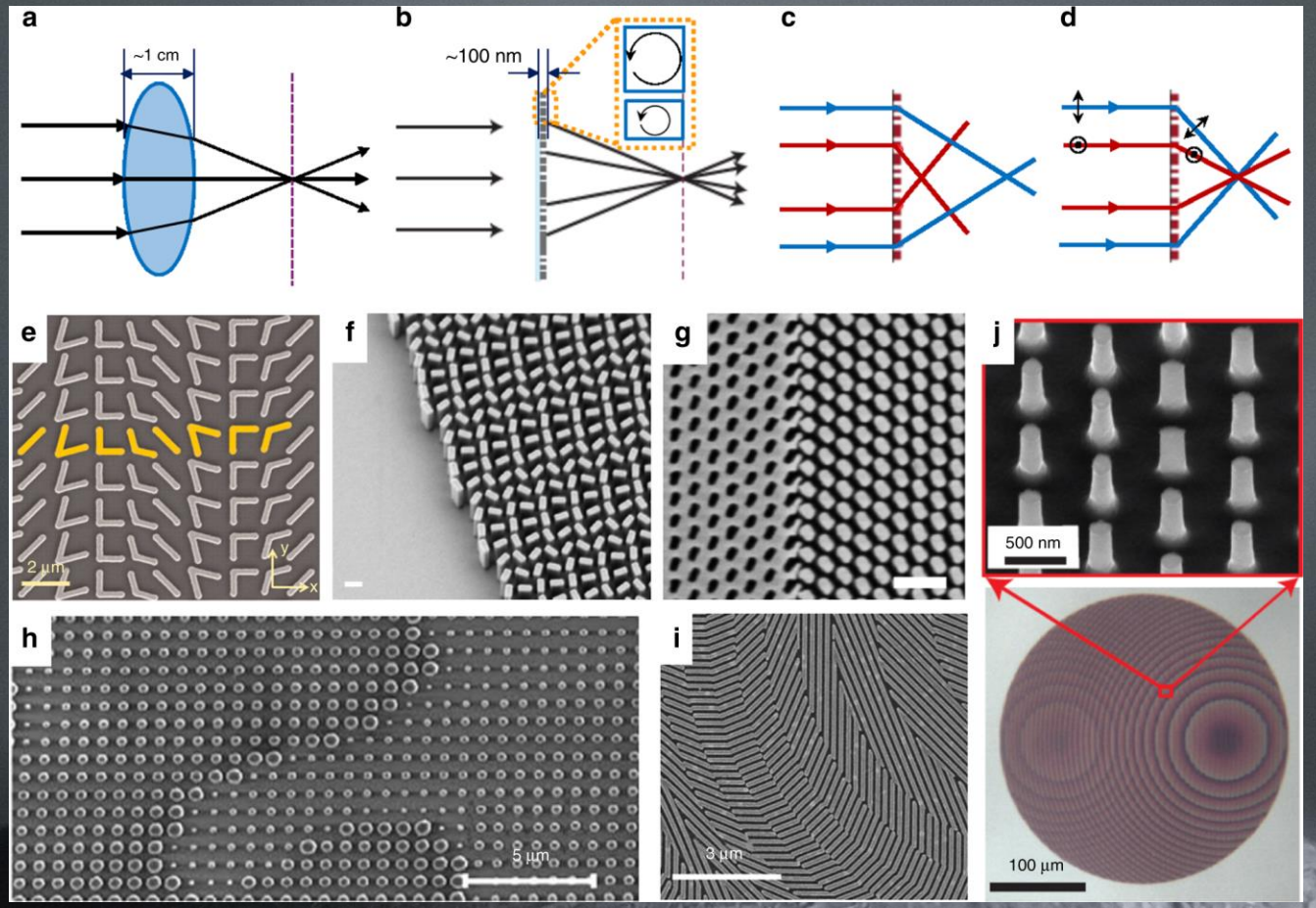
Figure 1. Photograph of an Iris AO PTT111-X deformable mirror.



Software-defined Space Systems for Optics - Hyperspectral Imaging



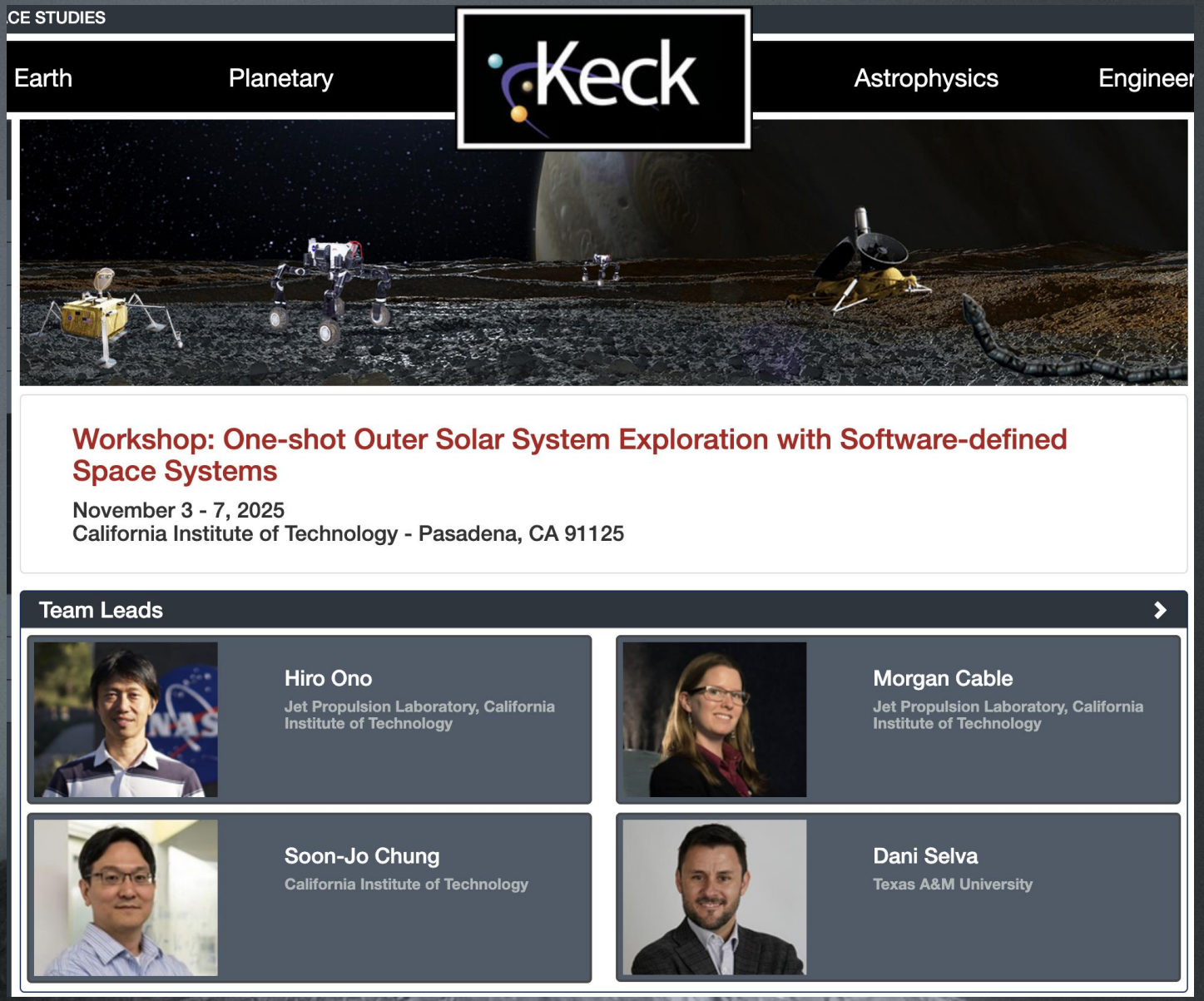
Software-defined Space Systems for Optics - Optical Metasurfaces



Neshev, D., Aharonovich, I. Optical metasurfaces: new generation building blocks for multi-functional optics. *Light Sci Appl* **7**, 58 (2018). https://doi.org/10.1038/s41377-018-0058-1

KISS Workshop

- Keck Institute for Space Studies (KISS) at Caltech
- Workshop to explore the viability and impacts of adaptable spacecraft
- November 3-7, 2025 (by invite only)

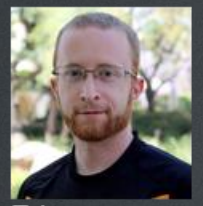


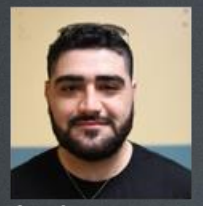
https://kiss.caltech.edu/workshops/oneshot/oneshot.html


The crews that made this possible

The EELS Team


Sina Aghil


Eric Ambrose


Avak Archanian


Joseph Bowkett


Morgan Cable


Kalind Carpenter

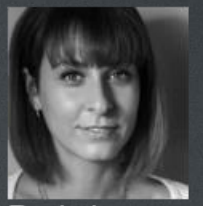

Guglielmo Daddi


Hendrik Dreger


Tomas Drevinskas


EELS1.0


EELS1.5


Rachel Etheredge


Alex Gardner


Peter Gavrilov


Nikola Georgiev


Matt Gildner


Tristan Hasseler


Ben Hockman


Mitch Ingham


Abhi Jain


Levi Janssen


Harrison Jenkins


Curtis Jin


Bryson Jones


Chris Lopez


Daniel Loret

Mike Malaska


Eloise Marteau


Daniel McGann


Hovhannes Melikyan


Paul Nadan


Jack Naish


Yashwanth Nakka


Benjamin Nuernberger


Hiro Ono


Melissa Pamer


Daniel Pastor


Mike Paton


Martin Peticco


Vedant Ranade

Rich Rieber

Matt Robinson

Jacob Rodriguez

Christiahn Roman

Rob Royce

Mirza Samnani

Lori Shiraishi

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