Lessons from Europa Clipper

Digital Twins for Solar System Exploration KISS Workshop

Erin Leonard

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OUTLINE AND PUNCHLINE

EUROPA

THE MISSION CONCEPTS BEFORE THE MISSION

EUROPA CLIPPER

HOW SCIENCE DRIVES MISSION STRUCTURE AND OPERATIONS

POTENTIAL DIGITAL TWIN APPLICATIONS

TAKEAWAYS

Europa Clipper's goal of understanding habitability requires system science and the integration of diverse but synergistic datasets, which is mirrored in the mission design and operation plan. Europa Clipper and similar missions would benefit from Digital Twin applications.

THE GALILEAN SATELLITES OF JUPITER

INGREDIENTS FOR LIFE?

WATER:

Much more than all of Earth's oceans

ESSENTIAL ELEMENTS:

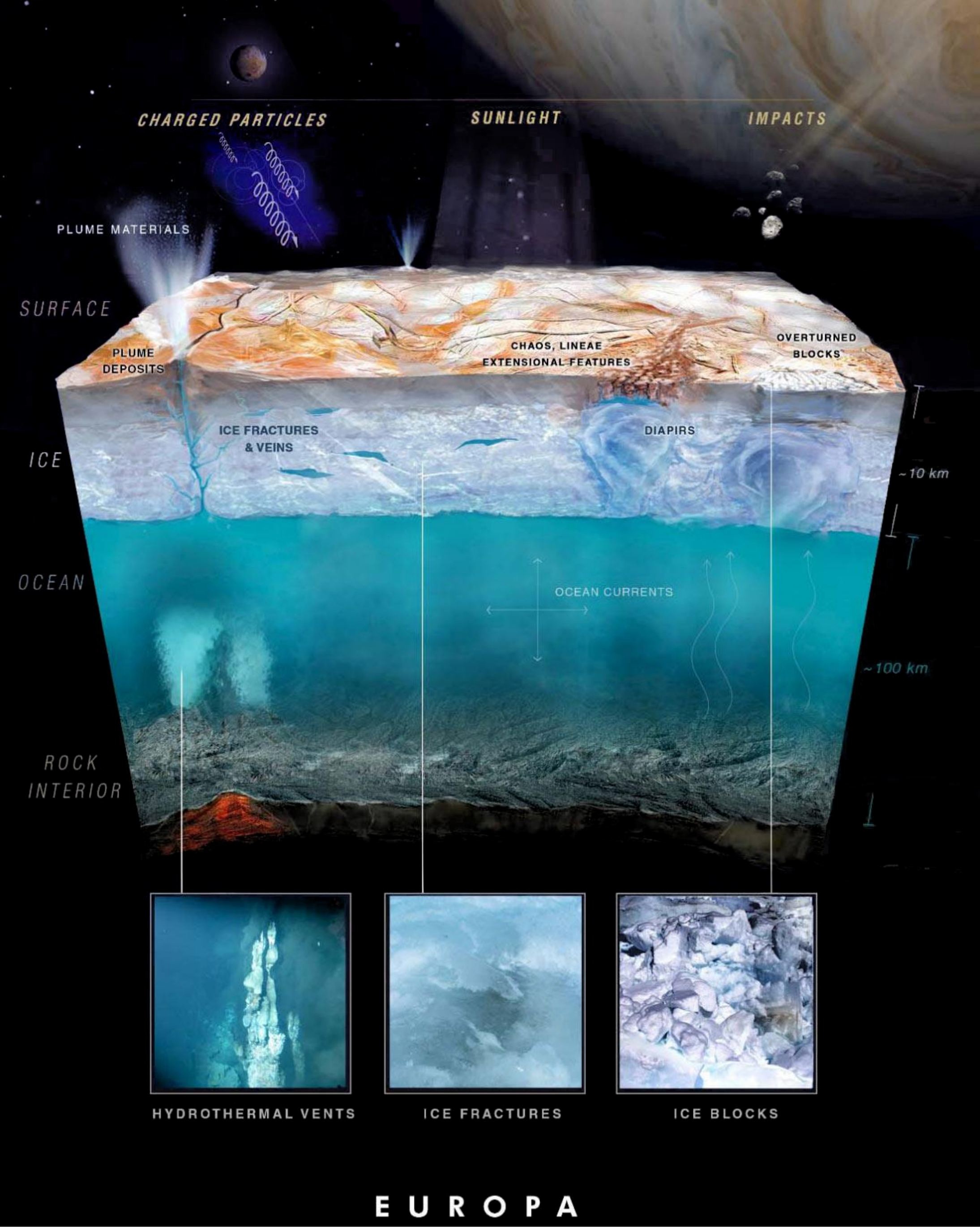
From formation and impacts

CHEMICAL ENERGY:

From above and below

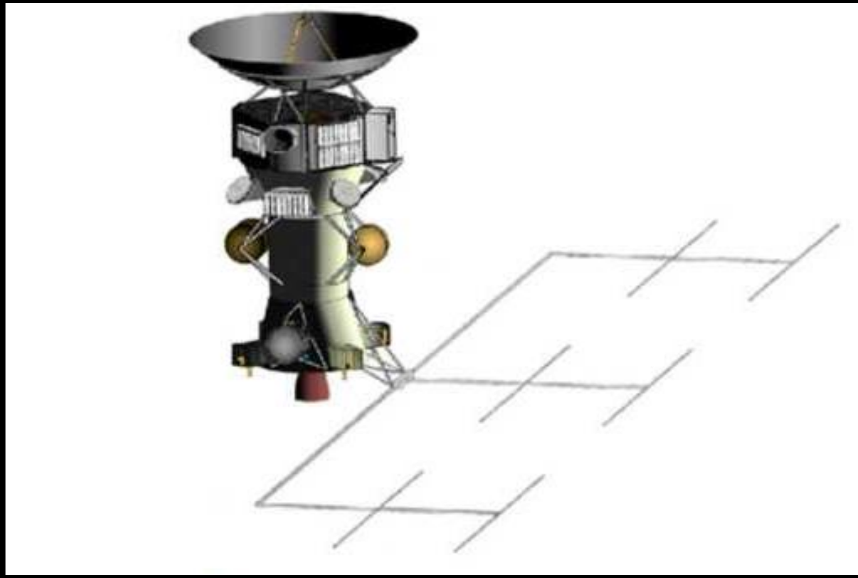
STABILITY:

"Simmering" for 4 billion years



THE MANY MISSION CONCEPTS TO EUROPA

Pappalardo et al. (2024)



EUROPA ORBITER (c. 1999)
- Discovery class concept
- Science objectives developed by the Science Definition Team (SDT) can be directly traced to Europa Clipper

JUPITER ICY MOONS ORBITER (c. 2003)
- Science Definition Team in 2003 to define goals and objectives for a mission to orbit each of the three icy Galilean satellites
- Resulted in a >$27B mission concept, but a very thorough SDT report

EUROPA JUPITER SYSTEM MISSION (c. 2010)
- Jupiter Europa Orbiter (JEO) from NASA + Jupiter Ganymede Orbiter from ESA
- 2nd Planetary Decadal Survey recommended JEO's scope be reduced to make it less expensive

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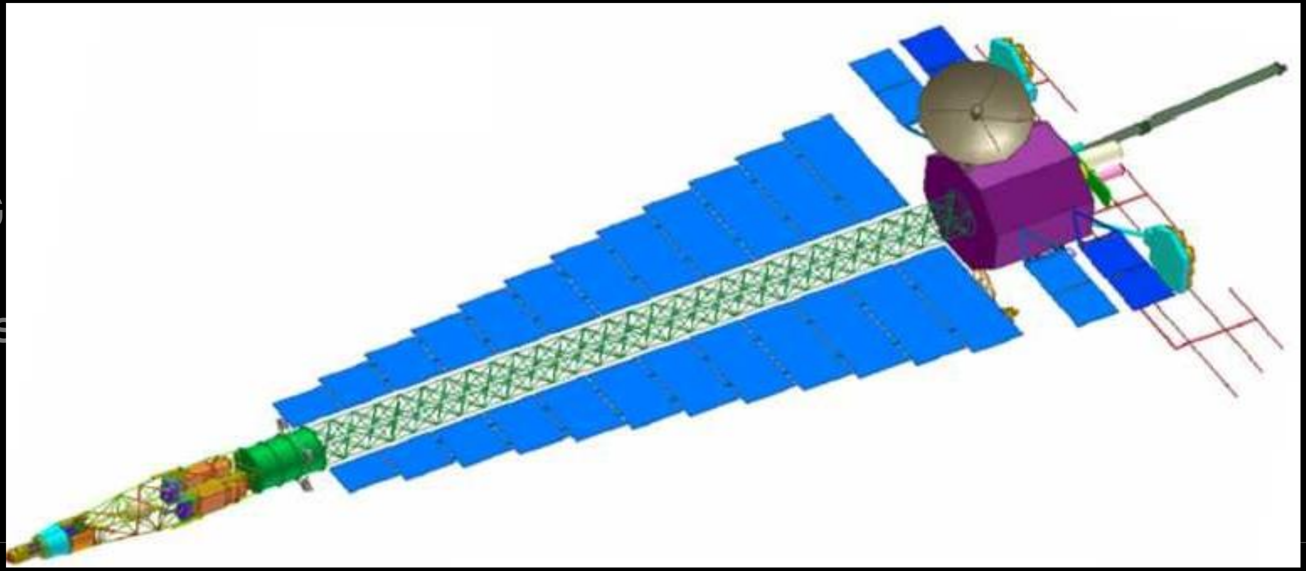

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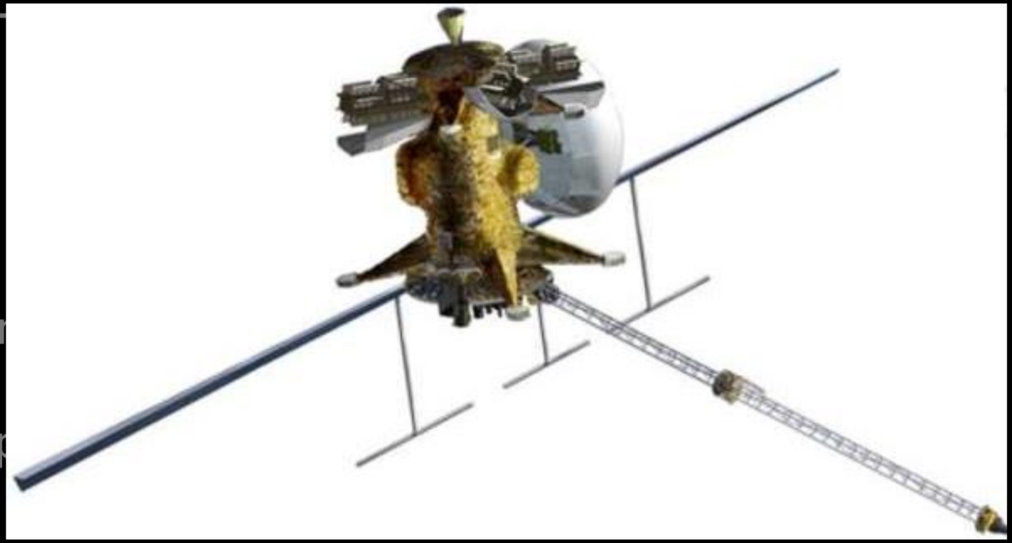

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THE MANY MISSION CONCEPTS TO EUROPA

THREE EUROPA MISSION STUDIES in 2011

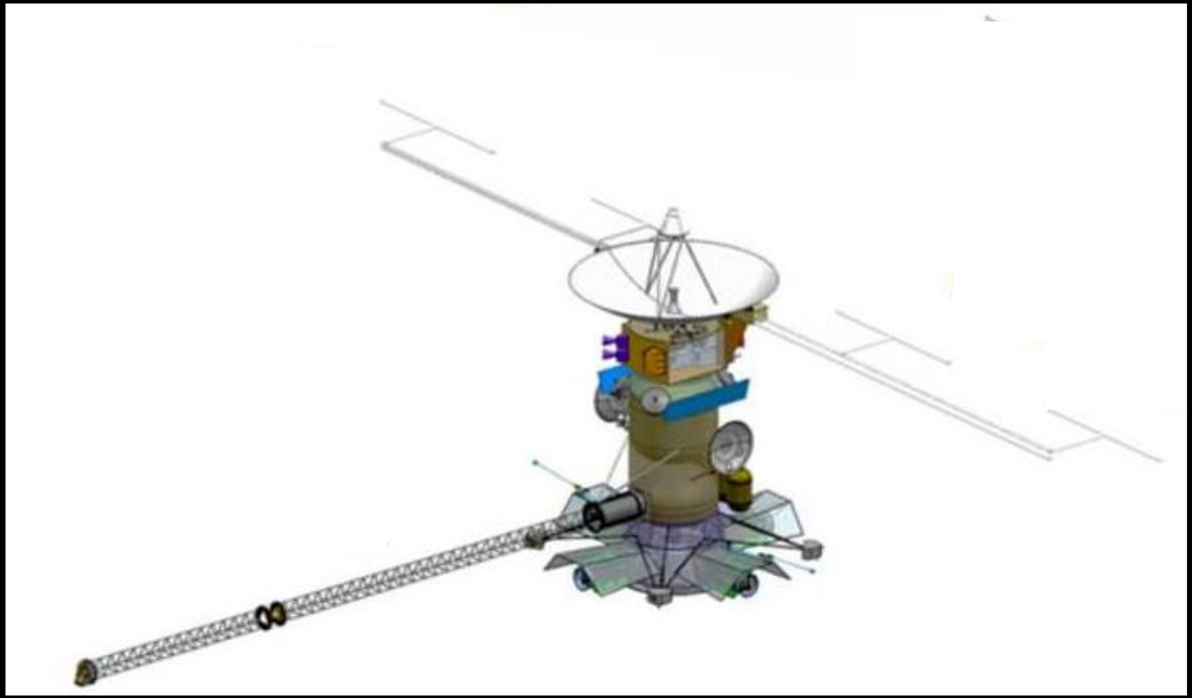
- Small, focused Europa Orbiter, Jupiter-orbiting Europa Multiple Flyby, and Lander
- Europa Study Team (2012) and community feedback found the Multiple Flyby Mission to be the greatest science return per dollar

FOCUSED EUROPA ORBITER OR EUROPA MULTIPLE FLYBY MISSION?

- Small augmentations were studied by the Europa Enhancement Science Definition Team in 2012
- 2013 call for Instrument Concepts for Europa Exploration (ICEE) to go on either mission concept
- Instrument AO in 2014 for instruments that could fly on either mission
- Instrument selections for the Europa Multiple Flyby Mission were announced in May 2015

EUROPA CLIPPER ENTERED PHASE A IN 2015

Pappalardo et al. (2024)



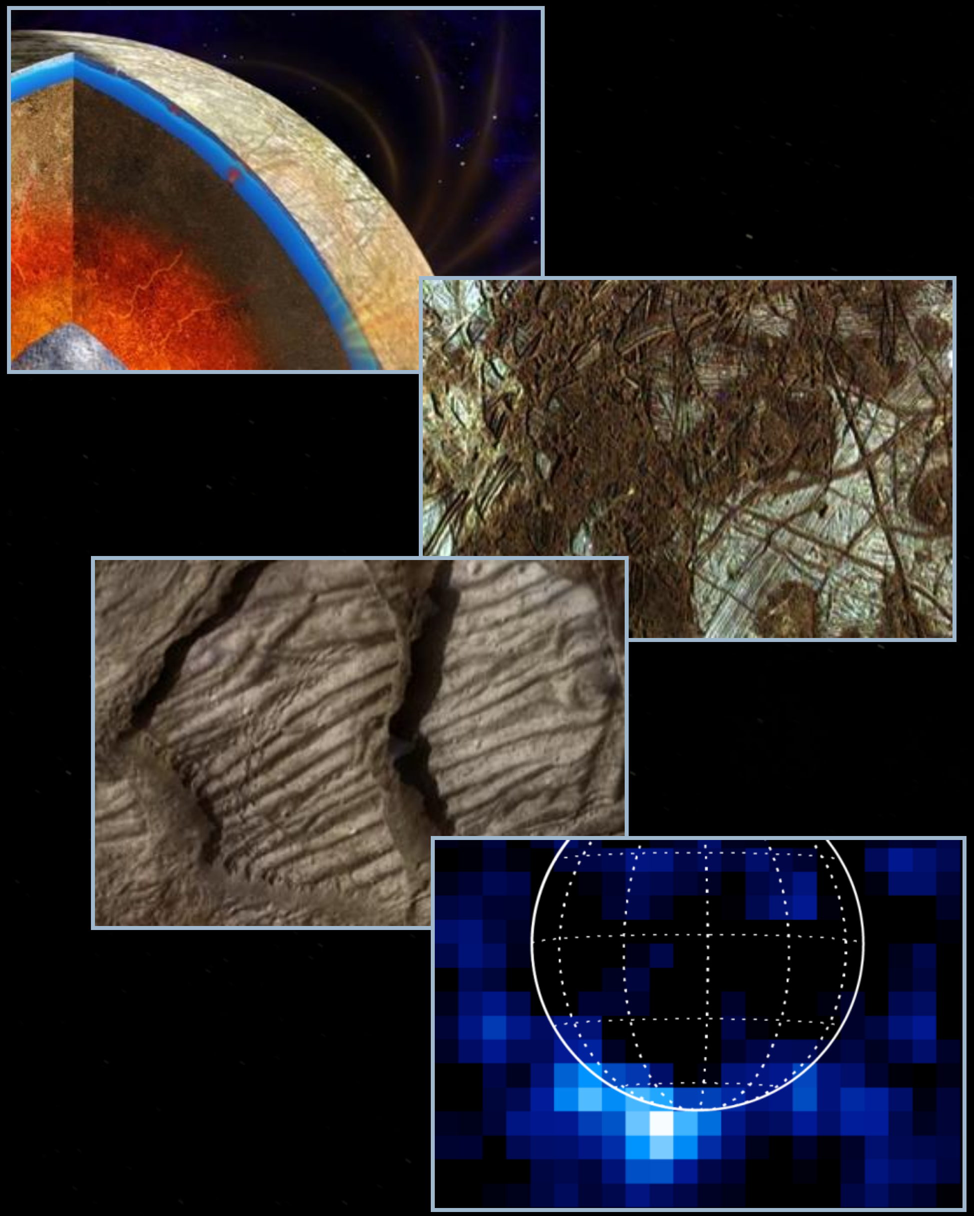
SCIENCE OVERVIEW

Science Goal: Explore Europa to investigate its habitability

Science Objectives:

- Ice Shell & Ocean: Characterize the ice shell and any subsurface water, including their heterogeneity, ocean properties, and the nature of surface-ice-ocean exchange
- Composition: Understand the habitability of Europa's ocean through composition and chemistry
- Geology: Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest localities

Current Activity cross-cuts through all three principal science objectives




Europa Clipper Investigations
MASPEX
Mass Spectrometer
PI: Jim Burch, SwRI
sniffing atmospheric composition
SUDA
Dust Analyzer
PI: Sascha Kempf: U. Colorado
detecting surface & plume composition
ECM
Magnetometer
TL: Margaret Kivelson, U. Michigan
revealing ocean properties
PIMS
Faraday Cups
PI: Joe Westlake, APL
measuring plasma environment
Europa-UVS
UV Spectrograph
PI: Kurt Retherford, SwRI
seeking plume glow
EIS
Narrow-angle Camera + Wide-angle Camera
PI: Zibi Turtle, APL
mapping alien landscape
MISE
IR Spectrometer
PI: Diana Blaney, JPL
detecting chemical fingerprints
E-THEMIS
Thermal Imager
PI: Phil Christensen, ASU
searching for hot spots
REASON
Ice-Penetrating Radar
PI: Don Blankenship, UTIG
probing the ice shell
G/RS
Doppler Gravity
TL: Erwan Mazarico, GSFC
sensing interior layers
Remote Sensing
In Situ

REMOTE SENSING INSTRUMENTS

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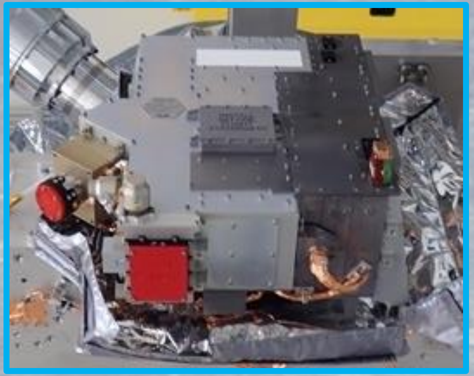
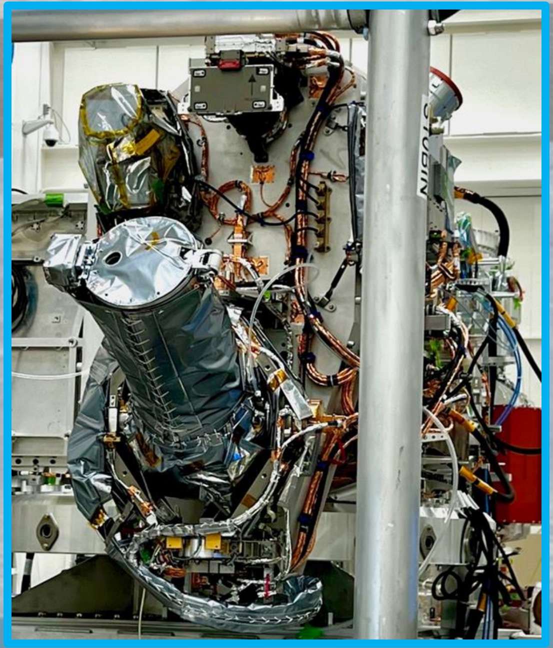


NASA / JPL-Caltech / SWRI



NASA / Johns Hopkins APL

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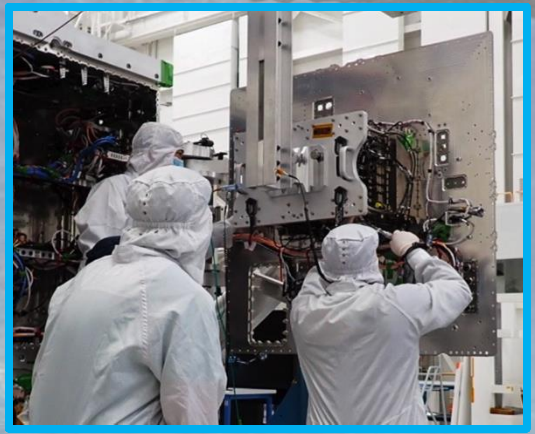
NASA / JPL-Caltech / ASU



NASA / JPL-Caltech

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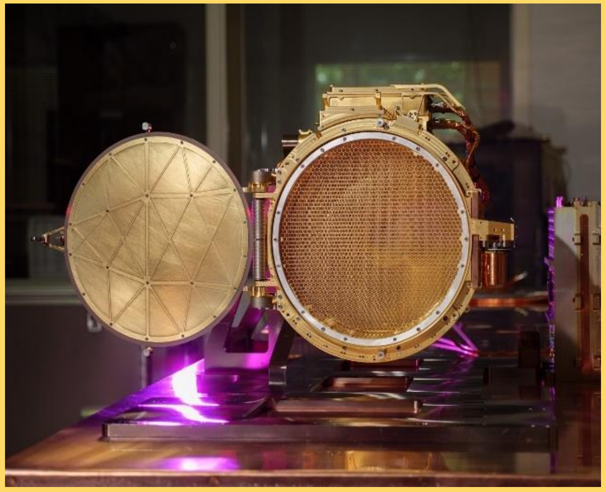
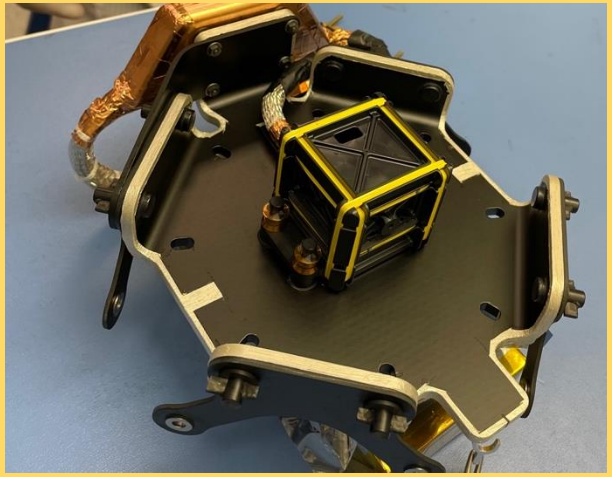
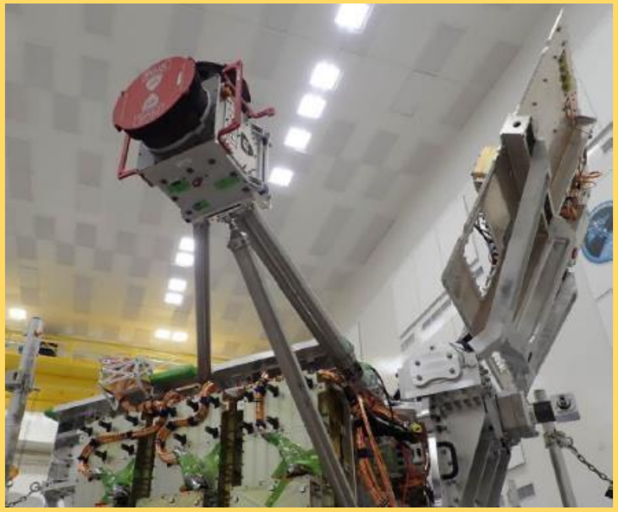

NASA / CU Boulder


NASA / JPL-Caltech / UCLA


NASA / Johns Hopkins APL

EUROPA CLIPPER LEVEL 1 SCIENCE REQUIREMENTS

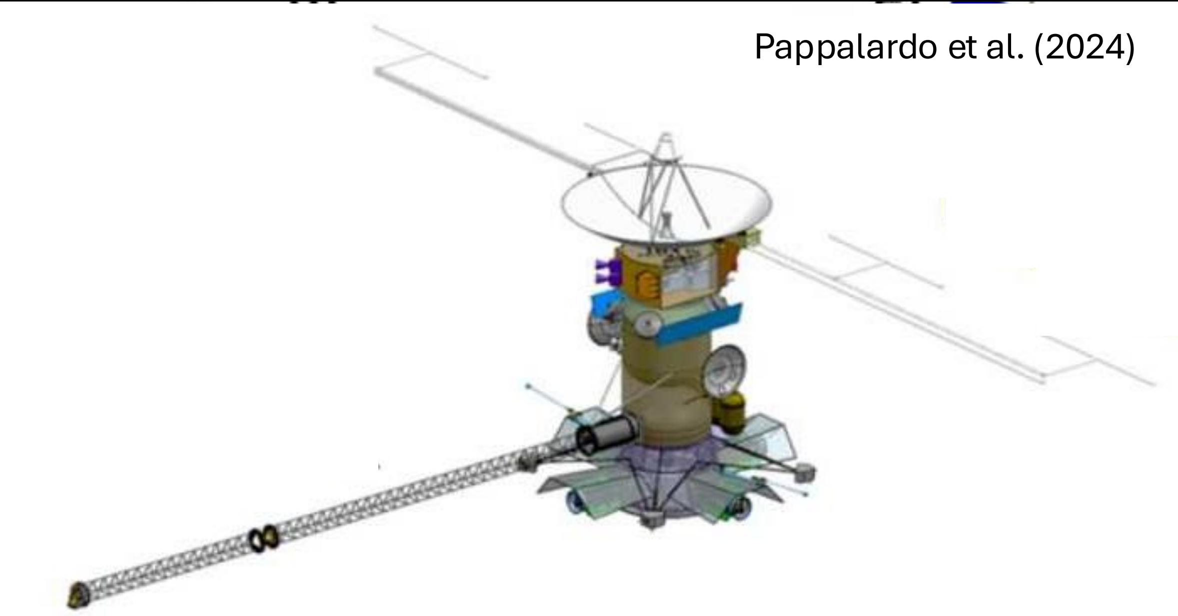
L1 RQ Number	Science Themes	Radar		Visible		Infrared	Thermal	UV	Magnetic	Plasma	IMS	NMS	Gravity
		HF	VHF	NAC	WAC								
RQ106.312	Full Depth Subsurface Exchange												
	Shallow Subsurface Structure												
RQ106.317	Ice Shell Properties												
	Ocean Properties												
RQ106.318	Global Compositional Surface Mapping												
RQ106.313	Regional Composition												
RQ106.316	Atmospheric Composition												
	Space Environment Composition												
RQ106.320	Global Surface Mapping												
RQ106.319	Landform Geology												
RQ106.311	Local-Scale Surface Properties												
RQ106.314	Remote Plume Search {and Characterization}												
	In-Situ Plume Search {and Characterization}												
	Surface Thermal Anomaly Search												
	Surface Activity Evidence												

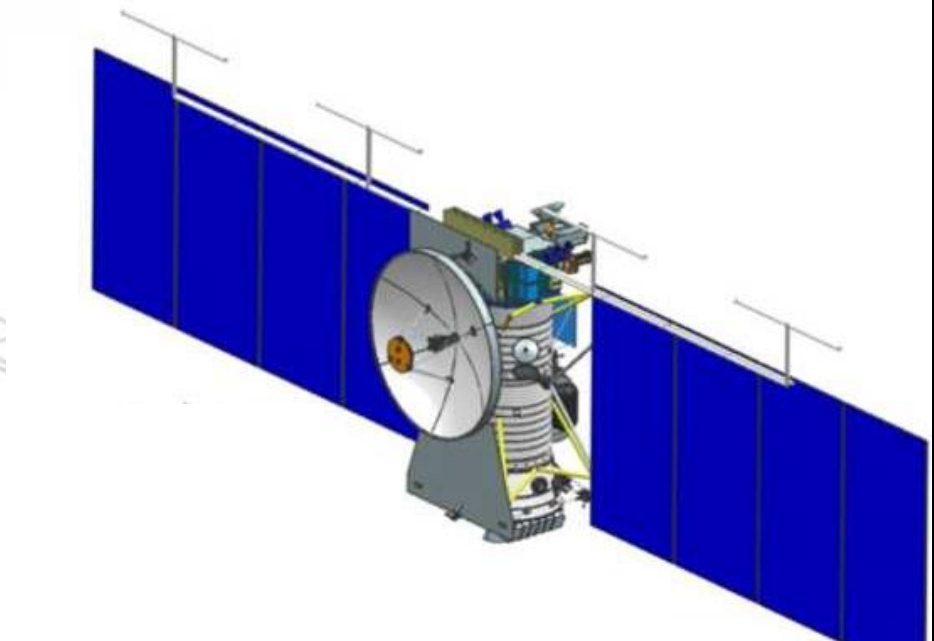
Primary
Supporting
Independent
Enhancing

EUROPA CLIPPER

- Entered Phase A in 2015
- In 2017, the Europa Multiple Flyby Mission officially became Europa Clipper after it was adopted by NASA when it passed into Phase B.
- There were many quite drastic changes and design finalization that happened after instrument selection and some even in Phase B/C, including:
  - Changing from a nuclear powered to a solar powered spacecraft
  - Removal of the helium scalar-vector magnetometer (and changed magnetometer boom)
  - Relatively late decision on launch vehicle
- All of these decisions had an impact on the science and/or operations of the spacecraft. While they were extensively analyzed at the time, they all presented challenges and shaped the mission as we know it today

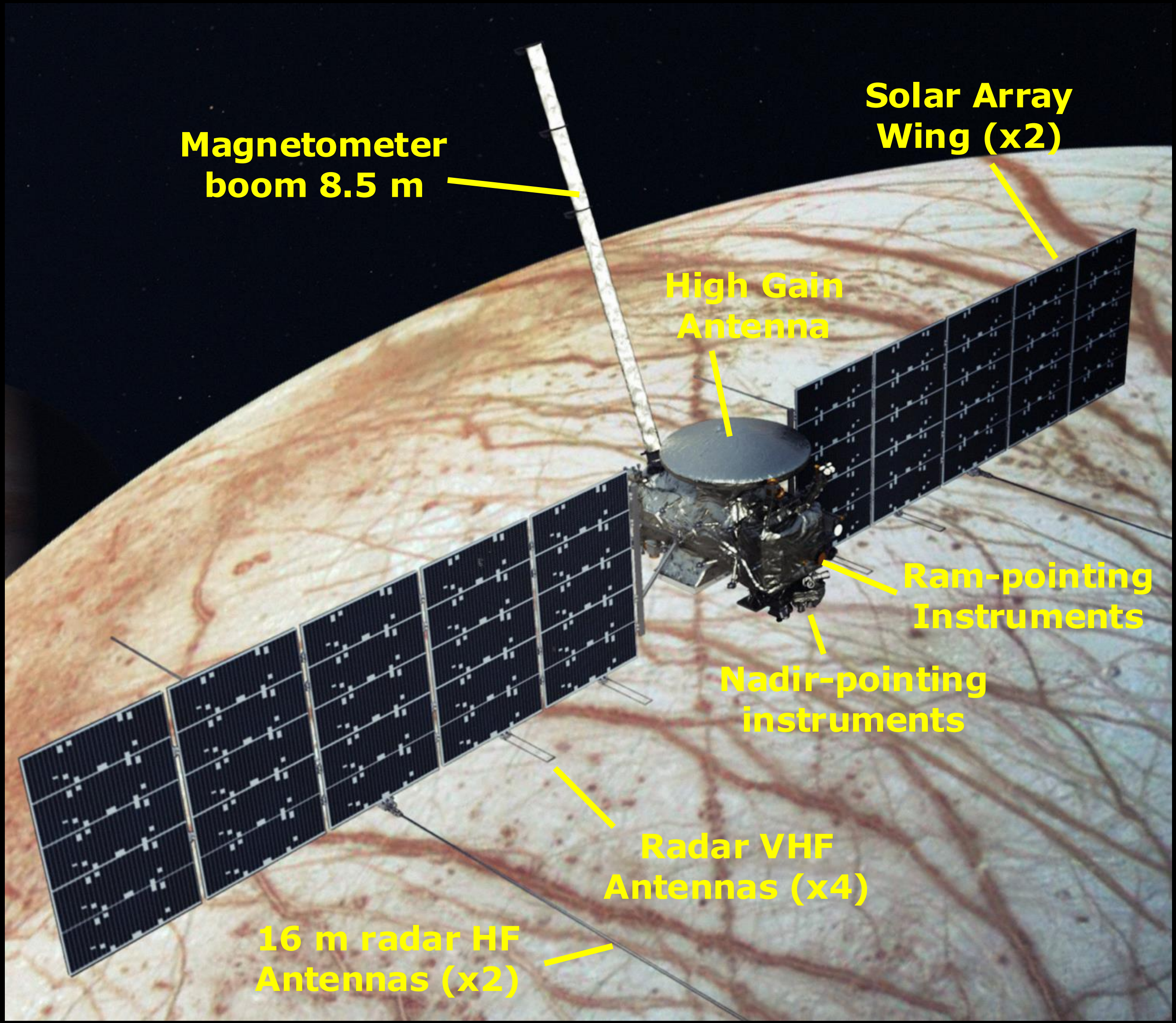
Pappalardo et al. (2024)

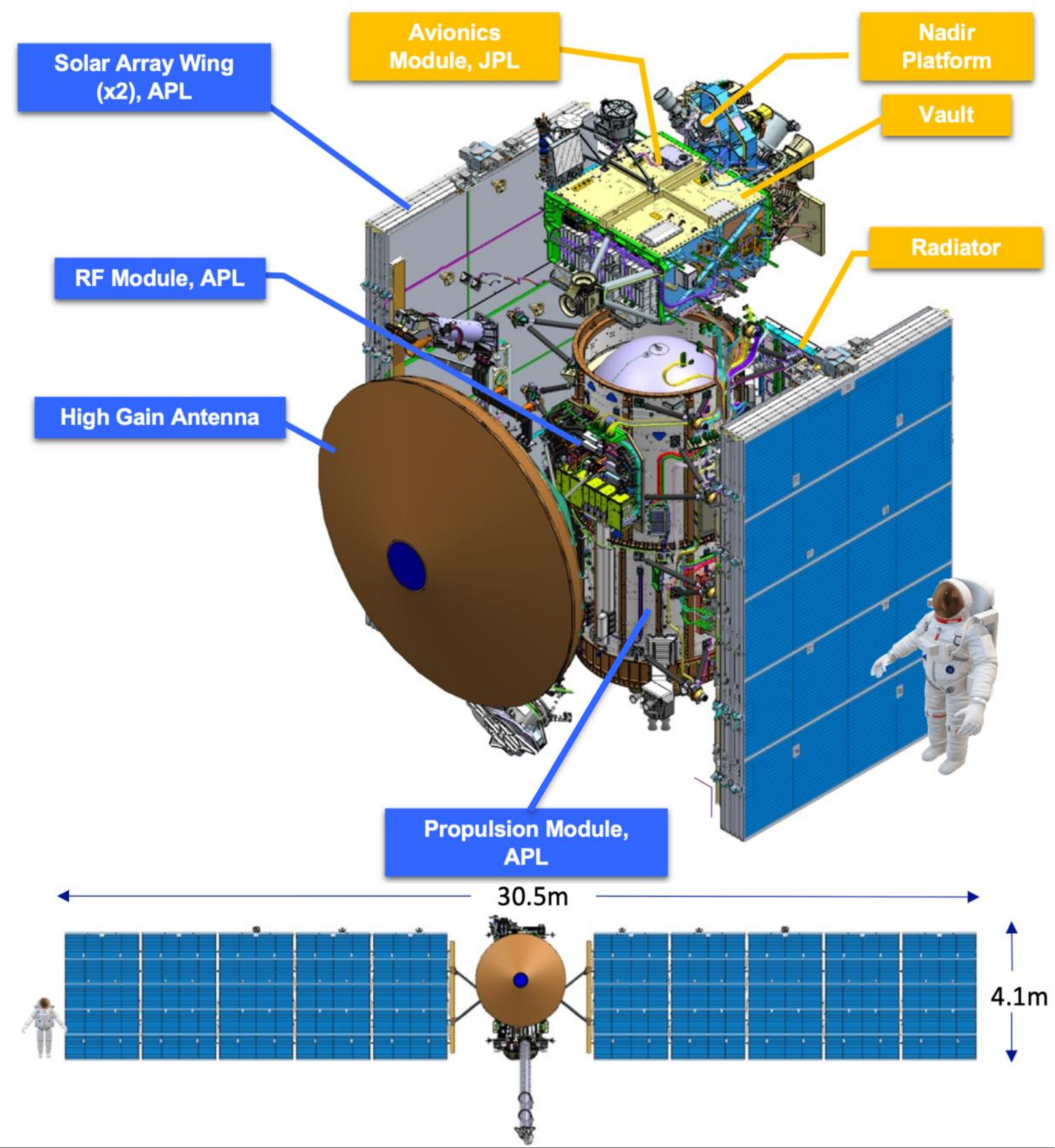




Pappalardo et al. (2024)

Europa Clipper Flight System






EUROPA CLIPPER LAUNCH
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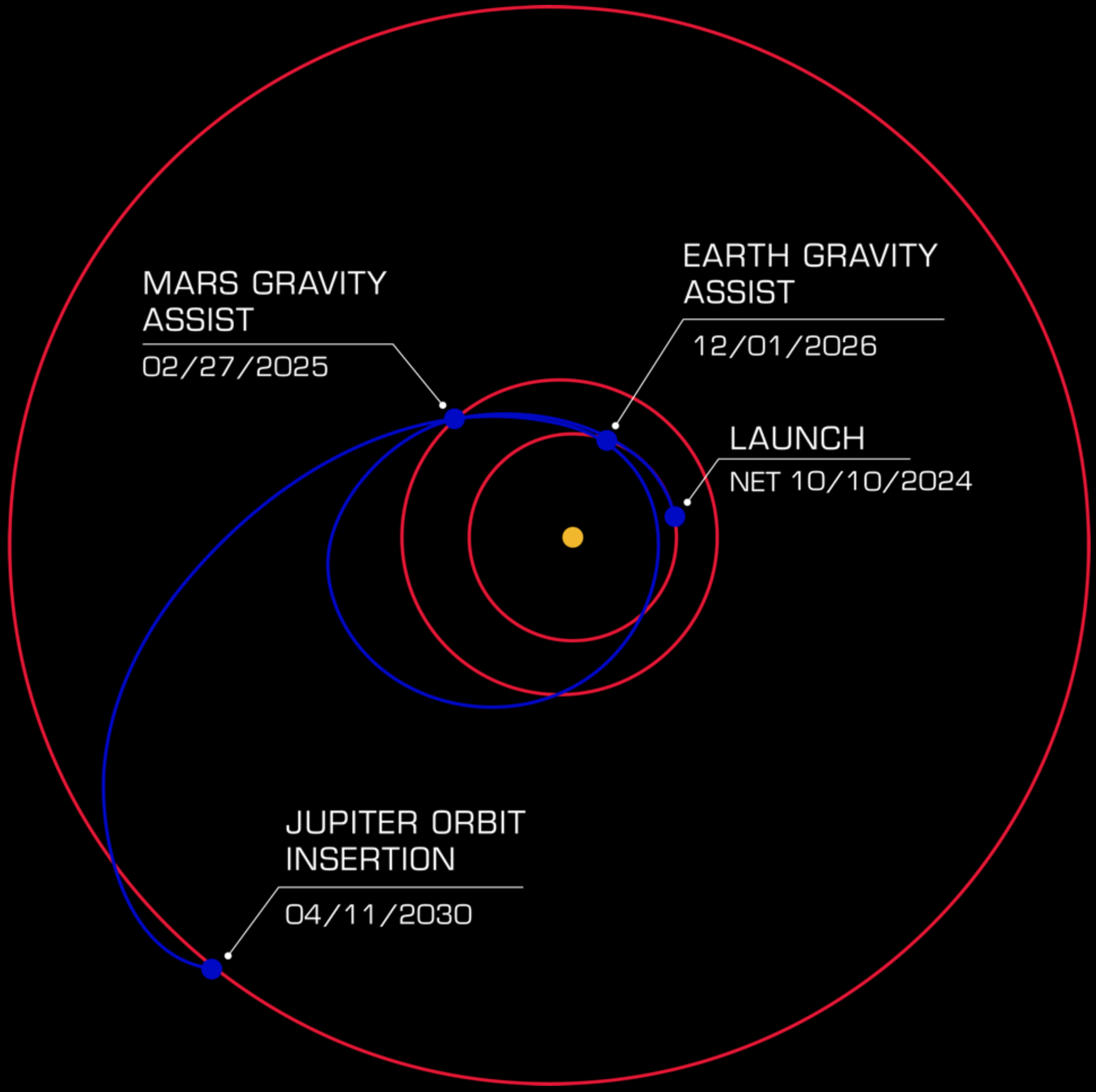
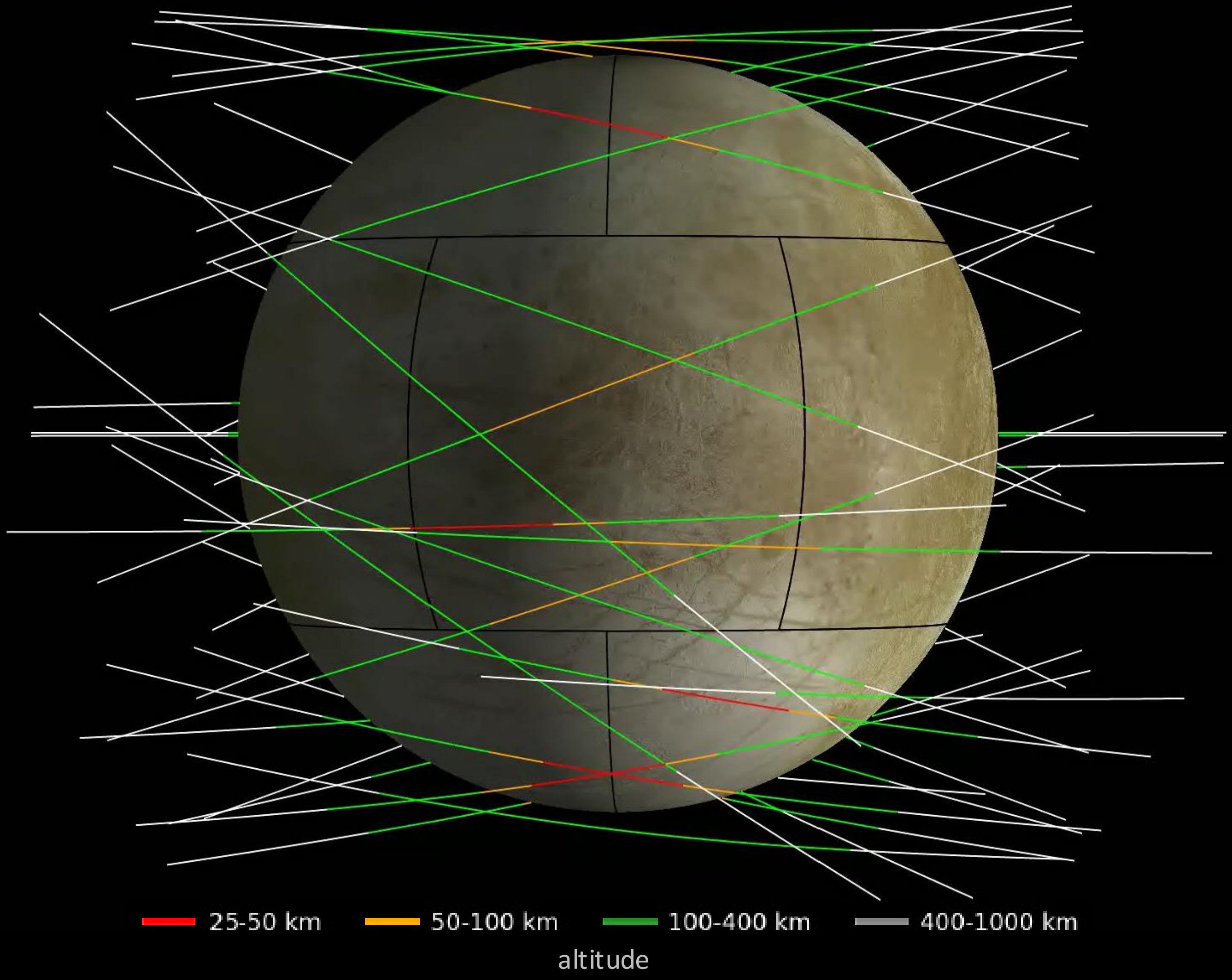
LAUNCH AND TRAJECTORY

- Launch Date: October 2024
- Launch Location: NASA Kennedy Space Center, Florida
- Launch Vehicle: SpaceX Falcon Heavy, fully expendable
- Jupiter Orbit Insertion: April 2030



SPACECRAFT RADIATION DOSAGE

GLOBAL WEB OF FLYBYS



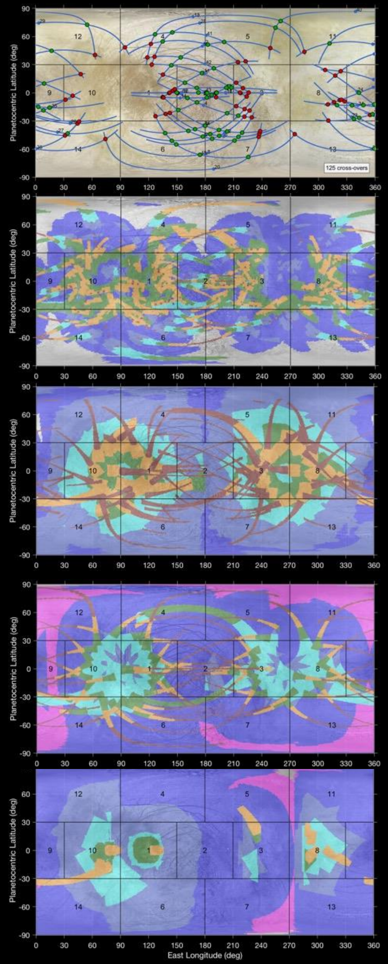
REASON
[Groundtracks & Crossovers]

EIS
[WAC + NAC: Framing Pan Mono]

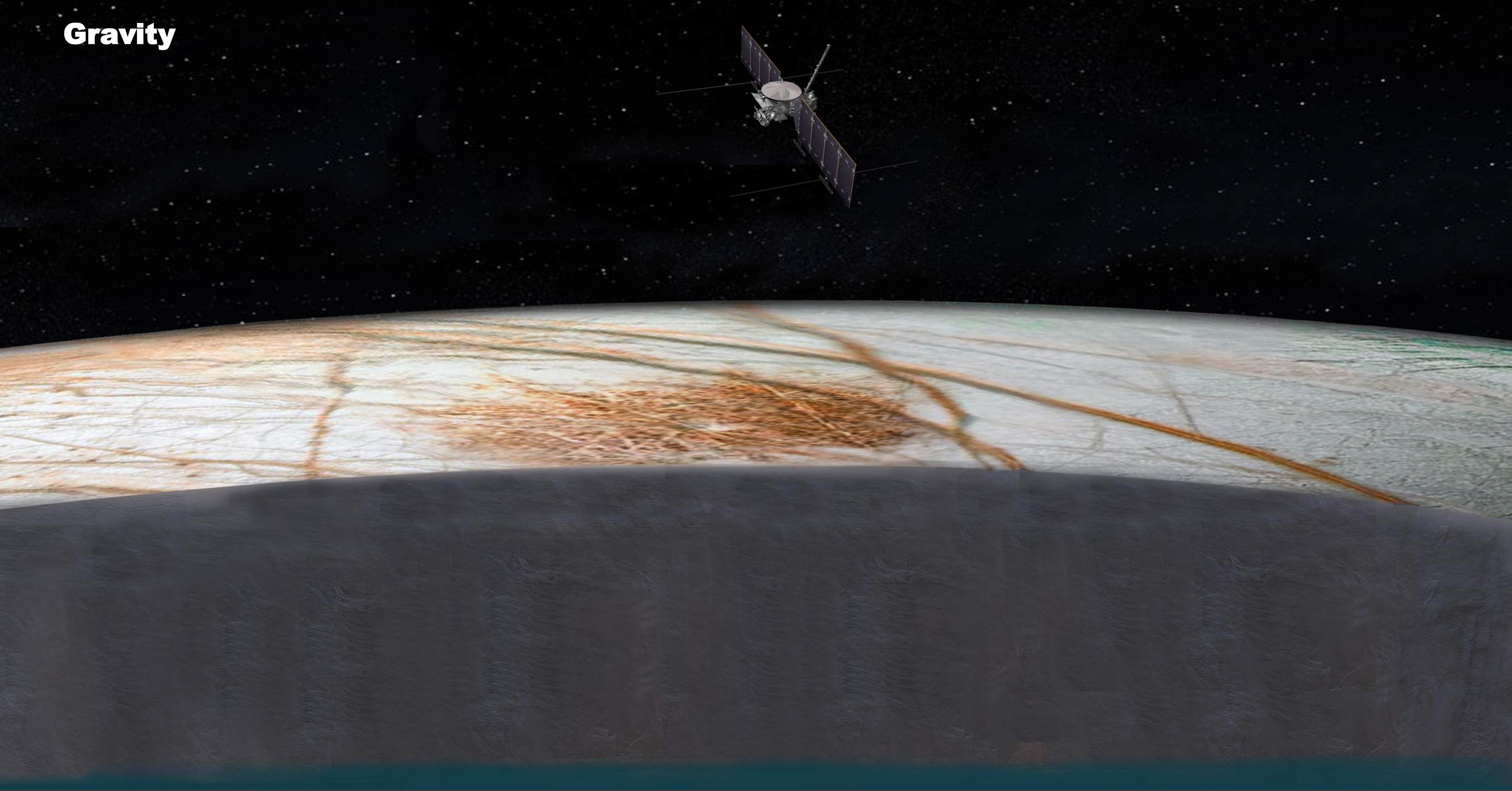
E-THEMIS
[Day/Night Coverage]

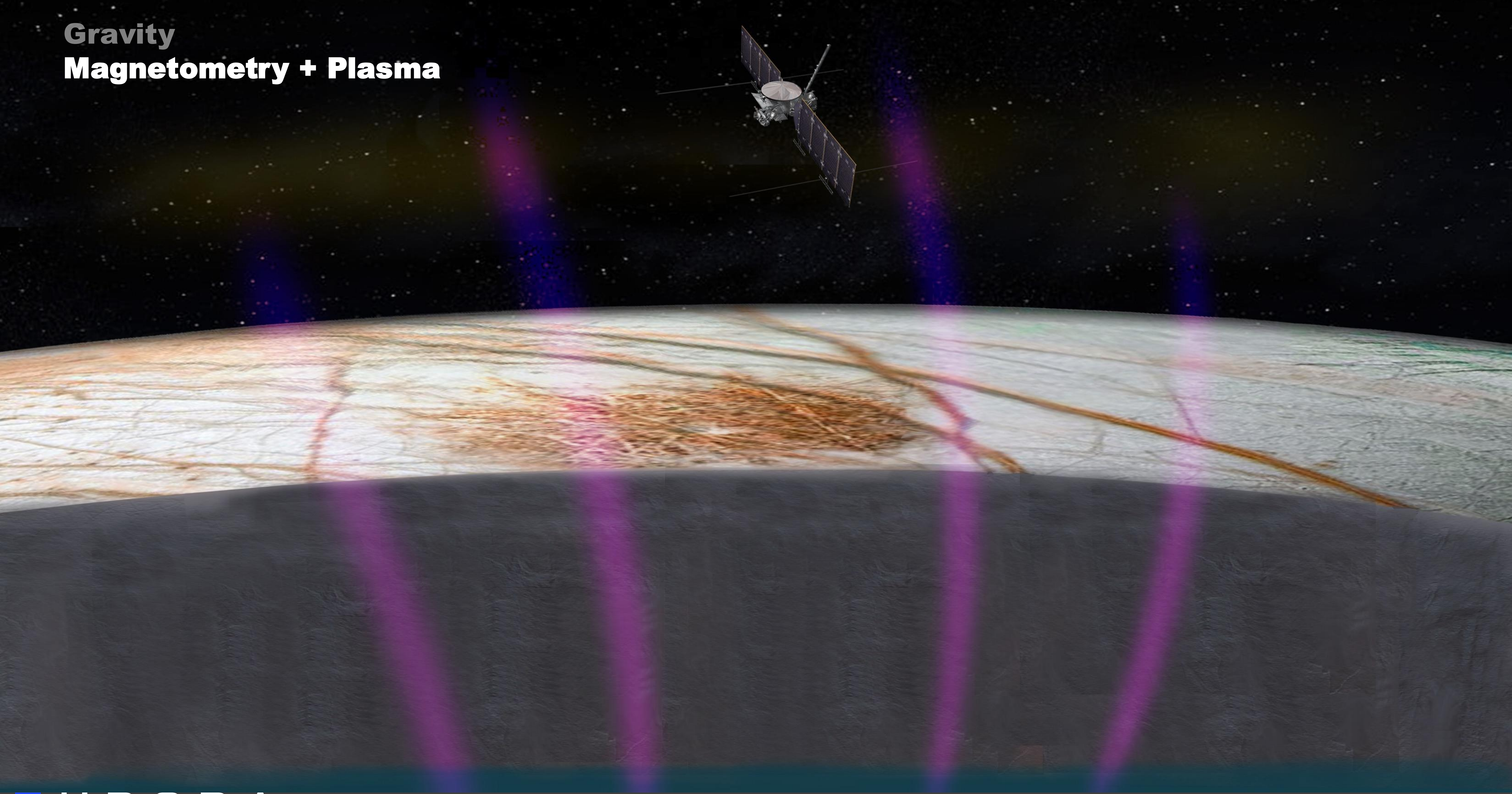
Europa-UVS
[Total Daytime Coverage]

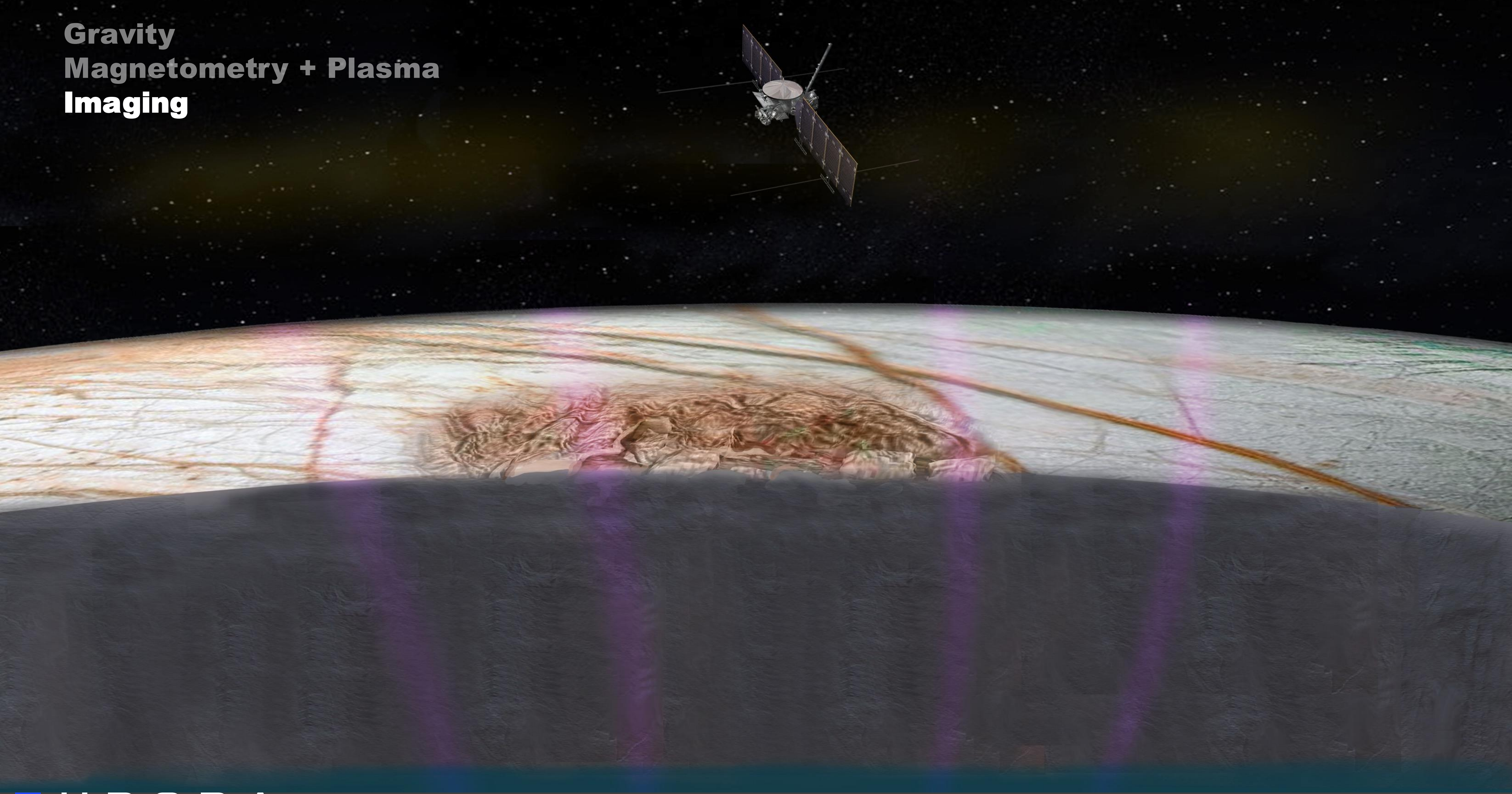
MISE
[Global Daytime Coverage]



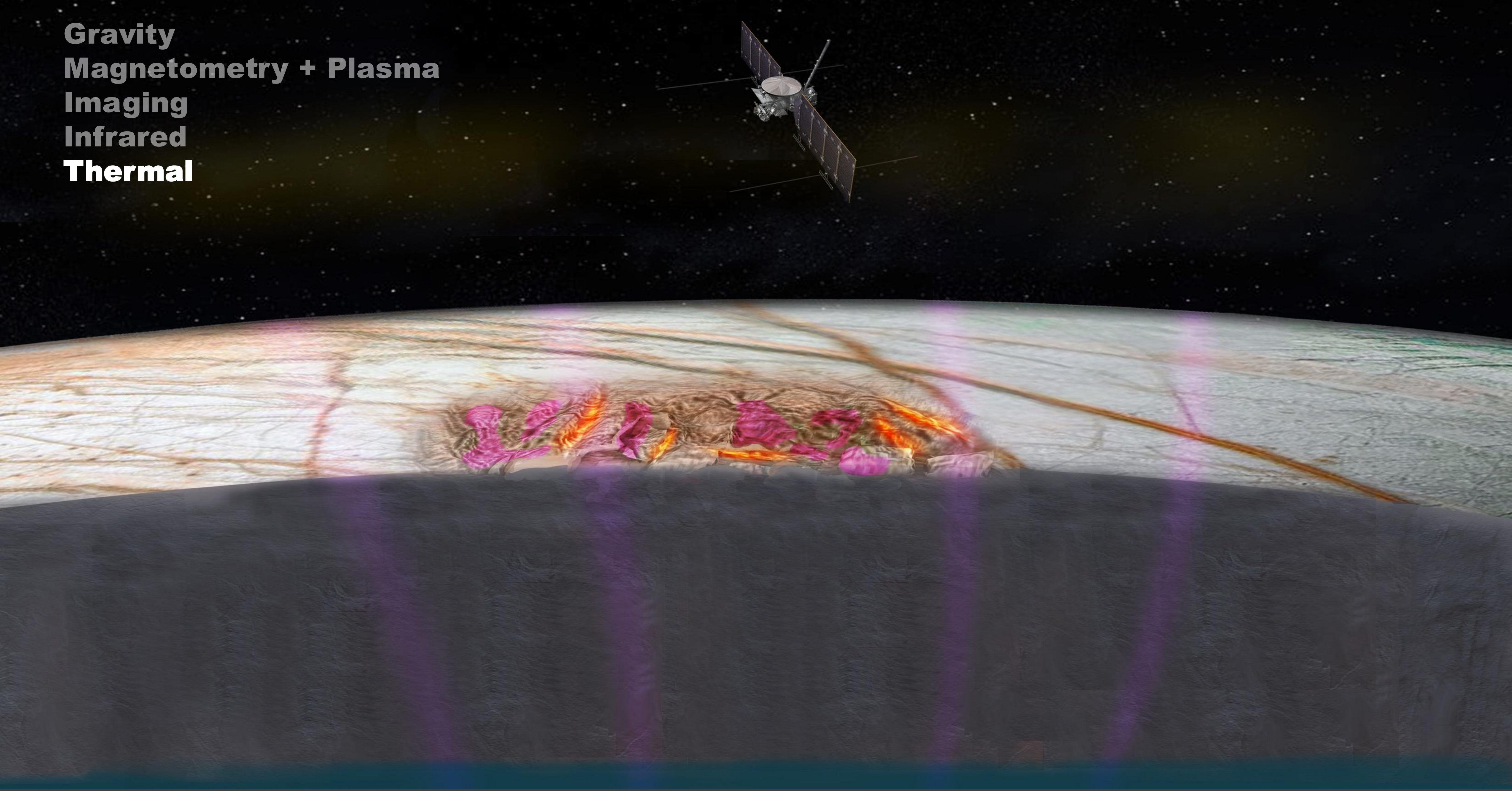
Gravity



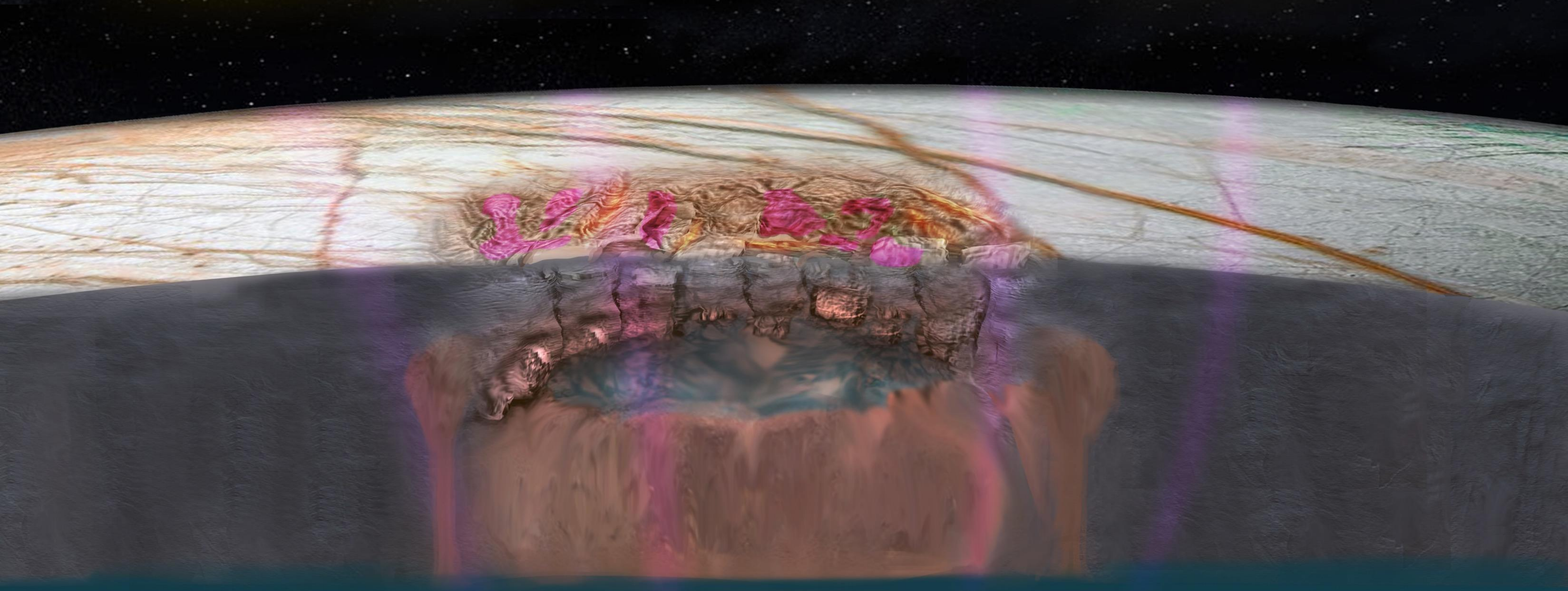

Gravity
Magnetometry + Plasma

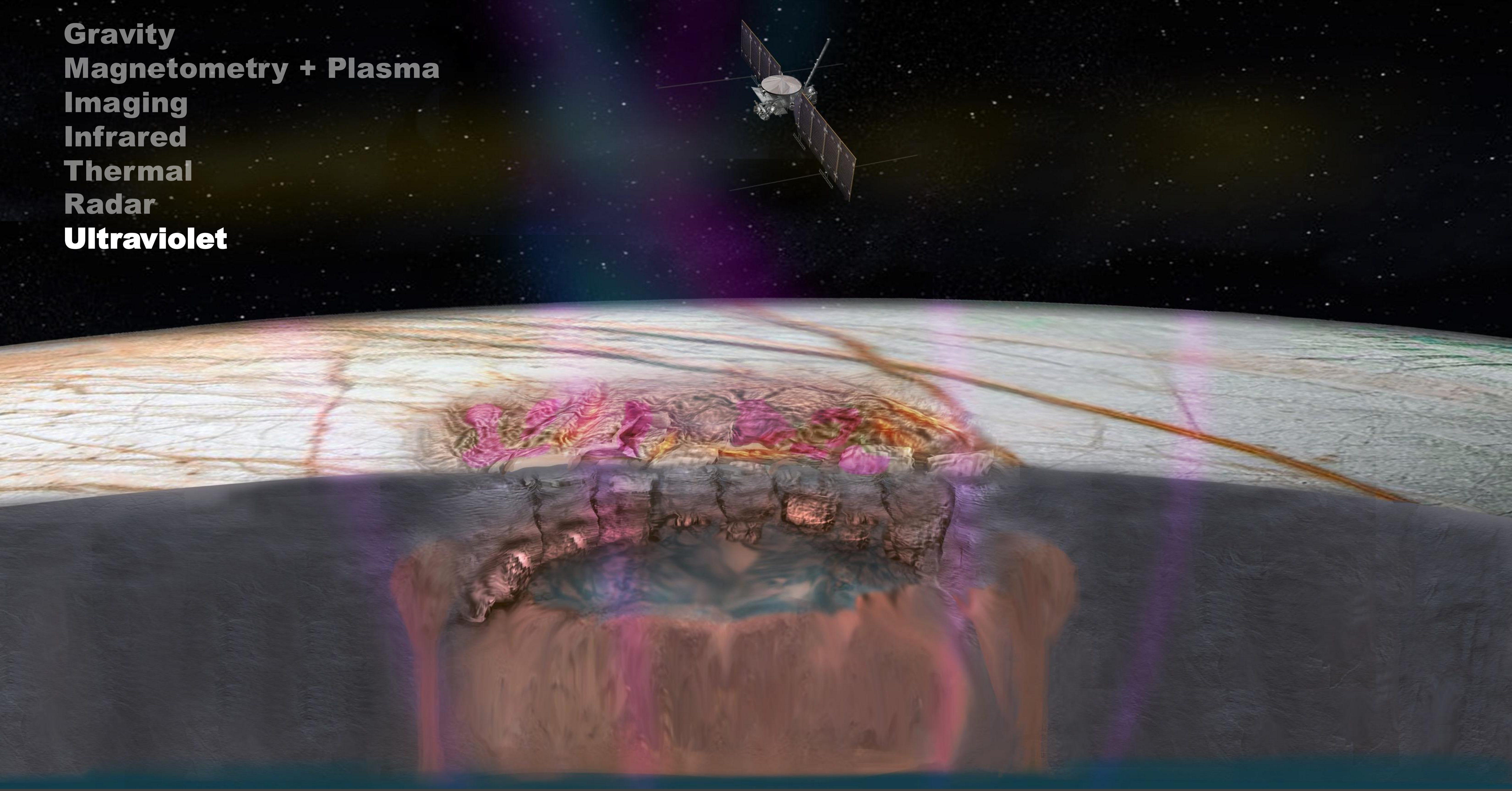

Gravity
Magnetometry + Plasma
Imaging

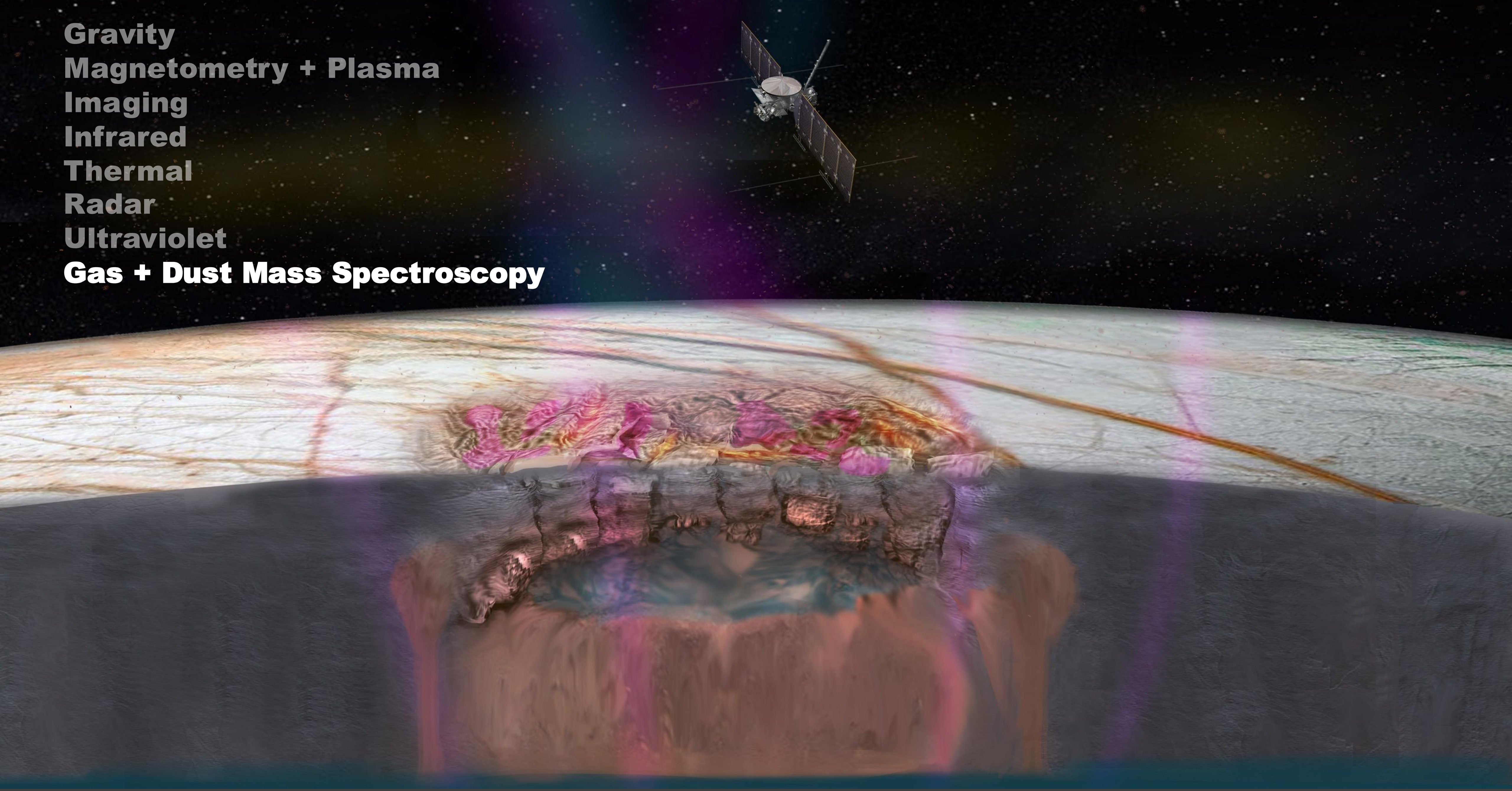

Gravity
Magnetometry + Plasma
Imaging
Infrared


Gravity
Magnetometry + Plasma
Imaging
Infrared
Thermal

Gravity
Magnetometry + Plasma
Imaging
Infrared
Thermal
Radar

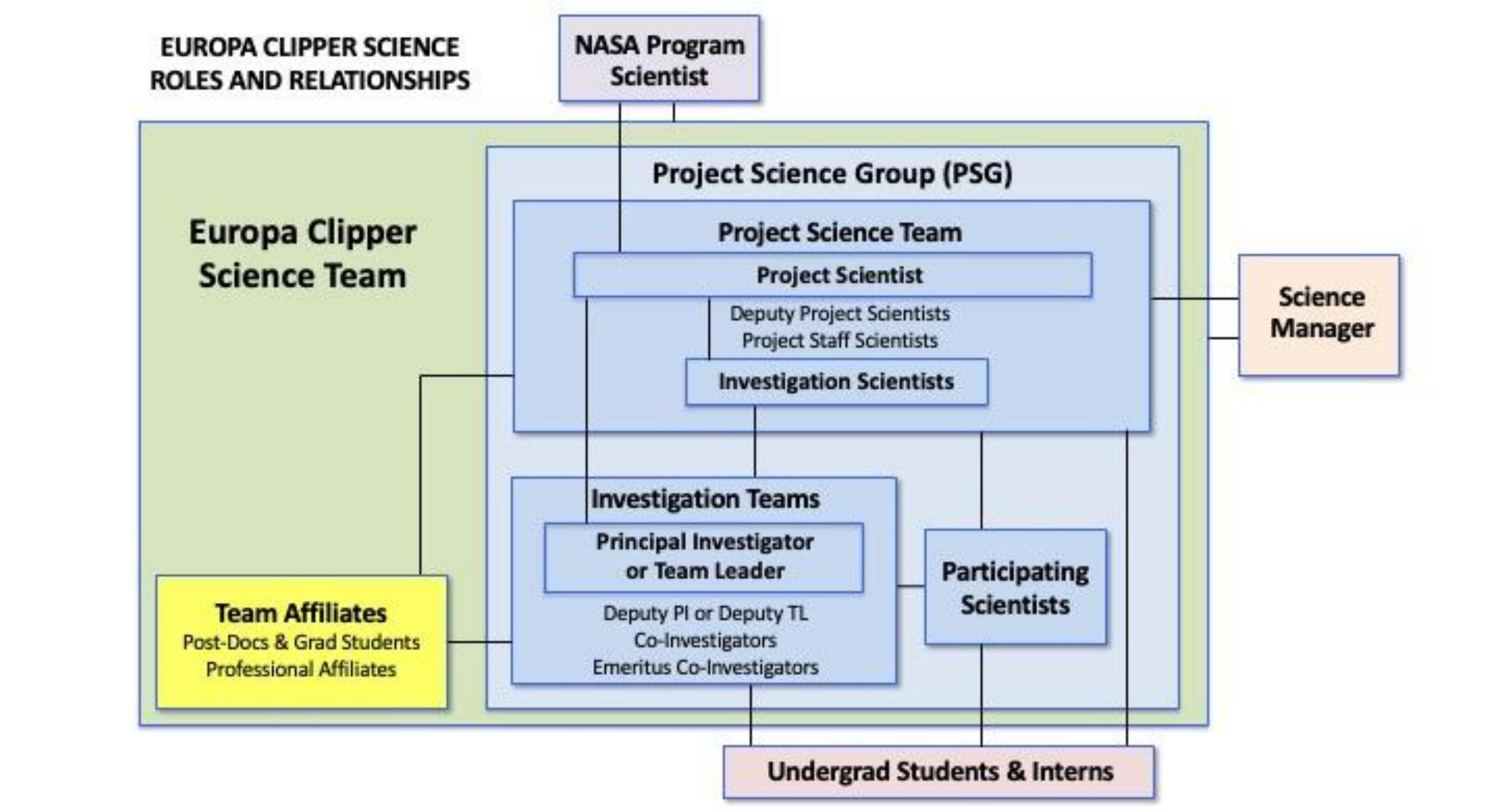



Gravity
Magnetometry + Plasma
Imaging
Infrared
Thermal
Radar
Ultraviolet


Gravity
Magnetometry + Plasma
Imaging
Infrared
Thermal
Radar
Ultraviolet
Gas + Dust Mass Spectroscopy

SCIENCE INFORMS THE NECESSARY TEAM STRUCTURE

- One single instrument cannot determine Europa's habitability.
- The goal of the Europa Clipper mission requires cross-investigation collaboration
  - Cross-investigation collaboration on a mission is not a given, the pathways must be put in place and used/practiced by the team
  - Collaborative team environment must be supported and nurtured (Rules of the Road!)
  - Also drives how we aim to operate the spacecraft in tour



SCIENCE INFORMS THE NECESSARY TEAM STRUCTURE

THEMATIC WORKING GROUPS (TWGs)

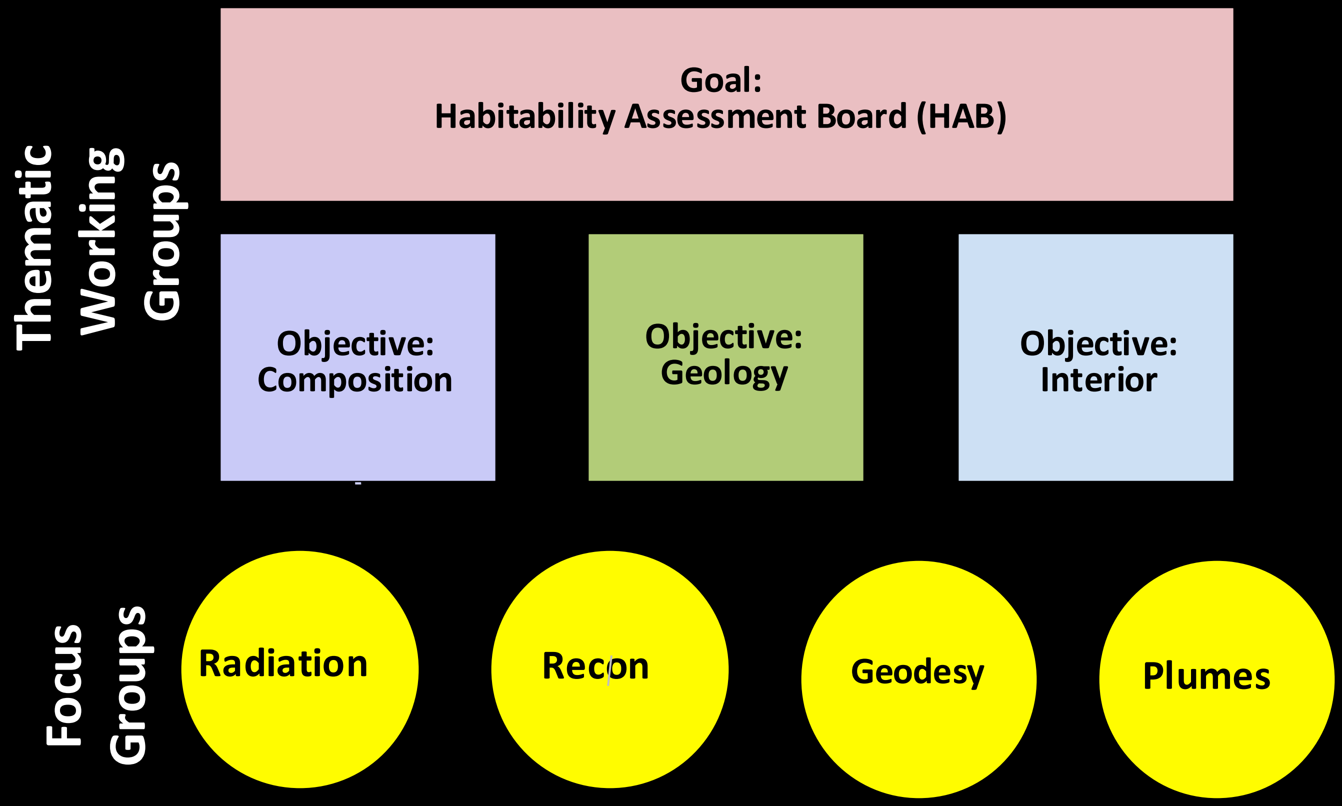
- Provide high-level, cross-instrument and cross-discipline science perspective, providing oversight of the mission's goal and objectives
- Coordinate Tour evaluation; lead Strategic Planning; coordinate cross-instrument science analyses and publications

FOCUS GROUPS (FGs)

- Consider and advocate cross-cutting science areas

MANAGEMENT STRUCTURE

- Rotating co-chairs funded to lead these groups, at regular remote meetings and full science team meetings
- Facilitators (project staff) provide expertise, aid logistics, and provide continuity to each group



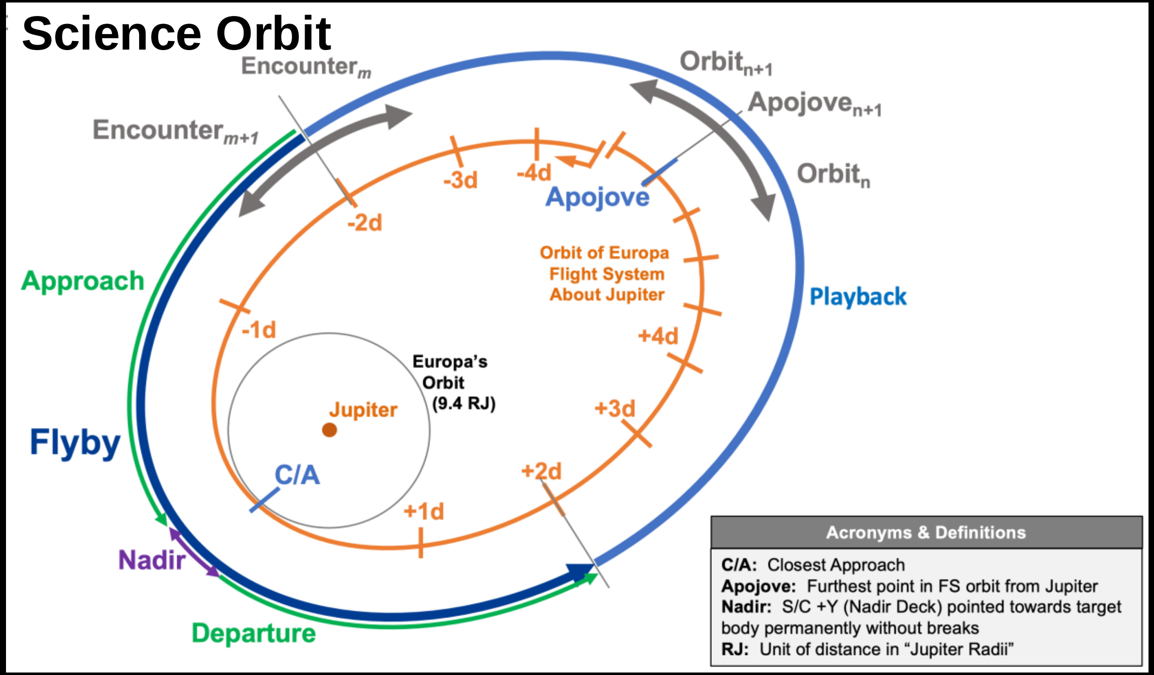
STRATEGIC SCIENCE PLANNING GUIDE (SSPG)

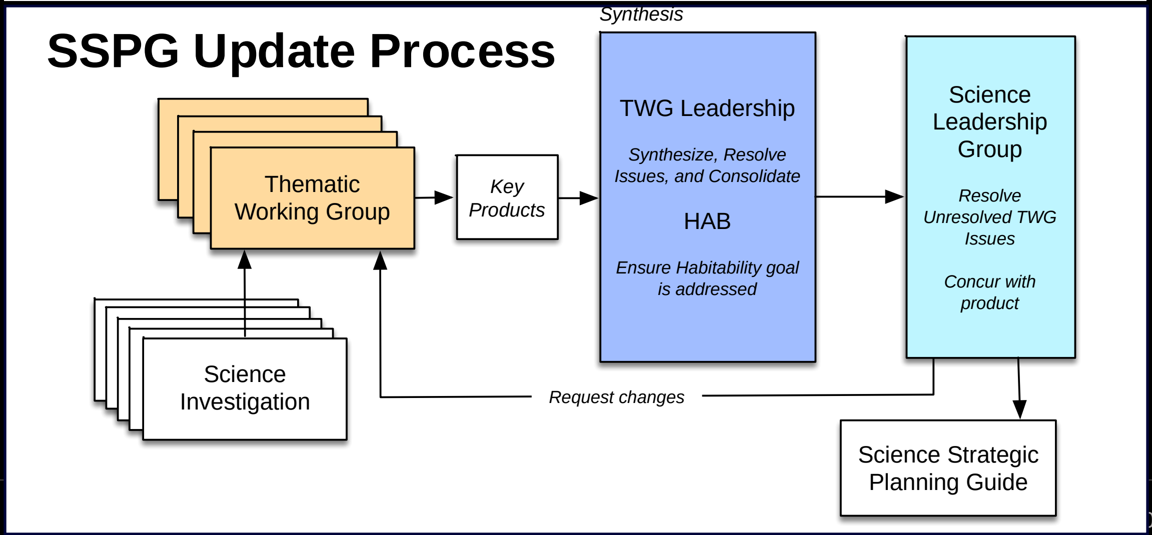
SSPG PURPOSE AND APPROACH

- Guides science-based resource use, as key interface between strategic and tactical operations
- Informs observation timeline development in cruise
- Investigation Teams provide initial input, then Thematic Working Groups filter through discipline-based synthesis
- Preliminary inputs now, revisited before JOI
- Nadir inputs focus on "sunny day" and "rainy day" because timeline incompatibilities are not expected, given synergistic flight system design
- Non-nadir inputs order science activities, toward addressing any potential timeline incompatibilities

HOLISTIC SCIENCE NECESSITATES HOLISTIC PLANNING

- Team-wide input works to prevent investigation team silos and orient the team toward achieving the unified goal of understanding habitability

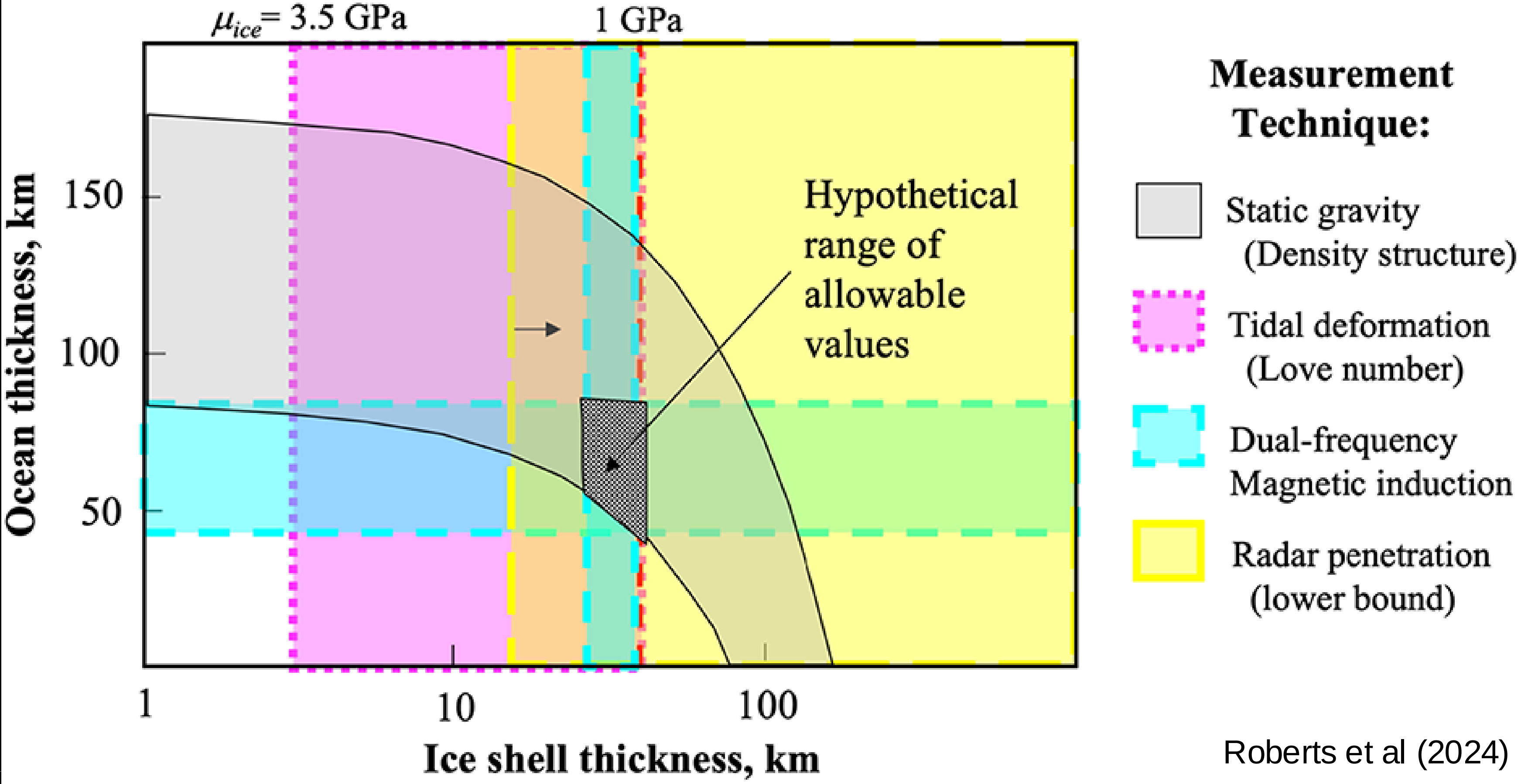




POTENTIAL DIGITAL TWIN APPLICATIONS

EUROPA

- Habitability is a very holistic topic. It will require understanding of many different and likely intertwined aspects of a dynamic system.
- Europa Clipper will produce a powerful synergistic datasets, but the interpretation of such datasets will not be simple.
- Example: Ice shell thickness
  - May look simple, but there is hidden interdependency (e.g., composition, ionosphere, etc.) in addition to variation from flyby to flyby combined with integrated datasets
  - This is just one aspect of the system that then needs to be combined with many others and incorporate spatial and temporal variations



Roberts et al (2024)

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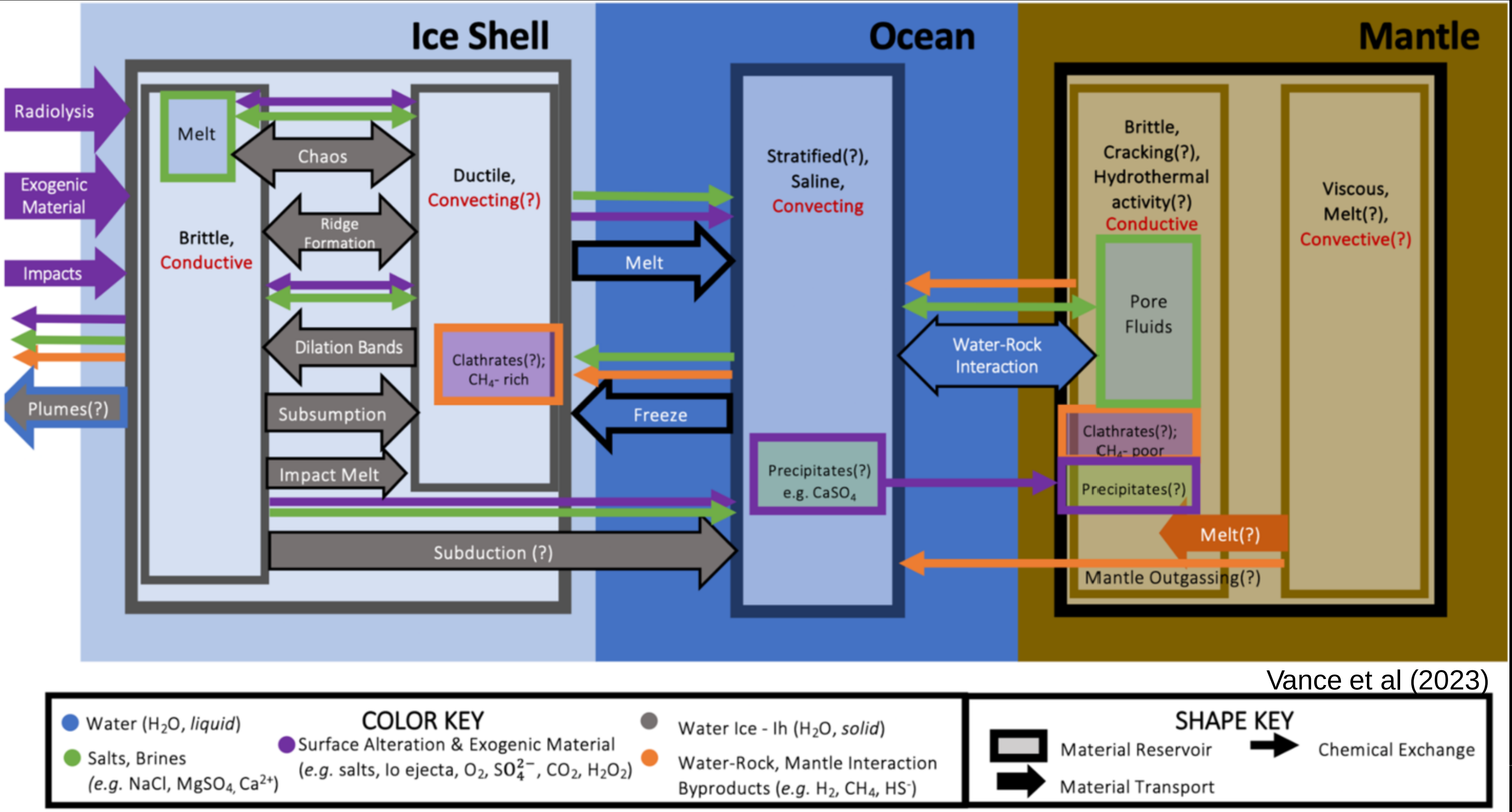


Vance et al (2023)

POTENTIAL DIGITAL TWIN APPLICATIONS

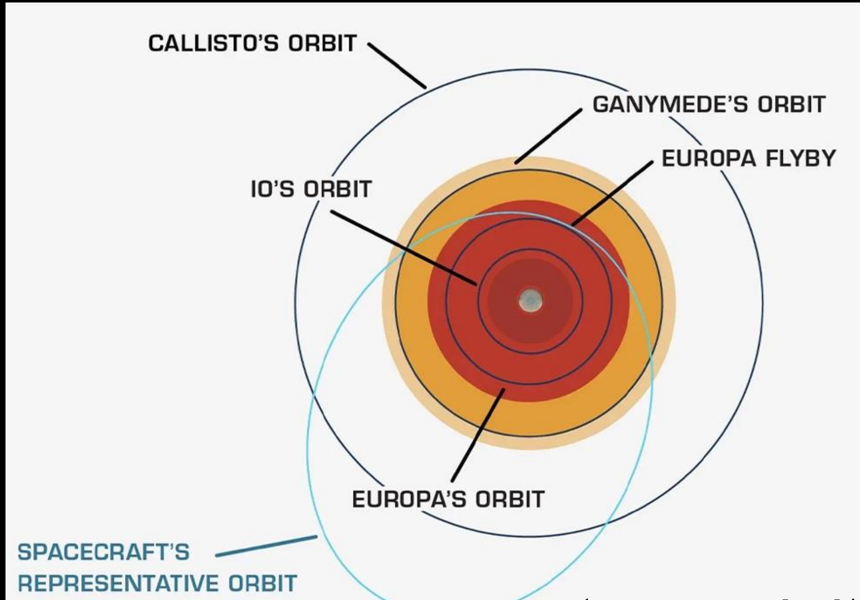
EUROPA CLIPPER (SPACECRAFT)

- The spacecraft and is designed to have simple operations: all of the instruments are on during every close approach to Europa and operations are simple and repeatable (e.g., non-targeted).
  - While in formulation and in Phases A-D, a Digital Twin would have aided in rapidly understanding how engineering decisions effect science return and trickle down effects on operations
  - In Phase E, optimizing operations, particularly in the non-nadir period, to maximize science return is still a challenge.
- The spacecraft is complex; parts failures can have significant trickle-down effects. MOSFETs are a prime example of this.

POTENTIAL DIGITAL TWIN APPLICATIONS

EUROPA CLIPPER (SPACECRAFT) continued

- MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors)
  - >1000 transistors are located all over the spacecraft. In May 2024 it was discovered that some were not as radiation hard as expected. Damage happens gradually, accumulates as the spacecraft mission progresses, and could potentially result in the electronic switches being stuck. There is no way to directly measure their degradation.
  - There are 200+ different applications: Different circuits, different part numbers, different thermal environments, different radiation exposure.
  - Monumental effort from the team over Summer 2024 (including testing, modeling, science evaluation, etc.) led to confidence that the mission will still be able to perform the full prime mission.
  - A new subsystem, the Canary Box contains MOSFETs of different applications and has the ability to monitor their degradation, but relating these to the rest of the spacecraft is a necessary task.
  - This issue is inherently tied to the ultimate science return of the mission as it has the potential to effect operations, extended mission potential, etc.
  - A Digital Twin could be very helpful in relating spacecraft MOSFETs to Canary Box MOSFETs to radiation data acquired in the system to understand implications for operations.



(NASA/JPL-Caltech)

TAKEAWAYS

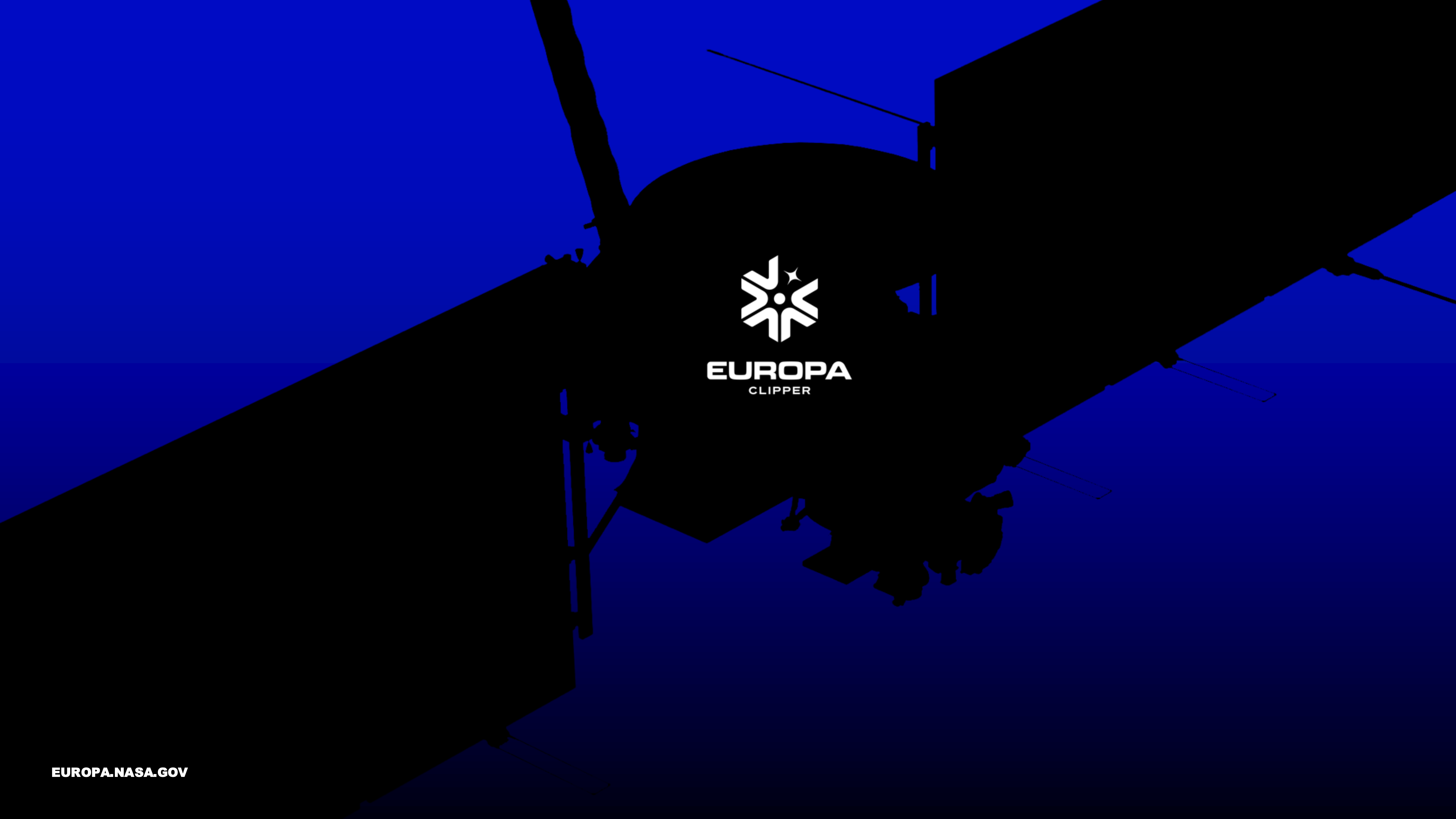
Europa Clipper – the scientific goal drives the structure of the mission and science team

- Answering questions about the habitability of a body requires a holistic approach and synergistic datasets.
- The spacecraft and the science team need to be structured in a way that enables this sort of science to be achieved to its full capacity.

Potential Digital Twin applications for Europa and Europa Clipper

- The spacecraft could have benefited from a Digital Twin in the design phase and build phases to relate how decisions being made on the engineering side would flow down to science
  - Late-breaking parts issue (e.g., MOSFETs) is a direct application of a Digital Twin of the spacecraft that would still impact the science and operations of the spacecraft while at target
- The science of Europa Clipper would also benefit from Digital Twin of Europa. The synergistic abilities of the datasets may only be able to be fully explored by something like a Digital Twin

Europa Clipper's goal of understanding habitability requires system science and the integration of diverse but synergistic datasets, which is mirrored in the mission design and operation plan. Europa Clipper and similar missions would benefit from Digital Twin applications.



EUROPA.NASA.GOV