Voyager 1 view of Io over Jupiter (NASA / JPL-Caltech / Alexis Tranchandon)

Io Science

James Tuttle Keane
james.t.keane@jpl.nasa.gov I @jtuttlekeane I he/him/his

Jet Propulsion Laboratory
California Institute of Technology

1 APRIL 2020

SPRING MEETING OF THE COMMITTEE ON ASTROBIOLOGY AND PLANETARY SCIENCE (CAPS)

NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE SPACE STUDIES BOARD

OUTLINE

— A primer on Io.

— The science rationale for exploring Io.

— What did *Vision and Voyages* say?

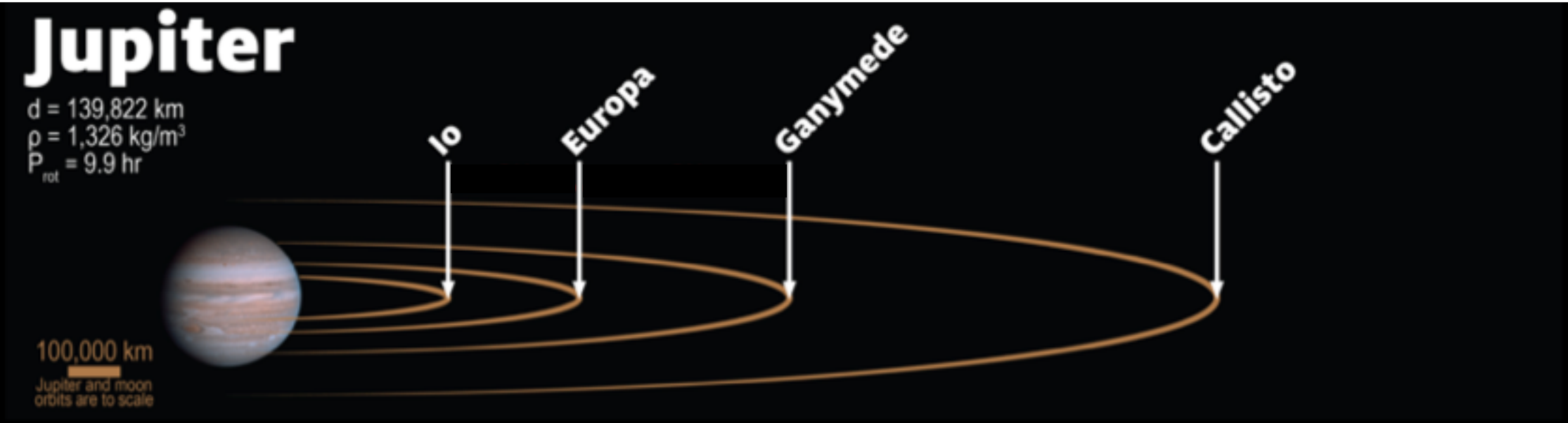
— What's changed since *Vision and Voyages*?

— *Io Volcano Observer*.

— Discovery vs. New Frontiers.

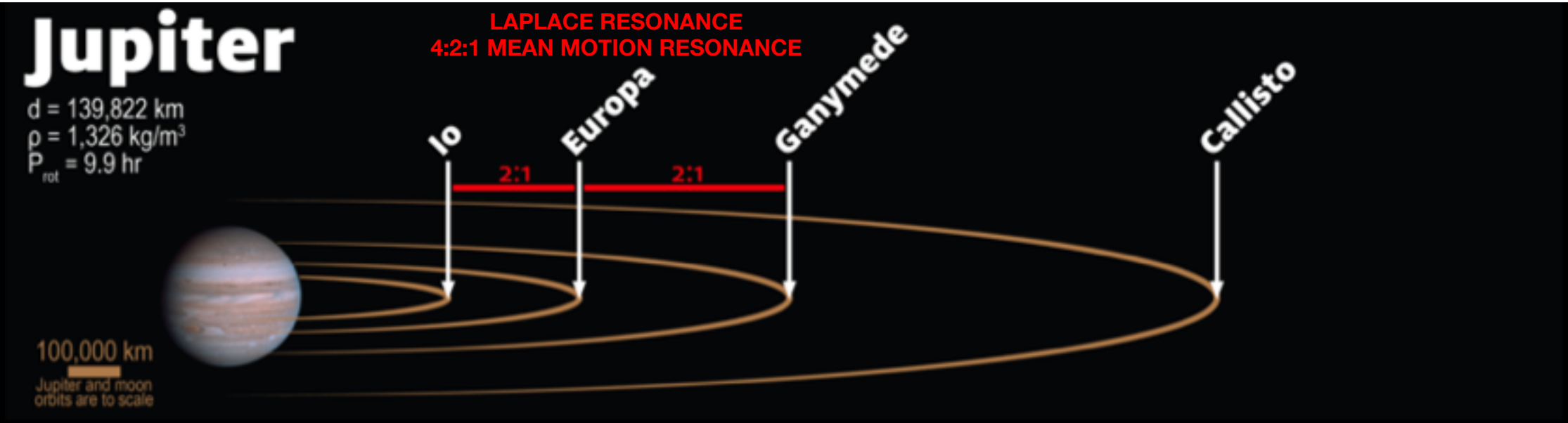
— Conclusion.

A PRIMER ON IO: JUPITER'S VOLCANIC MOON



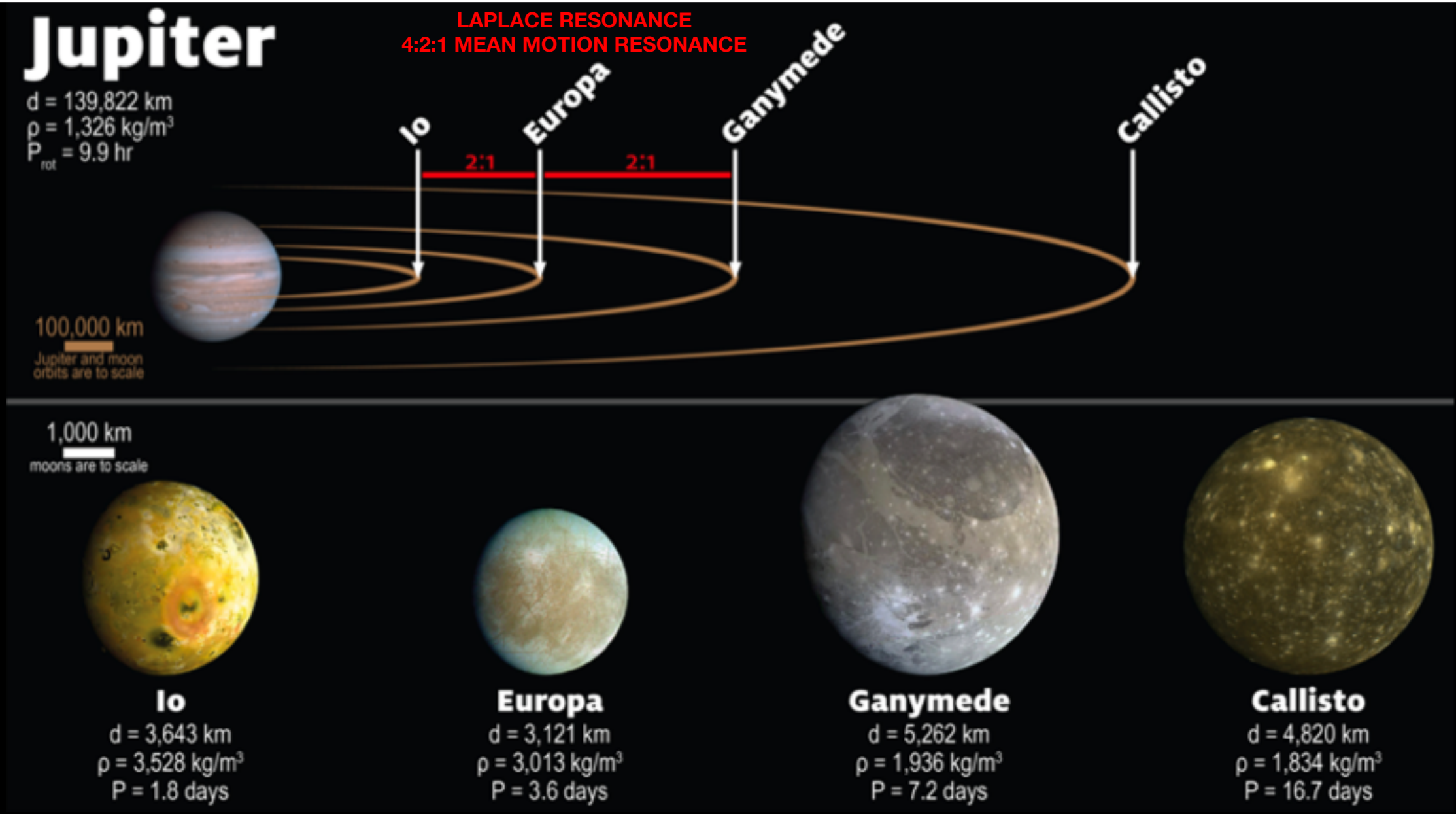
(NASA / JPL-Caltech / Voyager-ISS / Justin Cowart / Kevin M. Gill / Emily Lakdawalla / Jason Perry / Ted Stryk / Gordan Ugarkovic / Keck Institute for Space Studies /James T. Keane)

A PRIMER ON IO: JUPITER'S VOLCANIC MOON



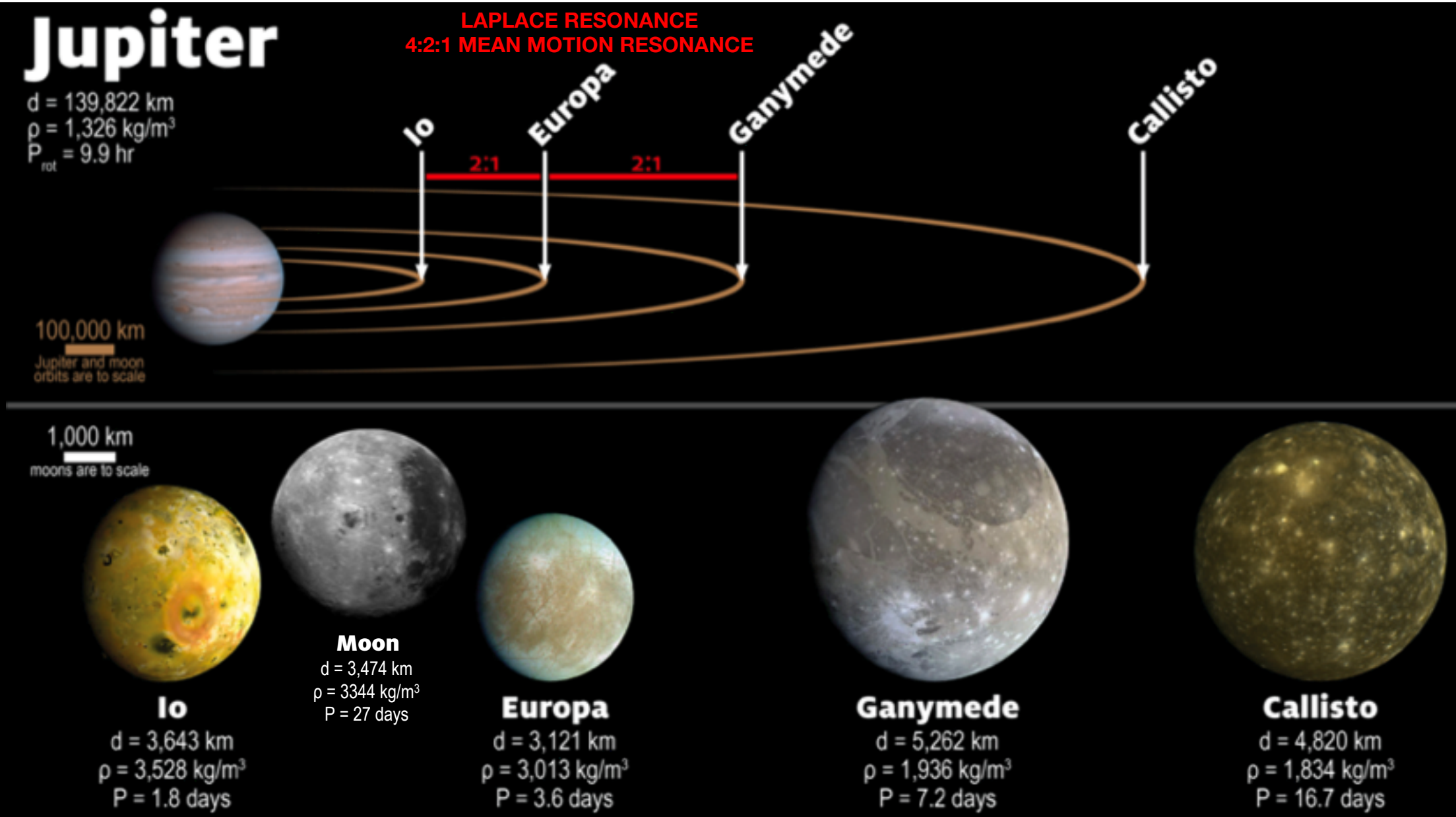
(NASA / JPL-Caltech / Voyager-ISS / Justin Cowart / Kevin M. Gill / Emily Lakdawalla / Jason Perry / Ted Stryk / Gordan Ugarkovic / Keck Institute for Space Studies /James T. Keane)

A PRIMER ON IO: JUPITER'S VOLCANIC MOON



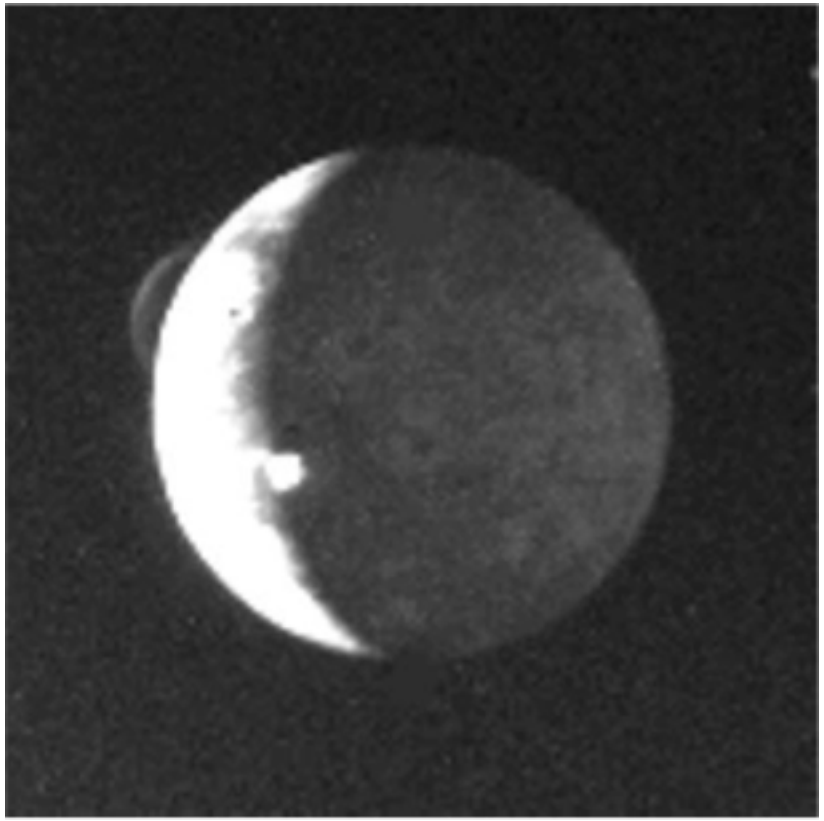
(NASA / JPL-Caltech / Voyager-ISS / Justin Cowart / Kevin M. Gill / Emily Lakdawalla / Jason Perry / Ted Stryk / Gordan Ugarkovic / Keck Institute for Space Studies /James T. Keane)

A PRIMER ON IO: JUPITER'S VOLCANIC MOON



(NASA / JPL-Caltech / Voyager-ISS / Justin Cowart / Kevin M. Gill / Emily Lakdawalla / Jason Perry / Ted Stryk / Gordan Ugarkovic / Keck Institute for Space Studies /James T. Keane)

A PRIMER ON IO: JUPITER'S VOLCANIC MOON

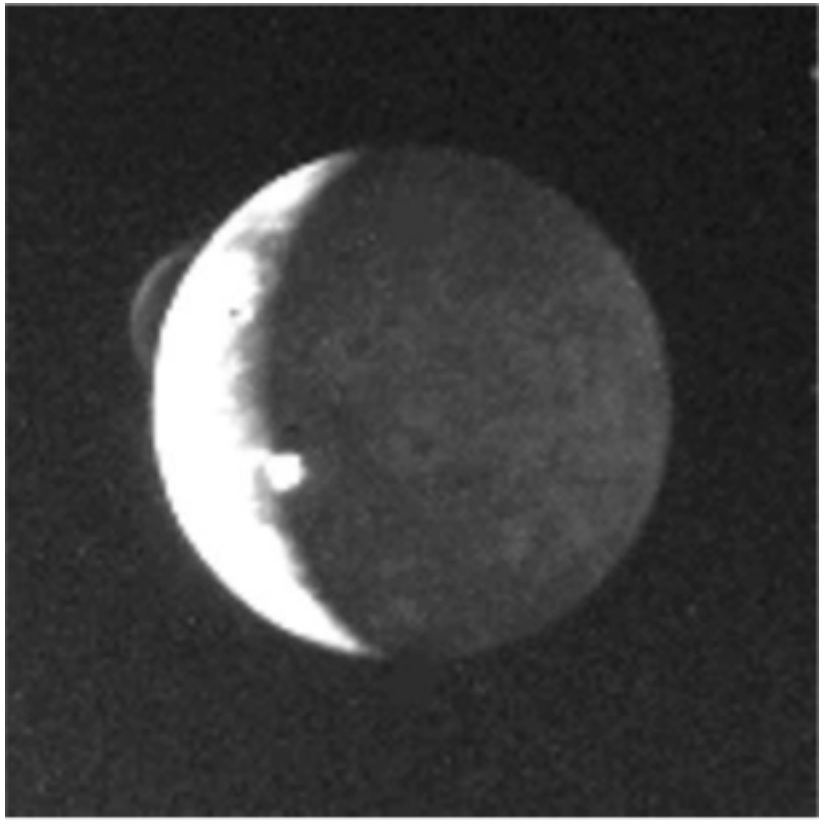


↑ *Voyager 1* discovery image if active volcanism and plumes on Io (NASA/JPL)

Peale et al.
"Melting of Io by tidal dissipation"
Science 203, 892-894 (2 Mar. 1979)

Morabito et al.
"Discovery of currently active extraterrestrial volcanism"
Science 204, 972 (1 Jun. 1979)

A PRIMER ON IO: JUPITER'S VOLCANIC MOON



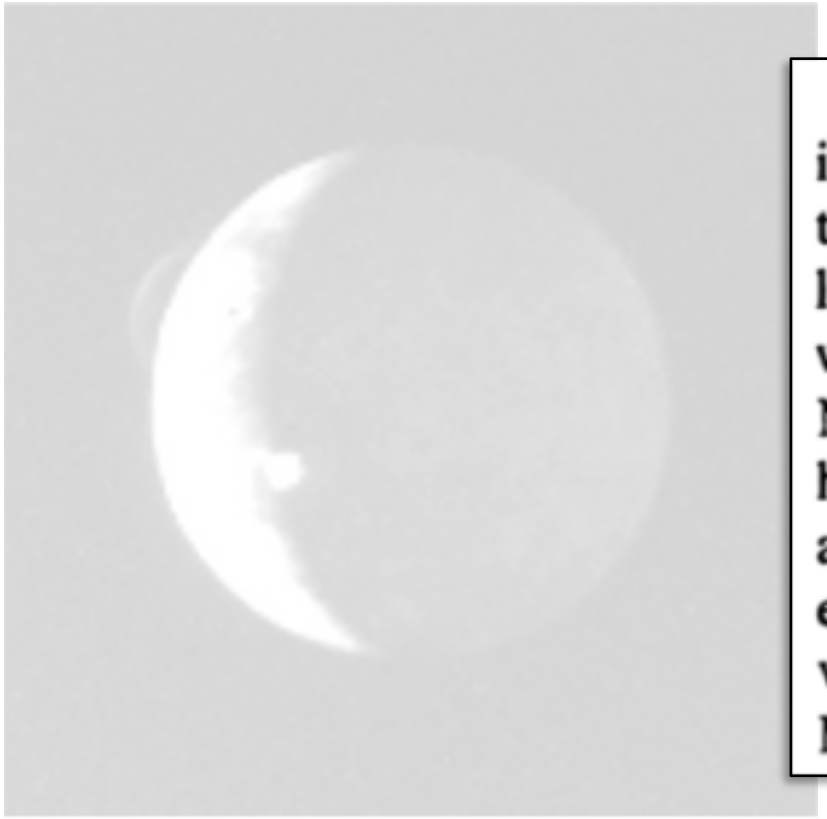
↑ *Voyager 1* discovery image if active volcanism and plumes on Io (NASA/JPL)

Witteborn et al.
"Io: an intense brightening near 5 micrometers"
Science 203, 643-646 (16 Feb. 1979)

Peale et al.
"Melting of Io by tidal dissipation"
Science 203, 892-894 (2 Mar. 1979)

Morabito et al.
"Discovery of currently active extraterrestrial volcanism"
Science 204, 972 (1 Jun. 1979)

A PRIMER ON IO: JUPITER'S VOLCANIC MOON



↑ *Voyager 1* discovery image if active volcanism and plumes on Io (NASA/JPL)

Reports

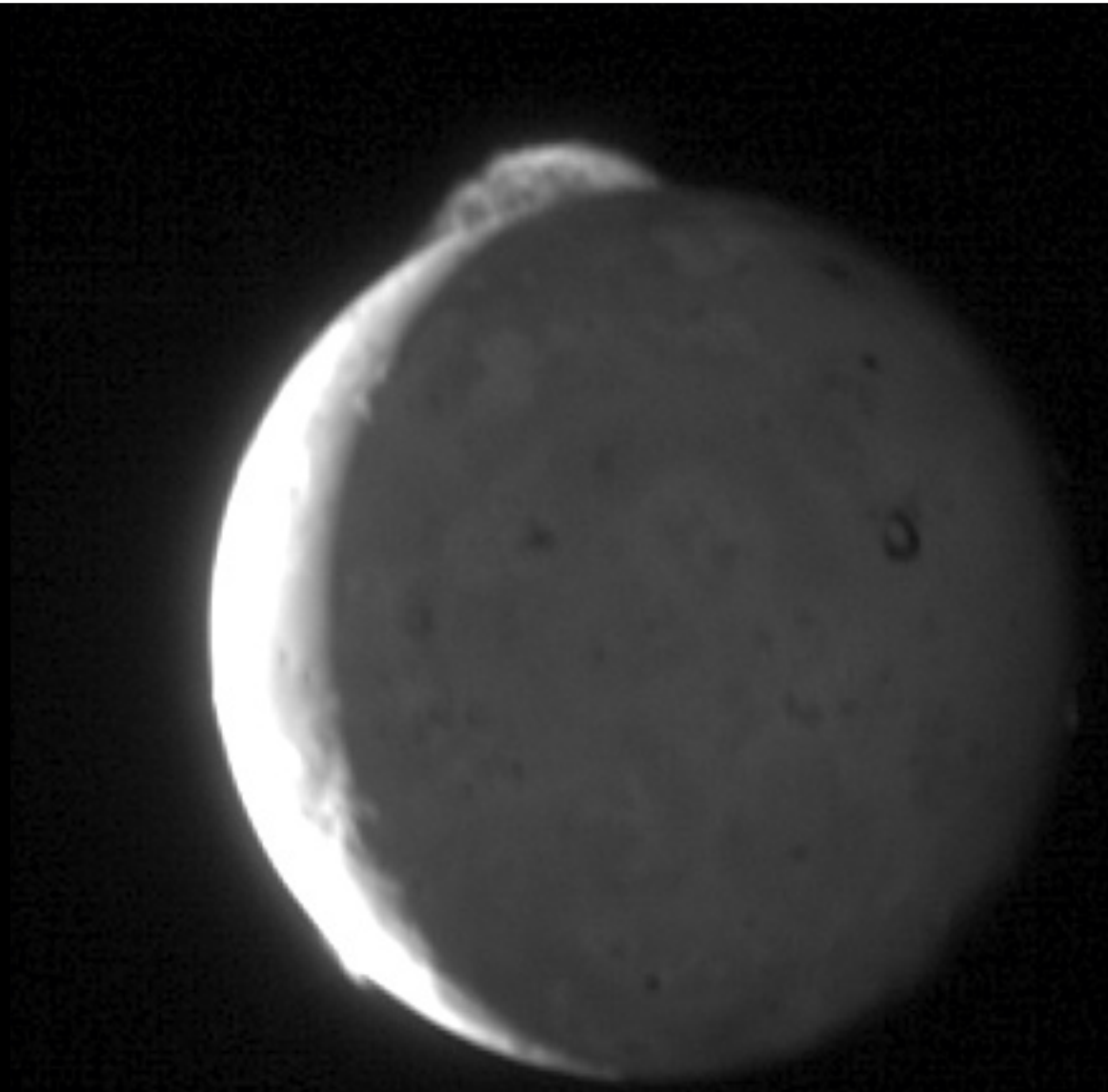
Although it is not possible to definitively rule out this explanation, we consider it to be unlikely by analogy with our experience with objects in the inner solar system. No such internally generated hot spot having the approximate size and temperature of the one postulated for Io has ever been observed on global infrared surveys of Earth, the moon, Mercury, or Mars (*11*).

Witteborn et al.
"Io: an intense brightening near 5 micrometers"
Science 203, 643-646 (16 Feb. 1979)

Peale et al.
"Melting of Io by tidal dissipation"
Science 203, 892-894 (2 Mar. 1979)

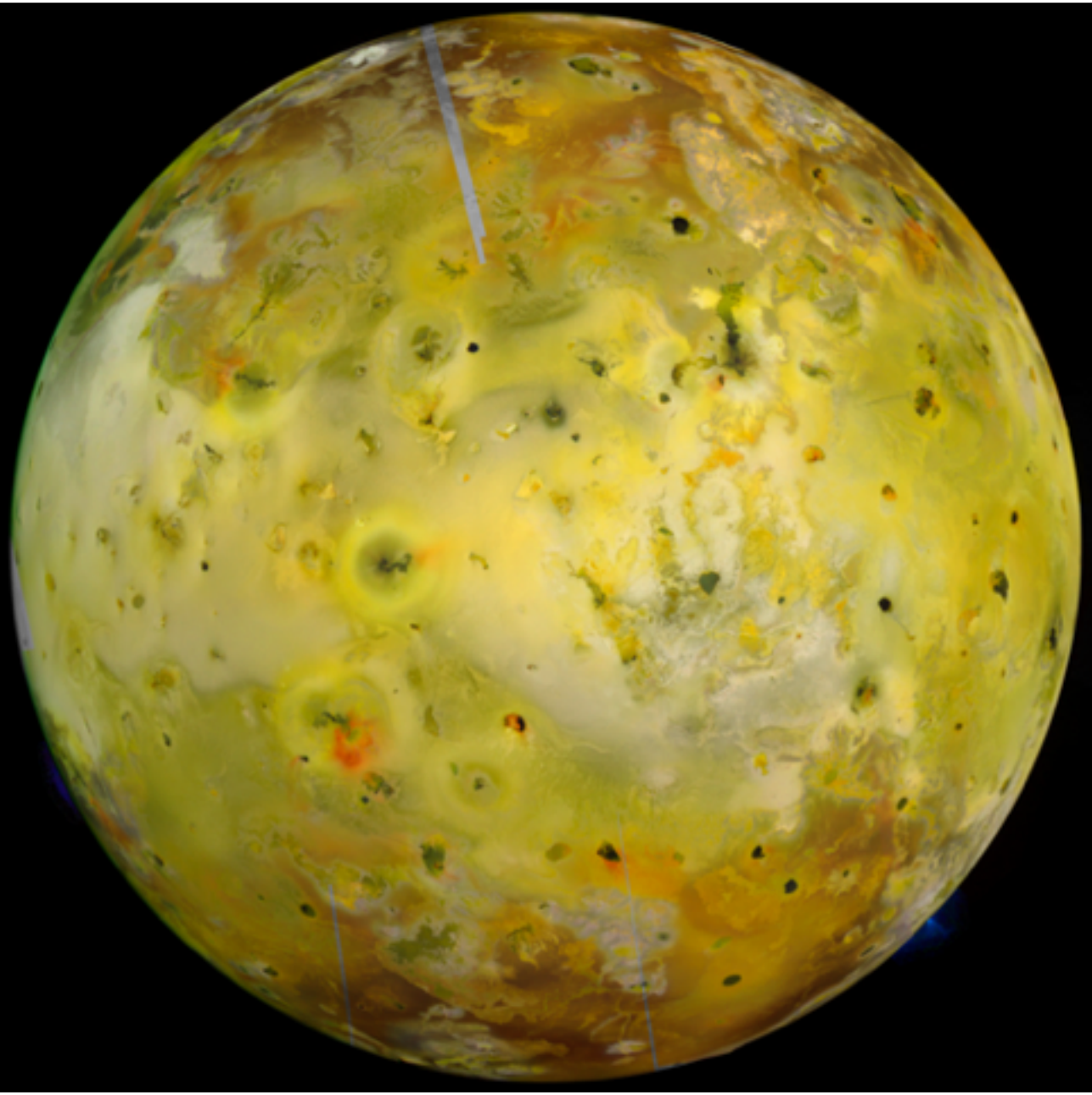
Morabito et al.
"Discovery of currently active extraterrestrial volcanism"
Science 204, 972 (1 Jun. 1979)

A PRIMER ON IO: JUPITER'S VOLCANIC MOON



← *New Horizons* movie of the Tvashtar plume, during its 2007Jupiter flyby (NASA / JHUAPL / SwRI)

A PRIMER ON IO: JUPITER'S VOLCANIC MOON



← *Galileo* image mosaic of Io's anti-Jovian hemisphere (NASA / JPL / Jason Perry)

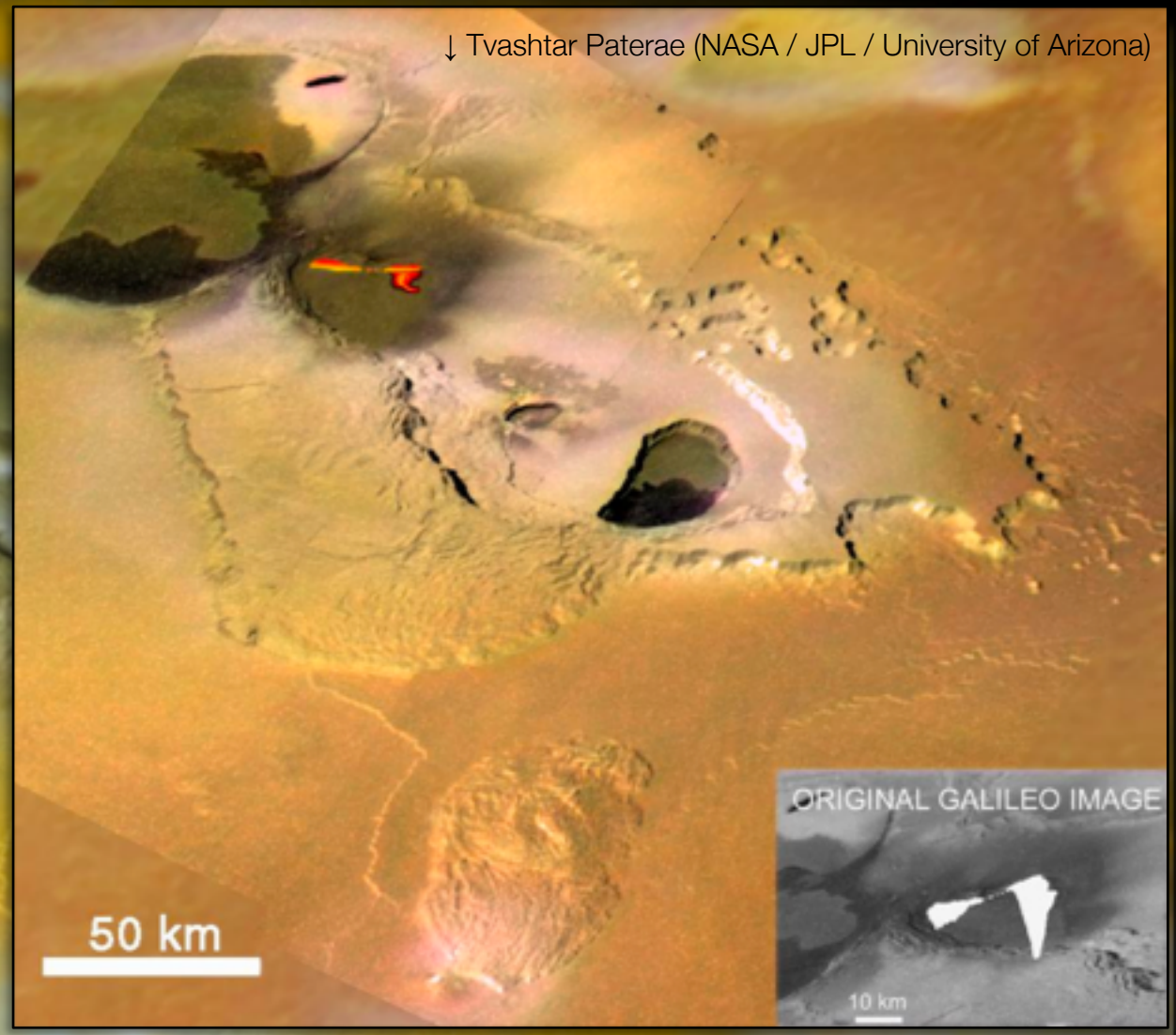
A PRIMER ON IO: JUPITER'S VOLCANIC MOON

↑ Tvashtar Paterae (NASA / JPL / Ricardo Nunes)

A PRIMER ON IO: JUPITER'S VOLCANIC MOON

50 km

↓ Tvashtar Paterae (NASA / JPL / University of Arizona)



↑ Tvashtar Paterae (NASA / JPL / Ricardo Nunes)

CROSS-CUTTING THEMES OF IO EXPLORATION

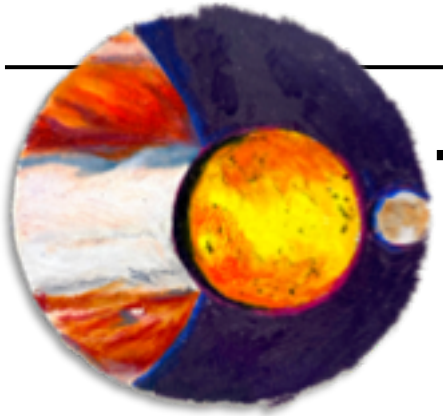
1. TIDAL HEATING

2. HIGH HEAT FLOW

3. EXTREME VOLCANISM

4. DYNAMIC ATMOSPHERE

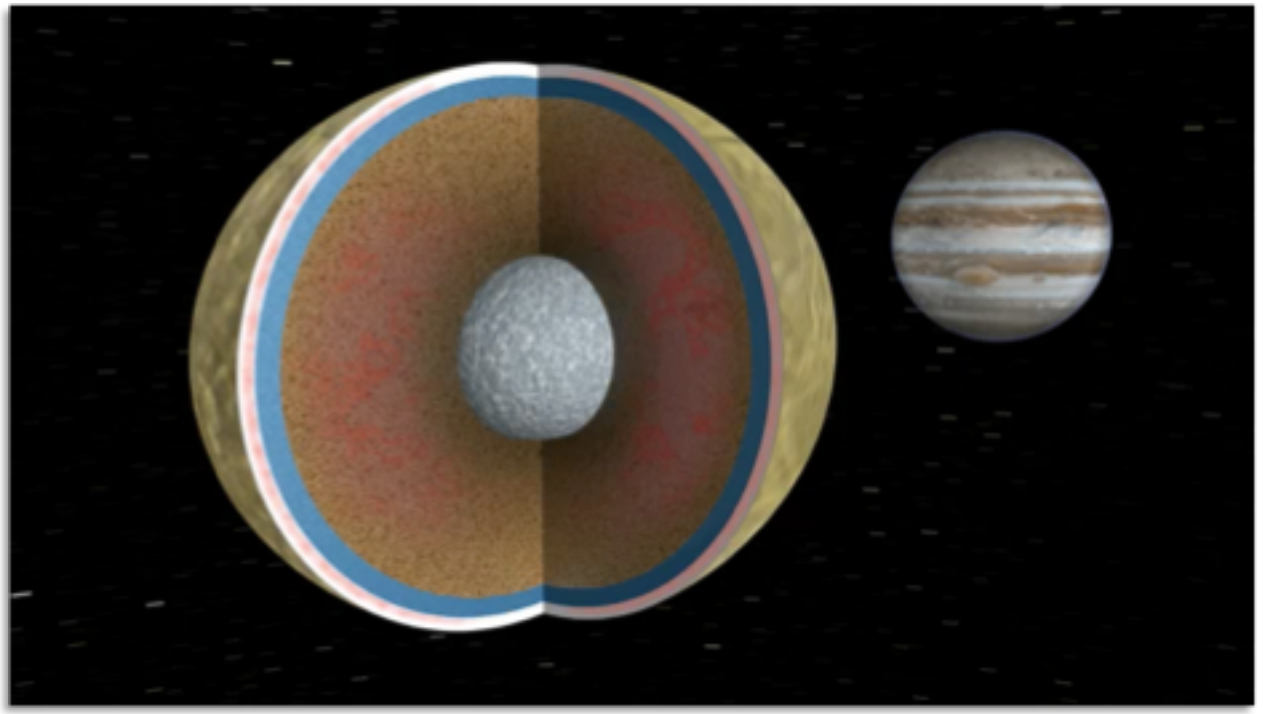
5. MAGNETOSPHERIC INTERACTIONS



CROSS-CUTTING THEME #1:

TIDAL HEATING

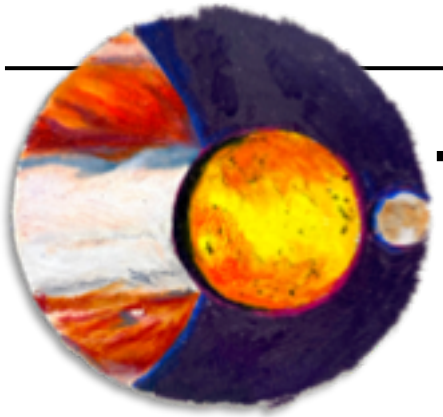
Io is the best place in the solar system to study tidal heating—a critical process for shaping planetary bodies and creating habitable environments across the cosmos.



→
Tidal flexing animation of Europa (NASA / JPL-Caltech)

PRIORITY SCIENCE QUESTIONS:

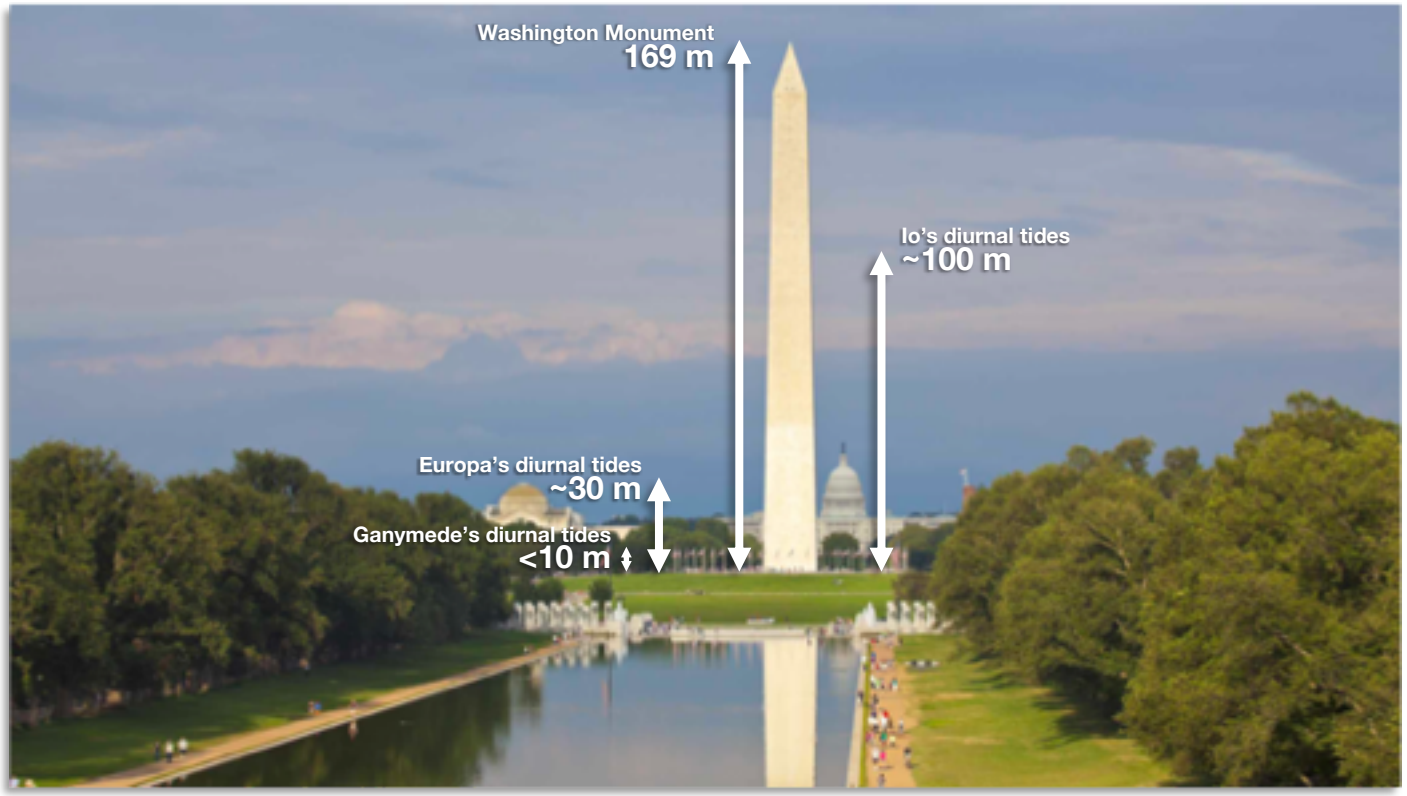
- *What is the magnitude and spatial distribution of Io's heat flow?*
- *What is Io's interior structure and does it have a magma ocean?*
- *Where and how is tidal heat dissipated in the interior?*
- *How is Io being tidally deformed?*
- *What are the present-day orbital migration rates of the Galilean satellites, and is the system in equilibrium?*
- *How does tidal heating shape crustal structure?*



CROSS-CUTTING THEME #1:

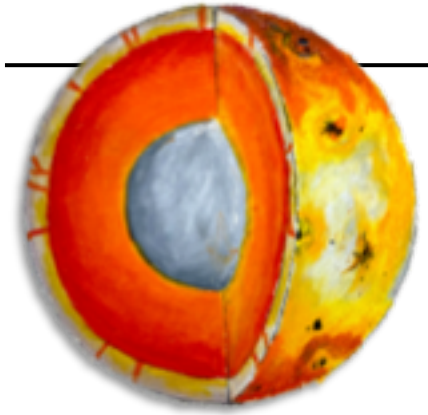
TIDAL HEATING

Io is the best place in the solar system to study tidal heating—a critical process for shaping planetary bodies and creating habitable environments across the cosmos.



PRIORITY SCIENCE QUESTIONS:

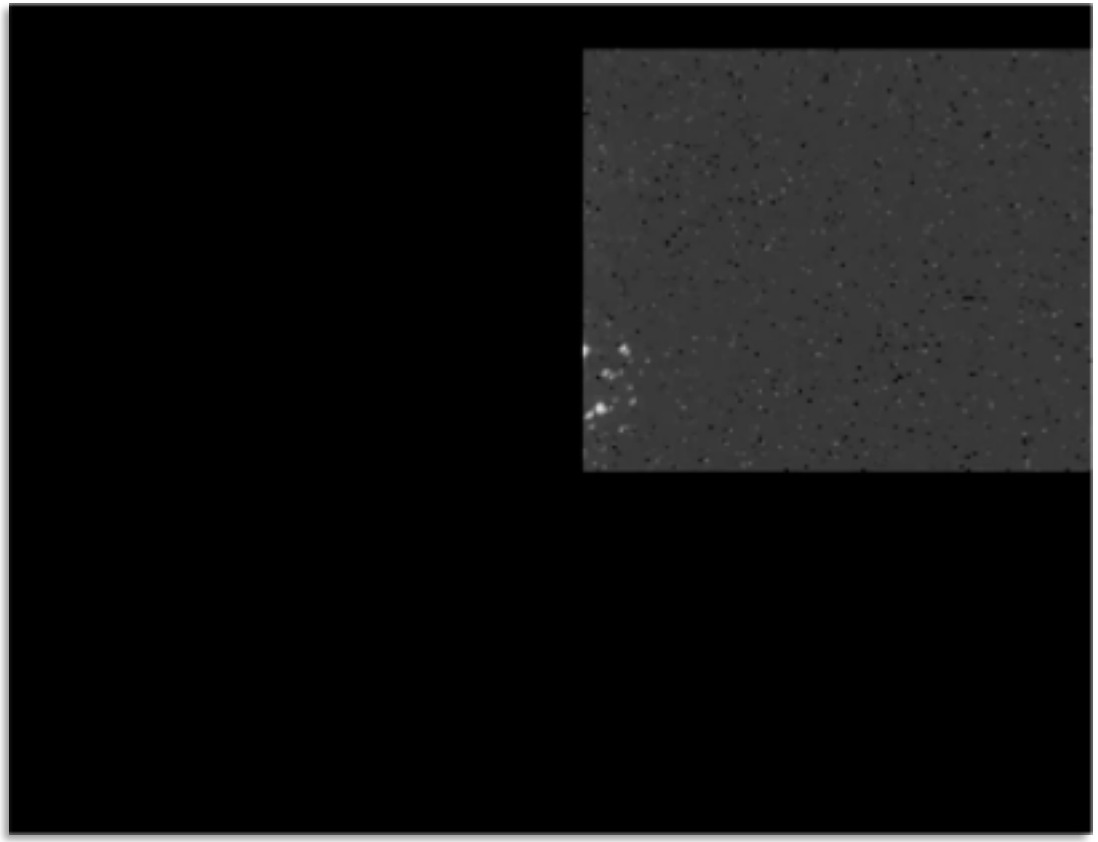
- *What is the magnitude and spatial distribution of Io's heat flow?*
- *What is Io's interior structure and does it have a magma ocean?*
- *Where and how is tidal heat dissipated in the interior?*
- *How is Io being tidally deformed?*
- *What are the present-day orbital migration rates of the Galilean satellites, and is the system in equilibrium?*
- *How does tidal heating shape crustal structure?*



CROSS-CUTTING THEME #2:

HIGH HEAT FLOW

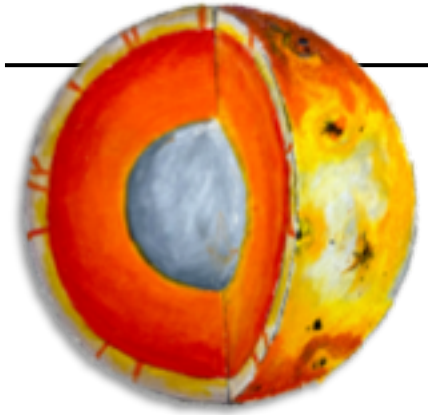
Io is a living example of how rocky planets respond to extreme heating, akin to the Earth when life first emerged.



→
Juno JIRAM observations of Io entering eclipse, December 2018 (NASA / JPL-Caltech / SwRI / ASI / INAF / JIRAM / J. Roger / @landru79)

PRIORITY SCIENCE QUESTIONS:

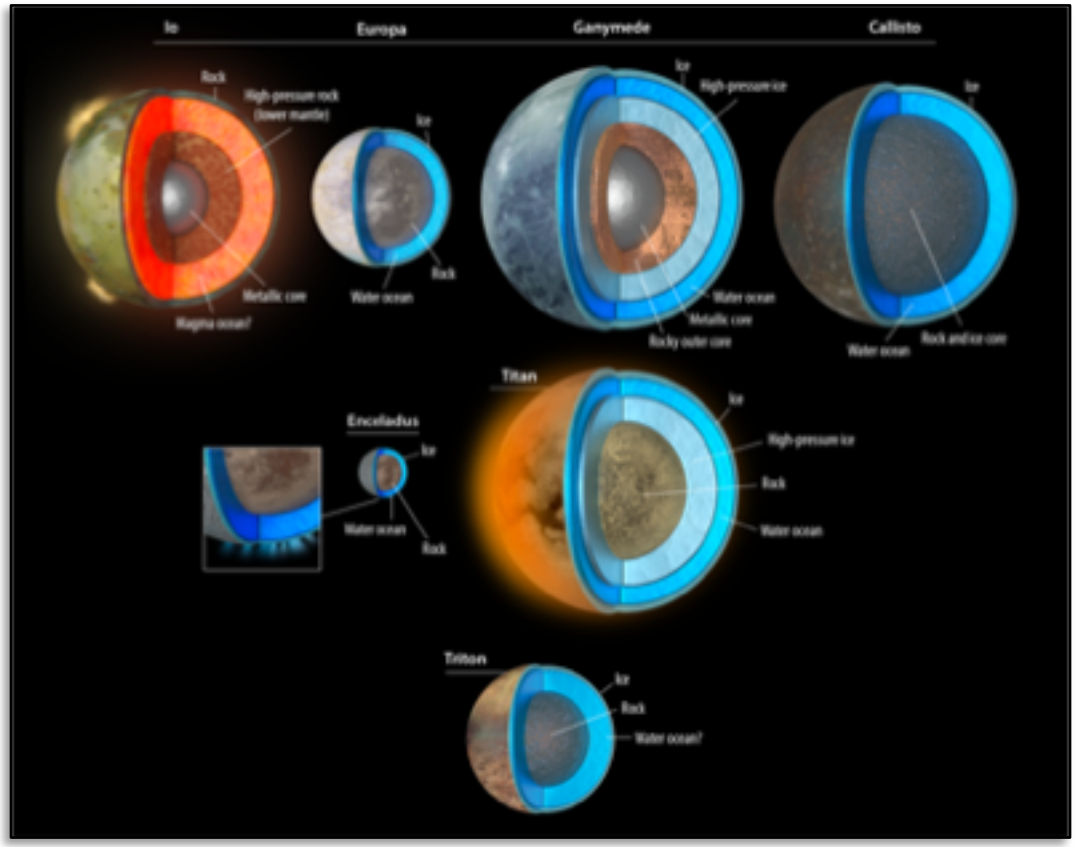
- *How does Io lose its internal heat, and what is the balance between heat loss mechanisms (conduction, heat-pipe volcanism, etc.)?*
- *How do volcanic eruptions and their characteristics relate to the deep interior?*
- *What is the thickness, composition, and stress-state of Io's lithosphere?*
- *Does Io have an internally-driven magnetic field?*
- *Can stable isotopes inform long-term evolution of Io?*



CROSS-CUTTING THEME #2:

HIGH HEAT FLOW

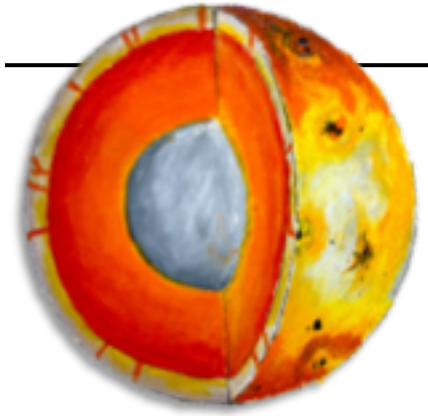
Io is a living example of how rocky planets respond to extreme heating, akin to the Earth when life first emerged.



→
The solar system's ocean worlds; scale of interior layers are only approximate (Chuck Carter / James T. Keane / Keck Institute for Space Studies)

PRIORITY SCIENCE QUESTIONS:

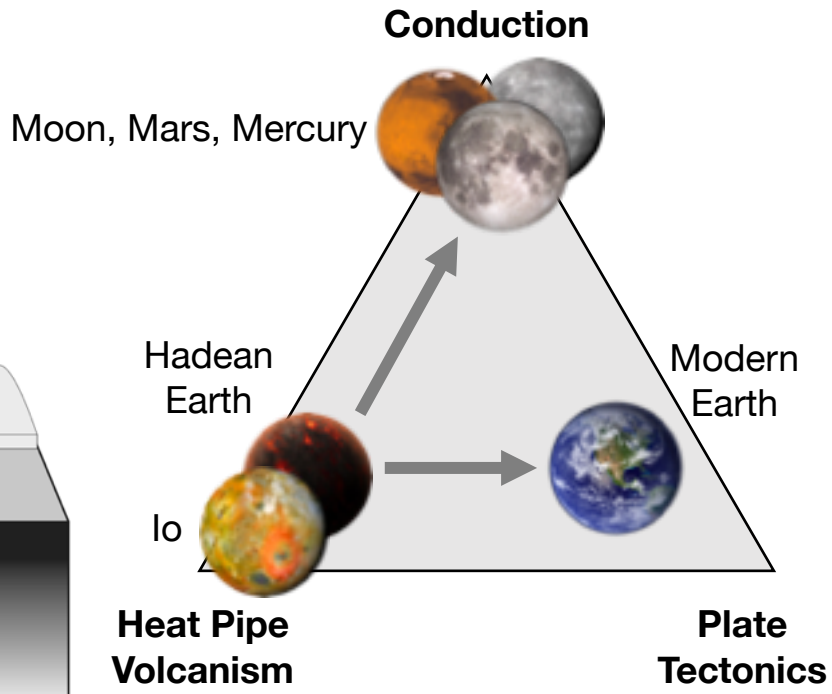
- *How does Io lose its internal heat, and what is the balance between heat loss mechanisms (conduction, heat-pipe volcanism, etc.)?*
- *How do volcanic eruptions and their characteristics relate to the deep interior?*
- *What is the thickness, composition, and stress-state of Io's lithosphere?*
- *Does Io have an internally-driven magnetic field?*
- *Can stable isotopes inform long-term evolution of Io?*



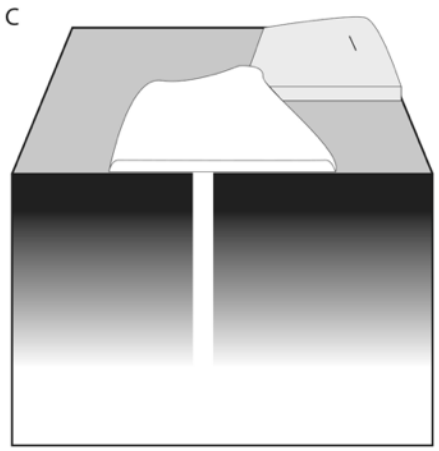
CROSS-CUTTING THEME #2:

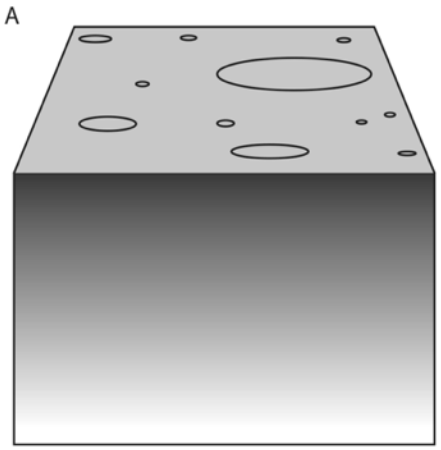
HIGH HEAT FLOW

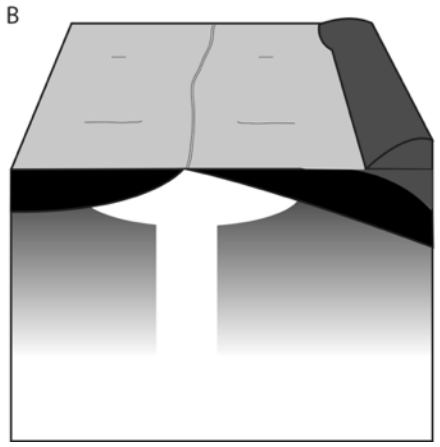
Io is a living example of how rocky planets respond to extreme heating, akin to the Earth when life first emerged.



End-members for planetary heat loss
(Lauren Jozwiak, James T. Keane)







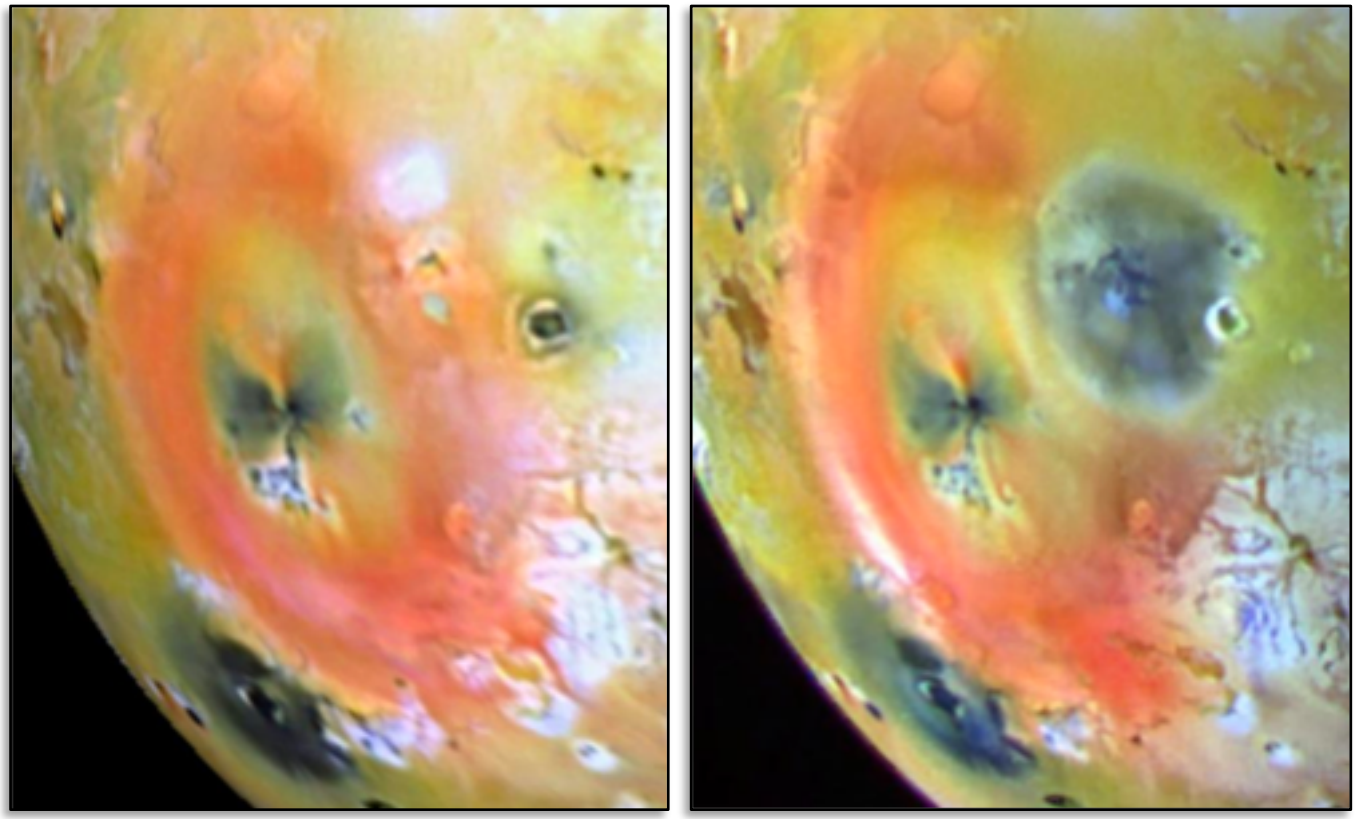
PRIORITY SCIENCE QUESTIONS:

- *How does Io lose its internal heat, and what is the balance between heat loss mechanisms (conduction, heat-pipe volcanism, tectonics)?*
- *How do volcanic eruptions and their characteristics relate to the deep interior?*
- *What is the thickness, composition, and stress-state of Io's lithosphere?*
- *Does Io have an internally-driven magnetic field?*
- *Can stable isotopes inform long-term evolution of Io?*

CROSS-CUTTING THEME #3:

EXTREME VOLCANISM

Io is the most volcanically active world in the solar system, and it is a window into volcanic processes both familiar and exotic.



→ *Galileo* images of Pele and Pillan, six months apart (NASA / JPL / University of Arizona)

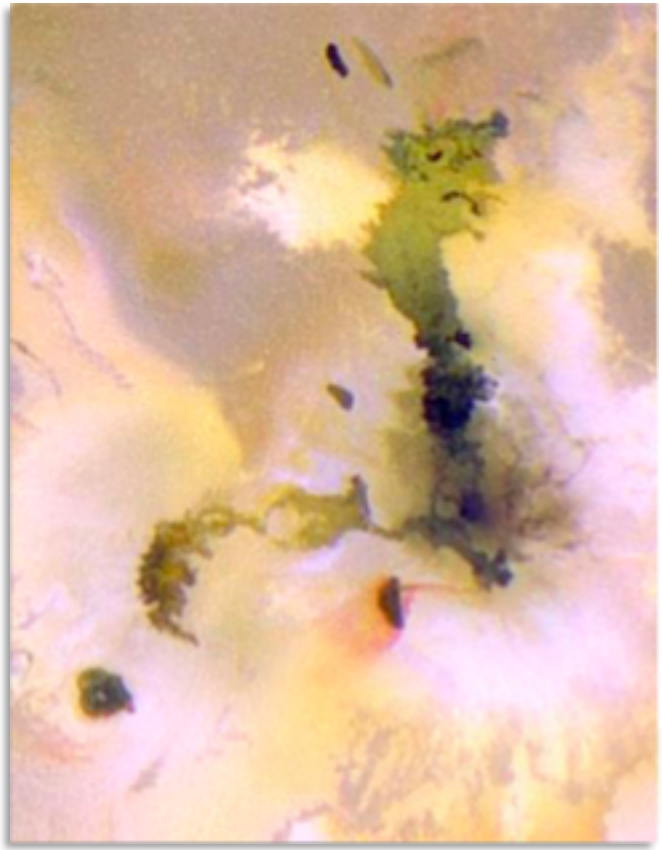
PRIORITY SCIENCE QUESTIONS:

- *What is the composition and chemistry of Io's magmas?*
- *How does volcanism operate in extreme environments?*
- *How do Io's large volcanic edifices (paterae) form?*
- *What processes create and destroy Io's mountains?*
- *How do tectonism and magmatism interact on both global and local scales?*
- *How do Io's plumes operate, and what can they tell us about Io's interior processes?*

CROSS-CUTTING THEME #3:

EXTREME VOLCANISM

Io is the most volcanically active world in the solar system, and it is a window into volcanic processes both familiar and exotic.



→
Amirani-Maui (NASA / JPL / University of Arizona)

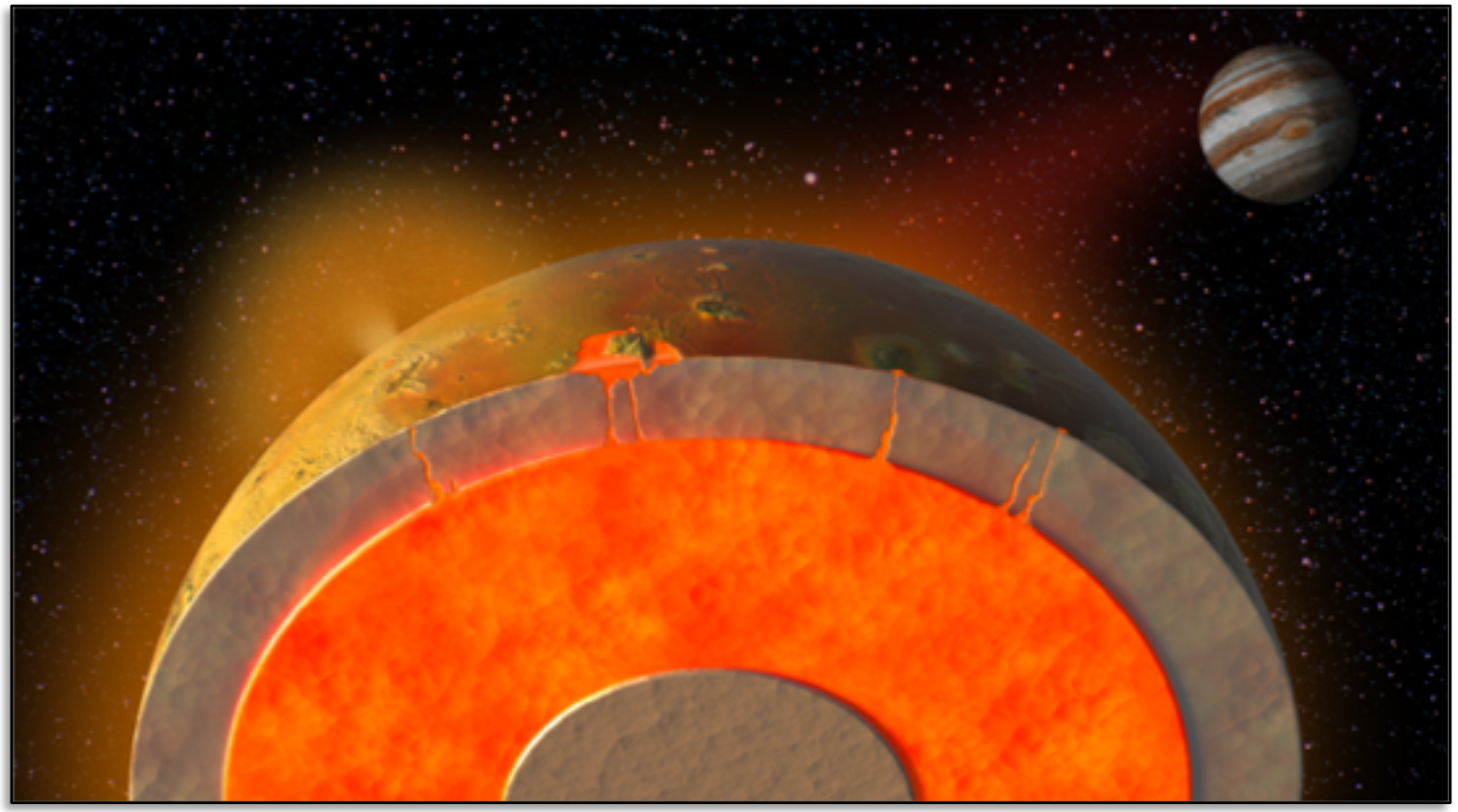
PRIORITY SCIENCE QUESTIONS:

- *What is the composition and chemistry of Io's magmas?*
- *How does volcanism operate in extreme environments?*
- *How do Io's large volcanic edifices (paterae) form?*
- *What processes create and destroy Io's mountains?*
- *How do tectonism and magmatism interact on both global and local scales?*
- *How do Io's plumes operate, and what can they tell us about Io's interior processes?*

CROSS-CUTTING THEME #4:

DYNAMIC ATMOSPHERE

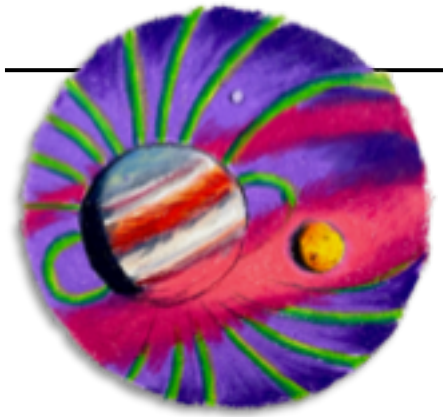
Io's atmosphere is unlike any other, with a rich array of interactions that test our understanding of fundamental planetary science.



→ *Io's dynamic atmosphere (Chuck Carter / James T. Keane / Keck Institute for Space Studies)*

PRIORITY SCIENCE QUESTIONS:

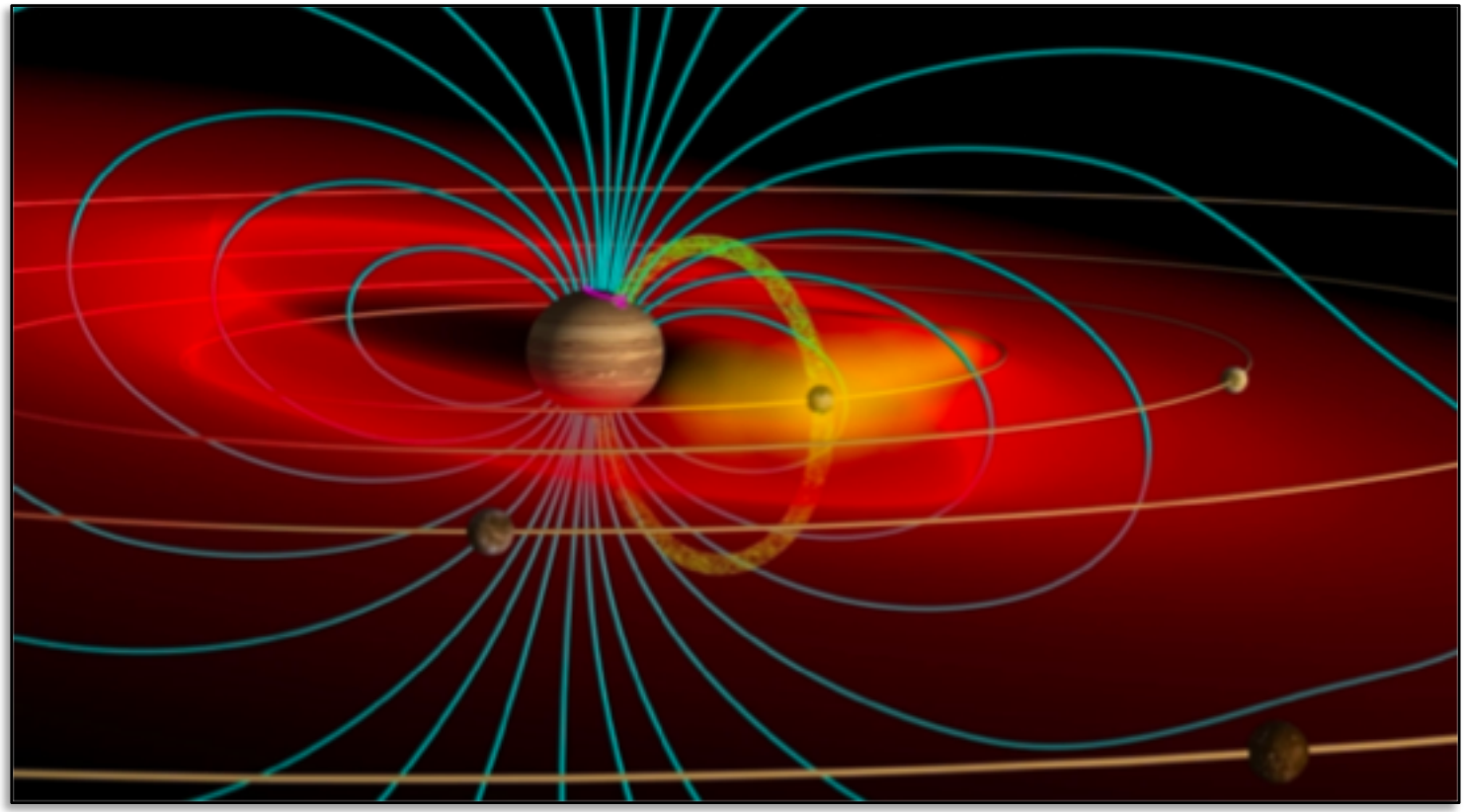
- *What are the dominant sources and sinks of Io's atmosphere?*
- *What are the dynamics of Io's atmosphere and plumes?*
- *What physical and chemical processes are responsible for Io's complex surface color patterns?*
- *What was Io's original volatile inventory, and how were those volatiles lost?*
- *What is the sulfur speciation in Io's volcanic plumes and atmosphere, and what does it tells about the chemical state of Io's deep interior?*



CROSS-CUTTING THEME #5:

MAGNETOSPHERES

Io drives the activity in the Jovian magnetosphere, yielding a wonderland for understanding fundamental planetary physics.



→ *The magnetosphere of Jupiter and Io plasma torus (John Spencer, SwRI)*

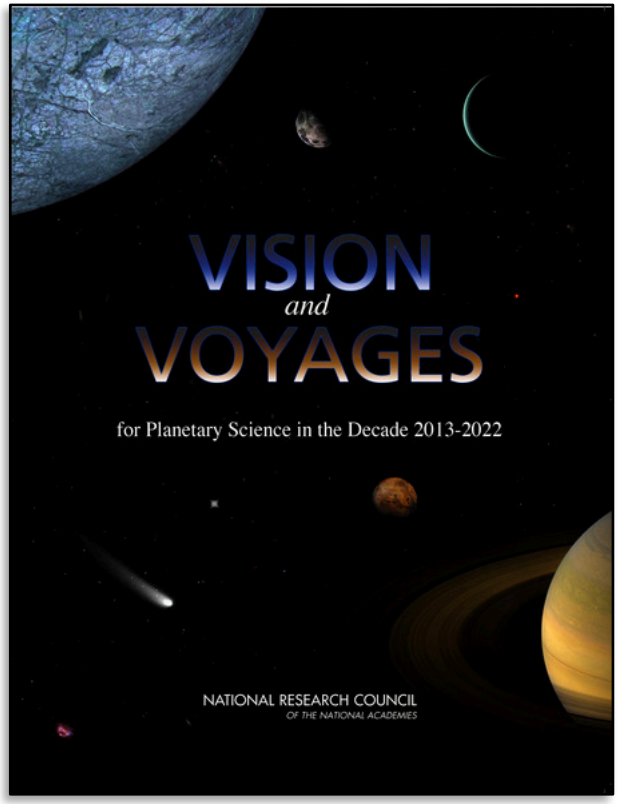
PRIORITY SCIENCE QUESTIONS:

- *Is Io's ionosphere global, does it vary, and how is it maintained?*
- *How do Io's volcanoes affect the supply of plasma, gas, and dust in the Jovian system?*
- *How much Iogenic material reaches the surface of Europa?*
- *How do plasma-atmosphere interactions vary with time and location around the moon?*
- *How does Io interact with the inward motion of plasma that can eventually rain onto Jupiter's ionosphere, generating aurorae?*

IO IS A WORLD OF SYNERGIES

IO IS A WORLD OF SYNERGIES

VISION AND VOYAGES RECOMMENDATIONS FOR IO



The science case for Io:

"[Io is] the ideal target to study tidal dissipation and the resulting variety of volcanic and tectonic processes in action, with fundamental implications for the thermal co-evolution of the Io-Europa-Ganymede system as well as for the habitable zone around other stars."

VISION AND VOYAGES RECOMMENDATIONS FOR IO

The science case for Io:

"[Io is] the ideal target to study tidal dissipation and the resulting variety of volcanic and tectonic processes in action, with fundamental implications for the thermal co-evolution of the Io-Europa-Ganymede system as well as for the habitable zone around other stars."

New Frontiers Io Observer mission concept:

"Io Observer—The focus of this mission is to determine the internal structure of Io and to investigate the mechanisms that contribute to the satellite's intense volcanic activity from a highly elliptical orbit around Jupiter, making multiple flybys of Io."

New Frontiers Io Observer science objectives:

1. *Study Io's active volcanic processes;*
2. *Determine the melt fraction of Io's mantle;*
3. *Constrain tidal heating mechanisms;*
4. *Study tectonic processes;*
5. *Investigate interrelated volcanic, atmospheric, plasma-torus, and magnetospheric mass- and energy-exchange processes;*
6. *Constrain the state of Io's core via improved constraints on whether Io generates a magnetic field; and*
7. *Investigate endogenic and exogenic processes controlling surface composition.*

VISION AND VOYAGES RECOMMENDATIONS FOR IO

New Frontiers 4 options:

- *Comet Surface Sample Return*
- *Lunar South Pole–Aitken Basin Sample Return*
- *Saturn Probe*
- *Trojan Tour and Rendezvous*
- *Venus In Situ Explorer*
- Ocean Worlds (Enceladus/Titan)

Additional New Frontiers 5 options:

- *Io Observer*
- *Lunar Geophysical Network*

VISION AND VOYAGES RECOMMENDATIONS FOR IO

VISION AND VOYAGES RECOMMENDATIONS FOR IO

Getting ready for the next decadal:

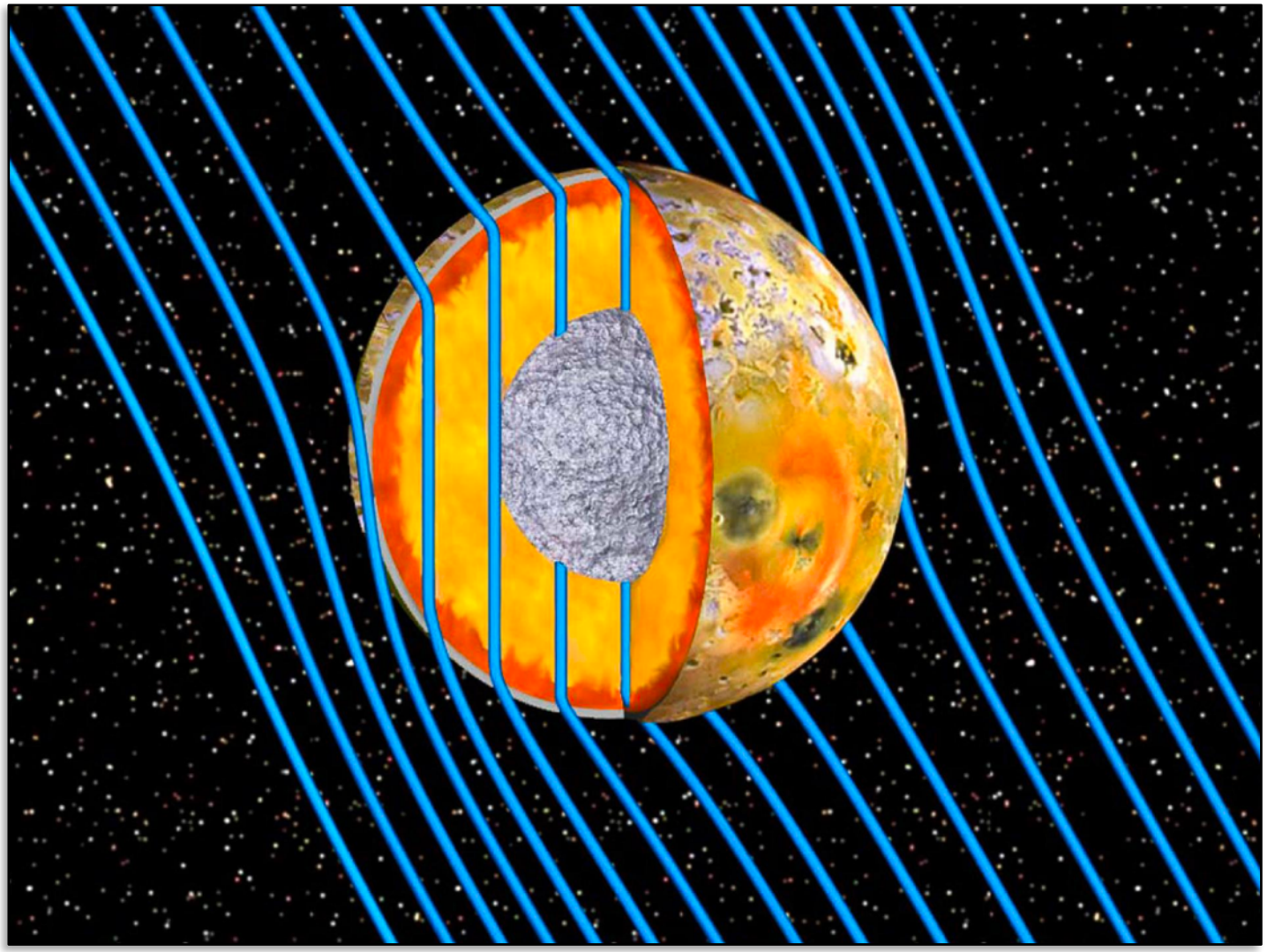
"Given that the announcement of opportunity for New Frontiers 5 will likely come in the early 2020s, the revalidation of the Io Explorer as having appropriate scientific merit for inclusion in the New Frontiers program will fall to the next planetary science decadal survey [...]. As such, the technical feasibility of the Io Explorer concept [...] could be fruitfully reexamined."

Midterm review:

"...the committee believes [Io Observer and Lunar Geophysical Network] still remain valid missions for New Frontiers 5."

WHAT HAS CHANGED IN THE LAST DECADE?

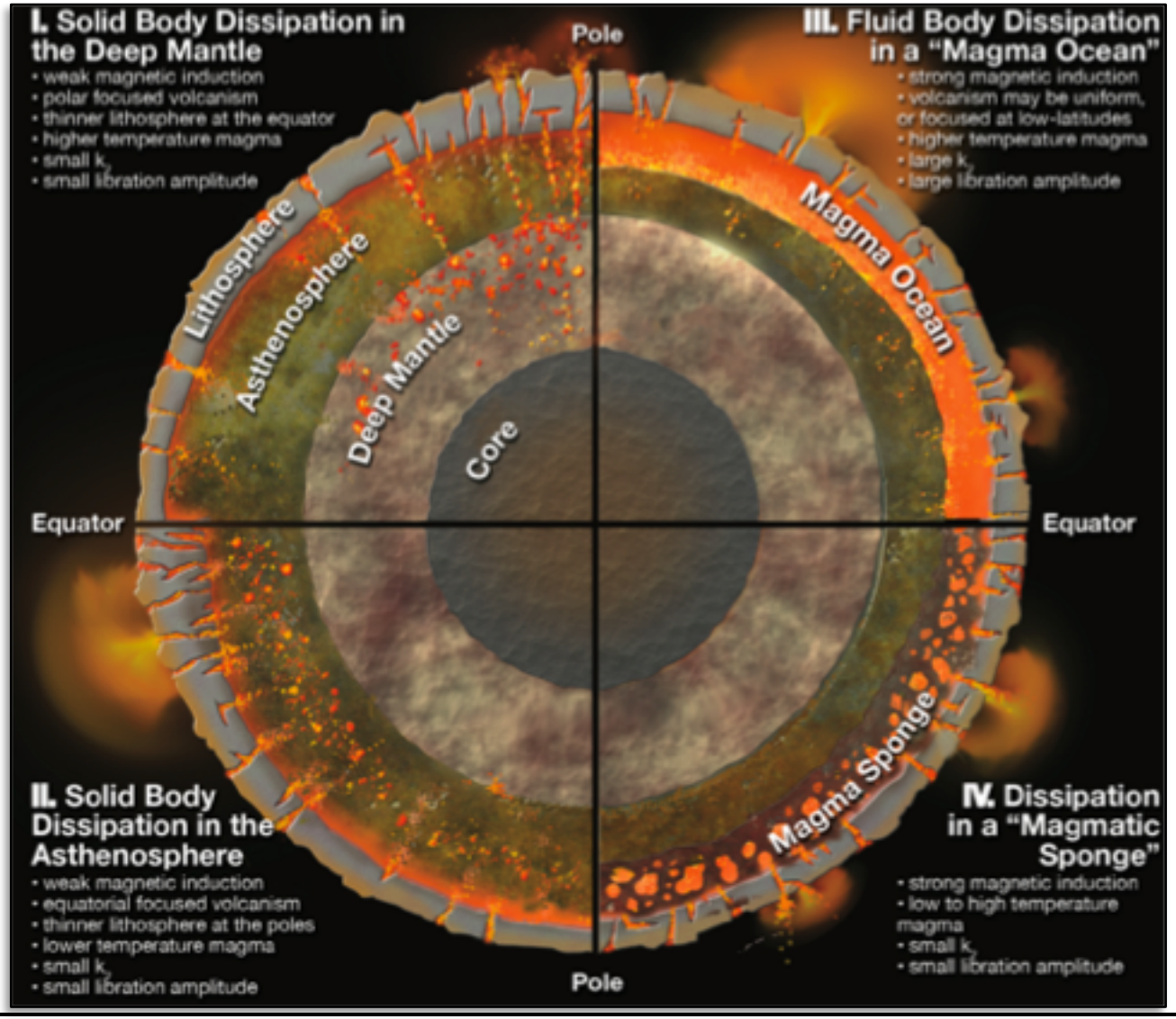
Example 1: EVIDENCE FOR A MAGMA OCEAN



Reanalysis of Galileo *magnetometer data suggests Io may have a global magma ocean (Khurana et al. 2011 Šebek et al. 2019), although this interpretation is debated (Roth et al. 2017, Blöcker et al. 2018).*

← Io's induced magnetic field
(Xianzhe Jia / Krishan Khurana)

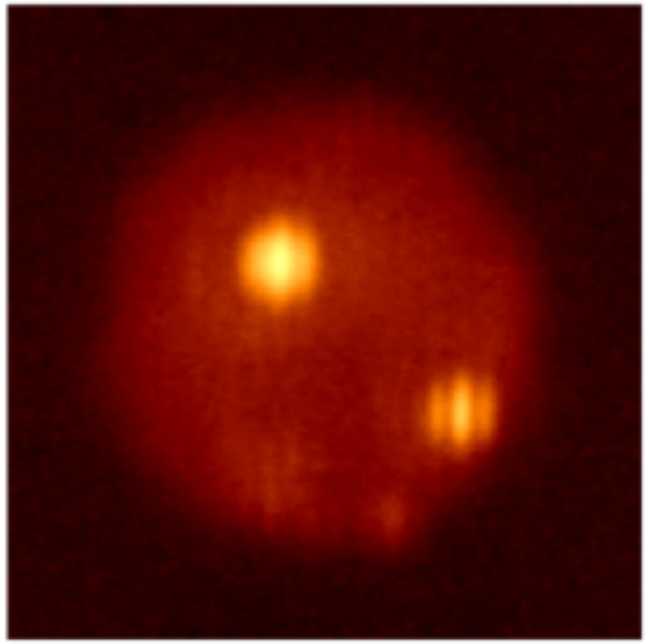
Example 1: EVIDENCE FOR A MAGMA OCEAN



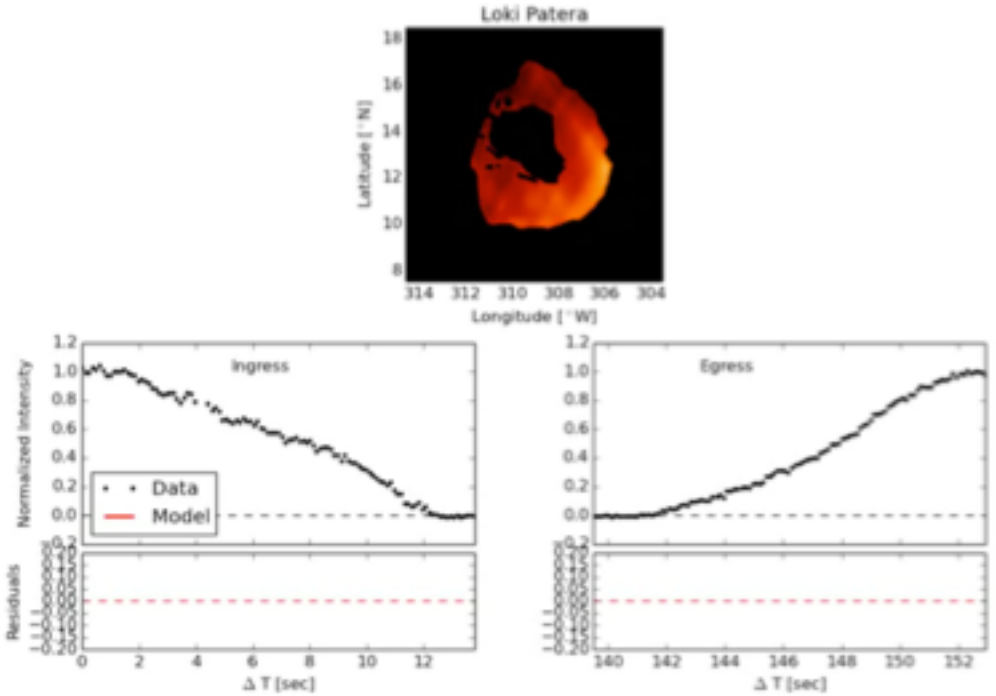
Reanalysis of Galileo *magnetometer data suggests Io may have a global magma ocean (Khurana et al. 2011 Šebek et al. 2019), although this interpretation is debated (Roth et al. 2017, Blöcker et al. 2018).*

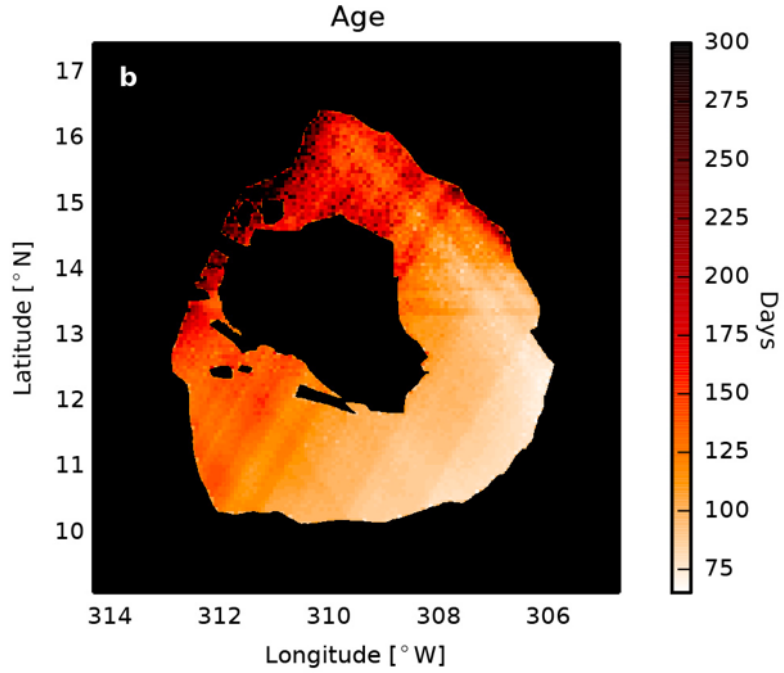
← Four competing models for Io's interior structure (Chuck Carter / James T. Keane / Keck Institute for Space Studies)

Example 2: ADAPTIVE OPTICS IMAGING



↑ Adaptive optics imaging of Europa's shadow transiting Io (courtesy of Katherine de Kleer).

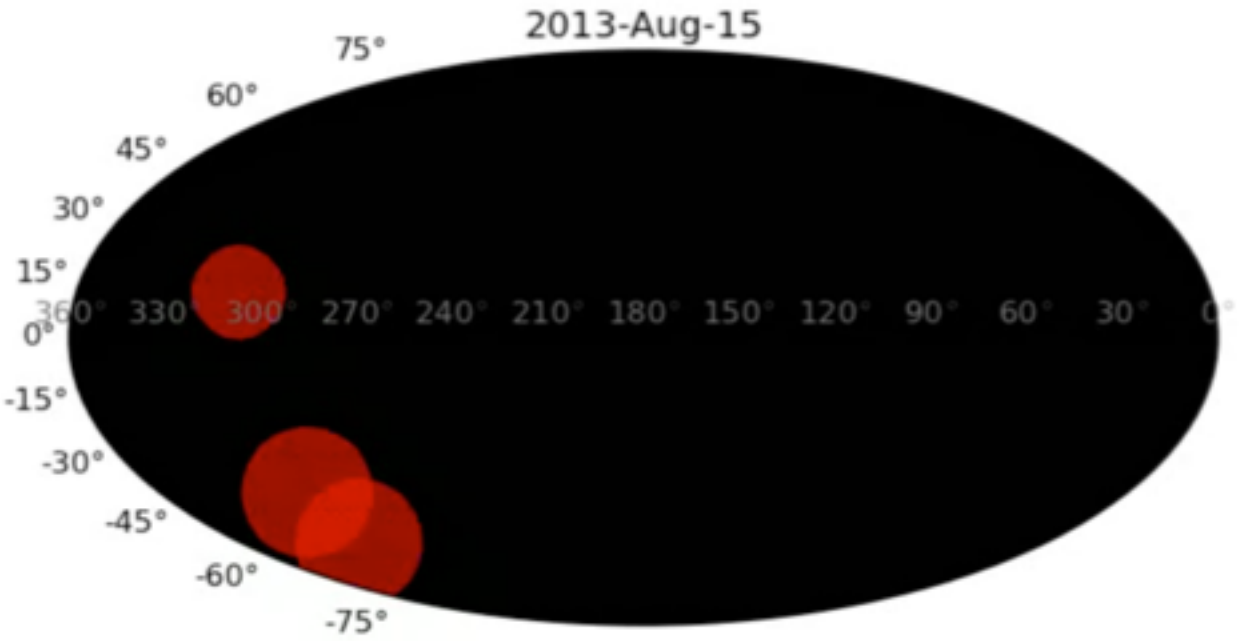




↑ Resurfacing model for Loki Paterae, based on adaptive optics imaging (courtesy of Katherine de Kleer)

Adaptive optics imaging has provided extremely high-resolution ground-based imaging of individual volcanoes, enabling unprecedented investigation of certain aspects of Io's volcanism (e.g., de Kleer et al. 2017).

Example 3: EVIDENCE FOR A MAGMA OCEAN



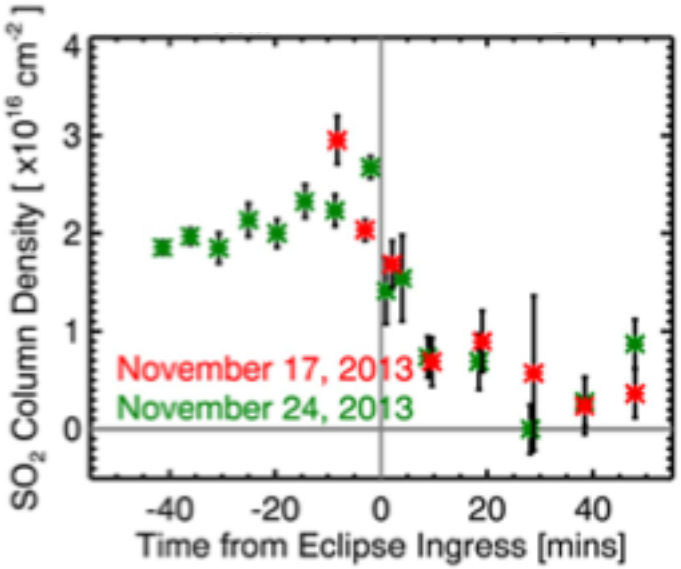
↑ Five years of Io observations (courtesy of Katherine de Kleer).

High-cadence monitoring of Io's volcanic activity from ground-based telescopes have revealed new trends in Io's volcanism, identified new volcanic outbursts, and hint at the geophysical processes modulating Io's activity (de Pater et al. 2016, Cantrall et al. 2018, de Kleer et al. 2019a–b).

Example 4: ATMOSPHERIC COLLAPSE

↑ *Keck* AO observations of Io coming out of eclipse (courtesy of Katherine de Kleer)

New observations from ground-based telescopes have been able to characterize some of the dynamics of Io's atmosphere—like its partial collapse during eclipse (Tsang et al. 2016).



↑ Atmospheric density during Io eclipse, as monitored by TEXES on *Gemini-north* (Tsang et al. 2016)

Example 5: ISOTOPES

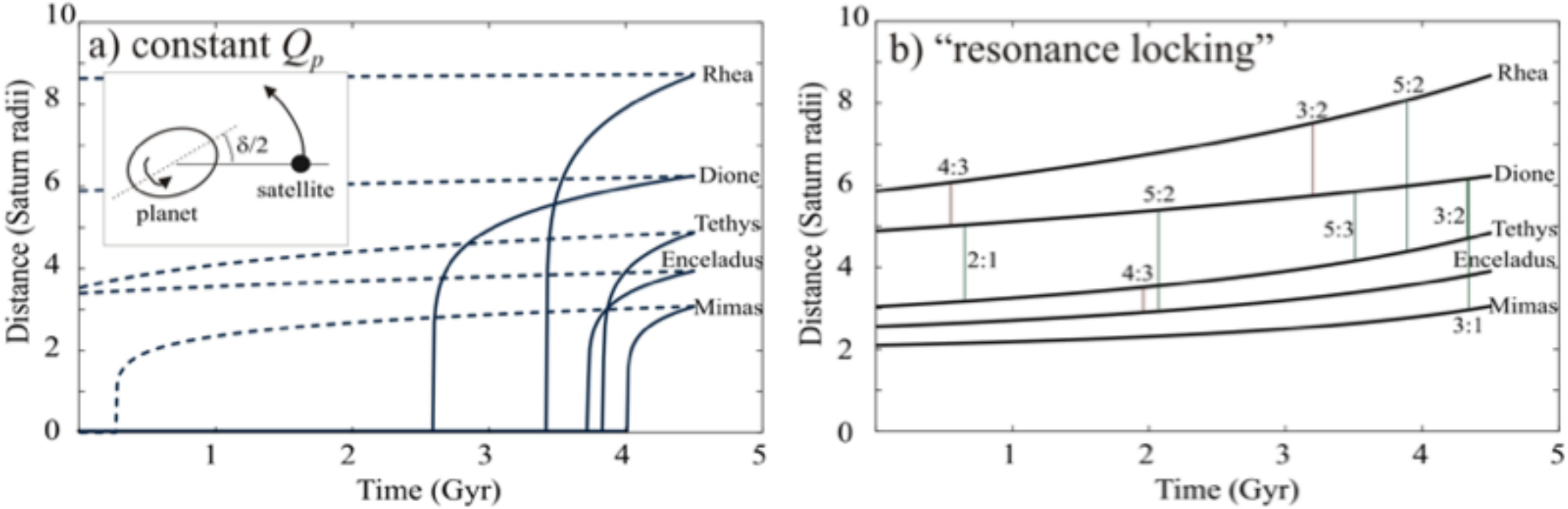
Isotopic ratios have been transformative for understanding the evolutionary histories of many bodies, from Titan to Pluto (e.g., Liang et a. 2007, Mandt et al. 2009, Mandt et al. 2012a-b, Nixon et al. 2012), Mandt et al. 2014, Mandt et al. 2017).

New millimeter and radio observatories have enabled the first measurements of isotopic ratios in Io's atmosphere ($^{34}S/^{32}S$, Moullet et al. 2013). Stable isotopes may provide a window into the deep history of Io, a world where geologic record is otherwise constantly obliterated.

← *Atacama Pathfinder Experiment* (*APEX*) telescope

Example 6: ASTROMETRY

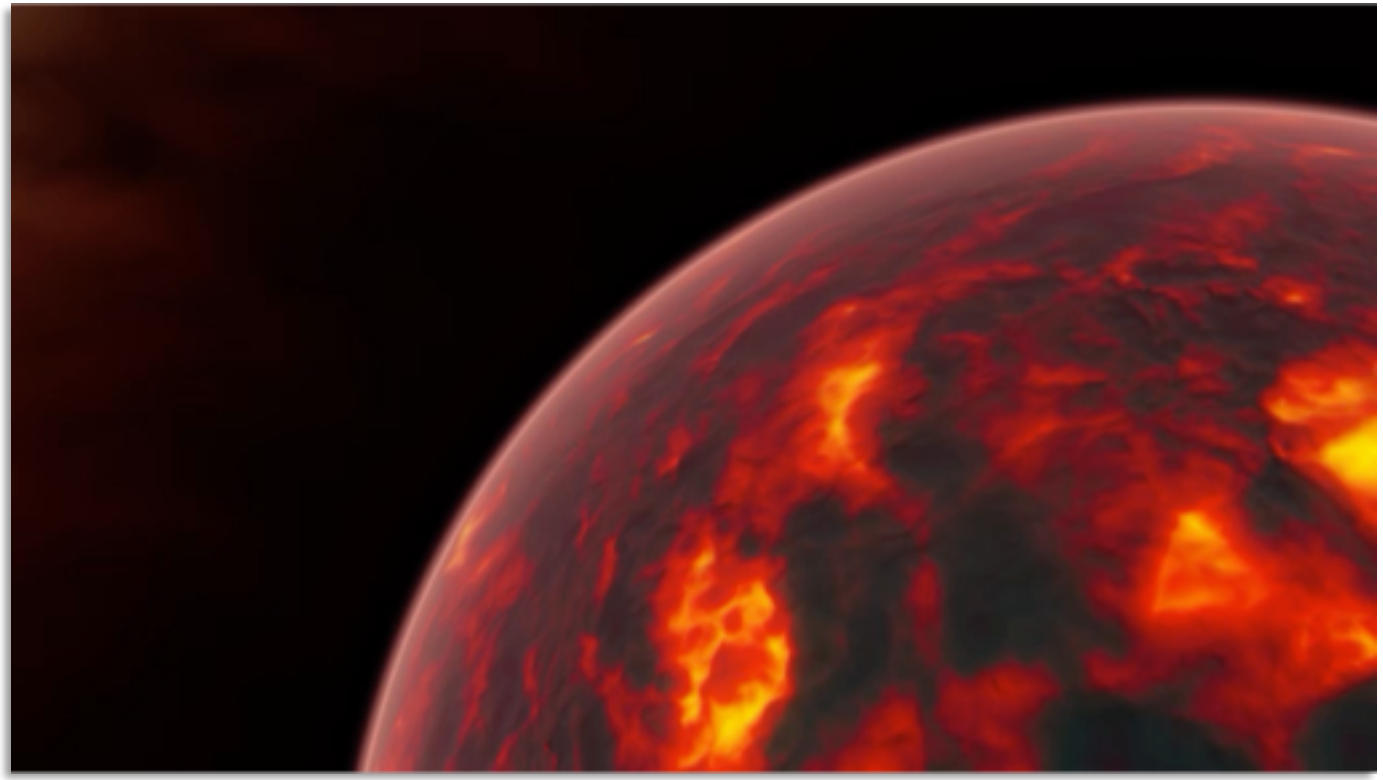
Astrometric observations of Saturn's moons by Cassini *(Lainey et al. 2012, 2017) have revealed that Saturn's moons are migrating much faster than expected. This has motivated a new generation of orbital evolution models (Fuller et al. 2016), which are still in their infancy.*



↑ Outward migration of Saturn's moons (Nimmo et al. 2018)

Example 8: THE EXOPLANET RENNAISSANCE

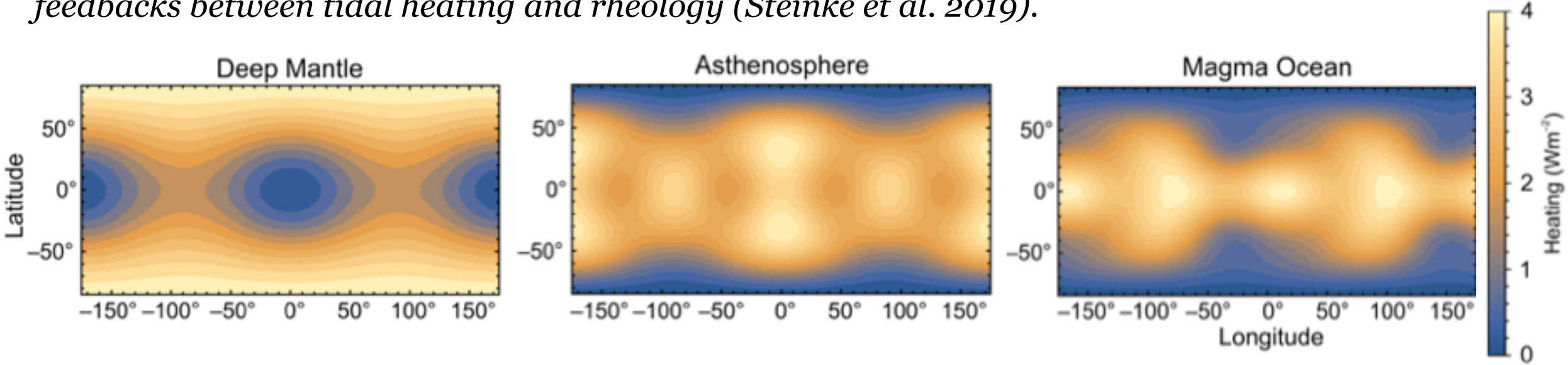
Io is an important analog for extremely heated exoplanets—including both tidally heated worlds (e.g., the resonant super-Ios in TRAPPIST-1, Barr et al. 2018), and worlds heated by extreme solar insolation (e.g., the close-in "lava worlds" like 55 Cnc e, Demory et al. 2016). Future telescopes may be able to characterize these worlds.



← Artist impression of 55 Cnc e
(ESA / *Hubble* / M. Kornmesser)

Example 9: THEORETICAL MODELS

Theoretical models for tidal heating have substantially improved, enabling exploration of more realistic and expansive parameter spaces, including dissipation in both solid and fluid layers (Beuthe 2013, Tyler et al. 2015, Matsuyama et al. 2018, Hay & Matsuyama 2019), modeling melt migration (Schools et al. 2019), accounting for mantle convection (Kiefer 2019), and modeling feedbacks between tidal heating and rheology (Steinke et al. 2019).



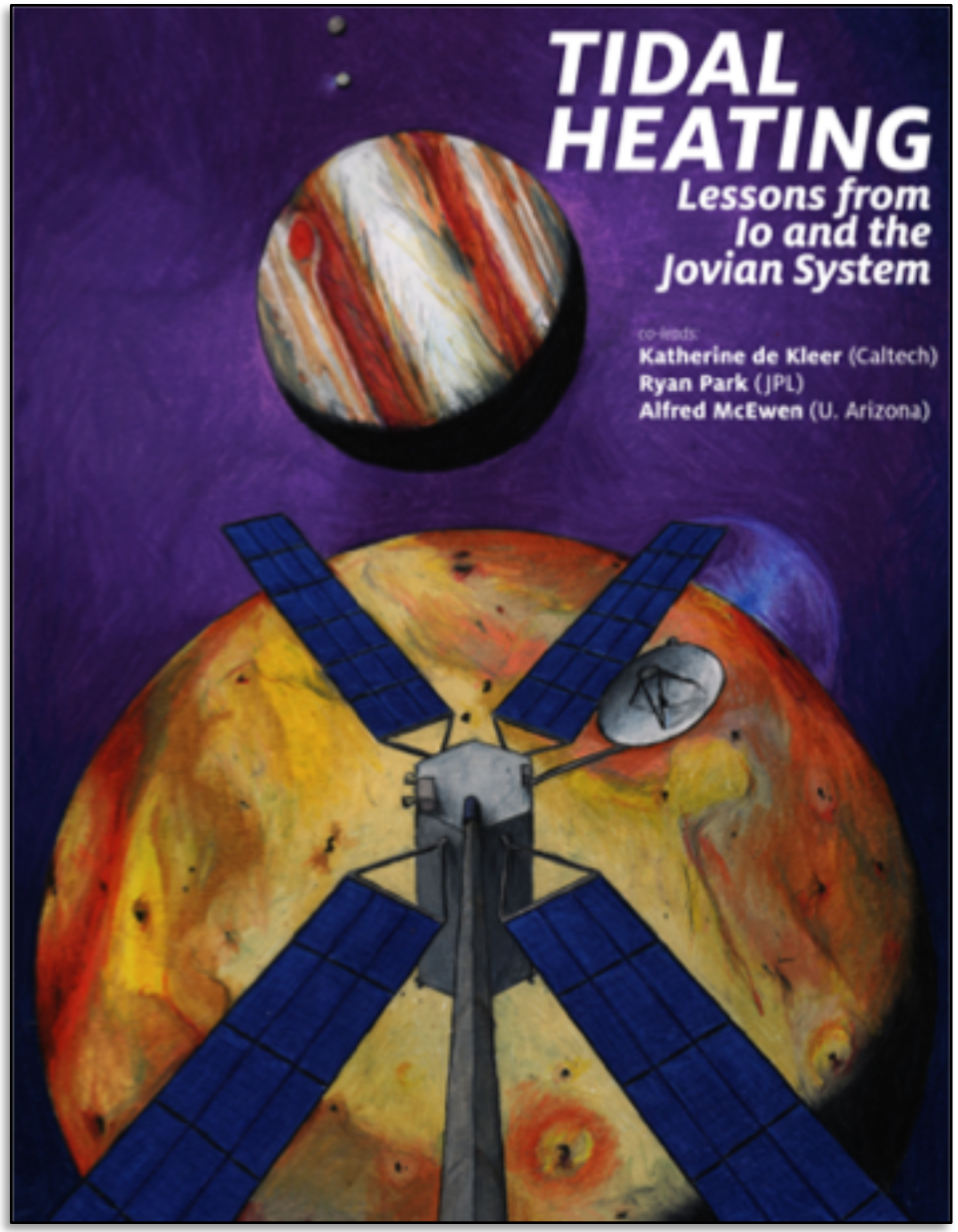
↑ Expected patterns of surface heat flux on Io for three end-member cases (Courtesy of Isamu Matsuyama, in de Kleer et al. 2019)

WHAT HAS CHANGED IN THE LAST DECADE?

↑ Participants of the October 2018 KISS workshop (Keck Institute for Space Studies)

Tidal Heating—Lessons from Io and the Jovian System
Caltech Keck Institute for Space Studies,
15–19 October 2018, 3 December 2018

WHAT HAS CHANGED IN THE LAST DECADE?



Tidal Heating—Lessons from Io and the Jovian System
Caltech Keck Institute for Space Studies,
15–19 October 2018, 3 December 2018

Full, 99-page report:
https://www.kiss.caltech.edu/programs.html#tidal_heating

Five key questions:

1. *What do volcanic eruptions tell us about the interiors of tidally heated bodies?*
2. *How is tidal dissipation partitioned between solid and liquid materials?*
3. *Does Io have a magma ocean?*
4. *Is the Jupiter/Laplace system in equilibrium?*
5. *Can stable isotope measurements inform long-term evolution of tidally heated bodies?*

← Report cover (James T. Keane / Keck Institute for Space Studies)

WHAT HAS CHANGED IN THE LAST DECADE?

WHAT HAS CHANGED IN THE LAST DECADE?

KEY POINTS:

1. *The limited* Voyager, Galileo, New Horizons, *and* Juno *datasets have revealed new mysteries.*

2. *Earth-based observations have dramatically improved, enabling new scientific discoveries.*

3. *Nonetheless, there are major knowledge gaps—particularly with regards to geophysical and geochemical measurements (e.g., gravity/magnetic fields, atmospheric chemistry, etc.). These can only be addressed by a new mission to Io.*

IO VOLCANO OBSERVER (IVO)

IVO is one of four finalists for the current round of NASA Discovery Program.

← Artist's conception of *Io Volcano Observer* (JHUAPL / U. Arizona)

More information about: https://ivo.lpl.arizona.edu/

PRE-DECISIONAL INFORMATION— FOR PLANNING AND DISCUSSION PURPOSES ONLY

IO VOLCANO OBSERVER (IVO)

IVO would be the first mission dedicated to Io, the most volcanically active world in the solar system. The IVO mission design and payload would transform our understanding of this unique world and how tidal heating shapes planetary worlds across the cosmos.

IVO's primary goal would be to 'Follow the Heat' and understand how tidal heat (A) is generated, (B) is lost, and (C) drives the evolution of Io.

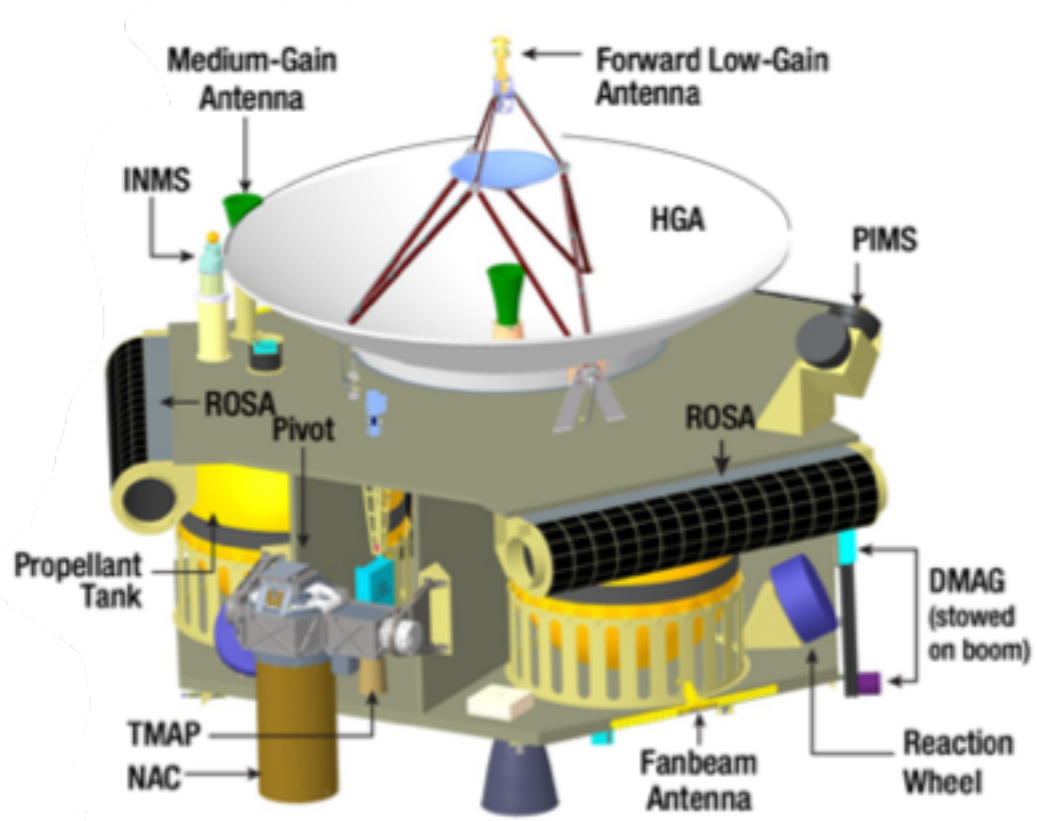
***IVO* science objectives:**

A1. Determine the degree and distribution of melt in within Io's interior.
B1. Determine Io's lithospheric structure.
B2. Determine where and how Io is losing heat.
C1. Determine Io's orbit evolution.
C2. Determine Io's volatile loss processes and rates.

← Artist's interpretation of *IVO* interrogating the interior structure of Io (James T. Keane)

PRE-DECISIONAL INFORMATION—FOR PLANNING AND DISCUSSION PURPOSES ONLY

IO VOLCANO OBSERVER (IVO)



↑ Artist's conception of *IVO* design, with solar arrays and boom stowed (JHUAPL / U. Arizona)

IVO mission design

— *Jupiter-orbit with 10 close (300-1,000 km altitude) flybys of Io over 3.9 years.*

— *Orbit is optimized for geophysics, near global mapping, and radiation mitigation (<10% total ionizing dose of* Galileo, Juice, *or* Europa Clipper).

IVO spacecraft design:

— *Solar powered.*

IVO baseline science experiments:

— *Narrow Angle Camera (NAC)*

— *Thermal Mapper (TMAP)*

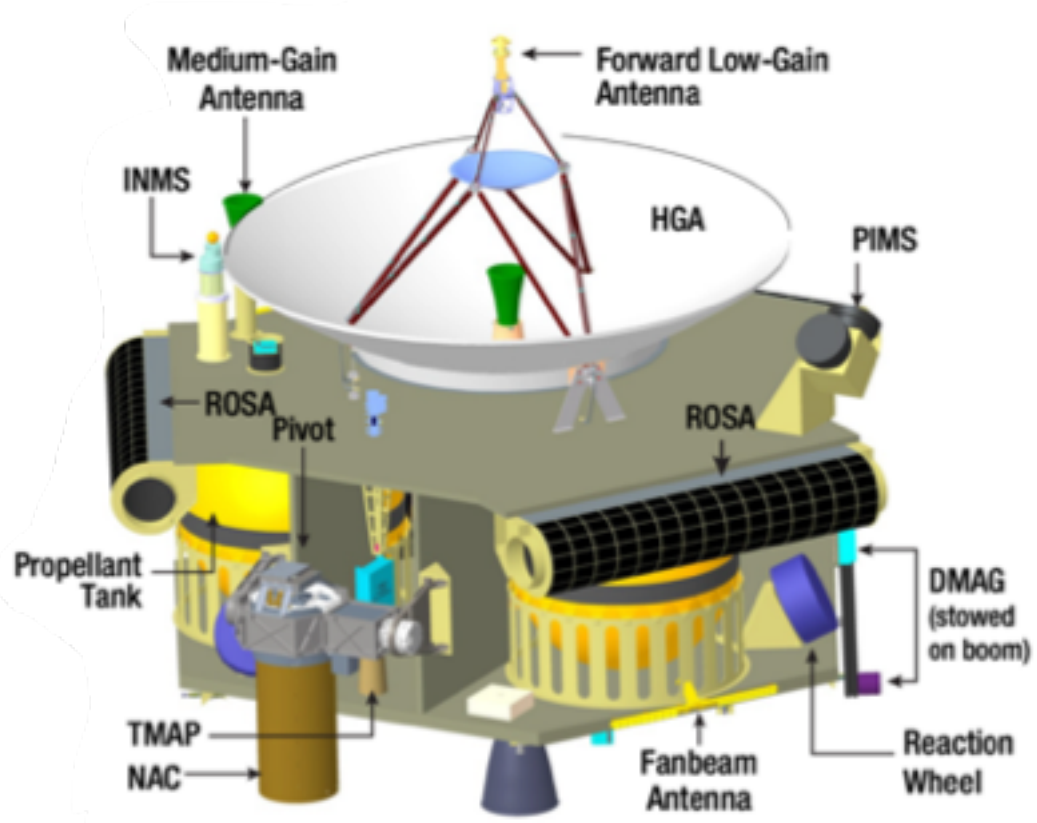
— *Dual Fluxgate Magnetometers (DMAG)*

— *Plasma Instrument for Magnetic Sounding (PIMS)*

— *Gravity Science (GS)*

— *Ion and Neutral Mass Spectrometer (INMS)*

IO VOLCANO OBSERVER (IVO)



↑ Artist's conception of *IVO* design, with solar arrays and boom stowed (JHUAPL / U. Arizona)

IVO mission design

— *Jupiter-orbit with 10 close (300-1,000 km altitude) flybys of Io over 3.9 years.*

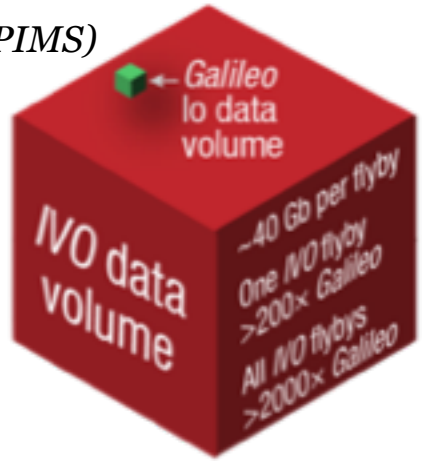
— *Orbit is optimized for geophysics, near global mapping, and radiation mitigation (<10% total ionizing dose of* Galileo, Juice, *or* Europa Clipper).

IVO spacecraft design:

— *Solar powered.*

IVO baseline science experiments:

— *Narrow Angle Camera (NAC)*
— *Thermal Mapper (TMAP)*
— *Dual Fluxgate Magnetometers (DMAG)*
— *Plasma Instrument for Magnetic Sounding (PIMS)*
— *Gravity Science (GS)*
— *Ion and Neutral Mass Spectrometer (INMS)*



→ *IVO* data volume (JHUAPL / U. Arizona)

THE BILLION DOLLAR QUESTIONS:

THE BILLION DOLLAR QUESTIONS:

#1. "Is Io still relevant for New Frontiers?"

or

#2. "Since IVO has been selected for Phase-A study, is Io exploration still relevant for New Frontiers 5?"

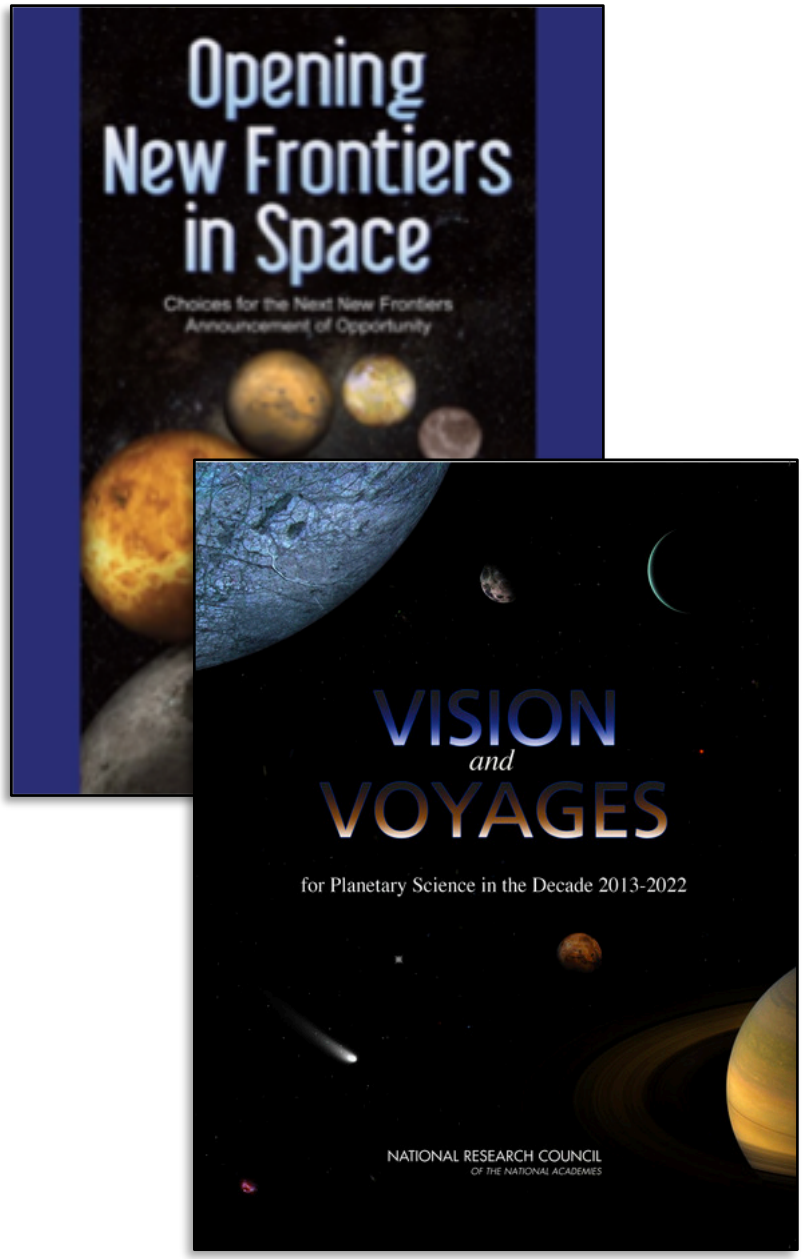
or

#3. "What would a New Frontiers mission do that a Discovery mission couldn't do?"

THE BILLION DOLLAR QUESTIONS:

#1. "Is Io still relevant for New Frontiers?"

NEW FRONTIERS v. DISCOVERY: Q: IS IO STILL RELEVANT?



Opening New Frontiers in Space:
"However, unlike Discovery, ***New Frontiers missions must be firmly grounded in scientific priorities established by the decadal survey*** *without relying on new scientific or technology developments."*

***Vision and Voyages*:**
"In contrast to those for the Discovery program, solicitations for New Frontiers are more ***strategic****, restricting proposals to a small number of specific mission goals.* ***New Frontiers missions address focused science goals*** *that cannot be implemented within the Discovery cost cap but that do not require the resources of a flagship mission."*

NEW FRONTIERS v. DISCOVERY: Q: IS IO STILL RELEVANT?

Midterm review:
"...the committee believes [Io Observer and Lunar Geophysical Network] still remain valid missions for New Frontiers 5."

Opening New Frontiers in Space:
*"However, unlike Discovery, **New Frontiers missions must be firmly grounded in scientific priorities established by the decadal survey** without relying on new scientific or technology developments."*

***Vision and Voyages*:**
*"In contrast to those for the Discovery program, solicitations for New Frontiers are more **strategic**, restricting proposals to a small number of specific mission goals. **New Frontiers missions address focused science goals** that cannot be implemented within the Discovery cost cap but that do not require the resources of a flagship mission."*

THE BILLION DOLLAR QUESTIONS:

#2. "Since IVO has been selected for Phase-A study, is Io exploration still relevant for New Frontiers 5?"

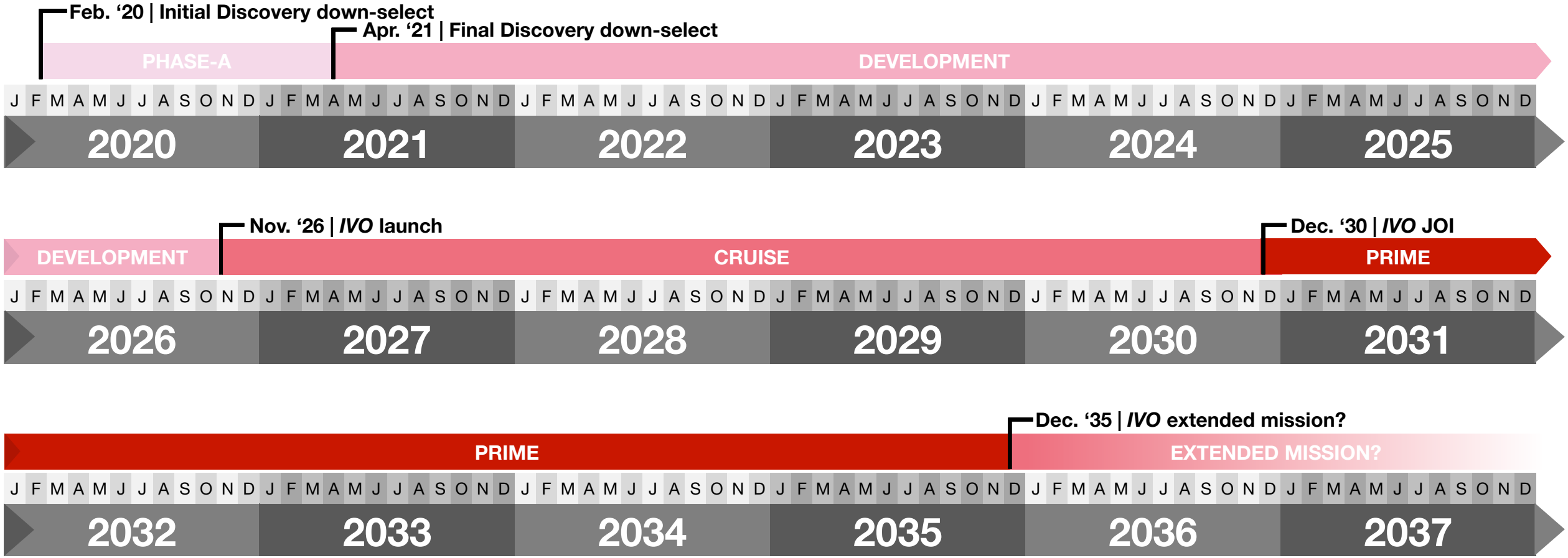
THE BILLION DOLLAR QUESTIONS:

#2. "Since IVO has been selected for Phase-A study, is Io exploration still relevant for New Frontiers 5?"

KEY POINT:

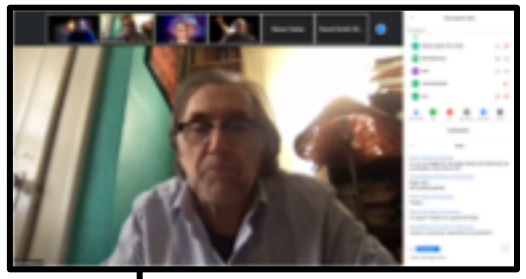
IVO *has not yet been selected for flight!*

IVO TIMELINE



PRE-DECISIONAL INFORMATION—FOR PLANNING AND DISCUSSION PURPOSES ONLY

IVO TIMELINE



Apr. ‘20 | CAPS meeting

Feb. ‘20 | Initial Discovery down-select

Apr. ‘21 | Final Discovery down-select

PHASE-A

DEVELOPMENT

J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D

2020 2021 2022 2023 2024 2025

Nov. ‘26 | *IVO* launch

Dec. ‘30 | *IVO* JOI

DEVELOPMENT

CRUISE

PRIME

J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D

2026 2027 2028 2029 2030 2031

Dec. ‘35 | *IVO* extended mission?

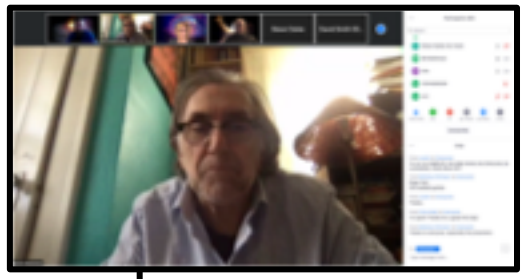
PRIME

EXTENDED MISSION?

J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D

2032 2033 2034 2035 2036 2037

IVO TIMELINE



Apr. ‘20 | CAPS meeting

Jul. ‘20 | Meetings start

Fall ‘21 | Draft report complete

Spring ‘22 | Report complete

DECADAL SURVEY

Feb. ‘20 | Initial Discovery down-select

Apr. ‘21 | Final Discovery down-select

PHASE-A

DEVELOPMENT

J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D

2020 2021 2022 2023 2024 2025

Nov. ‘26 | *IVO* launch

Dec. ‘30 | *IVO* JOI

DEVELOPMENT

CRUISE

PRIME

J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D

2026 2027 2028 2029 2030 2031

Dec. ‘35 | *IVO* extended mission?

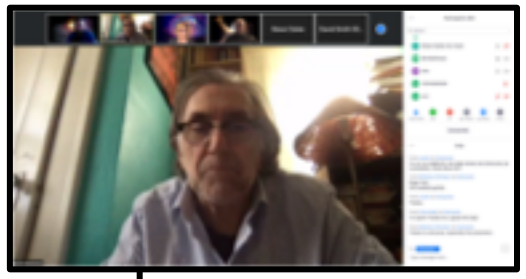
PRIME

EXTENDED MISSION?

J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D

2032 2033 2034 2035 2036 2037

IVO TIMELINE



Apr. ‘20 | CAPS meeting

Fall ‘22 | New Frontiers 5

Fall ‘21 | Draft report complete

Jul. ‘20 | Meetings start

Spring ‘22 | Report complete

DECADAL SURVEY

Feb. ‘20 | Initial Discovery down-select

Apr. ‘21 | Final Discovery down-select

PHASE-A

DEVELOPMENT

J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D

2020 2021 2022 2023 2024 2025

Nov. ‘26 | *IVO* launch

Dec. ‘30 | *IVO* JOI

DEVELOPMENT

CRUISE

PRIME

J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D

2026 2027 2028 2029 2030 2031

Dec. ‘35 | *IVO* extended mission?

PRIME

EXTENDED MISSION?

J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D

2032 2033 2034 2035 2036 2037

PRE-DECISIONAL INFORMATION—FOR PLANNING AND DISCUSSION PURPOSES ONLY

NEW FRONTIERS v. DISCOVERY: Q: DOES IVO'S SELECTION CHANGE THINGS?

THE BILLION DOLLAR QUESTIONS:

#2. "Since IVO has been selected for Phase-A study, is Io exploration still relevant for New Frontiers 5?"

KEY POINT:

IVO *has not yet been selected for flight!*

NEW FRONTIERS v. DISCOVERY: Q: DOES IVO'S SELECTION CHANGE THINGS?

NEW FRONTIERS 1
New Horizons

NEW FRONTIERS 2
Juno

NEW FRONTIERS 3
OSIRIS-REx

NEW FRONTIERS 4
Dragonfly

NEW FRONTIERS v. DISCOVERY: Q: DOES IVO'S SELECTION CHANGE THINGS?

NEW FRONTIERS 1
New Horizons

NEW FRONTIERS 2
Juno

Proposed three times in Discovery
(previously: INSIDE Jupiter)

NEW FRONTIERS 3
OSIRIS-REx

Proposed twice in Discovery
(previously: OSIRIS)

NEW FRONTIERS 4
Dragonfly

NEW FRONTIERS v. DISCOVERY: Q: DOES IVO'S SELECTION CHANGE THINGS?

NEW FRONTIERS 1
New Horizons

Never proposed to Discovery
(but many funded concept studies in/near the Discovery cost range: Pluto 350, Pluto Fast Flyby, etc.)

NEW FRONTIERS 2
Juno

Proposed three times in Discovery
(previously: INSIDE Jupiter)

NEW FRONTIERS 3
OSIRIS-REx

Proposed twice in Discovery
(previously: OSIRIS)

NEW FRONTIERS 4
Dragonfly

NEW FRONTIERS v. DISCOVERY: Q: DOES IVO'S SELECTION CHANGE THINGS?

NEW FRONTIERS 1
New Horizons

Never proposed to Discovery
(but many funded concept studies in/near the Discovery cost range: Pluto 350, Pluto Fast Flyby, etc.)

NEW FRONTIERS 2
Juno

Proposed three times in Discovery
(previously: INSIDE Jupiter)

NEW FRONTIERS 3
OSIRIS-REx

Proposed twice in Discovery
(previously: OSIRIS)

NEW FRONTIERS 4
Dragonfly

Never proposed to Discovery
(but other innovative Titan exploration has been proposed: TIME)

NEW FRONTIERS v. DISCOVERY: Q: DOES IVO'S SELECTION CHANGE THINGS?

NEW FRONTIERS 1
New Horizons

Never proposed to Discovery
(but many funded concept studies in/near the Discovery cost range: Pluto 350, Pluto Fast Flyby, etc.)

NEW FRONTIERS 2
Juno

Proposed three times in Discovery
(previously: INSIDE Jupiter)

NEW FRONTIERS 3
OSIRIS-REx

Proposed twice in Discovery
(previously: OSIRIS)

NEW FRONTIERS 4
Dragonfly

Never proposed to Discovery
(but other innovative Titan exploration has been proposed: TIME)

KEY POINT:

Discovery proposals are an important step in maturing concepts for New Frontiers proposals.

THE BILLION DOLLAR QUESTIONS:

#2. "Since IVO has been selected for Phase-A study, is Io exploration still relevant for New Frontiers 5?"

KEY POINT:

IVO *has not yet been selected for flight!*

We should let the Discovery proposal and selection process run its course. If IVO *is selected, then the decadal survey will certainly need to reevaluate Io's inclusion on any New Frontiers list.*

...Just like we are currently reevaluating the inclusion of Trojan Tour and Rendezvous and Ocean Worlds on the New Frontiers list after the selections of Lucy *(Discovery) and* Dragonfly *(New Frontiers). I assume the decadal survey would also reevaluate the inclusion of Venus In-Situ Explorer on the New Frontiers list if* VERITAS *(Discovery Phase-A) and/or* DAVINCI+ *(Discovery Phase-A) were selected, or even revisit the choice between Uranus and Neptune flagship if* Trident *(Discovery Phase-A) was selected.*

THE BILLION DOLLAR QUESTIONS:

#3. "What would a New Frontiers mission do that a Discovery mission couldn't do?"

NEW FRONTIERS v. DISCOVERY

THE BILLION DOLLAR QUESTIONS:

#3. "What would a New Frontiers mission do that a Discovery mission couldn't do?"

KEY POINT:

A New Frontiers mission could do exactly what IVO *is proposing to do.*

...It is entirely possible IVO *will not be selected for Discovery based on cost. As proposed to Discovery,* IVO *would address all of the science objectives outlined for a New Frontiers class Io Observer mission, and thus would be relevant to New Frontiers without any changes to the spacecraft, mission design, payload, etc.*

NEW FRONTIERS v. DISCOVERY

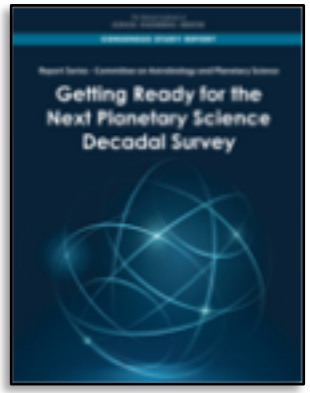
THE BILLION DOLLAR QUESTIONS:

#3. "What would a New Frontiers mission do that a Discovery mission couldn't do?"

KEY POINT:

A New Frontiers mission could do exactly what IVO *is proposing to do.*

...It is entirely possible IVO *will not be selected for Discovery based on cost. As proposed to Discovery,* IVO *would address all of the science objectives outlined for a New Frontiers class Io Observer mission, and thus would be relevant to New Frontiers without any changes to the spacecraft, mission design, payload, etc.*



KEY POINT:

The planetary science community would benefit from a new Io mission concept study.

This was also recommended in "Getting Ready for the Next Decadal"

RECOMMENDATION: A NEW FRONTIERS IO MISSION CONCEPT STUDY

At present, the only available mission concept study is the Io Observer concept from the previous decadal. While compelling, this study does now outdated due to scientific and technological advances.

RECOMMENDATION: A NEW FRONTIERS IO MISSION CONCEPT STUDY

At present, the only available mission concept study is the Io Observer concept from the previous decadal. While compelling, this study does now outdated due to scientific and technological advances.

From an engineering perspective, the two biggest advances are:

- ***Solar power at 5 AU** (Juno, Europa Clipper, Lucy).*
- ***Radiation hardening and mitigation**, including new radiation models, improvements in shielding, development of radiation hardened instruments.*

RECOMMENDATION: A NEW FRONTIERS IO MISSION CONCEPT STUDY

At present, the only available mission concept study is the Io Observer concept from the previous decadal. While compelling, this study does now outdated due to scientific and technological advances.

From an engineering perspective, the two biggest advances are:

- ***Solar power at 5 AU** (Juno, Europa Clipper, Lucy).*
- ***Radiation hardening and mitigation**, including new radiation models, improvements in shielding, development of radiation hardened instruments.*

Additional technologies include: high-dynamic range thermal imaging (Davies et al. 2016), geodetic cameras (Park et al. 2016), radar (Steinbrügge et al. 2018), microwave radiometers, penetrators, CubeSats, etc.

RESPONSE TO THE QUESTIONS IN THE CAPS STATEMENT OF TASK

1. Has scientific understanding or external factors such as programmatic developments or technological advances, significantly changed since the release of the planetary science decadal survey or its midterm review?

2. Has scientific understanding or external factors, such as programmatic developments or technological advances, been sufficiently substantial to warrant reconsideration of the four targets for inclusion in the New Frontiers 5 announcement of opportunity, scheduled for release in early 2022?

RESPONSE TO THE QUESTIONS IN THE CAPS STATEMENT OF TASK

1. Has scientific understanding or external factors such as programmatic developments or technological advances, significantly changed since the release of the planetary science decadal survey or its midterm review?

Yes; there have been substantial scientific, technological, and programmatic advances relevant for Io exploration since the decadal survey and midterm review.

2. Has scientific understanding or external factors, such as programmatic developments or technological advances, been sufficiently substantial to warrant reconsideration of the four targets for inclusion in the New Frontiers 5 announcement of opportunity, scheduled for release in early 2022?

RESPONSE TO THE QUESTIONS IN THE CAPS STATEMENT OF TASK

1. Has scientific understanding or external factors such as programmatic developments or technological advances, significantly changed since the release of the planetary science decadal survey or its midterm review?

Yes; there have been substantial scientific, technological, and programmatic advances relevant for Io exploration since the decadal survey and midterm review.

2. Has scientific understanding or external factors, such as programmatic developments or technological advances, been sufficiently substantial to warrant reconsideration of the four targets for inclusion in the New Frontiers 5 announcement of opportunity, scheduled for release in early 2022?

No; if anything, the scientific, technological, and programmatic advances since the last decade only further demonstrate the need for a dedicated Io mission in the coming decade. The science has been refined and focused, the technology has been advanced (largely due to* Europa Clipper *and other NASA investments), and the programmatic push for habitability highlights our critical knowledge gaps in the underlying physical processes (e.g., tidal heating).

While Io exploration is currently being considered in the Discovery program (*Io Volcano Observer*), this should not negatively impact the consideration of Io for New Frontiers at this time.

SUMMARY

Io is the best destination for studying tidal heating and extreme volcanism–prime processes shaping planetary evolution and habitability.

There have been multiple major scientific advances in the past decade that further motivate and focus Io exploration. There is a priority need for in situ geophysical and geochemical measurements.

While challenging, Io exploration is more compelling than ever before, and still entirely relevant for New Frontiers.

Io Volcano Observer *is a bold Discovery mission concept for exploring Io, however it is not yet selected and should not negate Io's inclusion on the New Frontiers list.*

A new mission concept study, if deemed appropriate by the decadal survey, could leverage major scientific and technological developments in the past decade.

↓ Io (Oil on Illustration board, Don Davis)