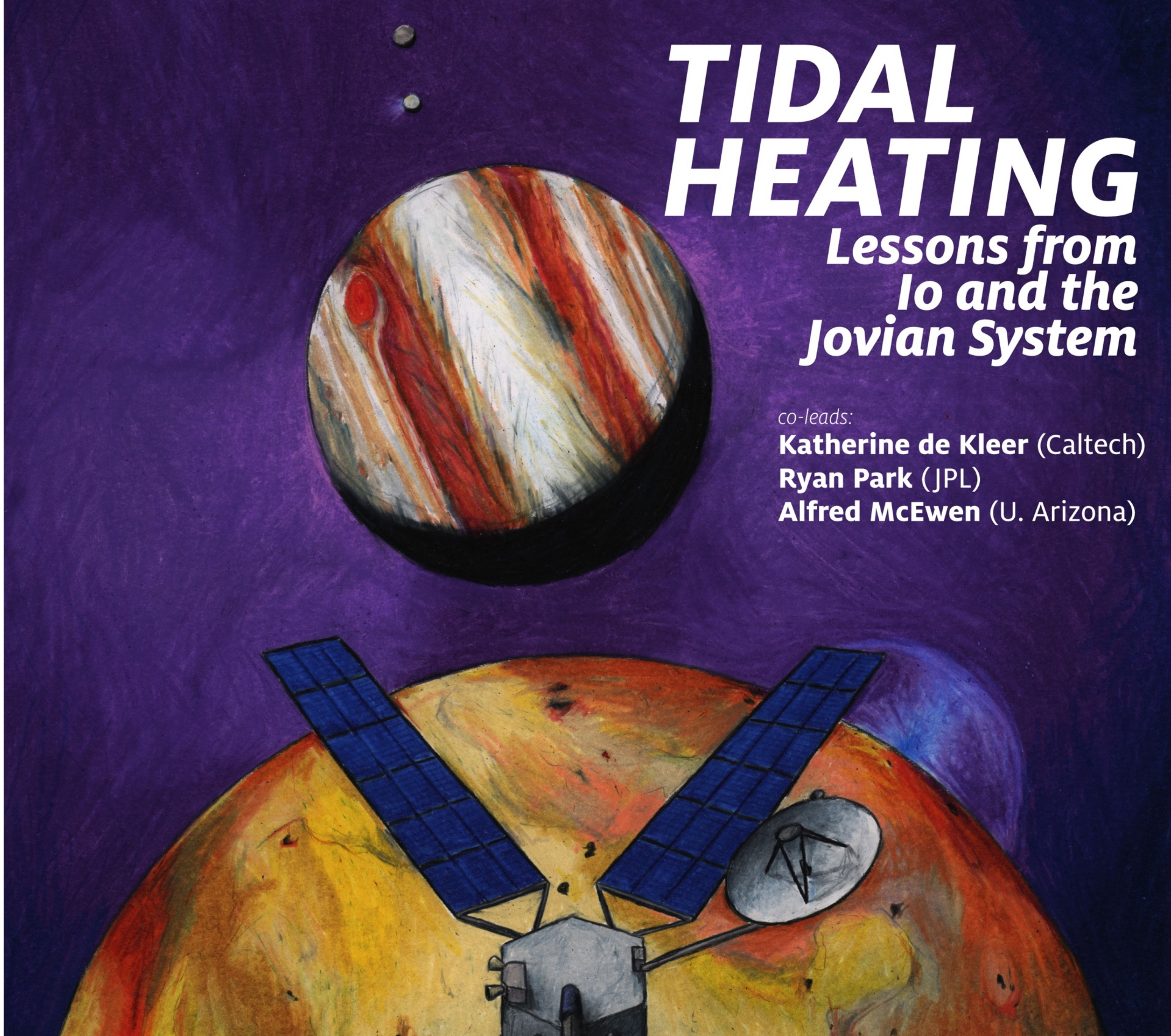
Study Vision and Goals

- Why is this important?
- High-level overview of study objectives
- Suggested main areas of focus for workshop
  - This can change
- Plans for final report



Why is this important?

- Tidal heating is a fundamental planetary process, important to Earth/Moon, outer planet satellites, exoplanets and exomoons
  - Heat flow affects internal structure and geologic activity
  - Coupled orbital-thermal evolution
- Tidal heating important to ocean worlds
  - Potentially habitable
  - Tidal heating maintains oceans over geologic time and sustains chemical disequilibria needed for life
- Why an emphasis on Jupiter system and especially Io?
  - Laplace resonance Io-Europa-Ganymede
  - Io is so intensely heated that we can see widespread volcanic activity and measure the heat flow
- Why now:
  - Juno in orbit; Europa Clipper and JUICE (approved missions) will provide important data
    - **Exploring Io is the major gap to understand the full system**
  - Other potential/proposed missions to relevant worlds: Dragonfly, Europa Lander; mission concepts to Io, Enceladus, Triton, etc.
  - Synthesizing new results from laboratories and orbital studies may already enable us to advance the paradigm.
- Key goal of this workshop: Determine the next steps needed to understand tidal heating.

Relevance to NASA's Decadal Survey for planetary science

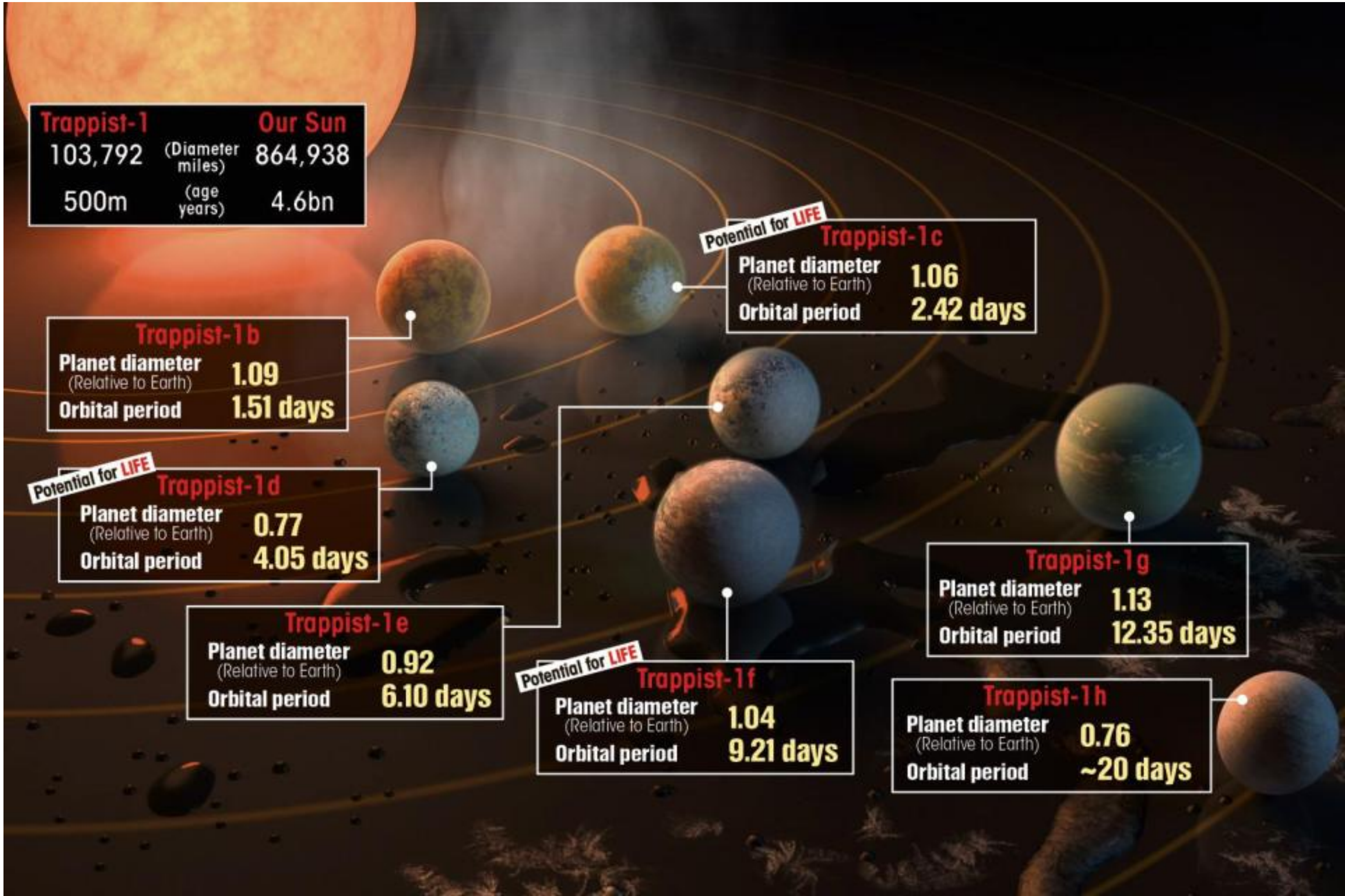
Tidal heating is relevant to 5/10 of the key questions from Vision & Voyages:

- Building New Worlds
  - How did the giant planets and their satellite systems accrete, and is there evidence that they *migrated to new orbital positions*?
  - What governed the accretion, supply of water, chemistry, and *internal differentiation* of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?
- Planetary Habitats
  - Beyond Earth, are there contemporary habitats elsewhere in the solar system with necessary conditions, organic matter, *water, energy, and nutrients* to sustain life, and do organisms live there now?
- Workings of solar systems
  - How do the giant planets serve as laboratories to understand Earth, the solar system, and extrasolar planetary systems?
  - How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?

Tidal heating in Trappist-1 system

Barr et al., 2018:

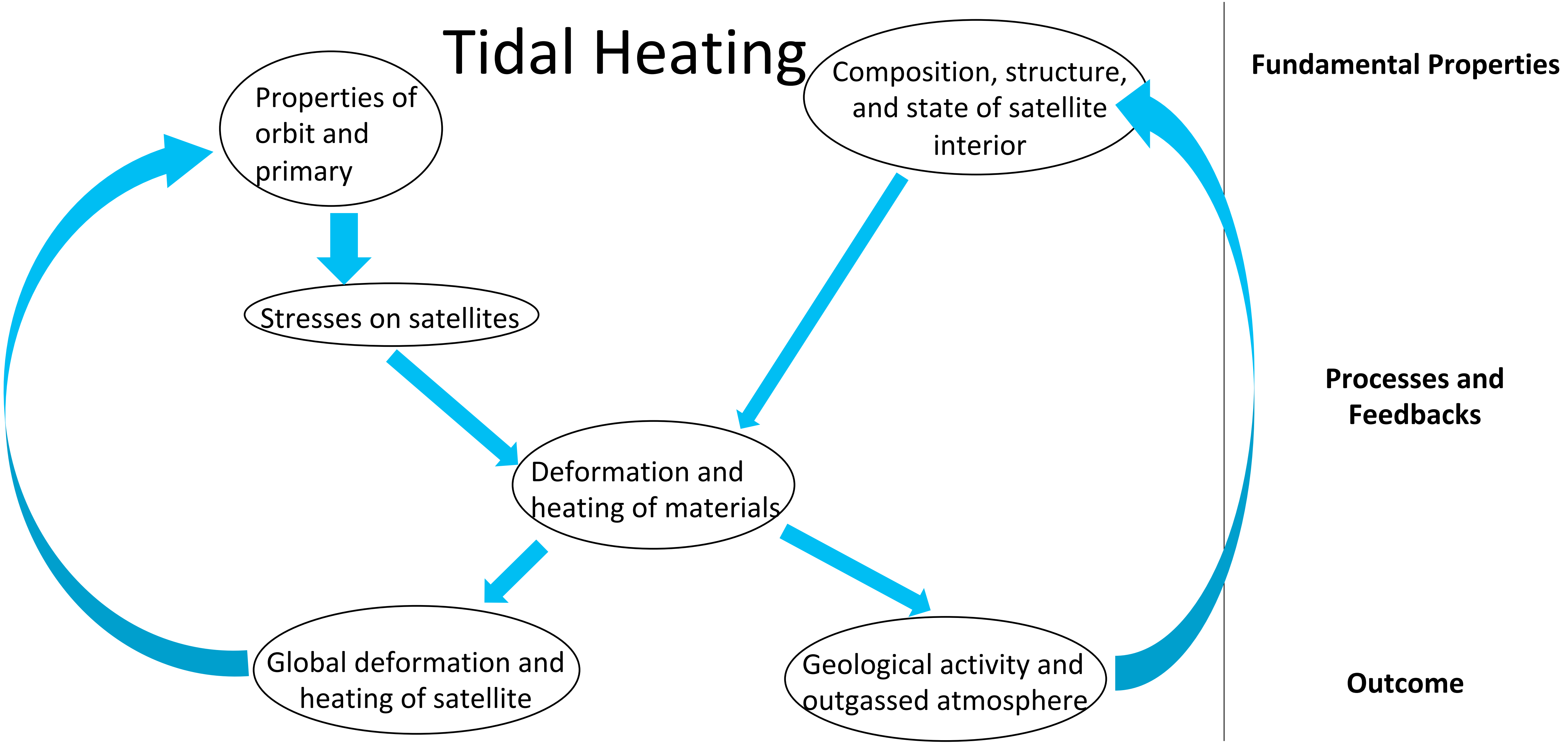
Planets b and c experience enough heating from planetary tides to maintain magma oceans in their rock mantles; planet c may have surface eruptions of silicate magma, potentially detectable with next-generation instrumentation. Tidal heat fluxes on planets d, e, and f are twenty times higher than Earth's mean heat flow.



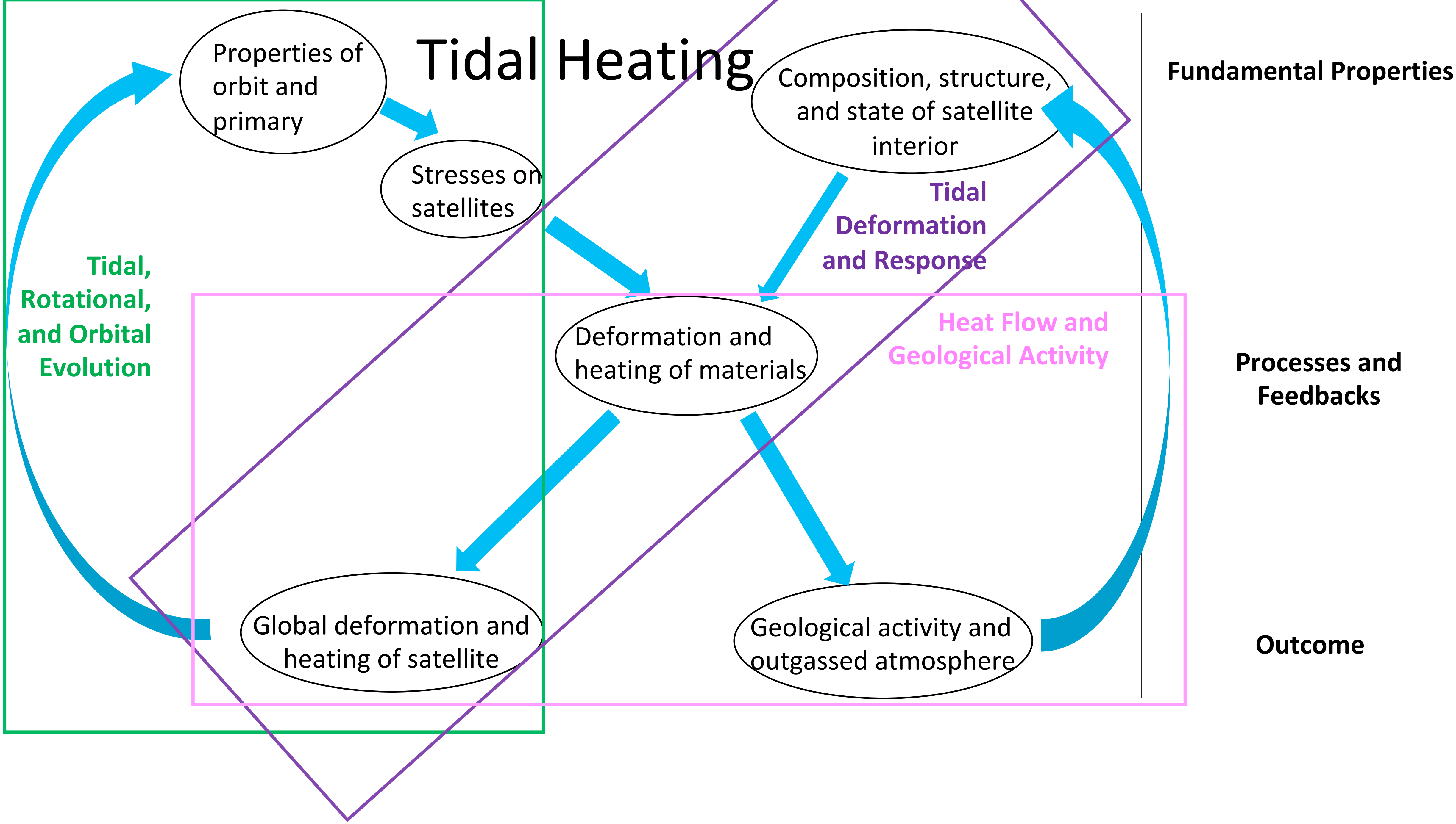
What have we learned about tidal heating from past spacecraft missions?

- Galilean Satellites were discovered by Galileo Galilei in 1610; in 1771 Laplace described the 4:2:1 resonance
  - Significance realized 200 years later
- Transient IR brightening of Io observed by Witteborn et al (1979)
- Peale et al. (1979) Melting of Io by Tidal Dissipation
  - Laplace resonance creates significant forced eccentricity in orbits of Io and Europa, so they are periodically deformed by massive Jupiter, generating internal heating
  - Predicted runaway melting of the interior of Io, thinning the lithosphere so that it could conduct away the heat.
  - Predicted that Voyager spacecraft might observe widespread and recurrent volcanism
- Prediction confirmed a few months later by *Voyager 1*
  - Many signs of active volcanism
  - But Io had large mountains up to 17 km high! How is that possible with a thin lithosphere over a molten interior?
- Galileo mission:
  - Magnetic induction signature from conducting layers
    - Salty water in Callisto, Ganymede, Europa; magma in Io [Kivelson, Khurana et al.)
  - Very high (ultramafic) lava temperatures on Io? [McEwen et al.]
- Cassini mission:
  - Enceladus: Active jets contains salts and organics, emanating from warm fissures
  - Evidence for subsurface oceans in Titan and Enceladus
- Astrometry of satellite orbit migration rates [Lainey et al.]
- Telescopic discoveries of exoplanet systems
- Observational results have spurred theoretical advances

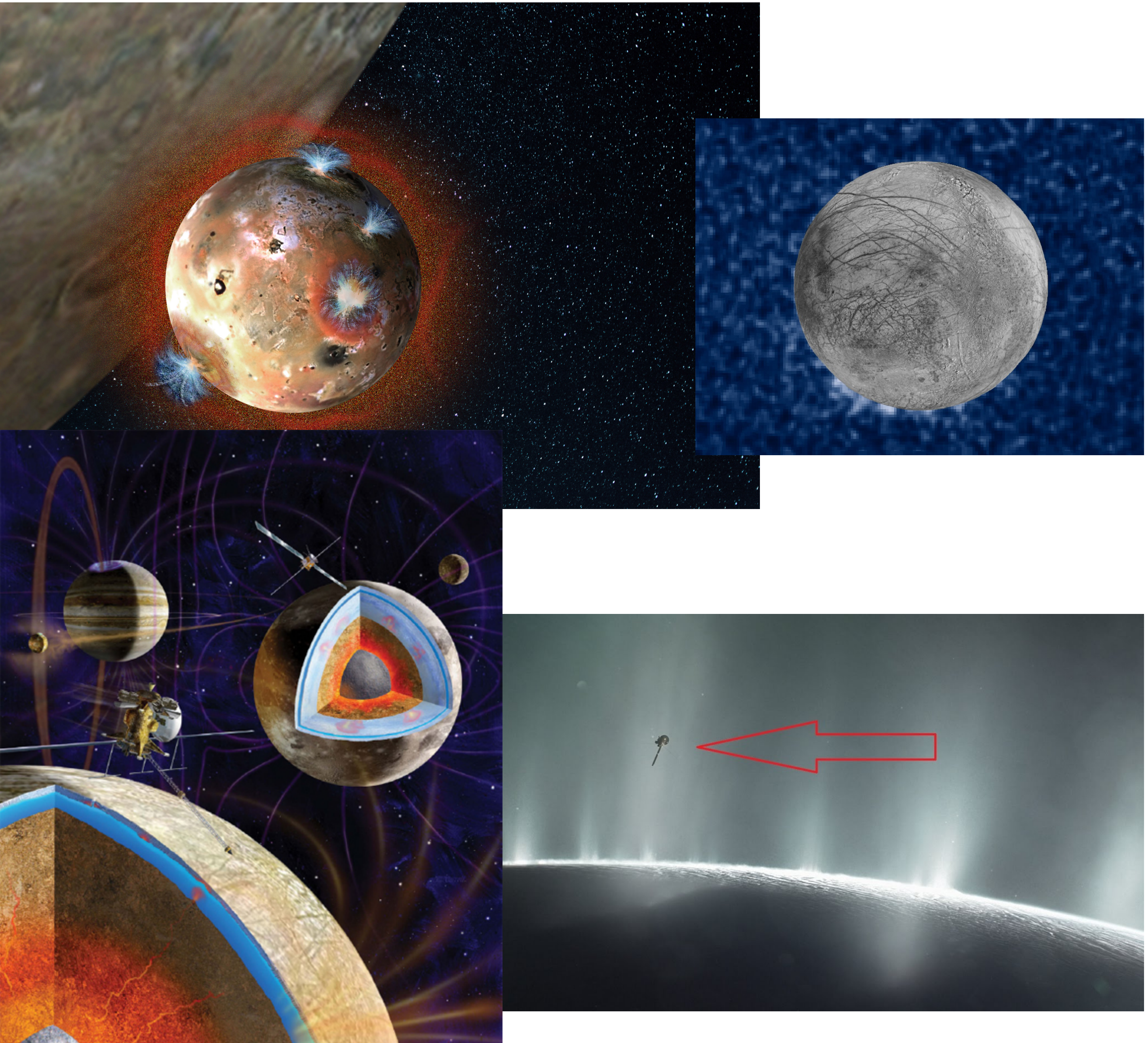
Tidal Heating



1. Identify the specific parts of this process that are not understood.
2. What experiments, measurements, or theoretical work are still needed?
3. What new technologies (spacecraft missions/instruments, telescope instruments, lab set-ups, algorithms) will be required?


Tidal Heating
Properties of orbit and primary
Stresses on satellites
Composition, structure, and state of satellite interior
Fundamental Properties
Tidal Deformation and Response
Tidal, Rotational, and Orbital Evolution
Deformation and heating of materials
Heat Flow and Geological Activity
Processes and Feedbacks
Global deformation and heating of satellite
Geological activity and outgassed atmosphere
Outcome

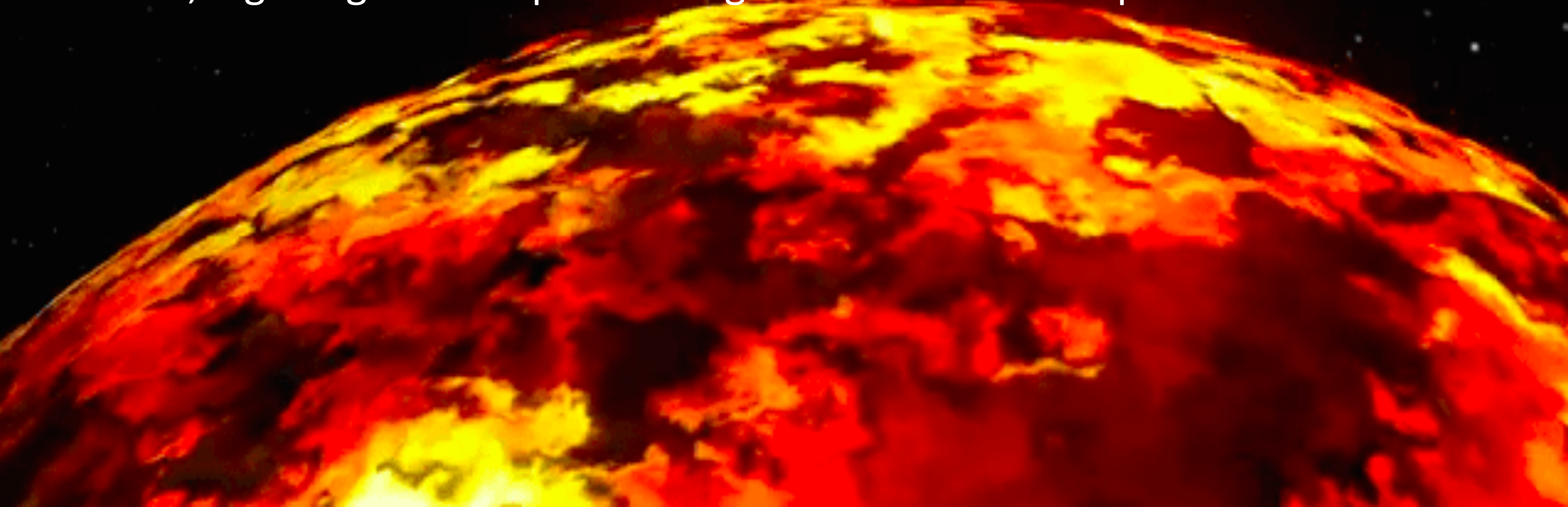
Heat Flow and Geological Activity: *Key Questions*



- **Water/magma oceans:** How do tides create and maintain subsurface water or silicate melt? Over what timescales are these liquids stable? What feedbacks do these materials have on where and how much tidal heat dissipation occurs?
- **Geological activity:** How do tides (as distinct from other heat sources) drive the specific nature of geological activity, including mountain formation, tectonics, plumes, and (cryo-)volcanism

Heat Flow and Geological Activity: *Key Questions*

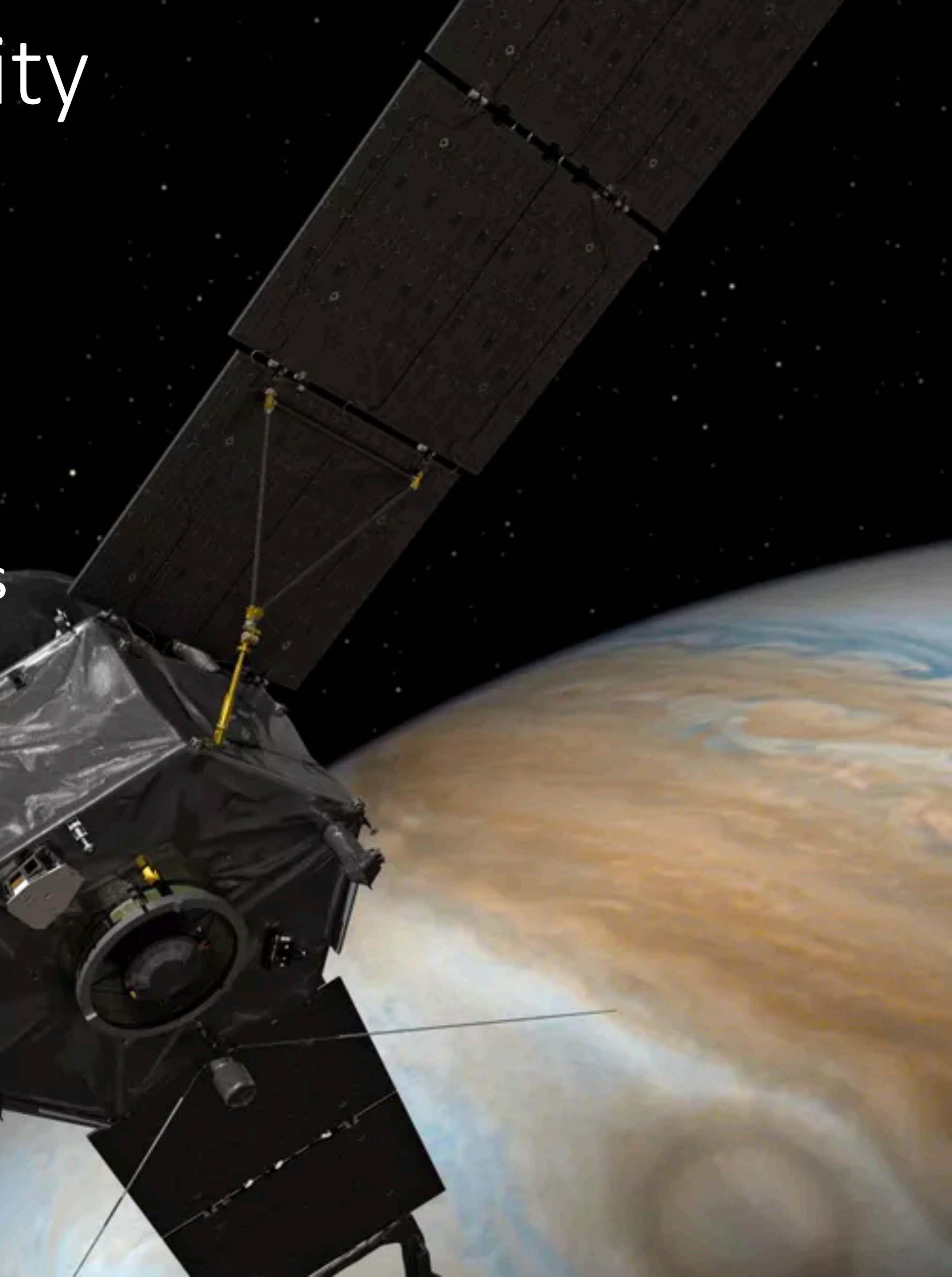
- **Heat deposition:** What is the 4D distribution of heating $(\mathbf{x},t)$ in a satellite's interior, and how does this translate to a magnitude and distribution of surface heat flow over time?
- **Heat transport:** How is heat transported through satellite interiors, and to the surface, e.g. magma transport through a crust under compression?



Heat Flow and Geological Activity
How do we make progress?

Addressing these questions requires studying what's going on in satellite interiors. How do we do this?

- How can we measure the state, temperature, and composition of a satellite's mantle, either from Earth, from orbit, or from the satellite's surface?
- What are the surface observables that give indirect information on the interior? What new laboratory or modeling efforts are needed to form a more robust link between observables and interior properties? What are the capabilities of the currently available instruments?



Tidal, Rotational, and Orbital Evolution

- The rotational and orbital dynamics of a satellite with a non-zero orbit eccentricity and non-spherical mass distribution is influenced by the tidal force raised by the primary body.
- Over long timescales, tides can alter the structure of a moon, changing its tidal response and driving feedbacks between the rotational, orbital, and thermal evolution of the satellite.

What do we need to know?

1. What are long-term (and short-term) tidal effects on the rotational and orbital evolution? How are they parameterized?
2. What are the required observations?
3. What observations are currently available (both astrometric and surface-based) and what do we know from these observations?
4. What technologies are needed to improve future observations?

Tidal Deformation and Response

- Tidal deformation can be measured directly, by detecting periodic changes in the shape and gravity field of a moon, and indirectly, by measuring the tidal heat produced or orbital motions such as libration.
- Moons with a weak region in the subsurface, such as liquid water or magma, are expected to show larger tidal response.
- The response of materials to periodic deformation has been studied in the laboratory, showing that temperature and forcing frequency both have a strong effect on deformation.

What do we need to know?

1. How partially molten materials respond to periodic forcing.
2. Observational constraints on tidal surface deformation and the associated phase lag (only measured for the Moon).
3. Models that do not assume spherically symmetry.
4. Better understanding of long-period forcing.

Draft topics for breakout sessions

- Typically 3-4 groups per session
- First breakout can address key questions is 3 groups from our proposal organization:
  - Tidal, rotational, and orbital evolution
  - Tidal deformation and response
  - Heat flow and geological activity
- Subsequent 4-5 breakouts; topics to be decided at workshop, but here are some ideas:
  - Make sure we mix and match people in different ways so we are not always talking to the same people
  - Techniques:
    - Magnetic induction and electrical conductivity of realistic planetary interiors
    - Seismology
    - Gravity science, tides
    - Measuring lava temperatures and heat flow on Io
    - Astrometry
    - Remote-sensing techniques
    - Laboratory experiments
    - Modeling
  - Key science questions
    - See other slides
  - Key places (Jupiter system, Saturn system, Io, Enceladus, exoplanets, Earth/Moon, etc.)

Draft topics for 10-minute lightning talks

- 10 minute talk + 5 minutes for questions
- Key issues the group should better understand
    - Use posters for your own latest research
    - Full group will decide what talks to solicit

The Final Report

- Develop outline and writing assignments on Friday
  - Decide on report audience/where to submit it & deadline for completion; identify authors for sections.
- Note-taking matters for the final report!
  - Everyone encouraged to take notes
  - Have one official note-taker for breakout sessions and plenary discussions
    - Slides provide information on more formal presentations and plenary summaries of breakouts

Determine **the most critical questions** that we need answer to advance our paradigm of how tidal heat is generated, transported, and expressed through time;

and identify the **measurements, experiments,** and **theoretical approaches**

that are required to answer these questions in the next 20 years.

Back-up slides after this point

Heat Flow and Geological Activity

Summary for easy reference

Key Questions

- **Water/magma oceans:** How do tides create and maintain subsurface oceans, water or silicate? Over what timescales are these oceans stable? What feedbacks do these oceans have on where and how much tidal heat dissipation occurs?
- **Heat deposition:** What is the 4D distribution of heating (**x**,t) in a satellite's interior, and how does this translate to a magnitude and distribution of surface heat flow over time?
- **Heat transport:** How is heat transported through satellite interiors, and to the surface, e.g. magma transport through a crust under compression?
- **Geological activity:** How do tides (as distinct from other heat sources) drive the specific nature of geological activity, including mountain formation, tectonics, plumes, and (cryo-)volcanism.

How do we get there?

Addressing these questions requires studying what's going on in satellite interiors. How do we do this?

- How can we measure the state, temperature, and composition of a satellite's mantle, either from Earth, from orbit, or from the satellite's surface?
- What are the surface observables that give indirect information on the interior? What new laboratory or modeling efforts are needed to form a more robust link between observables and interior properties?

Draft topics for 10-minute lightning talks

- Key issues the group should better understand
  - Use posters for your own latest research
  - Full group will decide what talks to solicit
- Example ideas:
  - How does deformation control melt extraction
  - Electrical conductivity of planetary materials
  - Telescopic capabilities relevant to tidal heating
  - How internal structure affects libration
  - How to measure libration
  - Spatial patterns of tidal heating
  - Mantle convection
  - ARGUS Io mission concept
  - Styles of volcanic eruptions
  - Plasma processes near Io and Europa
  - Radar sounding of planetary crusts
  - Seismic studies
  - Tectonic styles