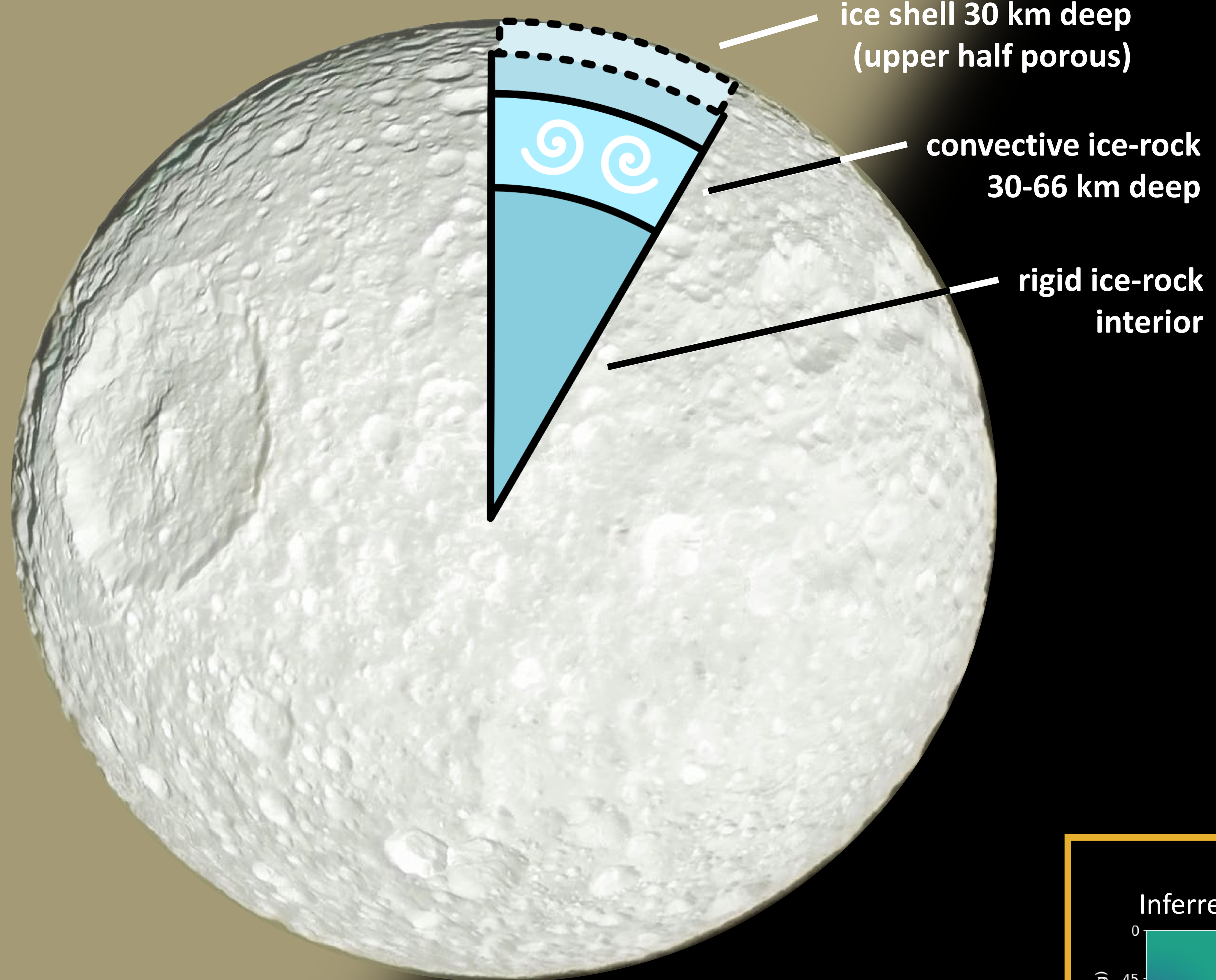
Ice-shell thickness variations betray a **past era of tidal heating** within a **solid Mimas**, driven by a transient, **high obliquity**



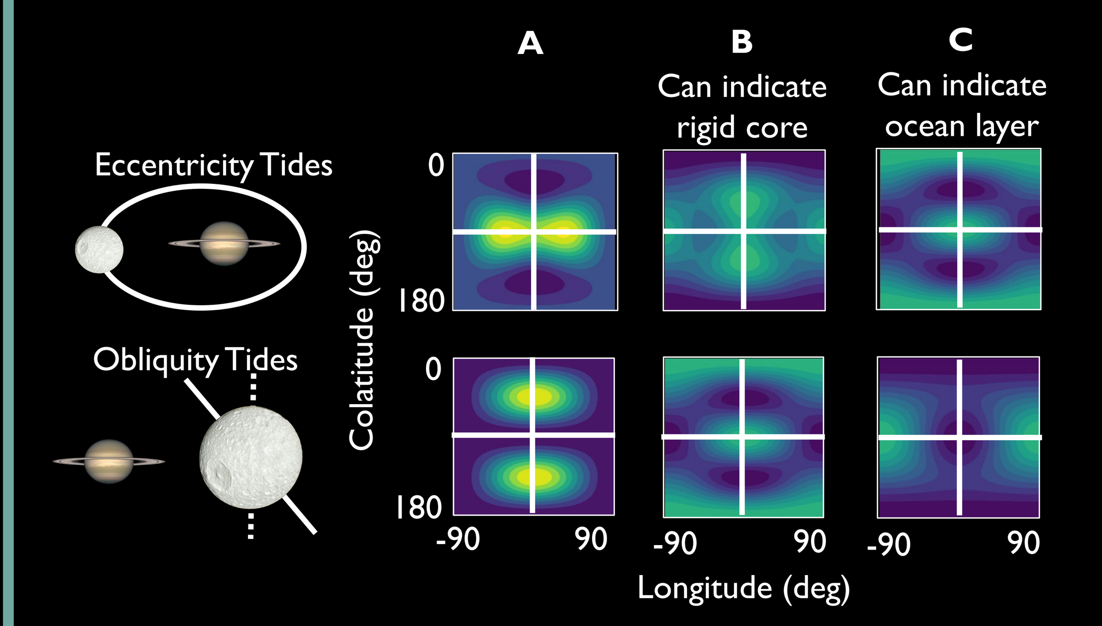


Figure 1: Tidal Heating Patterns (Beuthe 2013)

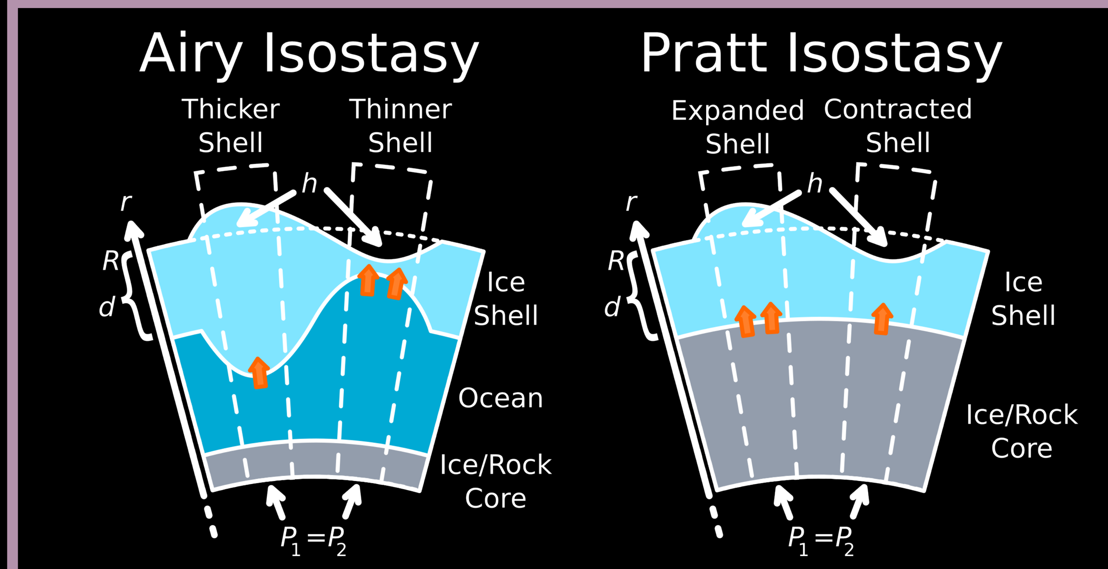


Figure 2: Isostasy (Gyalay & Nimmo 2023)

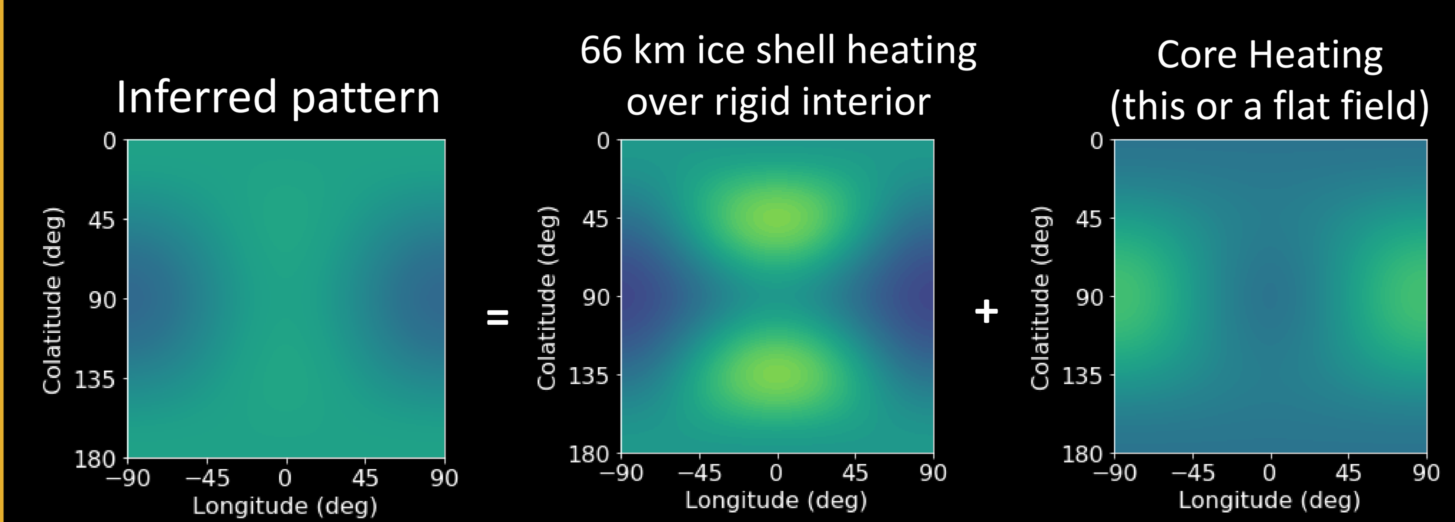


Figure 3: Tidal heating patterns inferred from Mimas' shape
(after removing hydrostatic shape for moment of inertia = 0.375 MR^2)

Image credit:
NASA/JPL-Caltech/Space Science Institute/Jason Major

That's No Ocean Moon:
Effects of Transient Obliquity Tidal Heating in Mimas' Warm Icy Interior Preserved as a Cold Fossil Figure

Szilárd Gyalay (sgyalay@ucsc.edu, @szizygy) & Francis Nimmo
University of California, Santa Cruz

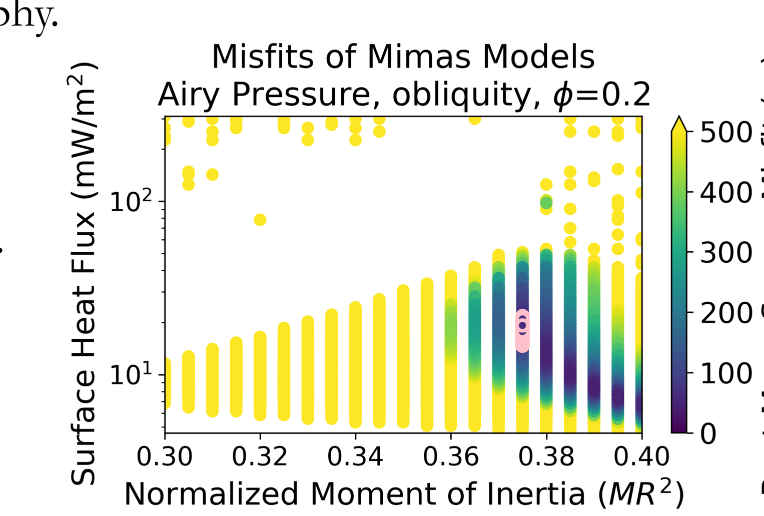
Mimas Appears Inactive Despite its Circumstances

- **Mimas** and **Enceladus** have a **similar size**, **semi-major axis**, and **eccentricity**
- **Mimas has a large physical libration** (orbital wobble in response to Saturn's tug on tidal bulge; 0.84° vs. 0.122°-0.156° for Enceladus; Tajeddine+ 2014, Thomas+ 2016, Nadezdhina+ 2016)
- This is circumstantial **evidence for a Mimatean ocean**, yet surface **appears inactive**
- But, one **can tidally heat an ocean without relaxing the surface** (Rhoden & Walker 2022)

Satellite Interior Determines its Tidal Heating Pattern
Variations in Tidal Heat Manifests in Satellite's Global Shape

- **Mimas' non-hydrostatic shape varies at the same length-scales over which tidal heating varies** (spherical harmonic degrees 2 and 4; Nimmo+ 2011).
- Tidal heating distribution is the linear combination of 3 basis tidal heating patterns, differing whether the tides are due to satellite's eccentricity or obliquity (Figure 1; Beuthe 2013). **For a given tidal heating pattern, we can infer if there is an ocean and how thick the ice shell is** (Gyalay & Nimmo 2023)
- If an ice shell is conductive, variations in heating drive global shape (topography) variations via isostasy, where pressure or mass is constant at depth (Figure 2; cf. Hemingway & Matsuyama 2017, Beuthe 2021)
- We iterate through assumptions (moment of inertia, ice shell thickness, basal ice shell temperature, etc.) to **infer a heating pattern from Mimas' long-wavelength topography** (e.g. Gyalay & Nimmo 2023 for Tethys). We check if the inferred pattern is indicative of tidal heating and whether the derived interior is self-consistent with our assumptions and observed topography.

Results



- No models with Pratt isostasy work, **leaving Airy isostasy**. This implies an **ice shell atop a denser, more-fluid interior**.
- **Obliquity tide** heating patterns have **better** (lower) misfit compared to eccentricity tides.
- Our **Mimas results** (**right**) with the **most self-consistent models** (pink circles) also **have the lowest** (purpliest) **misfit** between observed and forward-modeled topography.
- These **best-fit Mimas** results have a **30 km thick shell** with an **average heat flow of 20 mW m^{-2}**.
- The inferred heat pattern is **consistent with tidal heat produced in a 66 km thick ice shell** atop a **rigid ice-rock-mixture core with simultaneous tidal heating** (Figure 3)

Discussion

- If **the region 30-66 km deep is a warm ice-rock mixture**, it has 100x the critical Rayleigh number to be (weakly) **convecting**. It would also have the right rigidity and viscosity for tidal heating. This layer can then act as the "fluid" for the 30 km conductive shell's Airy isostasy.
- **Mimas** presently has a large eccentricity, but **not expected to have a high obliquity**.
- We believe **Mimas' obliquity was temporarily excited** following the tidal disruption of a former satellite that went on to form Saturn's rings (e.g. Wisdom et al. 2022). As chunks of this former satellite collide, their semi-major axes shrinks to the present value for ring particles (Hyodo+ 2017). Assuming Mimas is in a Cassini state, when the chunks' semi-major axes pass Mimas' semi-major axis, the exerted torque can lower the inclination needed for the high obliquity (1.7°) we predict.
- **Once Mimas' obliquity rapidly drops, the shell thickness variations will freeze in.**
- **The impact that created Herschel Crater** (Mimas' largest crater) could have **increased Mimas' eccentricity recently** (cf. Zhang & Nimmo 2012)
- It takes ~30 Myr to conduct heat through 30 km of ice: **shell thickness variations would not reflect** the heat pattern of a shell over **an ocean that formed more recently** (e.g. Denton & Rhoden 2022)

Acknowledgements: This project has benefited tremendously from conversations with **Brynna Downey**.