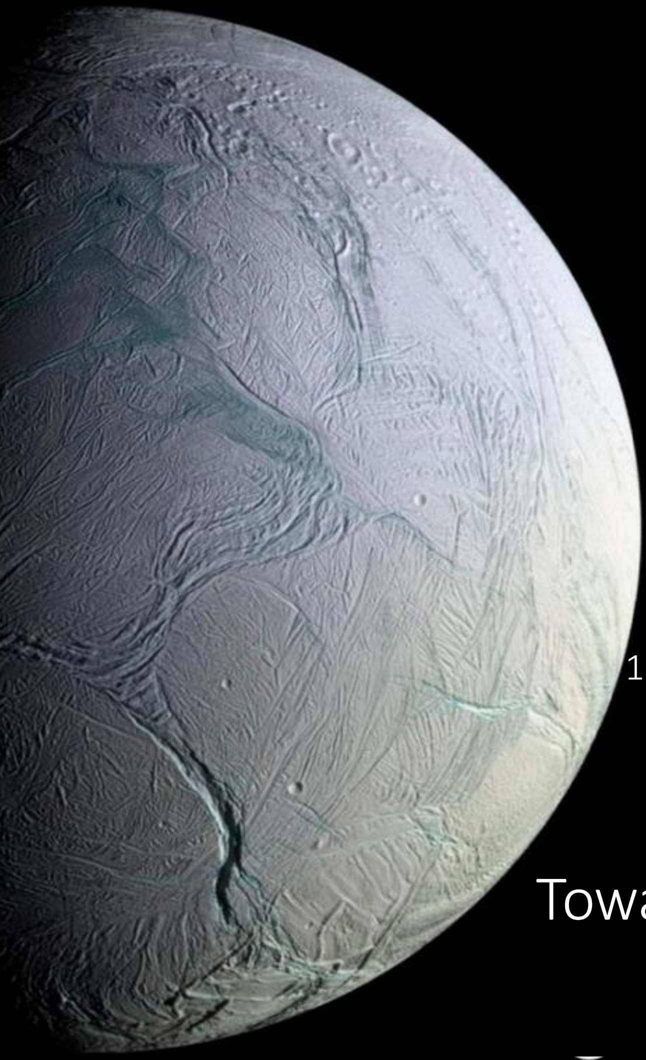
Cold Ocean Planets: Exoplanet Analogs of Our Solar System’s Icy Moons



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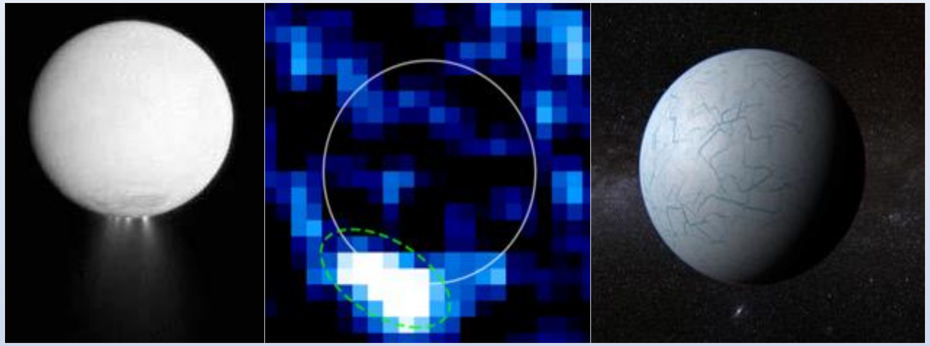
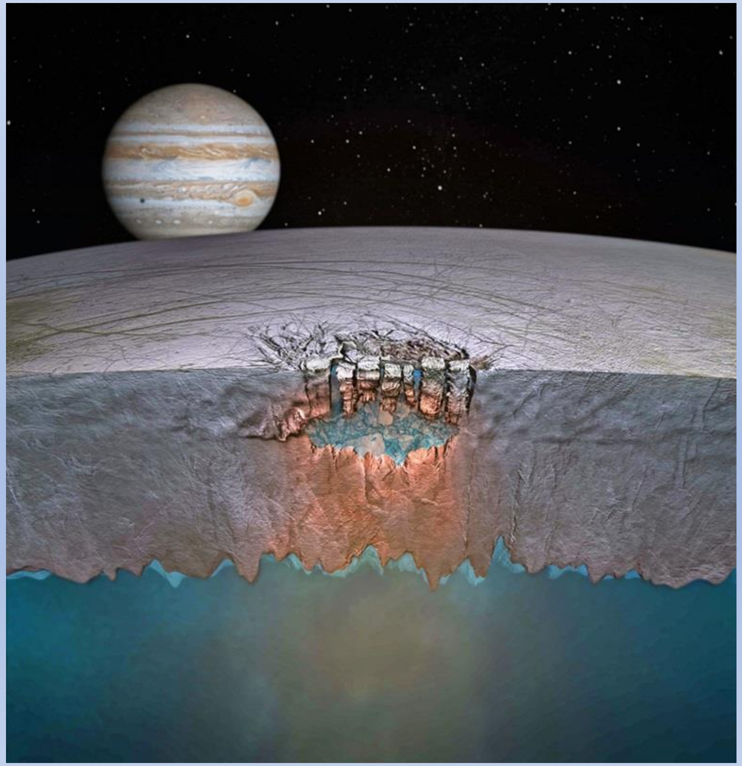
Towards the Habitable Worlds Observatory: Visionary Science and Transformational Technology
July 30, 2025

Cryovolcanism and Habitability

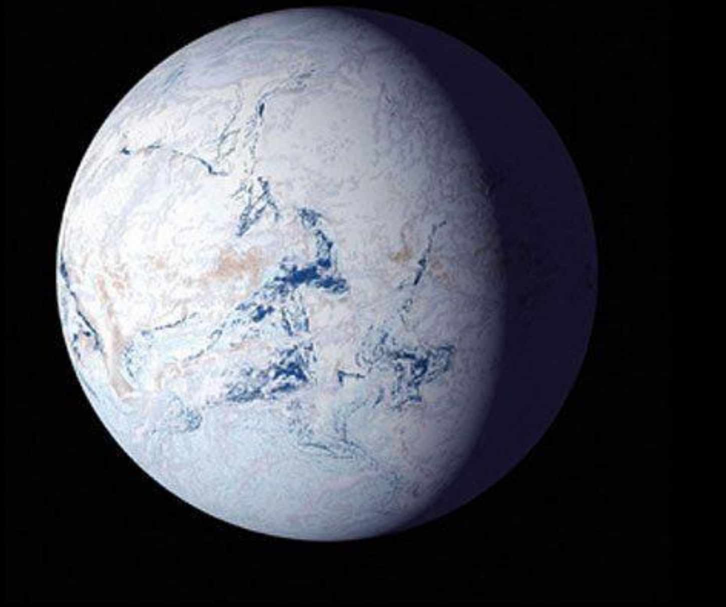
- Quick et al. (2020) constrained internal heating rates and the likelihood for geological activity on 53 low-mass, terrestrial exoplanets
    - 14/53 (26%) of "terrestrial" exoplanets are likely to be geologically active ocean worlds
    - 9/53 (17%) are likely to be cryovolcanically active cold ocean planets
    - many planets had poorly constrained T_S and cryovolcanic outgassing rates were not explored
- Each cryovolcanically-active moon in our solar system has internal reservoirs of liquid water that may serve as habitable niches
- Telescopic detection of cryovolcanic activity could serve as an indicator that low-mass extrasolar planets have:
    - subsurface oceans
    - geological activity that cycles liquid water, heat, and organics between their surfaces and interiors

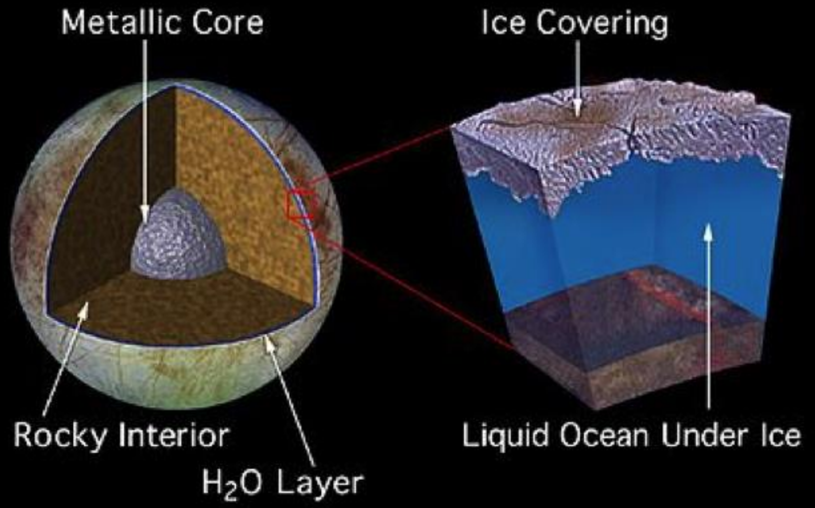




Cryovolcanism and Habitability

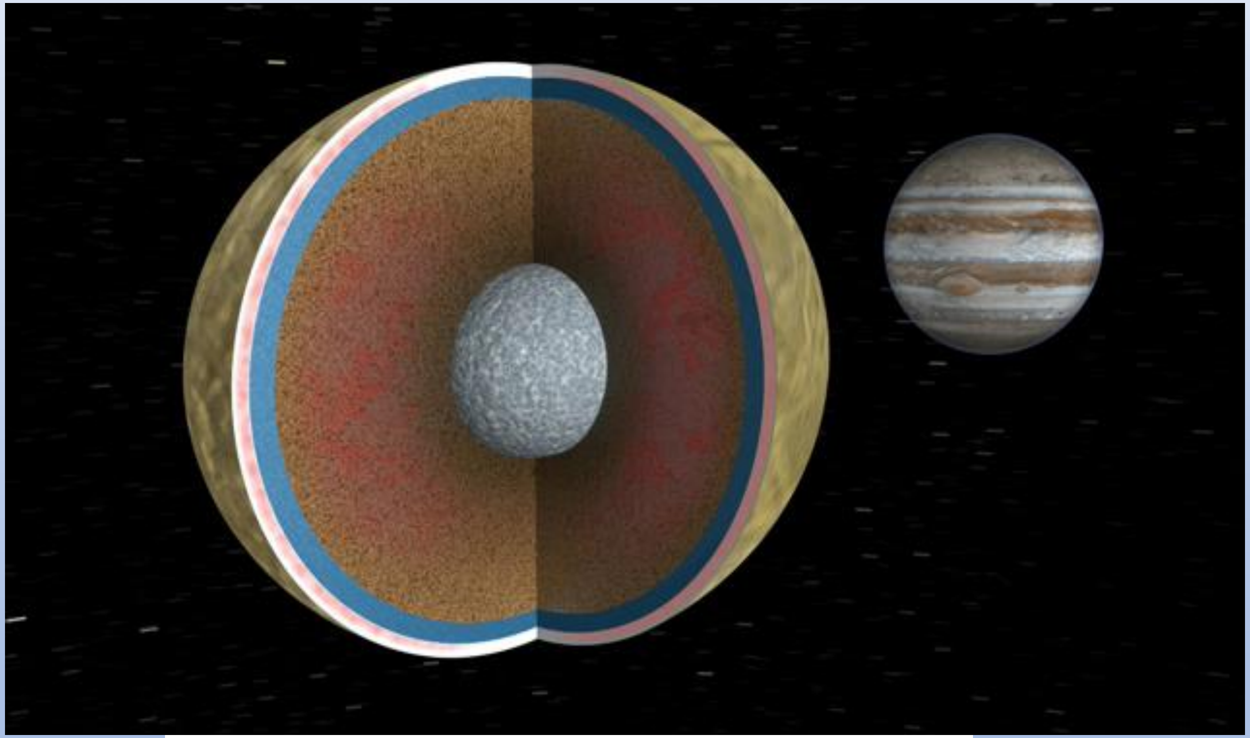
- We considered 17 Earth-sized exoplanets that may be H_2O rich, ice-covered ocean worlds based on their estimated effective temperatures, densities, orbital distances, and total internal heating rates
  - $M_P < 8M_E$ and $R_p \leq 2R_E$
  - $T_s = T_{eff} < 255$ K
  - 16/17 planets have bulk densities less than or equal to Earth's
  - 12/17 planets have bulk densities ≤ 3500 kg/m^3
- Need to constrain:
  - surface temperatures (T_S)
  - depth to internal oceans (D)
  - cryovolcanic outgassing rates ($\dot{M}_{\mathrm{volc}}$)





Total Internal Heating: $H_{\text{Tidal}} + H_{\text{Radiogenic}}$

H_{Tidal}



$$H_{\text{Tidal}} \sim \dot{E} = \frac{21}{2}\frac{k_2 \omega^5 {R_P}^5 e^2}{GQ}$$

$k_2 = 0.3$, $Q = 100$

$H_{\text{Radiogenic}}$

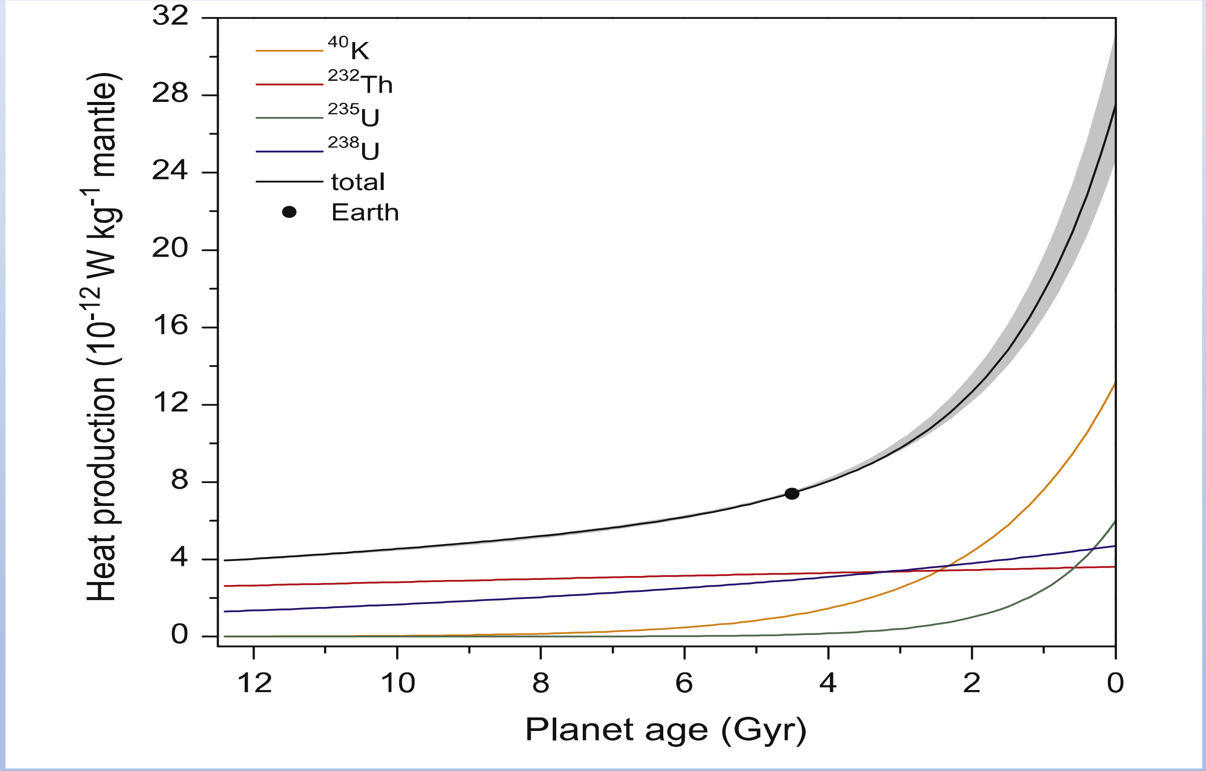
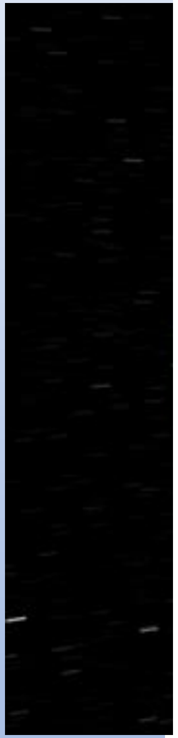


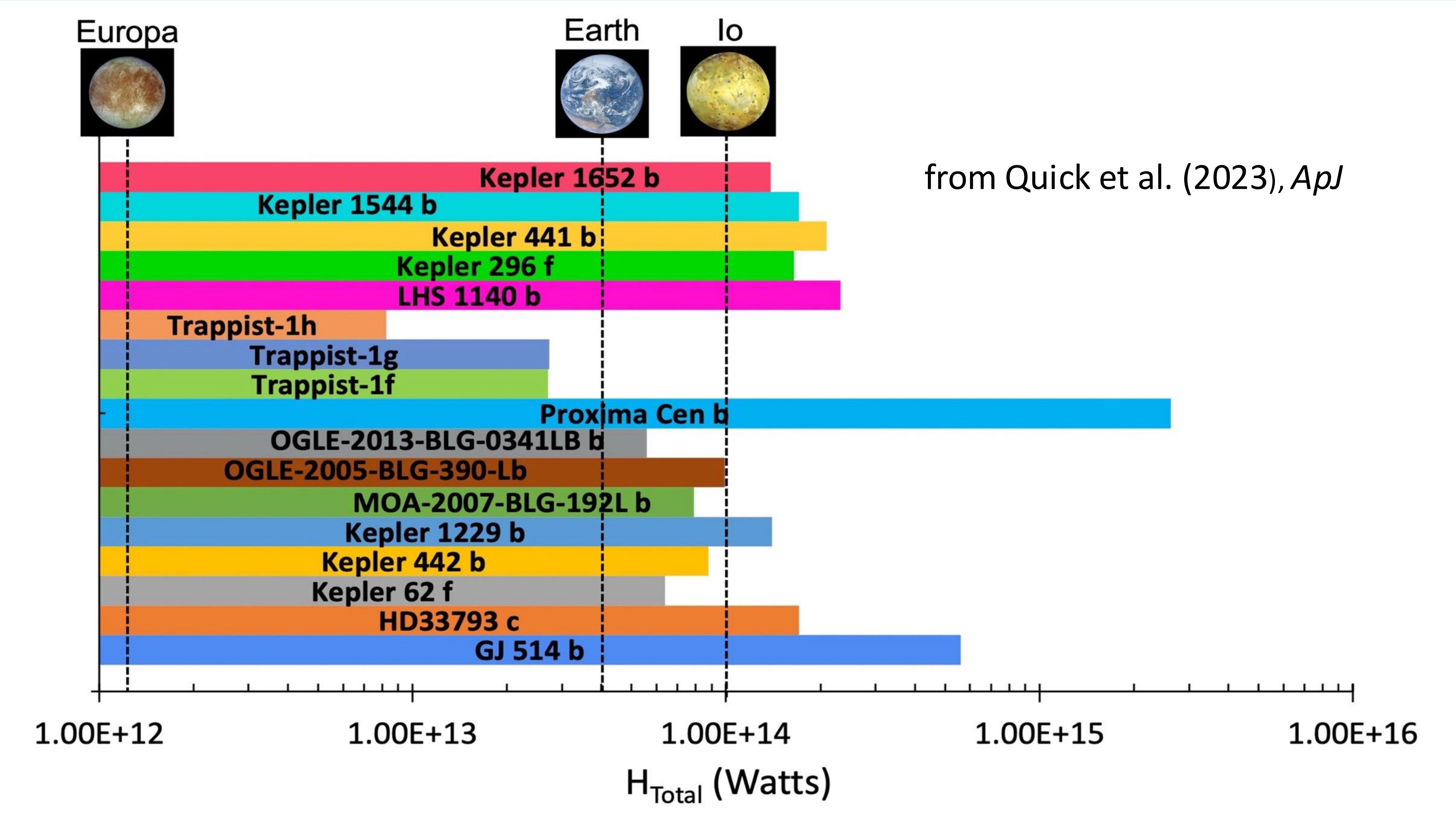
Figure from Frank et al. (2014)

$$H_{\text{Radiogenic}} = \dot{h}\, M_{\text{mantle}}.$$

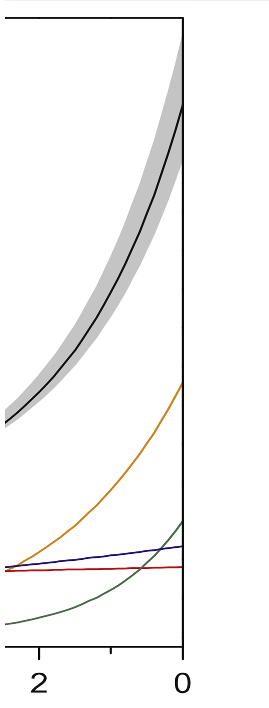
formula from Quick et al. (2023), *ApJ*

Total Internal Heating: $H_{Tidal} + H_{Radiogenic}$





from Quick et al. (2023), *ApJ*



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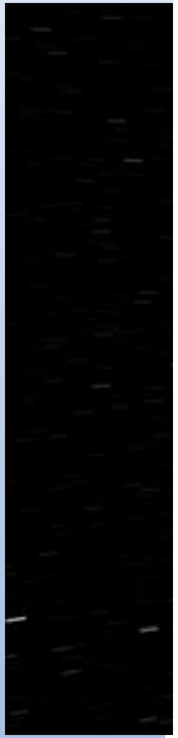
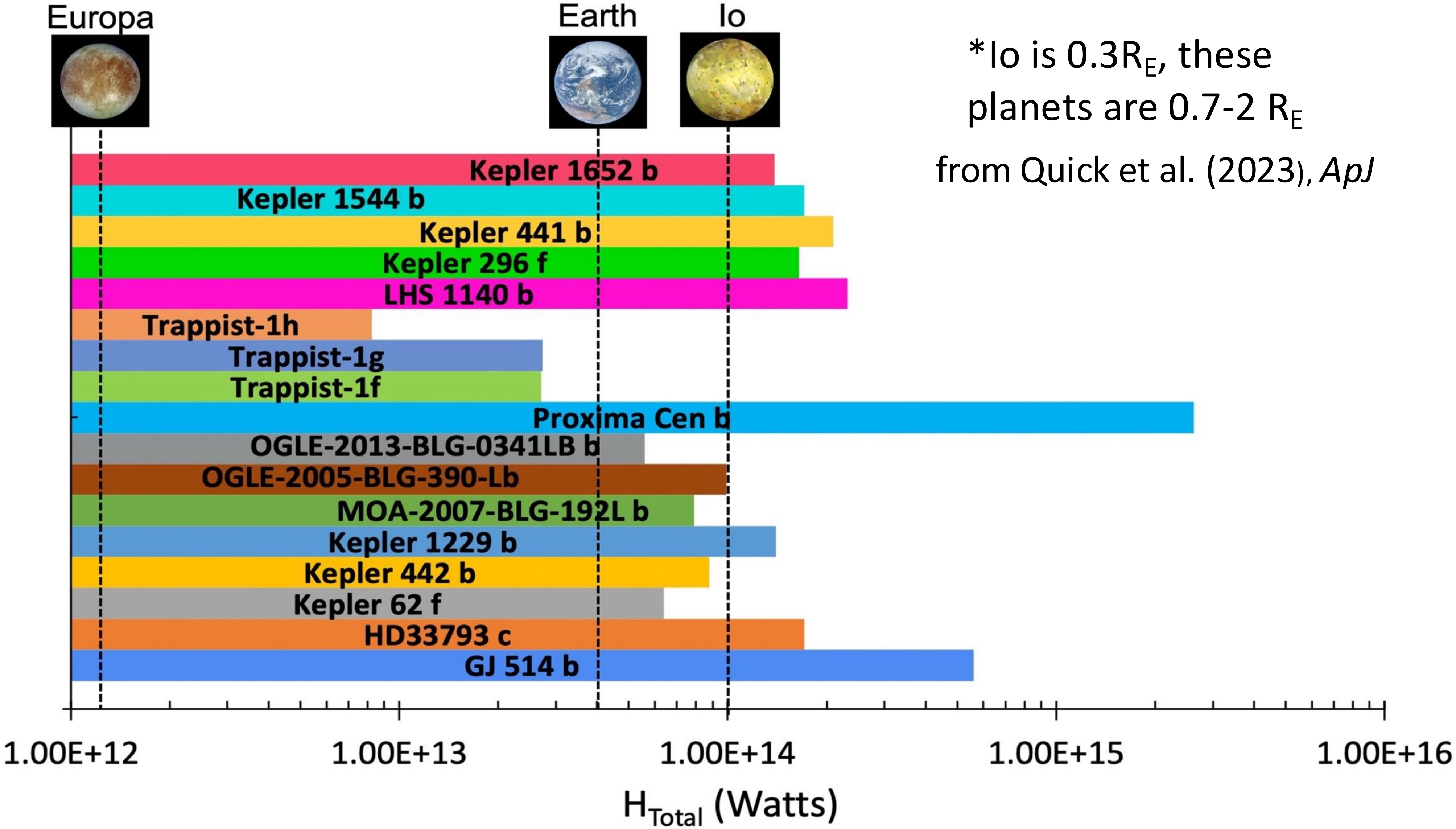
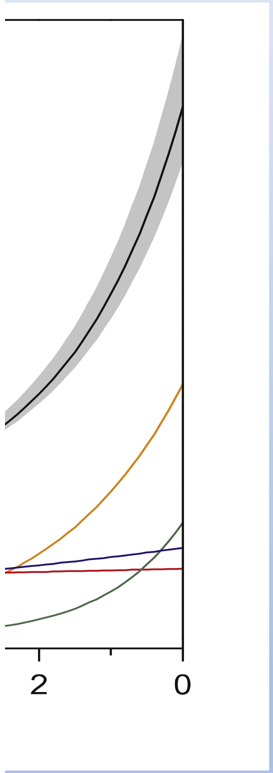




*Io is $0.3R_E$, these planets are 0.7-2 R_E

from Quick et al. (2023), *ApJ*



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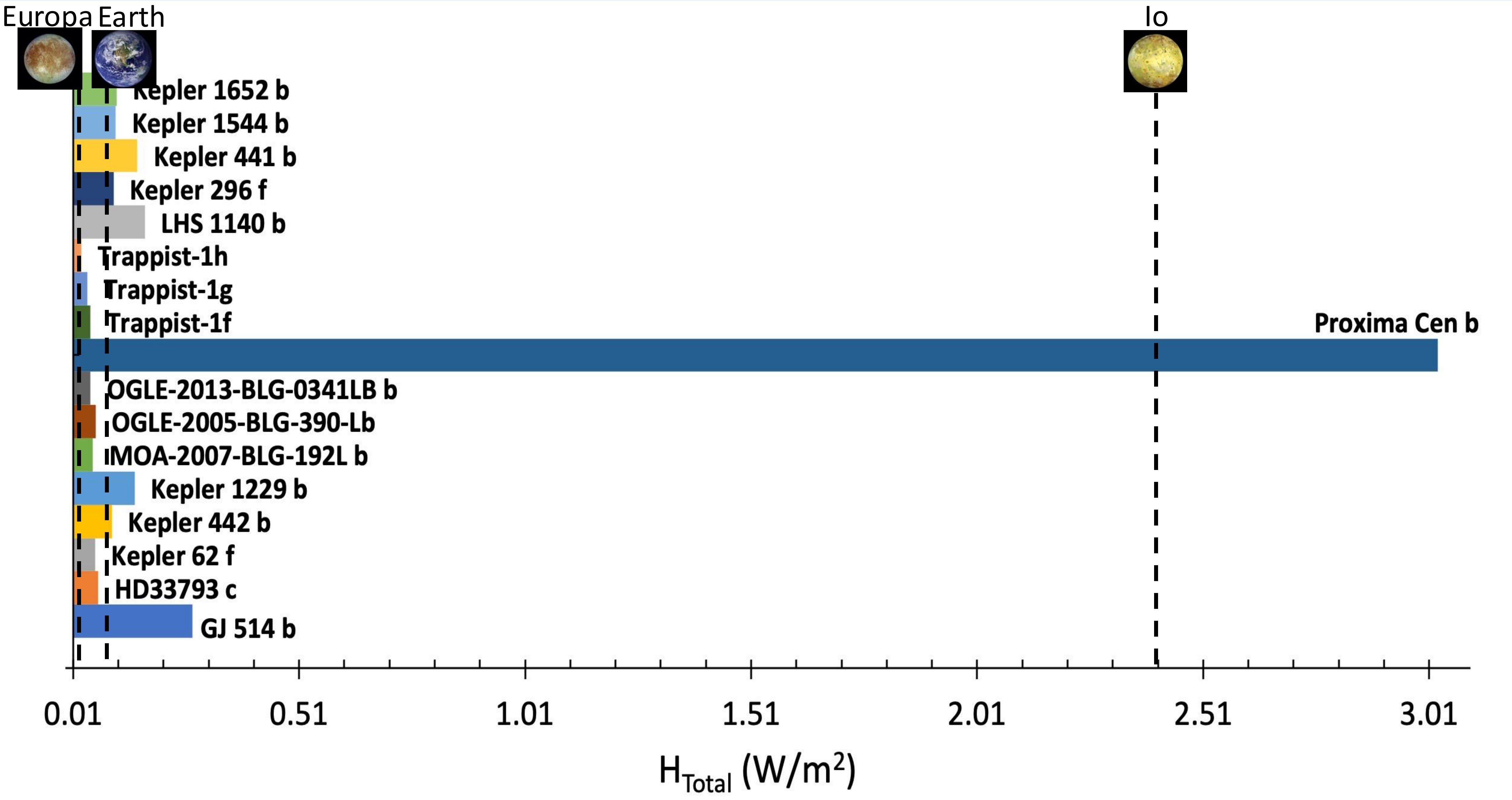
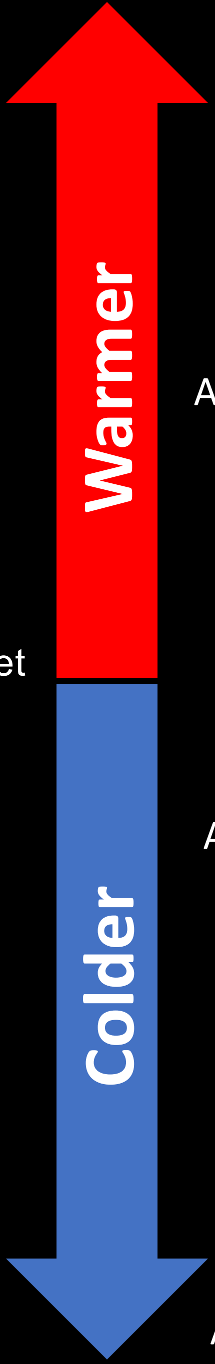


Constraining Surface Temperatures (T_S)

- estimated equilibrium surface temperatures in the literature assumed bond albedos (A) not characteristic of planets with icy or liquid water surfaces, regardless of estimated bulk densities:
  - “null” bond albedo assumed for Trappist-1 f, g, h (Gillon et al. 2017)
  - A= 0 assumed for LHS 1140 b and Proxima Cen b (Ment et al., 2019; Anglada-Escudé et al., 2016)
  - 0 ≤ A ≤ 0.5 assumed for Kepler 62 f (Borucki et al., 2013)
- investigated surface T_S assuming bond albedos (A) and emissivities (ε) consistent with Earth and ice-covered ocean worlds in our solar system

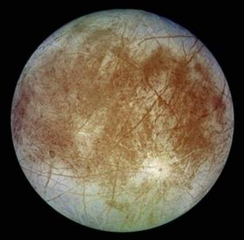
$$T_s = \left[\frac{L\,(1-A)}{16\pi\sigma\varepsilon a^2}\right]^{1/4}$$



Earth

A = 0.3; ε = 0.85

Europa



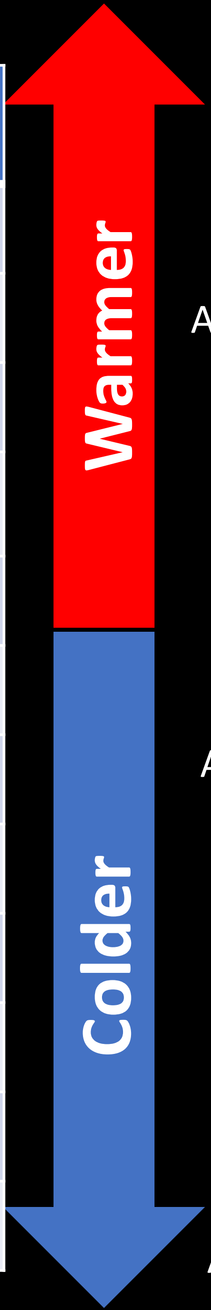
A = 0.55; ε = 0.9

Enceladus

A = 0.81; ε = 1

Constraining Surface Temperatures (T_S)

		Earth-like A = 0.3, ε = 0.85	Europa-like A = 0.55, ε = 0.9	Enceladus-like A = 0.81; ε ≅ 1
Planet	*Cited T_s (K)	T_s (K)	T_s (K)	T_s (K)
GJ 514 b	202	182.5	161	126.5
Kepler 62 f	208	224.6	198	155.6
Kepler 1229 b	212	238.6	210.6	165.4
Kepler 1544 b	269	249.4	220.2	172.9
Kepler 1652 b	268	254.2	224.4	176.2
LHS 1140 b	235	205	180.7	141.8
OGLE-2005-BLG-390-Lb	50	48	42.3	33.2
Proxima Cen b	234	238.8	210.8	165.5
Trappist-1f	219	237.8	209.9	164.8
Trappist-1g	198.6	188	166	130
Trappist-1h	168	163.5	144	113



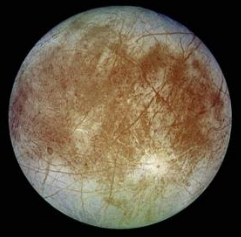
Warmer

Colder

Earth

A = 0.3; ε = 0.85

Europa



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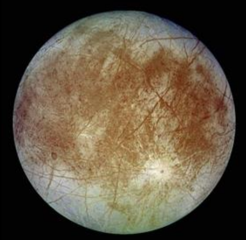


A = 0.55; ε = 0.9

Enceladus

A = 0.81; ε = 1

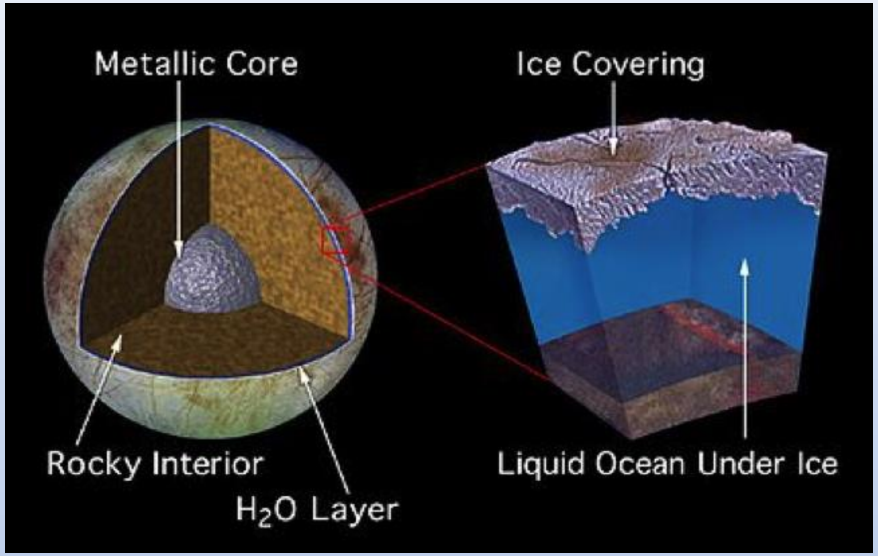
How Far Beneath The Surface Do Oceans Lie?

- Like the icy moons in our solar system, ice shells may form from top down (Quick and Marsh, 2015)
- internal heating due to tidal and radiogenic effects will forestall the freezing of subsurface oceans
- We have employed a Stefan-style solidification solution to constrain the depths to internal oceans on each planet; ice shells are in a conductive regime

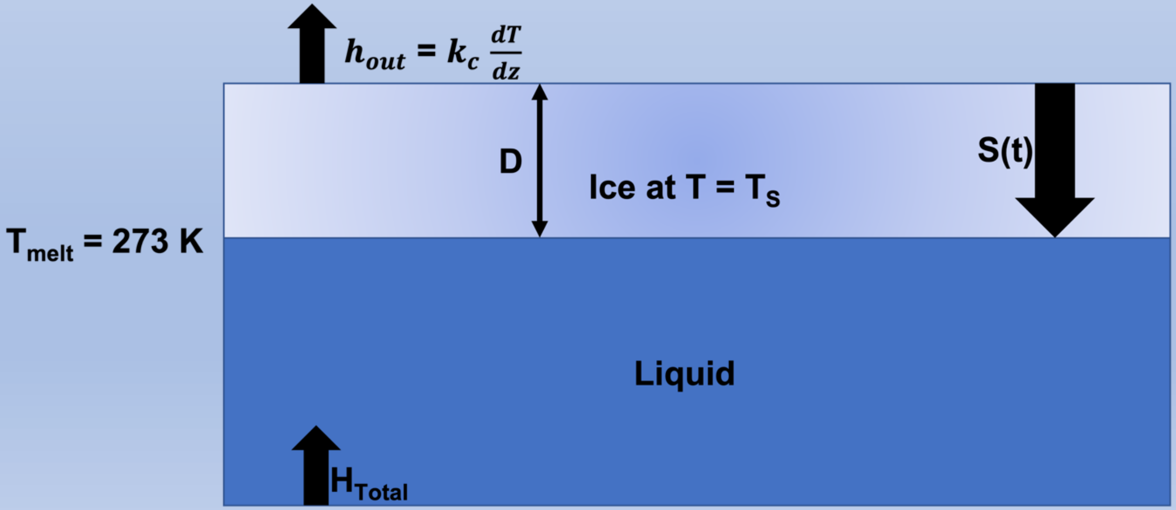
$$D = \frac{(273.16 - T_S)\mathrm{k}_{\mathrm{ice}} 4\pi R_P^2}{\mathrm{H}_{\mathrm{Total}} + (1.063 \times 10^{-7} \rho_{\mathrm{ice}} \mathrm{g} \mathrm{k}_{\mathrm{ice}} 4\pi R_P^2)}$$

(Quick and Marsh, 2015)

- $H_{Total} = H_{Tidal} + H_{Radiogenic}$



Europa internal structure



from Quick et al., 2023

How Far Beneath The Surface Do Oceans Lie?

Planet	D (km)
Proxima Cen b	0.058
Kepler 1229 b	1.2
Kepler 1544 b	1.3
LHS 1140 b	1.7
Kepler 296 f	2.6
Trappist-1f	3.52
Kepler 62 f	3.6
Trappist-1g	8
HD33793 c (Kapteyn c)	8.2
GJ 514 b	11.9
Trappist-1h	16.4
OGLE-2013-BLG-0341LB b	29.4
MOA-2007-BLG-192L b	38.7

Earth

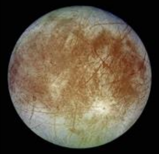
D = 0 km

H_2O at surface

Enceladus

D = 10 km
(S. Pole)

Europa



D = 30 km

- Found three sets of solutions for each planet based on Earth-, Europa-, and Enceladus- like albedos and emissivities
- Proxima Cen b’s ocean is closest to the surface: D = 0.058 km
- MOA-2007-BLG-192Lb: ocean located beneath > 38 km of ice
- Trappist-1f, g, h: oceans beneath 3.5 km, 8 km, and 16 km of ice
- Oceans closer to (farther from) the surface assuming Earth-like- (Enceladus-like) A and ε

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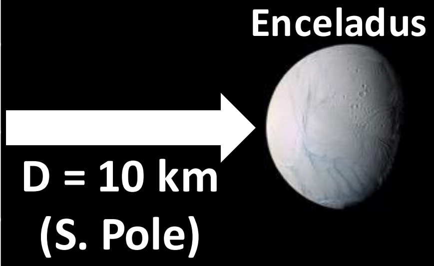

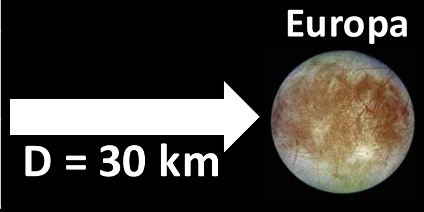

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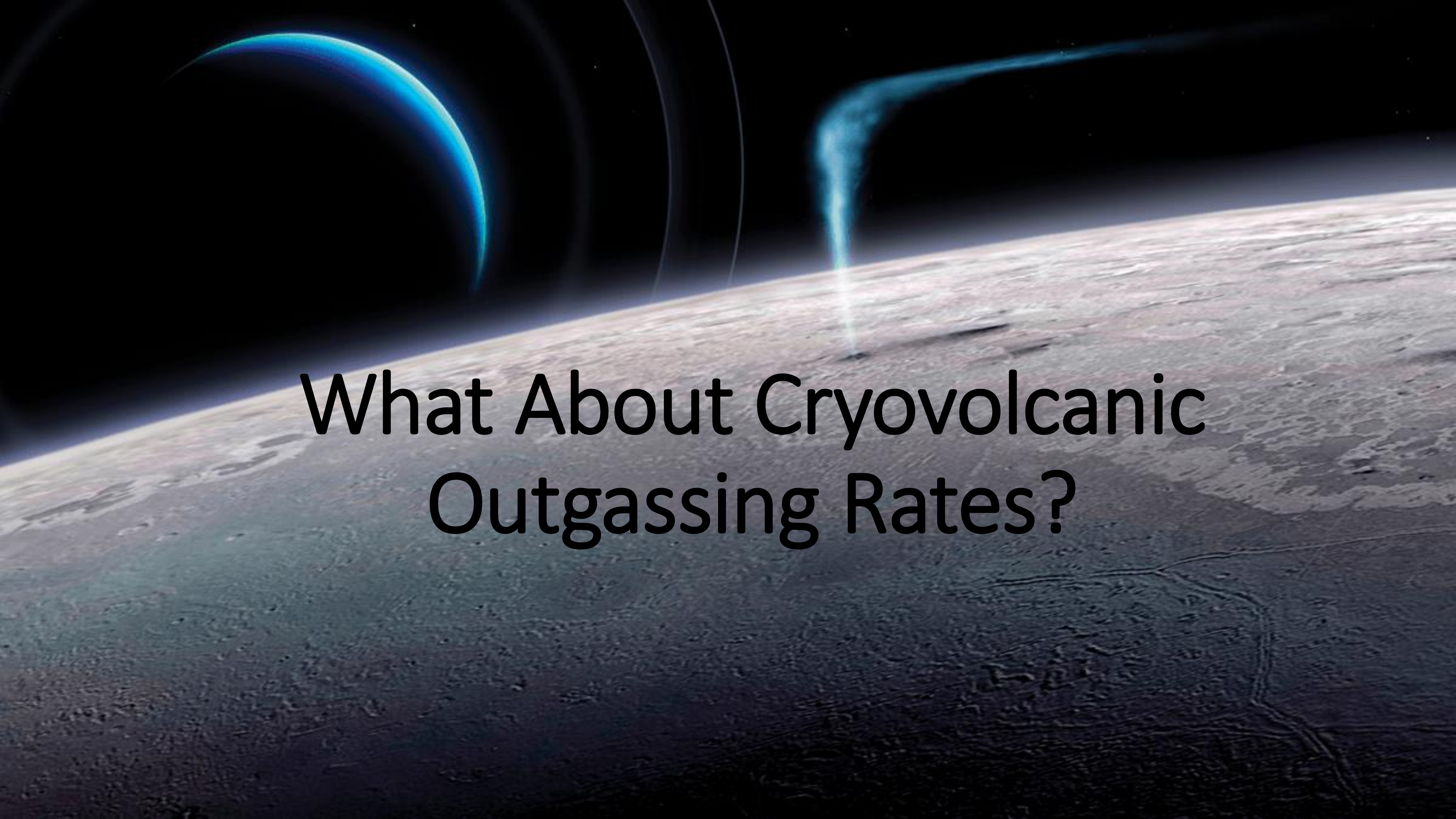
What About Cryovolcanic Outgassing Rates?



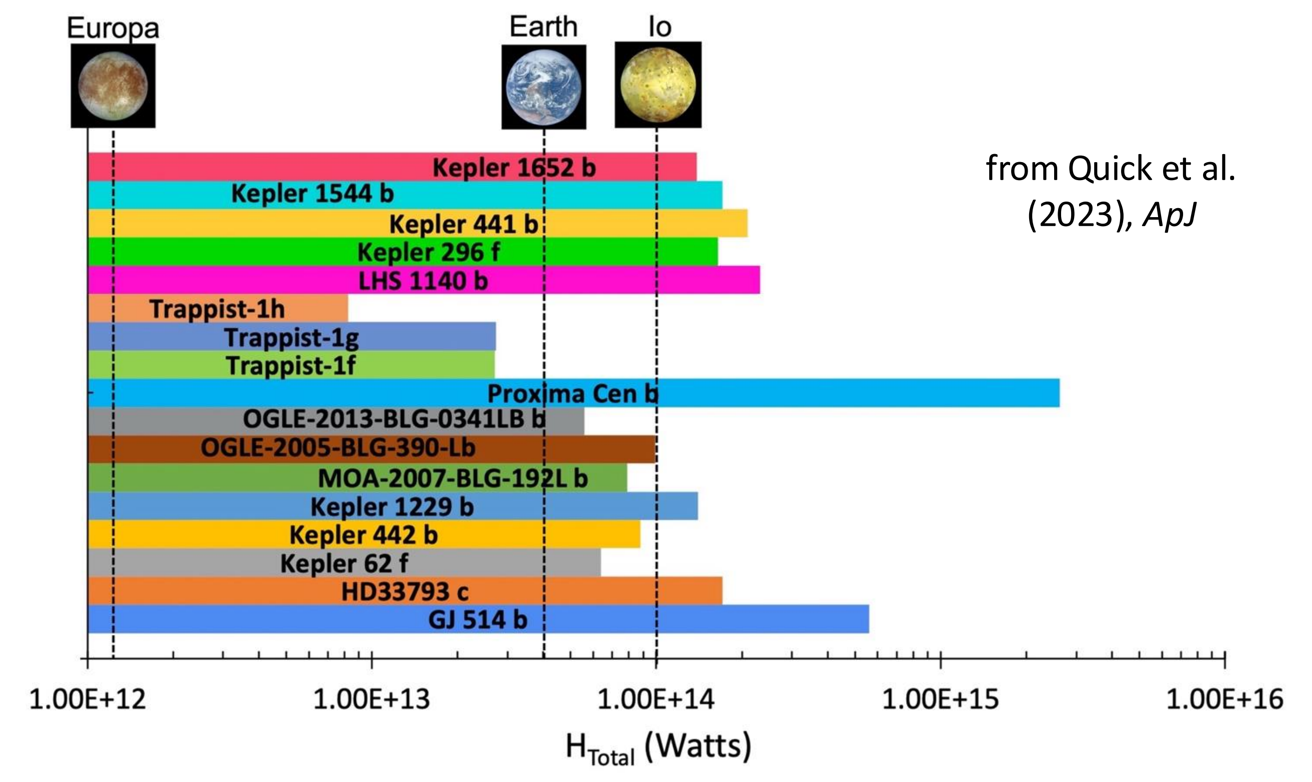
Constraining Cryovolcanic Outgassing Rates

- Assuming eruptions are tidally-driven, we used cryovolcanic activity rates in our solar system to constrain the mass of water vapor that would erupt on cryovolcanically active cold ocean planets with nonzero eccentricities

- Here we employ Europa’s cryovolcanic activity as a conservative baseline for explosive cryovolcanism on cold ocean planets

$$\dot{M}_{Volc} \cong \left(\frac{H_{Tidal}}{H_{Tidal_{Europa}}}\right)\dot{M}_{Volc_{Europa}}$$

Quick et al. (2023) modified from Oza et al. (2019)



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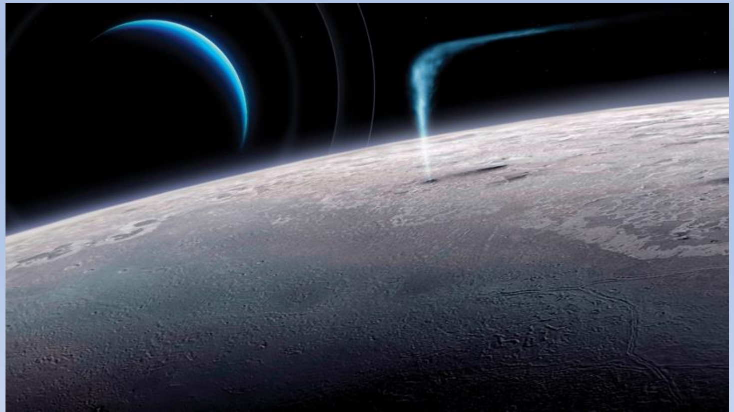
Constraining Cryovolcanic Outgassing Rates

- $\dot{M}_{Volc_{Europa}}$ = 2.4 x 10^3 kg/s is the output rate of water vapor from Europa's plumes (Paganini et al., 2020)
- N_{Volc} = 10^{19} molecules/m^2 is the water vapor column density of Europa's plumes (Paganini et al., 2020)



Planet	$\dot{M}_{Volc}$ (kg/s)	N_{Volc} (molecules/m^2)
Kepler 441 b	7.5	1.3 x 10^{13}
Kepler 442 b	9.4	3.4 x 10^{13}
Trappist-1h	82	7.2 x 10^{14}
Kepler 296 f	115	1.6 x 10^{14}
Trappist-1g	672	2.1 x 10^{15}
HD33793 c (Kapteyn c)	2.8 x 10^3	1.7 x 10^{15}
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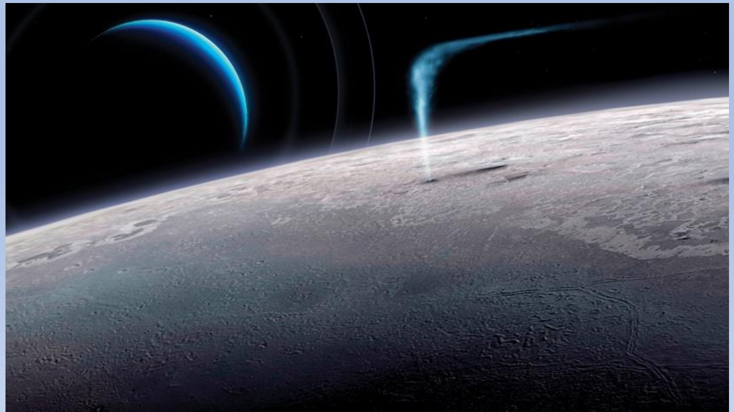

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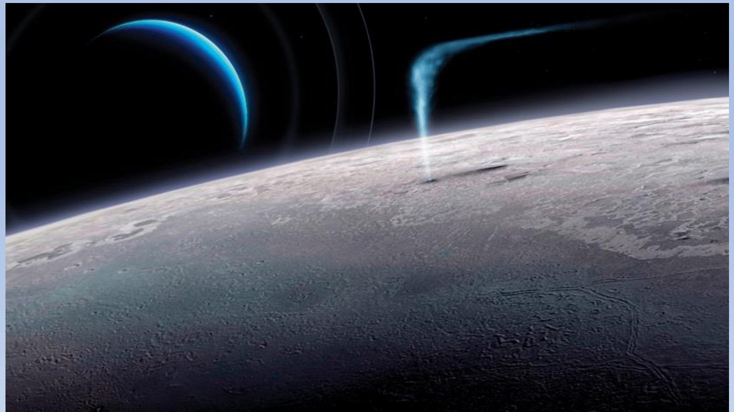

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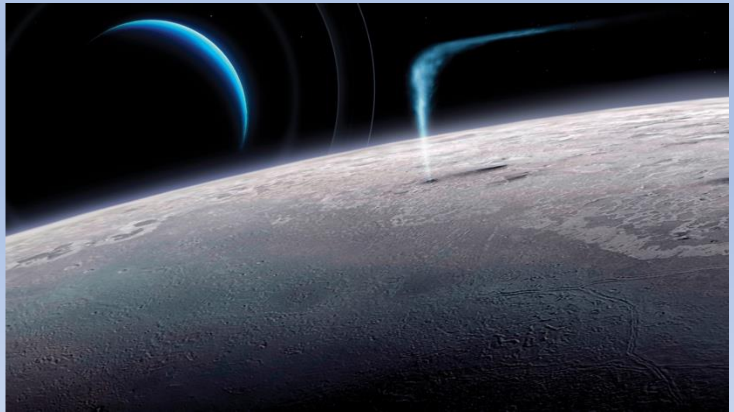

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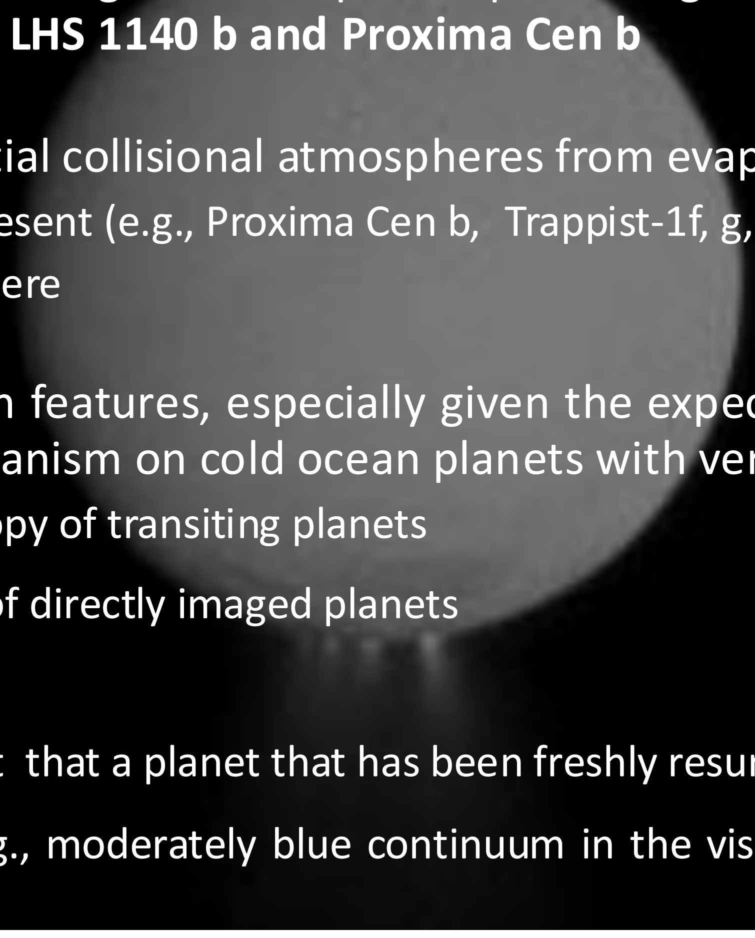
The Astrobiological Significance of Cryovolcanically-Active Cold Ocean Planets



- The detection of cryovolcanic activity on cold ocean planets could serve as an indicator that they are astrobiologically-significant worlds with abundant cycling of liquid water and energy, even if they are beyond the snowline

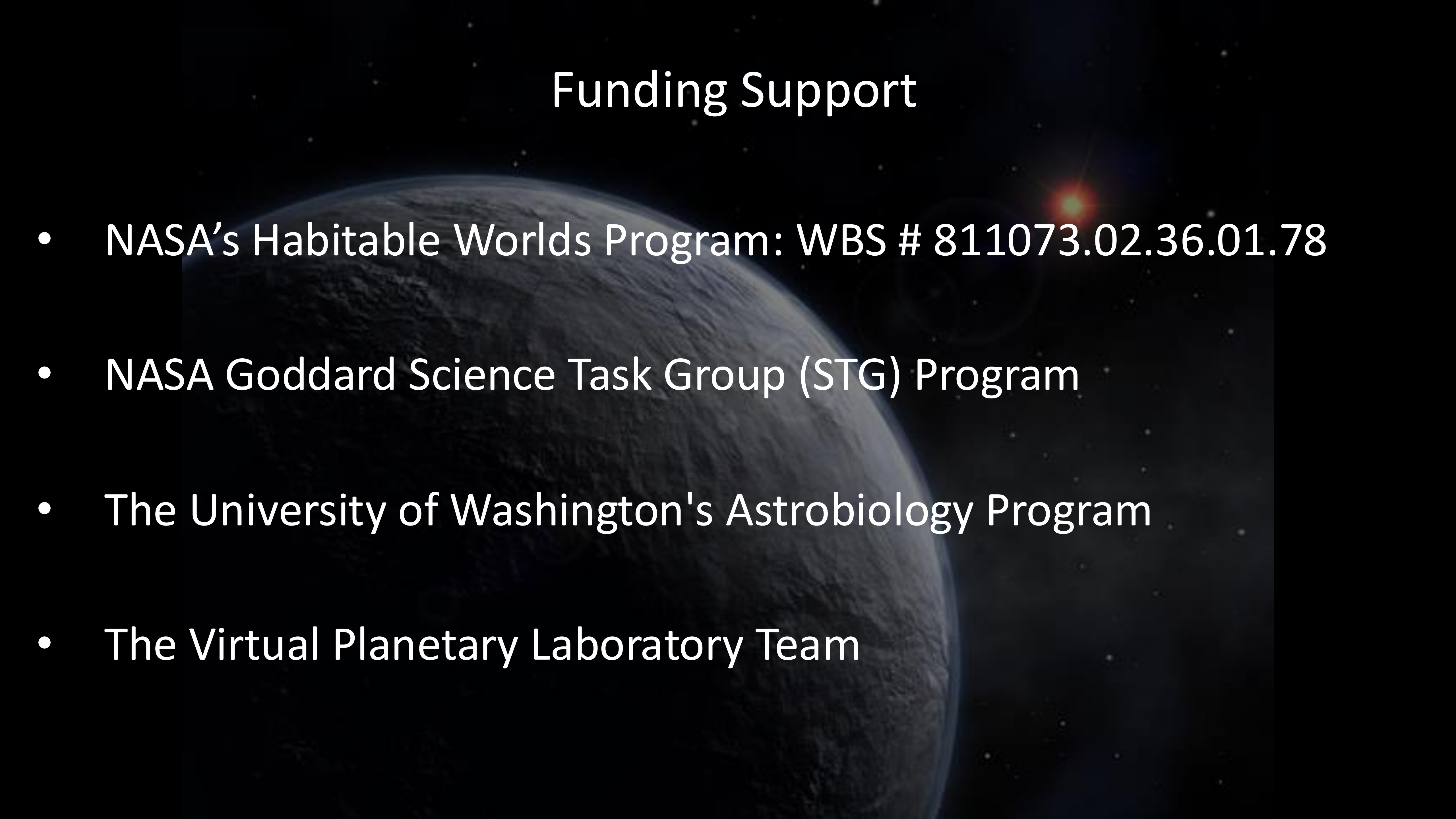
- Based on their thin ice shells and expected high water vapor output during tidally-driven eruptions, **cryovolcanic eruptions most likely to be detected on LHS 1140 b and Proxima Cen b**

- None of these planets will have substantial collisional atmospheres from evaporative outgassing (Quick et al., 2023)
  - in cases where atmospheres may be present (e.g., Proxima Cen b, Trappist-1f, g, & MOA-2007-BLG-192L), they would “freeze out” at the surface temps considered here

- The detection of water vapor absorption features, especially given the expected time-variability of water vapor output, could allow for the detection of cryovolcanism on cold ocean planets with very high H_2O column densities by:
  - transmission or eclipse spectroscopy of transiting planets
  - high-contrast reflectance spectra of directly imaged planets

- Indirect detection methods:
  - anomalously high albedos: suggest that a planet that has been freshly resurfaced
  - reflectance spectrum features, e.g., moderately blue continuum in the visible through near-IR (Enceladus) and solid-state ice absorption features

Quick et al. (2023), ApJ, doi: 10.3847/1538-4357/ace9b6



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