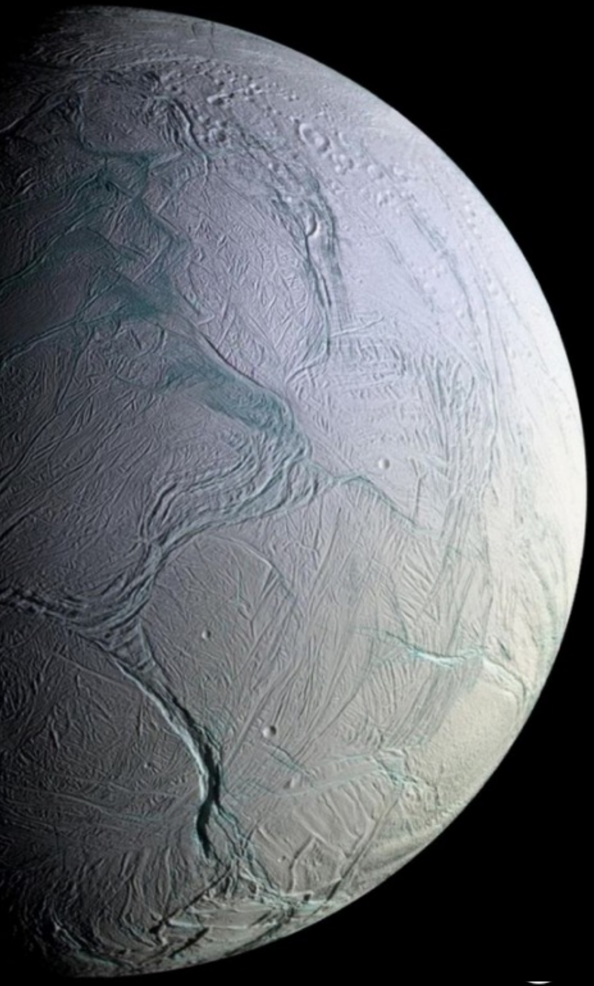


Cold Ocean Planets: Super-Earths or Super-Europas?

Dr. Lynnae C. Quick[1]

Aki Roberge[1], Guadalupe Tovar Mendoza[2,3]

Elisa V. Quintana[1], Allison A. Youngblood[1]

[1]NASA Goddard Space Flight Center, Greenbelt, MD, USA

[2]University of Washington, Seattle, WA, USA

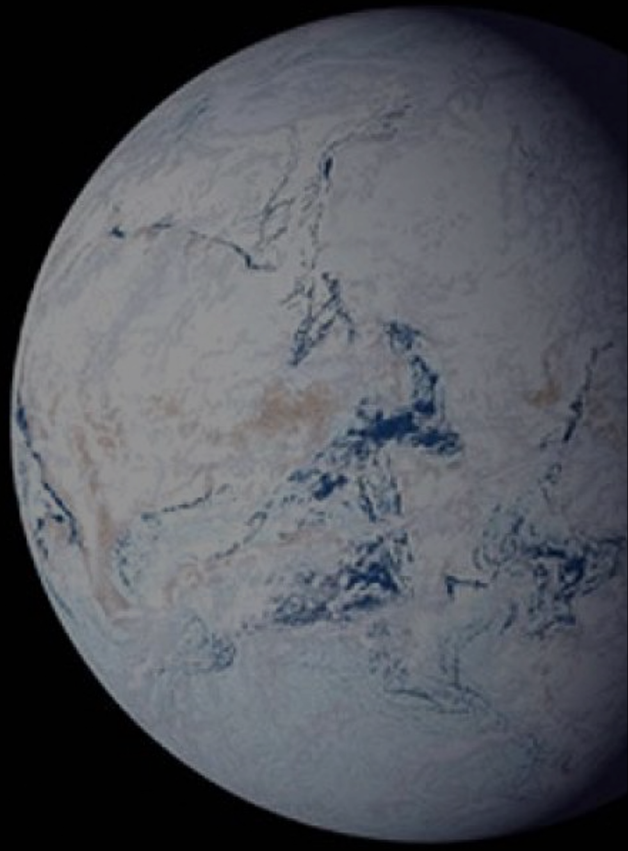
DPS/EPSC Press Conference

October 4, 2023

Email: Lynnae.C.Quick@nasa.gov

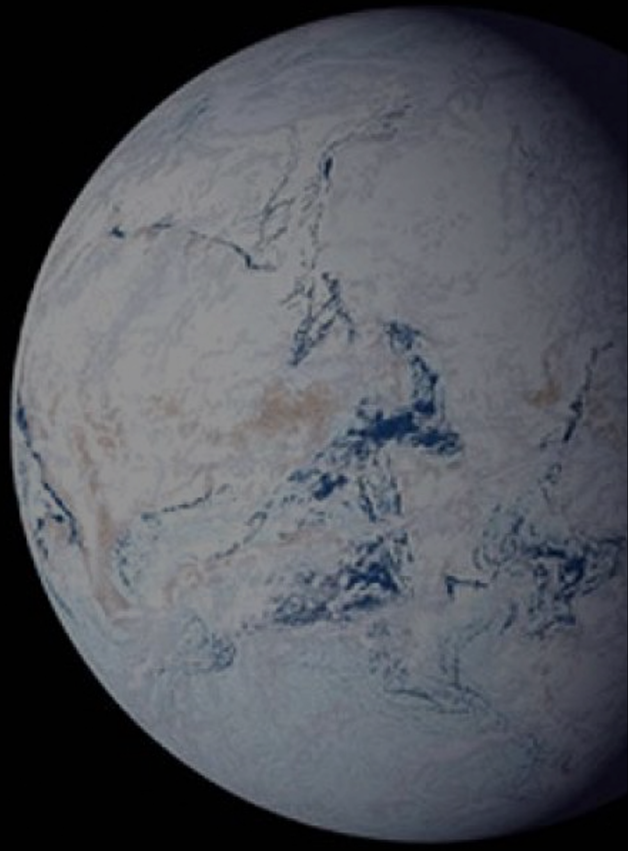
Cold Ocean Planets & Habitability

- Quick et al. (2020) constrained internal heating rates and the likelihood for geological activity on 53 Earth-sized, "terrestrial" exoplanets
  - 17% are likely to be ice-covered worlds with subsurface oceans
  - may exhibit cryovolcanic activity in the form of geyser-like plumes like Europa and Enceladus
  - may have internal structures similar to the ocean worlds in the outer solar system
- Telescopic detection of this cryovolcanic activity, regardless of distance from their host stars, could indicate that these worlds have:
  - subsurface oceans
  - geological activity that cycles liquid water and heat throughout
  - habitable environments & astrobiological significance

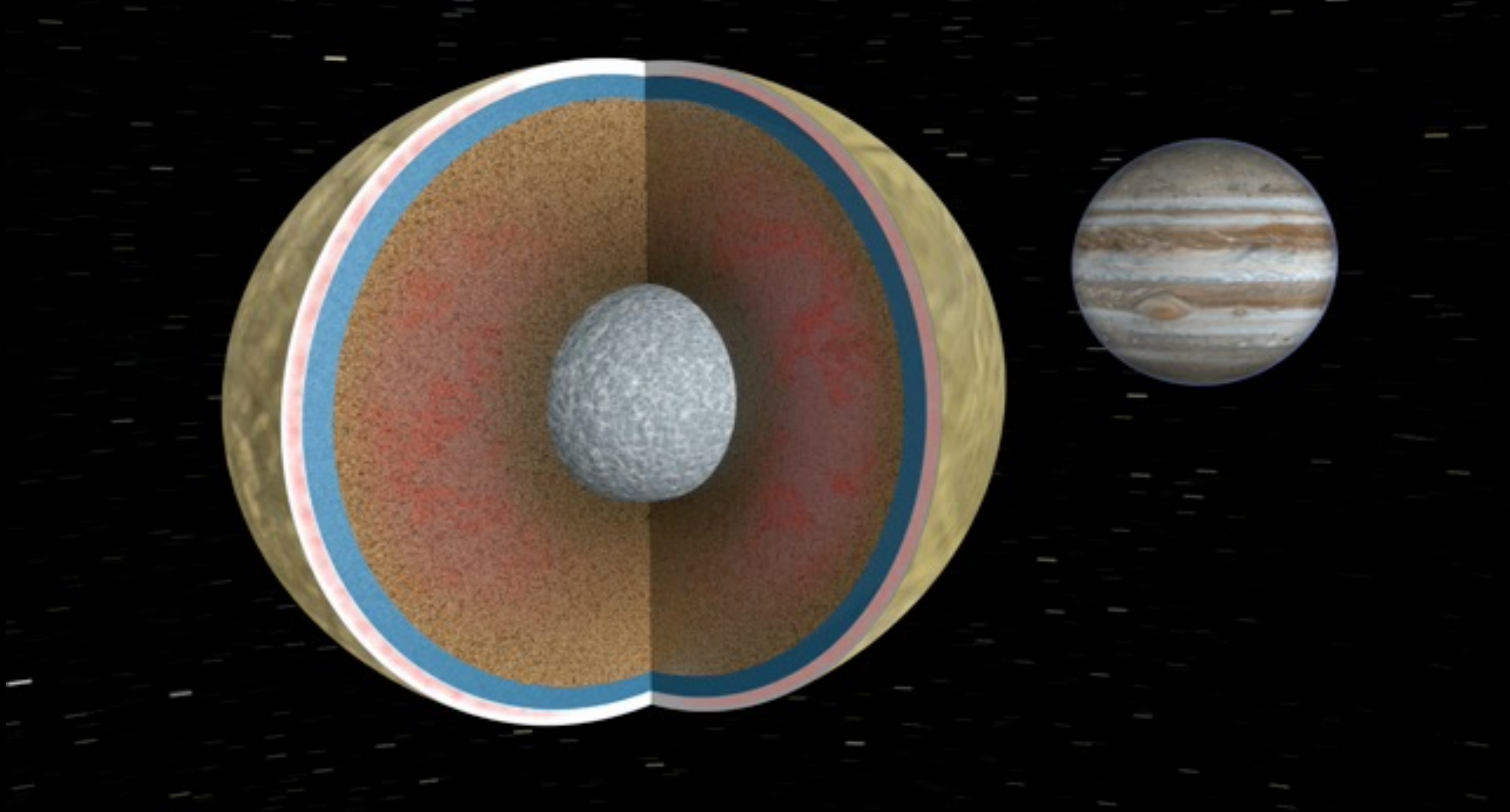


Cold Ocean Planets & Habitability

- We considered 17 Earth-sized exoplanets that may be ice-covered ocean worlds
  - including Trappist-1 f, g, & h, Proxima Centauri b, and several planets discovered by the *Kepler* telescope
- many planets had poorly constrained surface temperatures and cryovolcanic outgassing rates from geyser-like plumes were not explored
- We constrained:
  - surface temperatures
  - depth to to subsurface oceans
  - cryovolcanic outgassing rates for geyser-like plumes

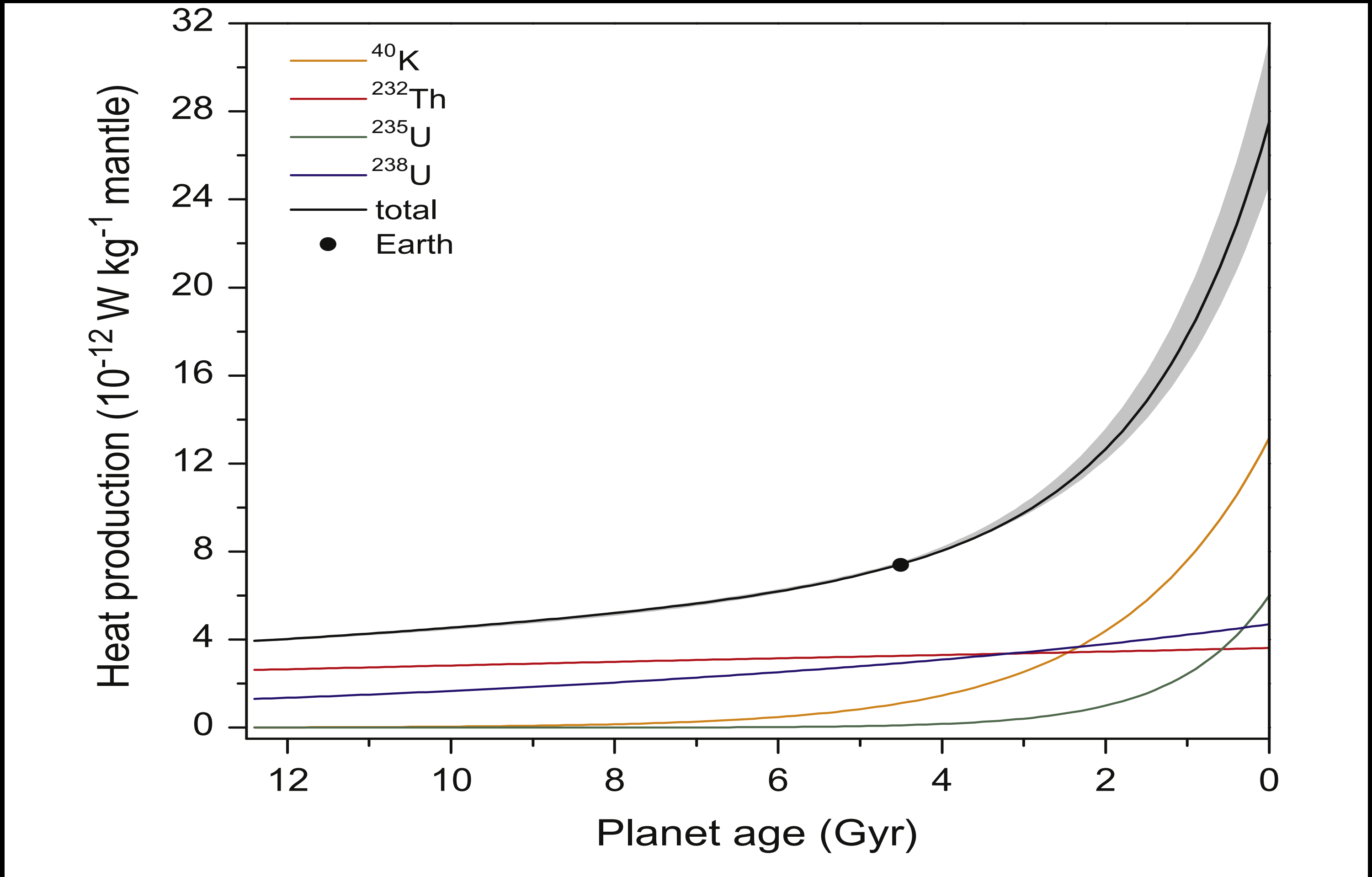


Constraining Total Internal Heating: Tidal Heating



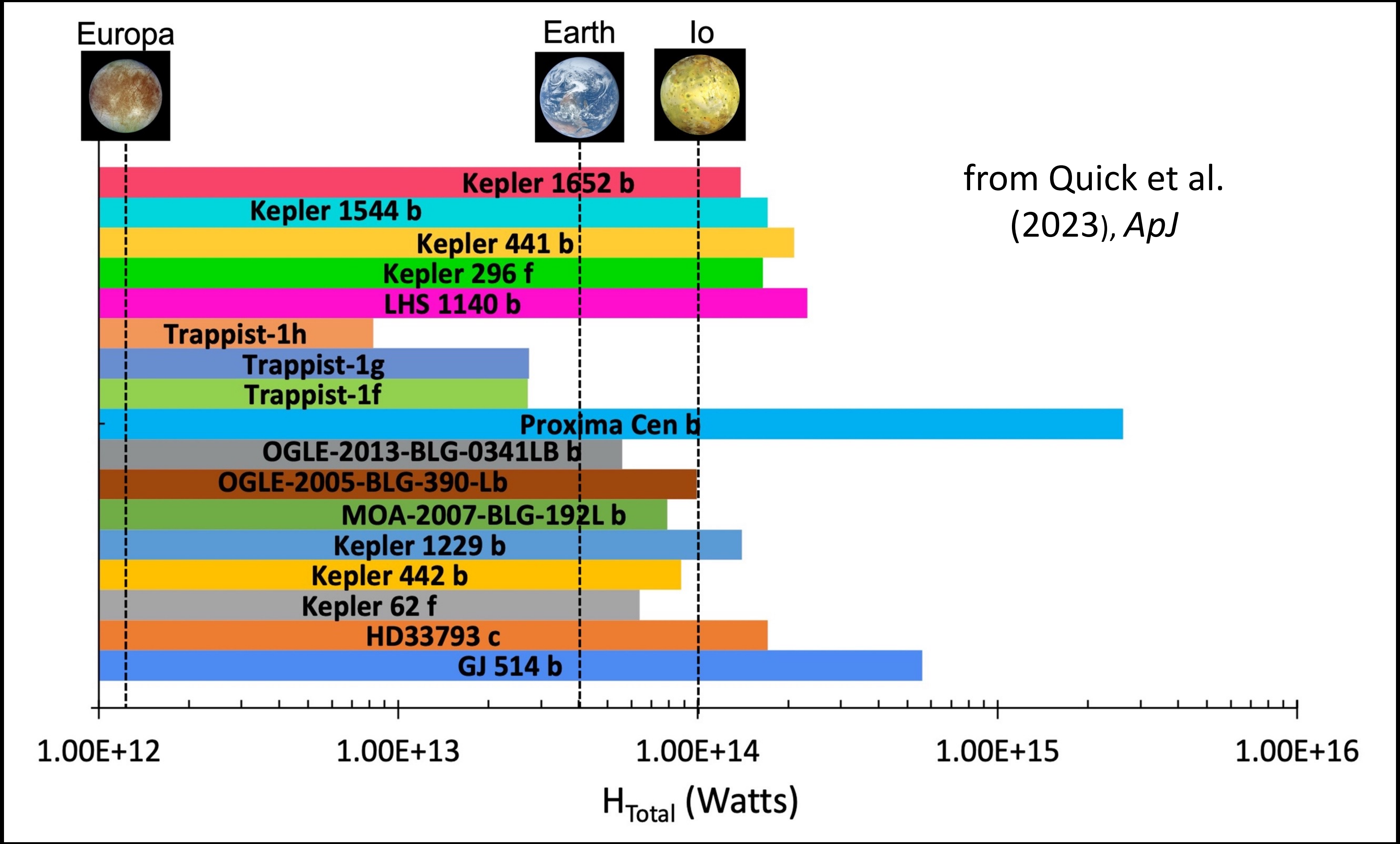
Tidal heating rates for each planet are obtained using an equation that relates the magnitude of heating caused by gravitational tugs from the parent star to planet size, orbital period, and eccentricity

Constraining Total Internal Heating: Radiogenic Heating



- radiogenic heating is caused by the decay of radioactive elements in planetary interiors
- Frank et al. (2014) provide radiogenic heating rates for Earth-sized exoplanets as a function of mass and age

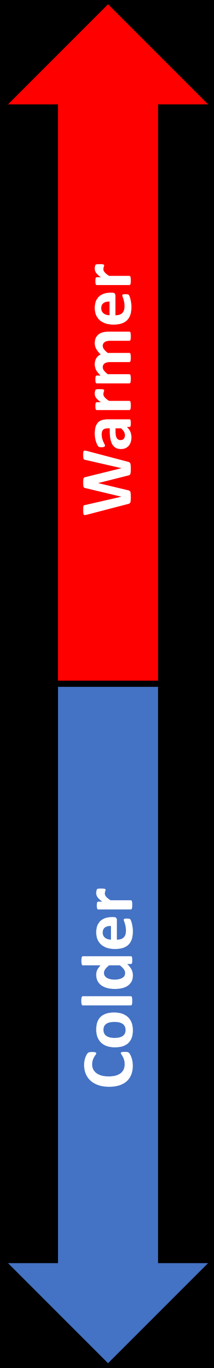
Constraining Total Internal Heating: Tidal + Radiogenic



- all planets have internal heating rates that exceed Europa's
- several planets have heating rates in excess of Io's
- both Europa and Io have internal liquid layers
- suggests that these ice-covered worlds have subsurface oceans

Constraining Surface Temperatures

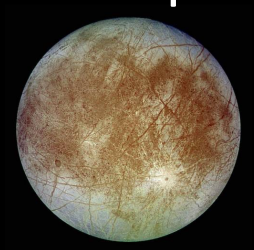
- estimated surface temperatures for many exoplanets assumed low-albedo (A), i.e., dark surfaces with no reflectivity
  - unlikely for ocean worlds with icy surfaces
- investigated surface temperatures assuming surfaces were as reflective of ocean worlds in our solar system
- Using reflectivity of Earth's, Europa's, and Enceladus' surfaces as comparative baselines, found estimated surface temperatures for each planet



Earth

A = 0.3

Europa



A = 0.55

Enceladus

A = 0.81

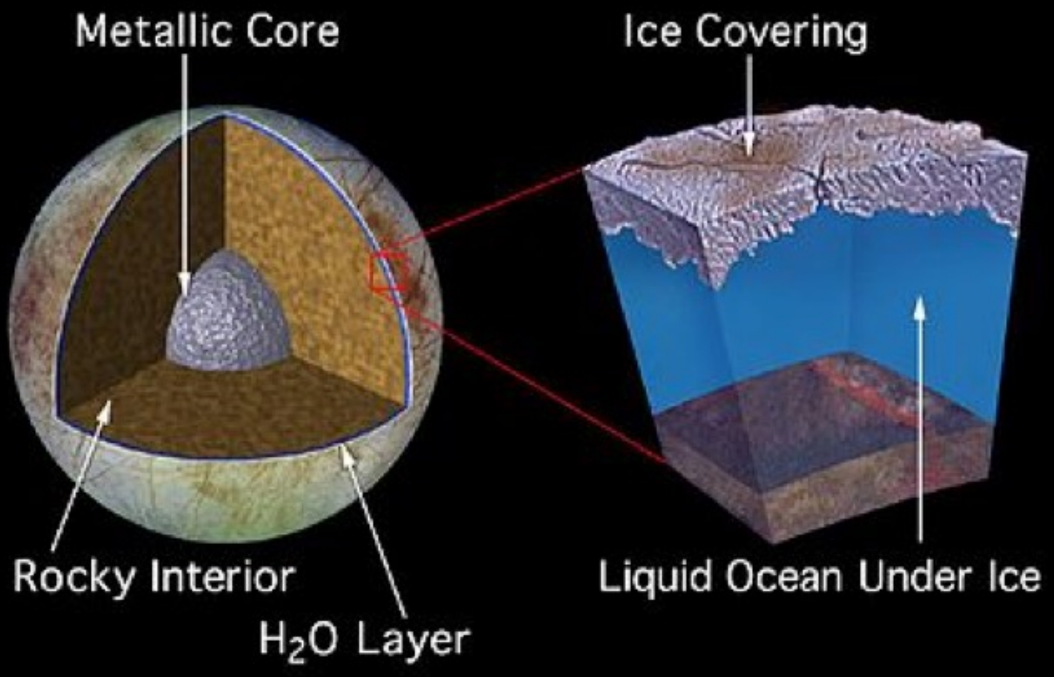
Constraining Surface Temperatures

- surface temperatures are up to 55° less than cited in previous literature
    - temperatures are even colder if we assume Enceladus-like albedos
- Earth's average effective surface temperature is 255 K
- Europa's average surface temperature is 100 K
- temperatures confirm that the exoplanets in our study have icy surfaces

	from literature	Europa-like surface
Kepler 1544 b	269 K	220 K
Kepler 1652 b	268 K	224 K
LHS 1140 b	235 K	181 K
GJ 514 b	202 K	161 K
Trappist 1h	168 K	144 K

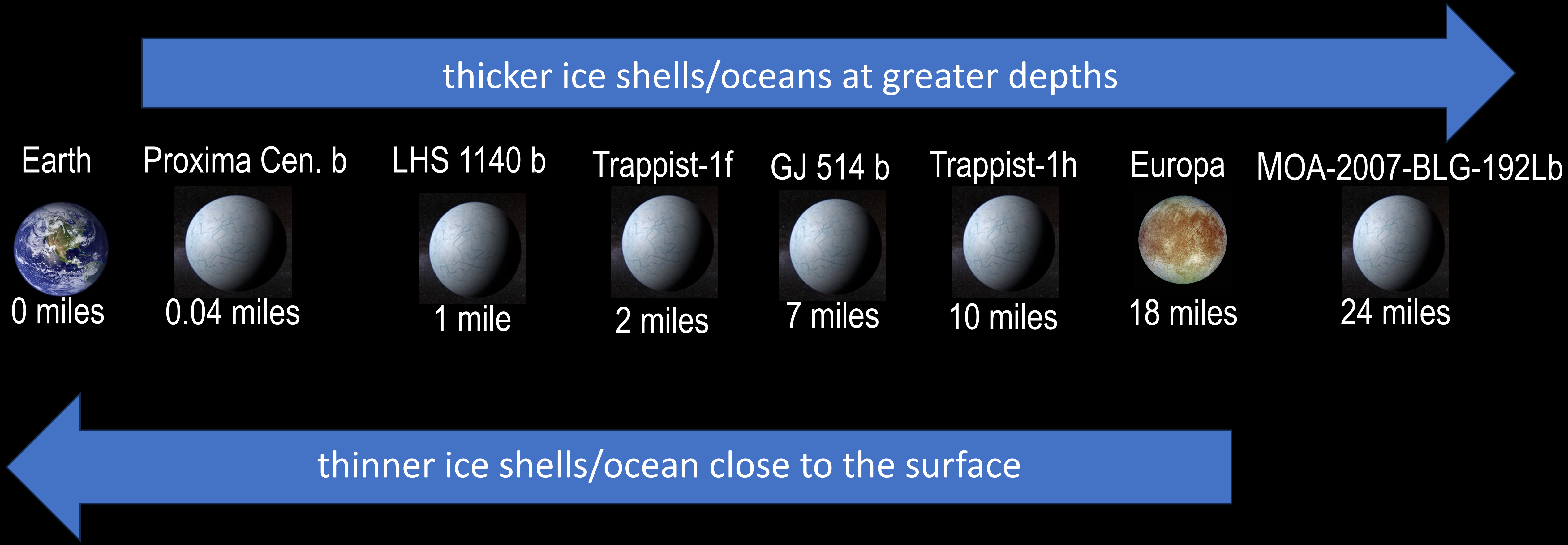
How Far Beneath The Surface Will Oceans Lie?

- oceans will lie beneath ice shells
  - tidal and radiogenic heating will prevent them from freezing
- like the icy moons in our solar system, external ice shells may form from top down
- ice shell thickness is a function of planet size, surface temperature, and total internal heating

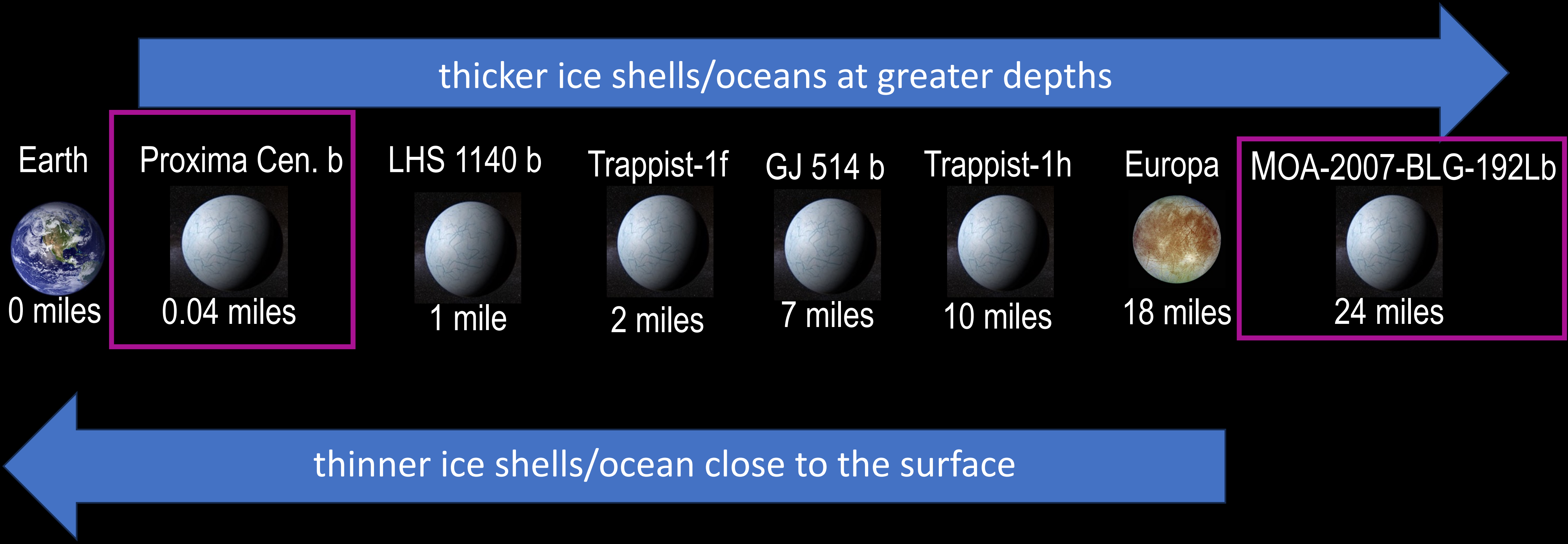


Europa’s internal structure

Depth to Subsurface Oceans

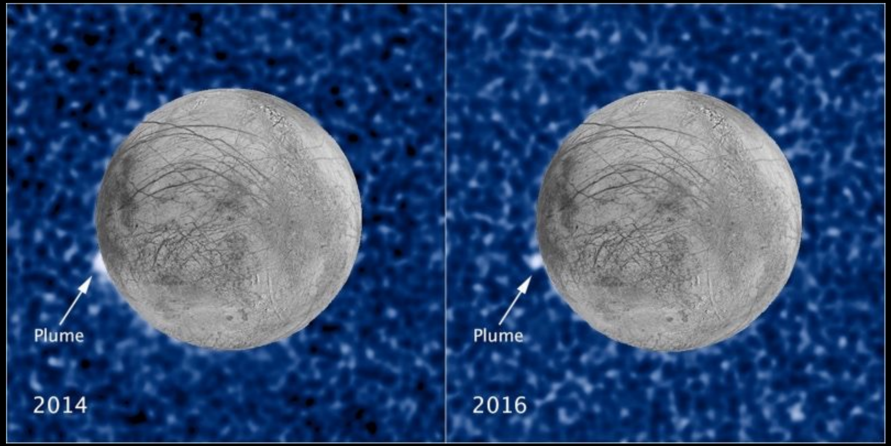


Depth to Subsurface Oceans

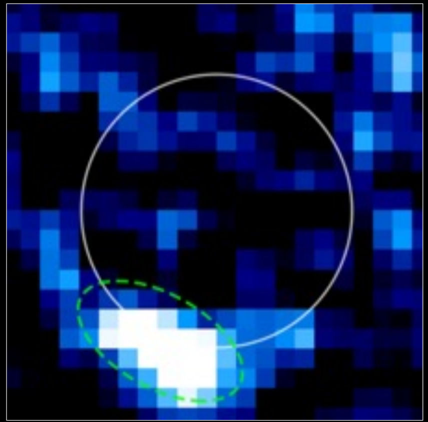


What are outgassing rates for geyser-like plumes?

- eruptions of Europa's geyser-like plumes may be facilitated by tidal forces from Jupiter
- geyser-like plume eruptions on cold ocean planets may be driven by tidal forces from their host stars
  - for planets with non-zero eccentricity
- outgassing rates from Europa's geyser-like plumes have been used as a conservative baseline to explore plume outgassing rates on cold ocean planets



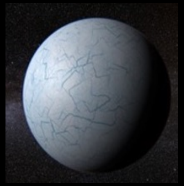
Composite Hubble Space Telescope and Galileo spacecraft images showing a geyser -like plume erupting on Europa in 2014 and 2016



Hubble Space Telescope Ultraviolet image of Europa's geyser-like plumes

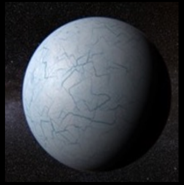
Constraining Geyser-Like Plume Outgassing Rates

Kepler 441 b



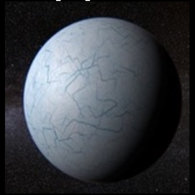
8 kg/s

Trappist-1h



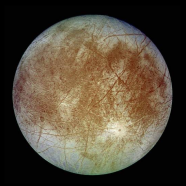
82 kg/s

Trappist-1g



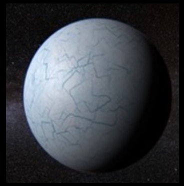
670 kg/s

Europa



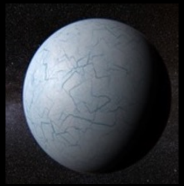
2000 kg/s

GJ 514 b



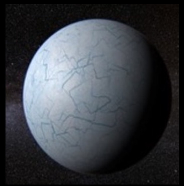
2900 kg/s

Trappist-1f



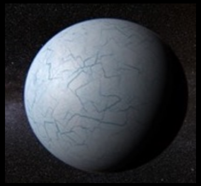
12,000 kg/s

LHS 1140 b



290,000 kg/s

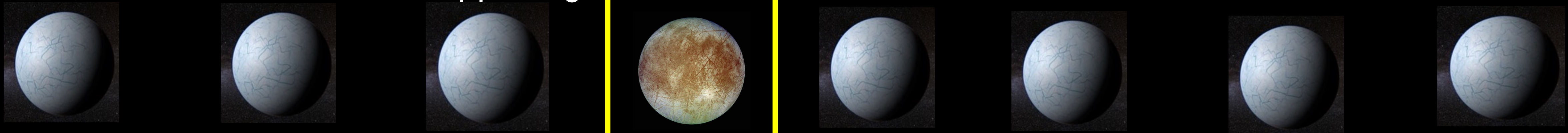
Proxima Cen. b



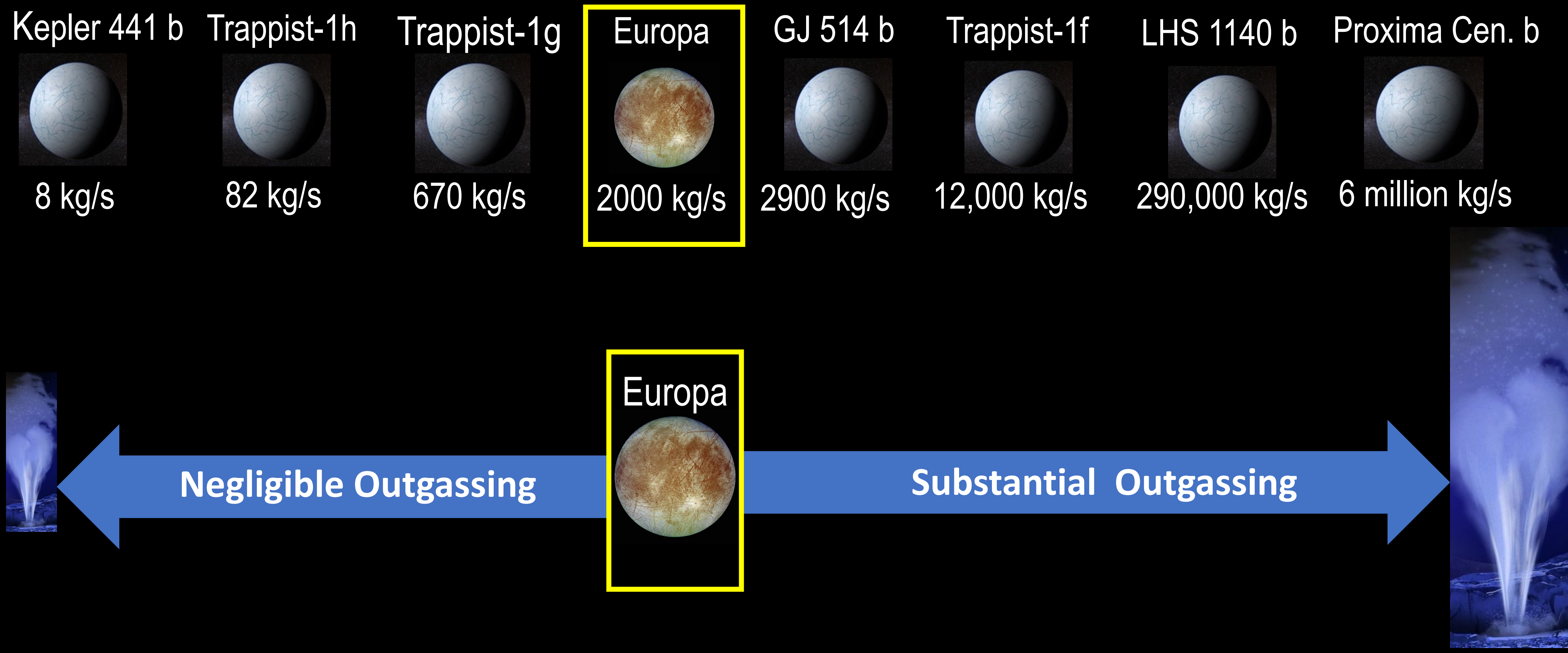
6 million kg/s

Constraining Geyser-Like Plume Outgassing Rates

Kepler 441 b	Trappist-1h	Trappist-1g	Europa	GJ 514 b	Trappist-1f	LHS 1140 b	Proxima Cen. b
8 kg/s	82 kg/s	670 kg/s	2000 kg/s	2900 kg/s	12,000 kg/s	290,000 kg/s	6 million kg/s



Constraining Geyser-Like Plume Outgassing Rates



Constraining Geyser-Like Plume Outgassing Rates

- Europa's geyser-like plumes erupt 2000 kg/s of water vapor
- mass of water vapor erupted from GJ 514 b would be very similar to Europa's plumes
- mass of water vapor erupted from Trappist-1f, LHS 1140 b, and Proxima Centauri b greatly exceeds that from Europa's plumes

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The Astrobiological Significance of Cold Ocean Planets

- planets are astrobiologically significant, regardless of their distance from their host stars, and may be more akin to worlds like Europa than to Earth

- based on the close proximity of oceans to their surfaces and expected high water vapor output, **geyser-like eruptions are most likely to be detected on LHS 1140 b and Proxima Cen b**

- cryovolcanic eruptions could be detected by telescopes via:
    - detection of water vapor absorption from transmission or eclipse spectroscopy of transiting planets
    - detection of water vapor absorption from high-contrast reflectance spectra of directly imaged planets
    - anomalously high albedos on atmosphere-less planets
        - suggest that a planet has been freshly resurfaced with bright, icy particles

- more details in Quick et al. (2023) published today in the Astrophysical Journal https://doi.org/10.3847/1538-4357/ace9b6. (Email: Lynnae.C.Quick@nasa.gov)