



# Planetary Diversity

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*Caltech*

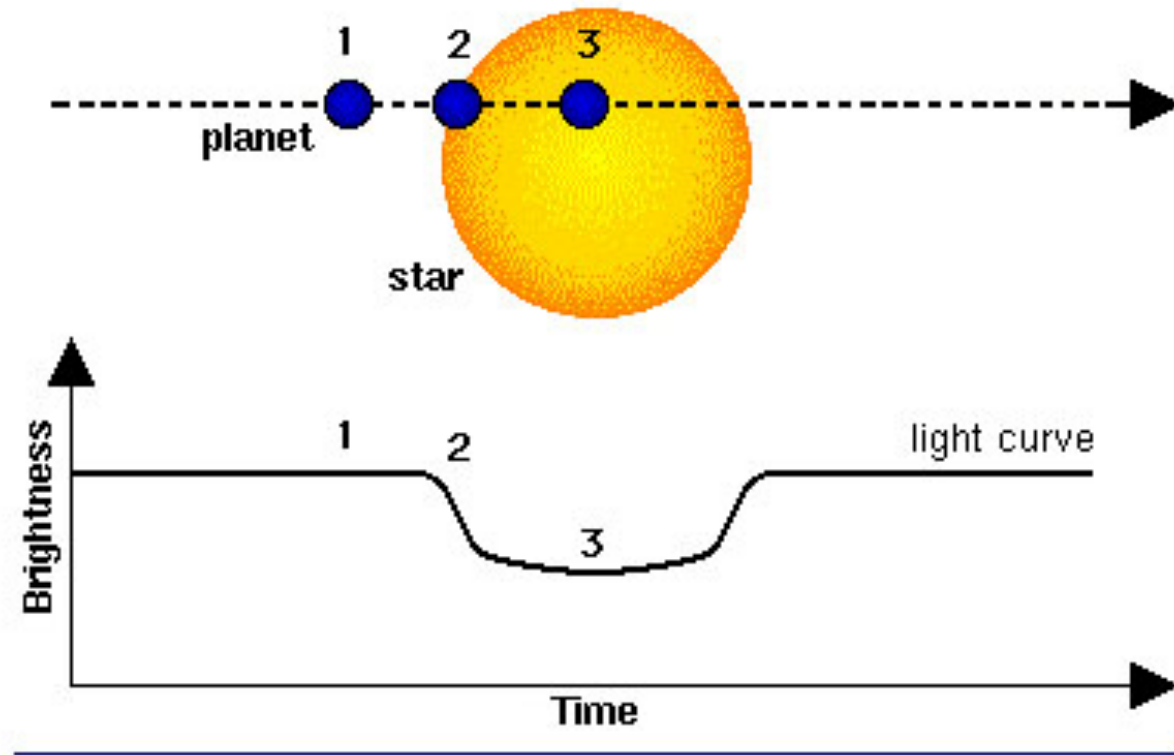
*"Sky and Telescope" Cruise 2010*

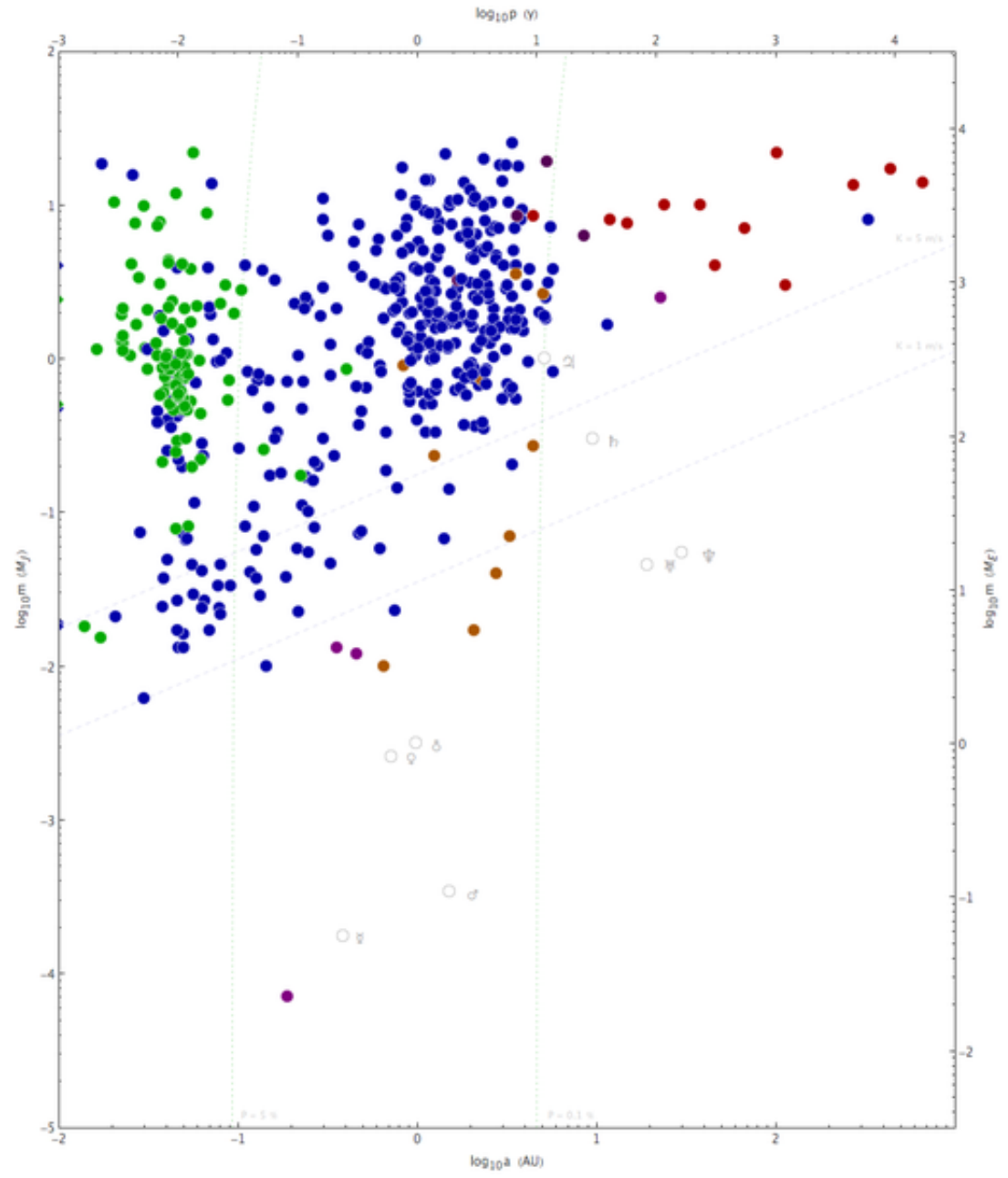
# How many planets in the Universe?

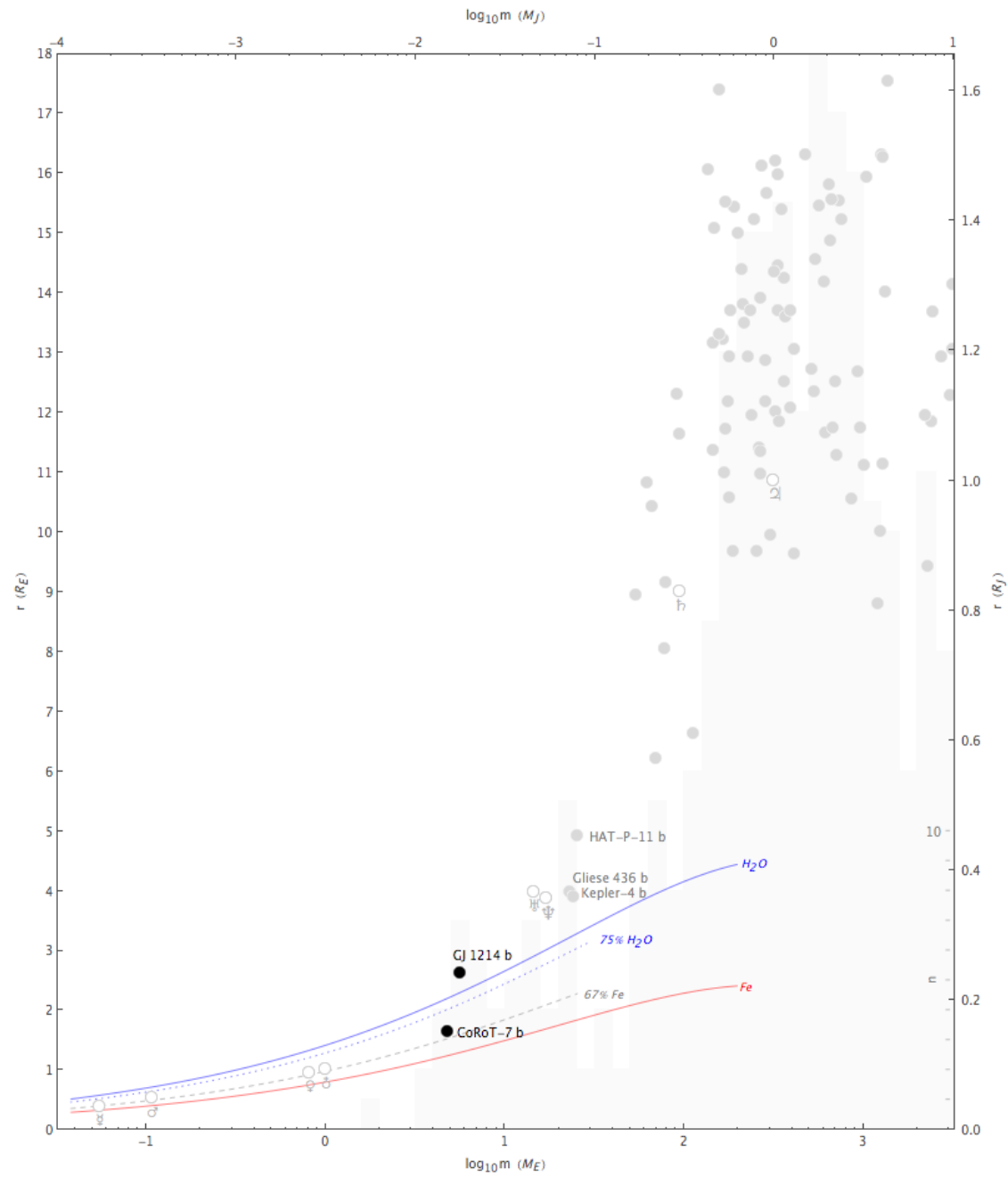
- There are roughly 100 billion ( $10^{11}$ ) stars in the milky way
- There are roughly 10 billion ( $10^{10}$ ) galaxies.
- So there are roughly  $10^{21}$  stars in the “known” universe.
- We think that there is 0.1 to several planets per star. (Some stars have none; some have several)
- So there are maybe  $10^{21}$  planets. Enormous compared to the number of known biological species ( $\sim 10^8$ ). What is their diversity?

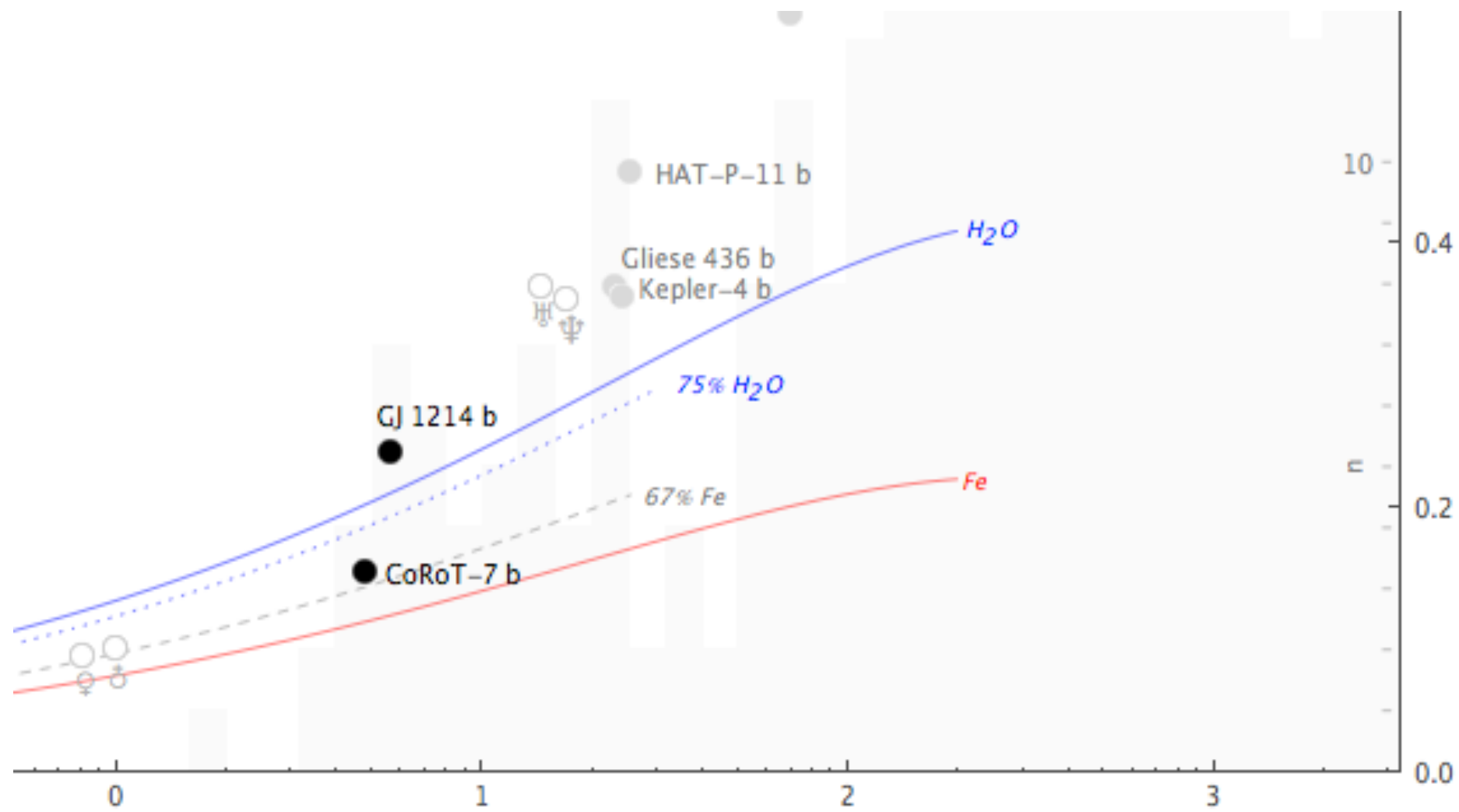
# Planets we know about

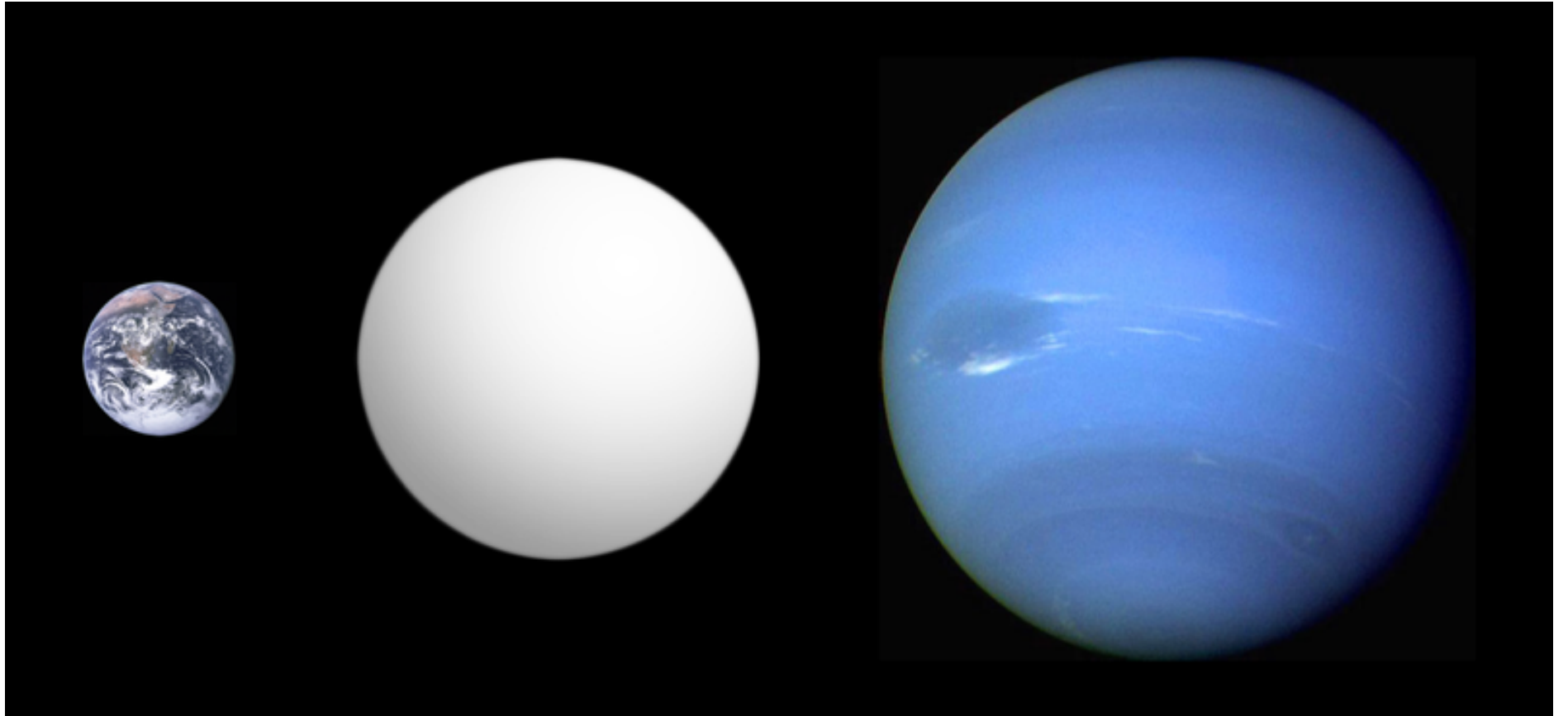
- Mostly found by Doppler (many hundreds)
  - Actually gives only  $M \sin i$  where  $M$ =mass and  $i$  is inclination of orbit along line of sight.
- Also found by transit- very important because you get radius of planet and (sometimes) atmospheric composition
- Direct imaging is difficult ; eventually possible (but at least a decade away for Earth mass bodies).









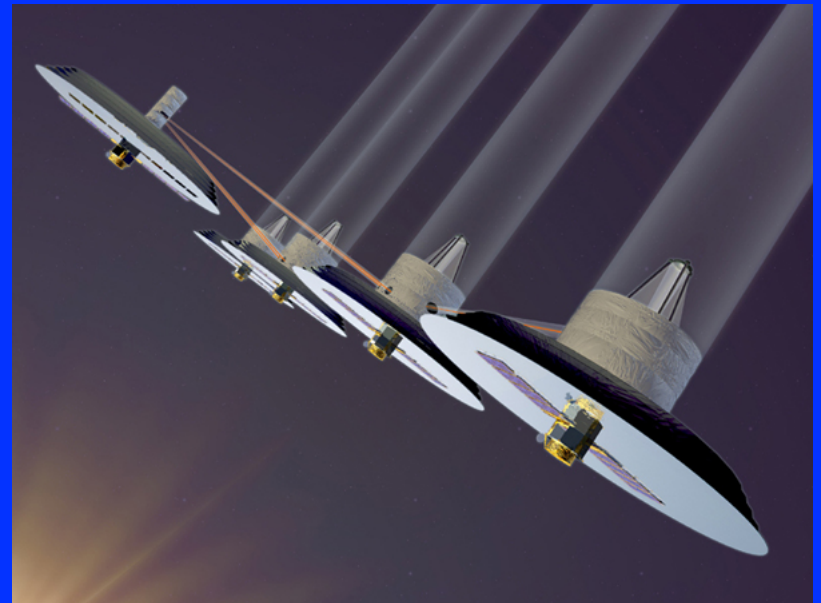


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# *Why is Planetary Diversity an Interesting Issue?*

- Remarkable *observed* diversity.
- NASA assumes “if we find an Earth mass planet at 1AU around a Sun-like star then it will be an Earthlike planet.” We need a more informed expectation!
- Life!



*Possible TPF design*

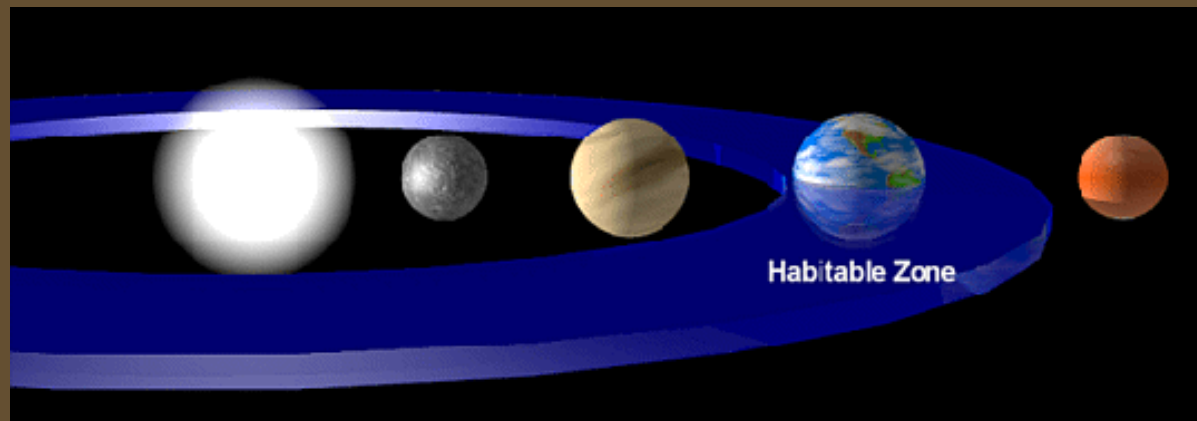




*Planet Earth -  
The Water Planet*

# Popular Concept of a Habitable Zone

## *Goldilocks scenario*

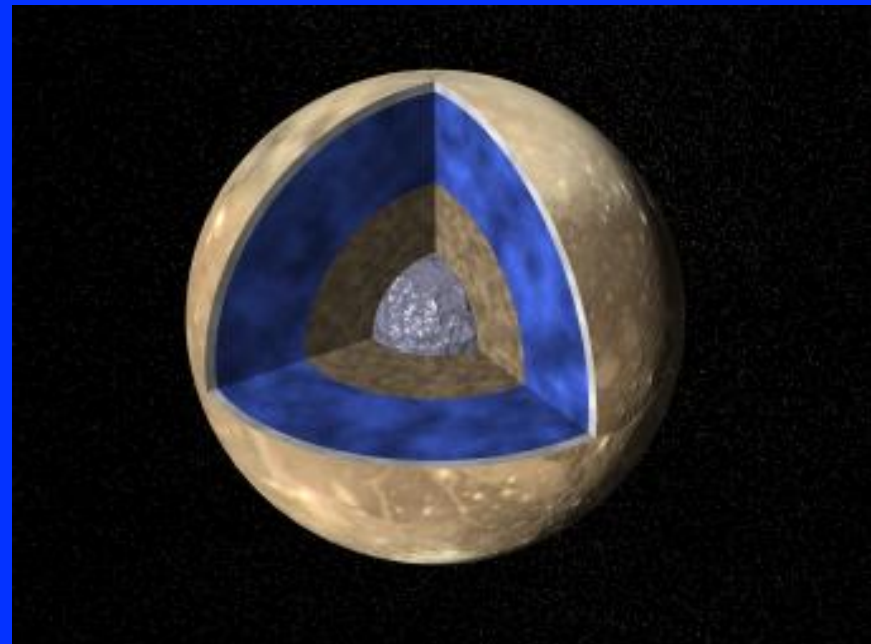


- Location, location, location!
- Size matters
- Also depends on availability of H<sub>2</sub>O. Very abundant in the Universe... very under-abundant on Earth



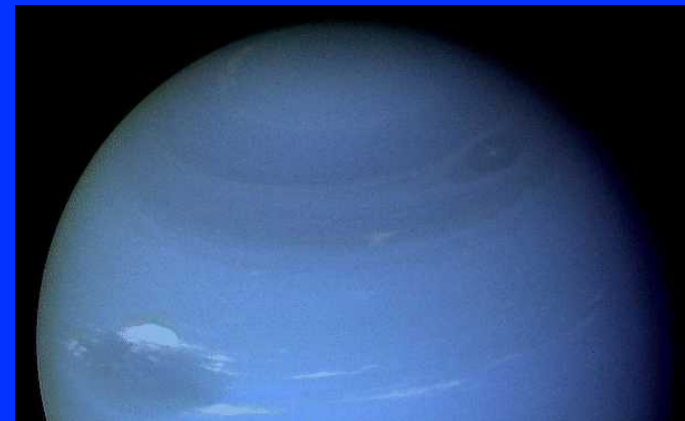
# Solid Planets

- *Terrestrial (silicates, oxides and iron alloy)-*  
Mercury, Venus, Earth, Moon, Mars, Io
- *Large icy satellites (terrestrial +ice)*  
Europa, Ganymede, Callisto, Titan, Triton, Pluto...



# Fluid Planets

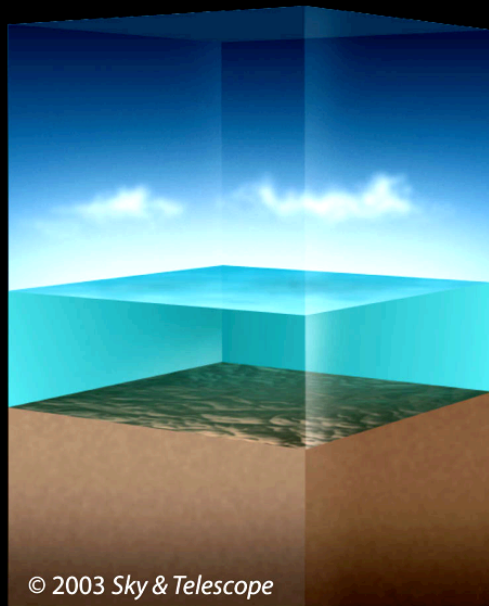
- *Gas Giants (primarily hydrogen and helium)-*  
Jupiter and Saturn
- *Ice Giants (everything, but including large amounts of  $H_2O$  at high  $P,T$ )* Uranus and Neptune



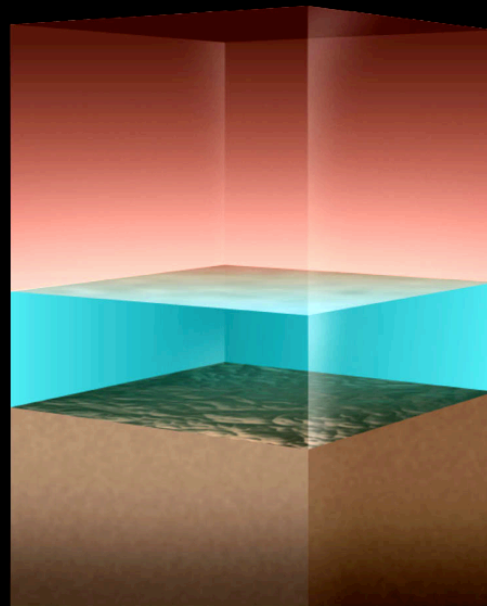
# *Main Propositions*

- The planets in our solar system exhibit great diversity
- The planets in our solar system are a small, unrepresentative sample of all planets.
- The extrasolar planets found thus far are different but still unrepresentative!
- Most notions of the habitable zone are anthropocentric. The habitable zone may be almost everywhere in the Universe if we include all places with energy sources & liquid water.

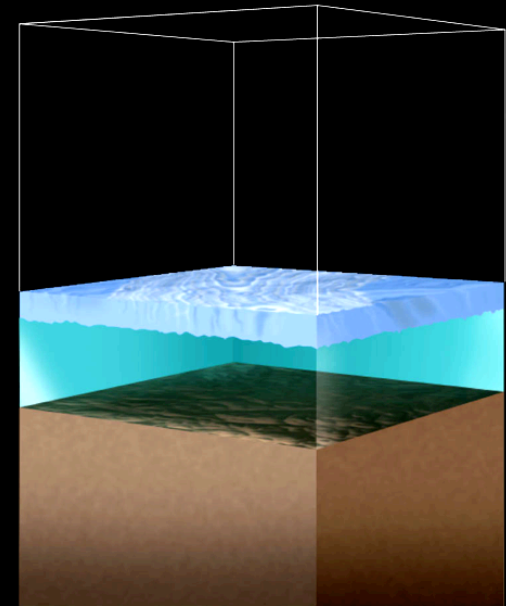
# Three Kinds of Oceans



Earthlike



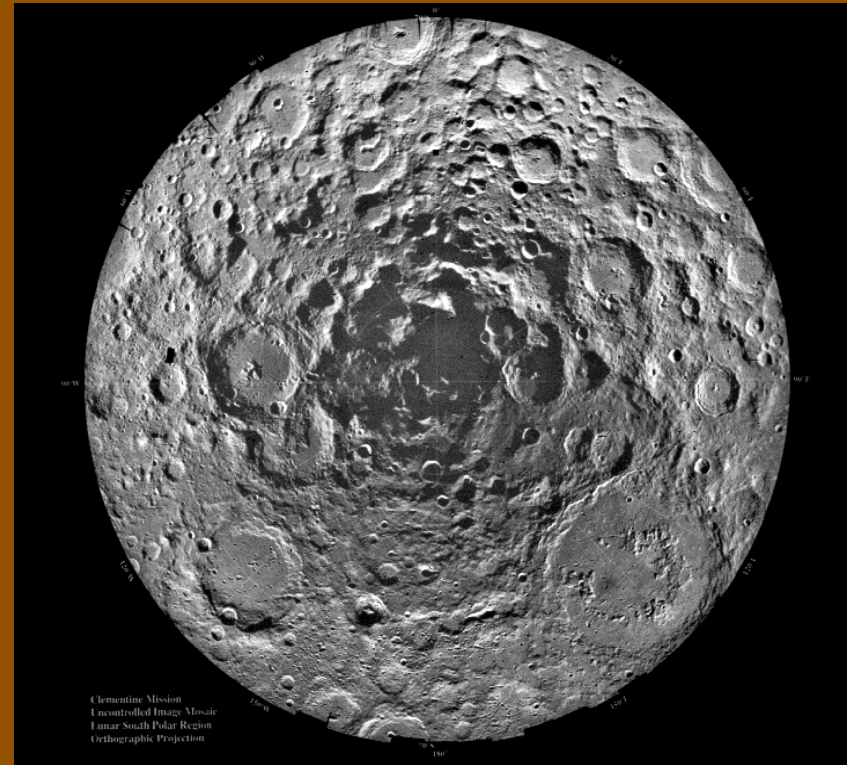
Protected by a  
dense atmosphere  
(e.g., greenhouse)



Protected by ice



←  
Mercury  
& Moon  
→

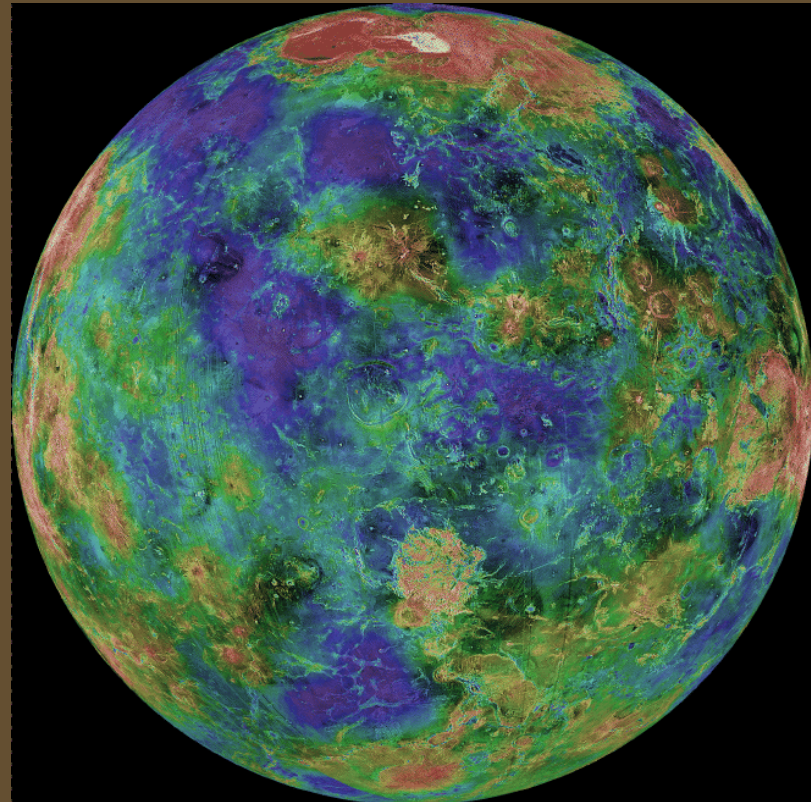


- High reflectivity for Radar near Mercury poles. Evidence of ice(?)
- Possible radar, neutron evidence on Earth's moon also.
- In either case, this is most likely exogenic and represents a very small reservoir.



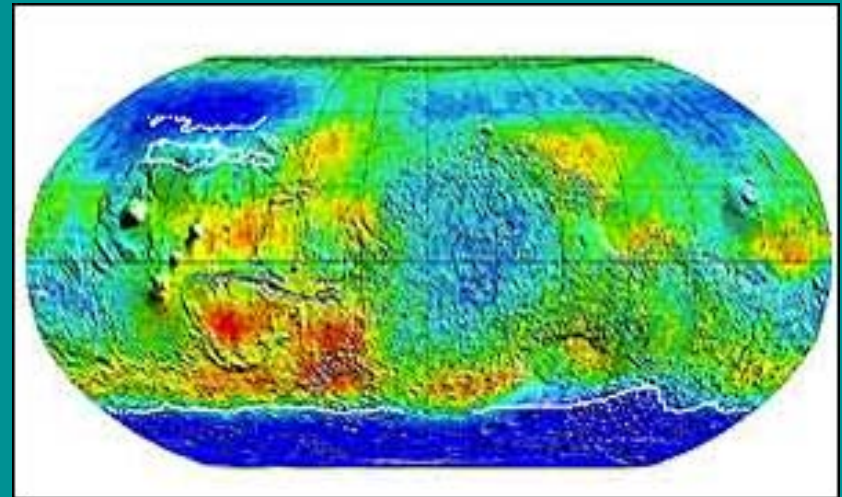
# Venus

- Surely received water (because Earth did).
- Dry now (even inside?)
- Hydrogen loss and lack of plate tectonics..all tied to a dense CO<sub>2</sub> atmosphere and strong greenhouse

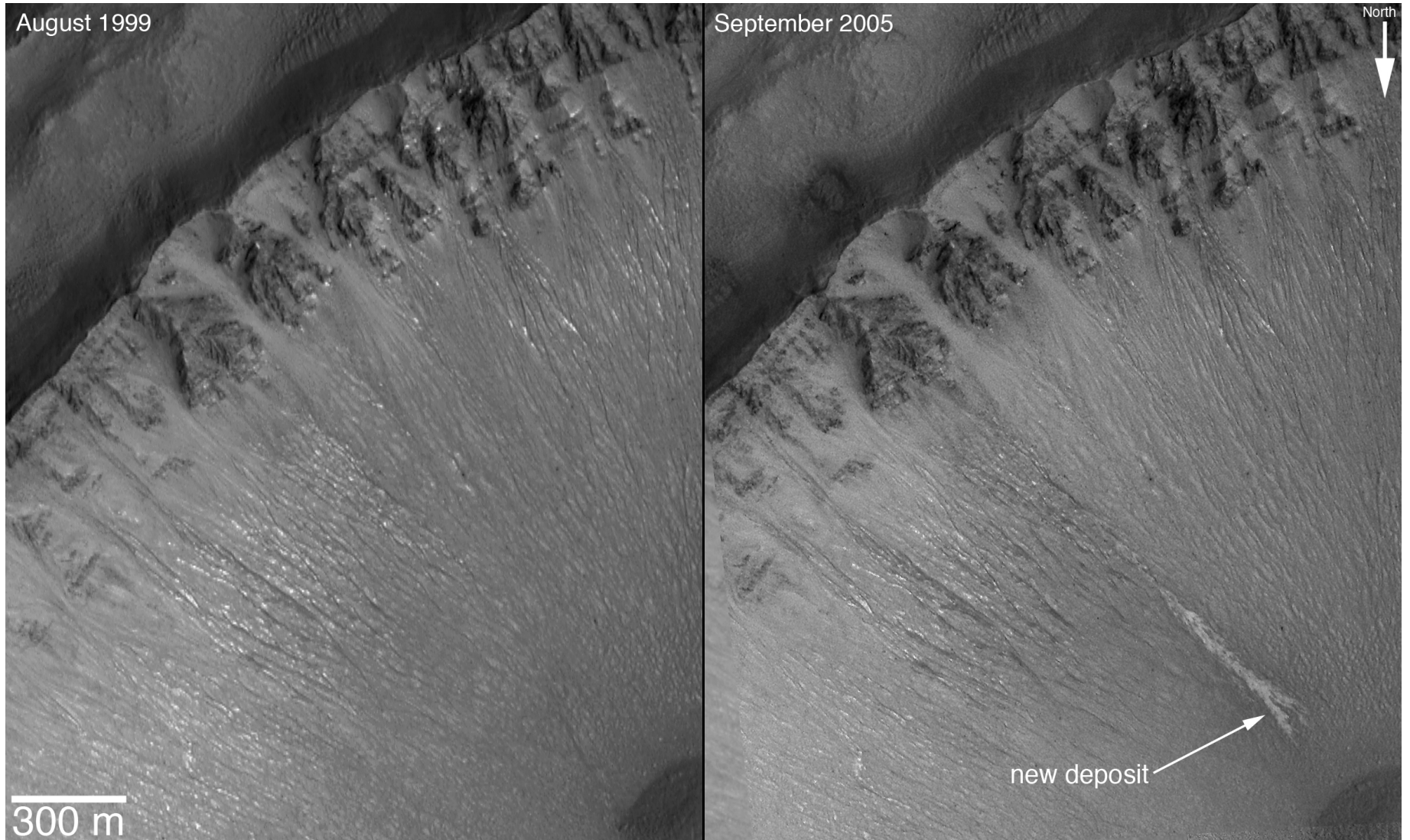


# Mars

- Water ice at the poles.
- Hydrogen detected subsurface at many latitudes
- Evidence of features that may have formed by flowing water
- Some people think there may have been oceans.
- Most likely, liquid water was very localized and ice-covered, all or most of the time



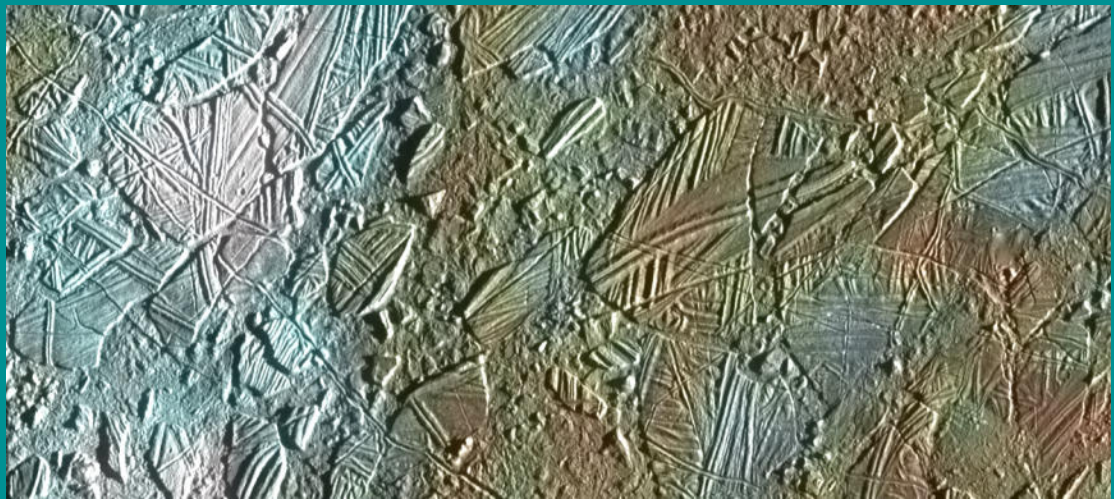
# Evidence for recent Water flows on Mars





# Europa

- Second large moon out from Jupiter (the first with lots of water ice)
- Surface shows remarkable evidence of geological activity (ice “rafting”)

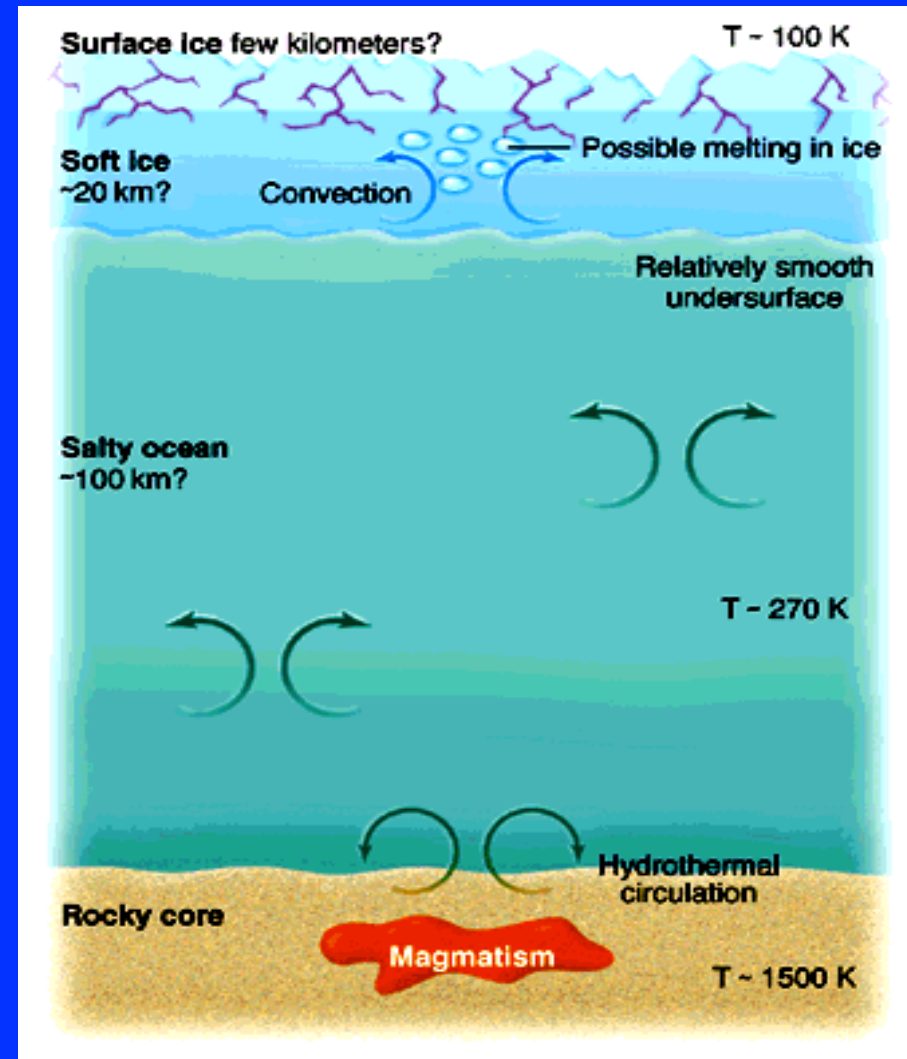


# Europa Surface



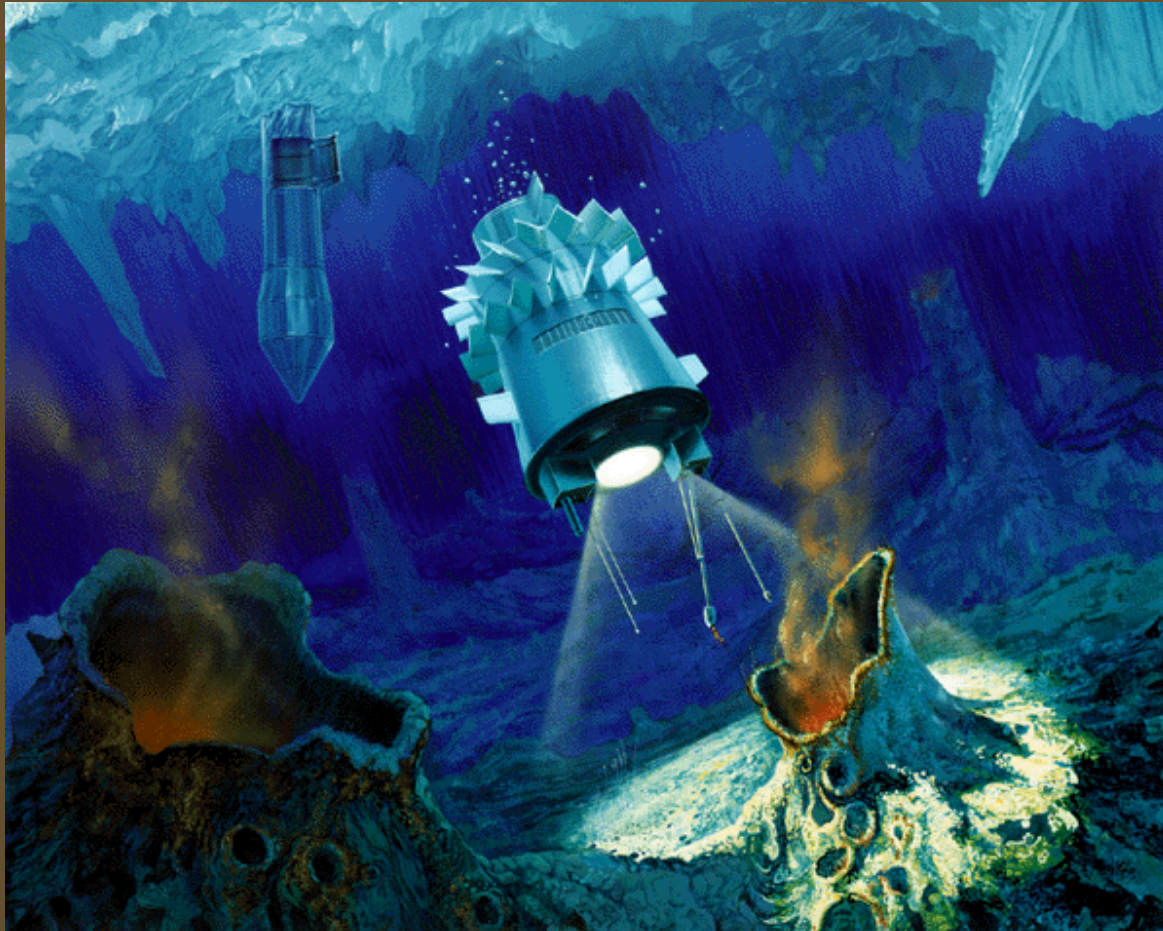
# Europa's Outer Structure

- Low pressure environment; thin ice layer maintained by tidal flexing
- Ice may convect and melt internally
- Salty water chemistry & hydrothermal chemistry



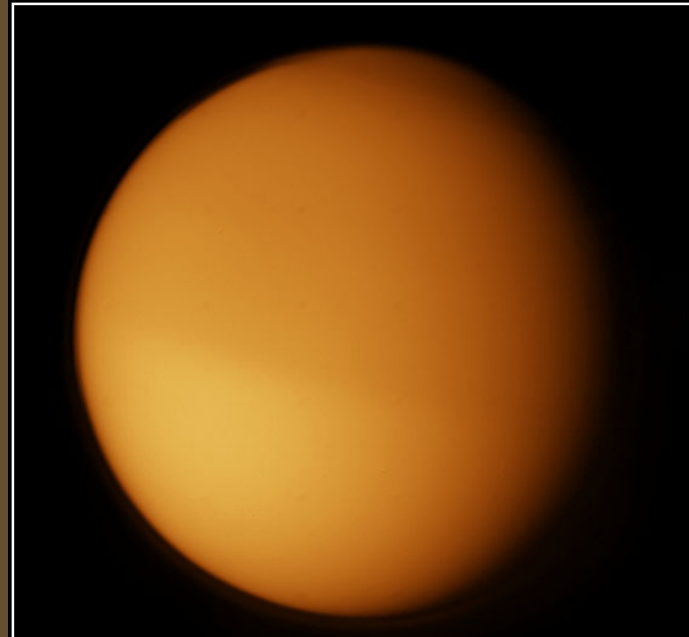
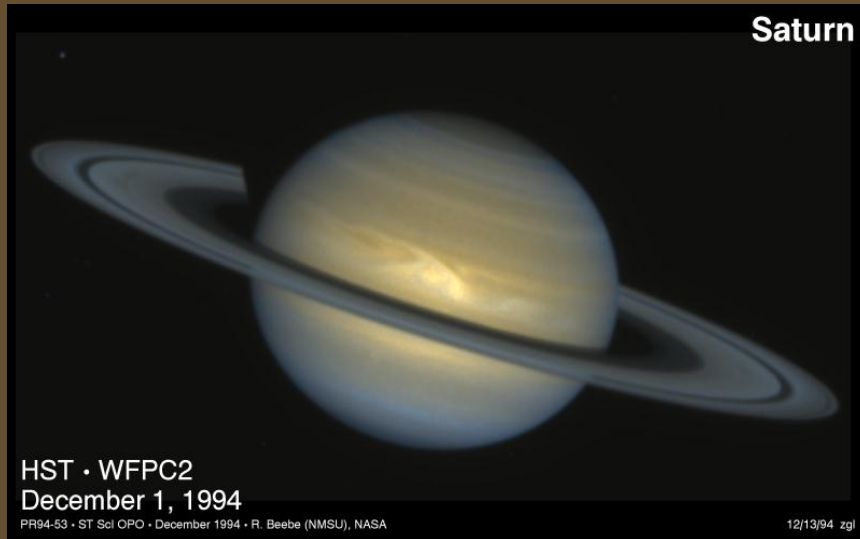


# Exploring Europa's Ocean



- Limited energy sources.. But there may be volcanism on the ocean floor
- If there is life, perhaps it is more “different” than on earth or Mars

# Titan

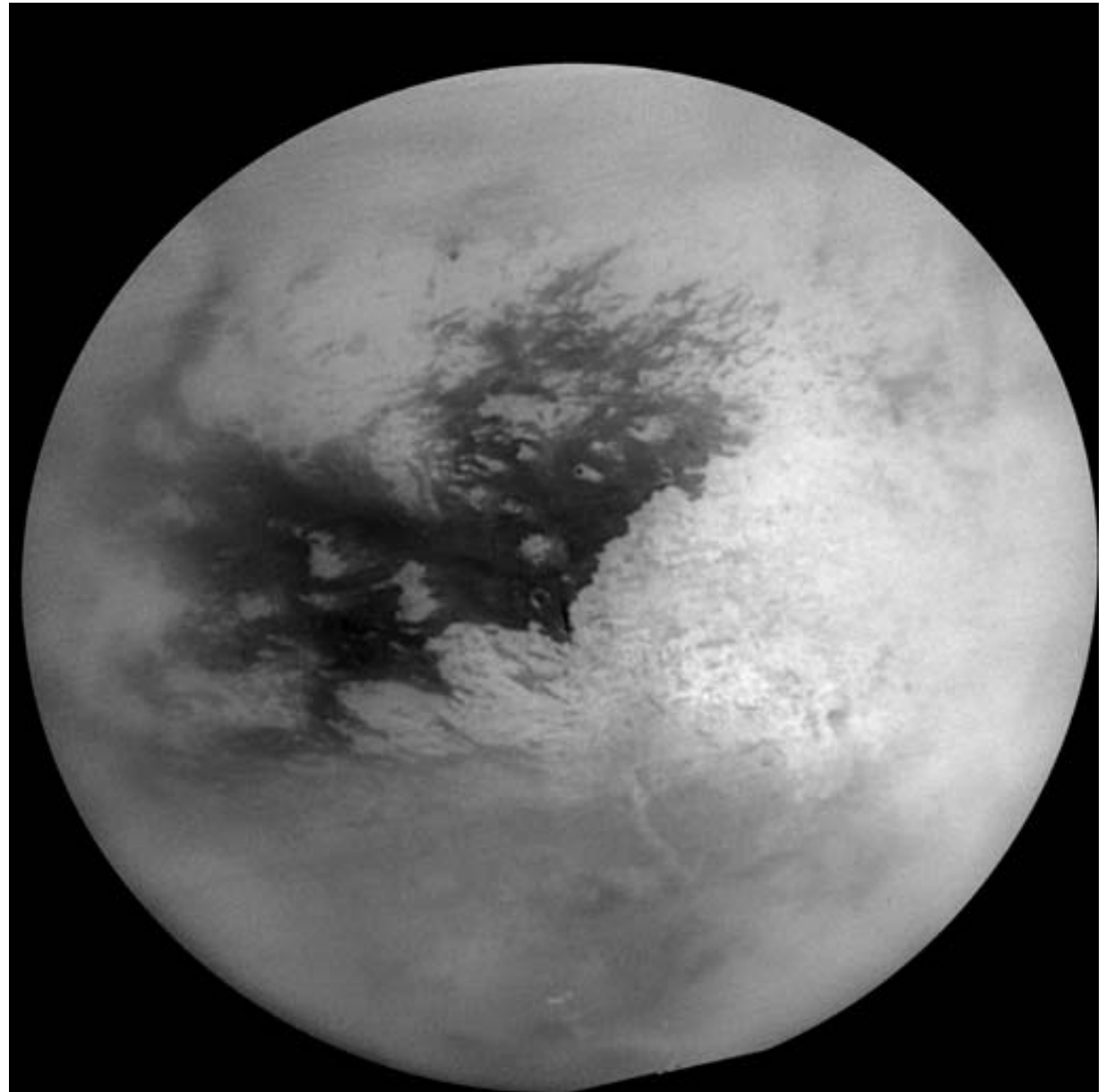


- Titan is the only large moon of Saturn
- Dense  $\text{N}_2$  - $\text{CH}_4$  atmosphere; the methane is continually resupplied from a surface or subsurface reservoir. Suggests more volatile ices than merely water ice.

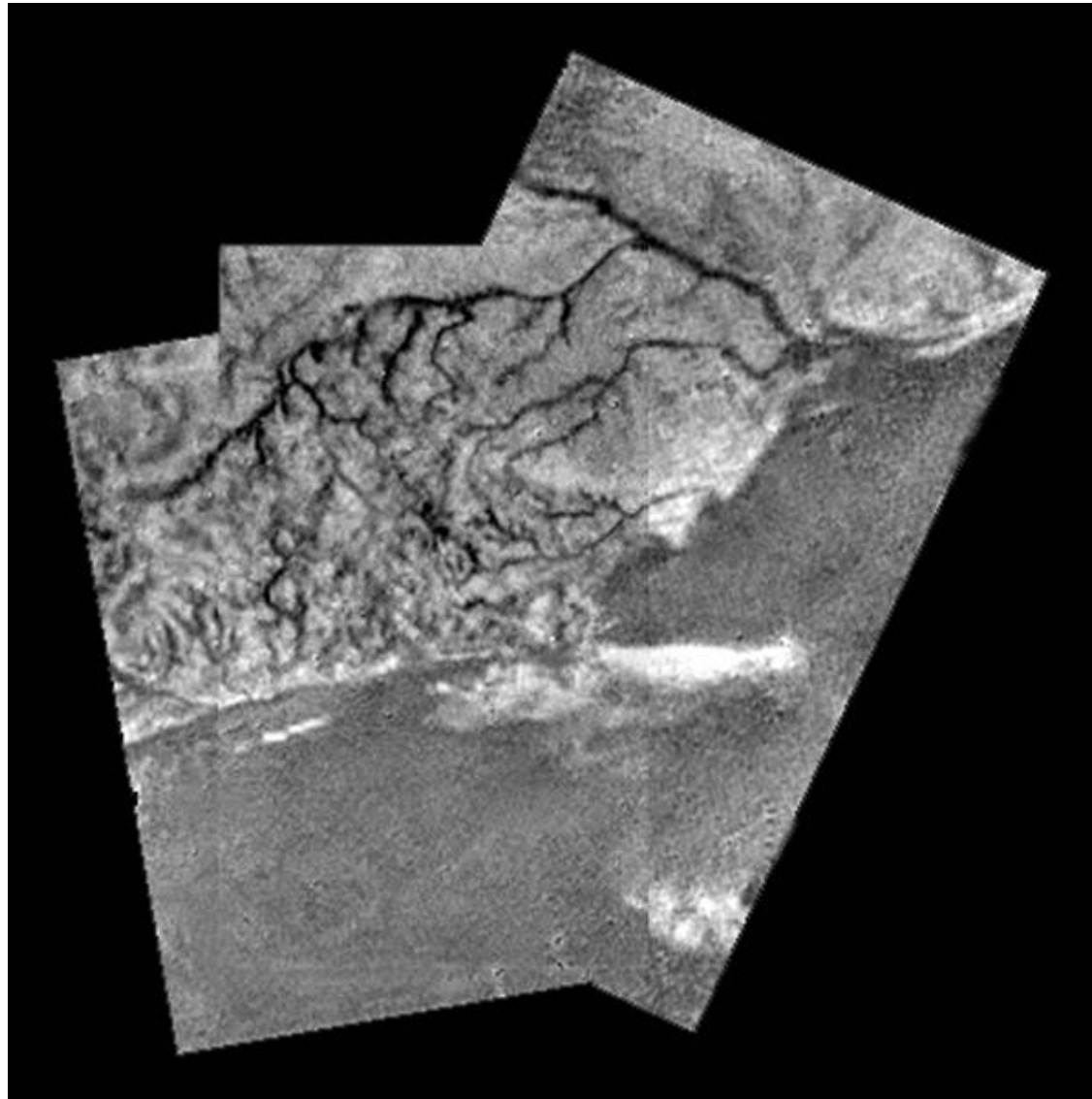


# Titan from Cassini

- Visual appearance (near IR)
- Quite sharp boundaries between dark (tarlike?) terrains and brighter terrains.

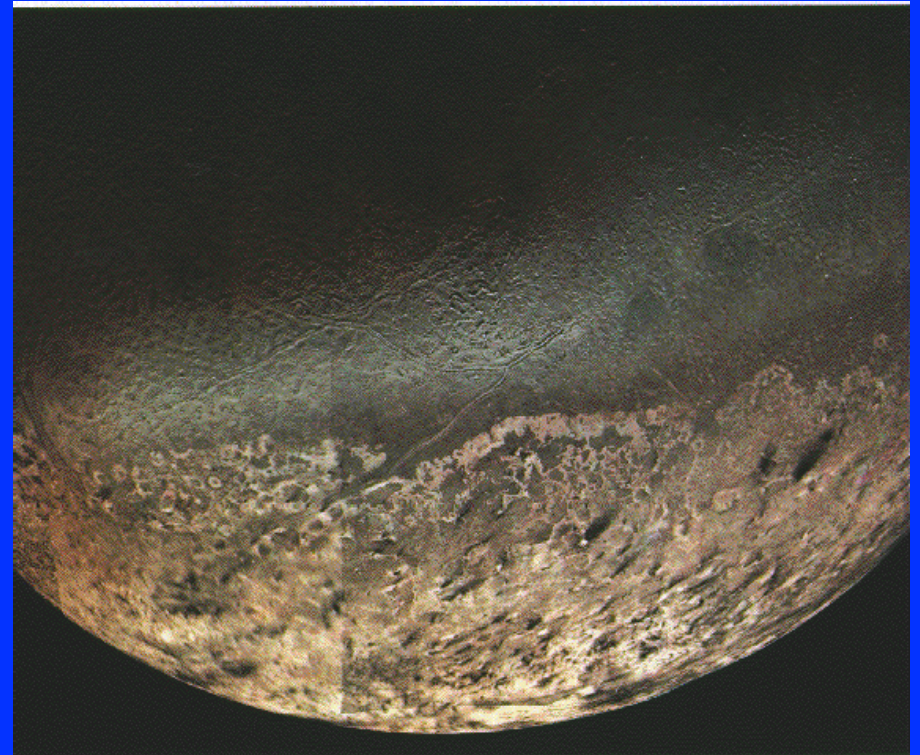
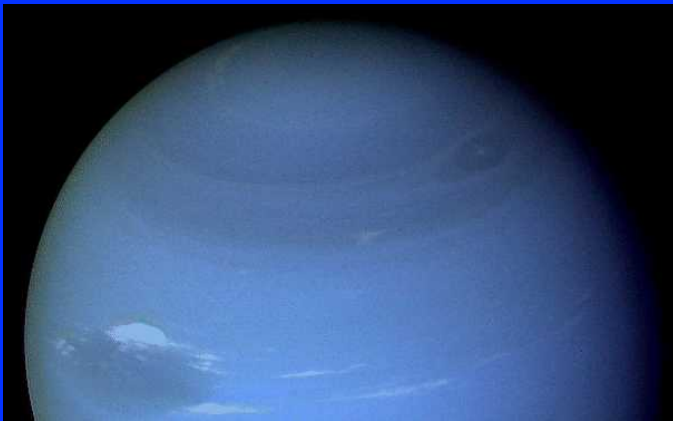


# Imaging from Huygens probe descent



# Triton

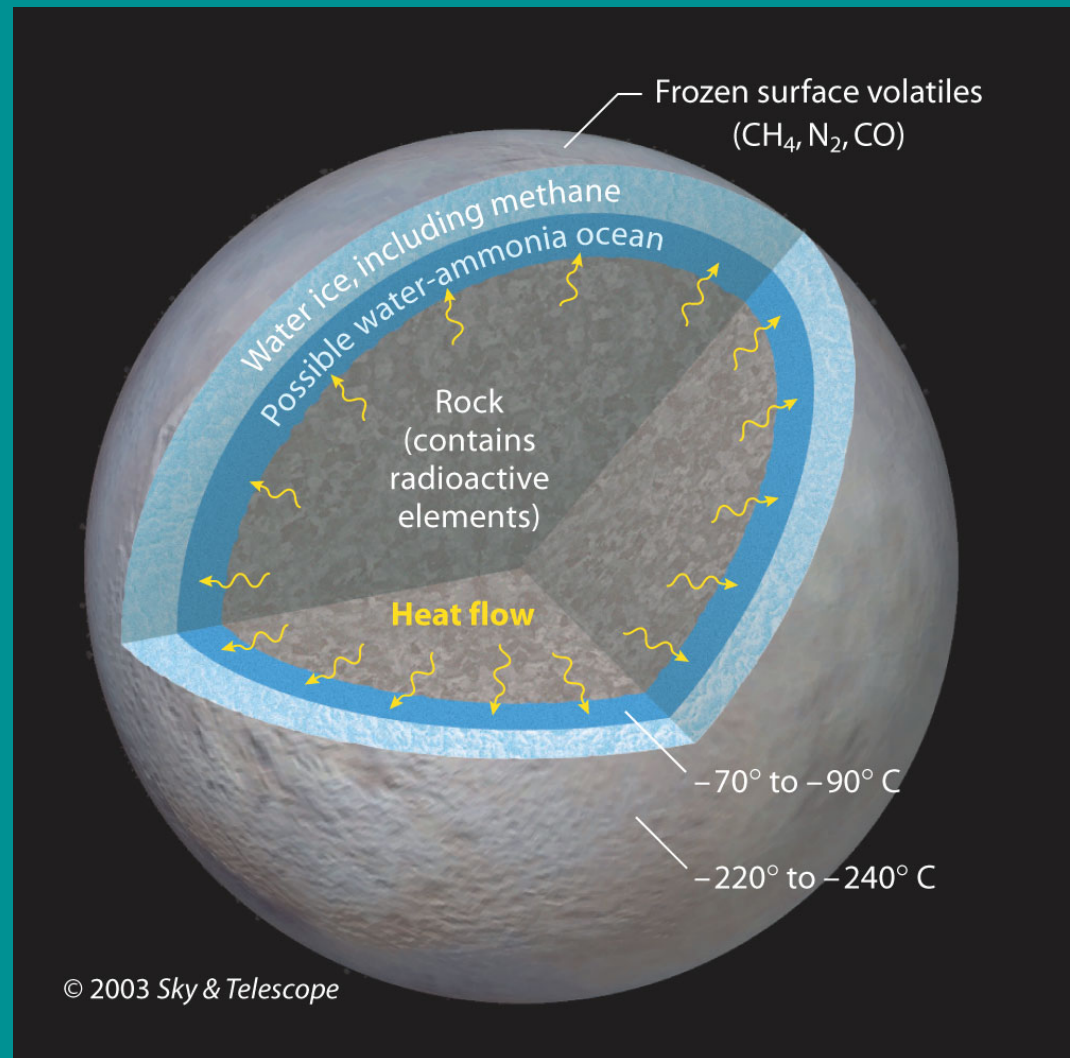
## Large Moon of Neptune



- Surface has nitrogen frost, methane ice.
- Impact craters not maintained; suggests underlying ocean?  $\text{H}_2\text{O}$ - $\text{NH}_3$  mixture.
- Also Pluto?

# Oceans in Triton and Pluto?

- May depend on presence of ammonia
- Also helped by presence of large rocky core



Planet (or spacecraft)  
headed for escape



Jupiter (for  
example)



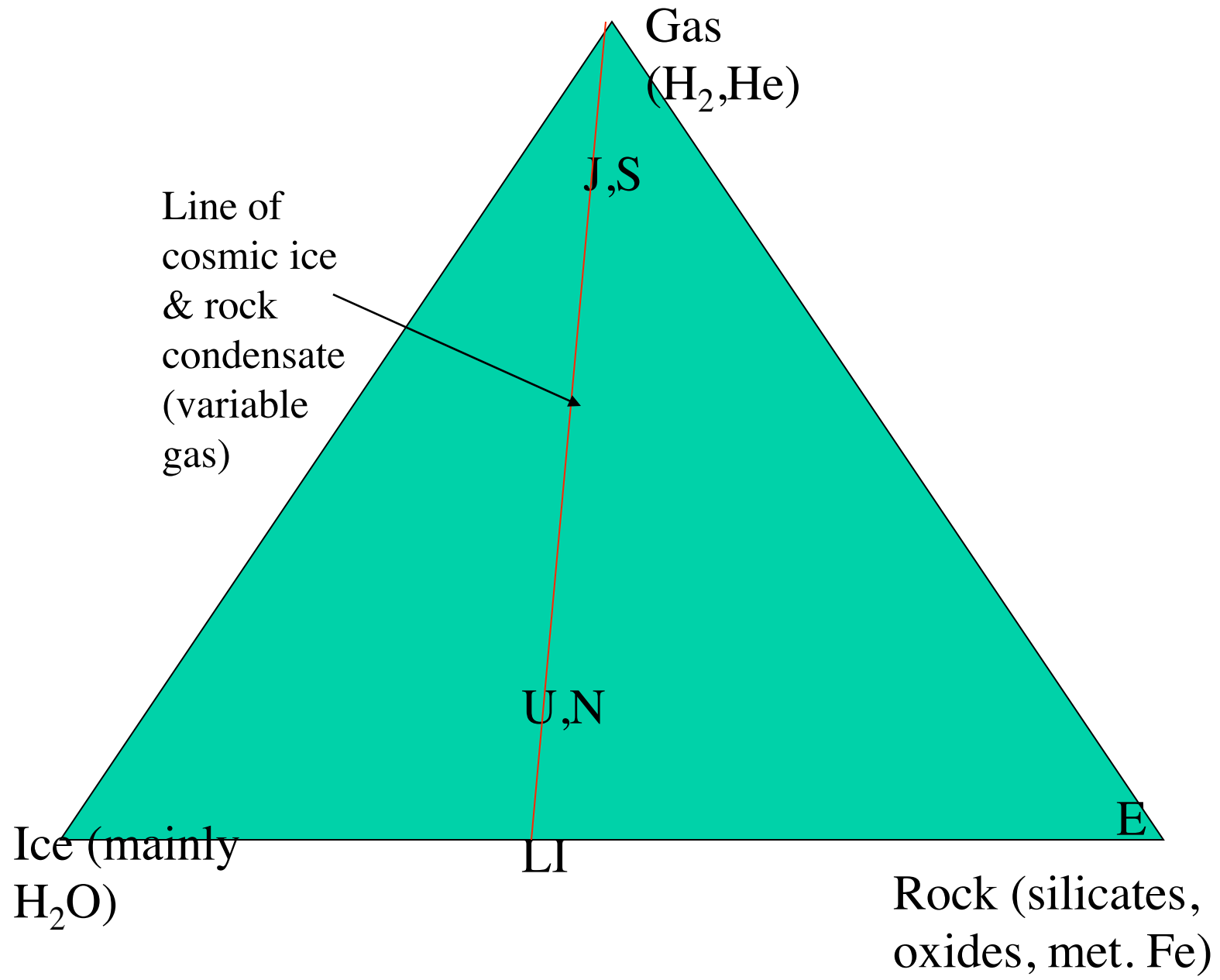
Interstellar Planets?

# What kinds of planets might we find (that are different from what we have?)

- SuperGanymedes (water worlds)
- Carbon-rich planets (lots of diamond)
- Low mass gas balls
- Livable moons around giant planets
- Interstellar planets
- Iron planets
- Planets with liquid hydrogen or neon oceans
- .....

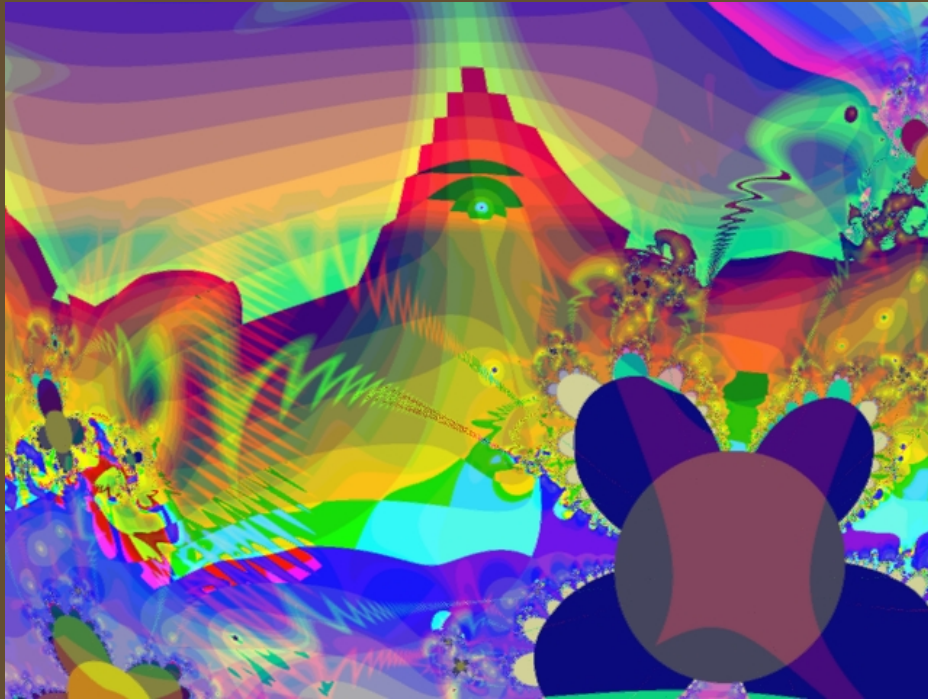
# *Cosmic (~Solar) Abundances*

| <b>Element</b> | <b>Number Fraction</b> | <b>Mass Fraction</b> |
|----------------|------------------------|----------------------|
| H              | 0.92                   | 0.71                 |
| He             | 0.08                   | 0.27                 |
| O              | $7 \times 10^{-4}$     | 0.011                |
| C              | $4 \times 10^{-4}$     | 0.005                |
| Ne             | $1.2 \times 10^{-4}$   | 0.002                |
| N              | $1 \times 10^{-4}$     | 0.0015               |
| Mg             | $4 \times 10^{-5}$     | 0.001                |
| Si             | $4 \times 10^{-5}$     | 0.0011               |
| Fe             | $3 \times 10^{-5}$     | 0.0016               |



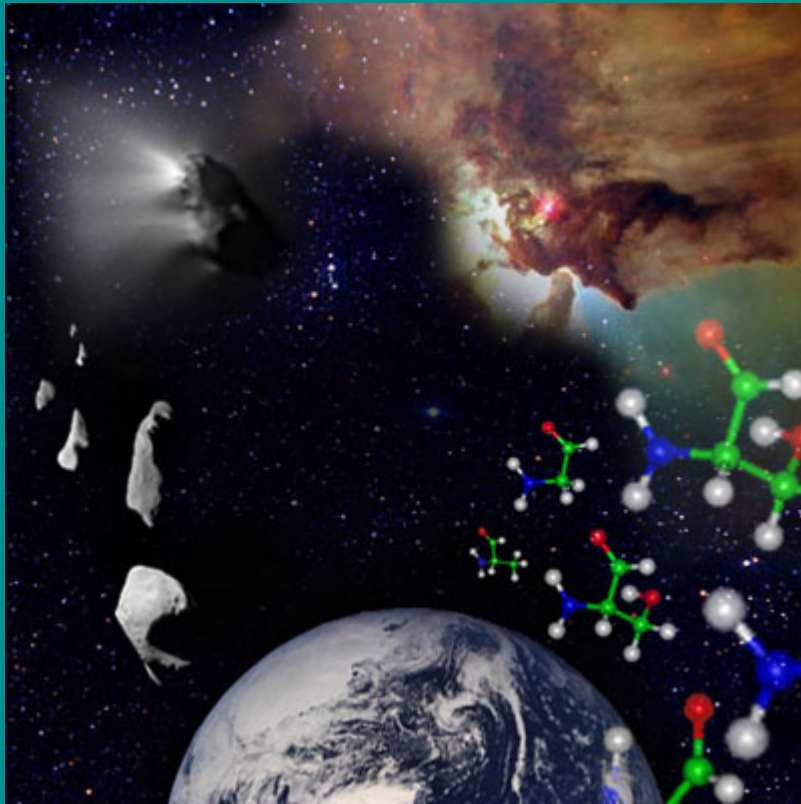


# Fantasy or Reality?



- Ideas firmly based in cosmochemistry & physics
- History of astronomy shows that all niches are occupied

# Legacy of the Earth and Other Waterworlds



- Stars provided the ingredients
- Planets provided the processing
- We are part of the process -but we haven't figured it out yet.



WEB SHOTS