

# Astrobiology - the science of life in the universe

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Are we alone?

Where do we come from?



# A Bayesian analysis of received wisdom...

Life arose 'quickly' in first few 100 Myrs on Earth...

Evidence for high abiogenesis probability?



# A Bayesian analysis of received wisdom...

Life arose 'quickly' in first few 100 Myrs on Earth

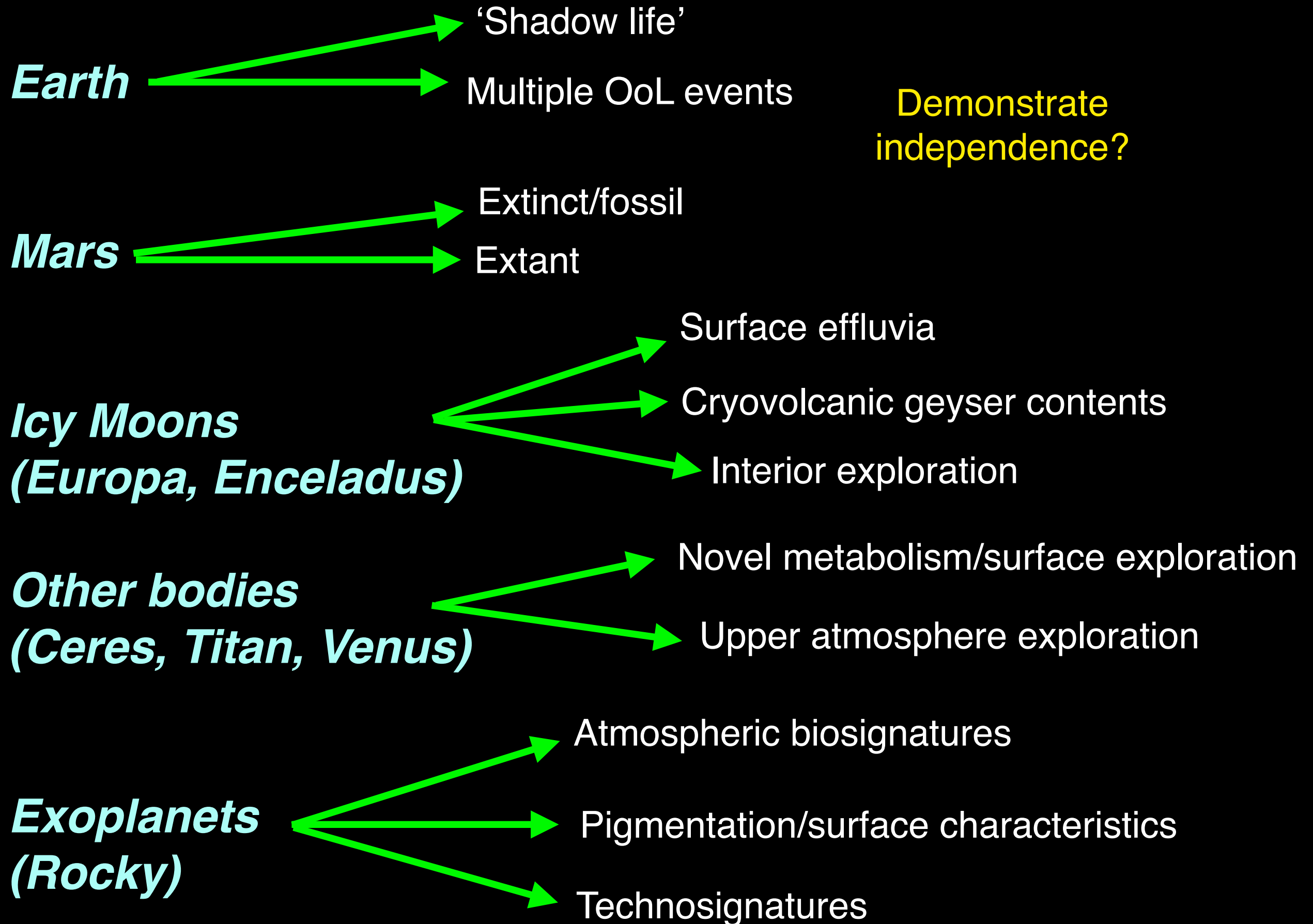
Evidence for high abiogenesis probability?

Not necessarily, choice of prior dominates posterior probability...life on Earth could be 1st in universe



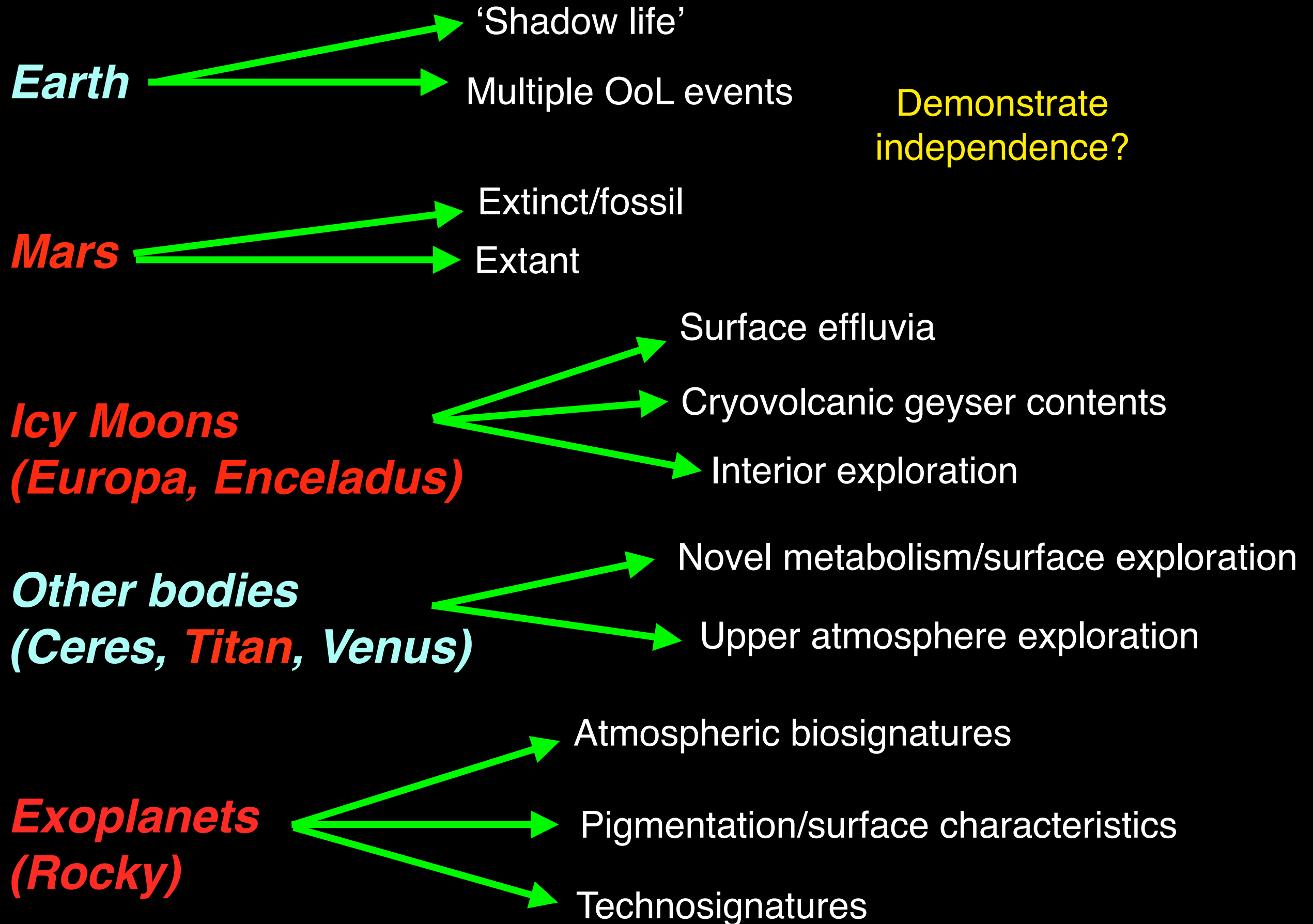
However, *one independent* example of abiogenesis would push posterior rate to  $>1$  per Gyr on suitable planets

# Where can we look to find an independent abiogenesis?





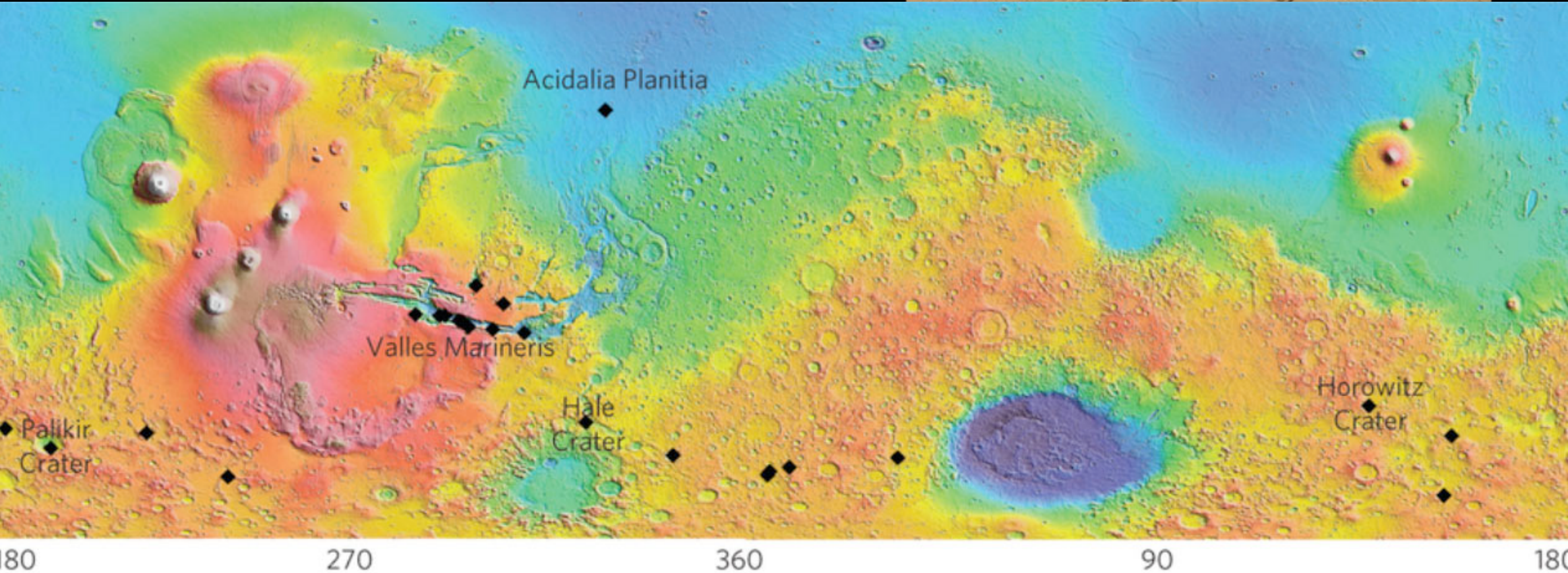
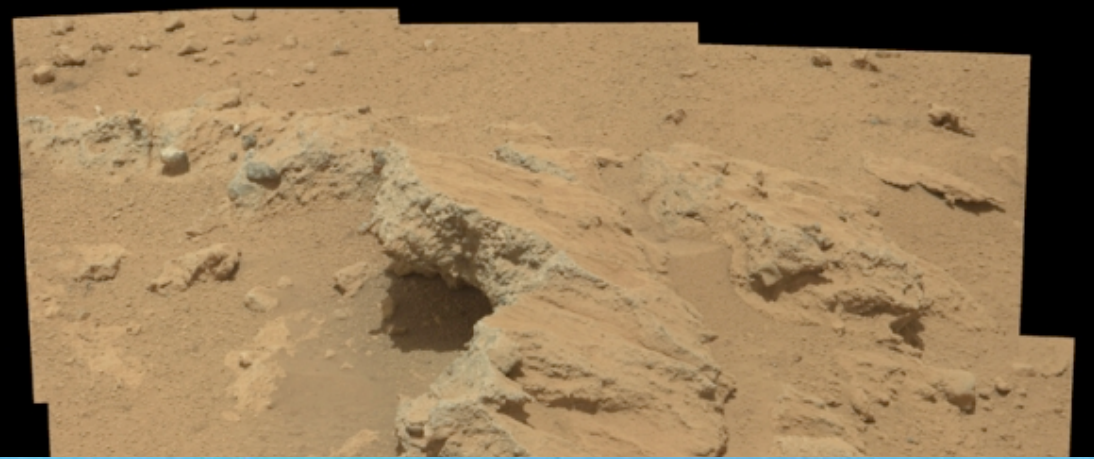
# Where can we look to find an independent abiogenesis?





# Mars

- Clear evidence of periods with substantial surface/near surface liquid water



- Increasing evidence of organic deposits (inc. 10 C-atom 'fatty acid-like' compound) in mudstone that could be indigenous (i.e. not meteoritic)

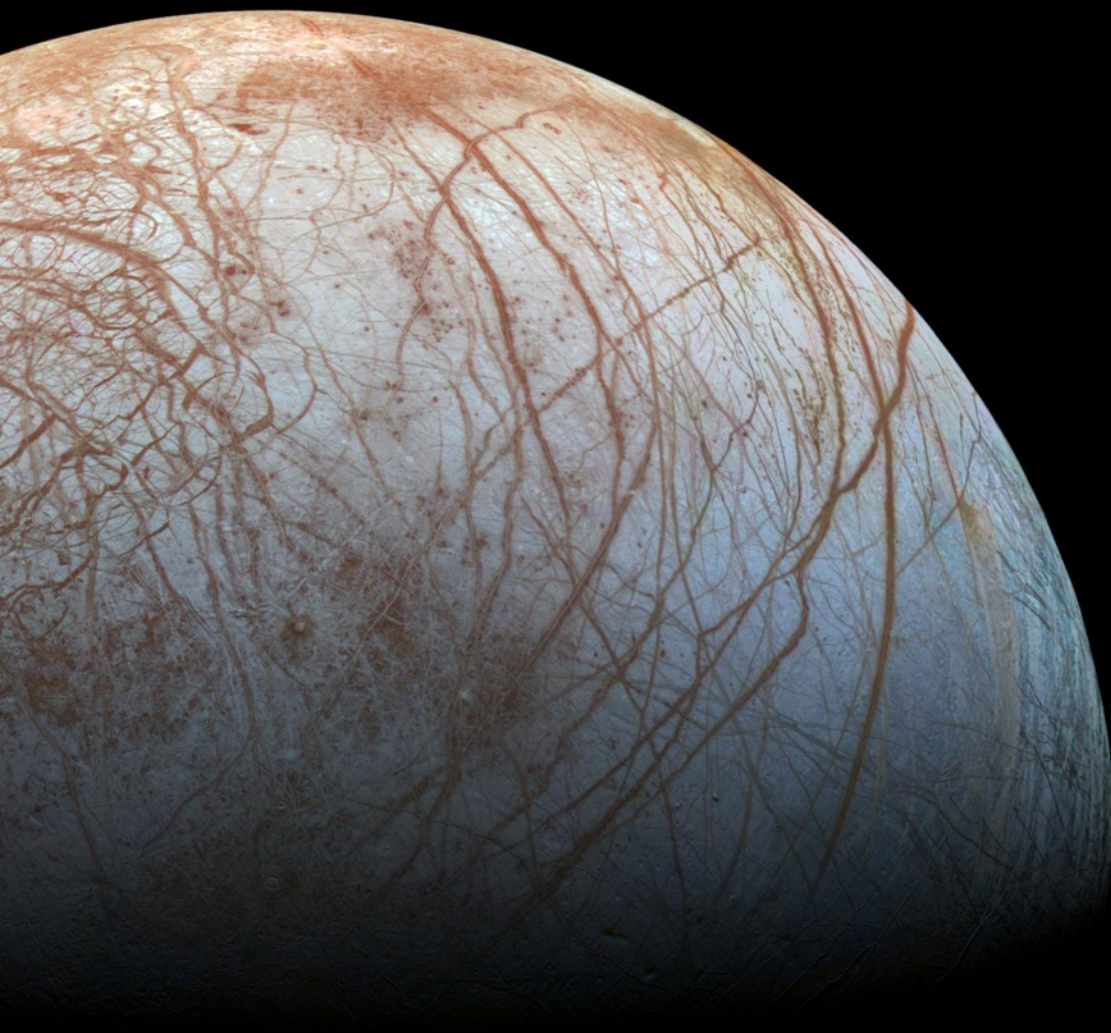




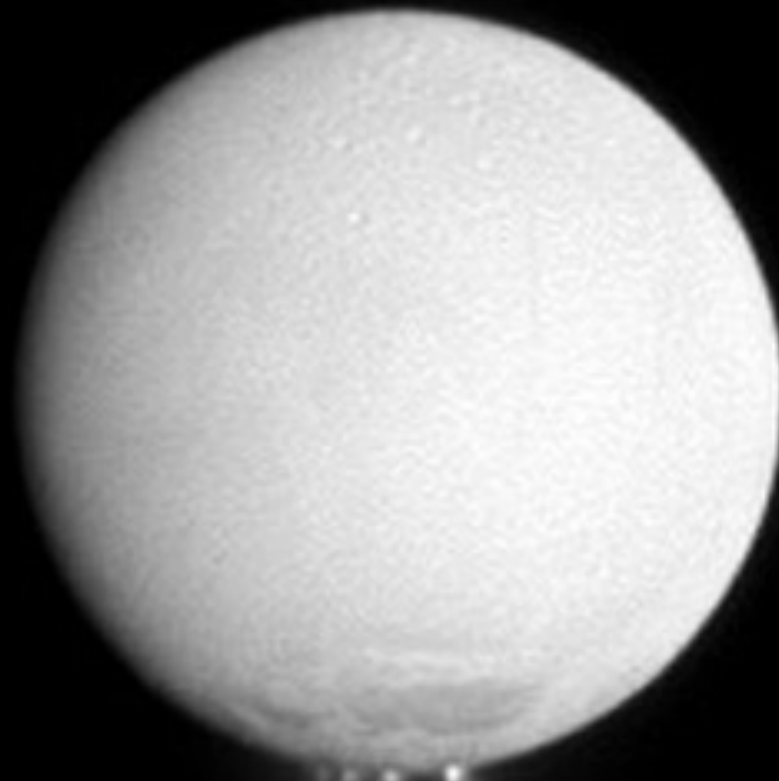
# Icy Moons

Good evidence of subsurface liquid zones (morphology, induced magnetic field, plumes).

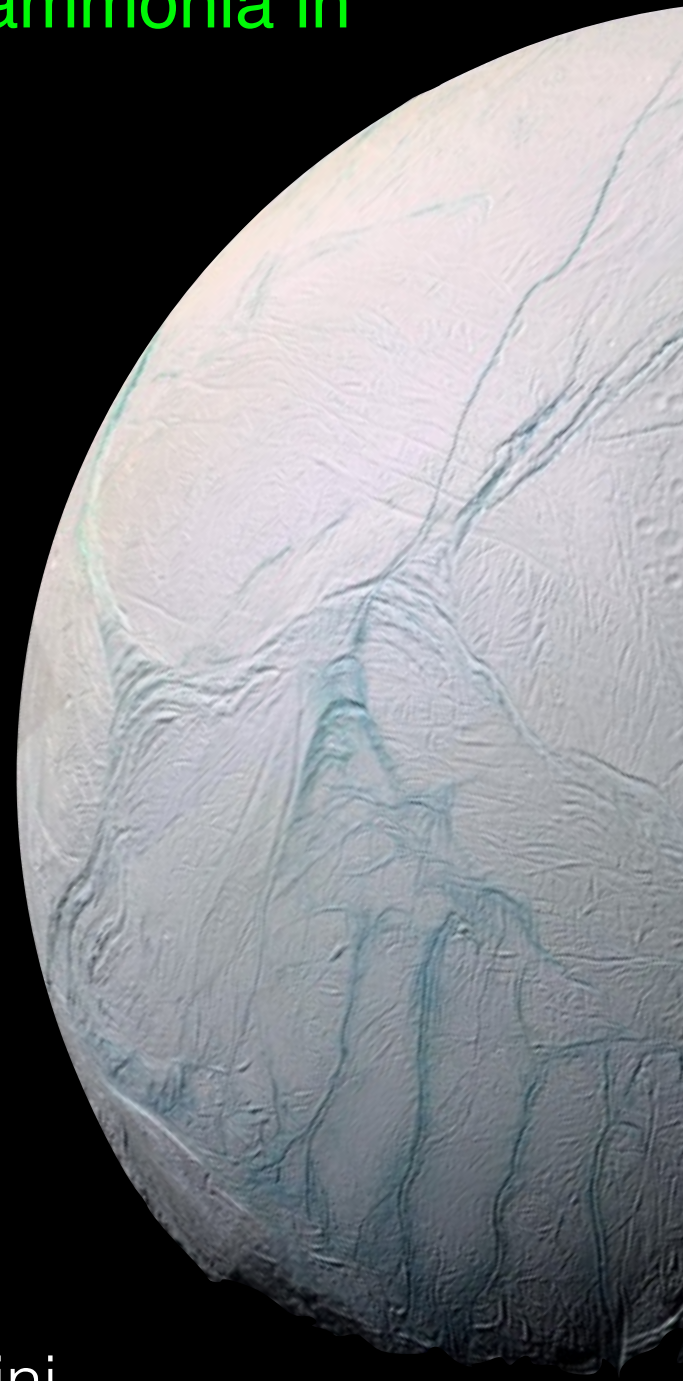
That water is modestly salty: sodium, calcium (seen in Enceladus plumes and Europa radiation-altered deposits). Some organics, some ammonia in Enceladus plumes.



Europa/Galileo



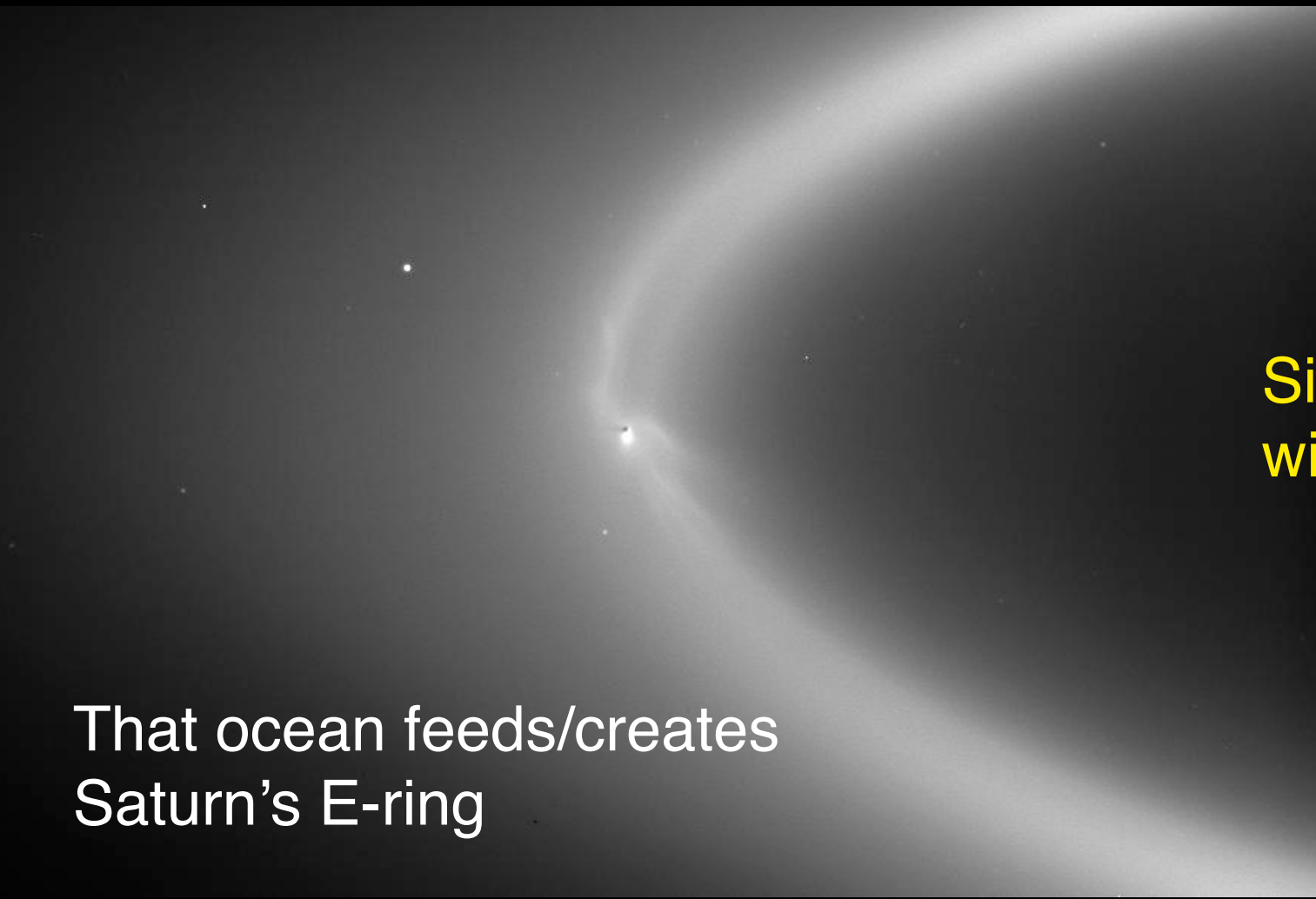
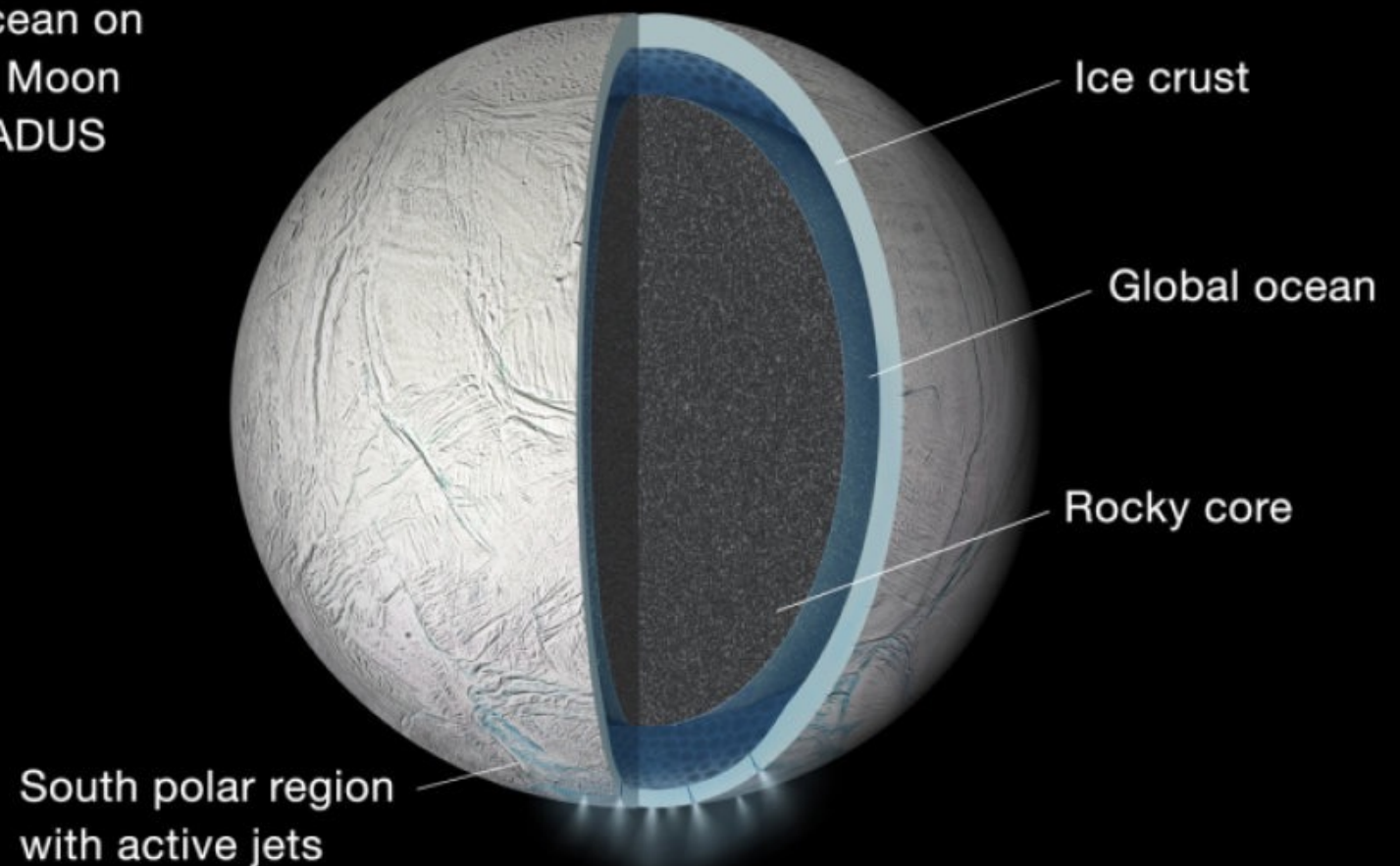
Enceladus/Cassini



# Icy Moons

Latest Cassini result on  $\pm 0.12$  degree Enceladus libration indicates *global* ocean

Global Ocean on  
Saturn's Moon  
ENCELADUS



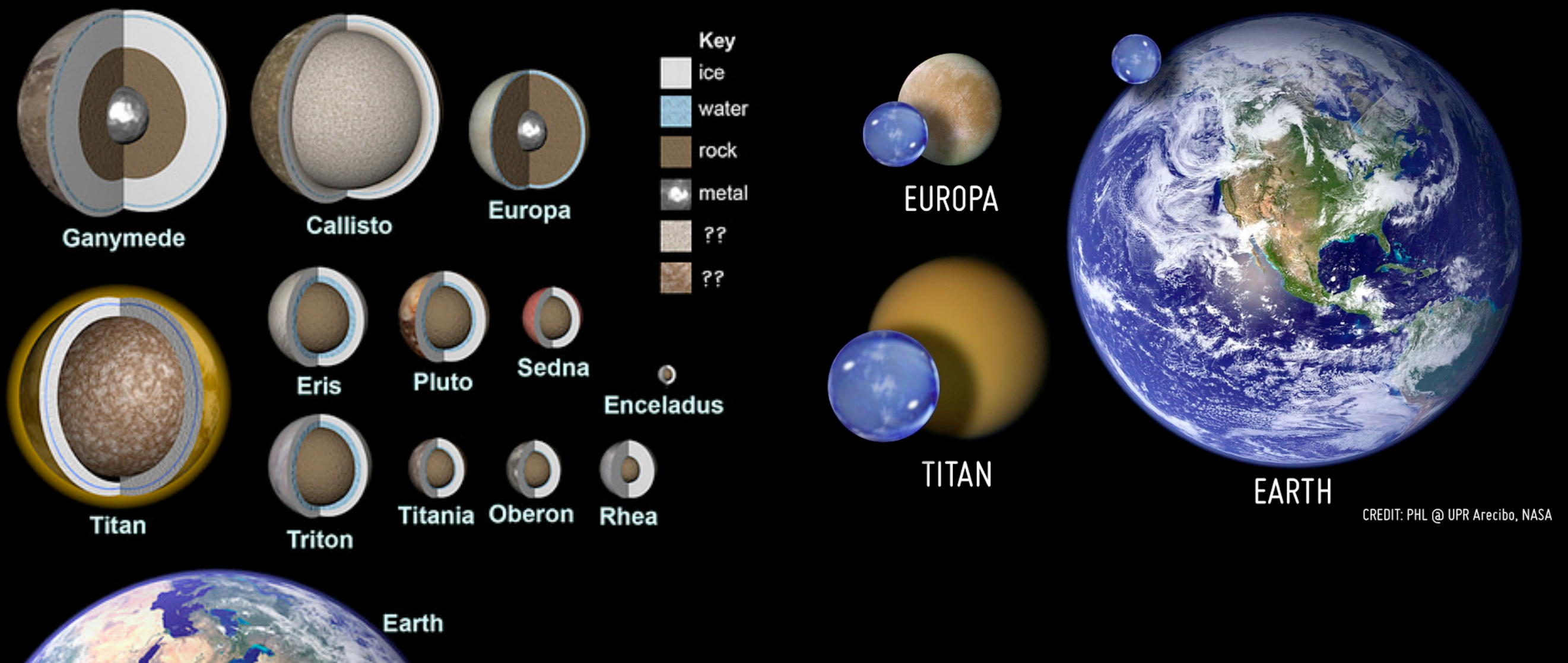
$\text{SiO}_2$  nanoparticles indicate contact with rocks & hydrothermal systems?

That ocean feeds/creates  
Saturn's E-ring



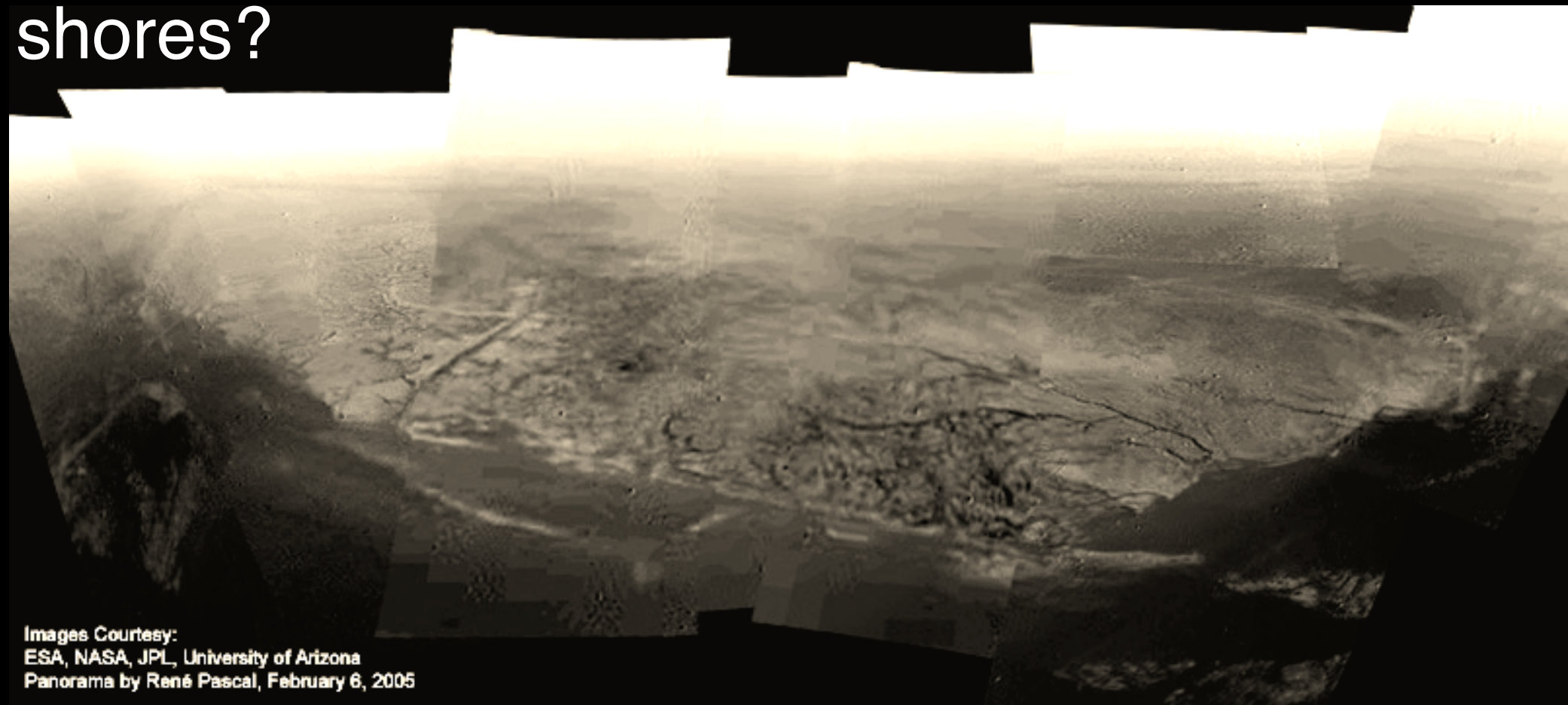
Longevity of oceans unknown - could be ancient, maintained by tidal heating and radiogenic heating + insulation (also, ammonia lowers eutectic point)

Altogether, crude models of interiors of water-rich solar system objects (moons, dwarf planets - inc. Pluto, Ceres) suggest **~15 times volume of all Earth's oceans** in subsurface environments.



# Titan's seas & shores?

~94 Kelvin  
surface



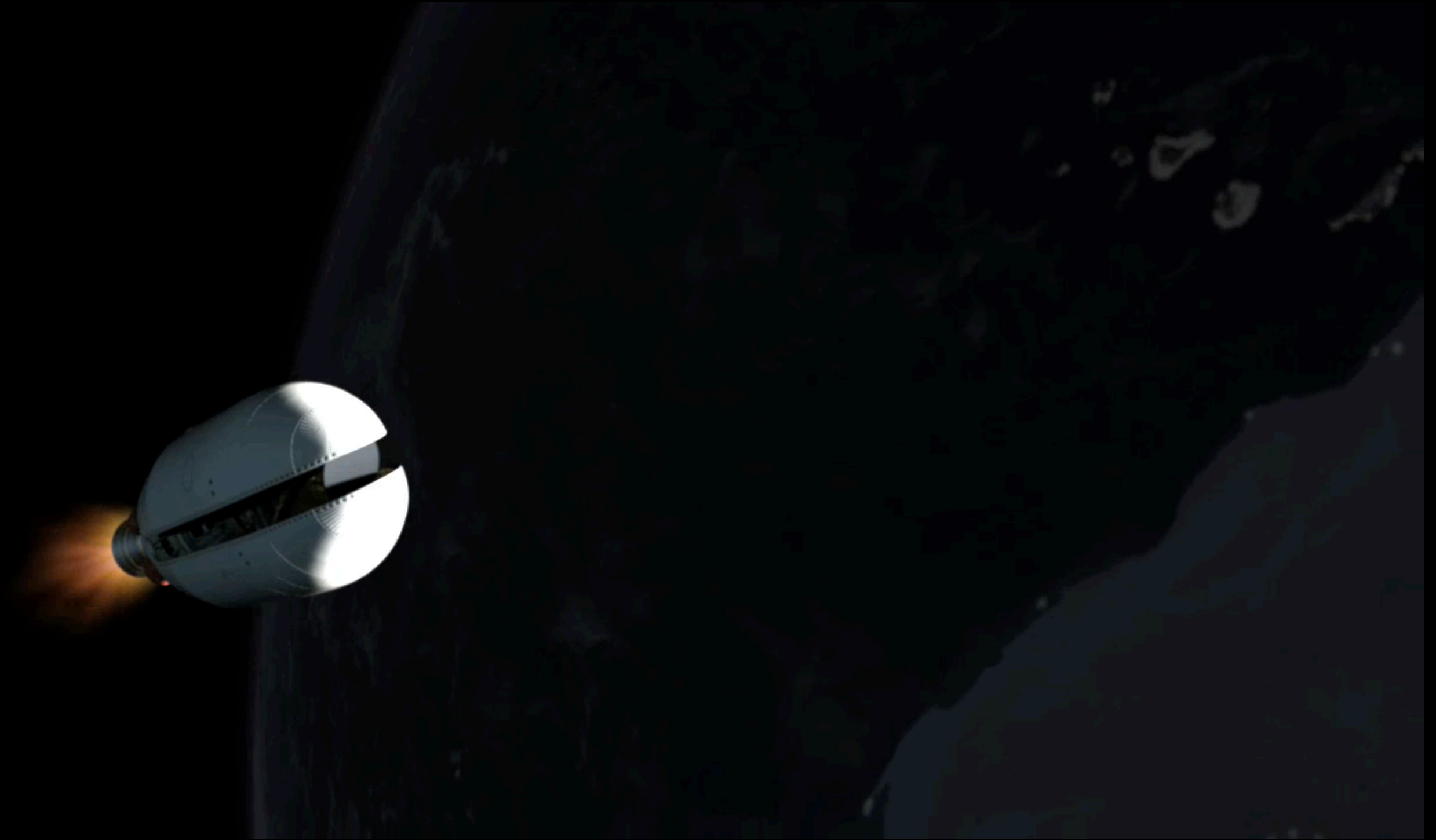
Energetically interesting: molecular  $H_2$  reacting with acetylene ( $C_2H_2$ ) - producing methane( $CH_4$ ).

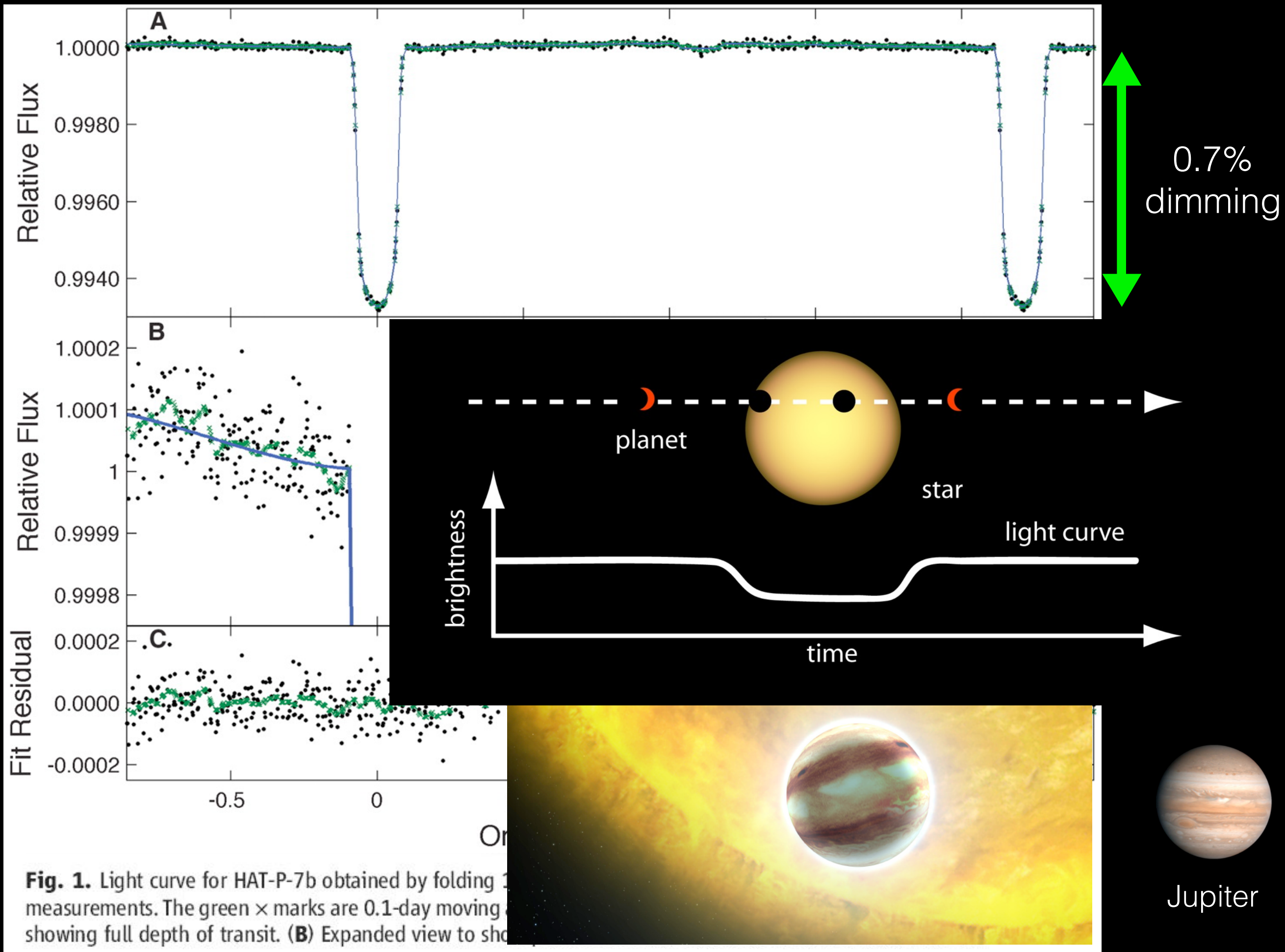
Downward flux of  $H_2$  (produced by photolysis of methane etc. in upper atmosphere) inferred in atmosphere (Strobel et al. 2010), but no accumulation on surface (likewise for acetylene), suggesting something is removing it...

$H_2$  unreactive in environment, catalyst needed - no obvious mineralogical culprit. Rates are consistent with biological use by methanogenic organisms...although this is **highly speculative** (McKay & Smith 2005) !



# Exoplanets



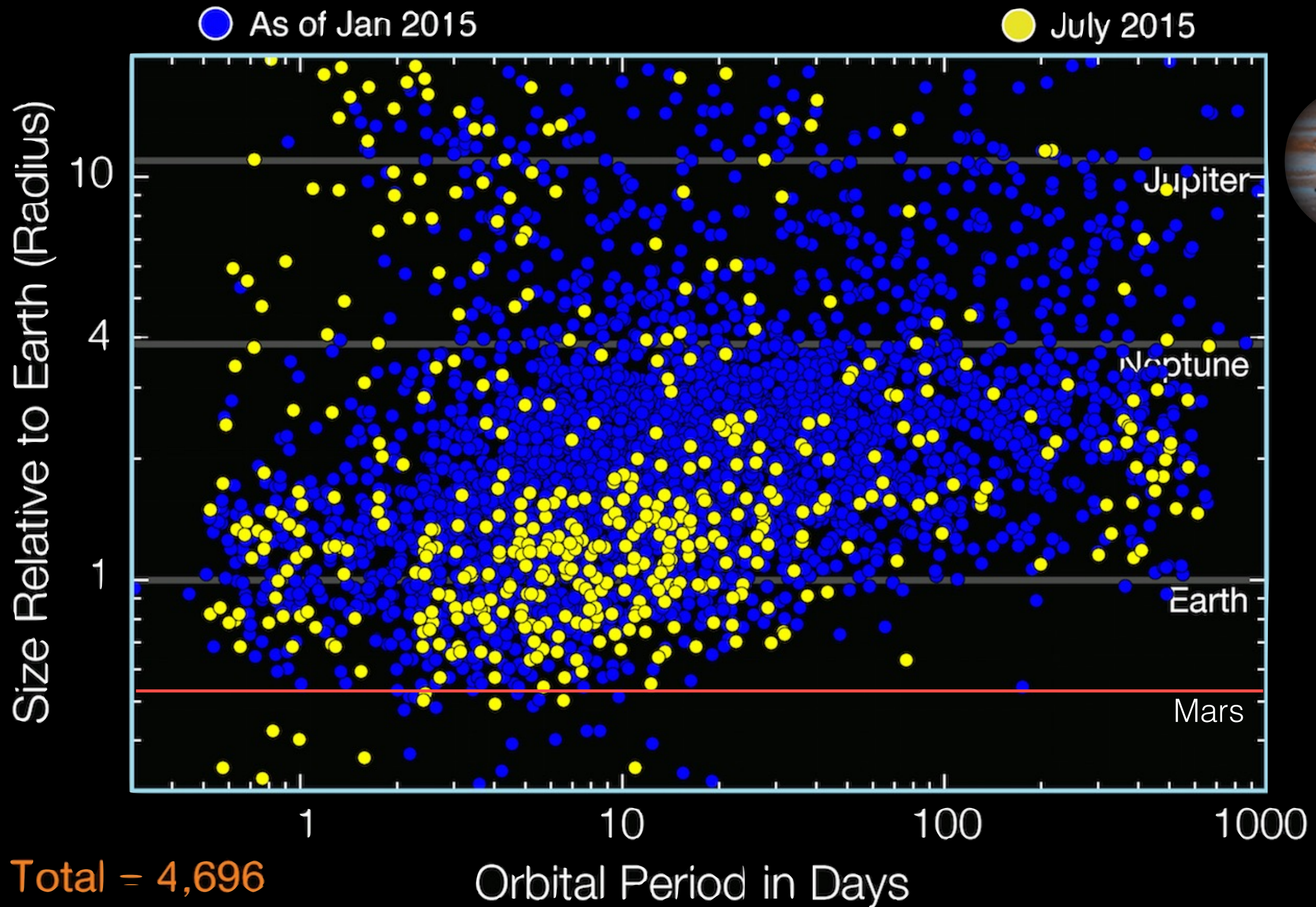




# Exoplanets

## New Kepler Planet Candidates

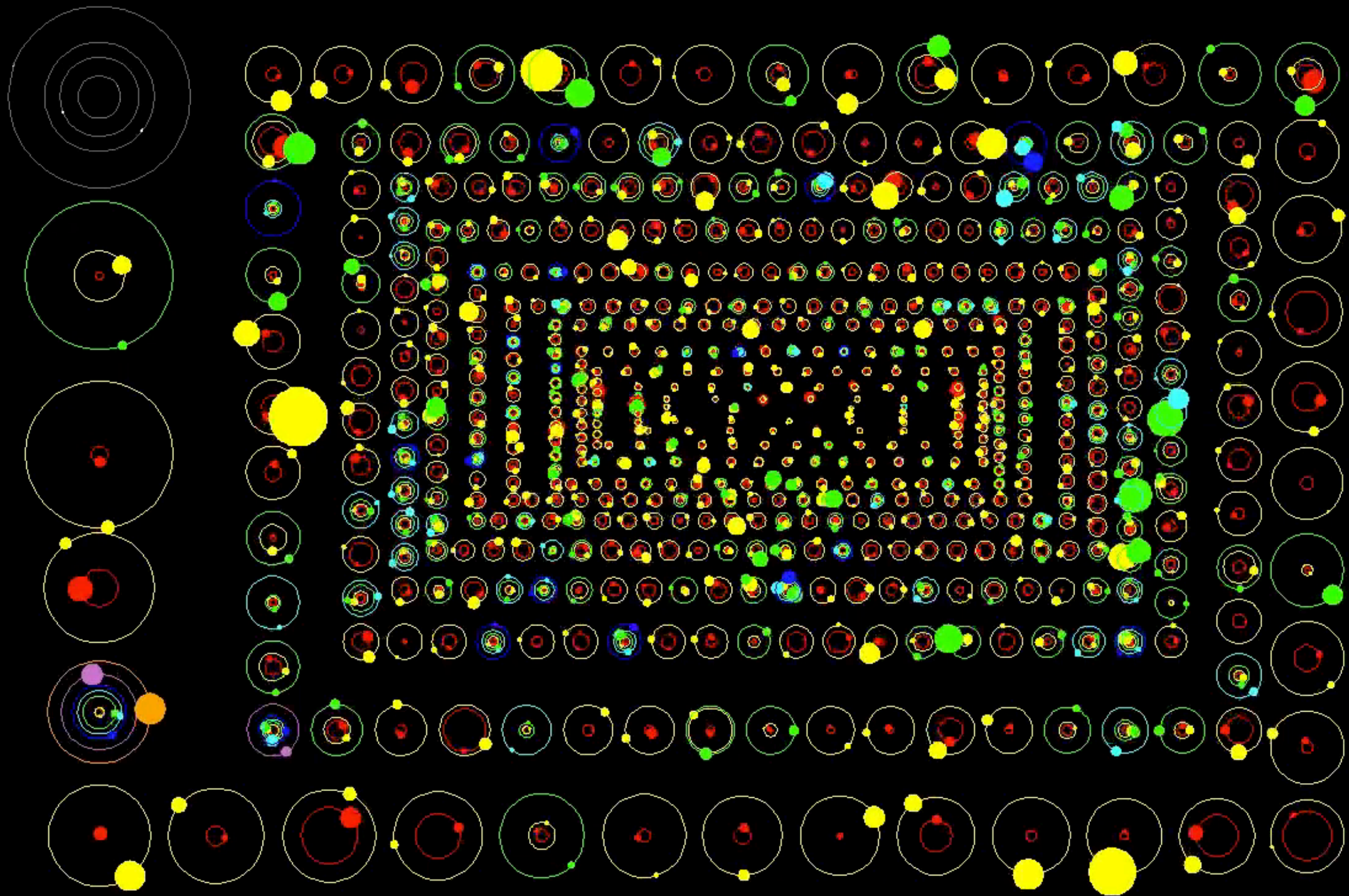
*As of July 23, 2015*





# The Kepler Orrery III

$t[\text{BJD}] = 2455723$





Radial velocity detections: total 1,952 planets in 1,235 systems.

Kepler: 4,737 planet candidates (inc. 1033 confirmed)

Across all techniques:

300 2-planet systems

98 3-planet systems

49 4-planet systems

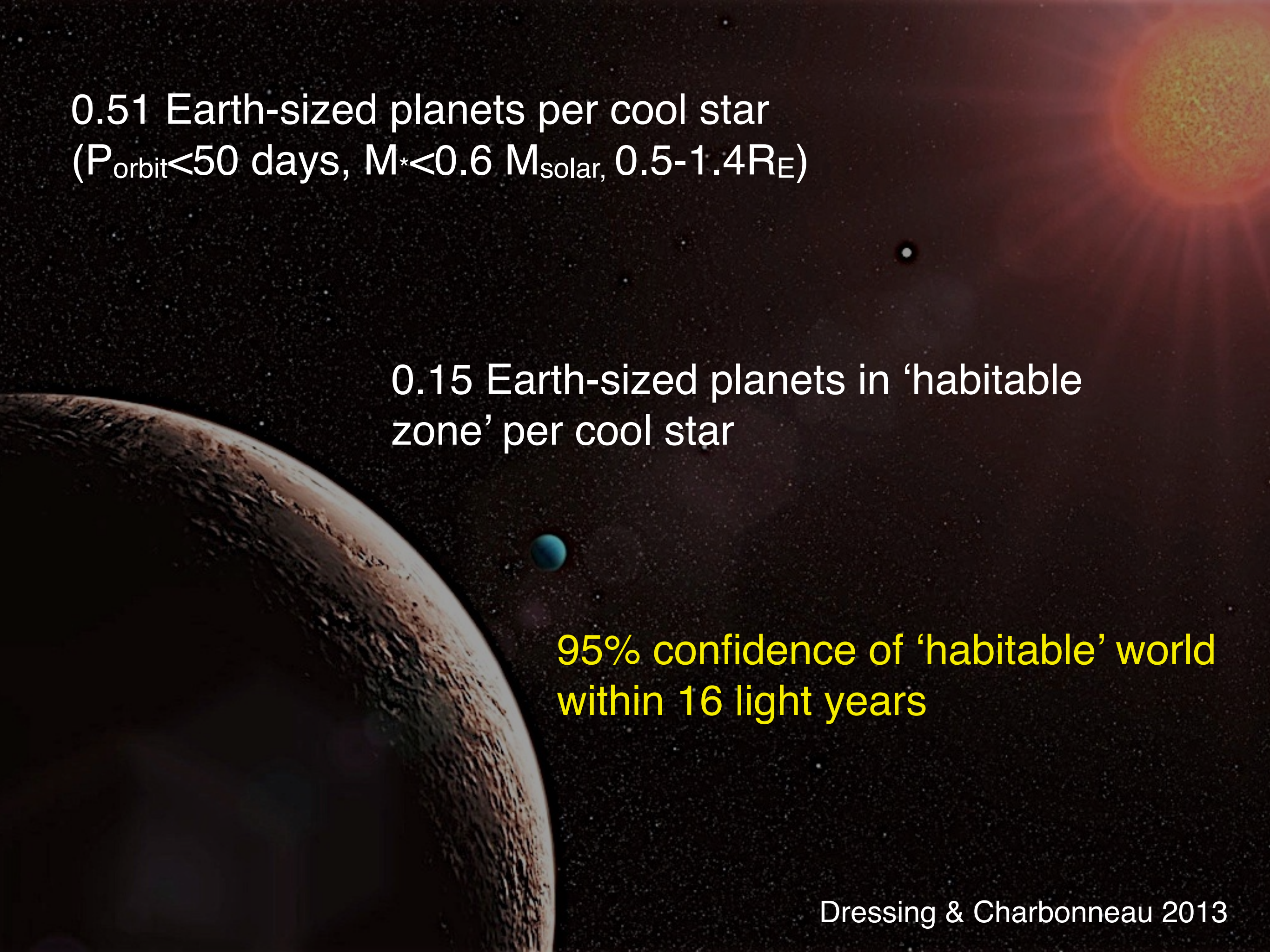
15 5-planet systems

2 6-planet systems

2 7-planet systems

Kepler data releases: 70% to 90% planet candidates smaller than Neptune (~20% 'Earth sized'  $<1.25 R_{\oplus}$ )





0.51 Earth-sized planets per cool star  
( $P_{\text{orbit}} < 50$  days,  $M^* < 0.6 M_{\text{solar}}$ ,  $0.5-1.4 R_{\text{E}}$ )

0.15 Earth-sized planets in 'habitable zone' per cool star

95% confidence of 'habitable' world  
within 16 light years



# An incredible diversity of worlds

Hot Jupiters

'Icarus' worlds

Retrograde orbits

Hydrogen rockys

'Packed' systems

Carbon-rich

Twin suns

'Super-Earths'

Elliptical orbits

Pitch black worlds

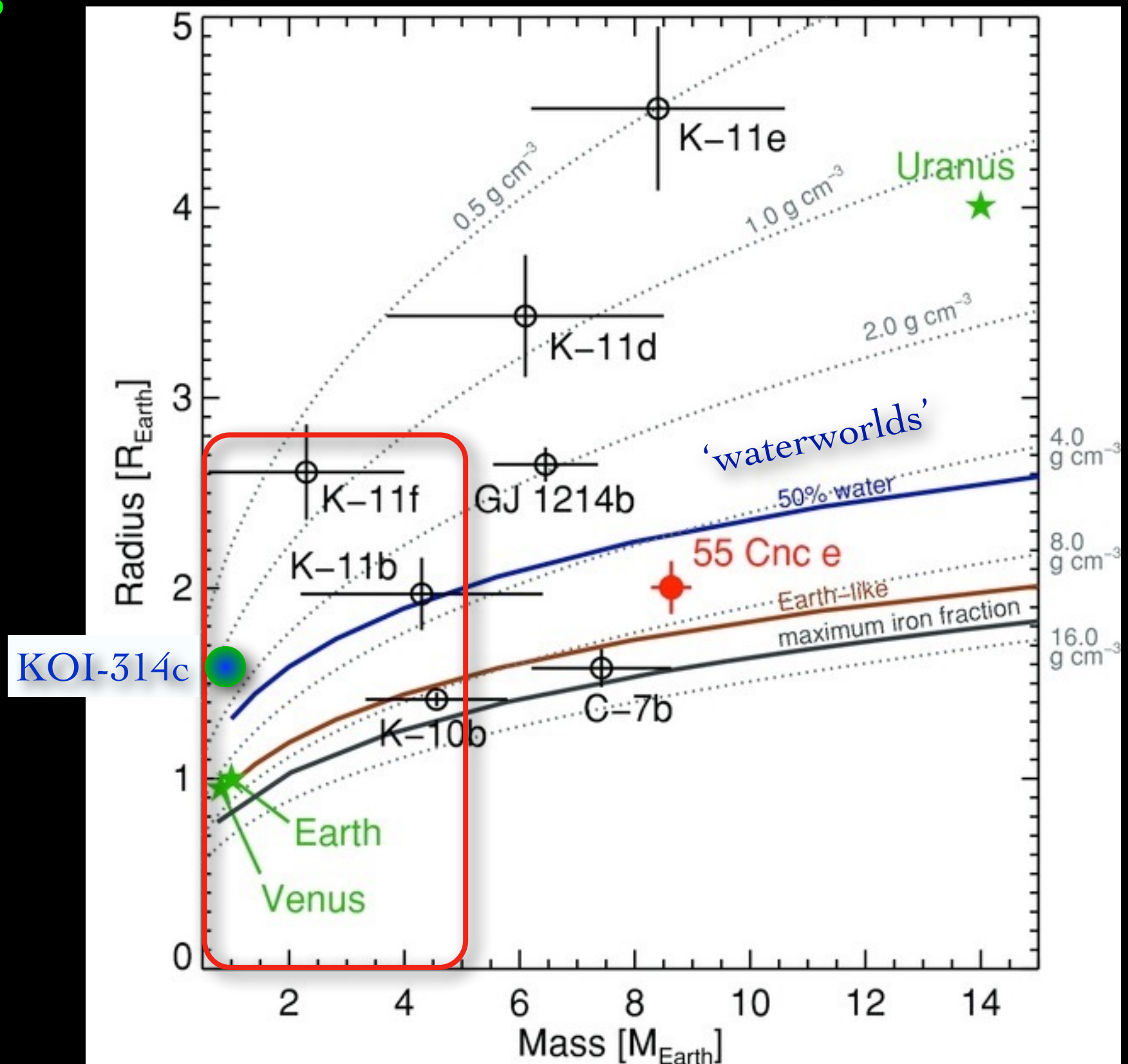
Ocean planets

Diamond layers

Rogue planets

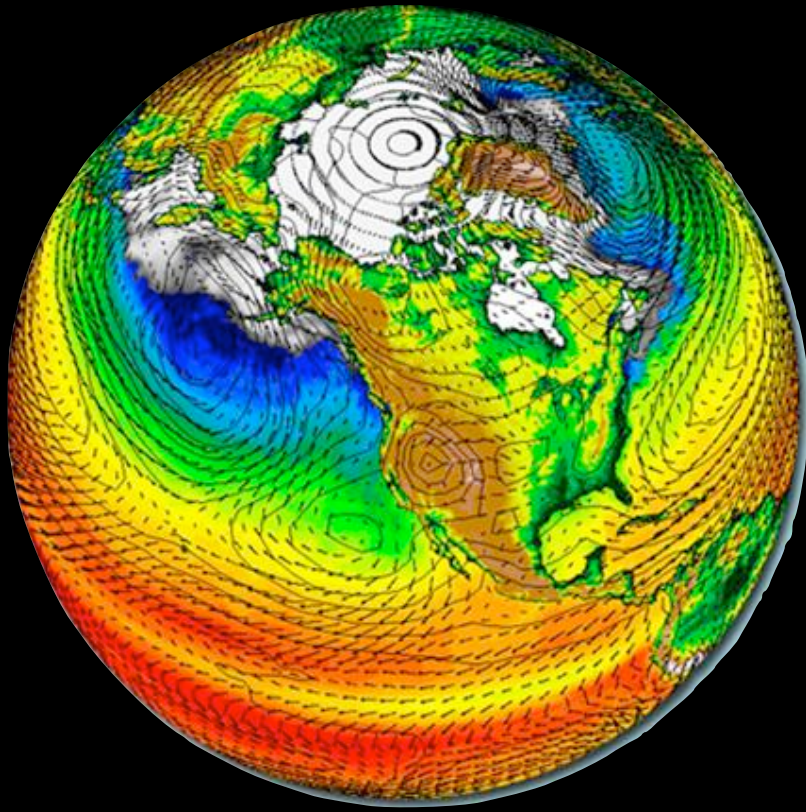


# Extraordinary diversity of system architectures, and likely planetary states



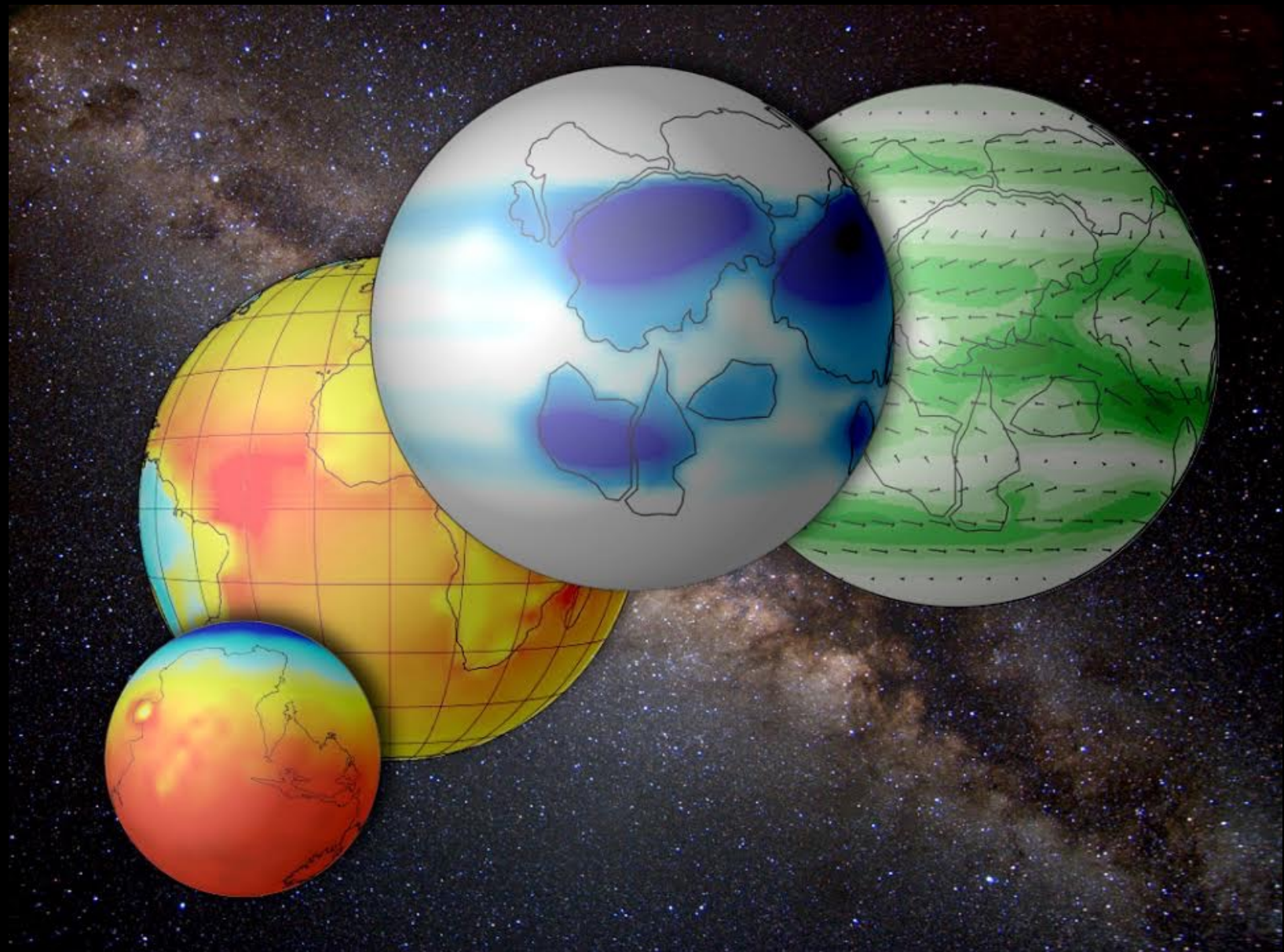


# How do we identify and study 'habitable' planets?



ROCKE3D - Based on the GISS Model E2 coupled atmosphere-ocean GCM

Calibrating climate states far from modern Earth using the solar system through time...

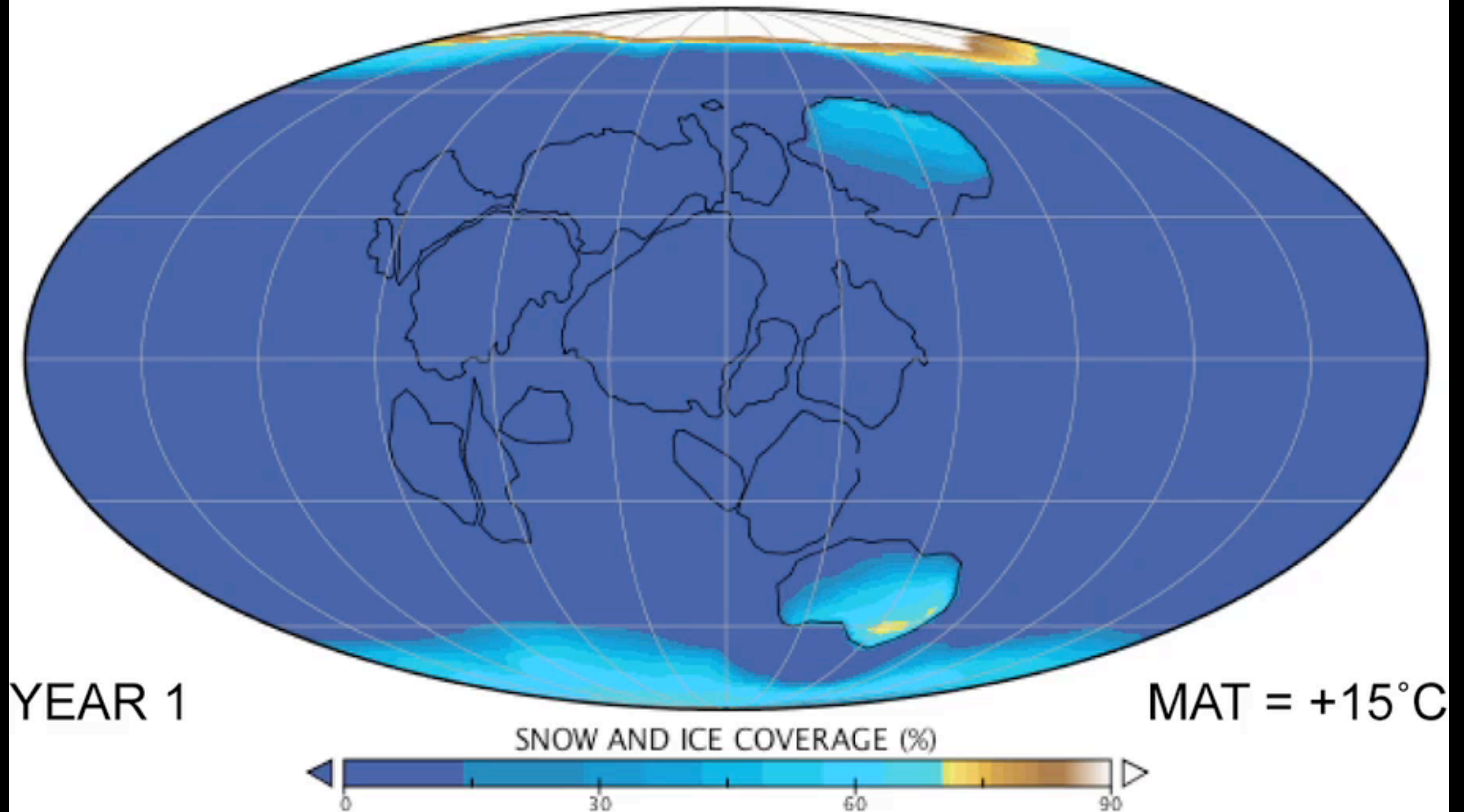




# Testing the edges of 'habitability' - the outer zones

0.5 to 1.0 Billion years ago

40ppm CO<sub>2</sub>, So 94%

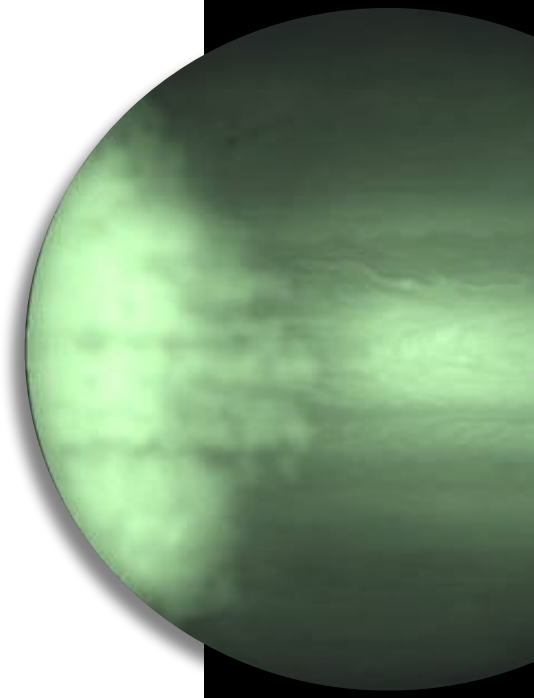
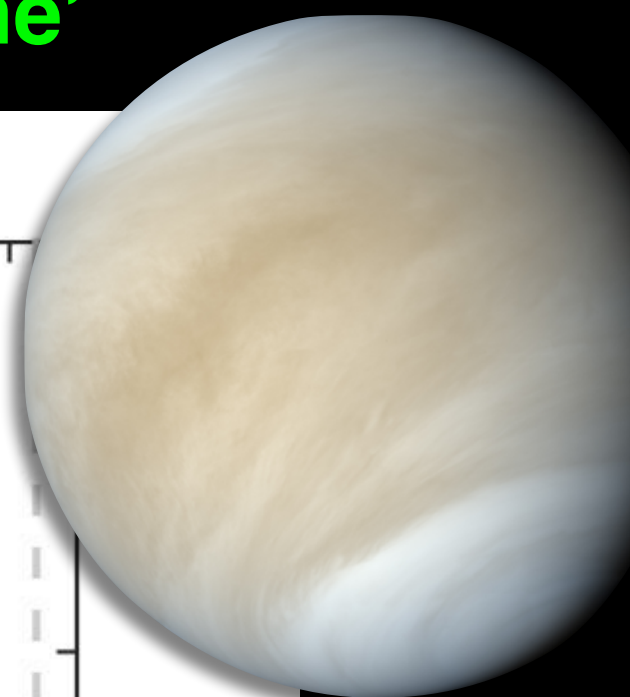
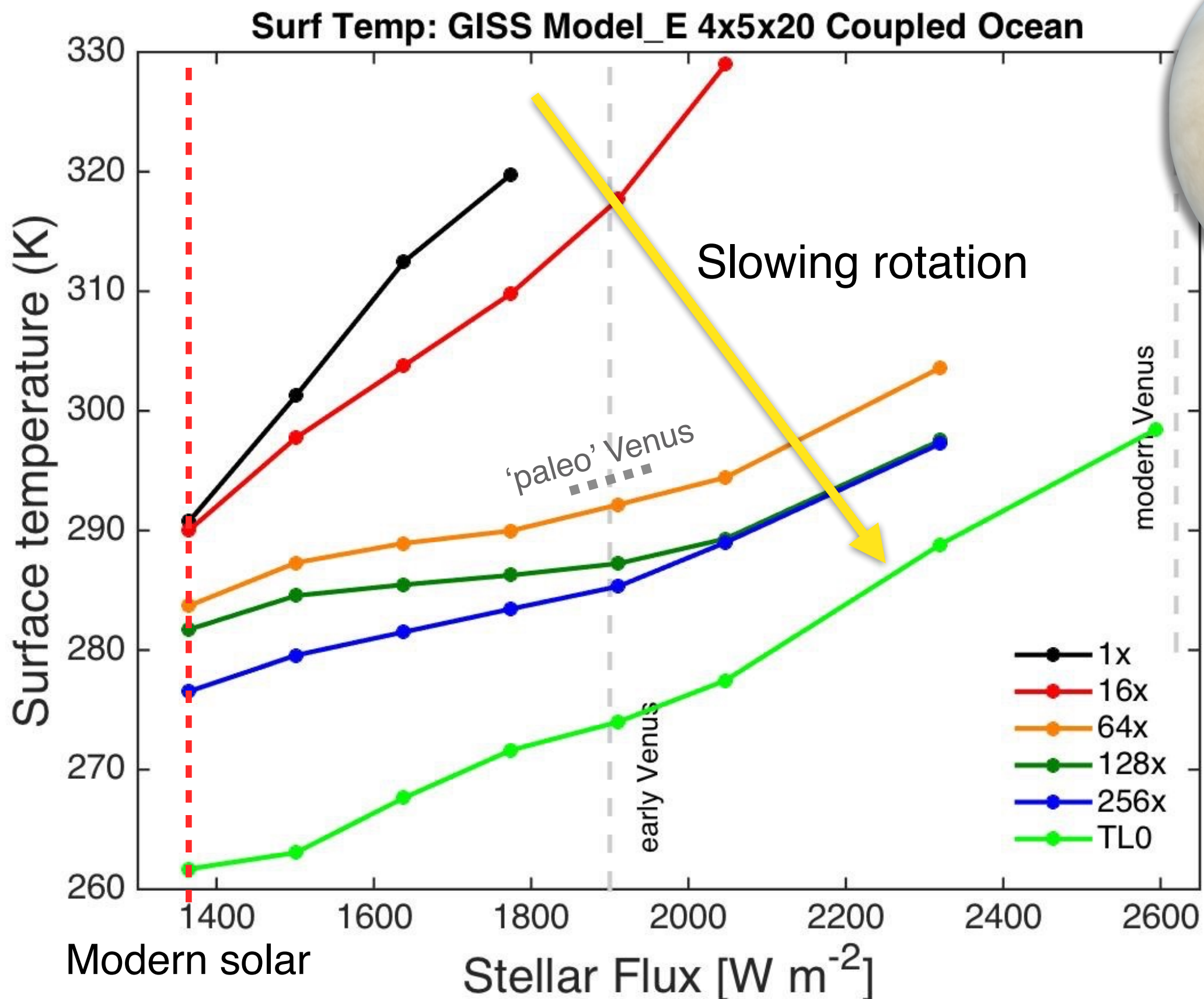


Neoproterozoic Earth does *not* enter full snowball state at low CO<sub>2</sub>, reduced insolation

(Sohl, Chandler, Jonas)

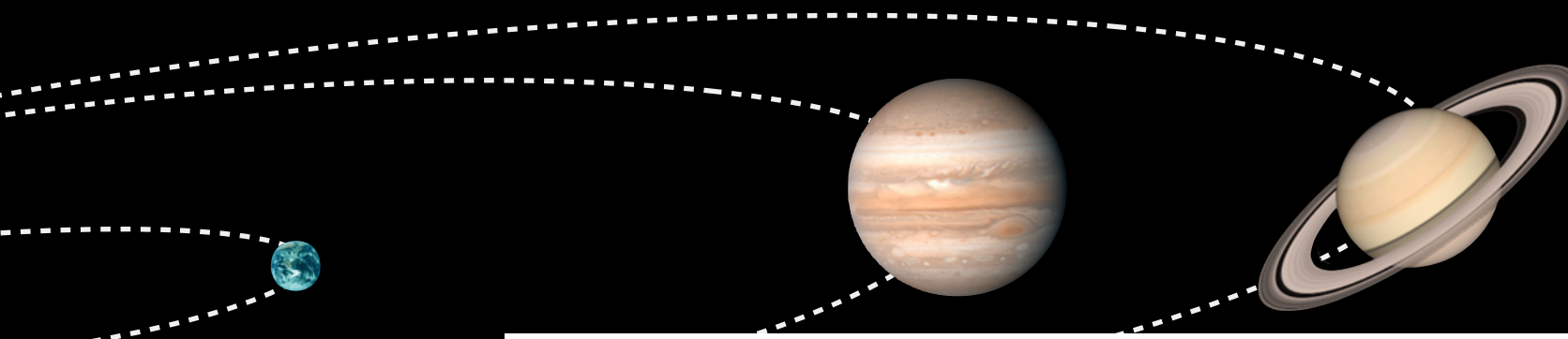


# Slow rotating planets and the 'inner habitable zone'

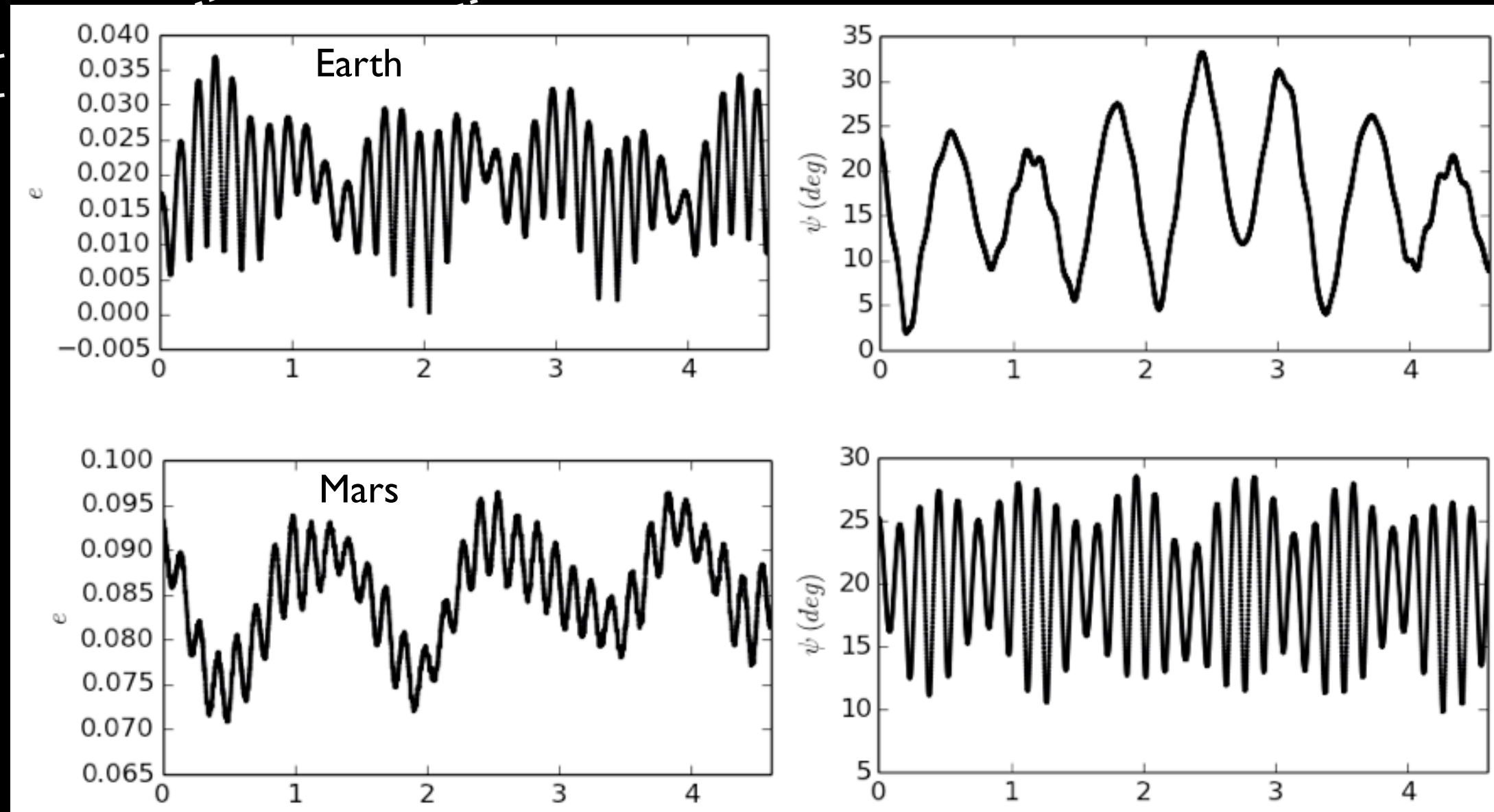


To address 'habitability' we must also couple climate dynamics to spin-orbit dynamics...

Total system architecture is therefore a critical ingredient...



'Compact'  
solar system  
epoch  
(~3.8-4.5  
Gya/Hadean)

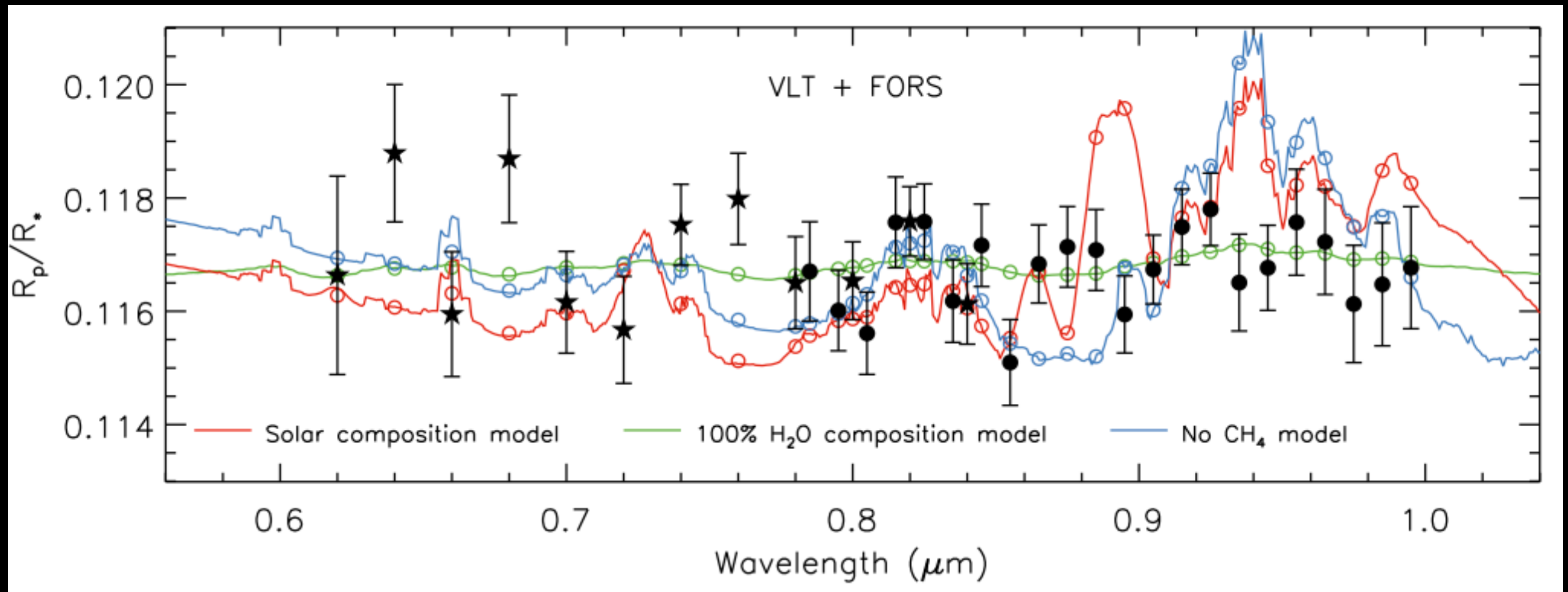




# Biosignatures

Primary focus on near future observables: spectroscopic ‘markers’ (oxygen, methane) in starlight filtered by atmospheres during transit.

But it's HARD - e.g. ‘spectrum’ of 6.5 Earth mass ‘ocean world’ GJ 1214b (clouds?)



Unclear if data will allow definitive claims - however, statistics could reveal populations of planets with life versus those without...

**“These worlds look *different*”**

# Technosignatures

Pollution? Artificial structures? Thermal output from energy conversion?

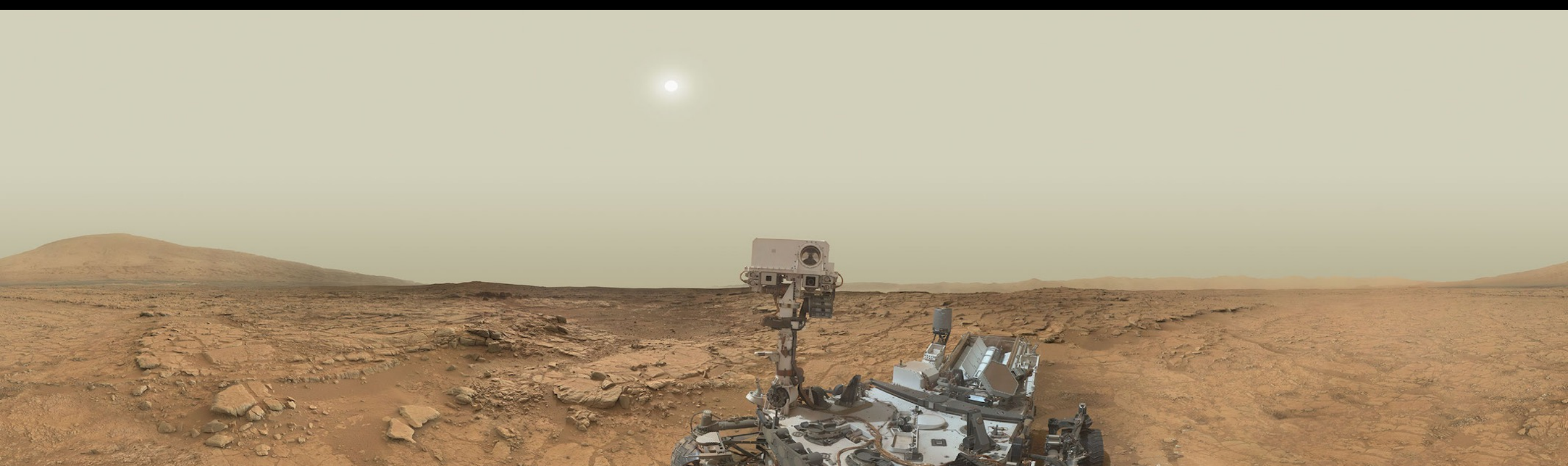
Recent survey work of infrared emission from nearby galaxies seems to rule out 'mega' civilizations (farming all stellar energy in a galaxy).





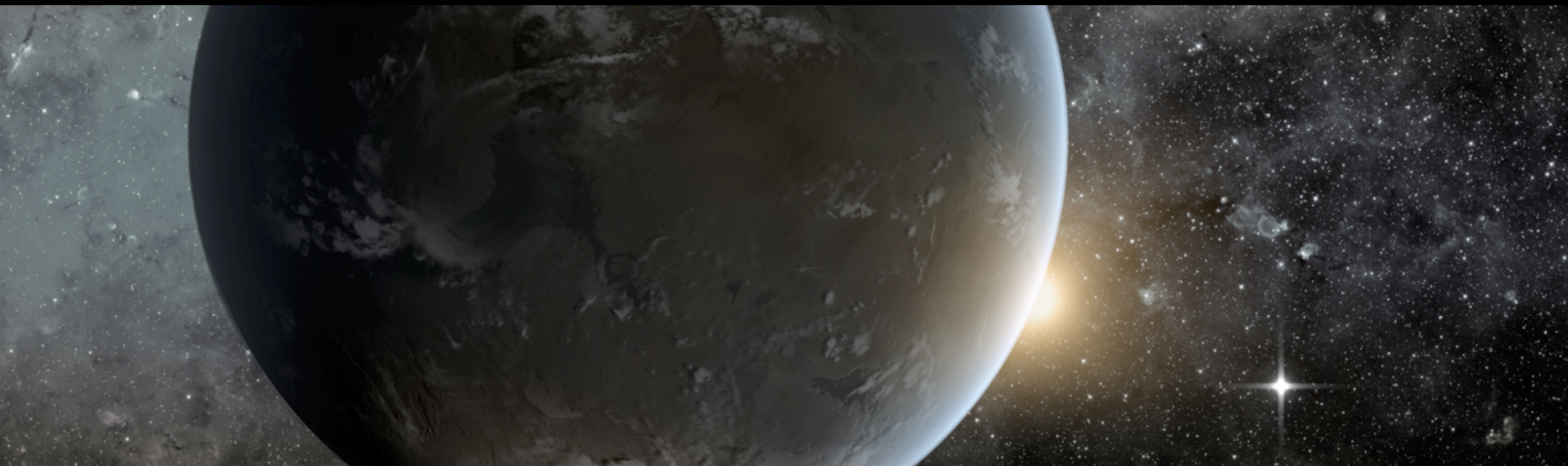
# A gloomy assessment: **The Great Filter and the Fermi Paradox**

- Finding independent life (e.g. on Mars) would indeed boost cosmic abiogenesis probability
- But then where is everyone else?
- Implication is that life simply never gets past a certain point, it never goes interstellar, it is filtered out...
- So finding life on Mars would actually be very bad news! (Bostrom 2008)



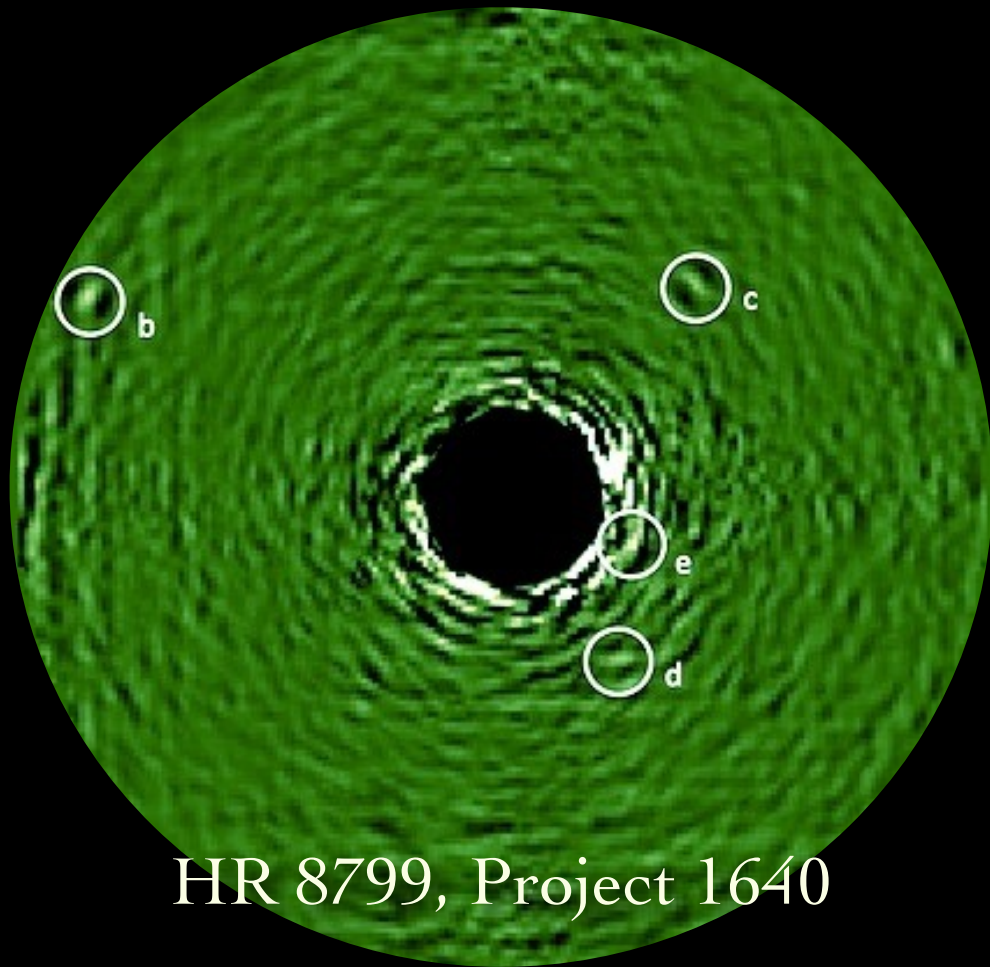
# An optimistic assessment

- We're closer than we've ever been to getting some proper answers
- The Fermi Paradox may simply be due to our still very limited measurements of 'what's out there' and our exceedingly short history ( $\sim 0.001\%$  age of universe)

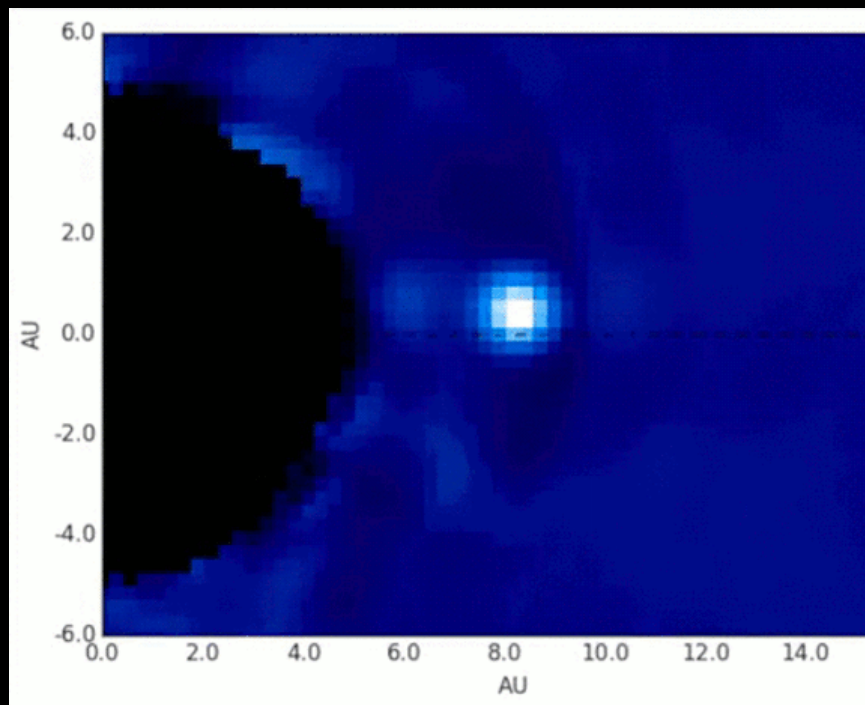
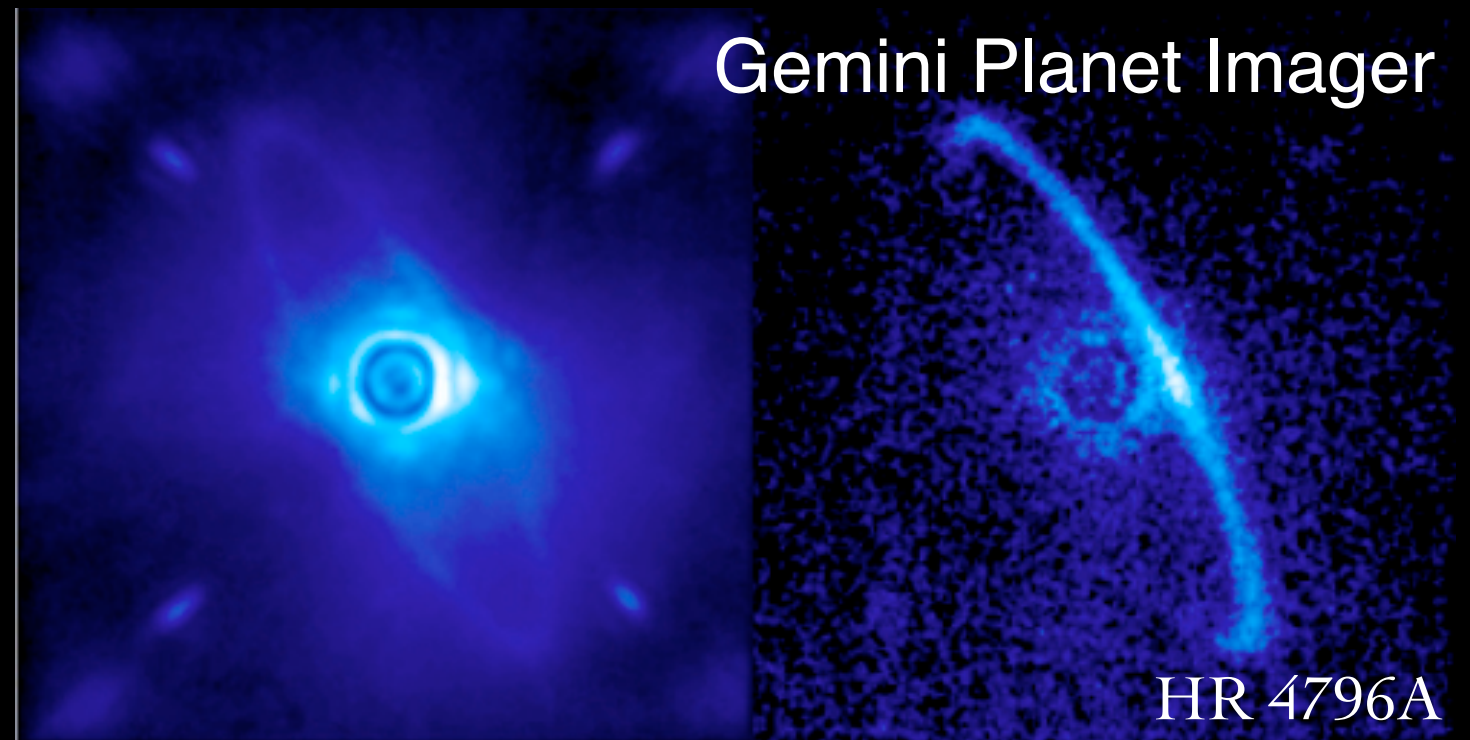




# New frontier: direct imaging of planetary systems



HR 8799, Project 1640





# Measuring abiogenesis probabilities by seeking origins?

# What *is* life?

*'Life is a self-sustaining trajectory in state-space'*  
(Cronin & Walker 2015)

# Genetics first or metabolism first?

Assume that a biological entity must be able to positively influence the production of its own components (reproduction/maintenance)

For example: finding natural autocatalytic processes necessary for metabolism (chemical species increases its own rate of production without biological catalysts)

