Comparative Planetology and the Inner Solar System as a Gateway to the Exoplanets

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Comparative Planetology

- The study of planetary processes, their manifestation, and their effects on multiple bodies. Often using Earth as a ‘baseline’, to understand the evolutionary pathways, similarities, and differences between planets.
- Geology
- Hydrology
- Atmospheres/Exospheres
- Surface Processes
- Interior processes
- Magnetospheres
- Interactions with Space
- Habitability / Biology (Astrobiology)

Differentiation
Clouds and Hazes
Volcanology
Climate
Impact Cratering
Tectonics
Aeronomy
Dynamics
Geochemistry
Space Weathering
Geomagnetism
Solar Wind Interactions
Seasons
Lightning Aurorae
Circulation, Wind, Storms

We may know most about the Earth, but the planets in our solar system give us context, improve understanding of our own planet, and provide baseline for understanding planets elsewhere.

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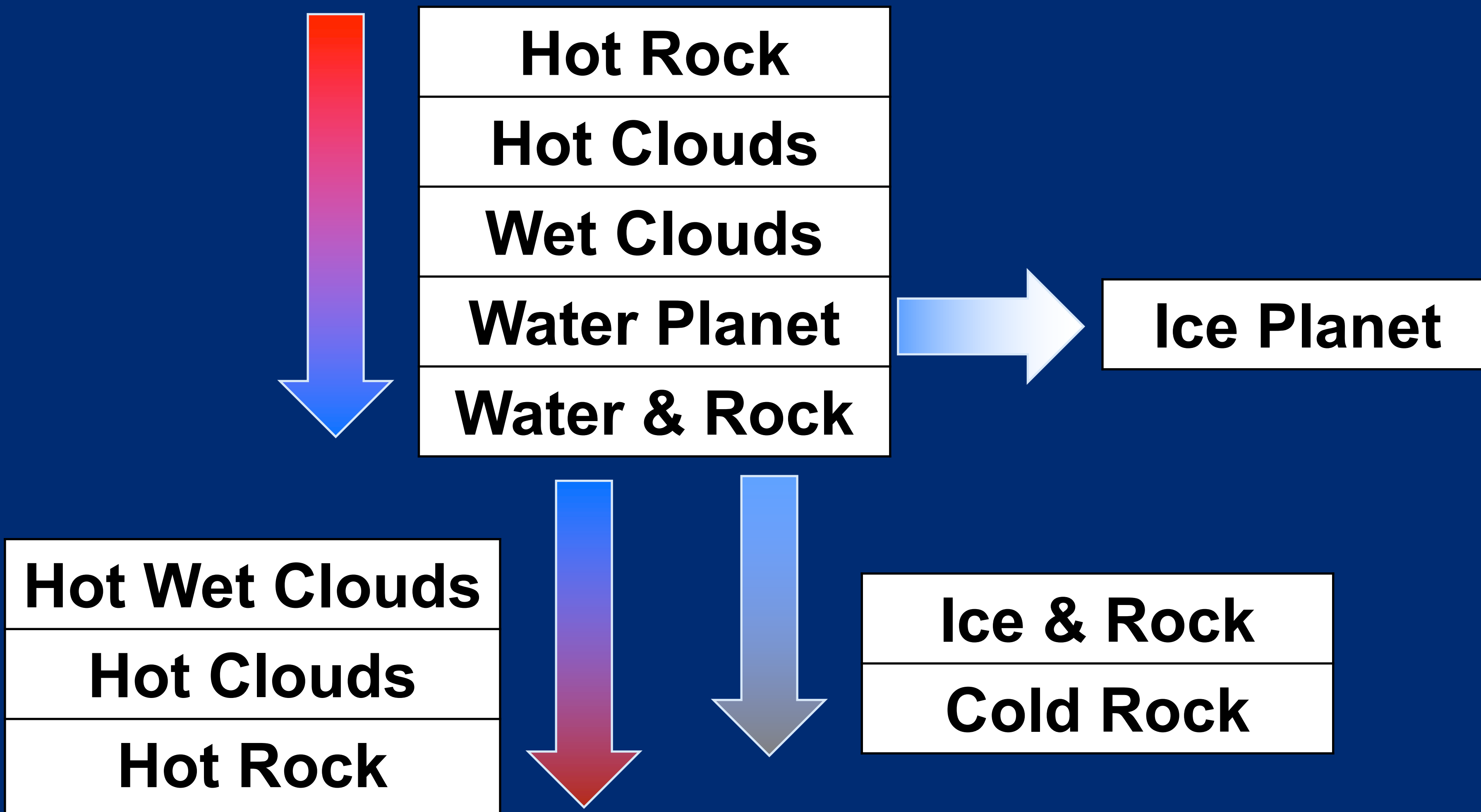
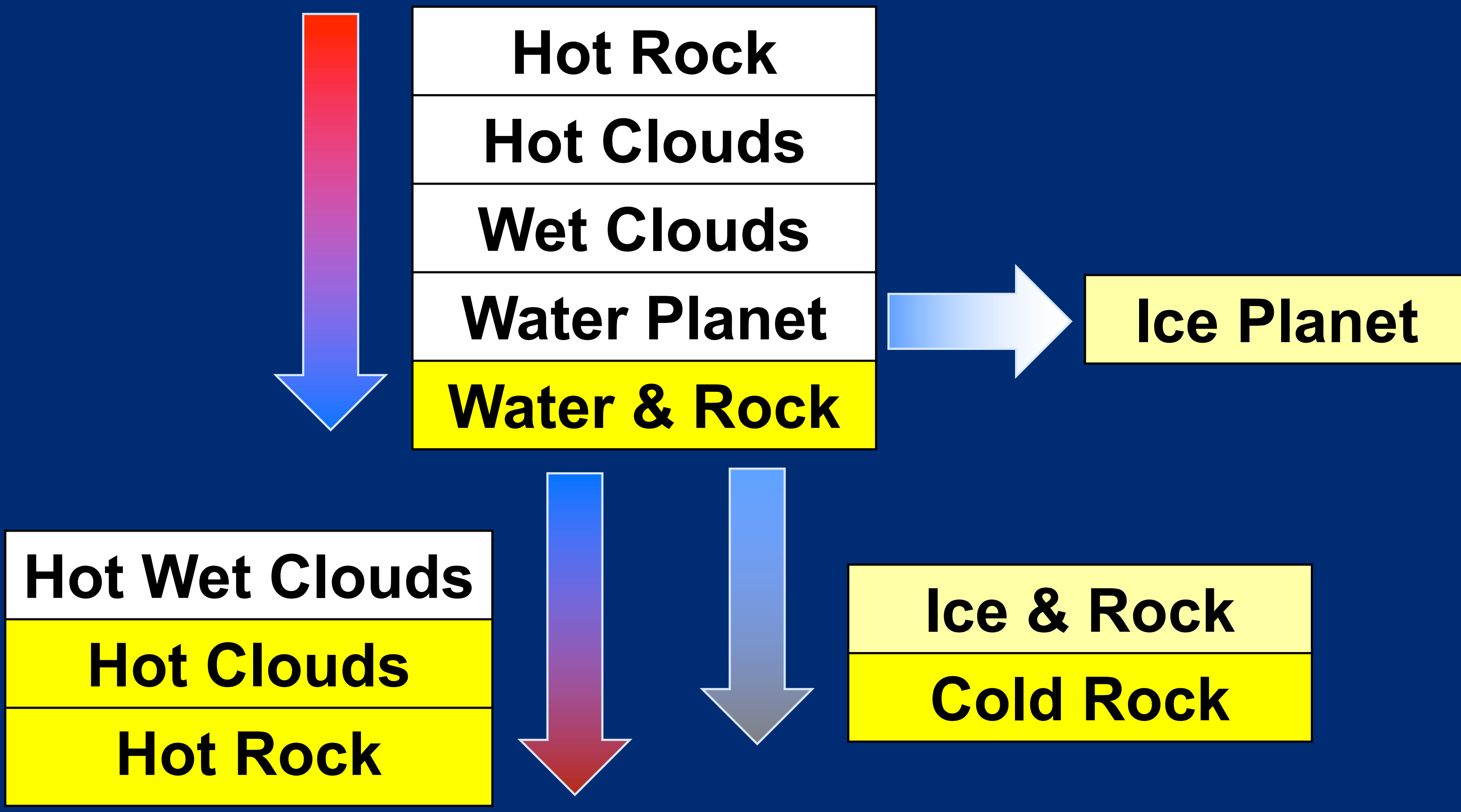
"As we discover new planets, the only basis we have for comparison are the planets in our own solar system"
-Lori Glaze

Our Windows Into Planetary Evolution



[After Vago (2018)]

Our Windows Into Planetary Evolution



[After Vago (2018)]

Individual Worlds, Interconnected

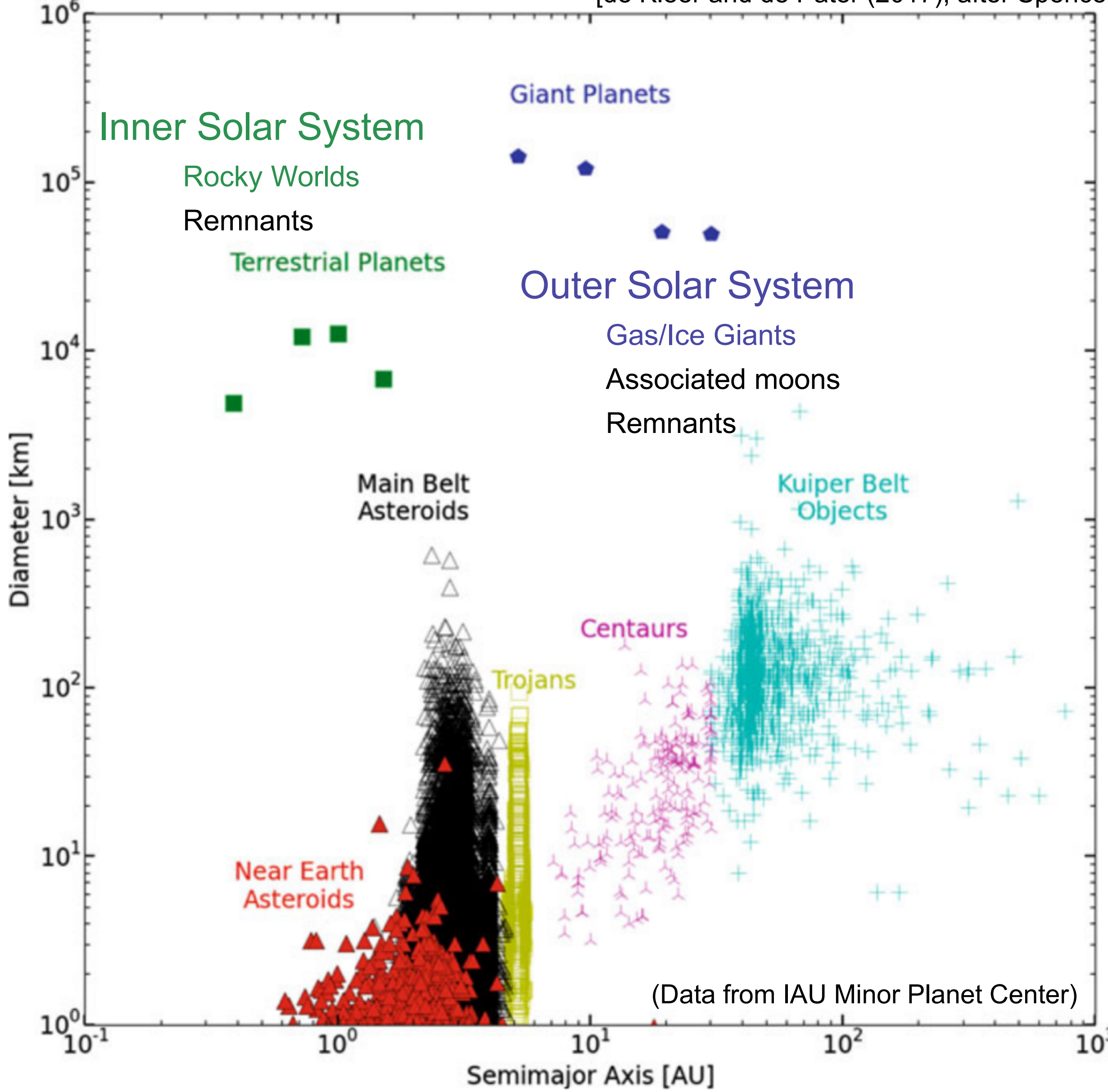
Inventory of the Solar System

Apparent increase in the minimum size of bodies with heliocentric distance is an ***observational bias*** - it is much harder to find small bodies at large geocentric distances.

Similar biases in search for Exoplanets constrain what we can find.

Our own solar system is imperfectly understood. Interiors, processes, even surfaces are still studied largely indirectly.

- [de Kleer and de Pater (2017), after Spencer]



The Search for Other Earths

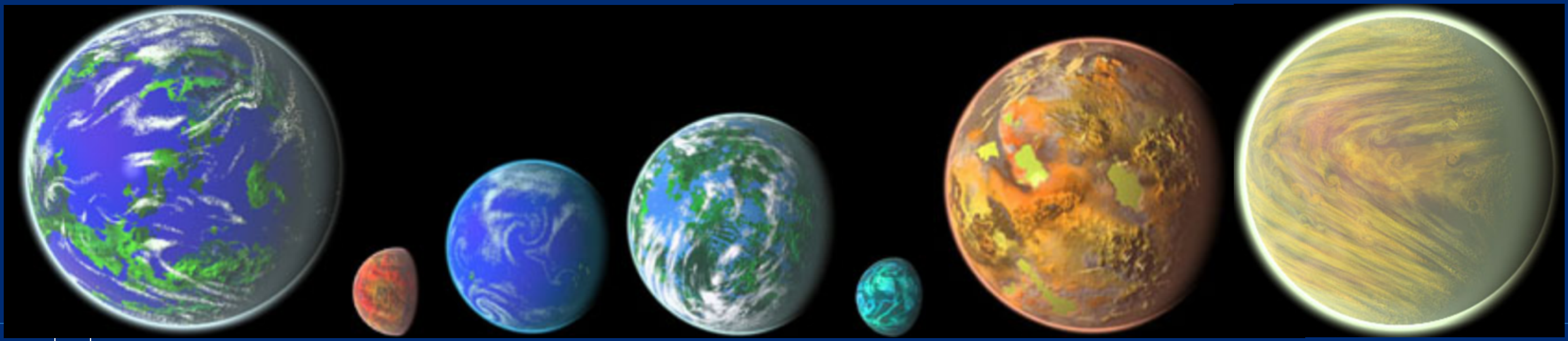
- Is that what we are really looking for?
  - Yes and no
  - Habitability

Solid Rocky Worlds

“Habitable Zones”

“Range of orbits around a star within which a planet’s surface could maintain liquid water given a sufficient atmosphere.”

Does this solely define ‘friendliness to life’? Not necessarily.



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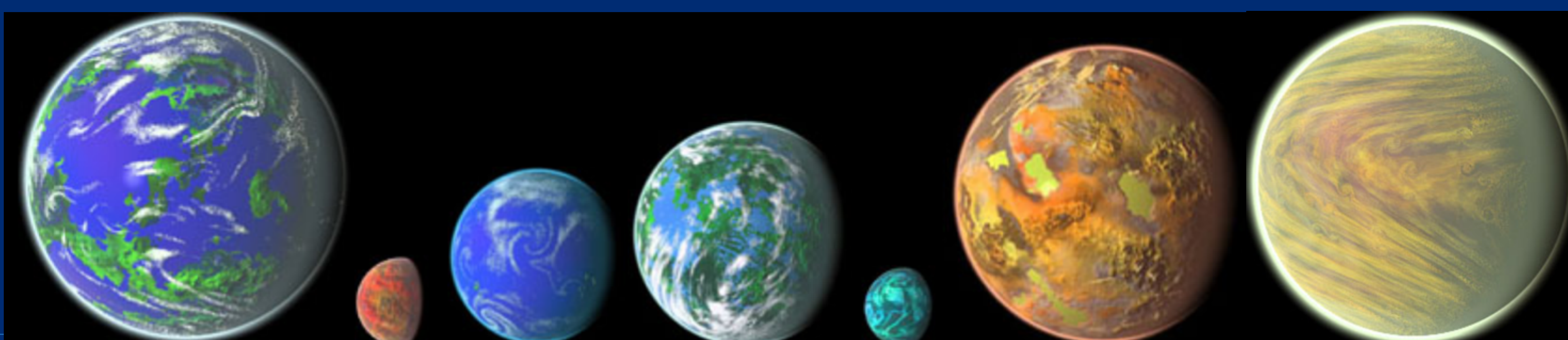
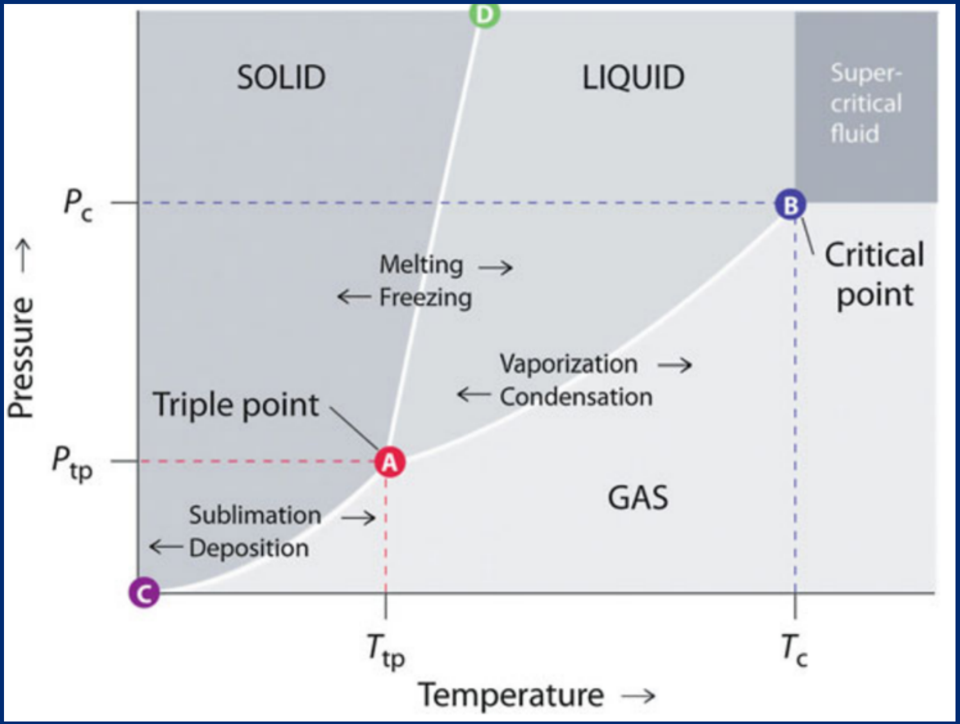
Exceptions… Moons of giants, interior oceans, other niches



“Habitability"

“…maintain liquid water given a sufficient atmosphere…”

That definition of habitability does not denote other conditions favorable to or necessary for life.



[extracted from Principles of General Chemistry (section 11.7) by Montmessin and Määttänen (2017)].

Schematic Phase Diagram showing temperature-pressure-dependent boundaries between the **solid**, **liquid**, and **gas** phases.

Triple point where the three phases are all in equilibrium and can coexist together.

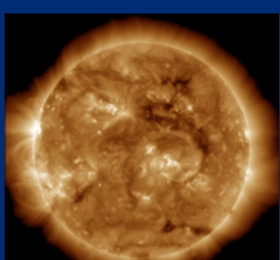
Earth’s surface exists near the triple point for water

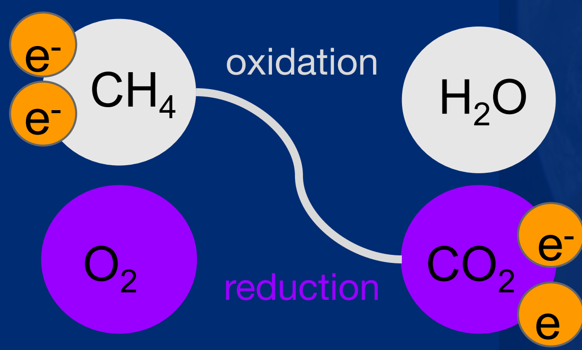
C-A: vapor pressure curve A-B: pressure curve

The Fundamental Bias of "Life as we know it"

water

essential elements

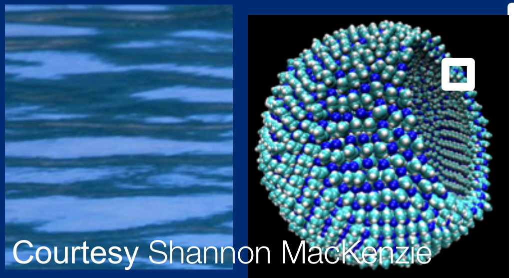


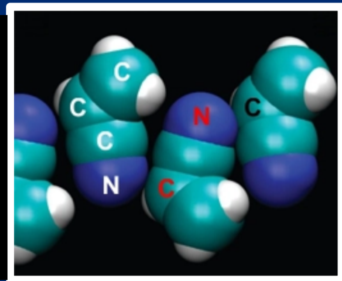


energy

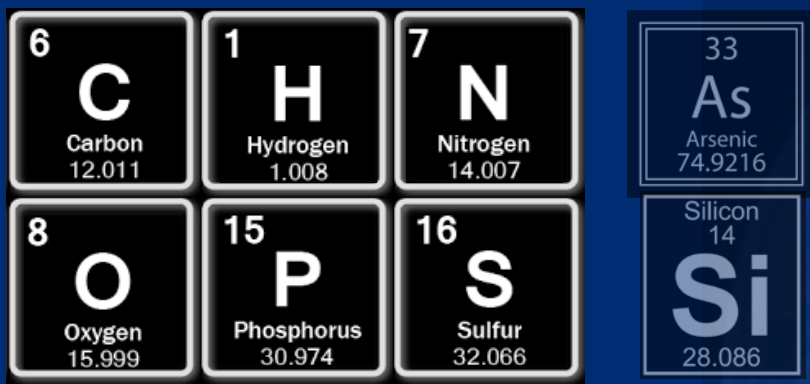
All life on Earth evolved and still exists in a highly varied, but still highly constrained system. N=1; Earth-biology chauvinistic attitude

The Fundamental Bias of "Life as we know it"


Courtesy Shannon MacKenzie



~~water~~ solvent



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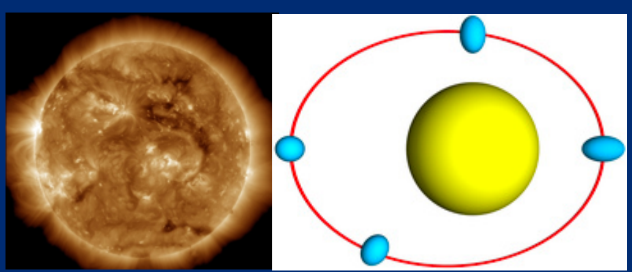
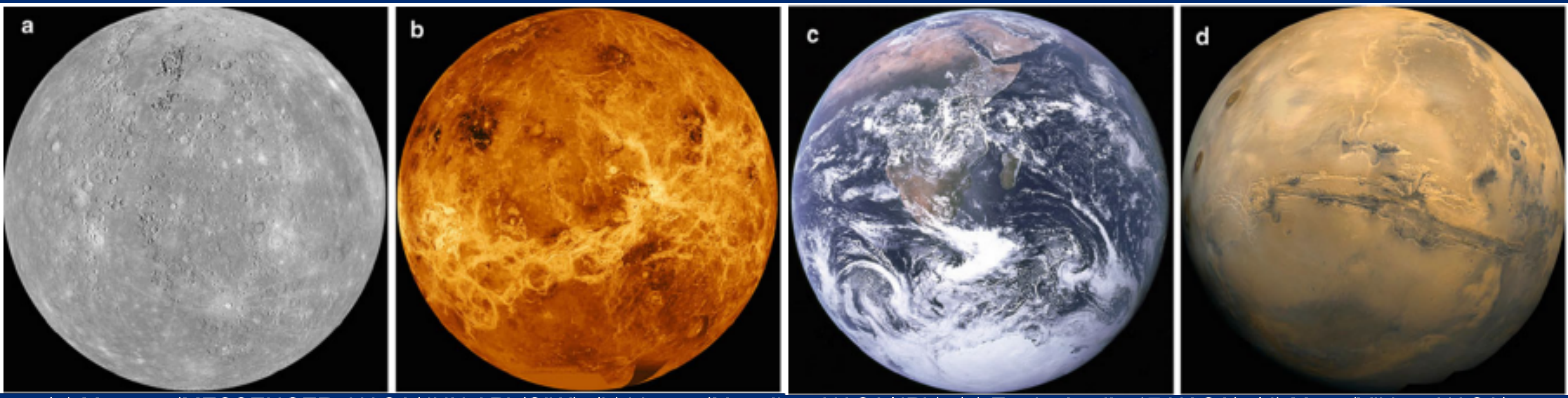


energy

Other "habitable" definitions, and therefore zones exist.

For now… we focus on what we can see, and find best.

Inner Solar System – The Terrestrial Planets



(a) Mercury (MESSENGER, NASA/JHU APL/CIW). (b) Venus (Magellan, NASA/JPL). (c) Earth Apollo 17 NASA). (d) Mars (Viking, NASA)

- A terrestrial planet: composed primarily of silicate rocks and metals and has a solid surface; AKA telluric or rocky planets
- Orbit relatively close to the Sun, having few or no moons
- Similar inner structures: each has a dense ferrous core, a silicate mantle, and a crust
- Rock exists mostly as a solid at the surface, and these rocky surfaces feature mountains, volcanoes, plains, valleys, impact craters, and other formations
- When they have atmospheres, these are secondary atmospheres, generated through volcanism and/or cometary and meteoritic impacts

[Fairén (2017)]

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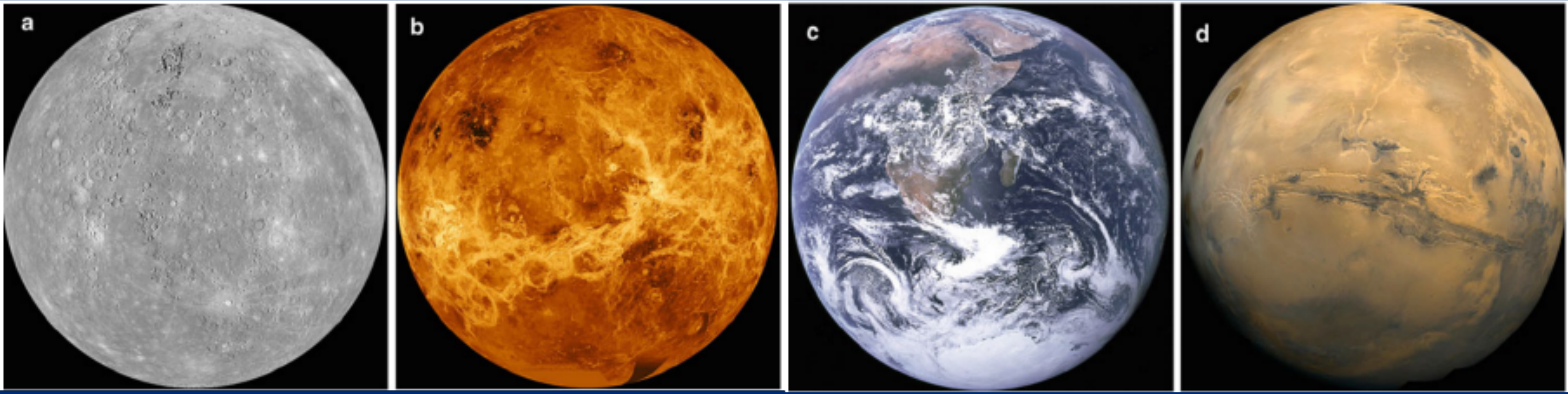

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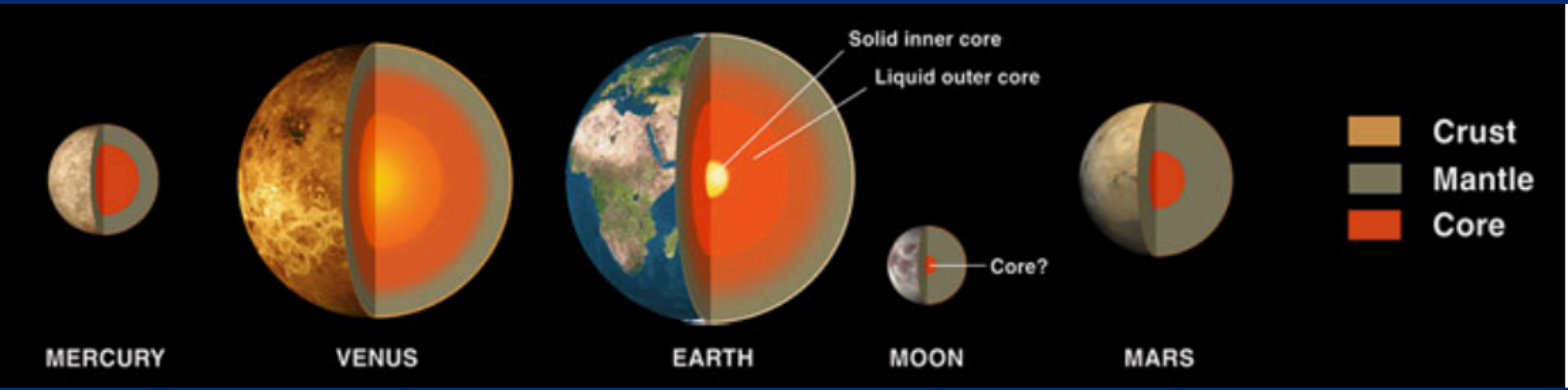

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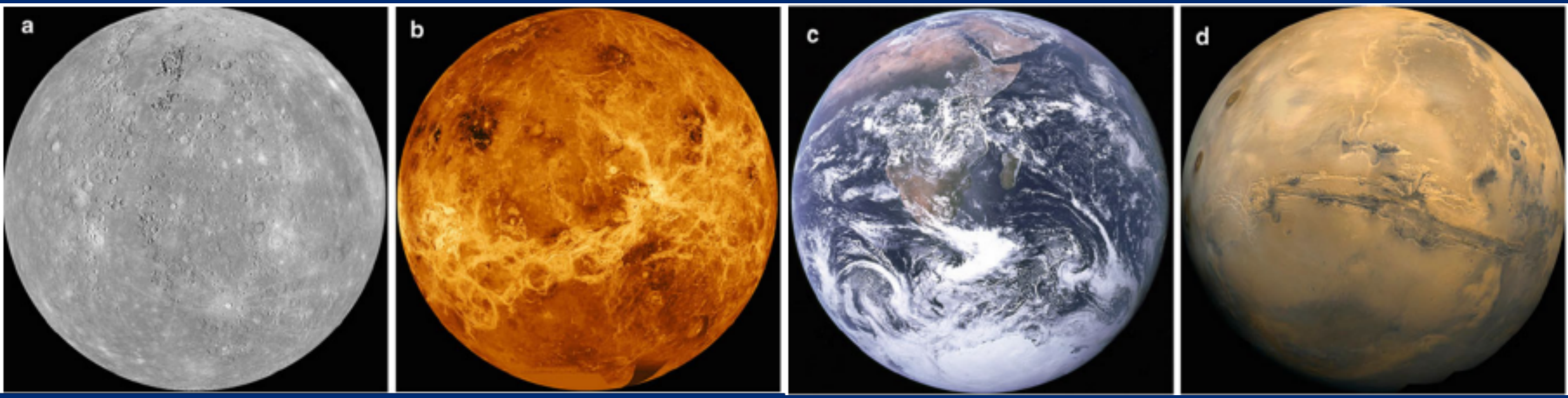

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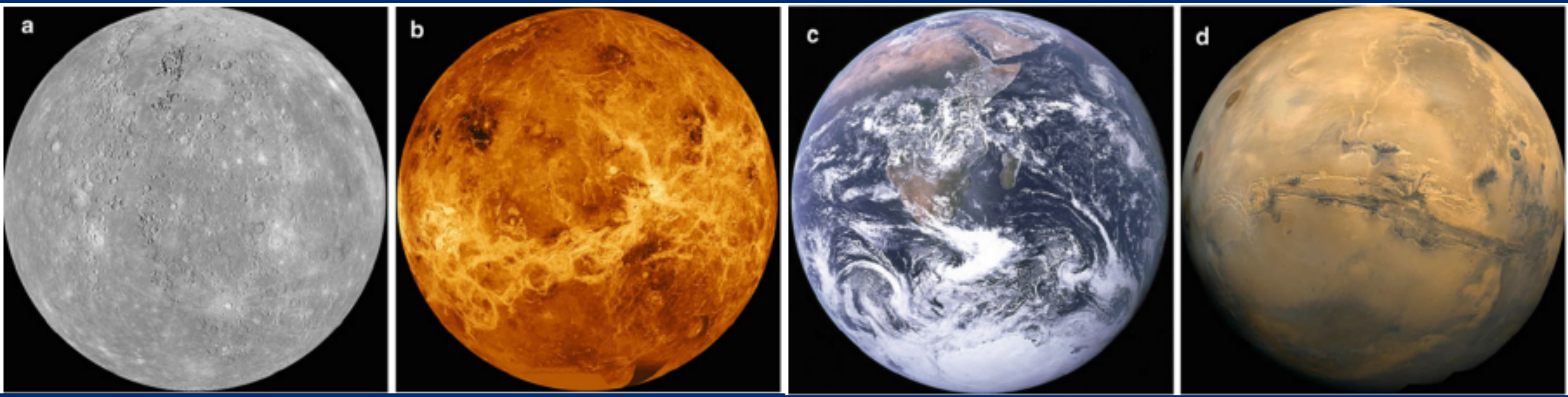

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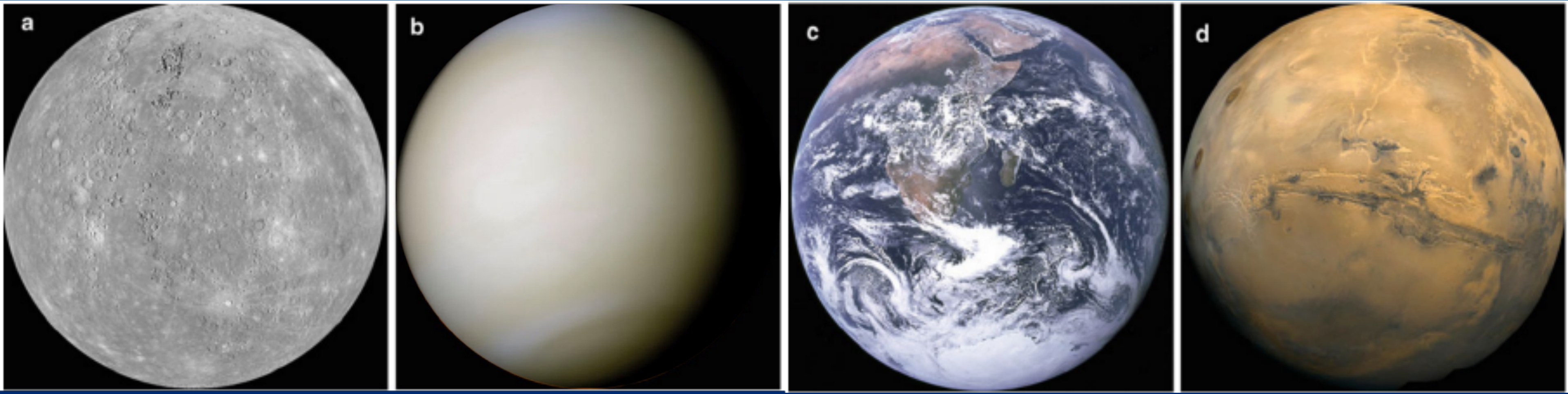
Planet	a (AU)	e	i (deg)	Obliquity (deg)	P_{orbit} (days)	$P_{rotation}$ (hours)
Mercury	0.387	0.205	7.0	0.01	88.0	1407.6
Venus	0.723	0.007	3.4	177.4	224.7	5832.5
Earth	1.000	0.017	0.0	23.4	365.2	23.9
Mars	1.523	0.094	1.9	25.2	687.0	24.6

Orbital and rotational parameters of inner solar system planets
[NASA archive, de Kleer &de Pater (2017)]

Inner Solar System In Comparison



Planet	Radius (km)	Albedo	Atmo (bar)	T (K)	Magnetic Field (Gauss-Rh³)	Mass (10^{24} kg)
Mercury	2437.6	0.068	$<10^{-12}$ (exo)	100-700	0.002	0.3302
Venus	6051.8	0.77	92	737	n/a	4.8685
Earth	6371.0	0.306	1.013	283-293	0.306	5.9736
Mars	1737.1	0.250	0.006	184-242	Fossil, local?	0.6419

Planetary properties
[NASA archive, Lodders & Fegley(1998)]

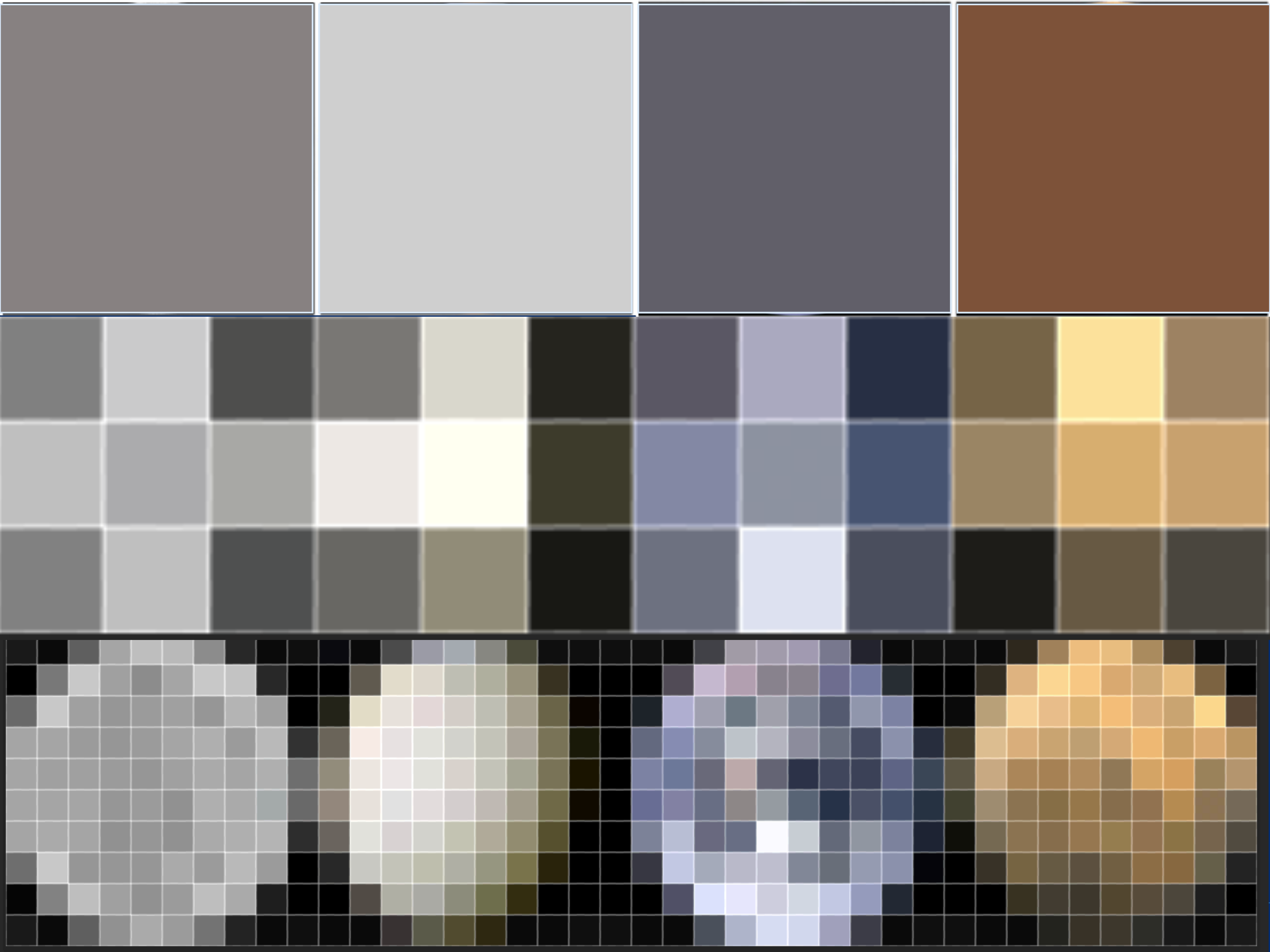
Inner Solar System as Exoplanets

Inner planets imagined as viewed from Trappist-1 [after McGouldrick (2017)]

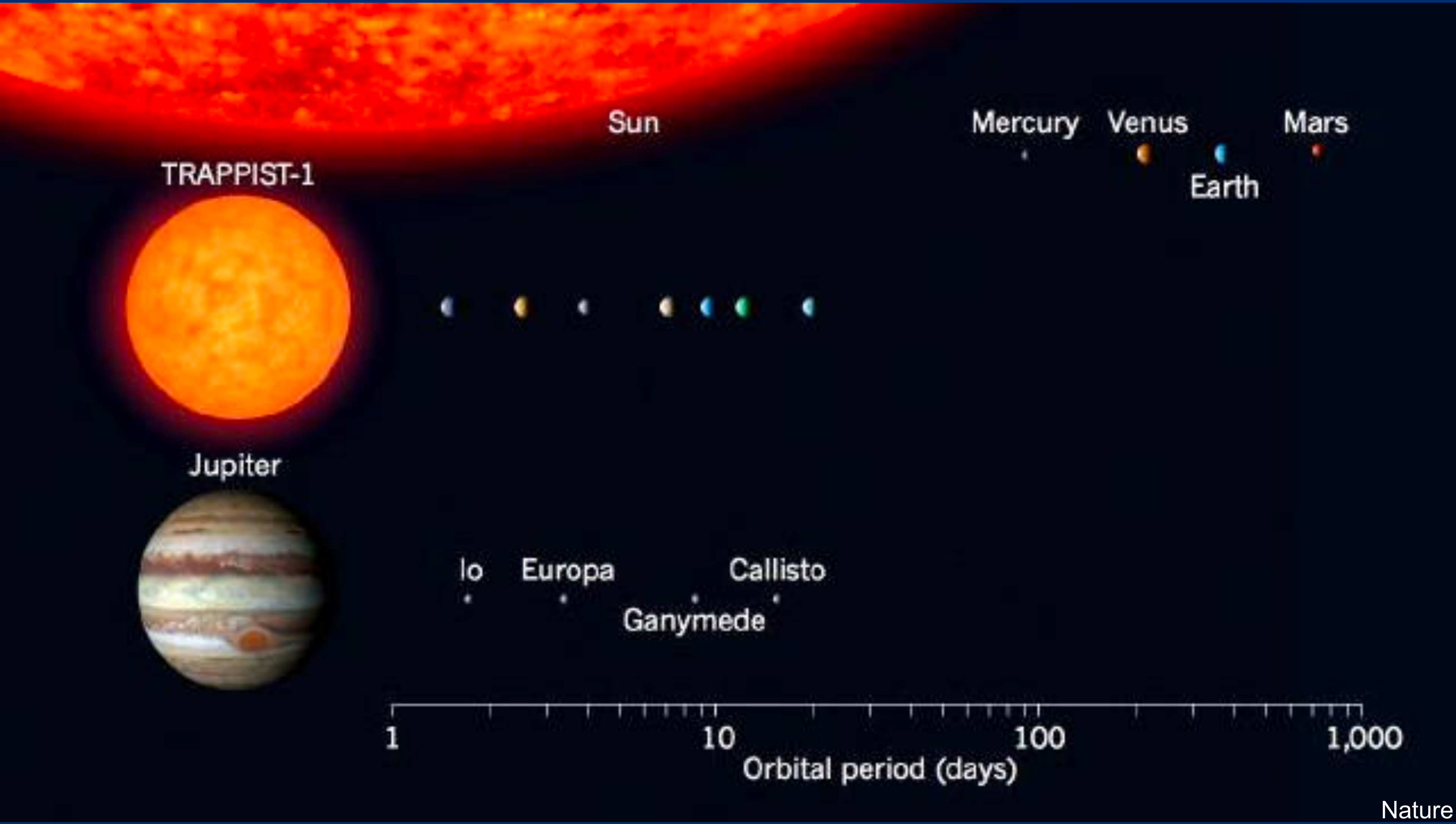
Trappist-1 is 29 light years away

"Single pixel planets"

Detectability:
Proximity, Brightness, Mass
Spectrum

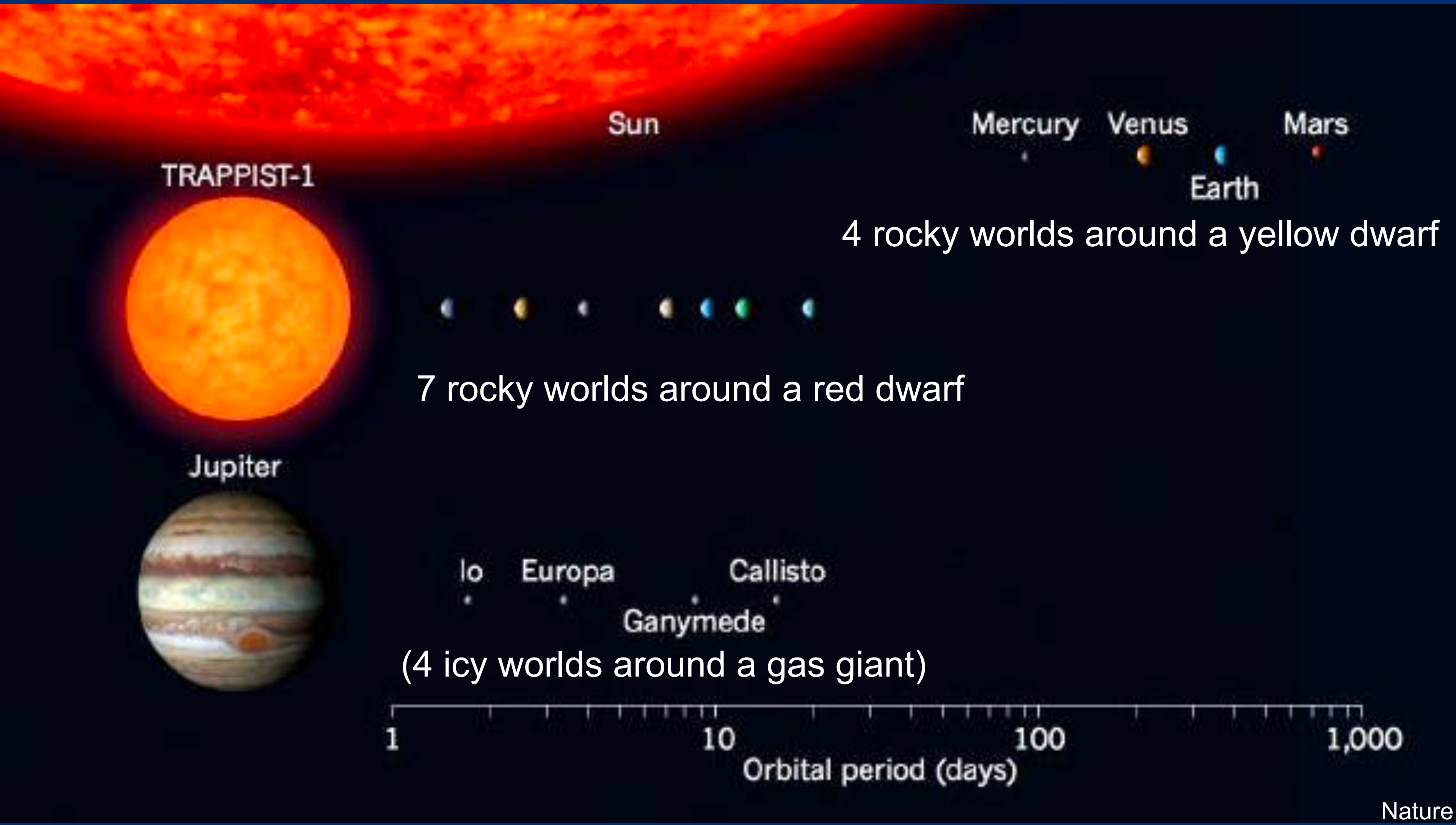


Inner Solar System as a Gateway



Nature

Inner Solar System as a Gateway



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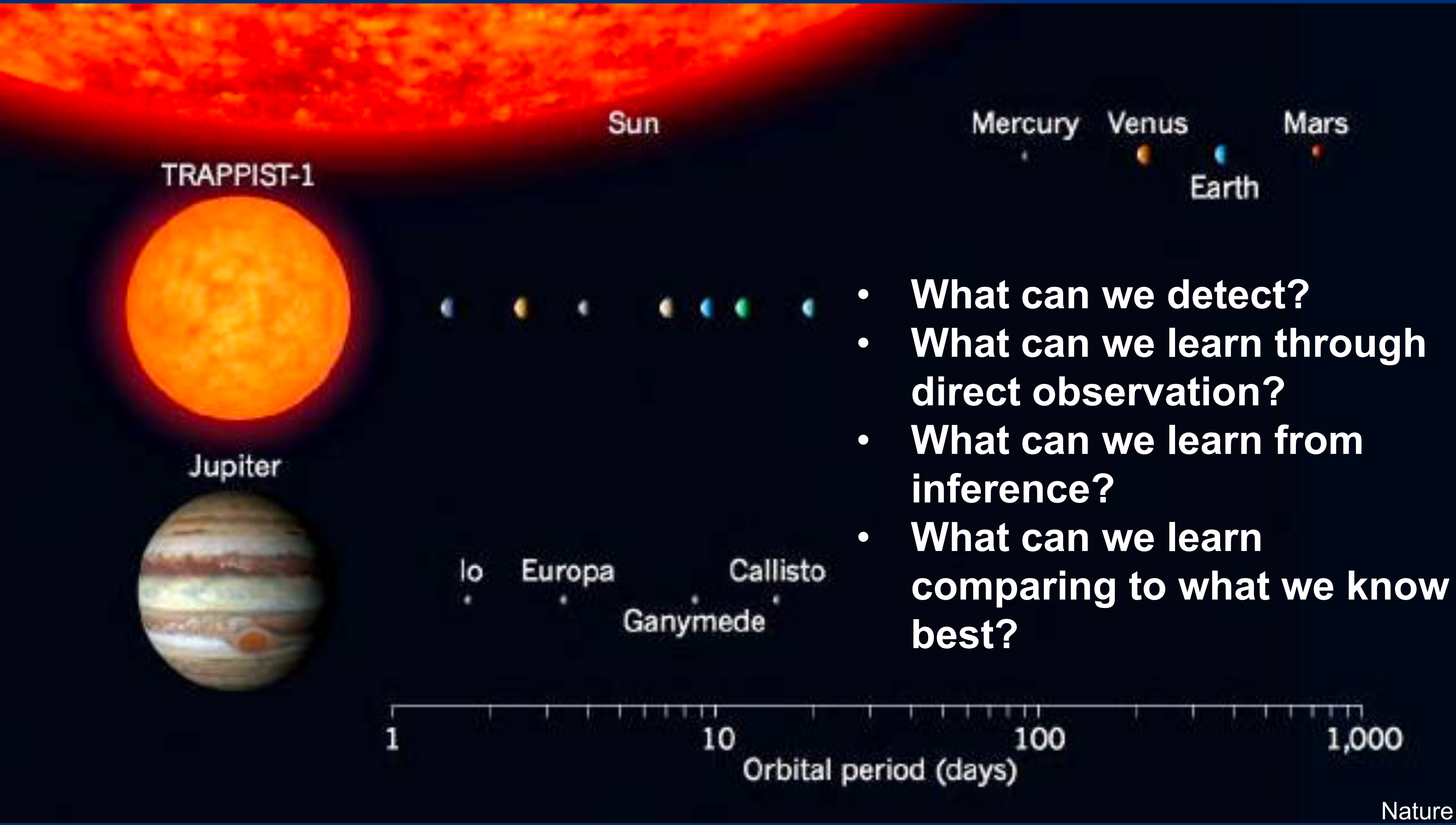
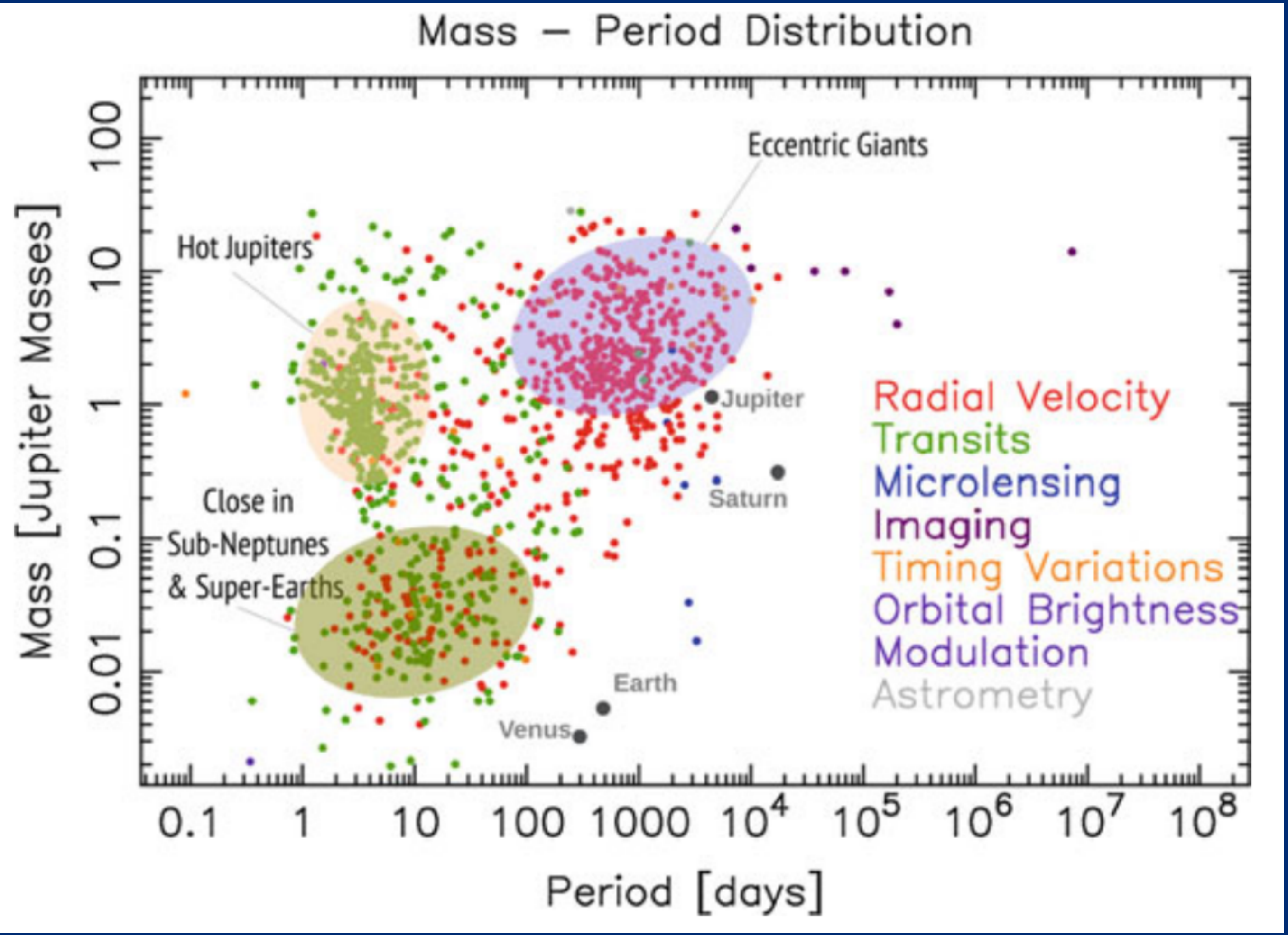


- What can we detect?
- What can we learn through direct observation?
- What can we learn from inference?
- What can we learn comparing to what we know best?

Nature

What can we detect? or How We Find Exoplanets (and determine mass)



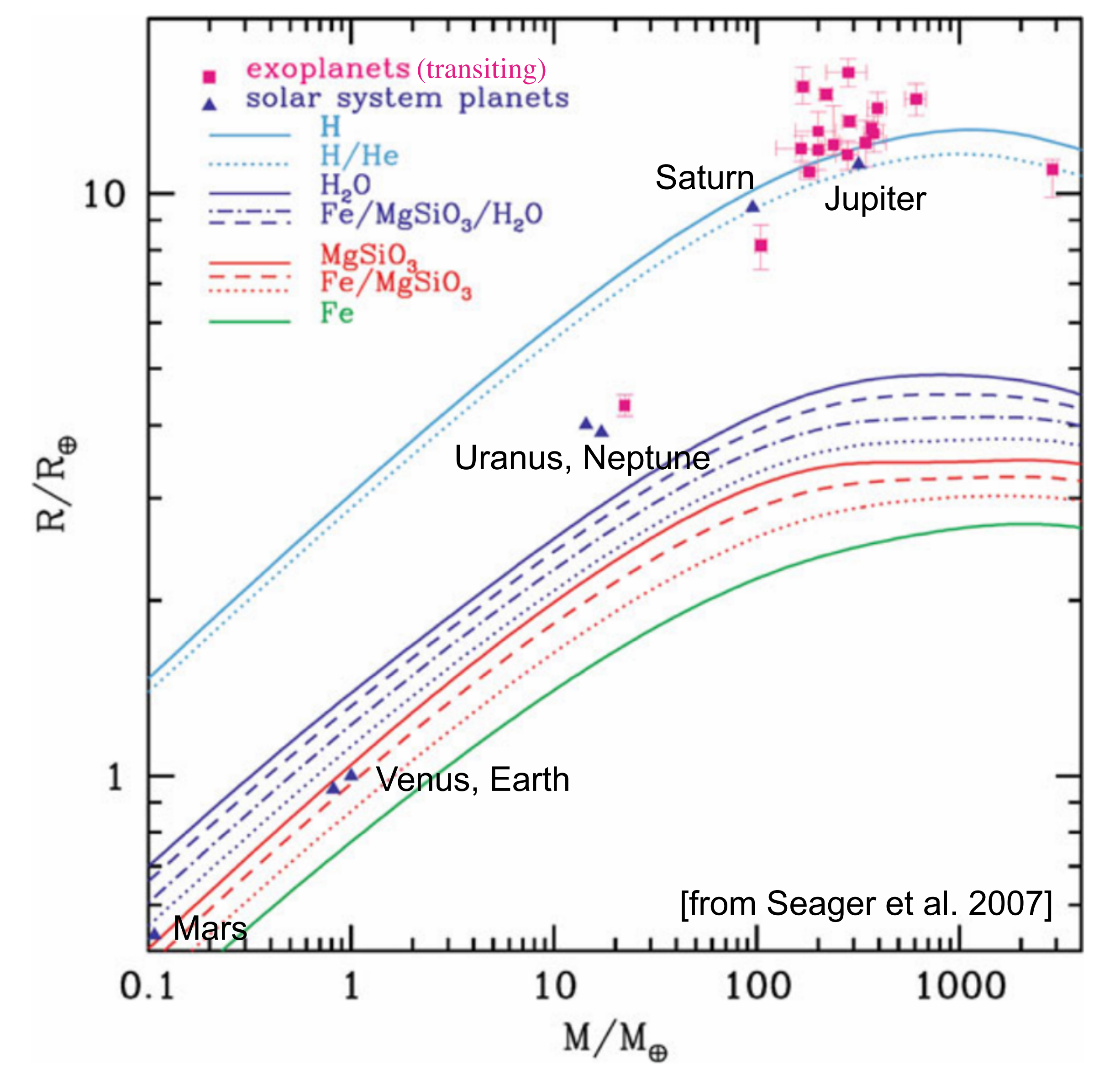
Mass – orbital period relationship of confirmed exoplanets based on a March 2017 query of the NASA exoplanet archive.

Techniques involve direct observation, model comparisons, mass ratios, other.

Montañés-Rodríguez and Pallé (2017)

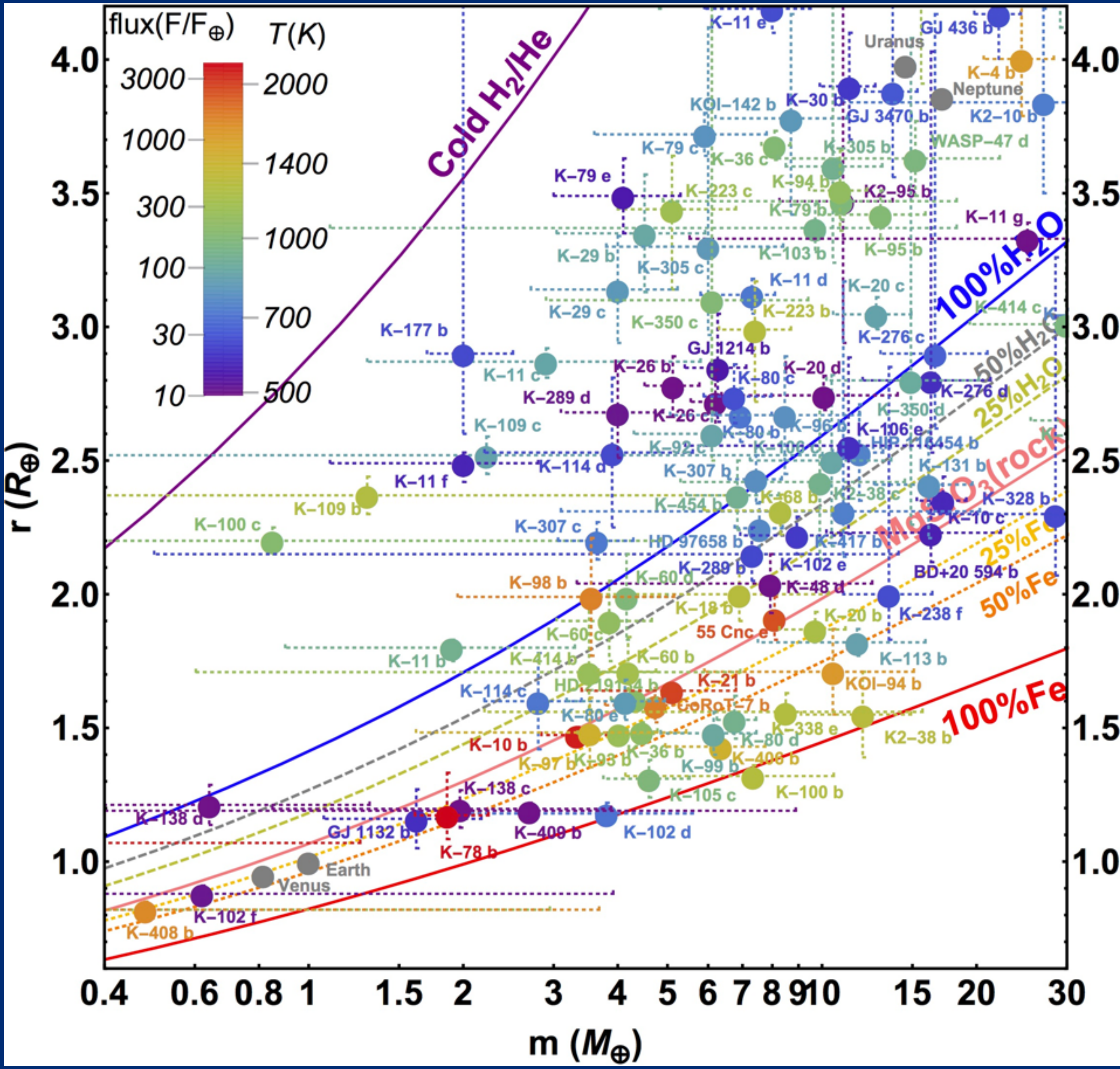
How Size Matters: Mass – Radius - Composition

- Homogeneous vs. Differentiated
- Gas Planets
- Water Planets
- Silicate planets
- Iron planets

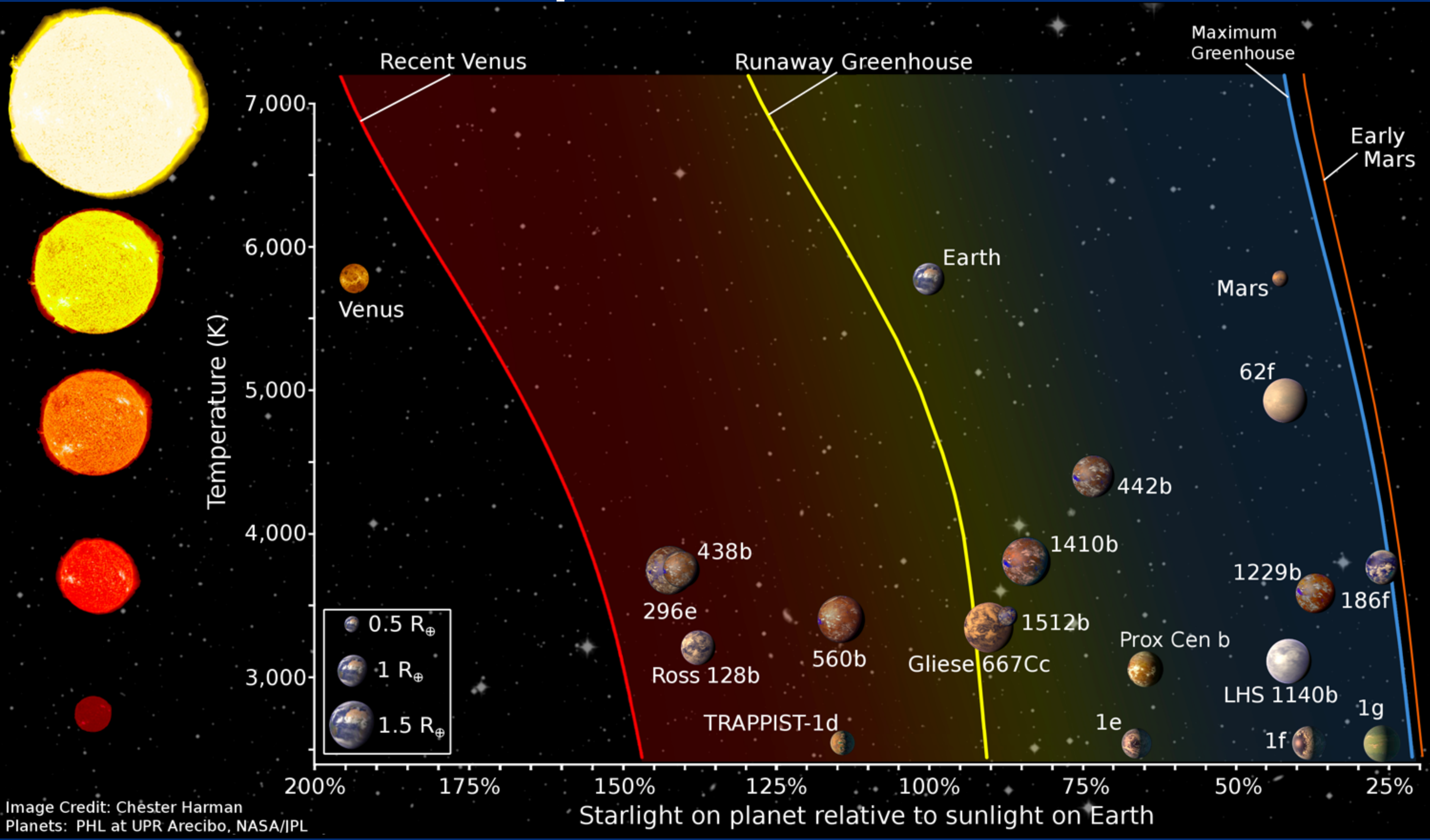


M, R, and Temperature of Rocky Worlds

- Detected exoplanets near terrestrial sizes/masses
- Most from Kepler (K-designations)
- Most/All are warmer to much hotter than Earth
- Blue to Green colors are Venus or Mercury temperatures
- Water & Silicate planets
- Detections are only going to increase with time

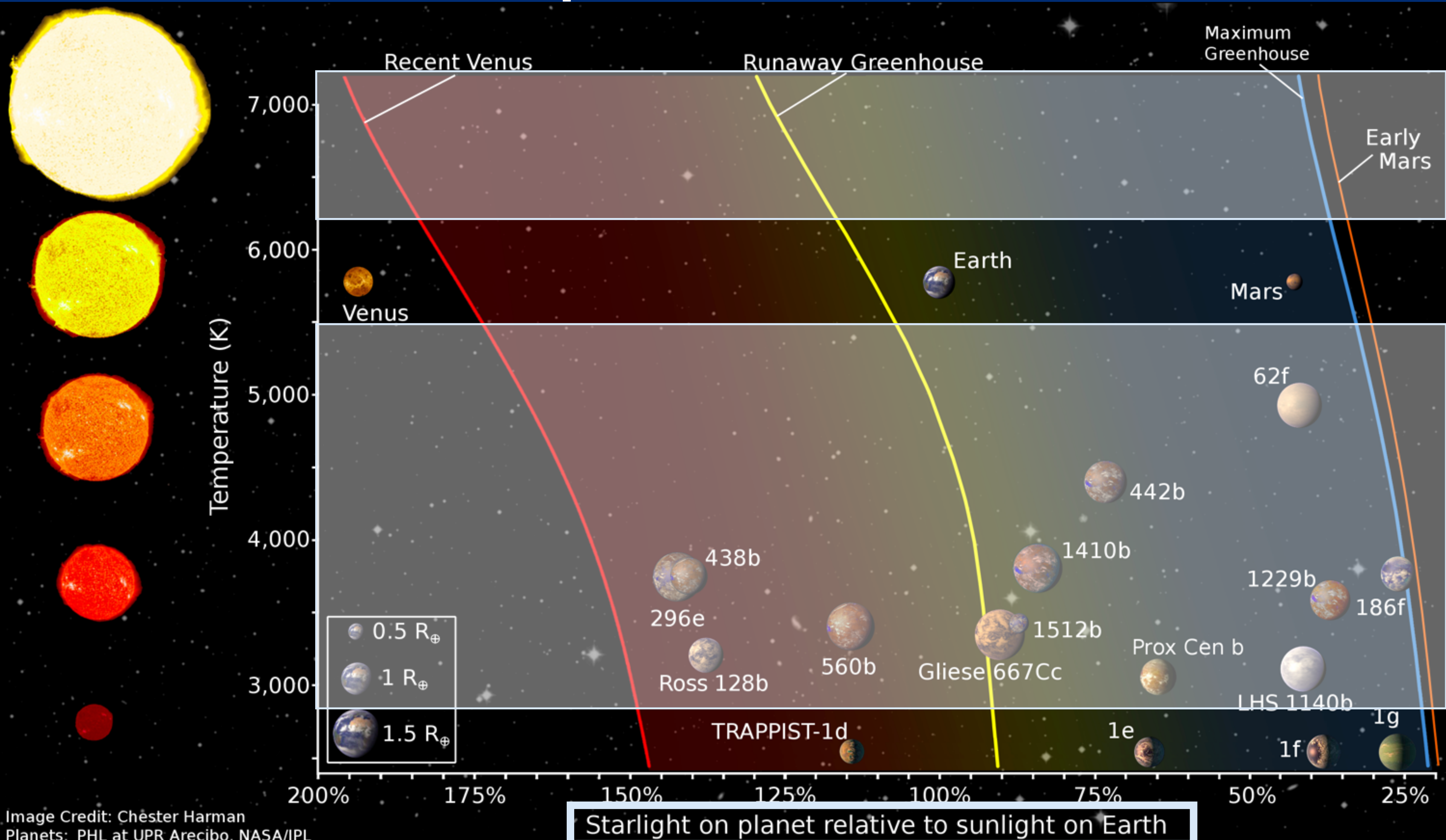


Inner Planets, Exoplanets, "Habitable Zones"



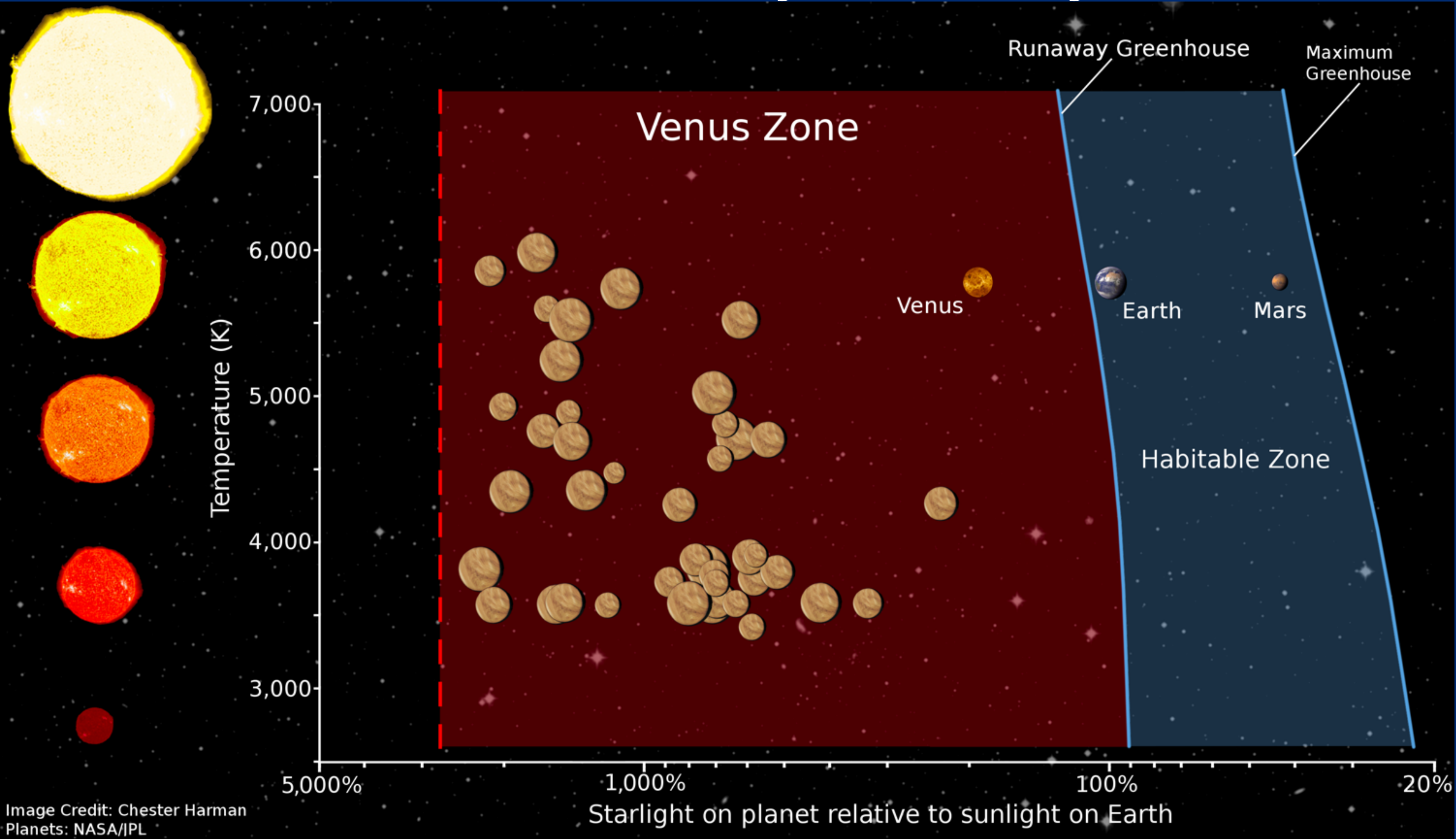
Habitable Zones Around Main-sequence Stars with confirmed planets.[Kopparapu, Harman (2016-2017)]

Inner Planets, Exoplanets, "Habitable Zones"



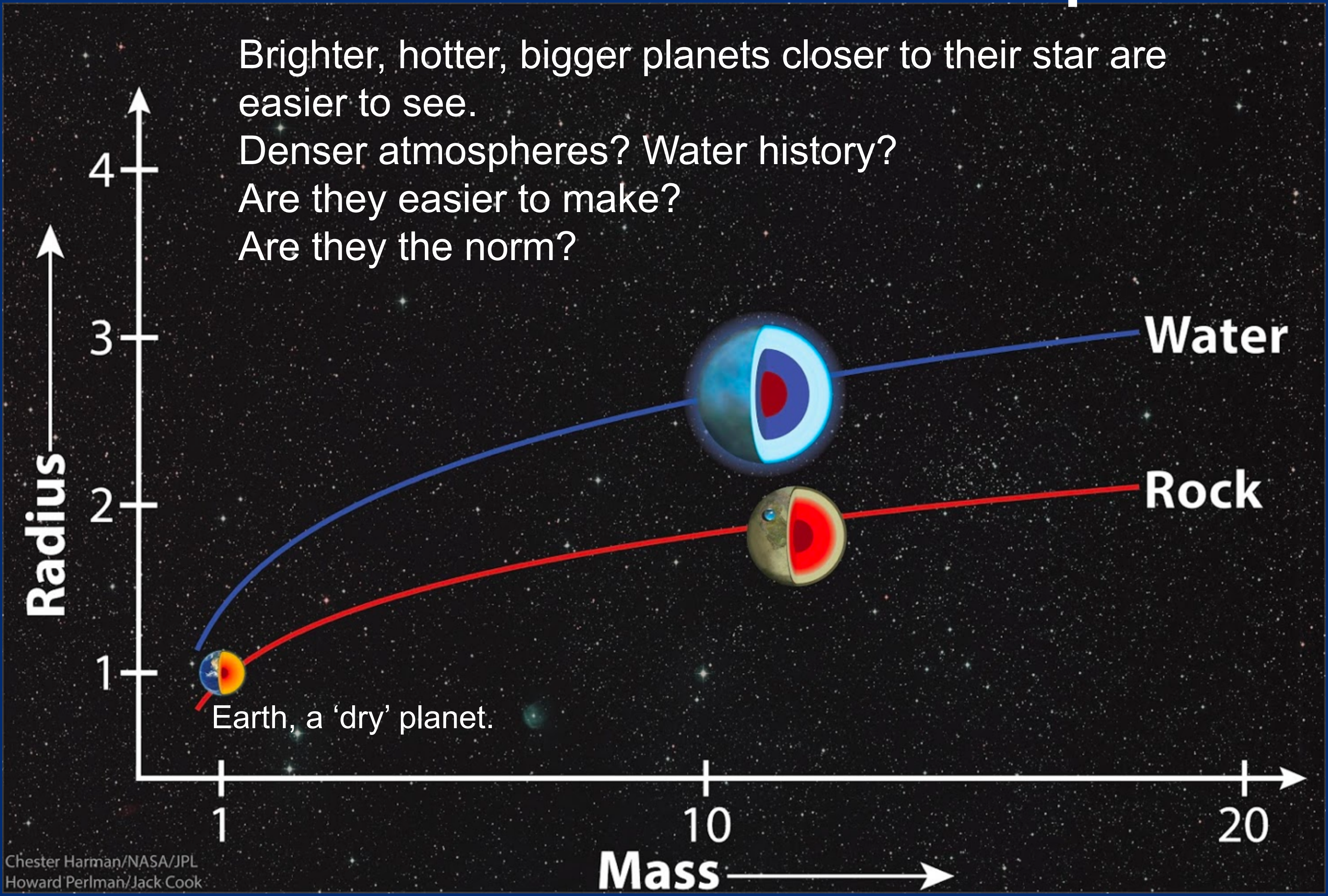
Habitable Zones Around Main-sequence Stars with confirmed planets.[Kopparapu, Harman (2016-2017)]

"Venus Zone" Detectability, Planetary Evolution



"Venus Zones" around Main-sequence stars with confirmed planets. 40%+ of Sun-like stars may have Venus-like planets.[Kopparapu, Harman (2016-2017)]

Inner Planets in the Context of Exoplanets



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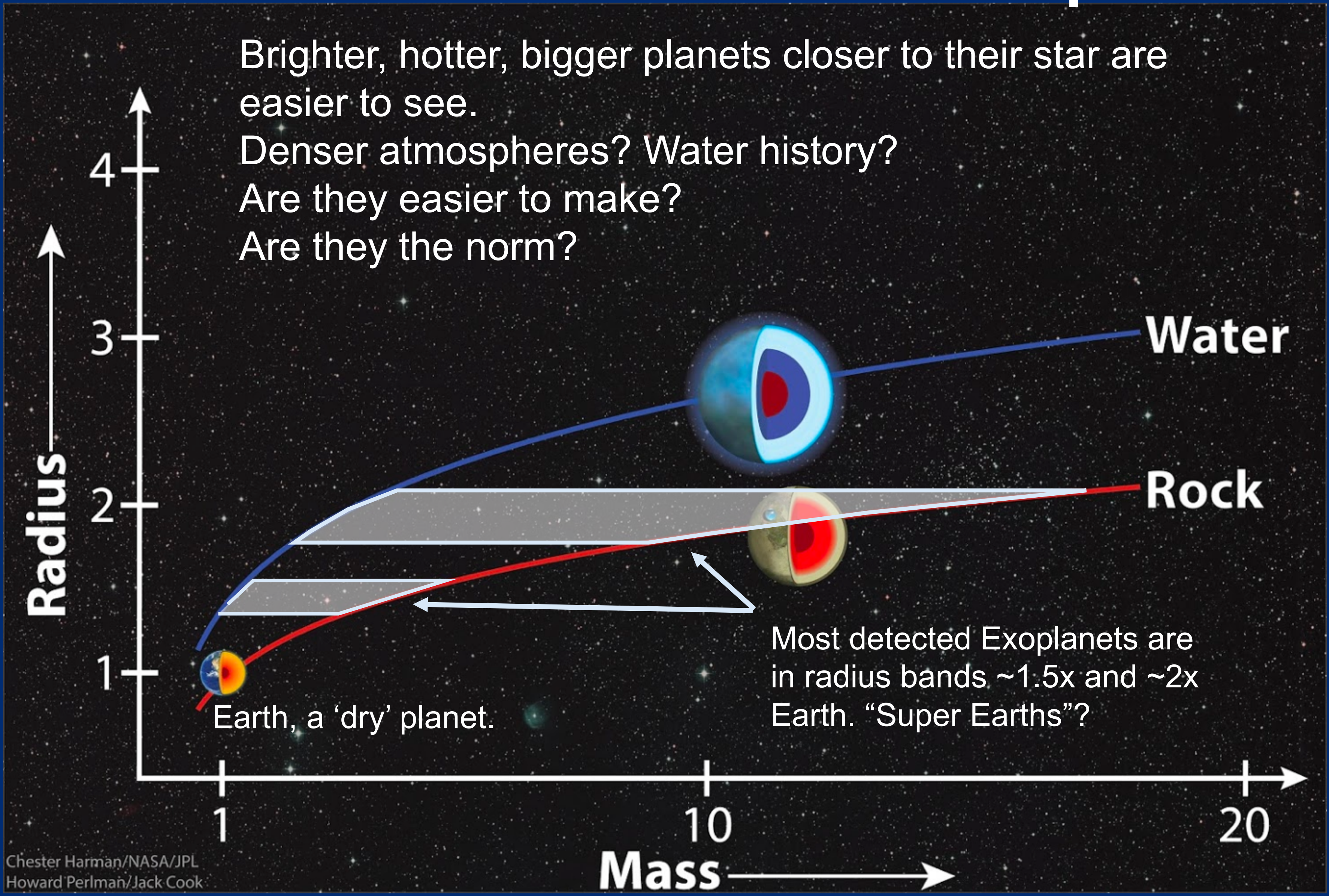
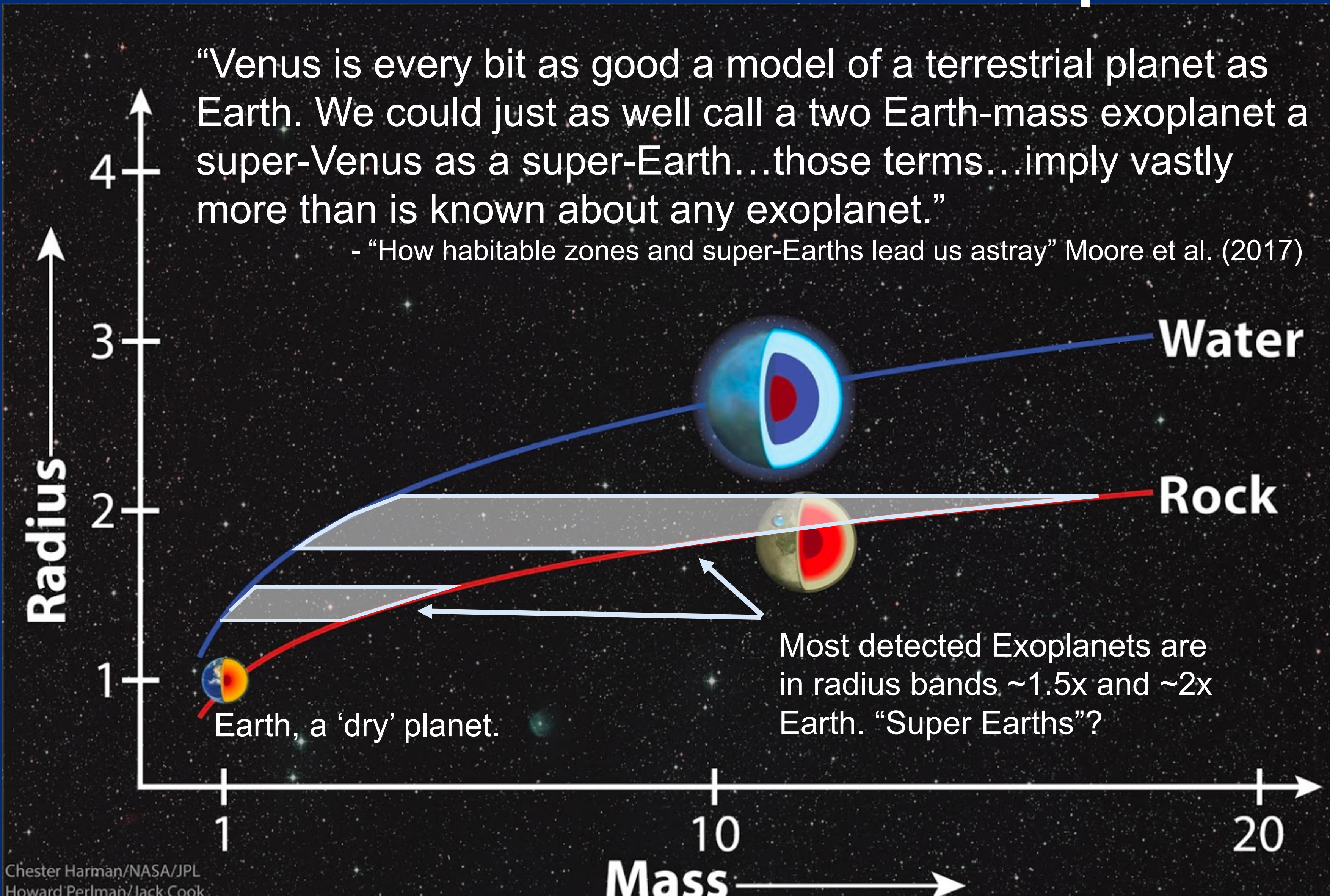


Inner Planets in the Context of Exoplanets

"Venus is every bit as good a model of a terrestrial planet as Earth. We could just as well call a two Earth-mass exoplanet a super-Venus as a super-Earth…those terms…imply vastly more than is known about any exoplanet."

- "How habitable zones and super-Earths lead us astray" Moore et al. (2017)



Planets Like Ours

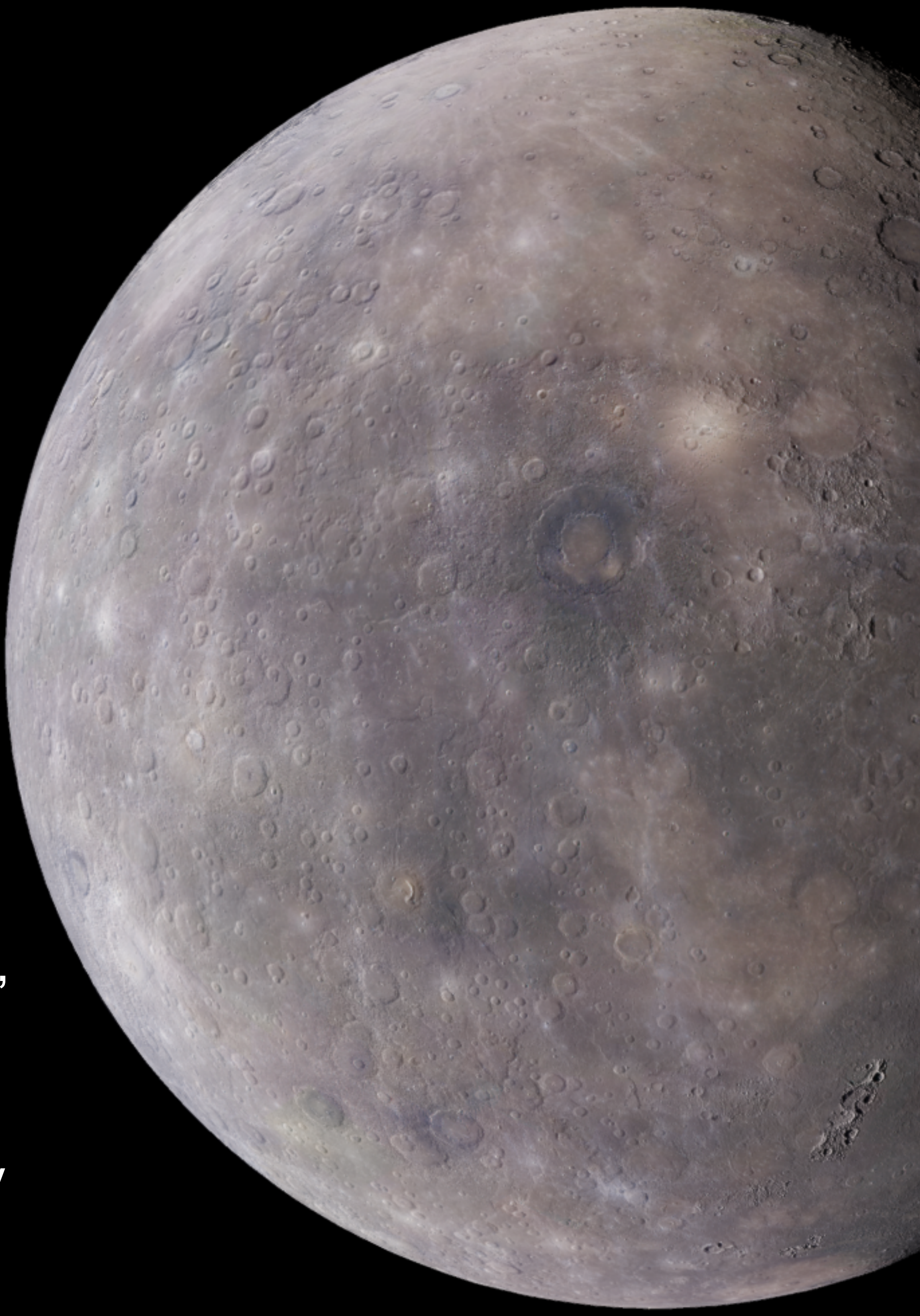
- What are we looking for in exoplanets?
- Use of reflected light, thermal emission, and orbital phase
- Spectroscopy as a major tool to characterize the surface and the atmosphere

- Characterization of the Surface of a Solid Planet: Solid, Liquid, or Clouds?
  - Inner solar system, case by case.
  - The single – or very few – pixel planet problem

[Bertaux (2017)]

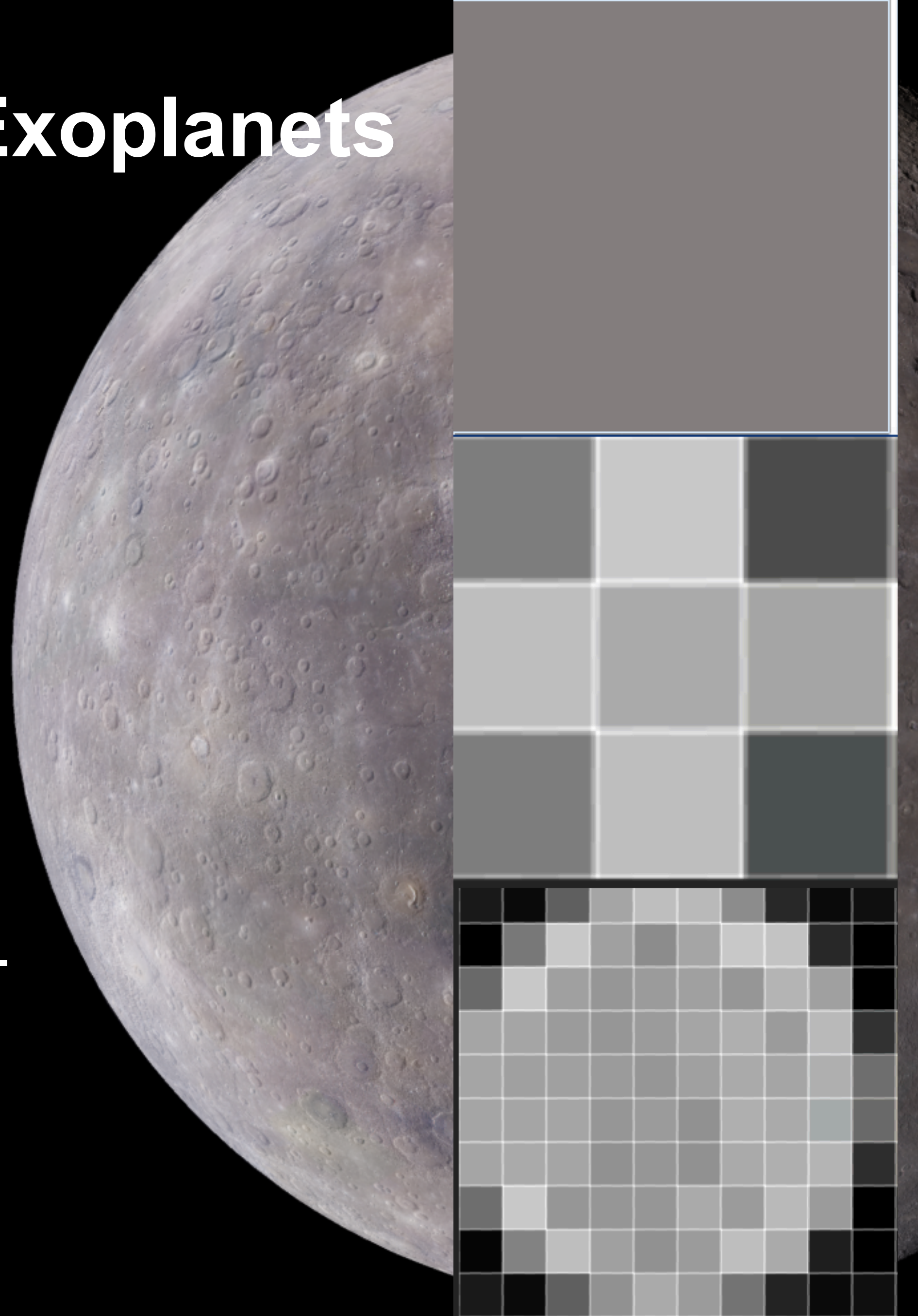
Mercury

- Very close to star (orbital/rotational relationship)
- Interactions with solar wind, Space weathering
- Criticality of magnetic field
- Tenuous exosphere
- Extreme temperature variation
- Direct observation of Surface, Composition
- Geologic History – Volcanism, Impact, Tectonics
- Interior history, Evolution through surface observations, Gravity, Density



Mercury from MESSENGER

Mercury – Mercurian Exoplanets



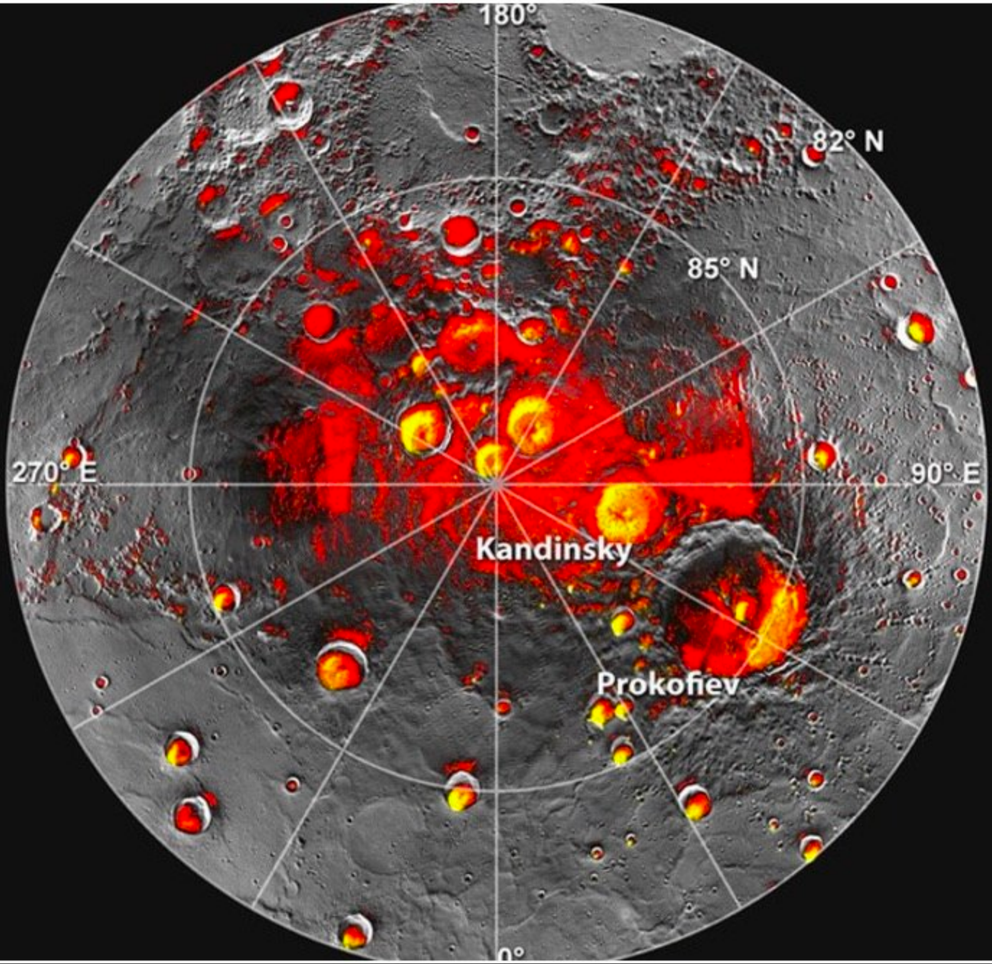
- Temperature
- Solid - Silicate spectrum
- Star-Planet Interactions
  - Magnetic field interactions
  - Atmosphere ablation
  - Silicate ablation

- Are Mercury-like states an end-member or end-state of terrestrial planetary evolution?

Mercury from MESSENGER

Habitability on a Mercurian World?

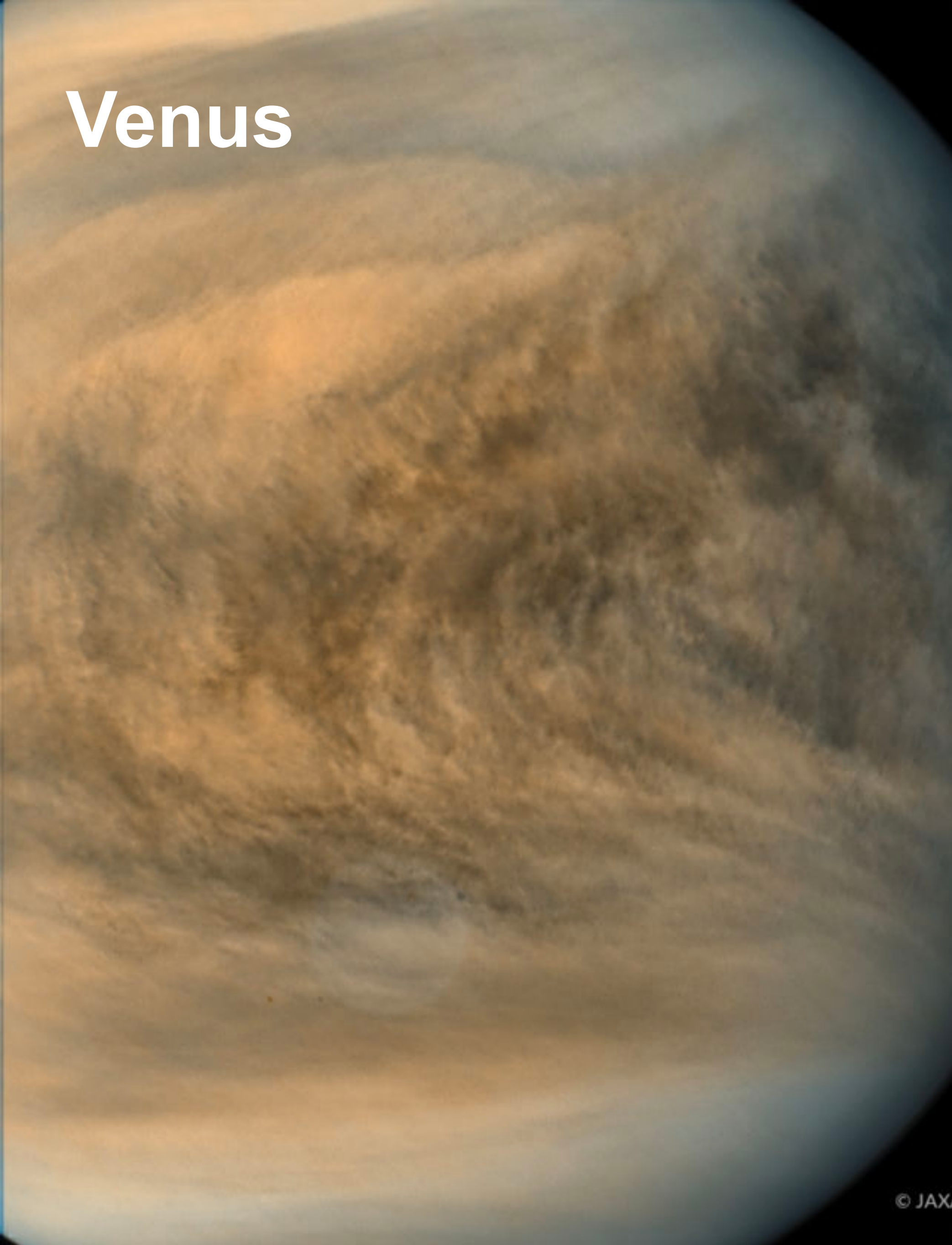
Water ice stable in polar permanently shadowed regions



Dark (organic?) mantling in many ice areas

Mercury from MESSENGER + Radar

Venus



© JAXA/ISAS/DARTS/Damia Bouic

- Dense CO_2 dominated atmosphere - Superrotation
- H_2SO_4 clouds
- Hazes, Aerosols
- Runaway Greenhouse
  - Nearly all water destroyed
  - Carbonate rocks in the atmosphere
  - Clues to a cooler, wetter past
- Strange Day (longer than year)
- Hellish very young surface
  - Bone dry
  - Volcanos, Tectonics (Active?)
  - Hard to see (radar, thermal)
- Similar building blocks, location to Earth, different history.

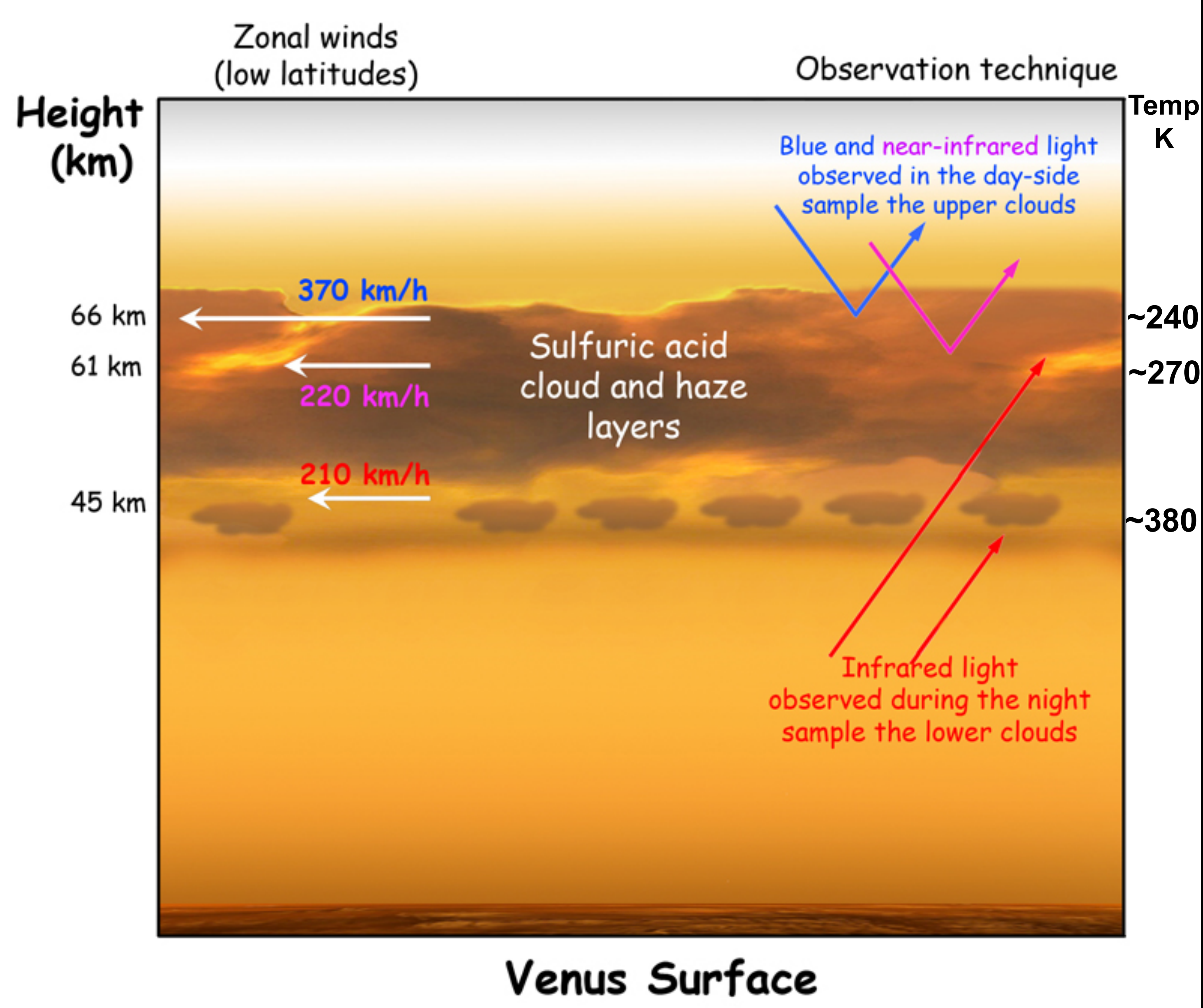
Venus – Venusian Exoplanets

- Temperature
- Clouds - CO_2 spectrum (H_2O? Other?)
- Atmosphere Variability
- Star-Planet Interactions
  - Atmosphere – Stellar Wind
  - Atmosphere ablation

"Once you break a planetary atmosphere…[it's] almost impossible to unbreak," Kane says. "Venus could be the eventual outcome of all atmospheric evolution."

– Stephen Kane

Habitability on a Venusian World?



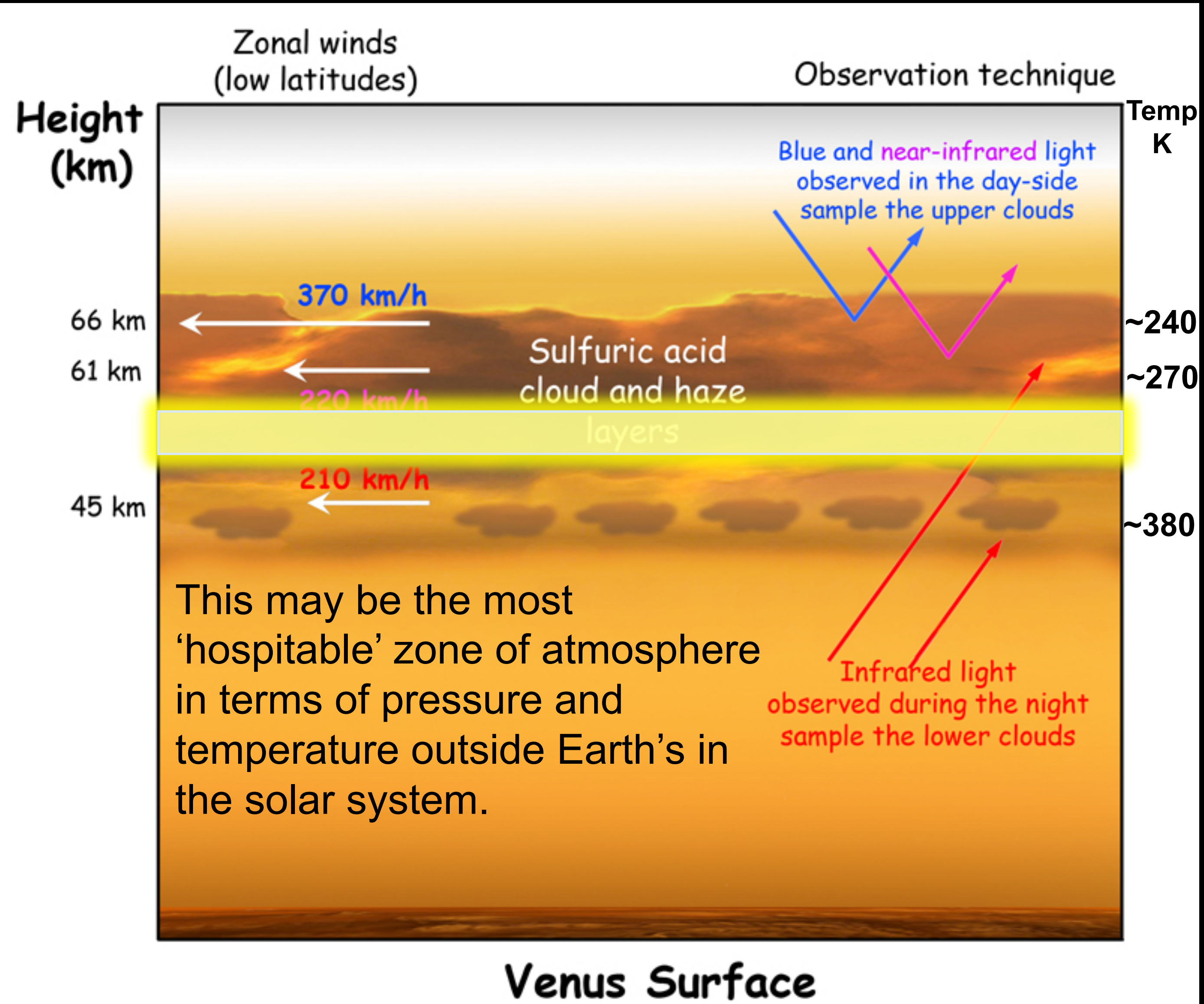
53-57 km alt

T: 0-30°C
P: 350-600+ mbar
CO_2 dominant atmosphere

Mt. Everest

5400 m: 533 mbar
8848 m: 337 mbar

Habitability on a Venusian World?



This may be the most 'hospitable' zone of atmosphere in terms of pressure and temperature outside Earth's in the solar system.

53-57 km alt

T: 0-30°C

P: 350-600+ mbar

CO_2 dominant atmosphere

Mt. Everest

5400 m: 533 mbar

8848 m: 337 mbar

Small problem of sulfur gases and H_2SO_4…

Earth(-Moon)

- The planet we know best
- History of planetary evolution
  - Atmosphere and Surface very different over time
- Details of many systems – but far from total knowledge
- Perfect for life…

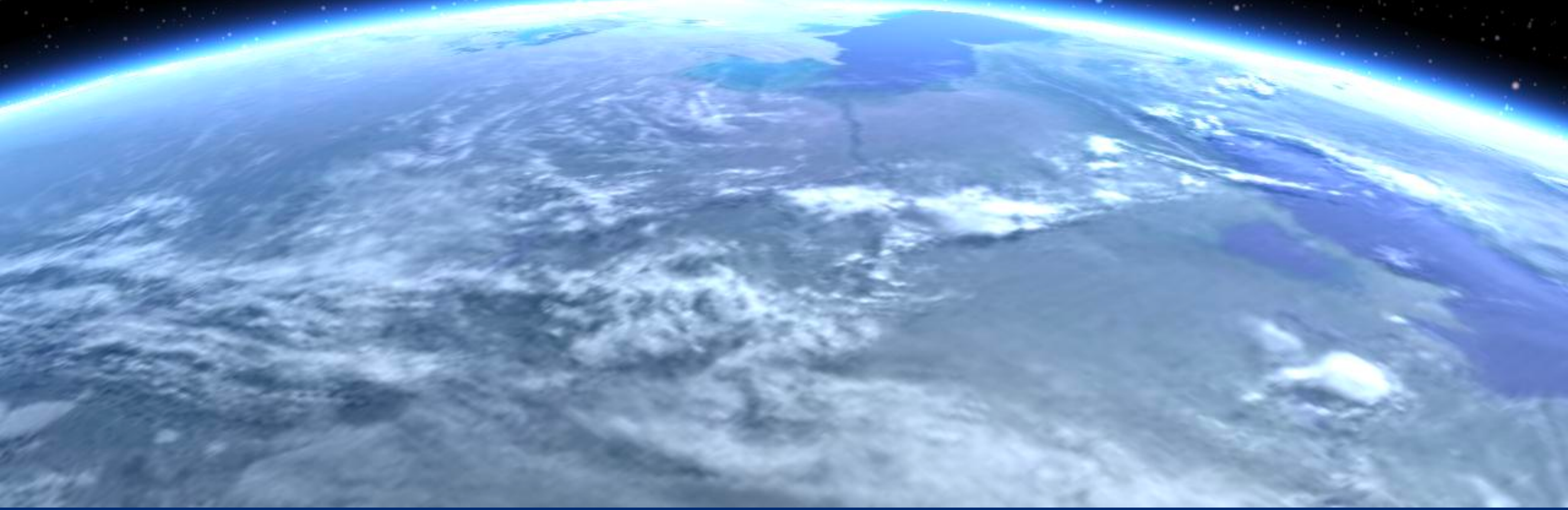
Earth(-Moon) – Earth-like Exoplanets

- Warm
- Water, Ice, Vapor, Silicate spectrum – Signs of extant life?
- Partial greenhouse
- Stellar – Planet Magnetic Field
- Variability (Seasonal, Rotational, Atmospheric)
- Giant moon

Habitability on an Earth-like world

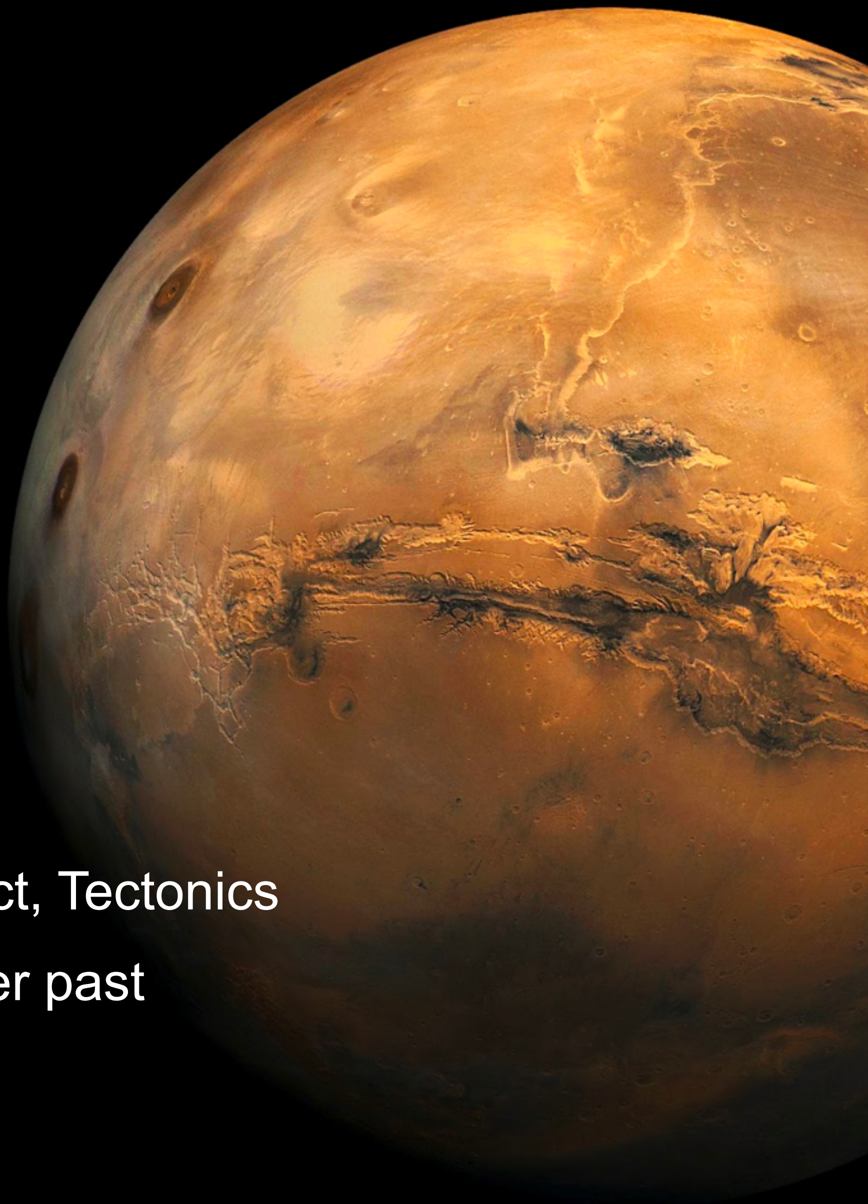
- Warm
- Water, Ice, Vapor, Silicate spectrum
- Partial greenhouse
- Stellar – Planet Magnetic Field
- Variability
- Giant moon

How long to favorable conditions last?
How critical are our seasons?
Our giant moon?
Our magnetic field?
Plate tectonics?
How easy is life to make?



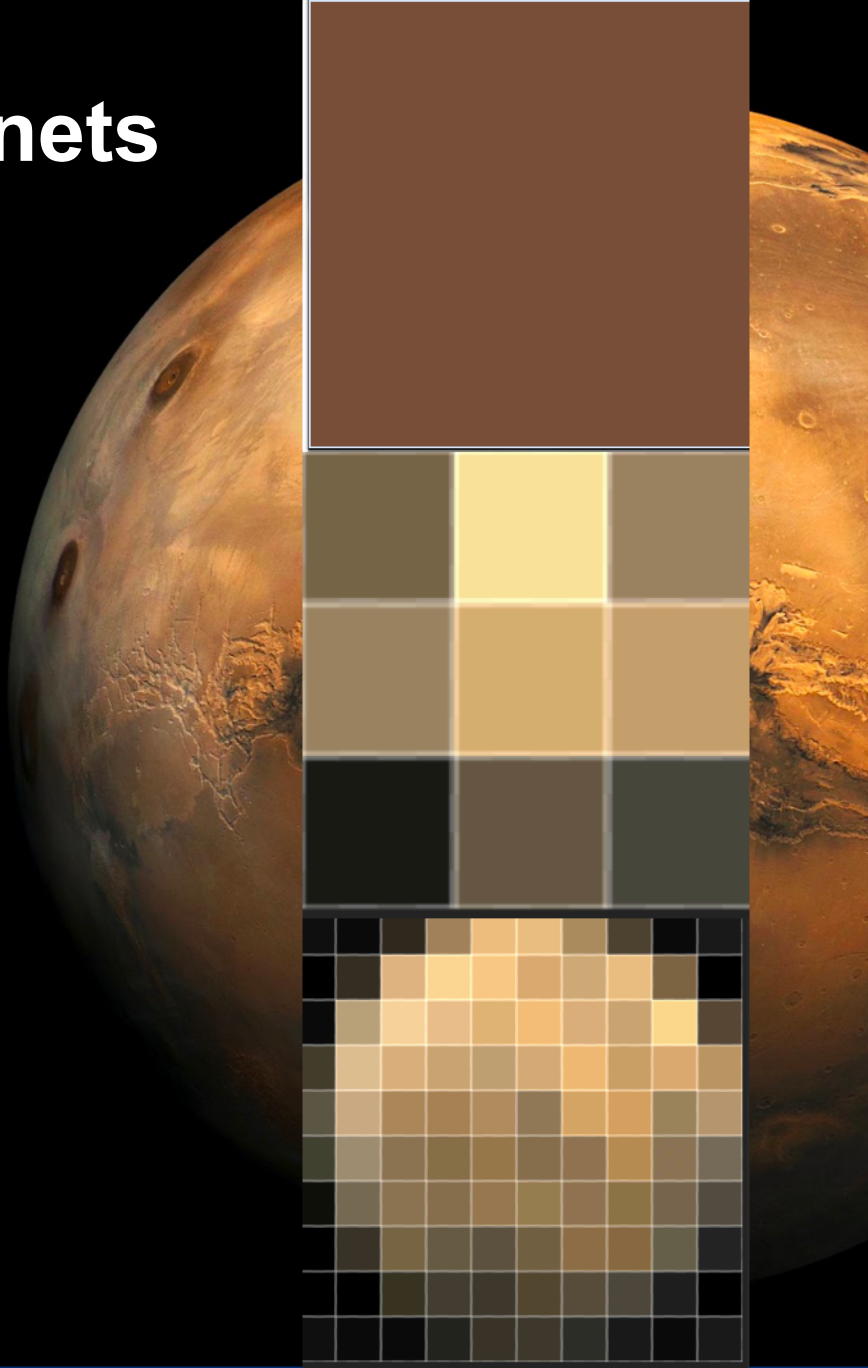
Mars

- Sparse CO_2 dominated atmosphere
- Low mass, weak gravity
- Hazes, Dust
- Silicate spectrum
  - iron
- Cool to cold
- Water, CO_2 ices
- Variability – Seasons, Dust, Icecaps
- Geologic History – Volcanism, Impact, Tectonics
- Hydrological history – Warmer, wetter past

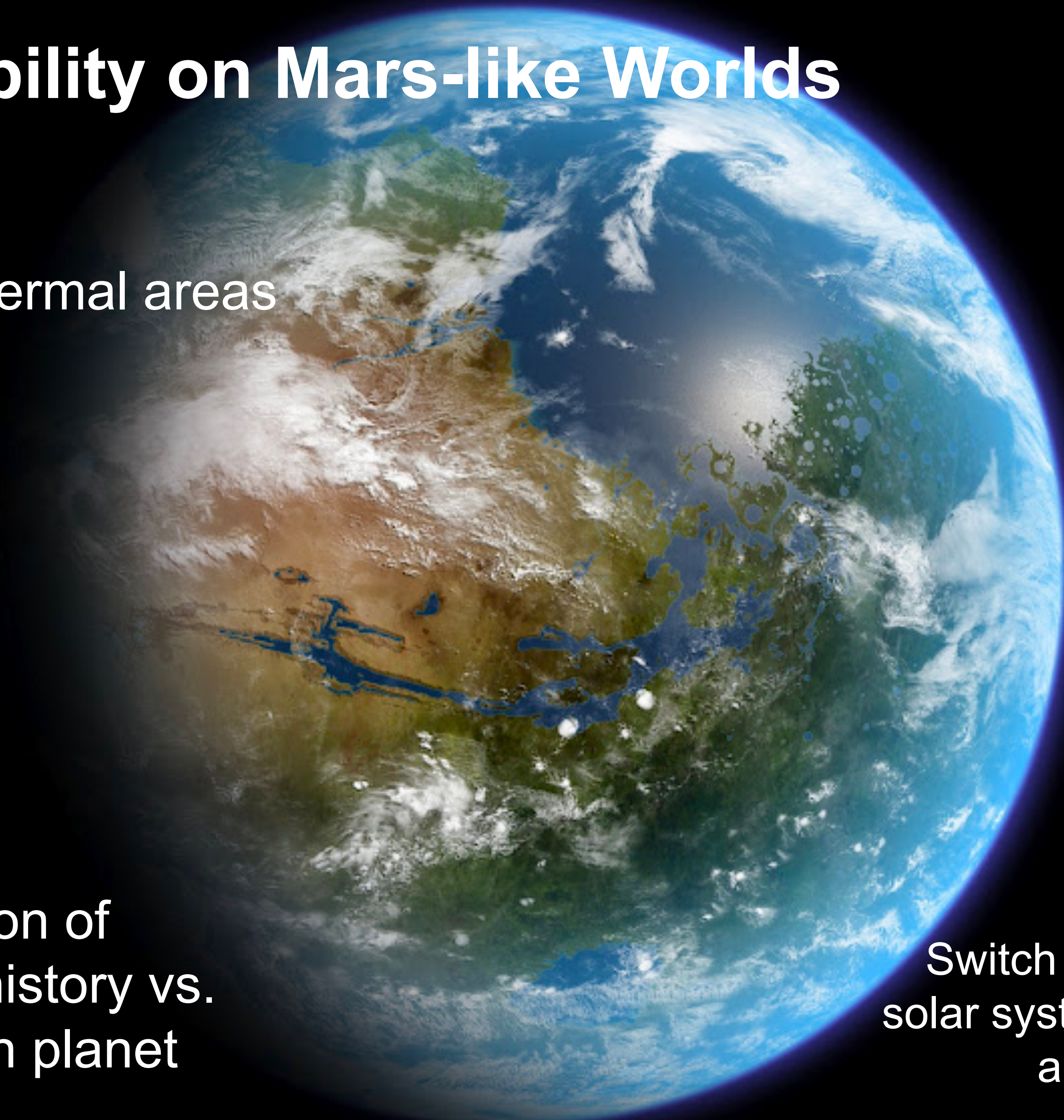


Mars – Mars-like Exoplanets

- Temperature
- Solid + Clouds (dust) -Silicate spectrum,
  - CO_2, H_2O gas and ices, iron oxide
- Star-Planet Interactions
  - Atmosphere ablation
- Mass-Atmosphere relationships
- Variability, Dust, Ice proportions



Habitability on Mars-like Worlds



- Brines
- Hydrothermal areas
- Ices

The question of "when" in history vs. where on/in planet

Switch locations in solar system of Mars and Venus…

Final thoughts

We're searching for other Earths, or other 'habitable' worlds, with an expanded definition of habitable; conditions in both place and time.

Our best understood example is not permanently stable. Earth's past and future are hostile. Currently hostile planets may not have always been so, may not be completely so now.

All inner planets together and in comparison provide examples of likely pasts, futures, and presents among the exoplanets.

Final thoughts

"The planets that we're studying around other stars are planets that we will never be able to go to, at least not in the next several hundred years. Venus is very much a warning to us, because if we did not have Venus in our solar system…we may very well be far more cavalier in discovering Earth-sized planets around other stars and just assuming that they're habitable."

-Stephen Kane

The inner planets are more than warnings. They are signposts, and beginner-guides to understanding not just the evolution of our own solar system, but all stellar systems we are encountering today.

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