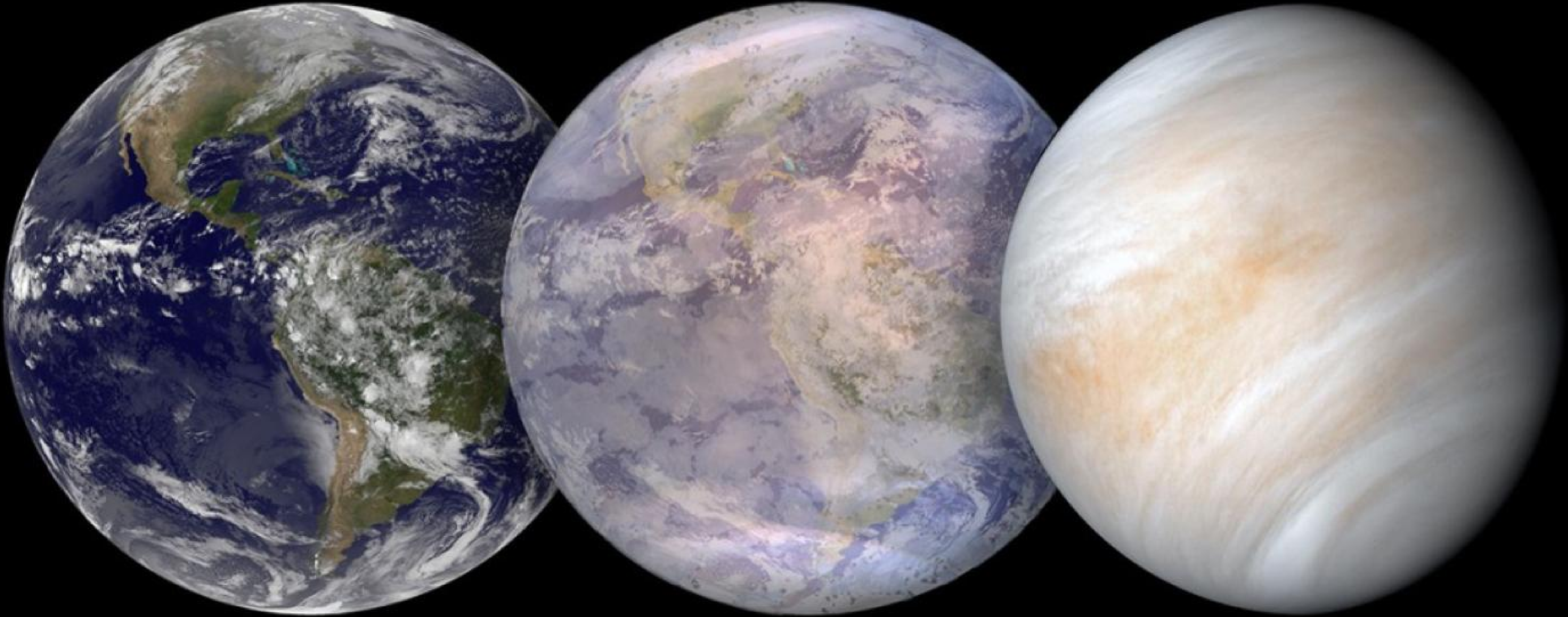
Planetary Habitability

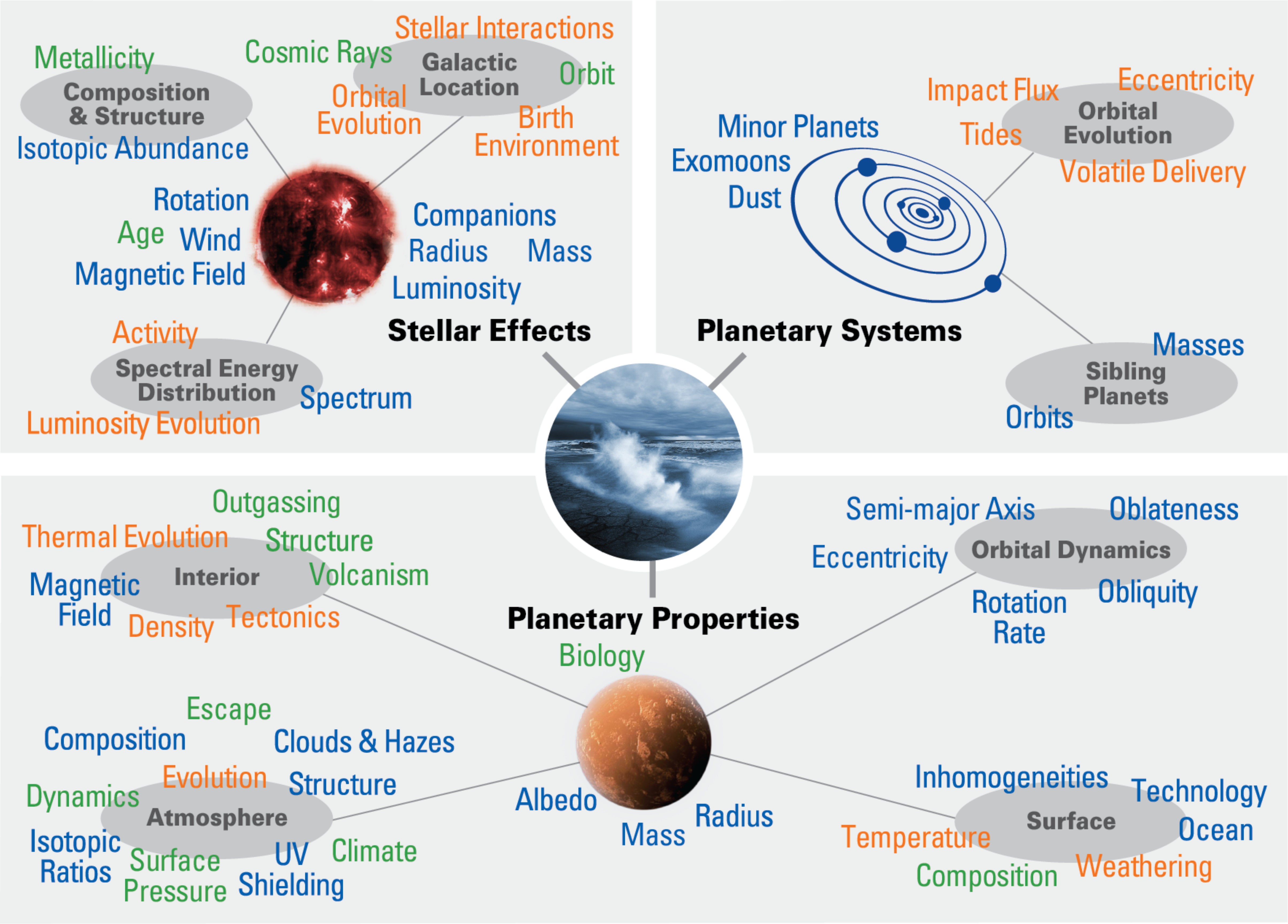


Stephen Kane

UNIVERSITY OF CALIFORNIA
UC RIVERSIDE

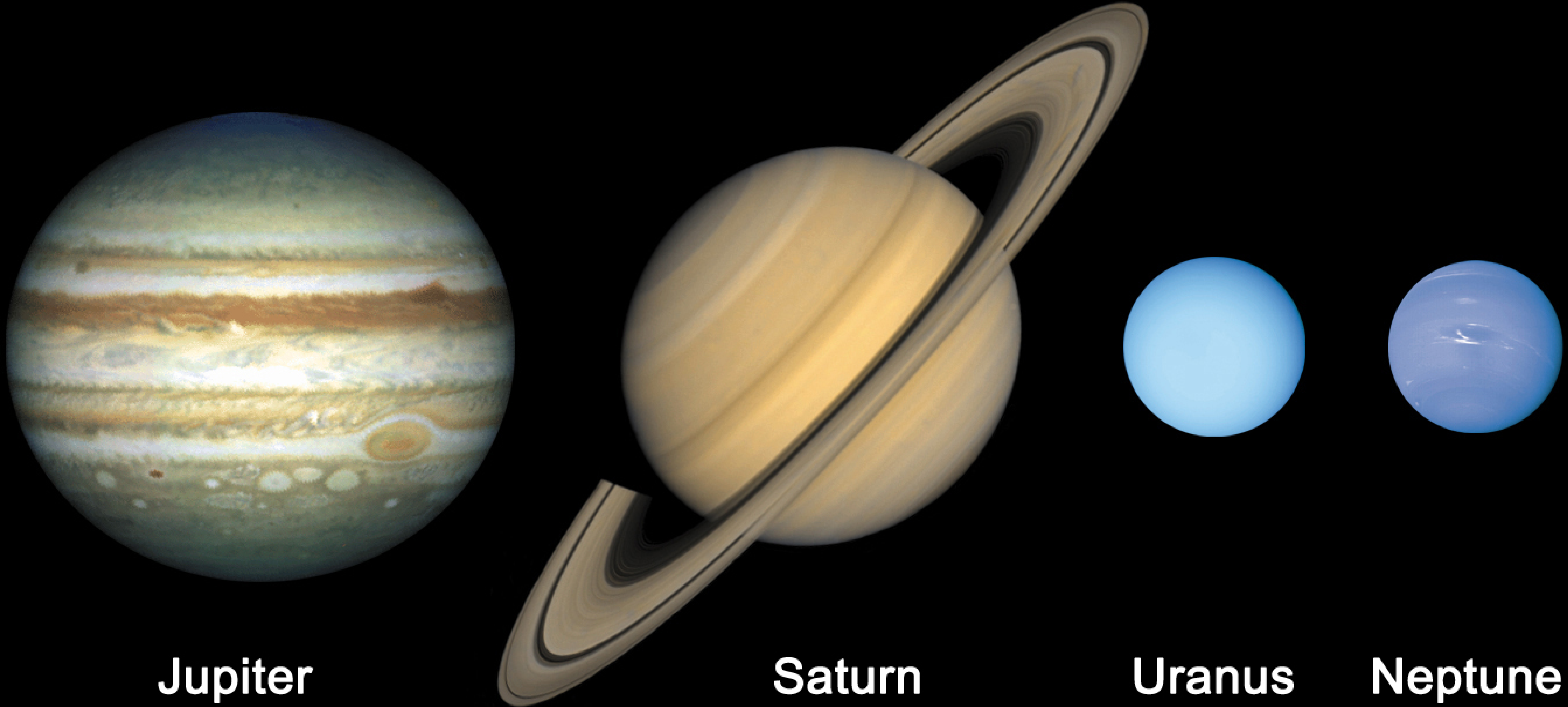
Planetary Habitability

- **Lecture 1: The Fundamentals of Planetary Habitability**
- **Lecture 2: Habitability Lessons Learned from our Sister Planet**
- **Lecture 3: Stars and the Planetary Energy Balance**
- **Lecture 4: The Habitable Zone and Orbital Dynamics**



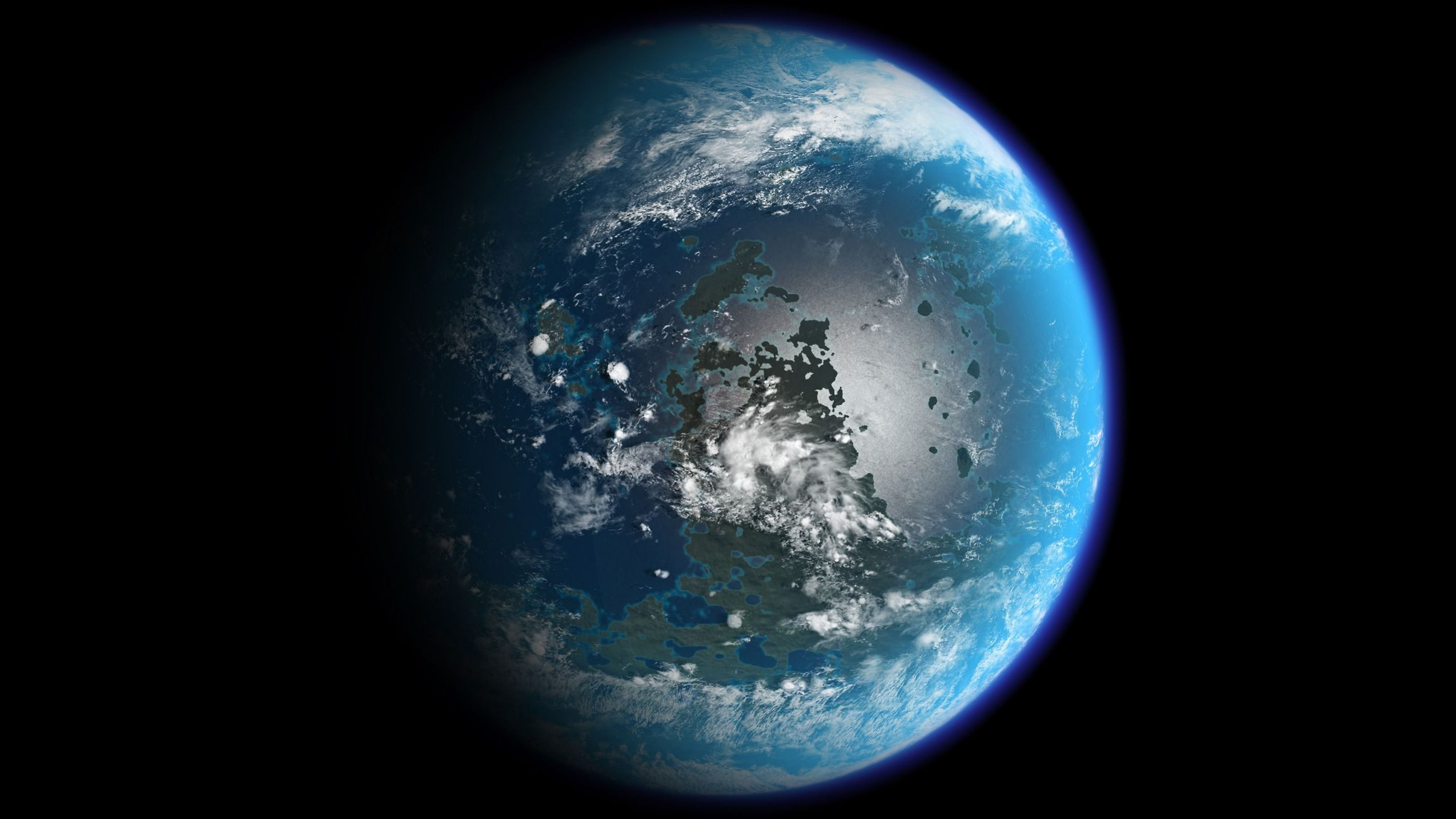
Stellar Effects
Metallicity
Composition & Structure
Isotopic Abundance
Cosmic Rays
Stellar Interactions
Galactic Location
Orbit
Orbital Evolution
Birth Environment
Rotation
Age
Wind
Magnetic Field
Companions
Radius
Mass
Luminosity
Activity
Spectral Energy Distribution
Spectrum
Luminosity Evolution
Planetary Systems
Minor Planets
Exomoons
Dust
Impact Flux
Eccentricity
Tides
Orbital Evolution
Volatile Delivery
Masses
Sibling Planets
Orbits
Planetary Properties
Outgassing
Thermal Evolution
Structure
Interior
Volcanism
Magnetic Field
Density
Tectonics
Biology
Semi-major Axis
Oblateness
Eccentricity
Orbital Dynamics
Obliquity
Rotation Rate
Escape
Composition
Clouds & Hazes
Evolution
Structure
Dynamics
Atmosphere
Isotopic Ratios
Surface Pressure
UV Shielding
Climate
Albedo
Mass
Radius
Inhomogeneities
Technology
Surface
Temperature
Ocean
Composition
Weathering

The role of giant planets

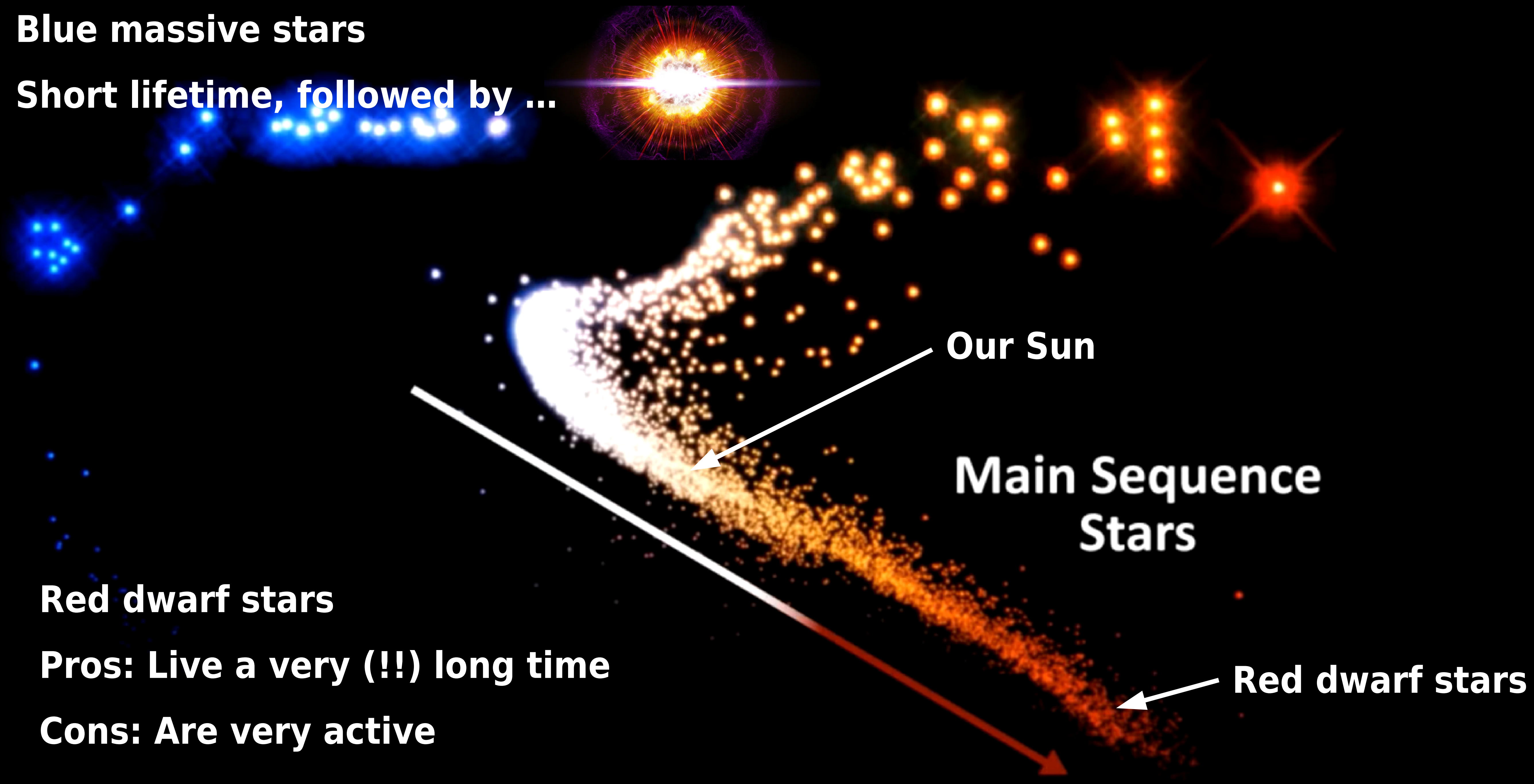


Is our solar system unusual?

Less than 10% of stars have Jupiter/Saturn analogs.

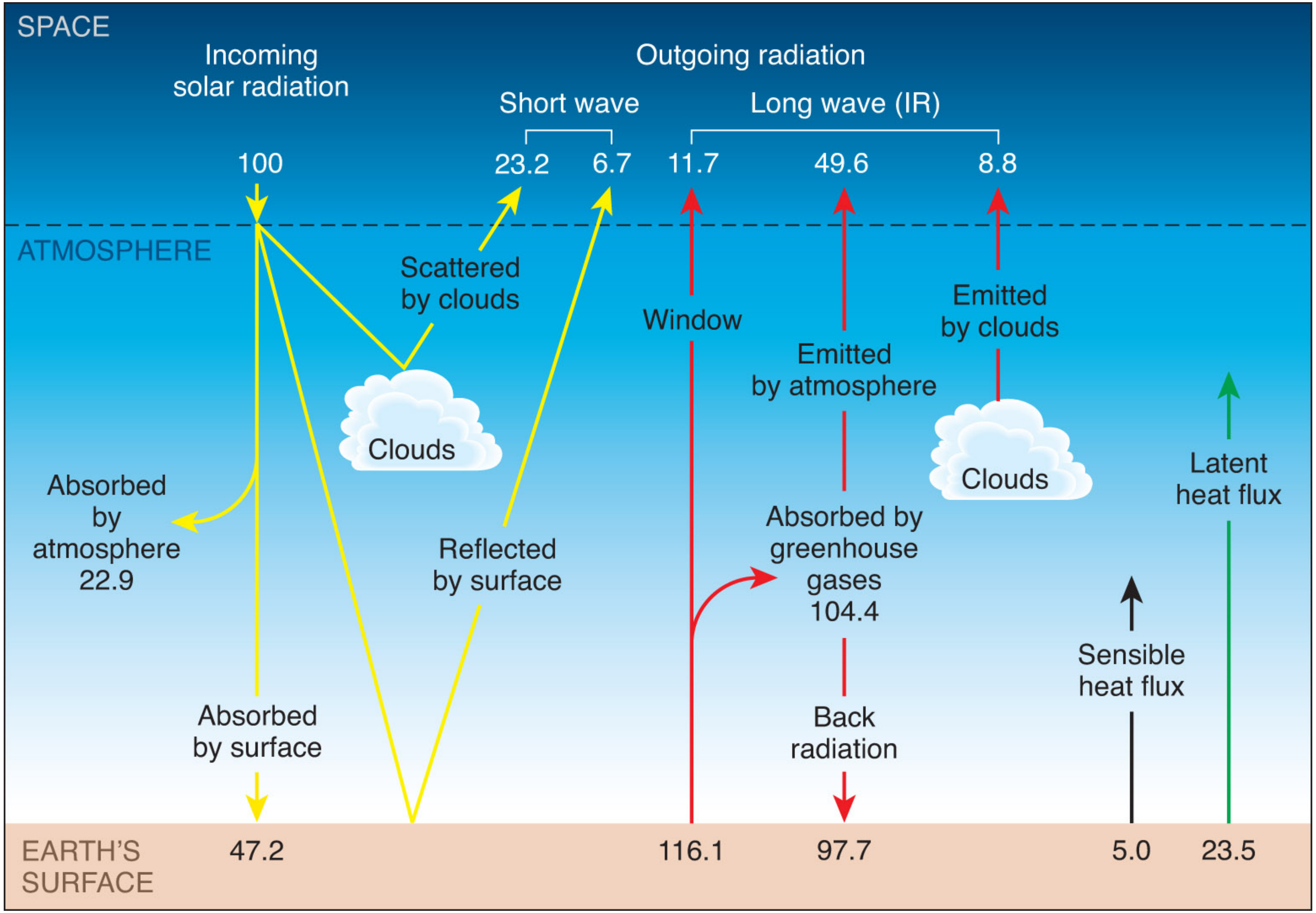


Stars have a vast variety of sizes and colors (temperatures), and luminosities.



Stars are (usually) the primary contributor to a planetary climate energy budget.

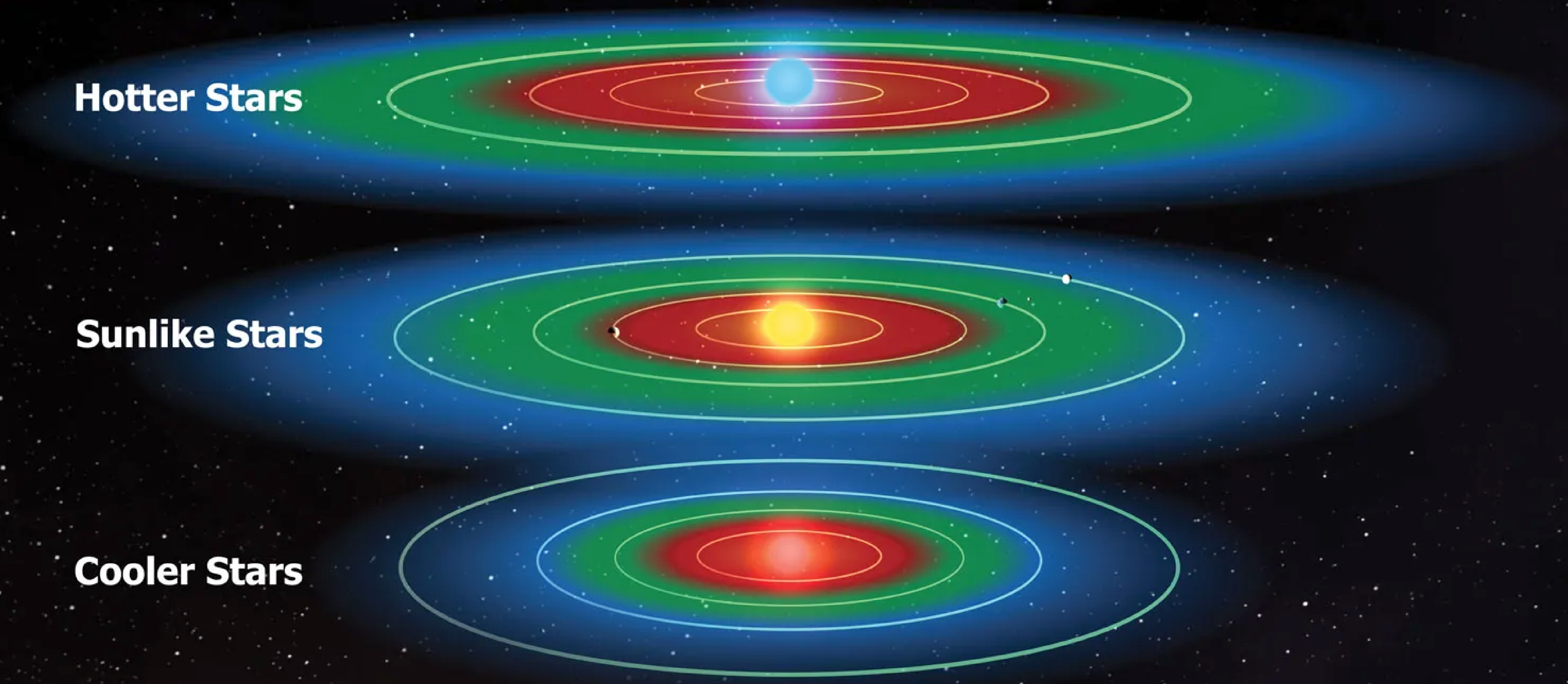
Planetary Energy Balance



Considerations:

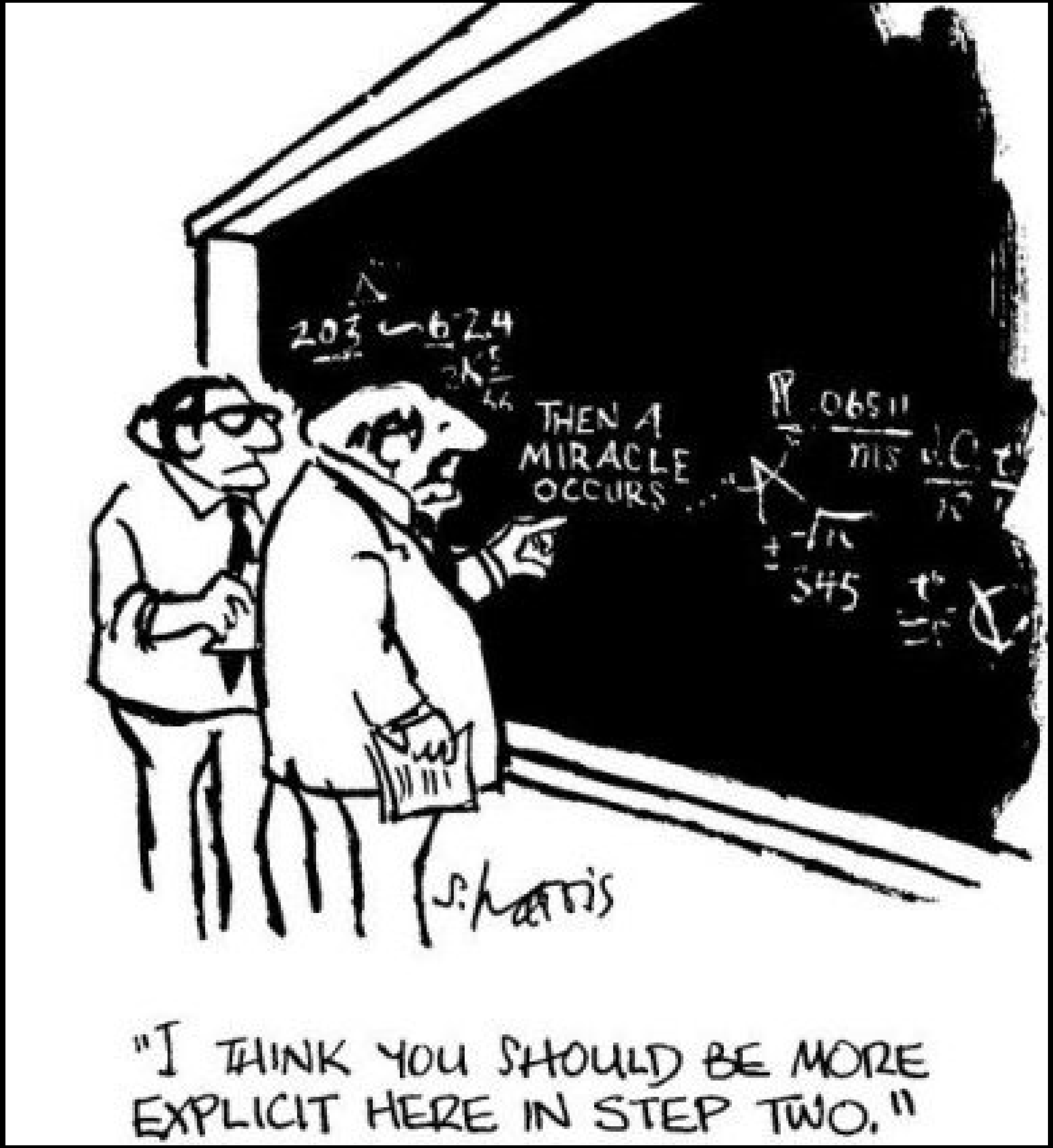
- Transparency of the atmosphere (optical and IR).
- Blackbody radiation.
- Idealized greenhouse model (emissivity).
- Obliquity and rotation.
- Radiative equilibrium timescale.

The "Habitable Zone": the region around a star where a planet **COULD** have surface liquid water **IF** it has sufficient atmospheric pressure.



The Habitable Zone is most useful for target selection. However, it does assume numerous aspects of the planet, including water delivery.

Planet in the Habitable Zone ≠ Habitable Planet



Huang, S-S., 1959, PASP, 71, 421

THE PROBLEM OF LIFE IN THE UNIVERSE AND THE MODE OF STAR FORMATION*

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GENERAL CONCLUSIONS CONCERNING THE OCCURRENCE OF LIFE IN THE UNIVERSE

In a recent paper we have discussed the problem of life, especially in its advanced form, in the universe, and derived some general conclusions concerning its occurrence.[1] We first compare the time-scales of biological and stellar evolution. Since the development of life requires a near constancy of temperature, we should expect that only those planets associated with main sequence stars would be able to support life. For only the main sequence stars keep their luminosities constant for considerable lengths of time. Now biological evolution results from mutation—a random process—and is therefore slow. In the case of our experience on the earth, its time-scale is of the order of 10^9 years. If we accept this as an average value for biological evolution in general, we find that the time-scale of evolution for main sequence stars of early spectral types (O, B, A, and perhaps early F) is too short for developing an advanced form of life on their planets even if the latter do exist.

Next we consider the size of the habitable zone around a star. One can determine this zone by computing the amount of energy received per unit time per unit area facing the star. All points at which the computed values lie between two given limits (which can be assigned numerically from biological and other considerations, but which are independent of the nature of the star itself) form the habitable zone of the star. A simple calculation shows

Habitable Zones around Main Sequence Stars

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Received April 27, 1992; revised October 2, 1992

A one-dimensional climate model is used to estimate the width of the habitable zone (HZ) around our Sun and around other main sequence stars. Our basic premise is that we are dealing with Earth-like planets with $CO_2/H_2O/N_2$ atmospheres and that habitability requires the presence of liquid water on the planet's surface. The inner edge of the HZ is determined in our model by loss of water via photolysis and hydrogen escape. The outer edge of the HZ is determined by the formation of CO_2 clouds, which cool a planet's surface by increasing its albedo and by lowering the convective lapse rate. Conservative estimates for these distances in our own Solar System are 0.95 and 1.37 AU, respectively; the actual width of the present HZ could be much greater. Between these two limits, climate stability is ensured by a feedback mechanism in which atmospheric CO_2 concentrations vary inversely with planetary surface temperature. The width of the HZ is slightly greater for planets that are larger than Earth and for planets which have higher N_2 partial pressures. The HZ evolves outward in time because the Sun increases in luminosity as it ages. A conservative estimate for the width of the 4.6-Gyr continuously habitable zone (CHZ) is 0.95 to 1.15 AU. CHZs around K and M stars are wider (in log distance) than for our Sun because these stars evolve more slowly. Planets orbiting late K stars and M stars may not be habitable, however, because they can become trapped in synchronous rotation as a consequence of tidal damping. F stars have narrower (log distance) CHZ's than our Sun because they evolve more rapidly. Our results suggest that mid-to-early K stars should be considered along with G stars as optimal candidates in the search for extraterrestrial life.

I. INTRODUCTION

Astronomers have been interested for many years in the possibility of life on other planets in our own Solar System and in other planetary systems. The region around a star in which life-supporting planets can exist has been termed the "habitable zone" (Huang 1959, 1960), or the "ecosphere" (Dole 1964, Shklovski and Sagan 1966). Its limits are defined by assumed climatic constraints which

The HITRAN Database

Introduction

HITRAN is an acronym for *hi*gh-resolution *tran*smission molecular absorption database. HITRAN is a compilation of spectroscopic parameters that a variety of computer codes use to predict and simulate the transmission and emission of light in the atmosphere. The database is a long-running project started by the Air Force Cambridge Research Laboratories (AFCRL) in the late 1960s in response to the need for detailed knowledge of the infrared properties of the atmosphere.

The HITRAN compilation, and its associated database HITEMP (high-temperature spectroscopic absorption parameters), are developed and maintained at the Atomic and Molecular Physics Division, Harvard-Smithsonian Center for Astrophysics under the continued direction of Dr Laurence S. Rothman.

HITRAN*online* provides access to the latest version of the HITRAN molecular spectroscopic database.

Scientific Objectives

The simultaneous developments of high-resolution laboratory instrumentation (such as the Fourier transform spectrometer), the digital computer and storage, and sensitive detectors and the means to carry them on board high-altitude balloons and space craft provided the stimulus to create a machine-readable archive of the fundamental properties of molecular transitions. It was then possible to simulate transmission and radiance in the terrestrial atmosphere by applying known radiative-transfer equations. Thus was born the original HITRAN molecular absorption line parameters database.

The initial HITRAN was limited to the seven main telluric atmospheric absorbers in the infrared: H_2O, CO_2, O_3, N_2O, CO, CH_4, and O_2. The most significant of the isotopologues of these molecular species was also included. The initial HITRAN database included only the basic parameters necessary to solve the Lambert-Beers law of transmission, namely the line center of a transition, the intensity of the transition, and the lower-state energy. In addition, the air-broadened Lorentz width was included as well as the unique quantum identifications of the upper and lower states of each transition.

HABITABLE ZONES AROUND MAIN-SEQUENCE STARS: NEW ESTIMATES

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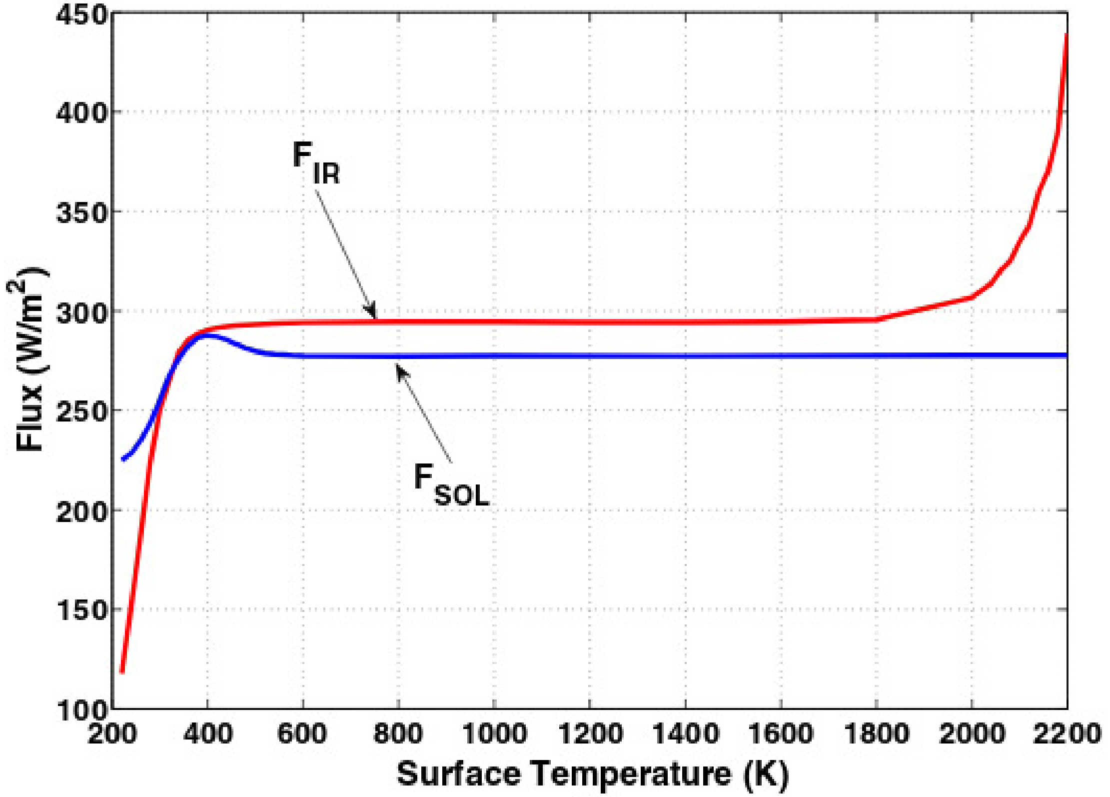
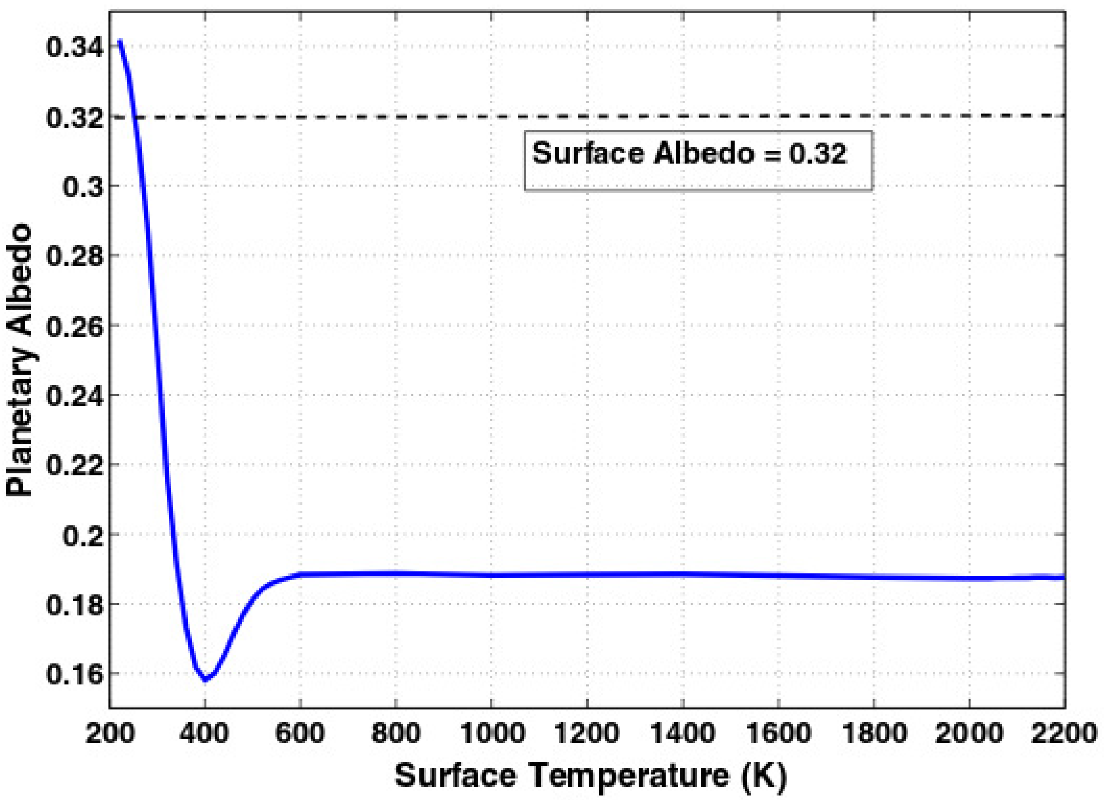
ABSTRACT

Identifying terrestrial planets in the habitable zones (HZs) of other stars is one of the primary goals of ongoing radial velocity (RV) and transit exoplanet surveys and proposed future space missions. Most current estimates of the boundaries of the HZ are based on one-dimensional (1D), cloud-free, climate model calculations by Kasting et al. However, this model used band models that were based on older HITRAN and HITEMP line-by-line databases. The inner edge of the HZ in the Kasting et al. model was determined by loss of water, and the outer edge was determined by the maximum greenhouse provided by a CO_2 atmosphere. A conservative estimate for the width of the HZ from this model in our solar system is 0.95–1.67 AU. Here an updated 1D radiative–convective, cloud-free climate model is used to obtain new estimates for HZ widths around F, G, K, and M stars. New H_2O and CO_2 absorption coefficients, derived from the HITRAN 2008 and HITEMP 2010 line-by-line databases, are important improvements to the climate model. According to the new model, the water-loss (inner HZ) and maximum greenhouse (outer HZ) limits for our solar system are at 0.99 and 1.70 AU, respectively, suggesting that the present Earth lies near the inner edge. Additional calculations are performed for stars with effective temperatures between 2600 and 7200 K, and the results are presented in parametric form, making them easy to apply to actual stars. The new model indicates that, near the inner edge of the HZ, there is no clear distinction between runaway greenhouse and water-loss limits for stars with $T_{\rm eff} \lesssim 5000$ K, which has implications for ongoing planet searches around K and M stars. To assess the potential habitability of extrasolar terrestrial planets, we propose using stellar flux incident on a planet rather than equilibrium temperature. This removes the dependence on planetary (Bond) albedo, which varies depending on the host star's spectral type. We suggest that conservative estimates of the HZ (water-loss and maximum greenhouse limits) should be used for current RV surveys and *Kepler* mission to obtain a lower limit on $\eta_\oplus$, so that future flagship missions like *TPF-C* and *Darwin* are not undersized. Our model does not include the radiative effects of clouds; thus, the actual HZ boundaries may extend further in both directions than the estimates just given.



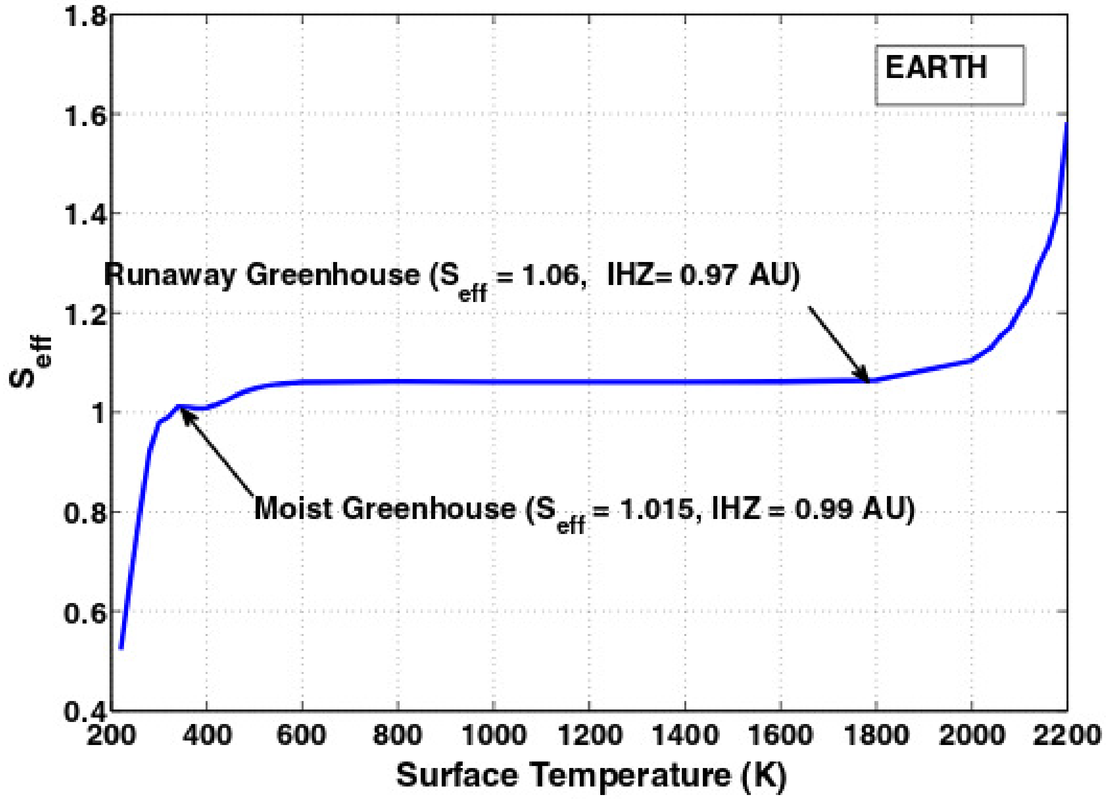
F_{IR}
F_{SOL}
Flux (W/m^2)
Surface Temperature (K)
100
150
200
250
300
350
400
450
200
400
600
800
1000
1200
1400
1600
1800
2000
2200

(a)



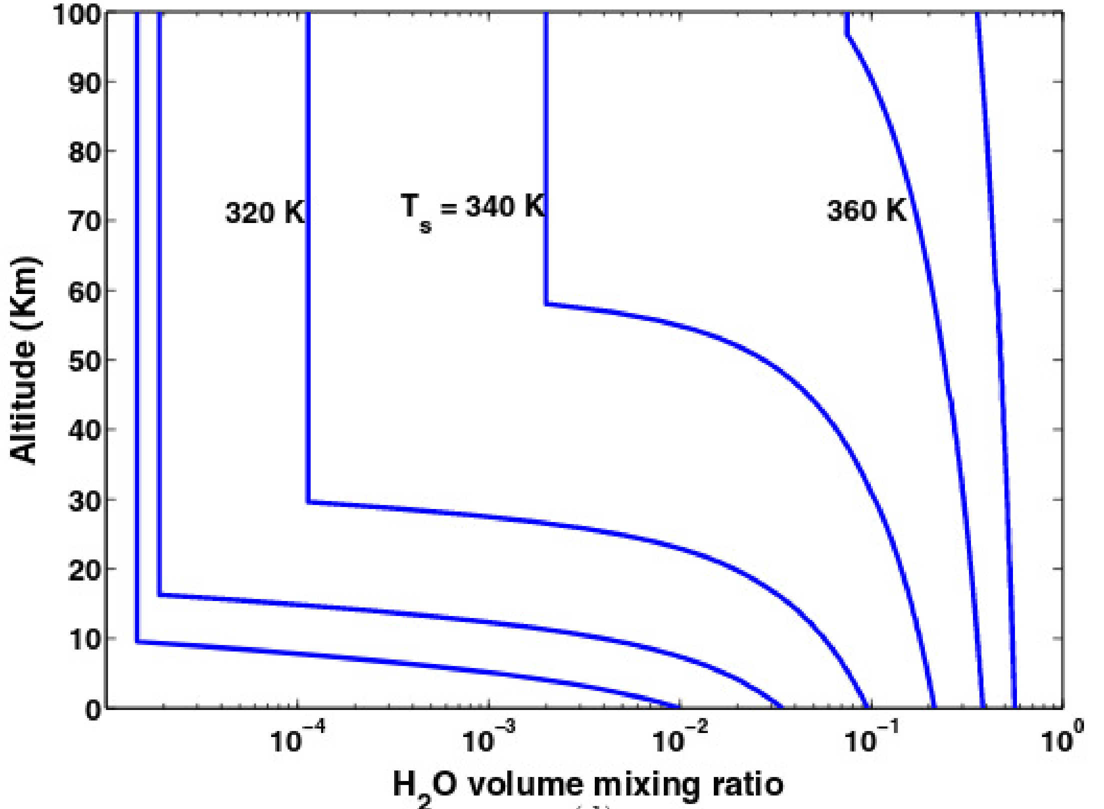
Surface Albedo = 0.32
Planetary Albedo
Surface Temperature (K)
0.16
0.18
0.2
0.22
0.24
0.26
0.28
0.3
0.32
0.34
200
400
600
800
1000
1200
1400
1600
1800
2000
2200

(b)



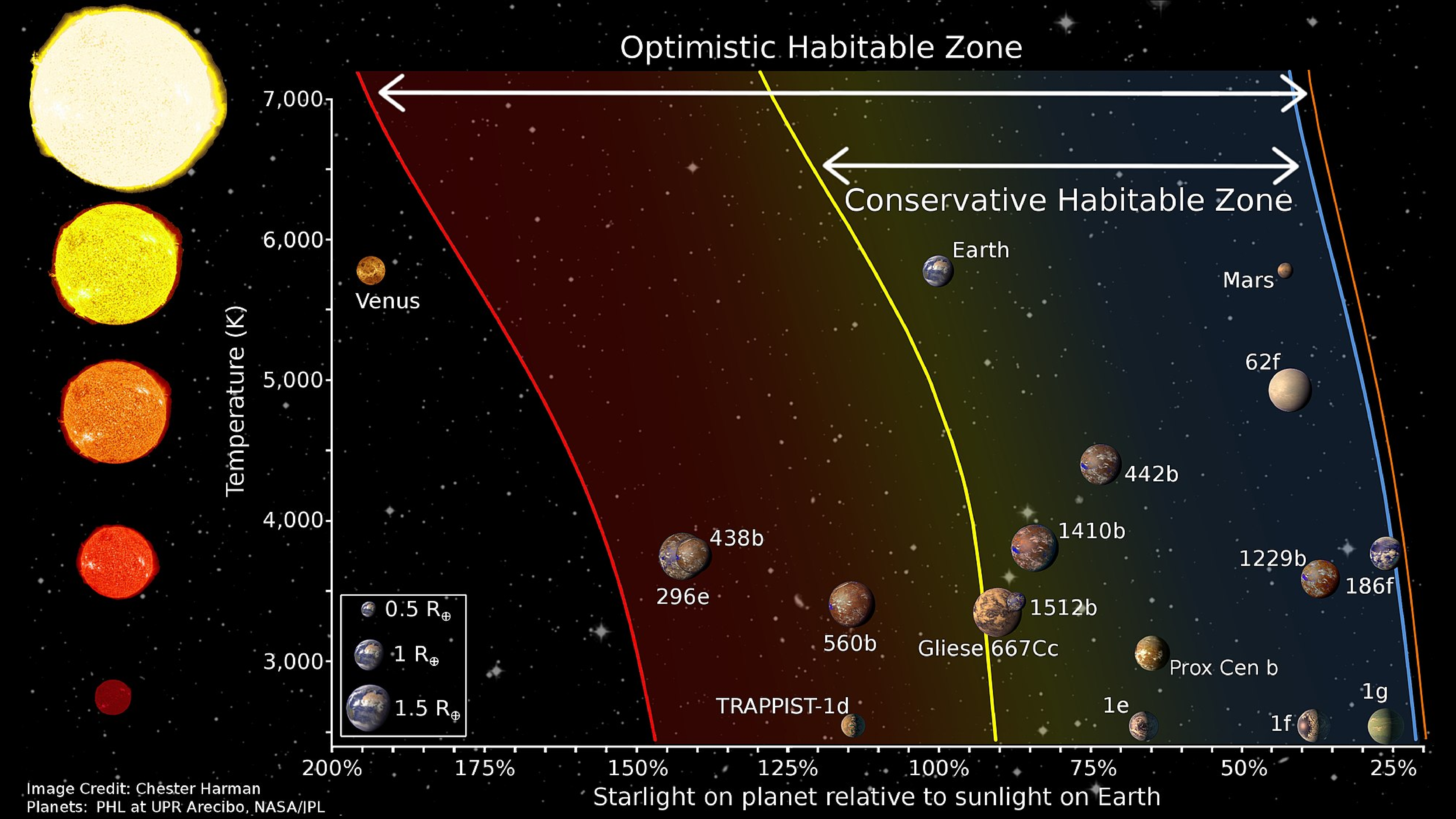
EARTH
Runaway Greenhouse (S_{eff} = 1.06, IHZ= 0.97 AU)
Moist Greenhouse (S_{eff} = 1.015, IHZ = 0.99 AU)
S_{eff}
Surface Temperature (K)
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
200
400
600
800
1000
1200
1400
1600
1800
2000
2200

(c)



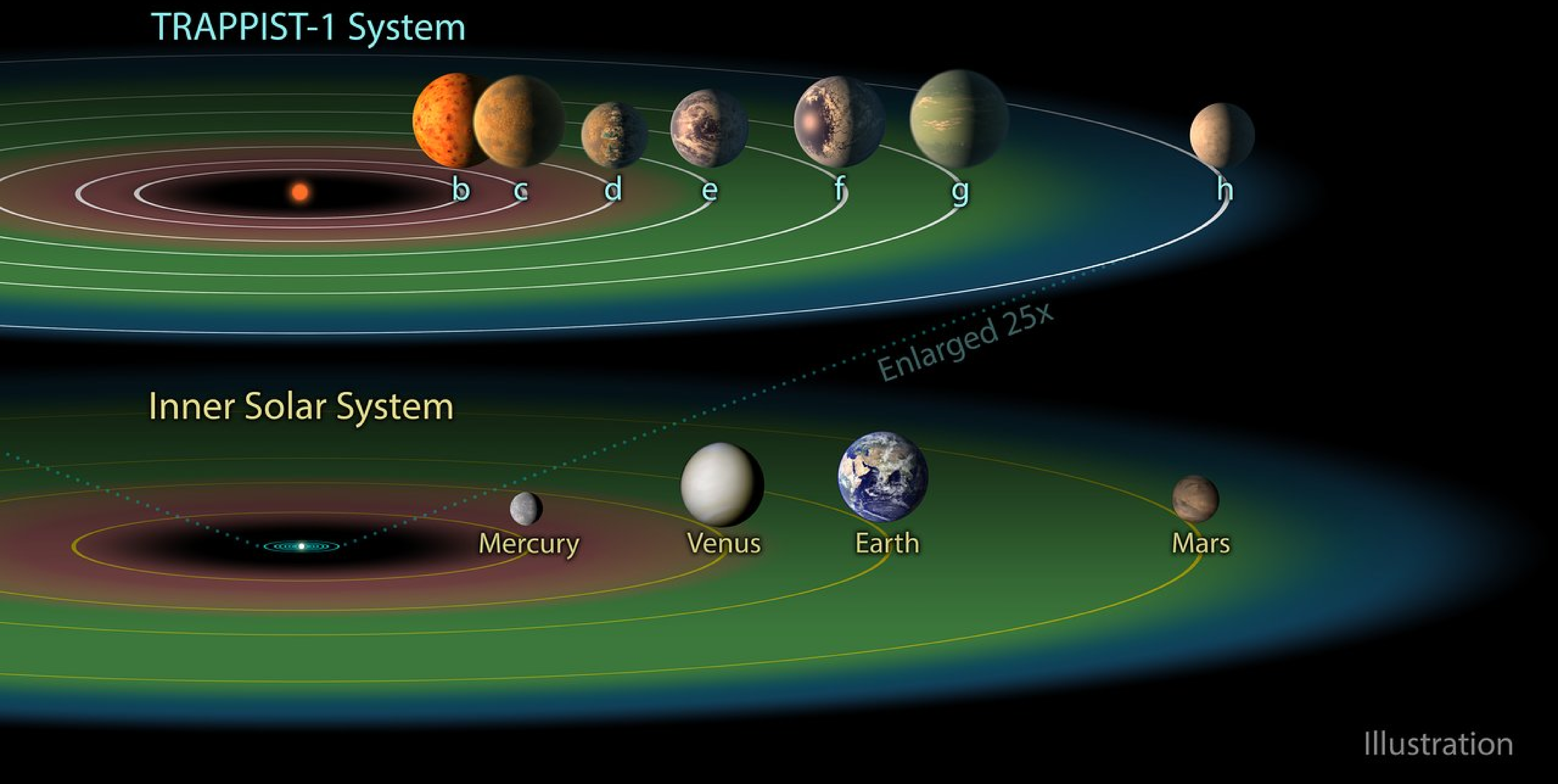
320 K
T_s = 340 K
360 K
Altitude (Km)
H_2O volume mixing ratio
0
10
20
30
40
50
60
70
80
90
100
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

(d)



Optimistic Habitable Zone
Conservative Habitable Zone
Temperature (K)
7,000
6,000
5,000
4,000
3,000
Venus
Earth
Mars
62f
442b
1410b
438b
296e
1229b
186f
1512b
560b
Gliese 667Cc
Prox Cen b
TRAPPIST-1d
1e
1f
1g
0.5 $R_\oplus$
1 $R_\oplus$
1.5 $R_\oplus$
200%
175%
150%
125%
100%
75%
50%
25%
Starlight on planet relative to sunlight on Earth
Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/JPL

The use of 3D GCMs is important for assessing individual cases.



http://hzgallery.org/

Habitable Zone Gallery

Home **Plots** **Table** **Gallery** **Movies** **About** **Links**

This site is dedicated to tracking the orbits of exoplanets in relation to their Habitable Zones.

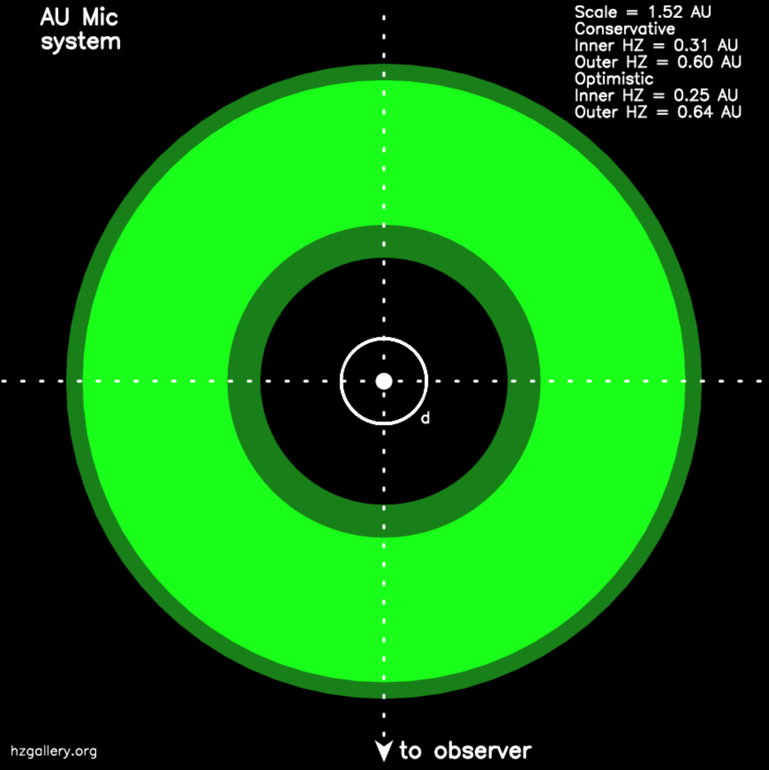
Planets: 5005 **Systems:** 3765
Planets with orbits entirely within the Habitable Zone: 158 [?]
Updated: 2024 09 06 13:52:19 PDT

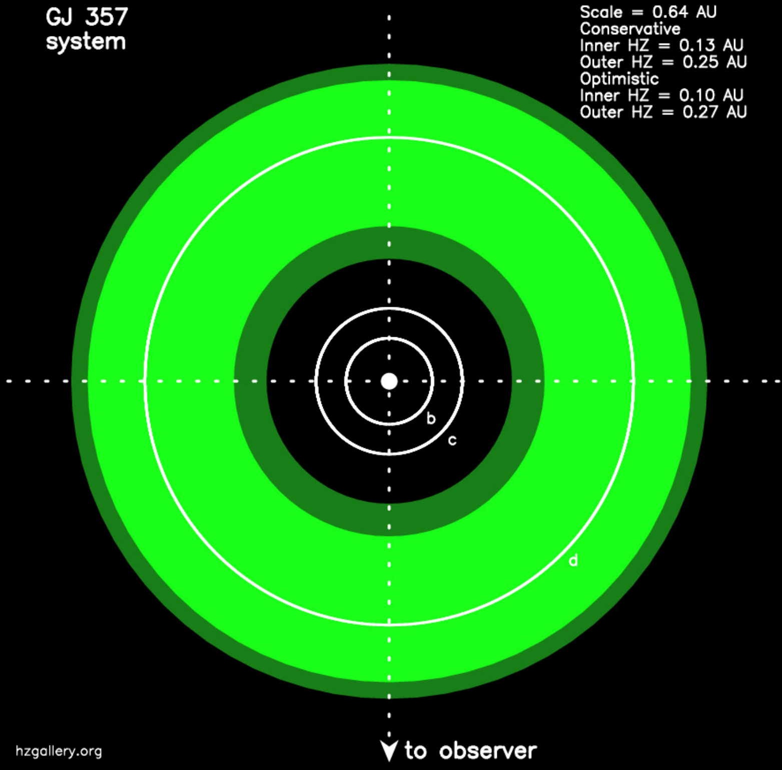
"The Earth is the only world known so far to harbor life. There is nowhere else, at least in the near future, to which our species could migrate. Visit, yes. Settle, not yet. Like it or not, for the moment the Earth is where we make our stand." - Carl Sagan

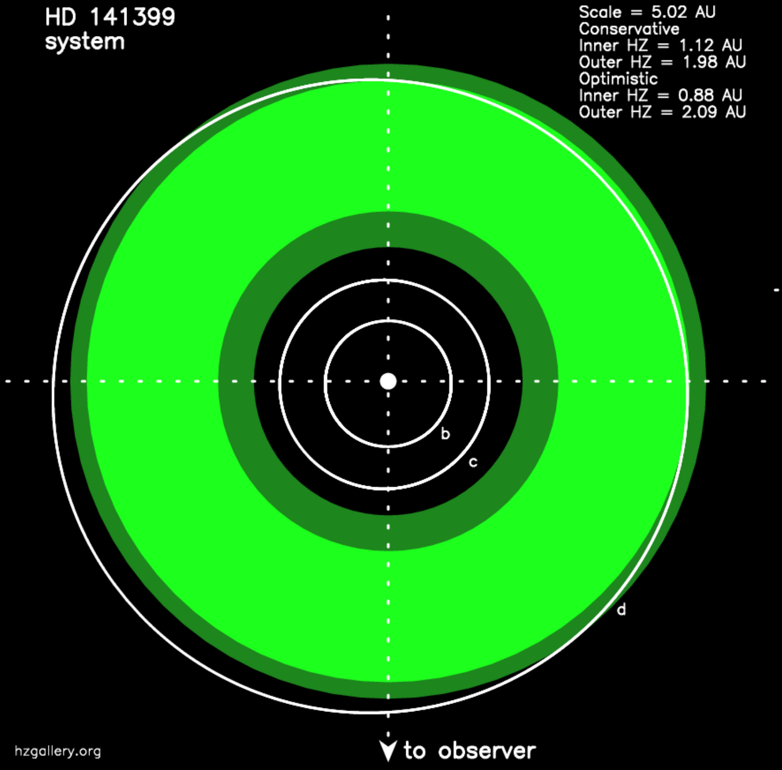
The effect of system architectures on planetary habitability

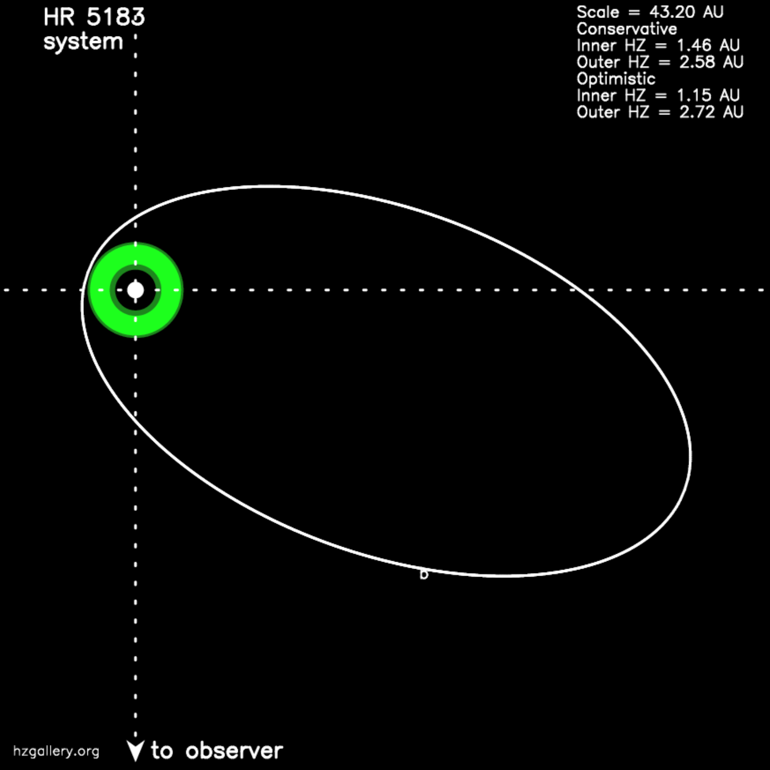
- Planetary architectures can dramatically influence the dynamics of (and sometimes prevent) terrestrial planet orbits within the Habitable Zone.

- Stable orbits with variable eccentricity can be maintained, resulting in significant climate effects.



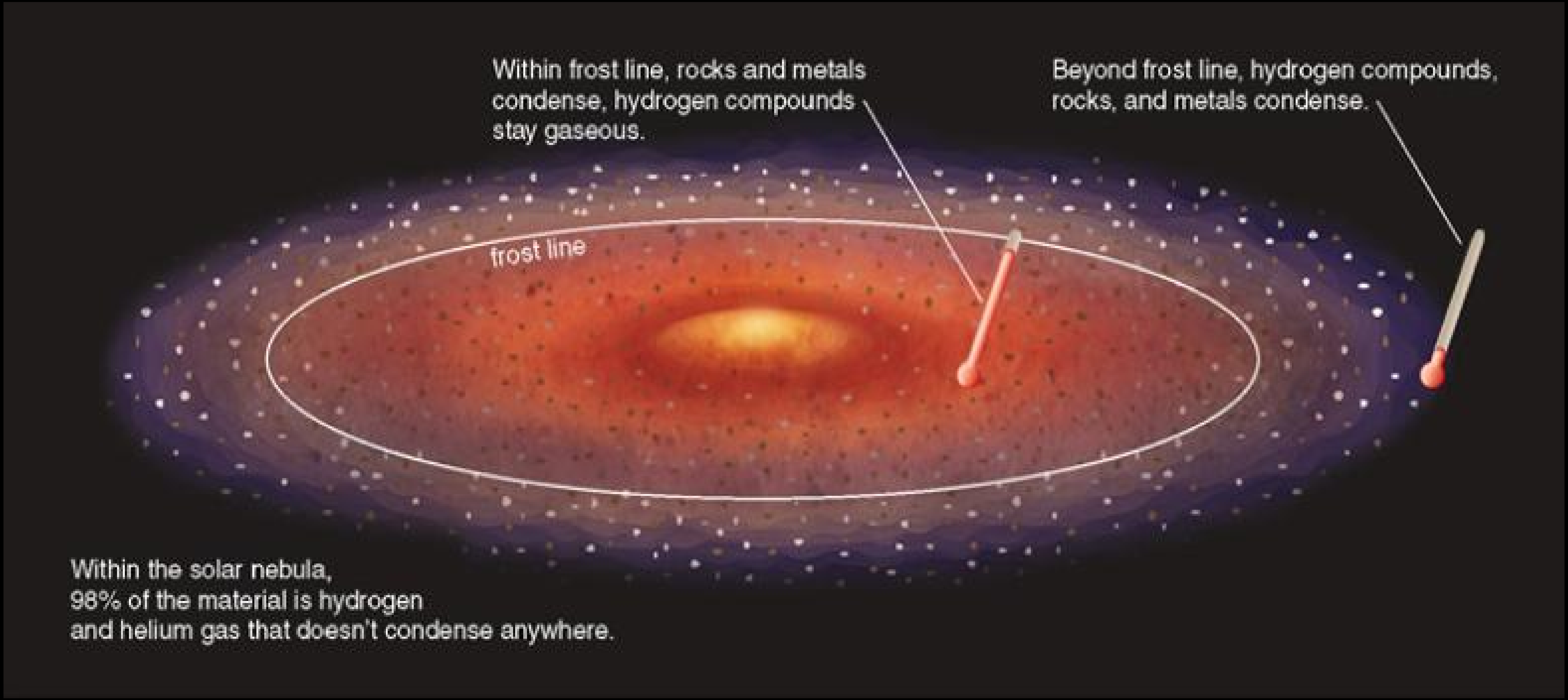




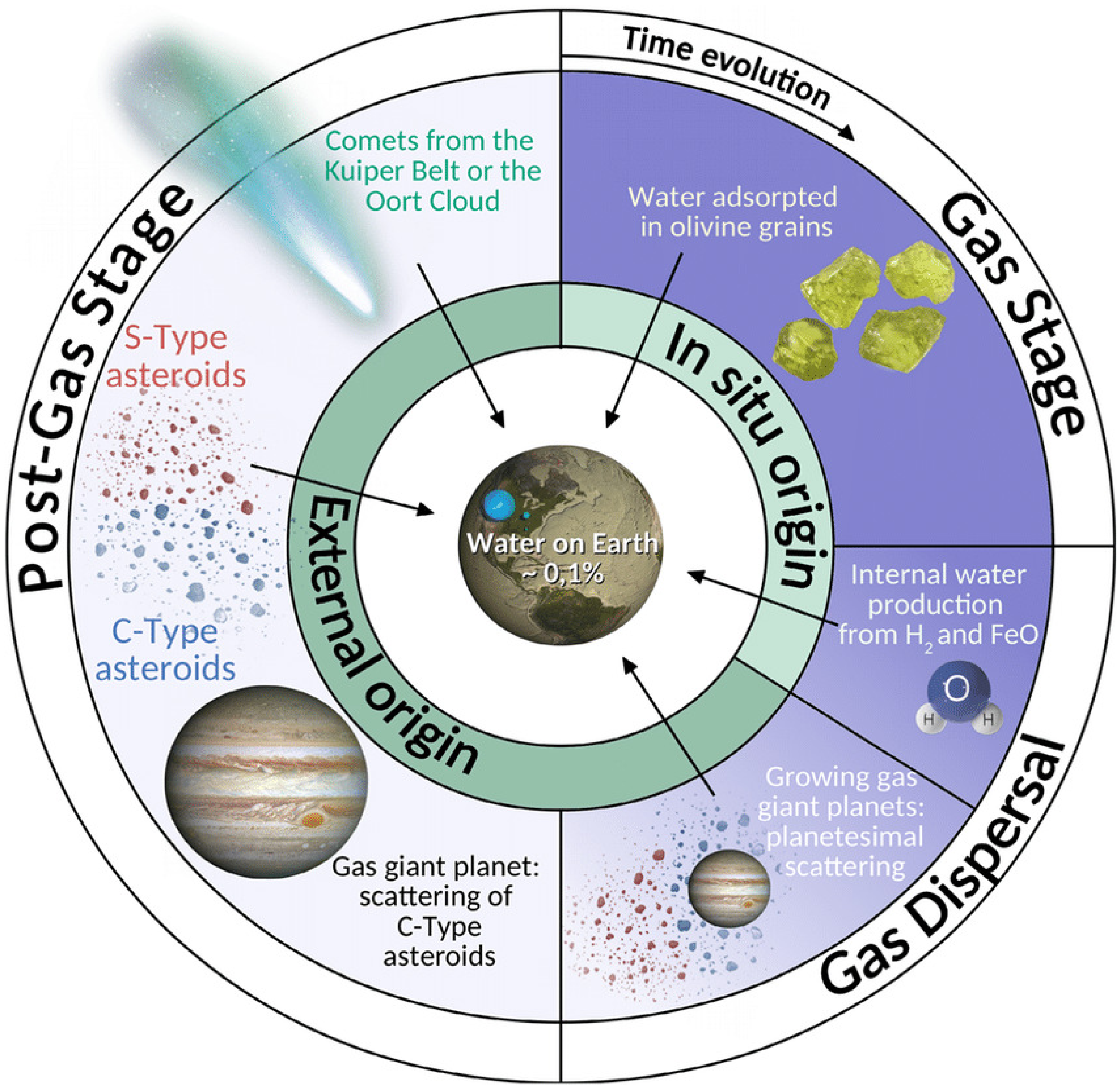


Kane & Blunt. “In the Presence of a Wrecking Ball: Orbital Stability in the HR 5183 System”, 2019, AJ, 158, 209
Kane et al. “Dynamical Packing in the Habitable Zone: The Case of Beta Cvn”, 2020, AJ, 160, 81
Kane et al. “Could the Migration of Jupiter Have Accelerated the Atmospheric Evolution of Venus?”, 2020, PSJ, 1, 42
Kane et al. “Eccentricity Driven Climate Effects in the Kepler-1649 System”, 2021, AJ, 161, 31
Kane et al. “Orbital Dynamics and the Evolution of Planetary Habitability in the AU Mic System”, 2022, AJ, 163, 20
Kane. “The Dynamical Consequences of a Super-Earth in the Solar System”, 2023, PSJ, 4, 38
Kane et al. “Revised Properties and Dynamical History for the HD 17156 System”, 2023, AJ, 165, 252
Kane. “Surrounded by Giants: Habitable Zone Stability Within the HD 141399 System”, 2023, AJ, 166, 187
Kane & Fetherolf. “GJ 357 d: Potentially Habitable World or Agent of Chaos?”, 2023, AJ, 166, 205

Where is all the water in planetary systems?



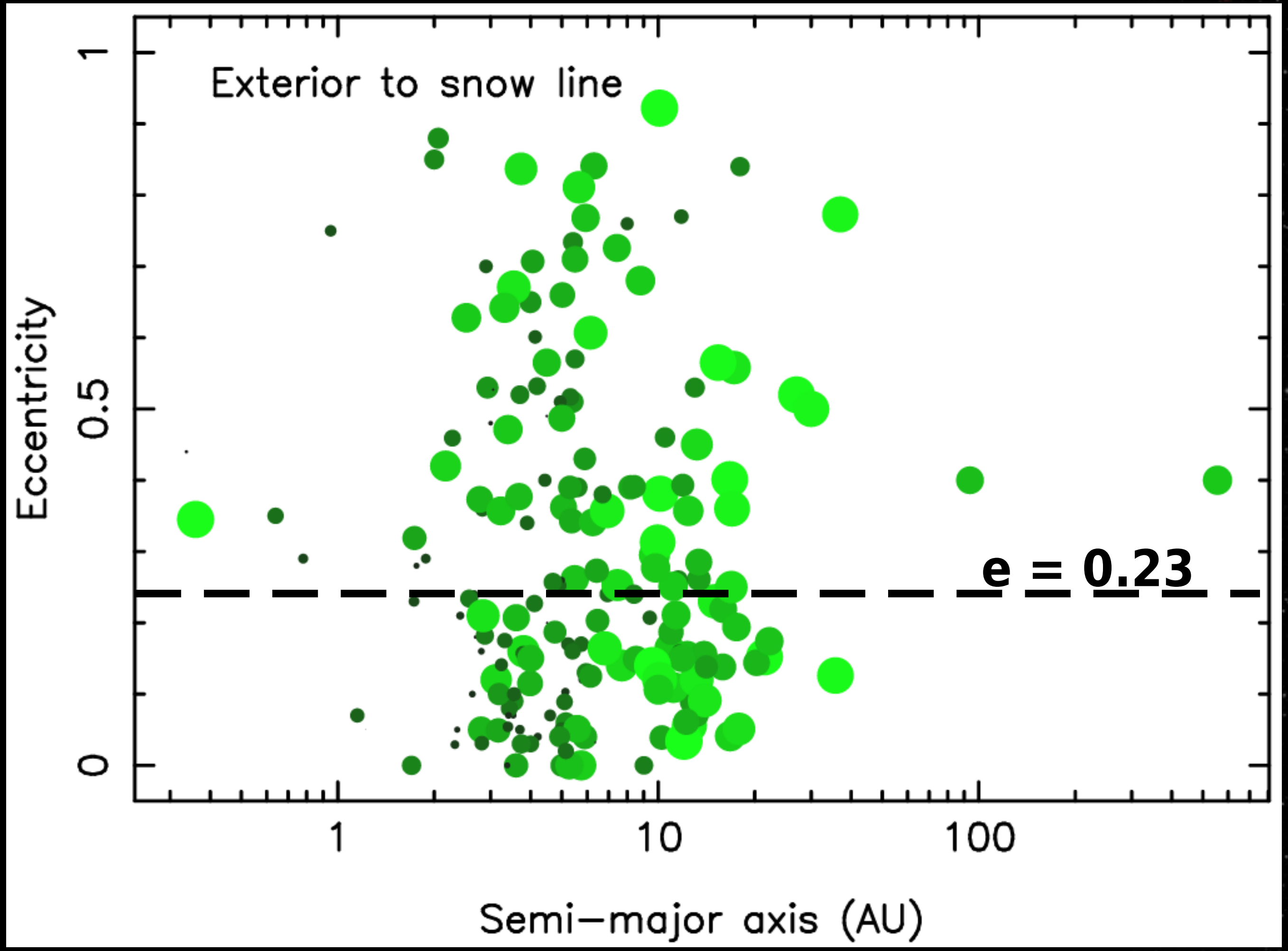
- **Inner parts of disk hotter than outer parts.**
- **Solidification: Condensation temperature.**
- **Inside snow/frost line: temperatures too hot for icy materials too condense.**
- **Outside snow/frost line: ices can form.**

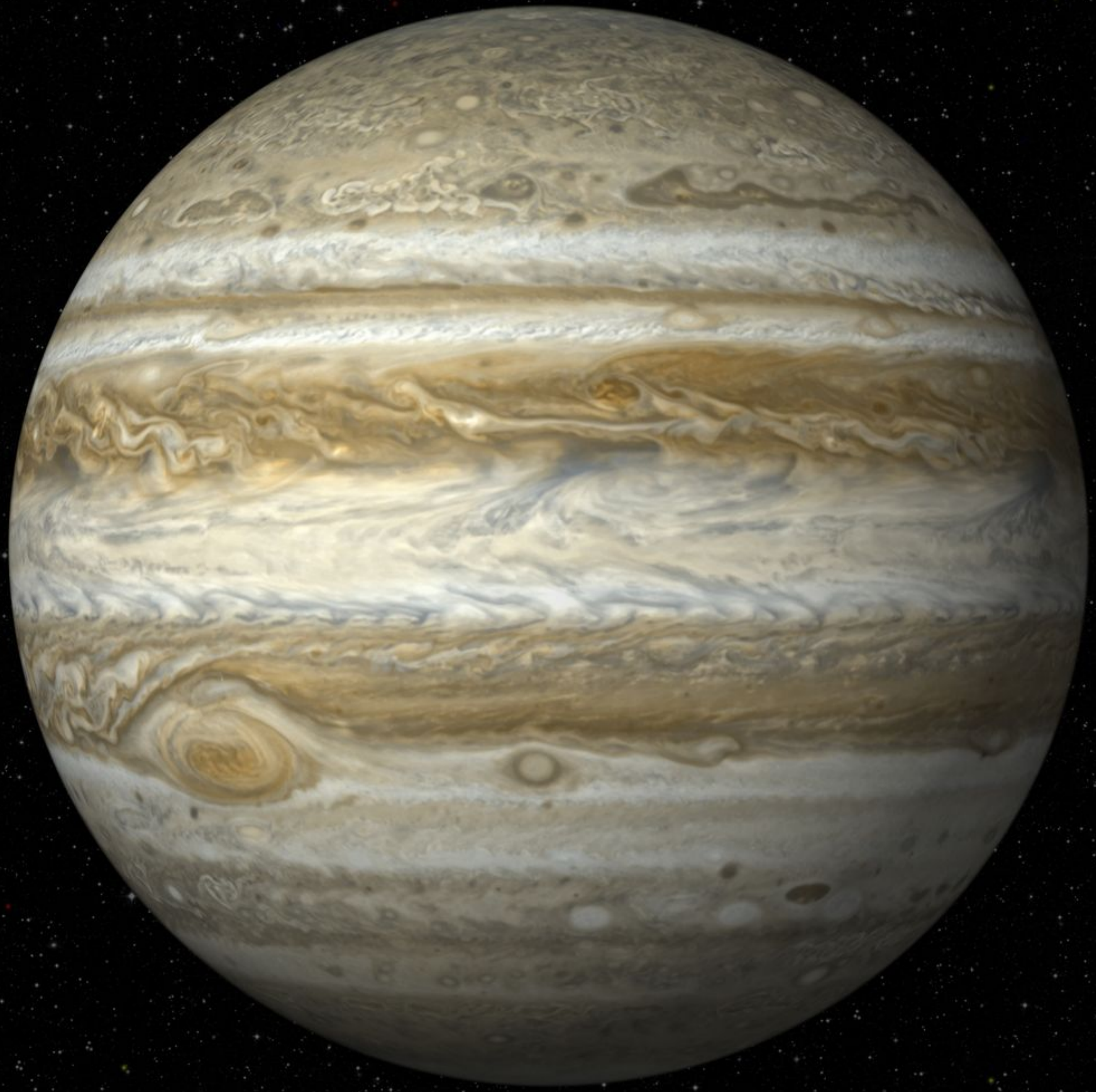


C-Type asteroids: dark carbonaceous objects (75% of known asteroids)
S-Type asteroids: stony (silicaceous) objects (17% of known asteroids)
Venturini et al. “Setting the Stage: Planet Formation and Volatile Delivery”, 2020, Space Sci Rev, 216, 86

What if the solar system had no Jupiter?

- Giant planets provide a primary mechanism for scattering volatiles within a system.
- The occurrence of giant planets beyond the snow line is ~10% (Wittenmyer et al. 2020; Fulton et al. 2021; Rosenthal et al. 2021; Bonomo et al. 2023).





Kane & Wittenmyer. "Eccentricity Distribution beyond the Snow Line and Implications for Planetary Habitability", 2024, ApJ, 962, L21

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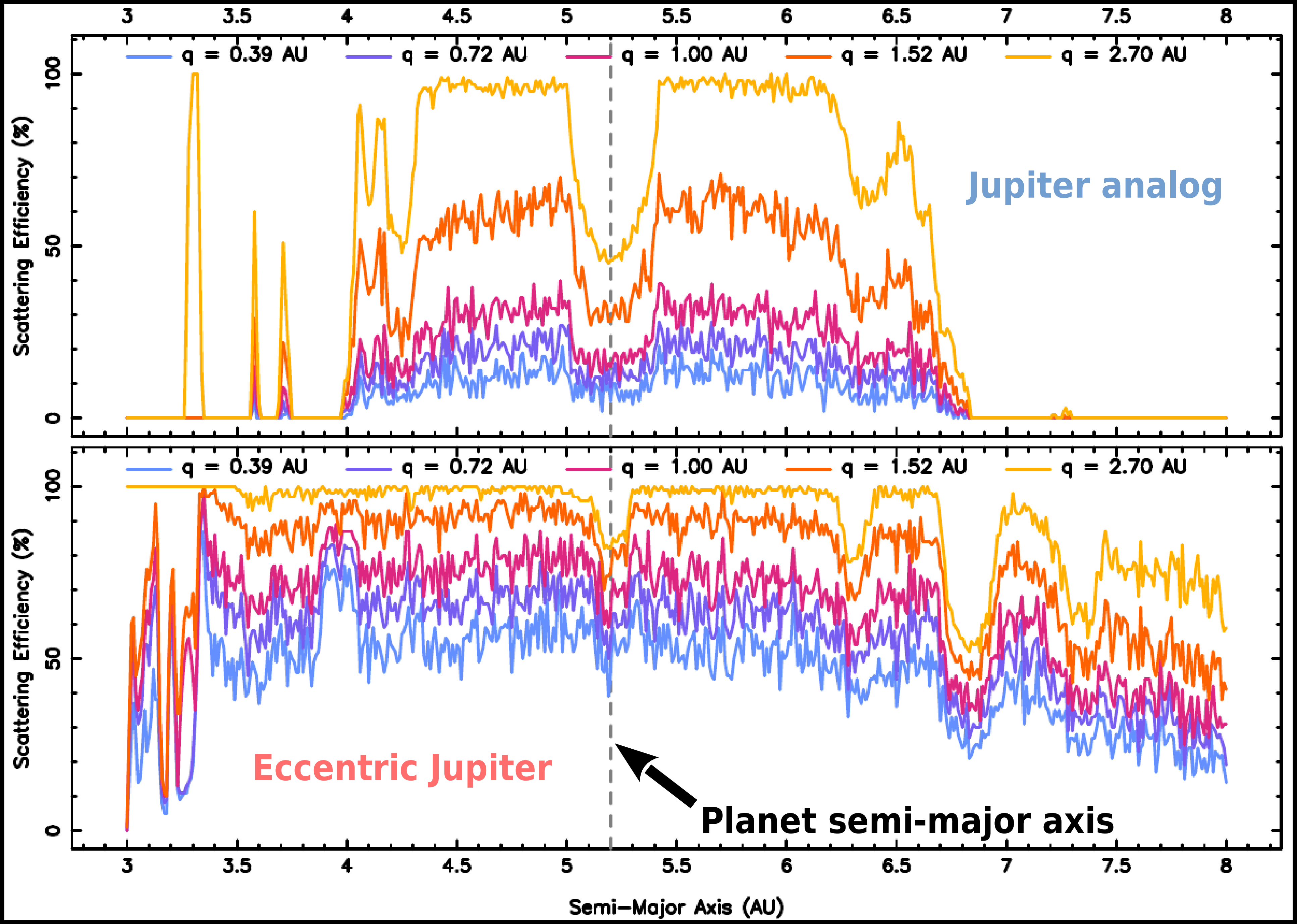
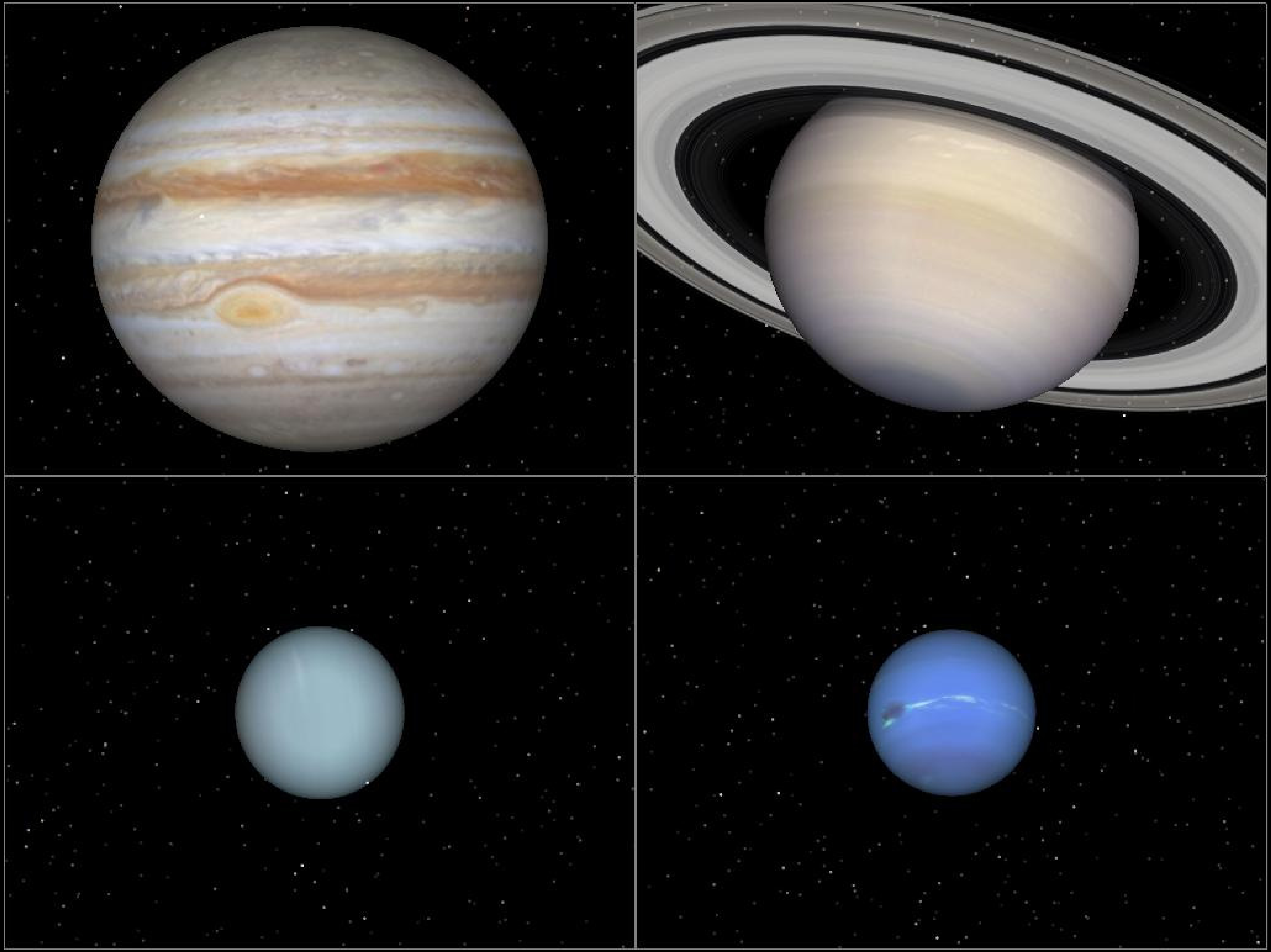


- Our dynamical simulations compare the volatile scattering potential of a Jupiter analog to an eccentric Jupiter.
- For the Jupiter analog case:
  Interior to snow line = 16.7%
  Interior to Earth orbit = 1.6%
- For the eccentric Jupiter case:
  Interior to snow line = 76.5%
  Interior to Earth orbit = 43.7%
- The eccentric Jupiter scatters 4.6x the amount of material interior to the snow line, and 27.3x the amount of material into Earth-crossing orbits, compared with the Jupiter analog case.

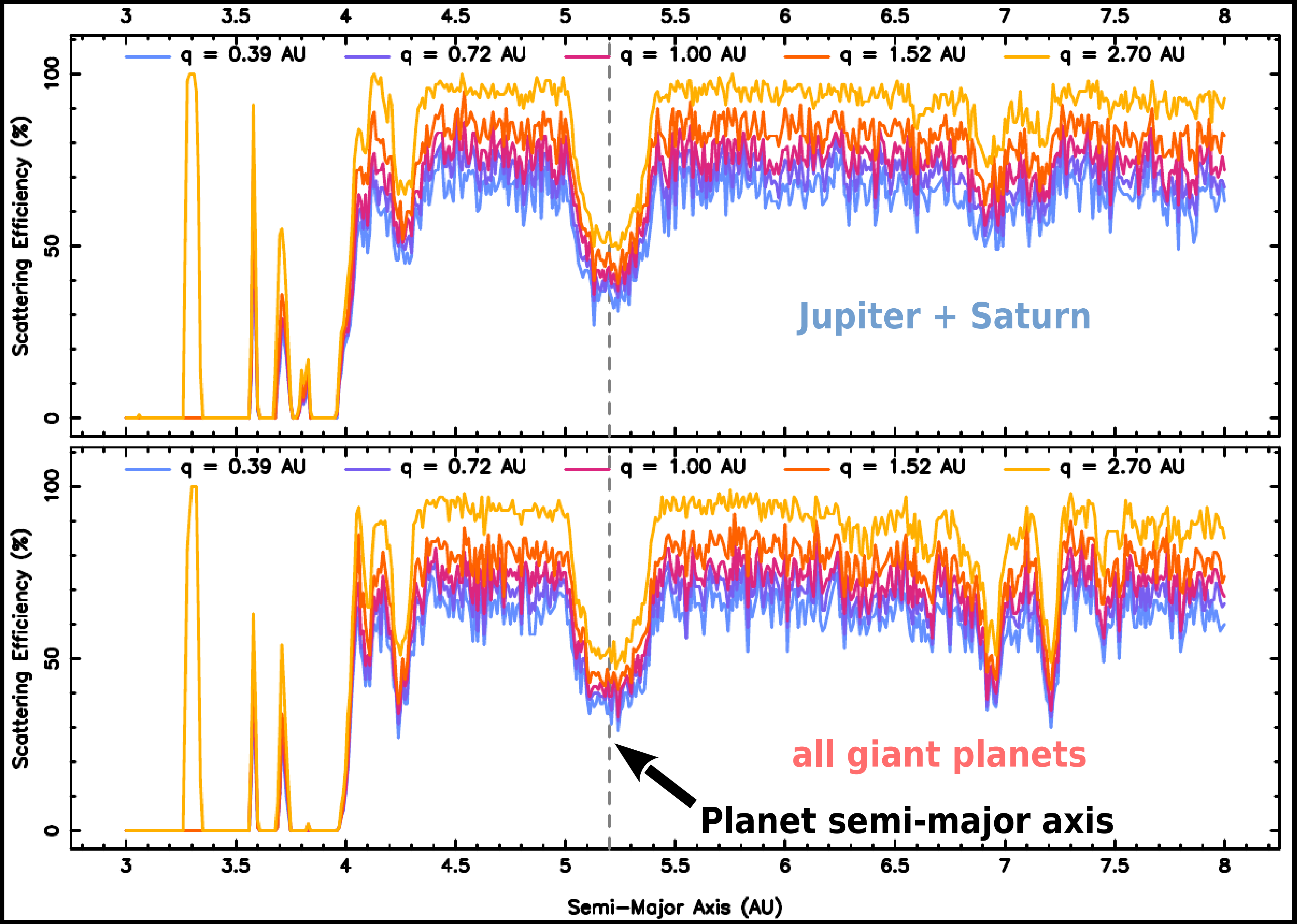
Kane & Wittenmyer. "Eccentricity Distribution beyond the Snow Line and Implications for Planetary Habitability", 2024, ApJ, 962, L21

Adding the full solar system giant planet inventory



Kane & Miles. “The Role of Solar System Giant Planets in Volatile Delivery to the Terrestrial Planets”, 2024, ApJ, submitted

Adding the full solar system giant planet inventory

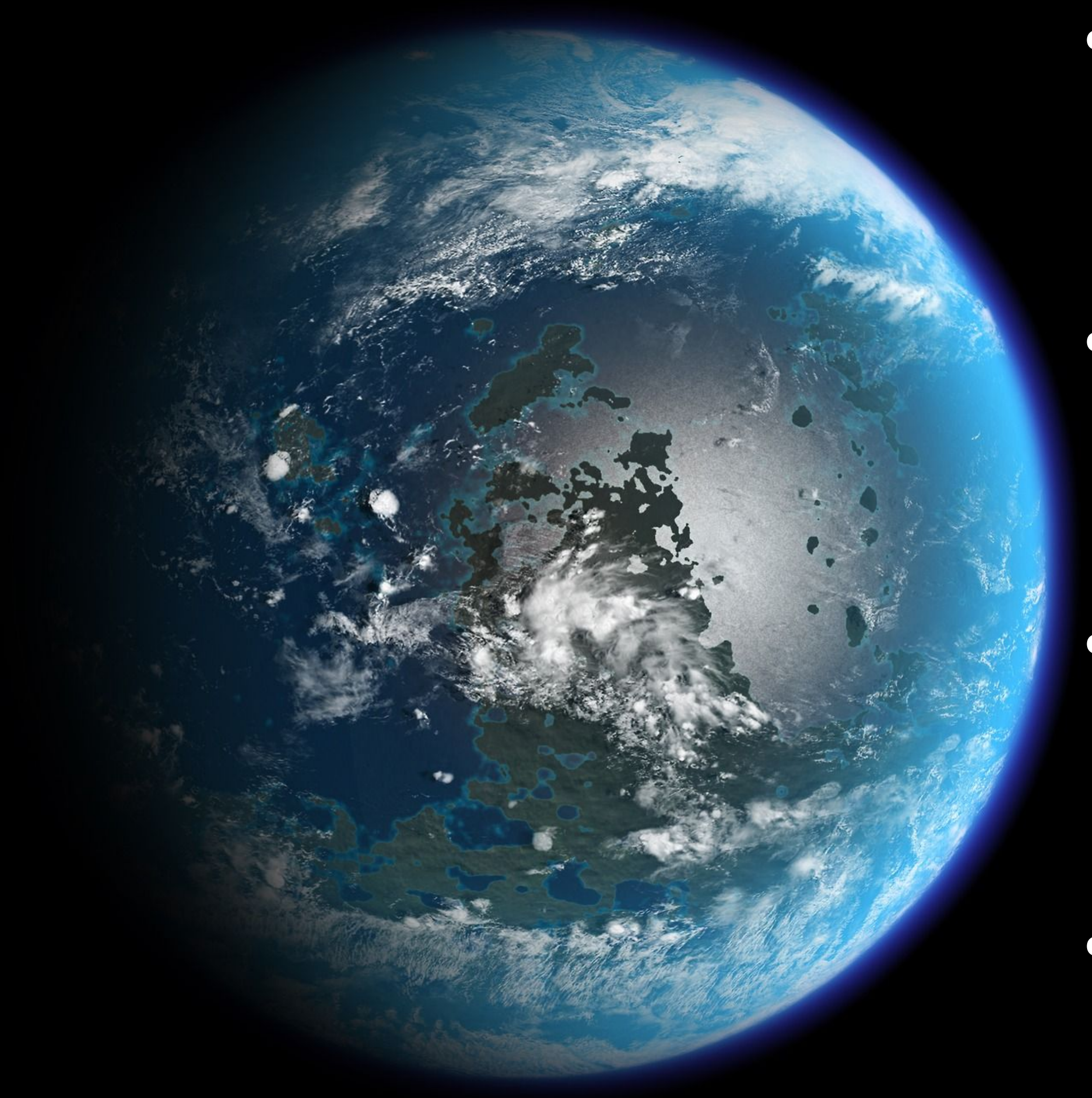


- Saturn's Hill radius is ~20% larger than Jupiter. Additional planets also result in angular momentum exchanges that oscillate eccentricity.
- For the Jupiter+Saturn case:
  Interior to snow line = 63.8%
  Interior to Earth orbit = 49.3%
- For the all giant planets case:
  Interior to snow line = 53.8%
  Interior to Earth orbit = 45.4%
- The inclusion of Uranus and Neptune in the all giant planets case results in a net decrease in inward volatile flux compared with the Jupiter + Saturn case. This is caused by increase outward flux and angular momentum transfer to the outer planets.

Kane & Miles. "The Role of Solar System Giant Planets in Volatile Delivery to the Terrestrial Planets", 2024, ApJ, submitted

Back to Venus!

- Impact probability for long period objects depends on orbital period of terrestrial planet and cross-sectional area.
- For the solar system terrestrial planets, the impact probabilities are 93%, 170%, and 12% for Mercury, Venus, and Mars, respectively, relative to Earth.
- Thus, for volatiles received from beyond the snow line, Venus received almost twice the amount of water than Earth, requiring substantial water loss until the present.



- For the Jupiter analog case:
  Interior to snow line = 16.7%
  Interior to Earth orbit = 1.6%
  Interior to Venus orbit = 0.9%

- For the eccentric Jupiter case:
  Interior to snow line = 76.5%
  Interior to Earth orbit = 43.7%
  Interior to Venus orbit = 36.5%

- For the Jupiter+Saturn case:
  Interior to snow line = 63.8%
  Interior to Earth orbit = 49.3%
  Interior to Venus orbit = 46.3%

- For the all giant planets case:
  Interior to snow line = 53.8%
  Interior to Earth orbit = 45.4%
  Interior to Venus orbit = 43.0%

Kane & Miles. “The Role of Solar System Giant Planets in Volatile Delivery to the Terrestrial Planets”, 2024, ApJ, submitted

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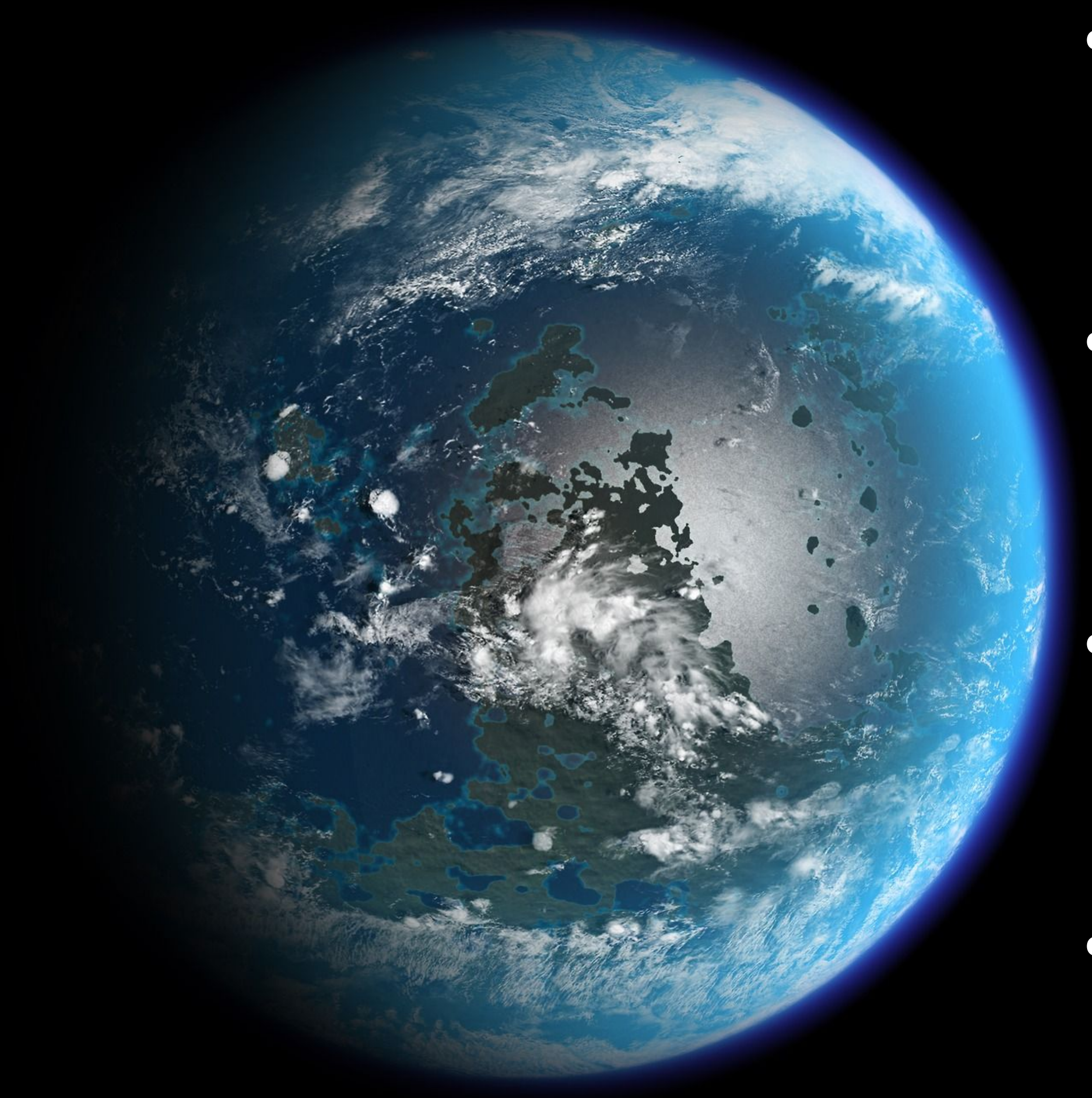

- For the Jupiter analog case:
  Interior to snow line = 16.7%
  Interior to Earth orbit = 1.6%
  Interior to Venus orbit = 0.9%

- For the eccentric Jupiter case:
  Interior to snow line = 76.5%
  Interior to Earth orbit = 43.7%
  Interior to Venus orbit = 36.5%

- For the Jupiter+Saturn case:
  Interior to snow line = 63.8%
  Interior to Earth orbit = 49.3%
  Interior to Venus orbit = 46.3%

- For the all giant planets case:
  Interior to snow line = 53.8%
  Interior to Earth orbit = 45.4%
  Interior to Venus orbit = 43.0%

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Kane & Miles. "The Role of Solar System Giant Planets in Volatile Delivery to the Terrestrial Planets", 2024, ApJ, submitted

Conclusions

1. Understanding the initial water inventory of terrestrial planets (e.g., Venus and Earth) and the relative contributions of accretion versus delivery remains an outstanding issue of planetary habitability evolution. Models of surface liquid water are fundamental to defining the Habitable Zone boundaries.

2. Giant planets can have a profound effect on the redistribution of volatiles within the system. A lack of giant planets beyond the snow line can significantly truncate volatile delivery to the inner region of planetary systems.

3. Even a moderate eccentricity (0.2-0.3) for Jupiter can result in more than an order of magnitude increase in volatile delivery rates compared with the Jupiter analog case.

4. Adding additional giant planets to a system changes the time-dependent angular momentum distribution throughout the system. For example, the addition of Saturn to the Jupiter scattering profile creates a scattering effect equivalent to an eccentric Jupiter, such as those detected in exosystems.

5. Distant ice giants, such as Uranus and Neptune, can decrease the volatile flux to the inner system by transferring angular momentum away from the primary scattering agents: Jupiter and Saturn.

6. Venus received at least as much water from beyond the snow line as Earth, emphasizing the need to study water loss processes for terrestrial planets.