

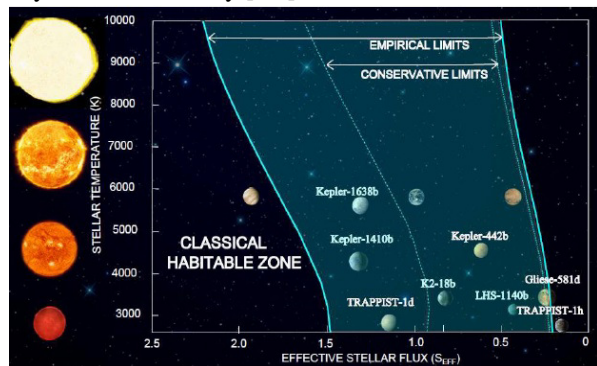
# IMPROVING THE HABITABLE ZONE USING MORE DYNAMIC DEFINITIONS OF HABITABILITY

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**Introduction:** The habitable zone (HZ) is the circular region around a star(s) where standing bodies of water could exist on the surface of a rocky planet (Figure 1) [1,2]. Space missions employ the HZ to select promising targets for follow-up habitability assessment. The classical HZ definition assumes that the most important greenhouse gases for habitable planets orbiting main-sequence stars are CO<sub>2</sub> and H<sub>2</sub>O [1]. Although the classical HZ is a useful navigational tool, recent HZ formulations demonstrate that it cannot thoroughly capture the diversity of habitable exoplanets.

In this review talk, I discuss the planetary and stellar processes considered in both classical and newer HZ formulations. Supplementing the classical HZ with additional considerations from these newer formulations improves our capability to filter out worlds that are unlikely to host life. Such improved HZ tools will be necessary for current and upcoming missions aiming to detect and characterize potentially habitable exoplanets.

In addition, as we consider next generation missions in the search for extraterrestrial life (e.g. HabEX, LUVOIR, and OST), I also discuss the importance of improved observations, and what needs to be done to advance future models of the HZ from a first principles approach in the burgeoning field of “dynamic habitability [2,3].”



**Figure 1:** Extended classical habitable zone for stellar temperatures from 2,600 to 10,00 K. Reproduced from ref [2]

## Rethinking the Classical Habitable Zone

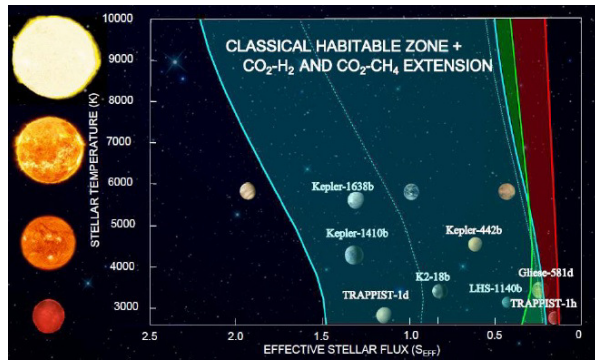
The HZ is still the best metric out there for finding life on other planets, but it needs a modern update. Here are a few example of topics I will be discussing in more detail in my talk.

## *Is the carbonate-silicate cycle really universal?*

Several Earth-centric assumptions define the standard habitable zone. This “classical HZ” is traditionally characterized by H<sub>2</sub>O-dominated planets near the inner edge and CO<sub>2</sub>-dominated planets at the outer edge [1]. This variation in atmospheric composition with distance is assumed to be dictated by the carbonate-silicate cycle, which is thought to regulate CO<sub>2</sub> levels over million-year timescales on our planet[1]. However, there is still no direct evidence that this cycle exists on Earth, and even if it does, the details are poorly understood and its universality elsewhere is completely untested [2,4]. That said, we should be able to test the existence of a universal carbonate-silicate cycle with upcoming missions that will measure CO<sub>2</sub> levels in planetary atmospheres in many stellar systems. Even should such a cycle prove common throughout the cosmos, this would not preclude the existence of other planets, including ocean worlds, which might be habitable on long timescales through other means [5].

## *The untested universality of habitable planets with CO<sub>2</sub>-H<sub>2</sub>O atmospheres*

The notion that CO<sub>2</sub> and H<sub>2</sub>O are the only greenhouse gases of importance in potentially habitable planets, is another related and untested assumption of the classical HZ. Moreover, CO<sub>2</sub> levels of planets near the outer edge of the classical habitable zone are so high that they would be poisonous to Earth-like life anyway [1], which makes its overall utility questionable for finding Earth-like life. However, less CO<sub>2</sub> is needed to foster habitable surface conditions if the additional warming from secondary greenhouse gases is considered. For instance, hydrogen outgassing from volcanoes, together with CO<sub>2</sub> and H<sub>2</sub>O, can increase HZ width by ~50% [6] (Figure 2). The solar system HZ can extend outward to near Saturn’s orbit if habitable planets can acquire primordial H<sub>2</sub> envelopes [7]. Such planets are also considerably easier to observe via transmission spectroscopy than are CO<sub>2</sub>-rich planets [6,8]. Other gases, like CH<sub>4</sub>, which are mostly produced by life on Earth, may play a bigger role on other planets, potentially being a major greenhouse gas for worlds orbiting hotter stars [9] (Figure 2).



**Figure 2:** The classical HZ (blue) with  $\text{CO}_2\text{-CH}_4$  (green) and  $\text{CO}_2\text{-H}_2$  (red) extension for stars of temperatures between 2,600 and 10,000 K. Classical HZ shown as in Fig. 1. Reproduced from ref [2]

### *Dynamic Habitability: A First Principles Approach*

It is for reasons (such as those above) that improving our understanding of planetary habitability (and, ultimately, life) outside of our solar system will require employing an approach from first principles. If we wish to better understand what makes planets habitable we cannot continue to a priori assume that randomly selected characteristics that are true on Earth *must* all apply elsewhere. This is yet another untested assumption that must be verified with observations. Indeed, there has been the push towards the concept of dynamic habitability, which holds that planetary habitability is a function of the planet and its environment over spatial and temporal scales [3].

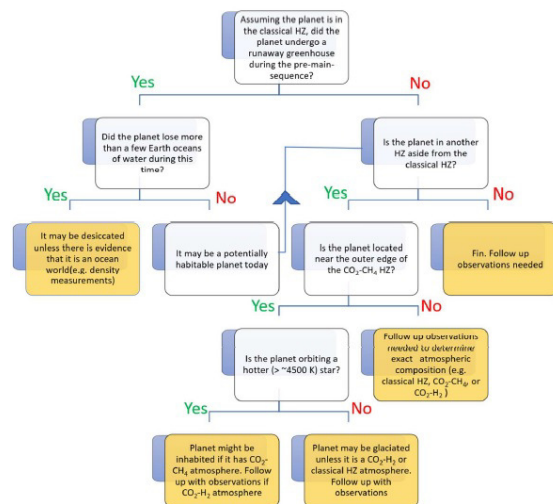
### *A more comprehensive habitable zone for finding life on other planets*

Ramirez [2] recently published the first review paper (to the author's knowledge) of dynamic habitability in the literature, showing how the HZ concept, which was once considered to be very Earth-centric, is really much more versatile than what has been credited in the past. Although the HZ can continue to be used to find potentially habitable planets that are similar to our own planet, it is also well-equipped to be used to search for those that we may not consider to be "Earth-like."

A few examples of planets that may exhibit life as *we-do-not-know-it* include, worlds with non-traditional hydrogen-rich or methane rich atmospheres, planets orbiting binary stars, worlds around white dwarfs, habitats orbiting red giants, environments around very young and luminous stars, and even ocean worlds (summarized in ref 2).

The main concepts in that review paper culminated in a discussion that provided many suggestions that current and upcoming mission concepts (e.g HabEX, LUVOIR, and OST) can employ in their search. An example of how this extended HZ can be applied is shown in Figure 3.

It is my hope that this review talk incites new discussion, leading to new research into the prospects for life elsewhere, and especially how we can best target it.



**Figure 3:** Sample flow chart using the classical HZ, along with  $\text{CO}_2\text{-H}_2$ ,  $\text{CO}_2\text{-CH}_4$ , and pre-main-sequence HZ extensions to assess the potential habitability of planets. End states are in yellow. Reproduced from ref [2]

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