Future Work on Potentially Habitable and Inhabited Rocky Planets

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Johns Hopkins APL | Senior Staff Scientist

Friday July 25, 2025

Are we alone?

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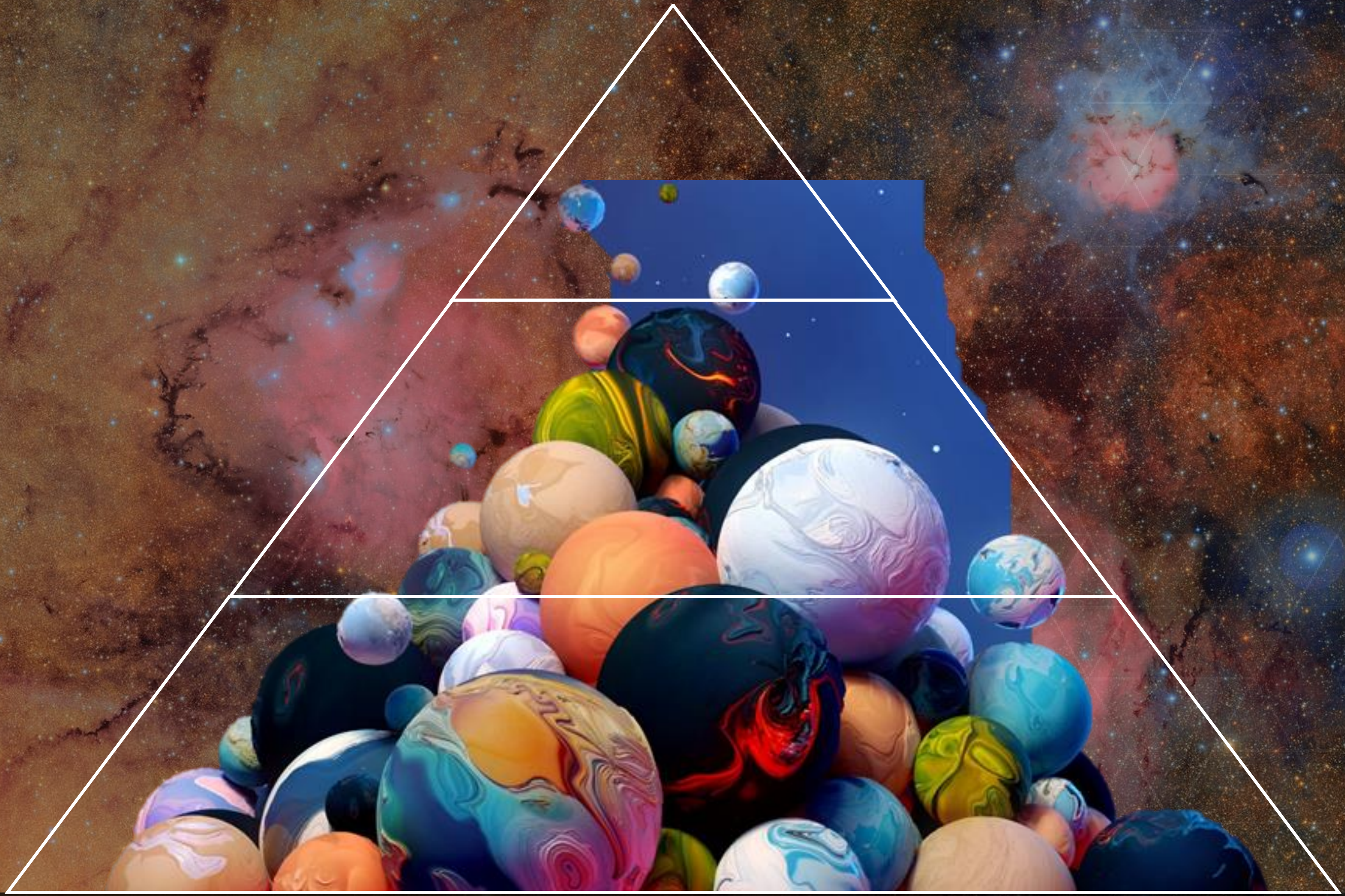

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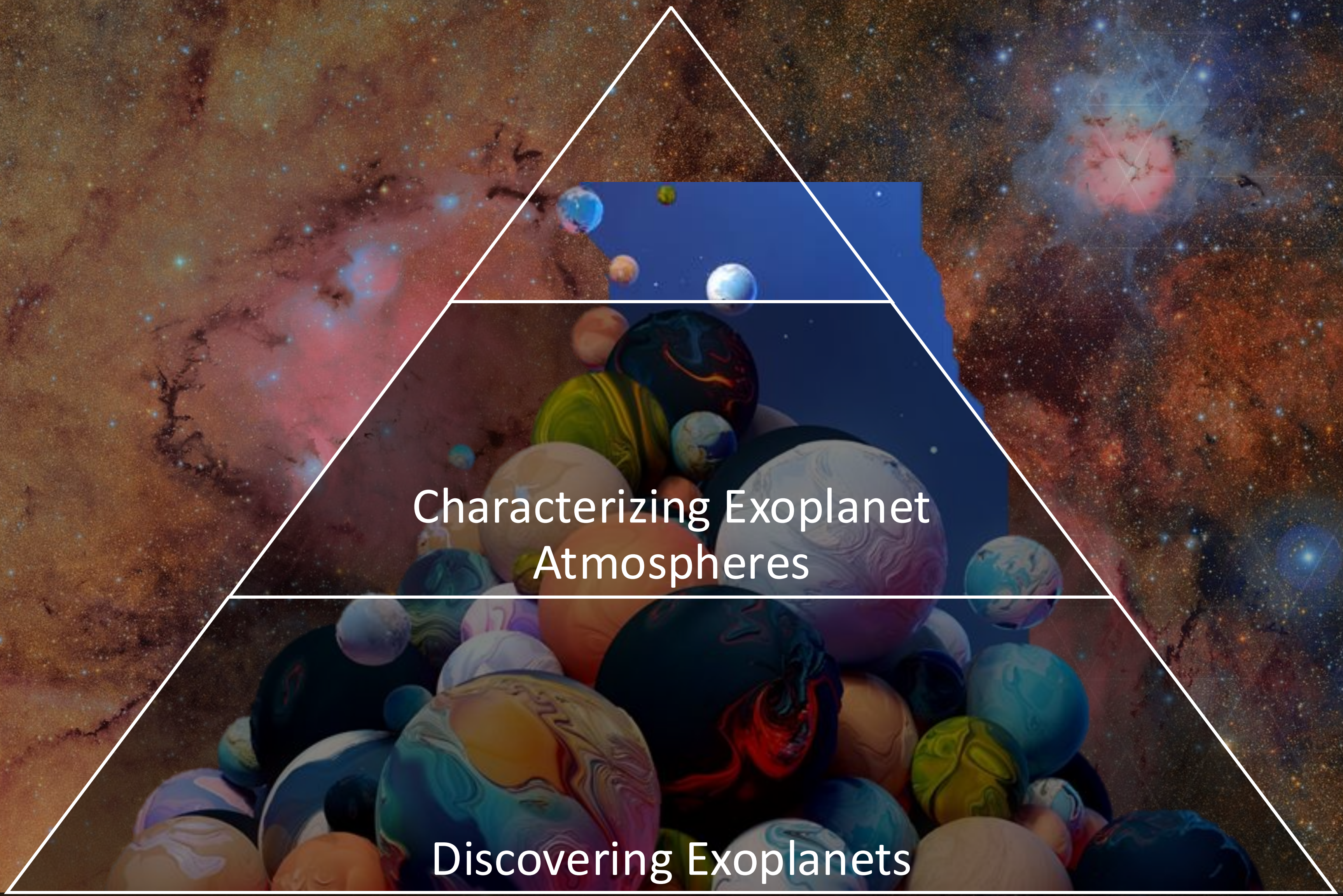
Characterizing Exoplanet Atmospheres
Discovering Exoplanets

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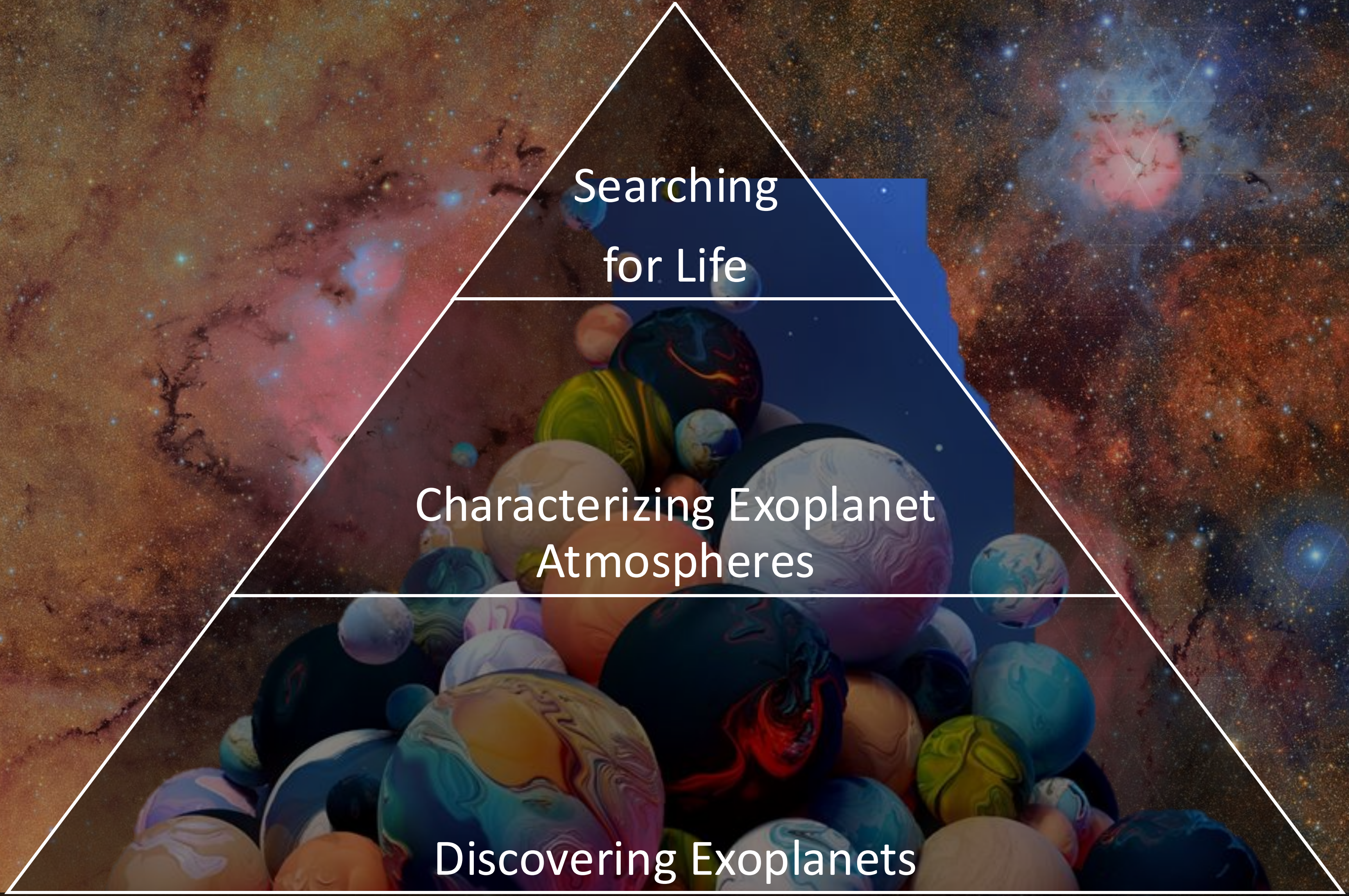
Searching
for Life
Characterizing Exoplanet
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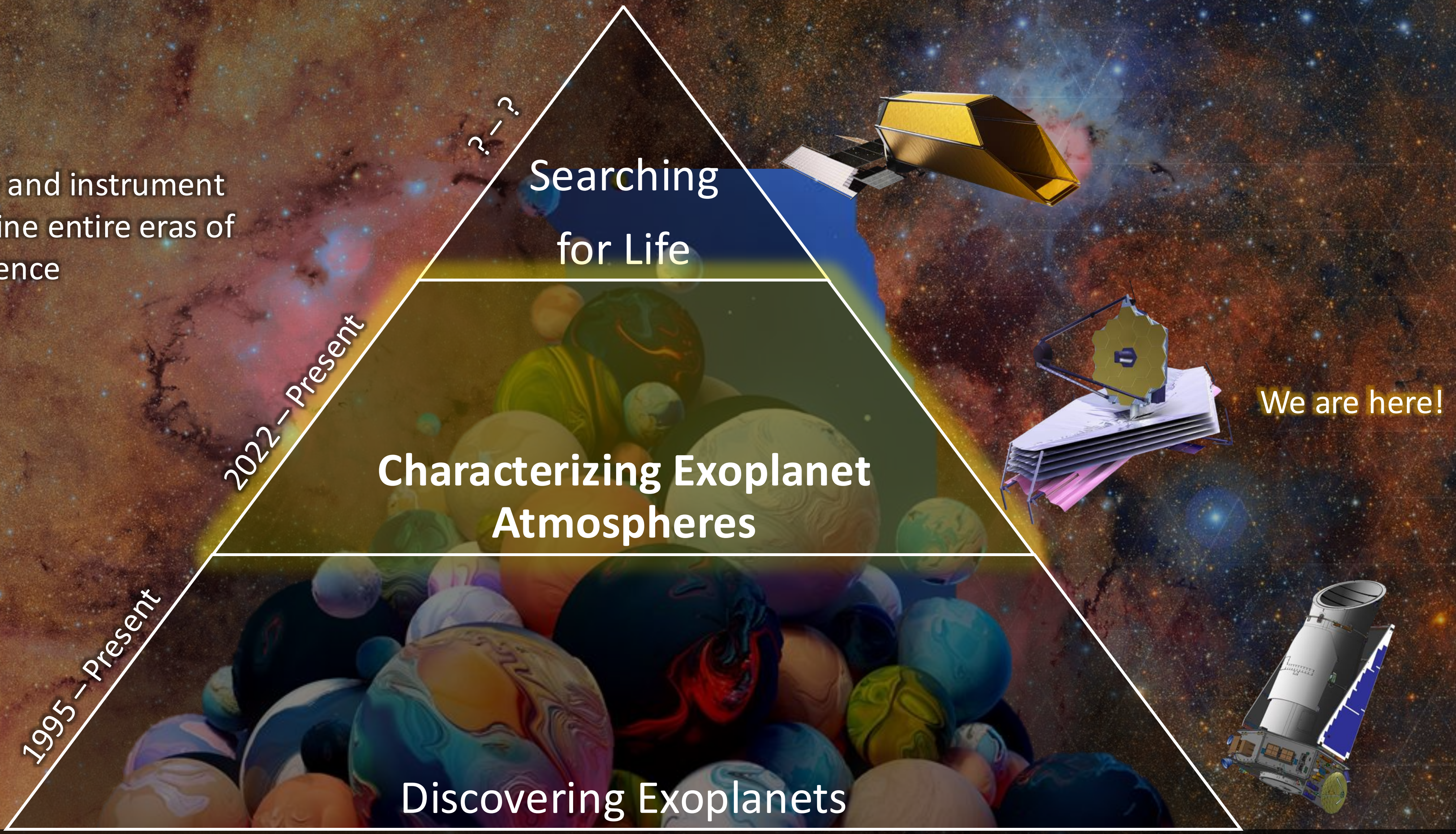
Are we alone?

New telescope and instrument capabilities define entire eras of science



What can we learn about rocky exoplanet environments in the coming decades?

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Astro2020; Exoplanet Science Strategy (2018)

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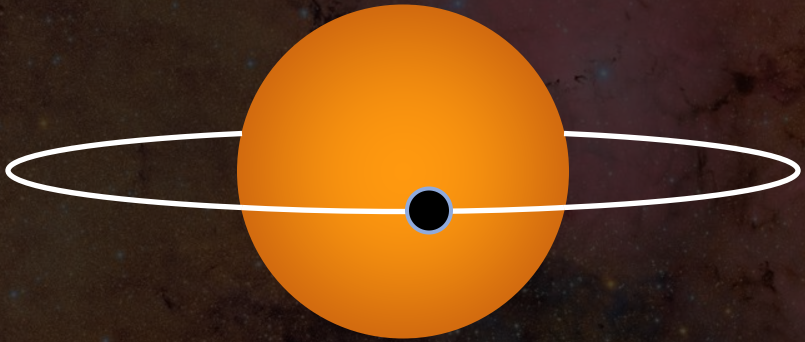
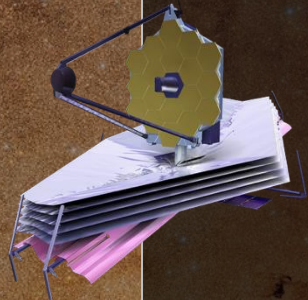
"The M-dwarf opportunity"

2020s+

M dwarfs

Transiting Exoplanet Science





Facilities: JWST, 30m Ground-based

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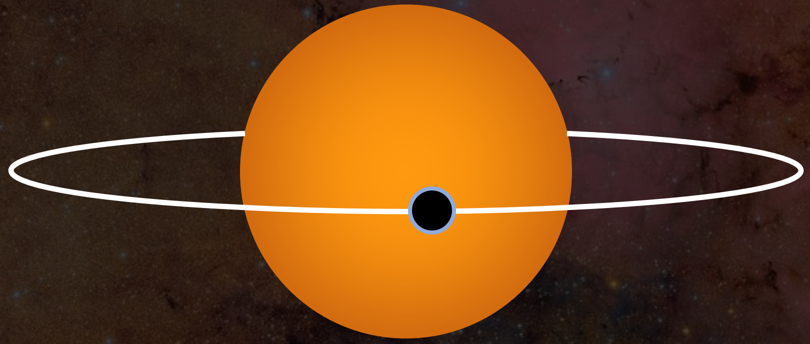

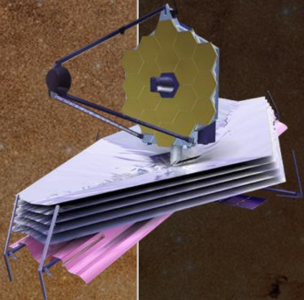

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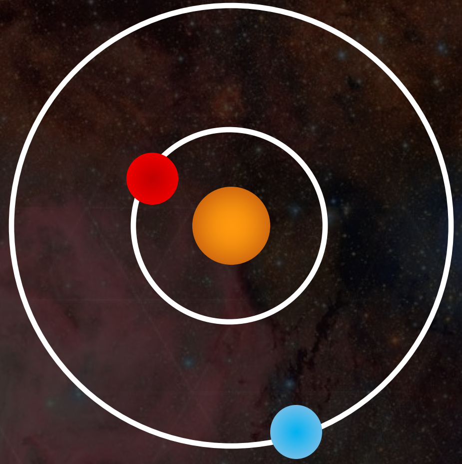
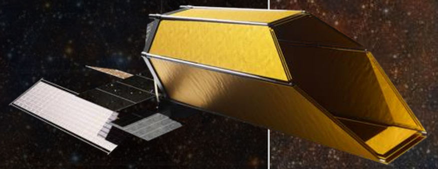
"Earth-like planets around Sun-like stars"

2030s+

F,G,K,M dwarfs

Exoplanet Direct Imaging

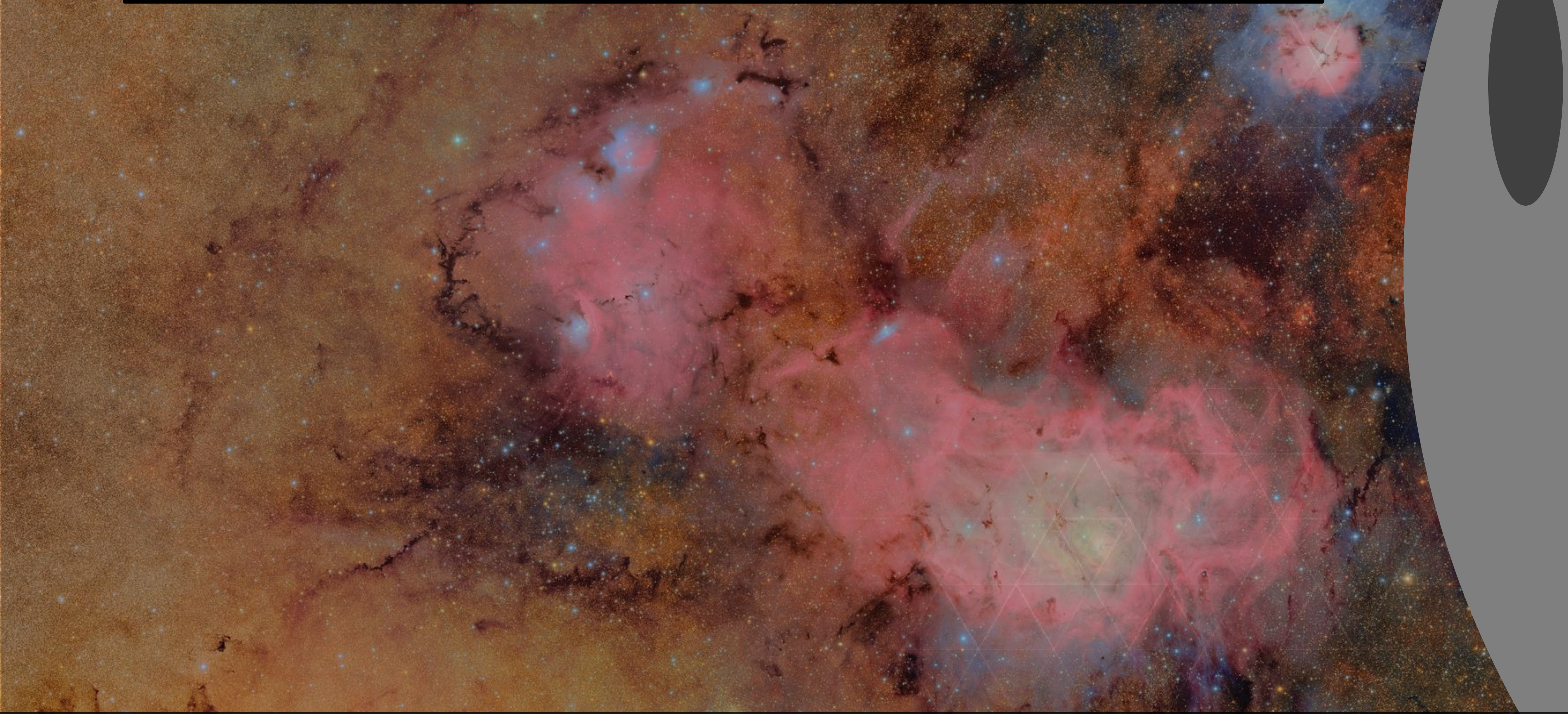




Facilities: NASA's Habitable Worlds Observatory, LIFE Mission Concept

Astro2020; Exoplanet Science Strategy (2018)

Rocky Exoplanet Characterization
Big Picture Questions:



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Big Picture Questions:

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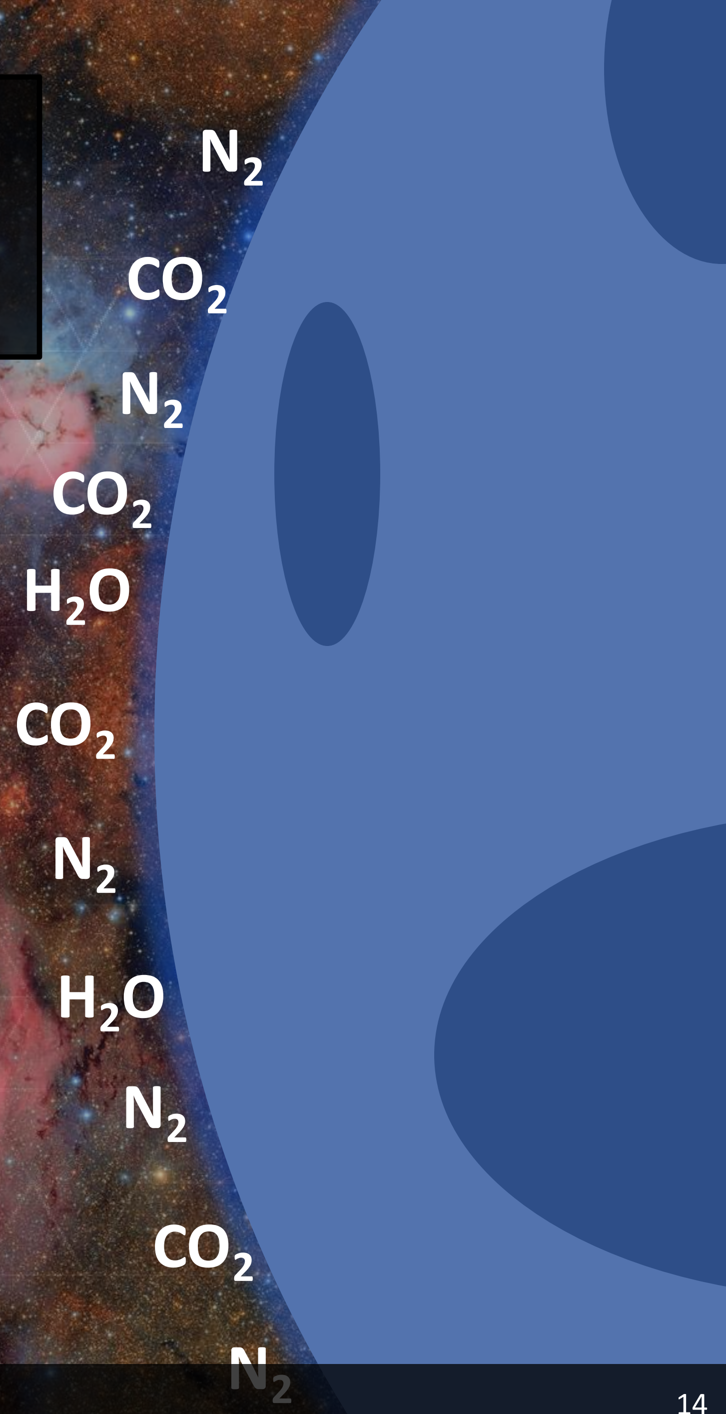
2. **What is the nature of the atmosphere?**



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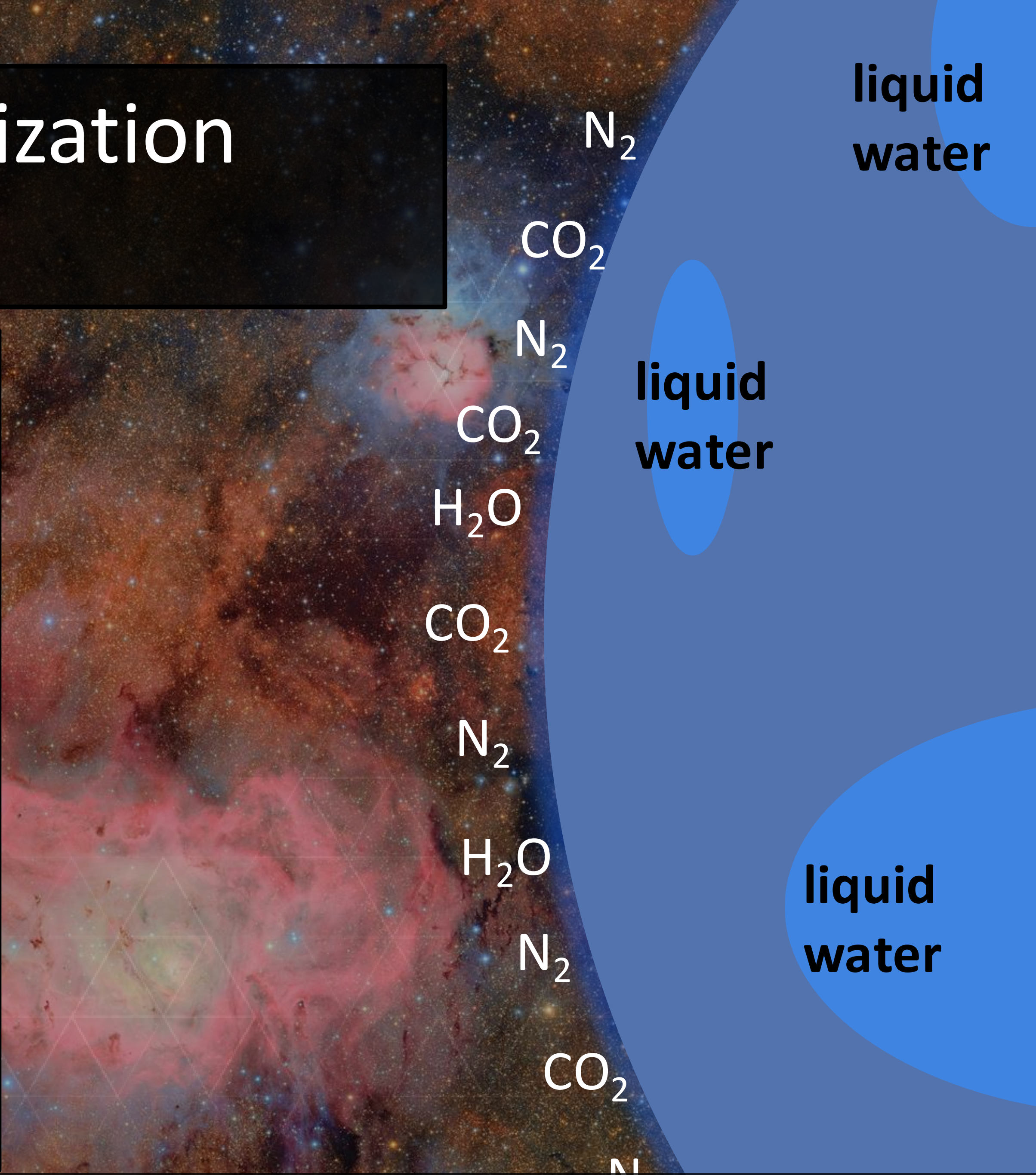
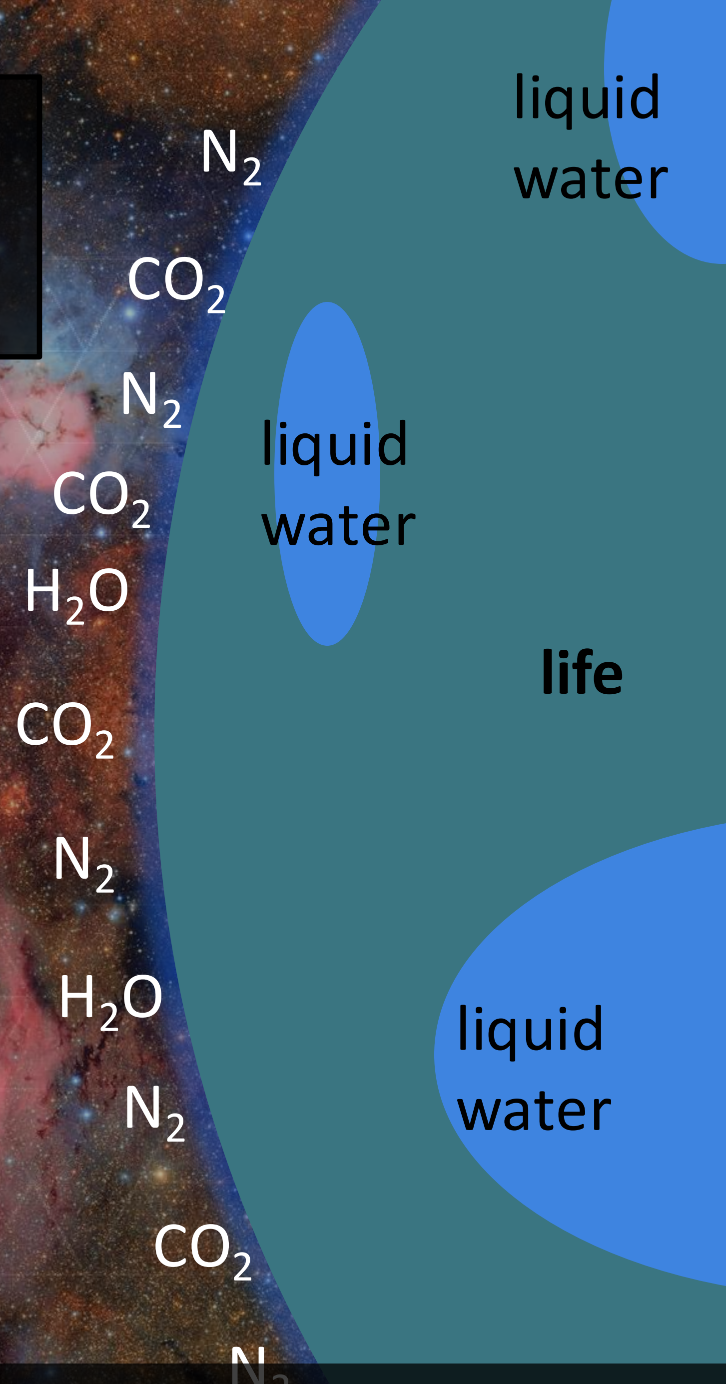
2. What is the nature of the atmosphere?
3. **Is the planet habitable?**



Rocky Exoplanet Characterization
Big Picture Questions:

1. Does the planet have an atmosphere?
2. What is the nature of the atmosphere?
3. Is the planet habitable?
4. **Does the planet have signs of life?**



Rocky Exoplanet Characterization
Big Picture Population Questions:

Atmospheric Demographics

1. How common are atmospheres on rocky exoplanets around different stellar types?
2. What physical and chemical processes shape the atmospheres of rocky exoplanets?
3. How prevalent are habitable conditions on rocky exoplanets?
4. Are we alone [and life in the universe is exceedingly rare]? Or is life in the universe common?

Future Work on Potentially Habitable and Inhabited Rocky Planets

Case 1 – The Cosmic Shoreline: How common are atmospheres on rocky exoplanets around different stellar types?

Case 2 – The Habitable Zone: How prevalent are habitable conditions on rocky exoplanets?

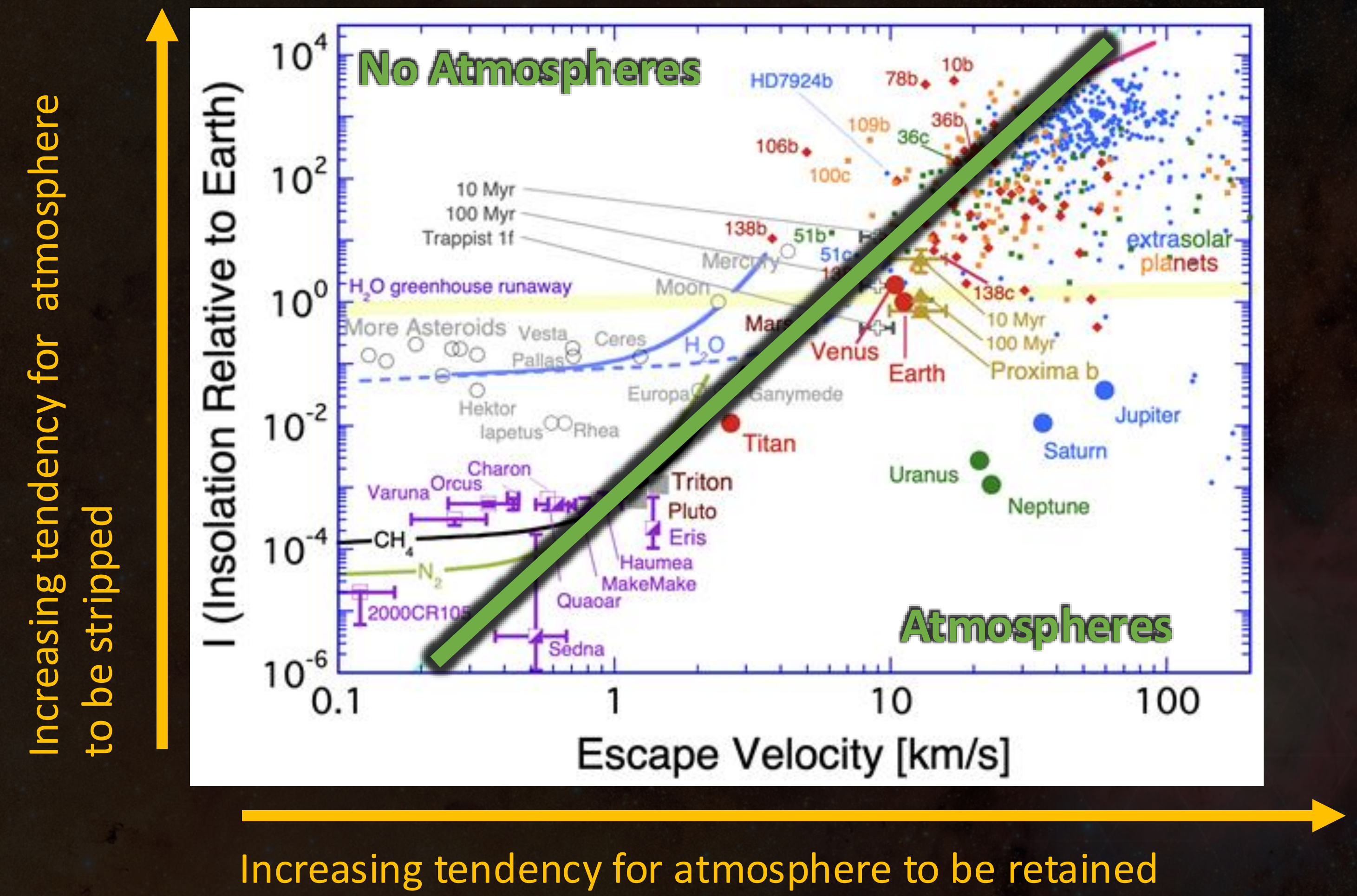
Case 3 – The Search for Life: Does life readily arise in habitable conditions or are we alone?

Case 1 – The Cosmic Shoreline: How common are atmospheres on rocky exoplanets around different stellar types?

A near-term population-level exoplanet characterization science case

The Cosmic Shoreline divides solar system bodies with and without atmospheres

Zahnle & Catling (2017)



In the solar system,

$$I \propto v_{esc}^4$$

may implicate thermal escape.

However, total cumulative XUV-driven escape

$$I_{XUV} \propto v_{esc}^4$$

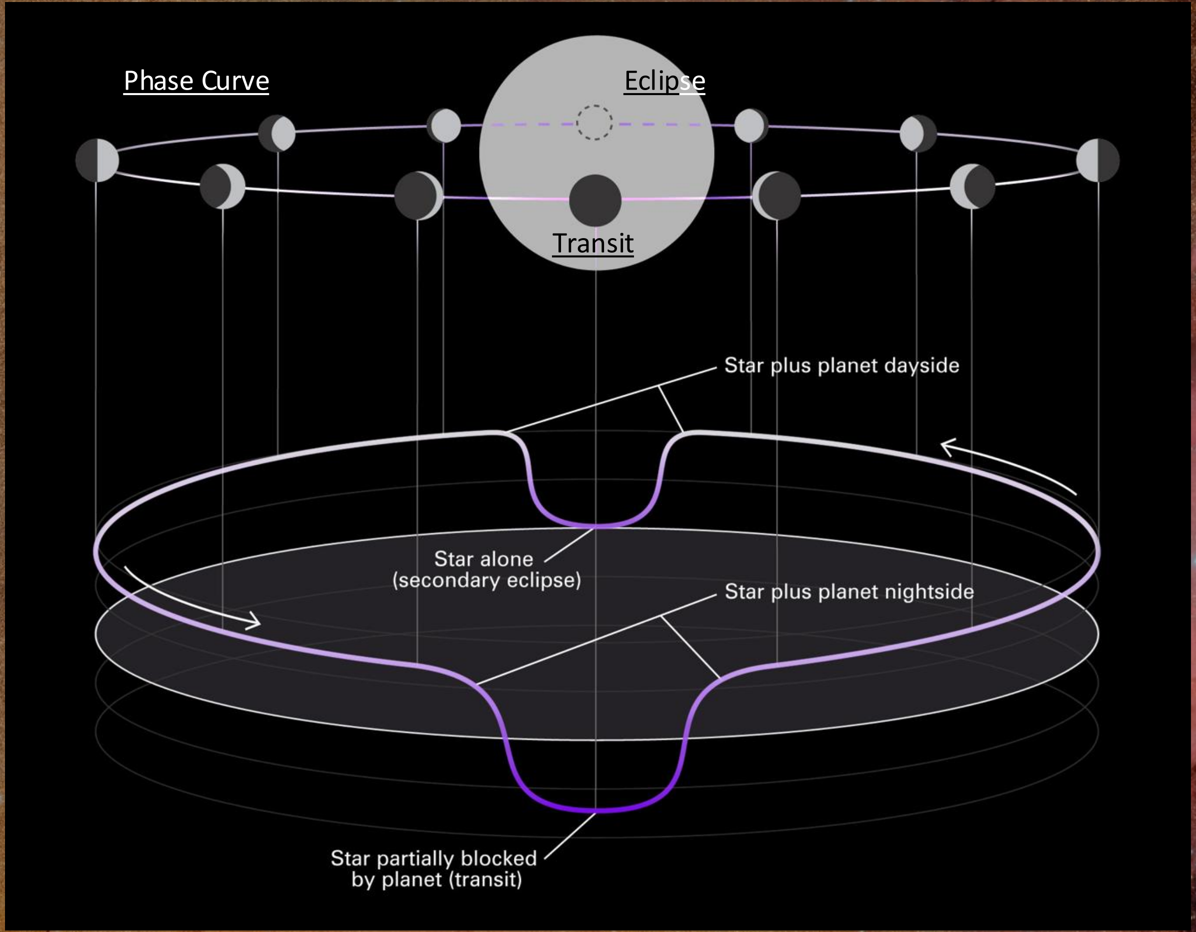
Or energy-limited escape

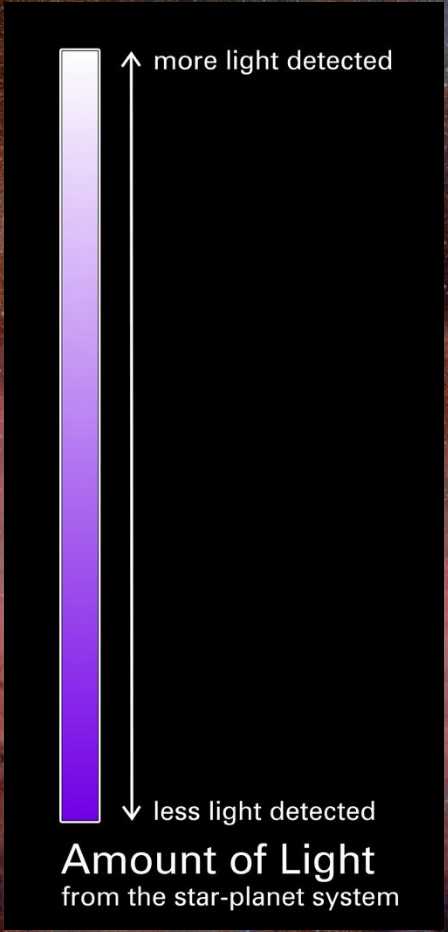
$$I_{XUV} \propto v_{esc}^3 \sqrt{\rho}$$

may instead shape the cosmic shoreline.

Does this hold in the exoplanet population? And if not, why?

Detecting Rocky Planet Atmospheres





Secondary eclipse and **thermal phase curves** are most sensitive to the strong emission signal expected from hot airless planets. However, many thin atmospheres (< 1 bar) can appear consistent with an airless planet.

Transit Transmission spectra are most sensitive to relatively extended and cloud-free atmospheres. However, compact and cloudy atmospheres can appear consistent with airless planets.

Thin atmospheres are a challenge and still slip under the detection sensitivity of both techniques.

Rocky Worlds 500-hr DDT Program

- Science Goals
  - Determine if rocky planets have atmospheres
  - Define the cosmic shoreline

- Observing Approach
  - Survey of rocky M-dwarf exoplanets
  - Secondary eclipses
  - 15 – 20 planets
  - 15 μm MIRI photometry

- Targets Under Consideration (TUC)
  - First Four planets identified in orange
  - More planets to come later in 2025

https://rockyworlds.stsci.edu/rw-website-targets.html

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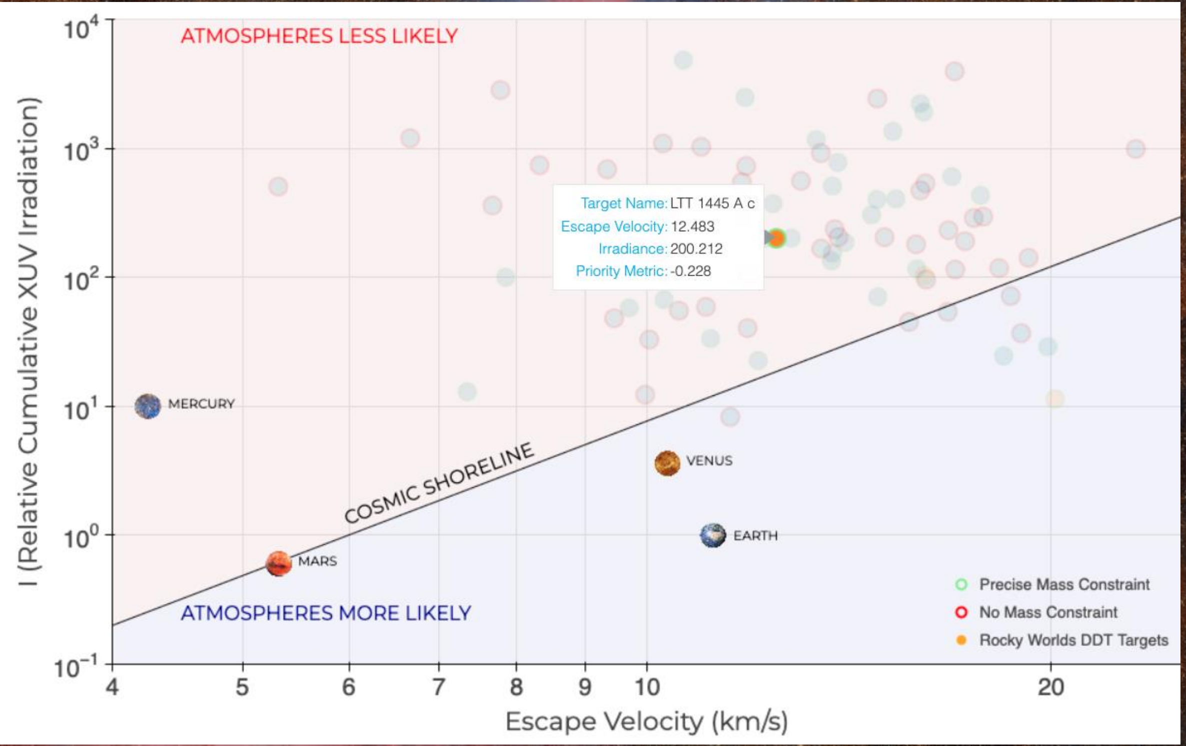

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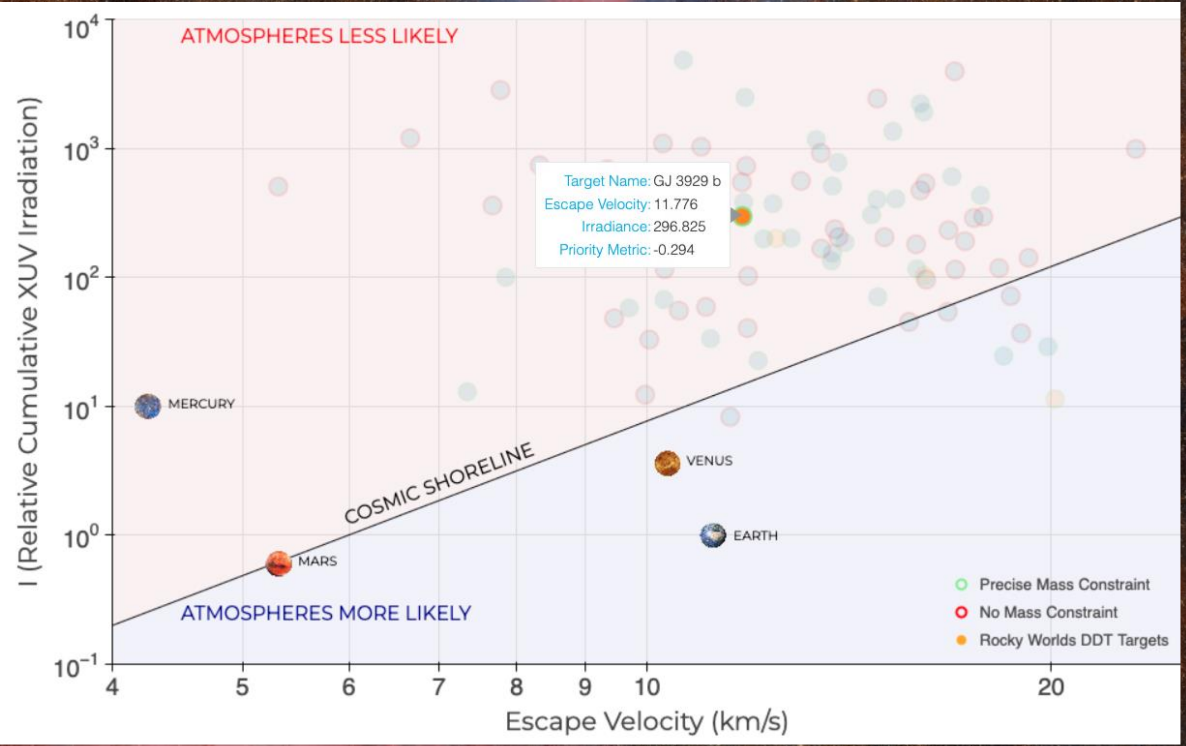

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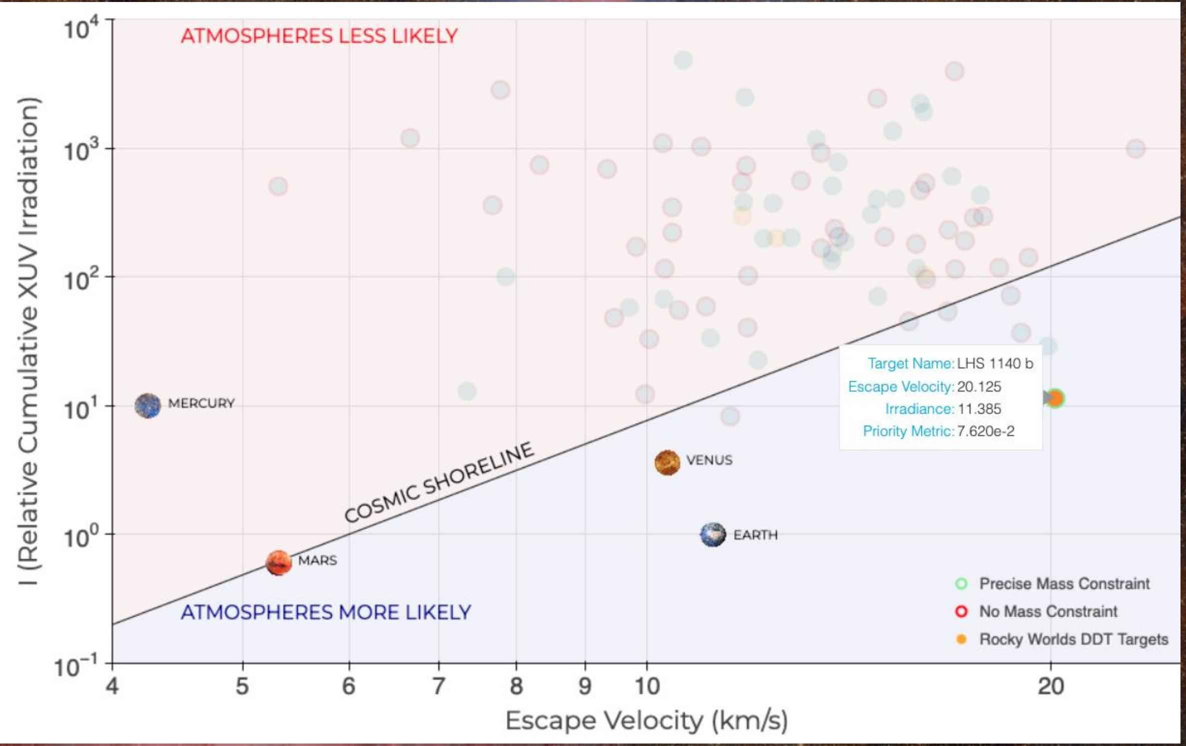

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Charting the Cosmic Shoreline

JWST GO Program 7073 (PIs Lustig-Yaeger & Stevenson)

- Science questions:
  1. Planet-Level: *Do temperate M-dwarf rocky planets possess secondary atmospheres?*
  2. System-Level: *Where is the cosmic shoreline located within a given multi-planet system?*
  3. Population-Level: *How does the presence of atmospheres correlate with stellar type?*

- Observing Strategy: Transmission spectroscopy from 1-5 µm
  - NIRSpec/G395H + NIRISS SOSS or NIRSpec PRISM

- Targets: 6 sibling planets in 3 different systems (245 hrs), including planets most likely to have atmospheres
  - $R_P = 1.1 – 1.7\ R_E$

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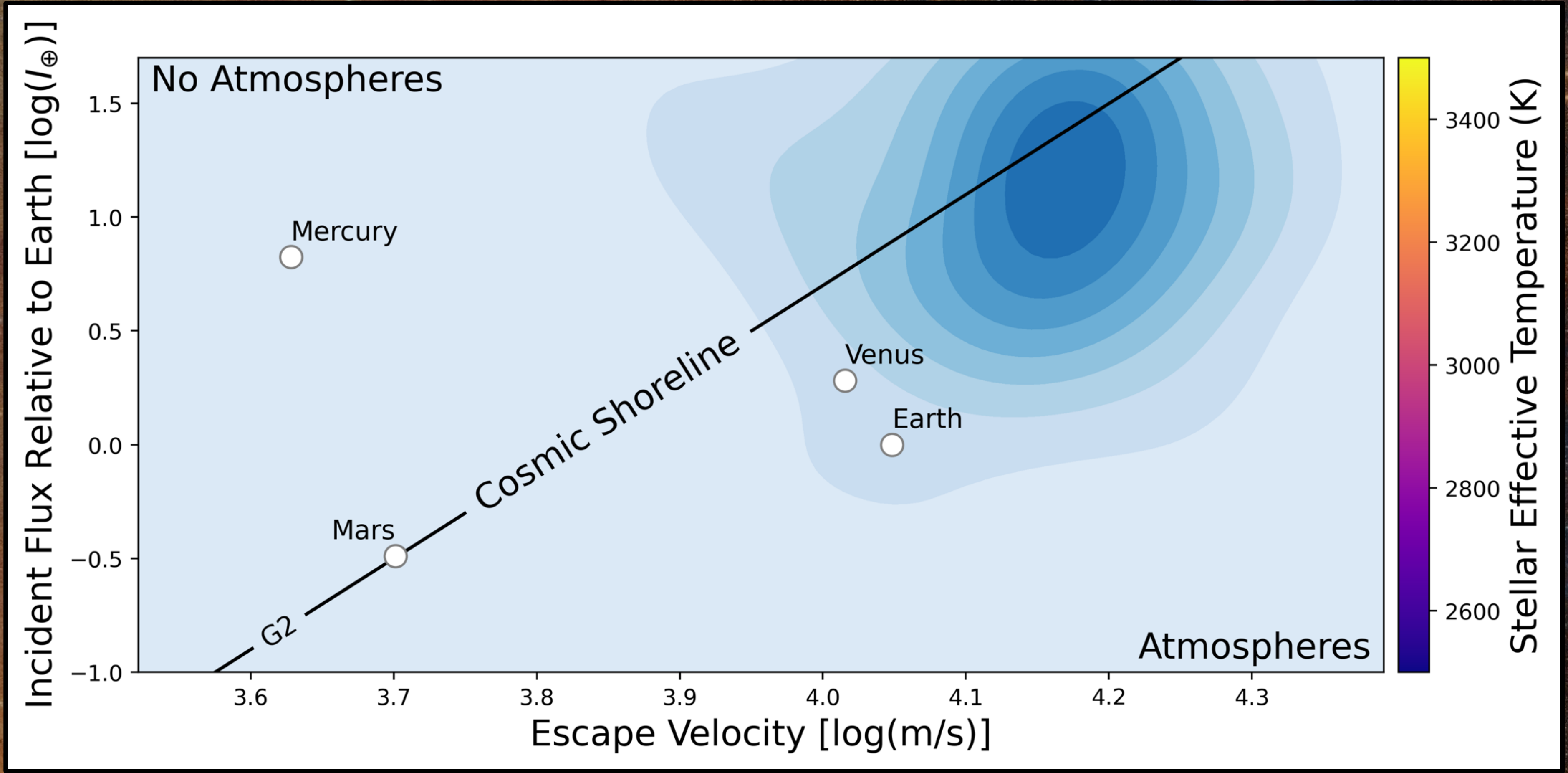

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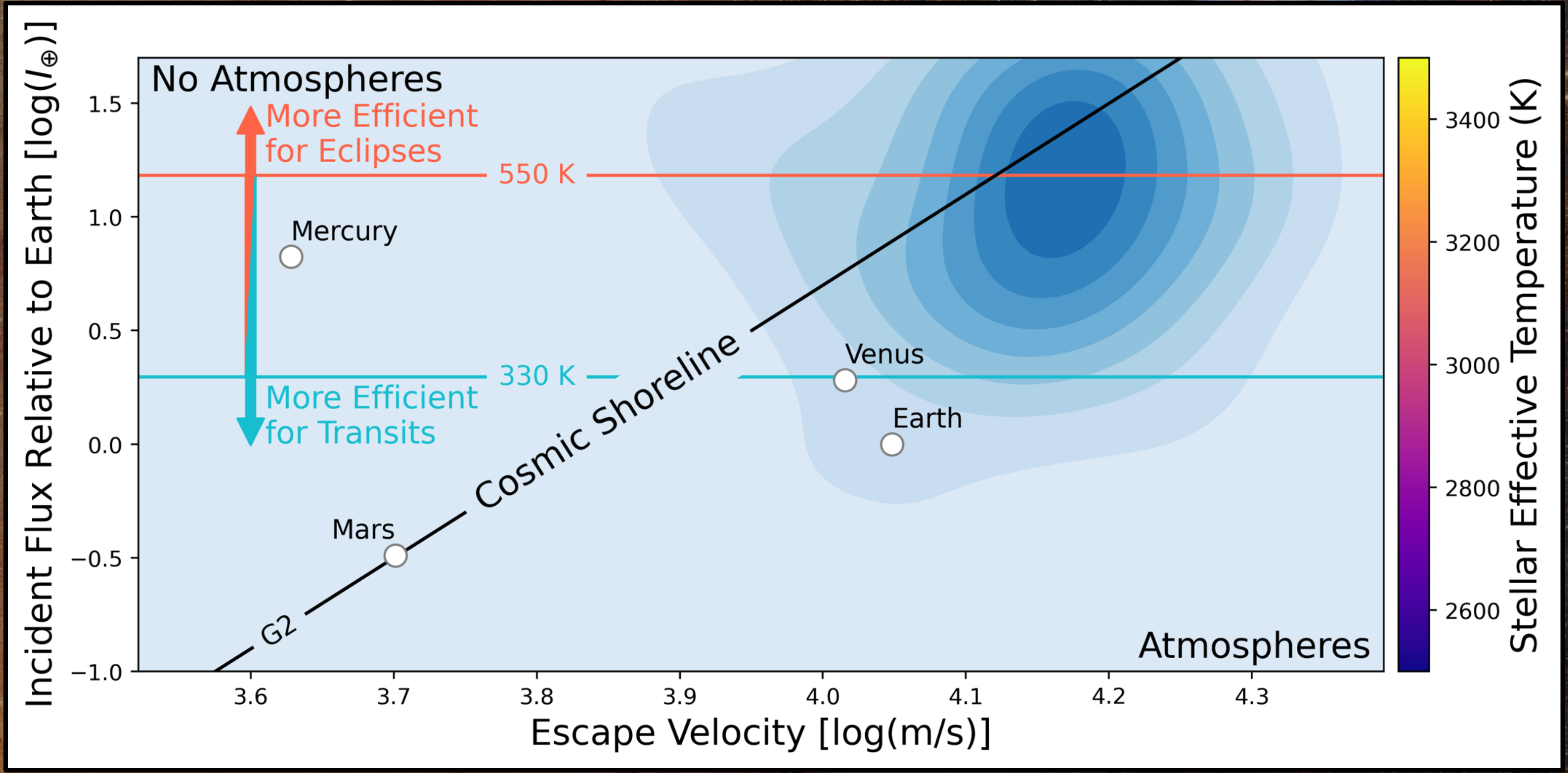

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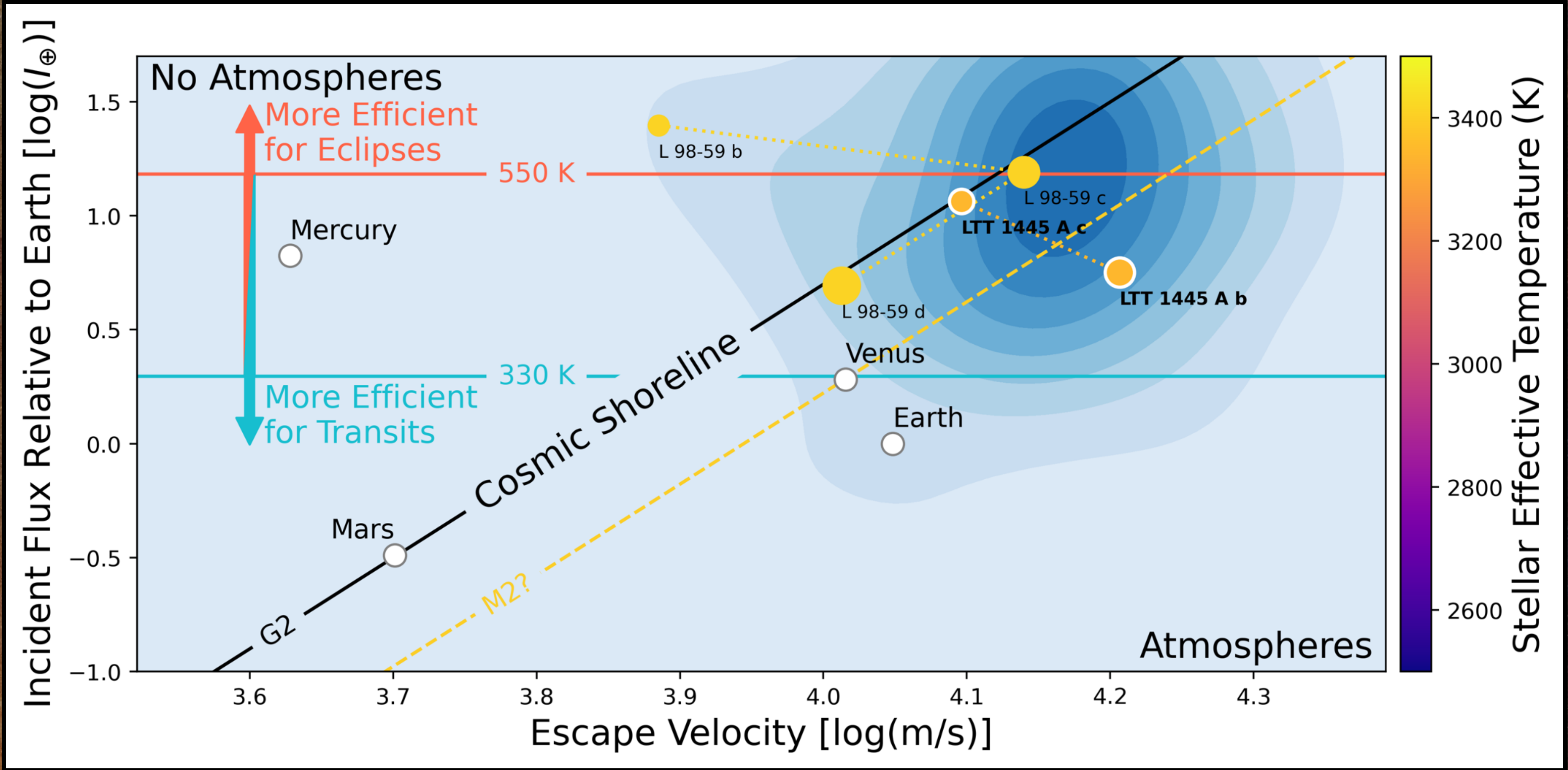

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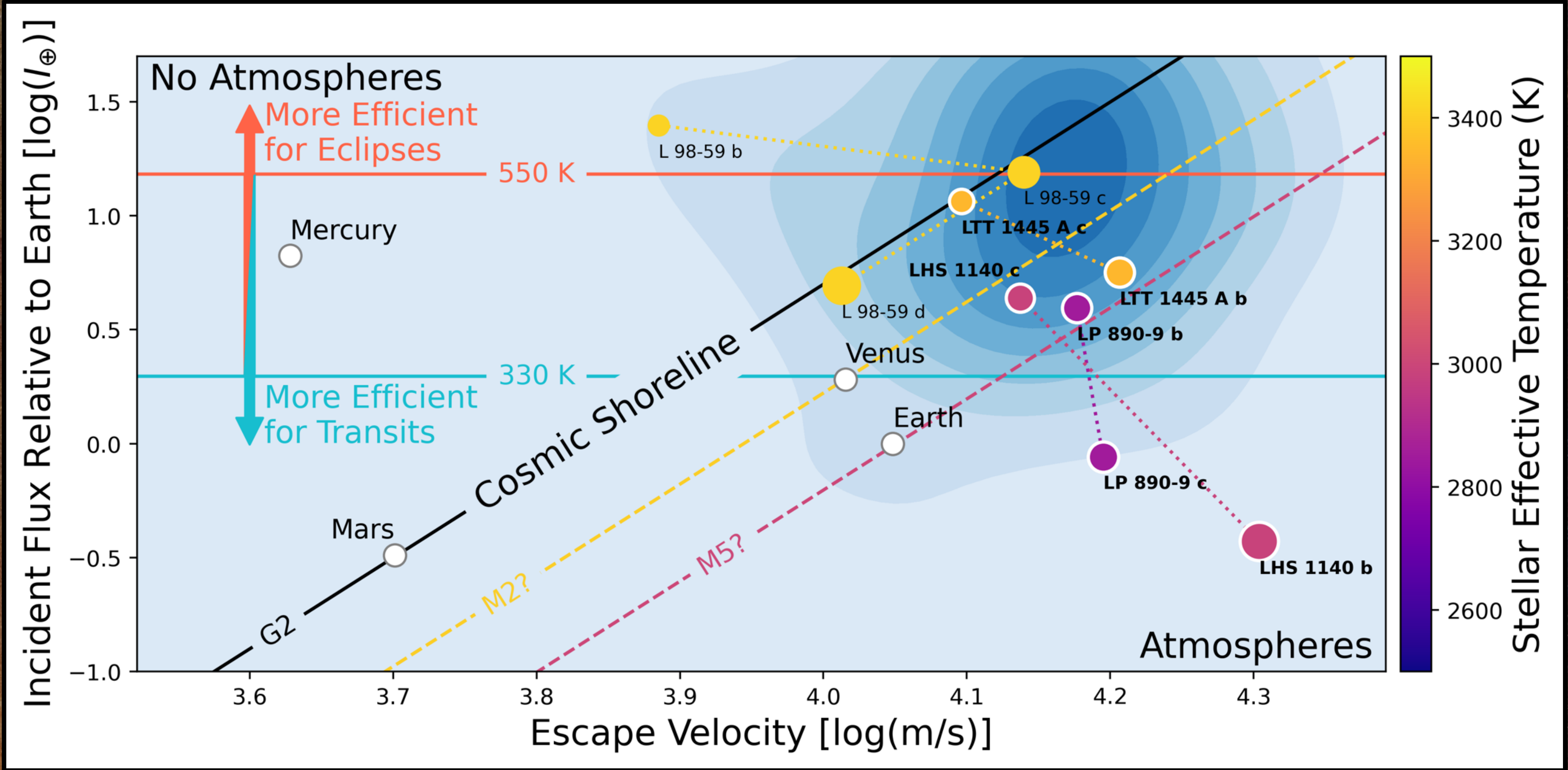

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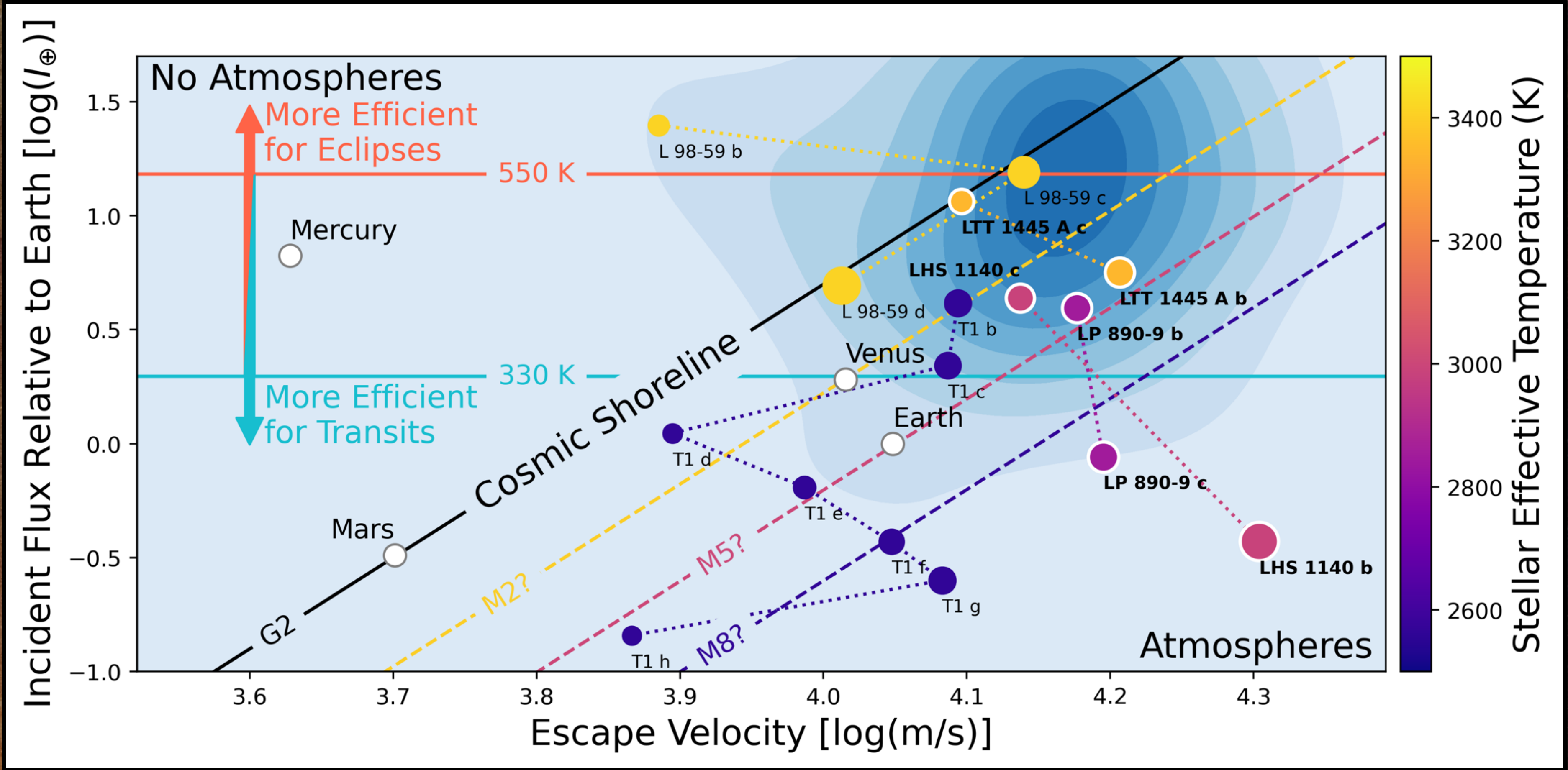

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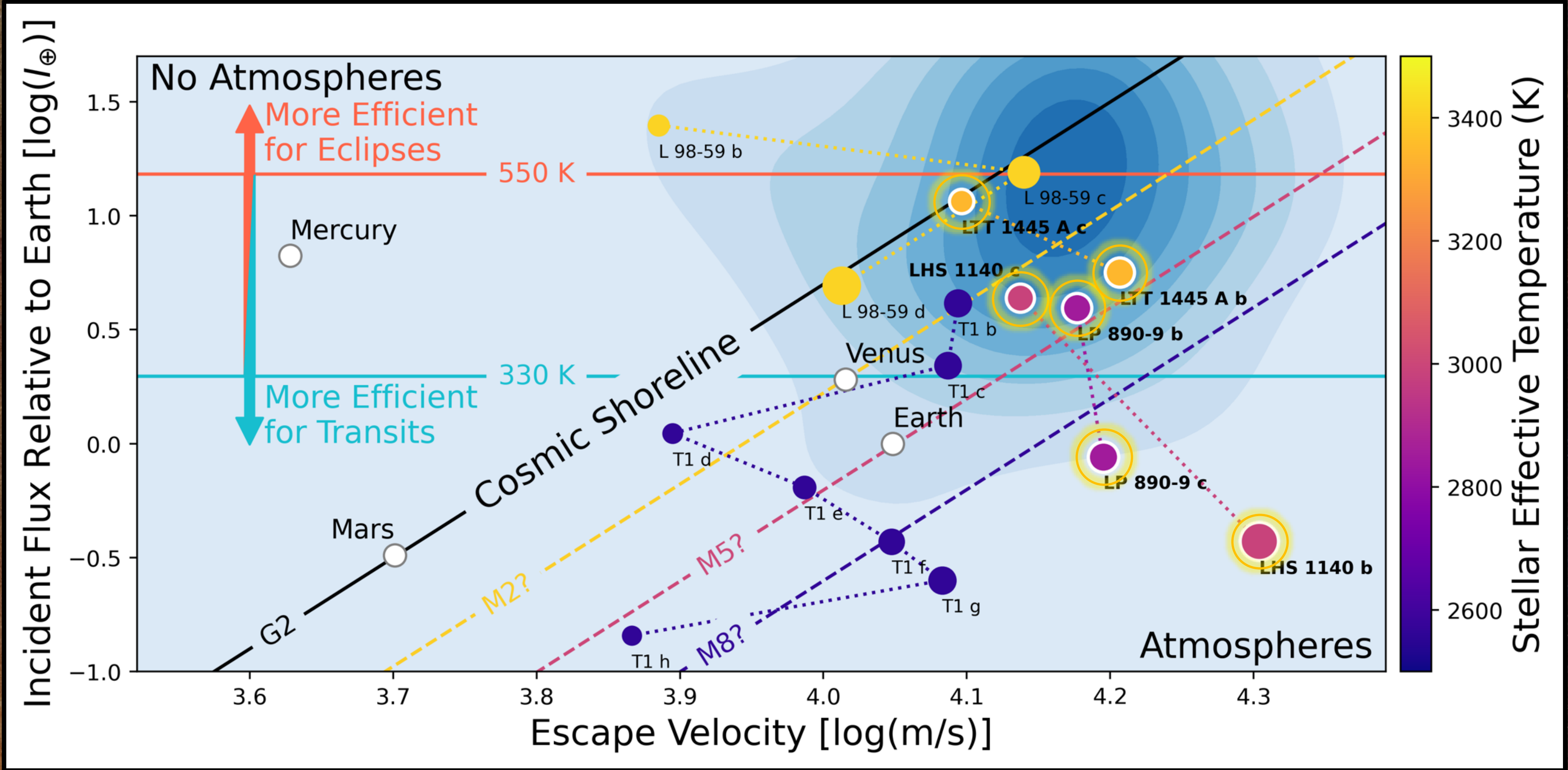
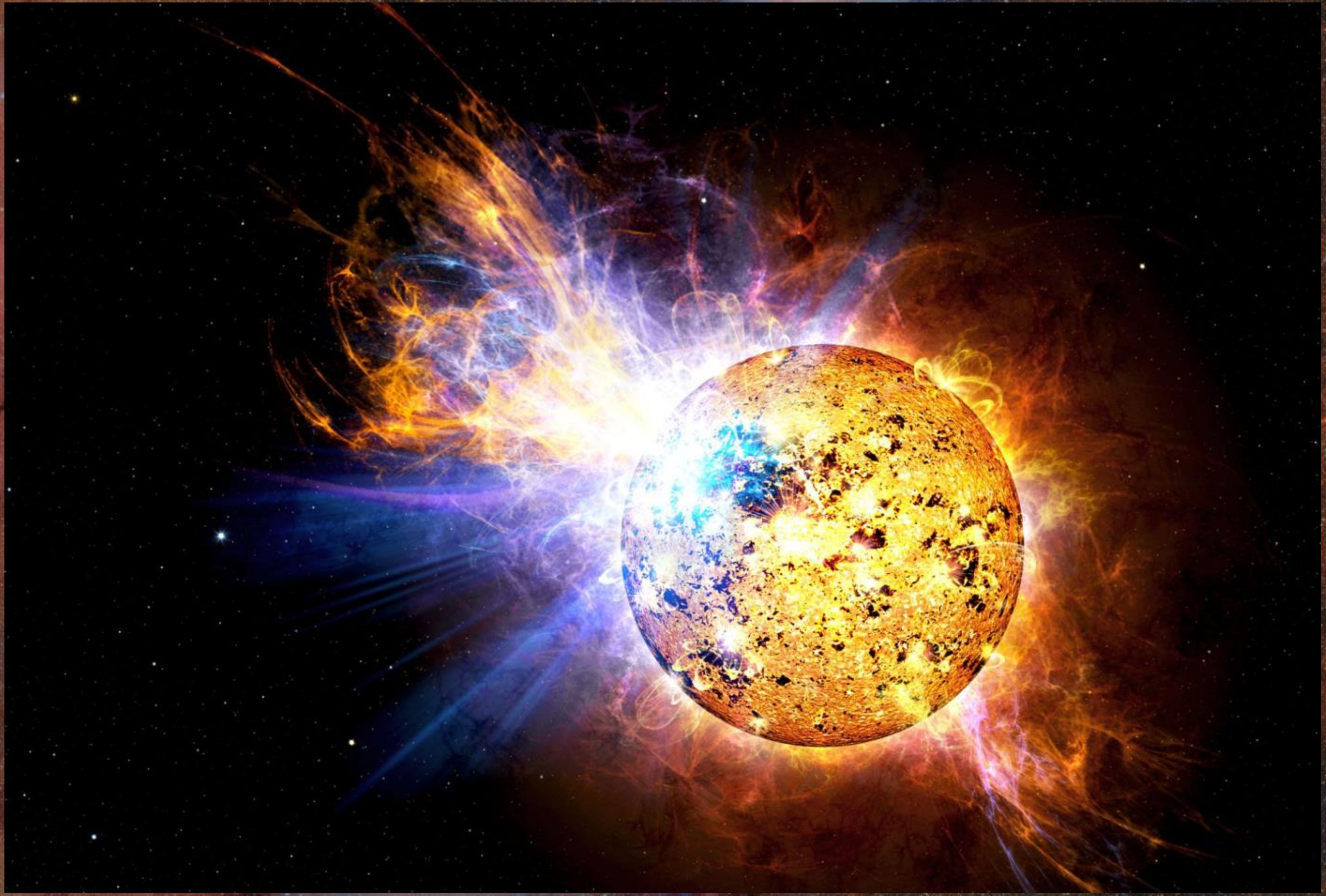


Finding atmospheres would be great, but not finding them would be profound

If we find that M dwarf rocky planets don't have atmospheres into (and beyond) the HZ, then we can effectively cross 75% of stars in the universe off our list of targets that could have habitable surfaces and host life (as we know it).

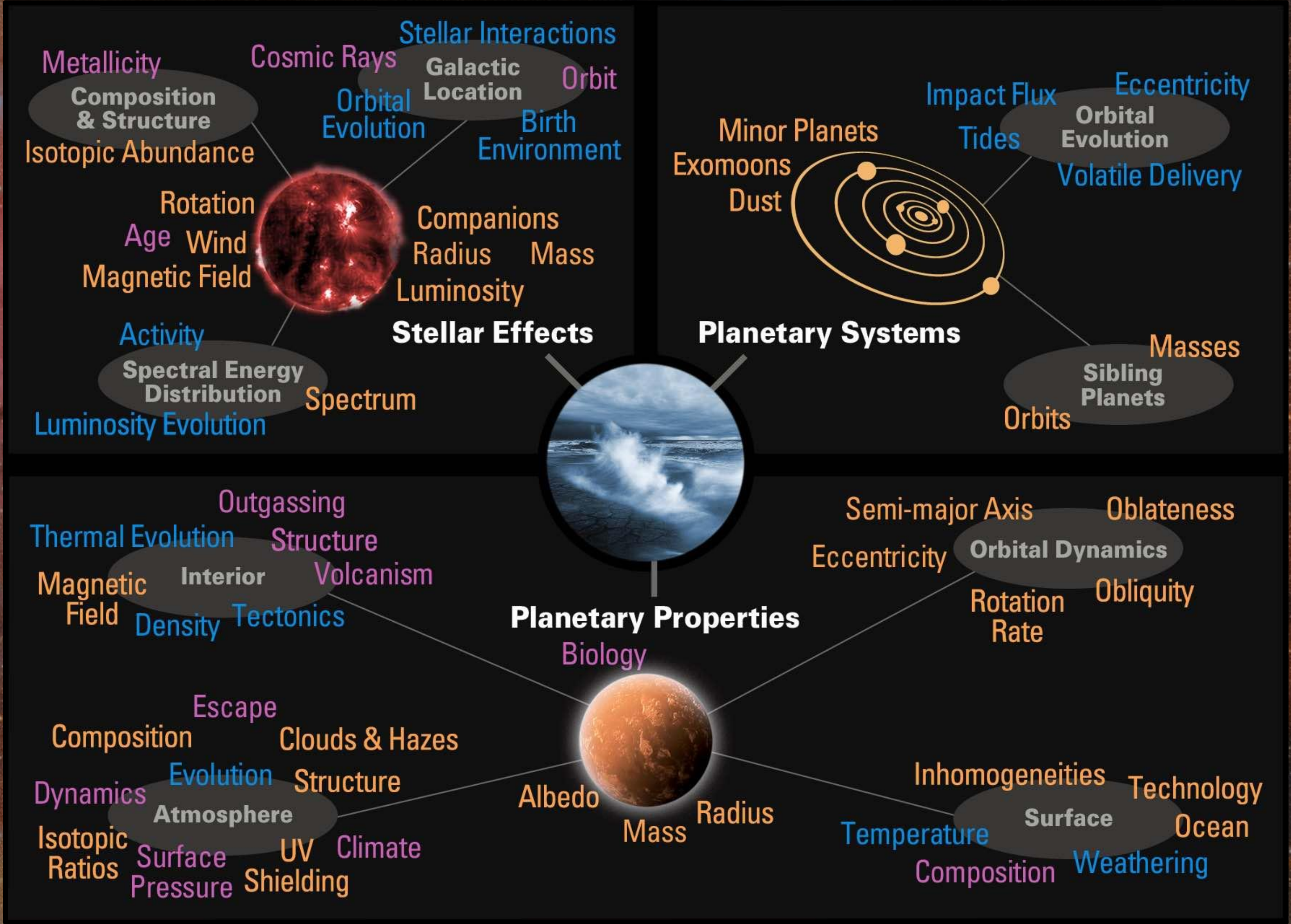


Case 2 – The Habitable Zone: How prevalent are habitable conditions on rocky exoplanets?

A long-term population-level exoplanet characterization science case

Planetary Habitability | Many factors affect habitability, not just the distance from the star

- Planets within the HZ are not guaranteed to actually be habitable (i.e., have liquid water on surface)
- Complicated interactions between the star, planet, and entire planetary system may work in concert to promote, destroy, or sustain habitable planetary conditions



Meadows & Barnes (2018)

Constraining Exoplanet Habitability

1. Direct evidence of surface liquid water
2. Indirect evidence of surface liquid water

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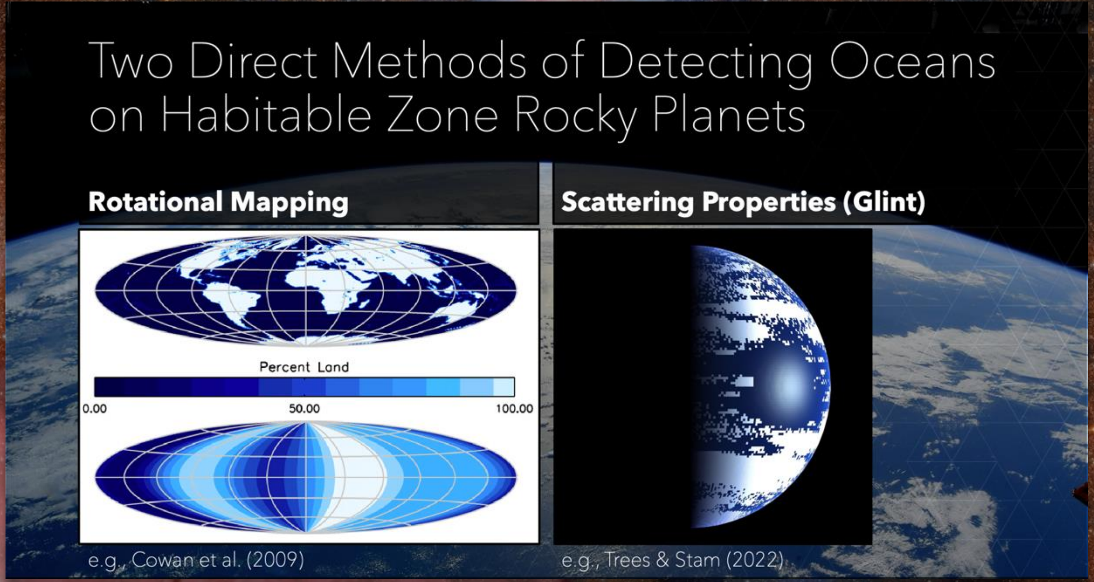

I'll be speaking about this next week at the HWO25 meeting in DC

Constraining Exoplanet Habitability

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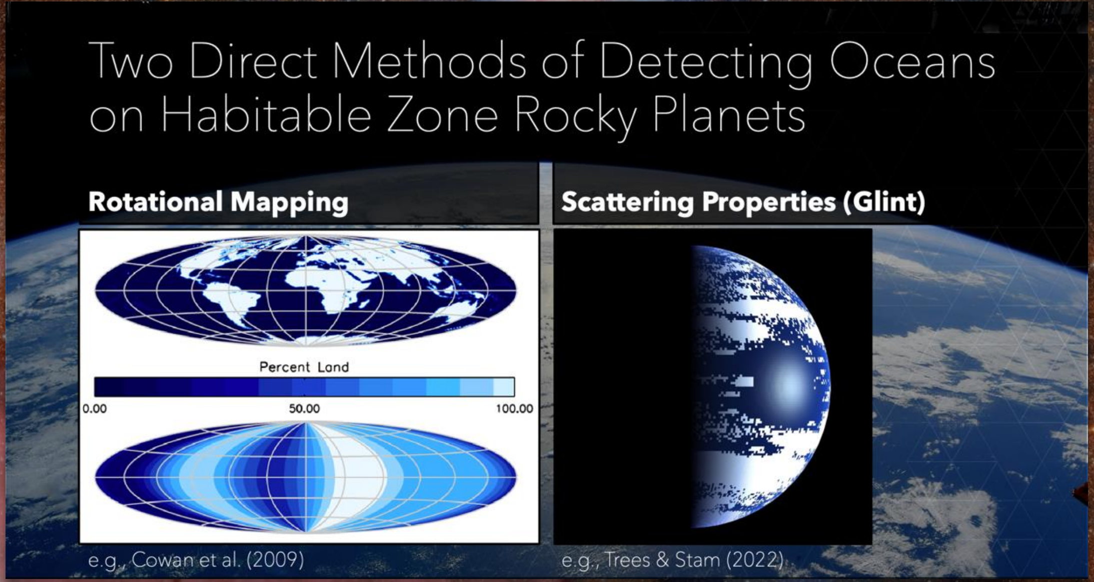

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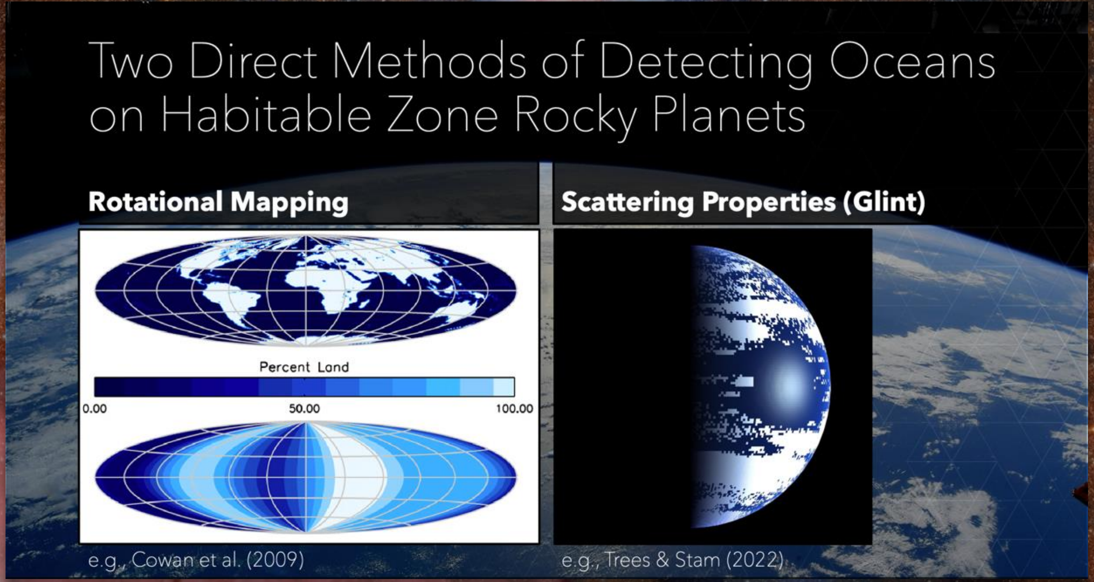
   - Trends among a population of HZ planets that exhibit climate stability due to the presence of oceans.



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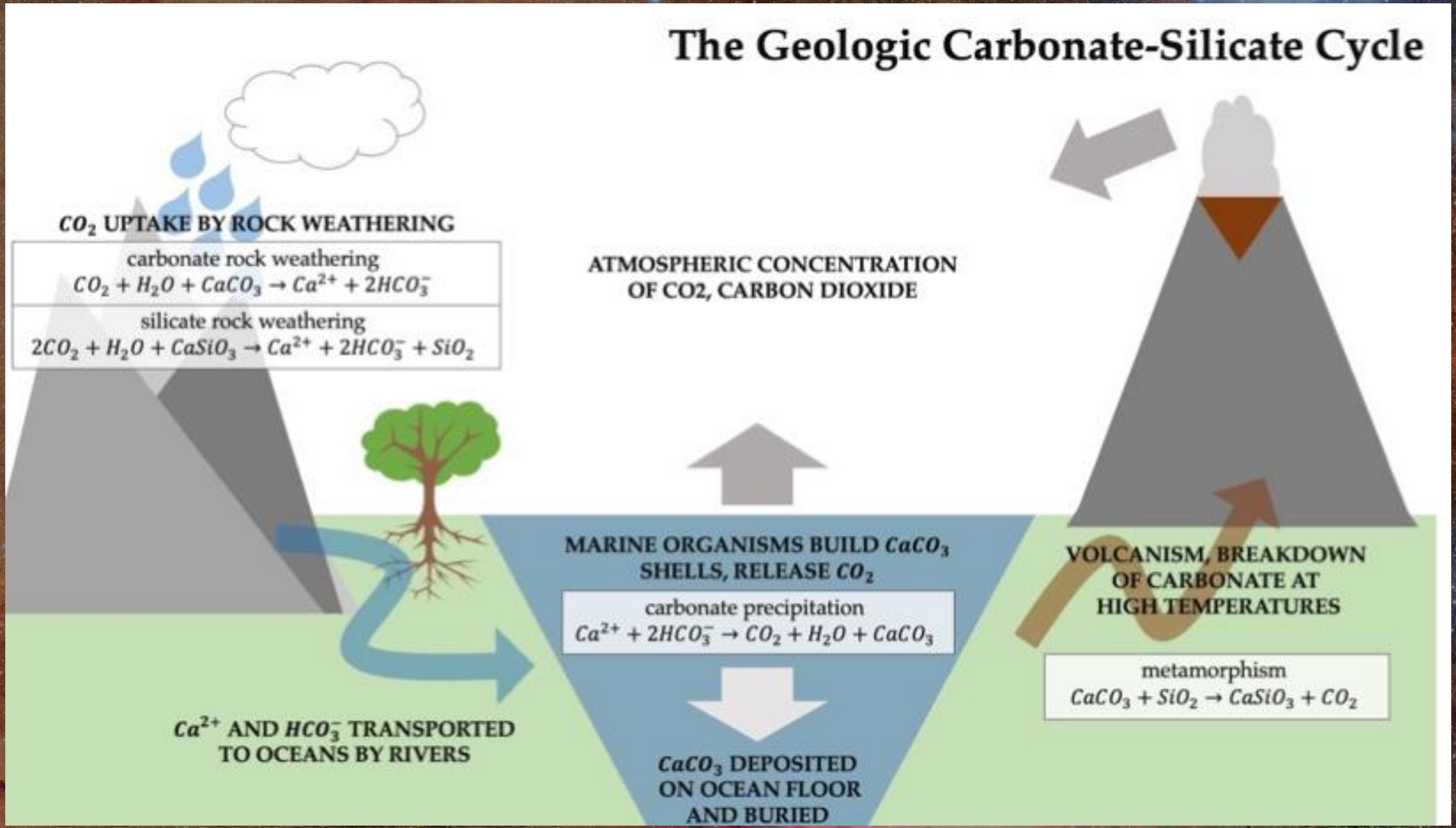
A Statistical Test of the Habitable Zone

Leveraging the Exoplanet Ensemble to Empirically test the silicate-weathering feedback



Bean et al. (2017)

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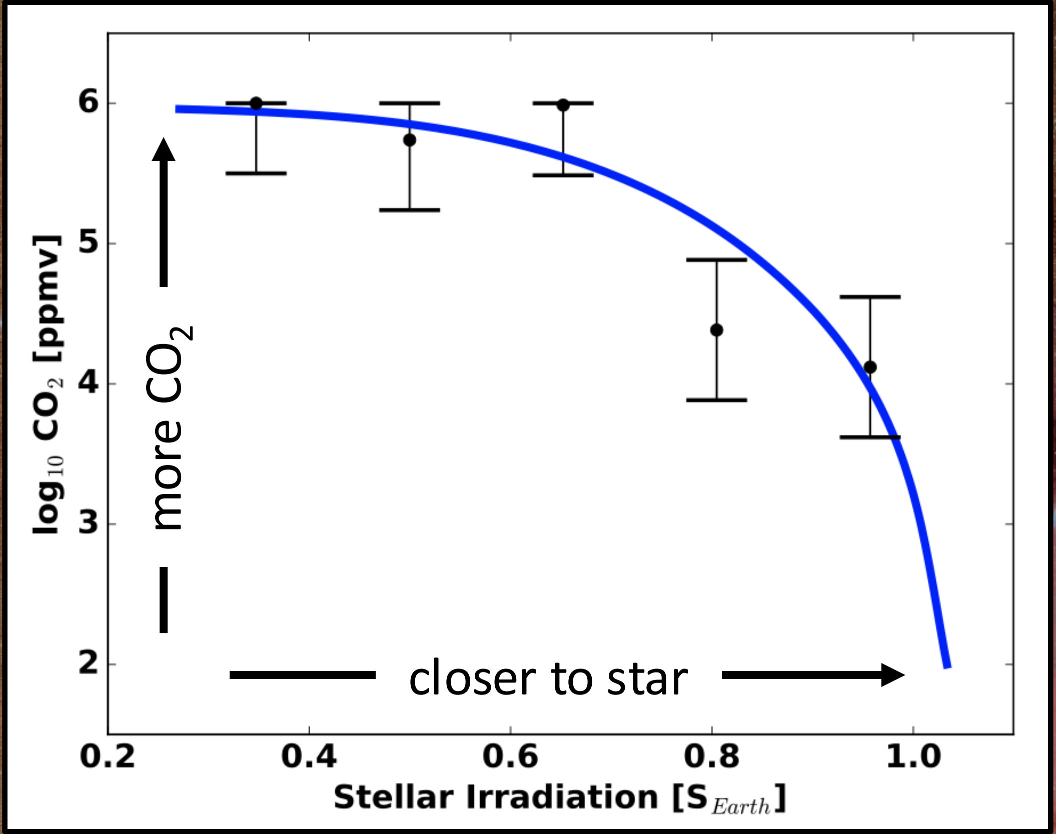


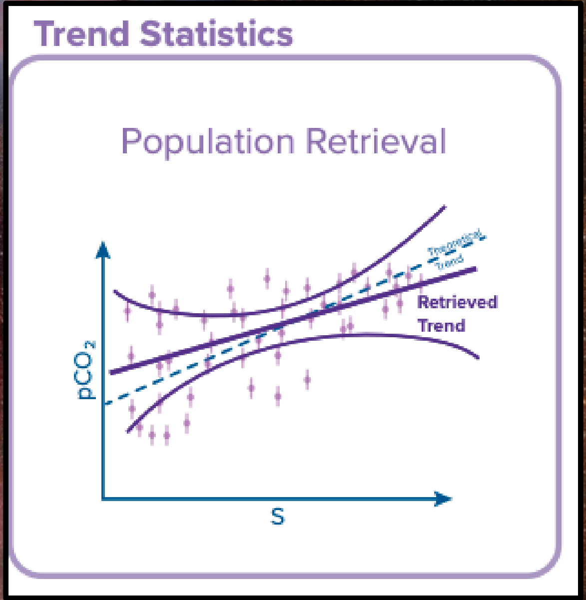
- The concept of the HZ rests on the assumption of a functioning **silicate-weathering feedback**
- Planets that receives less stellar radiation, ***should*** have more atmospheric CO_2 to maintain surface temperatures that allow liquid water
- This hypothesis can be tested by analyzing the atmospheres of *many* exoplanets

Future missions that can measure CO_2 in exoplanet atmospheres could perform this empirical test of the Habitable Zone!

Bean et al. (2017)

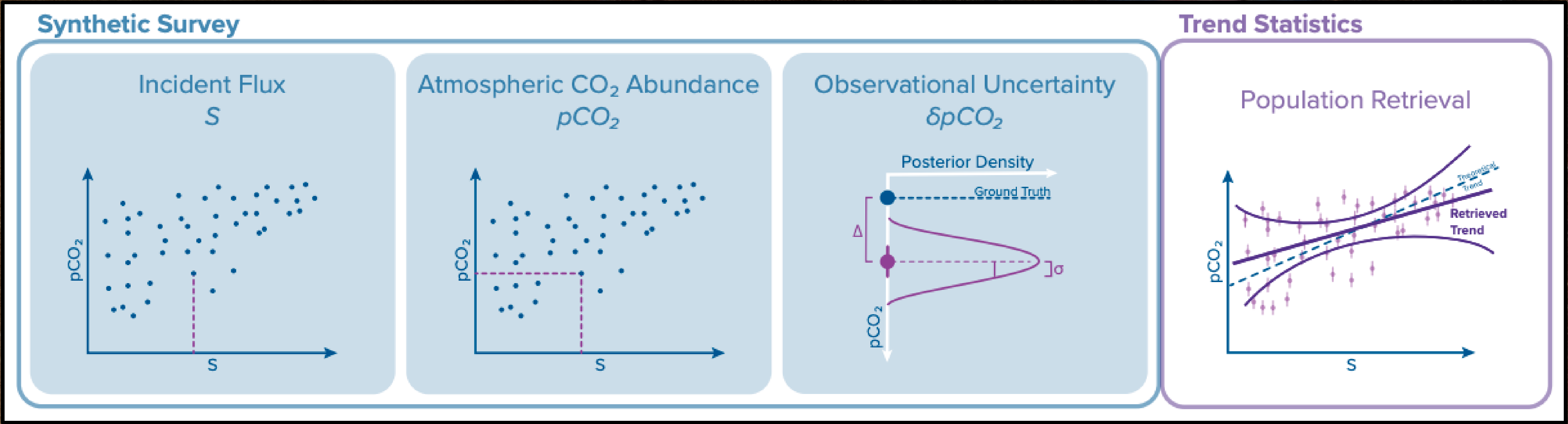
Detecting Atmospheric CO_2 Trends as Population-Level Signatures for Long-Term Stable Water Oceans

- We developed a Hierarchical Bayesian Atmospheric Retrieval (HBAR) numerical approach to investigate population-level trends in exoplanet atmospheres (Lustig-Yaeger et al. 2022).
- Impractical with JWST in terms of S/N and number of targets.



Hansen et al. (2025)

Detecting Atmospheric CO_2 Trends as Population-Level Signatures for Long-Term Stable Water Oceans



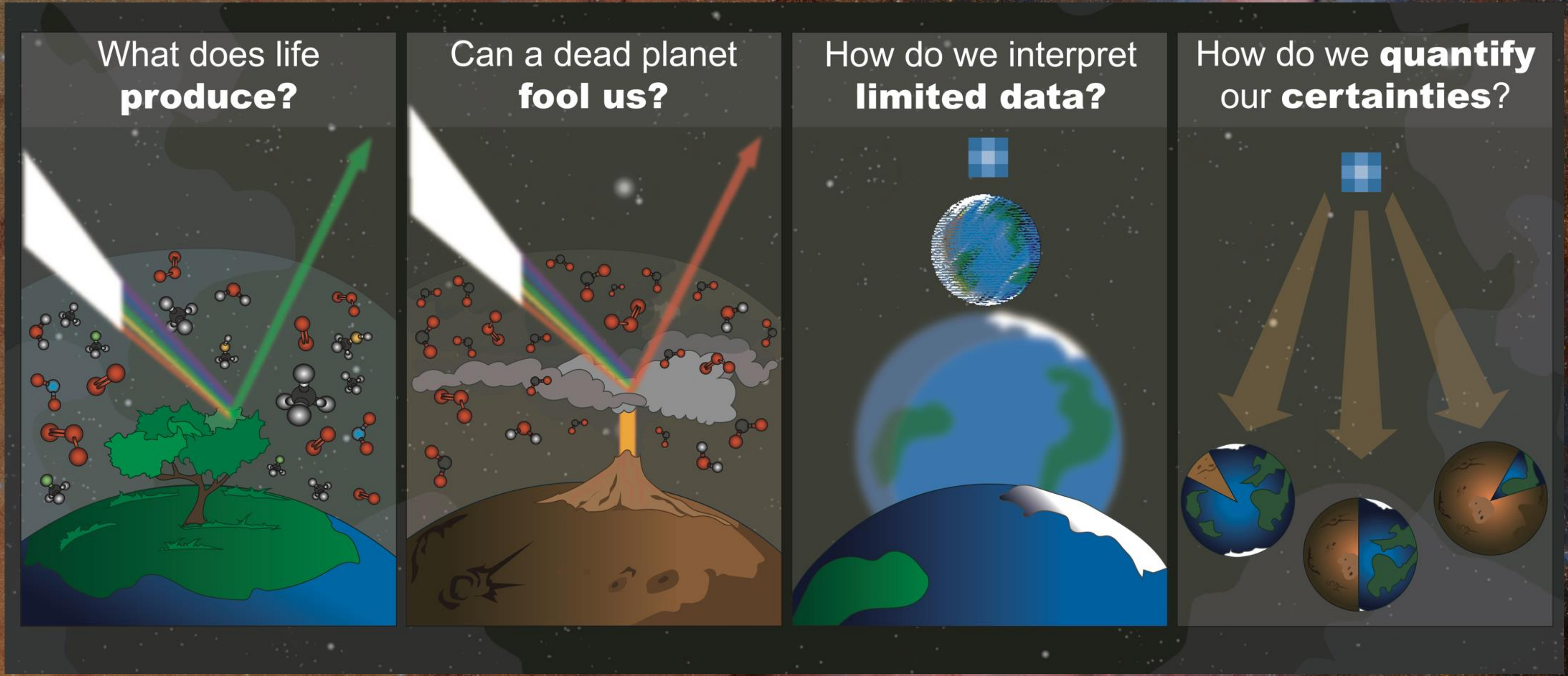
- Simulated LIFE survey results demonstrate the robust detection of population-level CO_2 trends
- But biased CO_2 partial pressure constraints hinder accurate differentiation between biotic and abiotic trends, underscoring the importance of testing atmospheric characterization performance against the broad diversity expected for planetary populations

Hansen et al. (2025)

Case 3 – The Search for Life: Does life readily arise in habitable conditions or are we alone?

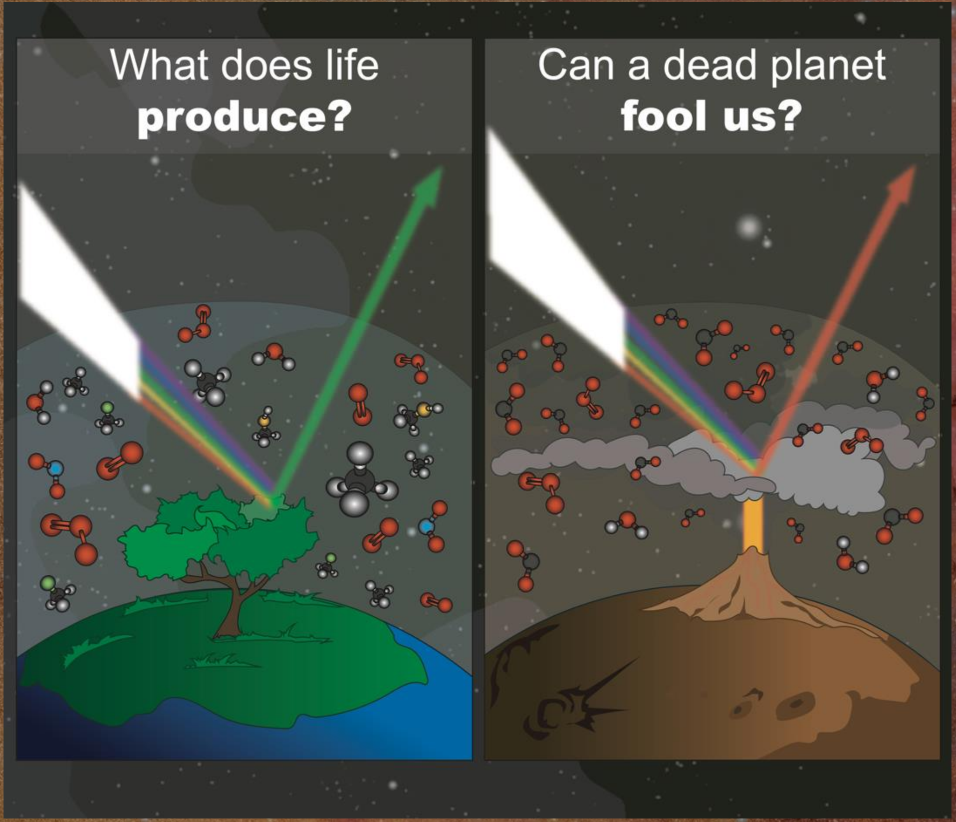
The ultimate long-term population-level exoplanet characterization goal

Biosignatures | Guiding questions



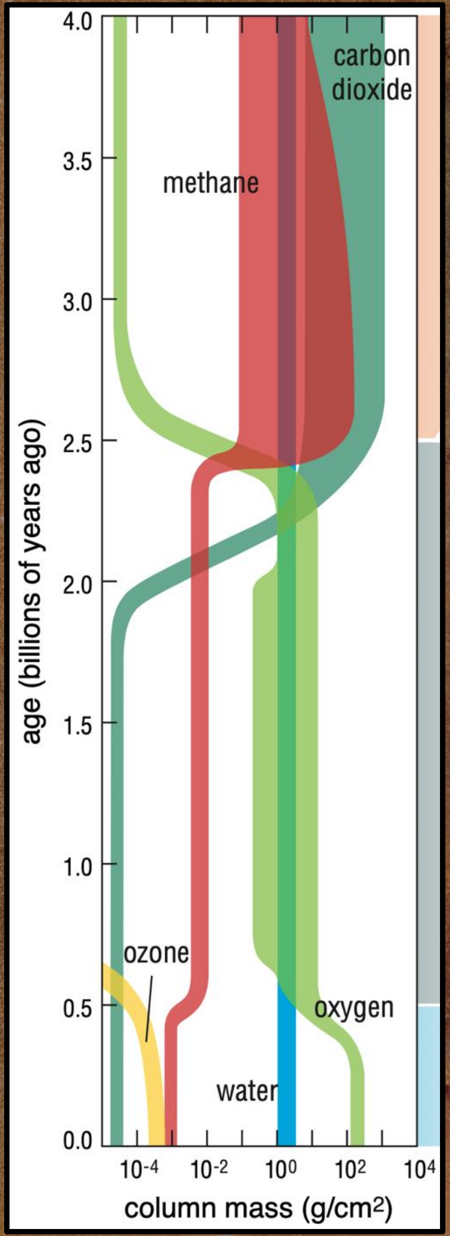
(Kiang et al., 2018; Schwieterman et al., 2018; Meadows et al., 2018; Catling et al., 2018; Walker et al., 2018; Fujii et al., 2018)

Biosignatures | What makes for a good biosignature?



Meadows (2017); Meadows et al. (2018)

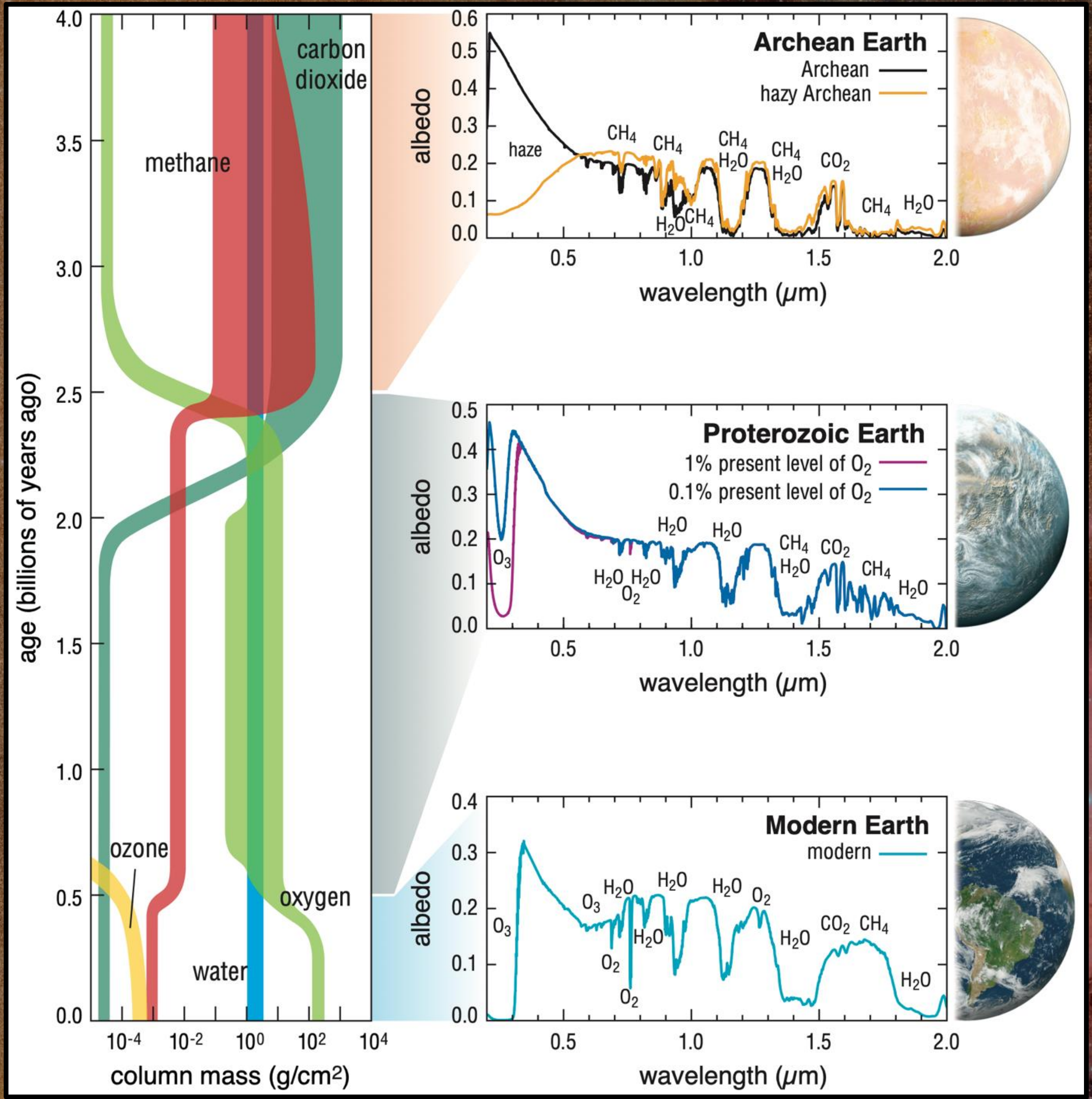
1. Reliability
   - *Does it have biological origin? Is it more likely to be produced by life than planetary processes e.g. geology, chemistry, etc.*
2. Survivability
   - *Does it avoid destruction in a planetary environment such that it can accumulate? e.g. destruction by reactions with volcanic gases, water, etc.*
3. Detectability
   - *Does it build up to detectable levels? Is it distinct from other gases?*



LUVOIR Final Report (2019)

Biosignatures on the
Earth Through Time

- Earth's atmospheric composition has changed with time over billions of years



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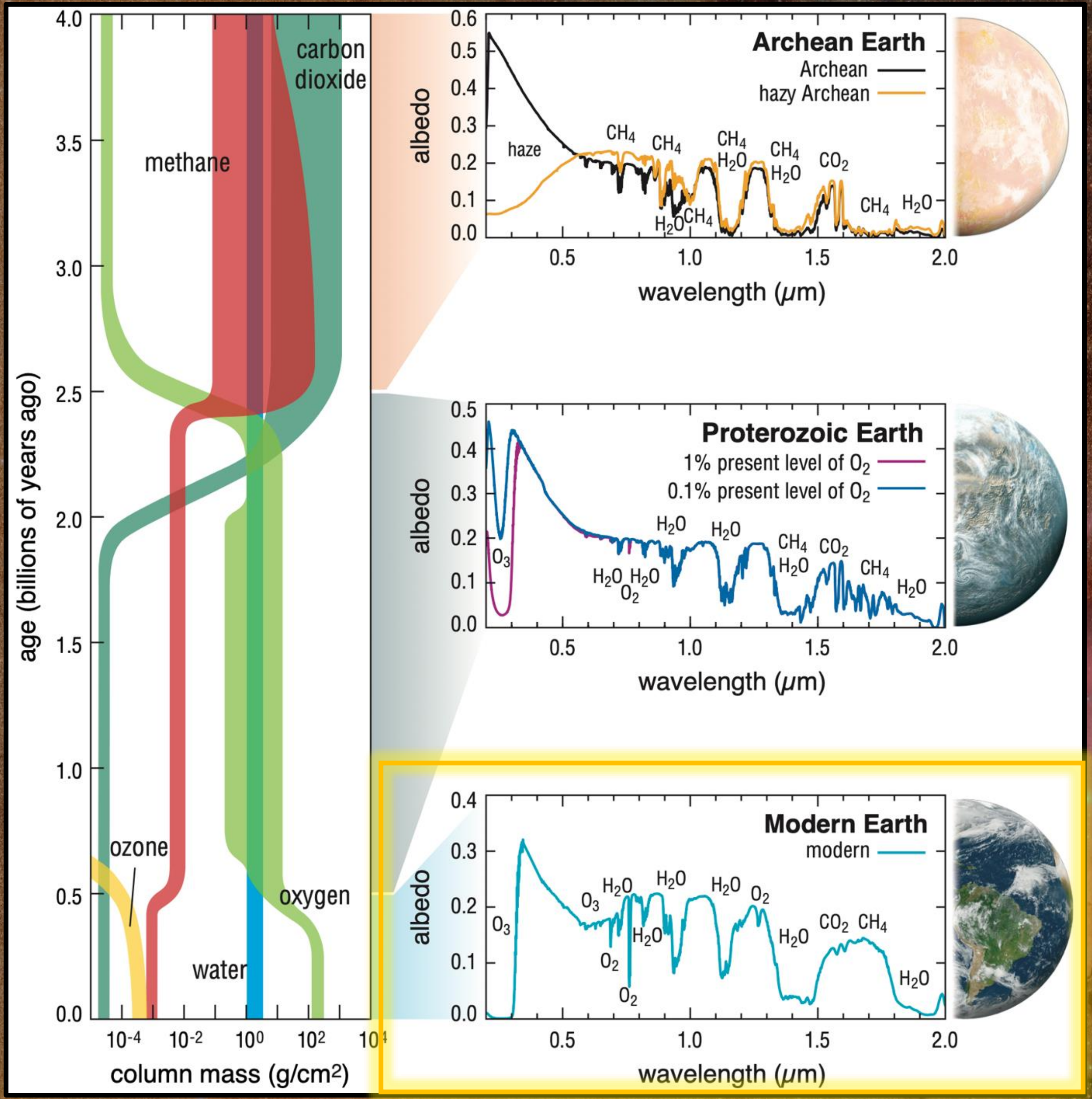

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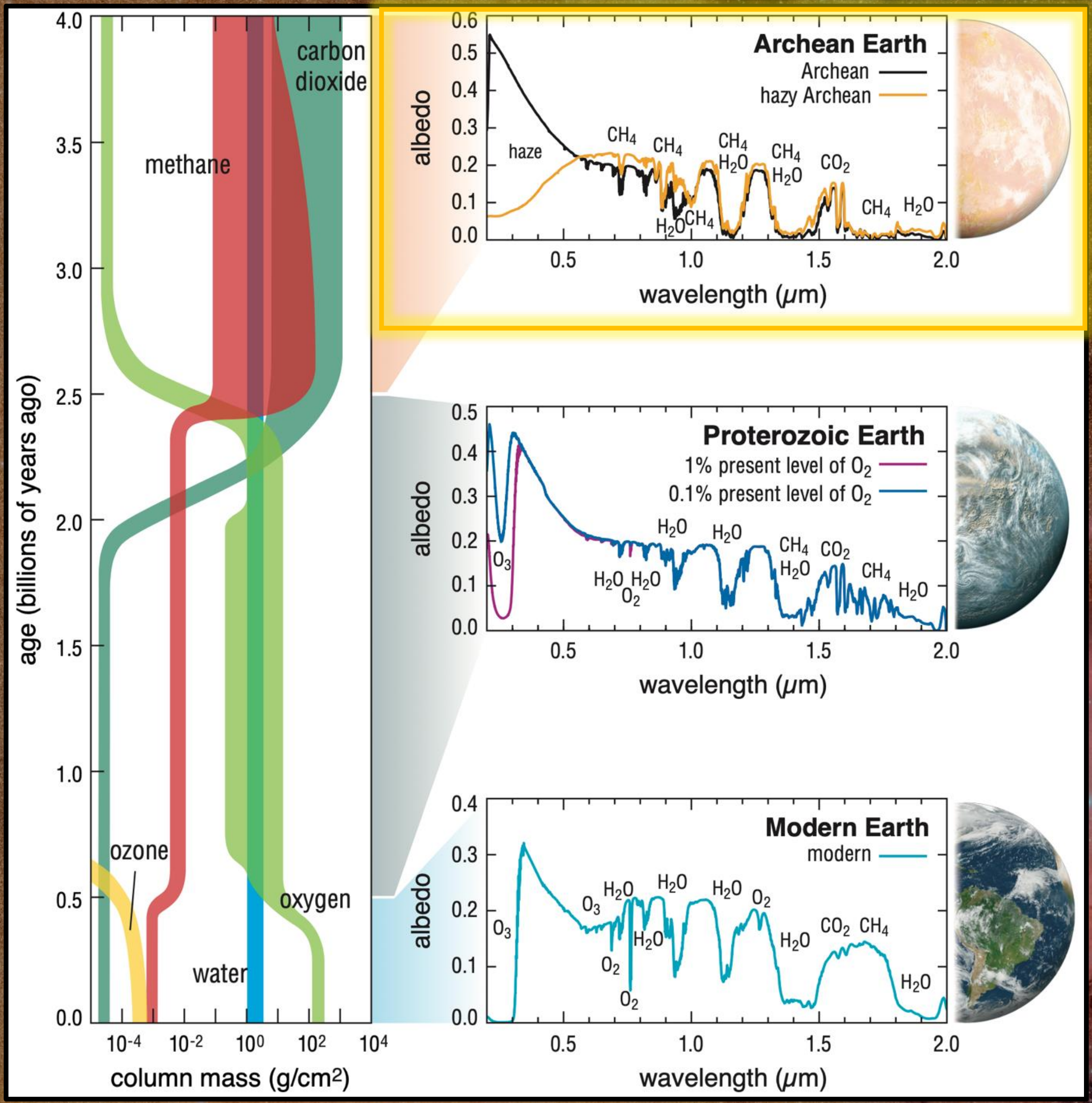

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Biosignatures on the
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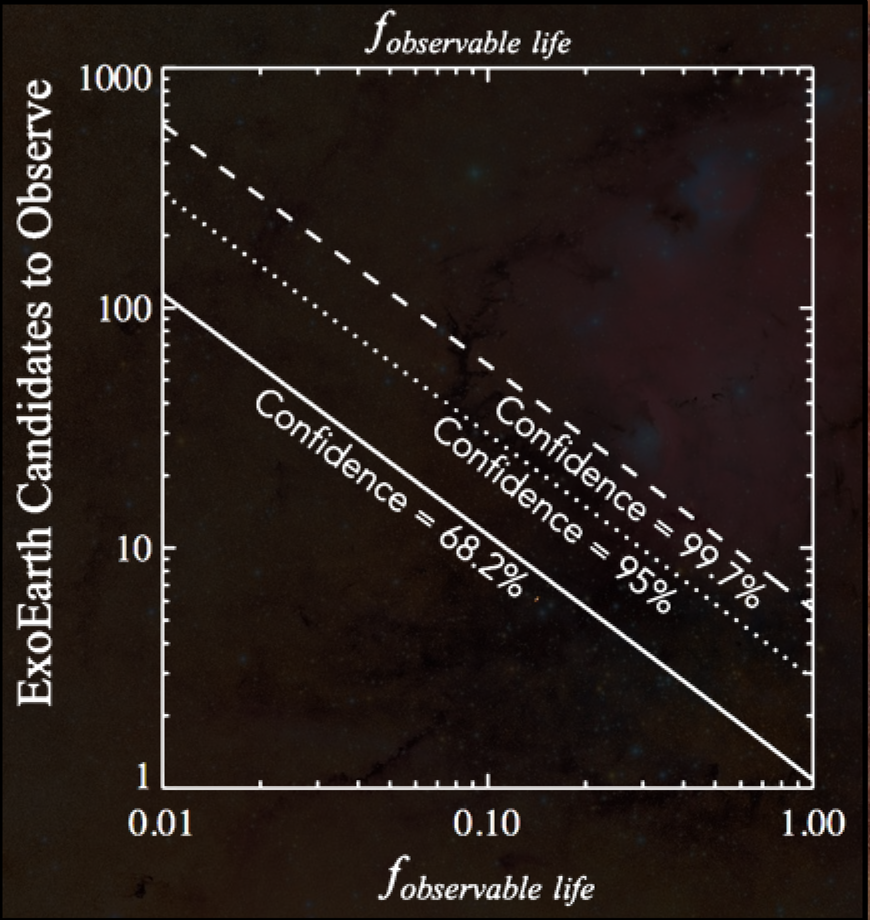
- On the Early Earth, methane and carbon dioxide together may be considered a biosignature

Designing HWO to Perform a Robust Search for Life



- The number of candidate exoplanets (N_{ec}) required to constrain the fraction of planets with a given characteristic *x* (f_x) at a given confidence level (*c*) can be written as:

$$N_{ec} = \frac{\log(1-c)}{\log(1-f_x)}$$

- **A non-detection of life still means something.**

    - If we examine 25 candidate spectra and do not see signs of life, then we can say that the frequency of habitable planets with observable signs of life is <10% of candidate planets in the nearby universe at 95% confidence, placing the first ever upper limit on the frequency of observable biospheres in the cosmos.

(Stark et al. 2014); See also, HWO Science Case: The Search for Life on Potentially Habitable Exoplanets

Pathways to Habitable Worlds | Astro2020

"Life on Earth may be the result of a common process, or it may require such an unusual set of circumstances that we are the only living beings within our part of the galaxy, or even in the universe. Either answer is profound.

If planets like Earth are rare, our own world becomes even more precious.

If we do discover the signature of life in another planetary system, it will change our place in the universe in a way not seen since the days of Copernicus—placing Earth among a community and continuum of worlds.

The coming decades will set humanity down a path to determine whether we are alone."

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If planets like Earth are rare, our own world becomes even more precious.

If we do discover the signature of life in another planetary system, it will change our place in the universe in a way not seen since the days of Copernicus—placing Earth among a community and continuum of worlds.

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Conclusions

- Constraining the demographics of atmospheric characteristics will enable an empirical classification of exoplanets, including the intrinsic diversity exhibited by the exoplanet ensemble and physical processes that drive these characteristics.
- The cosmic shoreline in M-dwarf systems presents the first tangible rocky planet atmospheric demographics survey.
- Longer term goals for next-generation telescopes will give an opportunity to empirically test the HZ and search for life outside the solar system.
- What other population-level questions will we answer along the way?