Beyond Habitability: A Multiscale Approach to Exoplanetary Biosignature Detection for HWO

Leveraging Extremophiles for Next-Generation Life Detection

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Our Journey Today

Questioning the Paradigm:
The Habitable Zone

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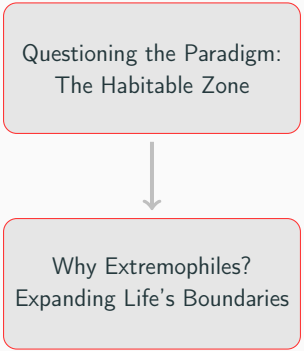

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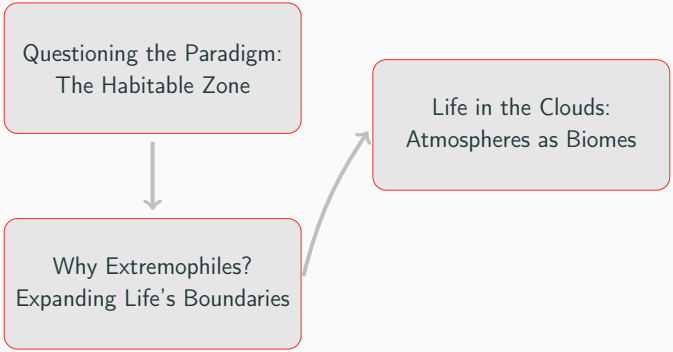

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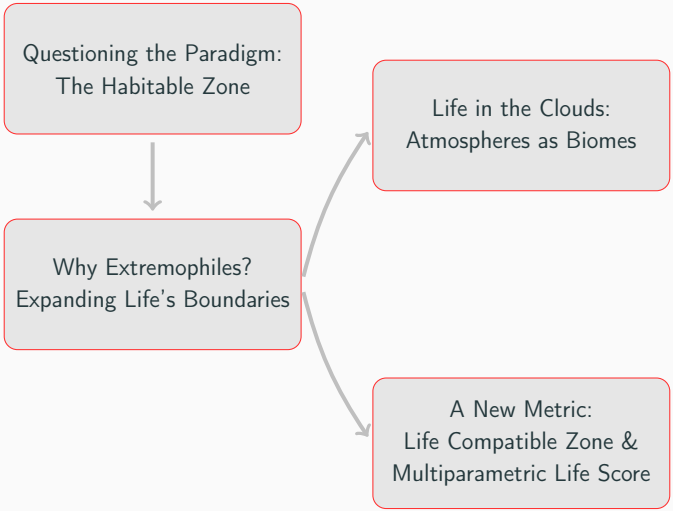

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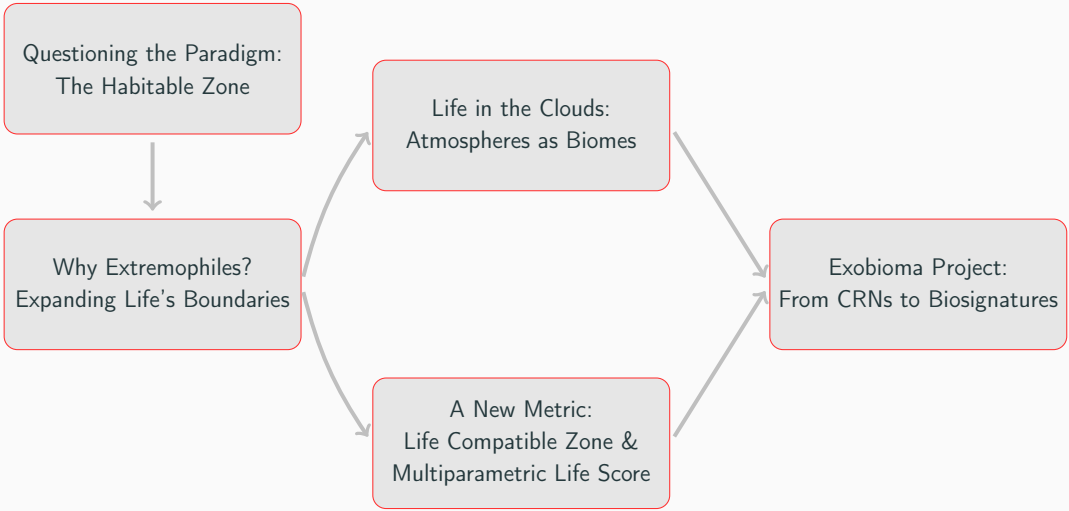

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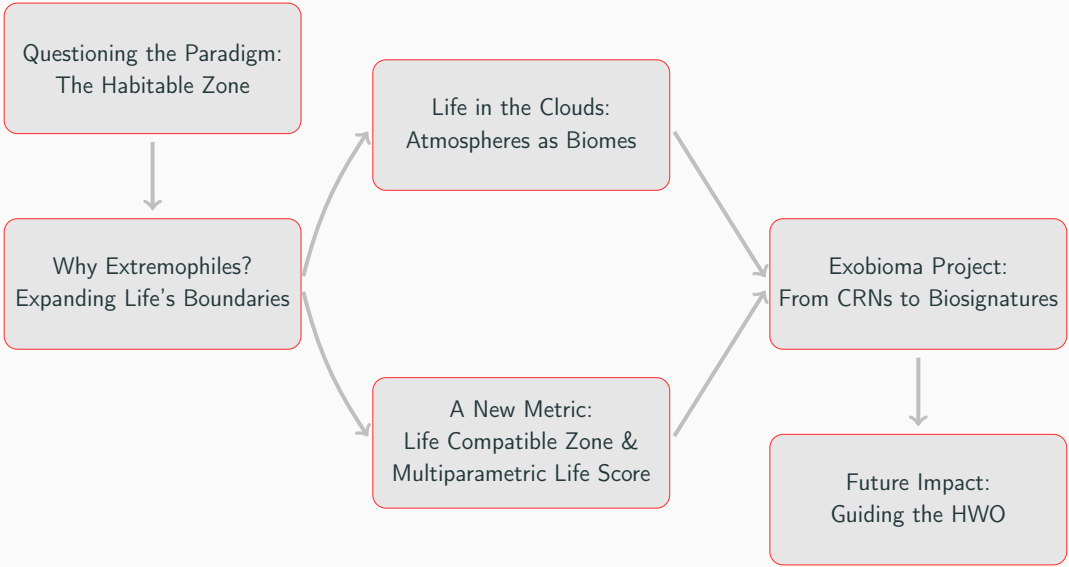
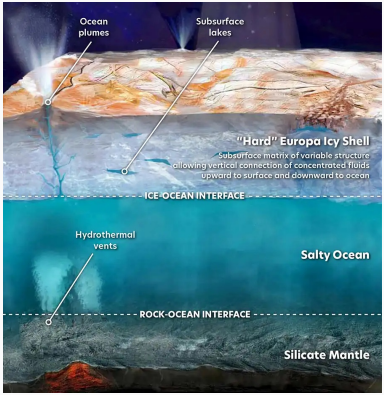


Questioning the Paradigm: Beyond the Habitable Zone

Liquid Water: Only at the "right" distance?

Subsurface Oceans



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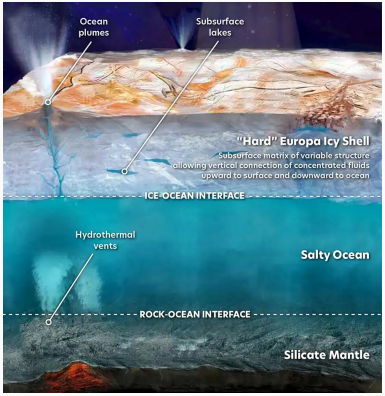

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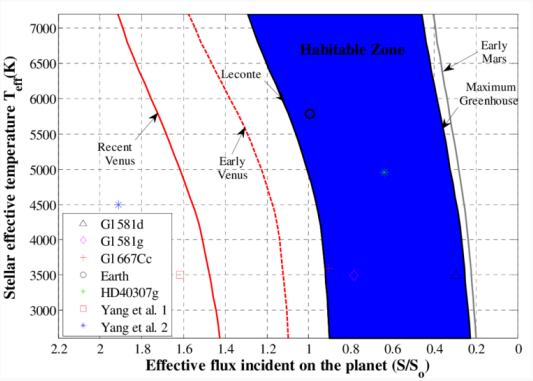
Extreme Greenhouse Effects



Atmospheres with potent greenhouse gases can maintain surface liquid water on planets much farther from star than conventional HZ models [R.M Ramirez 2014].

Why Extremophiles?
Expanding Life's Boundaries

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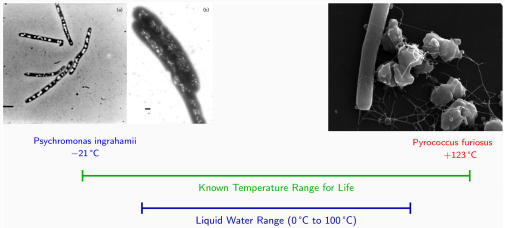
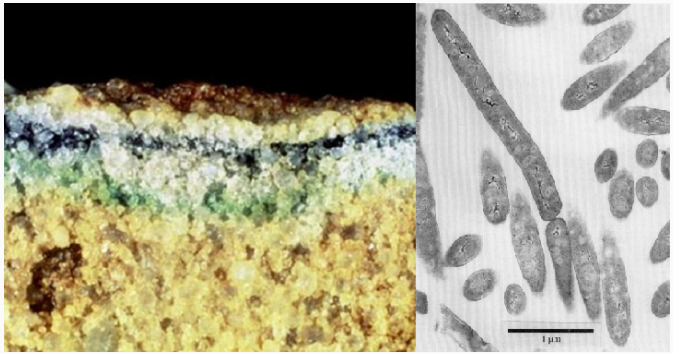
- They **redefine "Habitable"**. Their existence proves that life's environmental limits are far broader than the traditional Habitable Zone, providing data-driven basis for our search.



Why Extremophiles? Expanding Life's Boundaries

- They are active **Planetary Engineers**. They don't just survive; they drive biogeochemical cycles [1], weather rock to create micro-habitats [2], and can fundamentally alter a planet's atmospheric composition [3].

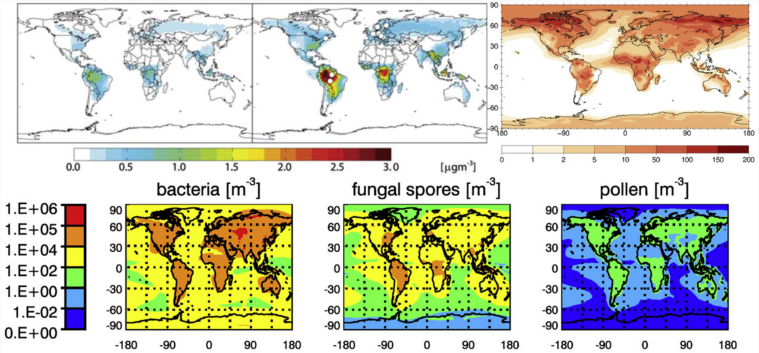
1: Quatrini R. & Johnson D.B.2019
2: Walker J.J. & Pace N.R. 2007
3: Taubner R.S. et al. 2018



Green and blue endolithic lichens growing in antarctic sandstone (NASA) Right: Endolithic bacteria found in rock samples almost 3 km below the earth's surface. (US Dep.of Energy)

Life in the Clouds: Atmospheres as Biomes

- They **validate atmospheres as viable niches**. The discovery of Earth's "aerial biosphere" [5] confirms that microorganisms can thrive in the exact environments that HWO will observe.



5:Fröhlich-Nowoisky J. et al.2016 Model results for annual-mean near-surface concentrations of PBA: fungi in fine mode aerosol and fungi in coarse mode aerosol, and number of bacteria tracers

Atmospheres: Plausible Niches for Life

- Earth's own **"Aerial Biosphere"** proves microorganisms can survive and even proliferate in atmospheric layers.
- This concept extends to worlds with hostile surfaces, which may host temperate, life-friendly layers in their atmospheres.

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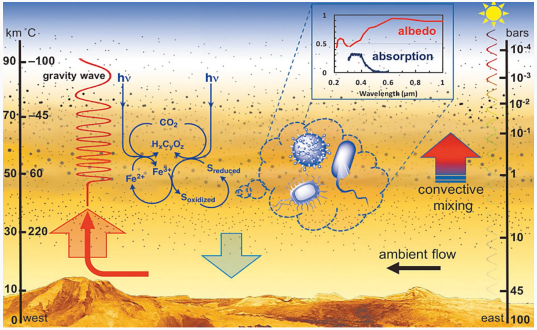

A hypothetical life cycle for microorganisms in the temperate cloud layers of Venus (Seager et al. 2021).

Surface conditions don't tell the whole story!

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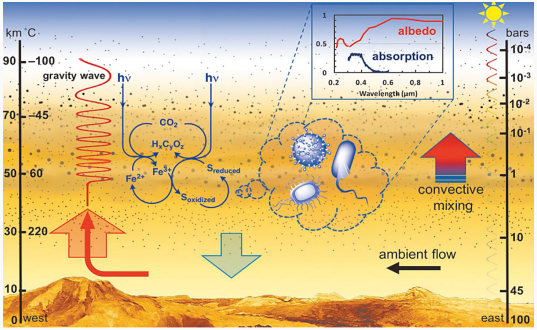

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Study (Author/ Year)	Organism(s) Tested	Simulated Atmospheric Conditions	Key Results (Survival, Growth, Gases Produced)
Kuzucan et al. 2025	*E. coli* K-12	Standard air, 100% CO_2, 90% N_2 + 10% CO_2, 80% CH_4 + 15% N_2 + 5% CO_2, 100% H_2; 22°C	Survival and growth in H_2 and CH_4-rich (after acclimation); stronger growth in air; slower growth in CO_2. Lag, log, stationary phases observed.
Seager et al. 2020	*E. coli*, *S. cerevisiae*	100% H_2; controls (air, CO_2/N_2, He)	Survival and reproduction in 100% H_2; lower growth rates compared to air. *E. coli* produced DMS, NH_3, N_2O, isoprene, etc.

Experimental data showing E. coli proliferation in 100% hydrogen atmospheres, validating gas giants as potential habitats.

Surface conditions don't tell the whole story!

A New Metric:
The Multiparametric Life Score

The Life-Compatible Zone & The MLS: Our Framework

Concept: The Life-Compatible Zone

- A **quantitative, local concept**: Identifies specific atmospheric layers where physical conditions (T, P, radiation) overlap with the known tolerance ranges of extremophiles.

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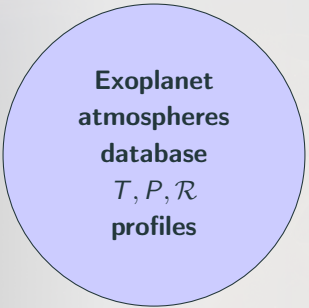
- It answers the question: **"How promising is this entire planet as a potential habitat?"**

This moves us from a binary "yes/no" to a nuanced, quantitative ranking.

Astrophysics & Microbiology to Map Life's Potential



Astrophysics & Microbiology to Map Life's Potential

Exoplanet atmospheres database
$T, P, \mathcal{R}$ **profiles**

Extremophile Tolerances
Min/Max/Optimal
$T, P, \mathcal{R}$ **ranges**

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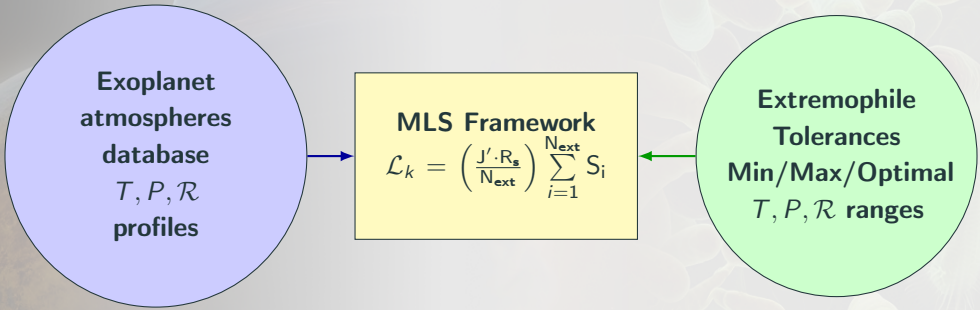

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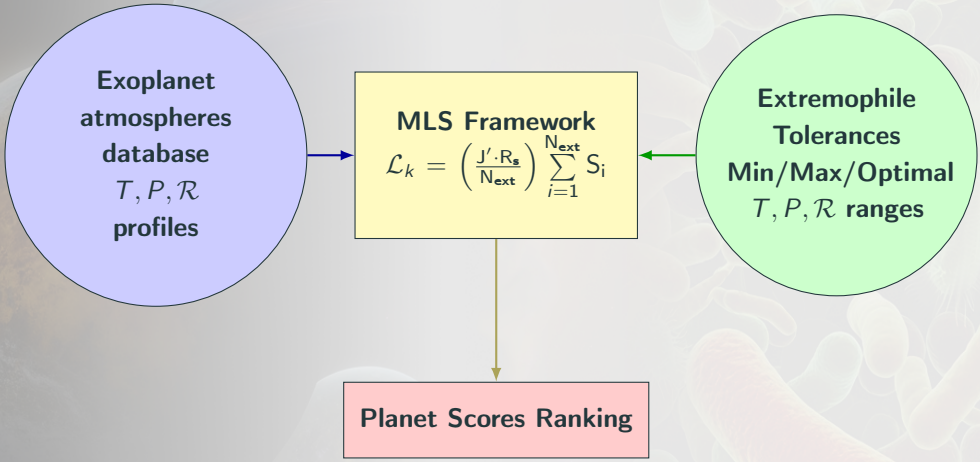

The Exobioma Project: From Data to Biosignatures

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The Modeling Process & Goal

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To: Could life survive here? —> From: **What chemical evidence would it produce?**

From Individual CRNs to a Full Atmospheric Model

Extremophile Database

- 300 species with metagenomic data
- Each species mapped to its bacterial CRN

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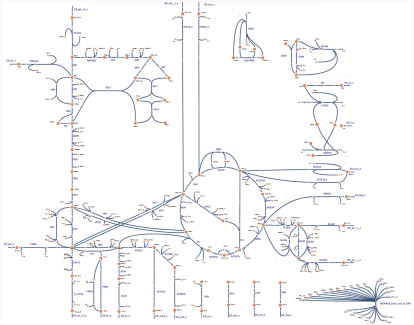

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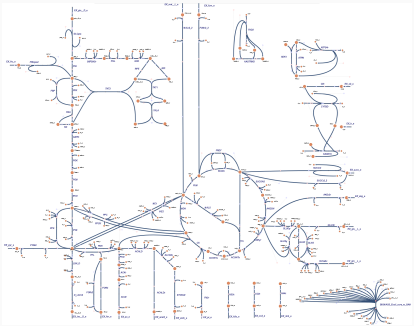
Integrates all 300 bacterial CRNs based on atmospheric compatibility (MLS score)



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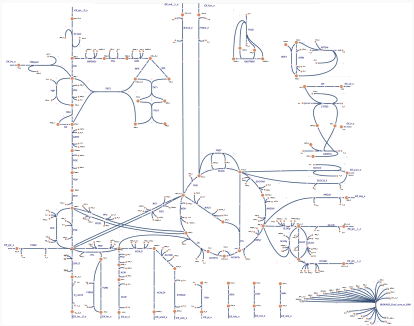

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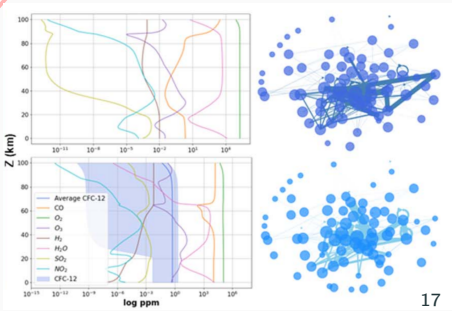

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Extremophile Database

- 300 species with metagenomic data
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We start from 300 individual networks to derive a single, complex atmospheric network.

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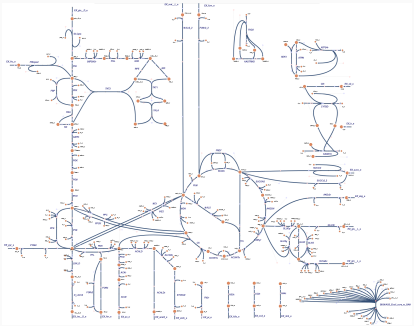

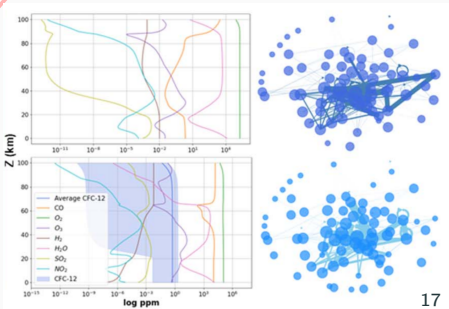

On Left: *E. coli* CRN from KEGG Database. On Right: Two CRNs of the Earth's atmosphere without the polluting molecule CFC at the top and with a minimal concentration at the bottom. Large changes in the abundances of many other chemical species are evident. T.Fisher et al. 2025

Guiding the Habitable Worlds Observatory

A Targeted Shopping List for HWO

Input:
Predicted
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Analysis Algorithm
Identifies most abundant and volatile species

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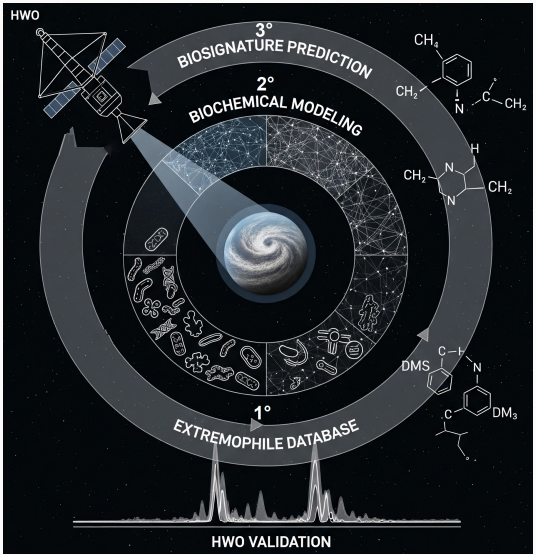
Targeted Campaign

A multiscale approach from extremophiles to Biosignatures



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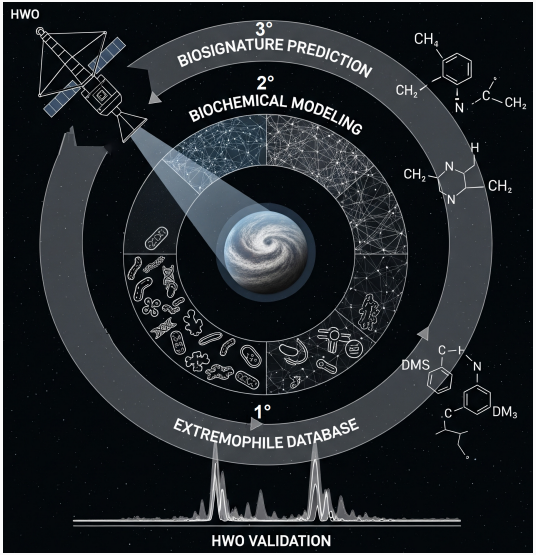

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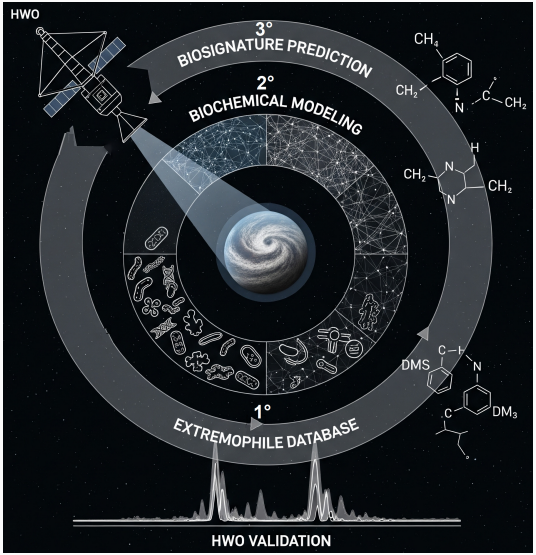

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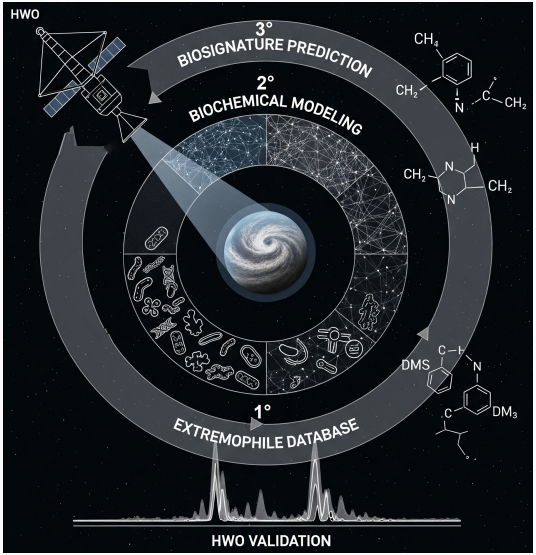

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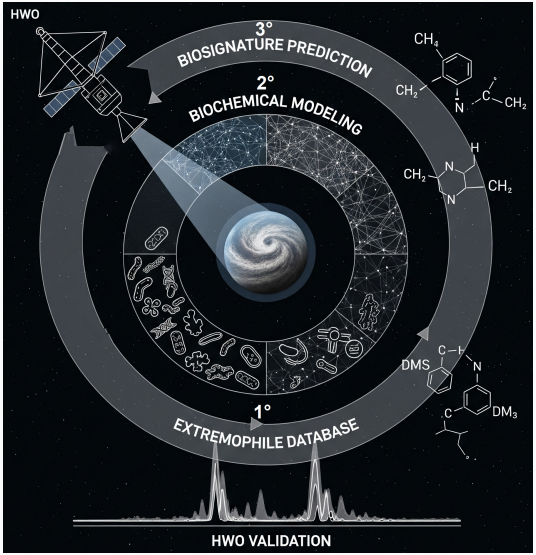
4. Validate: HWO
Use the Habitable Worlds Observatory to perform targeted observations and search for the predicted VOCs.



Key Takeaways

- The **Habitable Zone** is a starting point, but it is too limited for the search for life.
- Our **Multiparametric Life Score (MLS)** provides a data-driven method to rank planets based on their compatibility with known extremophiles.
- The **Exobioma Project** connects microbial biology to atmospheric chemistry to predict specific, observable biosignatures (VOCs).
- This framework will directly **guide HWO's strategy**, optimizing target selection and data interpretation.
- We are moving astrobiology from speculation to a **testable, data-driven field**.