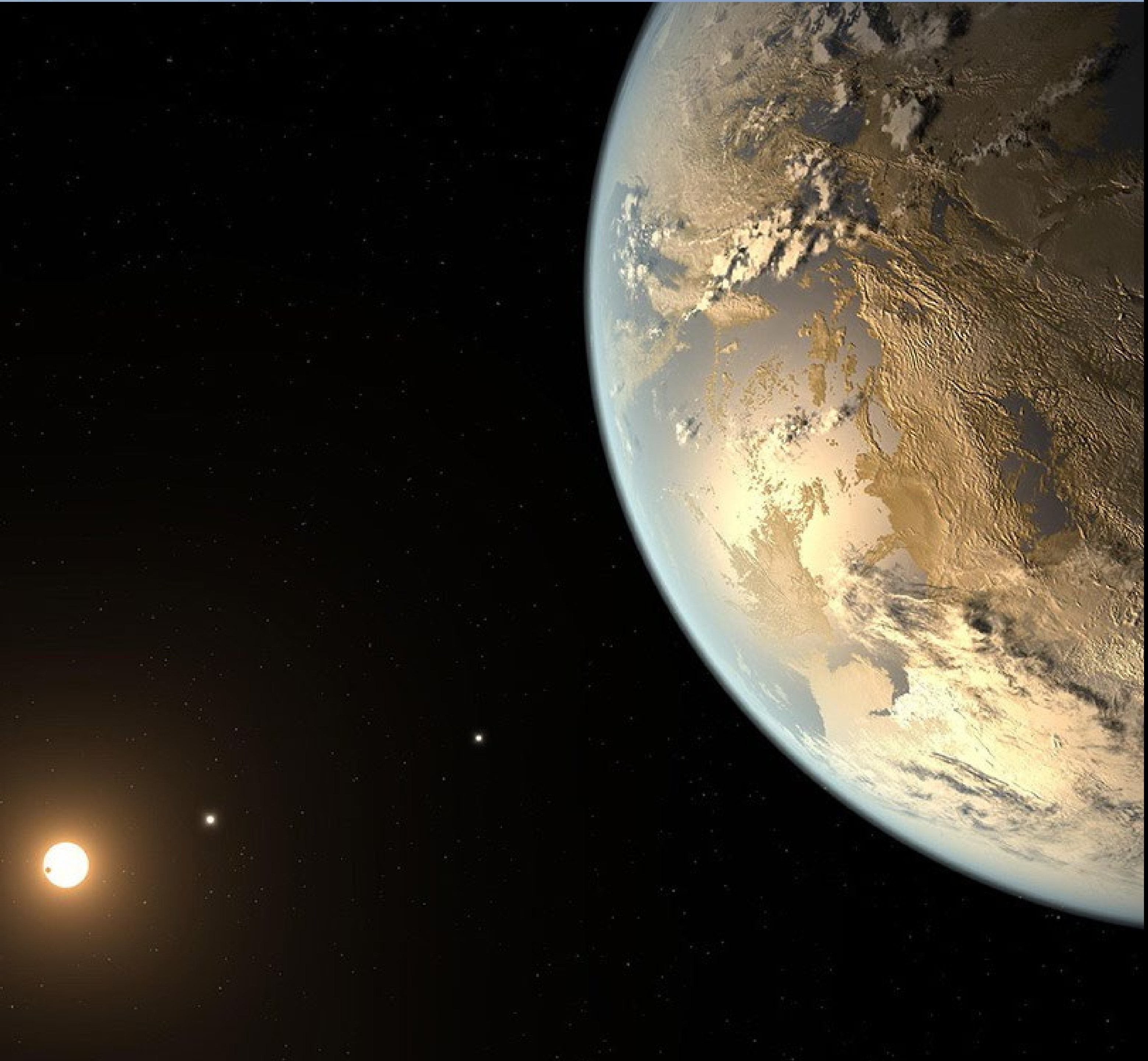
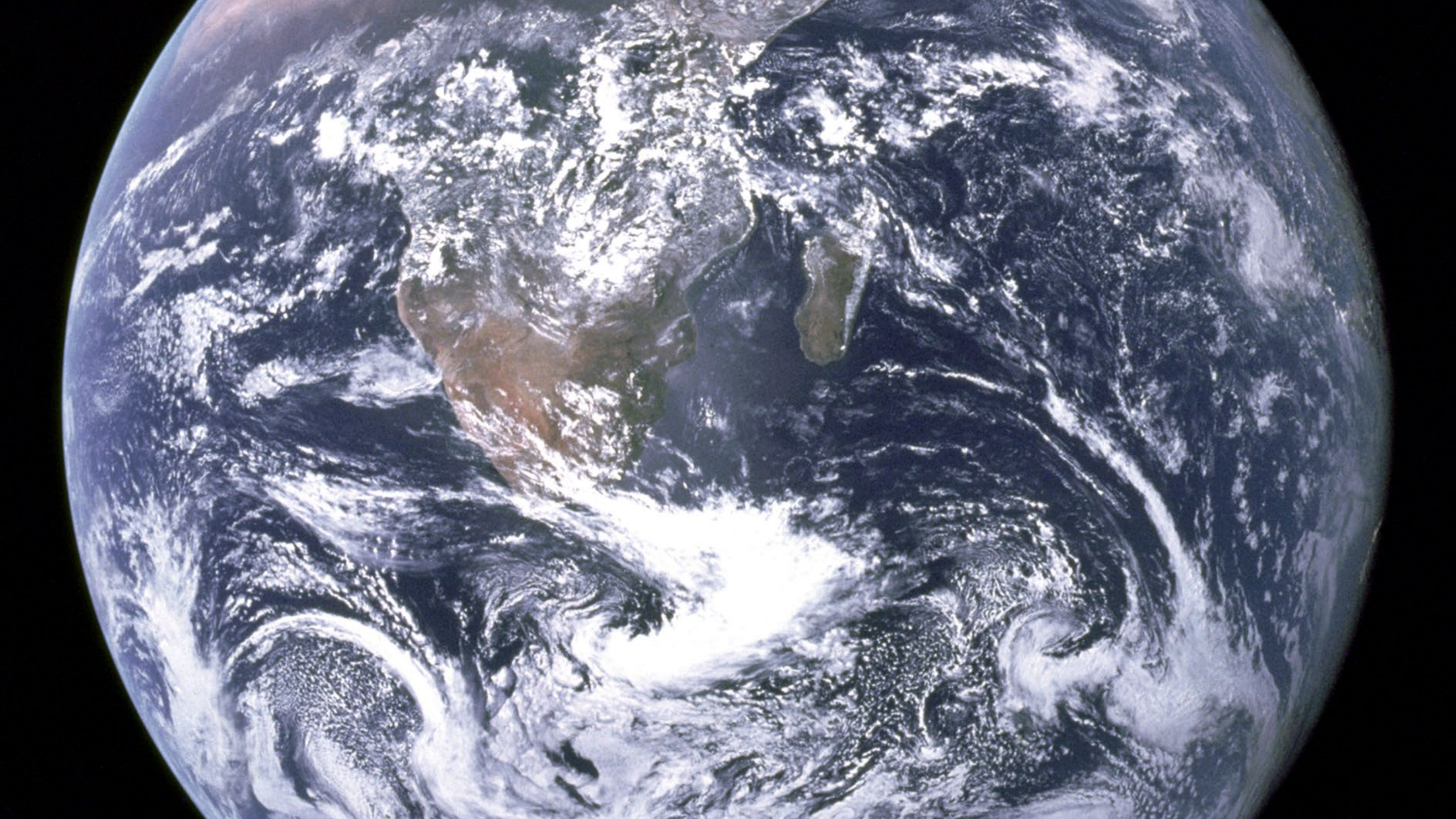


Searching for Life: General Motivation and Approaches

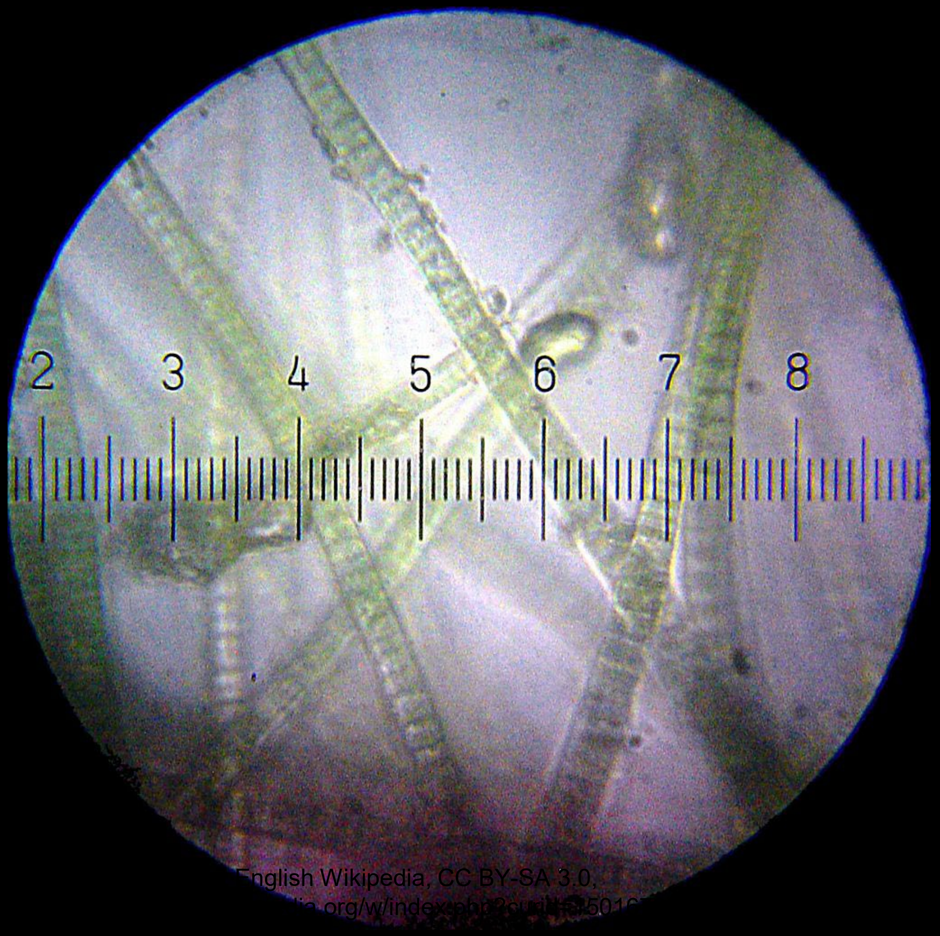
Dr. Tiffany Kataria

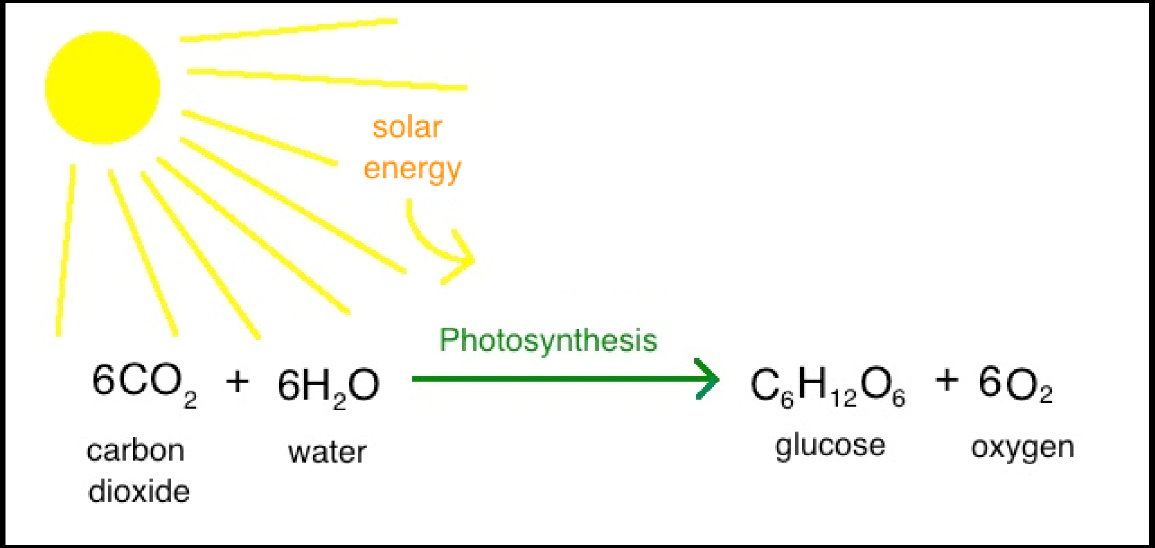
Jet Propulsion Laboratory, California Institute of Technology

Mon, Nov 28, 2022



Understanding Earth life helps us search for life elsewhere



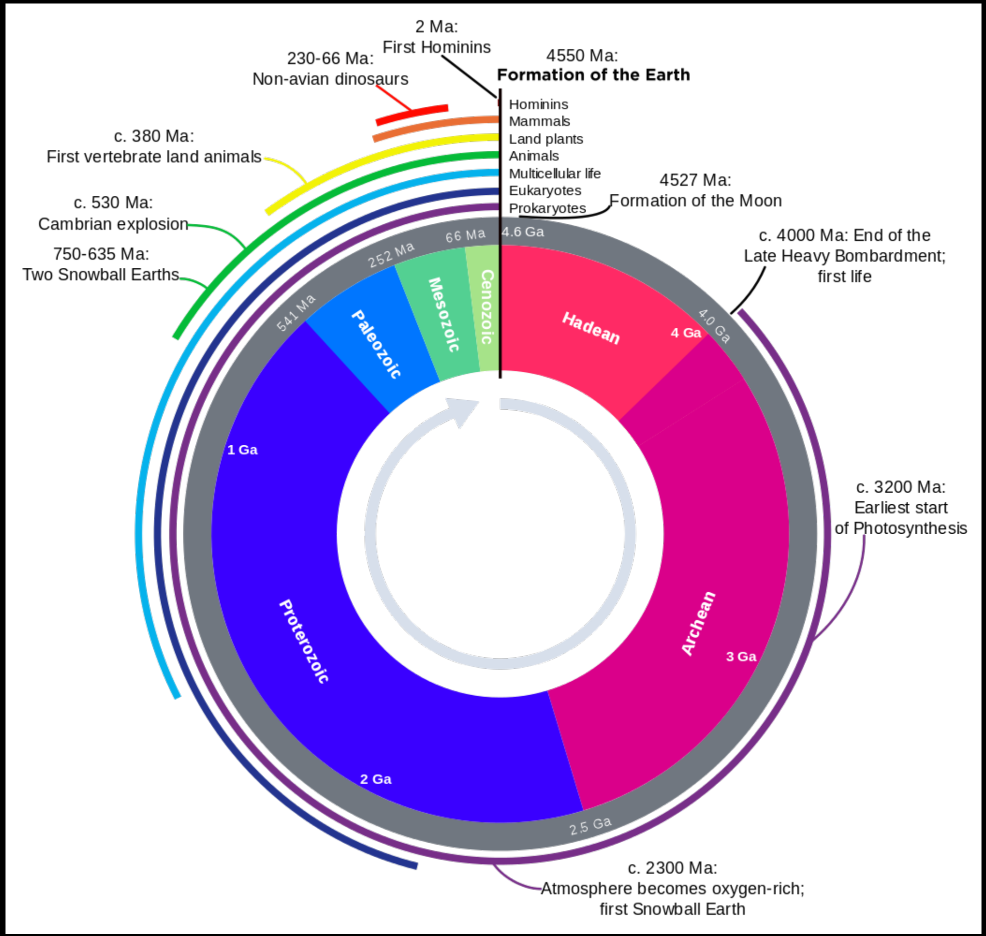


www.khanacademy.org/science/biology/photosynthesis-in-plants/introduction-to-stages-of-photosynthesis/a/intro-to-photosynthesis

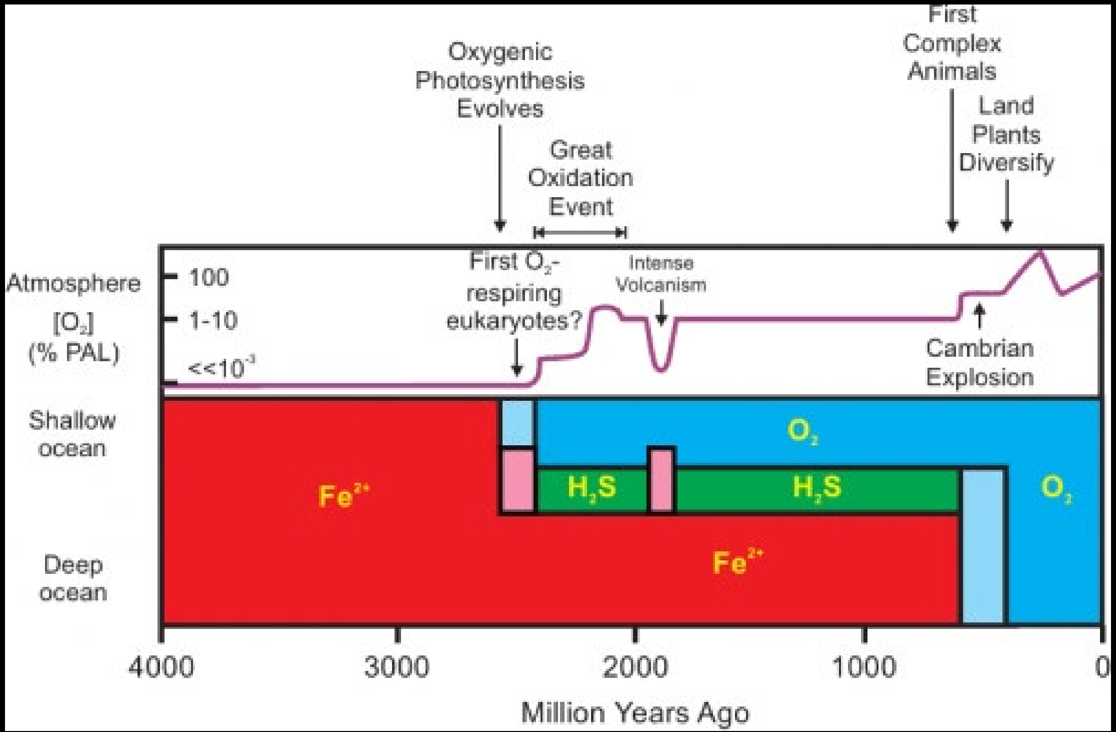
Credit: Laurie Barge

Earth and its life have evolved together,

which is why searching for life elsewhere requires combined perspectives from planetary science, geology, biology, chemistry (and astronomy!).



https://en.wikipedia.org/wiki/History_of_Earth

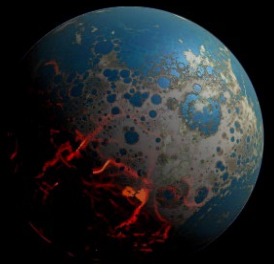


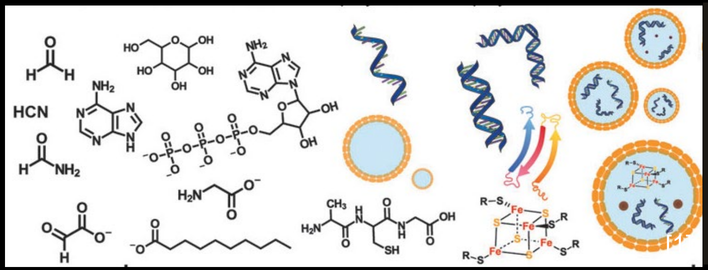
https://uwaterloo.ca/wat-on-earth/news/earths-oxygen-revolution

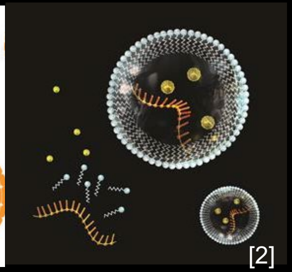
The history of life on Earth is also the history of **oxygen (O_2).**

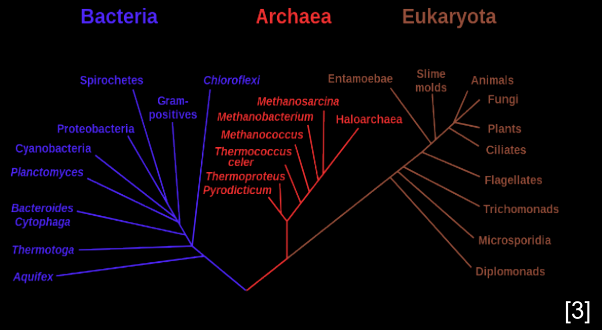
What would this timeline look like on another world?

Timeline of the Origin of Life (OOL) on Earth









Formation of Earth	Abiotic organic chemistry	Prebiotic chemistry	Origin of Life	Pre-LUCA genes / enzymes	Last Universal Common Ancestor (LUCA)	First evidence of life
4.5 Gya	- - - - - - - - - - - - - - - -		4.4 – 4.1 Gya	- - - - - - - - - - - - - - - -		4.1 – 3.7 Gya

ORIGINS AND HABITABILITY LAB

Experiments to replicate prebiotic chemistry in early Earth conditions

Bottom-up approach

Studies of modern life to infer traits of LUCA / pre-LUCA / OOL

Top-down approach

Credit: Laurie Barge

[1] Barge et al. 2022, *Astrobiology* [2] Image: Henning Dalhoff/Science Photo Library; [3] Wikipedia

Various environmental settings are proposed for Earth's OOL

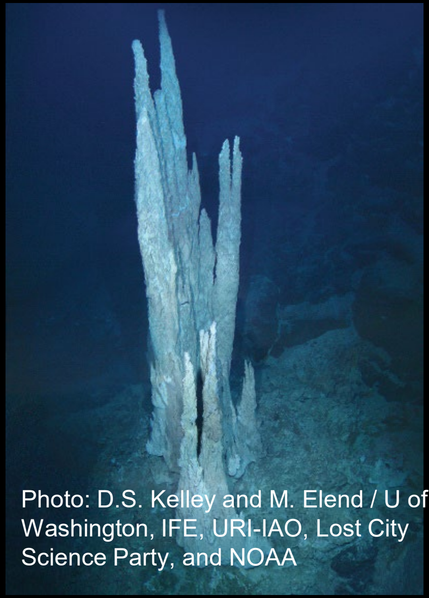
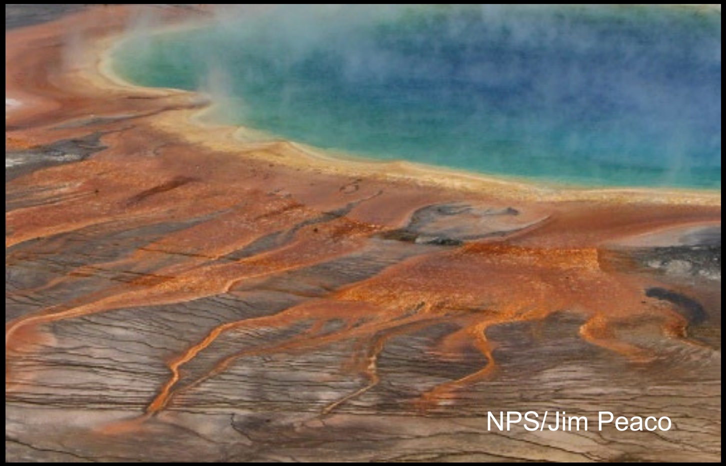


Photo: D.S. Kelley and M. Elend / U of Washington, IFE, URI-IAO, Lost City Science Party, and NOAA

Schmidt Ocean Institute

By Benjamint444 - CC BY-SA 3.0



NPS/Jim Peaco

Image: NASA

Possible solar system habitability includes many Ocean Worlds

Images: NASA

Credit: Laurie Barge

Questions for astrobiology / OOL on ocean worlds and exoplanets

- What gradients are present in putative ocean world vents?
- What minerals / metal catalysts are present?
- What is the geochemistry of the oceans / rock / ice?
- How would Earth-like prebiotic reactions be different under these conditions?
- What other prebiotic / biotic histories are possible?
- **What would the biosignature threshold be for this world?**

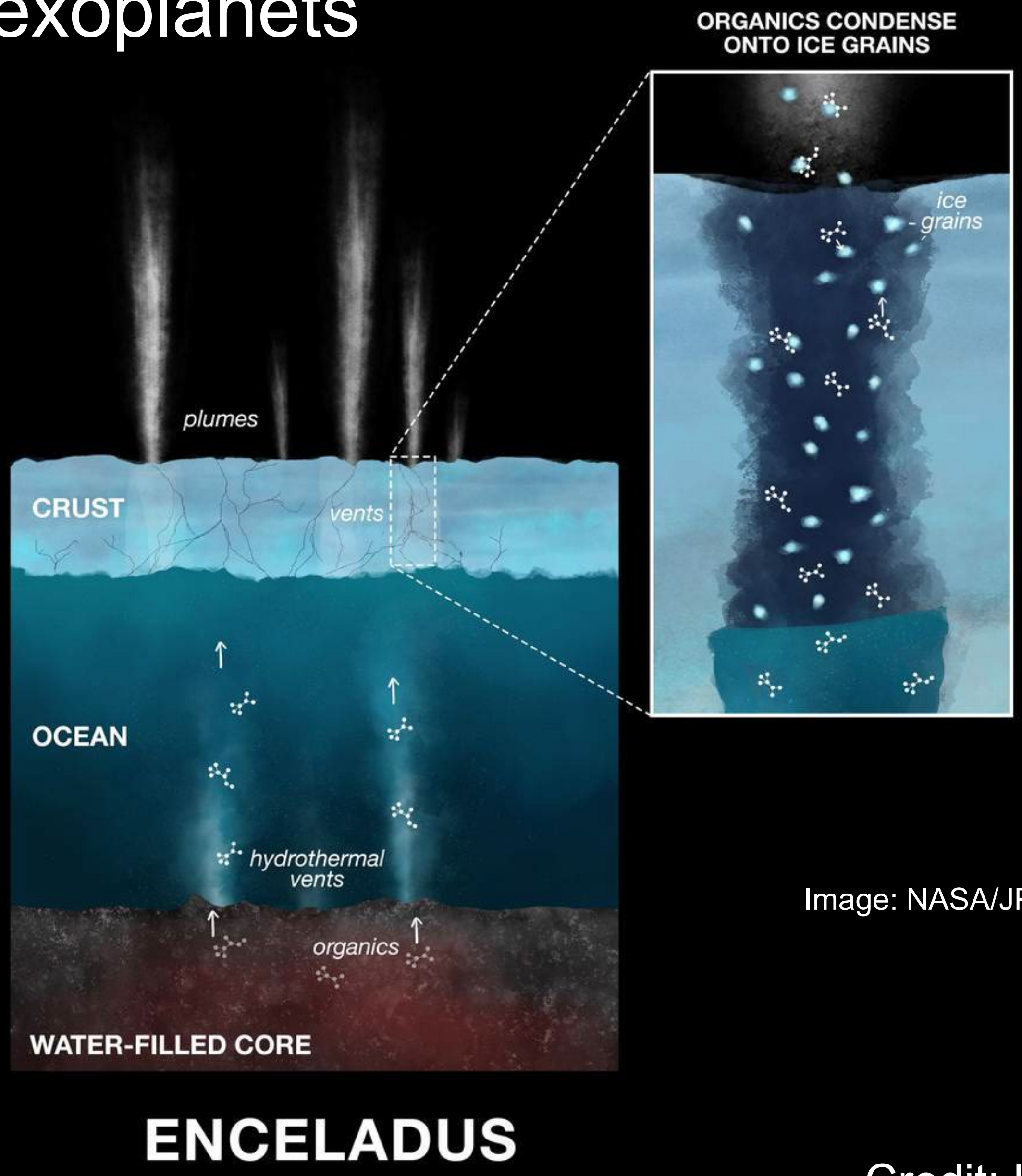
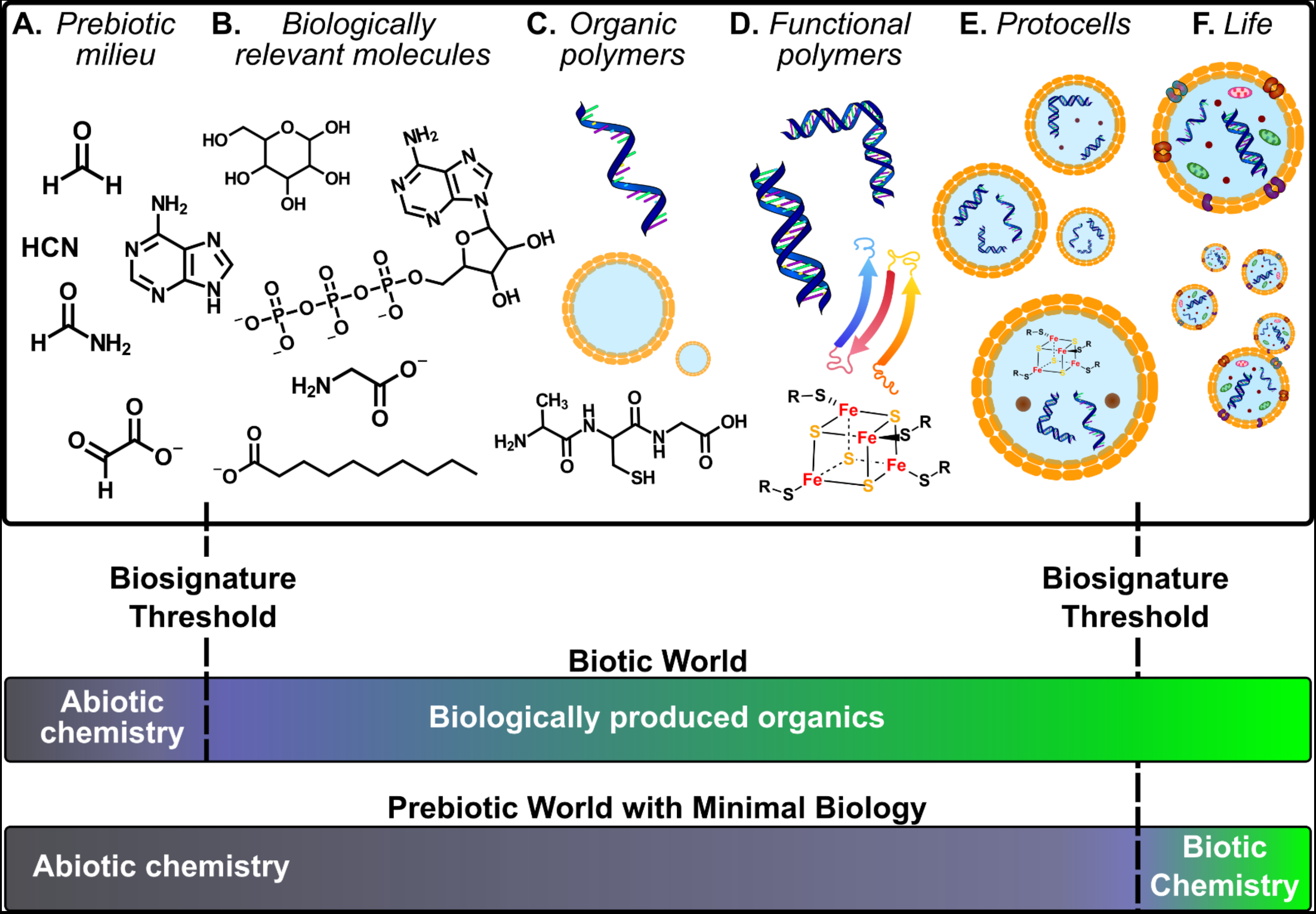


Image: NASA/JPL-Caltech

Credit: Laurie Barge

Investigating Biosignatures: How can we differentiate life from non life?



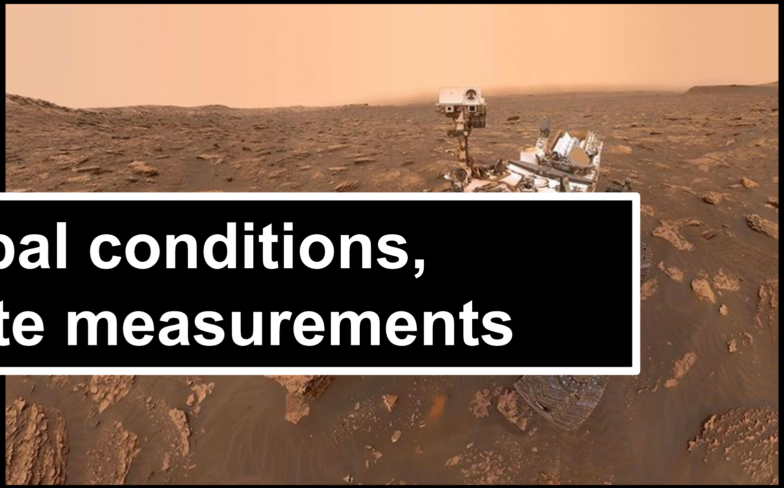
Barge L.M., Rodriguez L.E., Weber J.M., Theiling B.P. Determining the "Biosignature Threshold" for Life Detection on Biotic, Abiotic, or Prebiotic Worlds. Astrobiology 2021, http://doi.org/10.1089/ast.2021.0079.

Approahces to identifying Biosignatures

Local surface biology

Planetary Science

In-situ measurements



**Local and global conditions,
in situ and remote measurements**

Astrophysics

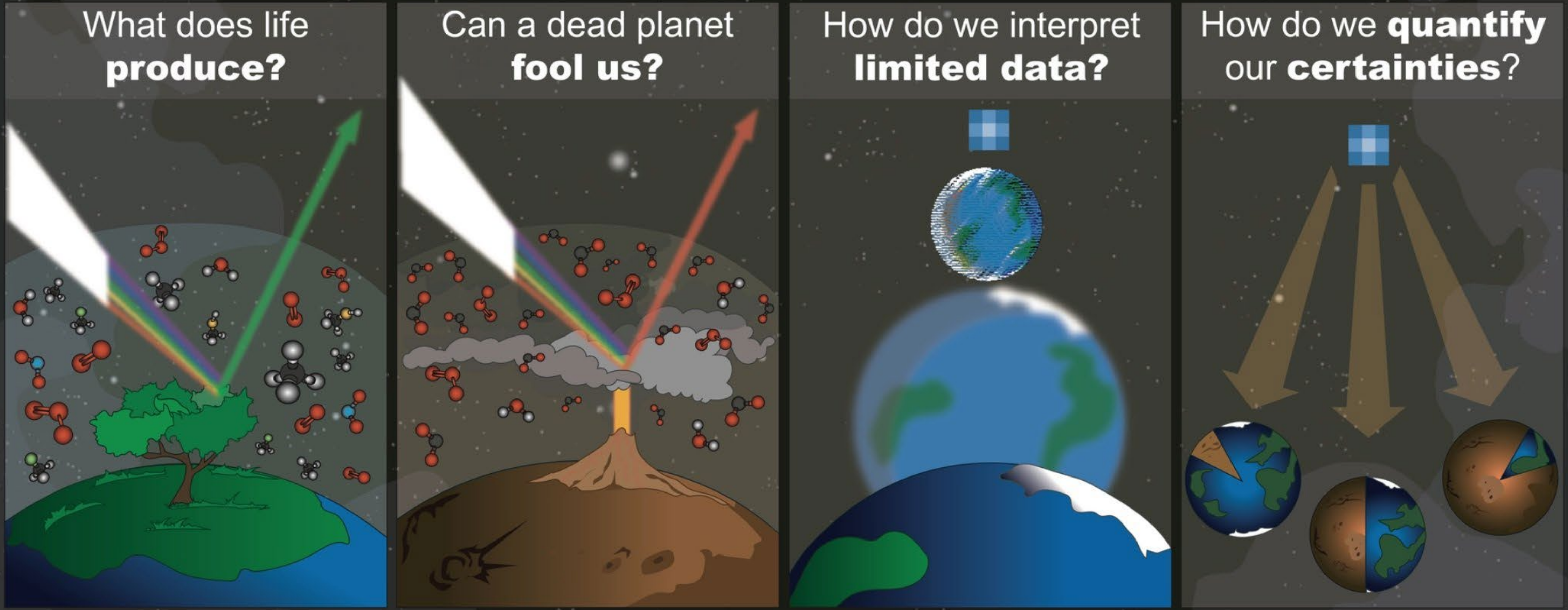
**Remote detections of
‘biosignature’ gases**

**Only (mostly) global conditions, only
remote measurements**

TABLE 7. DIFFERENT TYPES OF POTENTIAL *IN SITU* AND REMOTE BIOSIGNATURES

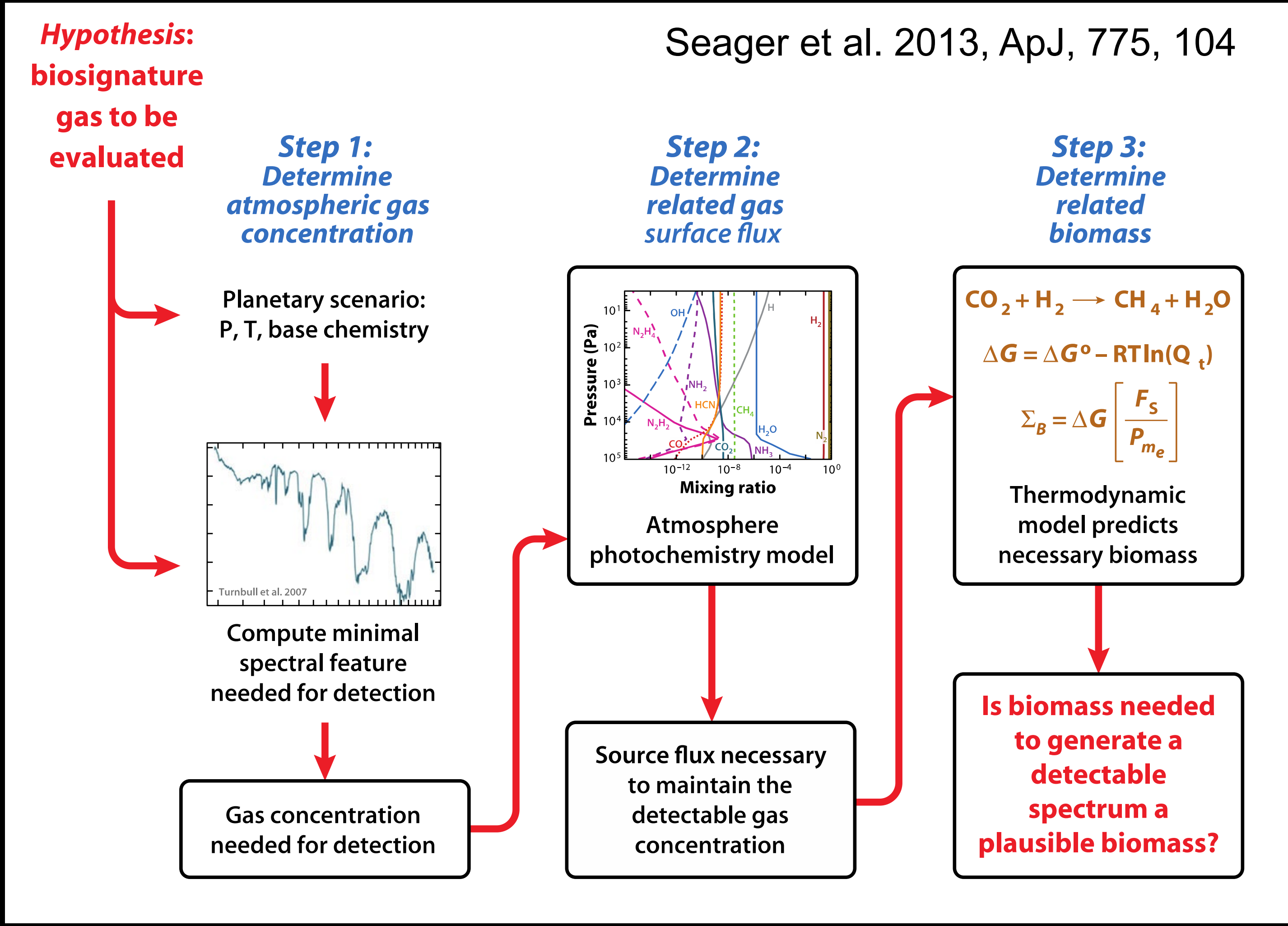
	Type	Biosignatures	Examples	Appropriate techniques
In situ	Visual biosignatures	Direct observation of active life	Cellular structures (possibly seen to be motile or reproducing)	Microscopy or macroscopic imagery
		Fossils	Fossilized cells	
		Artifacts of life	Stromatolites or endolithic microborings	
	Chemical biosignatures	Biological macromolecules	Proteins or nucleic acid polymers (*e.g.*, DNA, RNA)	Gas chromatography–mass spectrometry, Raman spectroscopy, X-ray spectroscopy
		Molecular fossils	Breakdown products of biomolecules, such as hopanoids or steranes	
		Molecular evidence of metabolism	Biogenic biases, such as isotopic fractionation or homochirality	
		Thermodynamic or kinetic disequilibrium within environment	Gradients of redox species in column of lake water	
		Biominerals	Certain silicate, carbonate, or iron minerals, or metal enrichments of, *e.g.*, Cu, Mo, Ni, W	
Remote	Spectral biosignatures	Large-scale environmental disequilibrium	Atmospheric disequilibrium, *e.g.*, O_2 and CH_4	IR and visible spectroscopy
		Photosynthetic life	Red edge of vegetation	
	Spatially resolved	Geometrical structures of intelligent life	Roads, cities, agriculture, large-scale landscape modification	Optical imaging
	Electromagnetic emissions	Intelligent broadcasts	Radio or optical signals from a civilization	Radio or optical sky surveys

Domagal-Goldman and Wright et al. 2016



from Astrobiology, published by Mary Ann Liebert, Inc., New Rochelle, NY

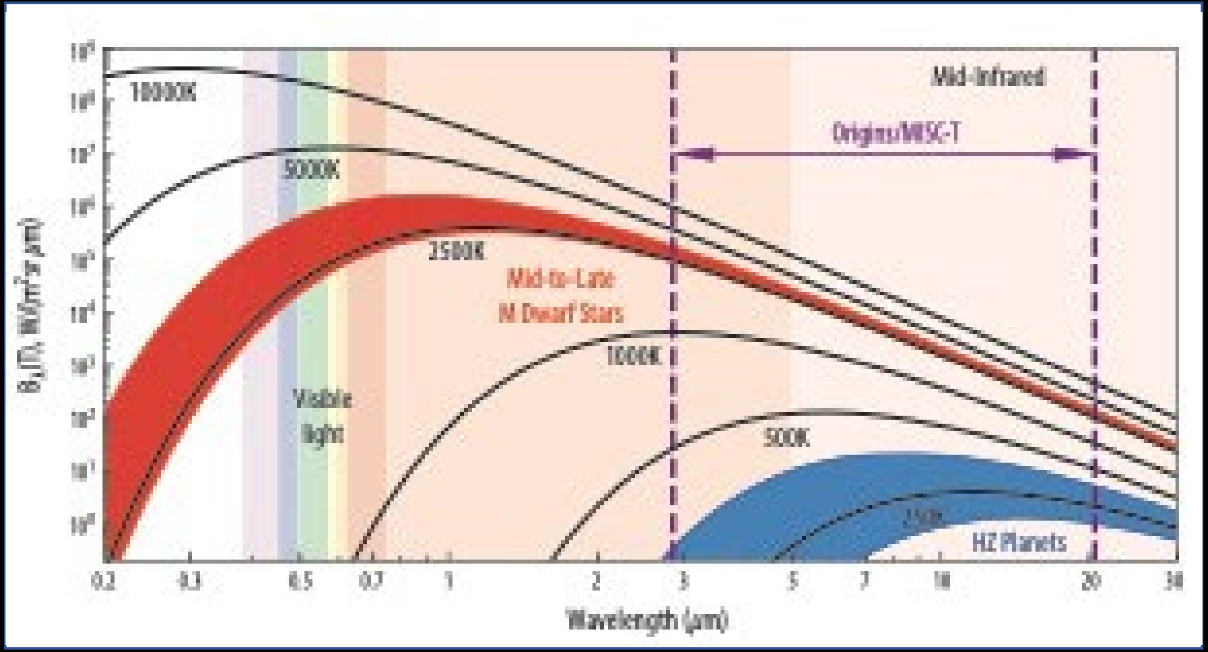
Biosignature investigations now take many forms
Linking biomasses and biosignature detection

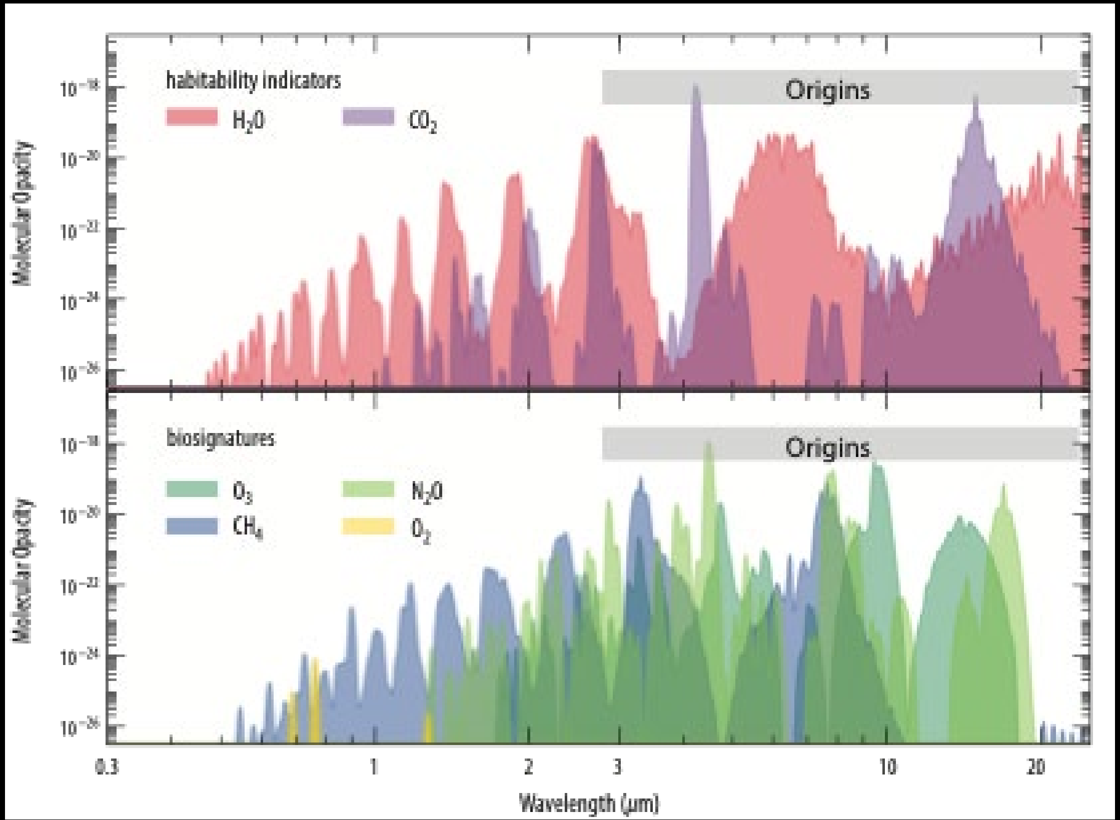


Link the detection of biosignature gases to biomass estimates from the literature

The Power of the Mid-IR in identifying biosignatures

- Access to thermal emission and the temperature structure of atmospheres
- Absorption features for a range of biologically interesting gases
- *Origins* considered O_3+CH_4 and O_3+N_2O biosignature pairs



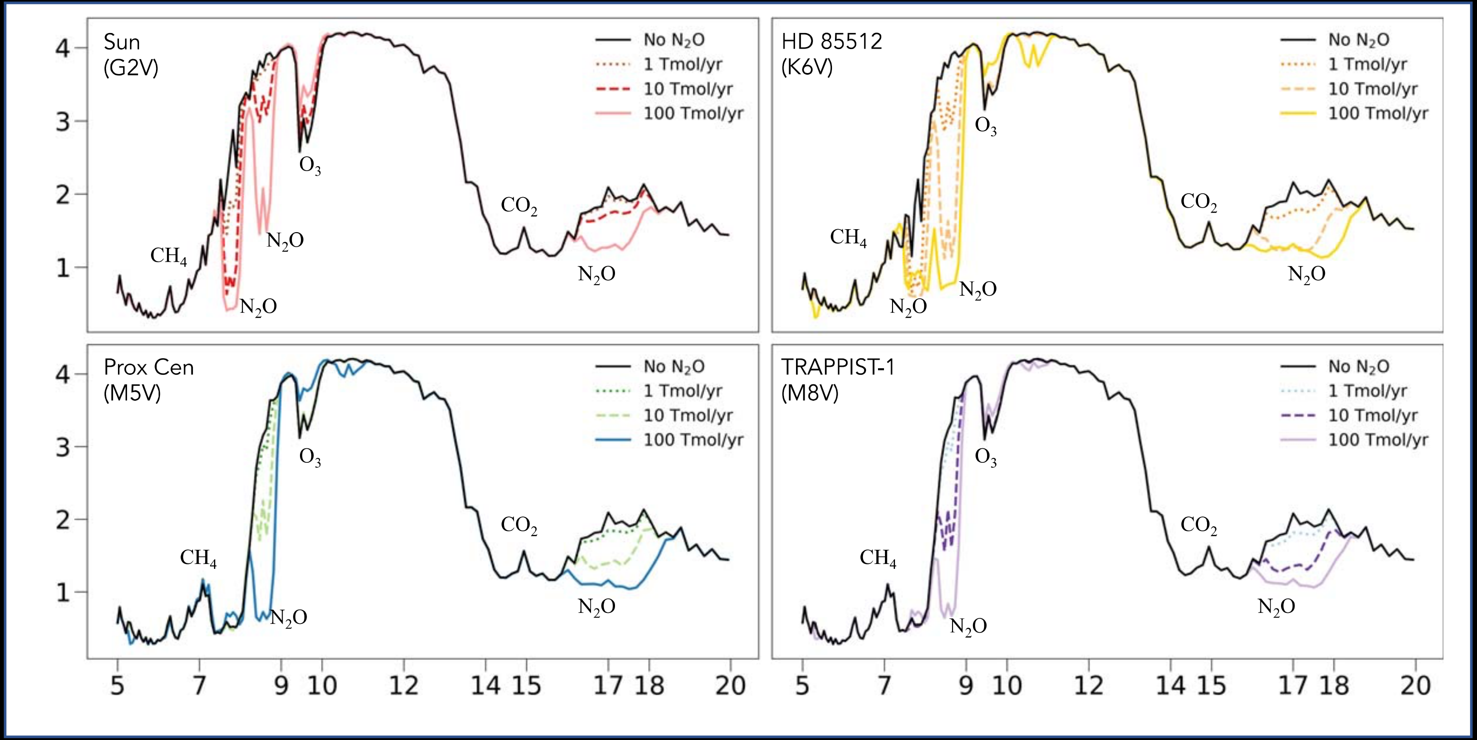


Figures from the Origins Space Telescope Concept Study Report

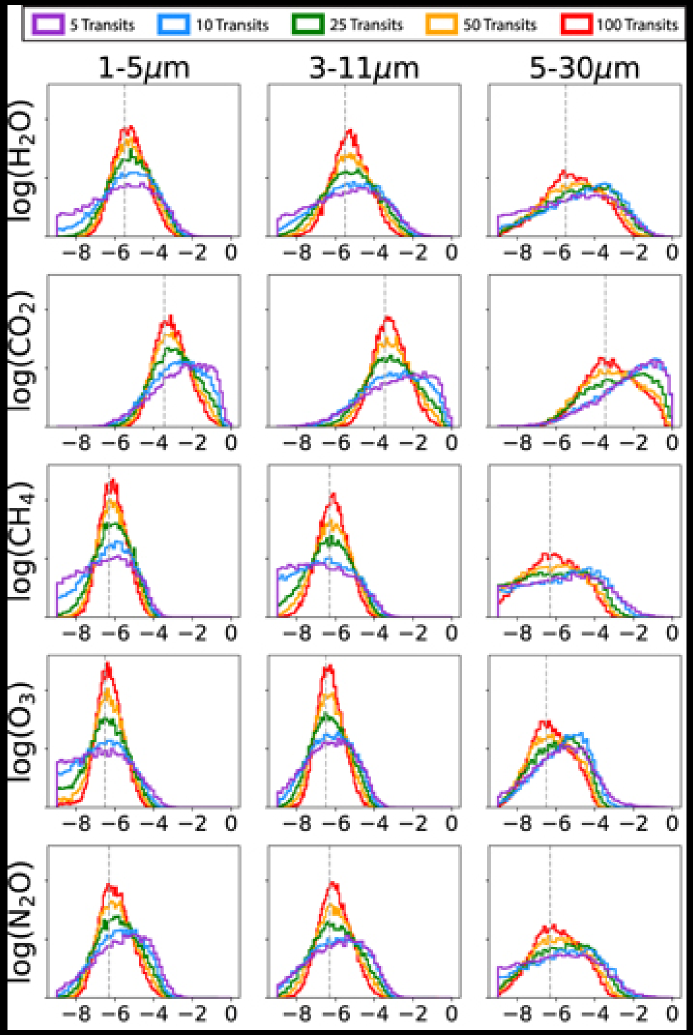
New investigations of novel (mid-IR) biosignatures

Methyl bromide as a biosignature (Leung et al. 2022)

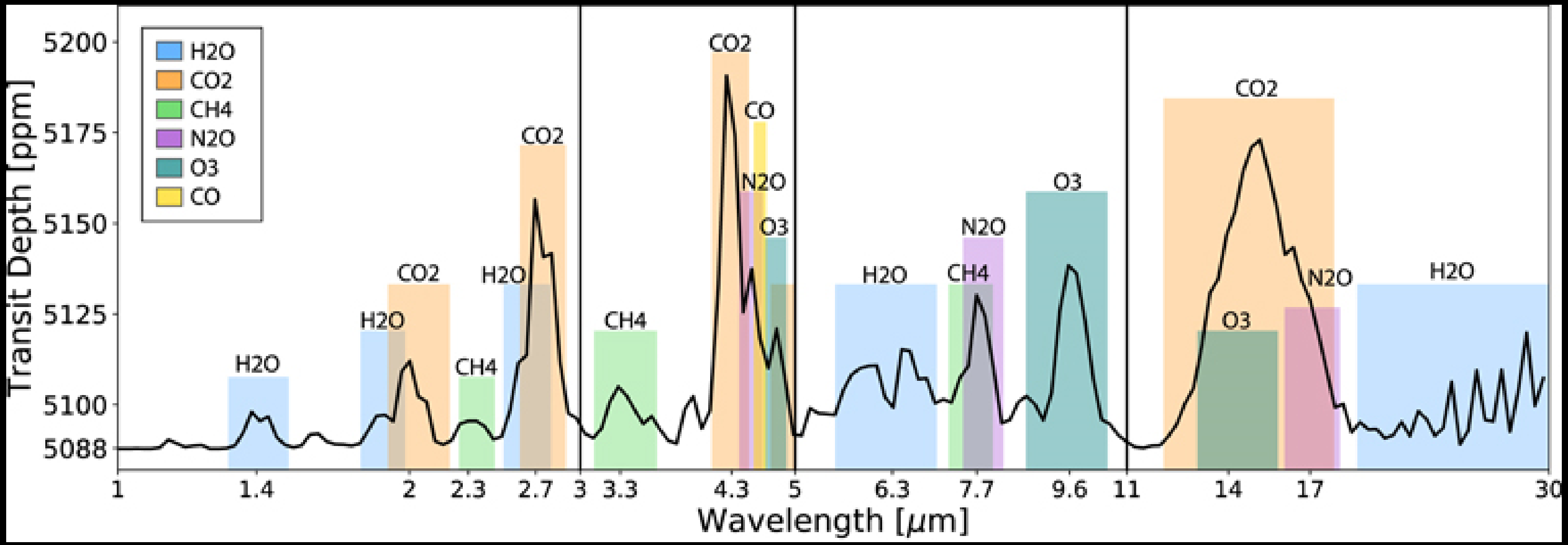
Investigating N_2O alone as a biosignature (Schwieterman et al. 2022)



Astro2020 mid-IR trade studies

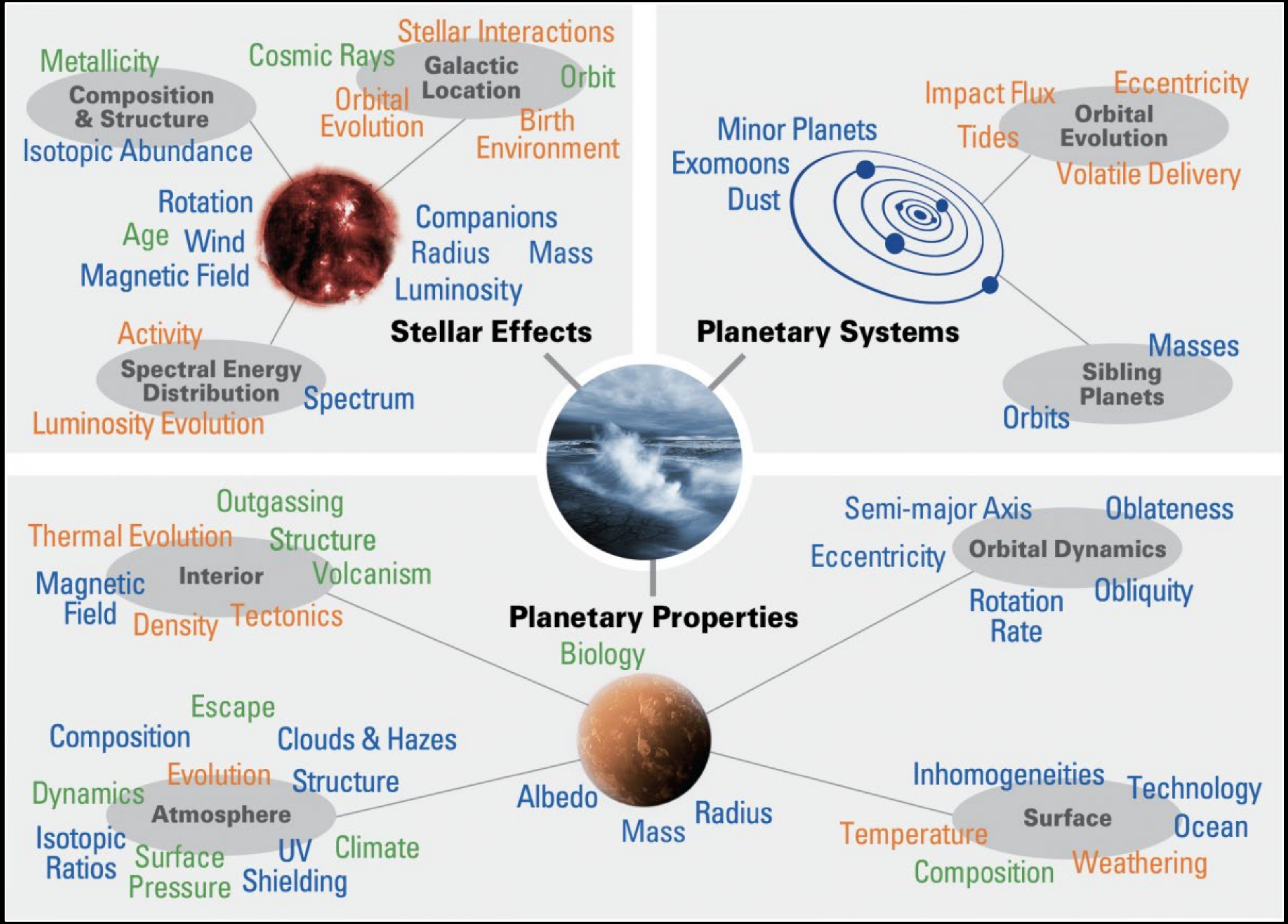


- For *Origins*, conducted detailed trade studies to identify ideal wavelength range for confidently detecting biosignatures and other biologically relevant gases
  - However, our studies were limited to M-dwarf HZ planets
- Future studies using mid-IR spectroscopy to determine habitability should explore a range of stellar and planet types



Tremblay et al. (2020)

Ultimately, the search for life will require complex trades and a holistic treatment of exoplanets and their environments



Meadows & Barnes, 2018

Additional slides

Life can use almost any energy source, and the first life on Earth was likely chemosynthetic.

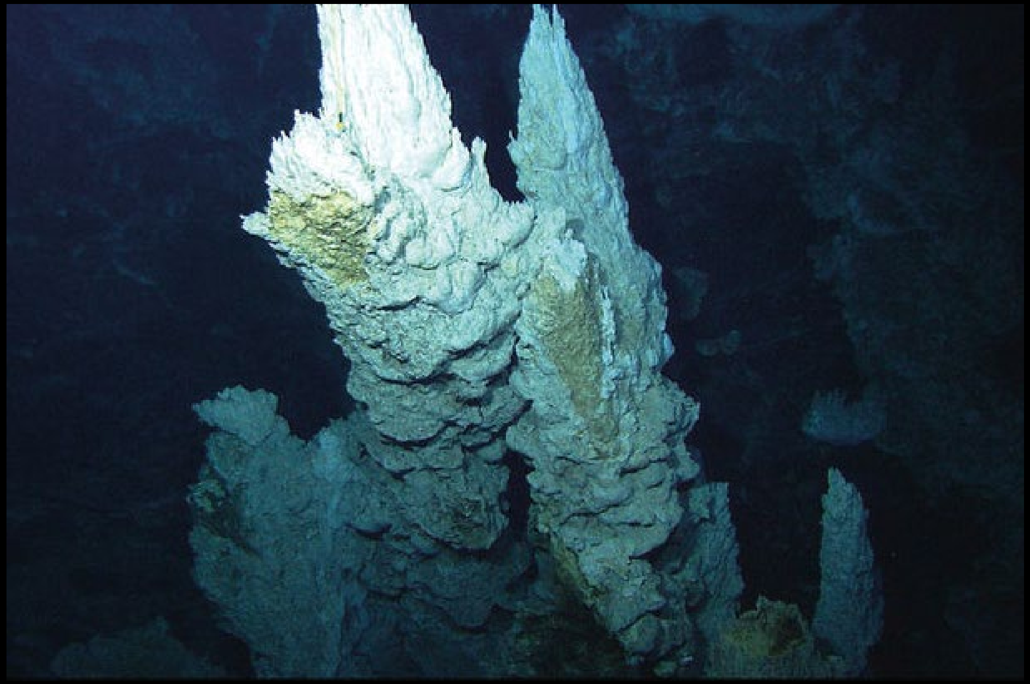
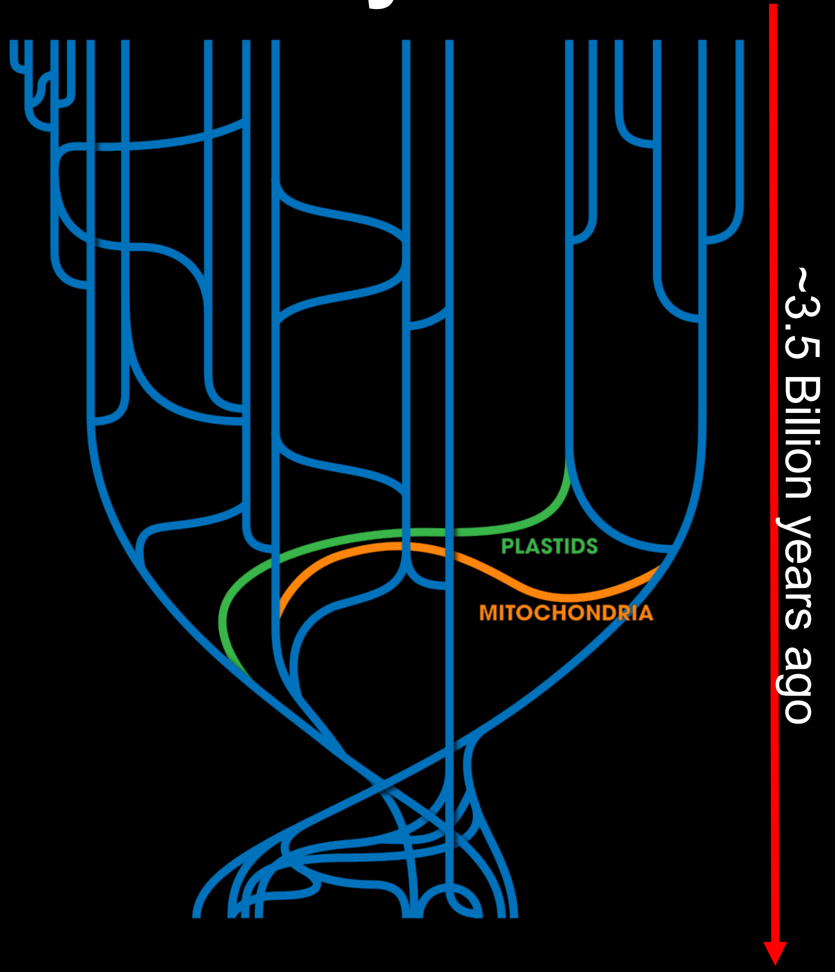


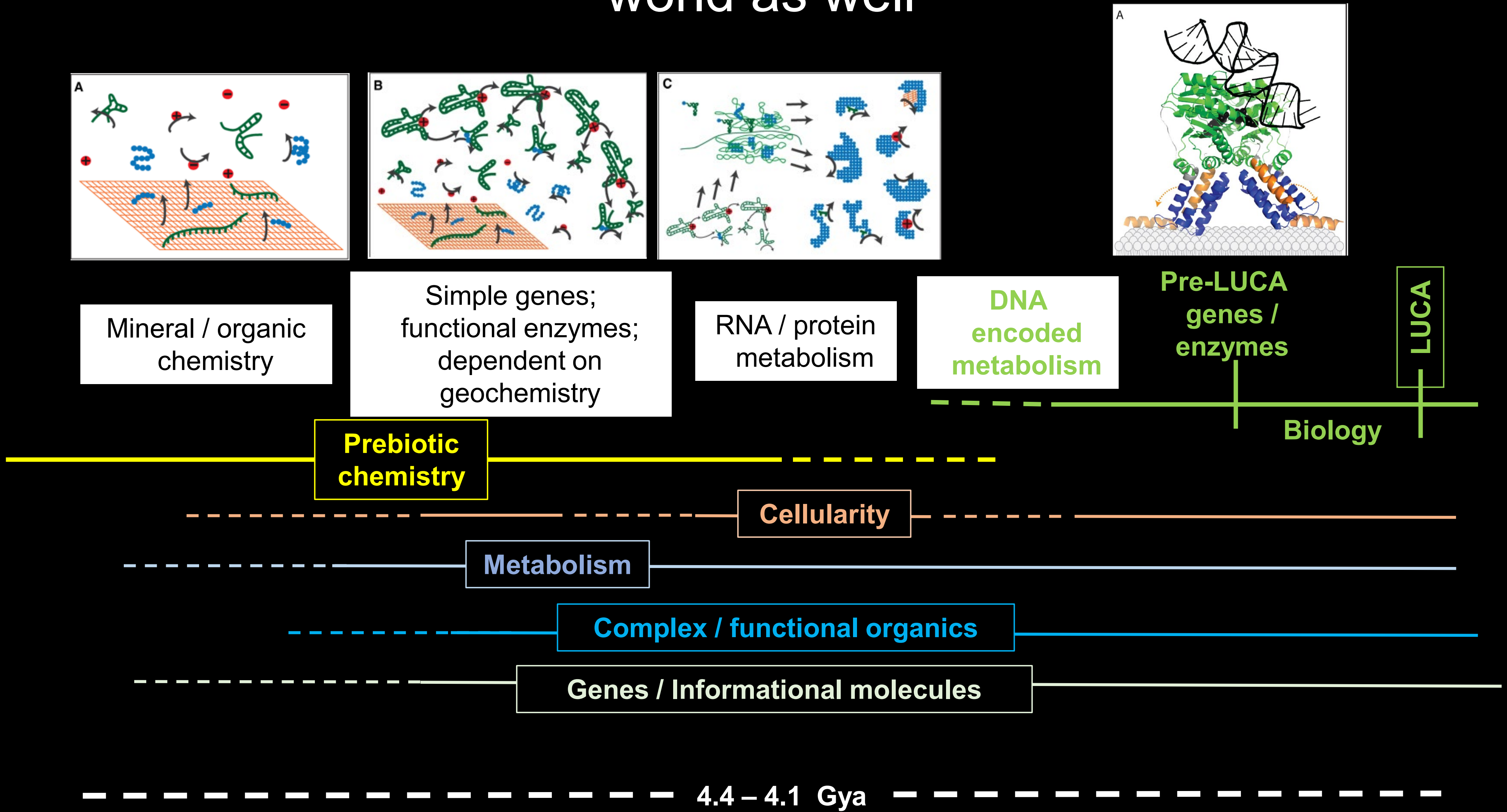
Image: IFE, URI-IAO, UW, Lost City Science Party;
NOAA/OAR/OER; Lost City 2005 Exp./CC BY 2.0



Barth F. Smets, Ph.D. / Nature Reviews Microbiology

Consider Early Earth, which was also a different planet

Some “biosignature” properties were present in the prebiotic world as well



[1] Goldman et al. 2016 *JME*; [2] Harris and Goldman 2020, *PLoS Comput Biol*

OOL research can help inform life detection

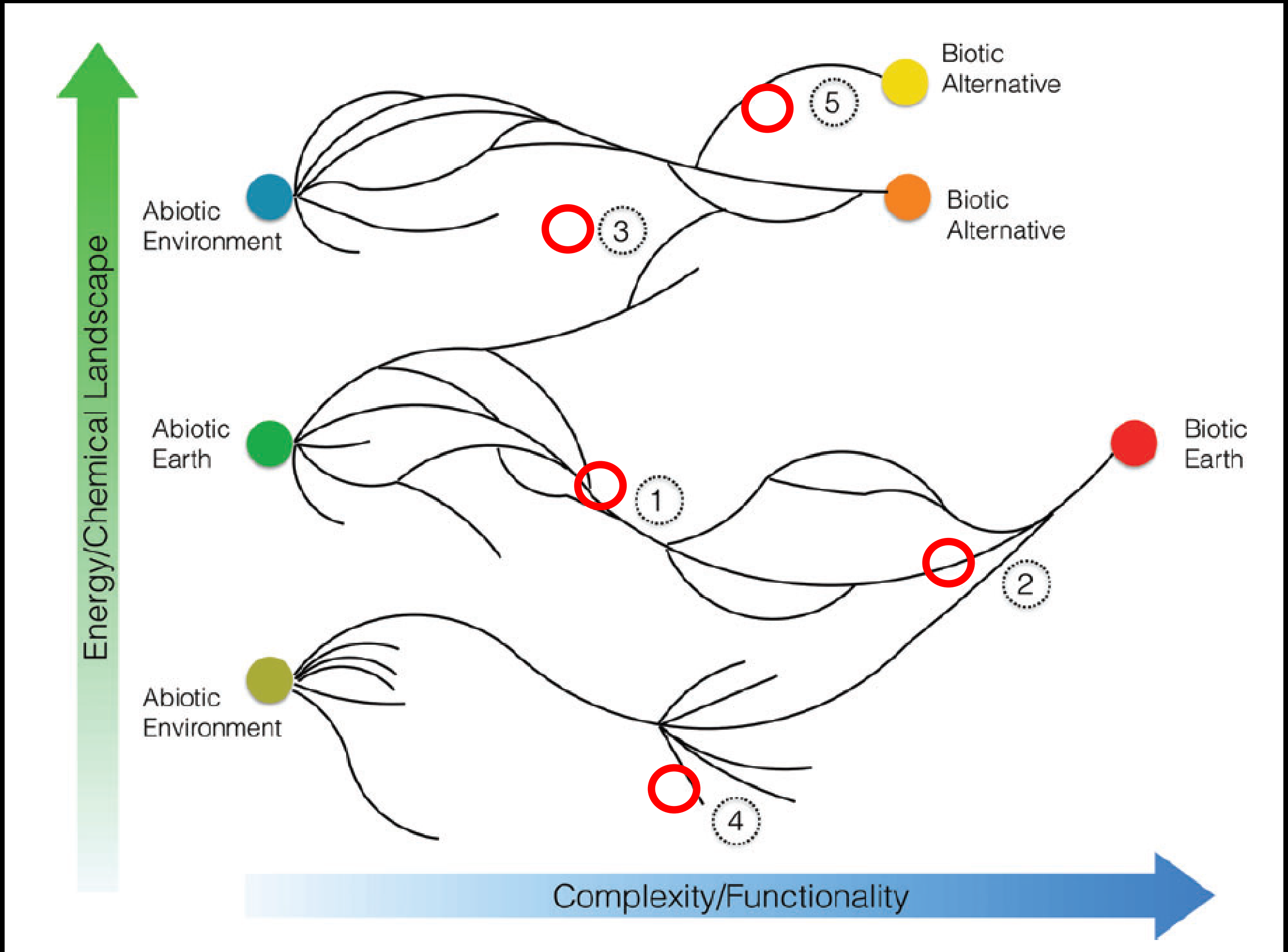
(1) Bottleneck: important exploration target

(2) Alternate prebiotic conditions leads to Earth-like life

(3) Earth-like OOL leads to alternate biotic system

(4) Rapid diversification of prebiotic systems but only one OOL event

(5) Multiple OOL events on the same planet



Scharf et al. 2017, ‘A Strategy for Origins of Life Research’, *Astrobiology*

What would each of these look like to an organic detection instrument?

EAS3: How do habitable environments arise and evolve within the context of their planetary systems?

The habitability of exoplanets is likely governed by a complex interplay of planet, star and planetary system processes over time.

EAS3.1: How are potentially habitable environments formed?

EAS3.2: What processes influence the habitability of environments?

EAS3.3: What is the range of potentially habitable environments around different types of stars?

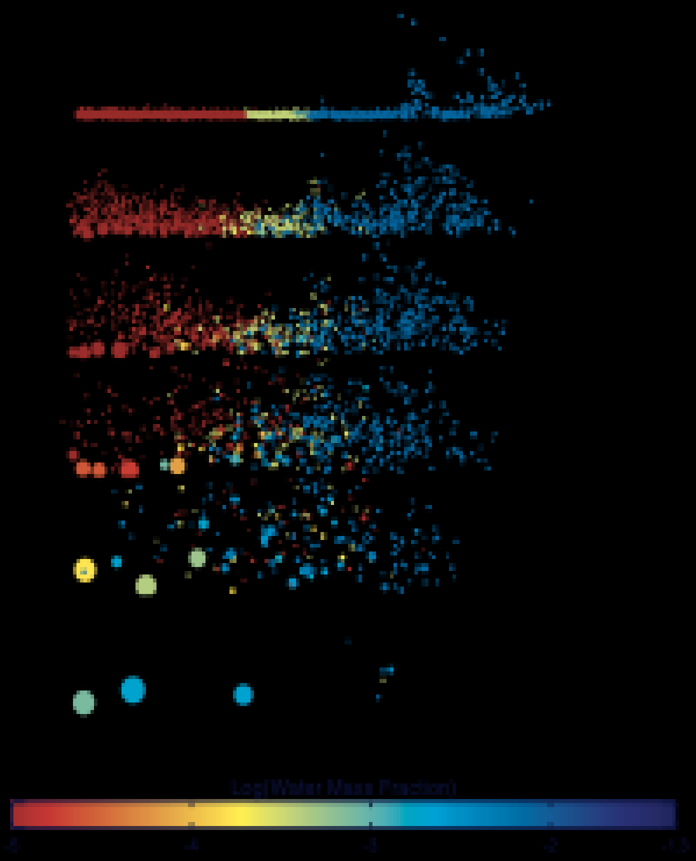
EAS3.4: What are the key observable characteristics of habitable planets?

EAS3.1: How are potentially habitable environments formed?

Delivery of volatiles and organics are key processes in habitable planet formation.

How do spectral type, stellar metallicity, disk composition, and planet migration influence the type and amount of volatile delivery?

Need to understand solar system volatile history and volatile distributions in exoplanetary systems to constrain models of volatile delivery to forming planets.



S. Raymond

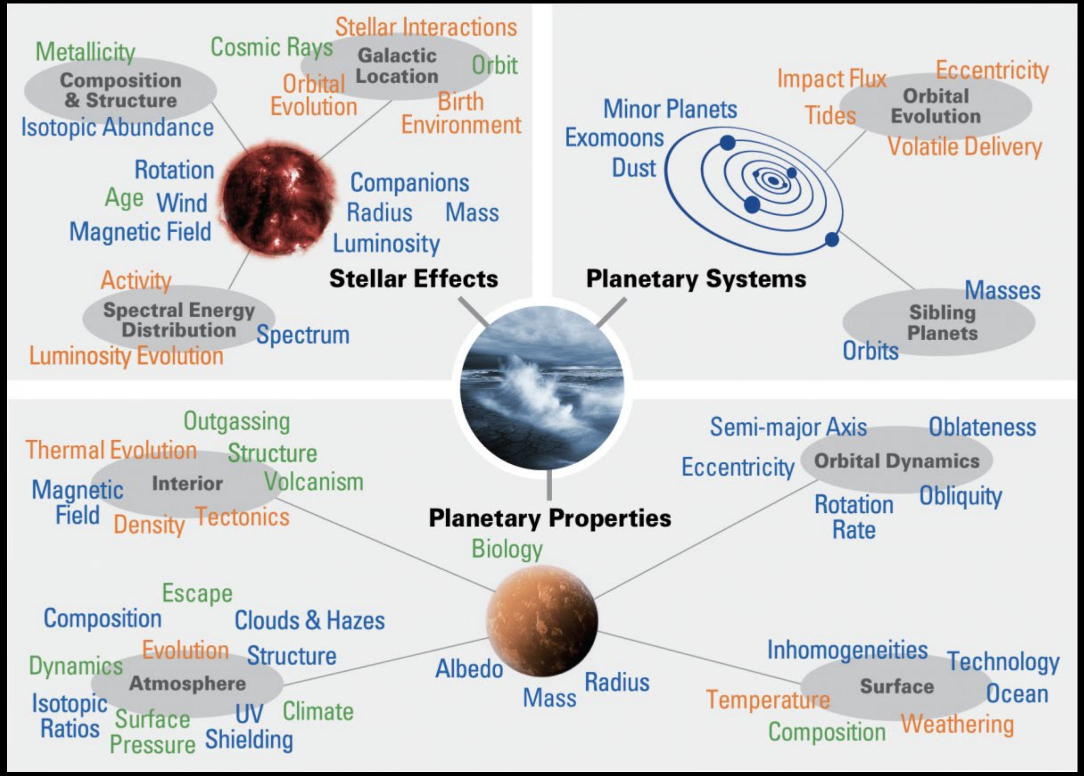
Approach: Determine volatile content for a range of solar system small bodies and across nearby planet forming disks to constrain theoretical models of dynamical evolution and volatile accretion and delivery.

EAS3.2: What processes influence the habitability of environments?

Need to take a systems science approach to understand the influence on habitability of the characteristics and evolution of the parent star, planetary system and planet properties, and the interactions between these components

Within the solar system, understand how processes like tidal heating, bombardment, volatile loss and gain and atmospheric change affect habitability

Improve our understanding of the Earth's habitable environments over time



Meadows & Barnes, 2018

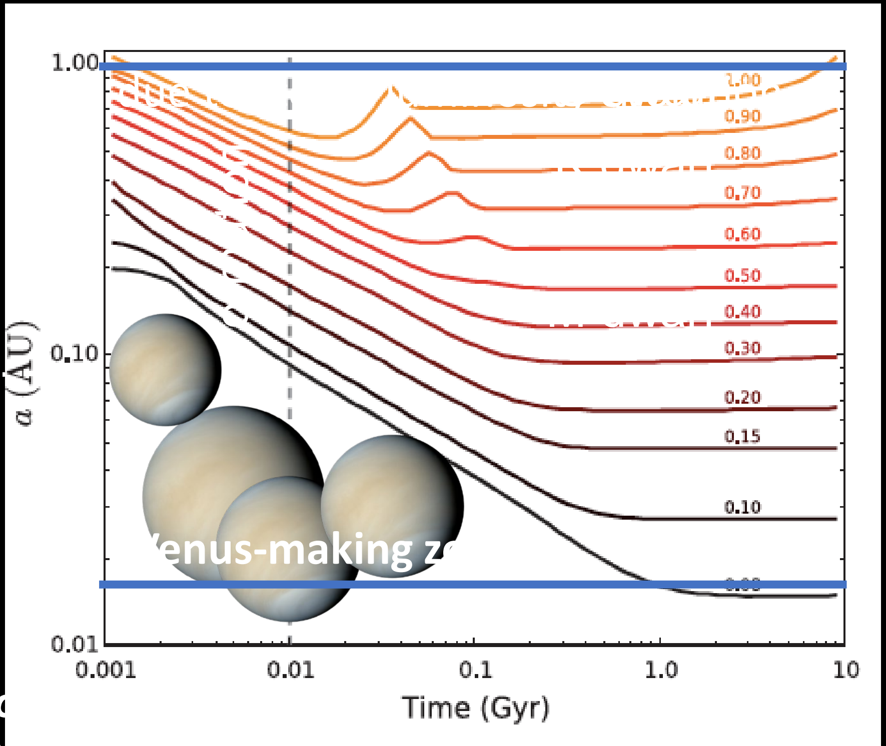
EAS3.3: What is the range of potentially habitable environments around different types of stars?

Different early luminosity environments for M dwarfs could drive ocean and atmosphere loss not seen for G dwarf planets.

Stellar energetic output - X-ray/EUV flux and flares, stellar wind, and CMEs - all influence atmospheric abundances and chemistry

Impact of magnetic field is not fully understood.

How do these factors influence terrestrial exoplanet evolution and habitability including atmospheric and ocean loss, orbital evolution, and tidal heating?



After Luger and Barnes, 2015 (see also Bolmont et al., 2016, Bourrier et al., 2017)

Approach: Determine stellar energetic output for a range of spectral types/temporal scales to understand impact on atmospheres for a large sample of systems. UV observations of multiple planets in the same systems to connect escape and stellar output. Theory to understand atmospheric outcomes.

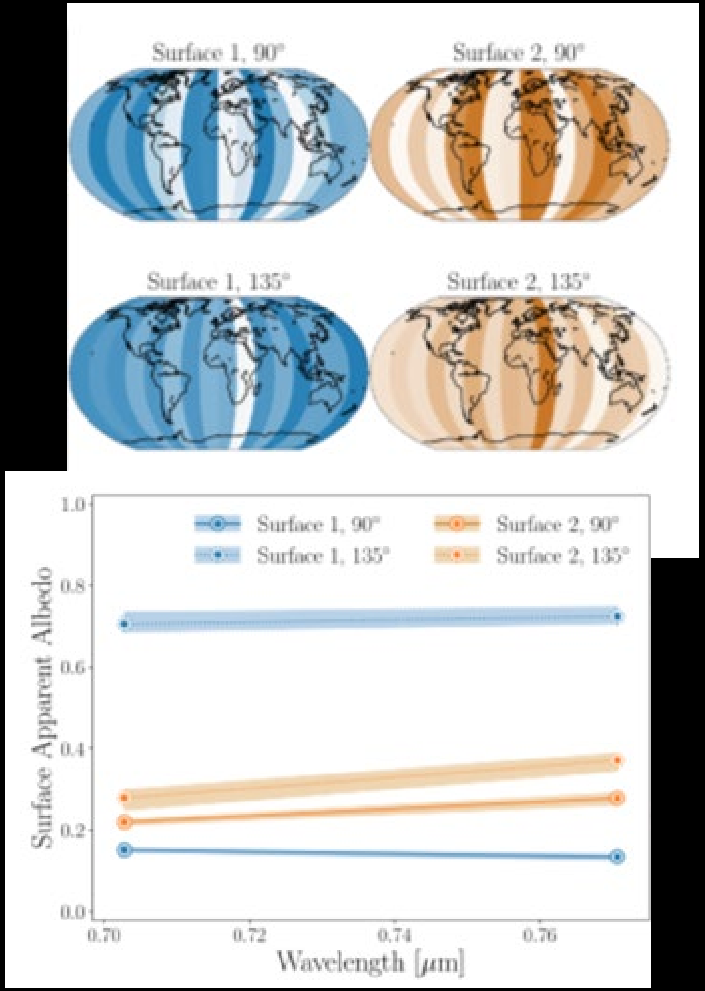
EAS3.4: What are the key observable characteristics of habitable planets?

The modern Earth provides the only observable example of a habitable surface environment.

We need to expand our understanding of habitable environments to include Earth through evolutionary time, as well as other potentially habitable environments.

Need to use atmospheric observations of Earth and potentially habitable exoplanets, as well as detailed theoretical models, to understand how to best constrain/observe these characteristics

Approach: Use theoretical modeling and observations of solar system planets to identify observations needed to discern exoplanet atmospheres and habitable surface conditions, including oceans.



Lustig-Yaeger et al., 2018

EAS3: Capabilities and Science Synergies

Question: How do habitable environments arise and evolve within the context of their planetary systems?

Capabilities:

Transmission, emission, & direct spectroscopy; solar system analog observations; laboratory work; theory

Coordination between exoplanet, planetary, earth science, and heliophysics communities through Cross-Division Data Analysis Programs, mission Participating Scientist/Guest Investigator Programs, and funding for collaborative meetings.
Support for laboratory investigations.

Overlap with other science panels:

SSSP Q3: *How do physical processes drive, and interact with, stellar asymmetries?*
SSSP Q4: *What are the properties and origins of the energetic phenomena of stars that influence their surrounding environment?*
Stellar magnetic fields and their corresponding stellar output (i.e., energetic photon flux, stellar wind, Coronal Mass Ejections, and stellar flares) influence exoplanetary atmospheres and their habitability.
Goals are in line with ESS & AB strategy reports

Overlap with other EAS research areas:

Q1 discovers planets for Q3
Q3 informs target selection for Q4 & DA

EAS4: How can biosignatures be identified and interpreted in the context of their environments?

In the next 10 years we will have the opportunity to undertake the first search for biosignatures on 10-20 nearby planets orbiting M dwarfs. Significant work is still needed to understand which biosignatures to search for and how to interpret whether an observed potential biosignature has a biological or planetary origin.

EAS4.1: What biosignatures should we look for?

EAS4.2: How will we interpret the biosignatures that we see?

EAS4.3: Do any nearby M dwarf planets exhibit biosignatures?

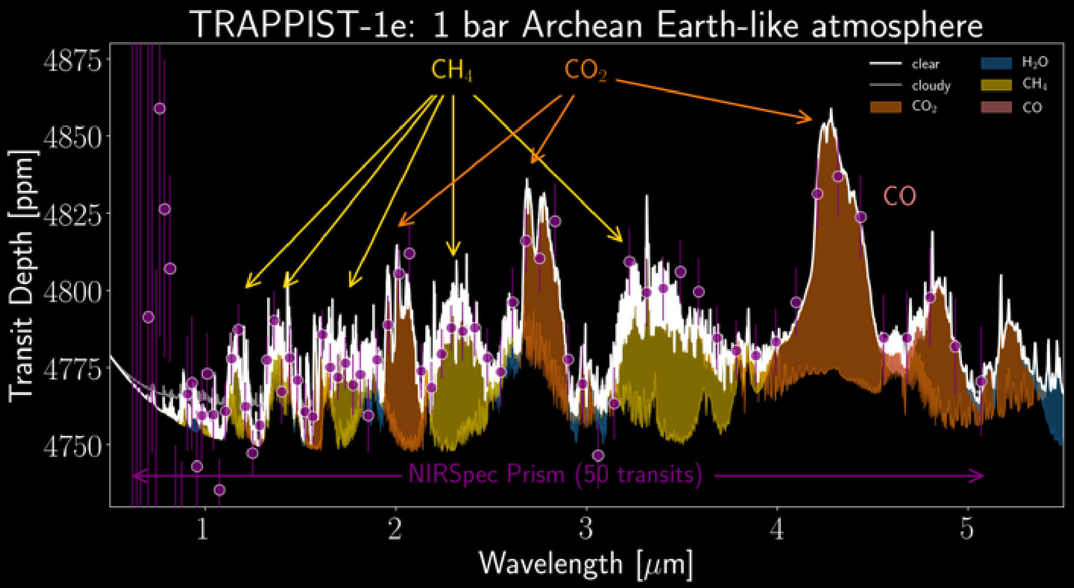
EAS4.1: What biosignatures should we look for?

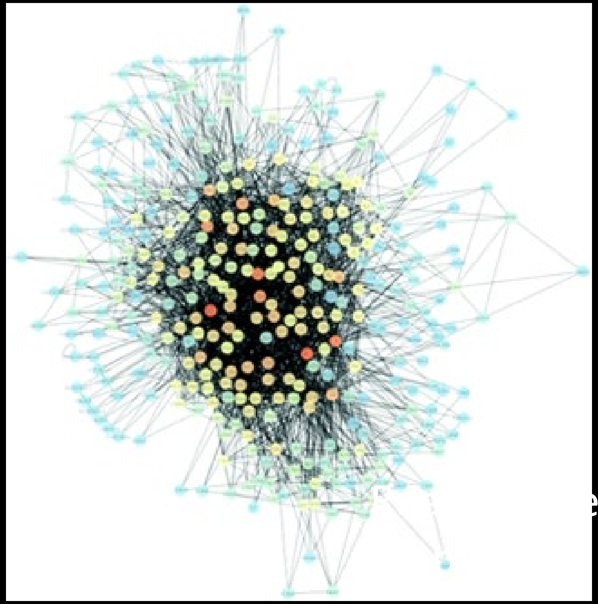
A handful of atmospheric, surface and temporal biosignatures known

Need to identify alternative metabolisms and their signatures

Develop the frontier of agnostic biosignatures

Need to understand planetary context through theoretical modeling and observations of a wide range of planets.





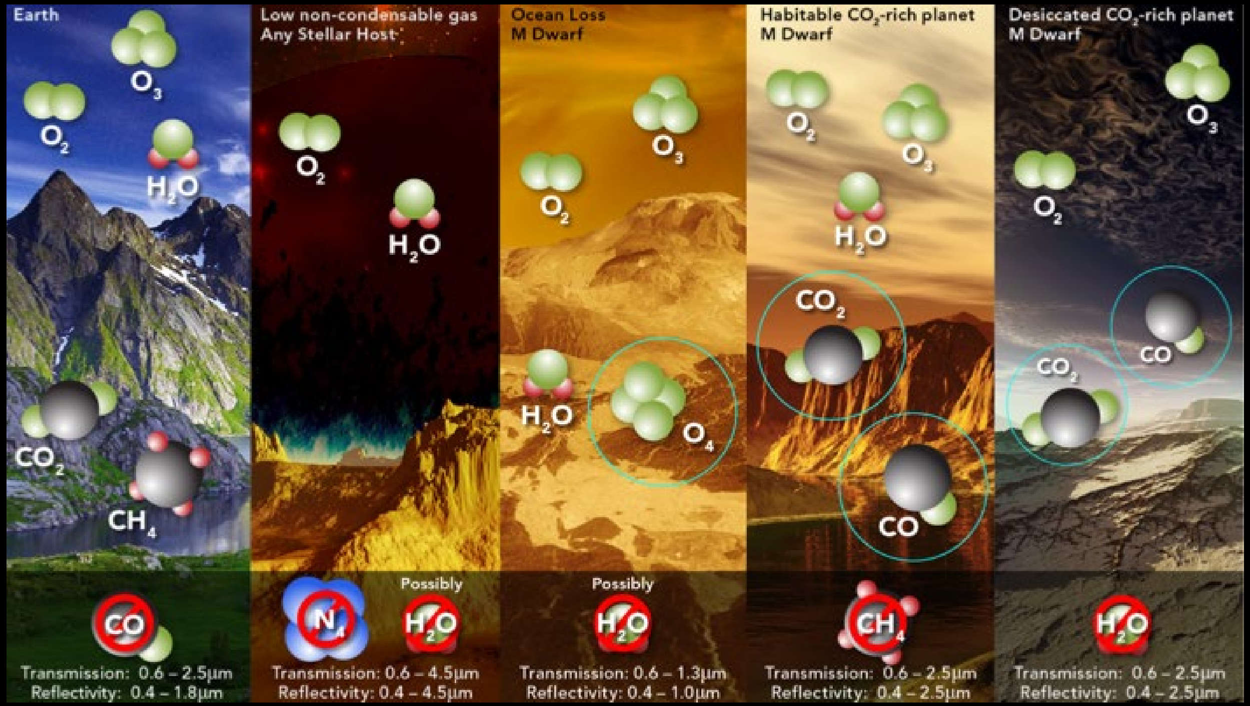
etwork

Approach: Use theoretical modeling and observations to identify atmospheric, surface and temporal biosignatures.

EAS4.2: How will we interpret the biosignatures that we see?

Biosignatures, including O_2 can have abiotic mimics, and can be enhanced or destroyed by their environments.

It is therefore not enough to detect a biosignature, we must also assess whether it is more likely to have a biological origin.



This assessment will need:

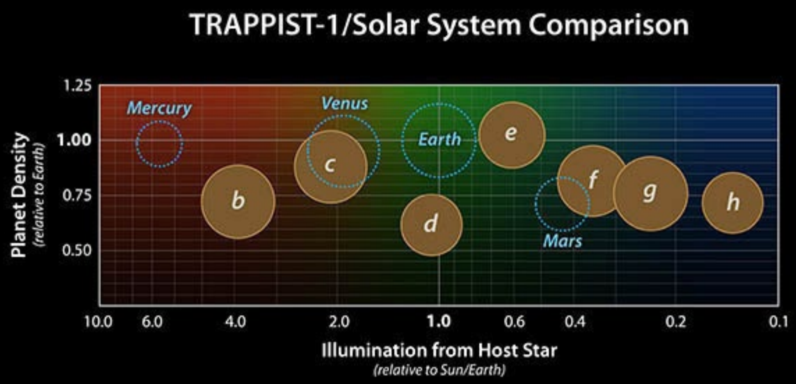
- false negatives
- false positives
- stellar and planetary environmental context
- a statistical framework to quantify life's likelihood.

Approach: Develop a comprehensive framework for statistical biosignature assessment in the context of the planetary environment.

EAS4.3: Do any nearby M dwarf planets exhibit biosignatures?

Initial characterization of up to a few tens of exoterrestrials over the next decade:

- JWST transmission observations of T-1 and similar planets (CO_2/CH_4 disequilibrium).
- Ground-based ELT spectroscopy of Proxima Centauri b and dozen+ M dwarf HZ planets (O_2).
- Thermal IR imaging and radiometric radii (+ RV masses) for a small handful of FGK HZ planets



Though limited to M dwarfs, these efforts may obtain the first empirical measurements of biosignature gases, if they exist on these worlds.

Approach: Ground- and space-based searches for biosignatures around M dwarfs.