>>> Exoplanet Biosignatures

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UCI joint *Physics* & *Astro-AirUCI* lunchtime seminar

01.15.19

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>>> Before we start...

- Thanks to Prof. Finlayson-Pitts & Prof. Bullock for organizing.

- Some definitions:

  - *Exoplanet*: a planet that exists outside of the solar system (mass range: ~0.05 to ~3000M_{Earth})

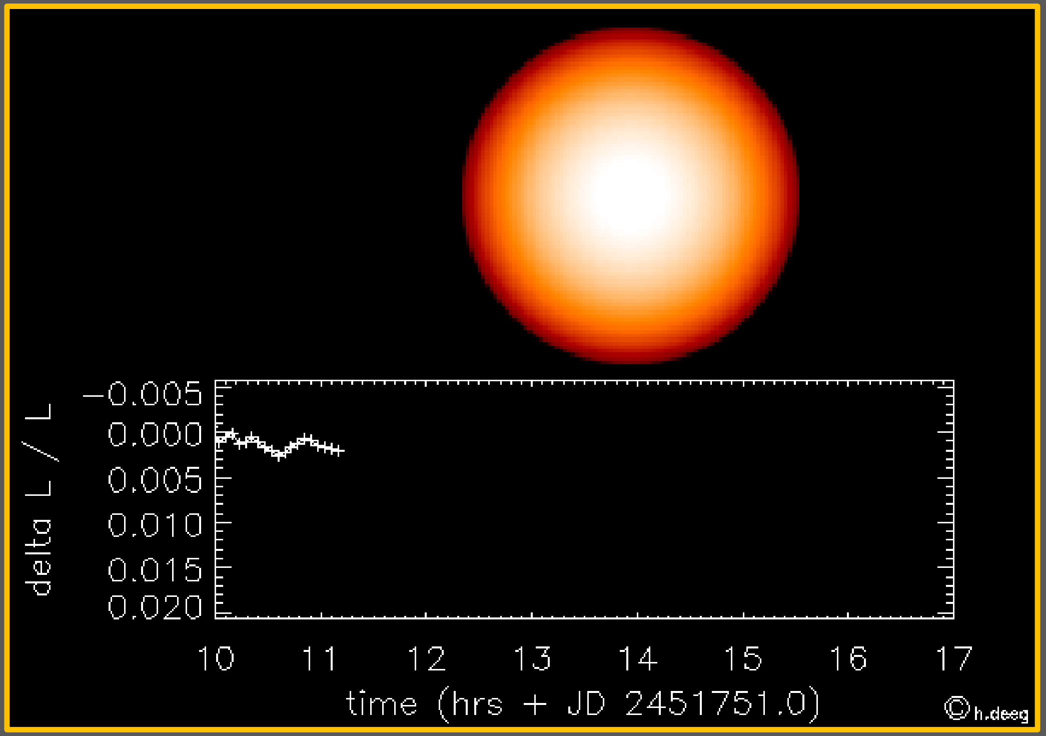
  - *Biosignature*: an object, substance, and/or pattern whose origin specifically requires a biological agent*

*Kiang *et* al., 2018; Des Marais & Walter, 1999; Des Marais *et al.*, 2008 - *Astrobiology*

>>> Finding Exoplanets

- Difficult
- ...but we're good at it now!
- >3800 exoplanets found since 1995, and the rate of discovery is accelerating.
- Direct imaging of exoplanets possible in some circumstances (hot, very young, very bright, high separation)
- Vast majority detected through *indirect* methods, by NASA's *Kepler* (and now *TESS*) and ground-based Doppler-spectroscopes.
- Characterization of atmospheres possible in some circumstances (see above).

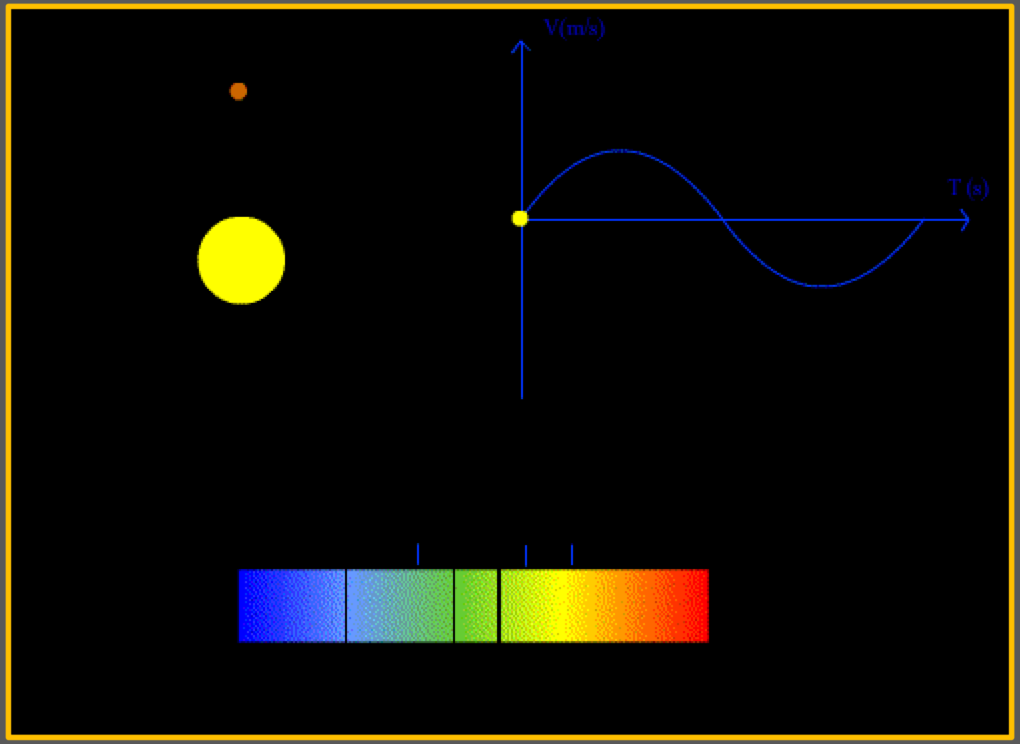
>>> Finding Exoplanets



Transit photometry

e.g. *Kepler*, *CoRoT*, *TESS*

radius, period



Doppler spectroscopy*

e.g. *HARPS*, *HIRES*

mass, period

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*image credit: Hannah Wakeford

>>> Finding Exoplanets

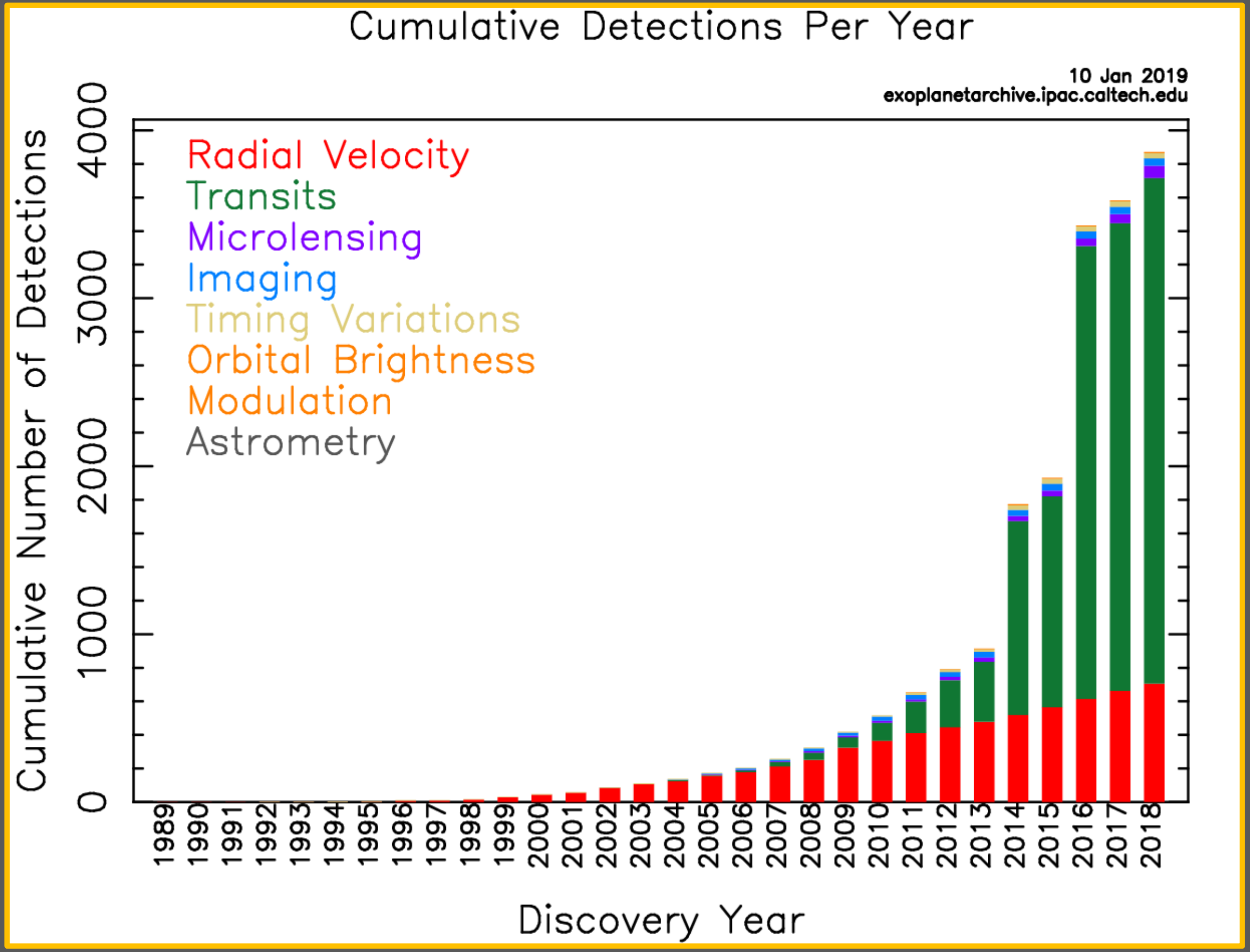
Confirmed planets: 3872

Multi-planet systems: 645

Earth-sized planets: 388
(<1.25 R_{Earth})

Kepler planets: 2331
(*Kepler* candidates awaiting confirmation: 2425)

TESS planets: 1



NASA Exoplanet Archive - exoplanetarchive.ipac.caltech.edu

>>> In the beginning...

- Voyager One's '*Pale Blue Dot*' (1990)
- Earth in <1 pixel.
- Sagan *et al.* (1993) - *A search for life on Earth from the Galileo spacecraft*

Can we detect life remotely?

>>> In the beginning...

- Voyager One's '*Pale Blue Dot*' (1990)
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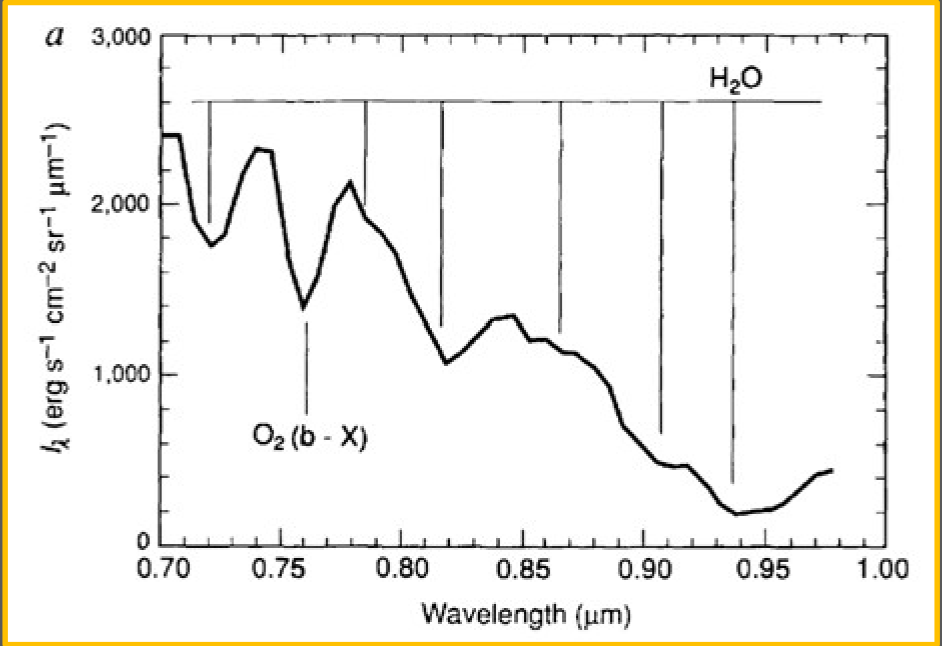
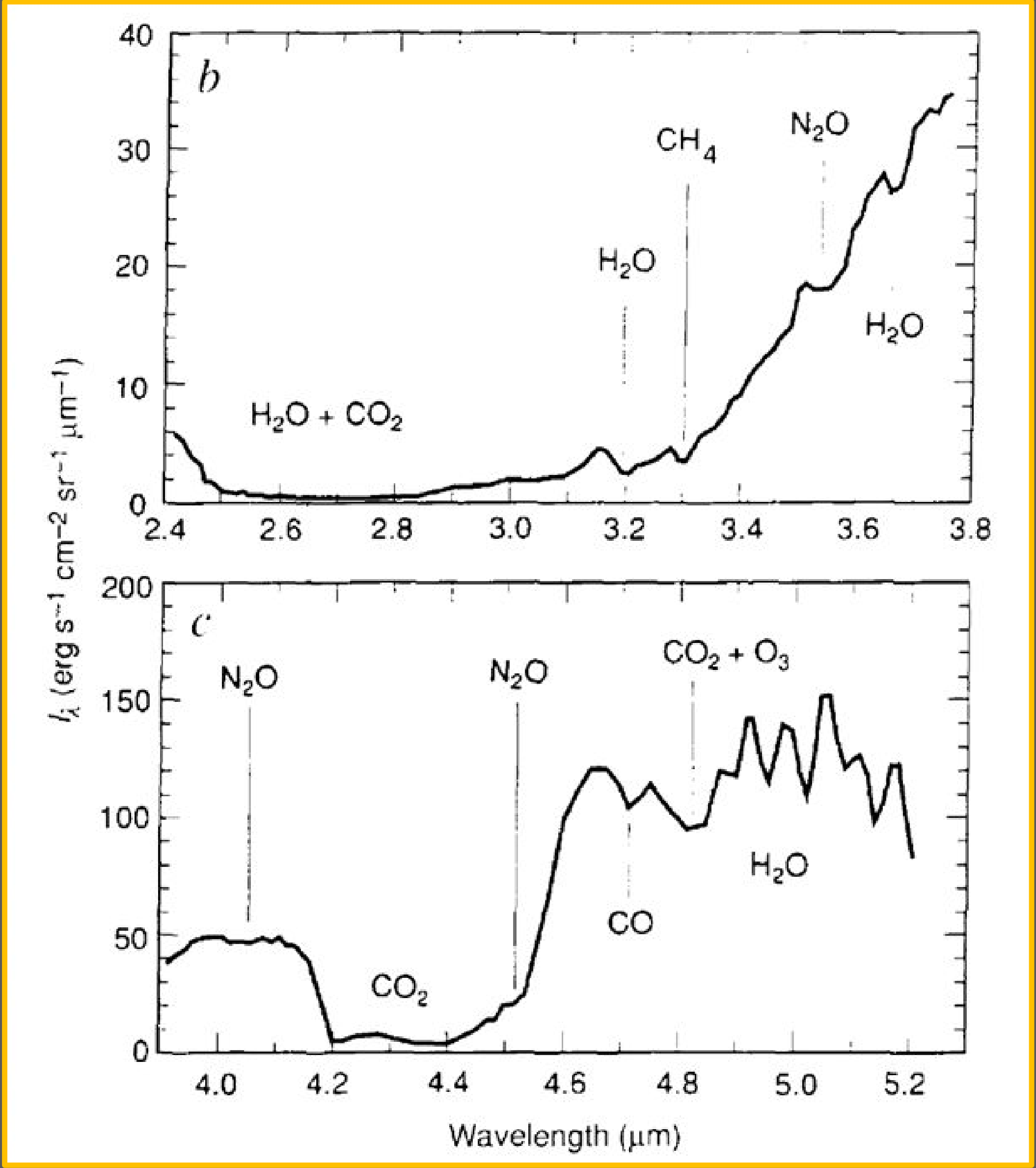
Can we detect life remotely?

>>> The Pale Blue Living Dot

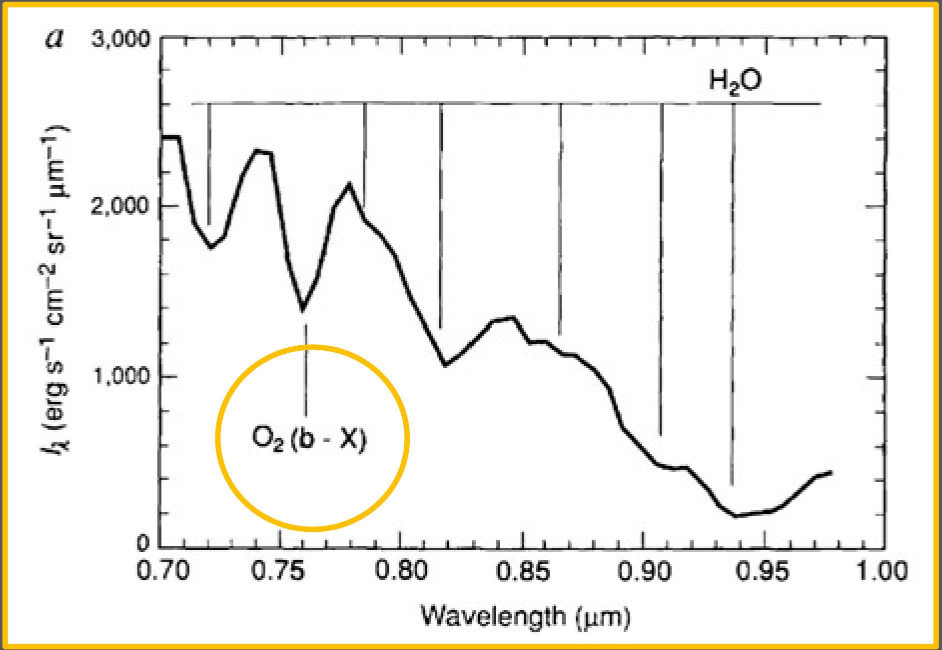


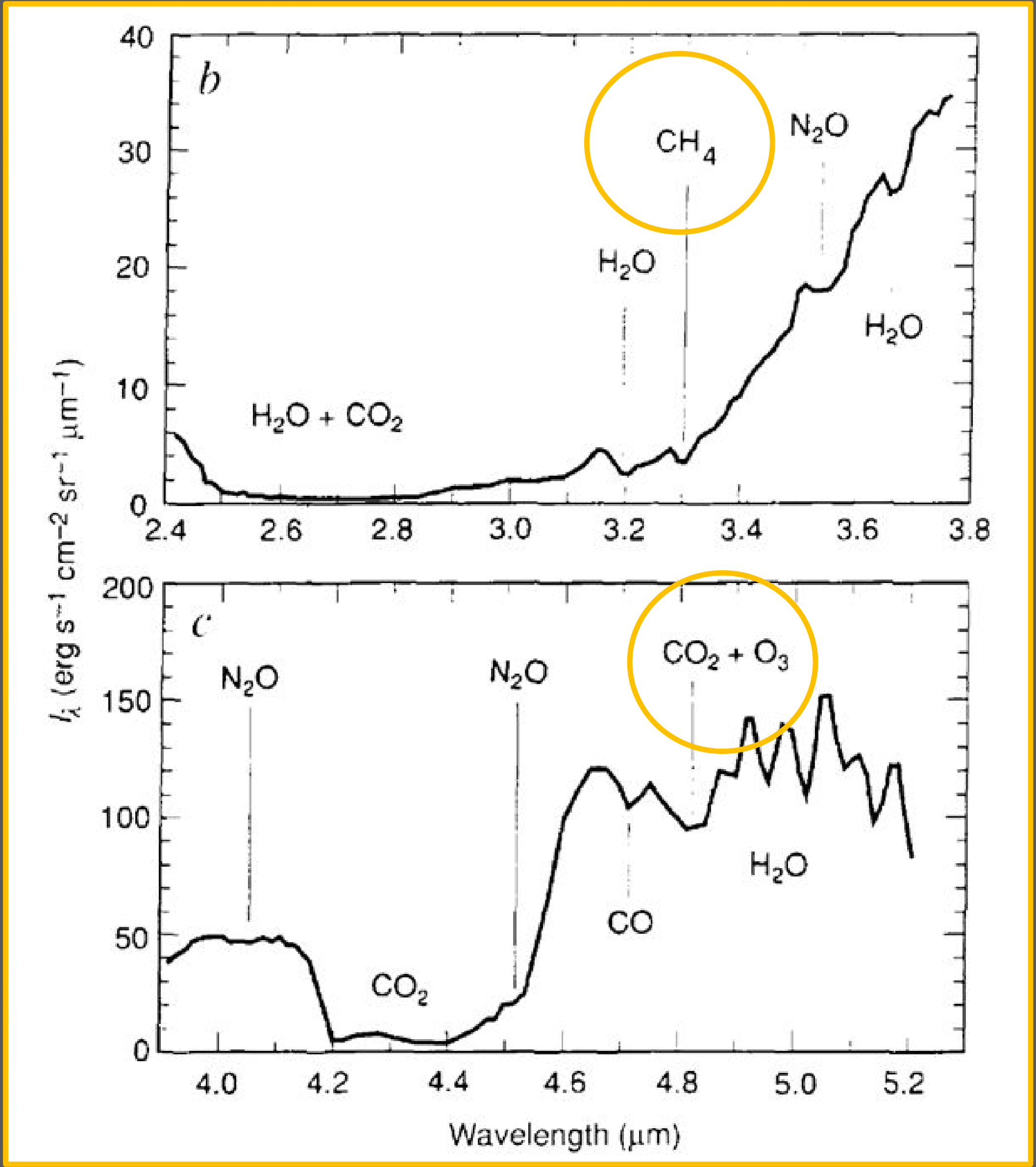
Reflectance spectrum (*earthshine*) features multi- and hyperspectral absorption features of atmospheric components.



Sagan *et al.* (1993) - *Nature*

>>> The Pale Blue Living Dot





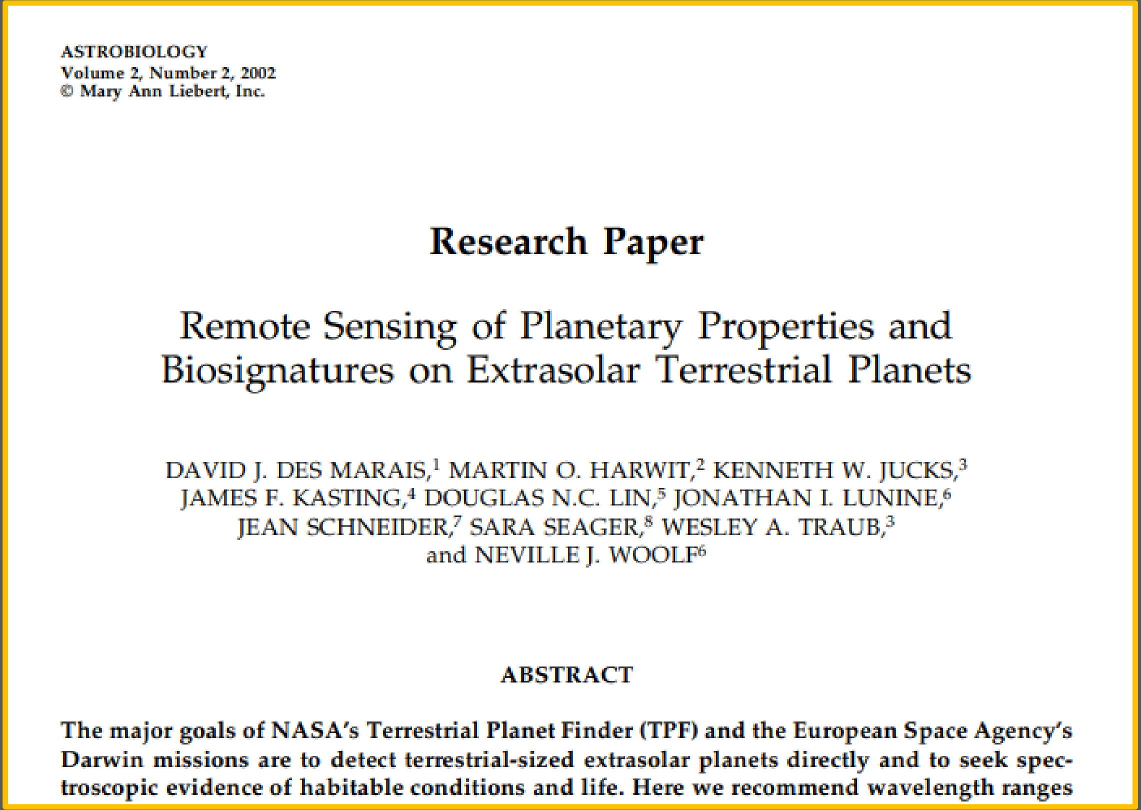
Simultaneous detection of oxygen and methane indicates thermodynamic disequilibrium ...life?

Sagan *et al.* (1993) - *Nature*

>>> EB: a brief history

- Since Sagan *et al.* (1993) many workshops dedicated to ‘biosignatures’ including NASA Astrobiology Roadmaps 1998, 2003, 2008.

- Prior to 2016 the last review of remotely detectable biosignatures relevant to exoplanets was Des Marais *et al.* (2002).



ASTROBIOLOGY
Volume 2, Number 2, 2002

Research Paper

Remote Sensing of Planetary Properties and Biosignatures on Extrasolar Terrestrial Planets

DAVID J. DES MARAIS,[1] MARTIN O. HARWIT,[2] KENNETH W. JUCKS,[3] JAMES F. KASTING,[4] DOUGLAS N.C. LIN,[5] JONATHAN I. LUNINE,[6] JEAN SCHNEIDER,[7] SARA SEAGER,[8] WESLEY A. TRAUB,[3] and NEVILLE J. WOOLF[6]

ABSTRACT

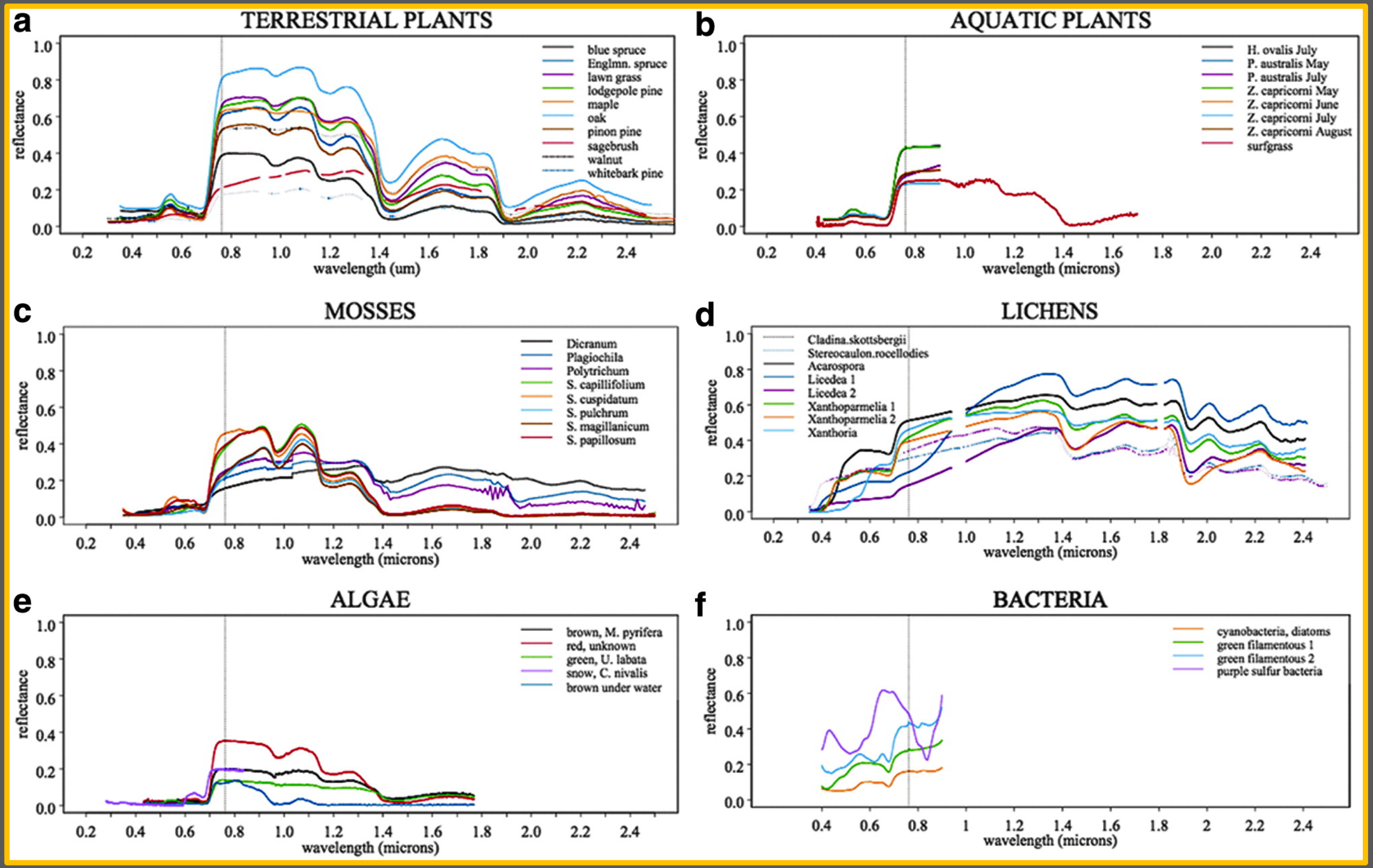
The major goals of NASA's Terrestrial Planet Finder (TPF) and the European Space Agency's Darwin missions are to detect terrestrial-sized extrasolar planets directly and to seek spectroscopic evidence of habitable conditions and life. Here we recommend wavelength ranges

>>> EB: a brief history

Primary biosignatures:

- biogenic gases in the atmosphere: oxygen (O_2), ozone (O_3), methane (CH_4), nitrous oxide (N_2O), methyl chloride (CH_3Cl)

- the vegetation "red edge" (VRE)



De Marais *et al.* (2002); Kiang *et al.* (2007) - *Astrobiology*

>>> EB: a brief history

In 2016, a joint NExSS/NASA Astrobiology Program Exoplanet Biosignatures ‘Workshop Without Walls’ (EBWwW) was organized with three goals in mind:

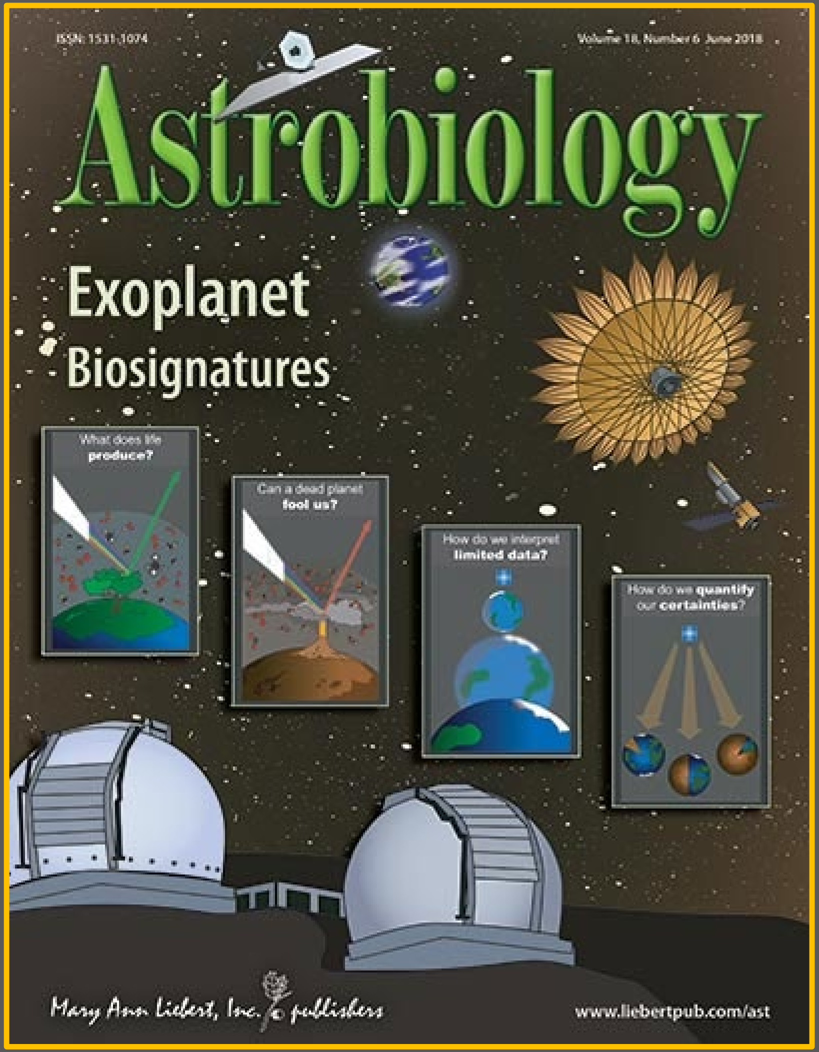
- State of the Science Review: What are known remotely-observable biosignatures, the processes that produce them, and their known non-biological sources?
- Advancing the Science of Biosignatures: How can we develop a more comprehensive conceptual framework for identifying additional biosignatures and their possible abiotic mimics?
- Confidence Standards for Biosignature Observation and Interpretation: What paradigm informed by both scientists and technologists could establish confidence standards for biosignature detection?

>>> Source material

Special open access edition of *Astrobiology* journal:

Exoplanet Biosignatures
vol. 18, no. 8 (June, 2018)

https://www.liebertpub.com/toc/ast/18/6



>>> Source material

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Scan with QR code reader app for link

NExSS biosignature workshop:

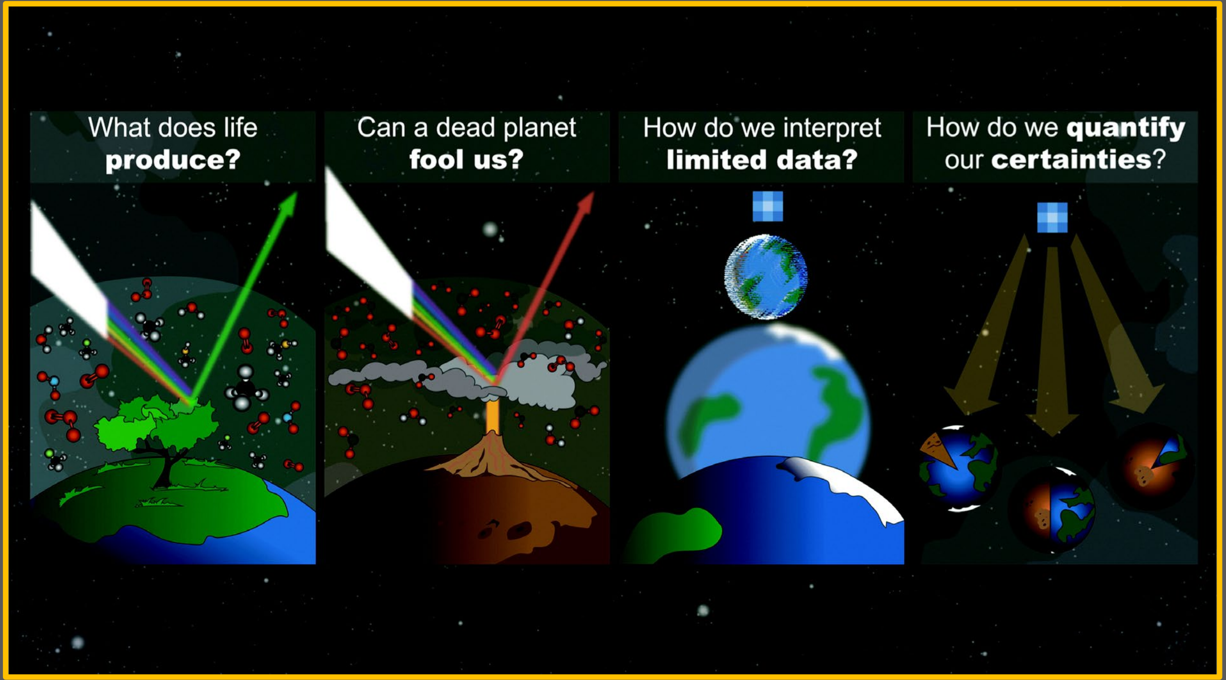
https://nexss.info/community/workshops/

>>> Source material

An overview of the past, present, and future of research on remotely detectable biosignatures.

Contributors from astrophysics, planetary science, Earth science, heliophysics.

Supporting NASA goals, 2020 Astrophysics Decadal Review.



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https://www.liebertpub.com/toc/ast/18/6

>>> Source material

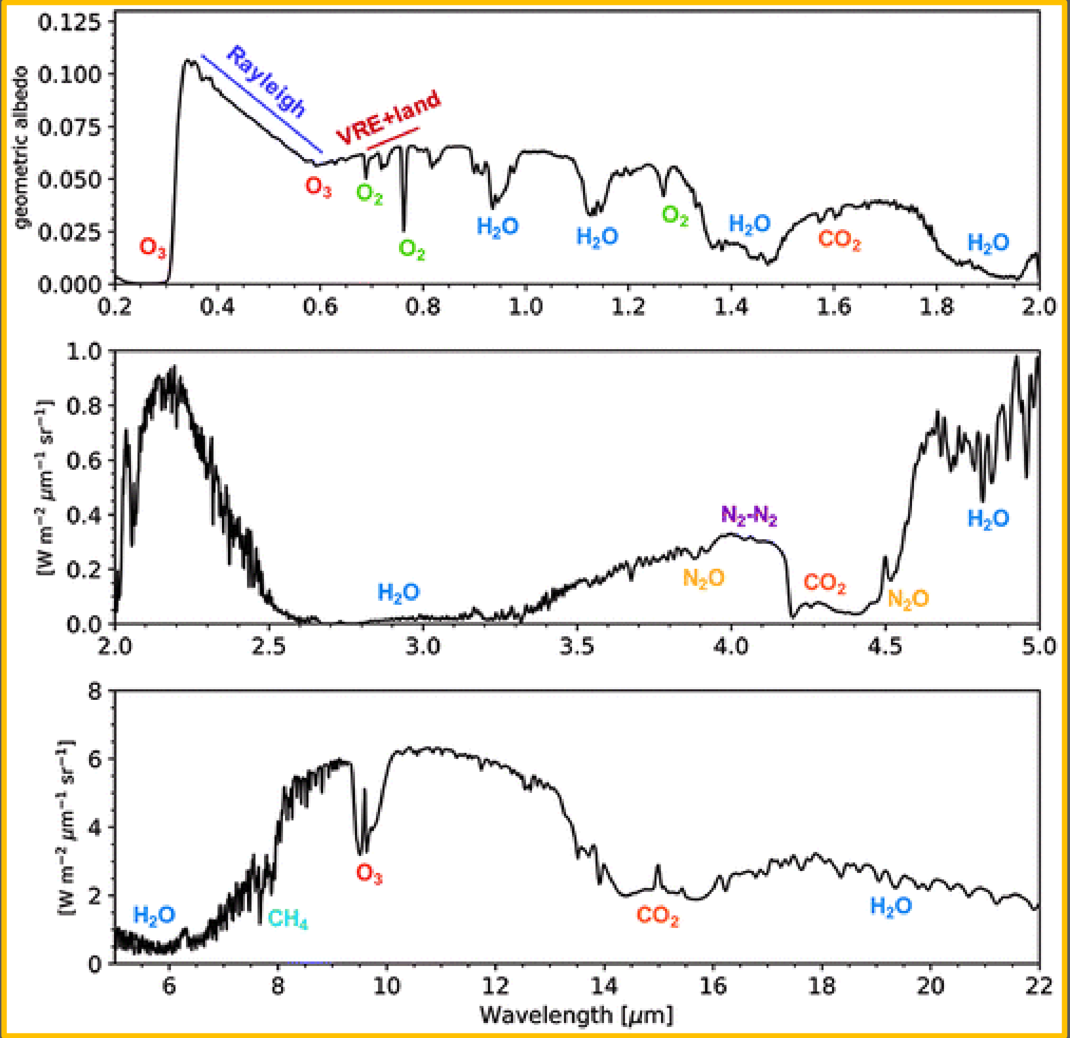
- Kiang *et al.* 2018 - Exoplanet Biosignatures (EB): At the Dawn of a New Era of Planetary Observations. (Review)
- Schweiterman *et al.* 2018 - EB: A Review of Remotely Detectable Signs of Life
- Meadows *et al.* 2018 - EB: Understanding Oxygen as a Biosignature in the Context of Its Environment
- Catling *et al.* 2018 - EB: A Framework for Their Assessment
- Fujii *et al.* 2018 - EB: Observational Prospects
- Walker *et al.* 2018 - EB: Future Directions

https://www.liebertpub.com/toc/ast/18/6

>>> 15 years of biosignature research

Contribution of coupled photochemical/climate modeling studies

Potential alternative biosignatures for non-oxygenic photosynthesis (e.g. Archean Earth): orange-hued organic hazes, ethane.

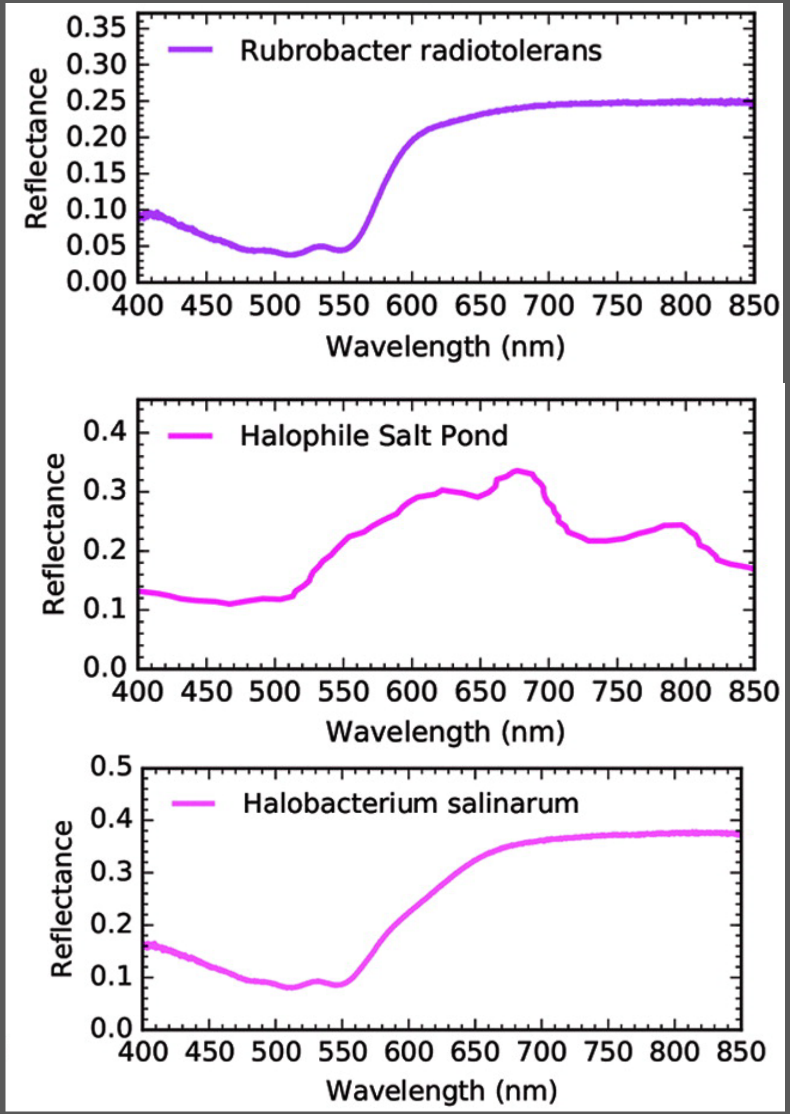


Schweiterman *et al.* 2018 - *Astrobiology*

>>> 15 years of biosignature research

Meta-analysis of chemical databases show 3.5k small volatile molecules produced by life, many more potentially so.

Improved classification of pigments (oxygenic & anoxygenic photosynthesis) including novel, recently-discovered chlorophylls & non-photosynthetic pigments.



Schweiterman *et al.* 2018 - *Astrobiology*

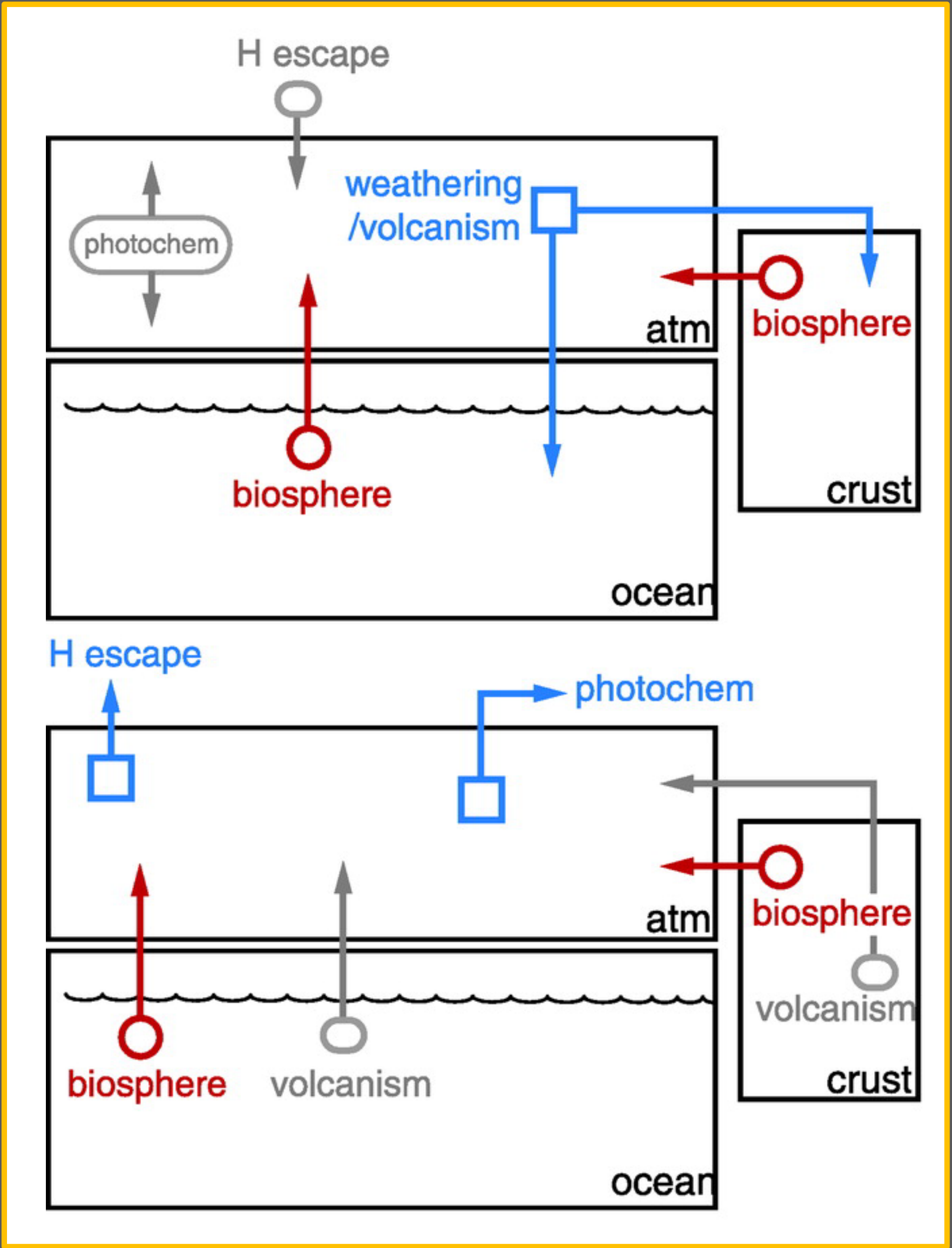
>>> O_2 & CH_4 reassessment

Oxygen reassessed as potential biosignature.

Abiotic processes for creation include:

- water/ocean loss
- CO_2 photolysis
- low N_2 inventories

Sources and sinks poorly constrained, especially over time.



Meadows *et al.* 2018 - *Astrobiology*

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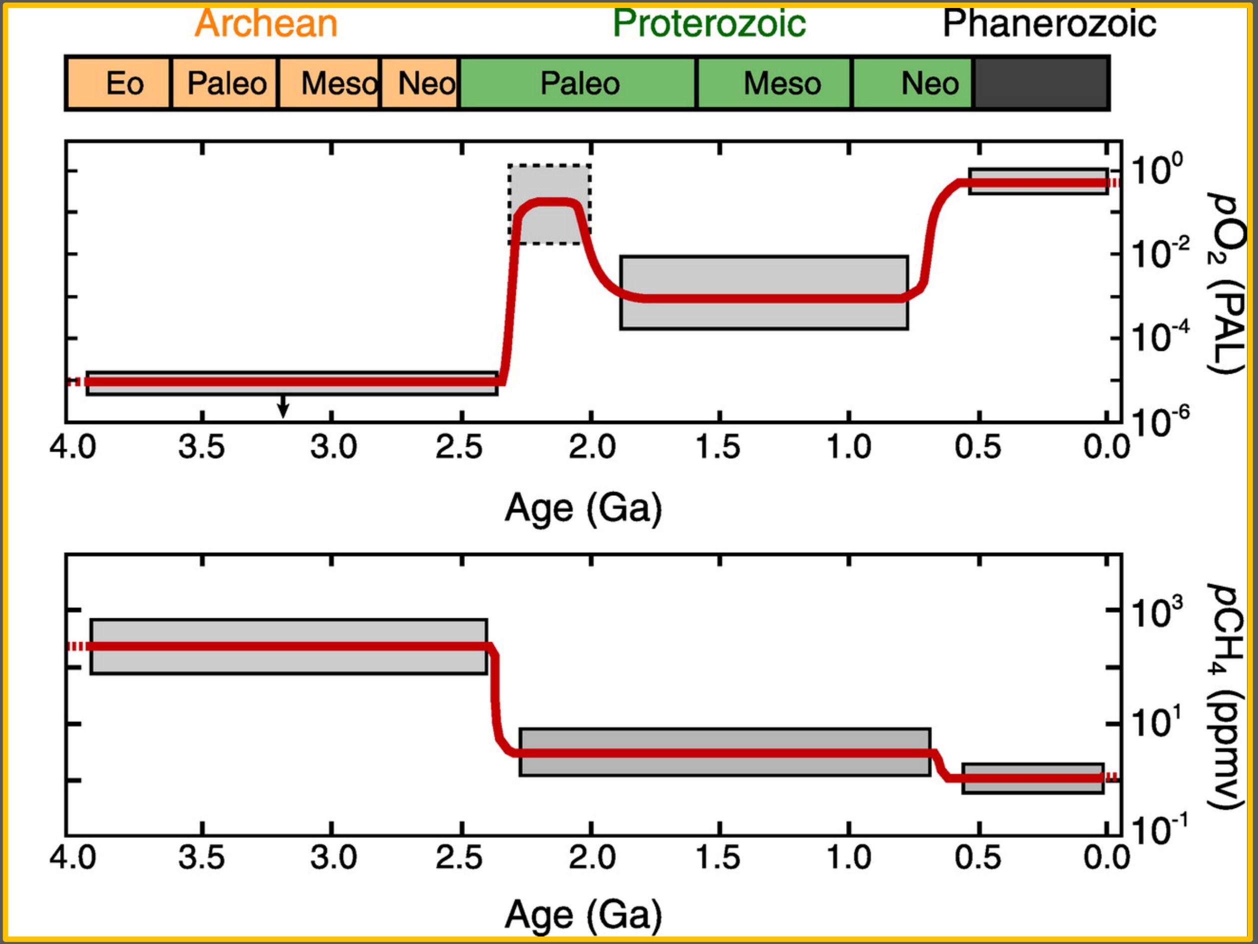
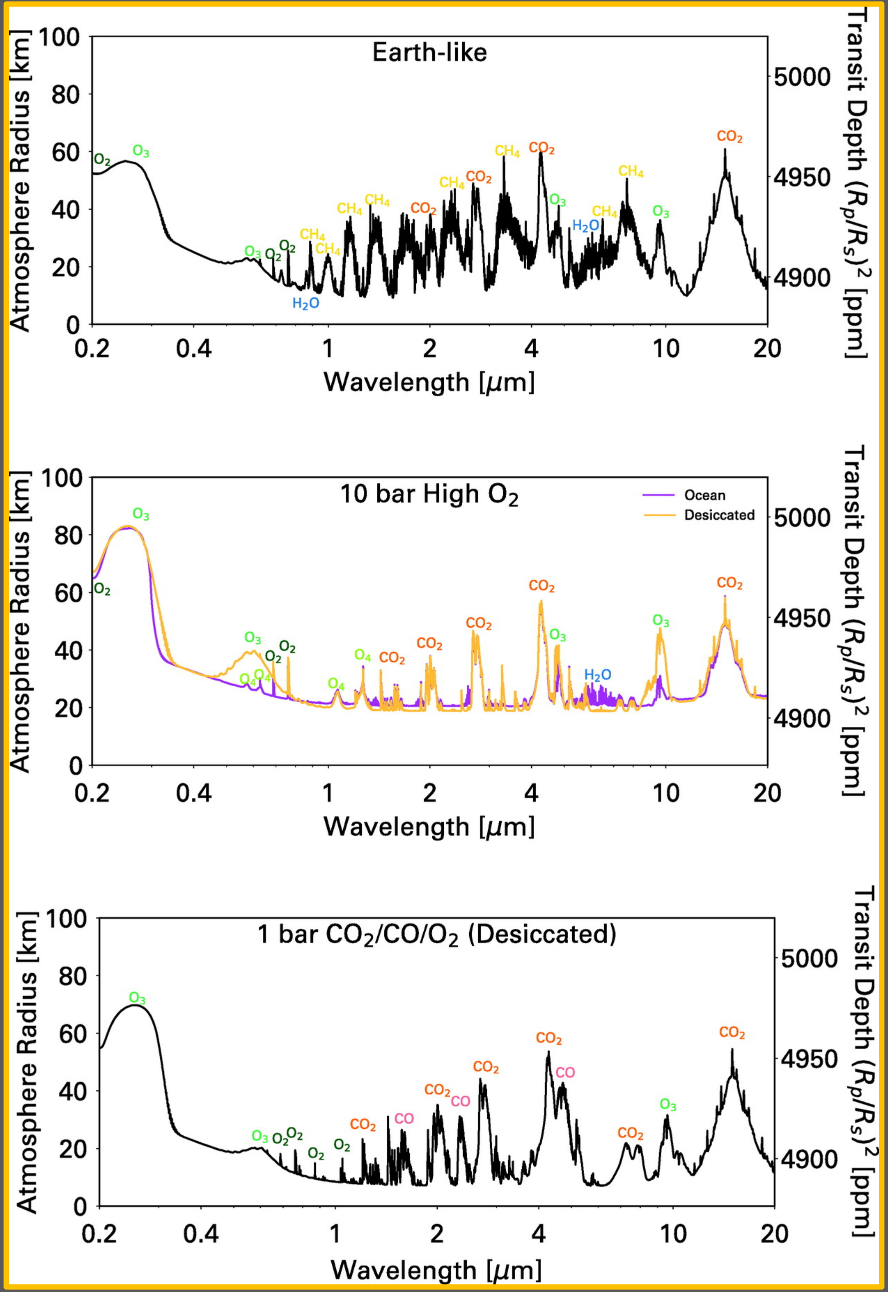


Meadows *et al.* 2018 - *Astrobiology*

>>> O_2 & CH_4 reassessment

Spectral features can distinguish photosynthetic from abiotically generated O_2:

- Water-rich high-O_2 cases: presence of O_4
- Desecciated high-O_2 cases: presence of CO, O_3 in 0.5-0.7 µm Chappuis band more abundant

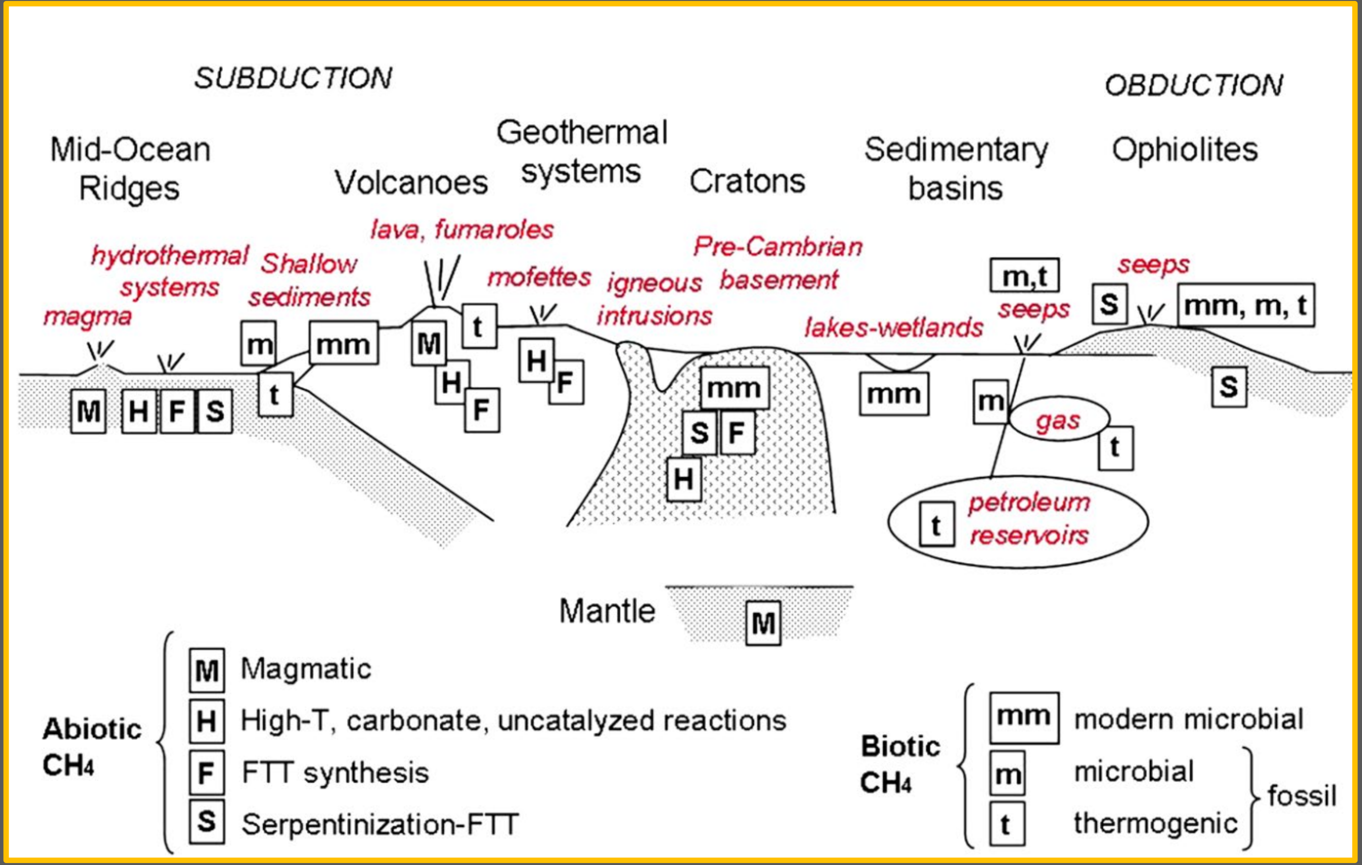


Meadows *et al.* 2018 - *Astrobiology*

>>> O_2 & CH_4 reassessment

CH4 is often viewed as a companion gas & indicates rapid destruction & replenishment of oxygen – most likely met by biological activity.

...but methane *can* be formed abiotically, primarily through rock-water interactions.



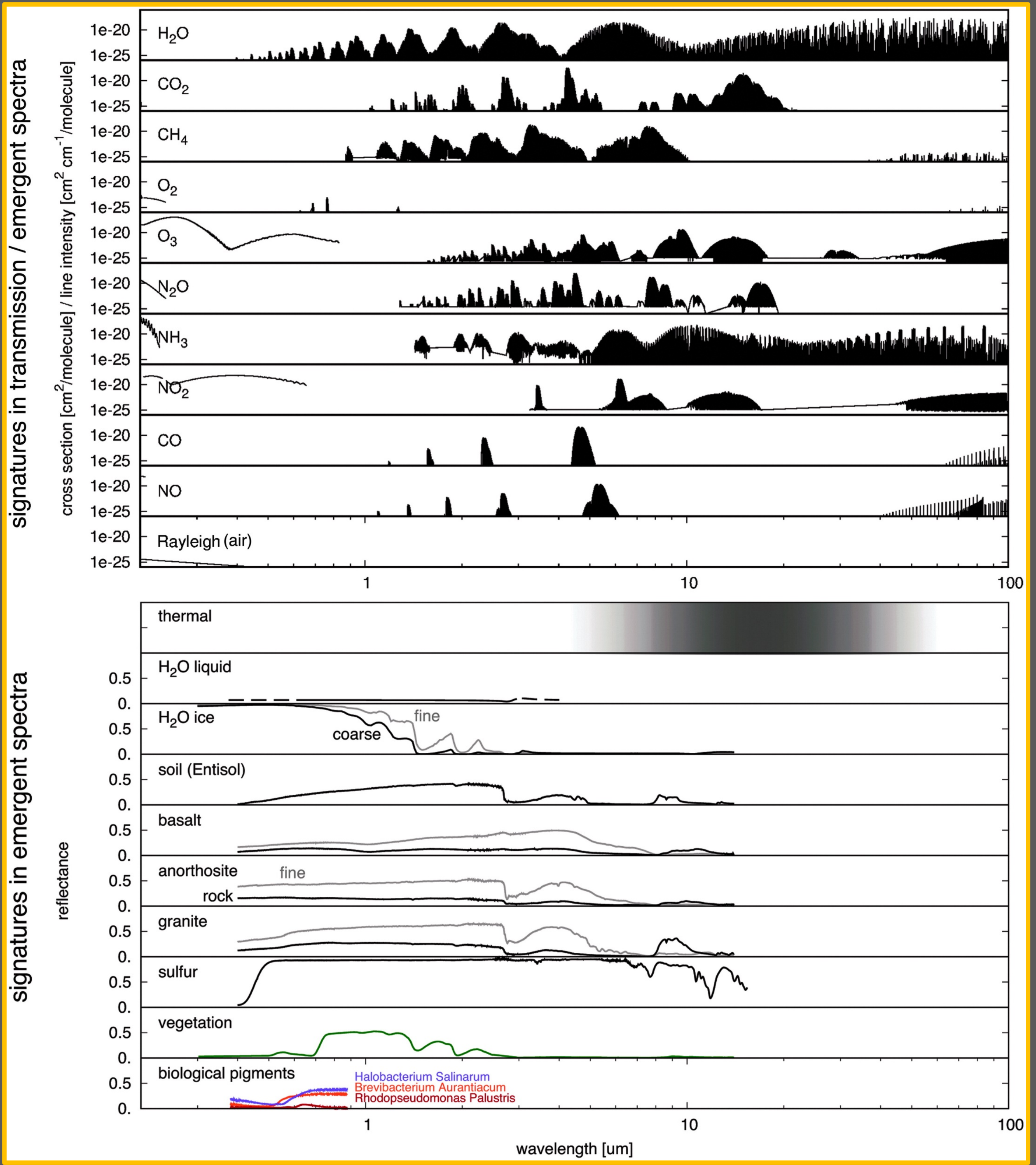
Etiope & Lollar (2013) - *Reviews of Geophysics*

>>> Summary

Atmospheric signatures remain primary focus.

Ruling out false positives and considering the planetary context.

Novel, alternative, non-oxygenic photosynthesis biosignatures, surface features, and non-photosynthetic pigments.



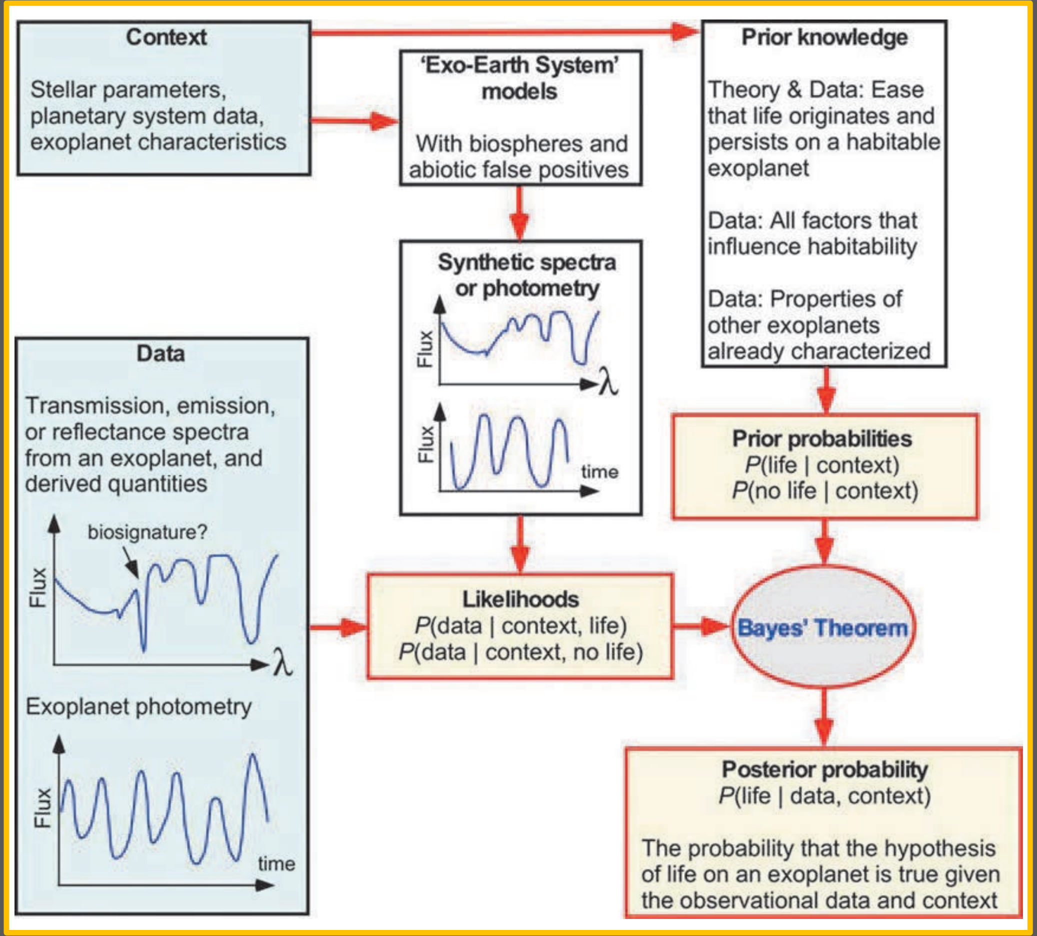
Fujii *et al.* (2018) - *Astrobiology*

>>> A Bayesian Biosignatures Framework

$$P(life|data, context) = \frac{P(d|c,l)P(l|c)}{P(d|c, no\ l)\big(1 - P(l|c)\big) + P(d|c,l)P(l|c)}$$

- *P(life|data, context)*: posterior, i.e. conditional probability; the likelihood that planet has life given the *data* and *context*.

- *P(life|context)*: prior probability that planet has life, given context



Catling *et al.* 2018 - *Astrobiology*

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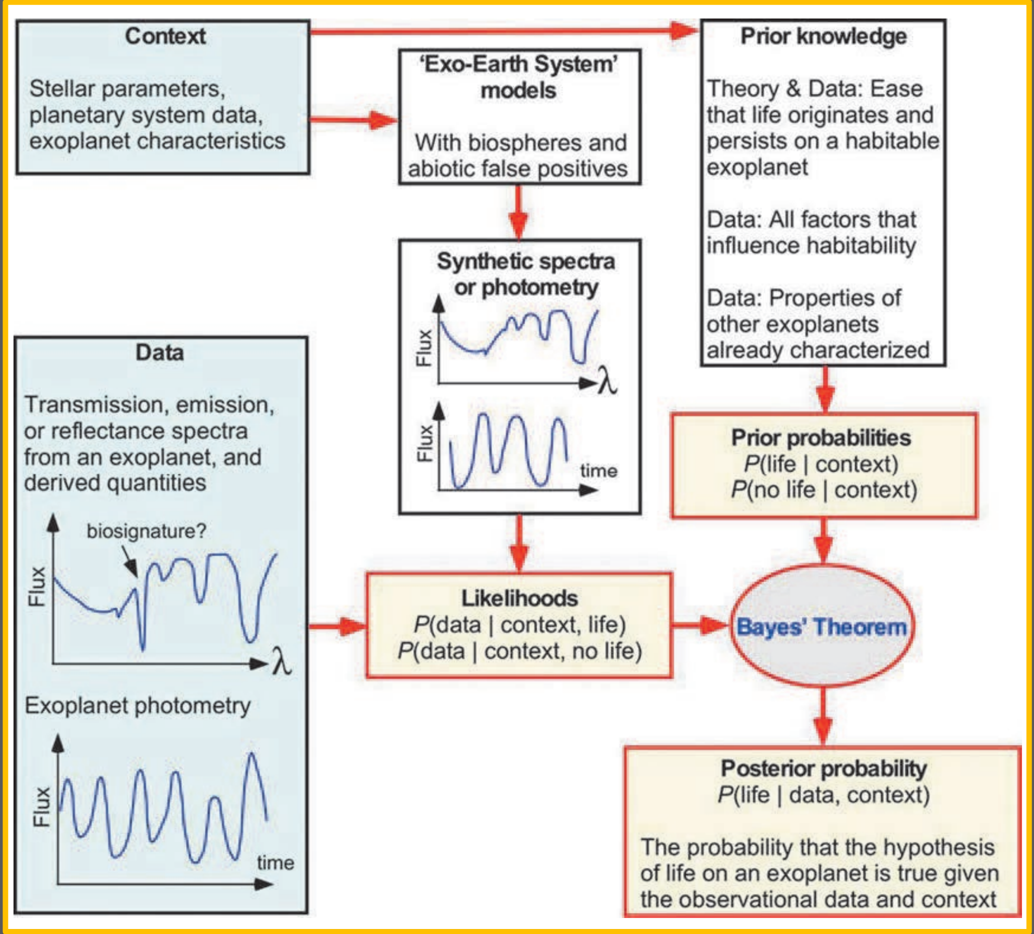
- *P(data|context, no life)*: likelihood (posterior) of observation of abiotic/non-living worlds.
- P(*data|context, life*): likelihood (posterior) of observation of a living world



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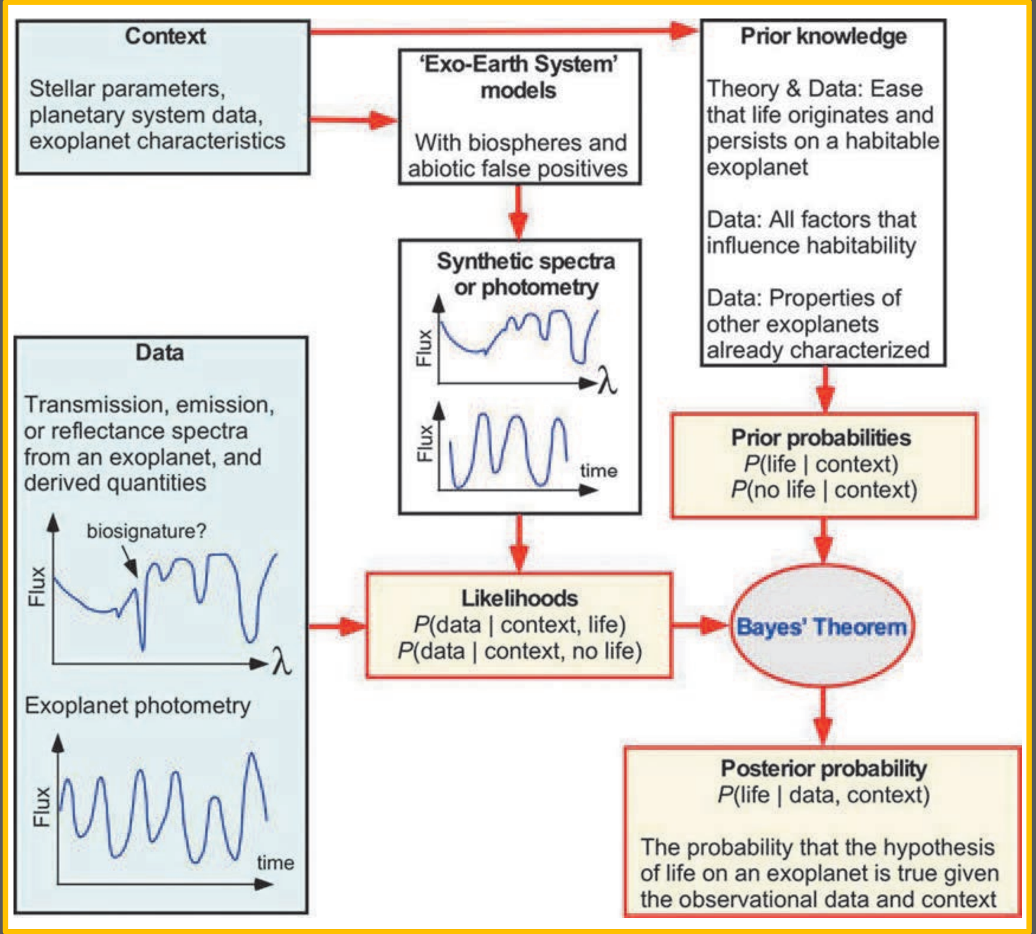
- Prior probabilities from *context* (the planetary environment) and theory (habitability studies, Earth's history & diversity of life, universality of biology, origin of life studies, false positives, detection bias...)
- *data* from transmission, emission, reflectance spectra



Catling *et al.* 2018 - *Astrobiology*

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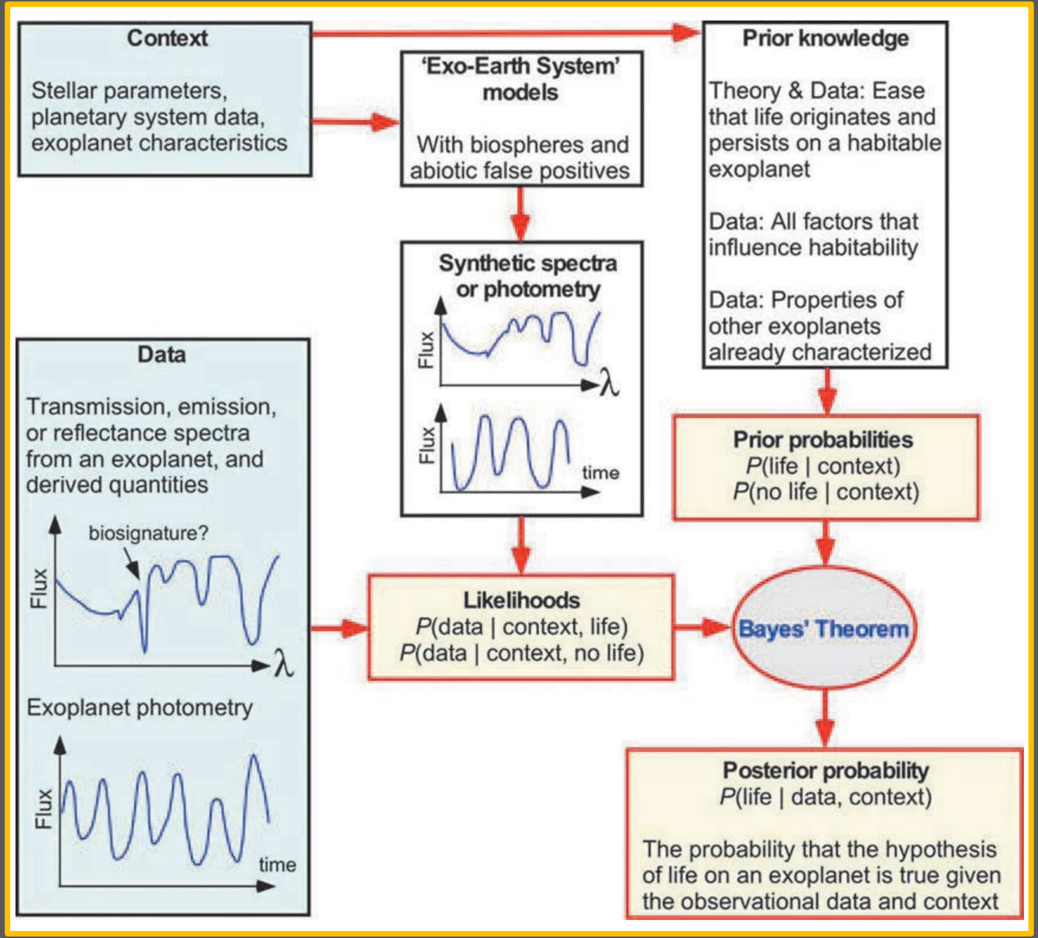
- proposed framework for classifying *confidence levels* for the likelihood of biosignature detection following IPCC approach to communicate uncertainty.
- (very) unlikely → (very) likely

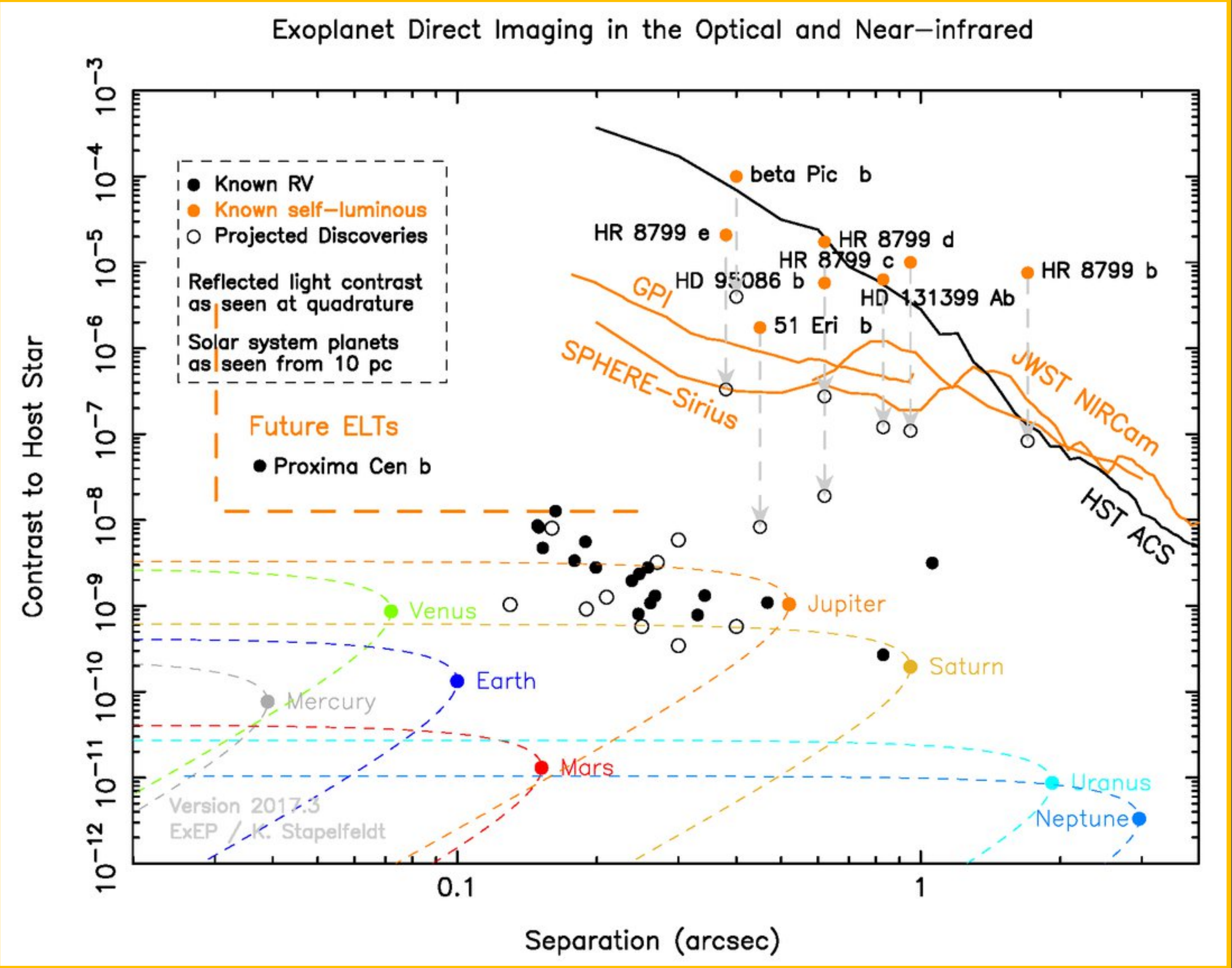


Catling *et al.* 2018 - *Astrobiology*

>>> Future Prospects

1st era: astrophysical characterization of planetary orbits and sizes (e.g., ground-based RV surveys, CoRoT, Kepler, K2, Gaia, CHEOPS, TESS, PLATO, WFIRST). Statistical population studies.

2nd era: chemical characterization of atmospheres (Hubble, Spitzer, JWST, the ground-based ELTs.)



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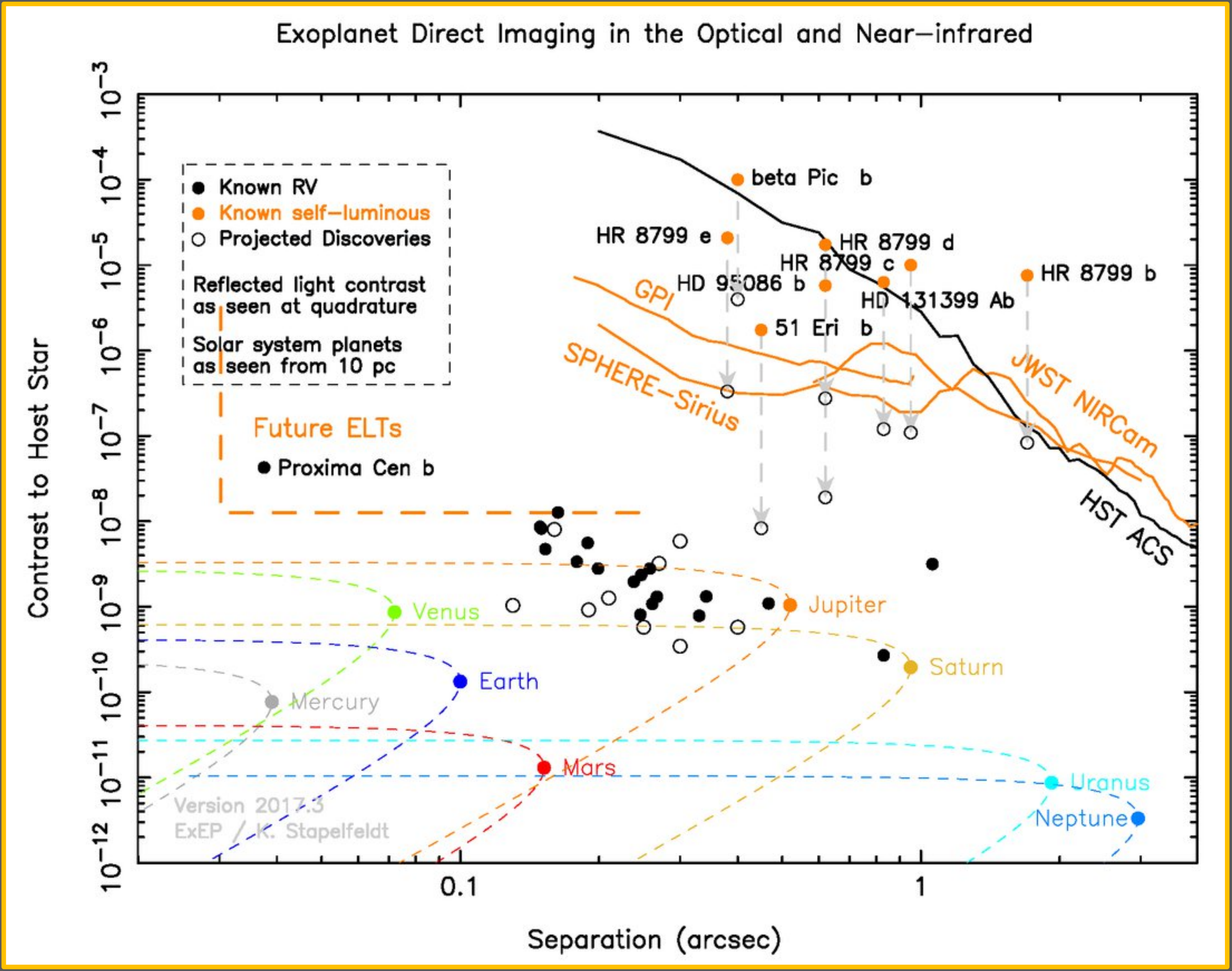
1995 - 2020s

2nd era: chemical characterization of atmospheres (Hubble, Spitzer, JWST, the ground-based ELTs.)

>2020s

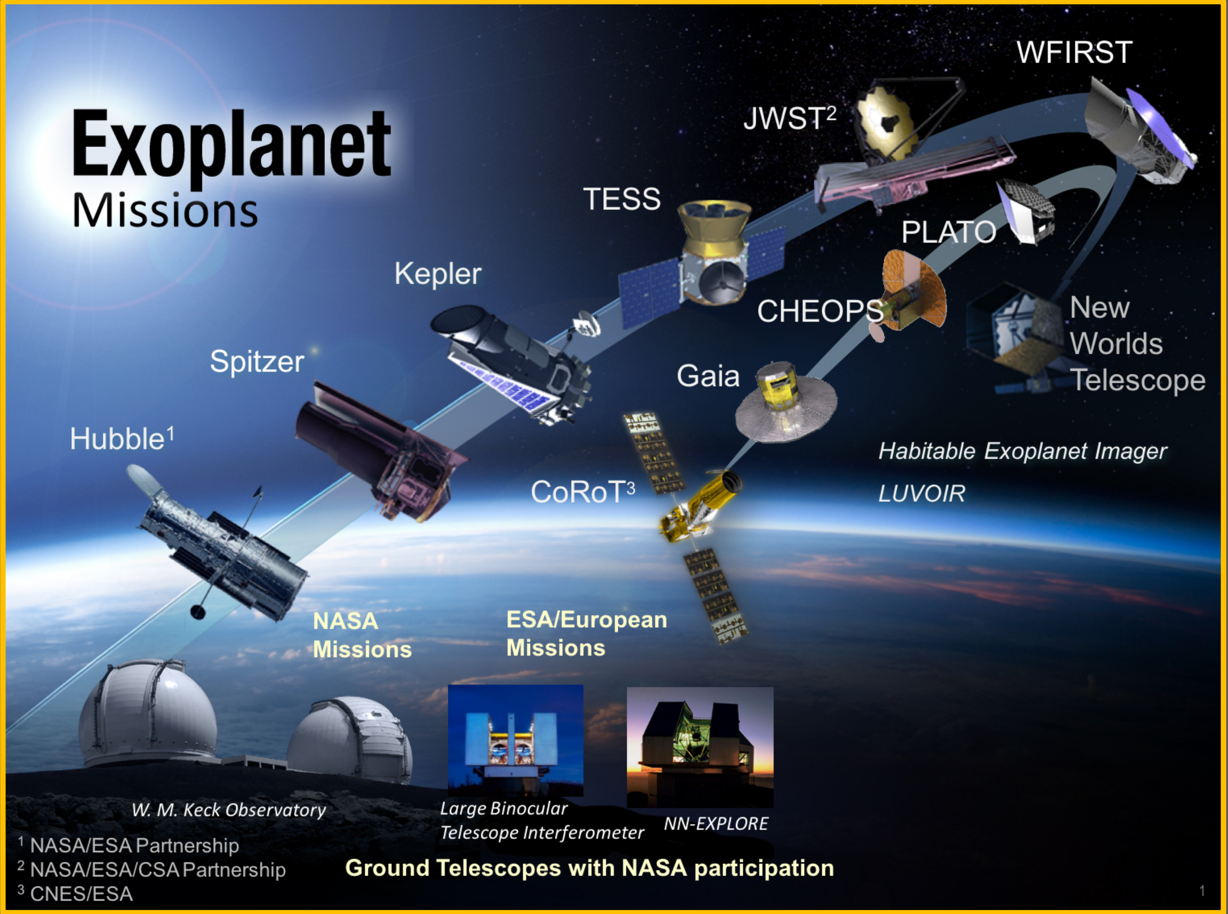


Fujii *et al.* 2018 - *Astrobiology*

>>> Future Prospects

Identification of "golden targets" to begin with *JWST* (2020-) and the *GMT*, *TMT*, *ELTs* (2020s-).

Follow up of biosignatures detections starts with next-generation space-based flagship telescopes: Origins Space Telescope (*OST*), the Habitable Exoplanet Observatory (*HabEx*), the Large UV/Optical/IR Surveyor (*LUVOIR*).



"...it is probably not unreasonable to expect the detection of the atmospheric signatures of a few potentially habitable planets to come before 2030,..." ushering in a "...golden era of comparative planetology of terrestrial planets"

Walker *et al.* 2018; Fijii *et al.* 2018 - *Astrobiology*

>>> UCI

Where does UCI fit in?

Expertise relevant to exoplanet biosignature detection?

Interdepartmental/interdisciplinary collaborations?

General UC benefits - Keck time, extensive network, labor pool

PhysAstro

Shields Center for Exoplanet Science and Interdisciplinary Education (*SCECIE*) in Department of Physics and Astronomy.

- Expertise in exoplanet detection, comparative planetology, climatology.
- Part of NExSS research coordination network.

Cosmology, galactic archaeology/evolution, high-energy physics

>>> Contact

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podcast: exocast.org

Astrobiology journal special edition:
https://www.liebertpub.com/toc/ast/18/6

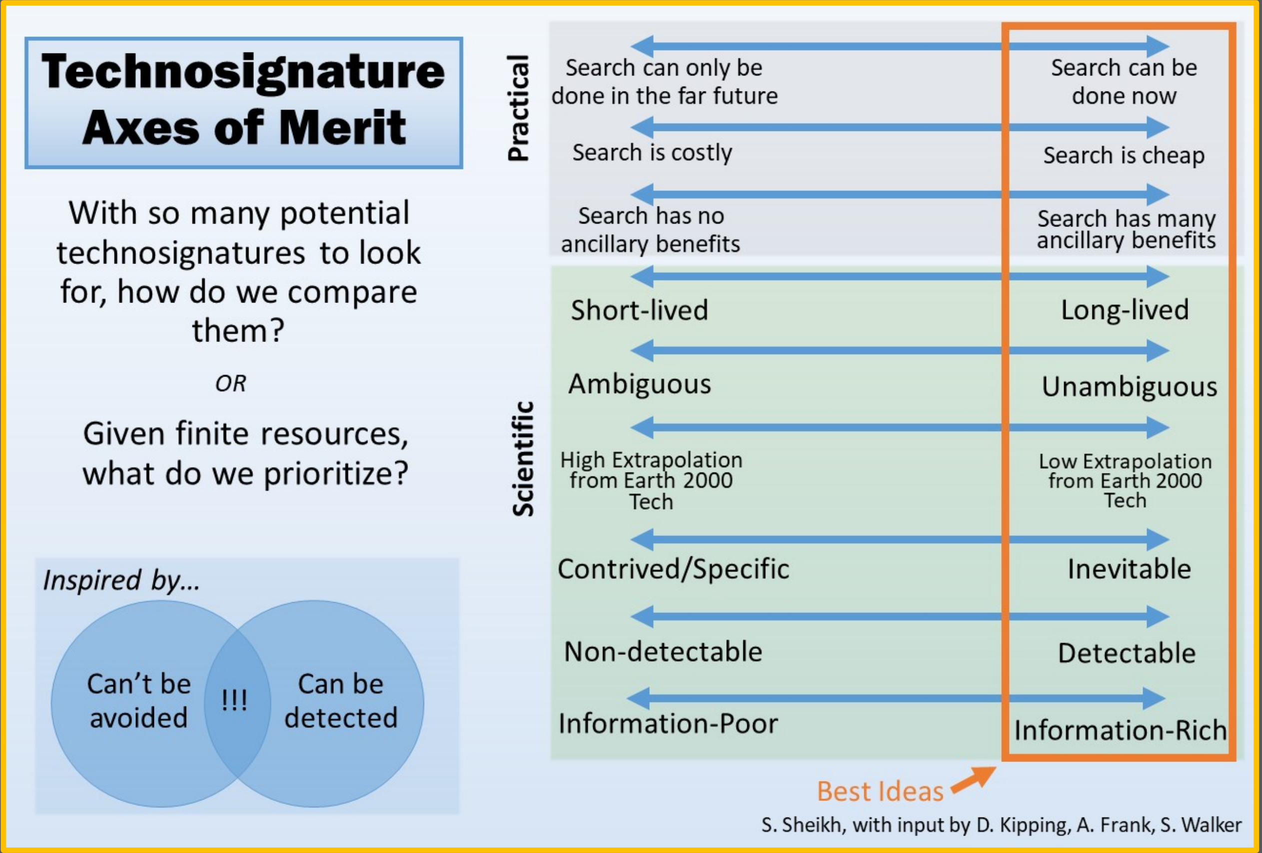
Scan with QR code reader app for link

NExSS biosignature workshop:
https://nexss.info/community/workshops/

>>> Technosignatures*

- NASA convened a workshop in Oct. 2018 to assess the state of the field and potential applications to NASA's astrobiology program, as well as current and future agency missions. Renewed investment a possibility.

- Broad field that extends from cosmology to planetary science, to the humanities and art.



*Wright *et al.* (2018) - *NASA Technosignatures Workshop 2018 - https://www.hou.usra.edu/meetings/technosignatures2018/agenda/*

>>> Examples of Technosignatures

- *Radio Signals*

Low frequency radiation in the 1.4 and 1.7 GHZ range, known as the ‘*cosmic watering hole*’ as it covers the natural frequencies of the hydroxyl radical *and* hydrogen, has been proposed as a possible frequency to start looking[1] and broadcasting*.

- *Optical Signals*

Infrared to ultraviolet radiation, including laser emissions. Intentional directed attempts at communication, or pollution/infrared excess from light sail propulsion (e.g. *The Planetary Society’s LightSail I* and *II*). Chromatic cloaking to intentionally swamp the transmission spectrum of a planet to obscure evidence of oxygen, pollutants, & bio- or technosignatures[1].

- *Mirrors & Megastructures*

On orbit mirrors for planetary terraforming e.g. Venus[2], or in response to climate change*, or to direct stellar radiation for power generation. We *could* find them when the planet is in transit. Other structures include the hypothetical Dyson sphere - a hypothetical means of capturing the entire radiative output of the star for power generation[3] - requires highly advanced technology.

- *Neutrinos*

Neutrinos propagate through space and rarely interact with normal matter. Advanced technology could hypothetically leveraging this property to communicate over astronomical distances[4].

- *Complex molecules in the atmosphere*

Industrially-produced complex molecules emitted into the atmospheres of planets would produce complex band-structures in spectroscopic surveys. Could be emitted unintentionally e.g. Chlorofluorocarbons(CFCs) in the Earth's atmosphere[5].

- *Warfare*

Evidence of war, particularly high-energy ordinance like nuclear weaponry could result in temporary bursts of luminosity on order of a billionth that of the Sun per second, and leave behind heavy isotopes in the atmosphere detectable by spectroscopy[6]*.

- *Artifacts, spacecraft, fossils*

Spacecraft sent as probes to distant star systems, or those served other purposes but also had onboard storage containing data pertaining to contact with ETI e.g. NASA’s *Voyager I & II*. Discovering extraterrestrial artifacts, fossils, in the Solar System*.

[1]Kipping & Teachey (2016) - *MNRAS;* [2]Birch (1991) - *J. British Interplan. Soc.*; [3]Zackrisson *et al.* (2018) - *ApJ.*; [4]Silagadze (2008) - *Acta Astron.*; [5]Lin *et al.* (2014) - *ApJ.*; [6]Stevens *et al.* (2017) - *Int. J. Astrobiology*