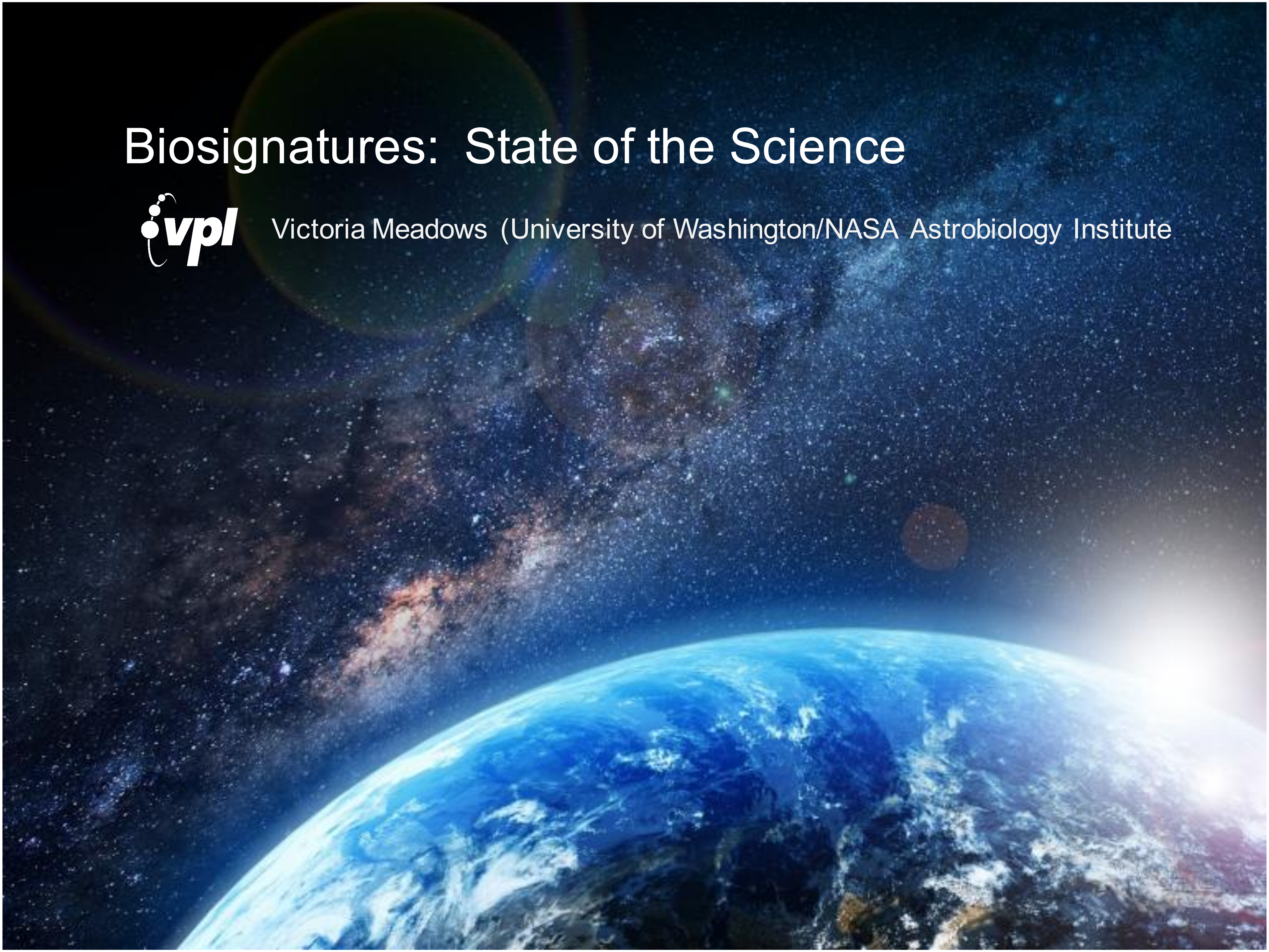
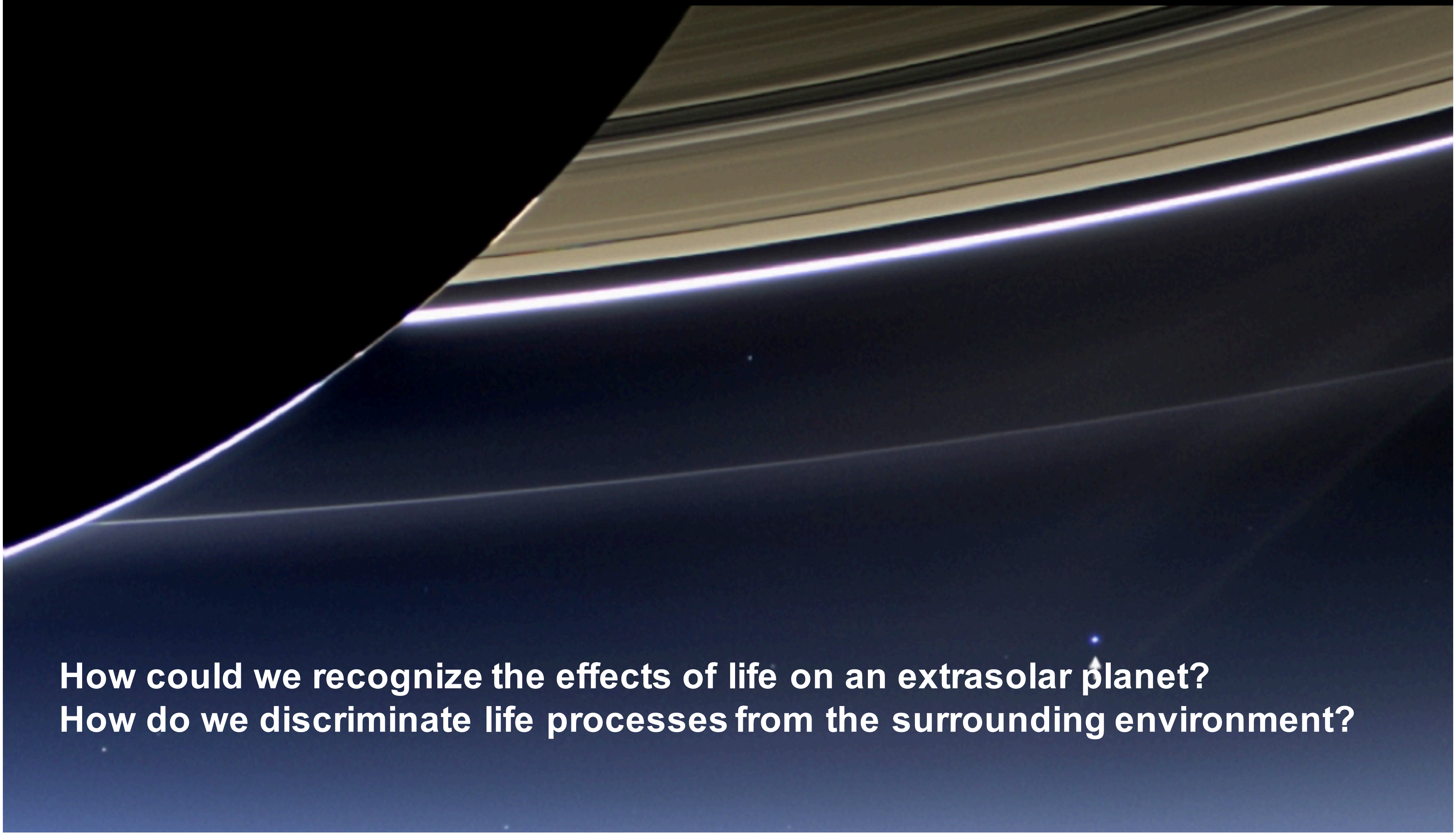
Biosignatures: State of the Science

Victoria Meadows (University of Washington/NASA Astrobiology Institute



Is The Pale Blue Dot Inhabited?



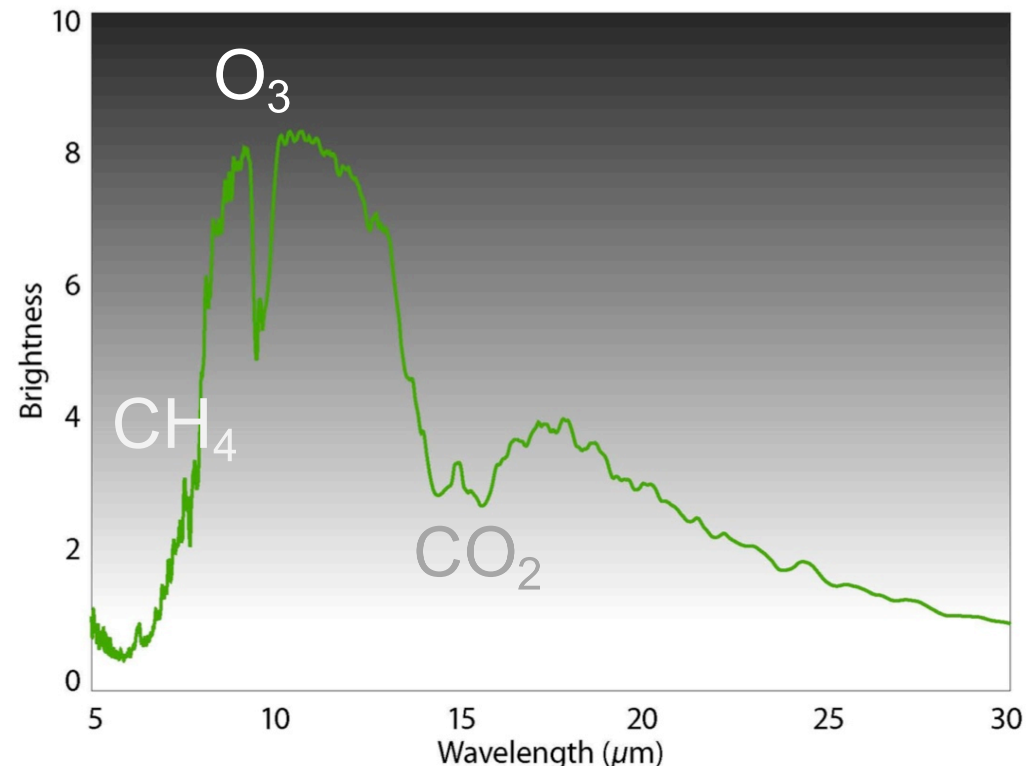
How could we recognize the effects of life on an extrasolar planet?
How do we discriminate life processes from the surrounding environment?

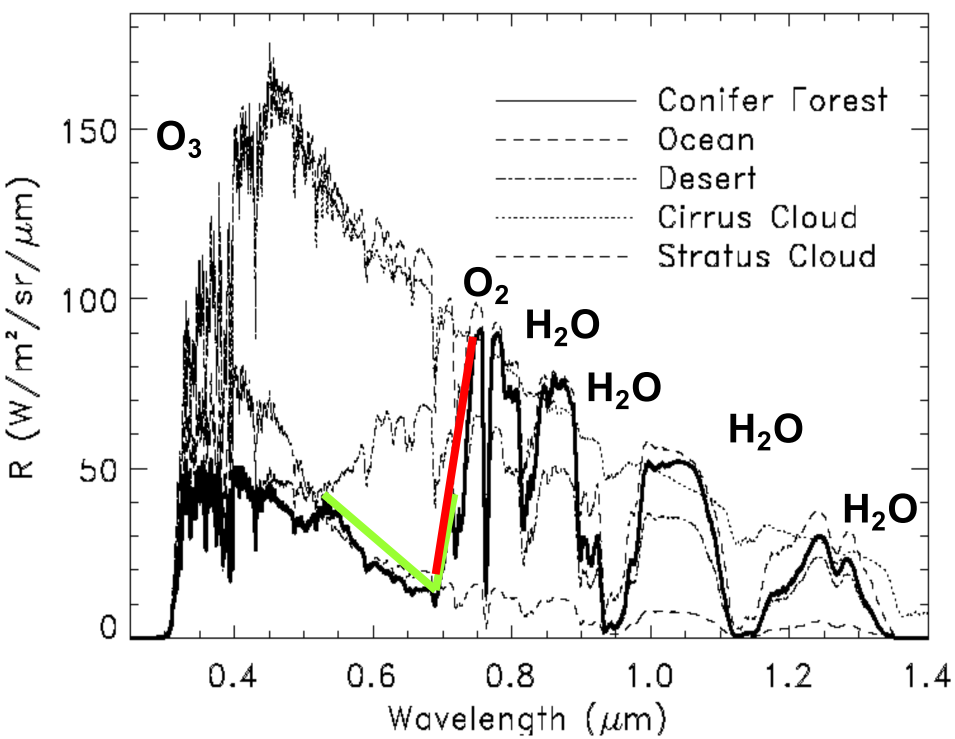
Life’s Global Impact

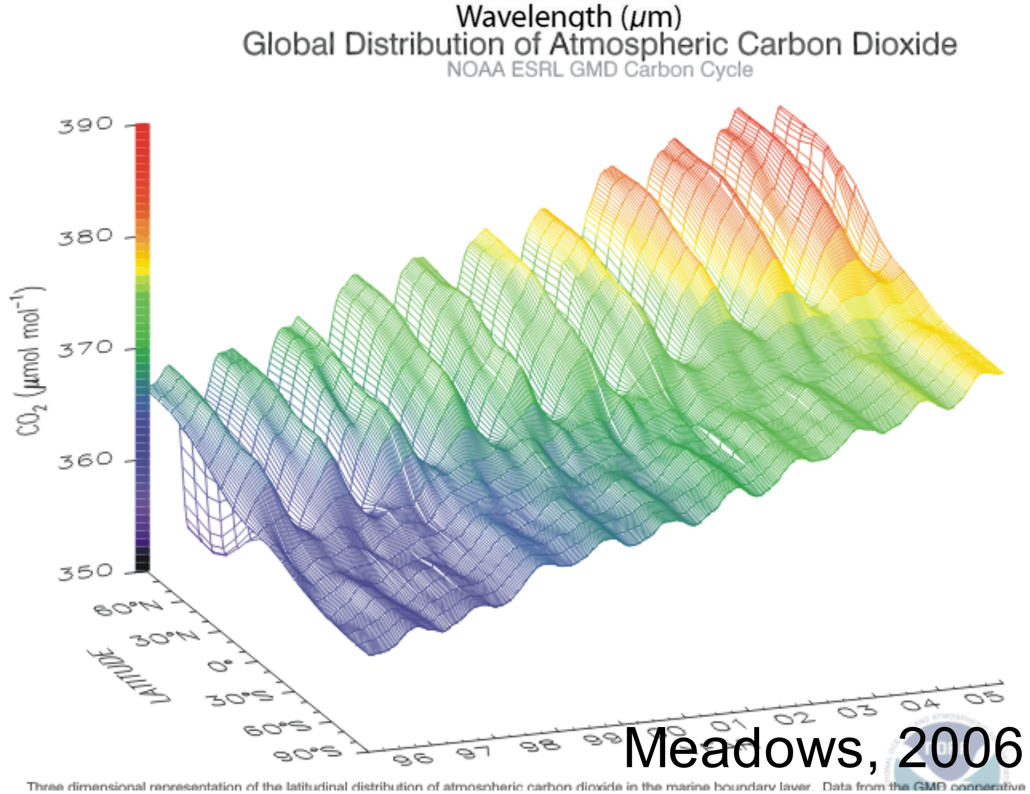
A planetary biosignature is a way that life has modified its environment in a potentially detectable way.

Biosignatures

- Earth exhibits global-scale modification of its:
  - Atmosphere
  - Surface
  - Temporal behavior
- Antibiosignatures
- False Positives
- False Negatives
- False Positive/Negative Discriminants







Meadows, 2006

Classic Biosignatures: Atmospheric Disequilibrium

TABLE 1 Constituents of the Earth's atmosphere (volume mixing ratios)

Molecule	Standard abundance (ground-truth Earth)	Galileo value*	Thermodynamic equilibrium value Estimate 1†	Estimate 2‡
N_2	0.78		0.78	
O_2	0.21	0.19 ± 0.05	0.21§	
H_2O	0.03–0.001	0.01–0.001	0.03–0.001	
Ar	9×10^{-3}		9×10^{-3}	
CO_2	3.5×10^{-4}	$5 \pm 2.5 \times 10^{-4}$	3.5×10^{-4}	
CH_4	1.6×10^{-6}	$3 \pm 1.5 \times 10^{-6}$	$< 10^{-35}$	10^{-145}
N_2O	3×10^{-7}	$\sim 10^{-6}$	2×10^{-20}	2×10^{-19}
O_3	10^{-7}–10^{-8}	$> 10^{-8}$	6×10^{-32}	3×10^{-30}

* Galileo values for O_2, CH_4 and N_2O from NIMS data; O_3 estimate from UVS data.

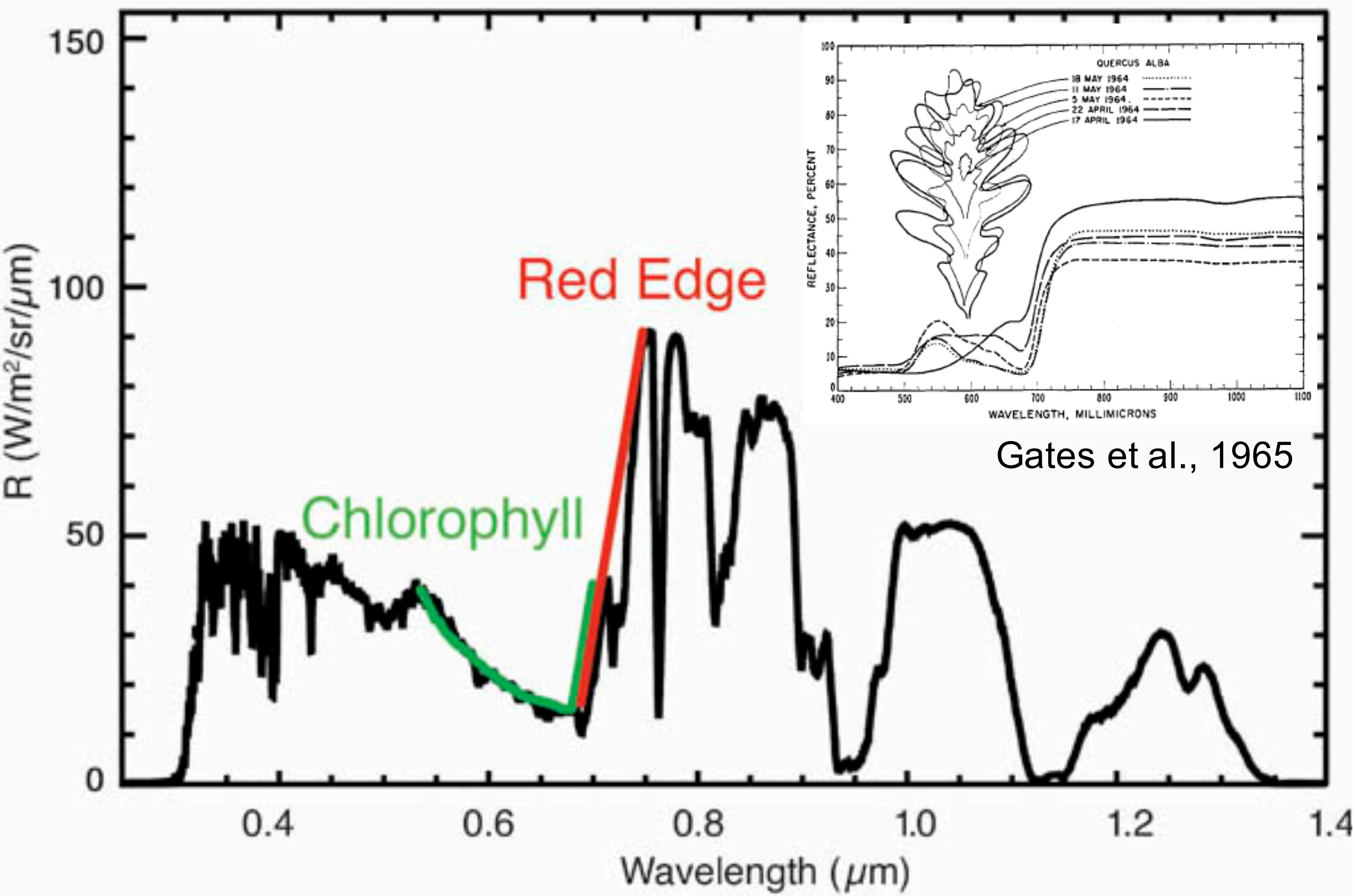
† From ref. 16 (P, 1 bar; T, 280 K).

‡ From ref. 17 (P, 1 bar; T, 298 K).

§ The observed value; it is in thermodynamic equilibrium only if the under-oxidized state of the Earth's crust is neglected.

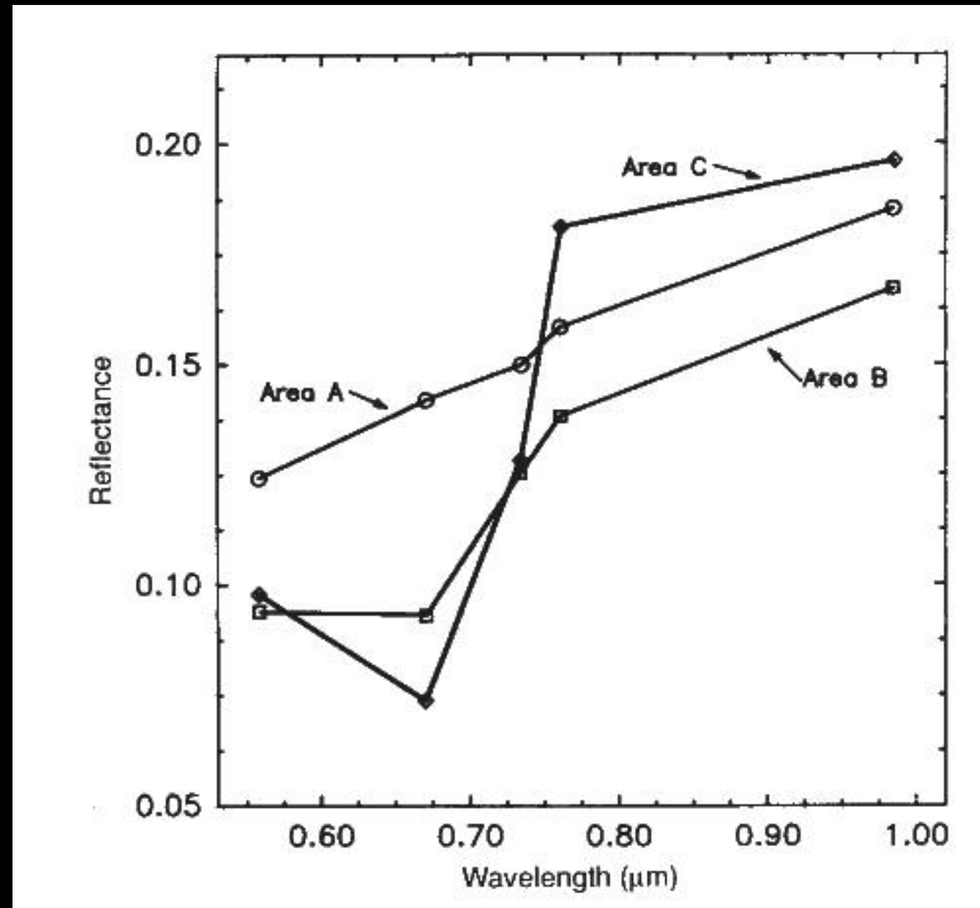
Sagan et al., 1993

Classic Biosignatures: Red Edge



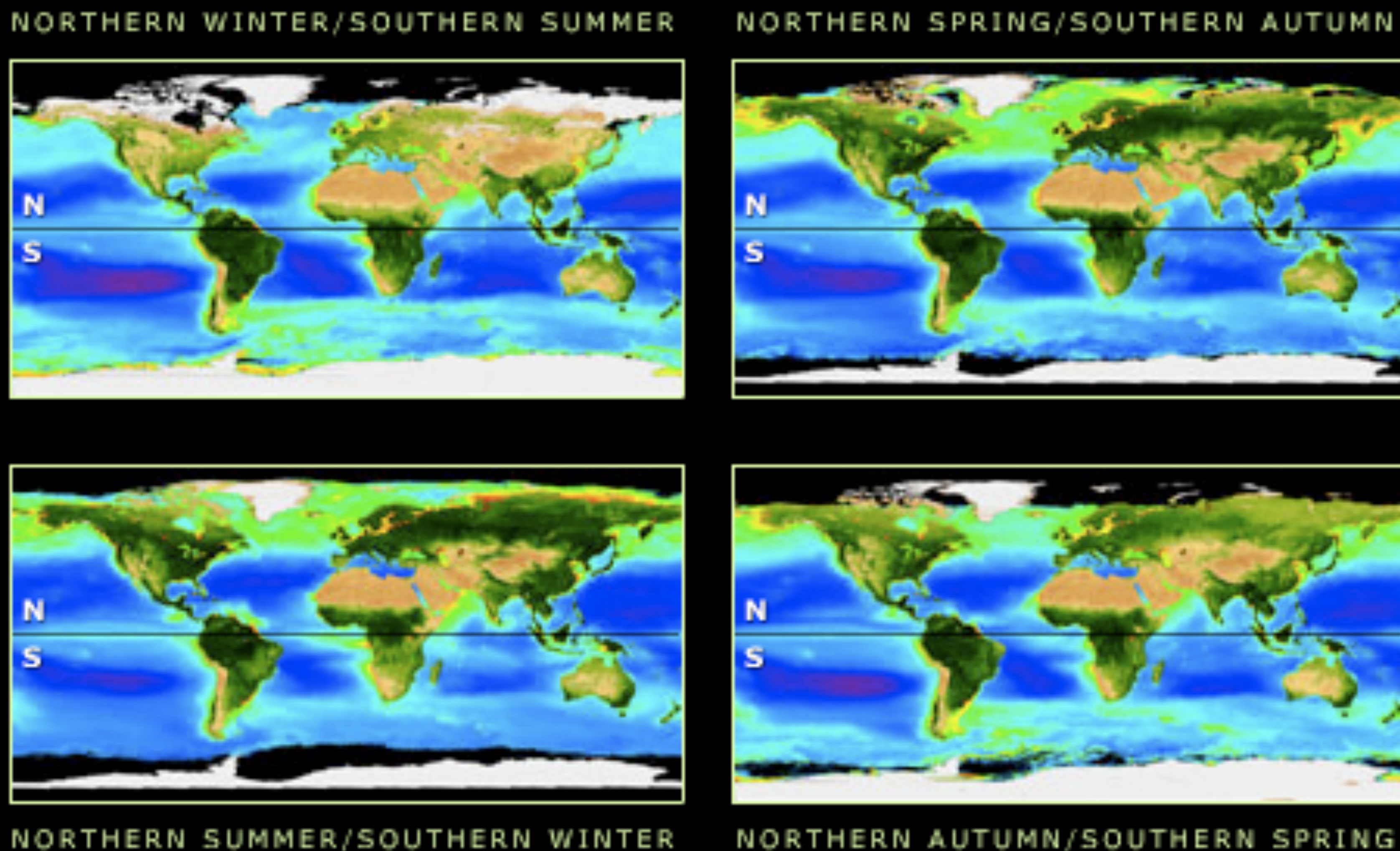
Gates et al., 1965

Classic Biosignatures: Red Edge



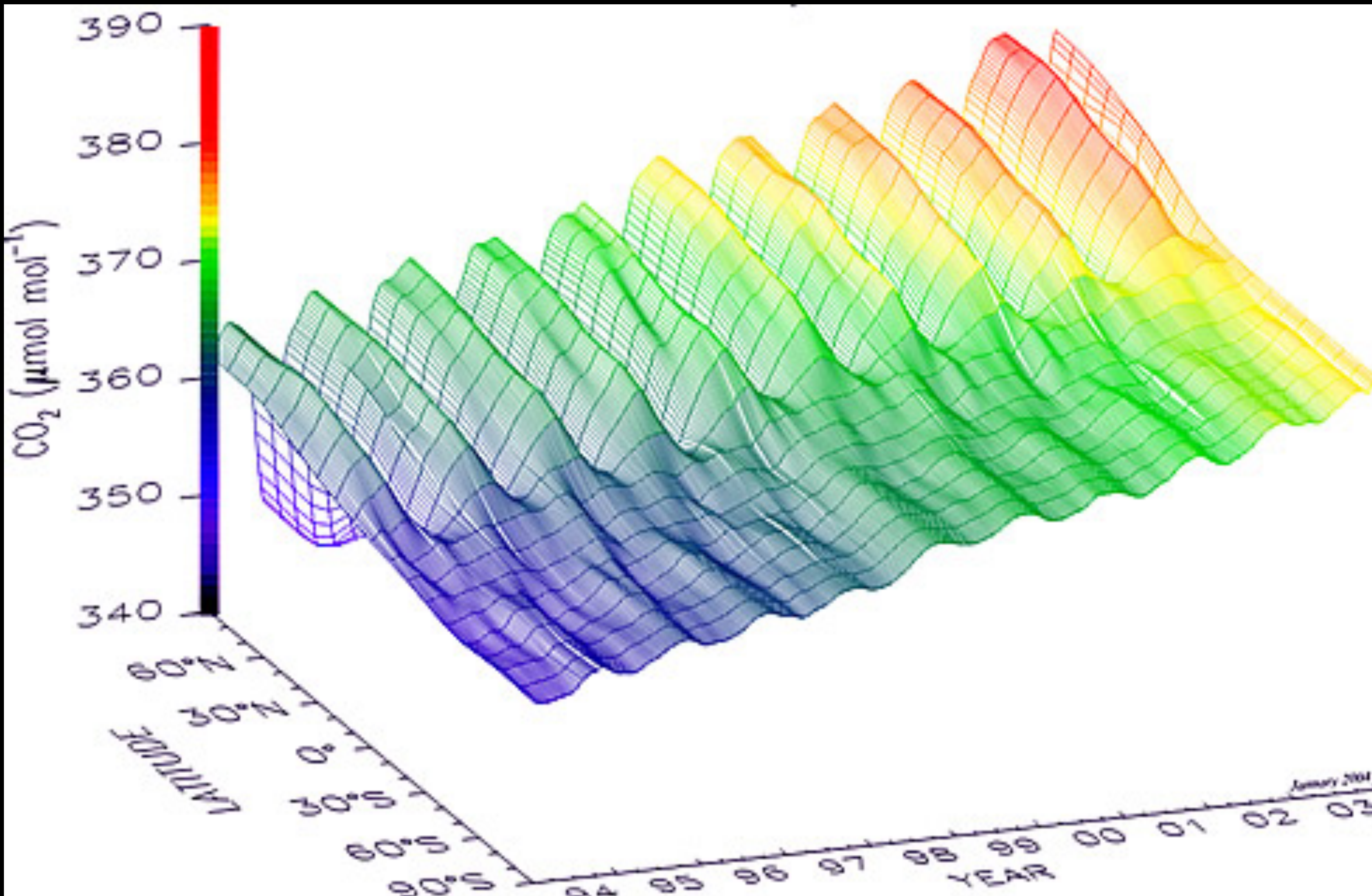
Sagan et al., 1993

Classic Biosignatures: Temporal Variability



Seasonal changes in vegetation coverage

Classic Biosignatures: Temporal Variability



Seasonal periodicities in both atmospheric CO_2 and CH_4 are associated with respiration in the land biosphere

Meadows, 2006

DesMarais et al., 2002

- The primary motivation for this paper was the downselection between TPF-C and TPF-I .

- Concentrated primarily on wavelength regions and the spectral features in each

- Molecules of importance that were identified included:
  - H_2O and CO_2 as habitability markers
  - O_2, O_3 ,N_2O and CH_4 as potential biosignatures

- Surface biosignatures such as the red edge were acknowledged.

- Temporal variability in temperature due to seasons and seasonal vegetation coverage was discussed.

- Oxygen or its proxy ozone was considered robust, and the only know false positives were outside the limits of the HZ

“For a “normal” Earthlike planet situated within the habitable zone, free O_2 is a reliable indicator of life” - DesMarais et al., 2002.

Our Pre-Workshop Spreadsheet

- Listed exoplanet missions and ground-based telescopes (and their accessible wavelengths)
  - Direct Imaging
    - Space-based: LUVOIR, HabEX, WFIRST-C/S
    - Ground-based: VLT, GPI, SPHERE, E-ELT/EPICS, TMT/PFI
  - Transit
    - Space-based: HST, JWST, WFIRST, LUVOIR, HabEx
    - Ground-based: ELT, TMT, GMT, Lots of other Ts

- Stellar characteristics (SED, activity, age)

- Habitability Indicators
  - H_2O, CO_2, CO, N_2, SO_2, T, P, clouds/hazes, ice, sulfur, silicates…

- Potential Biosignature gases
  - O_2, O_3, N_2O, CH_4, C_2H_6, DMS, DMDS, CH_3SH, CH_3Cl, NH_3, other volatiles

- Surface biosignatures
  - Red Edge, photosynthetic pigments, non-photosynthetic pigments, UV screening pigments, etc.

- Thermodynamic disequilibrium
  - O_2/CH_4, O_3/CH_4, N_2/O_2/ocean

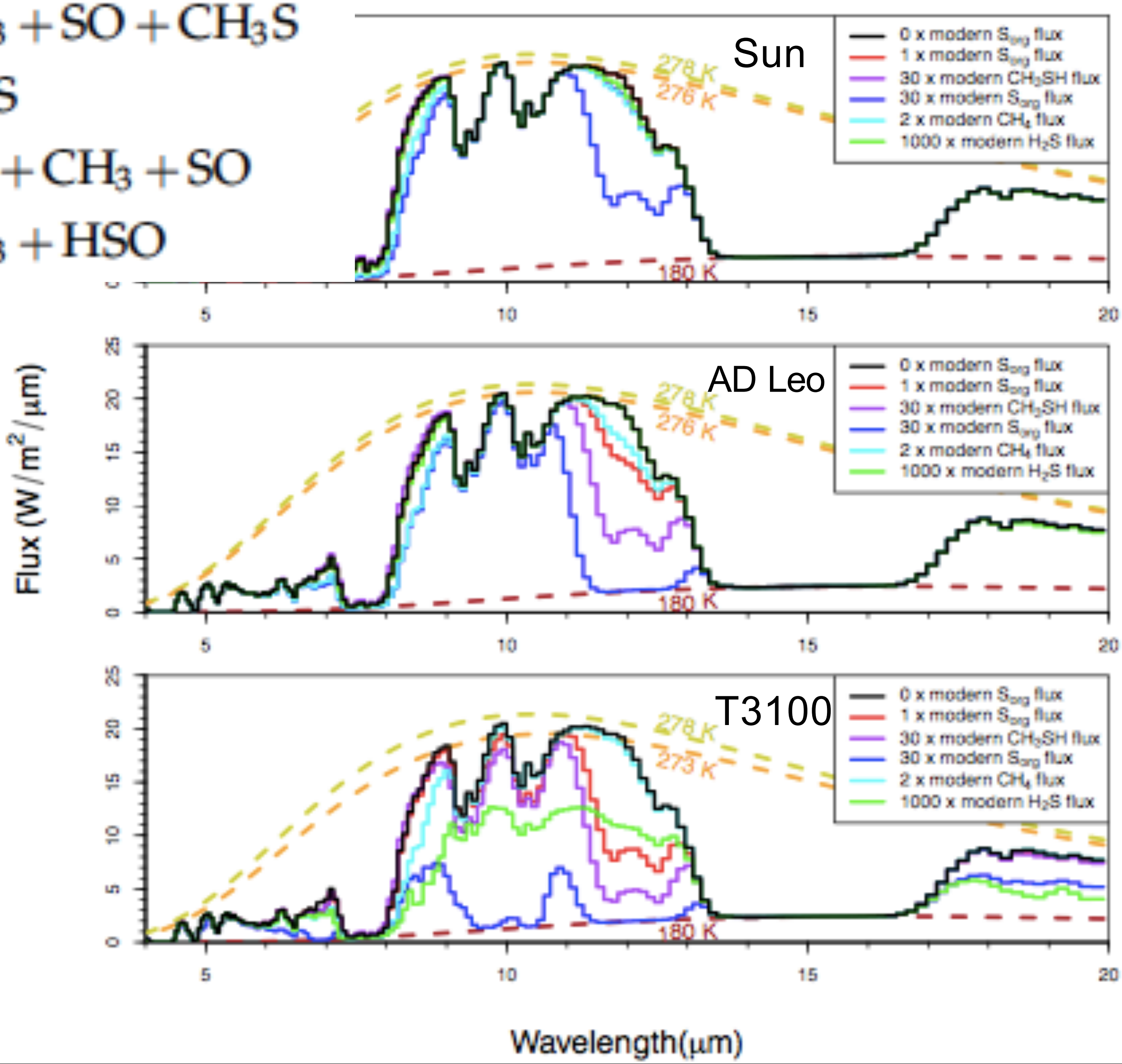
- Temporal Variability
  - Seasonal vegetation, CO_2, CH_4

- Isotopes, Hazes

Advances in Biosignatures: C_2H_6 from sulfur metabolism

$$C_2H_6S_2 + O \rightarrow CH_3 + SO + CH_3S$$
$$OCS + h\nu \rightarrow CO + S$$
$$C_2H_6S + O \rightarrow CH_3 + CH_3 + SO$$
$$CH_3SH + O \rightarrow CH_3 + HSO$$

Ethane is the Strongest signal from a sulfur dominated biosphere.



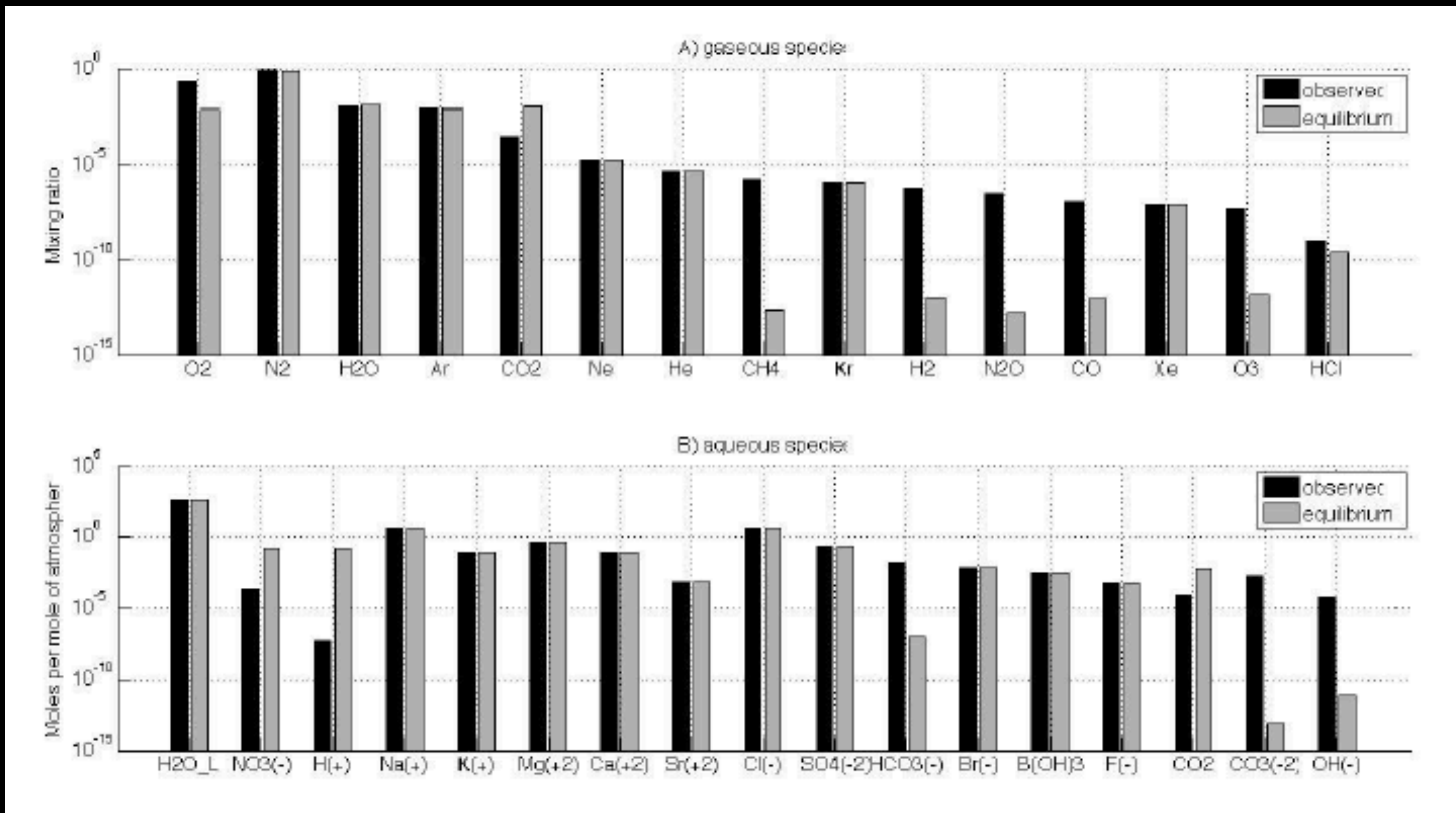
vpl

Domagal-Goldman, Meadows et al., *Astrobiology*, 2011

Advances in Biosignatures: Disequilibrium

Earth's thermodynamic disequilibrium is biogenic in origin, and the main contribution is the coexistence of N_2, O_2 and liquid water instead of a more stable nitrate-rich ocean

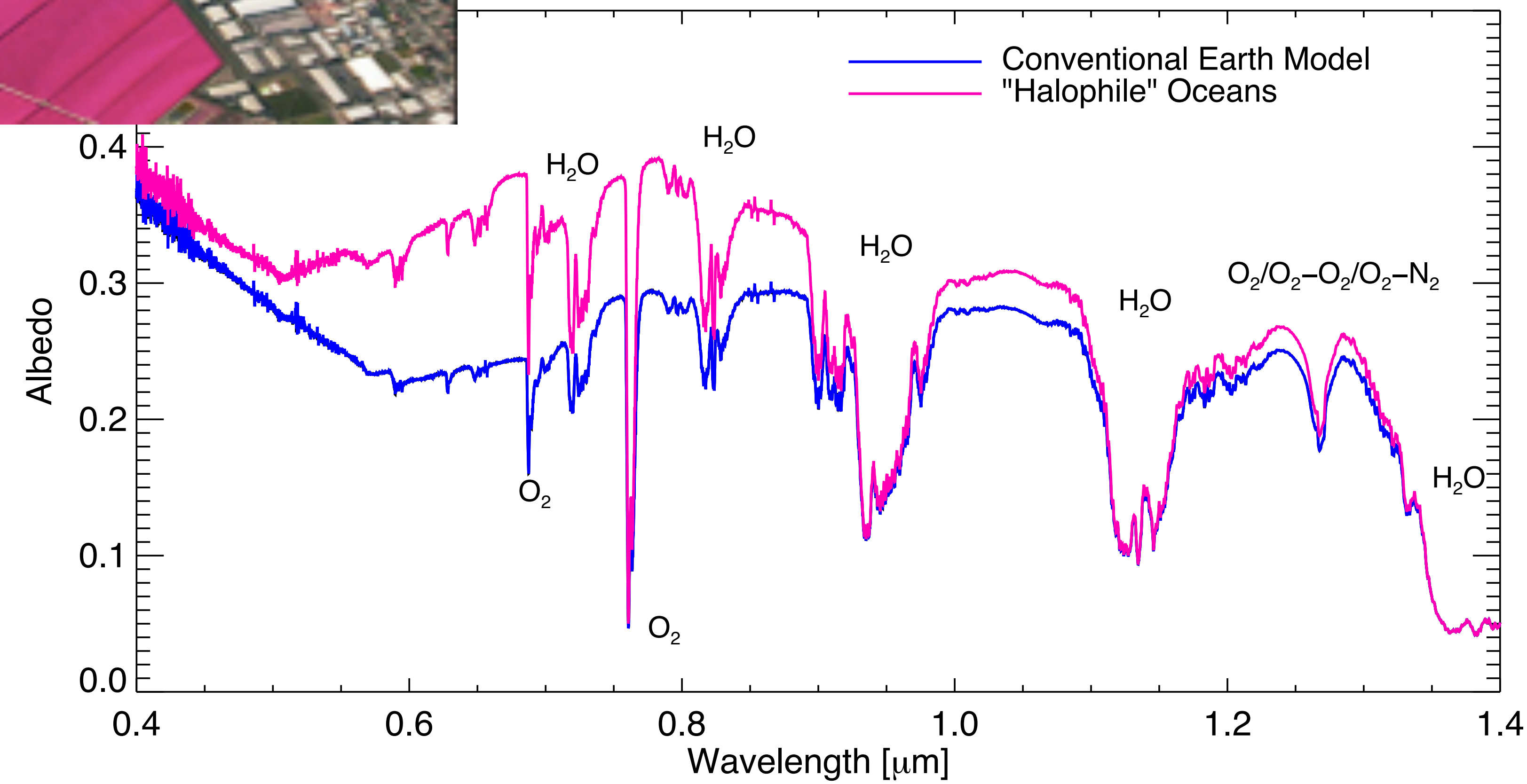
$2N_2(g) + 5O_2(g) + H_2O(l) \quad\quad 4H^+(aq) + 4NO_3^-(aq)$



Krissansen-Totton et al., 2016

Advances in Biosignatures: Surface Biosignatures

Schwieterman, Cockell, Meadows, *Astrobiology*, 2011



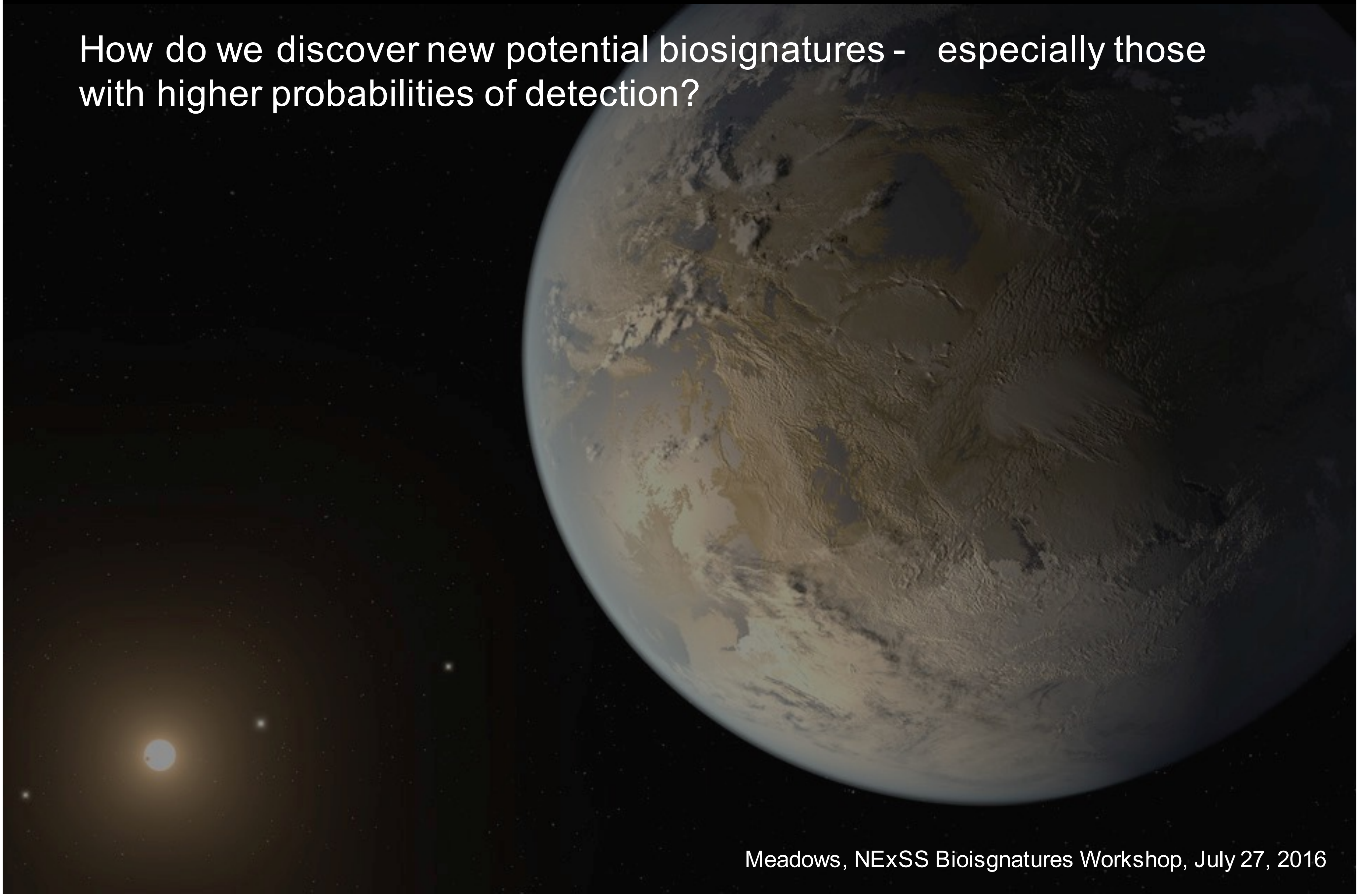
Moving the Field Forward

How do we discover new potential biosignatures - especially those with higher probabilities of detection?

How do we increase our confidence in the interpretation of the candidates we do have?

Moving the Field Forward

How do we discover new potential biosignatures - especially those with higher probabilities of detection?



Meadows, NExSS Bioisgnatures Workshop, July 27, 2016

Discovering Biosignatures (*a priori*)

1. Reliability

   Is it/could it be produced by life?

   Is it less likely to be produced by planetary processes such as geology and photochemistry?

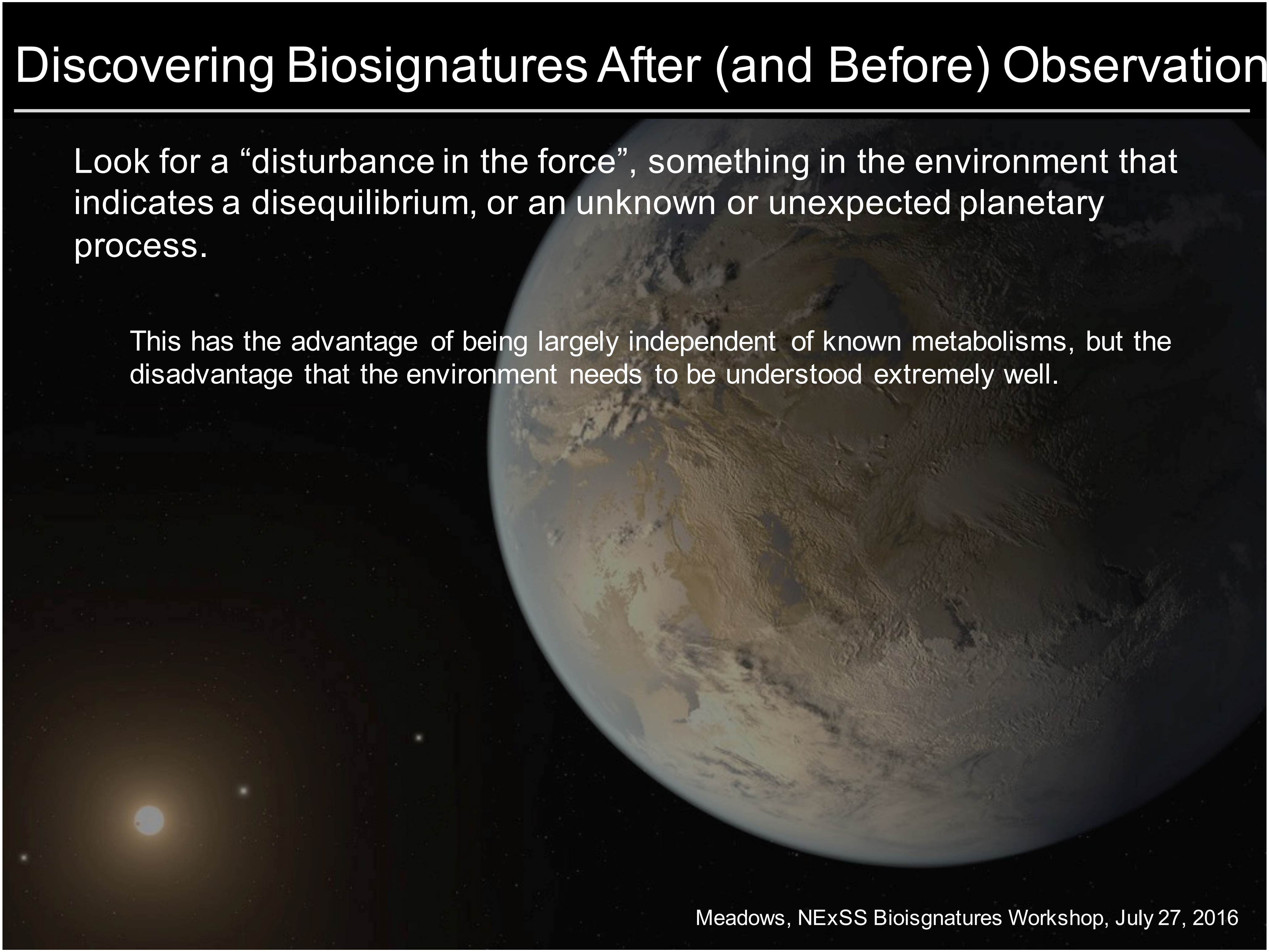
2. Survivability

   Does it avoid the normal sinks in a planetary atmosphere: destruction by photochemistry, reaction with volcanic gases, reaction with the surface, dissolving in an ocean?

3. Detectability

   Is it detectable via transmission, secondary eclipse, phase curves or direct imaging? Is it active in the observed wavelength region and is it clear of overlap with other common planetary species?

Meadows, NExSS Bioisgnatures Workshop, July 27, 2016


Discovering Biosignatures After (and Before) Observation
Look for a “disturbance in the force”, something in the environment that indicates a disequilibrium, or an unknown or unexpected planetary process.
This has the advantage of being largely independent of known metabolisms, but the disadvantage that the environment needs to be understood extremely well.
Meadows, NExSS Bioisgnatures Workshop, July 27, 2016

Choosing a Candidate Biosignature Gas

1. Explore the Earth's current biosignatures

   Has the advantage that we know these characteristics can be produced by life and are observed in a relevant environment. Survivability is already proven. The disadvantage is that it is limited to this one planet, and may not represent the diversity of biological processes and planetary environments.

2. Explore the Earth's past

   Early Earth provides geochemical evidence that different metabolisms were dominant in different time periods and in different environments, and we can understand their likely biosignatures from constraining these ancient environments and understanding the organisms that remain today. Still "Earth-centric".

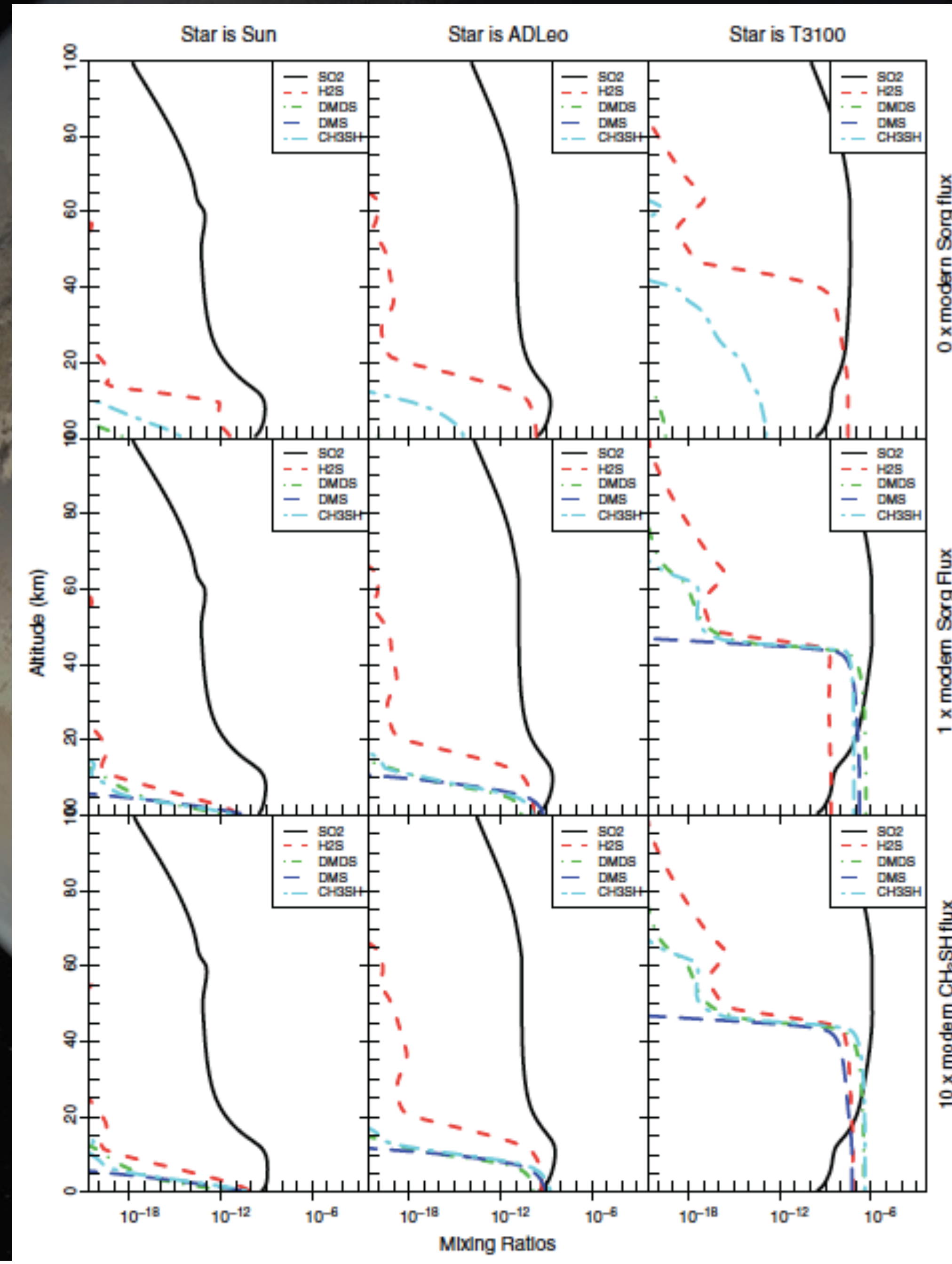
3. Survey a very large array of possible volatile molecules

   An advantage is that it is initially non-metabolism specific, but must still be tested for survivability, detectability, the likelihood that the gas will be produced by life, and without environmental context, understanding false positives will be challenging.

Discovering New Biosignatures: A Case Study

- In one approach, we can use known Earth metabolisms and current and past environments to develop a “Choose your own adventure” experiment - that explores the survivability and detectability of biosignature gases in a range of atmospheres and under different stellar illumination.

  - Early Earth atmosphere (3% CO_2)
  - S biosphere (0, 1, 10x modern)
  - Sun, AD Leo, T3100K



Domagal-Goldman, Meadows et al., *Astrobiology*, 2011

Advances in Biosignatures: C_2H_6 from sulfur metabolism

$$C_2H_6S_2 + O \rightarrow CH_3 + SO + CH_3S$$

$$OCS + h\nu \rightarrow CO + S$$

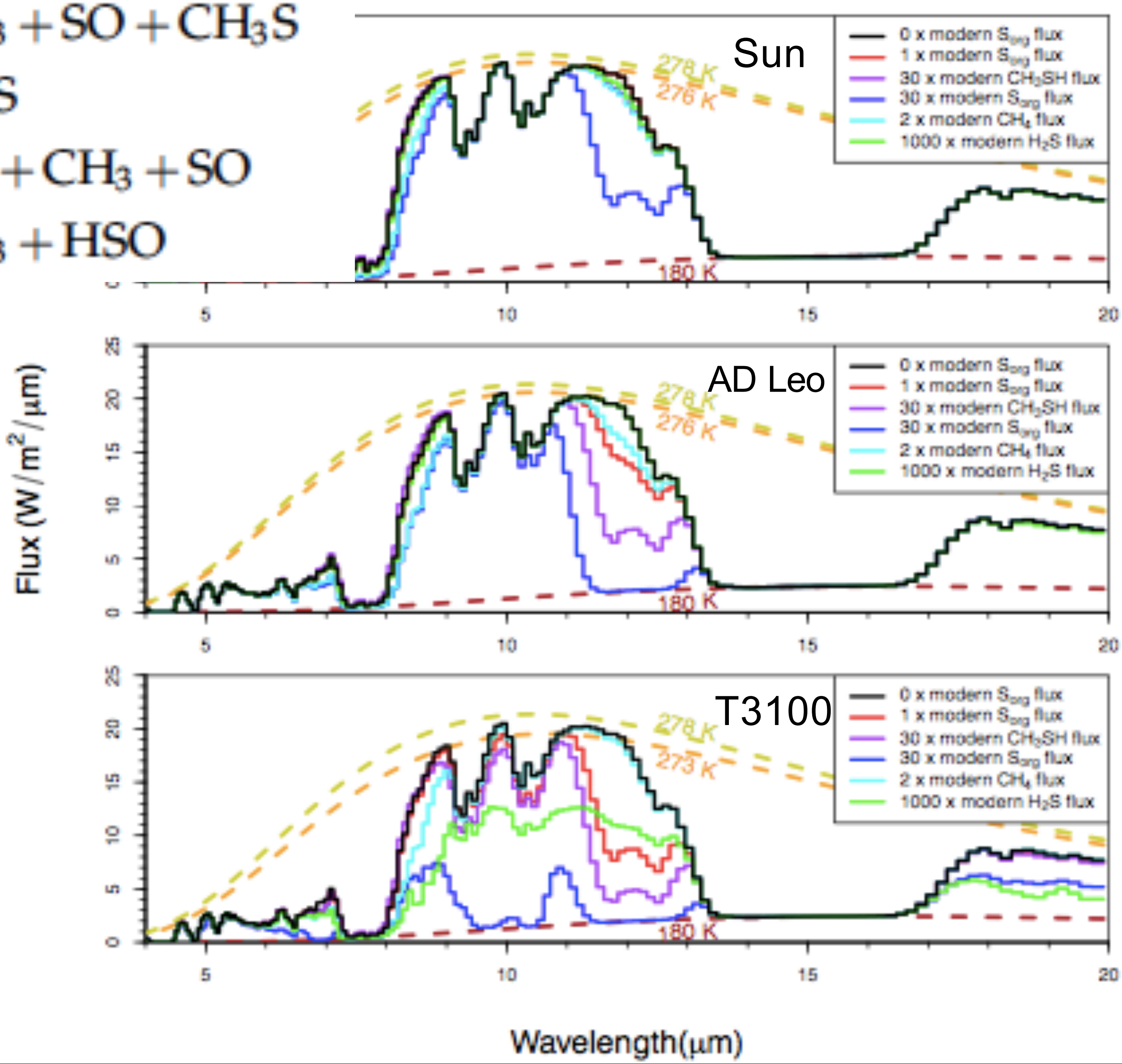
$$C_2H_6S + O \rightarrow CH_3 + CH_3 + SO$$

$$CH_3SH + O \rightarrow CH_3 + HSO$$

Ethane is the Strongest signal from a sulfur dominated biosphere. More detectable for M dwarf planets

Also note, the higher the complexity, the lower the survivability

False negatives must also be considered

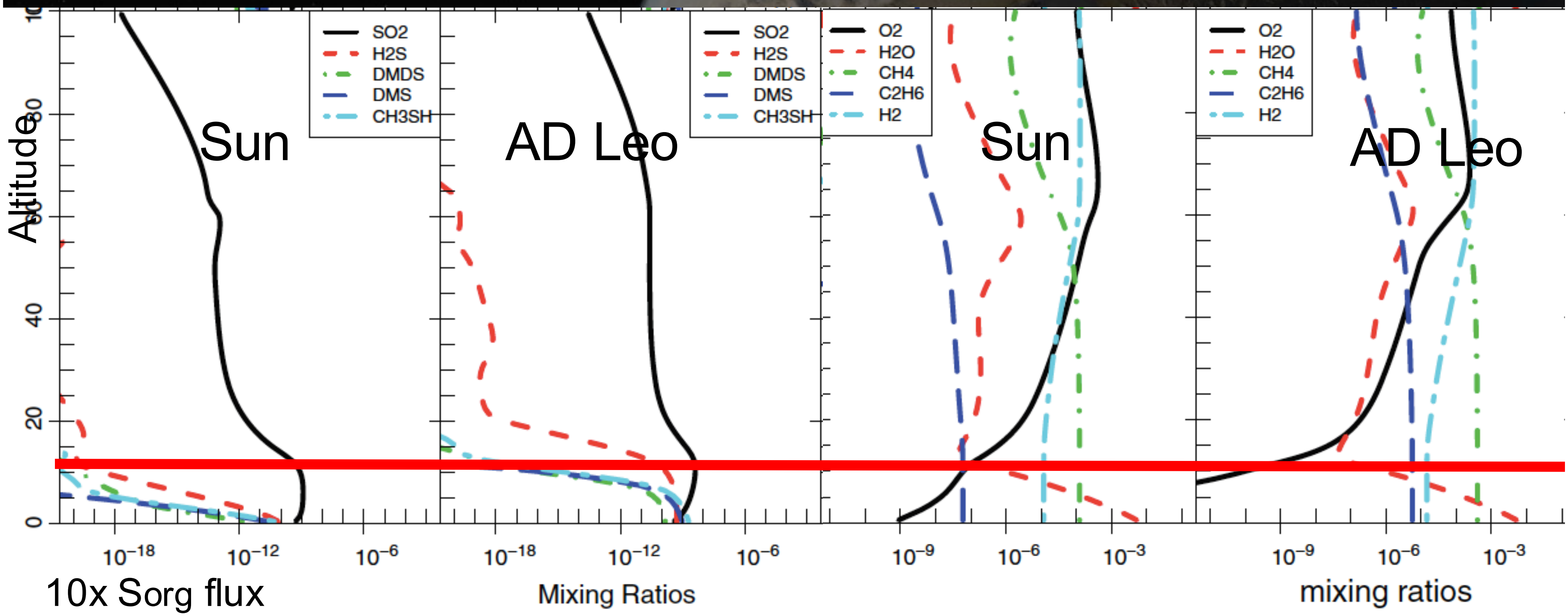


Domagal-Goldman, et al., *Astrobiology*, 2011

Issues with Detectability

In transmission spectroscopy, there will be a minimum altitude that the observation can probe down to. For terrestrial planets, this will typically be in the upper troposphere or stratosphere. Clouds and hazes may also limit access to the lower atmosphere.

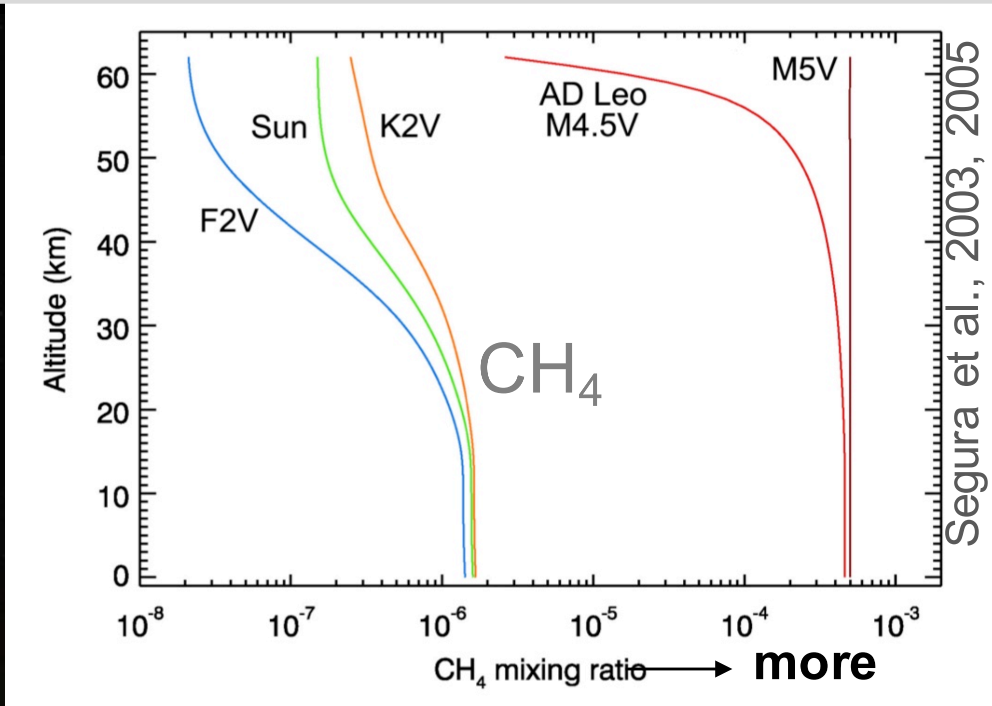
Garcia-Muñoz et al., 2012; Misra, Meadows and Crisp., 2014; Bertremieux & Kaltenegger, 2013, 2014

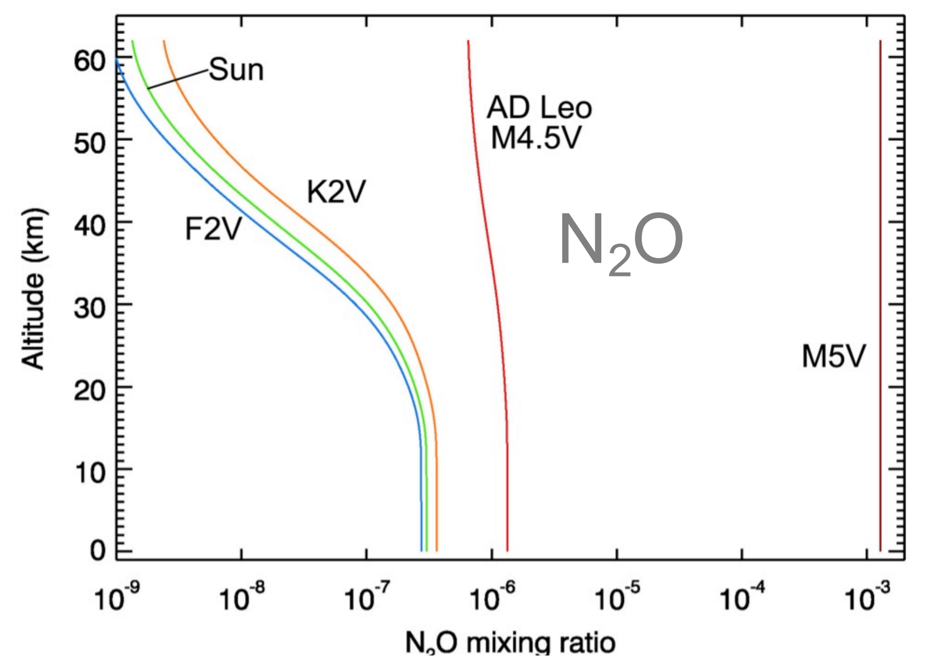


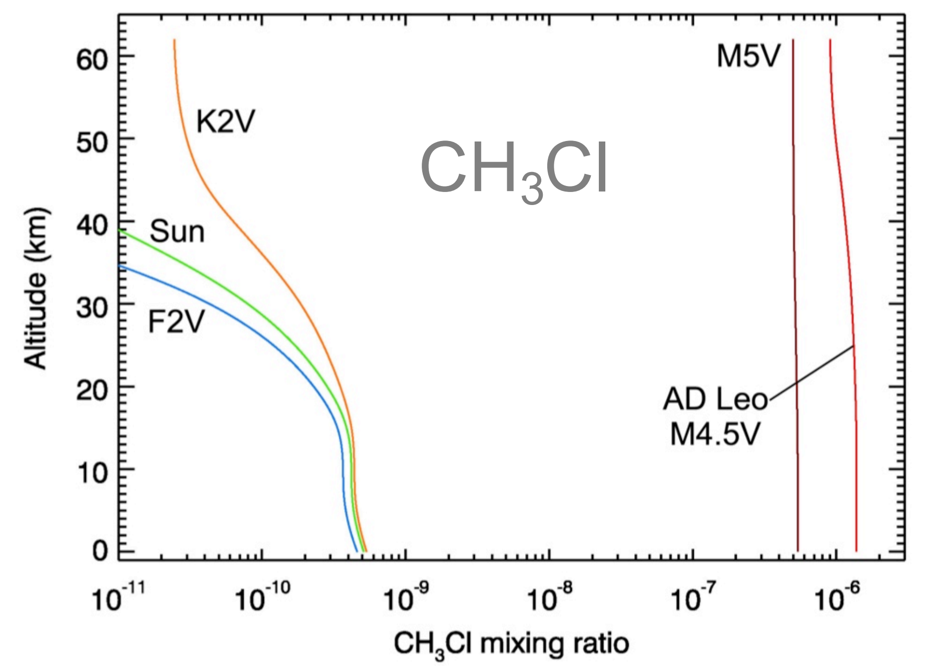
Domagal-Goldman et al., 2011

Biosignature molecules that are more susceptible to UV radiation will be found in the lower troposphere only, and may not be accessible to transmission.

Issues With Detectability: Stellar Spectrum

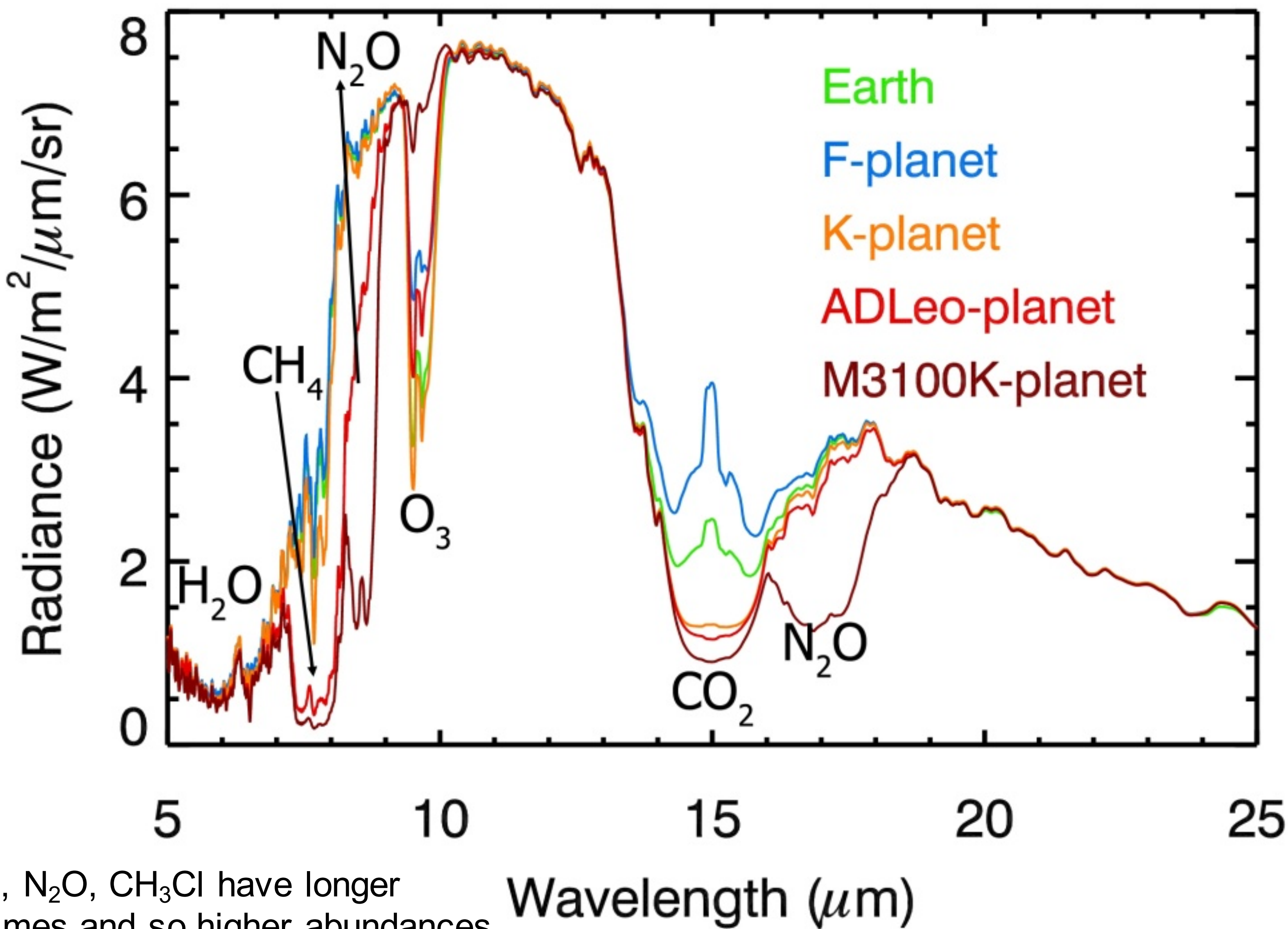






- Earth-like planets around cooler stars show enhanced biosignature abundances for the same surface fluxes (Segura et al., 2003, 2005)
  - M stars less effective at O_3 photolysis
- Enhancements in biosignatures, are *also* seen towards the outer edge of its habitable zone (Grenfell et al., 2006, 2007)
- False positives for O_2 can be generated depending on stellar spectrum.

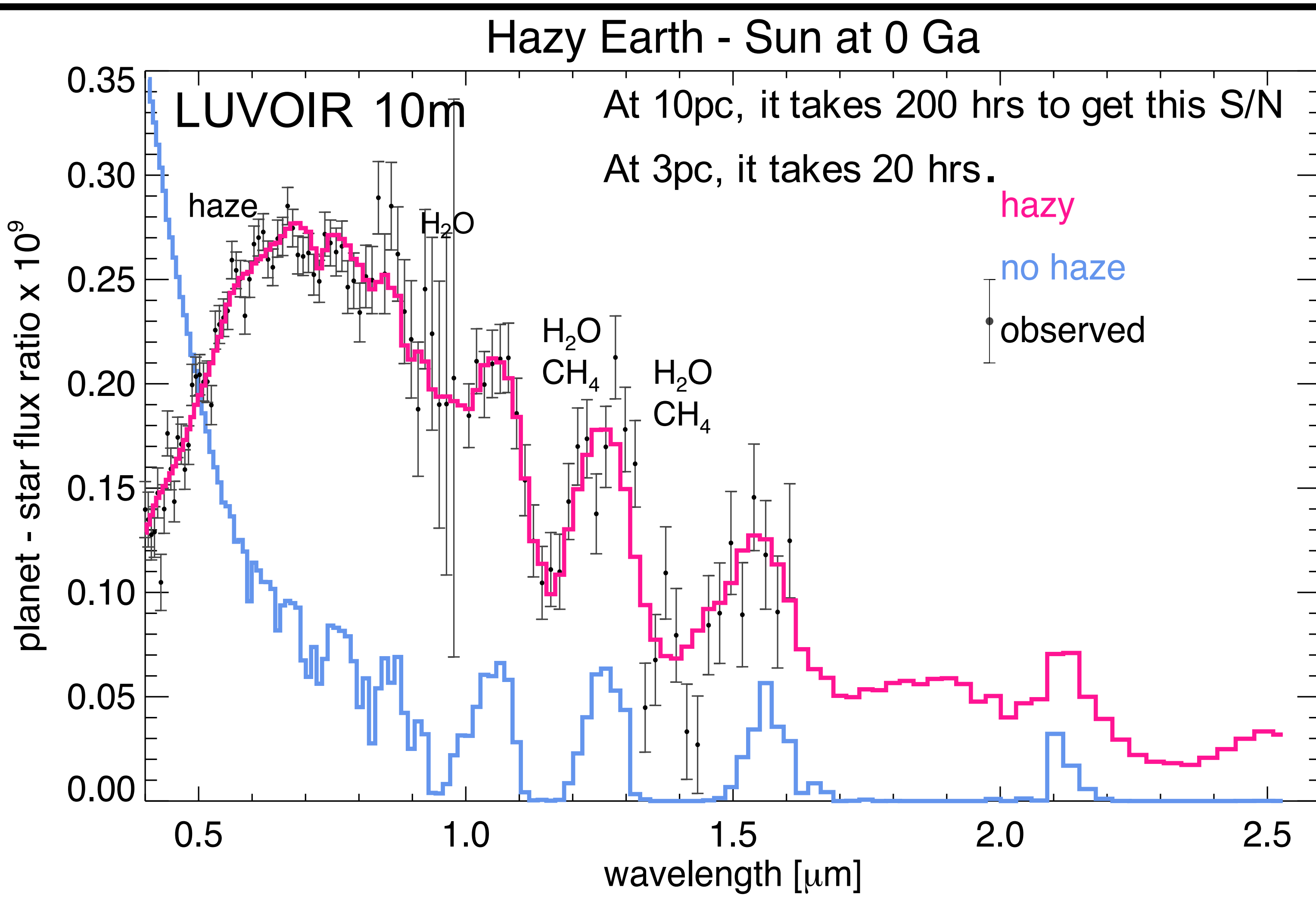
Enhanced Detectability of Biosignatures for M Dwarf planets



CH_4, N_2O, CH_3Cl have longer lifetimes and so higher abundances

Segura et al., 2003, 2005

Haze is not as big an issue for direct imaging

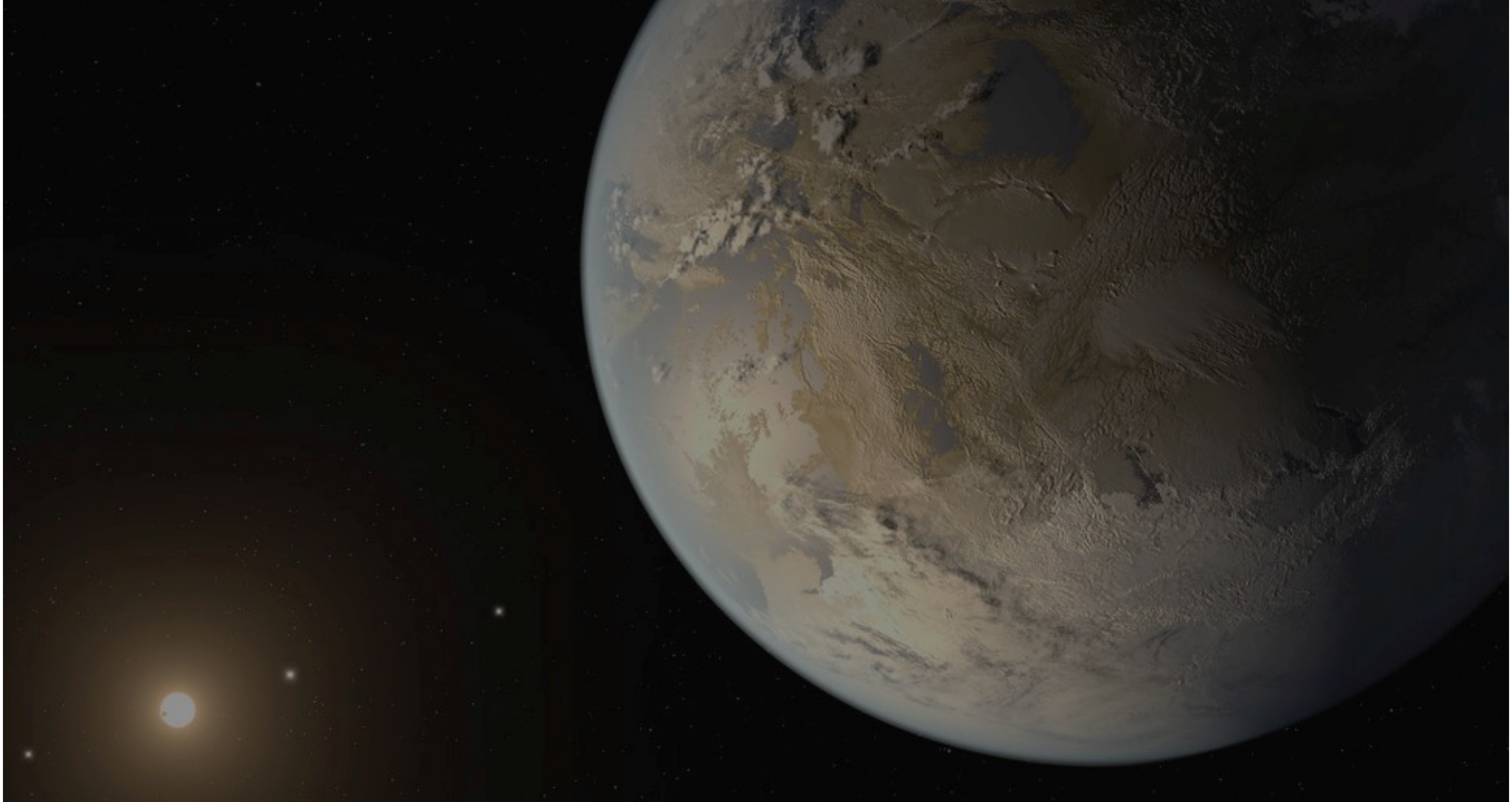


Arney et al., submitted

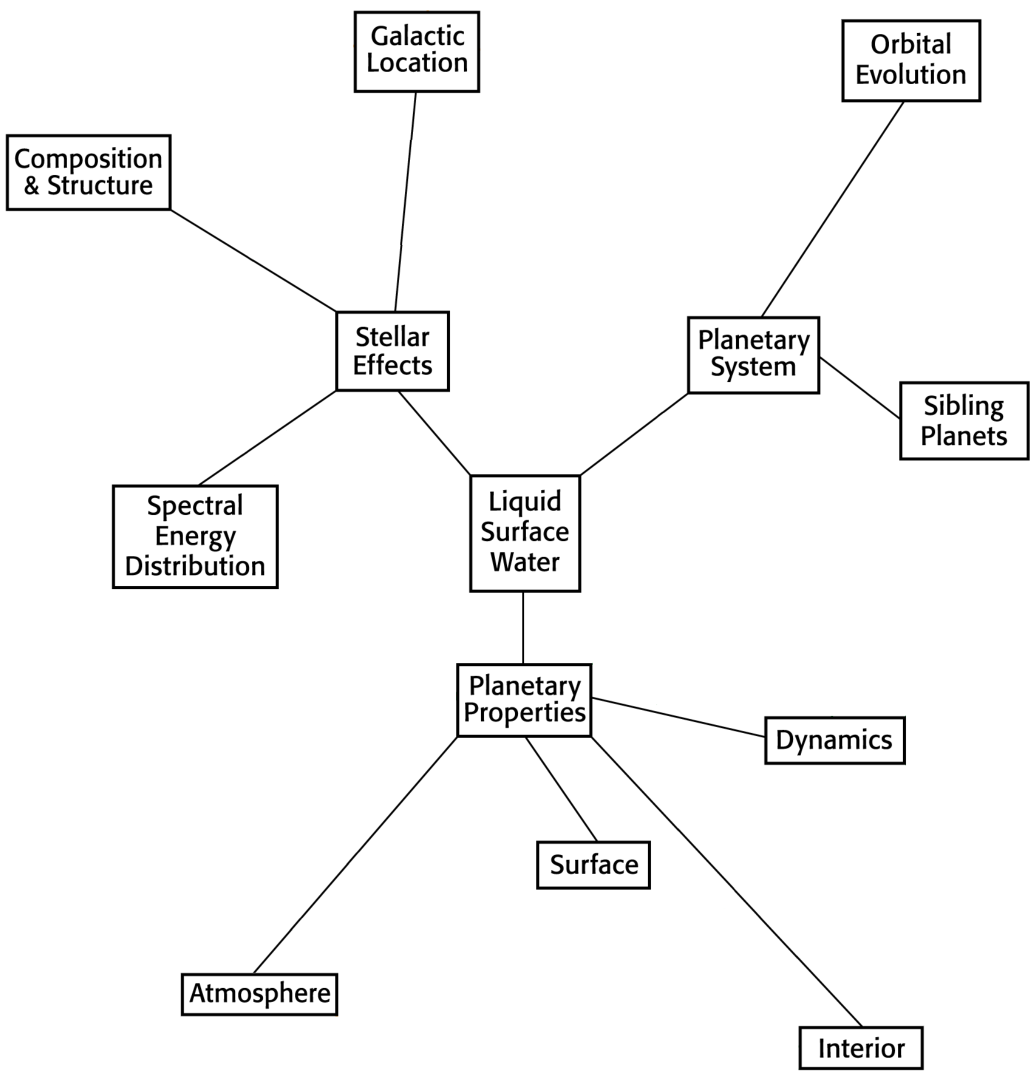
Thin haze still allows access to the deeper atmosphere, including detection of tropospheric water vapor, even at visible wavelengths.

Moving the Field Forward

How do we increase our confidence in the interpretation of the candidates we do have?



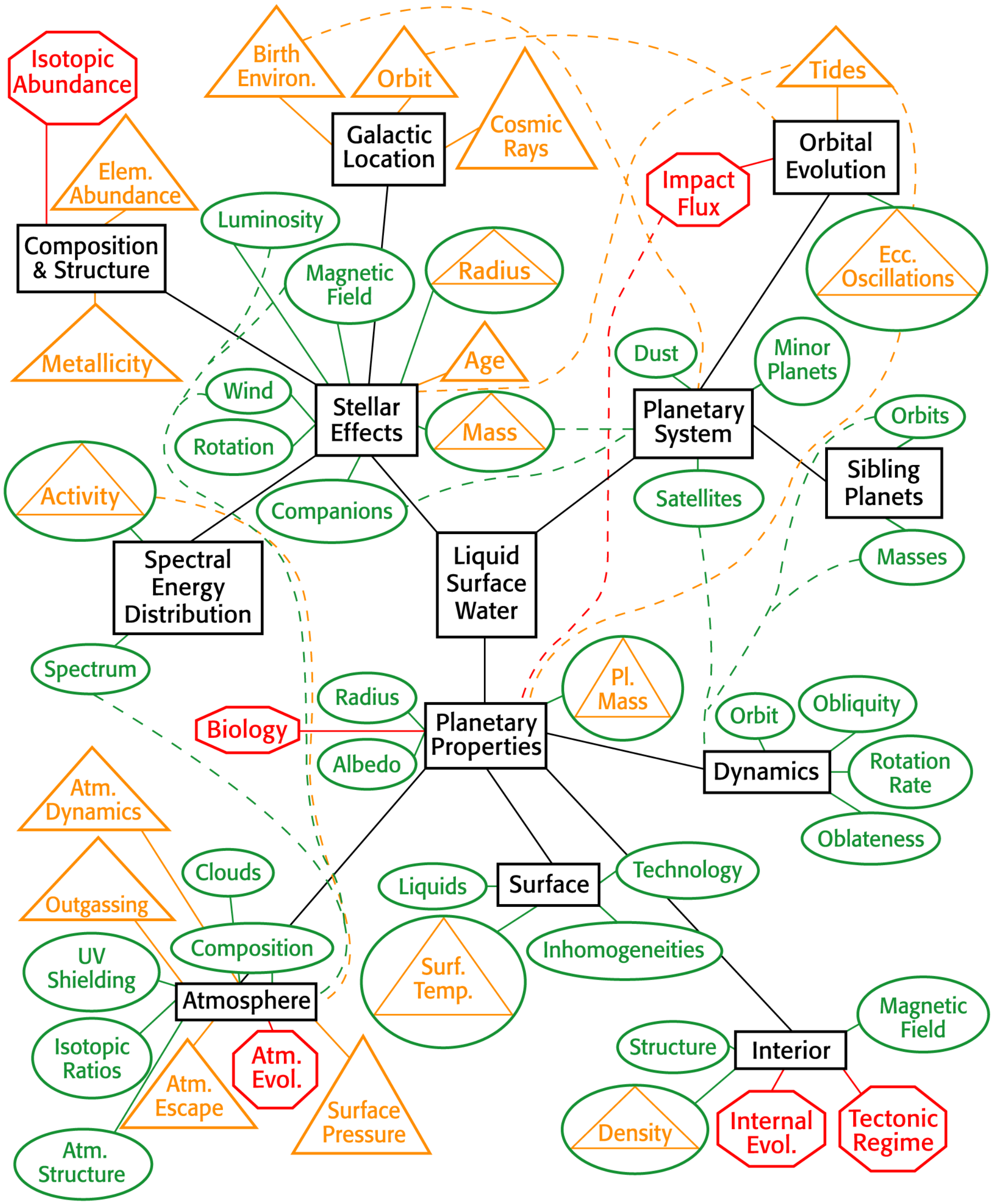
Environmental Context Will Be Key



Environment affects

- the survivability of a biosignature gas
- the generation of false positives
- Whether a biosignature "makes sense" in its environment will be an additional way to increase confidence.

But Environments Will be Complex!



…and quite frankly scary!

We originally developed this diagram to better understand the factors that affect habitability, but these characteristics and interactions are crucial for biosignatures also.

Meadows, Barnes, Kopparapu et al., in prep

Biosignature False Positives

A false positive is non-biological process that mimics the characteristics expected of a biosignature

These processes may be:

- **Geological or geochemical (volcanism, serpentinization)**
- **Mineralogical (surface reflectivity)**
- **Photochemical (photolytic O_2, seasonal changes in gas)**
- **Atmospheric evolution (O_2 production from water loss)**

How do we determine false positives?

How do we determine false negatives?

Which planetary processes will dominate, under which conditions?

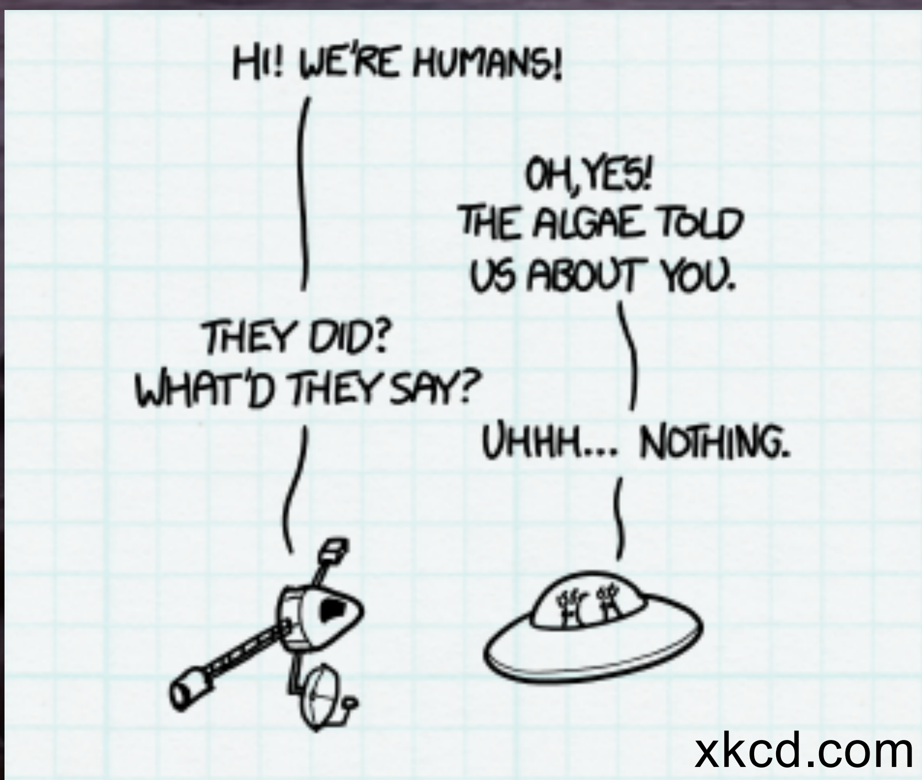
What should we look for?

What observations in addition to the biosignature do we need to make?

O_2 as a case study for improving biosignature confidence

Our abundant O_2 is the most detectable sign of life on this planet…
so let's choose this first!

- Photosynthesis is the killer app of metabolism, harnessing the dominant source of energy on our planet's surface - O_2 is its volatile byproduct
- Uses sunlight, H_2O and CO_2 – likely to be common on habitable planets
- O_2 is abundant and evenly mixed in the atmosphere
- O_2 has strong absorption in the visible and near-infrared.



But it is not enough to propose a biosignature gas. False positives also need to be excluded or identified.

If there are false positives, discriminants must be identified also.

Photo: Frans Lanting

Biosignature False Positives – O_2

Table 1.

Mechanism	Action	Targets Affected	Potential O_2 produced	Potential O_3 produced	Spectral discriminant	References
O_2 runaway from a super-luminous pre-main sequence star.	Massive H_2O evaporation and photolysis during the host star's super-luminous pre-main sequence phase.	HZ planets orbiting late-type M dwarfs.	Hundreds of bars, depending on initial water inventory	Possible, after complete loss of H_2O.	O_4 in transmission (NIR) and direct imaging (visible + NIR)	Luger& Barnes, 2015. Schwieterman et al., 2016.
Lack of non-condensable gases	Lack of cold trap allows water to enter stratosphere and be photolyzed.	HZ planets orbiting any stellar type.	15% O_2	Not calculated.	Quantification of O_2, and N_2 abundunce via the N_2-N_2 collisional pair at 4.1um.	Wordsworth & Pierrhumbert, 2014.
Desiccated planets	Lack of water inhibits catalytic recombination of CO_2	HZ planets orbiting late-type M dwarfs, also volatile poor planets.	15% O_2	0.2 times Earth	Absence of water absorption in direct imaging. O_3 looks similar to Earth's.	Gao et al.,
Photochemical production from CO_2 photolysis.	High stellar FUV/NUV, reduction of O_2 sinks.	HZ planets orbiting K and M dwarfs	< 0.02% for F and G star planets < 6% for M dwarf planets with O_2 saturated oceans.		Presence of CO, CO_2, M dwarf spectral host.	Harman et al.,
Photochemical production on CO_2-rich, H poor planets	High stellar FUV/MUV photolysis CO_2 and produces O_3.	HZ planets orbiting F dwarfs and some M dwarfs.	40ppm	0.1 times Earth's	Presence of CO, absence of H-bearing gases such as CH_4.	Domagal-Goldman et al.,
Photochemical production from CO_2 photolysis an stellar inhibition of recombination.	High stellar FUV/NUV destroys HOx species and inhibits CO_2 recombination.	HZ planets orbiting M dwarfs, CO2-rich (< 10%) atmospheres.	0.2% for M dwarfs with high FUV/NUV ratios.		Presence of CO, CO_2, high FUV/NUV ratio for the parents star with low absolute NUV.	Tian et al.,
Photochemical production from CO_2 photolysis.	CO_2 photolysis and no CO_2 or CH_4 surface flux.	1-bar CO_2-rich (90%) atmospheres orbiting a G2V.	0.1% O_2	0.3 times Earth's	Presence of CO, CO_2.	Hu et al.,

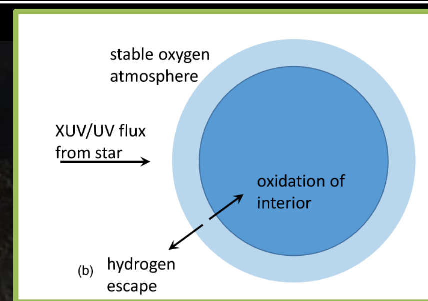
Meadows, 2016, Reflections on O_2 as a Biosignature, submitted

There are a lot of them!

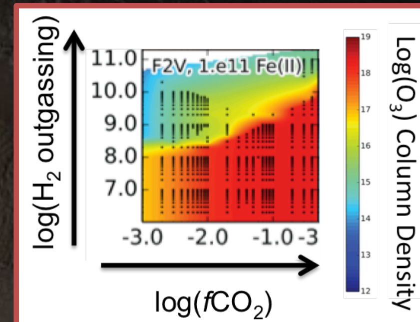
Most have the potential to affect M Dwarf planets

Example False Positives for O_2

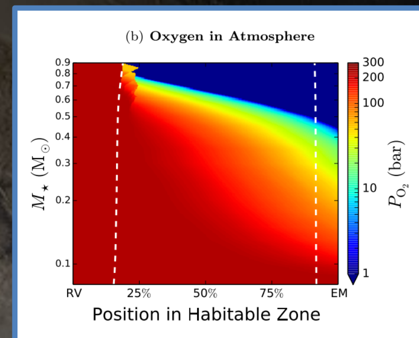
1. H Escape from Thin N-Depleted Atmospheres
(Wordsworth & Pierrehumbert 2014)



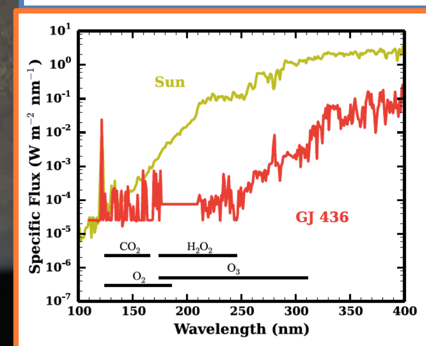
2. Photochemical Production of O_2/O_3 (Domagal-Goldman et al.; Tian et al., 2014, Harman et al., 2015)



3. O_2-Dominated Post-Runaway Atmospheres from XUV-driven H Loss (Luger & Barnes 2014)



4. CO_2 Photolysis in Dessicated Atmospheres
(Gao, Hu, Robinson, Li, Yung, 2015)



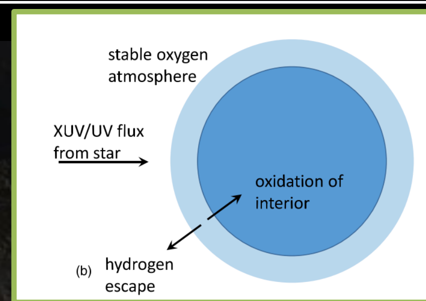
False Positive Discriminants

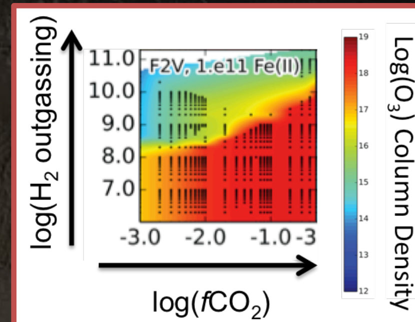
1. **H Escape from Thin N-Depleted Atmospheres**
   $(N_2)_2$ collisional pairs near 4.1um (Schwieterman et al., 2015b)

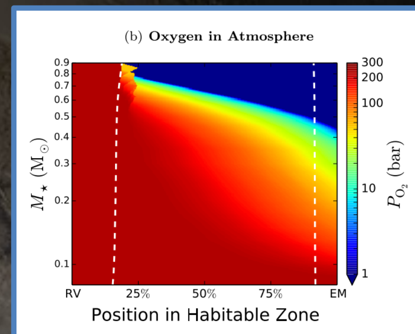
2. **Photochemical Production of O_2/O_3**
   Weak signal, presence of CO, CH_4 (Domagal-Goldman et al., 2014; Schwieterman et al., 2016)

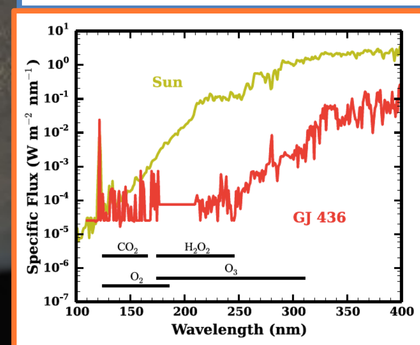
3. **O_2-Dominated Post-Runaway Atmospheres from XUV-driven H Loss**
   O_4 dimers present for massive O_2 atmospheres (Misra et al., 2014; Schwieterman et al., 2016)

4. **CO_2 Photolysis in Desiccated Atmospheres**
   Lack of H_2O vapor and presence of CO_2 (Gao et al.,2015)

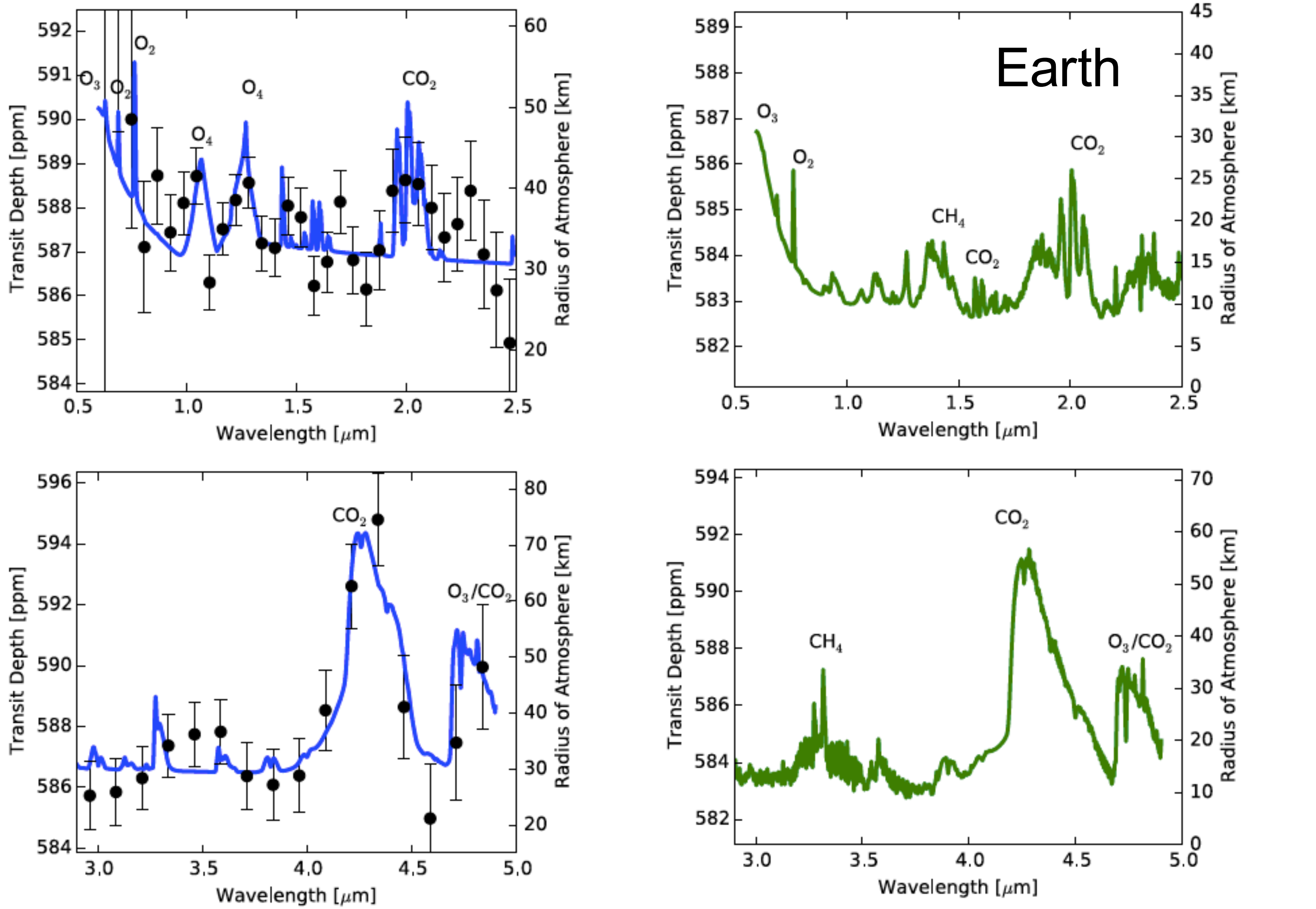








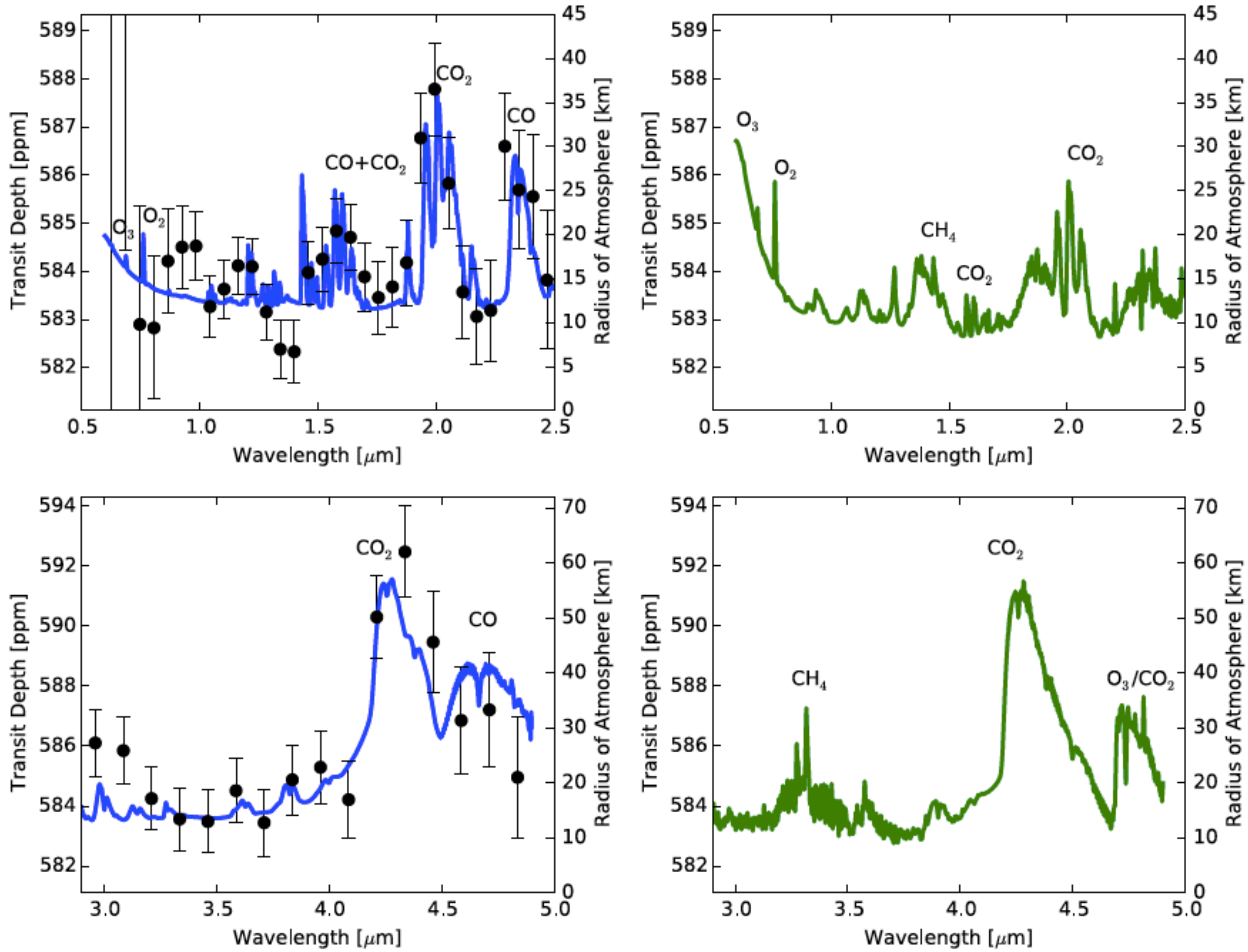
Massive O_2 atmospheres will likely have O_4



JWST transmission simulations (65 hrs)

Schwieterman et al., 2016

CO may help identify abiotic O_2 generation



Schwieterman et al., 2016

The CO absorption is stronger *and more detectable* than the abiotic O_2

False Positives for Oxygen, Their Spectral Discriminants and Desired Observational Wavelength Ranges

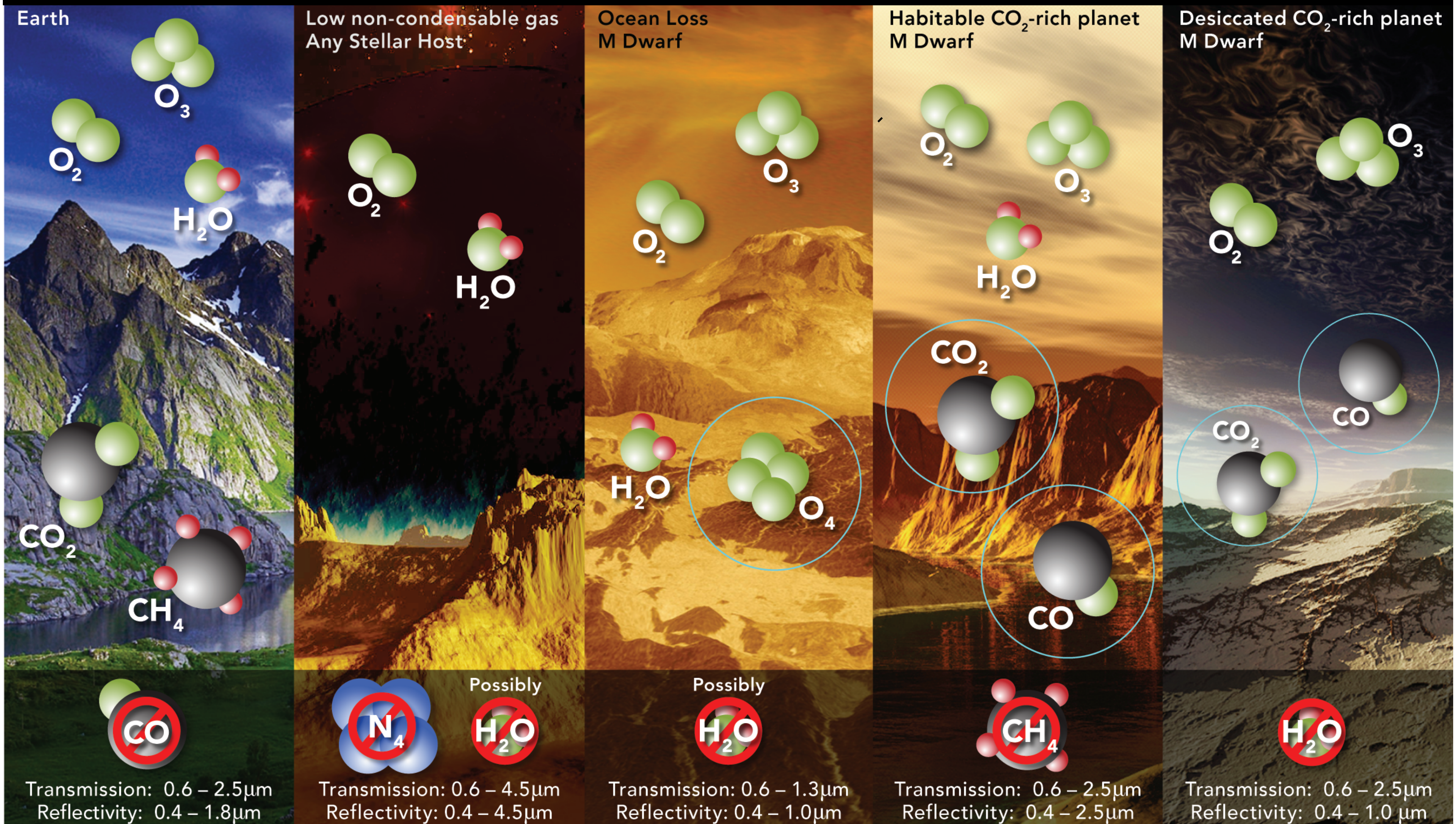


Figure Credit: Hasler/Meadows/Domagal-Goldman

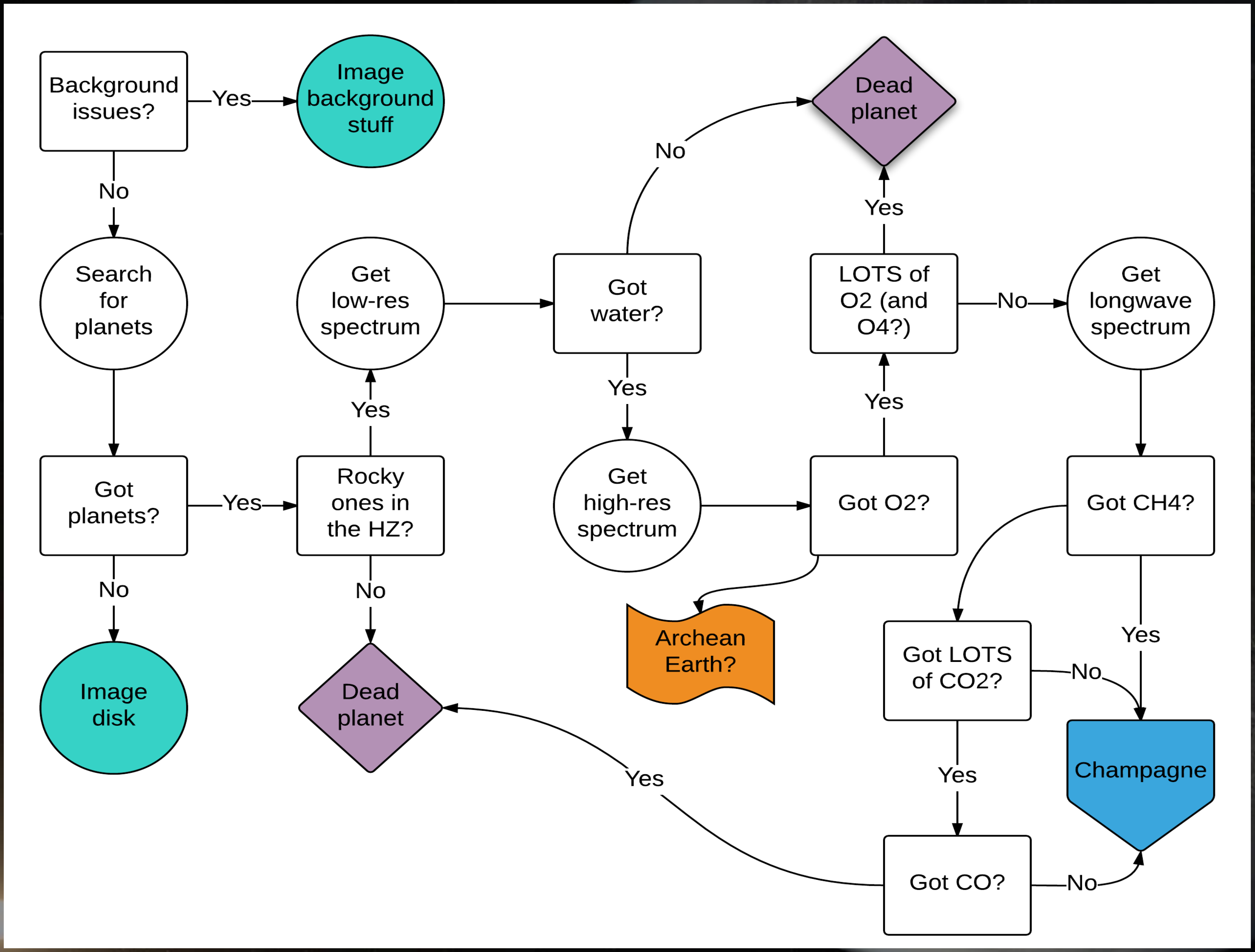
Meadows, 2016, submitted

Moving the Field Forward

To increase our confidence and improve our ability to interpret planetary spectra and search for life we will need to consider environmental context and false positives for all new candidate biosignature gases.

The rigorous treatment currently being given to O_2 should ideally be applied to all biosignatures.

Observation Strategies to Enhance Confidence



S. Domagal-Goldman

The State of the Field

- ✧ We have long lists of potential biosignatures, but we now need to turn to a more rigorous exploration to identify environmental context and search for false positives and their discriminants.
- ✧ Biosignature identification must be made in the context of the planetary environment
  - ✧ many different measurements may be needed.
  - ✧ Biosignature identification will likely be given as a probability
- ✧ The host star can enhance or destroy biosignatures.
- ✧ False positives for life will occur and will depend on planetary composition and environment, stellar spectrum and photochemistry.
- ✧ Identifying, searching for and ruling out potential false positives enhances our confidence in biosignature detection.
- ✧ Biosignatures may be most detectable on planets orbiting M dwarfs, but these planets may have the highest probability for false-positives as well.
- ✧ When exploring possible biosignatures, we must also focus on its ultimate detectabilty, and how we will make the measurements to increase our confidence.
- ✧ The generation and detectability of biosignatures are the product of an interacting, multi-parameter phase space that can be explored with modeling, lab and field work, prior to observational study.