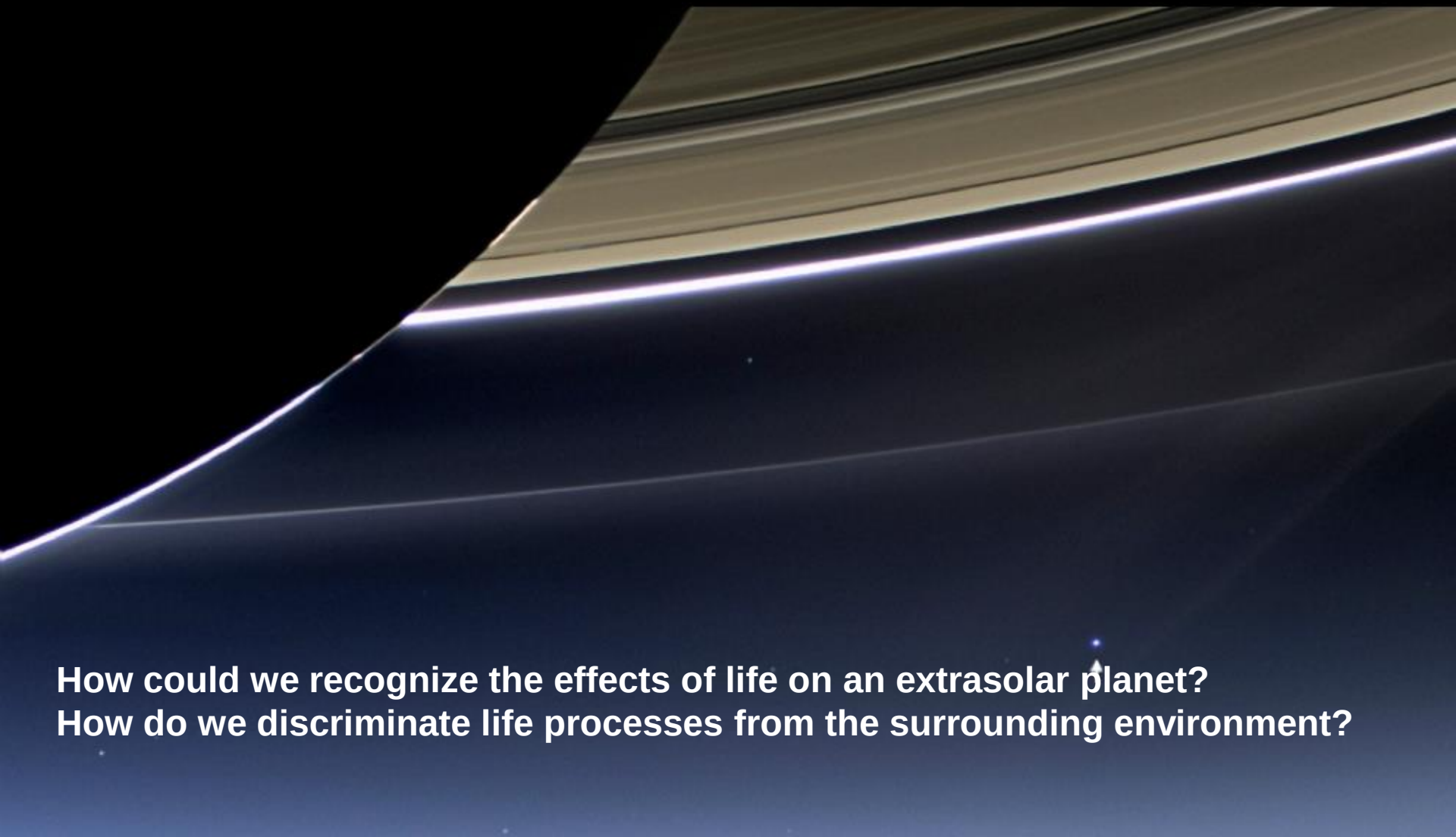
Extrasolar Biosignatures: Developing a Comprehensive Framework for Biosignature Recognition

Overview of the NExSS/NAI Biosignatures Workshop 2016

Victoria Meadows (University of Washington/NASA Astrobiology Institute)

Is The Pale Blue Dot Inhabited?

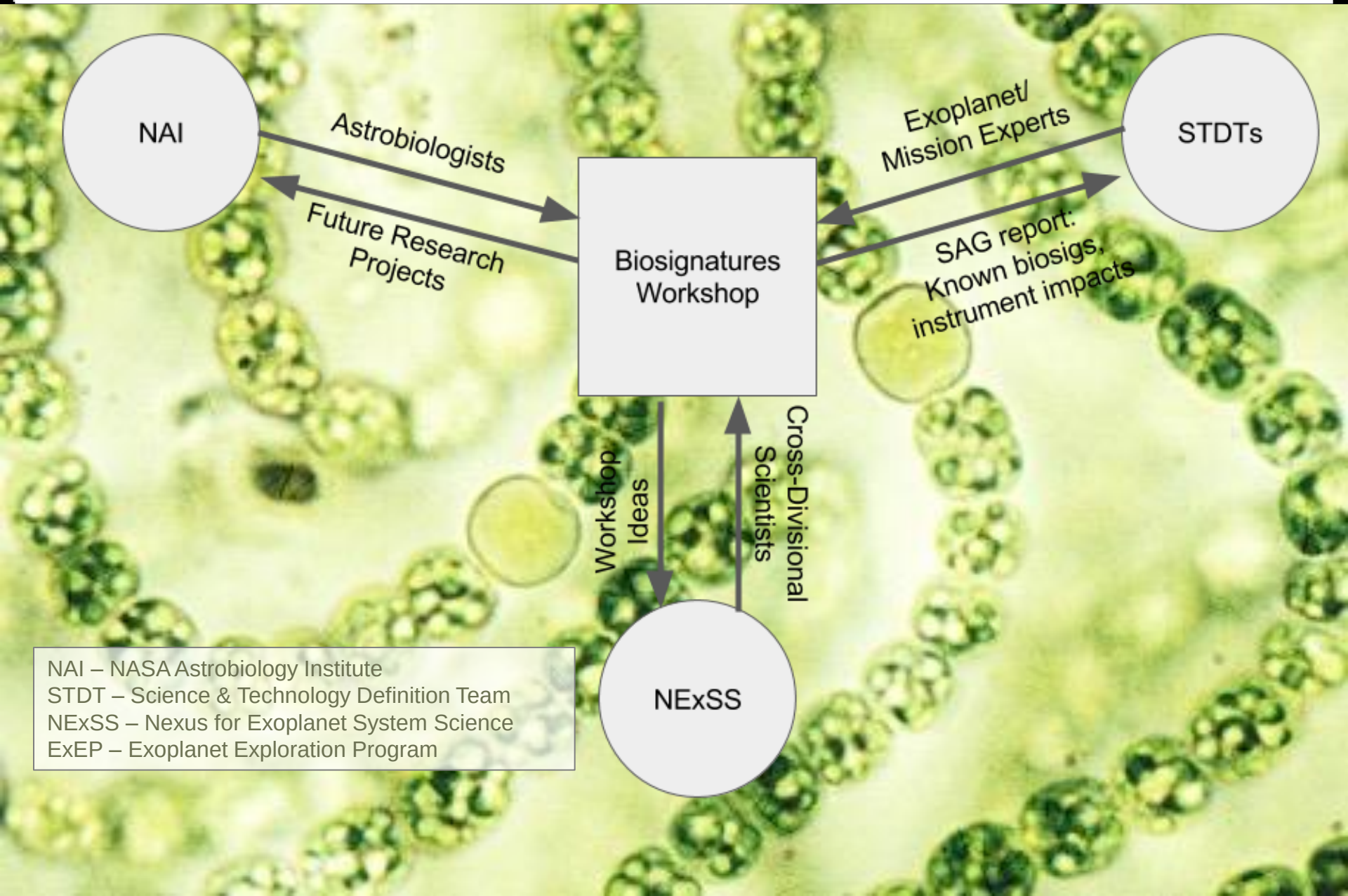


How could we recognize the effects of life on an extrasolar planet?
How do we discriminate life processes from the surrounding environment?

Life's Global Impact

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

Synergistic Interaction Between Communities



Science Organizing Committee

Daniel Apai	Univ. of Arizona, USA	planet imaging
Gary Blackwood	JPL/ExEP, USA	mission planning design
Shawn Domagal-Goldman	**NASA GSFC, USA (NAI-VPL)**	**astrobiology, missions**
Heike Rauer	DLR, ESA, Germany	European biosigs work
Yuka Fujii	ELSI, Japan, and NASA GISS, USA	remote surface biosignatures, Super-Earths
Nancy Kiang	**NASA GISS, USA (NAI-VPL)**	**photosynthetic biosignatures**
Adrian Lenardic	Rice Univ., USA	geophysics, mantle evolution
Nicole Lewis	STSci, USA	bridging models and instrumentation for exoplanet characterization
Tim Lyons	Univ. of California, Riverside, USA (NAI- UCR)	geochemistry, Earth history, systems science, geochemistry of the early Earth
Hilairy Hartnett	Arizona State Univ., USA	biogeochemistry
Bill Moore	Hampton Univ., USA	planetary interior evolution, atmospheric escape
Enric Palle	Instituto de Astrofísica de Canarias, Spain	remote biosignatures
Niki Parenteau	**SETI / NASA ARC, USA (NAI-VPL)**	**microbiologist, photosynthesis**
Karl Stapelfeldt	NASA GSFC/JPL, USA	mission design
Sara Walker	Arizona State Univ., USA	physicist, information in biological systems and origin of life

Science Goals

1. **State of the Science Review:** What are known remotely-observable biosignatures, the processes that produce them, and their known non-biological sources?

2. **Expanding and Maturing the Science of Biosignatures:** How can we develop a more comprehensive framework for identifying additional biosignatures and their possible abiotic mimics?

3. **Confidence Standards for Biosignature Observation:** What standards can we agree to use for assessing biosignature observations - both known biosignatures and those we have yet to identify?

Workshop Products

5 coordinated papers on 5 key aspects of the workshop

- Biosignature Review
  - Advances in our understanding since DesMarais et al., 2002.
- Lessons Learned from O_2
  - O_2 as an exemplar for exoplanet biosignature detection
- Assessing Exoplanet Biosignatures
  - General framework for biosignature observation and interpretation
- Novel Biosignatures and Biosignature Frameworks (William Bains)
  - Looking at co-evolution and information transfer
- Synthesis and Future Research (Shawn Domagal-Goldman)
  - Instrumentation and modeling needs to move the field forward

ExoPAG SAG 16 report will be an executive summary of these papers

Poster on this by Kiang, Domagal-Goldman

Exoplanet Biosignature Review

So, how do we detect life at a distance of 10 pc?

We look for global scale modifications of the planet's environment that could be due to life.

Identifying Biosignatures (*a priori*)

1. Reliability

   Is it/could it be produced by life?

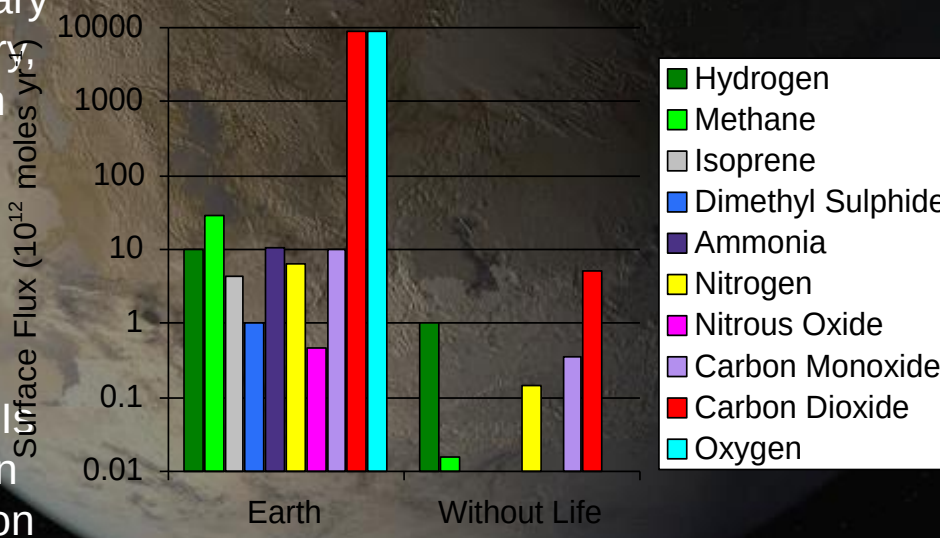
   Is it less likely to be produced by planetary processes such as geology and photochemistry?

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

   Does it build up to detectable levels? Is it detectable using likely observing modes? Is it active in the observed wavelength region and is it clear of overlap with other common planetary species?

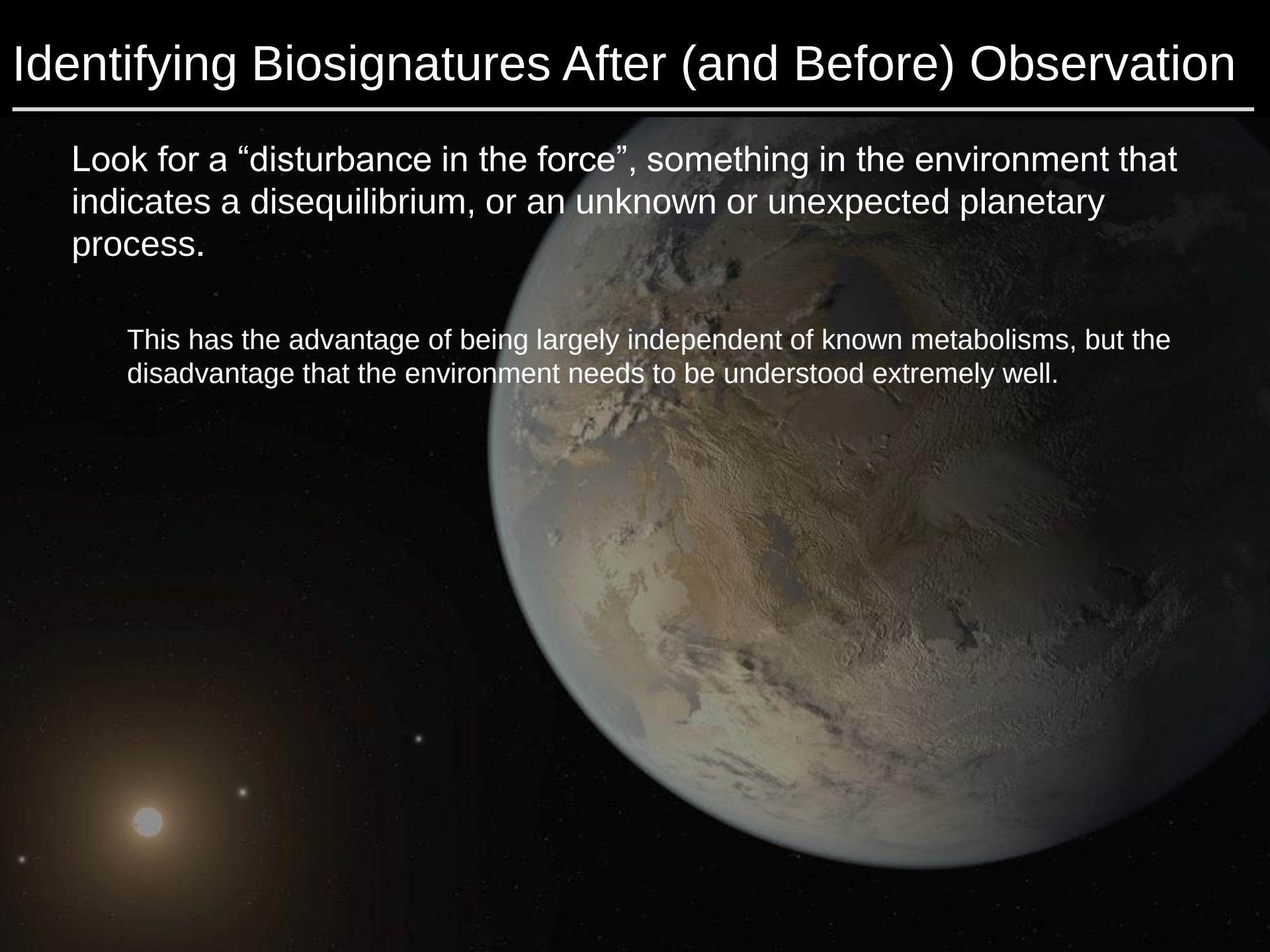


Tim Lenton, Nature, 1998

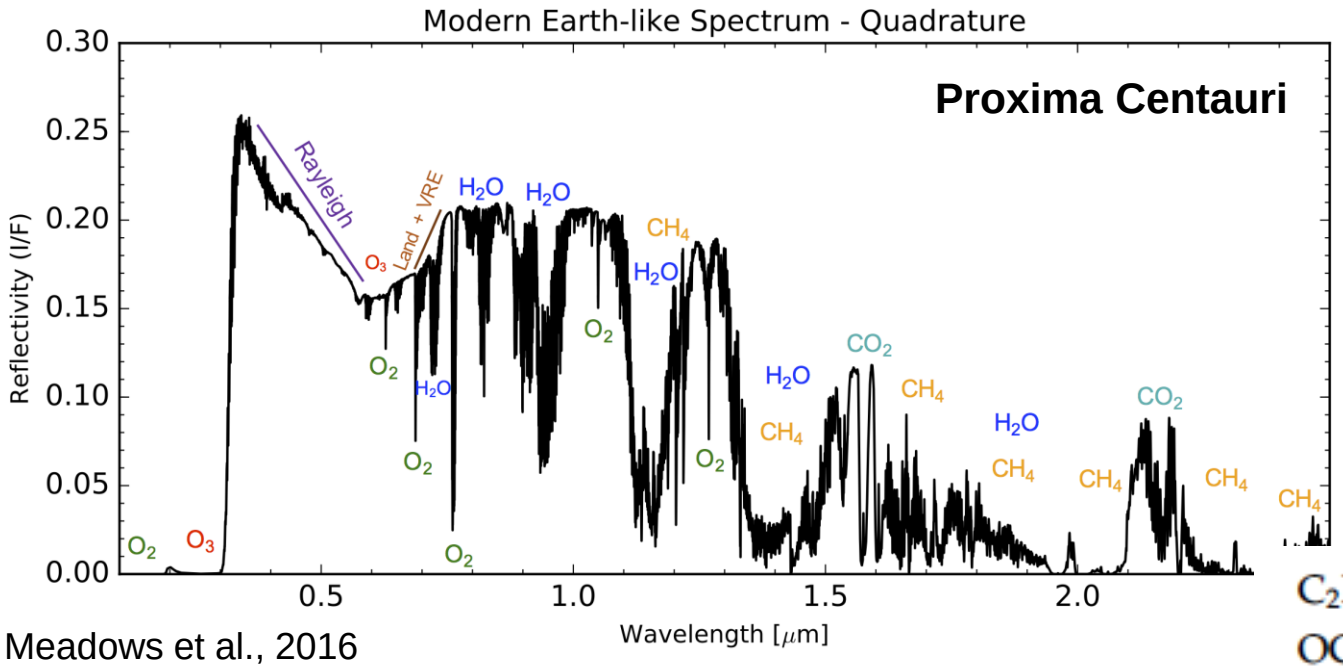
Identifying Biosignatures After (and Before) Observation

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.



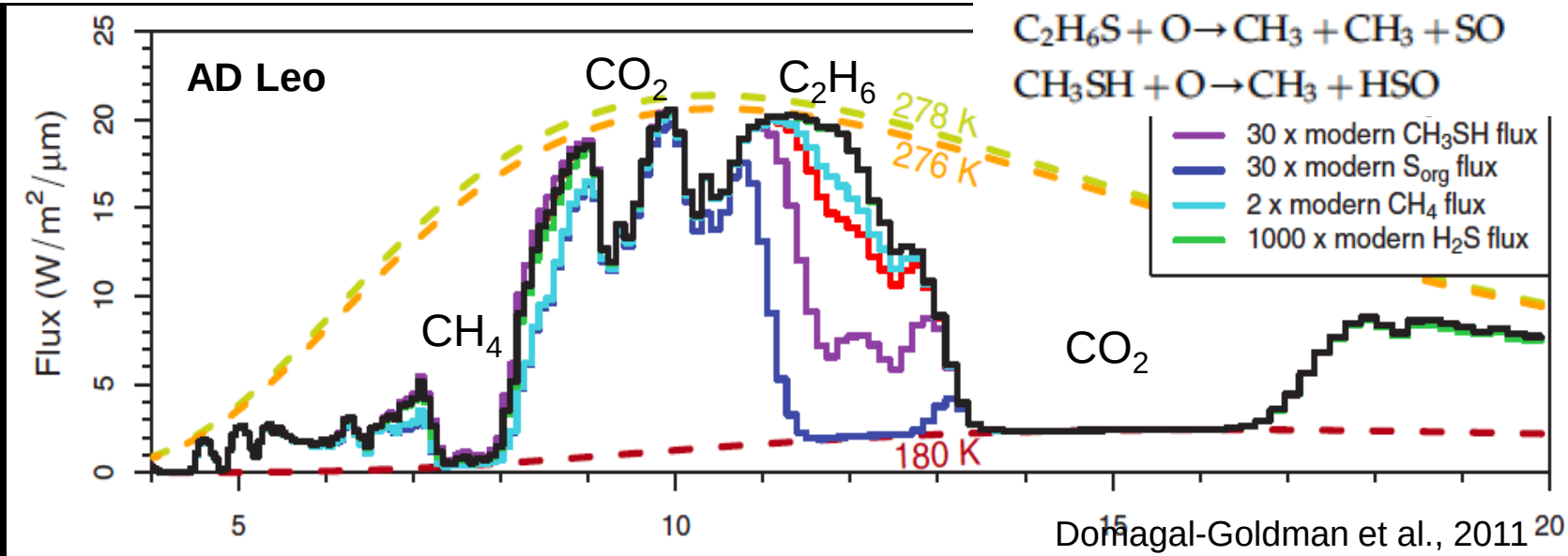
Atmospheric Biosignatures



Meadows et al., 2016

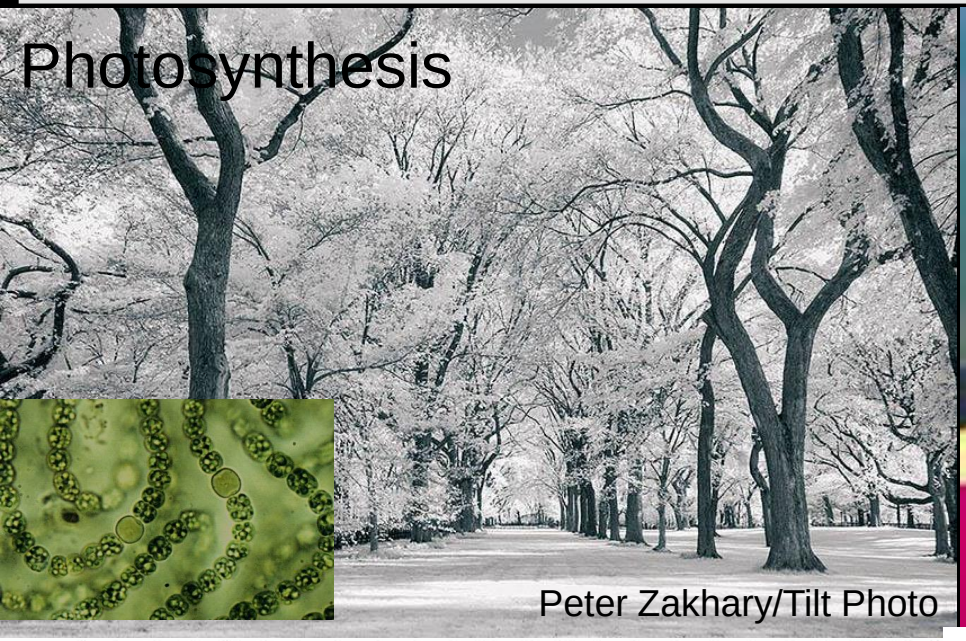
Gases whose nature, abundance, surface flux, or combination with other gases suggest a biological, rather than planetary process.

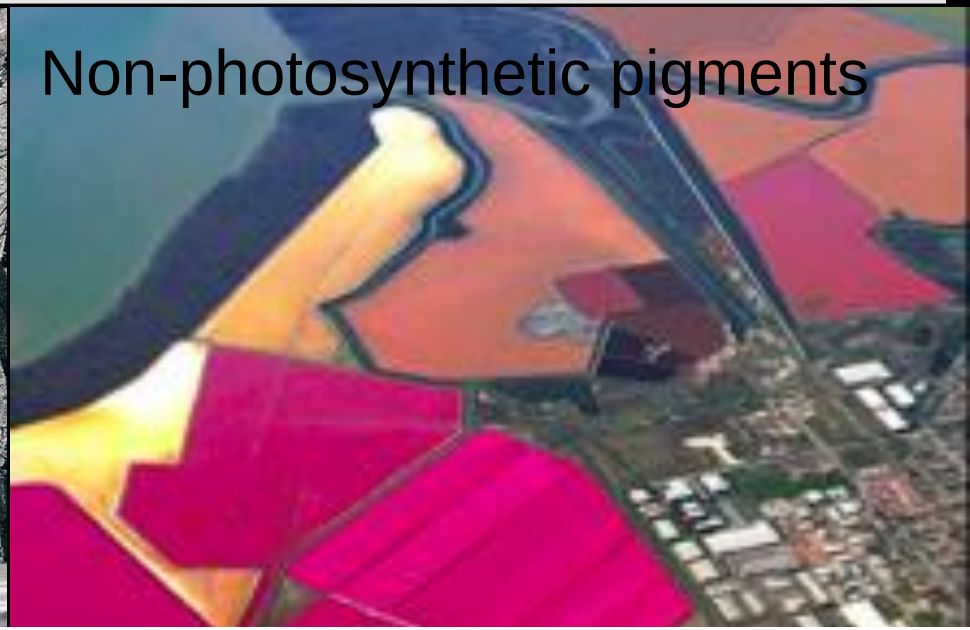
$$C_2H_6S_2 + O \rightarrow CH_3 + SO + CH_3S$$
$$OCS + h\nu \rightarrow CO + S$$
$$C_2H_6S + O \rightarrow CH_3 + CH_3 + SO$$
$$CH_3SH + O \rightarrow CH_3 + HSO$$

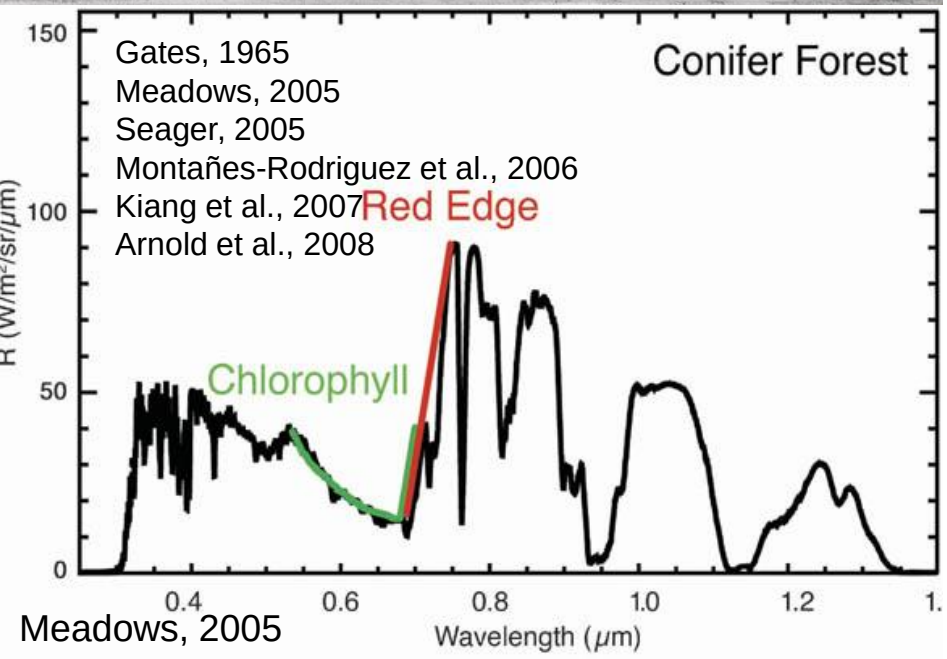


Domagal-Goldman et al., 2011

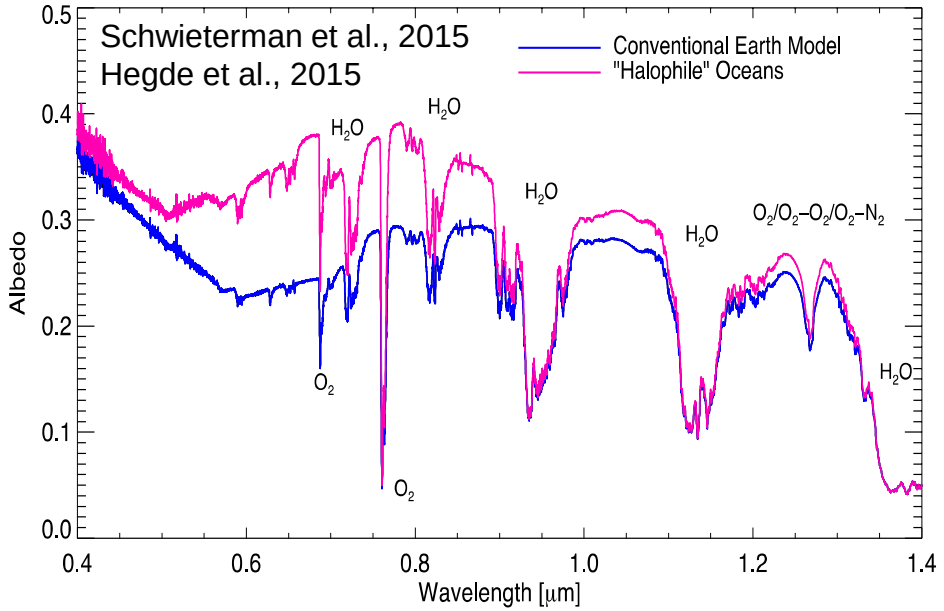
Surface Biosignatures





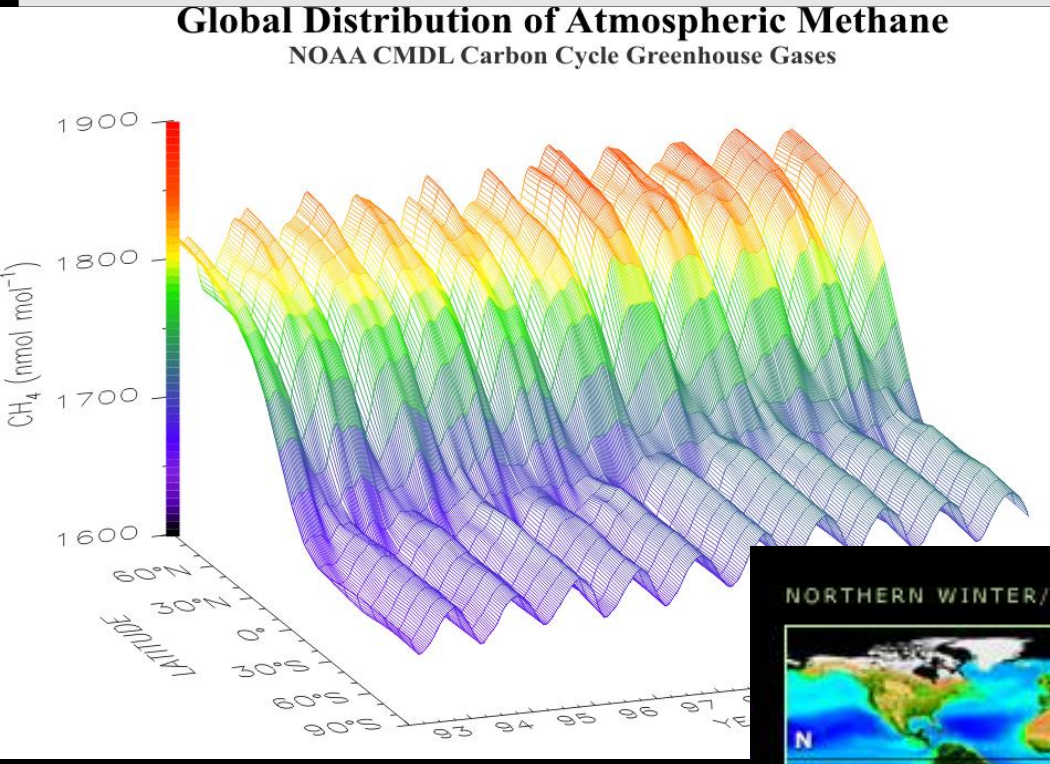


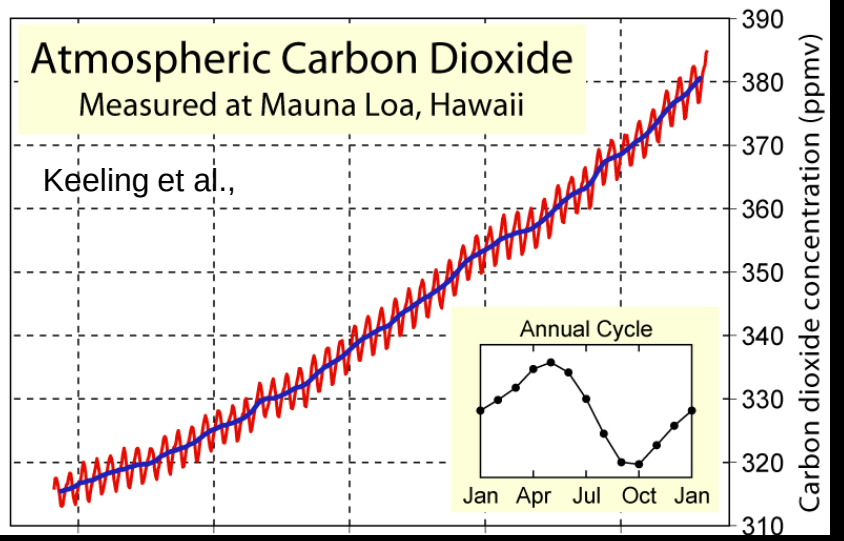
Meadows, 2005

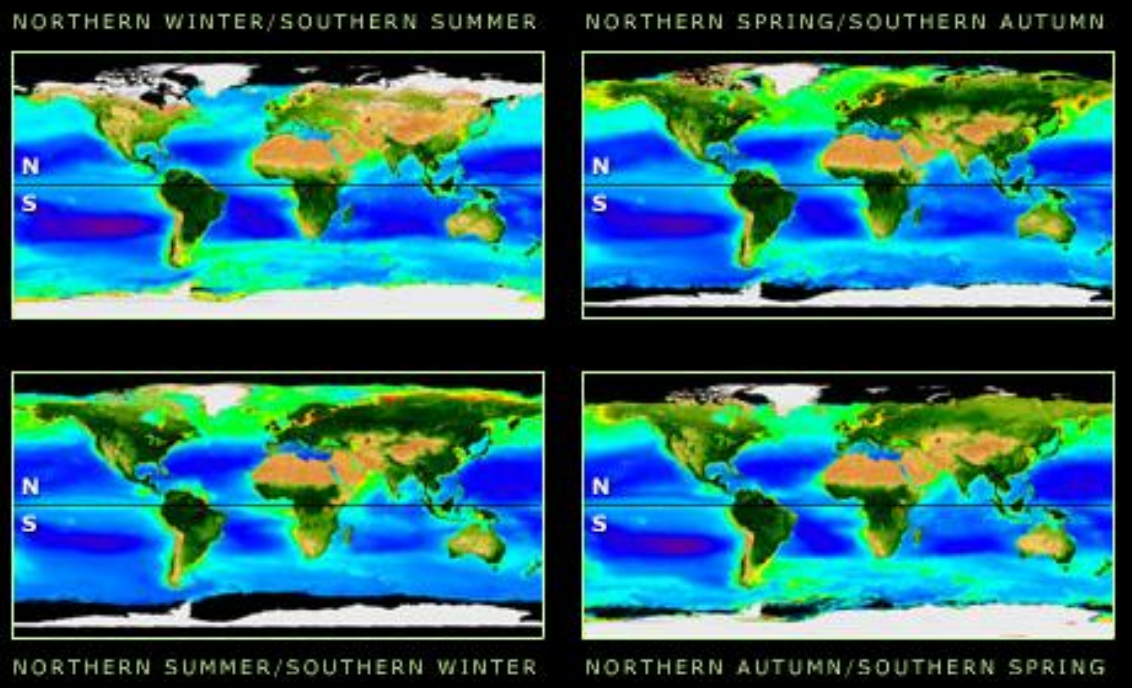


Schwieterman, Cockell, Meadows, *Astrobiology*, 2015

Temporal Biosignatures







Daily or seasonal changes in a gas, surface albedo, or some other planetary property

Meadows, 2005

Chemical Disequilibrium

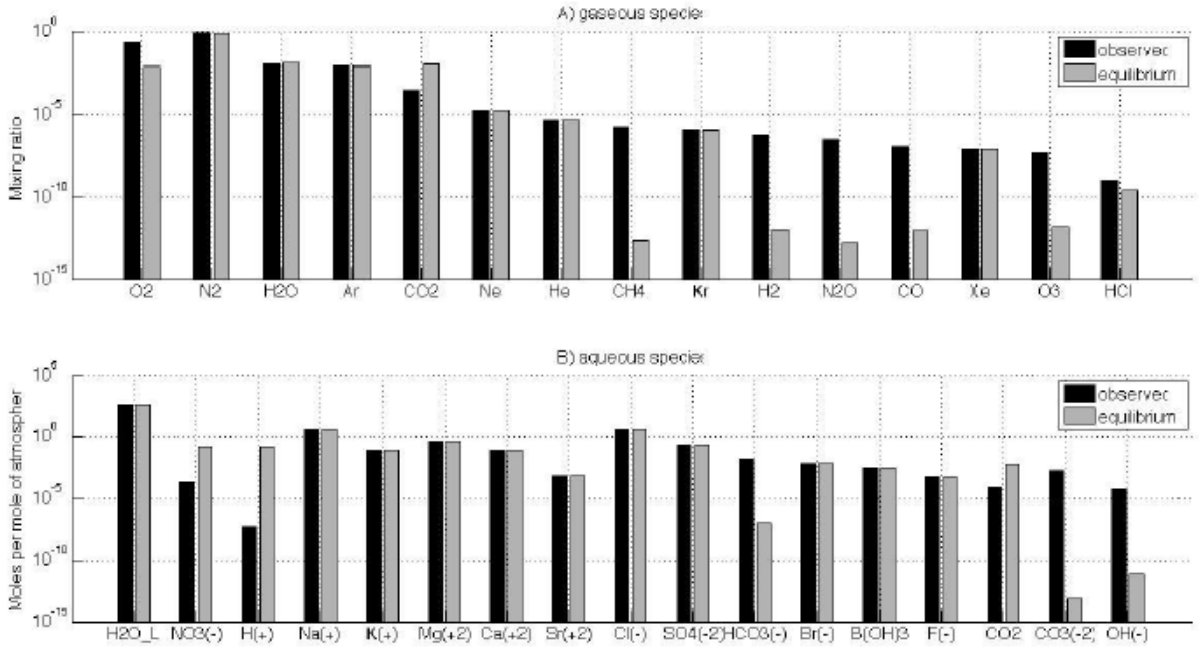
Sagan et al., 1993

O_2 and CH_4 is the classic disequilibrium signature.
Earth's CH_4 lifetime is ~10 years.
(Lederberg, 1965; Hitchcock & Lovelock, 1967)

Krissansen-Totton et al., 2016

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}



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.

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

Antibiosignatures, False Positives, False Negatives

An antibiosignature is a feature of the environment that you would NOT expect to see if life were present.

e.g. CO on Mars (Zahnle et al., 2011)

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

e.g. Photolytic production of O_2 from H_2O or CO_2 in a planetary atmosphere (Luger & Barnes, 2015; Wordsworth & Pierrehumbert, 2014; Gao et al., 2016; Harman et al., 2016)

A false negative is a planetary process or suite of processes that suppresses the detectability of a biosignature

e.g. oxidation of a planetary surface suppressing free O2 in the atmosphere from photosynthesis. (Lyons et al., 2014; Planavsky et al., 2015).

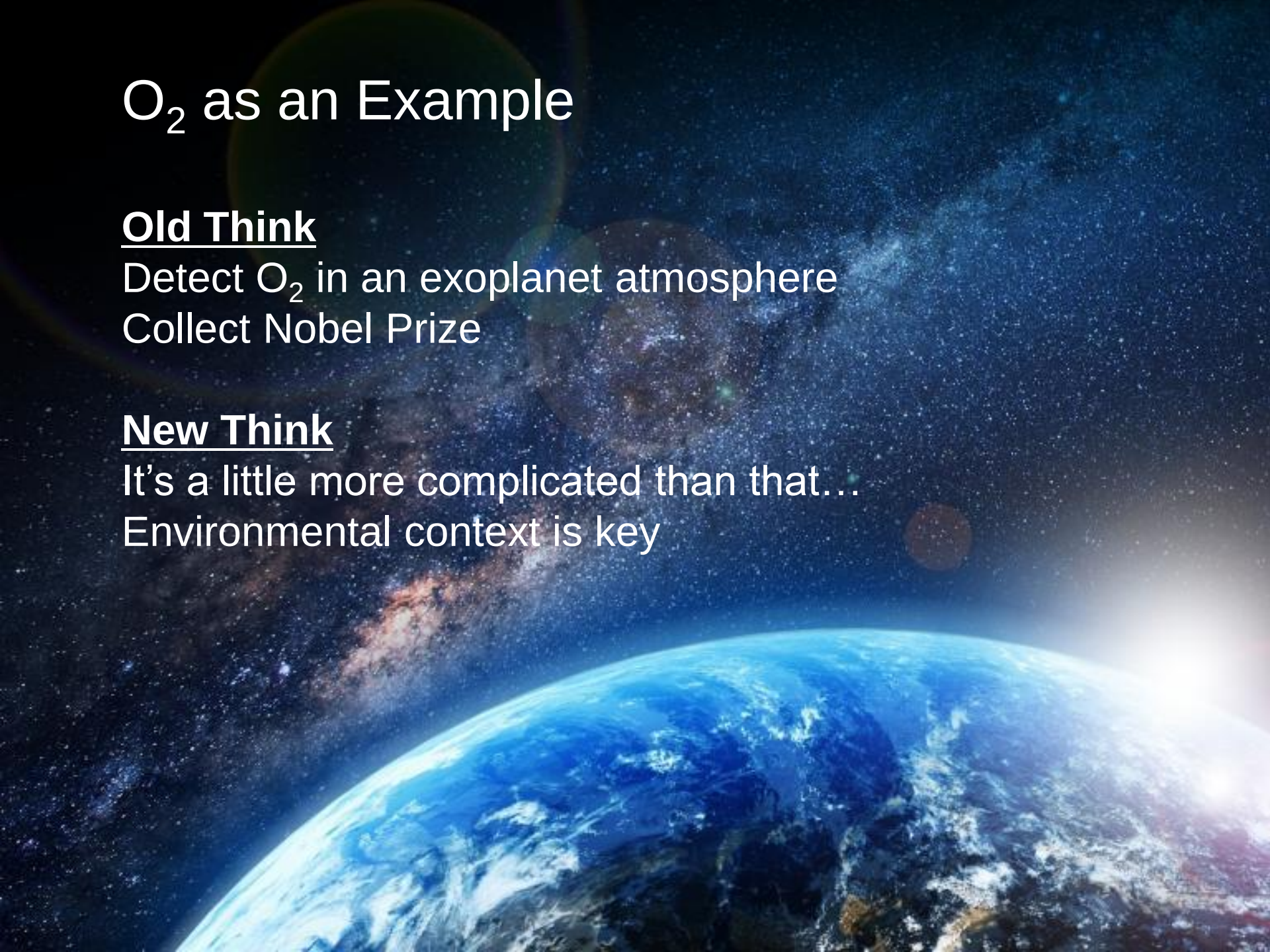
O_2 as an Example

Old Think

Detect O_2 in an exoplanet atmosphere
Collect Nobel Prize

New Think

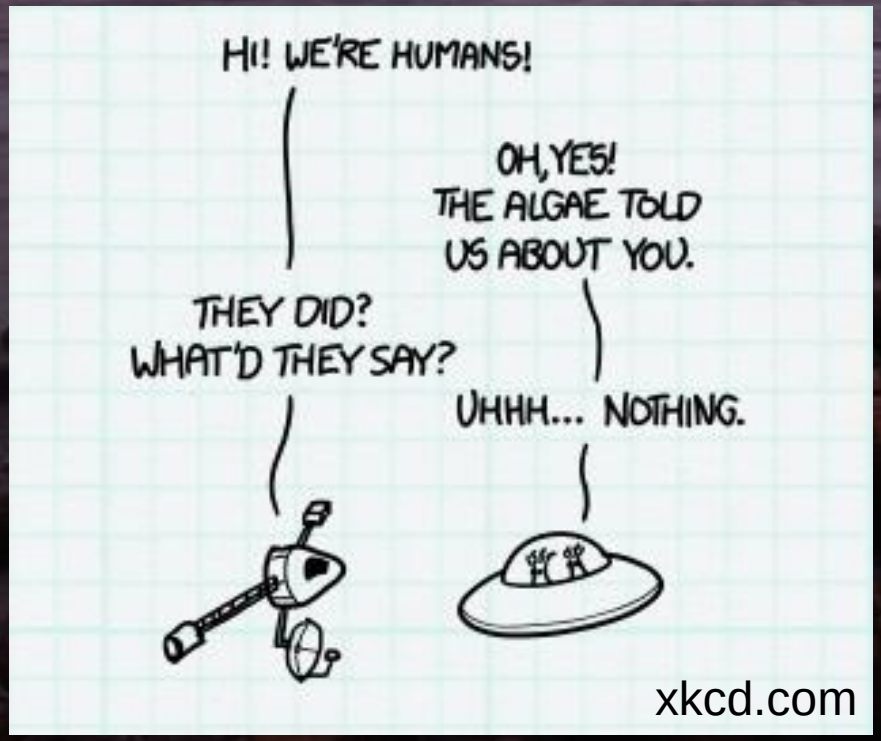
It's a little more complicated than that…
Environmental context is key



O_2 is an excellent biosignature for many reasons

Our abundant O_2 is the most detectable sign of life on this planet

- 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.

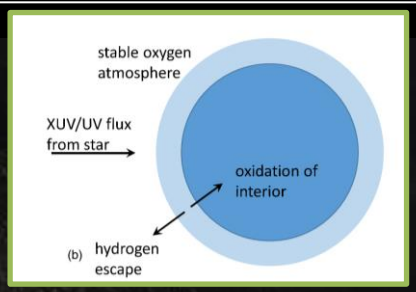


And there's just SO much of it, that it couldn't possibly be produced by anything other than life. Right?

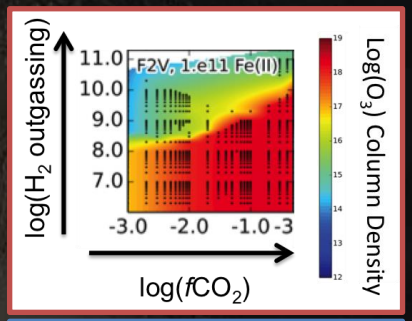
Photo: Frans Lanting

Example False Positives for O_2

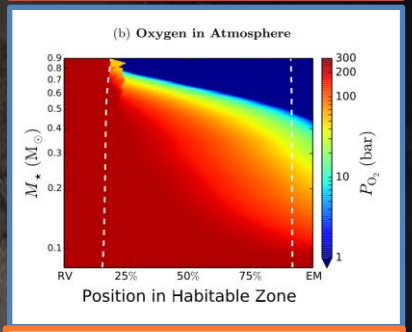
1. H Escape from Thin N-Depleted Atmospheres (Wordsworth & Pierrehumbert, 2014)



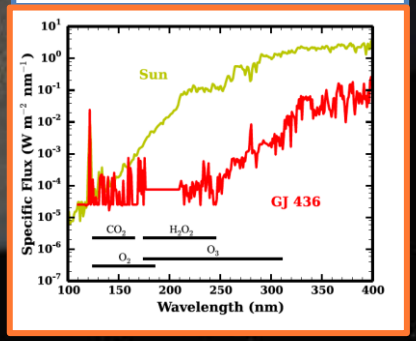
2. Photochemical Production of O_2/O_3 (Domagal-Goldman et al. 2015; Tian et al., 2014, Harman et al., 2015, Hu et al., 2012)



3. O_2-Dominated Post-Runaway Atmospheres from XUV-driven H Loss (Luger & Barnes 2015)



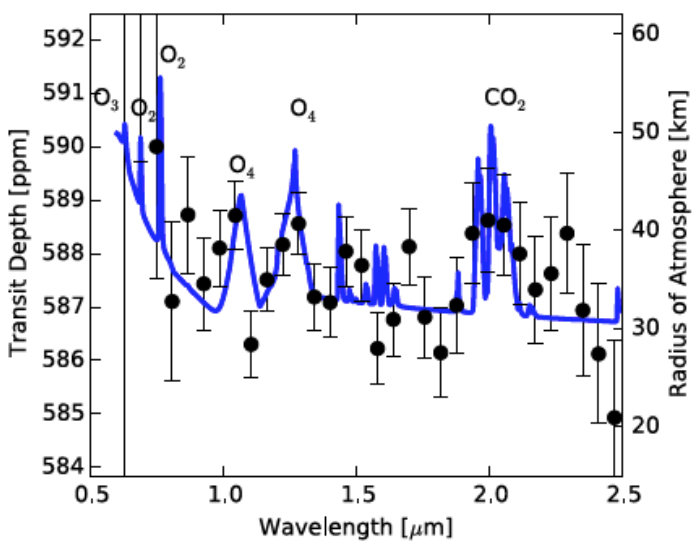
4. CO_2 Photolysis in Cold, Dessicated Atmospheres (Gao et al., 2015)

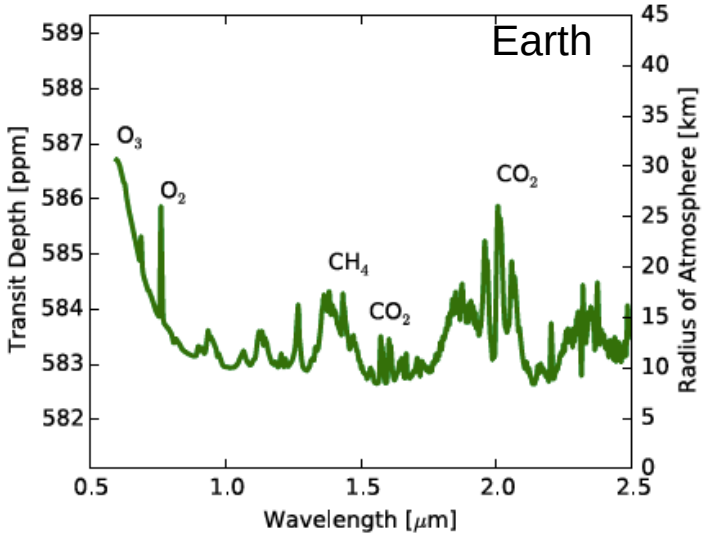


Meadows, *Astrobiology*, in review

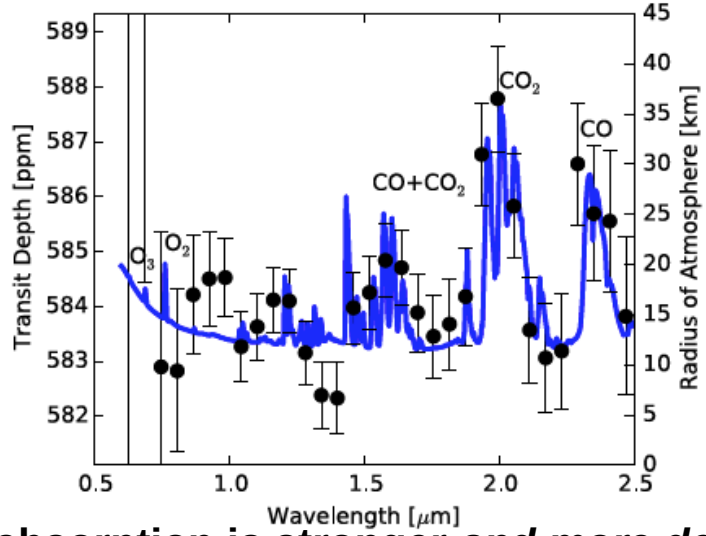
False Positives Can Have Discriminants

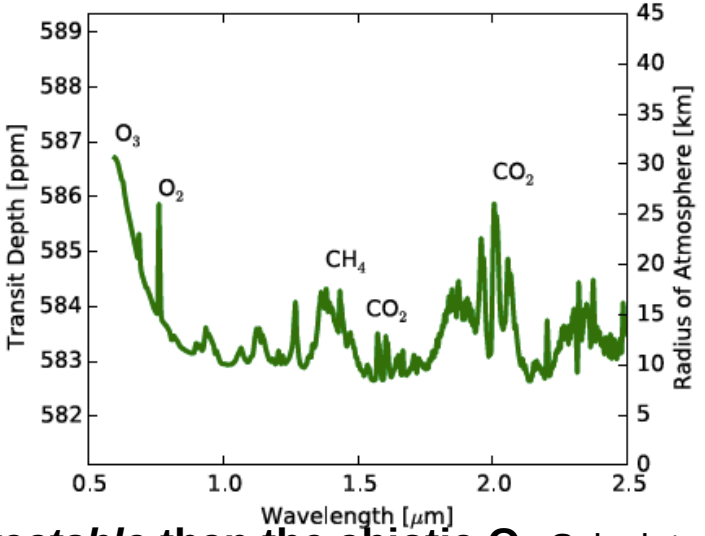
For example, massive O_2 atmospheres will likely have O_4





CO and CO_2 may indicate a photolytic source for the O_2.





The CO absorption is stronger *and more detectable* than the abiotic O_2 Schwieterman et al., 2016

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

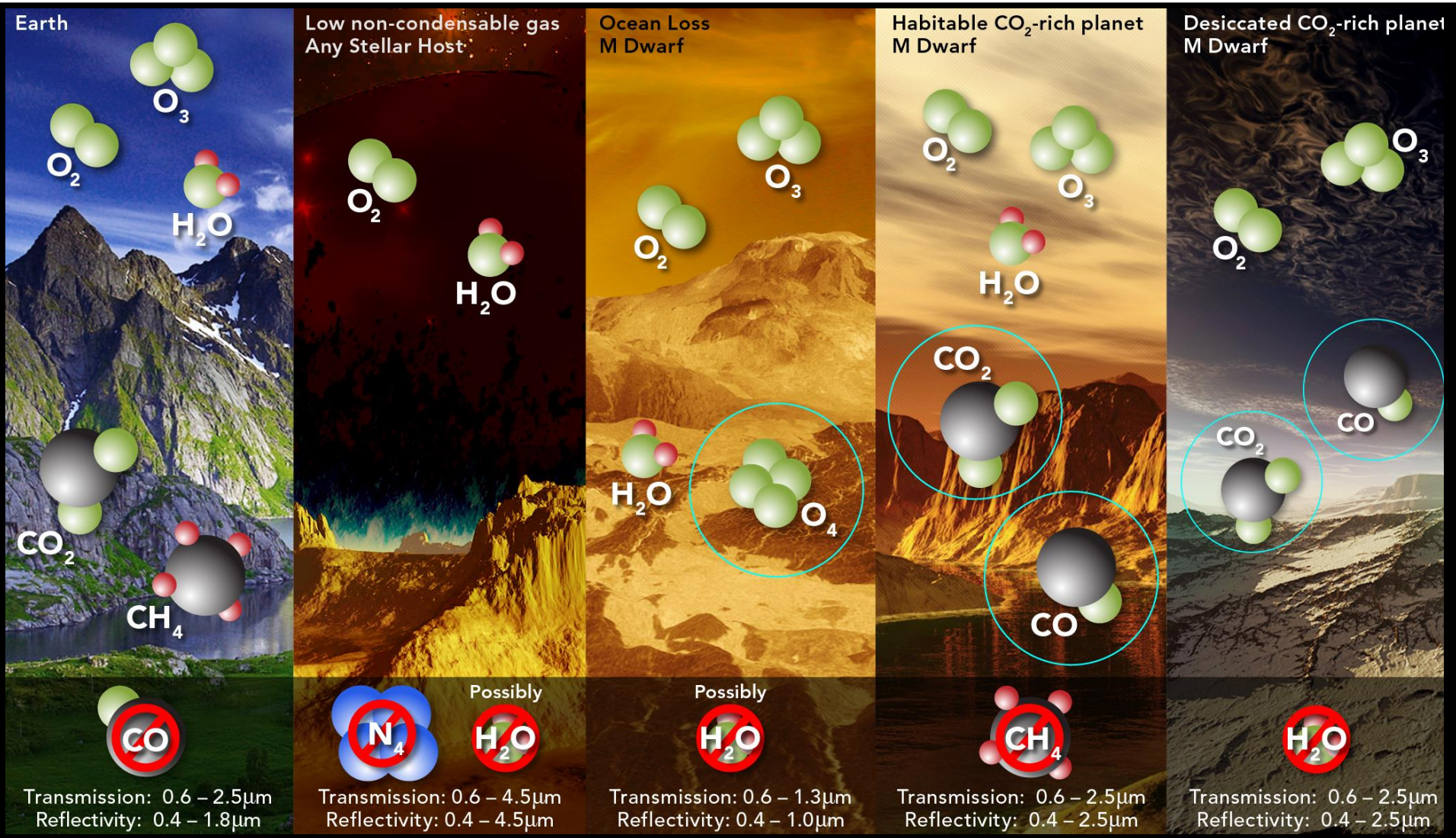
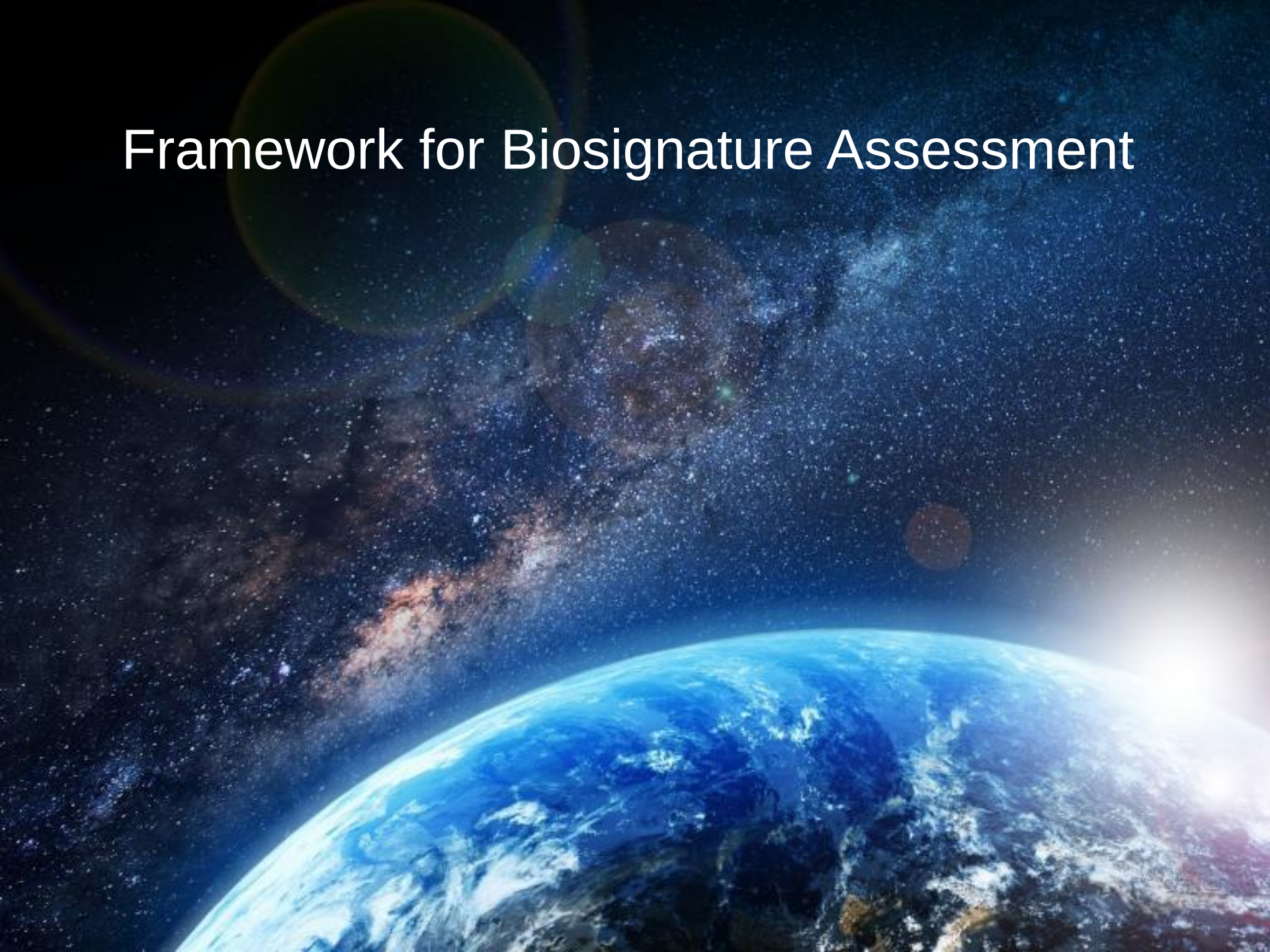


Figure Credit: Hasler/Meadows/Domagal-Goldman

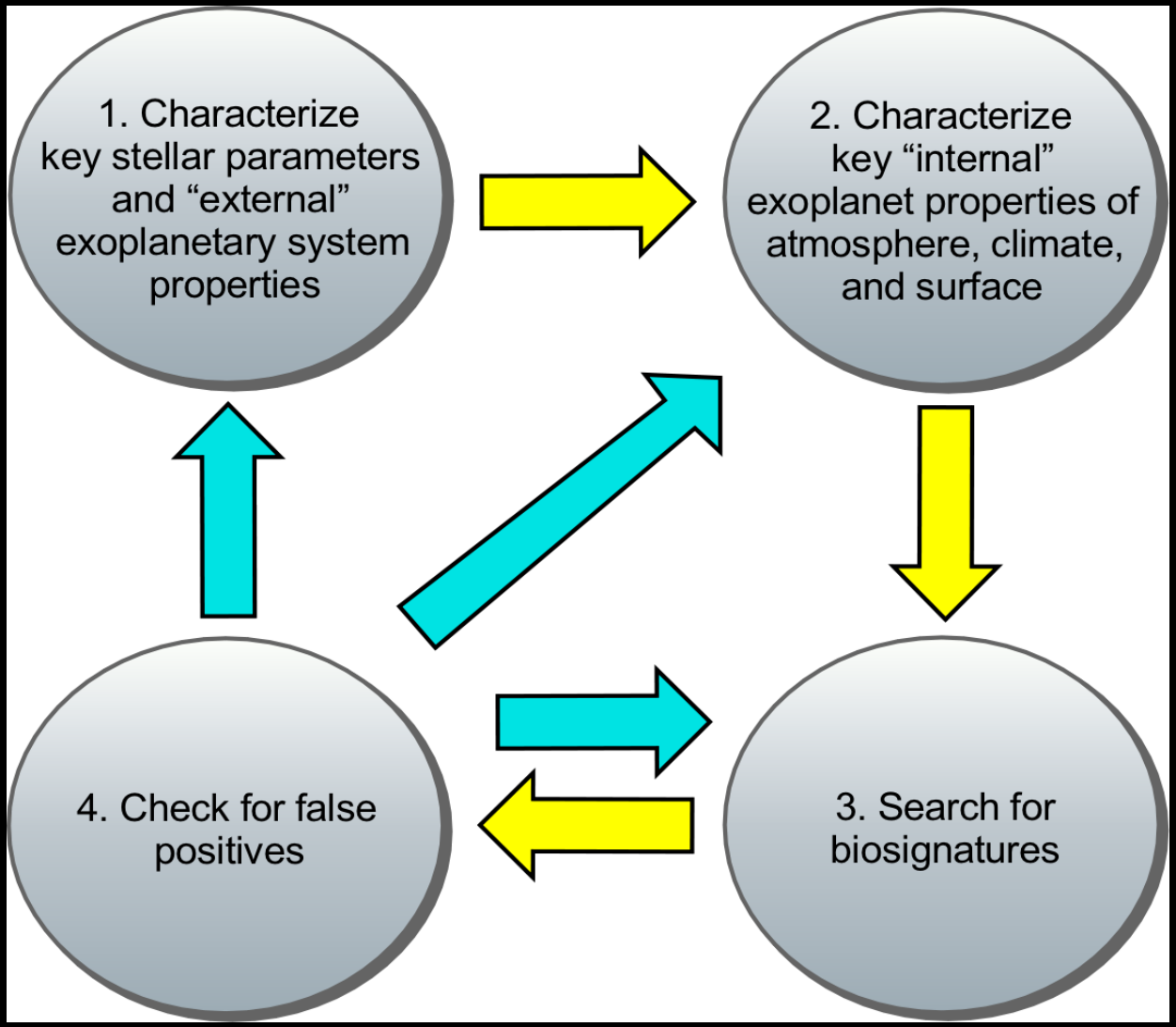
Meadows, *Astrobiology*, in review

See poster by Eddie Schwieterman

Framework for Biosignature Assessment



Conceptual Framework for Biosignature Detection and Recognition.



Catling et al., in prep.

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

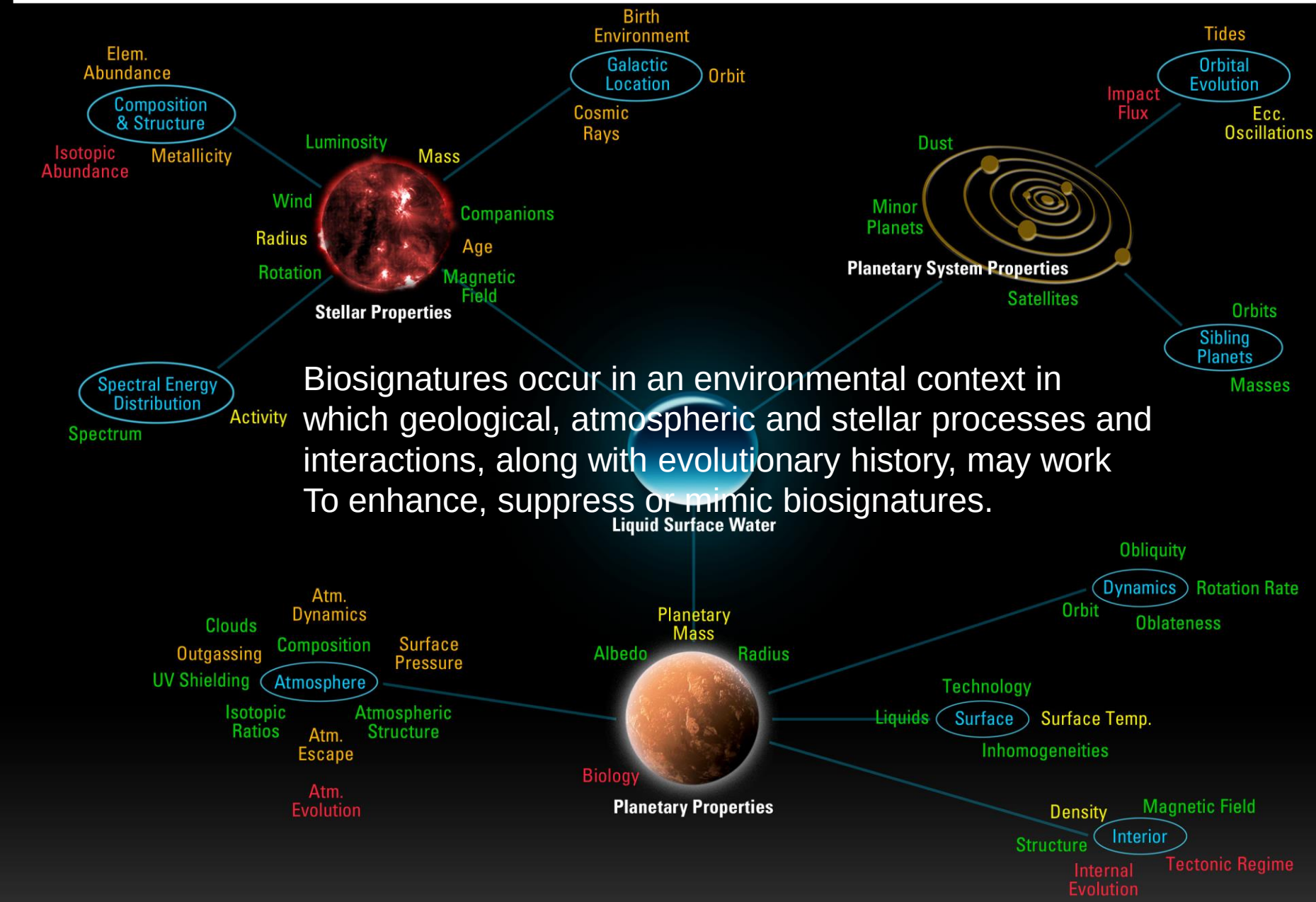
   An advantage is that it is initially non-metabolism specific, but must still be tested for survivability, detectability, the likelihood that the gas will be produced by life, and without environmental context, understanding false positives will be challenging.

Example Biosignatures

Biosignature	Spectral band center, μm or (cm^{-1})	Band interval cm^{-1}	Biogenic source	Abiogenic false positive
O_2	1.58 (6329) 1.27 (7874) 1.06 (9433) **0.76 (13158)** 0.69 (14493) 0.63 (15873)	6300-6350 7700-8050 9350-9400 **12850-13200** 14300-14600 14750-15900	*Photosynthesis*: splitting of water	Cases of water photodissociation and preferential escape of hydrogen, with lack of O_2 sinks
O_3	4.74 (2110) 3.3 (3030) 0.45-0.85	2000-2300 3000-3100 10600-22600	*Photosynthesis* (photochemically derived from O_2)	As above
CH_4	3.3 (3030) **2.20 (4420)** 1.66 (6005)	2500-3200 **4000-4600** 5850-6100	*Methanogenesis*: reduction of CO_2 with H_2, often mediated by degradation of organic matter	Geothermal or primordial methane
N_2O	4.5 (2222) 4.06 (2463) 2.87 (3484)	2100-2300 2100-2800 3300-3500	*Denitrification*: reduction of nitrate with organic matter	No significant truly abiotic sources*
NH_3	4.3, 3.0, 2.9, 2.25, 2, 1.5, 0.93, 0.65, 0.55		*Ammonification*: Volatilization of dead or waste organic matter	Non-biogenic, primordial ammonia
$(CH_3)_2S$	TBD		plankton	No significant abiotic sources
CH_3Cl			algae	Volcanism?
Chlorophyll	0.67-0.76 (sharp slope)	14925-13160	*Photosynthesis*: "red edge" due to sudden lack of absorption in near-IR by pigment	?

Catling et al., in prep

Habitability and Environment Impacts Biosignatures



Atmospheric Environmental Parameters

Substance	Spectral band center, μm	Significance for the planetary environment and habitability
CO_2	4.3, 4.8, 2.7, 2.0, 1.6, 1.4	- Non-condensable greenhouse gas - Well-mixed gas, enabling retrievals of atmospheric structure
N_2	4.15 for N_2-N_2	- Pressure-broadening that enhances the greenhouse effect
H_2O	2.7, 1.87, 1.38, 1.1, 0.94, 0.82, 0.72, 0.65, 0.57, 0.51	- Greenhouse gas - Relatively high abundance inferred from spectral features may suggest a wet planetary surface
CO	4.67, 2.34, 1.58	- *Anti-biosignature* gas - May indicate lack of liquid water
H_2	2.12	- *Anti-biosignature* gas if a relatively high abundance co-exists with abundant CO_2
H_2S	7, 3.8, 2.5	- Potentially volcanic gas
SO_2	8.8, 7.4, 4, 0.3	- Potentially volcanic gas
H_2SO_4 (aerosol)	TBD	- Transient behavior potentially indicates active volcanism - May indicate an oxidizing atmosphere
Organic haze	TBD	- Indicates a reducing atmosphere with $CO_2/CH_4 < 0.1$ - May derive from biogenic methane
Rayleigh scattering	0.3-1	- May indicate cloud-free atmosphere and help constrain the main scattering molecule (bulk atmospheric composition)
Clouds	0.3-5	- Radiative transfer calculations with scattering (Rayleigh and Mie multiple scattering) may be able to set constraints on cloud particle sizes and possibly composition

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?

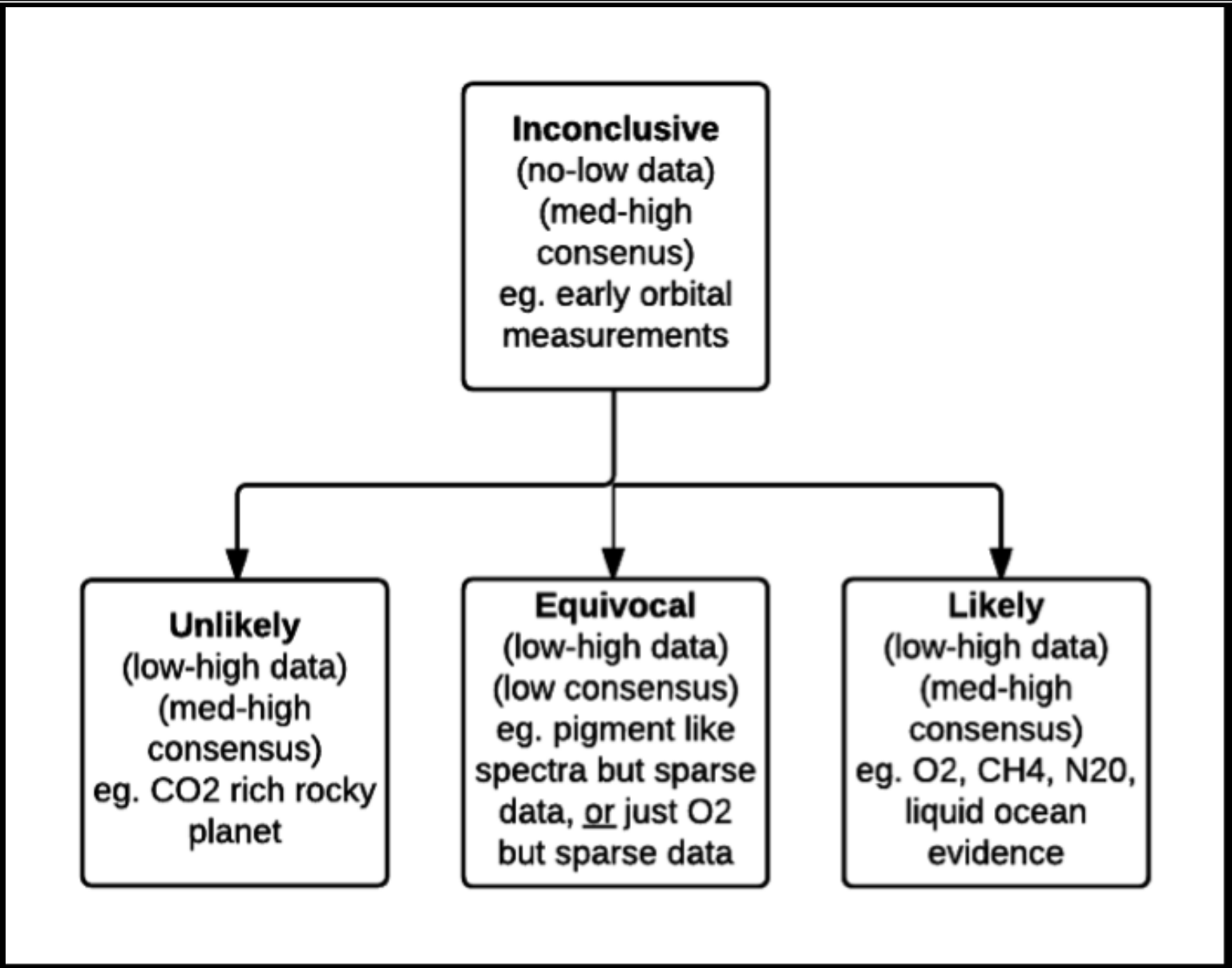
How do we determine false negatives?

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?

Confidence Levels for Detection



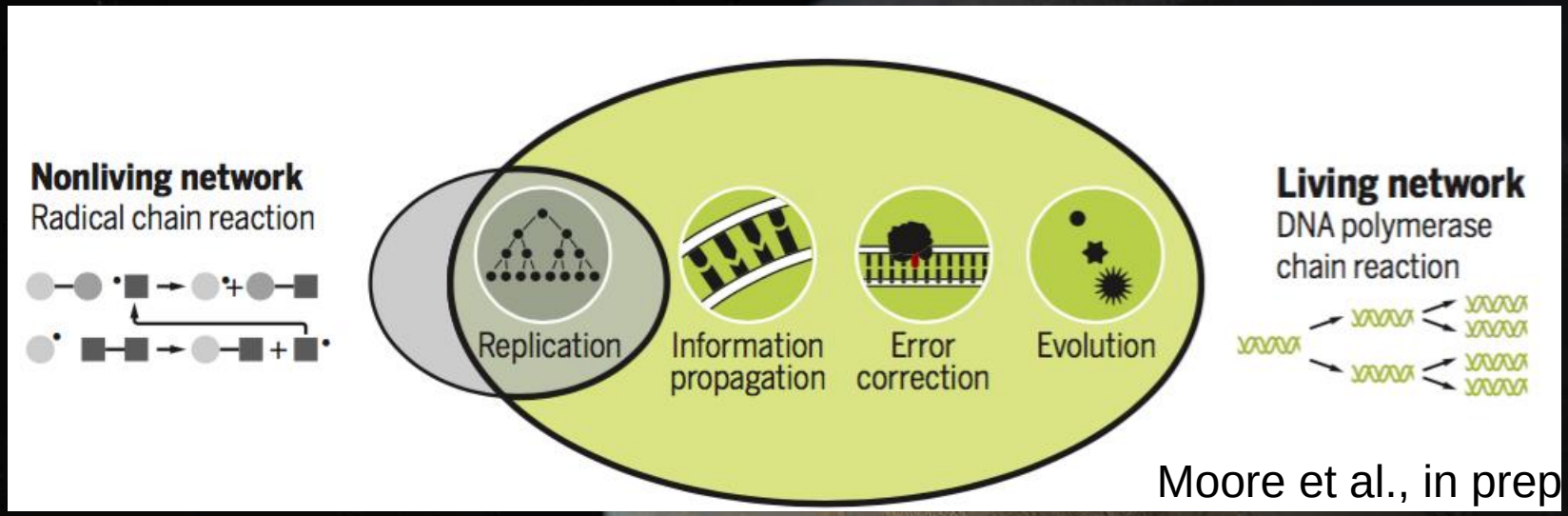
Catling et al., in prep

Novel Biosignatures

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

See next talk by William Bains for more detail

Life Signs from Information and Coevolution



Moore et al., in prep

Life is an information producing (entropy reducing) process

Biosignatures that identify information flow (e.g. chemical networks)

Life is in a co-evolutionary relationship with its planet/star/system

Biosignatures that identify co-evolution (e.g. pigments filling atmospheric windows)

Modeling, field and laboratory measurements are needed to advance these new concepts.

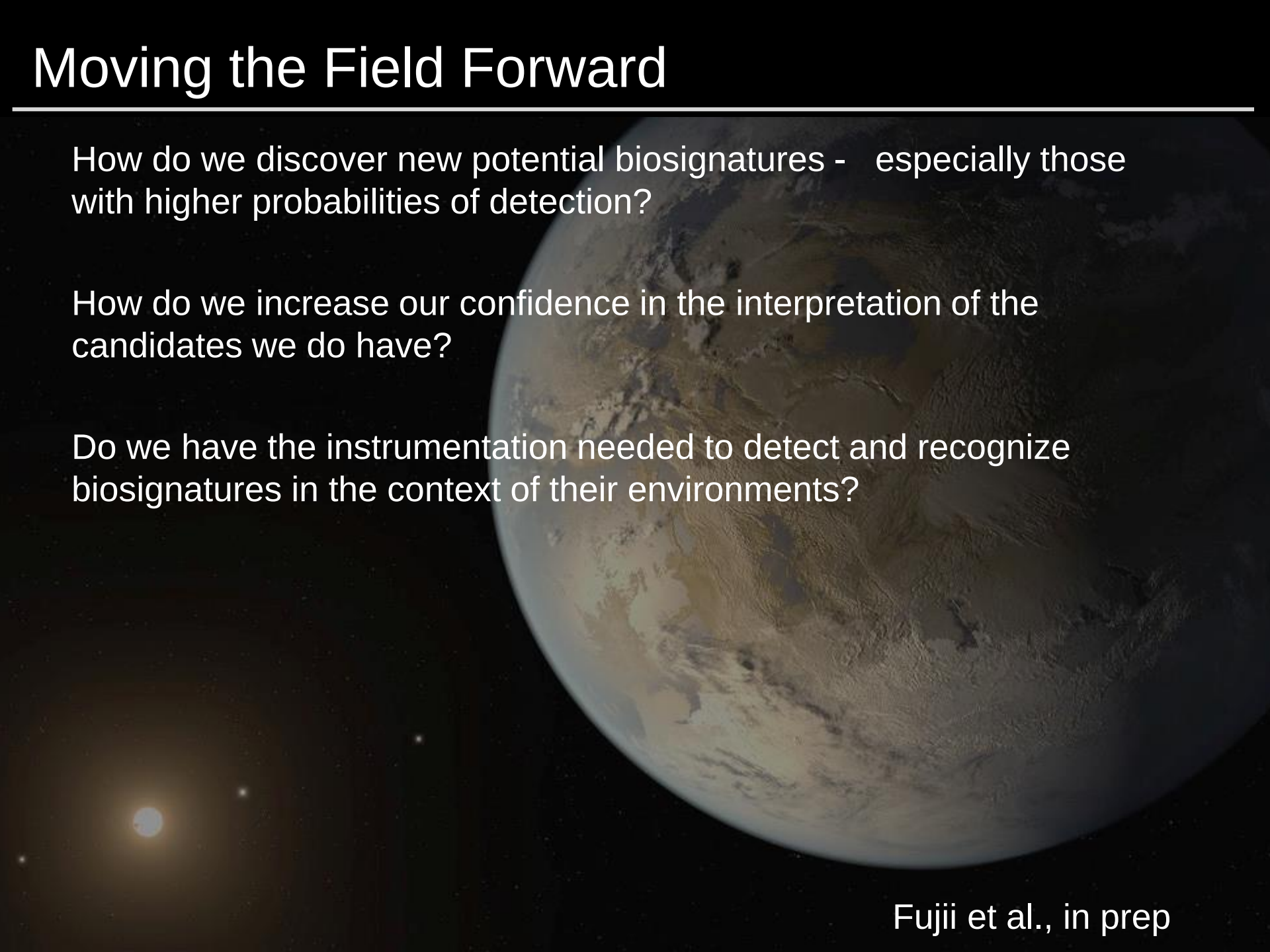
Future Research Directions

Moving the Field Forward

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

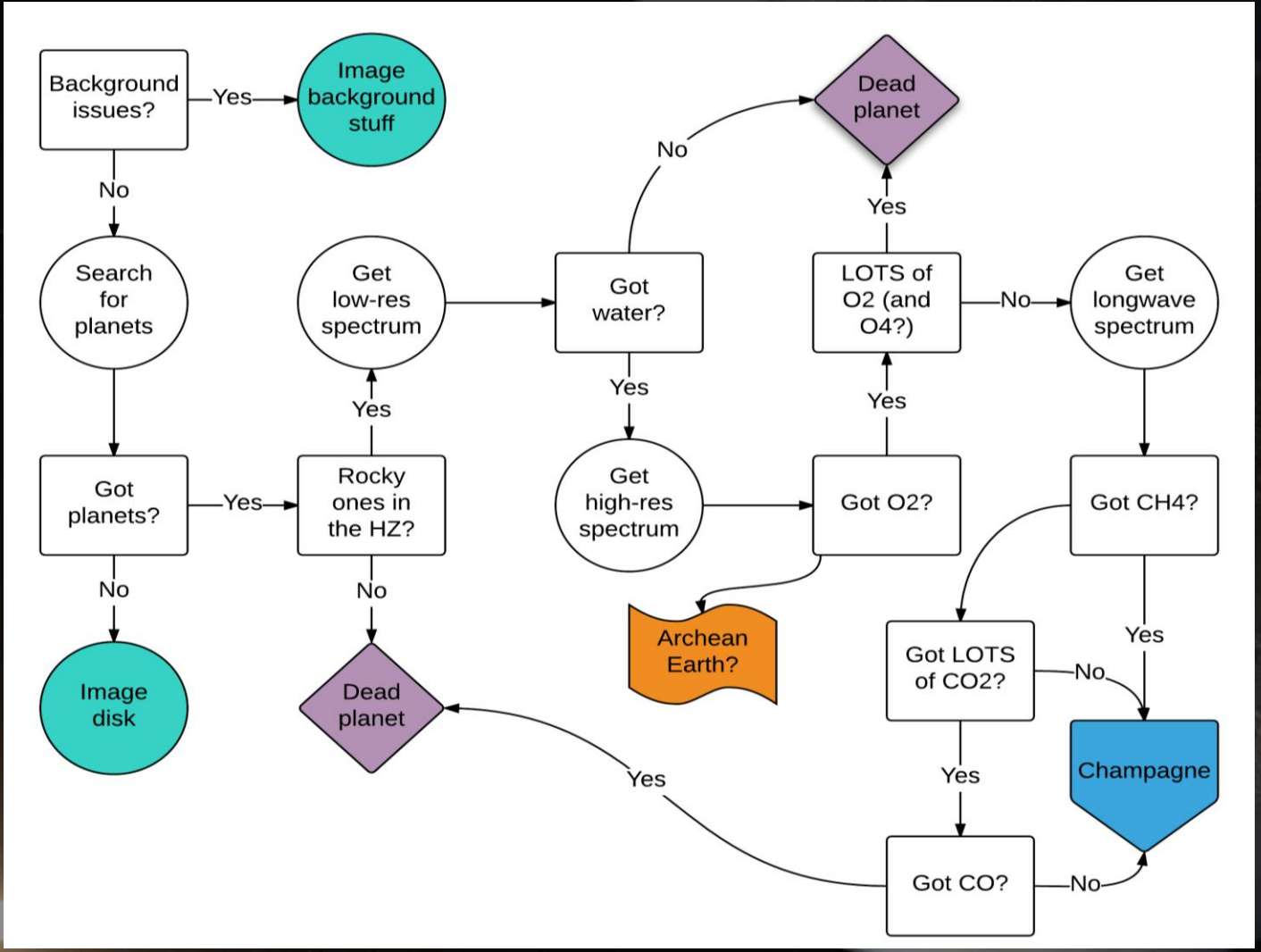
How do we increase our confidence in the interpretation of the candidates we do have?

Do we have the instrumentation needed to detect and recognize biosignatures in the context of their environments?



Fujii et al., in prep

Develop Observation Strategies to Enhance Confidence



S. Domagal-Goldman

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.

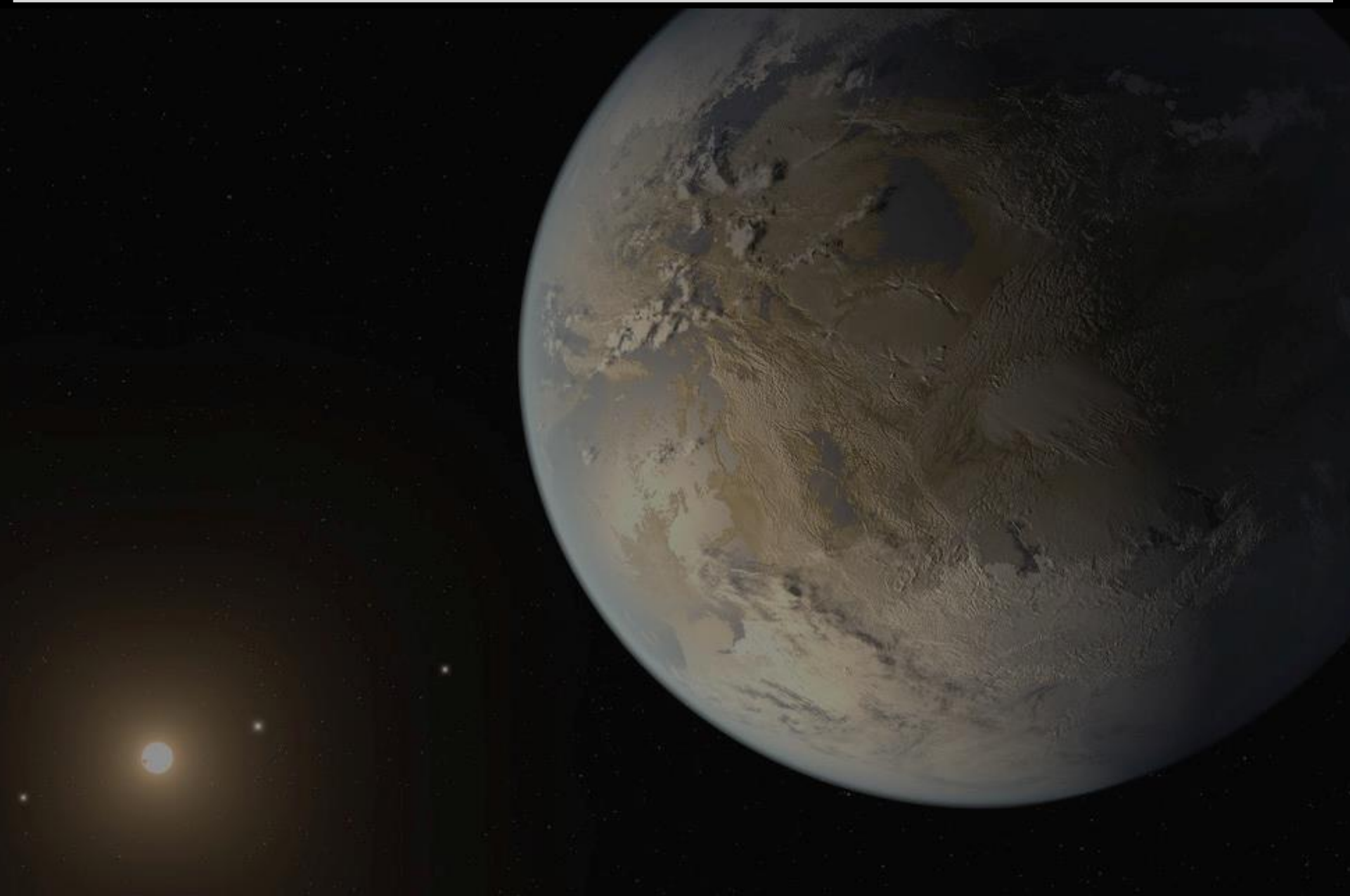
The rigorous treatment currently being given to O_2 should ideally be applied to all candidate biosignatures.

We should understand the capabilities of TESS, CHEOPS, PLATO, JWST, WFIRST and the GMT, E-ELT and TMT for exoplanet discovery, characterization and the search for biosignatures.

Similarly, biosignature research is and will be a key driver for mission requirements on the HabEx, LUVOIR and FIRS mission concepts.

We should design observing strategies to enhance confidence.

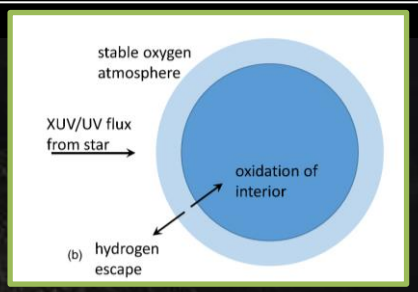
Questions



False Positive Discriminants

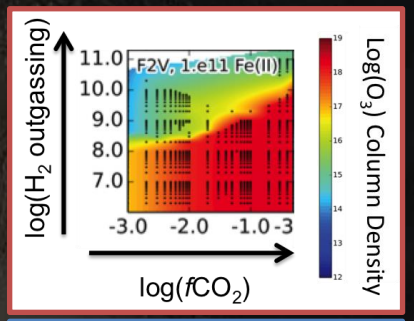
1. H Escape from Thin N-Depleted Atmospheres

   $(N_2)_2$ collisional pairs near 4.1um (Schwieterman et al., 2015b)



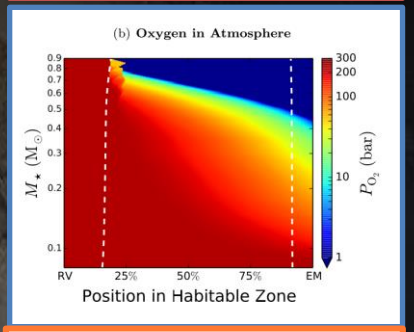
2. Photochemical Production of O_2/O_3

   Weak signal, presence of CO, CH_4 (Domagal-Goldman et al., 2014; Schwieterman et al., 2016)



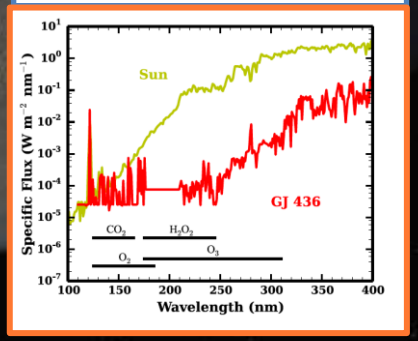
3. O_2-Dominated Post-Runaway Atmospheres from XUV-driven H Loss

   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)



Workshop Summary

- We have 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
  - e.g 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.
- When exploring possible biosignatures, we must also focus on its ultimate detectabilty and the detectability of its false positives, and how we will make the measurements to increase our confidence.
- Strategy for Robust Biosignature Detection
  - Characterize the stellar host and the planetary environment.
  - Search for potential biosignatures
  - Exclude potential false positives.
  - Biosignature identification be given as a probability based on confidence levels

Day 1 – July 27

- 8:30 - 8:45 Introduction/welcome/agenda overview: Mary Voytek
- Advice on how to participate remotely: Shawn/Mike Toillion
- 8:45 - 9:30 "Around the room" intros of everyone
    - Submit 1 Powerpoint slide for book and in-person, 30 seconds each.
- 9:30 - 9:45 BREAK
- Theme 1: Talk on the "State of the Science"
    - Moderator: Shawn
- 9:45 - 10:45 *Vikki Meadows*
- 10:45 - 11:30 Plenary discussion
  - Lunch 11:30 - 12:30
- 12:30 - 3:30 Afternoon session
  - Theme 2: Making, breaking, and making new frameworks for biosignatures science
    - 12:30 - 12:35: Part 1 Moderator: Tim Lyons - Geochemical context for rise of O_2
    - 12:35 - 1:05: O_2 as a biosignature: "How likely is it for photosynthesis (especially oxygenic photosynthesis) to evolve?" (*Bob Blankenship*)
    - Q&A/Discussion
    - 1:05 - 1:35: How can we think outside the box and develop alternative atmospheric biosignatures? (*William Bains*)
    - 1:35 - 1:45: Q&A/Discussion
    - 1:45 - 2:00: Break
    - 2:00 - 2:45: Breakout questions/leads: *Prepare questions and solicit ideas/modifications from participants*
      - *Breakout groups 1, 2, 3, Online breakout group*
    - 2:45 – 3:30 Reconvene and Report-back
- Break 3:30 - 6:00
- Dinner 6:00 - 8:00
- Evening work session (includes Asia, and allow East Coast to edit in the morning)

Pre-workshop Online Activities

75 minute meetings were held twice a week at different times to ensure maximum participation from international participants

Meeting 1: June 13 at 13:00 EDT and June 16 at 19:00 EDT

Topic: Review biosignatures described in Des Marais et al., 2002 (Dave DesMarais)

- Moderators: Shawn Domagal-Goldman, Nikole Lewis.
- Goal/work session: After presentation, filled in rubric recording characteristics of biosignatures described in the review.

Meeting 2: Week of June 27 - June 30, time TBD

Topic: Discuss advances in biosignature research since 2002 review

- Moderator: Hilairy Harnett
- Goal/work session: Continued to fill in rubric with published atmospheric and surface biosignature research since 2002.

Meeting 3: Week of July 11 - 14, time TBD

Topic: History of observation technologies (Karl Stapelfeldt and Drake Deming)

- Moderators: Maggie Turnbull, Daniel Apai, Enric Palle
- Goal/work session: Mission capabilities and measurements.

Day 2 – July 28

- 8:30 - 11:30 Morning session
  - Theme 2: Making, breaking, and making frameworks for biosignatures science
    - 8:30 - 8:35: Part 1 Moderator: Lee Grenfell
    - 8:35 - 9:05: Statistical search for life (*Sara Walker*)
    - 9:05 - 9:35: How is a biosignature responsive to its environment (chemistry, climate) and geography (distribution)? *David Catling*
    - 9:35 - 9:45: Q&A/Discussion
    - 9:45 - 10:00: Break
    - 10:00 - 10:45: Breakout questions/leads: *TBD*
      - *Breakout groups 1 (Renyu Hu), 2, 3, online.*
    - 10:45 – 11:30 Reconvene and Report Back.
- 11:30 - 12:30 Lunch
- 12:30 - 3:30 Afternoon session
  - Theme 3: Developing evaluation/interpretation standards/goals for biosignatures
    - 12:30 - 12:50: Part 1 Moderator: Nick Siegler
    - 12:50 - 1:20: What can we measure now and in the future? Heike Rauer
    - 1:20 - 1:50: What can we model/ascertain now and in the future? Tony Del Genio
    - 1:50 - 2:00: Q&A/Discussion
    - 2:00 - 2:15: Break
    - 2:15 - 3:00: Breakout questions/leads: *Mapping tiered confidence levels to measurements/models*
      - *Breakout groups, 1, 2, 3 and online.*
    - 2:45 – 3:30 Reconvene and Report Back.
- Break 3:30 - 6:00
- Dinner 6:00 - 8:00
- Evening work session – start white paper outline

Day 3 – July 29

- Breakfast 7:30 - 8:30
- 9:00-9:10: Bringing it all together - charge for “work sessions”
- 9:10 - 11:15 Breakout Group Work (Writing/Synthesis)
- Breakout Group 1 - Outline white paper
- Breakout Group 2 - Review/synthesize confidence levels and frameworks
- Breakout Group 3 - “Case study” in tracing desired knowledge to types of observations and models. (Take an example biosignature such as O2 or Chl and apply rubrics to it.)
- 11:15 - 11:20: Reconvene
- 11:20 - 12:20: Review work from breakout groups
- 12:20 - 12:30: Next steps/thank yous
- 12:30:

Workshop Organization

- Two active groups organizing:
  - Science Organizing Committee (SOC) – International workshop planning group
    - Nancy Kiang, Niki Parenteau, Shawn Domagal-Goldman leading.
  - ExoPAG Study Analysis Group (SAG) – All participants who contribute to writing of report and white paper

- On-line Pre-Workshop Activities: June-July, 2016.
  - Group discussions and writing of the State-of-the-Science

- 3-Day In-Person Workshop (and online broadcast/podcast) : 27-29 July 2016, Seattle, WA
  - Plenaries on the 3 Science Goals, and intensive Breakout Discussion Groups

- Post-Workshop Activities
  - Deliverables

Post-workshop Deliverables

- Draft of workshop findings (powerpoint slides): August, 2016
- Draft of SAG report: Oct - Nov 2016
- Circulation of report for community input: Nov, 2016 – January, 2017
- Final report: February 2017
- Report Draft Structure
  - Chapter 1: Review of current state of exoplanet biosignature science
  - Chapter 2: Proposed comprehensive framework for identifying novel biosignatures
  - Chapter 3: Application of the biosignature assessment framework
  - Chapter 4: Future Work
  - Chapter 5: Conclusions

- Research needs to advance biosignature science and/or the frameworks for identifying them;
- A "how-to guide" for STDTs on types of observations needed for biosignature assessment to guide mission development or prioritize technology investment.