The Virtual Planetary Laboratory

Advancing the search for extraterrestrial life with a massively interdisciplinary collaboration

Dr. Victoria S. Meadows
University of Washington
Box 351580, Seattle, Washington 98195-1580

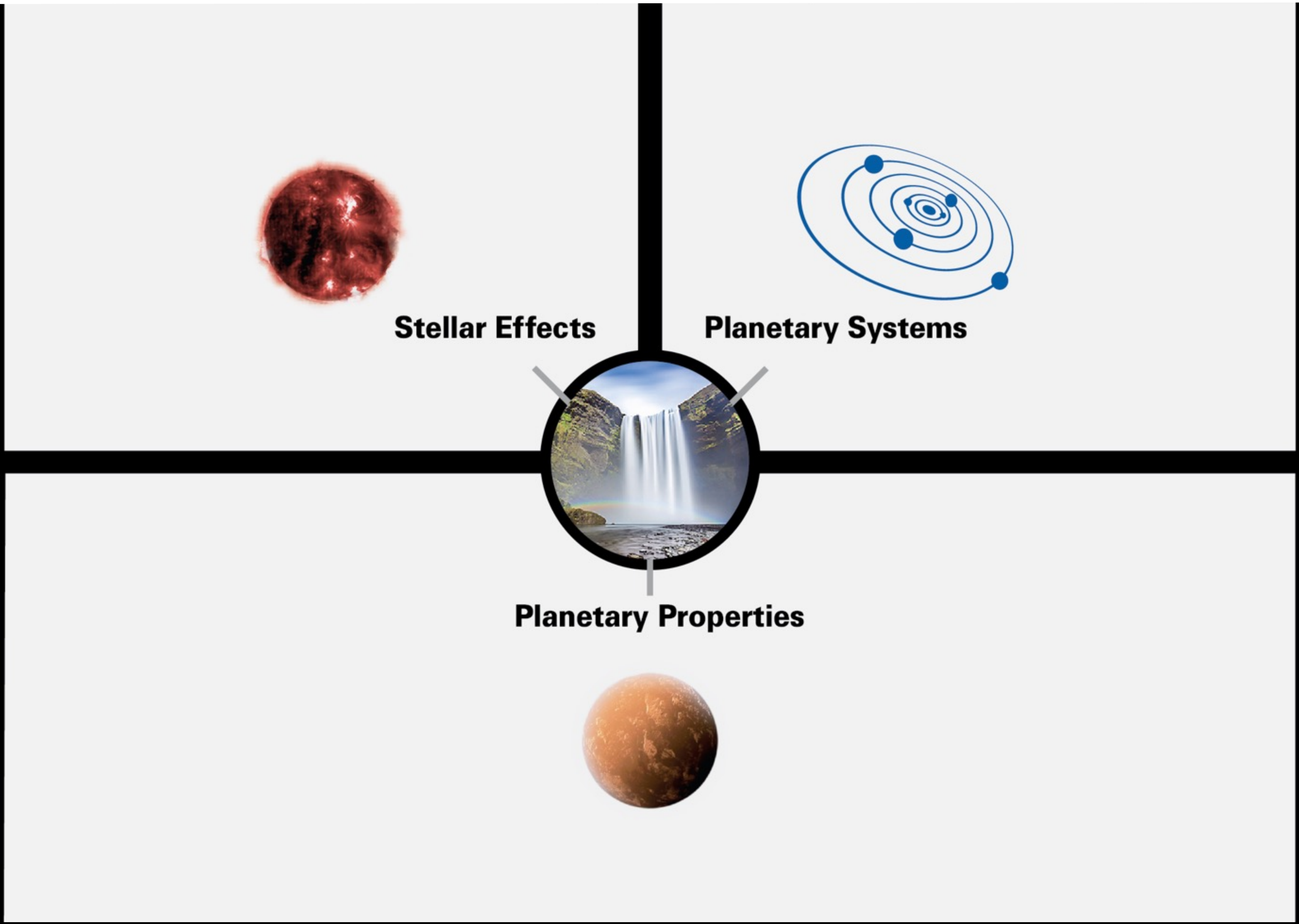
NASA Ames Research Center
Arizona State University
California Institute of Technology
University of California, Riverside
Carleton College
University of Chicago
University of Colorado - Boulder
Carnegie Institution of Washington
Laboratoire d'Astrophysique de Bordeaux
Georgia Institute of Technology
NASA Goddard Institute for Space Studies
Harvard University
NASA Jet Propulsion Laboratory
LESIA, Observatoire de Paris
University of Maryland, College Park
Universidad Nacional Autónoma de Mexico
NASA Goddard Space Flight Center
University of New South Wales
Northern Arizona University
University of Oxford
Rice University
University of St. Andrews
Space Telescope Science Institute
Stanford University
University of Victoria
Washington University - St. Louis
Weber State University
Yale University

VPL’s Question

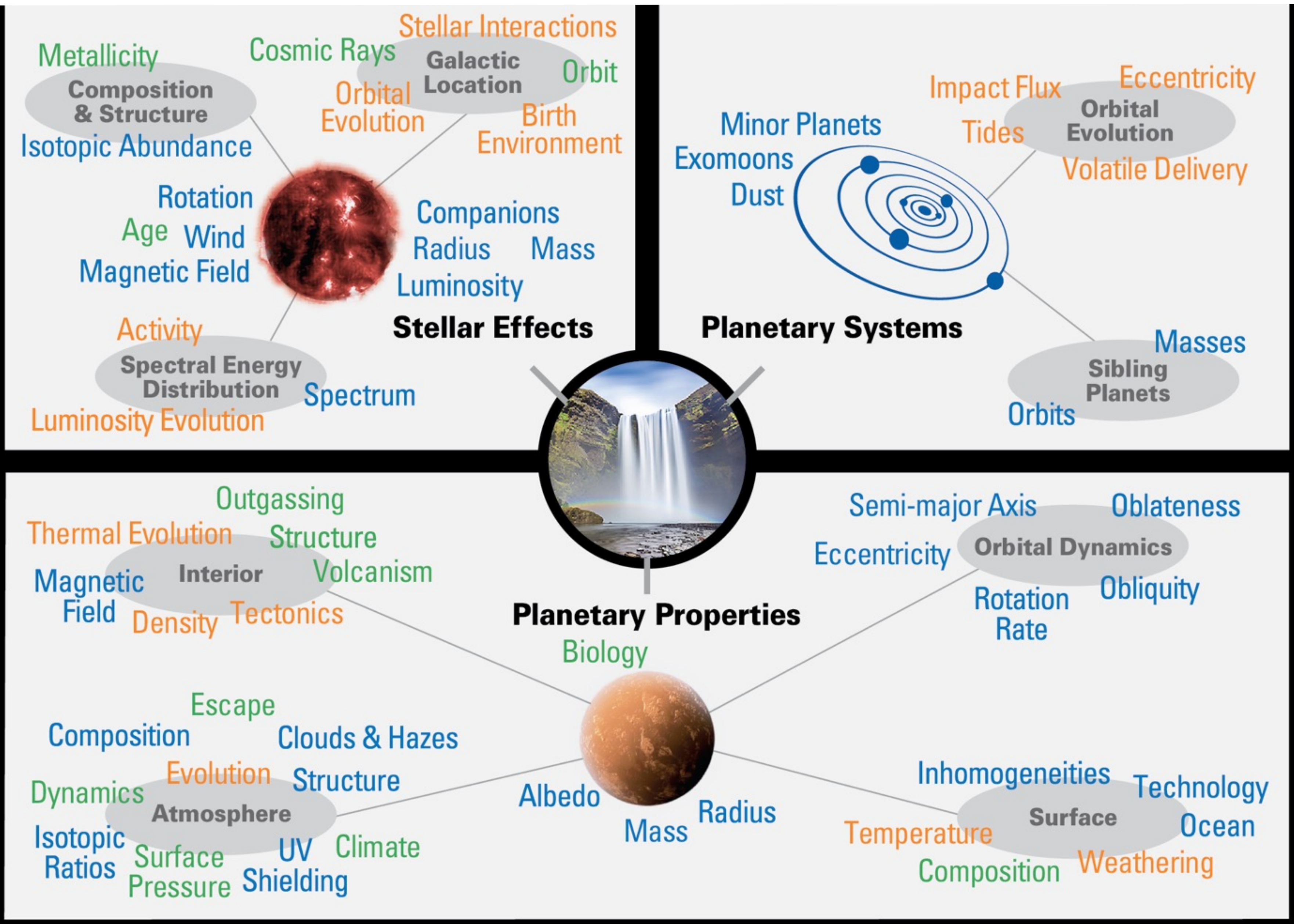
How do we recognize whether an extrasolar planet can or does support life?

The Search For Life is a Search for Liquid Water

Many Things Affect Whether a Planet Has Liquid Water



Many, Many Things.....



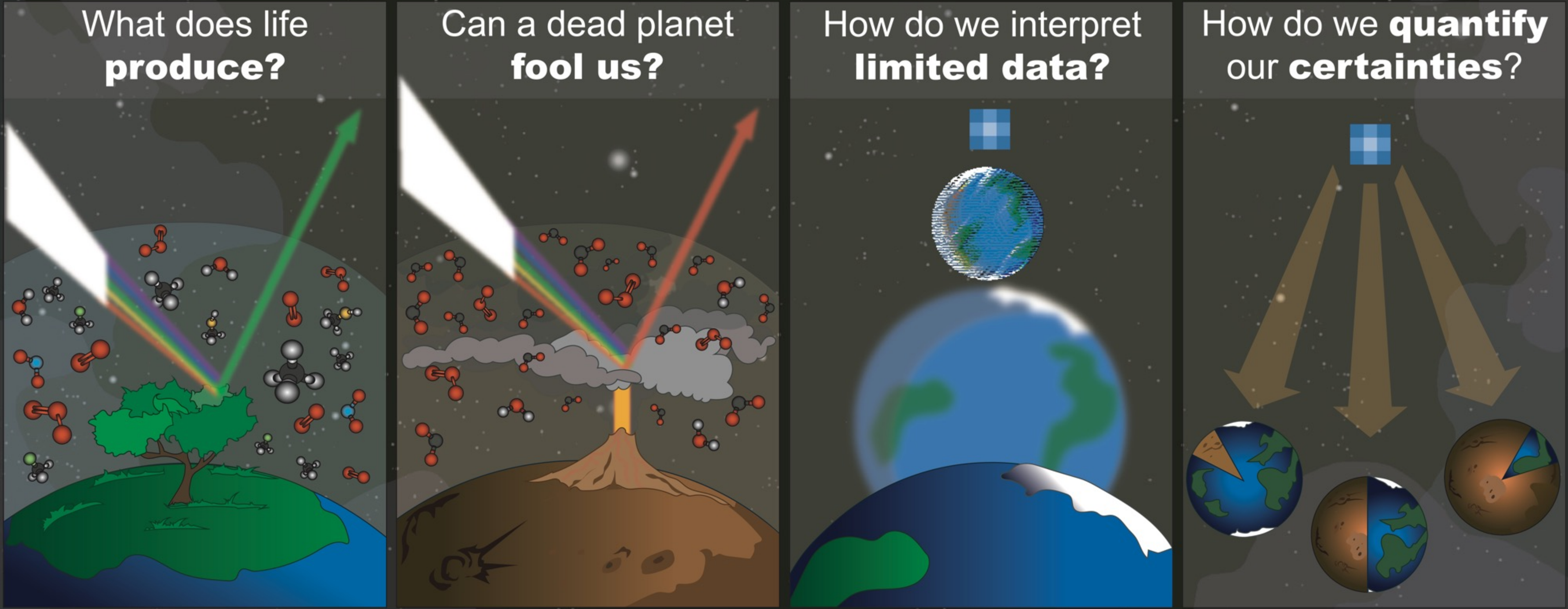
Meadows & Barnes, 2018

Key Questions: Searching for Habitability

Does it have an atmosphere?
What is the nature of its atmosphere?
Does it have an ocean?
Are there signs of life?

Image Credit: NASA

Key Questions: Searching for Life



(Kiang et al., 2018; Schwieterman et al., 2018; Meadows et al., 2018; Catling et al., 2018; Walker et al., 2018; Fujii et al., 2018)

Key Theme: Exoplanet and Solar System Synergies

- To model exoplanets credibly it is *extremely* important to validate our models against measurements of planets in our own Solar System.
- Solar System planets allow us to measure ground-truth (to compare with remote sensing) and provide exquisite spatial and temporal resolution to understand planetary processes that may be common elsewhere.
- In turn, exoplanet science provides a large, statistical sample of planets, that can be queried for trends, and that set our Solar System in a broader context.

Image Credit: NASA

Key Theme: Interdisciplinarity

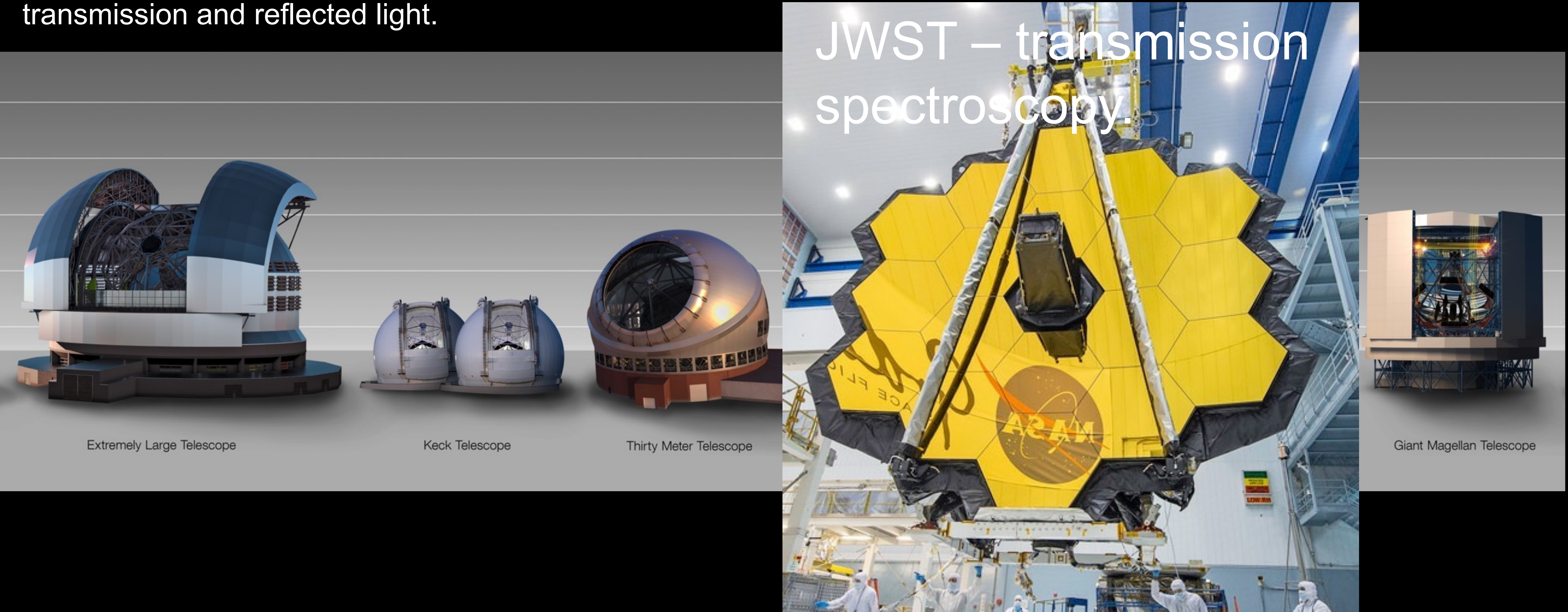
- Complexity of planetary habitability: "It takes a village to model a planet"
- Need for a probabilistic assessment of life: "It's one thing to detect a biosignature, it is another thing to interpret it"
- "Biosignatures must always be interpreted in the context of their environment"

Massively interdisciplinary science is needed to search for extraterrestrial habitability and life.

Image Credit: NASA

JWST and the ELTs in the next decade

JWST and ground-based telescopes that will allow us to get spectra of the planetary atmospheres using transmission and reflected light.



JWST – transmission spectroscopy.

Future missions may expand our opportunities to search for life

Credit: Grant Tremblay

Ground-based high-resolution spectroscopy can also be used to observe M dwarf planets

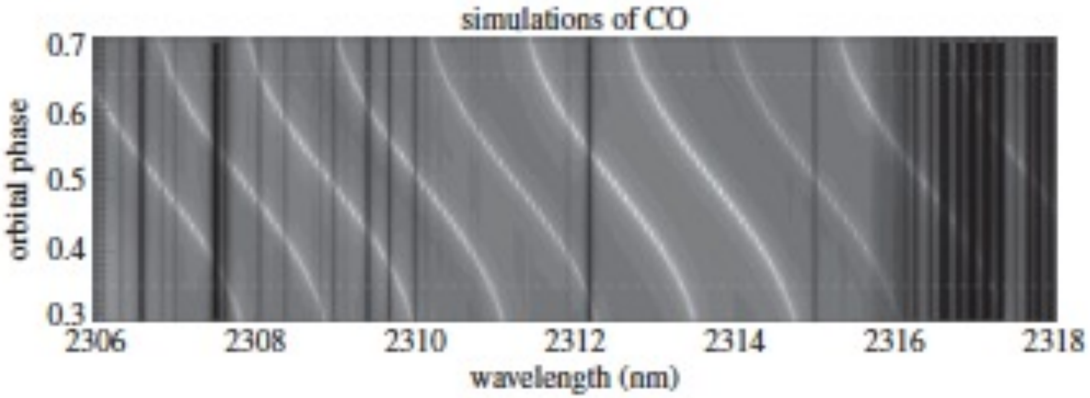
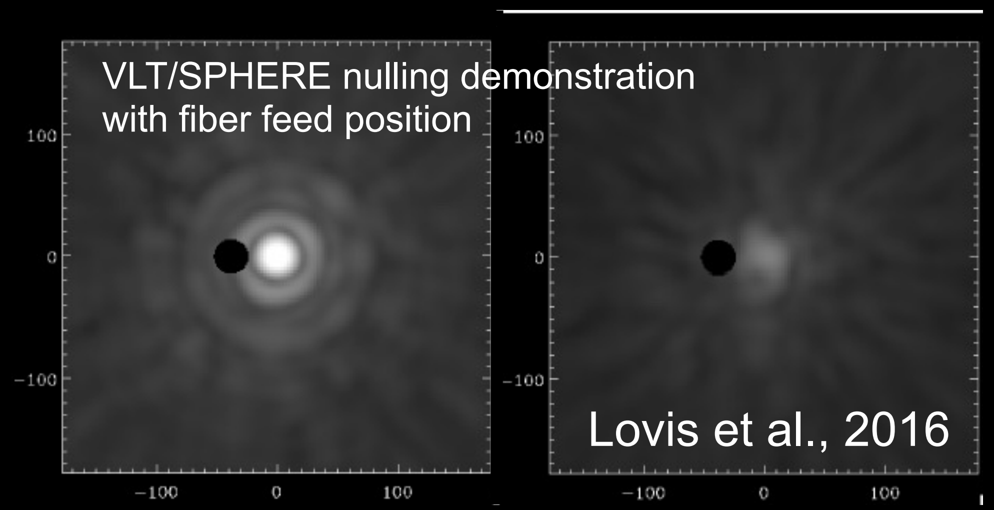
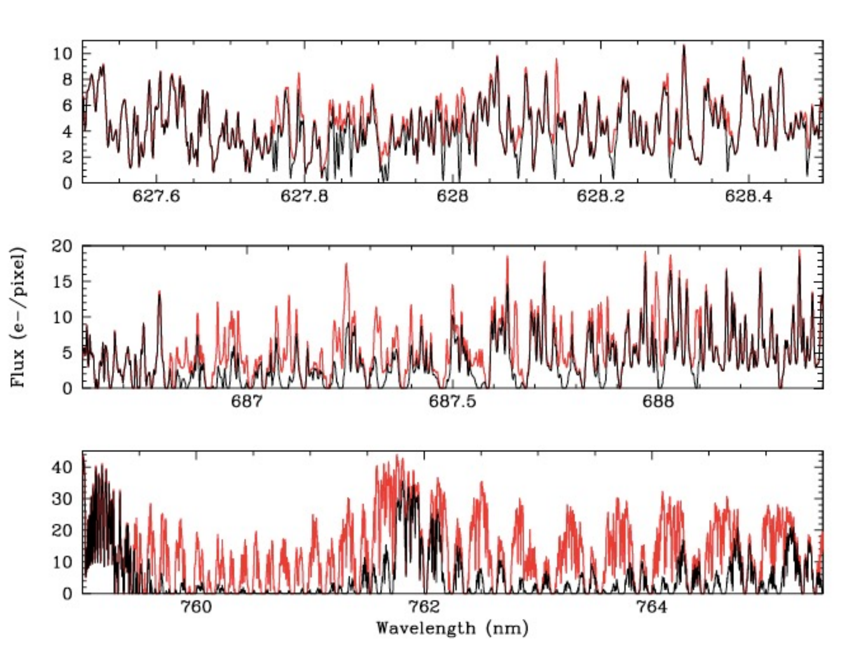


Figure 2. Graphical representation of high-dispersion spectroscopic observations of carbon monoxide in the thermal spectrum of a hot Jupiter. The white curved lines indicate the planetary carbon monoxide lines, which significantly change in wavelength owing to the change in the radial component of the exoplanet orbital velocity. The dark vertical features are telluric absorption, which is stationary with time and which can therefore be filtered out.

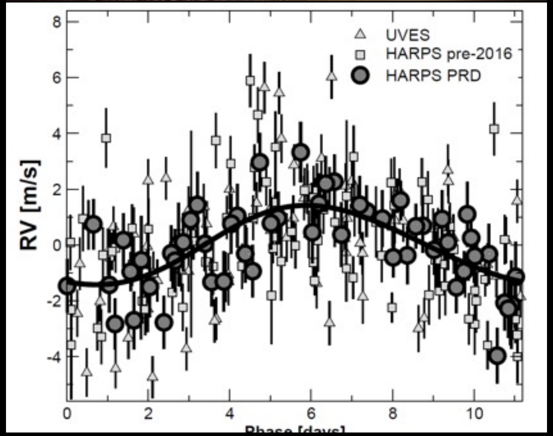
Snellen et al., 2014

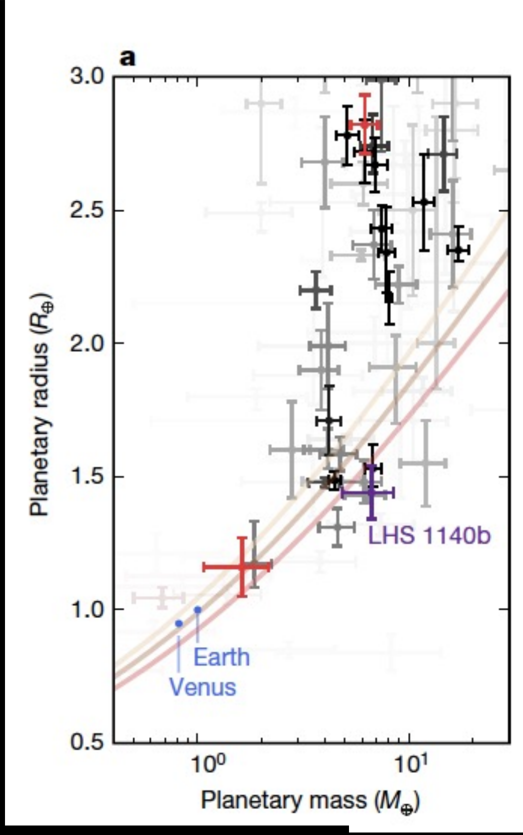




- From the ground, terrestrial planets can either be observed in transit, or via reflected light
- In both cases, the motion of the planetary system and the planet's orbit around its star shifts absorption lines from their rest position, and so shifts them out of similar absorption in the Earth's atmosphere.
- Hi-res ground-based and low-res space-based observations could be combined (Brogi et al., 2016).
- The most anticipated targets for this technique are M dwarf planets within 7pc of the Earth.
- Ground-based surveys and TESS may find these targets.

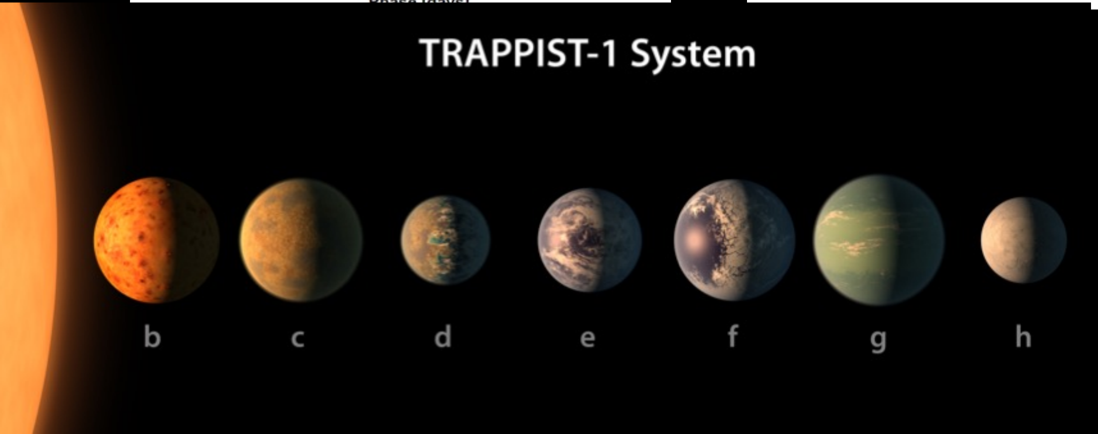
Excellent Nearby (M Dwarf)Targets for More Detailed Study Are Already Identified.

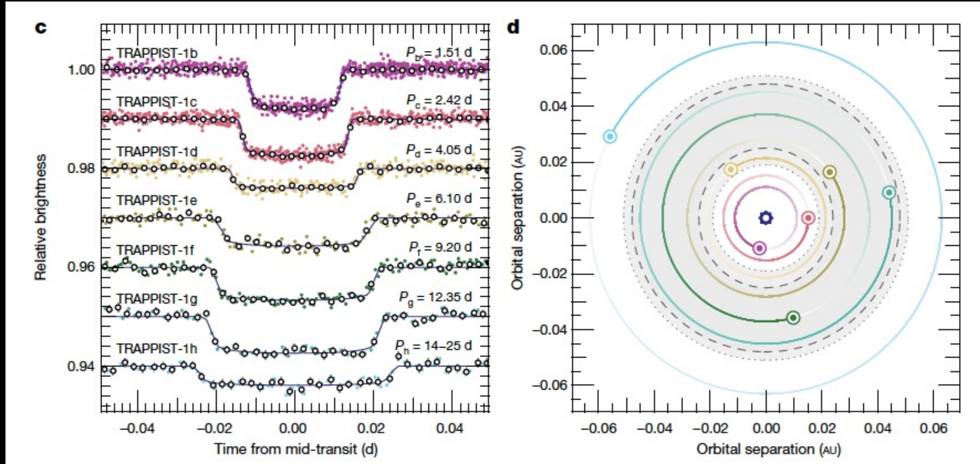




Nearby Systems Include:

- Transiting exo-Venuses
  - GJ1132 b (Berta-Thompson et al., 2016; Dittman et al., 2017)
- HZ Terrestrial Planets
  - Proxima Centauri b (Anglada-Escude ; non-transiting)
  - LHS 1140 b (Dittman et al., ; transiting 12pc, M4V)
- Transiting exo-Venuses and HZ Terrestrials
  - TRAPPIST-1 (Gillon et al., 2016;2017; Luger et al., 2017)
  - 12pc distance orbiting an M8V
  - b,c,d exo-Venuses, e,f,g, HZ planets.





Key Theme: Photons Are Coming

- Near-term: Observations of terrestrial exoplanets with JWST + ELTs
- Longer-term: Development of a terrestrial exoplanet capable telescope.

Theoretical modeling is needed to support upcoming observations and the development of future instrumentation to study terrestrial exoplanets for signs of evolution, habitability and life.

Image Credit: NASA

The Virtual Planetary Laboratory

- Founded in 2001 at the Jet Propulsion Laboratory
- Funded as a member of the NASA Astrobiology Institute for a proposal call with Earth Science funding included.
    - We were as responsive to the call as possible!
- I've been the PI for the whole 20 years
- Started out with 17 team members, now 74, with 130 in Slack!
- Publish 60-80 papers a year
- This is a massively interdisciplinary, highly collaborative project.

Image Credit: NASA

VPL Goals and Objectives

Goal: How do we recognize whether an exoplanet can or does support life?

Objective 1: Inform exoplanet evolution, habitability and biosignatures using Solar System observations and models.

Objective 2: Characterize the environment, habitability and biosignatures of the Earth through time.

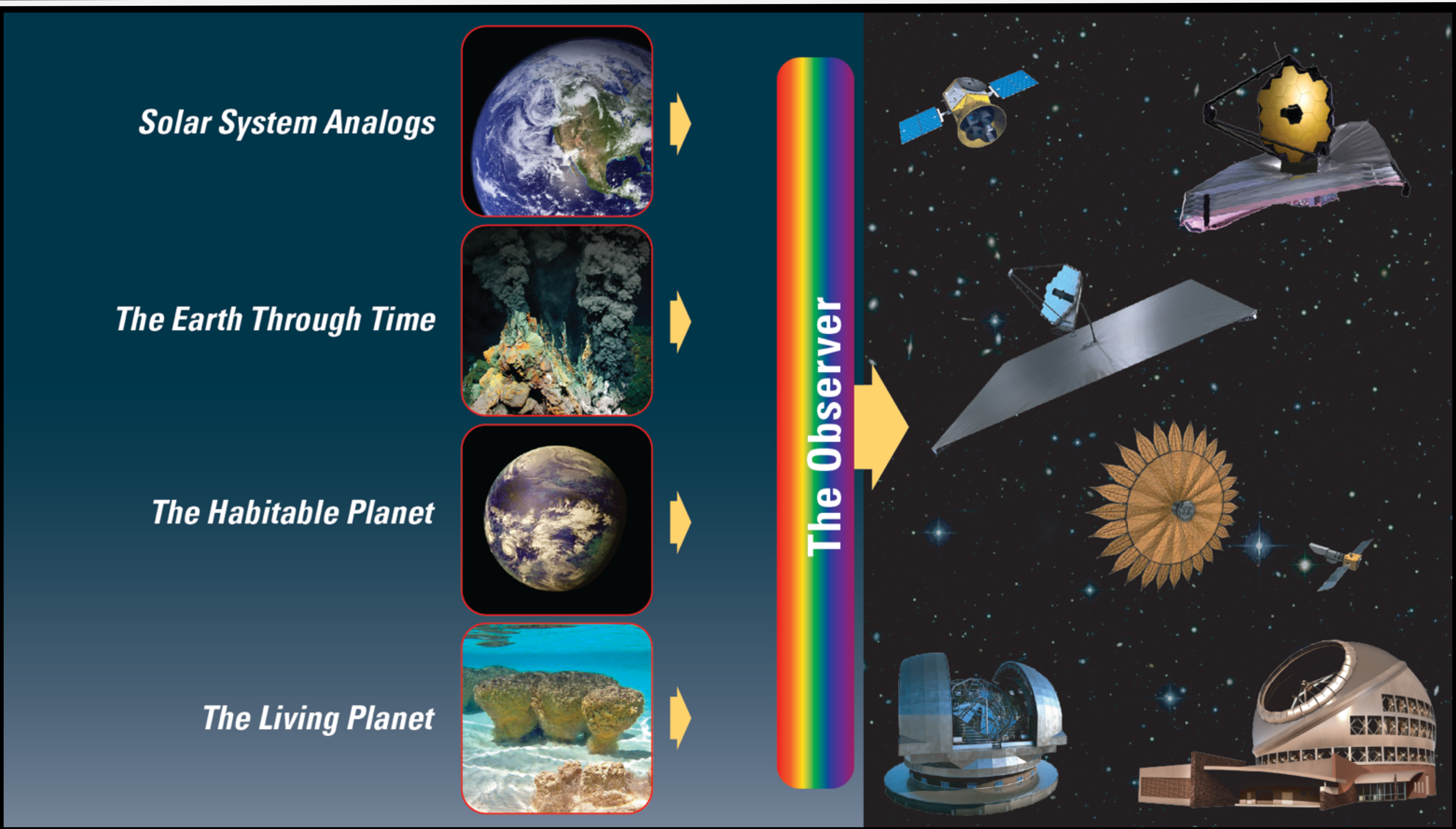
Objective 3: Develop interdisciplinary, multi-parameter characterization of terrestrial exoplanet evolution and habitability.

Objective 4: Determine the impact of life on terrestrial planet environments and the generation of biosignatures

Objective 5: Define required measurements and optimal retrieval methods for exoplanet characterization missions.

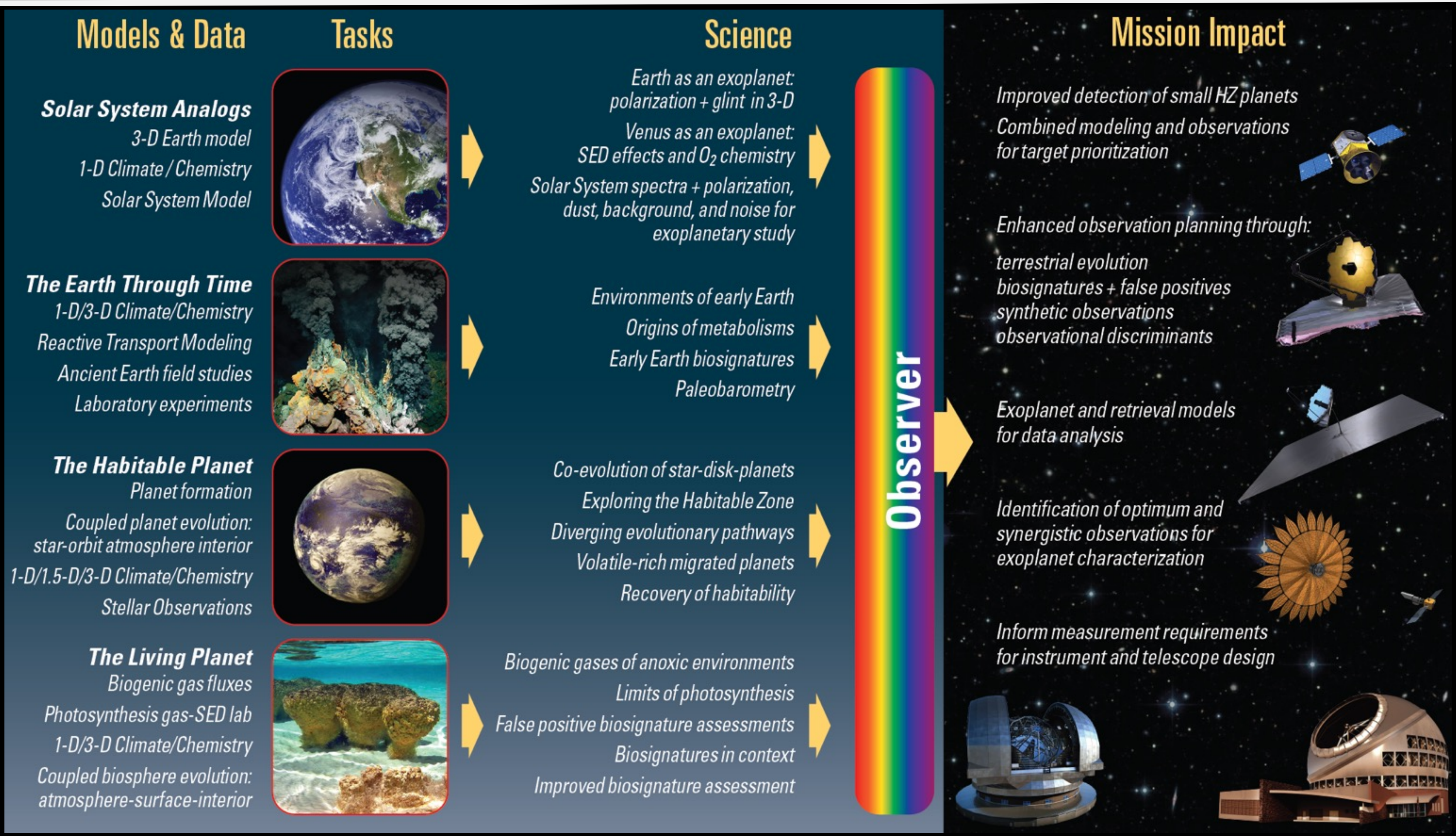
Image Credit: NASA

These objectives map on to five Tasks



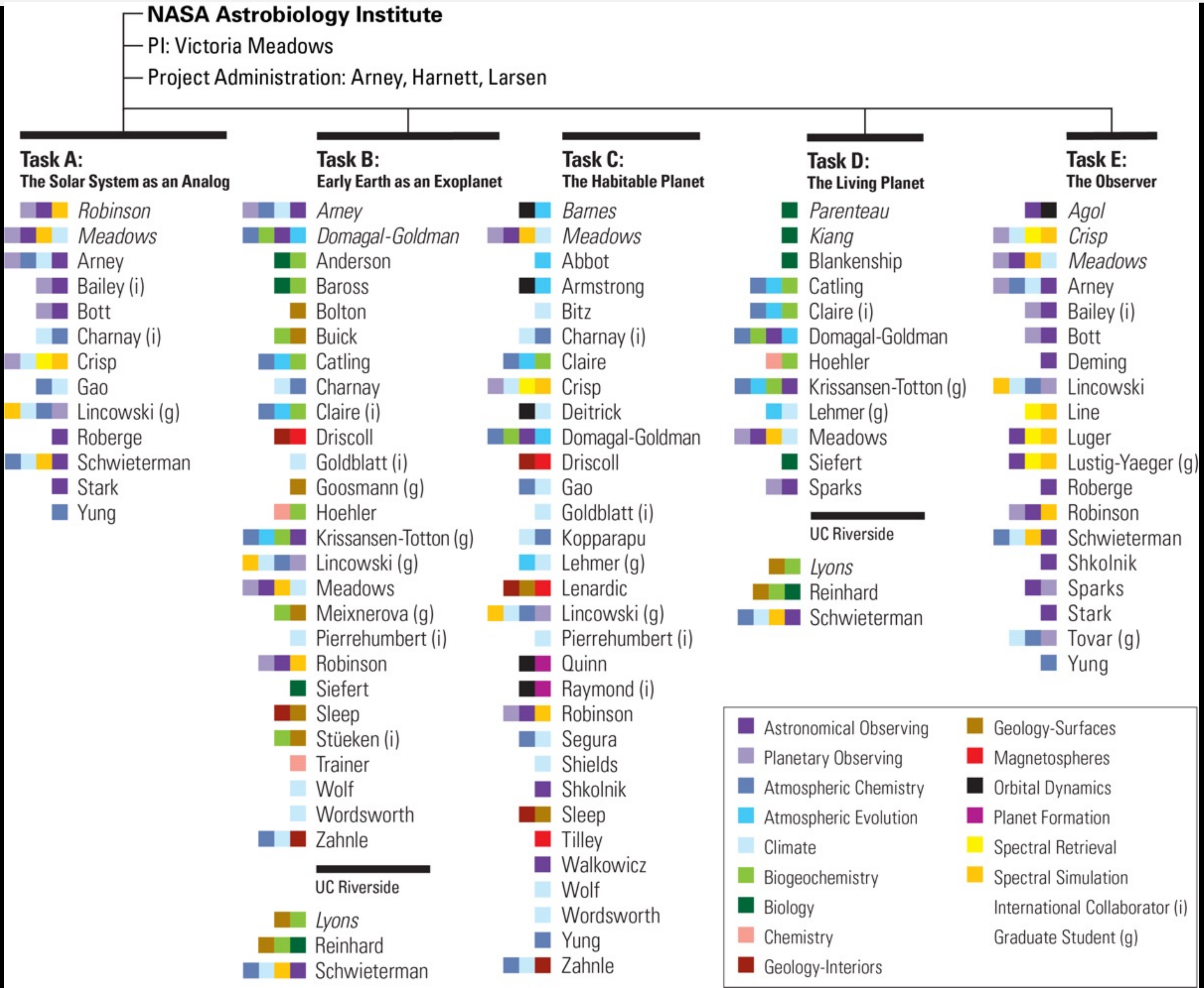
Combining expertise from Solar System, early and modern Earth, and exoplanetary science to model terrestrial exoplanet evolution, environments and observations.

These tasks produce science deliverables with mission impact

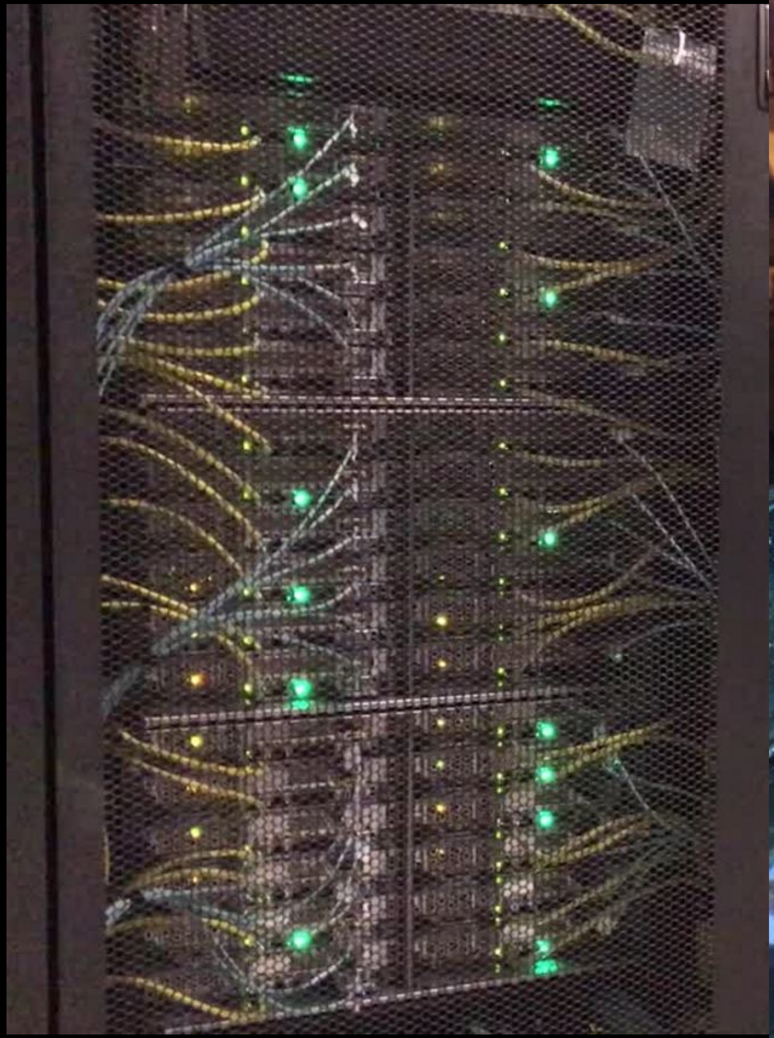


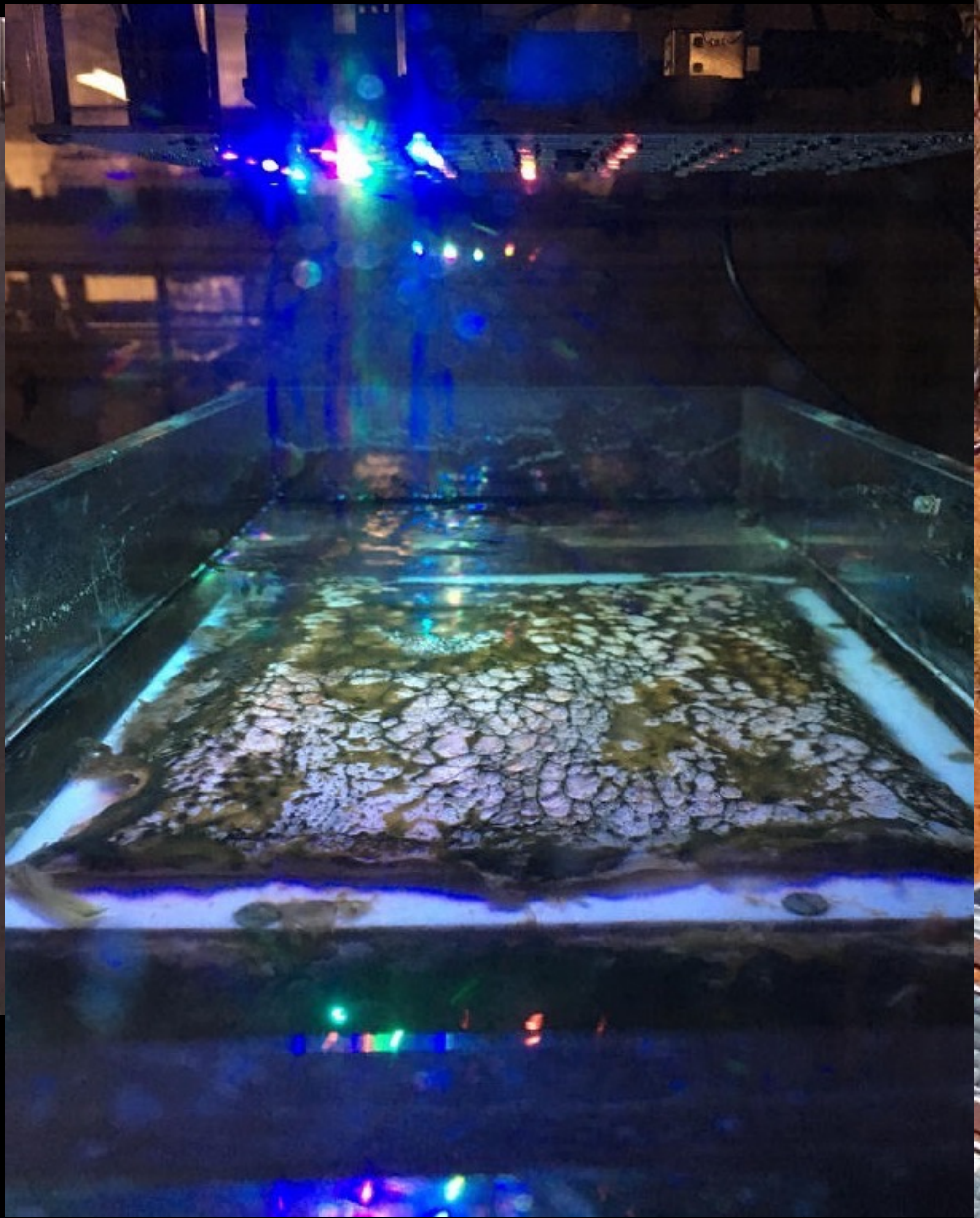
Combining knowledge and expertise from Solar System, early and modern Earth, and exoplanetary science to model terrestrial exoplanet evolution, environments and observations.

The team working on *each* Task is massively interdisciplinary



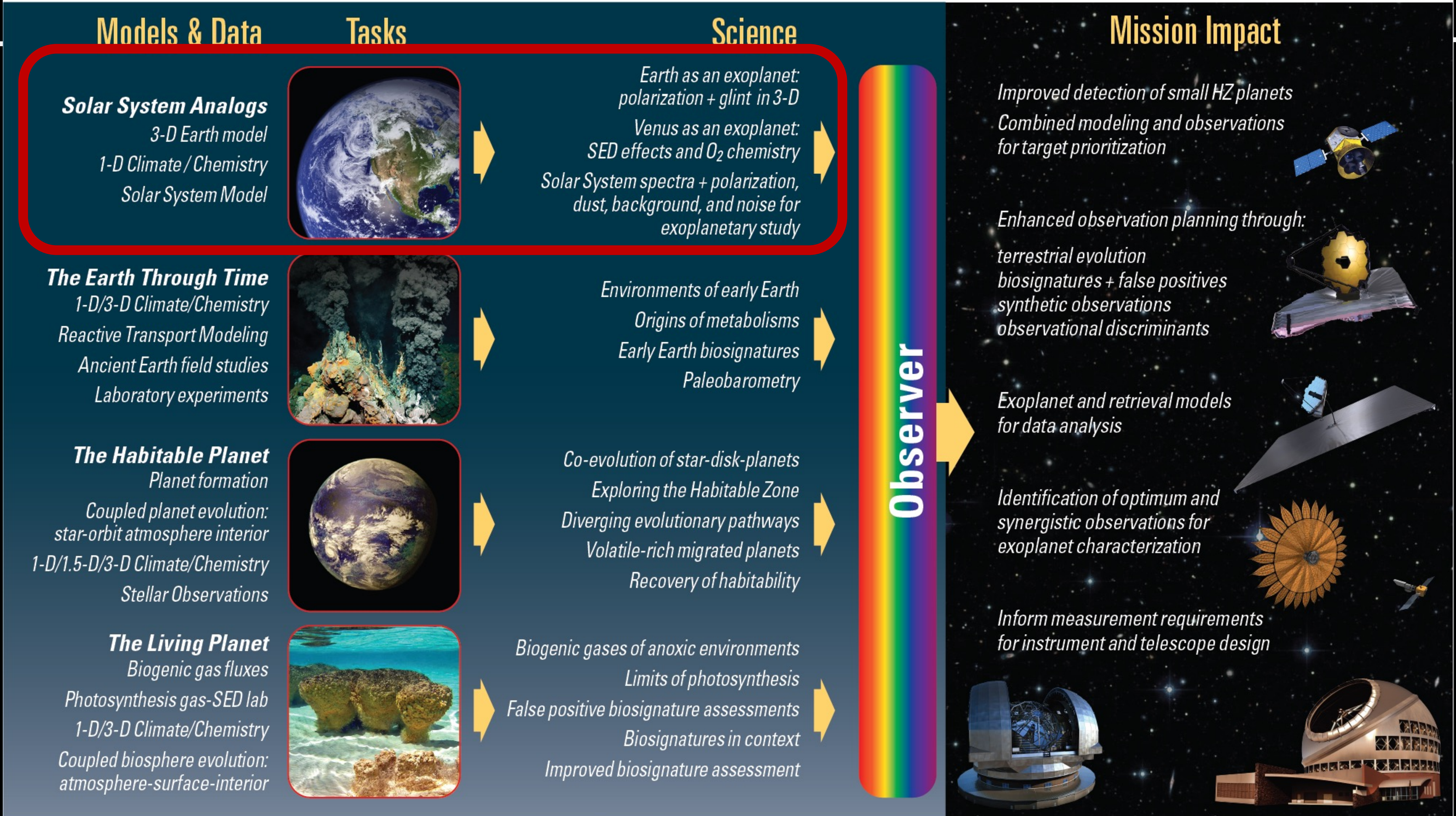
VPL’s work is done primarily with planetary computer models





Augmented with inputs from laboratory and field

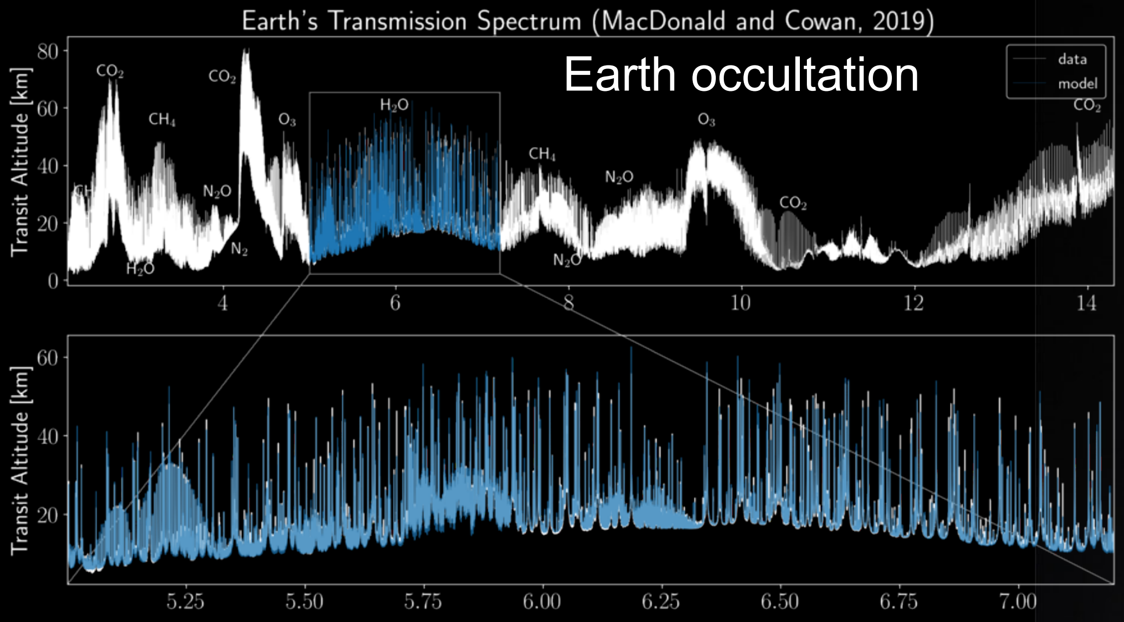
The Virtual Planetary Laboratory



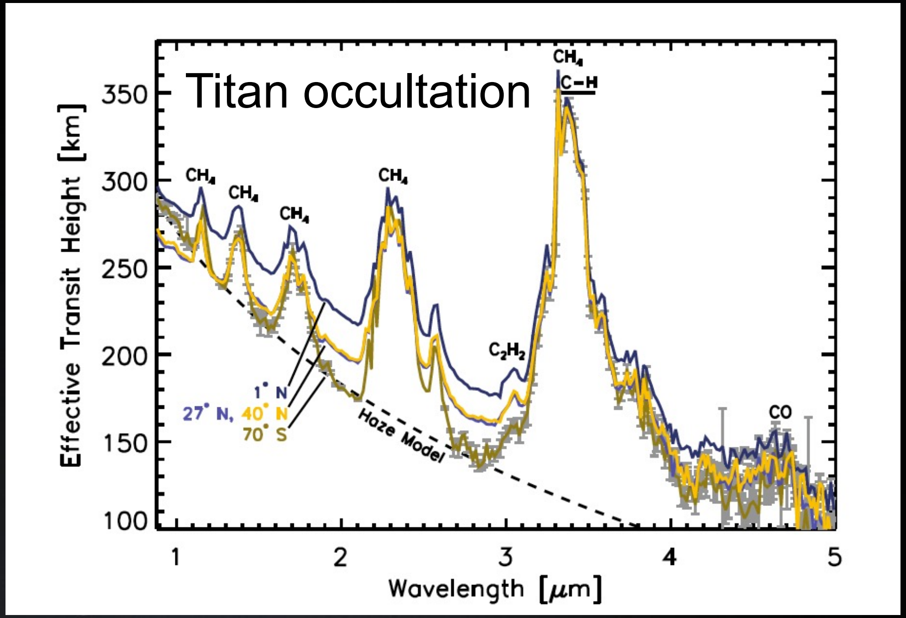
What is Task A about? Exoplanet/Solar System Synergies

Uses observations and models of Earth, Venus and other Solar System objects to explore processes and remote-sensing discriminants relevant to exoplanets, biosignatures and biosignature false positives.

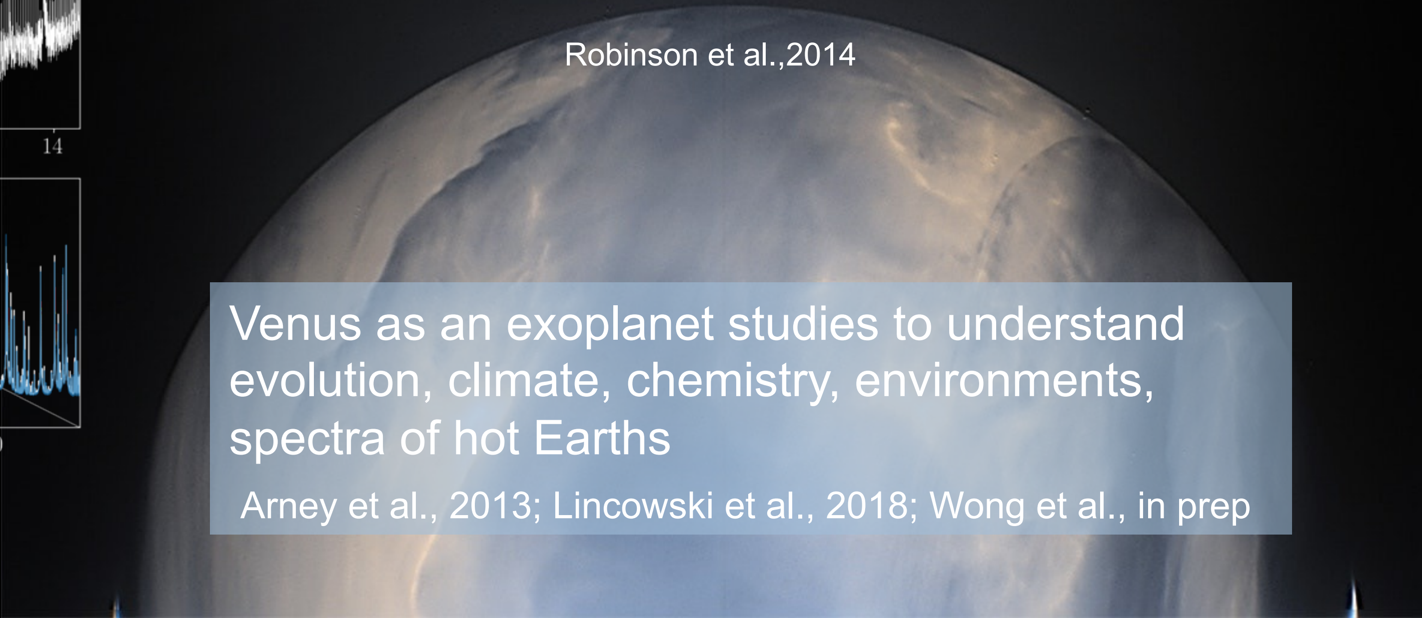
Originally Earth-centric, but expanded to use other Solar System observations as test cases for exoplanet observing scenarios, model validation, or insight into key planetary processes.



Model validation, Lustig-Yaeger et al., in prep.



Robinson et al.,2014



Venus as an exoplanet studies to understand evolution, climate, chemistry, environments, spectra of hot Earths

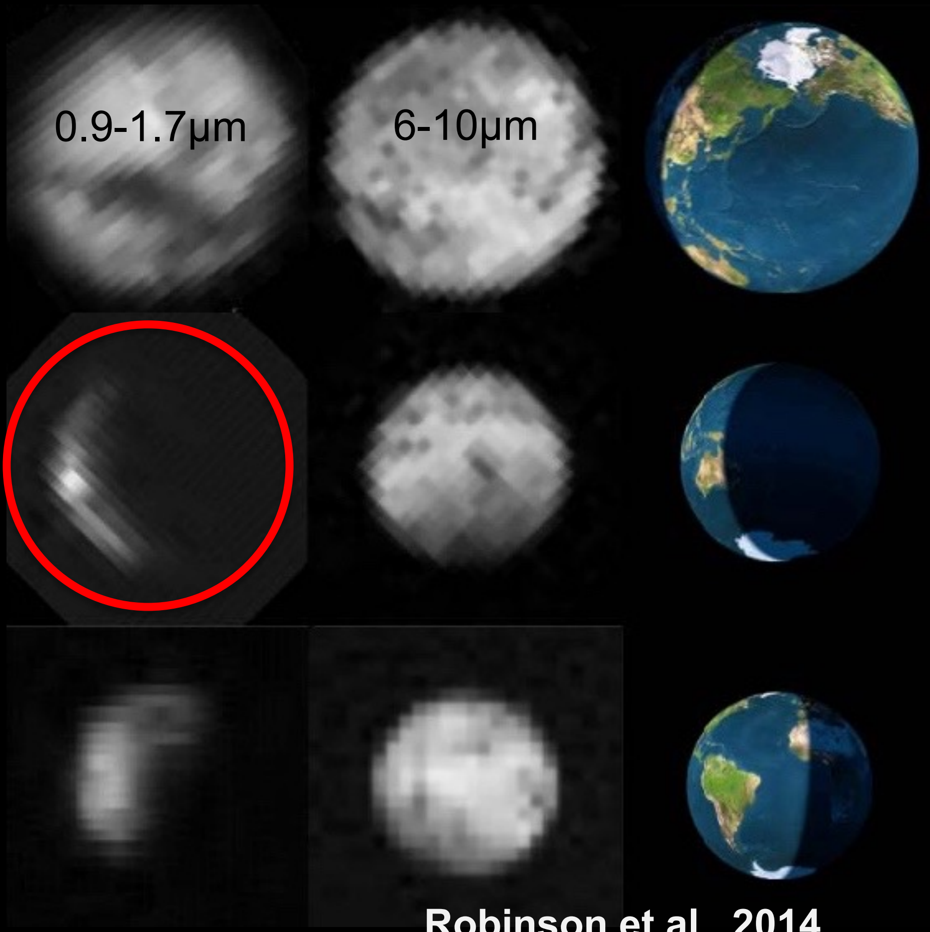
Arney et al., 2013; Lincowski et al., 2018; Wong et al., in prep

Does It Have an Ocean? Solar System Direct Imaging

Titan

Stephan et al., 2010
Cassini VIMS image of Kraken Mare

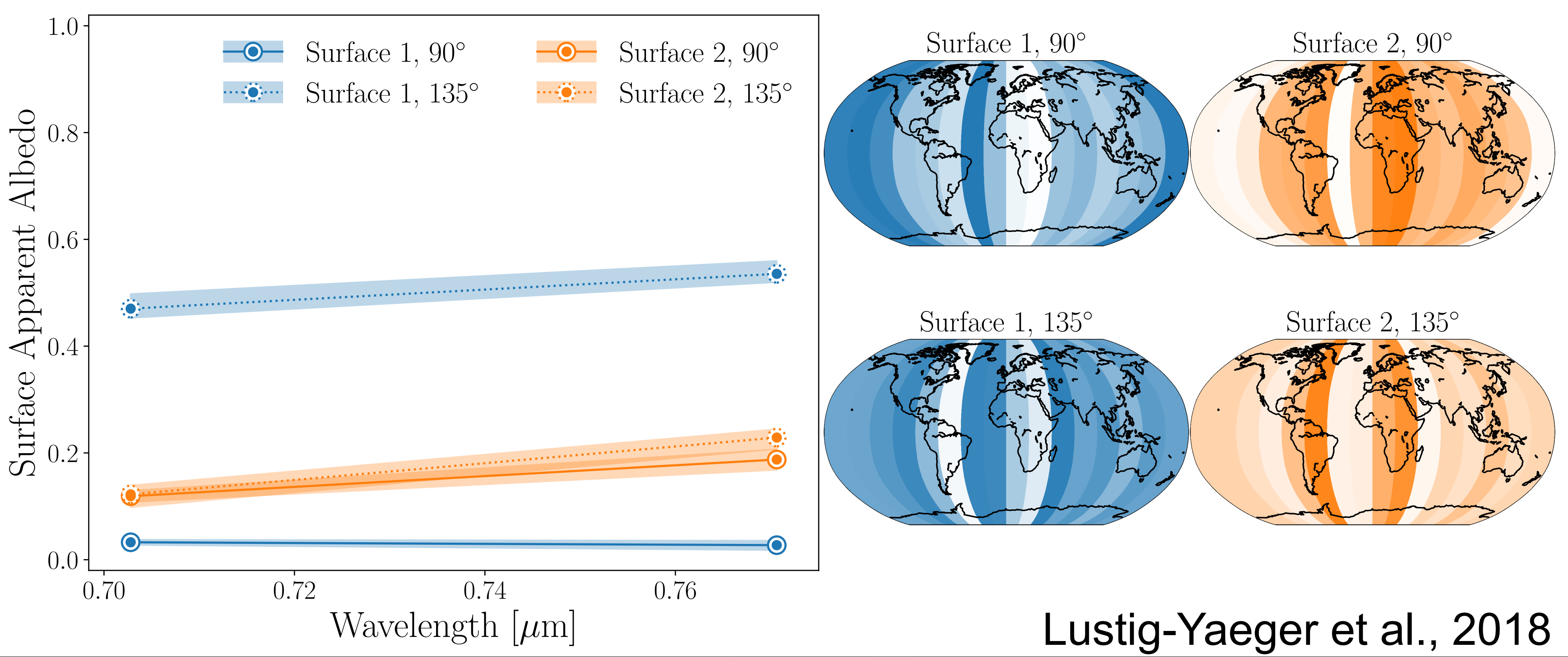
Earth



Robinson et al., 2014
LCROSS images of Earth

Ocean glint at NIR wavelengths will **not** be possible for Proxima Cen b with JWST (Meadows et al., 2018b)
Ocean glint will be possible for some targets with future direct imaging missions such as LUVOIR (Lustig-Yaeger et al., 2018).

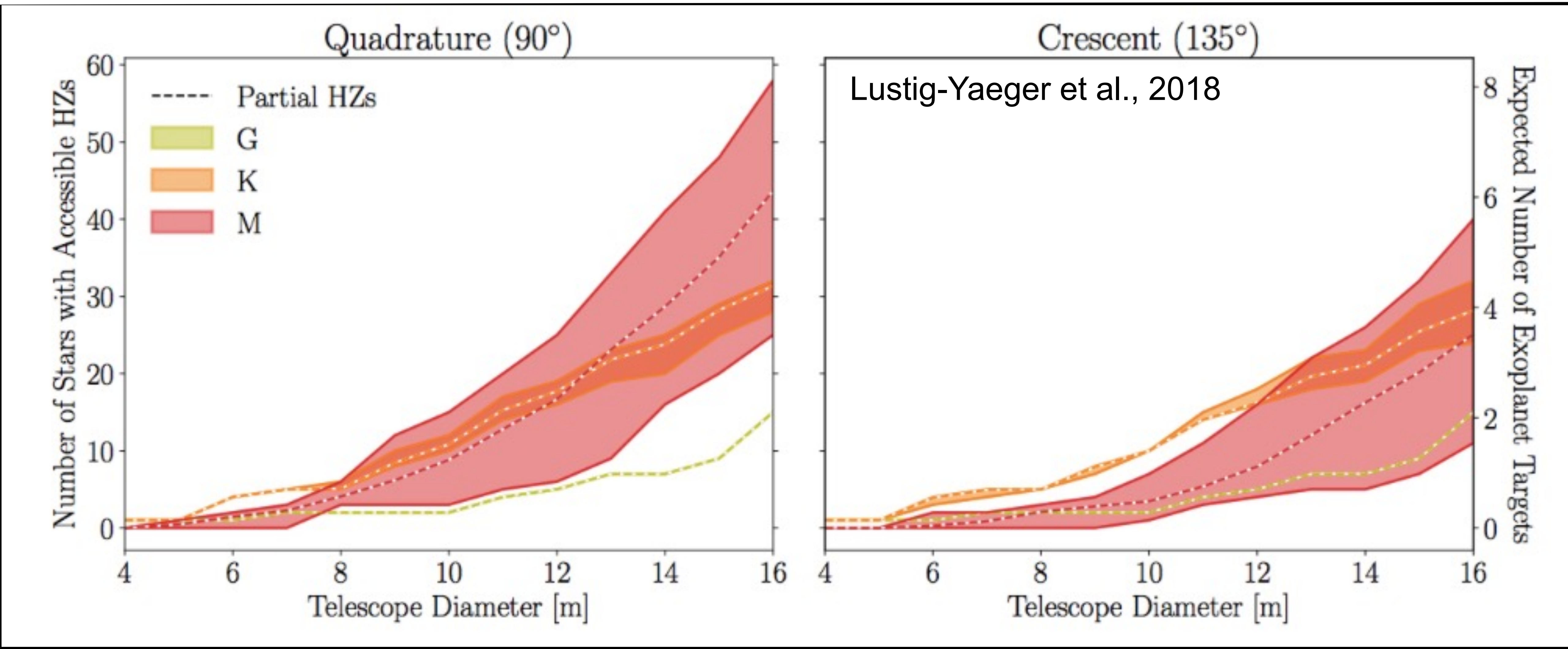
Exoplanet Temporal Sampling and Ocean Mapping



Lustig-Yaeger et al., 2018

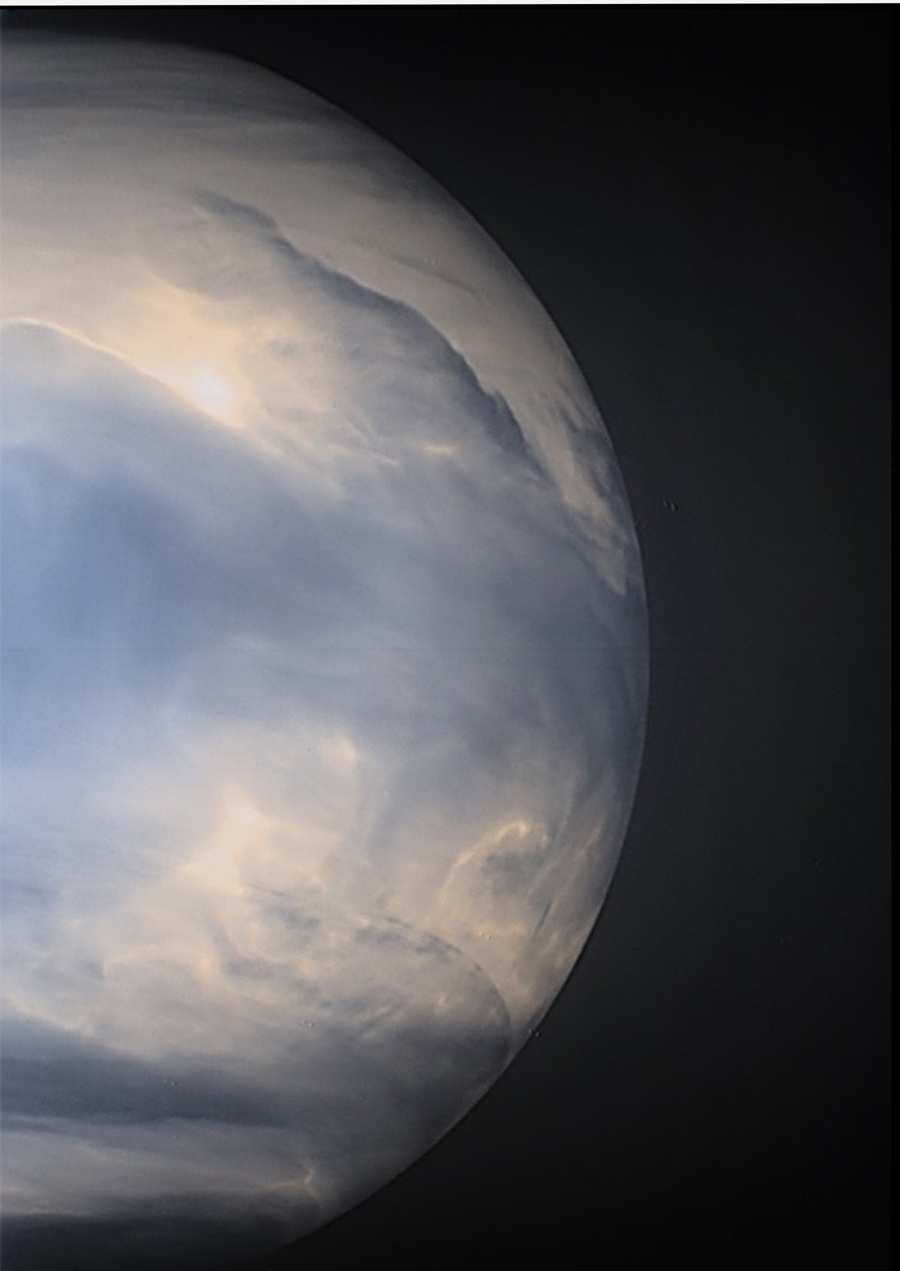
- Time-resolved (1hr), multi-wavelength observations map and identify surfaces that change reflectivity behavior with phase – more sensitive for ocean detection.
- *We can do this while acquiring a long-duration spectrum on a target.*
- The presence of an ocean can also be important for disequilibrium biosignature interpretation (Krissansen-Totton et al., 2016; 2018).

Ocean Mapping Yields



Yield could be 1-10 detectable oceans for a direct imaging mission with a 6-15m mirror

Venus as an Exoplanet



Venus' history of ocean loss may be common for terrestrial exoplanets, especially those with very high levels of insolation.

Venus has very high rates of CO_2 photolysis, in an H-poor environment, but does NOT build up O_2. This is due to catalysts…we think.

Better understanding these catalytic reactions can improve our understanding of O_2 false positives for M dwarf planets. (Wong et al., in prep)

Task B: The Earth Through Time

VPL geologists and geochemists work to understand the environment and life on early Earth

What is Task B about? Early Earth as a series of habitable planets

- What were the prevailing environmental conditions for different phases of early Earth?
- How and when did the metabolisms that dominated early Earth evolve?
- How do we recognize signs of habitability and life on planets like early Earth?

Origins of Biological Processes on Earth Earth

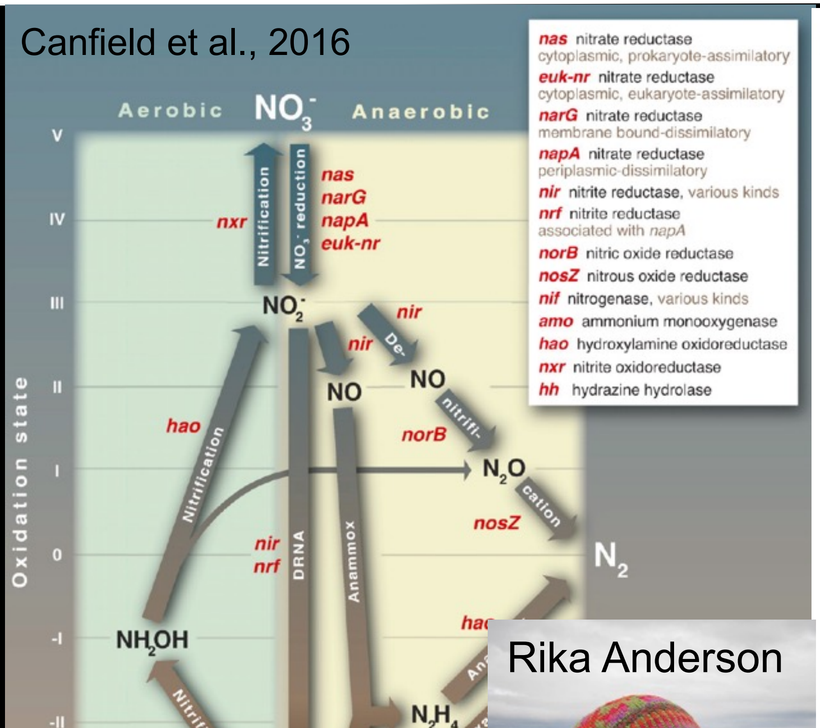
- Origins of Methanogenesis: Examine rocks from early Neoarchean to Paleoarchean to search for evidence of methanogenesis using C isotope analysis coupled to new tool of Ni isotope fractionation (independent proxy for CH4 cycling)

- The Early Nitrogen Cycle: Top-down and bottom-up geochemical and bioinformatics techniques to understand N over Earth history.

- N cycle in Proterozoic oceans: denitrification experiments under Cu limitation and excess to test whether incomplete denitrification causes N and/or C fractionation → then see if these signatures exist in rock record

Nitrogen throughout Earth's History

Canfield et al., 2016



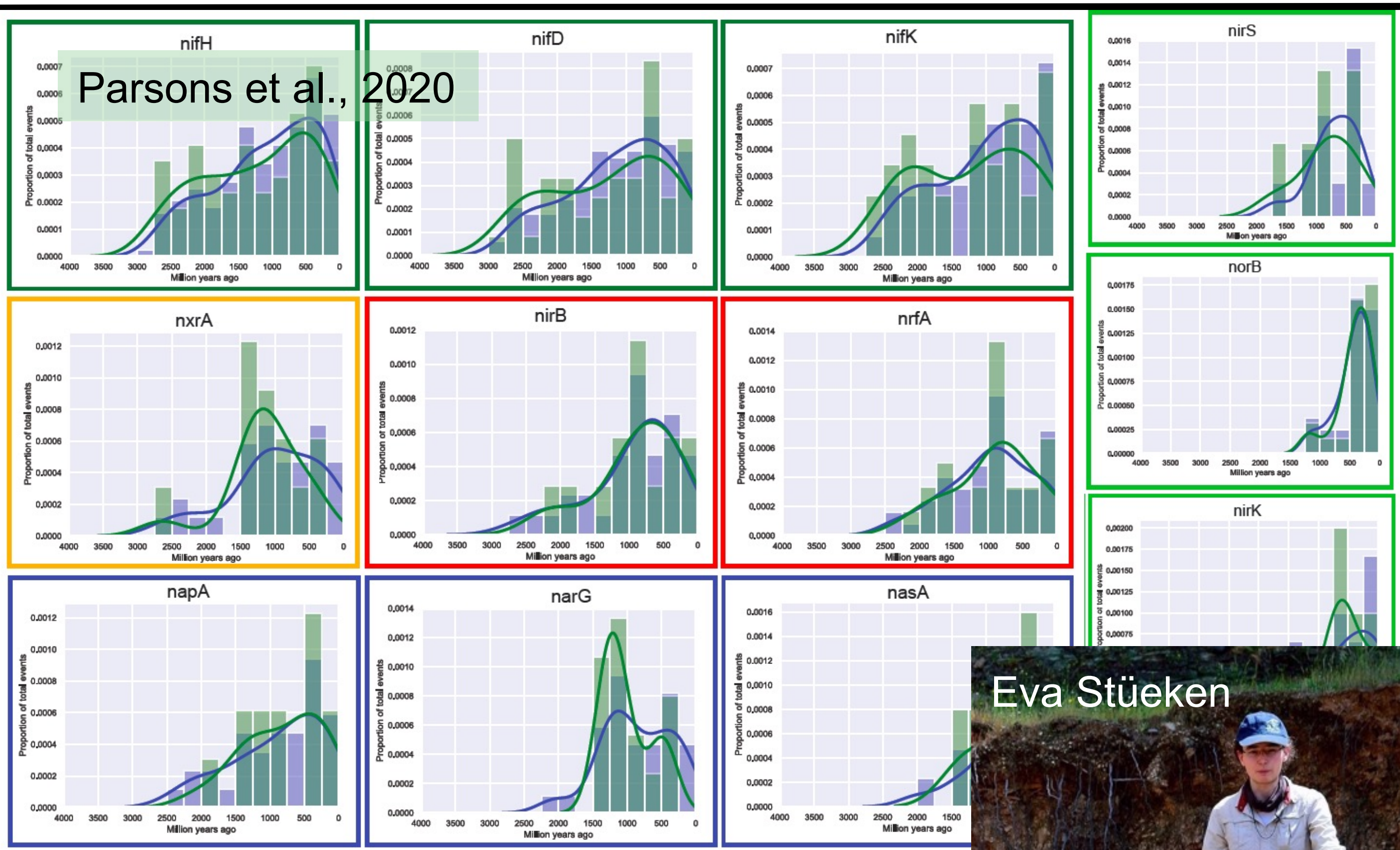
Rika Anderson

Results Summary

1. Nitrogen fixation **early**
2. Relatively early rise of **DNRA**
3. Denitrification from **nitrate** spread earlier than denitrification from **nitrite**
4. Rise in HGT of **nitrite** metabolism ~1.5 Ga: mid-Proterozoic **rise in** O_2.

R. Anderson

Parsons et al., 2020



speciation, loss, HGT events: blue bars
HGT events: green bars

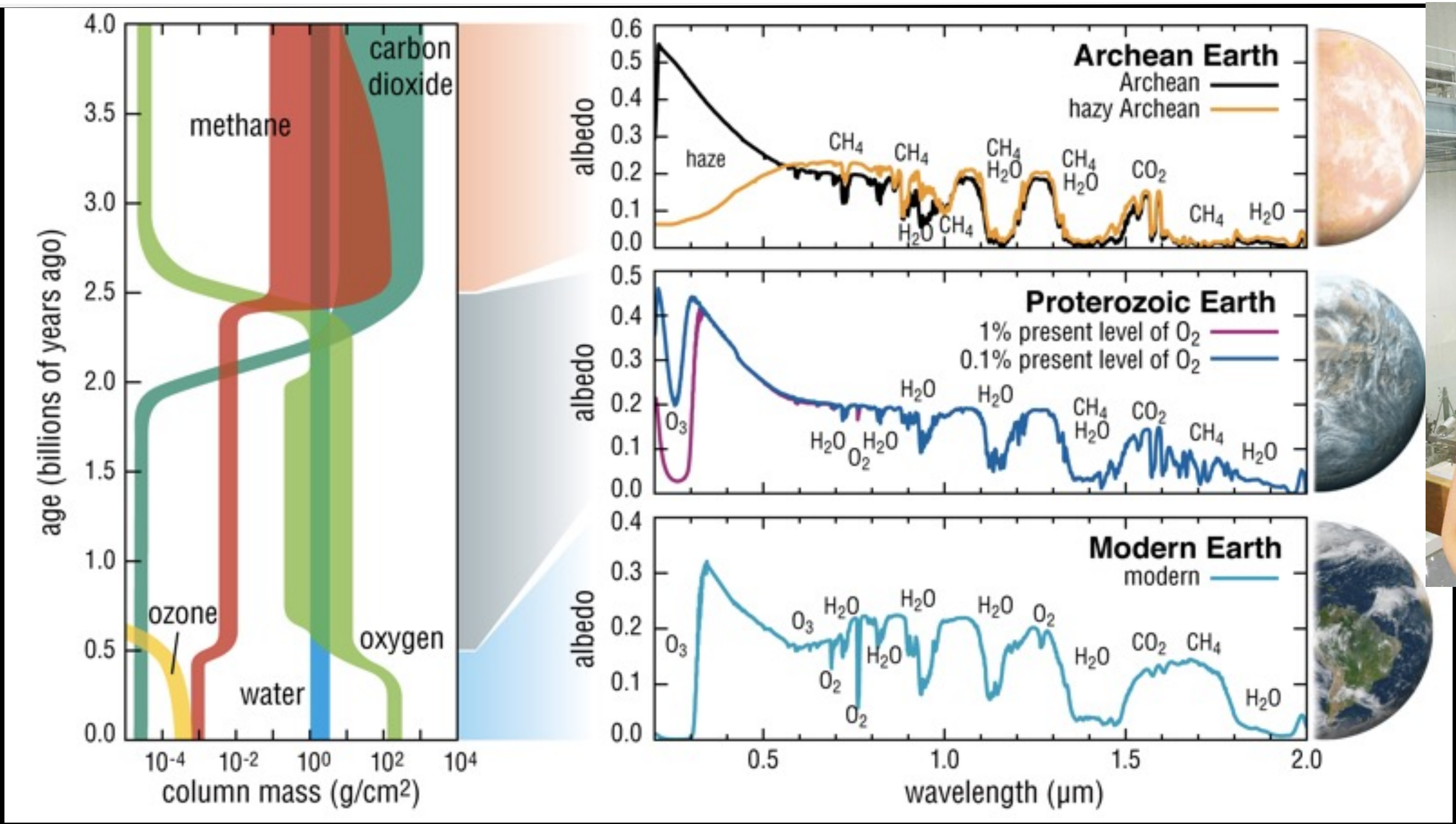
- nitrogen fixation
- denitrification from nitrate
- denitrification from nitrite
- nitrification
- DNRA

Eva Stüeken

By combining knowledge of when new metabolic processes first evolved (from the rock isotope record) with when those capabilities transferred to multiple organism (from the genomic record) we can estimate when certain metabolisms dominated the early Earth environment.

This helps us understand new potential biosignatures in their environmental context.

Simulating Life's Impact on Observables Over Eons



Segura et al., 2007; Meadows et al., 2008; Arney et al., 2016, 2017; Olson et al., 2018

The Virtual Planetary Laboratory

Models & Data | Tasks | Science | Mission Impact

Solar System Analogs
3-D Earth model
1-D Climate / Chemistry
Solar System Model

Earth as an exoplanet: polarization + glint in 3-D
Venus as an exoplanet: SED effects and O_2 chemistry
Solar System spectra + polarization, dust, background, and noise for exoplanetary study

The Earth Through Time
1-D/3-D Climate/Chemistry
Reactive Transport Modeling
Ancient Earth field studies
Laboratory experiments

Environments of early Earth
Origins of metabolisms
Early Earth biosignatures
Paleobarometry

The Habitable Planet
Planet formation
Coupled planet evolution: star-orbit atmosphere interior
1-D/1.5-D/3-D Climate/Chemistry
Stellar Observations

Co-evolution of star-disk-planets
Exploring the Habitable Zone
Diverging evolutionary pathways
Volatile-rich migrated planets
Recovery of habitability

The Living Planet
Biogenic gas fluxes
Photosynthesis gas-SED lab
1-D/3-D Climate/Chemistry
Coupled biosphere evolution: atmosphere-surface-interior

Biogenic gases of anoxic environments
Limits of photosynthesis
False positive biosignature assessments
Biosignatures in context
Improved biosignature assessment

Observer

Mission Impact

Improved detection of small HZ planets

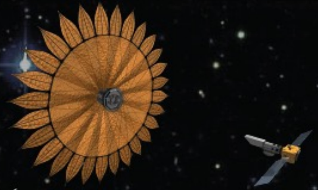
Combined modeling and observations for target prioritization

Enhanced observation planning through:

terrestrial evolution
biosignatures + false positives
synthetic observations
observational discriminants

Exoplanet and retrieval models for data analysis

Identification of optimum and synergistic observations for exoplanet characterization

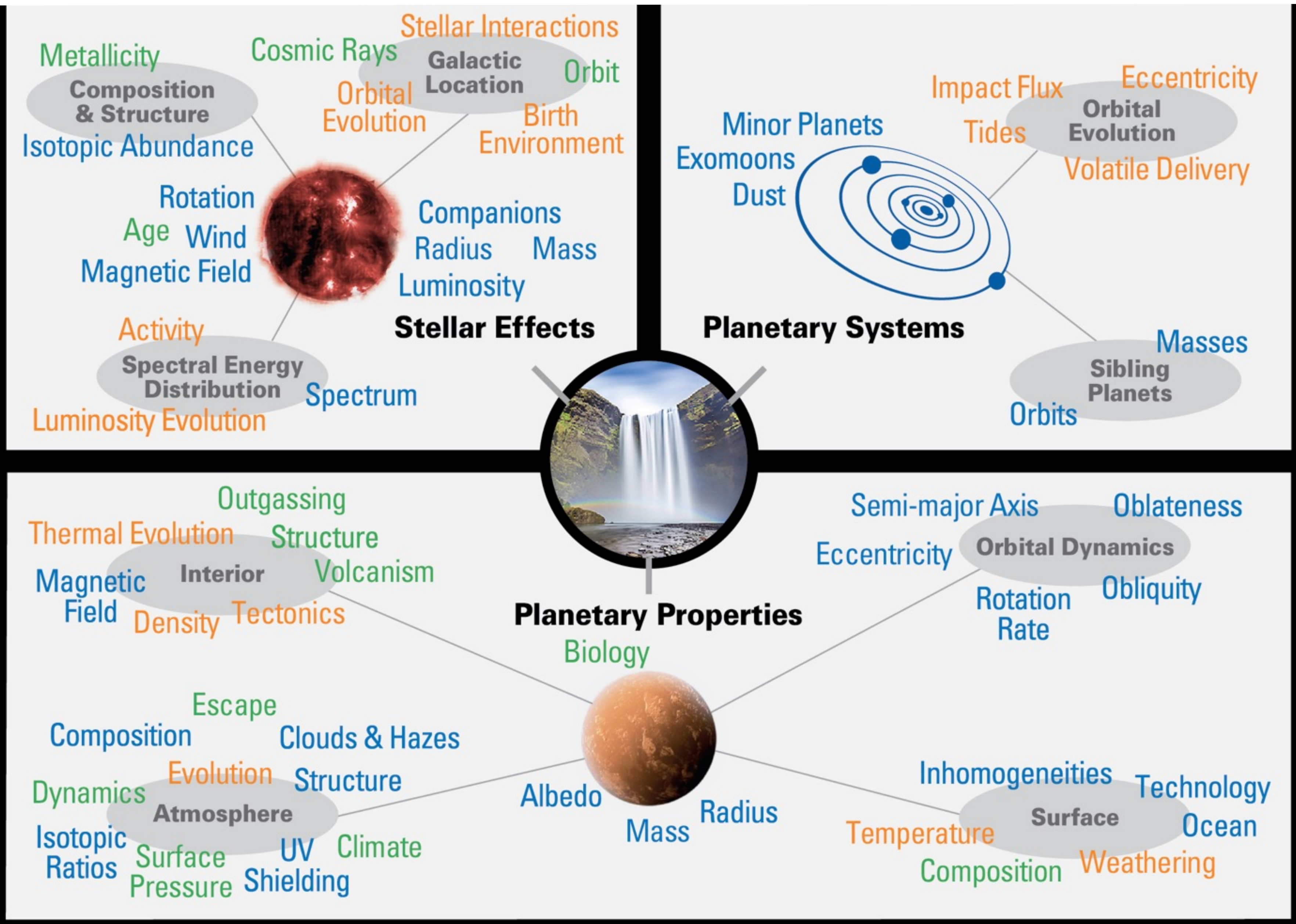


Inform measurement requirements for instrument and telescope design

What is Task C About? The factors and interactions affecting habitability

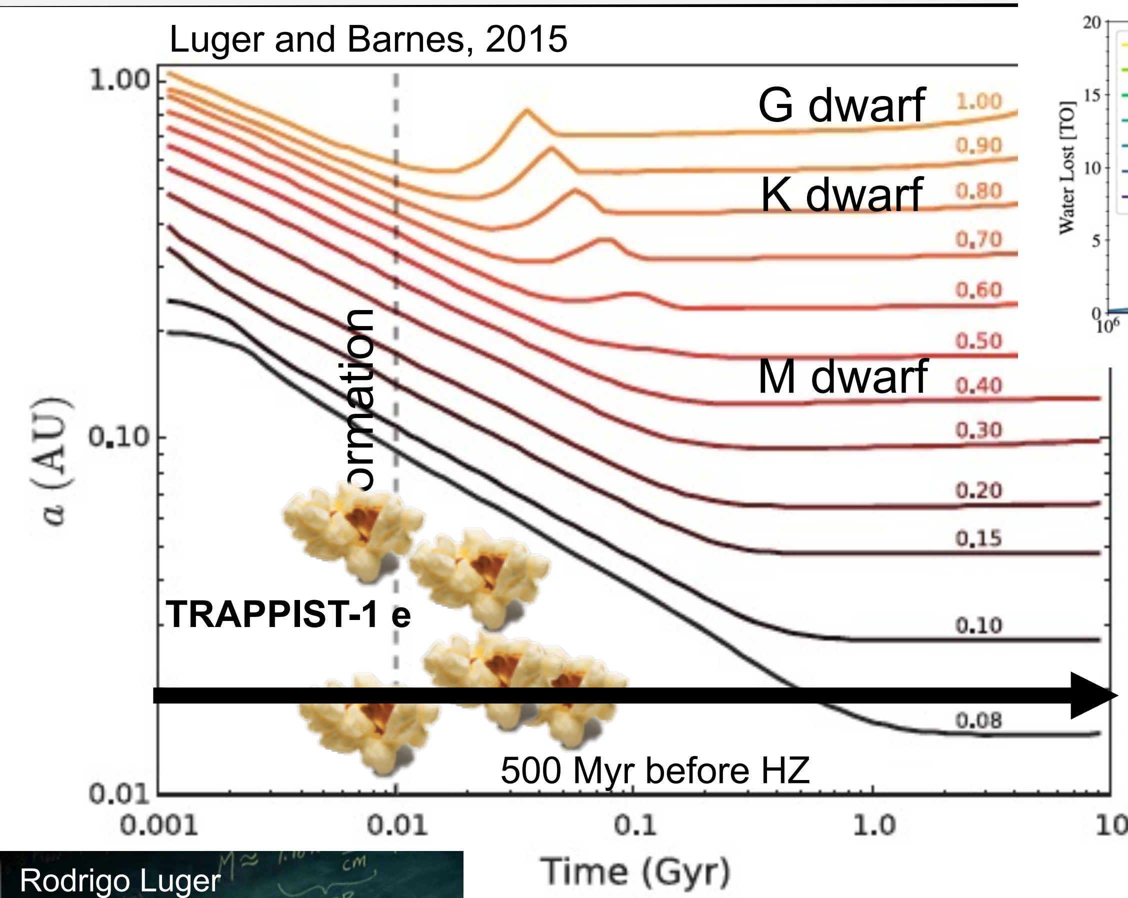
- Planet Formation and Migration (processes of formation, initial planetary properties)
- Planetary Evolution (diversity of plausible environments, likelihood that primordial atmosphere lost, water retained; track atmospheric escape, outgassing, surface sinks, heat fluxes, atmospheric evolution for terrestrial, volatile-rich and synchronously rotating planets)
- Planetary Environments and Observational Discriminants (assess habitability for evolutionary paths modeled and identify key environmental observational discriminants).

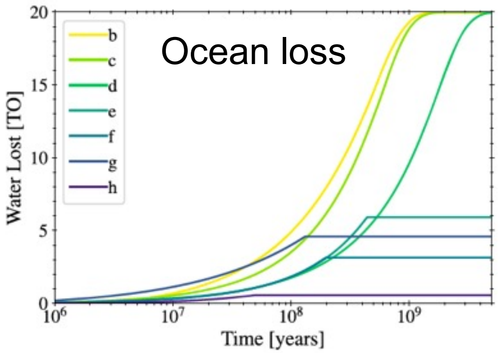
Factors and Evolutionary Processes Affecting Habitability

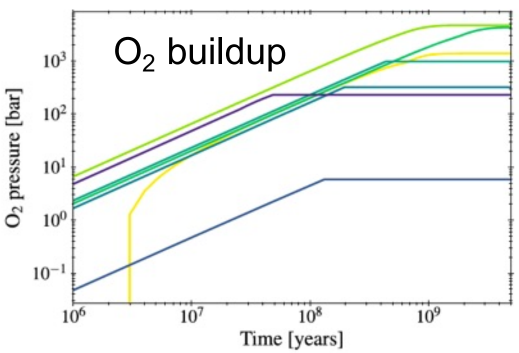


Meadows & Barnes, 2018

Stellar evolution impacts atmospheric composition, climate and habitability

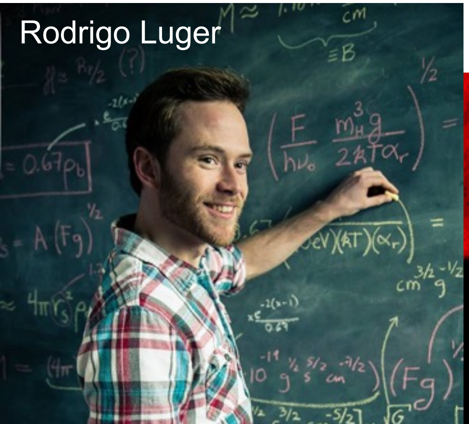






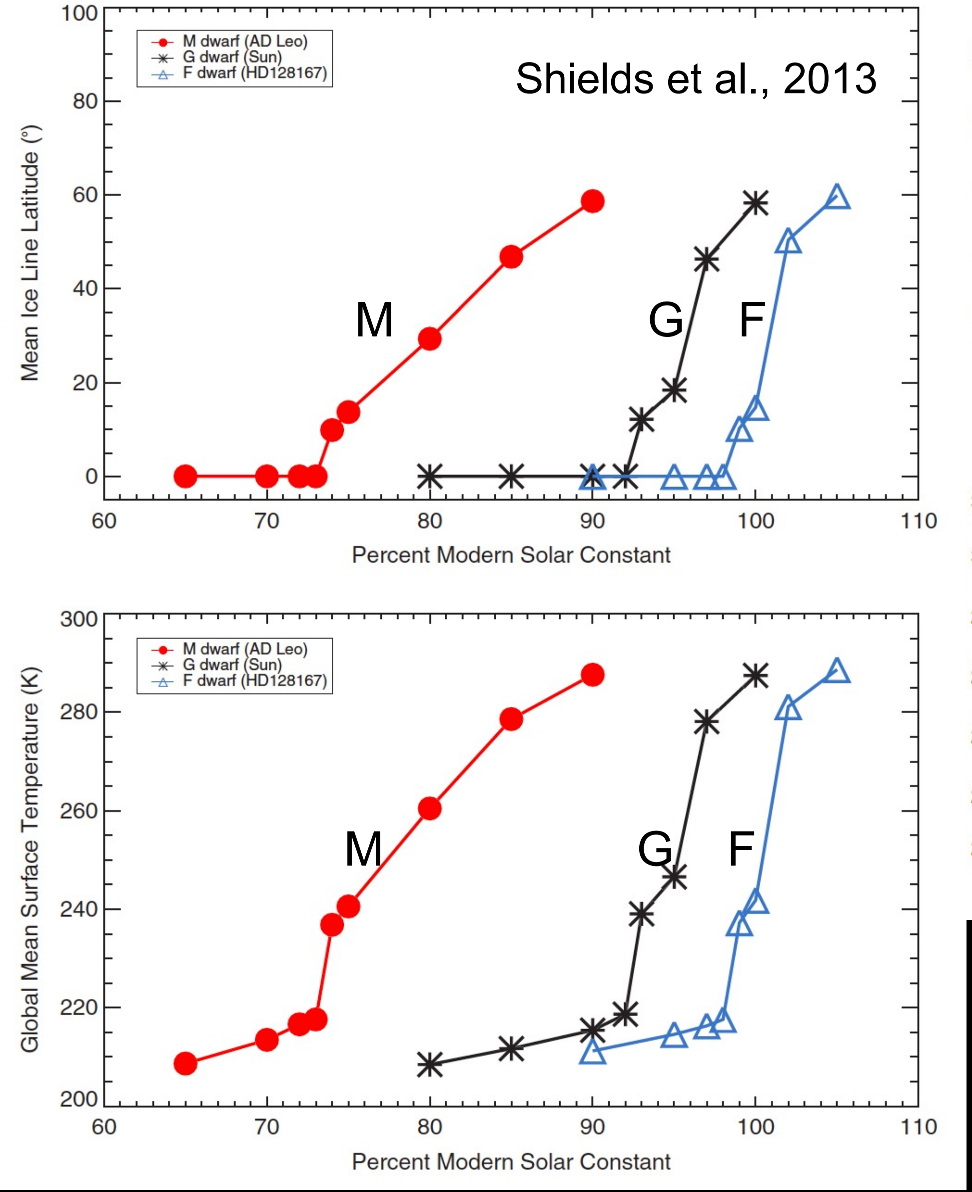
TRAPPIST-1 — Surface T (K) — Lincowski et al., 2018

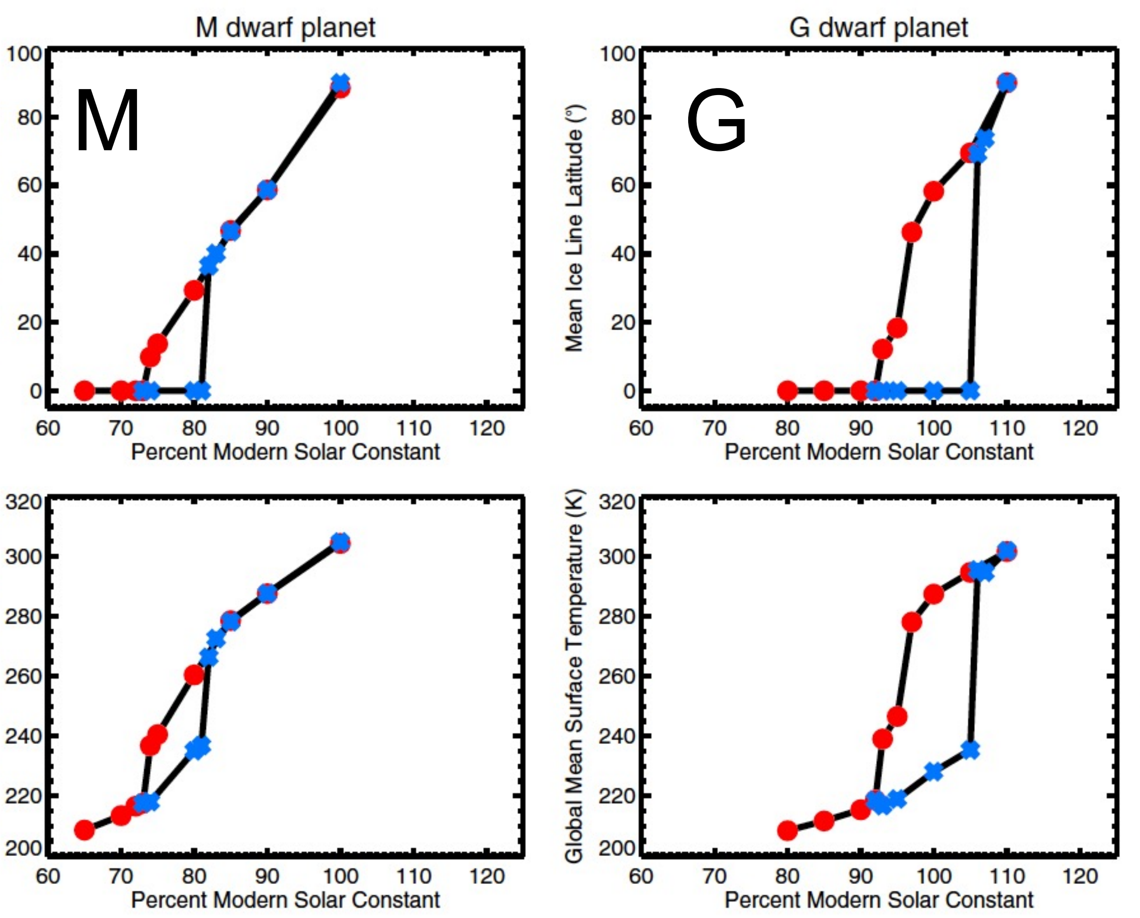
	b	c	d	e	f	g	h
Aqua planet, clear				279			
Aqua planet, cloudy 1 bar				282			
O_2, desiccated 10 bar	406	343	284	244	208	183	152
O_2, desiccated 100 bar	386	329	273	237	201	180	153
O_2, outgassing 10 bar	560	438	343	271	225	200	166
O_2, outgassing 100 bar	556	476	407	314	261	201	163
Venus, cloudy 10 bar		616	398	304	263	243	200
Venus, clear 10 bar	714	633	593	496	407	336	259
Venus, cloudy 92 bar		779	634	551	527	491	398
Venus, clear 92 bar	927	816	743	689	642	572	465



- Late K and and all M dwarfs undergo a significant super-luminous phase as they contract
- Any planet that forms in what will become the main sequence habitable zone of these stars can be subjected to very high levels of radiation for up to a Gyr which may severely modify atmospheric composition and climate.

Stellar spectrum impact on ice-albedo climate feedback



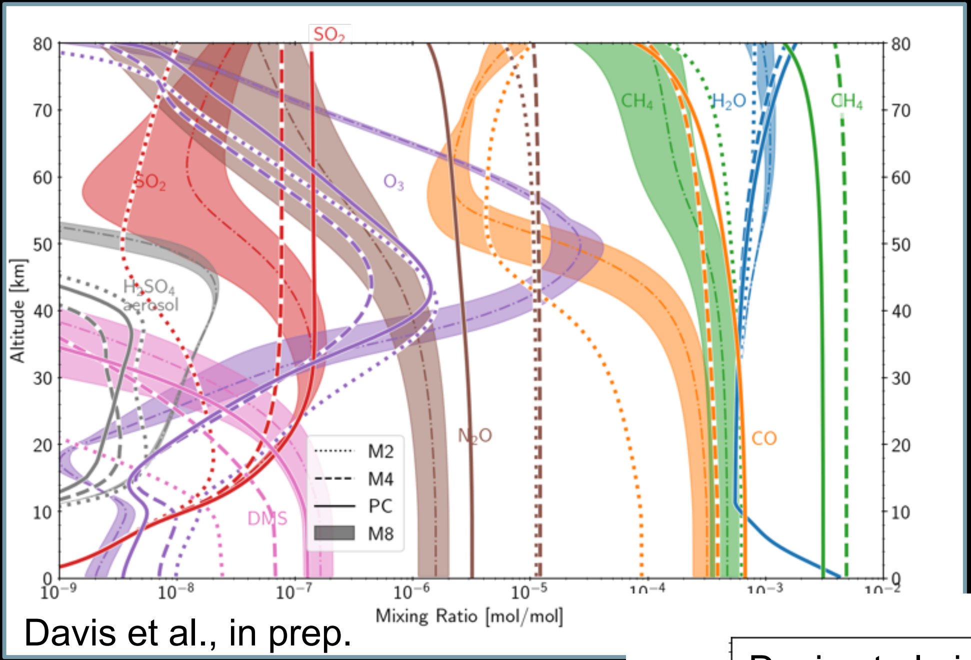


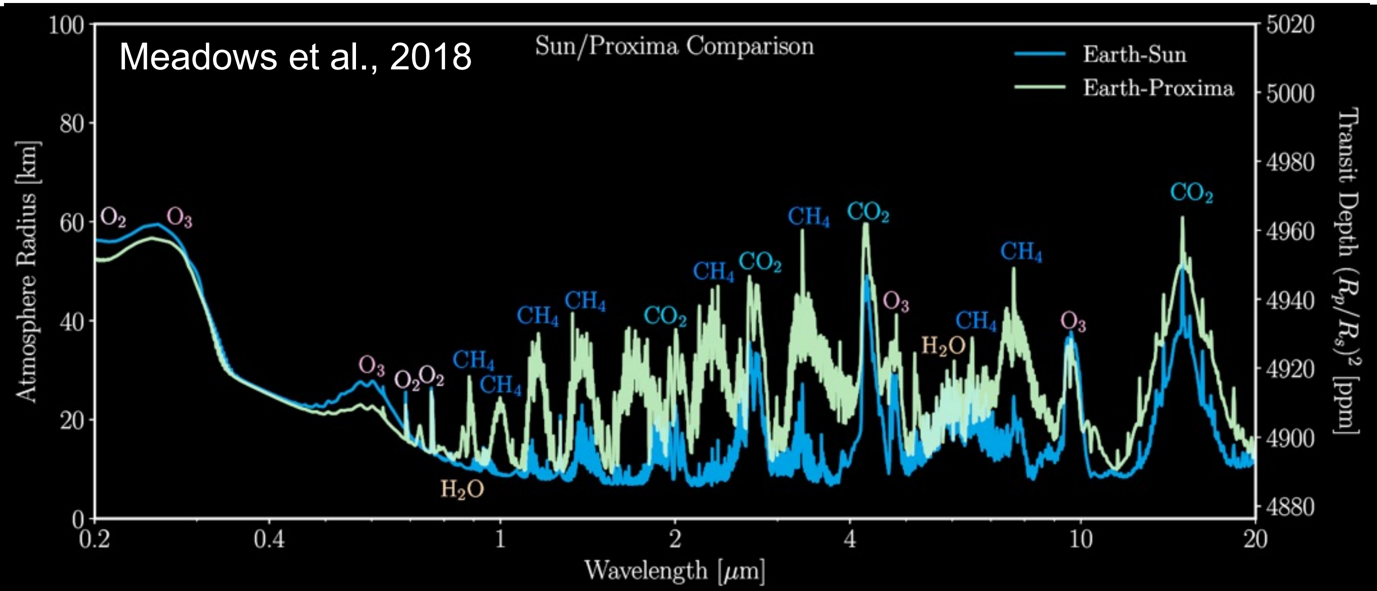
Shields et al., 2014

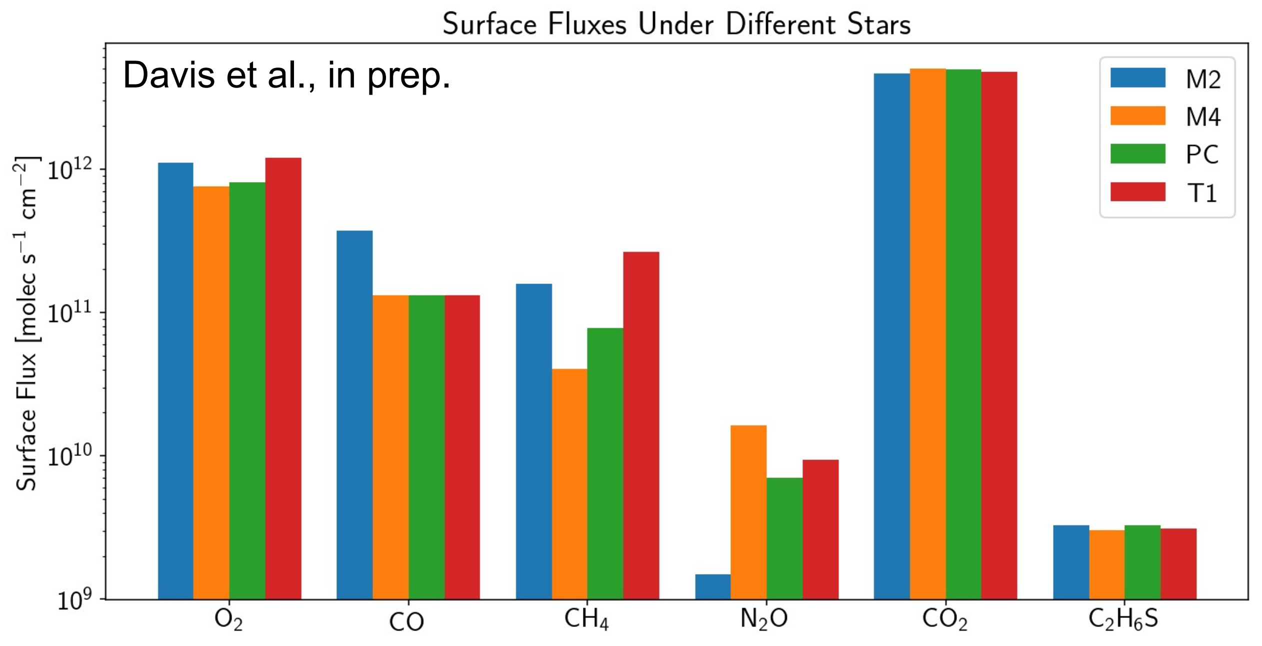
3D GCM modeling showed that the interaction of the host star with a planet's surface type could strongly affect the climate outcome, compared to Earth. Ice absorbs radiation in the near-infrared but reflects visible light, so that:

- M dwarf planets can remain ice free or with small polar caps under far lower insolation.
- M dwarf planets take very little extra insolation to melt out of a snowball state.

Stellar spectra modify atmospheric composition







CH_4, N_2O and O_3 are strongly affected (and all are terrestrial biosignatures).

Compositional modification impacts observed spectra and retrieved surface fluxes for biosignatures.

The Virtual Planetary Laboratory

Models & Data	Tasks	Science
The Solar System Analogs 3-D Earth model 1-D Climate / Chemistry Solar System Model		Earth as an exoplanet: polarization + glint in 3-D Venus as an exoplanet: SED effects and O_2 chemistry Solar System spectra + polarization, dust, background, and noise for exoplanetary study
The Earth Through Time 1-D/3-D Climate/Chemistry Reactive Transport Modeling Ancient Earth field studies Laboratory experiments		Environments of early Earth Origins of metabolisms Early Earth biosignatures Paleobarometry
The Habitable Planet Planet formation Coupled planet evolution: star-orbit atmosphere interior 1-D/1.5-D/3-D Climate/Chemistry Stellar Observations		Co-evolution of star-disk-planets Exploring the Habitable Zone Diverging evolutionary pathways Volatile-rich migrated planets Recovery of habitability
The Living Planet Biogenic gas fluxes Photosynthesis gas-SED lab 1-D/3-D Climate/Chemistry Coupled biosphere evolution: atmosphere-surface-interior		Biogenic gases of anoxic environments Limits of photosynthesis False positive biosignature assessments Biosignatures in context Improved biosignature assessment

Observer

Mission Impact

Improved detection of small HZ planets

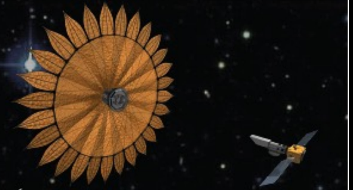
Combined modeling and observations for target prioritization

Enhanced observation planning through:

terrestrial evolution
biosignatures + false positives
synthetic observations
observational discriminants

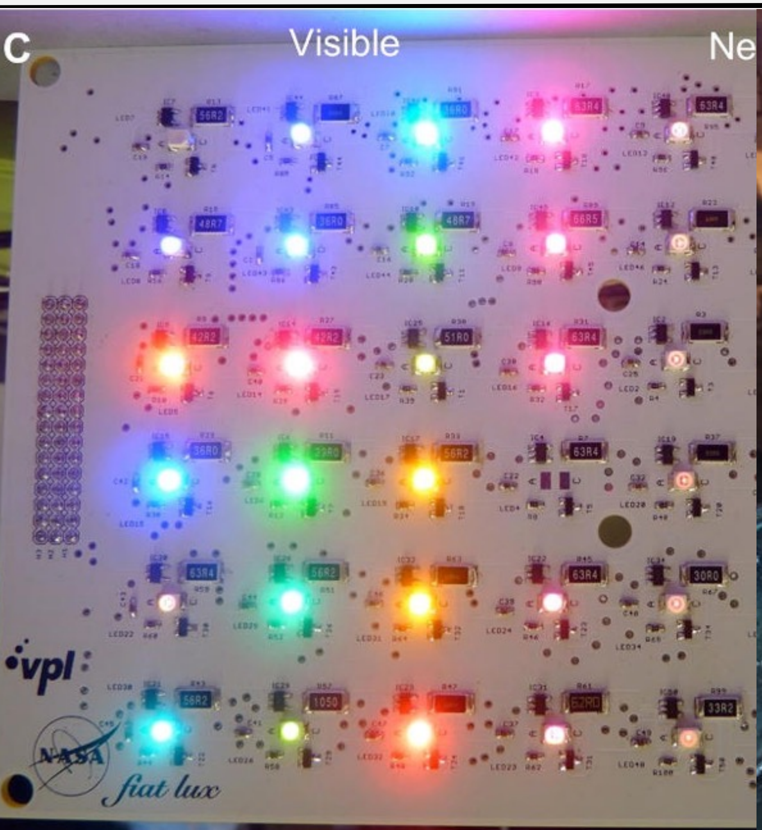
Exoplanet and retrieval models for data analysis

Identification of optimum and synergistic observations for exoplanet characterization



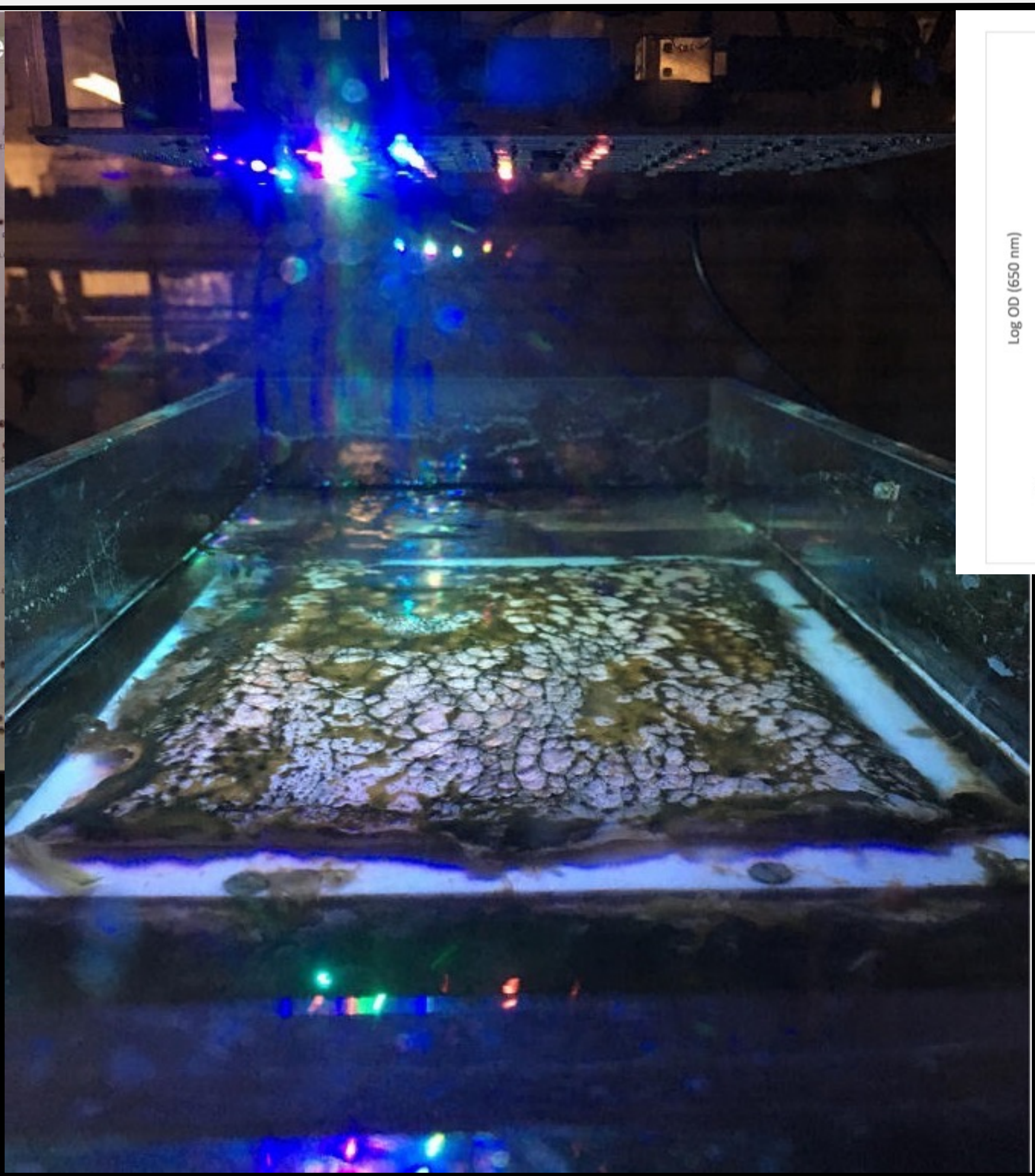
Inform measurement requirements for instrument and telescope design

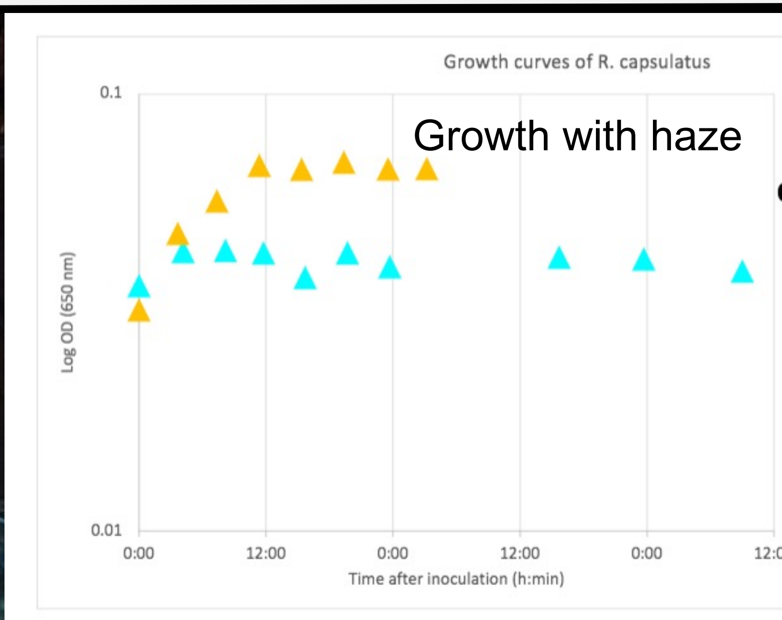
What is Task D about? Biosignature Identification and Assessment



Parenteau et al., 2018

Task D: Combines field and lab experiments with coupled chemical/climate/ecosystem models to explore the nature and detection of biosignatures

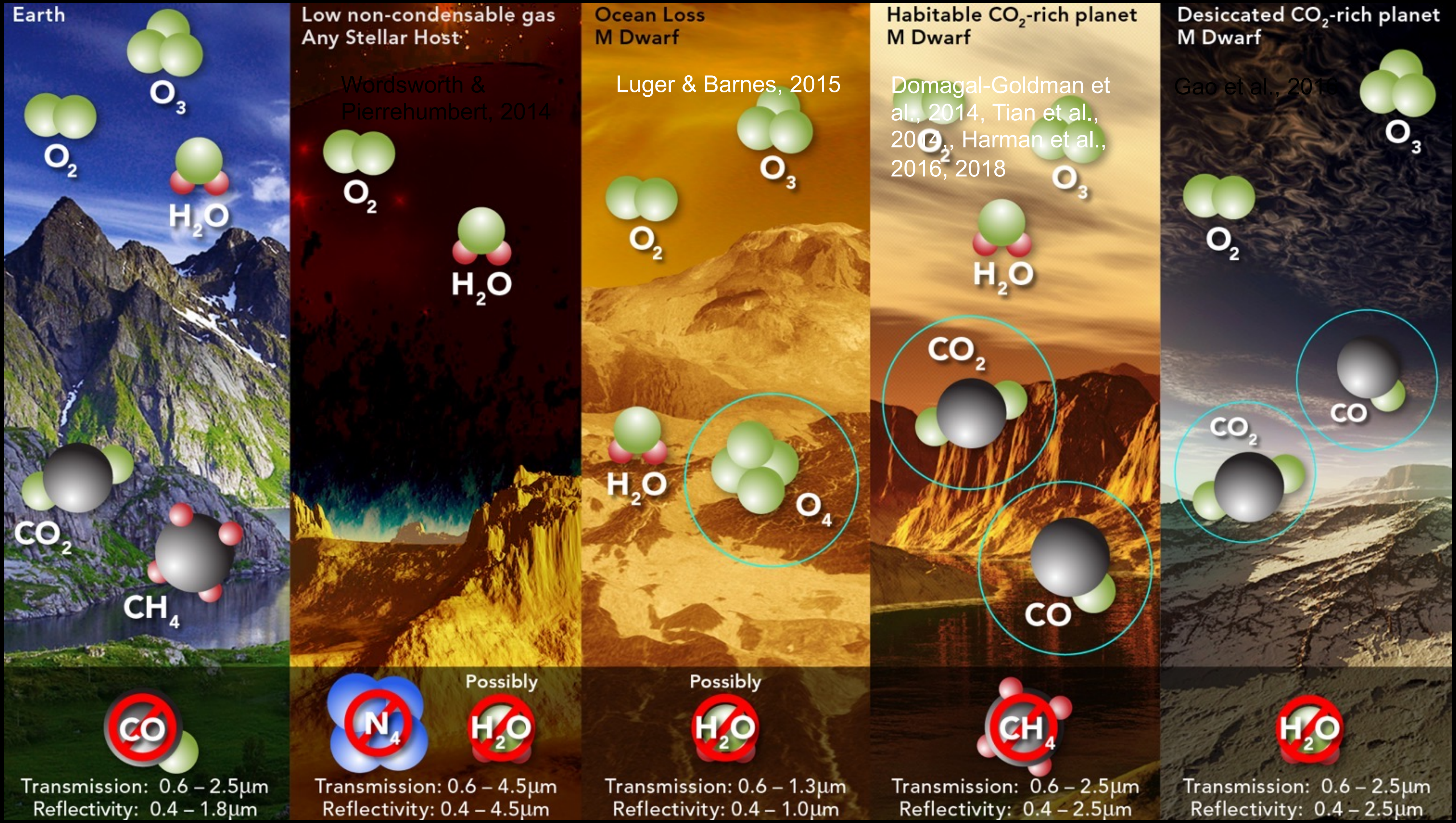




Identifies new biosignatures in the context of their environments

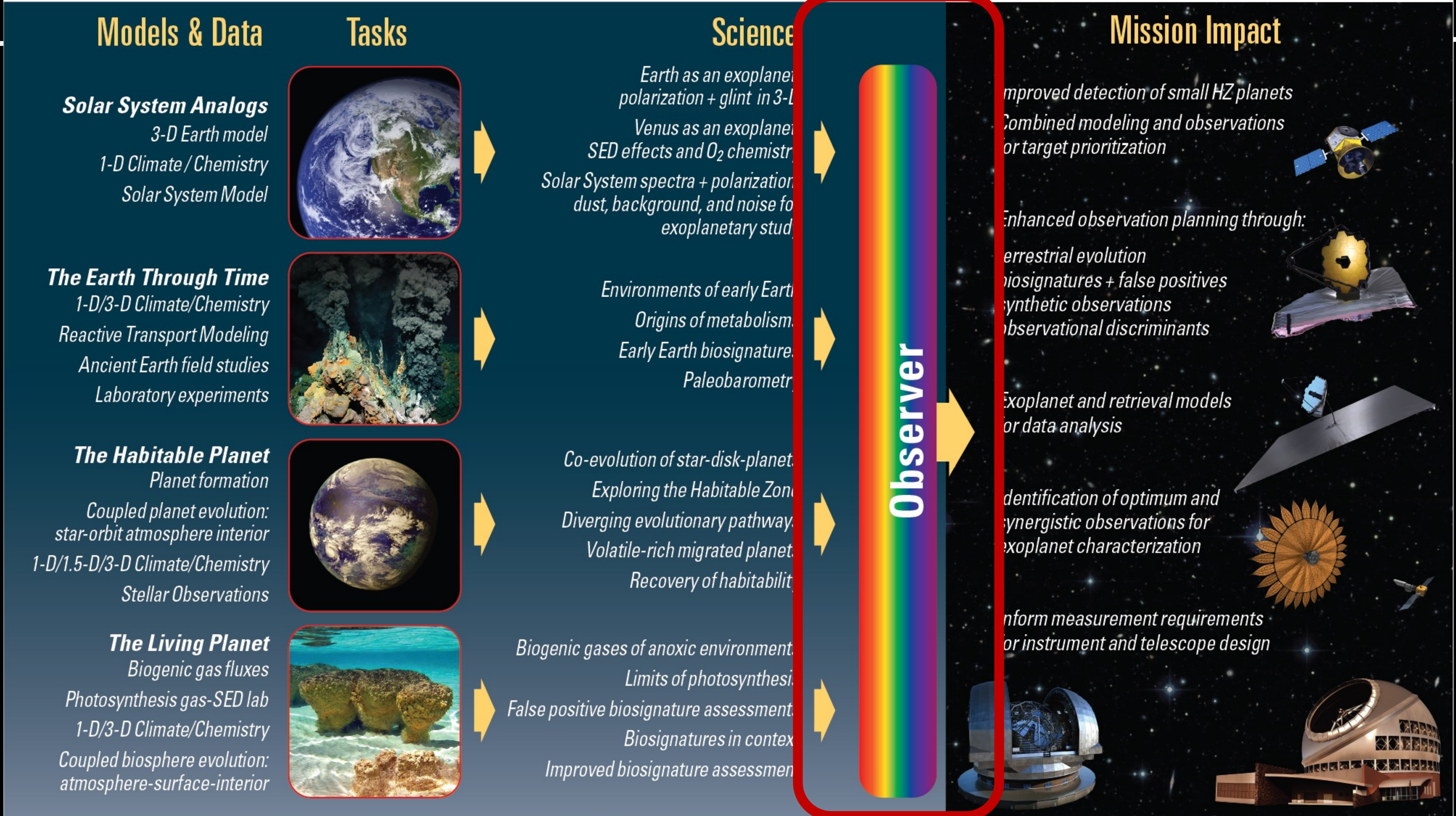
Develops probabilistic framework for biosignature detection including false positives and negatives.

Developing New Frameworks for Biosignature Interpretation

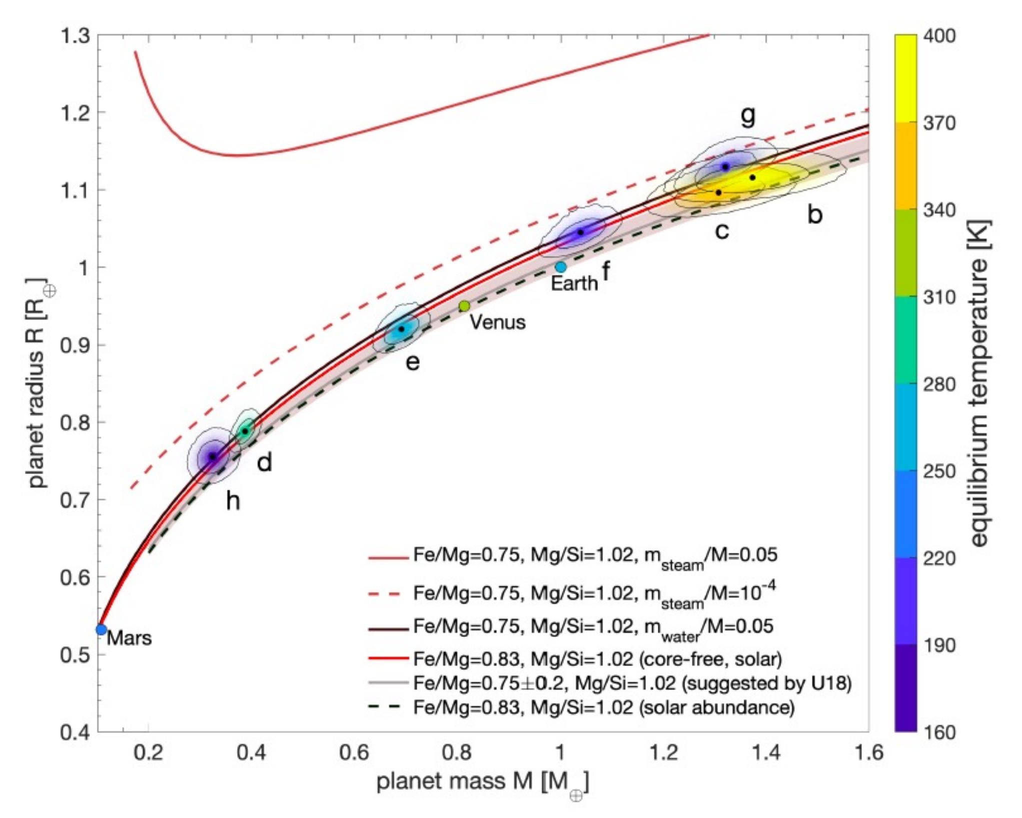


Holistic deep study of O_2, including false positives/negatives used as a prototype for biosignature assessment protocols (Meadows, 2017; Meadows et al., 2018b)

The Virtual Planetary Laboratory

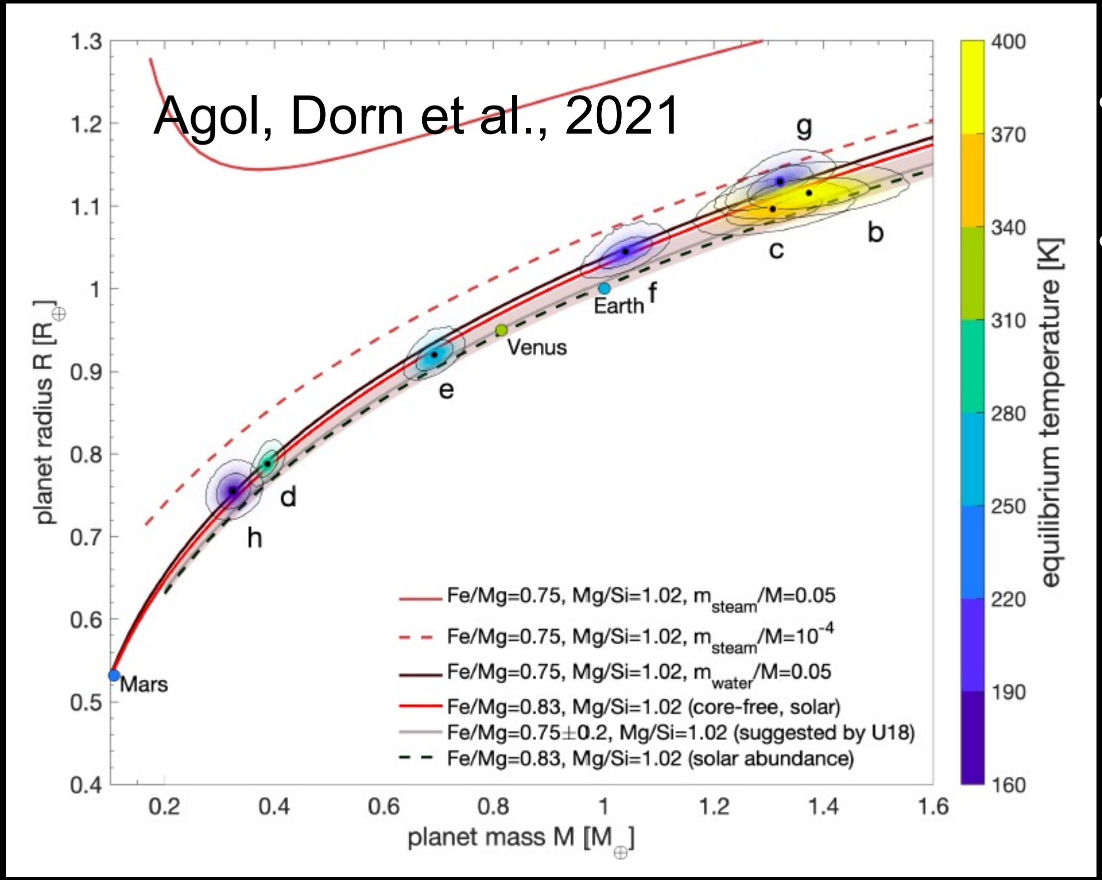


What is Task E about? Terrestrial exoplanet characterization

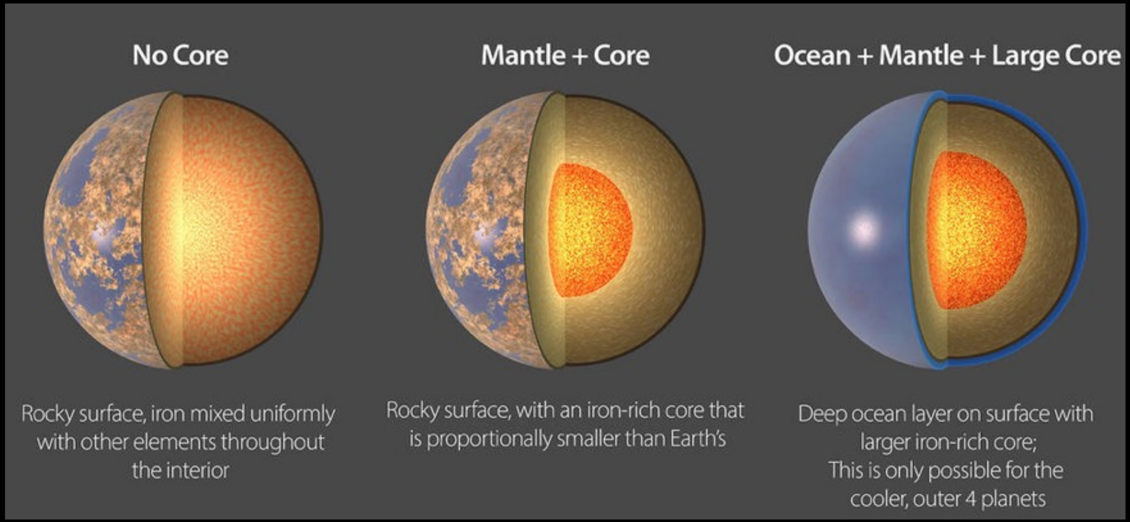


- Small exoplanet detection and assessment for target prioritization
- Characterizing the host star
- Spectroscopic simulation, detectability assessment and retrieval
- Testing observational techniques using JWST.

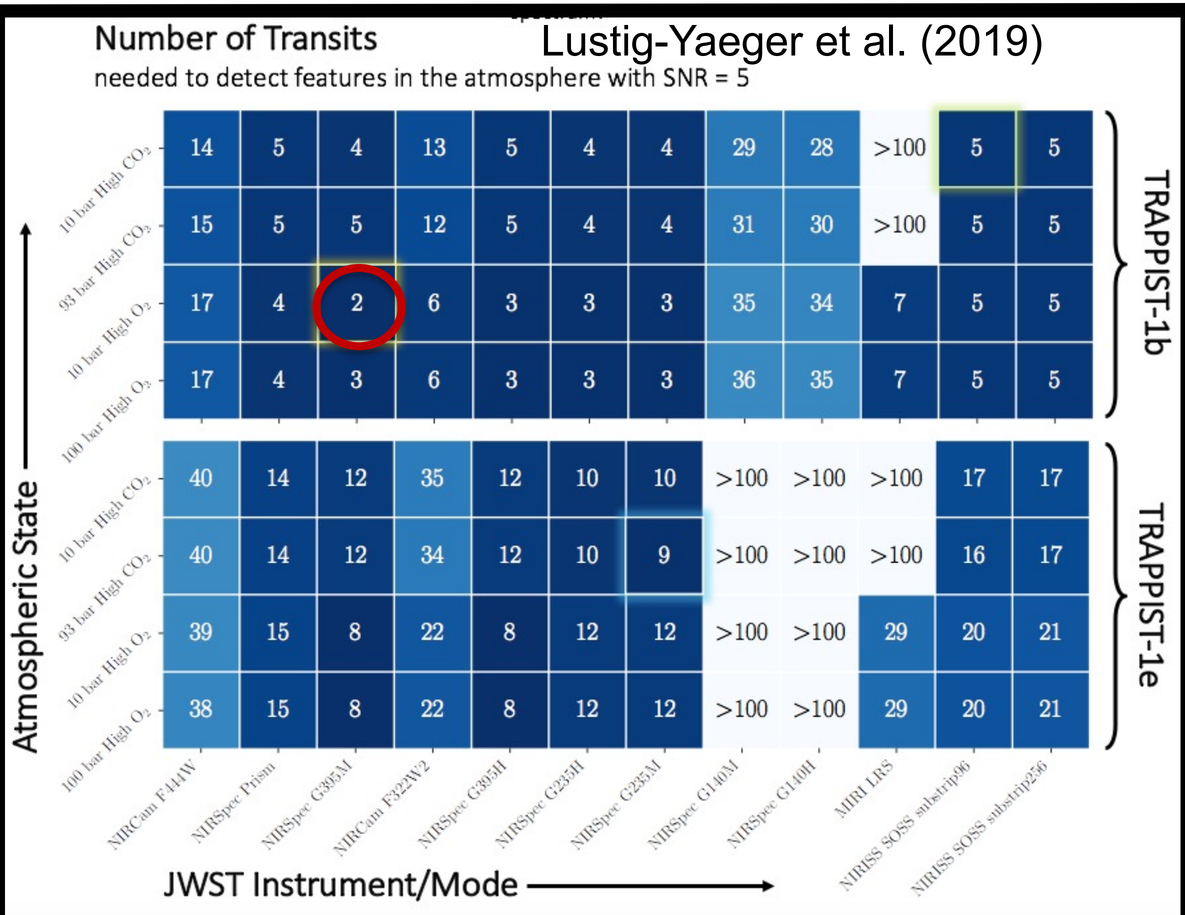
TTVs and high precision masses for tiny planets



- Transit timing variations provide masses for the TRAPPIST-1 planets that are terrestrial planets that are precise to 3-5%
- This is equivalent to an EPRV precision of 2.5 cm s^{-1} (2 orders of magnitude more precise than current limits!!).
- The sizes and precise masses now show the majority of the TRAPPIST-1 planets lying a long a similar compositional curve with a density less than Earth's.
  - Smaller iron core
  - No iron core (oxidized iron instead)
  - High volatile content (surface ocean or steam atmosphere).



Does It Have An Atmosphere?: Transmission and Emission.



Moreley et al., 2017, arXiv

Table 1. Number of transits or eclipses required to detect a Venus-like atmosphere[a]

Planet	Emission P = 0.1 bar	Emission P = 1.0 bar	Emission P = 10.0 bar	Transmission P = 0.01 bar	Transmission P = 0.1 bar	Transmission P = 1.0 bar
TRAPPIST-1b	6 (11)	9 (18)	17 (30)	23 (89)	11 (40)	6 (21)
TRAPPIST-1c	19 (37)	29 (58)	48 (92)	–	73 (50)	36 (25)
TRAPPIST-1d	–	–	–	59 (–)	25 (46)	13 (24)
TRAPPIST-1e	–	–	–	15 (–)	6 (66)	4 (71)
TRAPPIST-1f	–	–	–	73 (–)	27 (92)	17 (54)
TRAPPIST-1g	–	–	–	36 (–)	15 (–)	10 (76)
TRAPPIST-1h	–	–	–	16 (–)	6 (90)	4 (56)
GJ 1132b	2 (2)	2 (3)	3 (6)	27 (38)	13 (20)	11 (13)
LHS 1140b	–	–	–	–	– (96)	– (64)

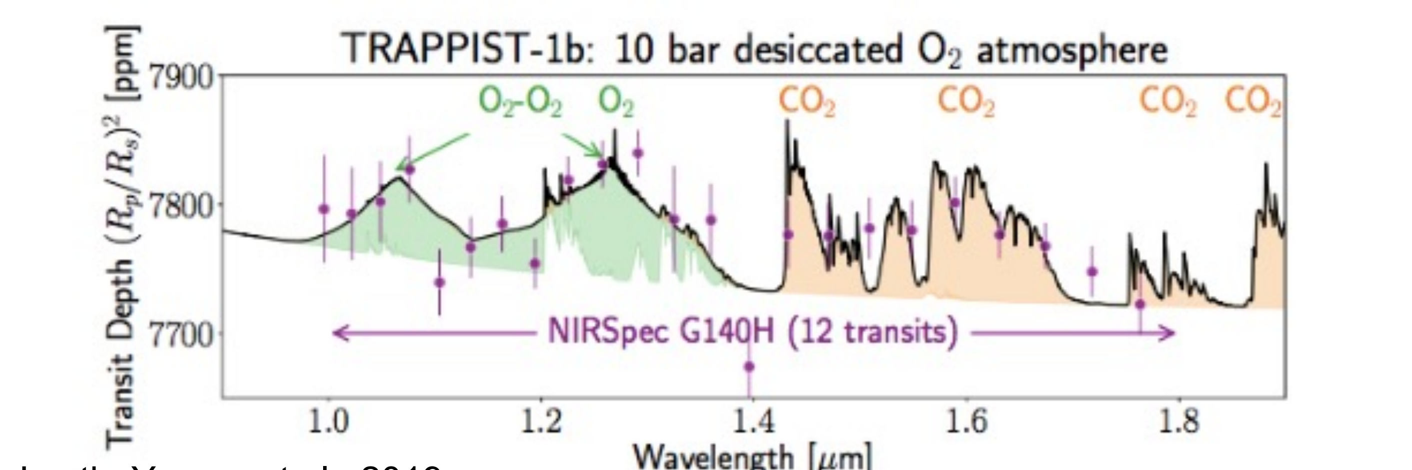
[a] The detection criteria are (1) for transmission spectra, the simulated data must rule out a flat line at 5σ confidence on average, and (2) for emission spectra, the band-integrated secondary eclipse must be detected at 25σ. We base our calculations on models with a Venusian composition, zero albedo, and planet mass equal to the measured values from TTVs or RVs. For the case in parentheses, we use an albedo of 0.3 and planet mass predicted by the theoretical mass/radius relation. The – mark denotes cases where over 100 transits or eclipses are needed.

Lustig-Yaeger et al., 2018 (see also Selsis et al., 2011; Turbet et al., 2016, Kreidberg & Loeb, 2016)

High hopes for JWST!

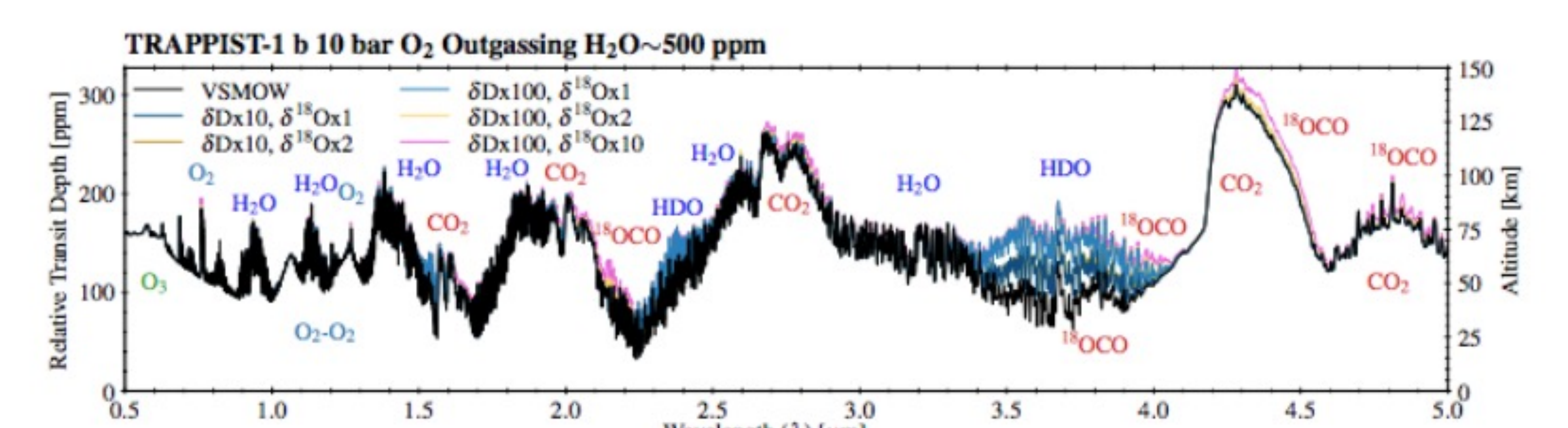
- A high molecular-weight atmosphere may be detected in as little as 2 transits with JWST, depending on atmospheric composition.

Does it have an ocean? JWST and TRAPPIST-1



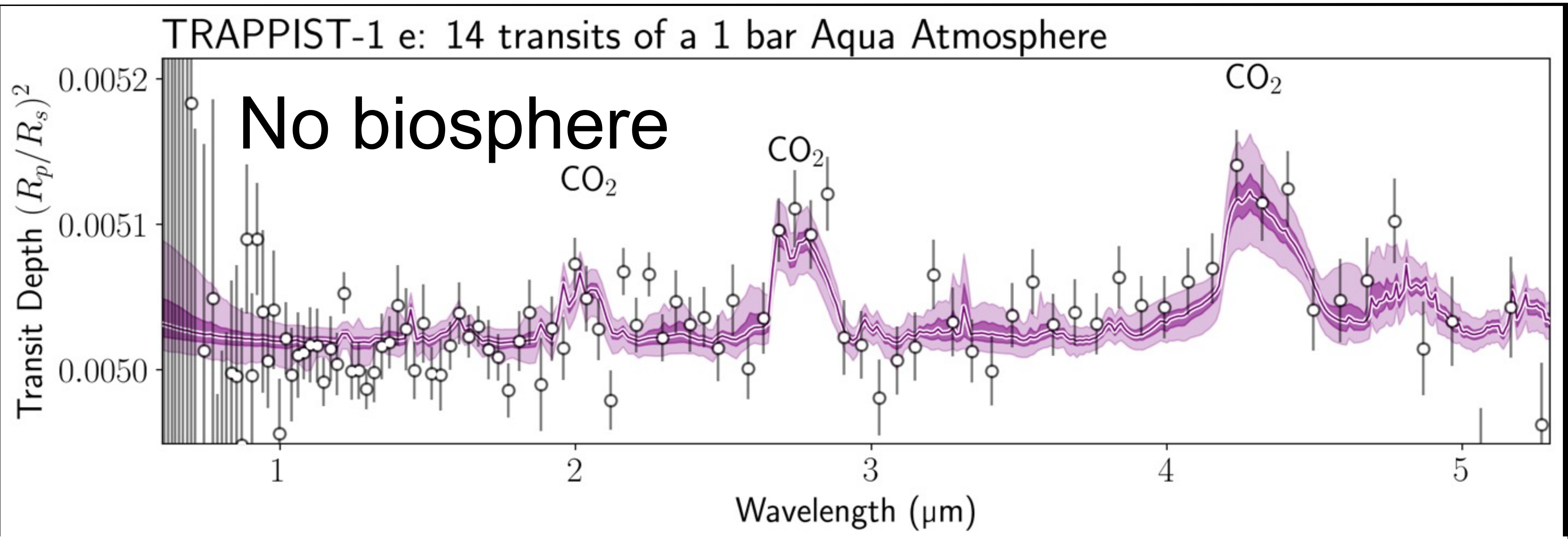
Lustig-Yaeger et al., 2019

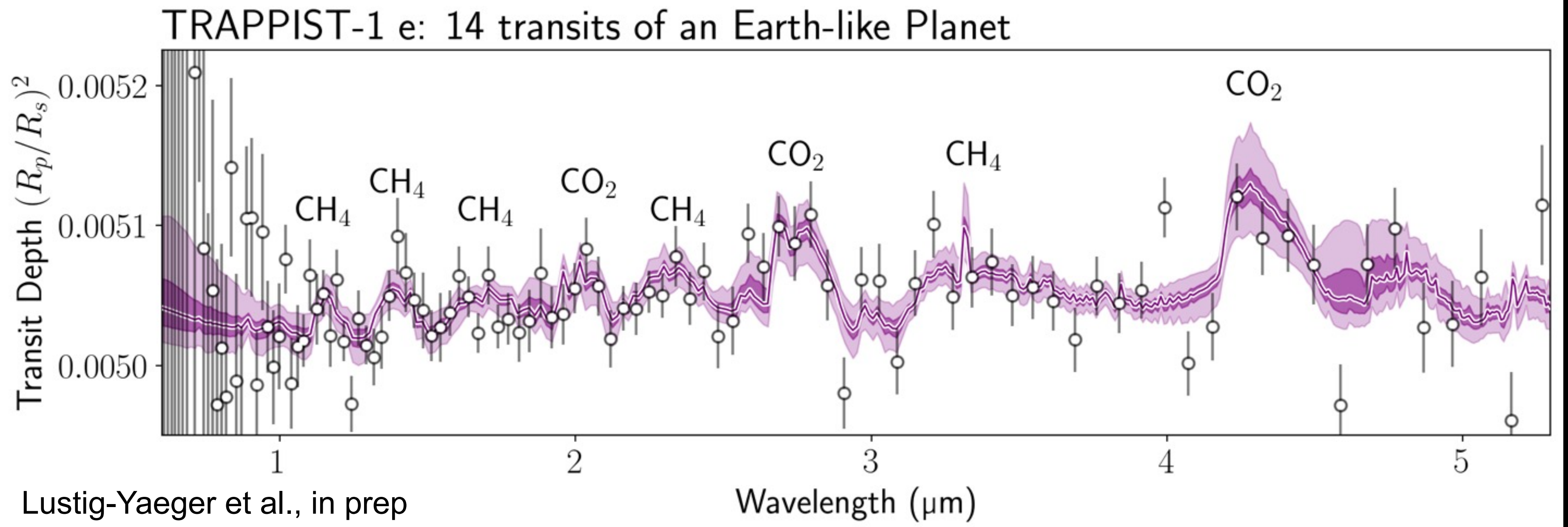
- Signs of ocean loss can be sought including O_2-O_2 and even HDO to attempt to determine D/H ratio.
- May detect HDO in as few as 10 transits
- Might be relatively straightforward to prove no ocean…rather than ocean presence.



Lincowski et al., 2019

Does it have life? JWST and TRAPPIST-1





Lustig-Yaeger et al., in prep

A CO_2/CH_4 disequilibrium may be observable for TRAPPIST-1 e with JWST. (Krissansen-Totton et al., 2018).

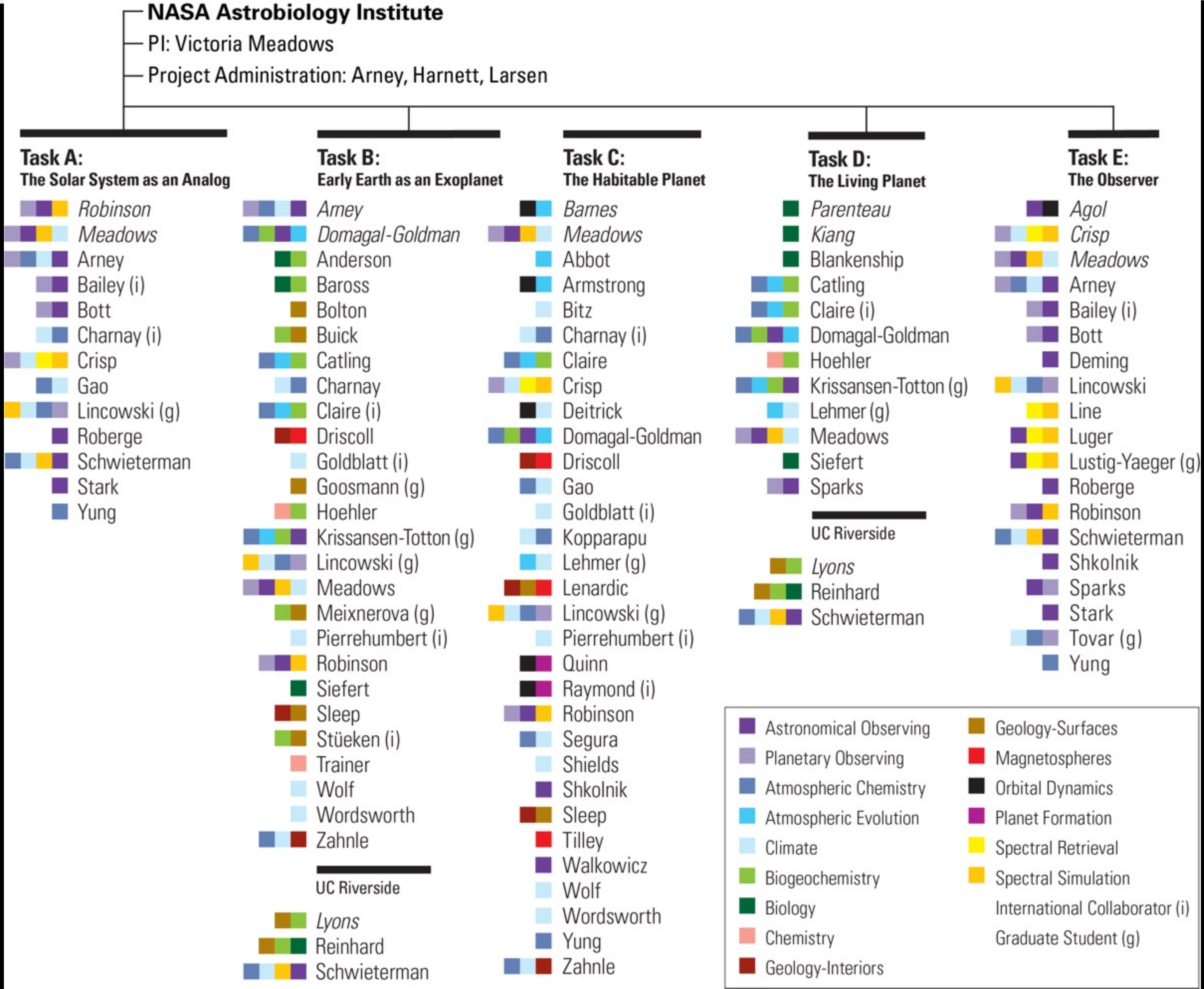
Especially with the enhanced lifetime of CH_4 for M dwarfs (Segura et al., 2005).

And throughout most of Earth's history (Meadows et al., in prep)

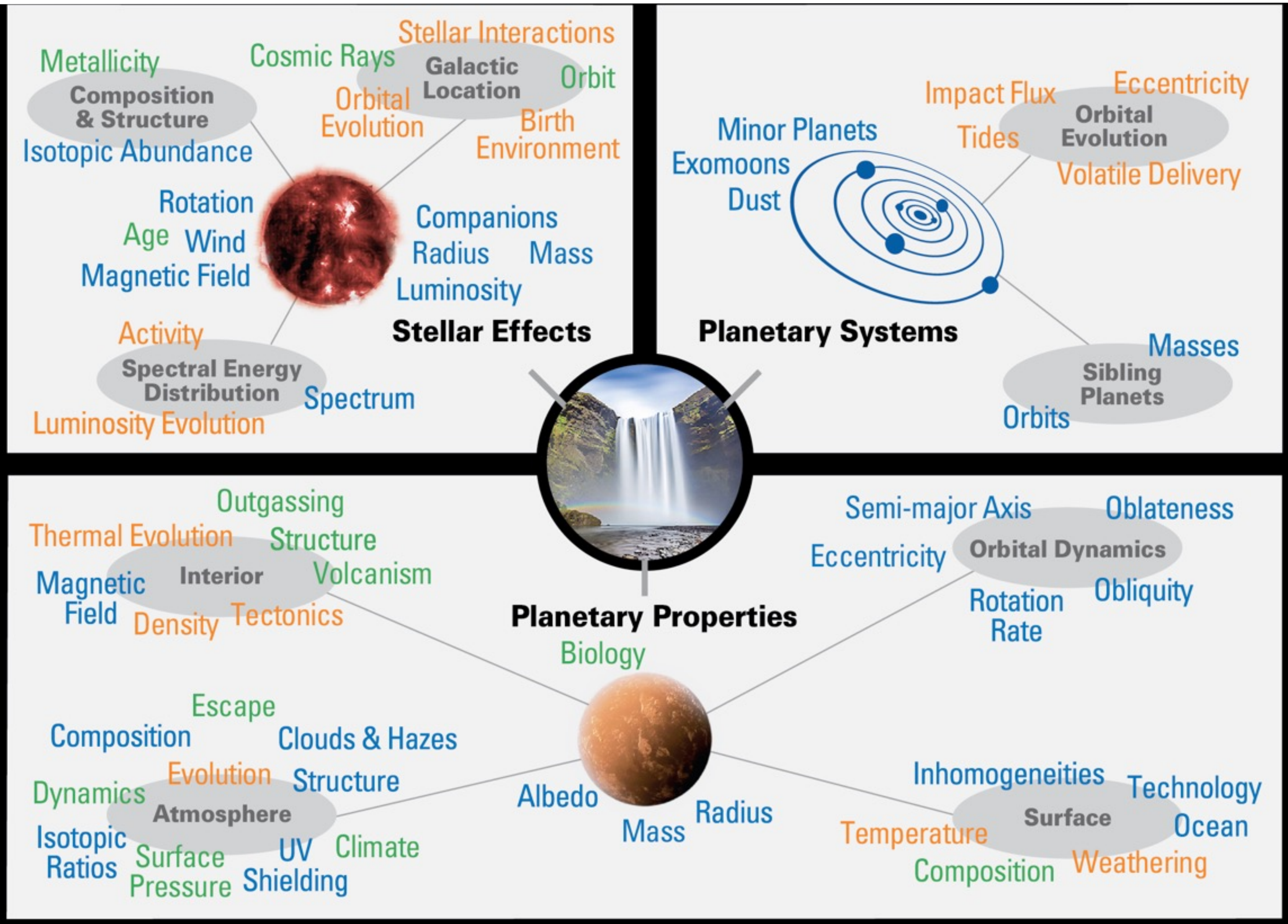
The VPL's Interdisciplinary Impact on Exoplanet Astrobiology

- Pioneered exoplanet/Solar System synergy
- Harnessed terrestrial planet and exoplanet evolution
  - The Earth through time
  - Terrestrial evolution coupled to stellar evolution for different types of stars.

It takes a village…to model a planet.



VPL's Systems Science Approach to Habitability



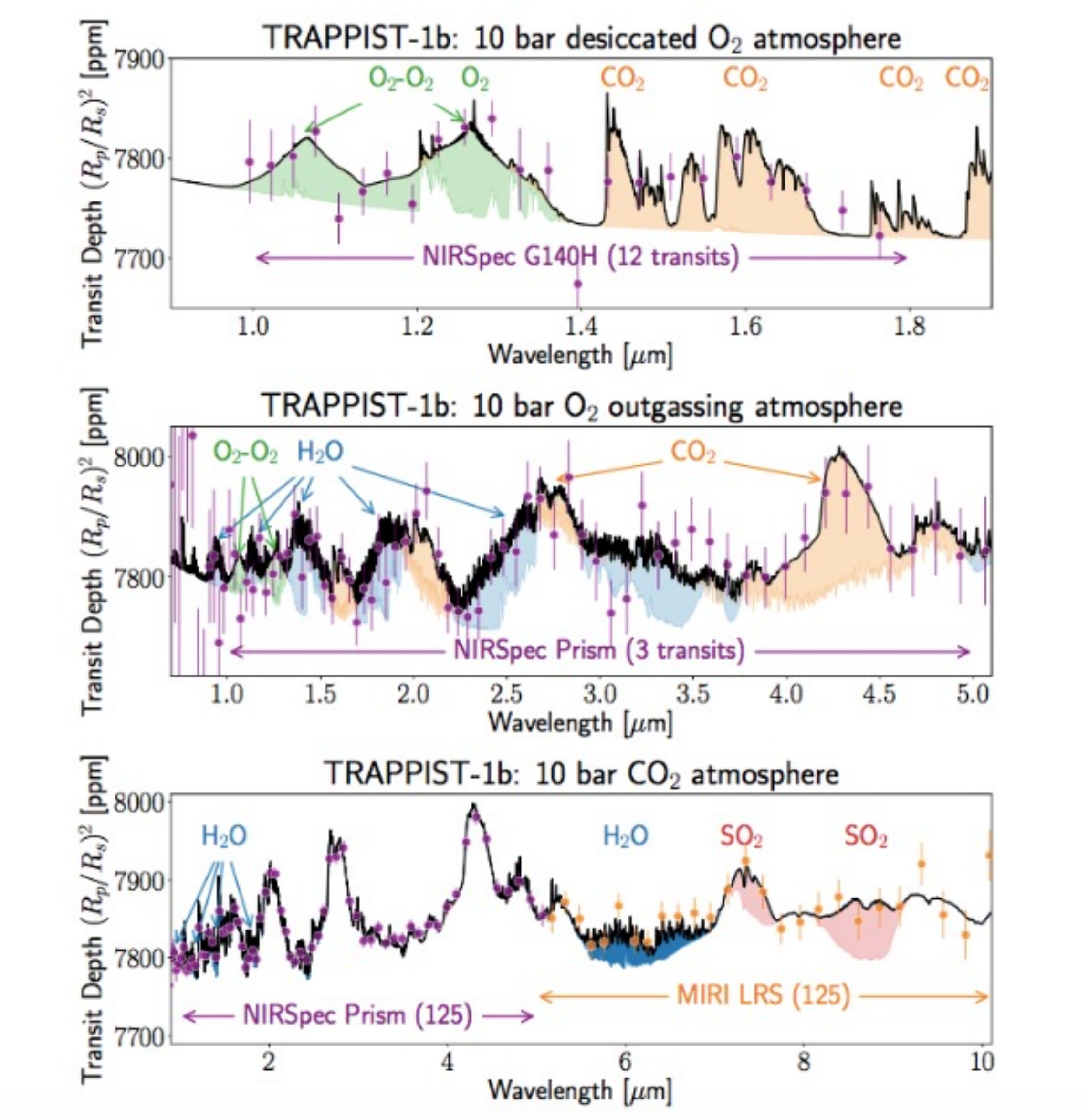
Meadows & Barnes, 2018

The VPL experiment in massive interdisciplinarity for exoplanet science was successful and scaleable (NExSS)

VPL Has Strong Mission Relevance (What the sponsor wants…)

VPL's tools, science and small exoplanet observing expertise are playing an integral role in NASA exoplanet mission and mission concept development.

- Simulated environments, spectra, and detectability calculations inform upcoming JWST observations.
- VPL Team members serve on the Science and Technology Definition and/or Study Teams for LUVOIR, HabEx and OST, providing yield estimates, biosignatures and habitability science cases for these proposals.



Lustig-Yaeger et al., 2019

Training the Next Generation of Astrobiologists/Mission Scientists

Things I've Learned Running the VPL

- You have to have a vision and a focused question. Proximity does not spawn interdisciplinarity, a common goal does.
- There is a pyramid of interdisciplinarity. EVERYONE contributing to the common goal can participate in interdisciplinarity, even with a single discipline component.
- Collaborations run on trust, communication and good will
- Pick your team members well.   Really. This is key.
- Interact often. Find both formal and informal ways to interact.
- Encourage a culture based on *scientific rigor* and *cooperation* rather than competition. Help each other, challenge each other, learn from each other, build a research community.
- There's *nothing* more rewarding than training future colleagues. Also engage them in the non-research aspects of being a scientist.
- Have fun!! You are getting paid to search for life elsewhere!

Questions?