Pathways to Habitable Worlds: How to Most Efficiently Recognize Habitable Planets?

Arnaud Salvador

Tyler Robinson, Jonathan Fortney, Mark Marley

Lunar & Planetary Laboratory
Habitability, Atmospheres, and Biosignatures Laboratory
University of Arizona

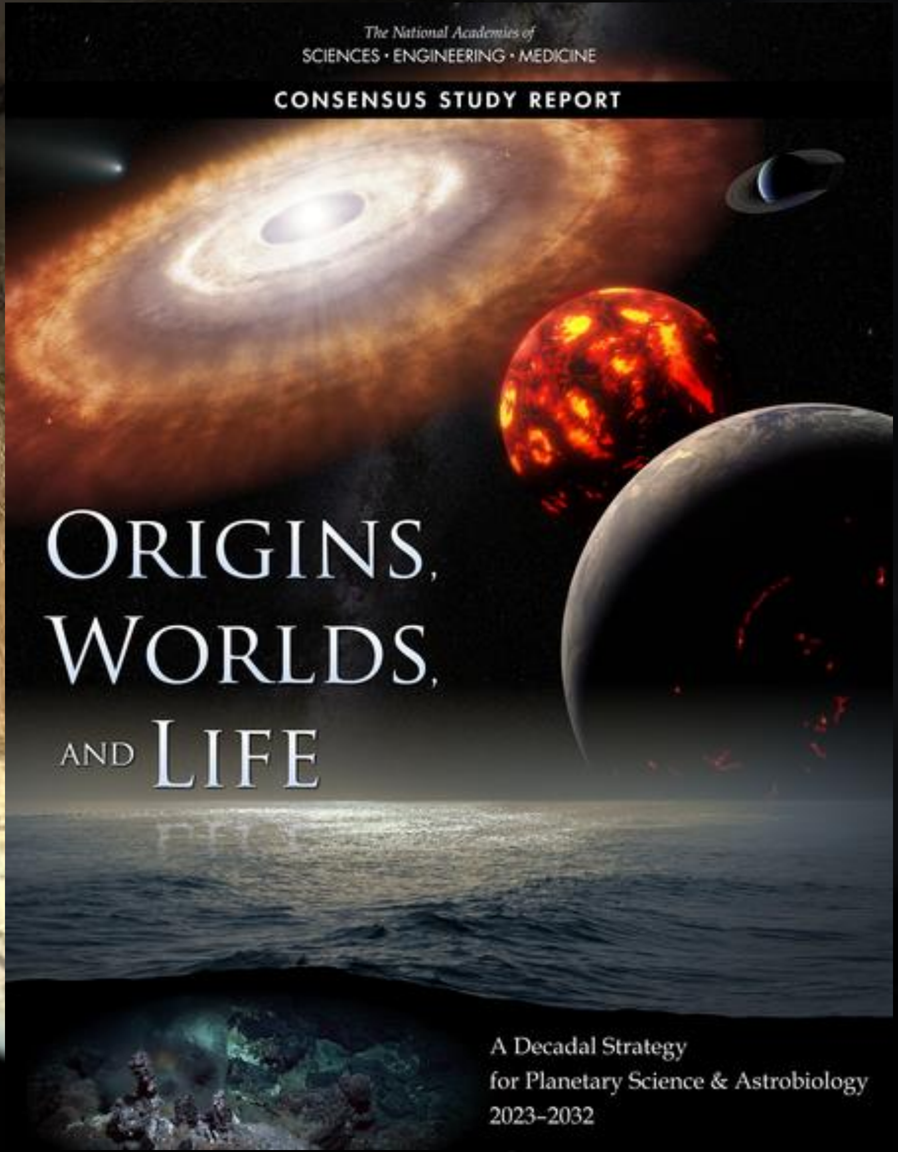
Habitability & Life on Other worlds (HALO) workshop – Fréjus, France

December 5, 2024

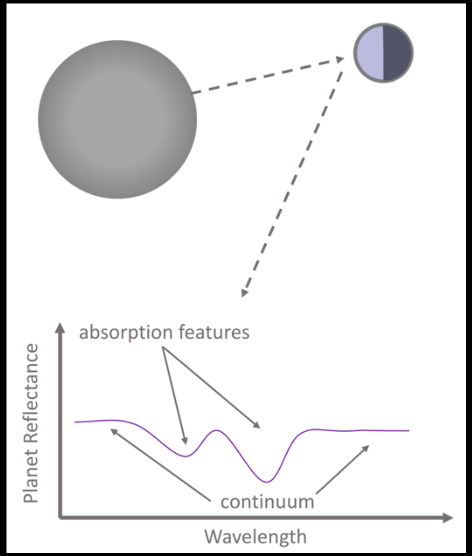
arnaudsalvador@arizona.edu

Search for Life Elsewhere

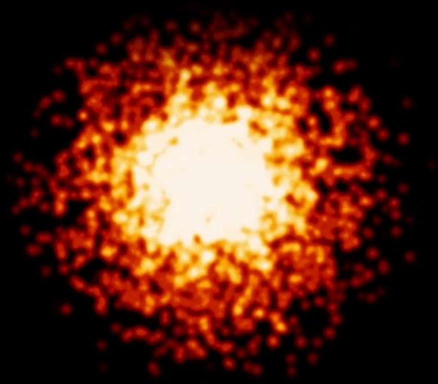
- Q11. Is there evidence of past or present life in the solar system beyond Earth and how do we detect it?
- Habitable Worlds Observatory
- Detection and characterization of ~25 habitable zone planets

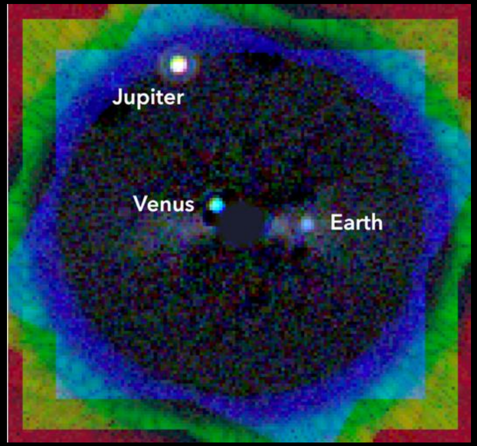


What would Earth look like if observed from afar?
An example in reflected light



© Ty Robinson

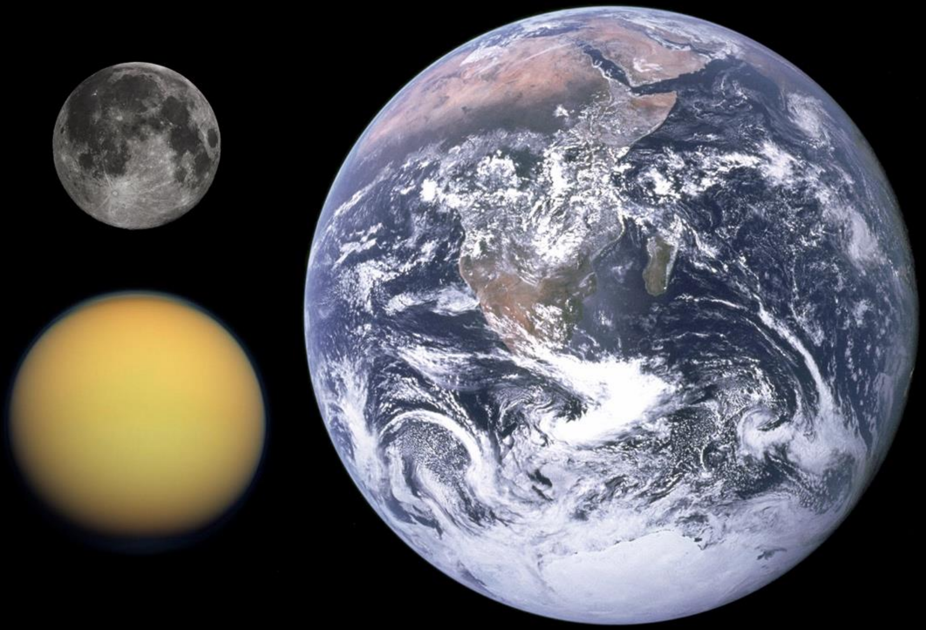


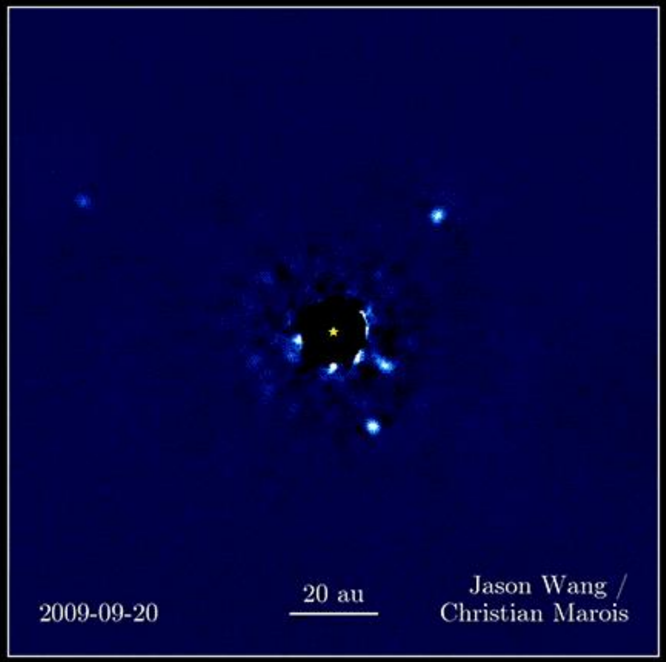


© LUVOIR Final Report

- Direct imaging is like taking a picture of the planet but not *yet* as good as that
  - No direct detection of surface liquid water
  - No direct measurements of surface pressure and temperature

Local vs. Distant Observations





- In-situ and abundant measurements
- Direct observations
- Time- and spatially-resolved

=> Highly constrained parameters

- Distant and few measurements
- Sometimes indirect detections only
- Time- and spatially-averaged

=> Highly unconstrained parameters

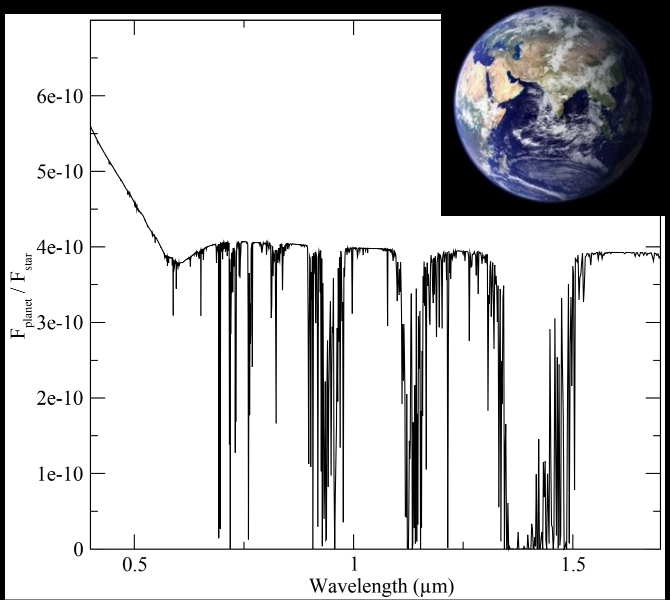
Pathways to Habitable Worlds

- If we were observing an Earth analog, would we be able to tell that it is an Earth analog?

- What are the requirements to effectively and efficiently recognize a habitable planet?

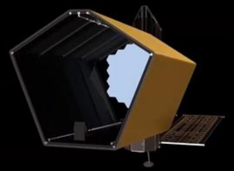
Future Observations of Earth Analogs in Reflected Light

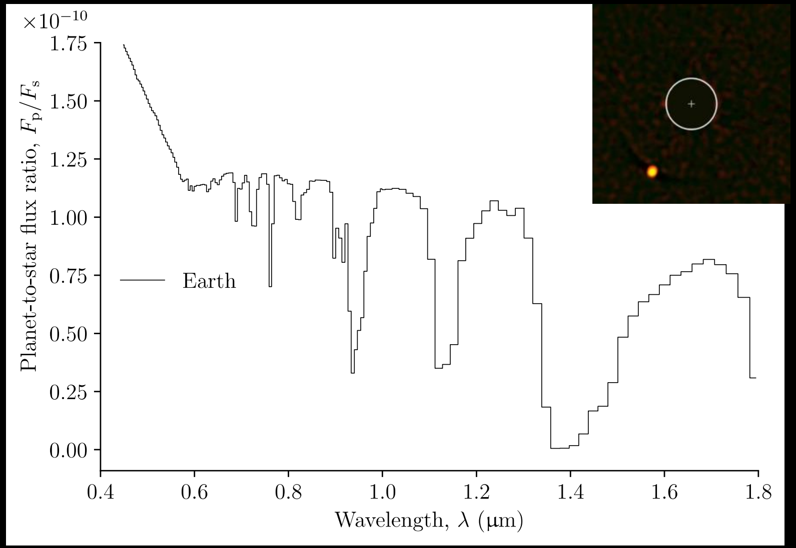
- What parameters can be confidently constrained/retrieved?
  e.g., Lupu+ 2016; Nayak+ 2017; Feng+ 2018; Carrión-González+ 2020; Damiano+ 202X; Alei+ 202X; Susemiehl+ 2023; Latouf+ 2023s; Young+ 2024s; Salvador+ 2024



Robinson et al., 2011

Instrument simulator

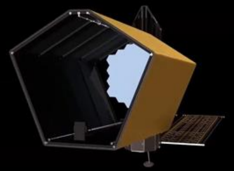


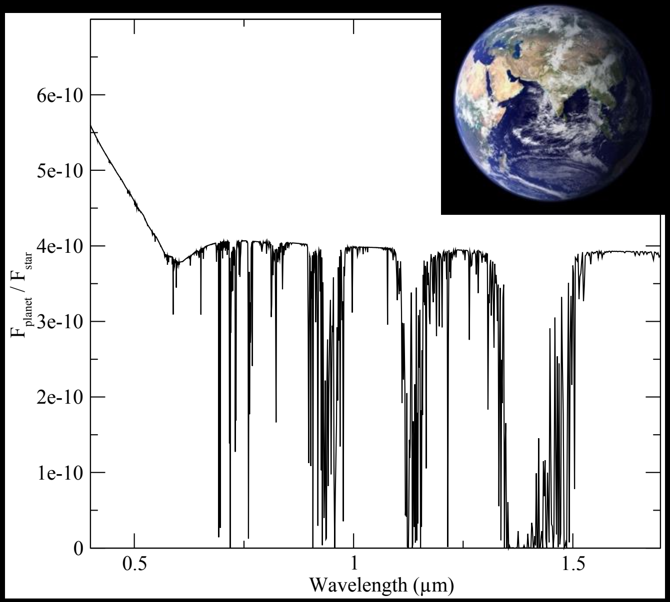


Future Observations of Earth Analogs in Reflected Light

- What parameters can be confidently constrained/retrieved?

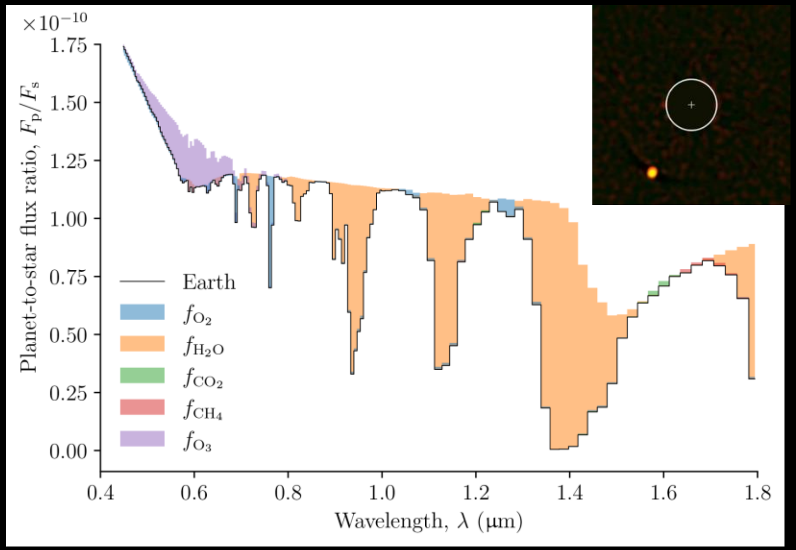
  e.g., Lupu+ 2016; Nayak+ 2017; Feng+ 2018; Carrión-González+ 2020; Damiano+ 202X; Alei+ 202X; Susemiehl+ 2023; Latouf+ 2023s; Young+ 2024s; Salvador+ 2024





Robinson et al., 2011

Instrument simulator



Observing Strategy

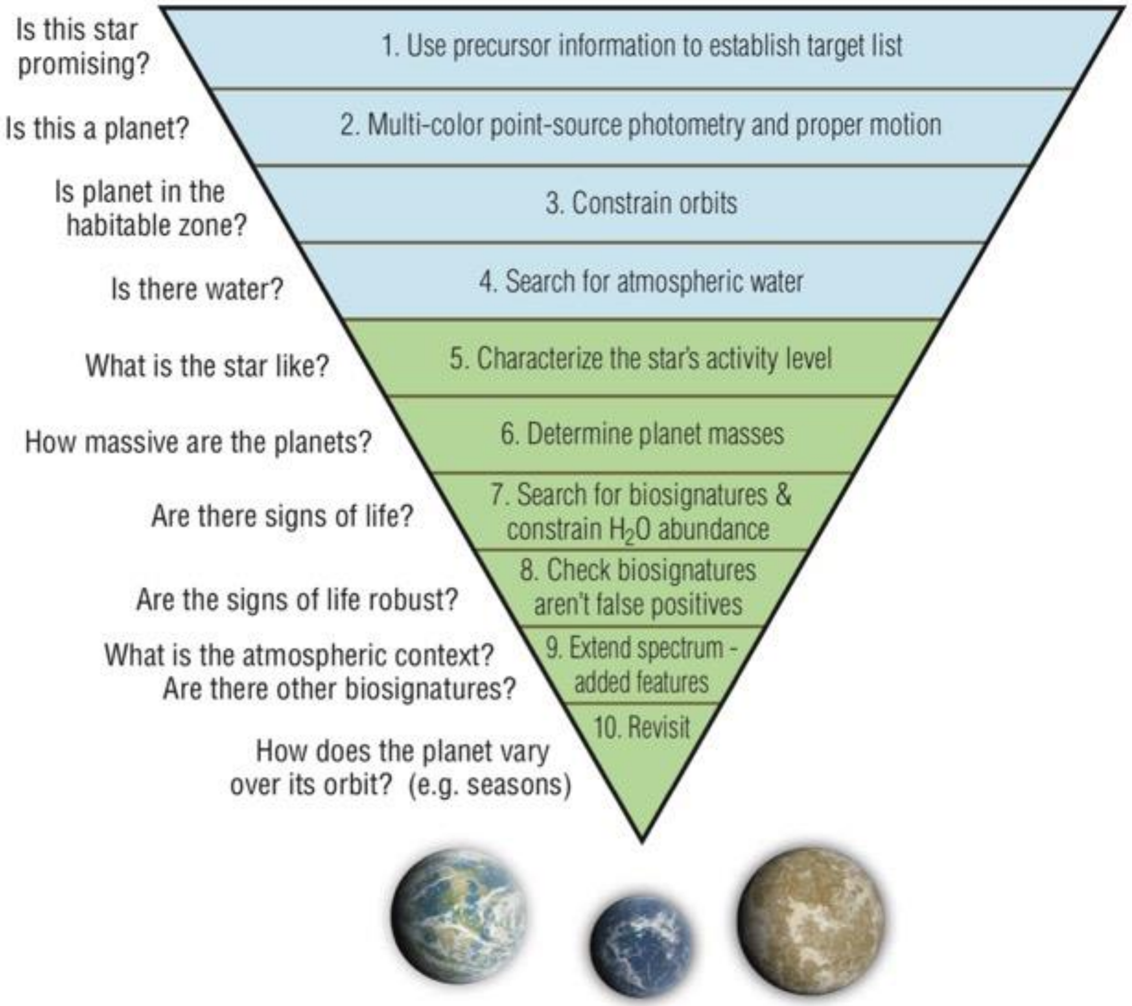


Figure 1-5. *The LUVOIR strategy for the searth for life. Blue steps at the top of the figure represent an initial survey optimized to discover habitable planets. Green steps at the bottom of the figure refer to characterization of those planets, confirming habitability and searching for biosignatures. Credit: T. B. Griswold (NASA GSFC)*

Observing Strategy

The Large UV Optical Infrared Surveyor LUVOIR

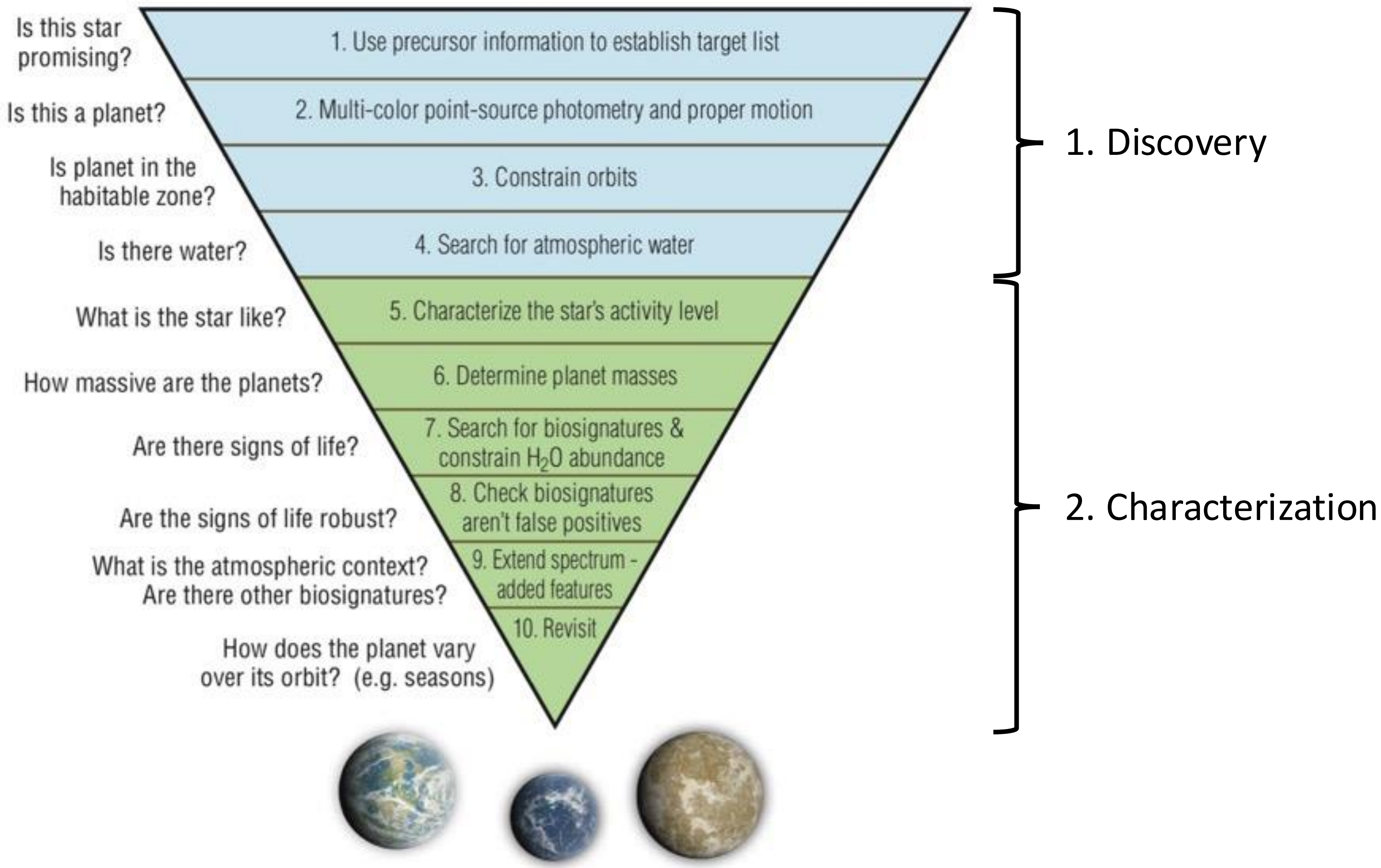


Figure 1-5. *The LUVOIR strategy for the searth for life. Blue steps at the top of the figure represent an initial survey optimized to discover habitable planets. Green steps at the bottom of the figure refer to characterization of those planets, confirming habitability and searching for biosignatures. Credit: T. B. Griswold (NASA GSFC)*

Observing Strategy

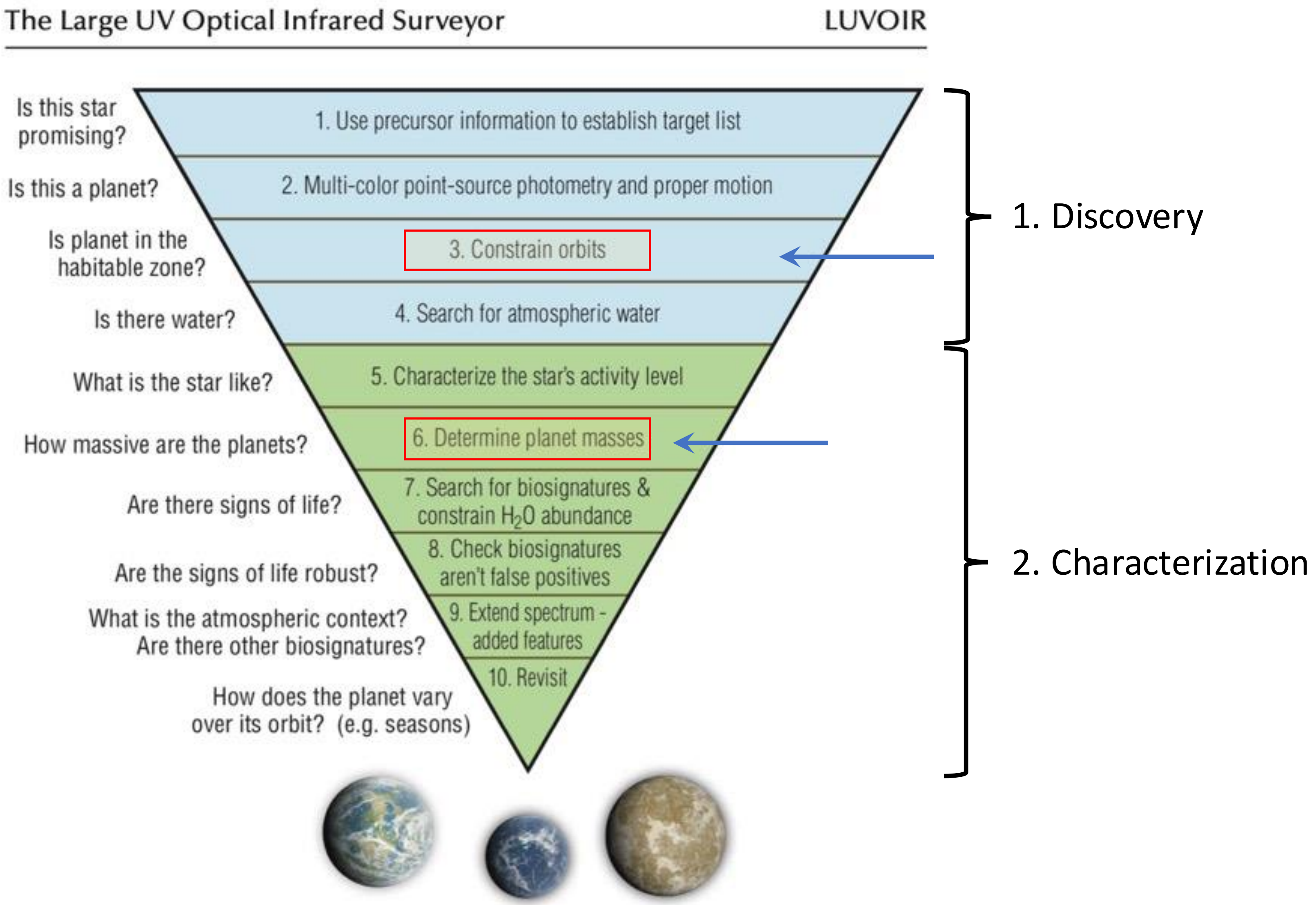


Figure 1-5. *The LUVOIR strategy for the searth for life. Blue steps at the top of the figure represent an initial survey optimized to discover habitable planets. Green steps at the bottom of the figure refer to characterization of those planets, confirming habitability and searching for biosignatures. Credit: T. B. Griswold (NASA GSFC)*

Observing Strategy

Prior Radial Velocity survey and/or astrometry

⇒ Planetary mass and orbit already constrained at the time of detailed characterization

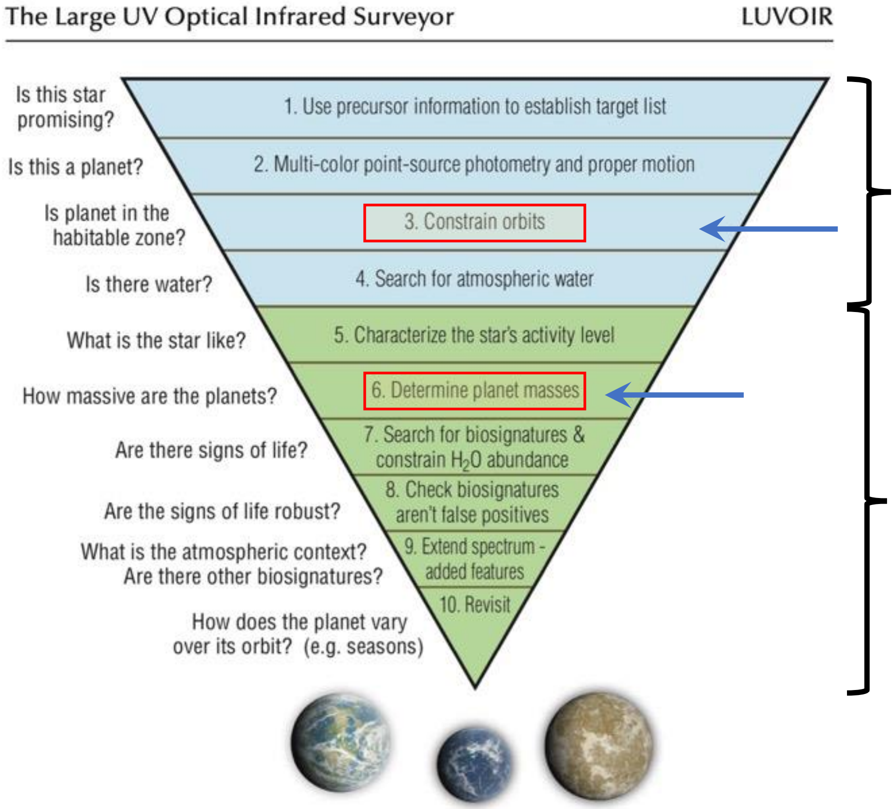


Figure 1-5. *The LUVOIR strategy for the searth for life. Blue steps at the top of the figure represent an initial survey optimized to discover habitable planets. Green steps at the bottom of the figure refer to characterization of those planets, confirming habitability and searching for biosignatures. Credit: T. B. Griswold (NASA GSFC)*

1. Discovery

2. Characterization

Different scenarios of prior knowledge

- No prior information
- Orbit already constrained
- Mass already constrained
- Orbit & mass constrained

Future Observations of Earth Analogs in Reflected Light

- What parameters can be confidently constrained/retrieved?
  e.g., Lupu+ 2016; Nayak+ 2017; Feng+ 2018; Carrión-González+ 2020; Damiano+ 202X; Alei+ 202X; Susemiehl+ 2023; Latouf+ 2023s; Young+ 2024s; Salvador+ 2024

What observing strategies most efficiently recognize a habitable planet?

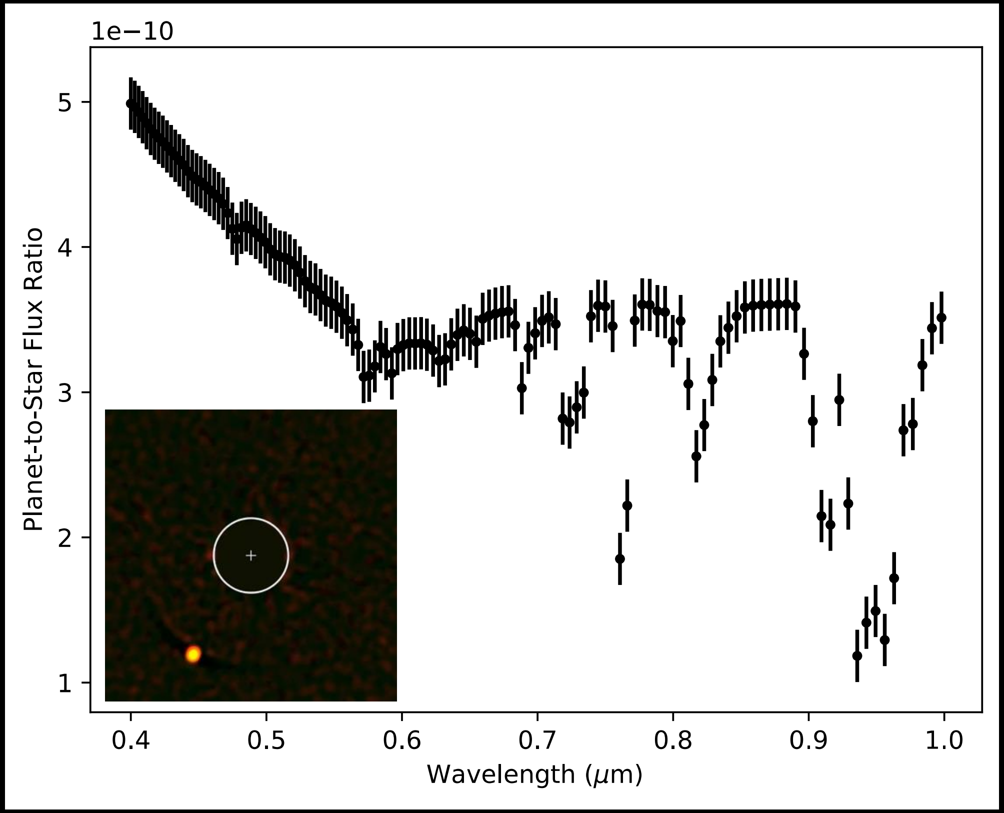
- How do ***prior observations*** and ***observational constraints*** affect our ability to ***characterize the planetary environment***?

A versatile atmospheric retrieval tool: **rfast**

Atmospheric "retrieval" tools are used to "find back" (retrieve) the range of model parameters that best reproduce/fit a given set of noisy observations.

A versatile atmospheric retrieval tool: **rfast**

Atmospheric "retrieval" tools are used to "find back" (retrieve) the range of model parameters that best reproduce/fit a given set of noisy observations.



- Reflected-light, partial and noisy Earth degraded spectrum: "faux" observations

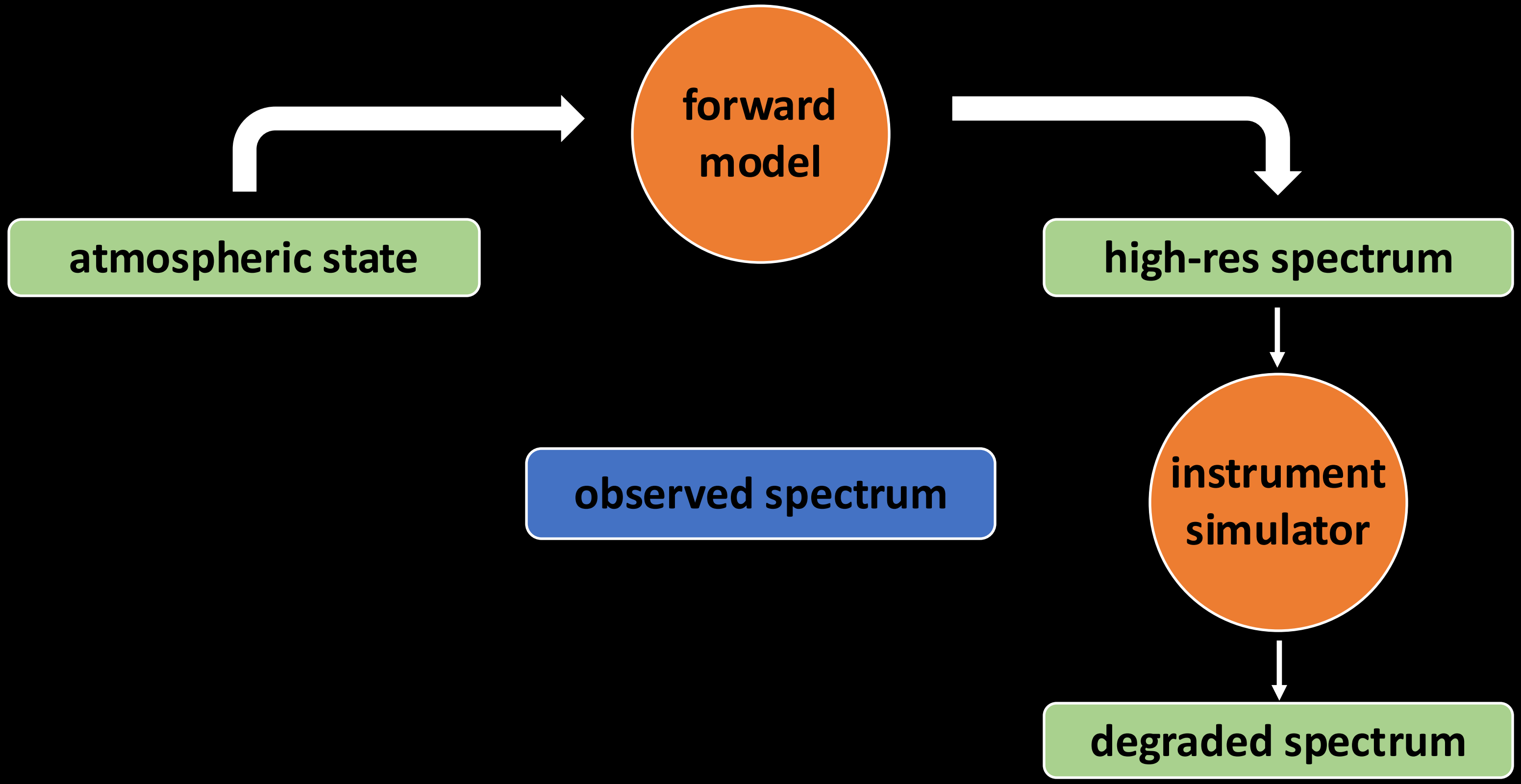
observed spectrum

A versatile atmospheric retrieval tool: rfast

Atmospheric “retrieval” tools are used to “find back” (retrieve) the range of model parameters that best reproduce/fit a given set of noisy observations.

- Initial guess for planet’s atmospheric state (informed by priors): planet size, gravity, atmospheric composition, cloud profiles, thermal profile
- Forward model, i.e., radiative transfer model that generates the corresponding high-res planetary spectrum
- Instrument simulator: add noise and mimic instrument’s effects

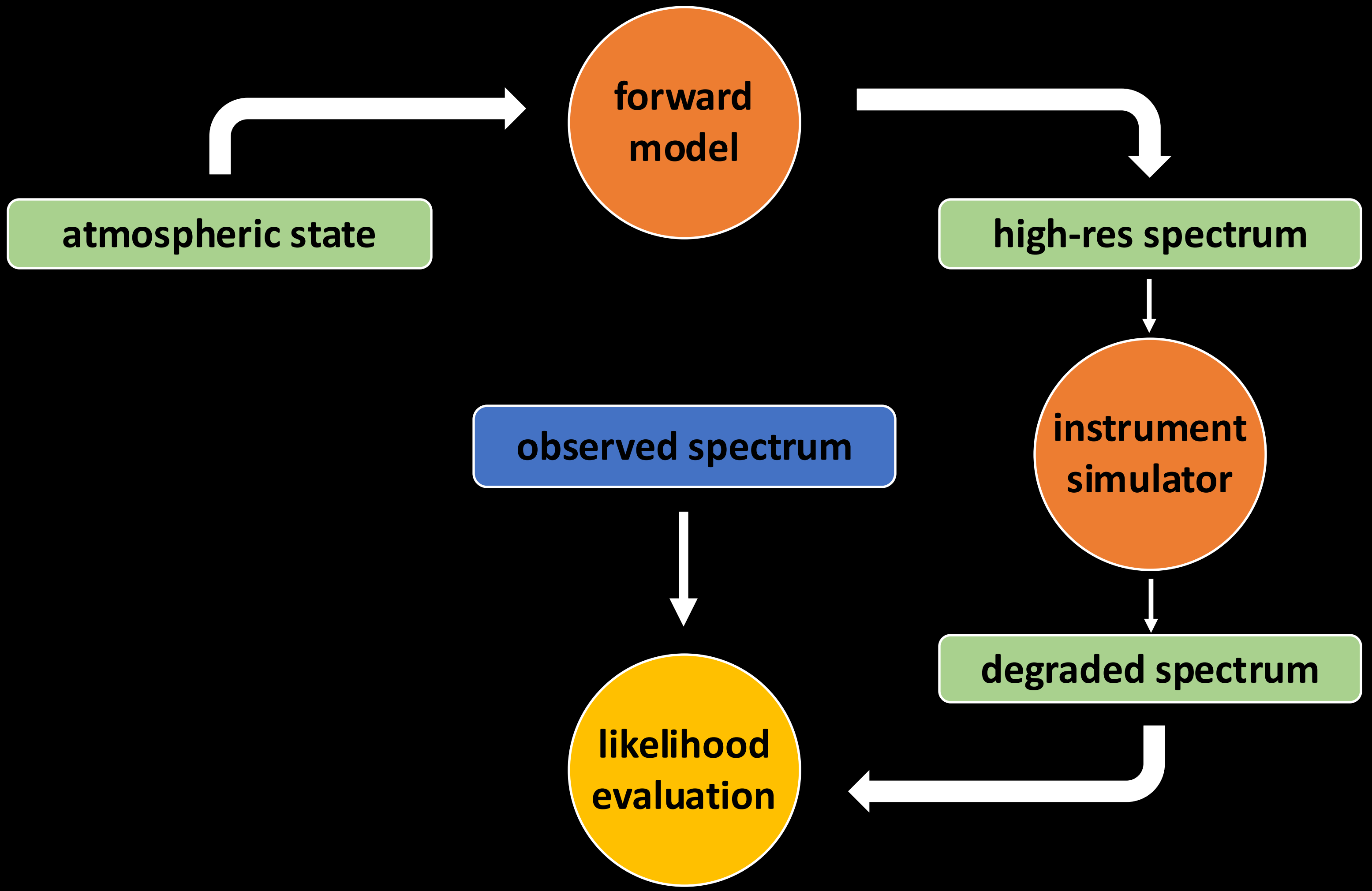
=> **degraded, modeled spectrum**



A versatile atmospheric retrieval tool: rfast

Atmospheric “retrieval” tools are used to “find back” (retrieve) the range of model parameters that best reproduce/fit a given set of noisy observations.

How well does the degraded, model-generated spectrum fit the observed spectrum?

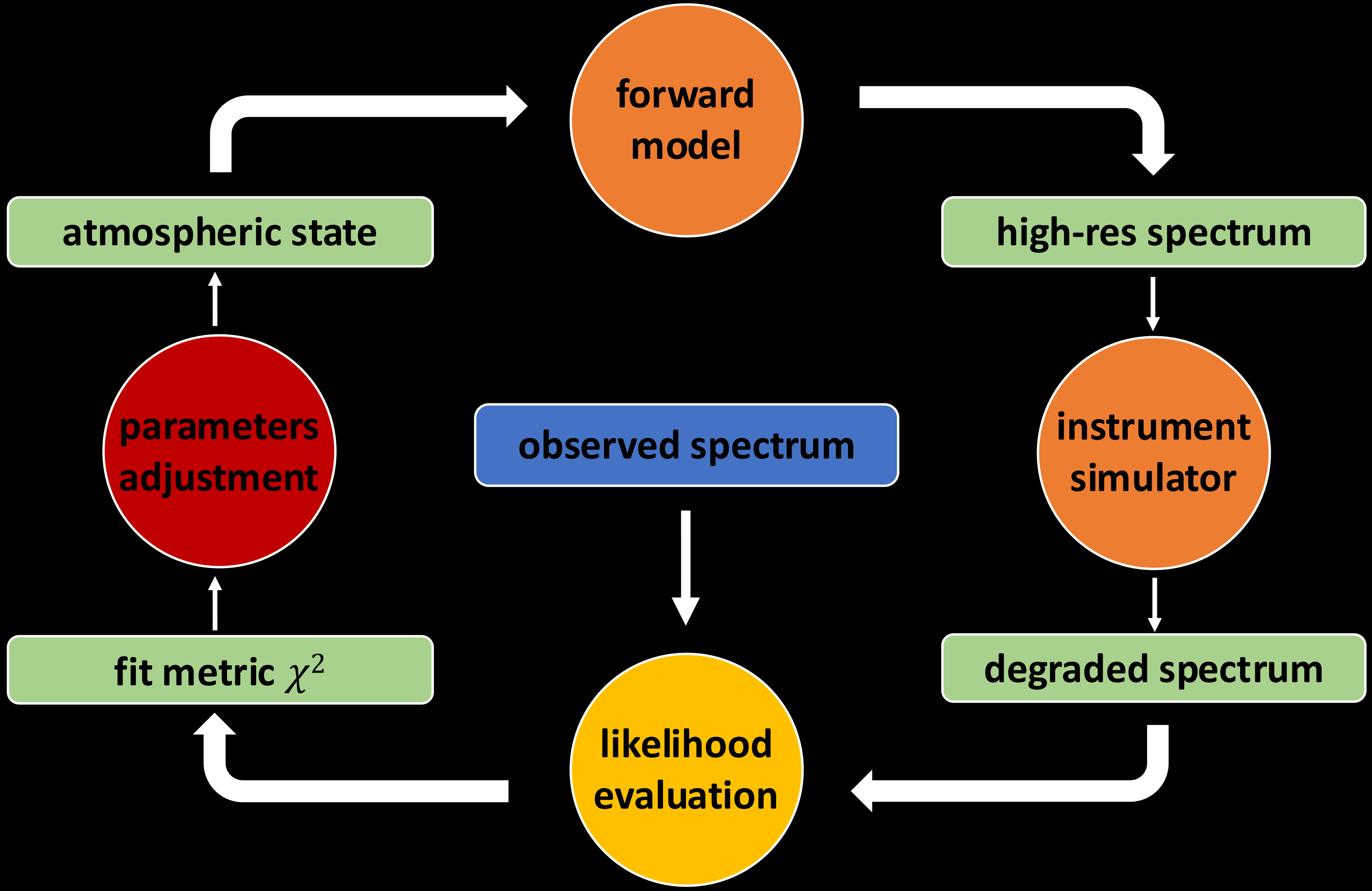


A versatile atmospheric retrieval tool: rfast

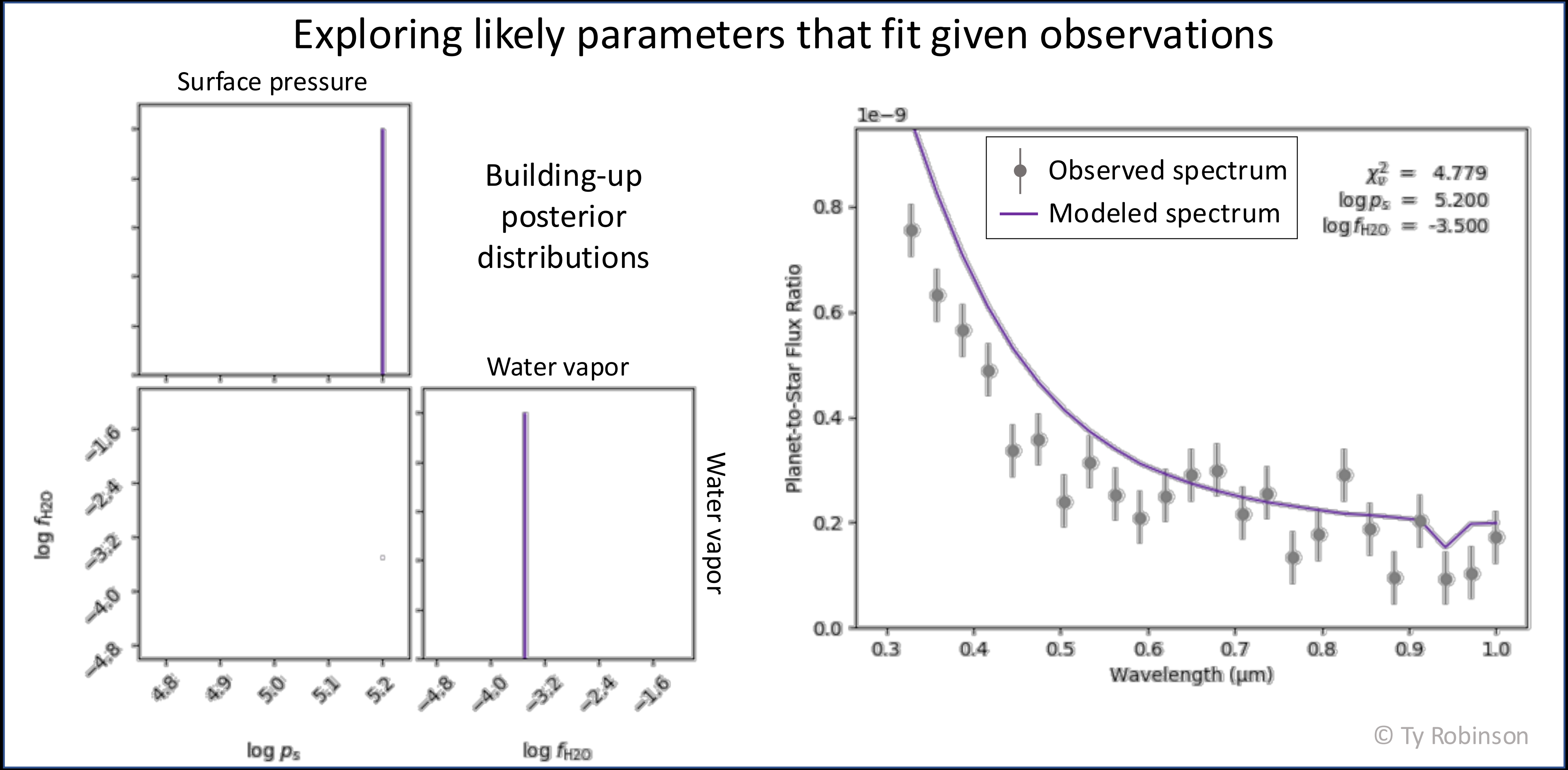
Atmospheric "retrieval" tools are used to "find back" (retrieve) the range of model parameters that best reproduce/fit a given set of noisy observations.

How well does the degraded, model-generated spectrum fit the observed spectrum?
$\Rightarrow$ fit metric (χ^2)

Markov Chain Monte Carlo (MCMC) model (emcee)
$\Rightarrow$ which "direction" in parameter space should be further explored
$\Rightarrow$ new atmospheric state

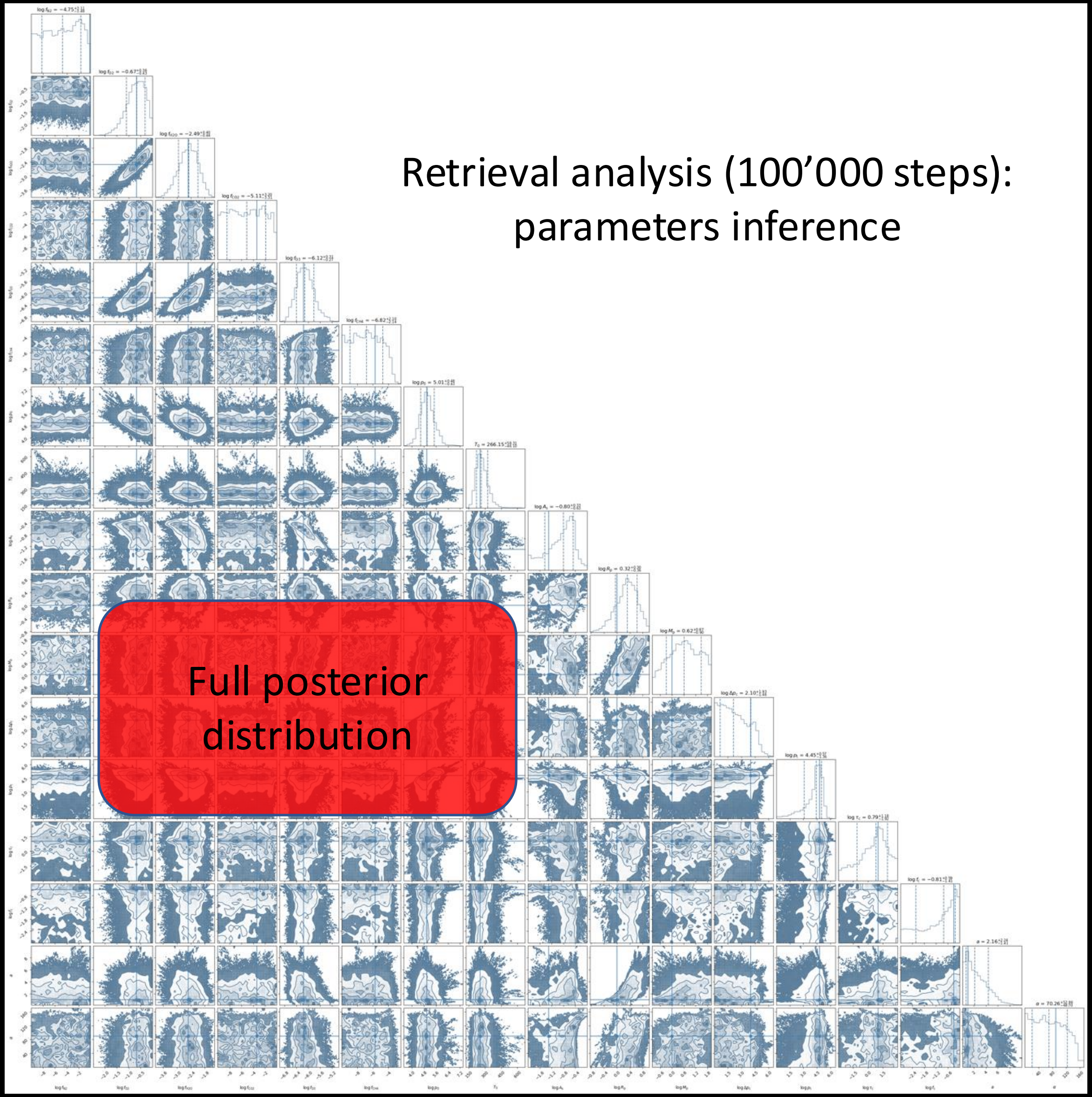


A versatile atmospheric retrieval tool: **rfast**

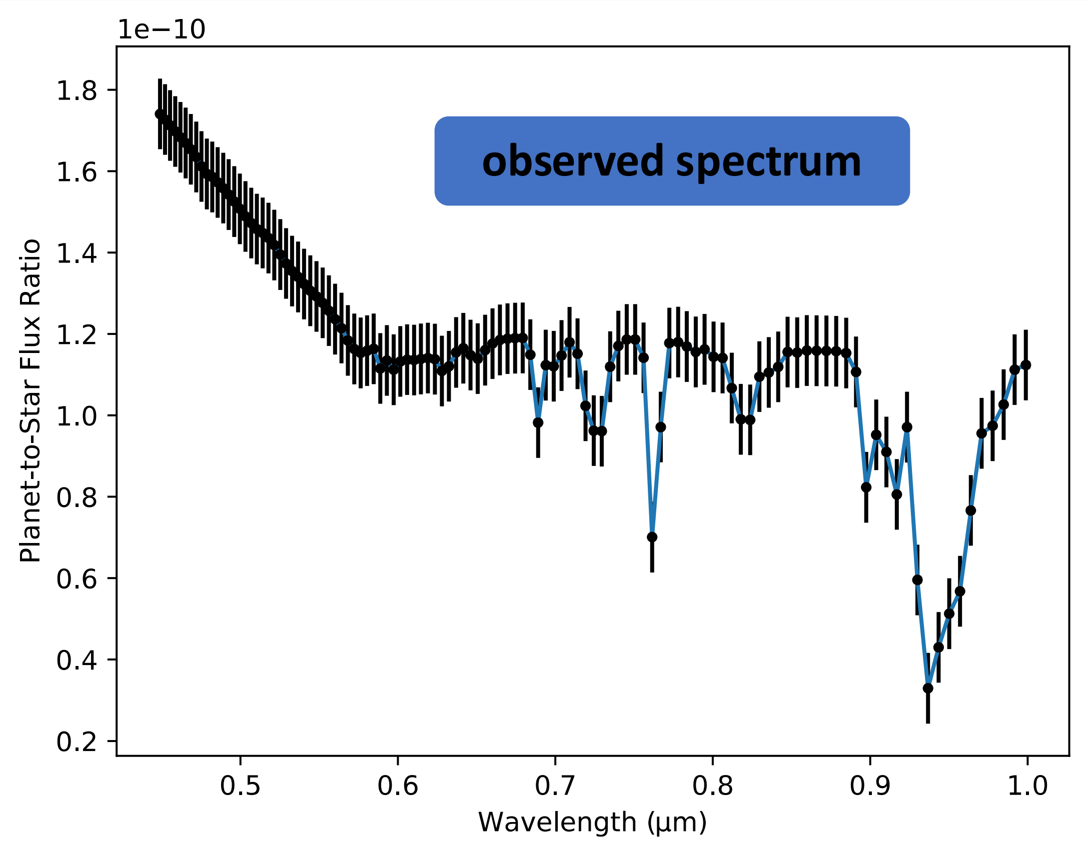


A versatile atmospheric retrieval tool: rfast

arXiv: 2204.04231



Visible range, SNR = 20, no constraints



Retrieval setup

17 retrieved parameters

Parameter	Description	Input	Prior
	Surface conditions		
$\log p_{\rm surf}$	Surface pressure (Pa)	$\log(10^5)$	$[1, 10^8]$
T	Atmospheric temperature* (K)	255	[100, 1000]
$\log A_{\rm surf}$	Surface albedo	log(0.05)	[0.01, 1]
	Gas abundances†		
$\log f_{N_2}$	Molecular nitrogen mixing ratio	log(0.78)	$[10^{-10}, 1]$
$\log f_{O_2}$	Molecular oxygen mixing ratio	log(0.21)	$[10^{-10}, 1]$
$\log f_{H_2O}$	Water vapor mixing ratio	$\log(3 \times 10^{-3})$	$[10^{-10}, 1]$
$\log f_{CO_2}$	Carbon dioxide mixing ratio	$\log(4 \times 10^{-4})$	$[10^{-10}, 1]$
$\log f_{CH_4}$	Methane mixing ration	$\log(2 \times 10^{-6})$	$[10^{-10}, 1]$
$\log f_{O_3}$	Ozone mixing ratio	$\log(7 \times 10^{-7})$	$[10^{-10}, 10^{-2}]$
	Cloud parameters		
$\log p_{\rm c}$	Cloud-top pressure (Pa)	$\log(6 \times 10^4)$	$[1, 10^8]$
$\log \Delta p_{\rm c}$	Cloud thickness (Pa)	$\log(10^4)$	$[1, 10^8]$
$\log \tau_{\rm c}$	Cloud optical depth	log(10)	$[10^{-3}, 10^3]$
$\log f_{\rm c}$	Cloudiness fraction	log(0.5)	$[10^{-3}, 1]$
	Planetary bulk parameters		
$\log R_{\rm p}$	Planet radius ($R_\oplus$)	log(1)	[0.1, 10]
$\log M_{\rm p}$	Planet mass ($M_\oplus$)	log(1)	[0.1, 100]‡
	Orbital parameters		
a	Planetary orbital distance (AU)	1	[0.1, 10]‡
α	Planetary phase angle (°)	90	[0, 180]‡

*Isothermal atmosphere temperature.

†The remaining atmosphere is back-filled with argon.

‡Constrained to 10% of Earth's value when considering precursor observation.

Retrieval setup

Parameter	Description	Input	Prior
Surface conditions			
$\log p_{\mathrm{surf}}$	Surface pressure (Pa)	$\log(10^5)$	$[1, 10^8]$
T	Atmospheric temperature* (K)	255	[100, 1000]
$\log A_{\mathrm{surf}}$	Surface albedo	$\log(0.05)$	[0.01, 1]
Gas abundances†			
$\log f_{\mathrm{N_2}}$	Molecular nitrogen mixing ratio	$\log(0.78)$	$[10^{-10}, 1]$
$\log f_{\mathrm{O_2}}$	Molecular oxygen mixing ratio	$\log(0.21)$	$[10^{-10}, 1]$
$\log f_{\mathrm{H_2O}}$	Water vapor mixing ratio	$\log(3 \times 10^{-3})$	$[10^{-10}, 1]$
$\log f_{\mathrm{CO_2}}$	Carbon dioxide mixing ratio	$\log(4 \times 10^{-4})$	$[10^{-10}, 1]$
$\log f_{\mathrm{CH_4}}$	Methane mixing ration	$\log(2 \times 10^{-6})$	$[10^{-10}, 1]$
$\log f_{\mathrm{O_3}}$	Ozone mixing ratio	$\log(7 \times 10^{-7})$	$[10^{-10}, 10^{-2}]$
Cloud parameters			
$\log p_{\mathrm{c}}$	Cloud-top pressure (Pa)	$\log(6 \times 10^4)$	$[1, 10^8]$
$\log \Delta p_{\mathrm{c}}$	Cloud thickness (Pa)	$\log(10^4)$	$[1, 10^8]$
$\log \tau_{\mathrm{c}}$	Cloud optical depth	$\log(10)$	$[10^{-3}, 10^3]$
$\log f_{\mathrm{c}}$	Cloudiness fraction	$\log(0.5)$	$[10^{-3}, 1]$
Planetary bulk parameters			
$\log R_{\mathrm{p}}$	Planet radius ($R_\oplus$)	$\log(1)$	[0.1, 10]
$\log M_{\mathrm{p}}$	Planet mass ($M_\oplus$)	$\log(1)$	[0.1, 100]‡
Orbital parameters			
a	Planetary orbital distance (AU)	1	[0.1, 10]‡
α	Planetary phase angle (°)	90	[0, 180]‡

*Isothermal atmosphere temperature.
†The remaining atmosphere is back-filled with argon.
‡Constrained to 10% of Earth's value when considering precursor observation.

17 retrieved parameters

Surface conditions
P_{surf}, T, A_{surf}

Gas abundances
N_2, O_2, H_2O, CO_2, CH_4, O_3

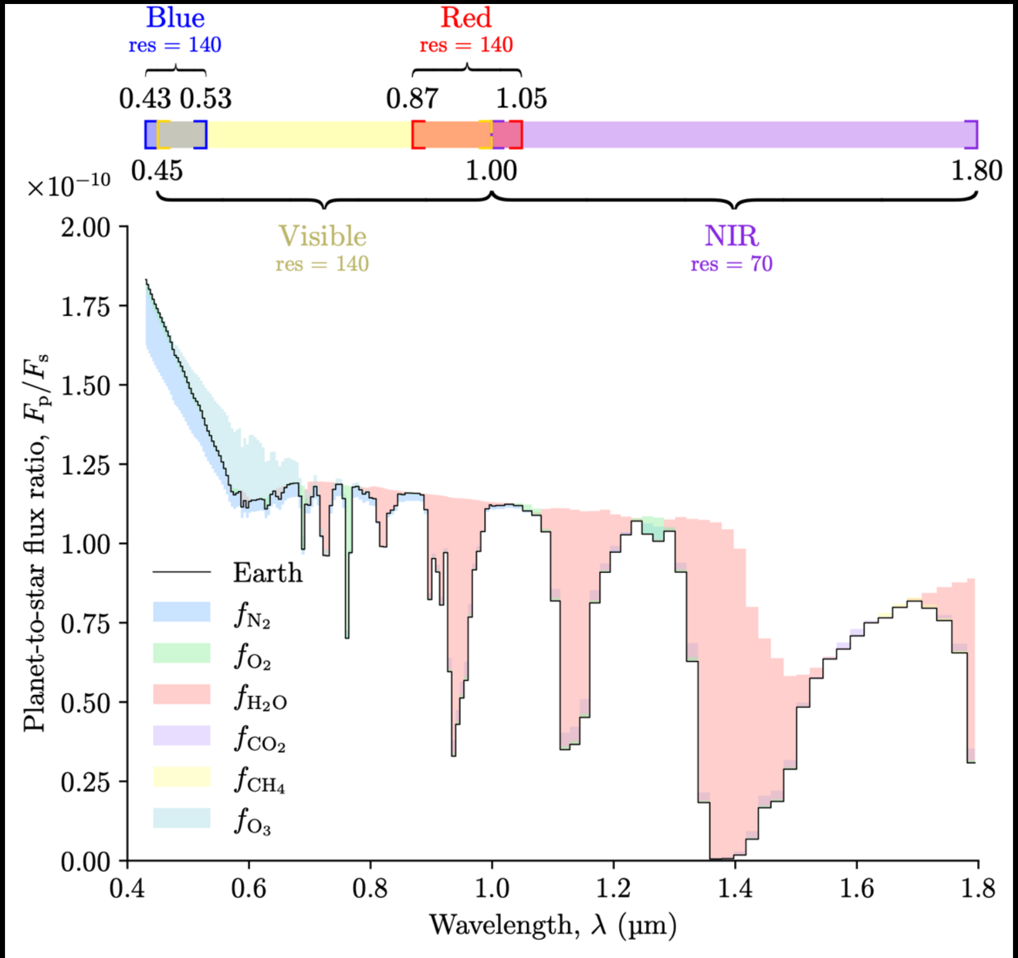
Cloud parameters
Vertical location and extent, optical depth, cloudiness fraction

Planetary bulk parameters*
R_p, M_p*

Orbital parameters*
Orbital distance, phase angle

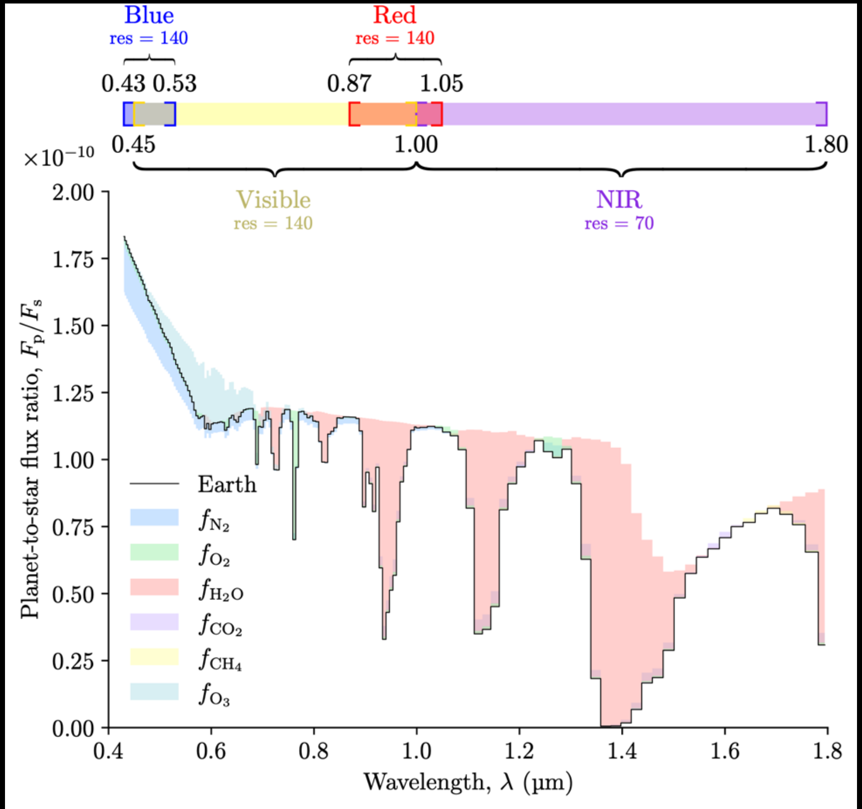
How do ***prior observations*** and ***observational constraints*** (wavelength coverage + SNR) affect our ability to **characterize the planetary environment**?

Parameter	Variations	Case Description
Wavelength coverage	5	**blue & red**; **red**; **visible**; **visible & NIR**; **NIR**



How do ***prior observations*** and ***observational constraints*** (wavelength coverage + SNR) affect our ability to **characterize the planetary environment**?

Parameter	Variations	Case Description
Wavelength coverage	5	**blue & red**; **red**; **visible**; **visible & NIR**; **NIR**
Orbit/mass precursor	3	no constraints; α & a to 10%; M_p, α, a to 10%

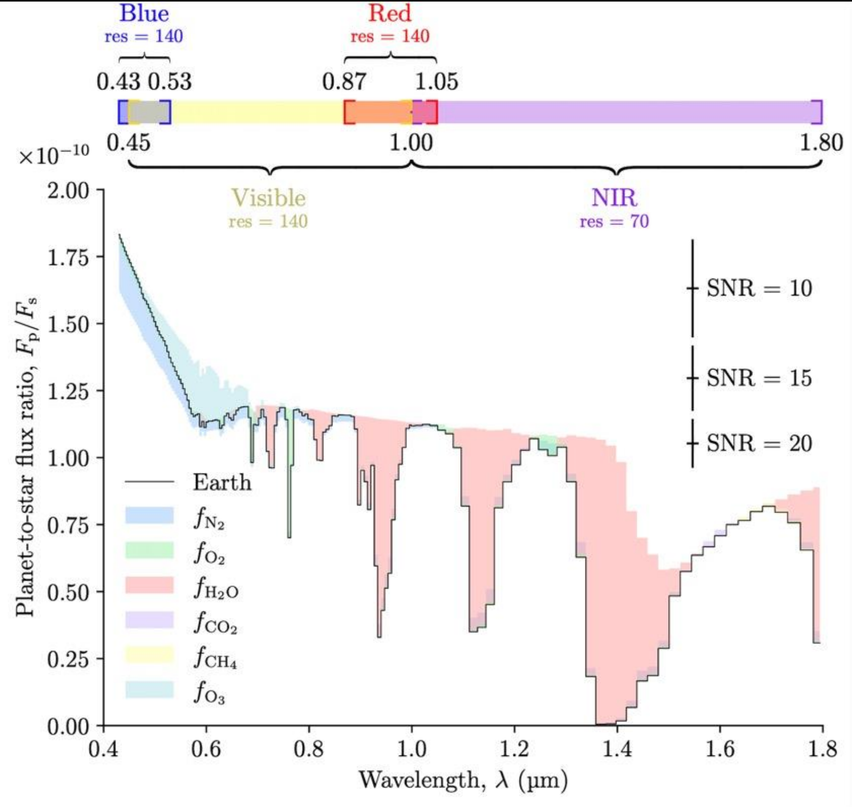


Different scenarios of prior knowledge

- No prior information
- Orbit already constrained
- Orbit & mass constrained

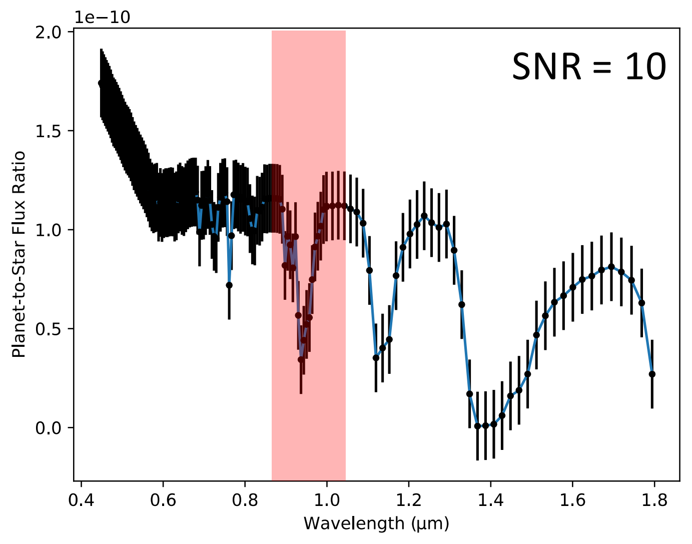
How do ***prior observations*** and ***observational constraints*** (wavelength coverage + SNR) affect our ability to **characterize the planetary environment**?

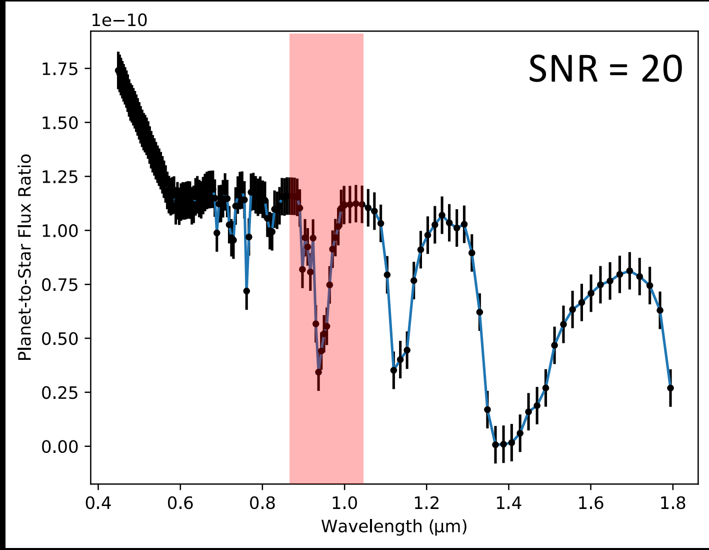
Parameter	Variations	Case Description
Wavelength coverage	5	**blue & red**; **red**; **visible**; **visible & NIR**; **NIR**
Orbit/mass precursor	3	no constraints; α & a to 10%; $M_{\rm p}$, α, a to 10%
Spectrum SNR (V-band)	3	10; 15; 20



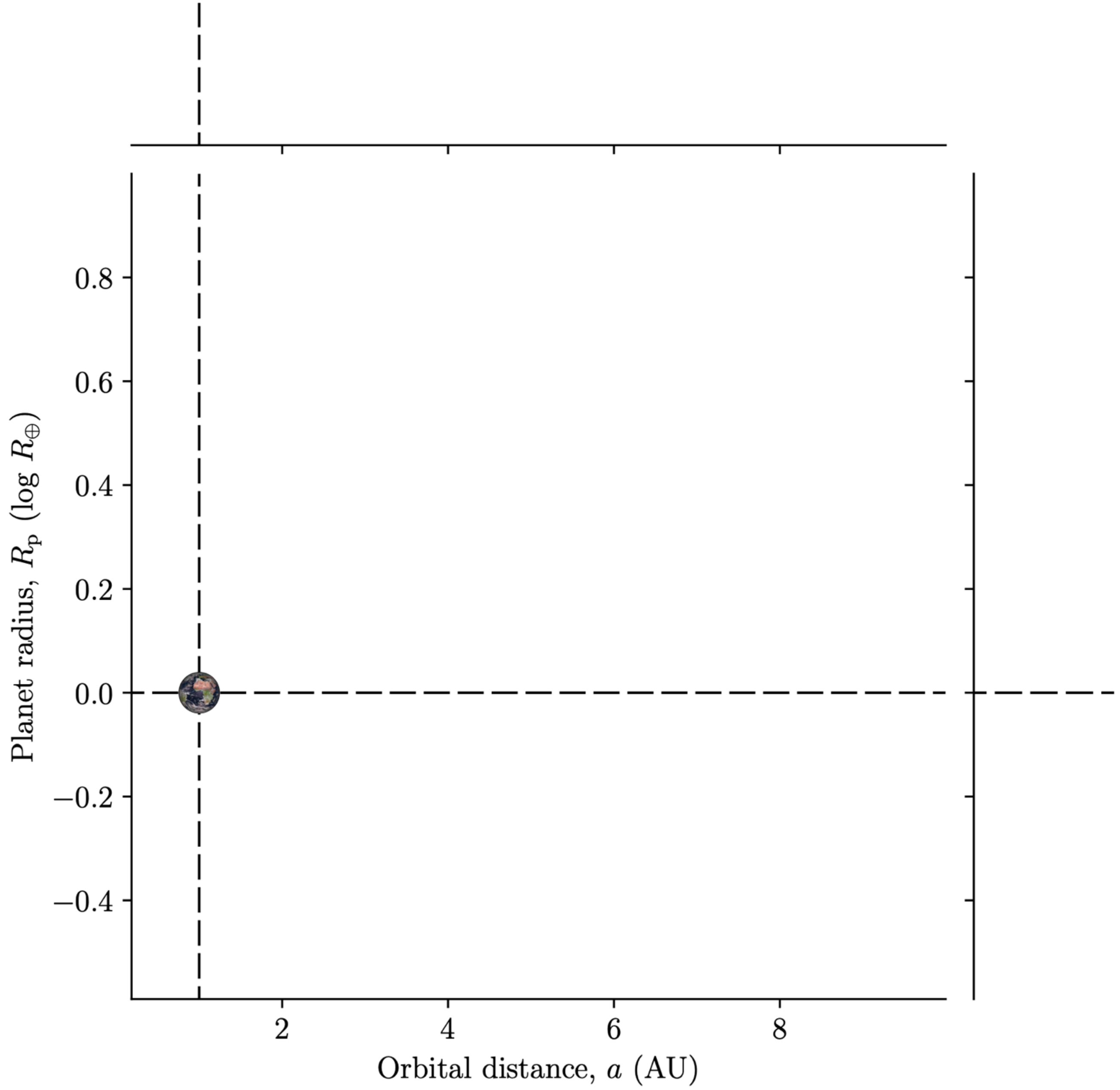
Different scenarios of prior knowledge

- No prior information
- Orbit already constrained
- Orbit & mass constrained

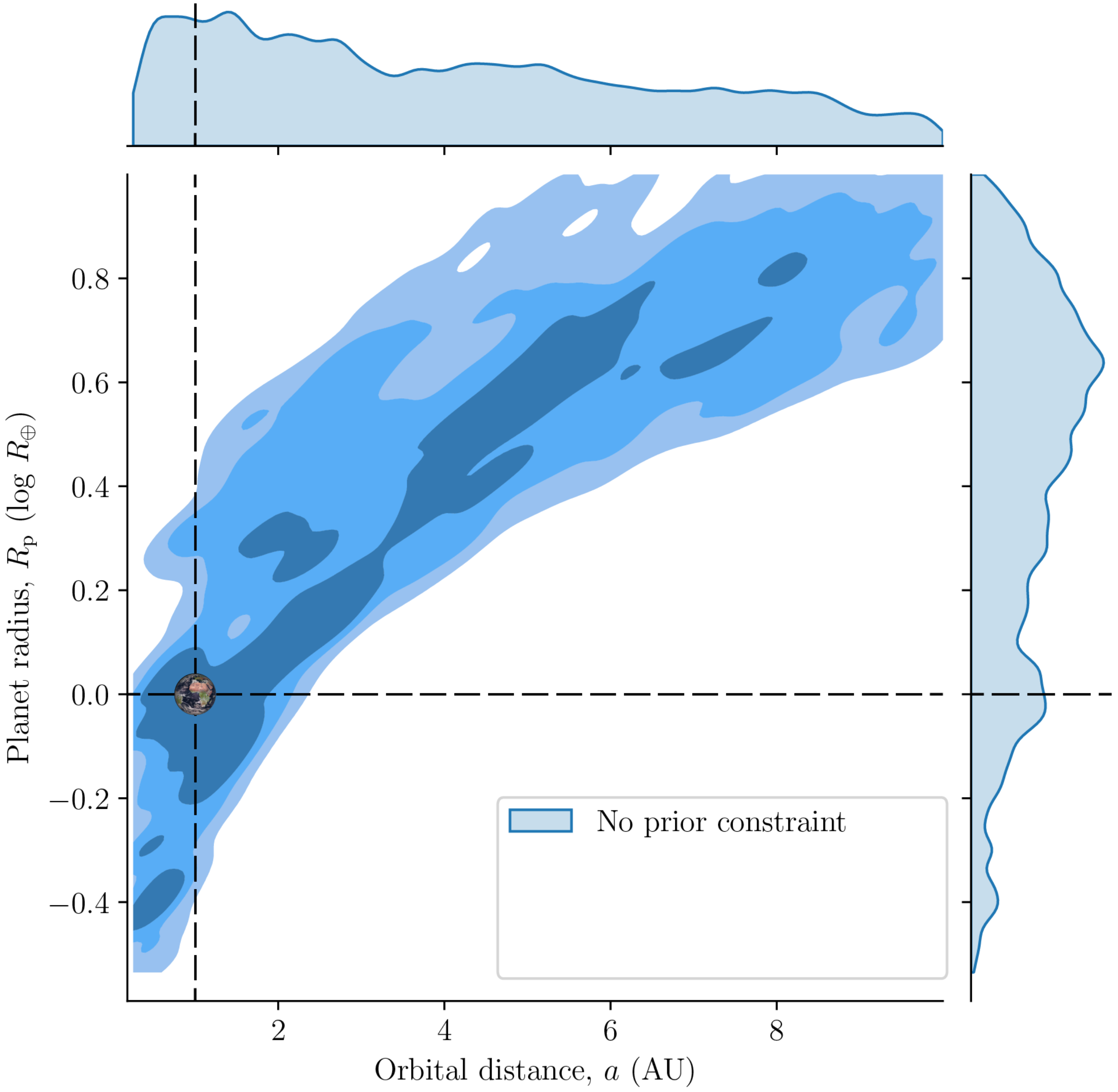




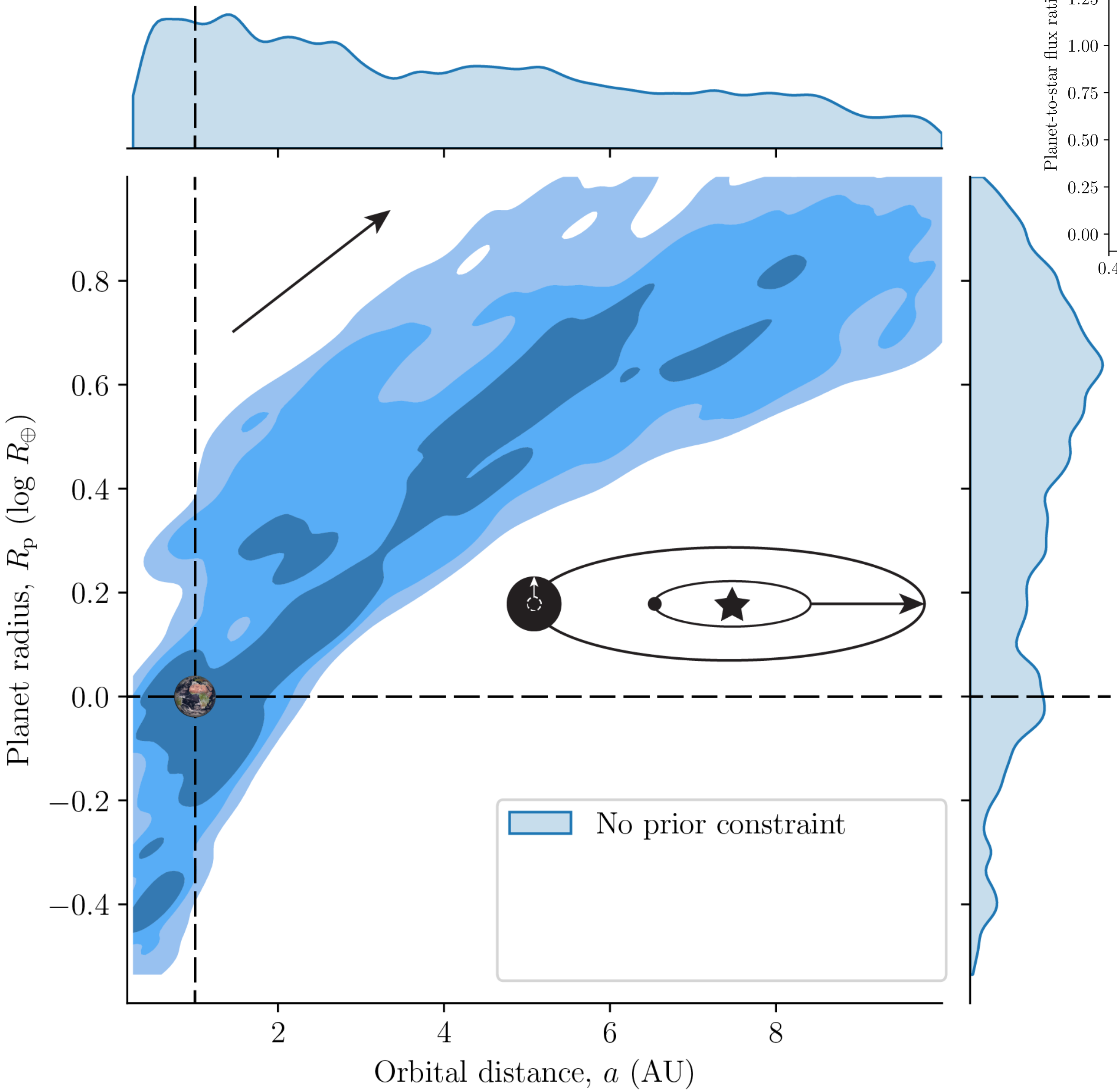
Influence of Prior Information

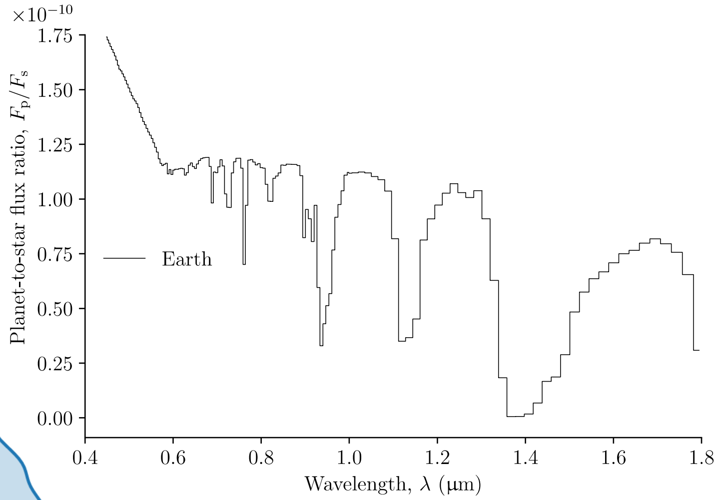


Influence of Prior Information

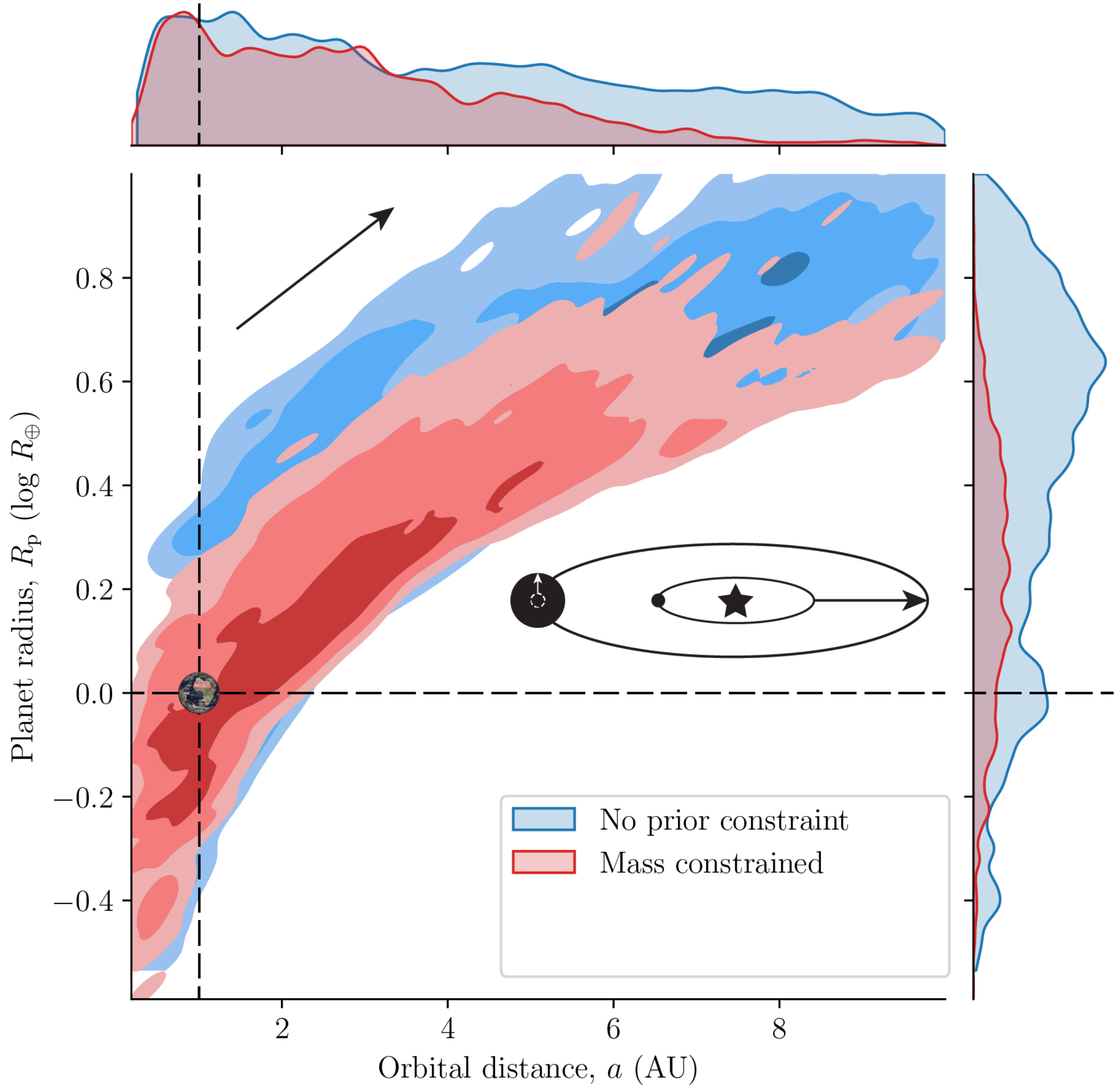


Influence of Prior Information

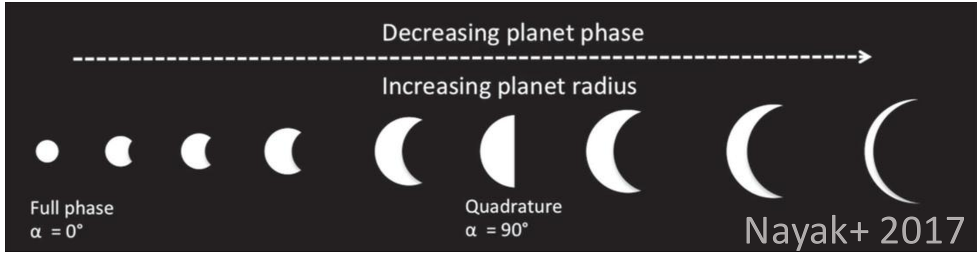


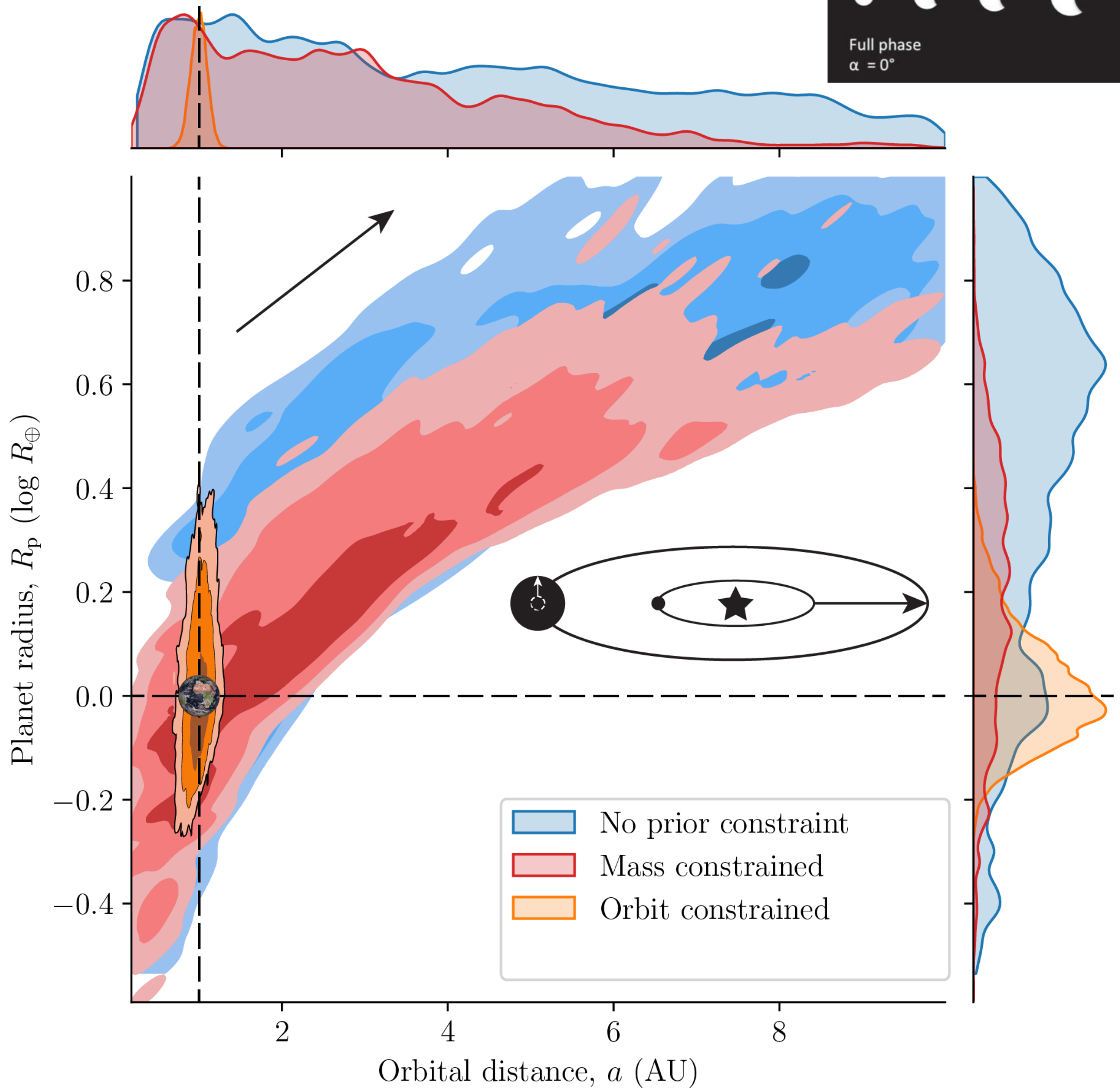


Influence of Prior Information

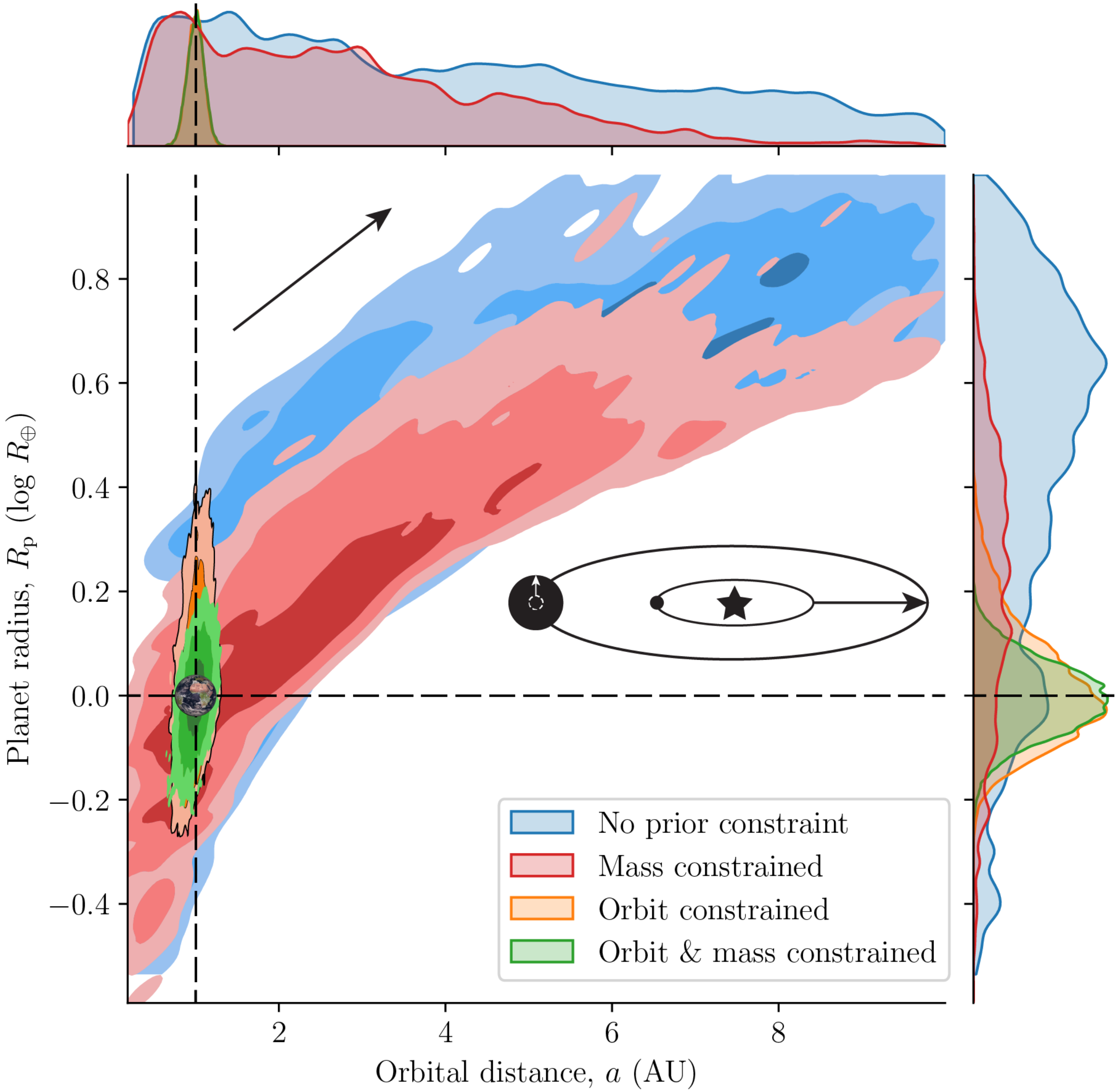


Influence of Prior Information



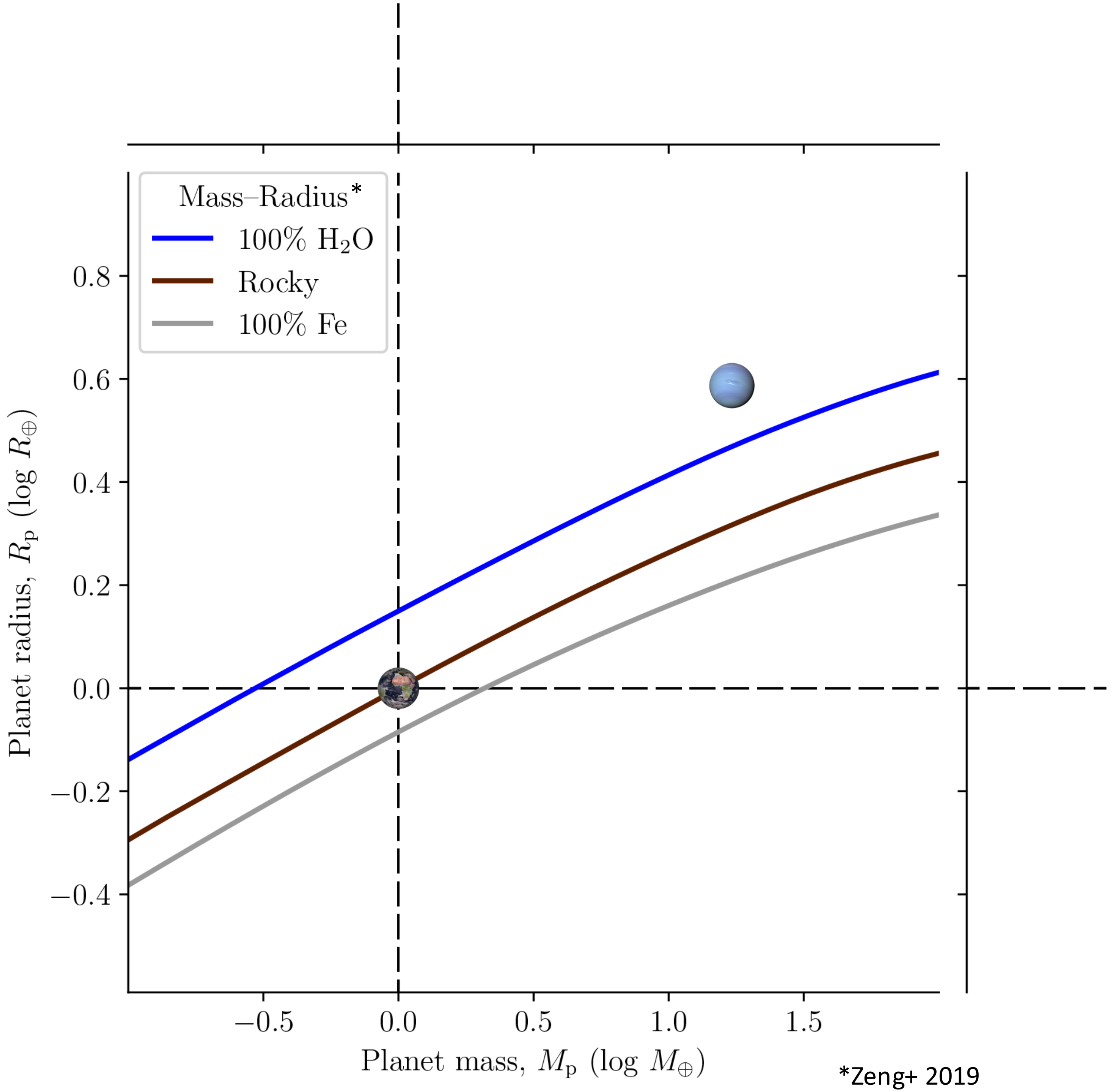


Influence of Prior Information



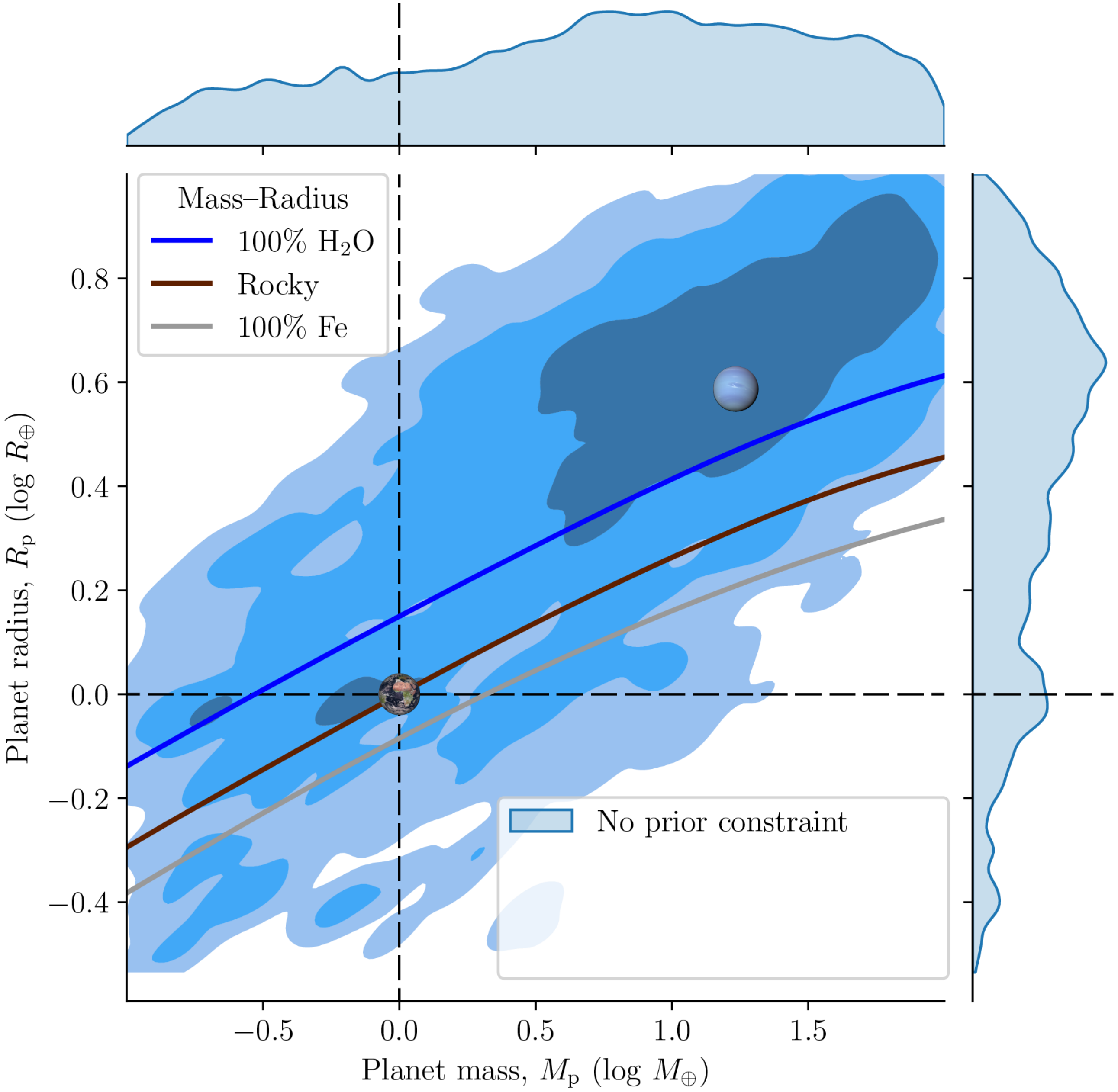
Salvador et al., ApjL (2024)

Influence of Prior Information

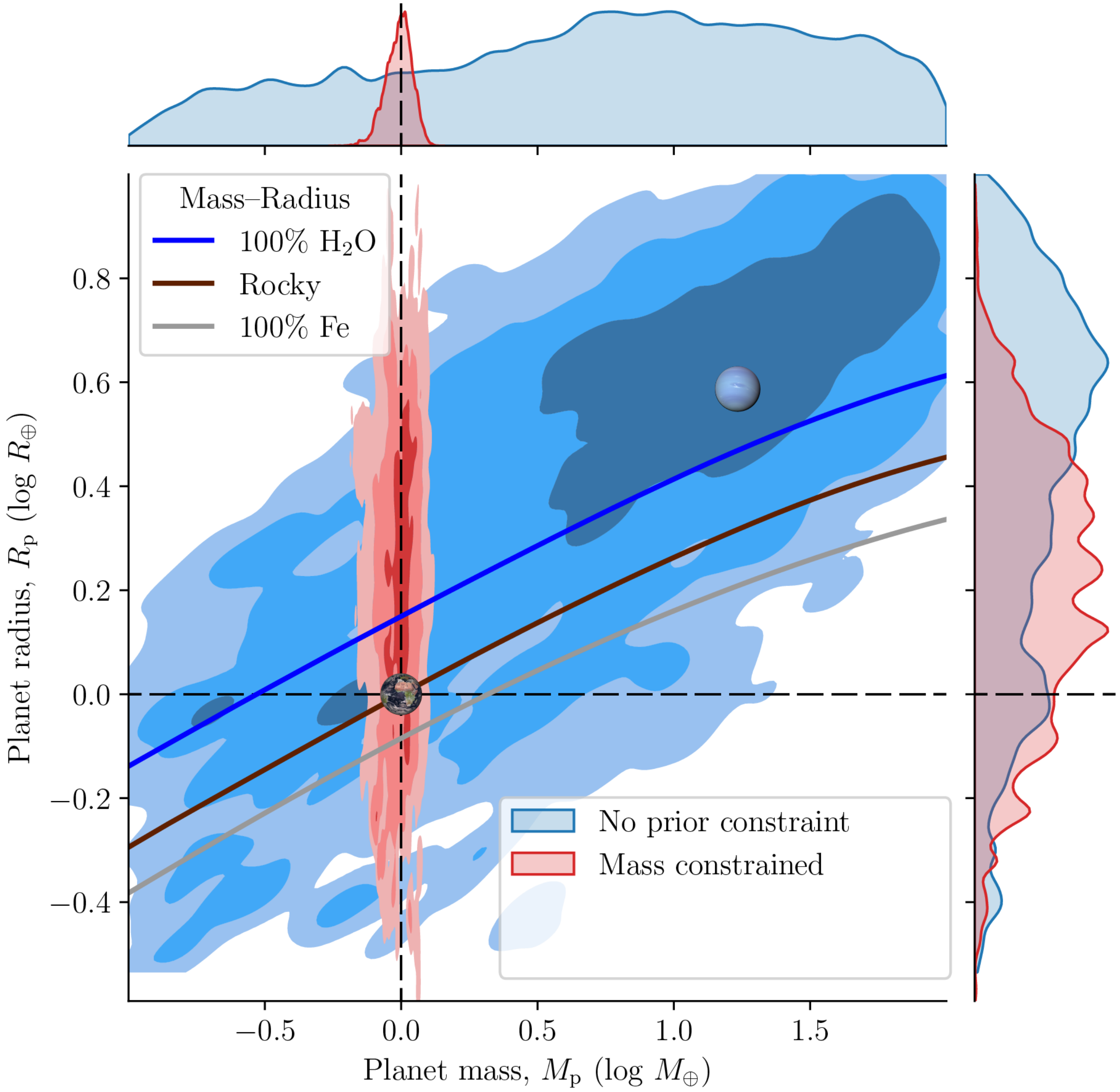


*Zeng+ 2019

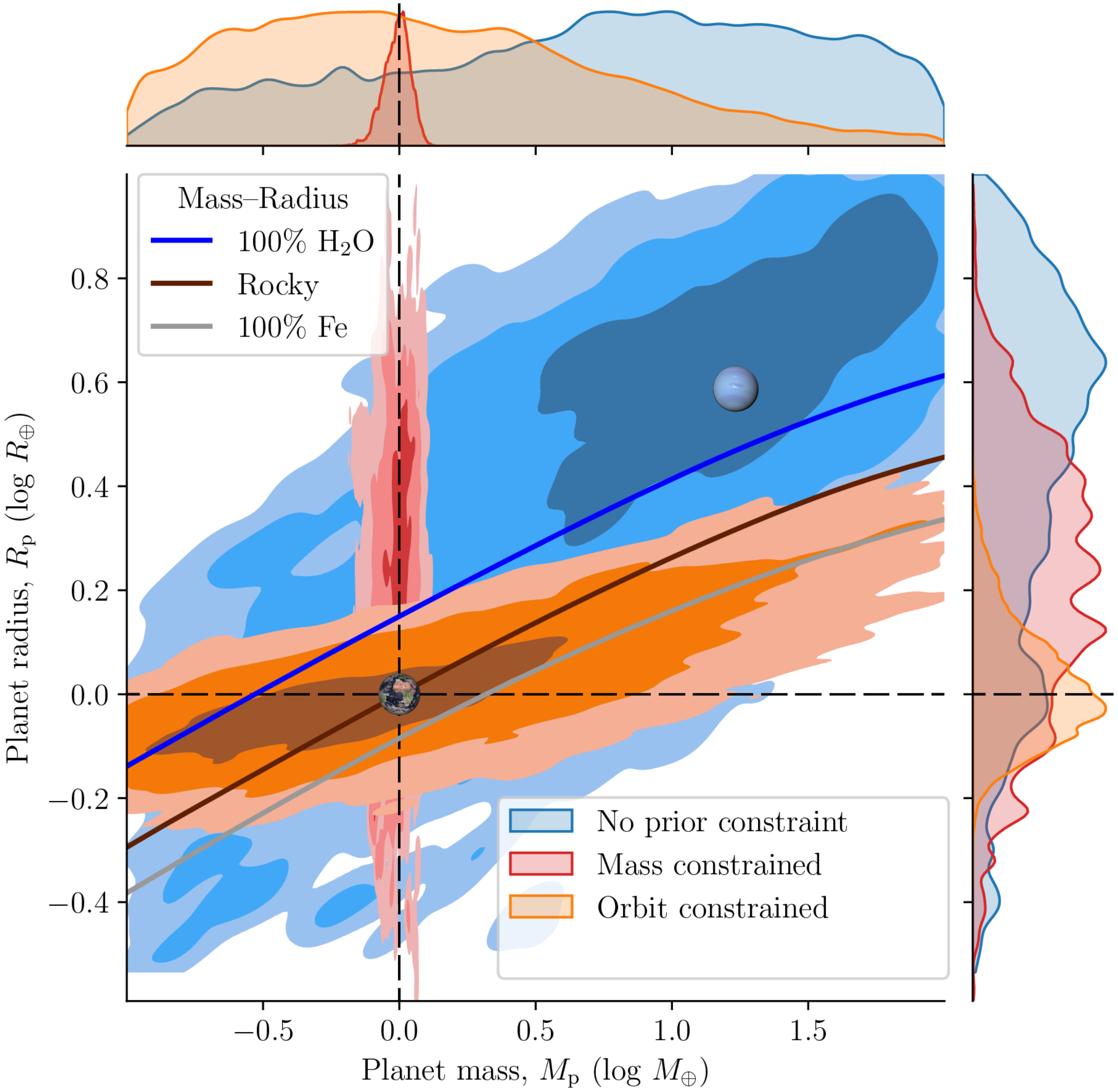
Influence of Prior Information



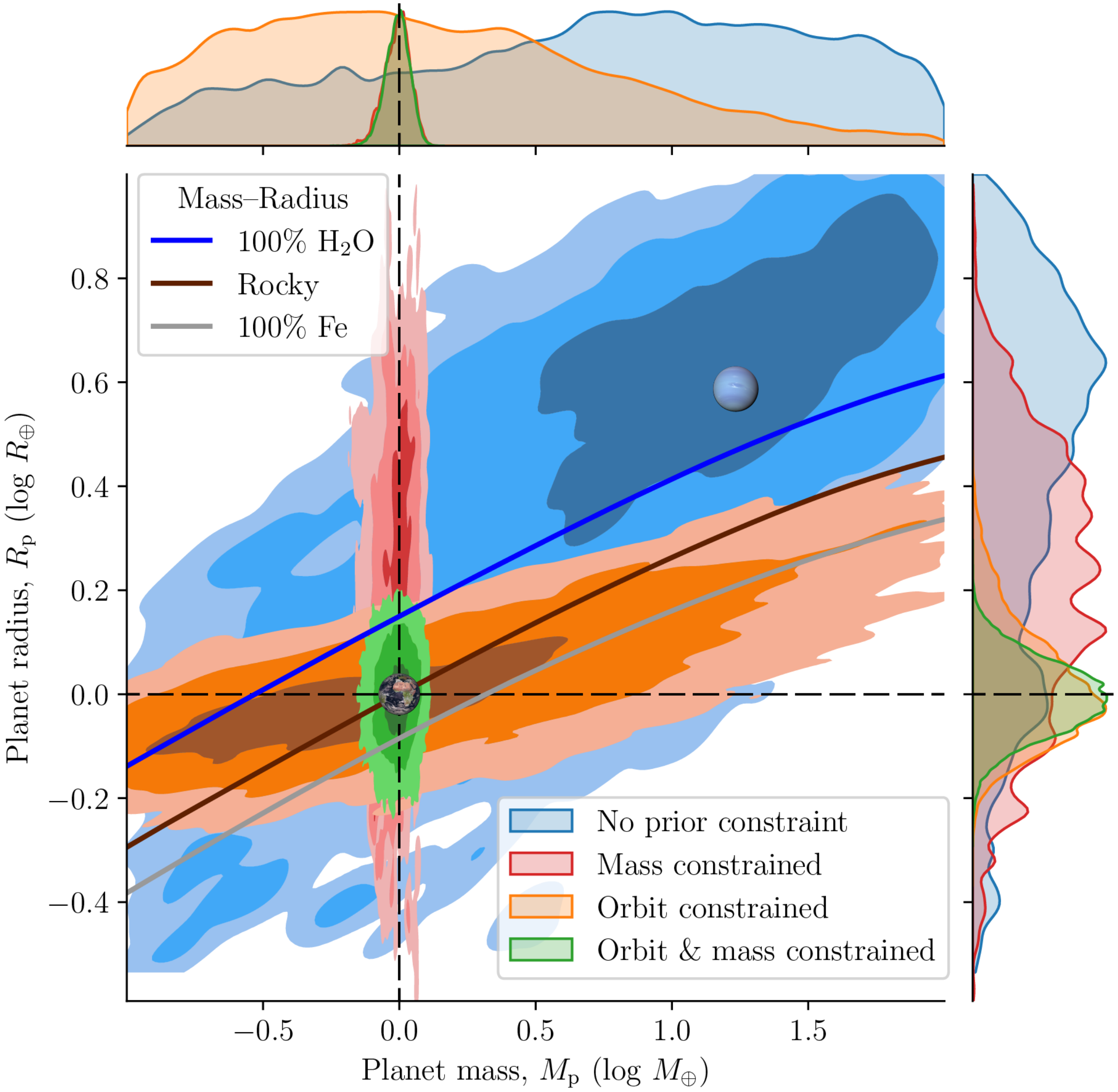
Influence of Prior Information



Influence of Prior Information

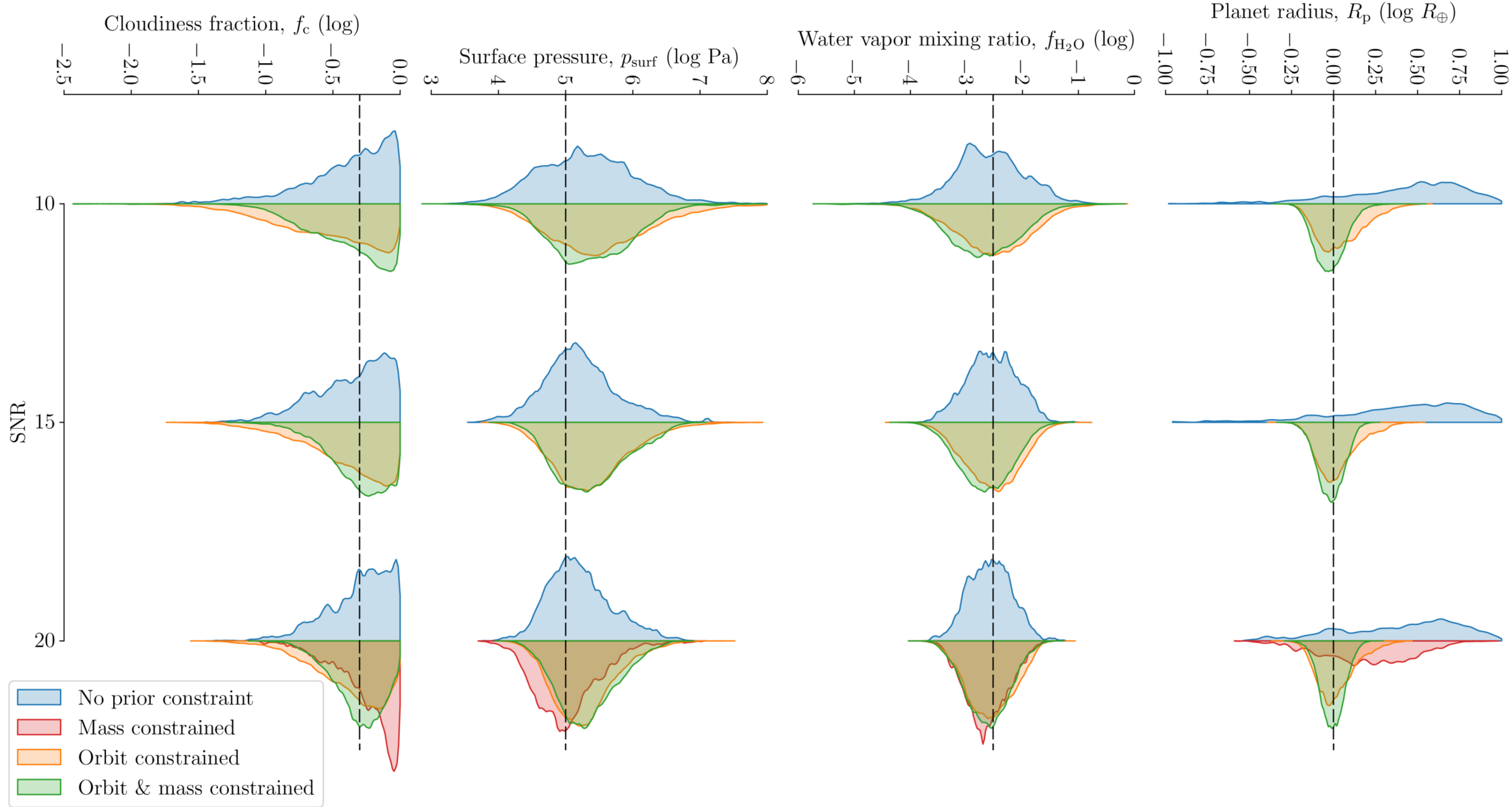


Influence of Prior Information



Salvador et al., ApjL (2024)

Influence of Prior Information



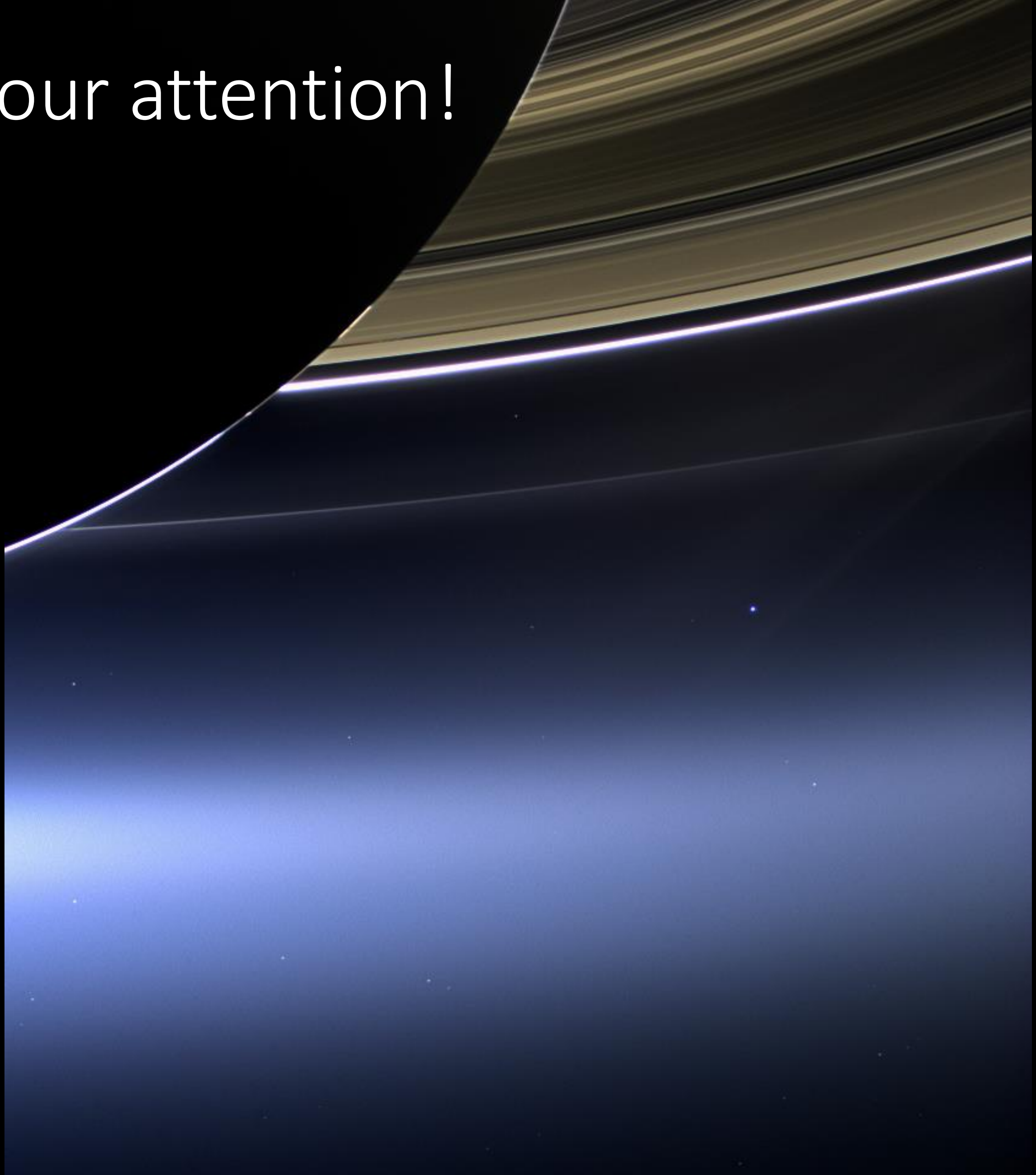
Conclusions

- ***Prior orbit knowledge*** allows planet radius determination
- ***Mass prior knowledge*** does *not* improve atmospheric characterization

Conclusions

- ***Prior orbit knowledge*** allows planet radius determination
- ***Mass prior knowledge*** does *not* improve atmospheric characterization
- ***Spectral coverage*** is of major importance in recognizing a habitable environment
- ***Higher SNR*** helps for broad spectral coverages

Thank you for your attention!



Funding source:
Habitable Worlds

Pictures credits:
ISS, NASA, ESO,
HabEx, LUVOIR,
HABLab, ESA,
Cassini