Exoplanet Detection and Characterization in the Ultraviolet using a Starshade Complement for Habitable Worlds Observatory

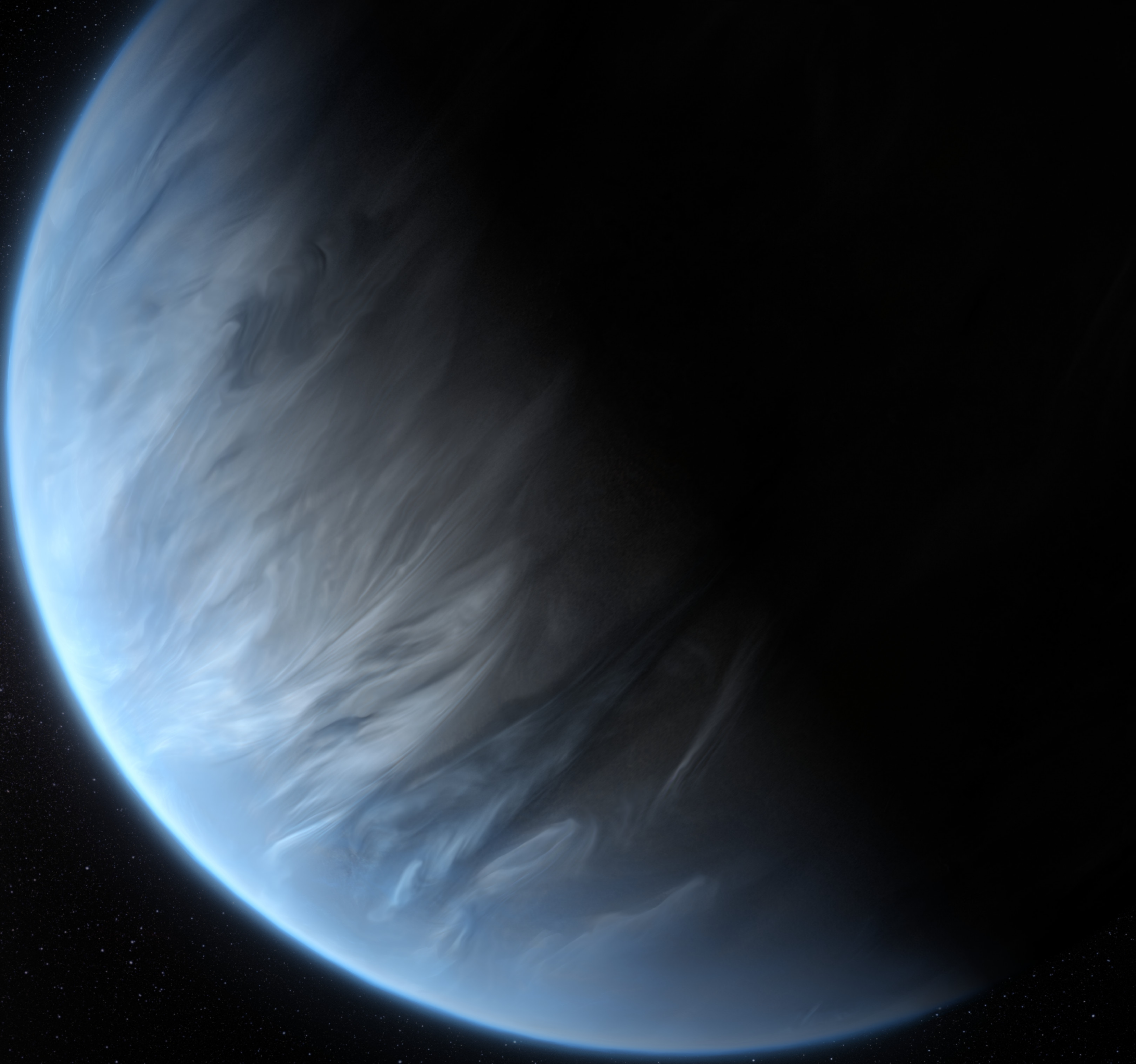
Zahra Ahmed, Stuart Shaklan, Simone D’Amico

ExoExplorers Science Series
June 14, 2024

Source: ESA/Hubble

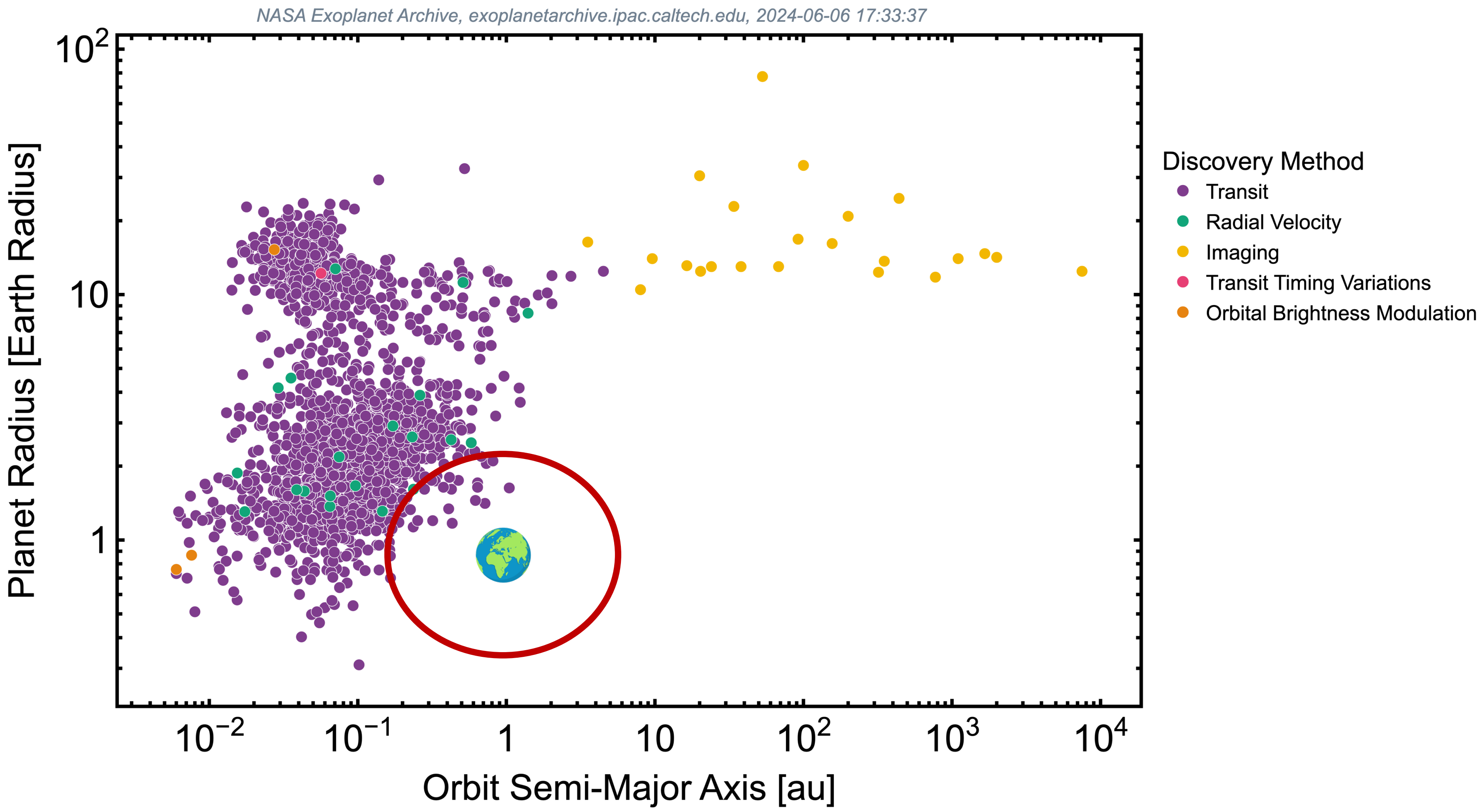
Overview

- Background & Motivation
  - The Search for Habitable Worlds
  - Starlight Suppression
  - Data Reduction Pipelines
- Project Goals
- Data Simulation
- Background Subtraction
- Conclusions & Way Forward



Source: ESA/Hubble

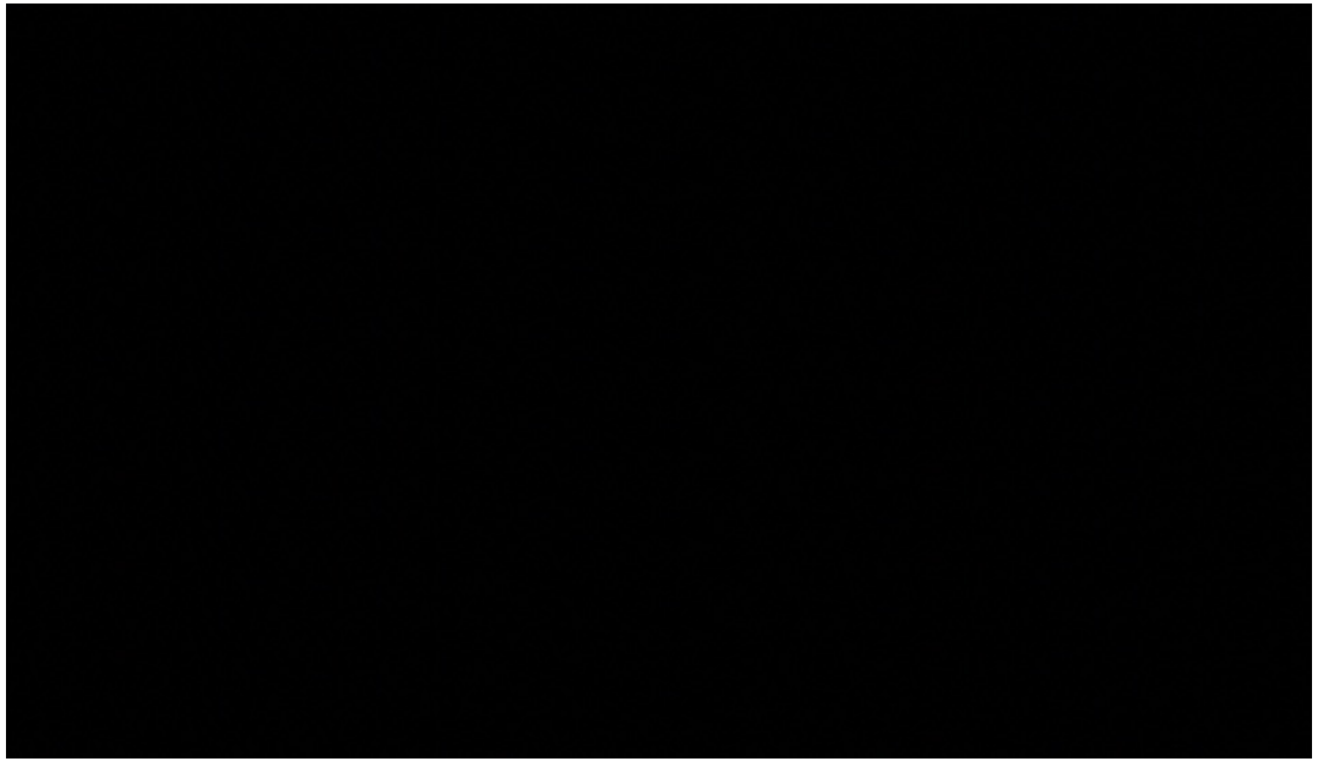
The Search for Habitable Worlds



Achieving Habitable Worlds Observatory's goal of imaging and characterizing ~25 habitable worlds will require advancements in starlight suppression as well as data simulations and analysis pipelines

Starshades: A Powerful Characterization Tool

- Starshades are external telescope occulters that can work in tandem with ground- or space-based telescopes
- Optical tests have shown starshades can achieve > 10^{-10} contrast
- Small inner working angle (IWA)
- High throughput
- Large Bandwidth
- Ideal for operating in the UV
- Tradeoff is reconfiguration time and fuel, which limits the number of targets that can be imaged



Source: NASA /JPL-Caltech

Starshades' ability to achieve high contrast coupled with their small IWA and broad bandwidth make them a powerful characterization tool in the ultraviolet spectrum

Starshades: A Powerful Characterization Tool

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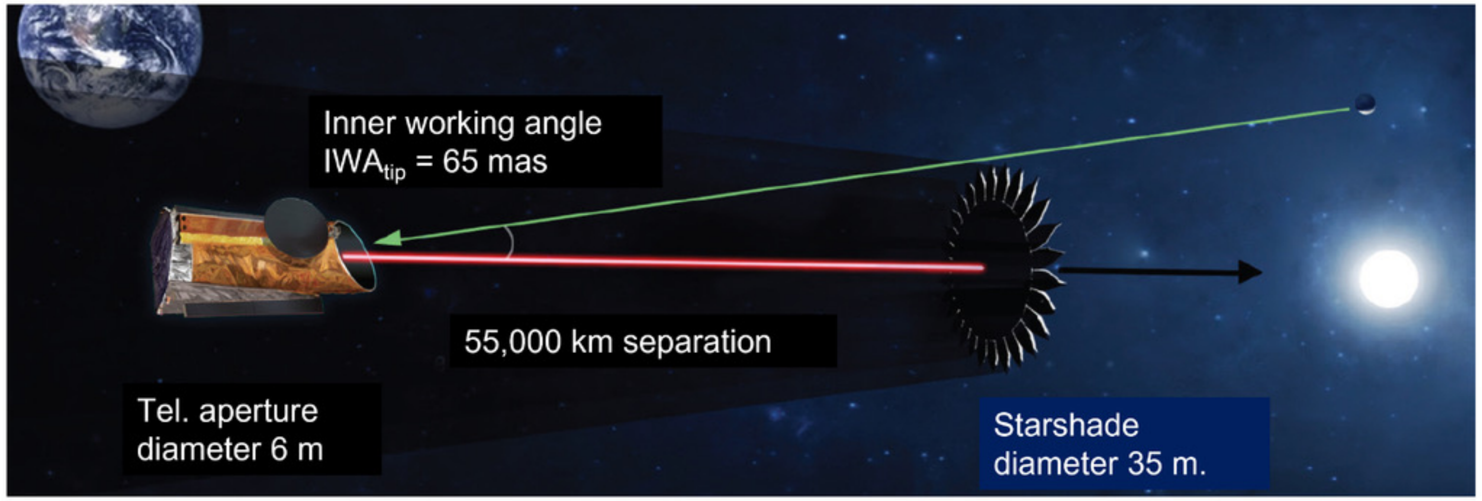
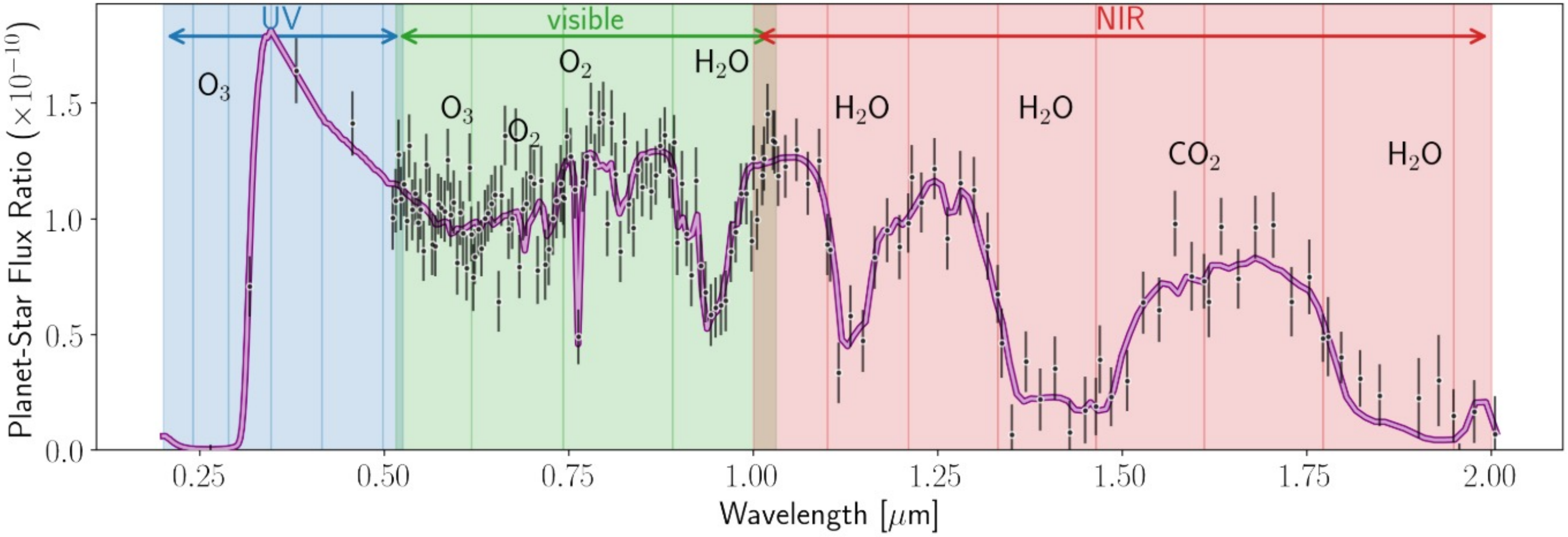


Shaklan, S. et al. 2023 Proc. SPIE 12680

Source: NASA /JPL-Caltech

Biosignatures in the Ultraviolet

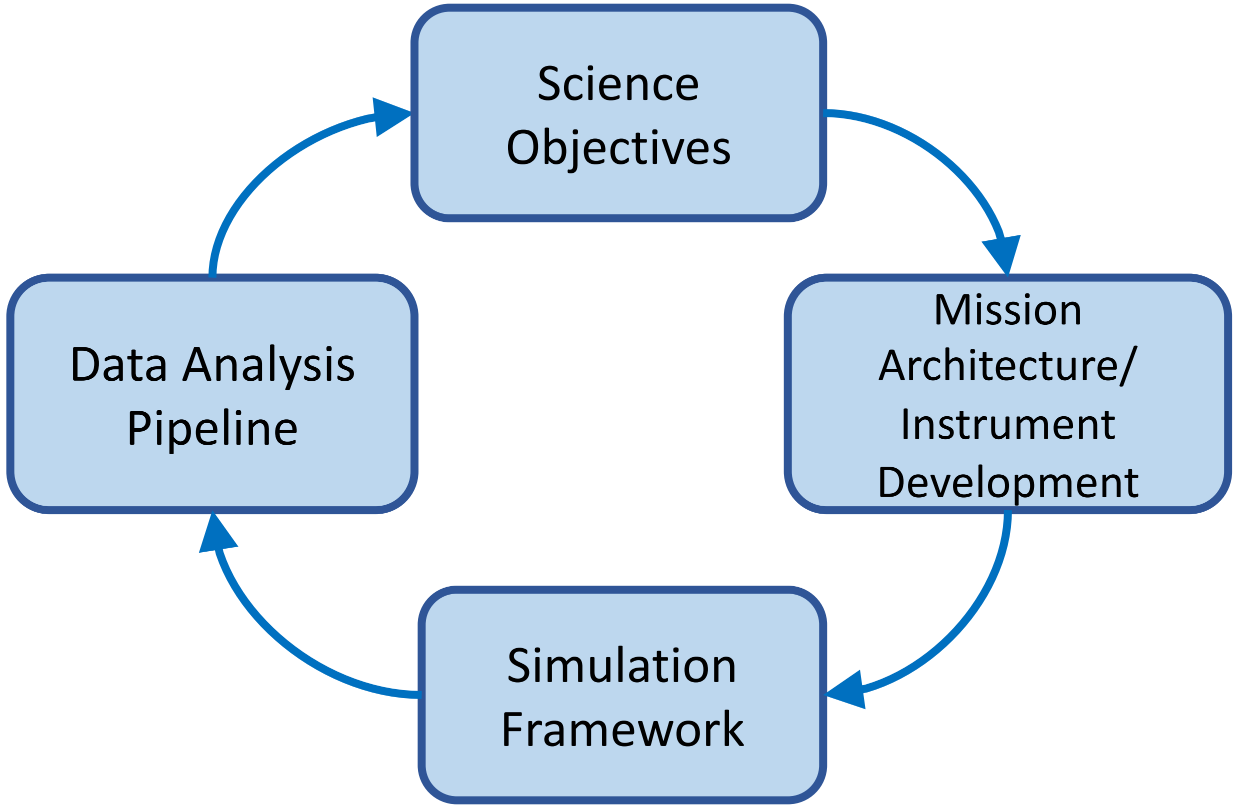


LUVOIR Final Report, Credit: Jacob Lustig-Yaeger

The 0.25 μm ozone feature is a key biosignature both in modern and Proterozoic Earth-like atmospheres

The Importance of Simulated Data and Analysis Pipelines

- Data Challenges
  - Starshade Exoplanet Data Challenge
  - Exoplanet Imaging Data Challenge
  - Roman Space Telescope Exoplanet Data Challenge
- Open-Source Software Libraries



Simulation frameworks and data analysis pipelines are necessary to assess the performance and limitations of mission architectures and inform noise budget requirements

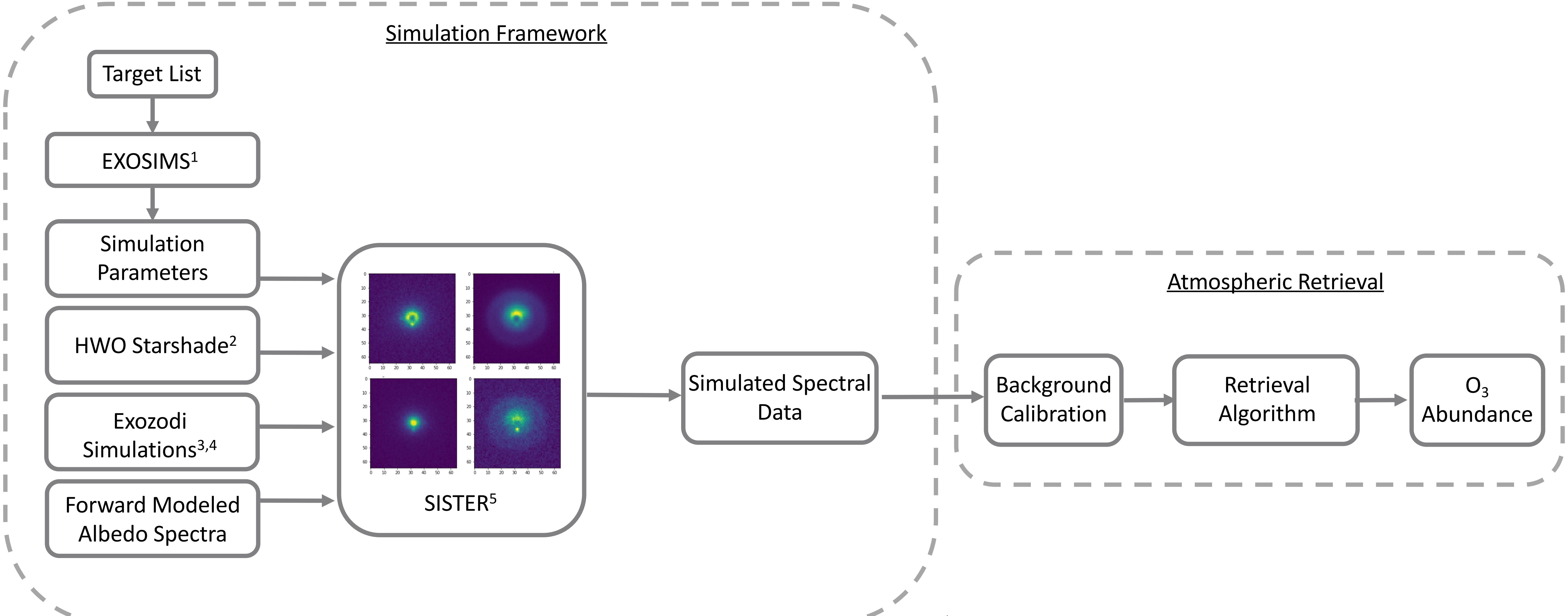
Project Overview

Objective: Investigate the ability to characterize Earth-like exoplanets using a starshade in the ultraviolet to constrain ozone abundance with low resolution spectroscopy

1. Data Simulation: Simulate end-to-end starshade spectral data cubes that include systematic noise sources for a variety of observing conditions

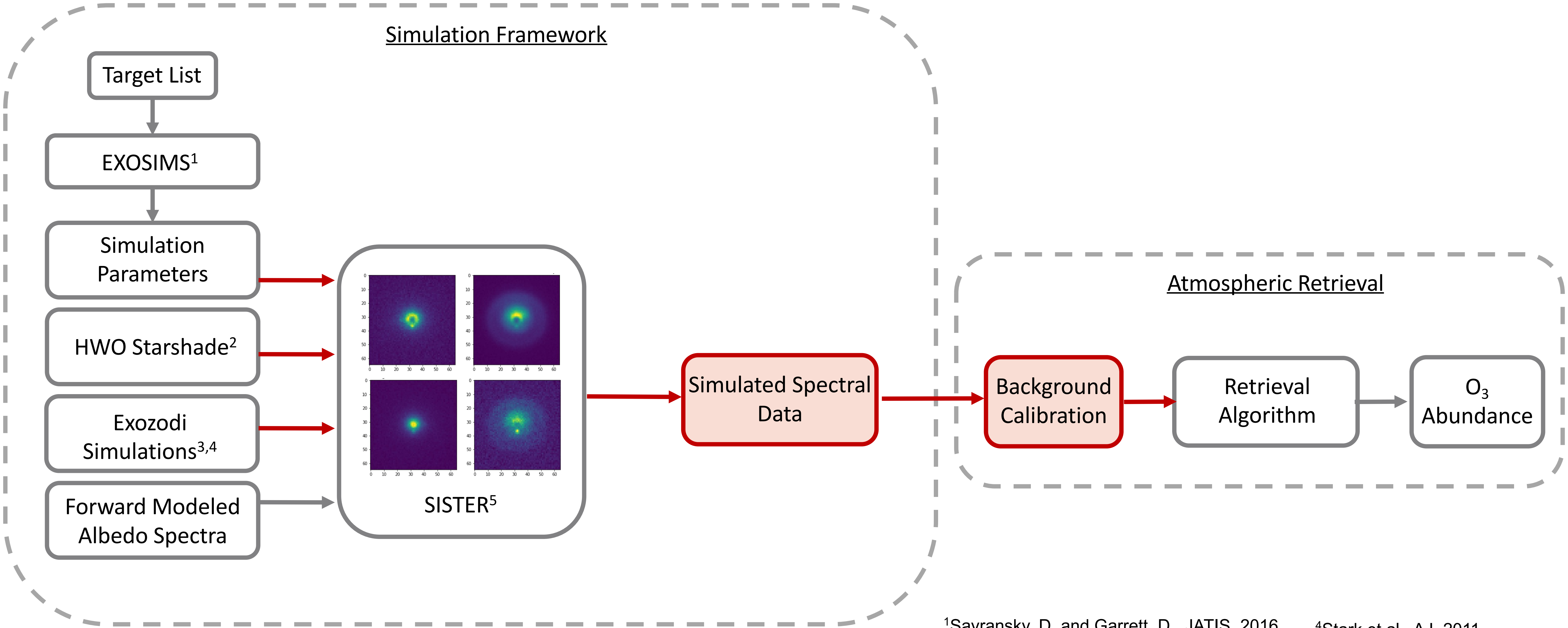
2. Analysis: Extract the exoplanet spectrum from the noisy data and perform a sensitivity analysis to quantify under what conditions can the 0.25 μm ozone feature be constrained

Project Overview



[1]Savransky, D. and Garrett, D., JATIS, 2016
[2]Shaklan, S. et al, SPIE Proc. 12680, 2023
[3]Currie et al., AJ, 2023
[4]Stark et al., AJ, 2011
[5]Hildebrandt, S. et al. JATIS, 2021

Project Overview



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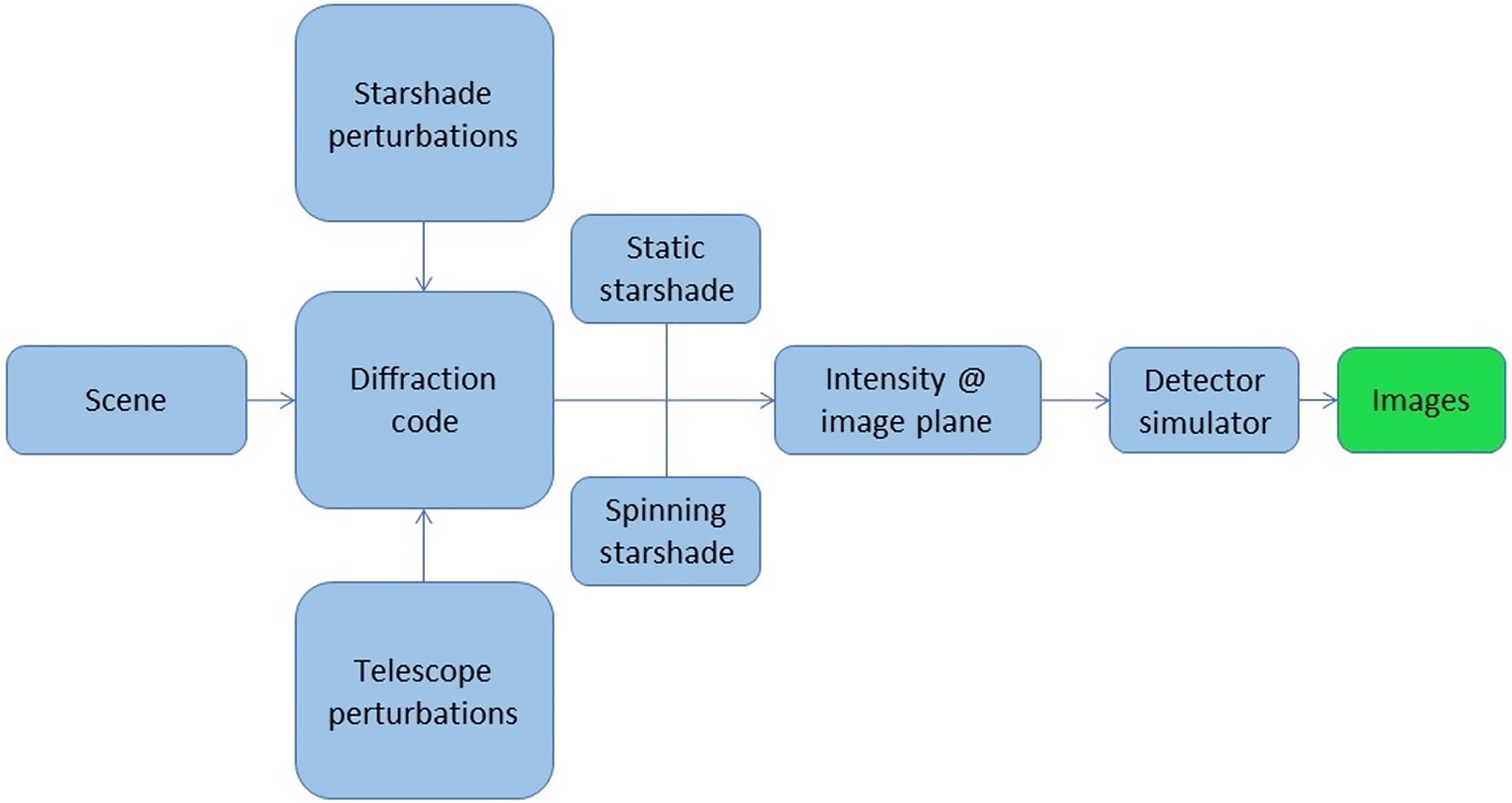
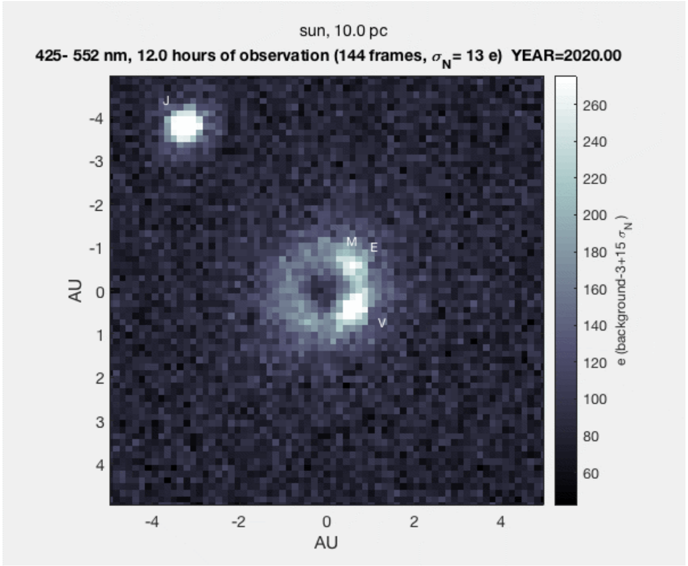
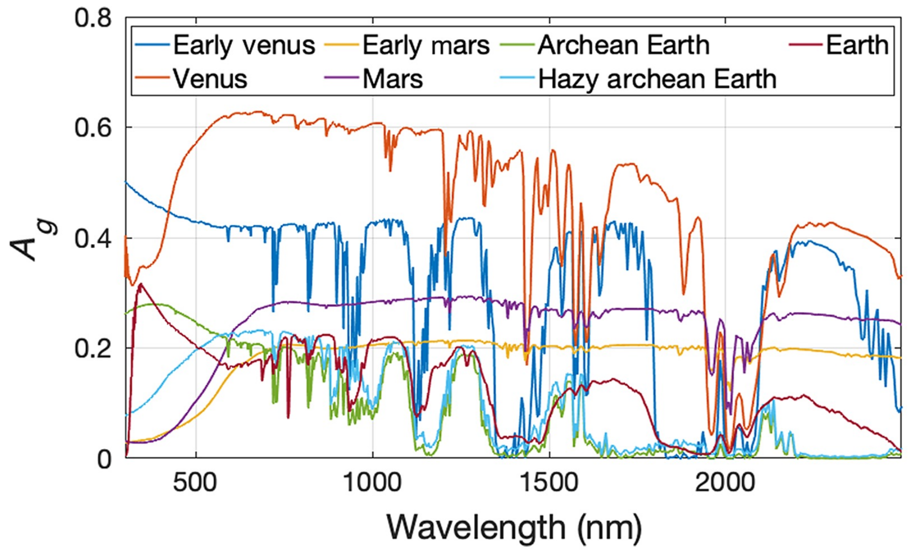
Starshade Imaging Simulation Toolkit for Exoplanet Reconnaissance (SISTER)



Hildebrandt, S. et al. 2021 JATIS



Source: Sister.Caltech.edu/JPL-Caltech

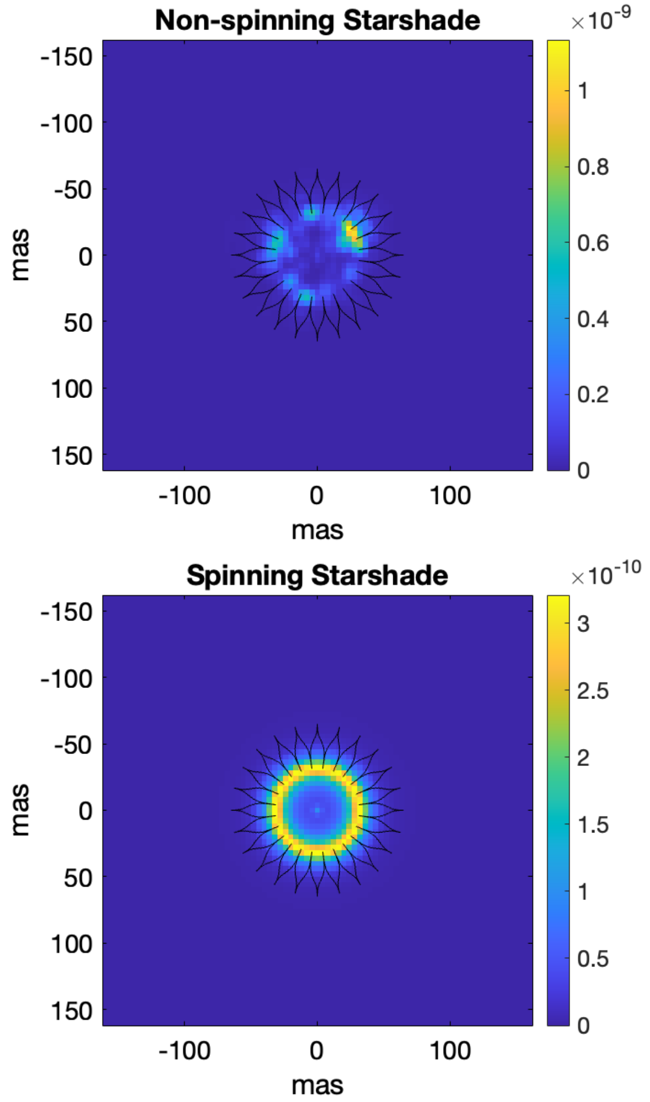


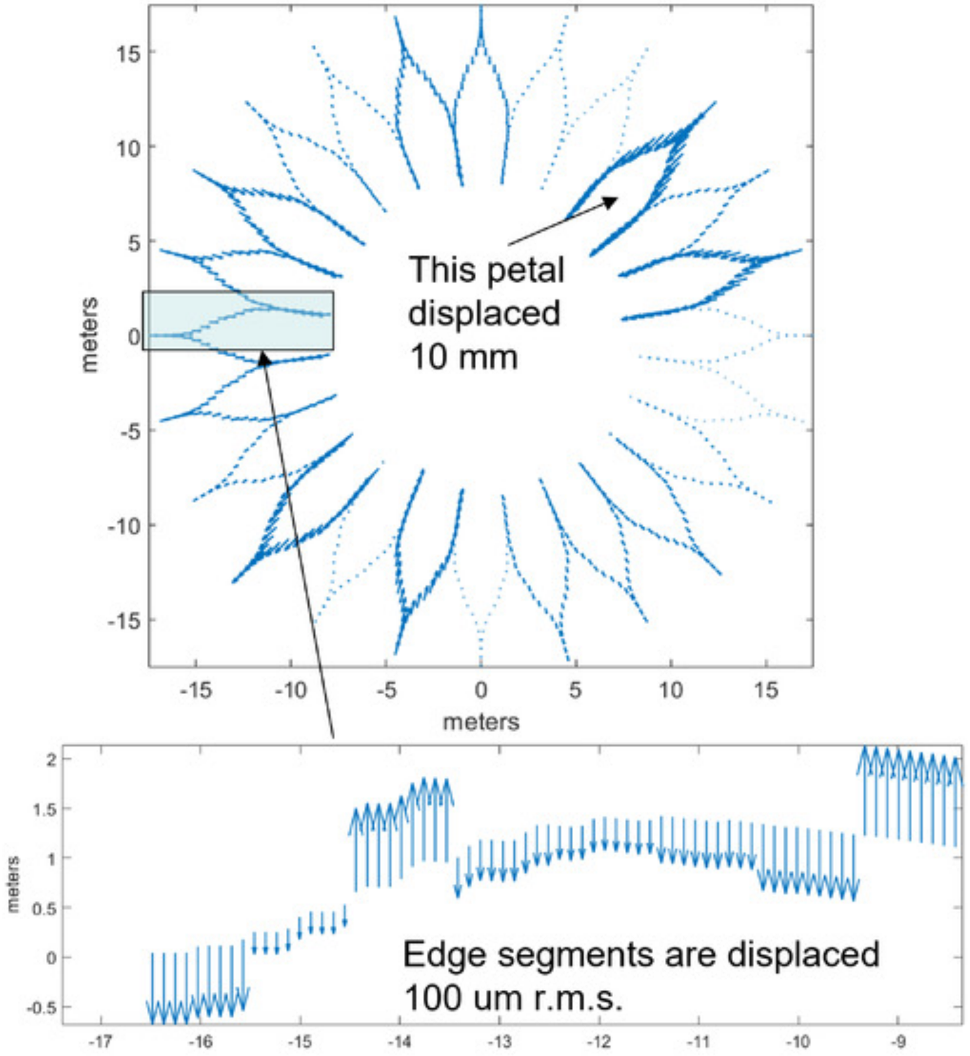
Hildebrandt, S. et al. 2021 JATIS

UV Starshade Design

- UV Starshade design introduced in Shaklan, S. et al. 2023

Parameter	Value
Starshade Diameter (tip-to-tip)	35 m
Telescope Diameter	6 m
Number of Petals	24
Inner Working Angle	65 mas
Nominal Separation from Telescope	55,000 km
Nominal Operating Bandpass	250 - 500 nm





Shaklan, S. et al. 2023 Proc. SPIE 12680

Data Simulation Parameters

Parameter	Value(s)
Imaging Bandpass	250 - 500 nm with 25 nm bands
System Distance	10 pc
Target Star	Solar-type star
Planet	Modern Earth-twin in a circular 1 AU orbit
Planet True Anomaly	0, 30, 60, 90, 120, 150, 180 degrees
Disk Inclination	0, 30, 60 degrees
Exozodi Density	1, 5, 10, 20, 50, 100 zodi

Data Simulation Parameters: Phase Angle

Parameter	Value(s)
Imaging Bandpass	250 - 500 nm with 25 nm bands
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$$\cos(\alpha) = \cos(\nu)\sin(i)$$

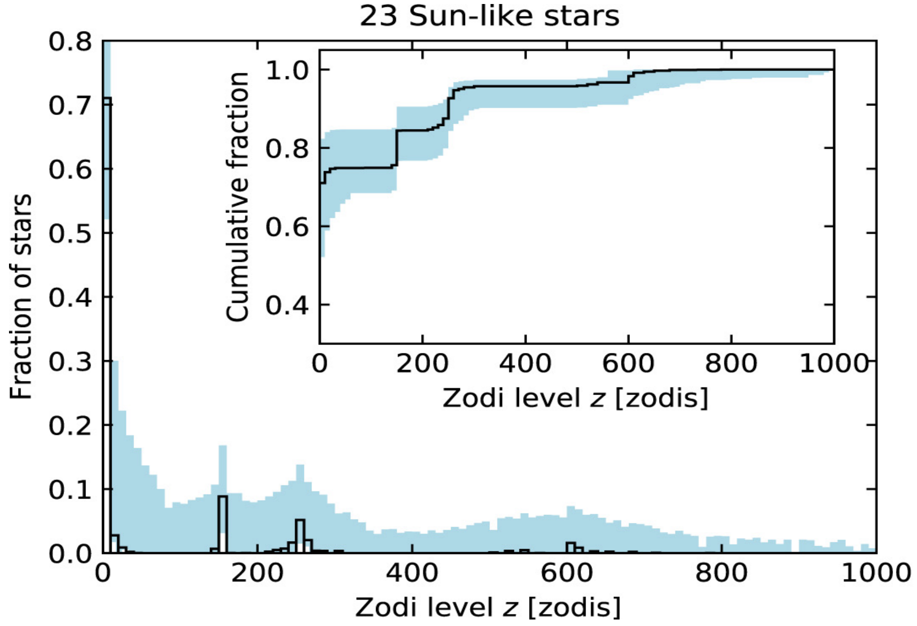
α = planet phase angle

ν = planet true anomaly

i = inclination

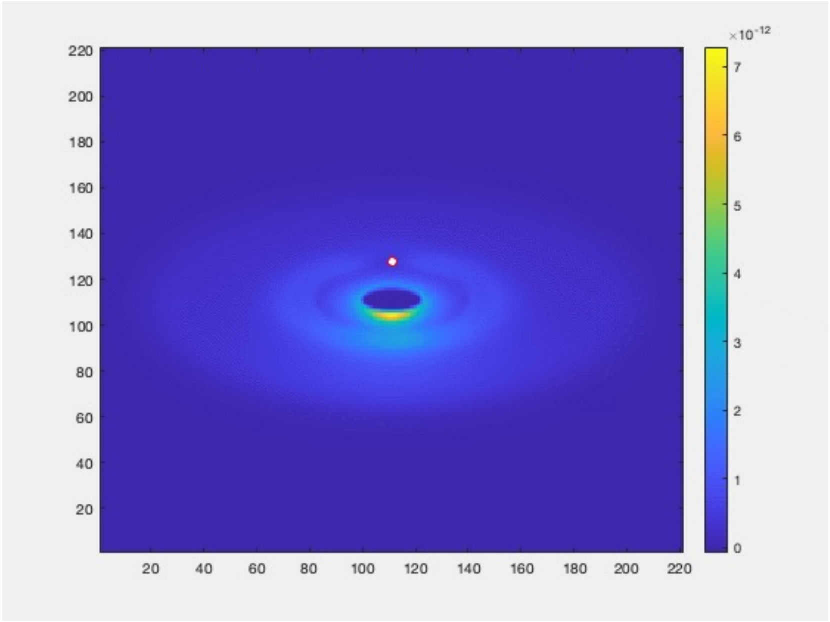
Data Simulation Parameters: Exozodiacal Dust

Parameter	Value(s)
Imaging Bandpass	250 - 500 nm with 25 nm bands
System Distance	10 pc
Target Star	Solar-type star
Planet	Modern Earth-twin in a circular 1 AU orbit
Planet True Anomaly	0, 30, 60, 90, 120, 150, 180 degrees
Disk Inclination	0, 30, 60 degrees
Exozodi Density	1, 5, 10, 20, 50, 100 zodi



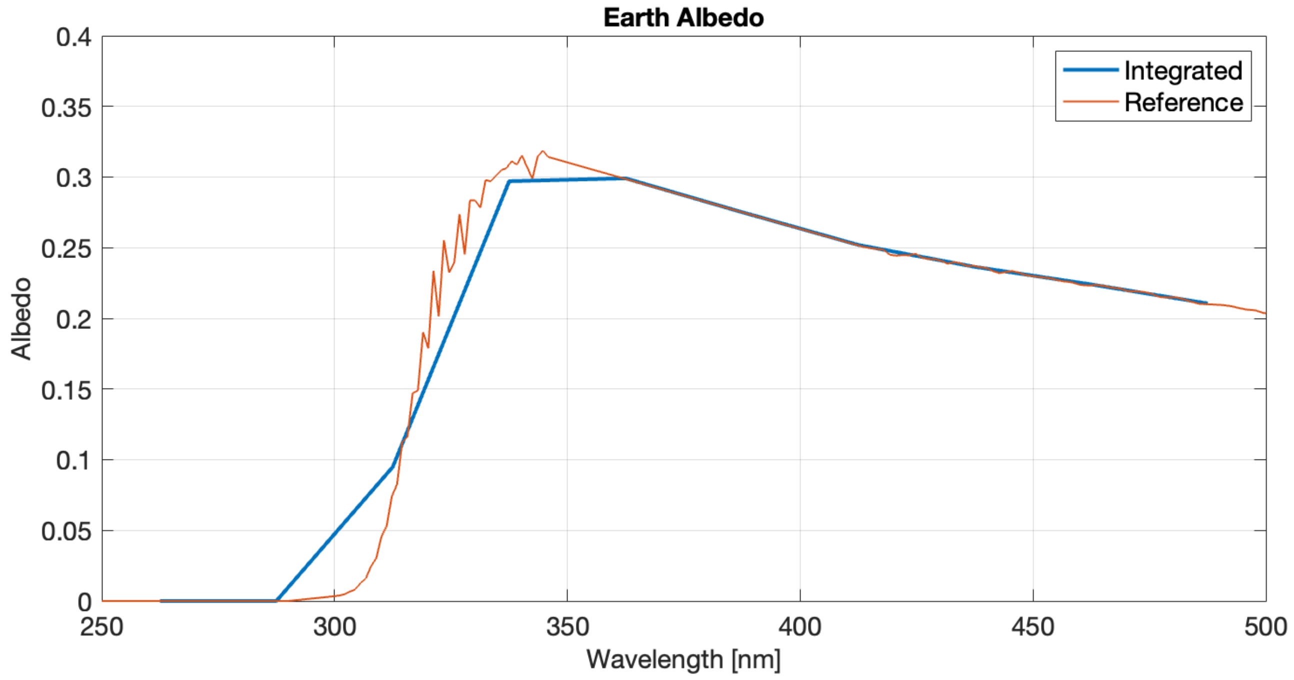
Source: Ertel, S. et al. 2020 AJ

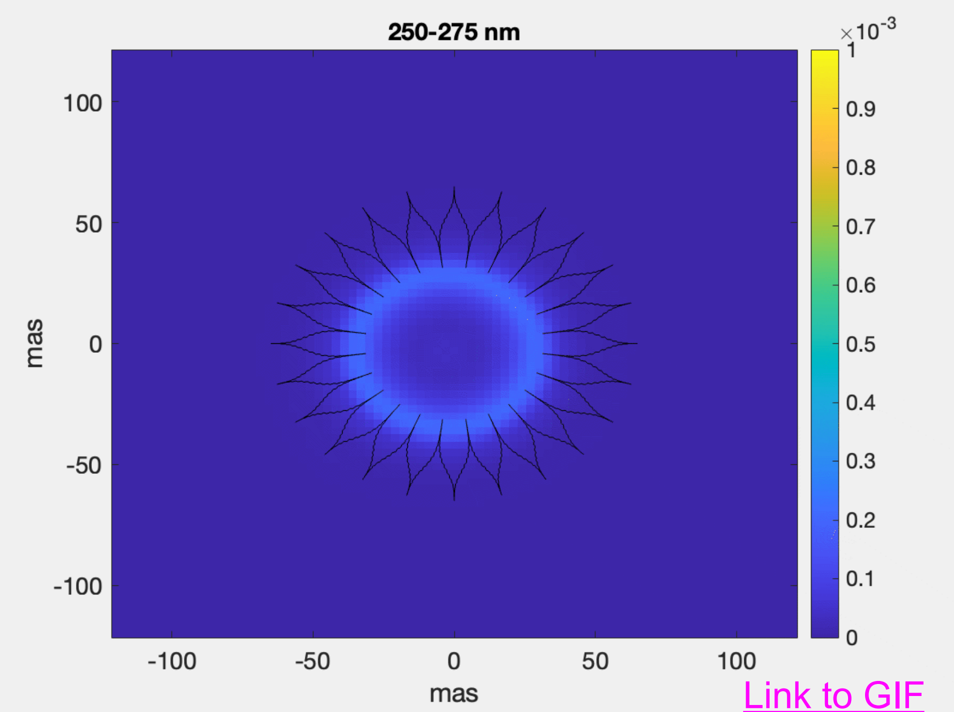
- Post-processing techniques for directly imaged exoplanets in the habitable zone will need to account for resonant exozodiacal debris disks
- Exozodi models (Stark, C. 2011 AJS) generated via n-body simulations
- Scattered light exozodiacal dust images provided by Miles Currie (UW), used in Currie, M. et al., 2023 AJ



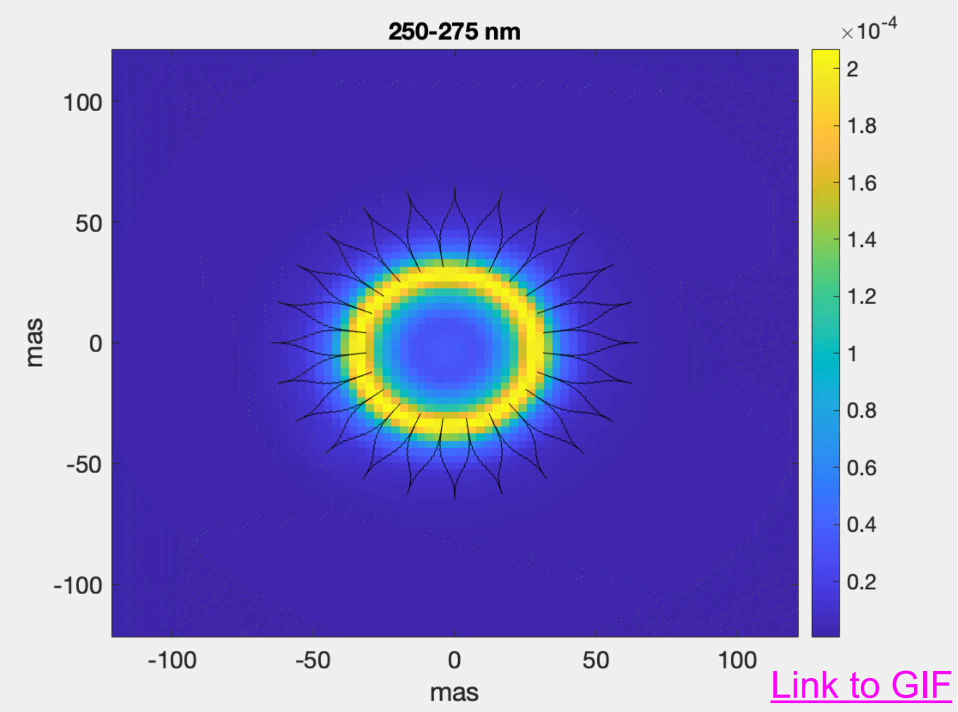
Data Simulation Results

- 24-hour integration time
- Modeling stellar diffraction, solar glint, exozodi, local zodi, photon and detector noise w/ single injected planet
- Both animations are the same simulation, just with different scales
- All simulations shown in units counts/pixel





Link to GIF

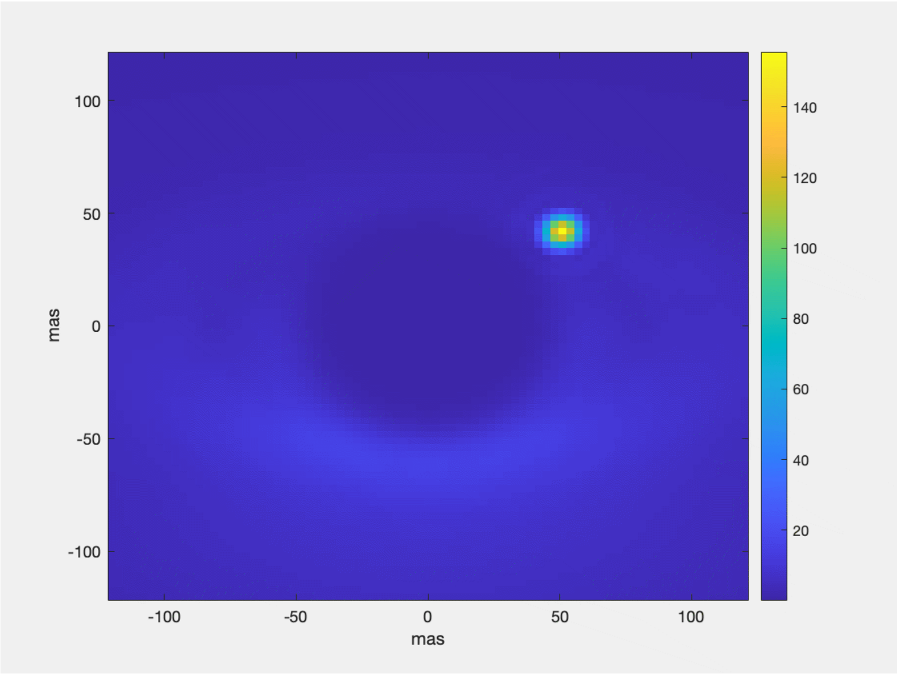


Link to GIF

Data Simulation Results: Phase Angle

- 5-day integration time
- Stellar leakage subtracted off, only including exozodi, photon and detector noise
- 60° inclined system, 1 zodi

<u>Noiseless (Exozodi + Planet Only) shown with different scales</u>



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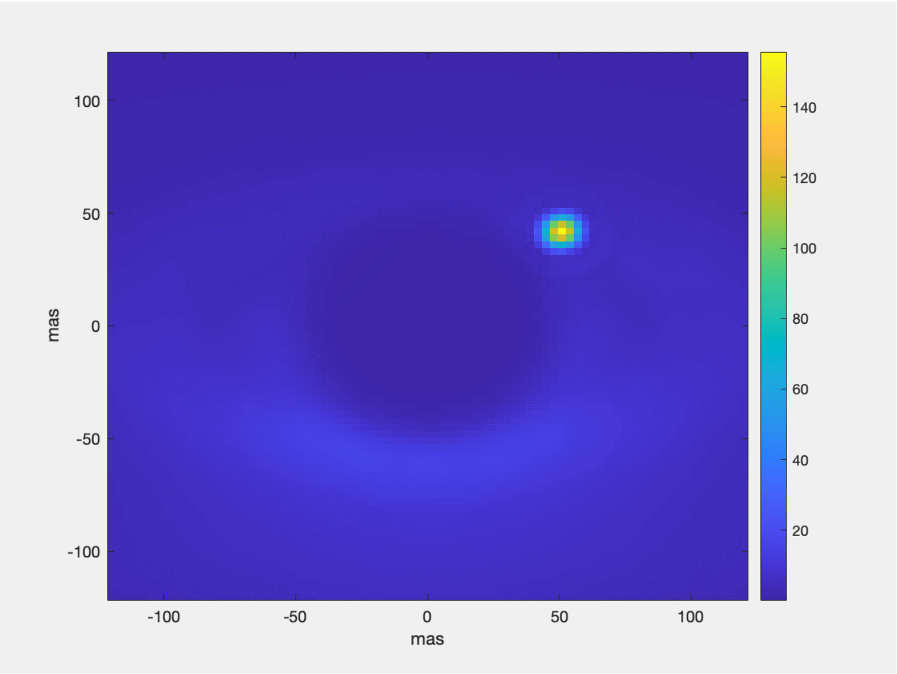

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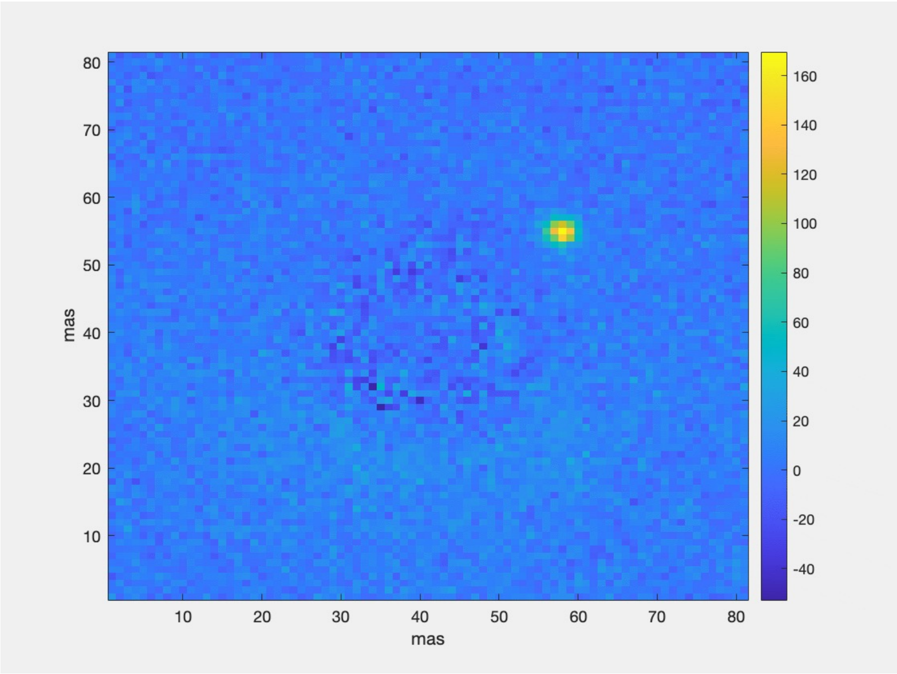
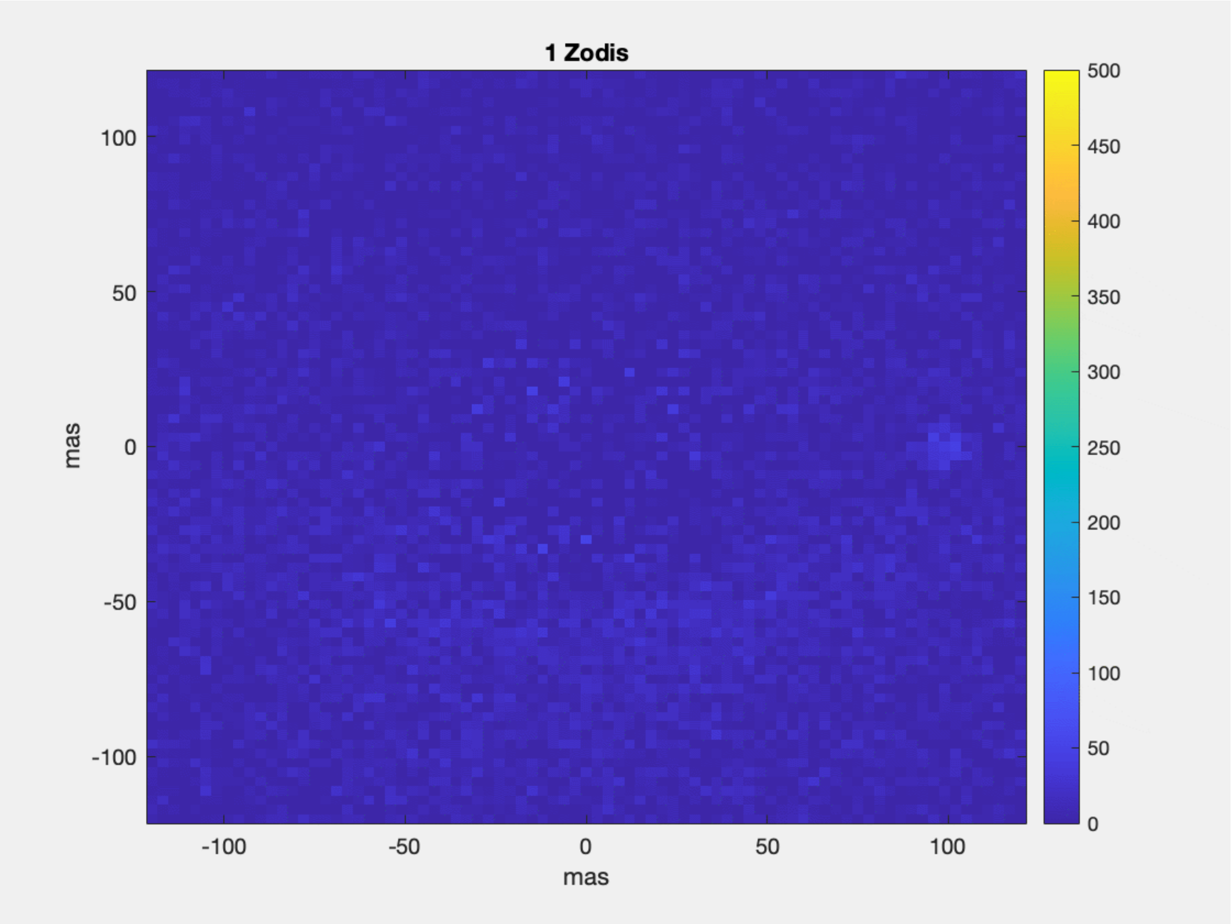
<u>With Noise</u>



Link to GIF

Data Simulation Results: Exozodiacal Dust

- 5-day integration time
- Stellar leakage subtracted off, only including exozodi, photon and detector noise
- 60° inclined system
- 300– 325nm band
- Planet injected at quadrature



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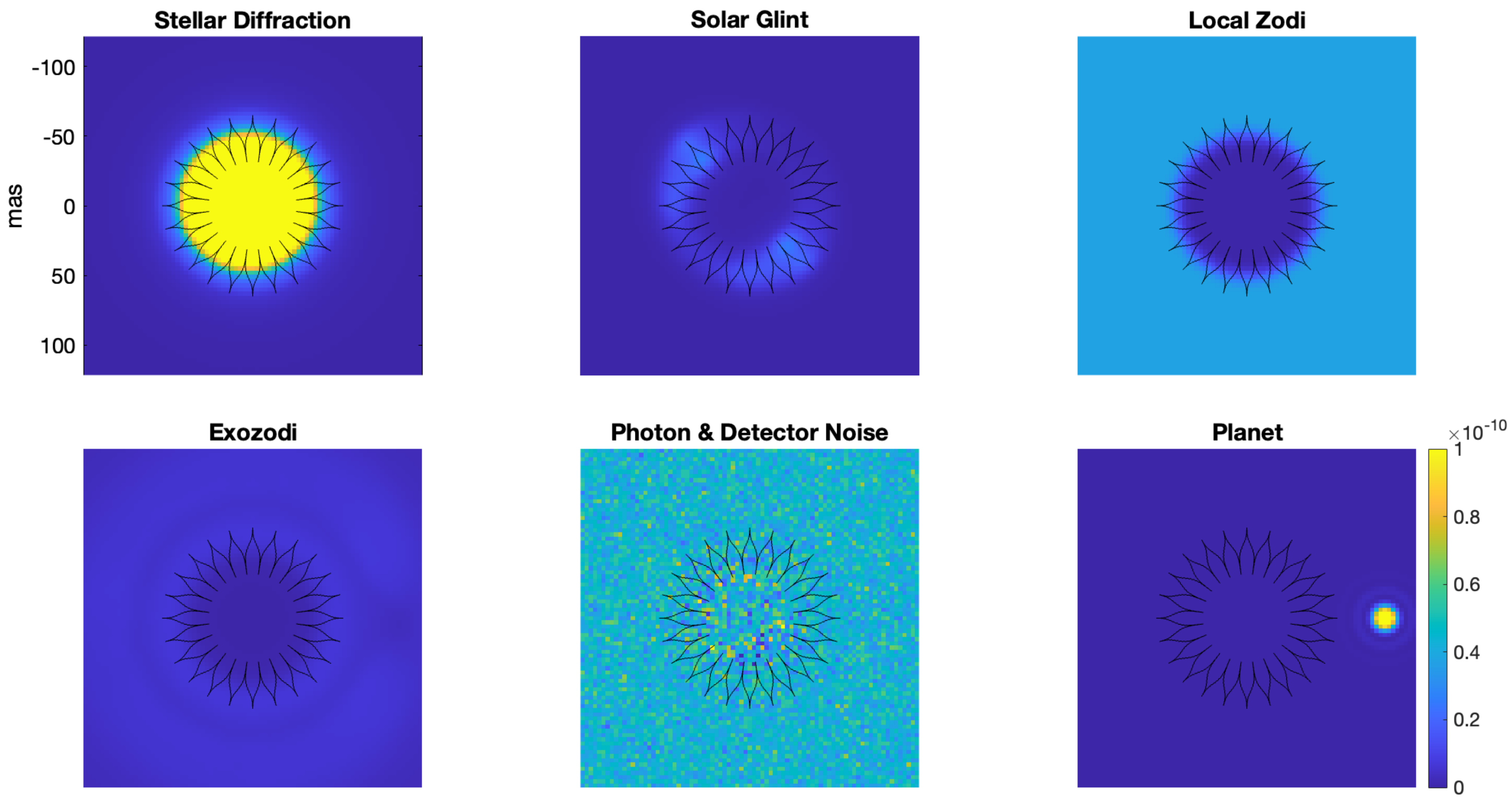
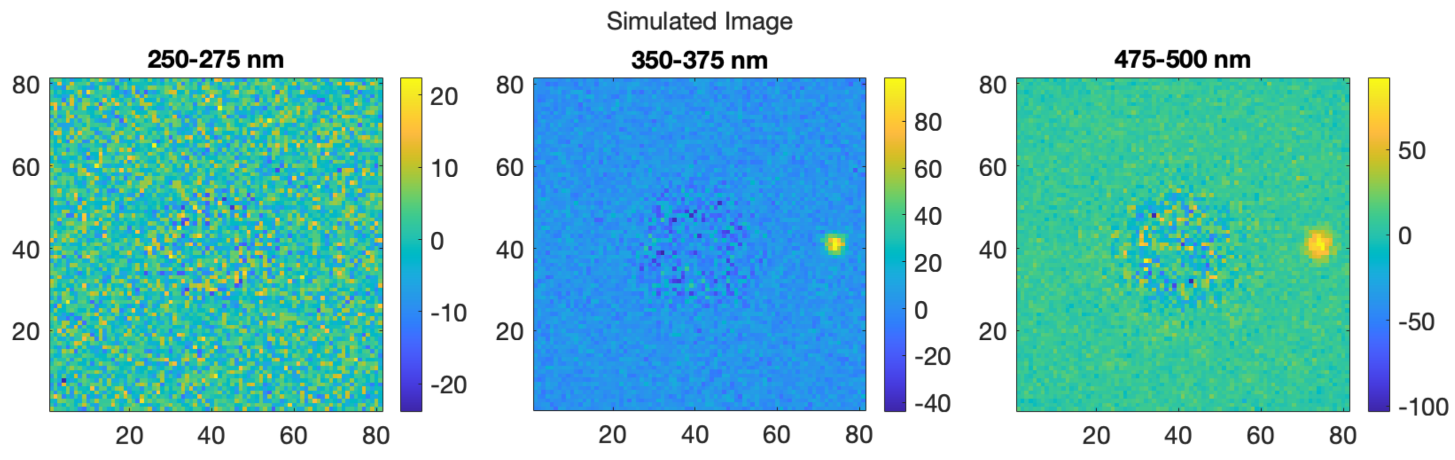
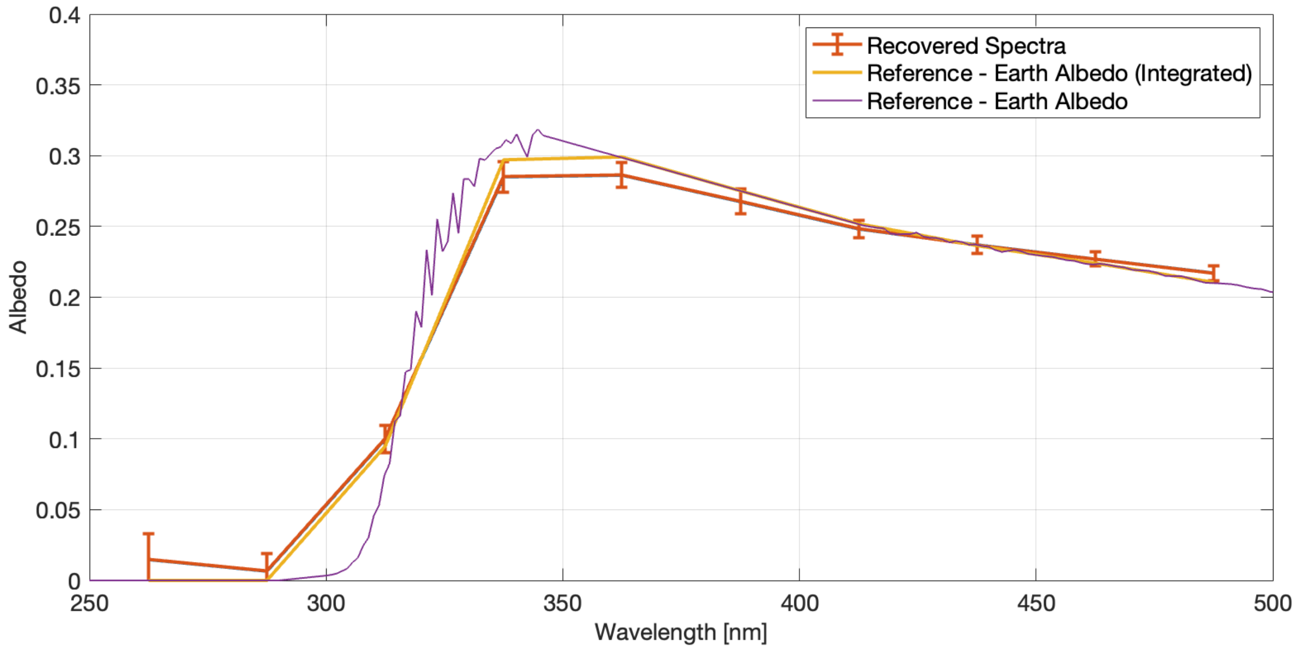
Data Analysis: Extracting Planet Spectra



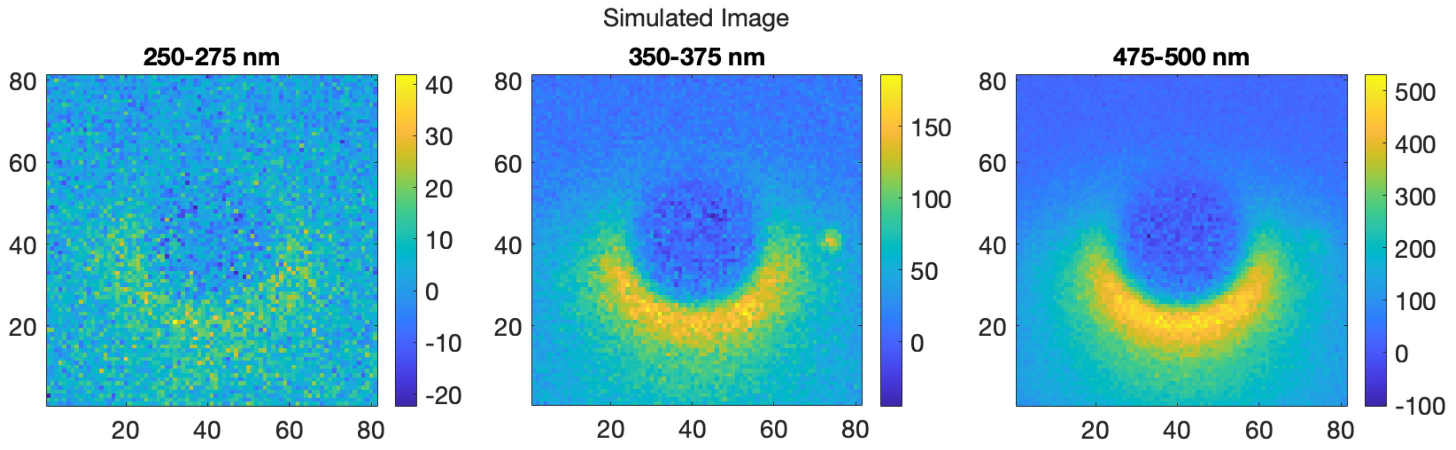
Filtering Results



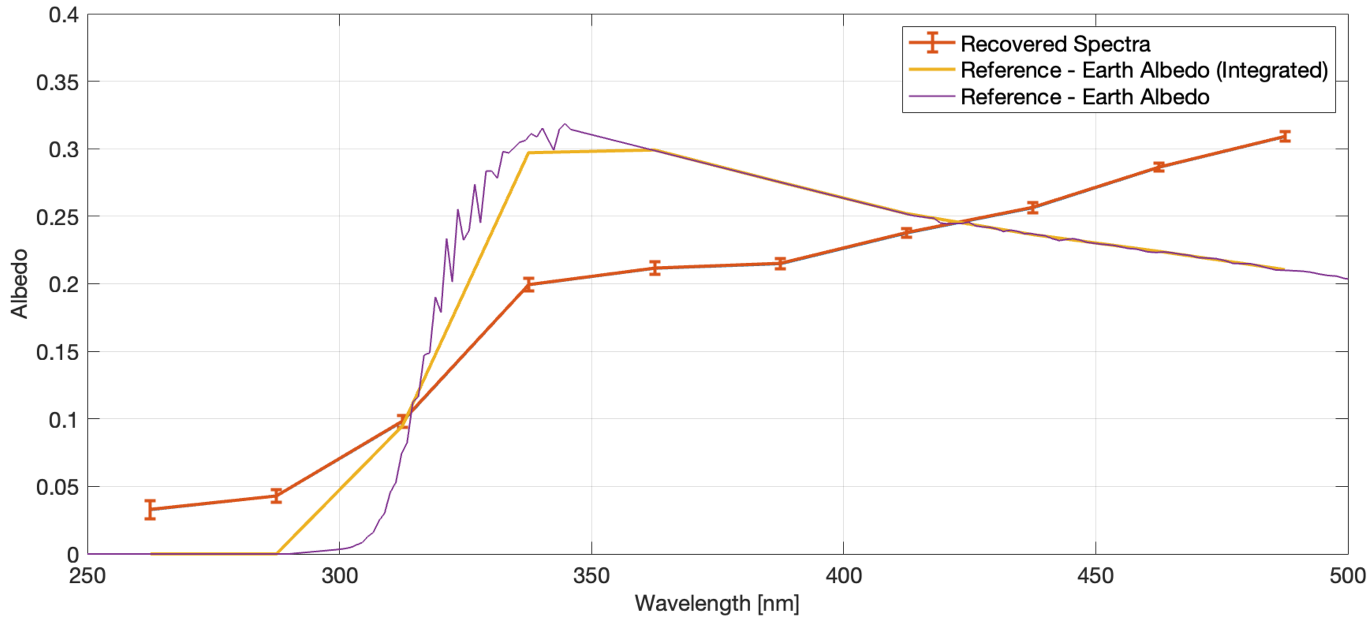


Simulation Parameters	
Planet Phase Angle	90° (quadrature)
System Inclination	0° (face-on)
Exozodi Density	1 zodi

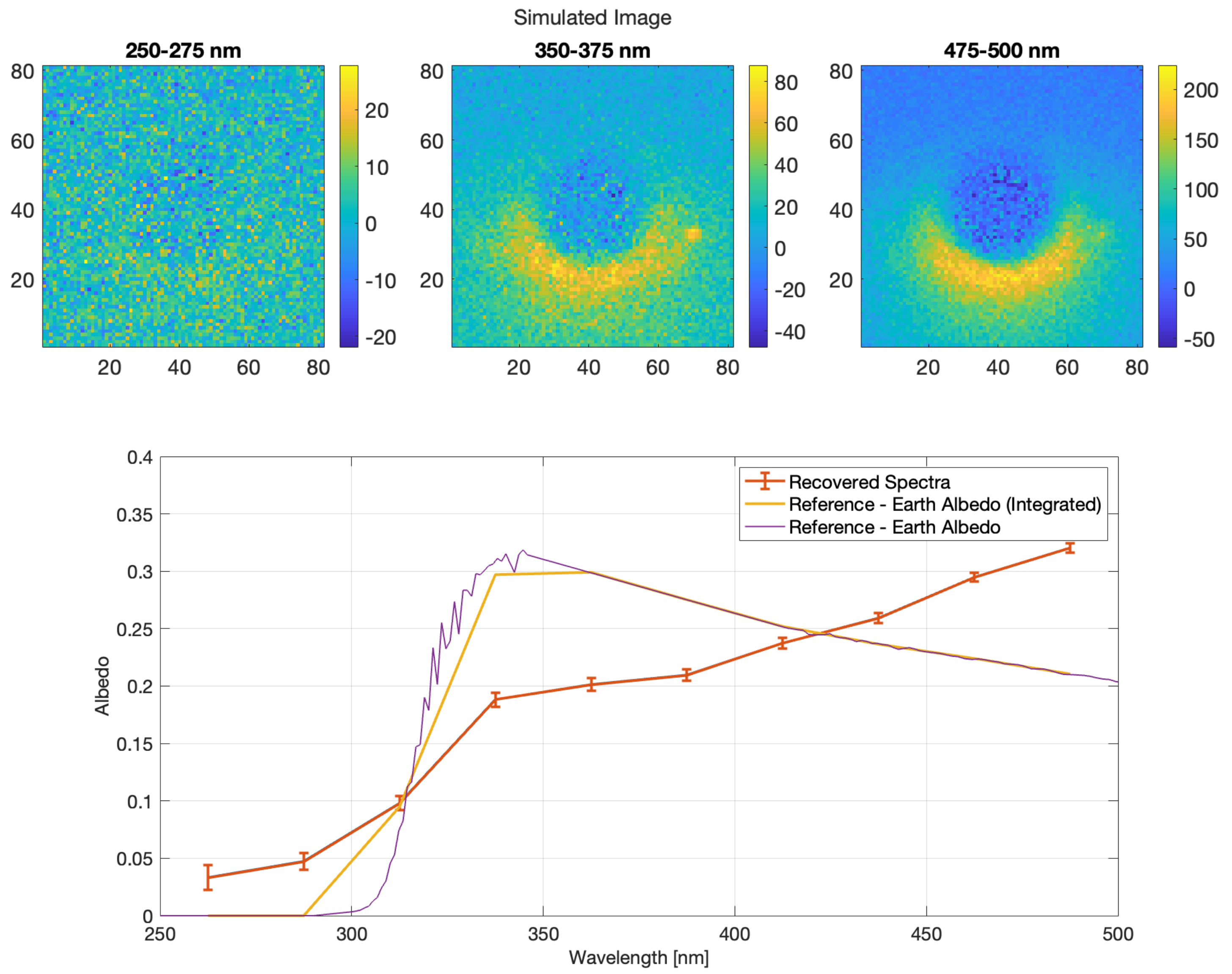
Filtering Results



Simulation Parameters	
Planet Phase Angle	90° (quadrature)
System Inclination	60°
Exozodi Density	10 zodi

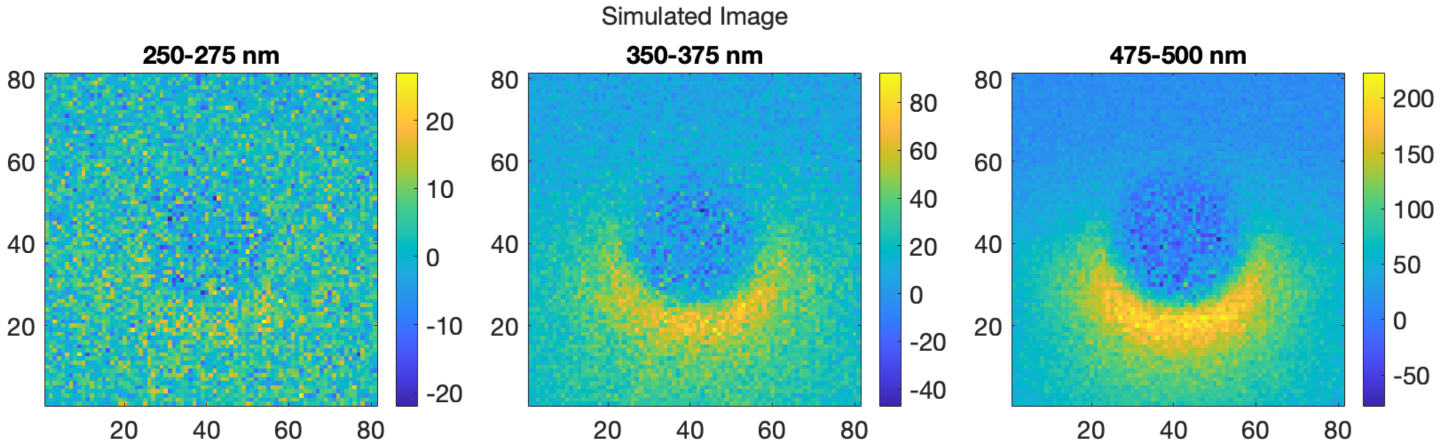


Filtering Results

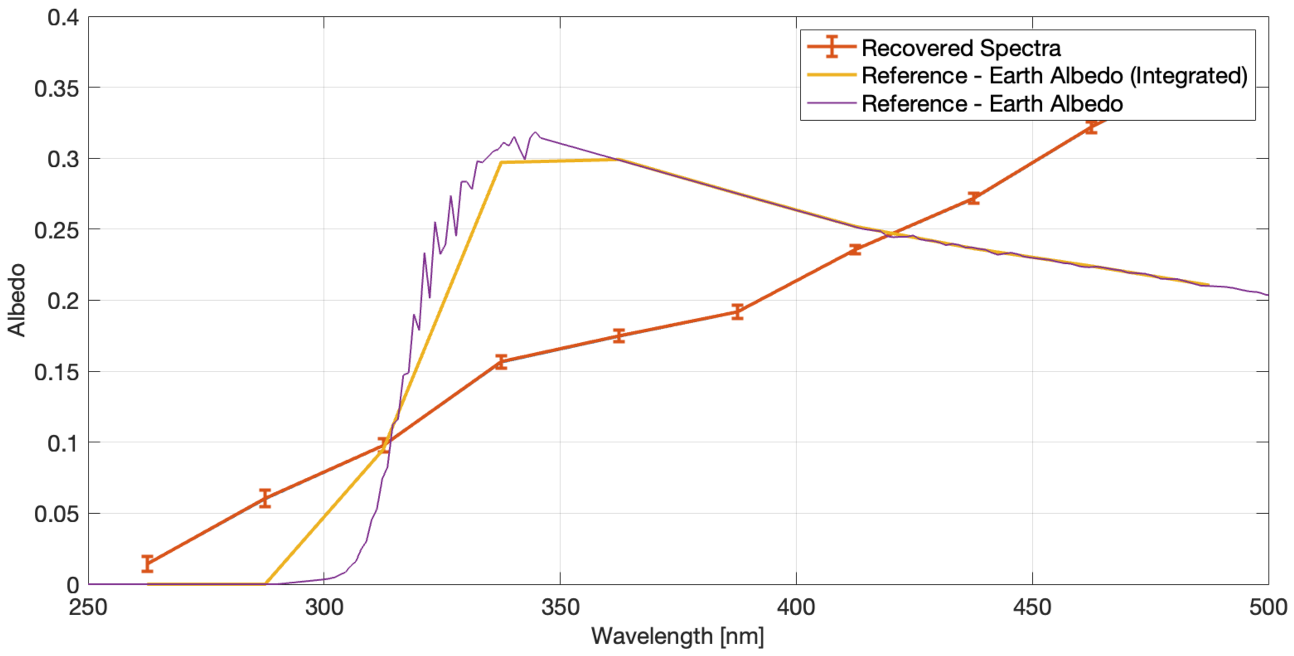


Simulation Parameters	
Planet Phase Angle	115°
System Inclination	60°
Exozodi Density	5 zodi

Filtering Results

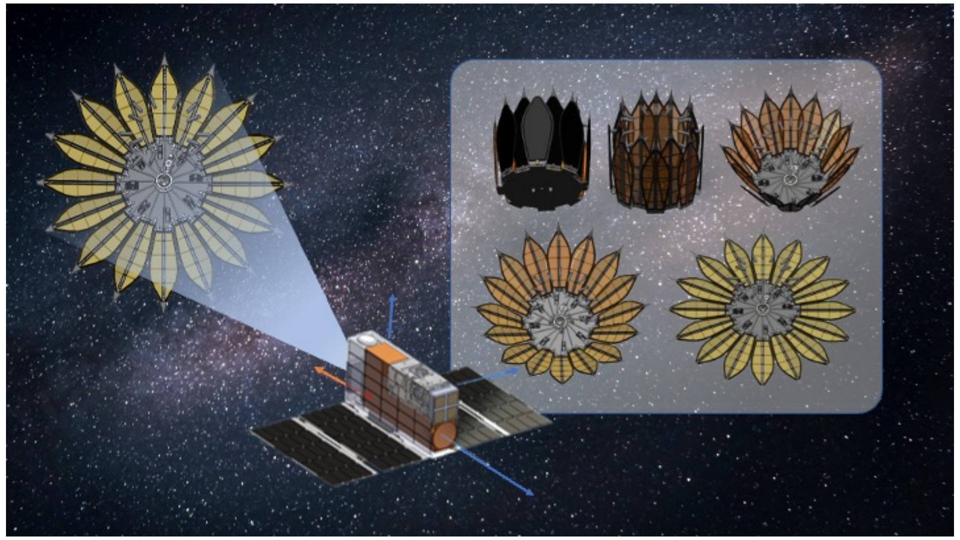


Simulation Parameters	
Planet Phase Angle	139°
System Inclination	60°
Exozodi Density	5 zodi



Summary

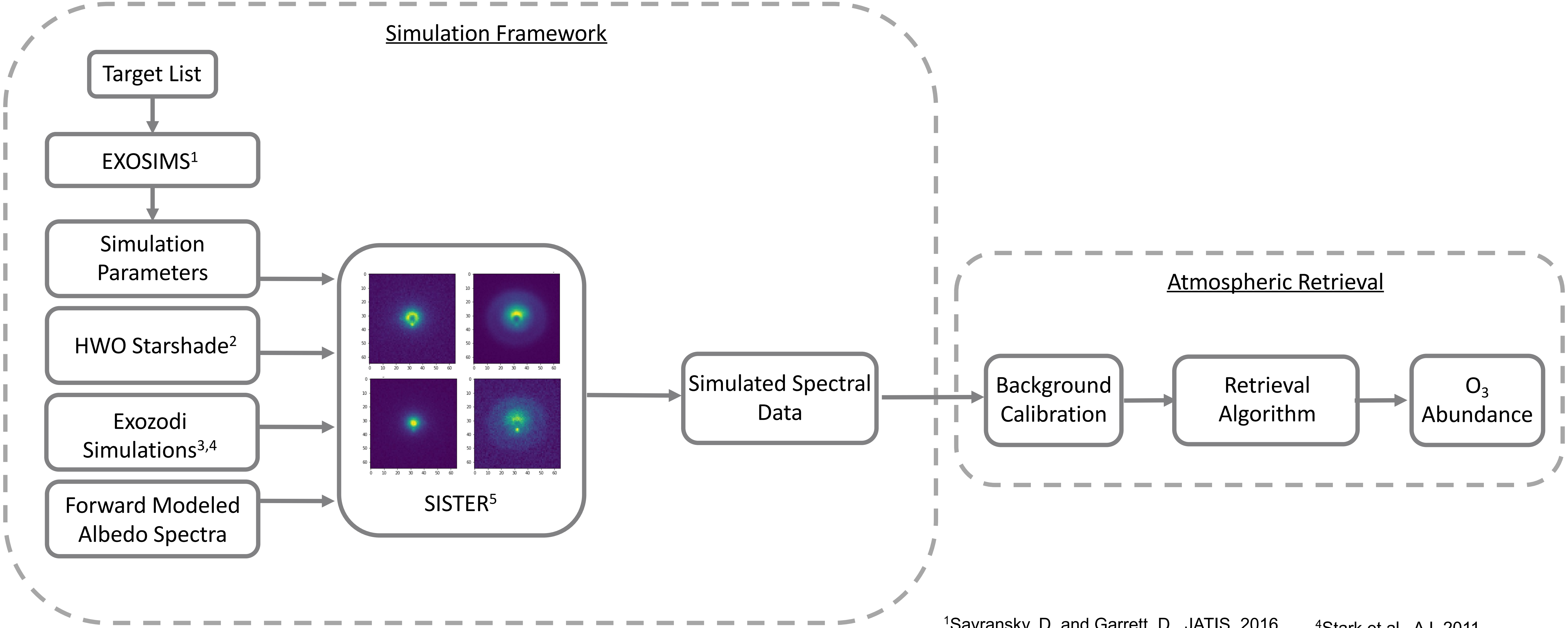
- Starshades are an alternative starlight suppression technology to coronagraphs with possible complementary capabilities for constraining exoplanet biosignatures in the UV
- There is ongoing work to understand the complementary science value of starshade observations through ExoPAG SAG 24
  - My work supports these efforts through increasing our simulation capabilities and eventually conducting a sensitivity analysis of our ability to constrain the 0.25 μm ozone feature



Source: Sam Low, Space Rendezvous Lab

Source: NASA GSFC

Stay Tuned!



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Acknowledgements

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Questions?

Email: zjahmed@stanford.edu

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