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Occulting Ozone Observatory (O_3)
a briefing to the NAS EOS-1 Panel

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Astro2020 APC White Paper

The Occulting Ozone Observatory (O_3) Mission

Thematic Area: Planetary Systems

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Historical Perspective

- **After submitting the THEIA flagship mission study to Astro 2010, the original O_3 study of 2009-2010 was launched with intent to expand the mission option set**
  - Targeted $1B total mission cost including telescope
  - Both THEIA and O_3 were led by David Spergel and Jeremy Kasdin

- **The original O_3 study was JPL's first foray into starshade mechanical design and produced the starshade architecture presented multiple times at this meeting**
  - Mechanical lead Mark Thomson applied deployable antenna heritage to the problem, plus a rapid prototyping technology environment that resonated with a low-cost mission paradigm

- **We now revisit the O_3 concept with the same intent - to expand the mission option set**

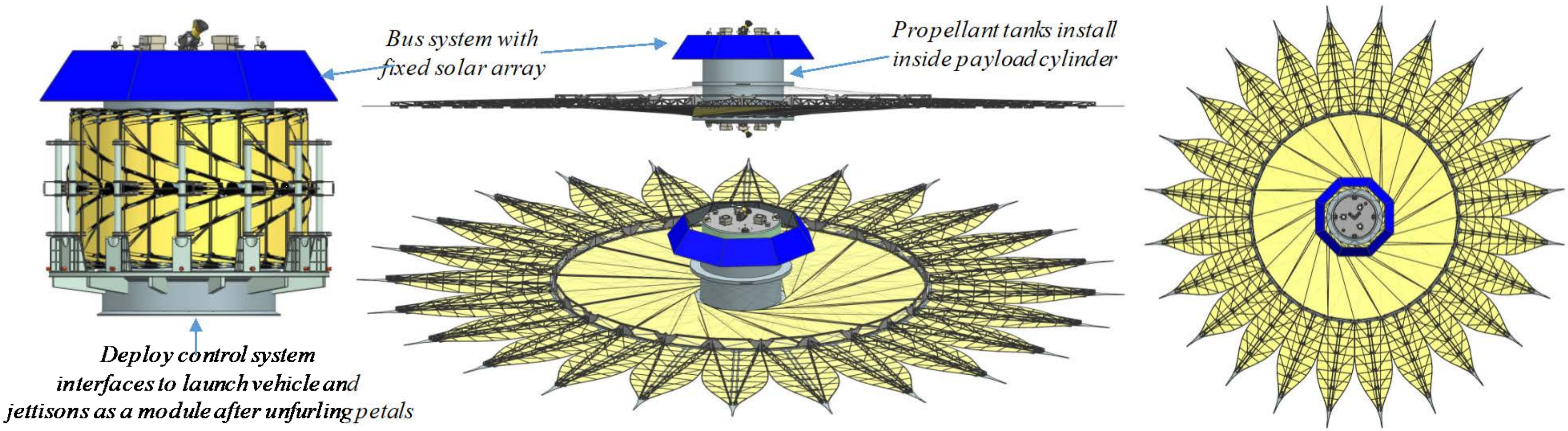
Overview

- **O_3 is a small starshade mission with focused science objectives to:**
  - **Image** a wide range of previously undetectable planets (Rocky-Gas Giants) and, after multiple observations, constrain their orbit and size to inform planetary system diversity and exozodi levels
  - **Detect O_3** presence (not abundance) at rocky planets, plus Rayleigh scatter slope to rule out Venus-type UV-absorption, or to characterize the scatter properties of larger gas planets
  - **Inform** a follow-on flagship mission (required to positively ID life) and demonstrate key capabilities, including background noise calibrations and planet extraction

- **These large spectral features at short wavelengths yield smaller telescopes & starshades**
  - The O_3 APC paper discusses 3 telescope cases: 60-cm dedicated, 1-m shared and 1.5-m shared
  - Here we focus on a 1-m telescope, notionally CASTOR, a CSA study mission proposed to LRP 2020, with a **16-m starshade** that operates at 16-Mm separation for excellent retarget agility and low ΔV
  - The exact telescope is flexible, but separate funding to deliver diverse science, utilizes the majority of mission time that the starshade spends maneuvering to line up on the next target star

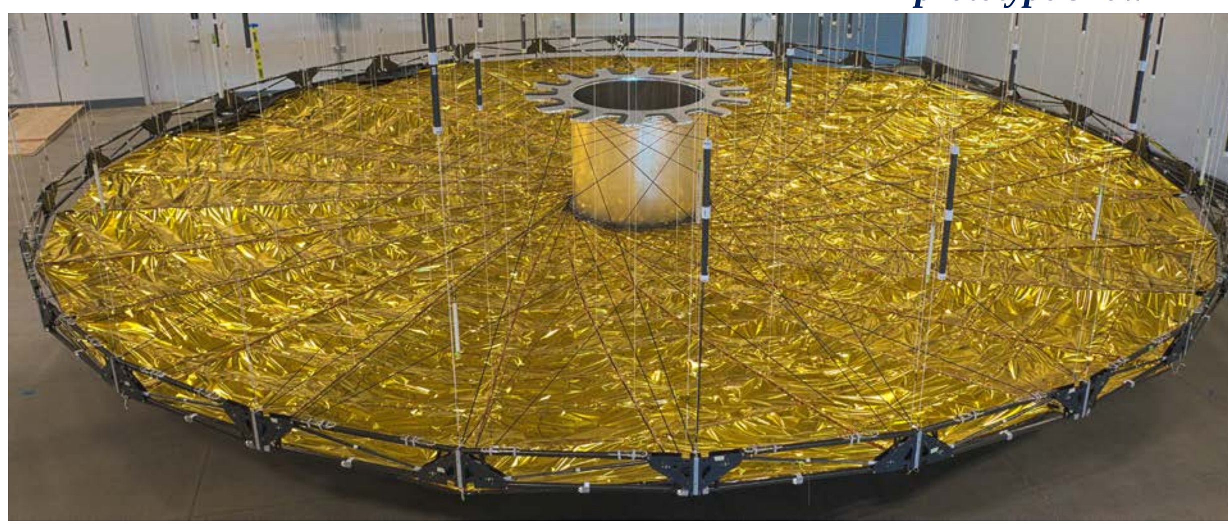
- **A 3-year mission allows a dedicated 1-year search phase to inform a target down-select**
  - Years 2 & 3 are then spent revisiting the select stars to constrain planet orbits and size and search a subset for O_3 or to characterize scatter properties

O_3 16-m Starshade Design



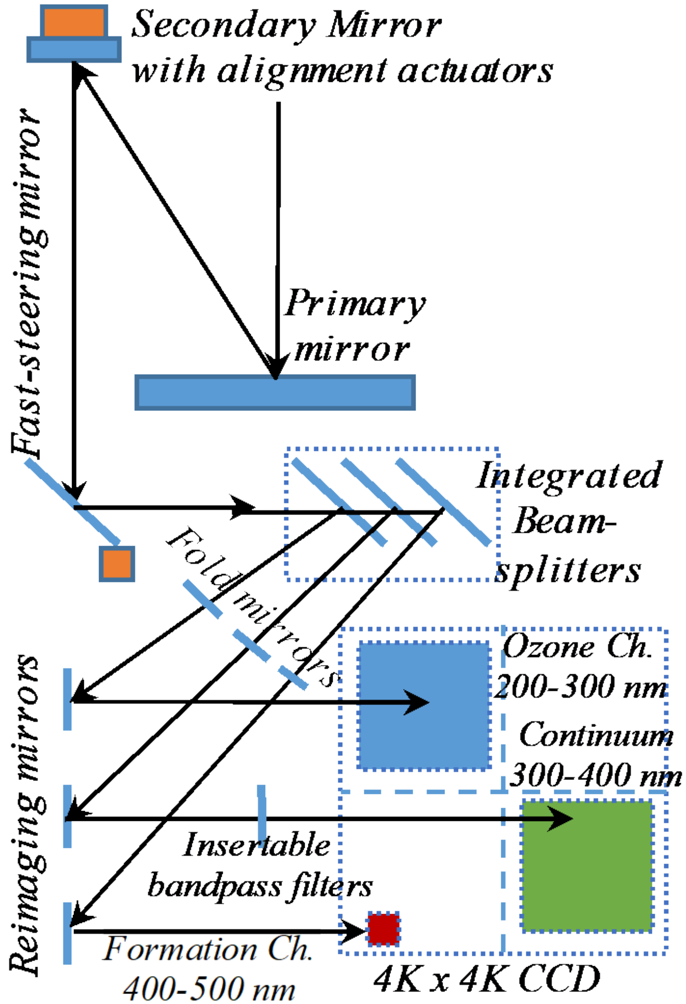
O_3 petal is 4-m long, same as pathfinder shown, on commercial shape metrology tool

O_3 disk is 8-m vs. 10-m prototype shown



O_3 16-m starshade leverages current prototypes to reduce cost and risk

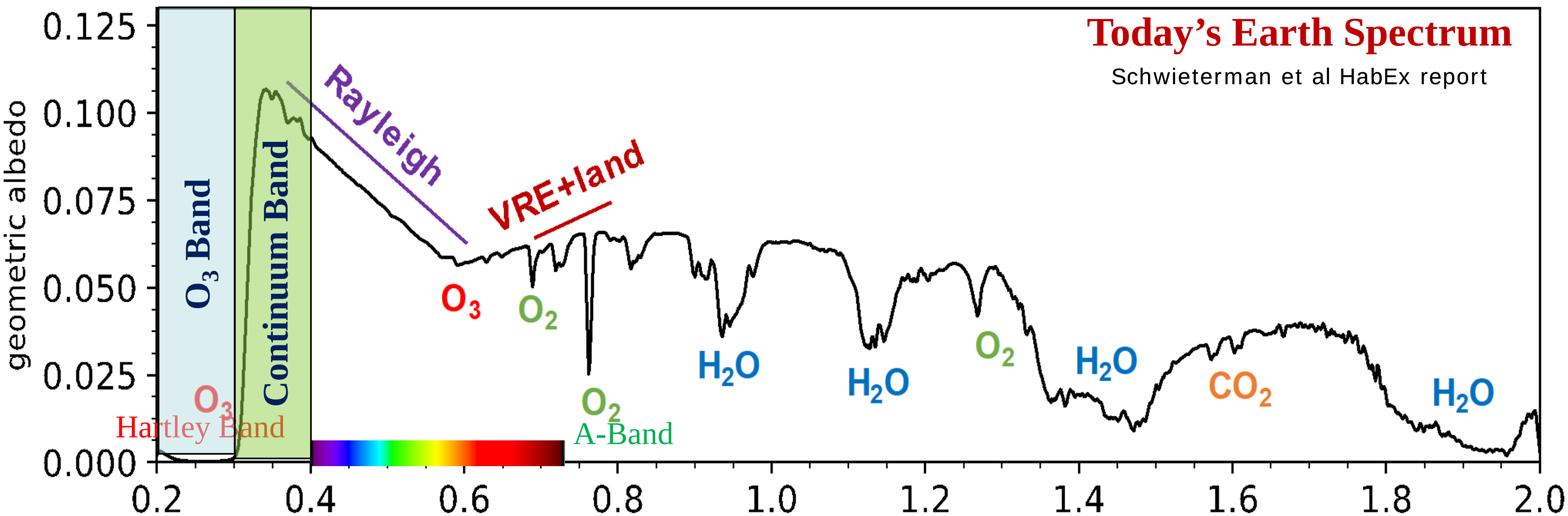
O_3 Instrument Design



Design by Stefan Martin, JPL

A simple 2-channel photometer can detect the presence of Ozone.
Narrowband filters in the continuum channel yield the Rayleigh slope.
A 3rd channel performs lateral formation sensing in out of band starlight.

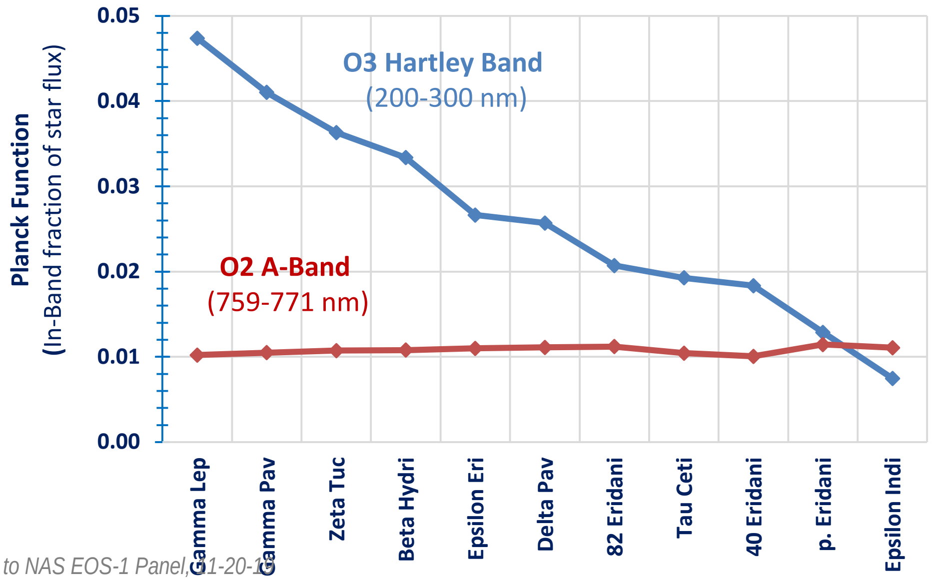
Comparison of O_2 and O_3 spectral features



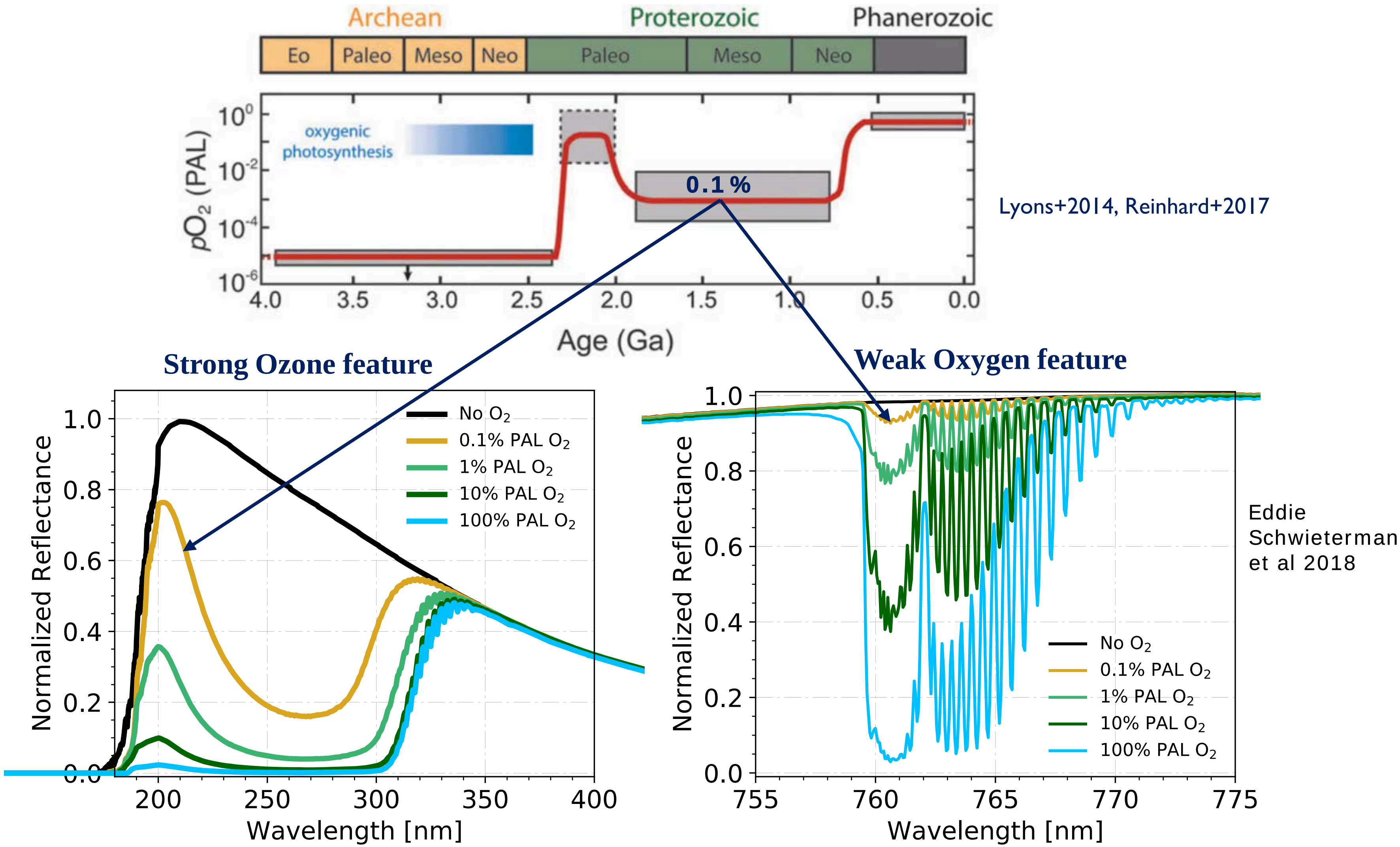
O_2 A-Band detection requires SNR of 20 per Feng et al 2018.

At SNR of 5, the O_3 Hartley Band has > 3-sigma probability of detection for 0.1% pO2

O_3 Hartley Band receives more in-band flux than O_2 A-Band, except for the coldest targets.

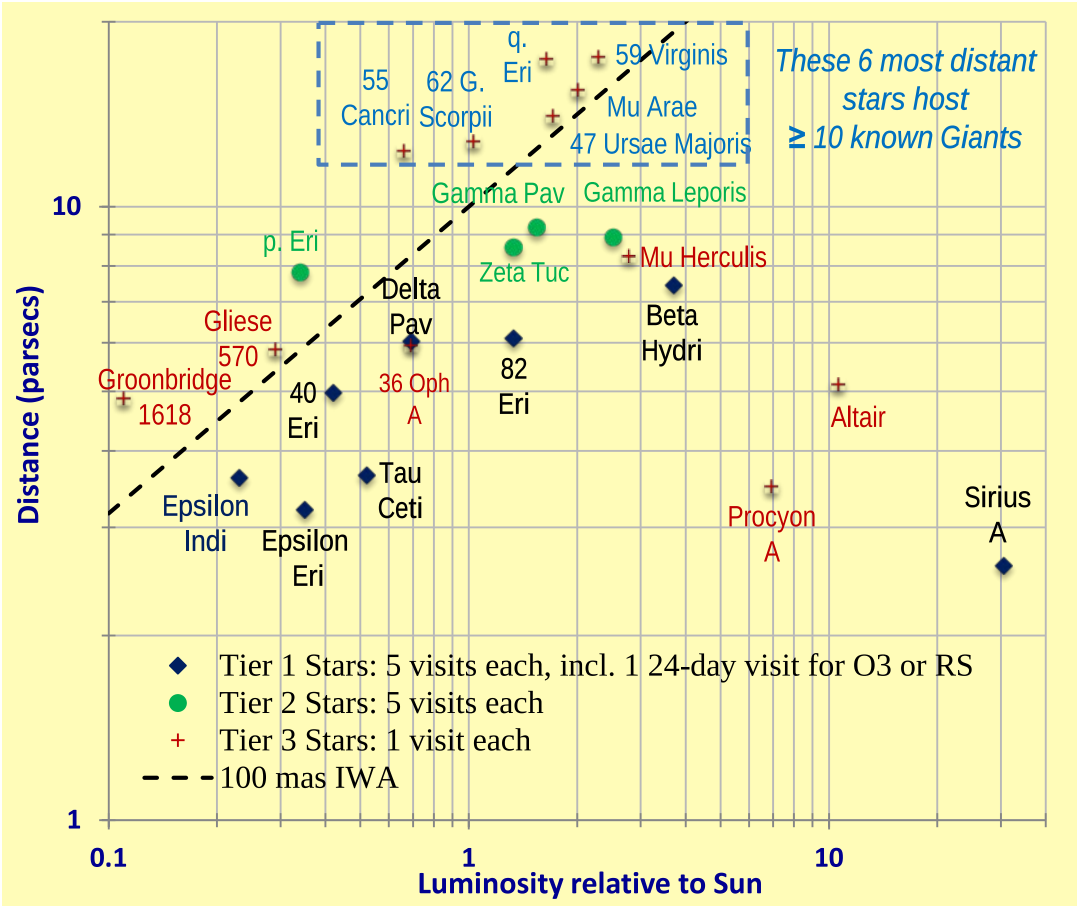


Hartley Ozone Band – a high sensitivity O_2 proxy



O_3 is a sensitive marker of Earth's photosynthetic biosphere and is detectable over much of Earth's history, when O_2 is not.

Target Stars and Observation Strategy

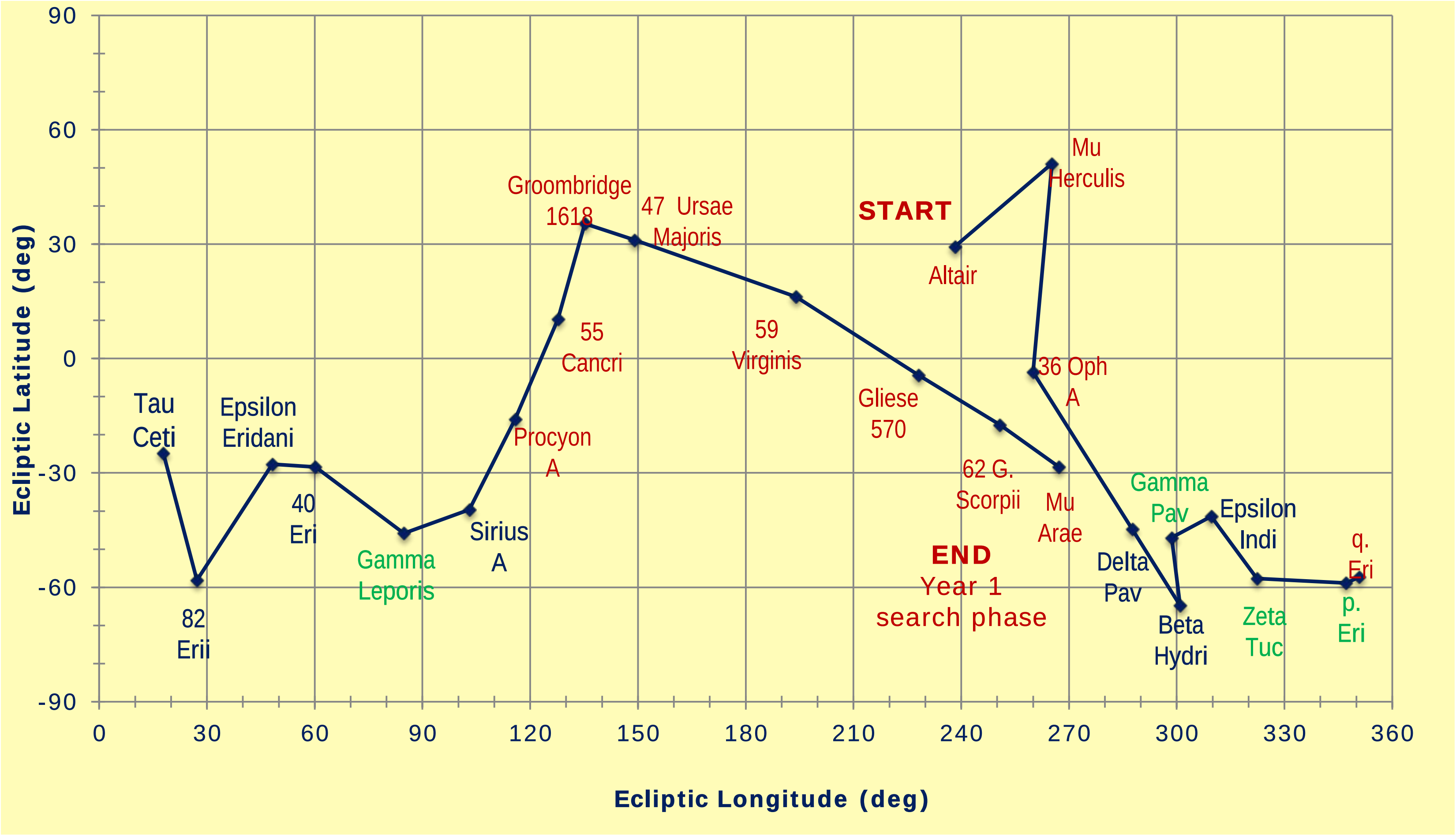


24 target stars all observed 1x in Year-1 Search Phase

12 select stars (Tier 1 & 2) are revisited 4x each in Years 2 & 3

8 out of 12 select stars (Tier 1) are searched once for 24 days for O_3 or scatter properties

Year 1 Search Phase Observation Sequence



With favorable star spatial distribution and small separation distance, O_3 can observe all 24 stars in the first year, with limited ΔV.

Yield Calculations

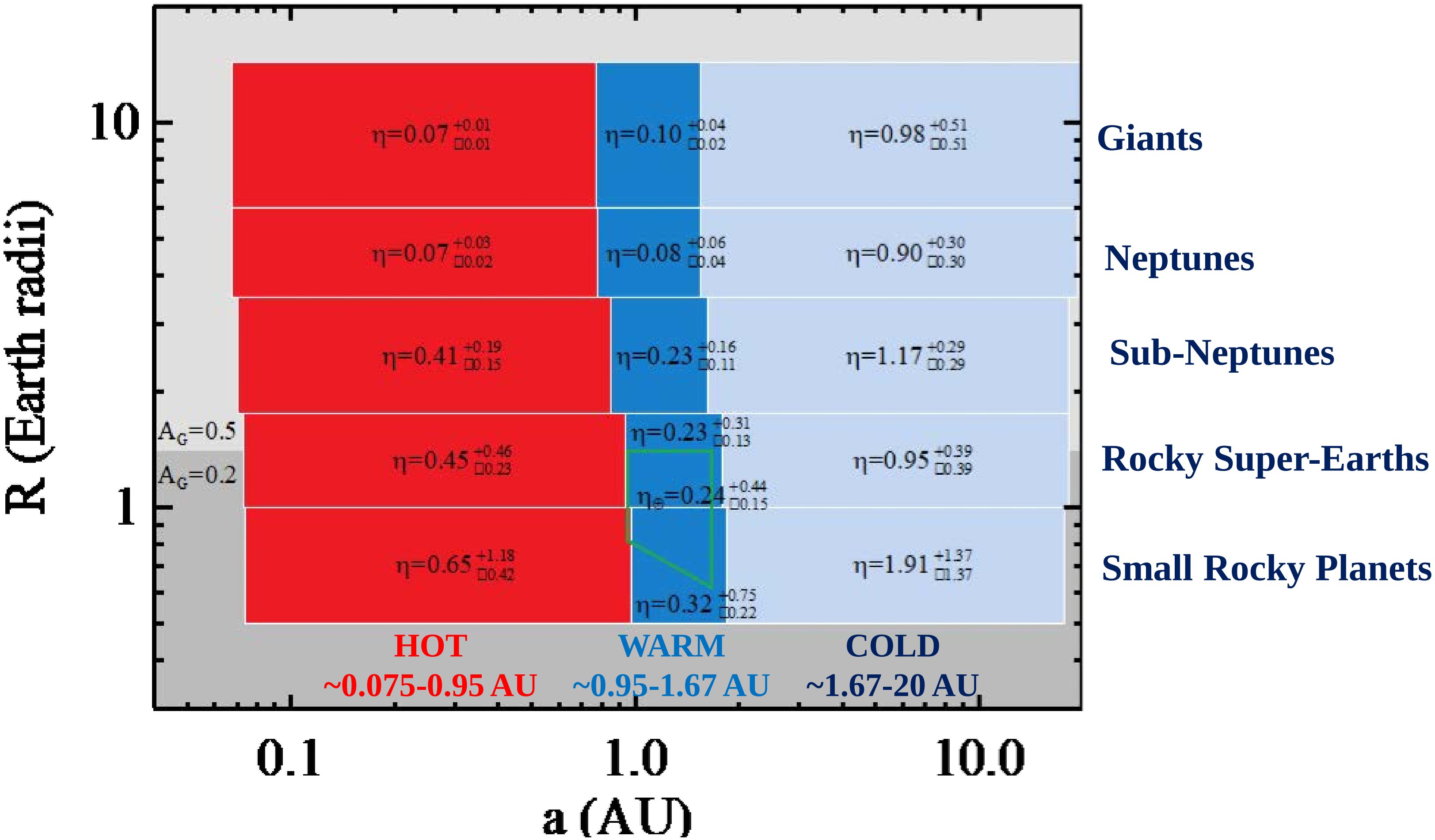
- **Planet contrast sensitivity is set to achieve SNR of 4 relative to residual exozodi after calibration to within 5% accuracy**
  - Exozodi is set at the estimated median level of 4 zodis, with a 1 zodi brightness of 22 mags/arc-sec^2
  - Solar scatter estimates are currently brighter than exozodi at the IWA, but it rolls off faster and we expect to greatly reduce it via coating the optical edges

- **Single visit completeness is computed by numerically integrating completeness in log-weighted concentric shells over the range of orbit size**
  - Planet size and albdedo are set at the average value for each planet/orbit category
  - Assumes Lambertian Phase Function

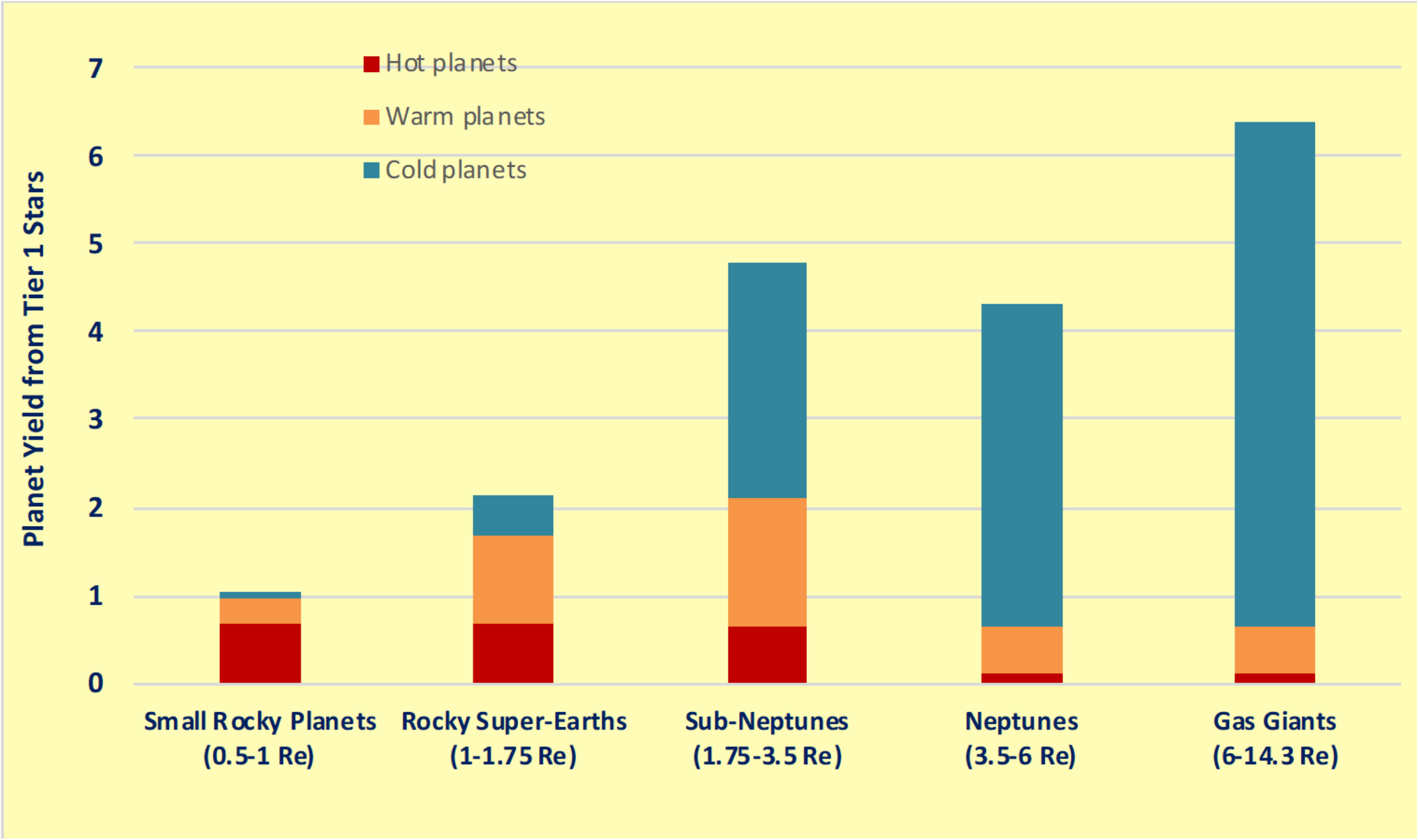
- **Planet categories and occurrence rates per HabEx Report (see next slide)**
- **Yield is for planets detected and characterized, which for O_3 means: orbit and size constrained, searched for O_3 or scatter properties characterized**
  - Planet detection is confirmed at beginning and characterization is rescheduled if necessary
  - Neglects potential for planets to move out of the detection zone

Planet categories and occurrence rates

- **Planet categories and ccurrence rates are per the HabEx Report**
  - Categories per Kopparapu et al 2018, occurrence rates per SAG-13, compiled by Chris Stark
  - Here we approximate 3 fixed orbit size ranges



Estimated planet yield from 8 Tier 1 Stars



8 Tier 1 stars are observed 5X each and searched once for O_3 or scatter properties
Expected Tier 1 yield is ~18 planets, including maybe 1 true Earth analog
4 Tier 2 stars add ~4 gas planets with 5 observations to constrain orbit/size
12 Tier 3 stars add ~16 unconfirmed detections (single visits only)

Telescope Time for Starshade Observations

- **The starshade observations described above consume this telescope time**
  - Year 1: 24 days (24 stars, 1-day each)
  - Year 2: 120 days (12 stars 2 2-days each + 4 24-day observations)
  - Year 3: 120 days (same as Year 2)

Launch Mass Margin

Element	Mass (kg)	Comments
16-m Starshade Payload CBE	410	8-m dia. Inner disk & 4-m long petals (Qty 24)
Starshade Bus System CBE	450	Deck mounted WISE bus with prop tanks inside starshade central cylinder
43% mass growth	370	Same as 30% margin against launch capacity
Max expected EOM starshade dry mass	**1230**	
Max starshade propellant for 3 yr mission	1000	1600 m/s ΔV at 308s Isp with 6% residual prop
Max Telescope spacecraft launch wet mass	1150	CASTOR including contingency
Max Starshade Deployment Control System	200	Module is jettisoned after deployment
Total Launch Mass	**3600**	
Launch Mass Capacity	3900	Falcon-9 direct to E-S L2
Extra launch mass margin	**300**	Applies to extended mission ΔV

O3 provides ample launch mass margin for extended mission ΔV.

Expected Mission Cost

Element	Cost ($M)	Comments
16-m Starshade Payload	110	TRL-6 cost at same size as TRL-5 with no facility or shape metrology development needed
Starshade Bus System	60	Spin-stabilized, loose pointing, fixed solar array, no science data no primary structure, includes prop module
Telescope System	0	Contributed via mission partnership
Project Wrapper Cost	170	Includes 30% Reserves, Project Mgt., SE, MA, MOS/GDS, ATLO, Science
Total Flight System Cost	**340**	
Launch Service Cost	160	Falcon-9
Likely Nominal Cost	**500**	
Cost Uncertainty factor	170	50% on flight system due to brevity of JPL Foundry study and cost model fidelity
Likely Maximum Cost	**670**	

O_3 mission cost is likely in the range of $500M to $670M

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

Conclusions

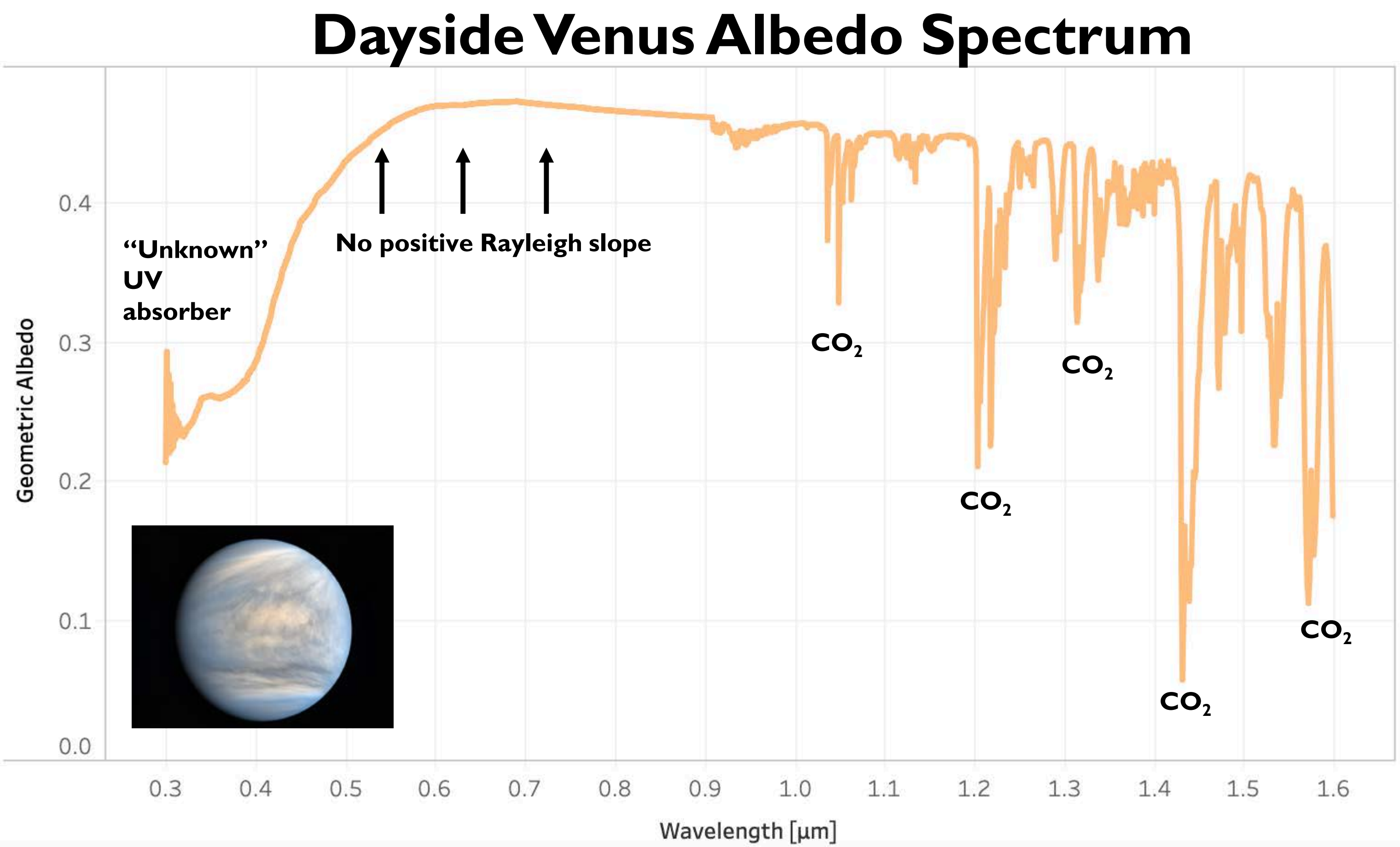
- **A 3-year O_3 mission with 16-m starshade and 1-m telescope can significantly advance our understanding of exoplanets and smooth the way for a flagship mission**

- **O_3 is expected to yield ~18 total planets and demonstrate key capabilities needed for a flagship mission**

- **O_3 provides ample launch mass margin, likely costs in the range of \$500M to \$670M and limits development risk by flying current prototype sizes**

Backup Slides

Venus type planets



Source: Virtual Planetary Laboratory
http://depts.washington.edu/naivpl/content/vpl-spectral-explorer

Venus has an "unknown" UV absorber to confuse O_3 detections.
But, Venus has no Rayleigh slope so measuring this slope can resolve the confusion.