THE EXO-S PROBE-CLASS STARSHADE MISSION

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Exoplanet Exploration Program

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NASA's Recent Exoplanet Probe Studies

- The discovery of exoEarths, via a space-based direct imaging mission, is a long-term priority for US astrophysics
- Two studies of "probe sized" exoplanet direct imaging missions: one coronagraph (Exo-C), one starshade (Exo-S)
  - Total mission cost targeted at $1B (FY15 dollars)
  - New start in 2017
  - Compelling science must be beyond the expected ground capability at the time of mission
- Studies also intended as a design input to the exoplanet community to help formulate ideas for the next Decadal Survey in 2020

Exo-S Team Members

STDT

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JPL Design Team

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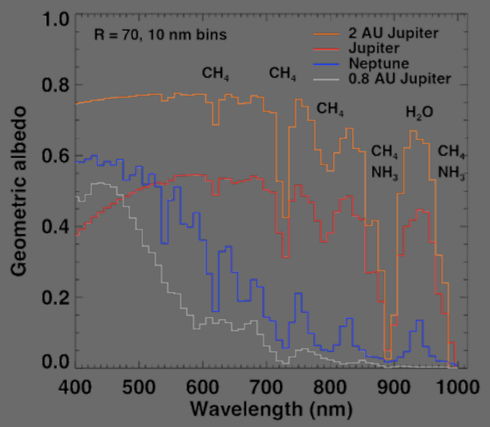
Key Areas of Advance

Science

- Quantification of ability to find and identify exoEarths with a small-aperture space telescope
- Retrieval studies to understand what can be learned from giant planet atmosphere observations
- Direct imaging planet discovery challenges and solutions

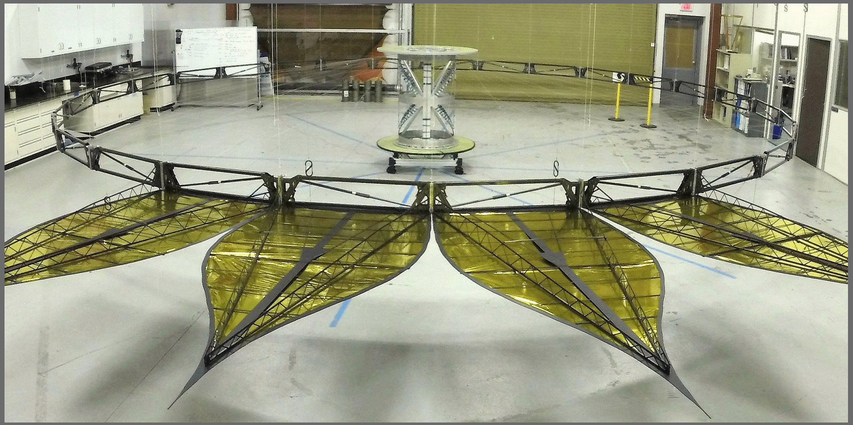
Technology

- Created technology gap list for establishing TRL-5
- Developed testbed for new inner disk design that is customized to accommodate petals
- Developed concepts for optical shields, launch restraints and deployment control systems
- Focused formation flying challenge on sensing but not control



Giant planet R=70 spectra of solar system and modeled giant planets.

A one arcmin^2 FOV (corresponding to the planet detection field for Exo-S),

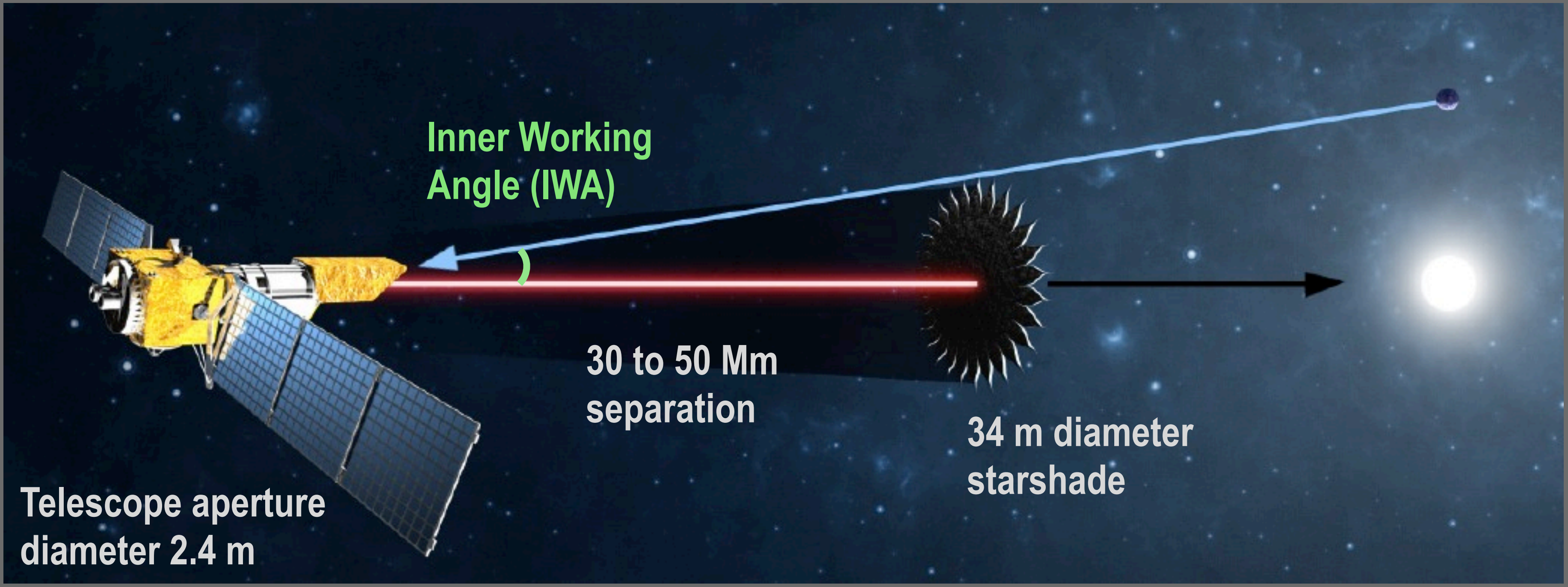


JPL half scale model starshade deployment test bed

"Can we find another planet like Earth orbiting a nearby star? To find such a planet would complete the revolution, started by Copernicus nearly 500 years ago, that displaced Earth as the center of the universe. . . The observational challenge is great, but armed with new technologies. . . astronomers are poised to rise to it."

–New Worlds, New Horizons, 2010

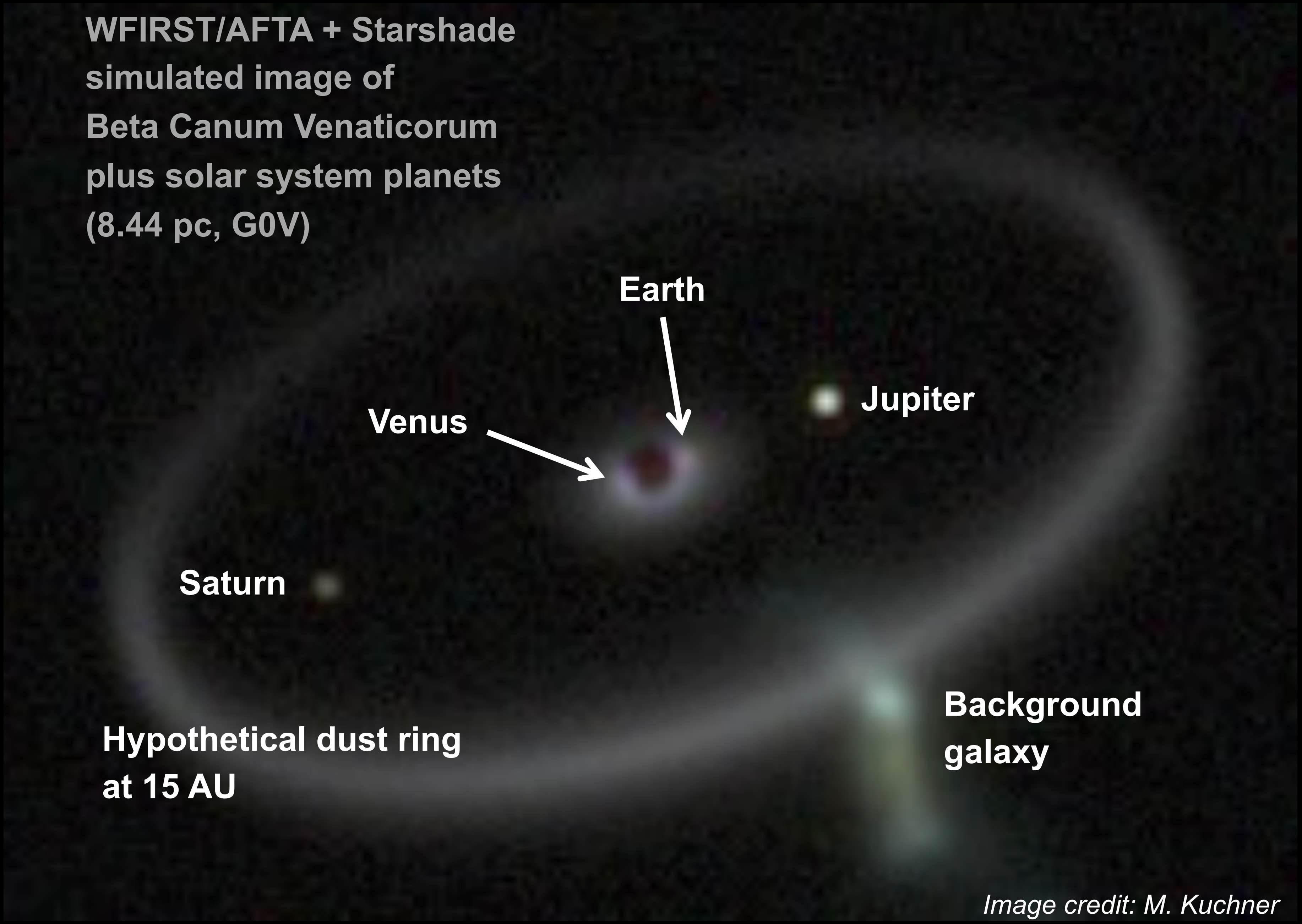
Starshade Basics



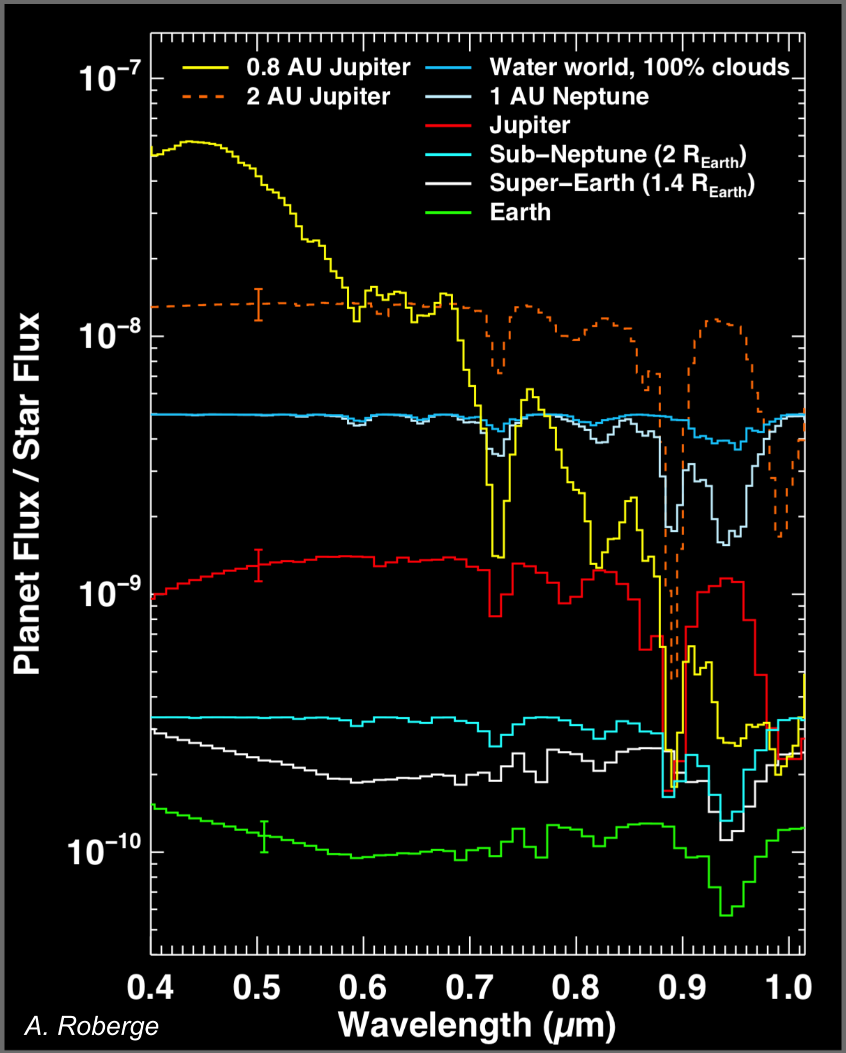
- Contrast and IWA decoupled from telescope aperture size
- No outer working angle
- High throughput, broad wavelength bandpass
- High quality telescope not required
  - Wavefront correction unnecessary
- Retargeting requires long starshade slews (days to weeks)

Two Cost Constrained Exo-S Concepts

- Exo-S Dedicated Co-Launched Mission
  - Starshade and telescope launch together to conserve cost
  - Telescope: low-cost commercial Earth observer, 1.1 m diameter aperture
  - Starshade: 30 m diameter
  - Orbit: heliocentric, Earth-leading, Earth-drift away
- Exo-S Rendezvous Mission
  - Starshade launches for a rendezvous with an existing telescope
  - Telescope: WFIRST/AFTA 2.4 m is adopted
  - Starshade: 34 m diameter
  - Orbit: Earth-Sun L2 (assumption for the purposes of the Exo-S study)
  - Three year Class C mission
  - Minimal impact to current mission design
    - No stringent requirements are imposed on the WFIRST/AFTA spacecraft
    - No new instrument, only modification to the existing coronagraph


WFIRST/AFTA + Starshade
simulated image of
Beta Canum Venaticorum
plus solar system planets
(8.44 pc, G0V)
Earth
Jupiter
Venus
Saturn
Background
galaxy
Hypothetical dust ring
at 15 AU
Image credit: M. Kuchner

Exo-S Science Goals

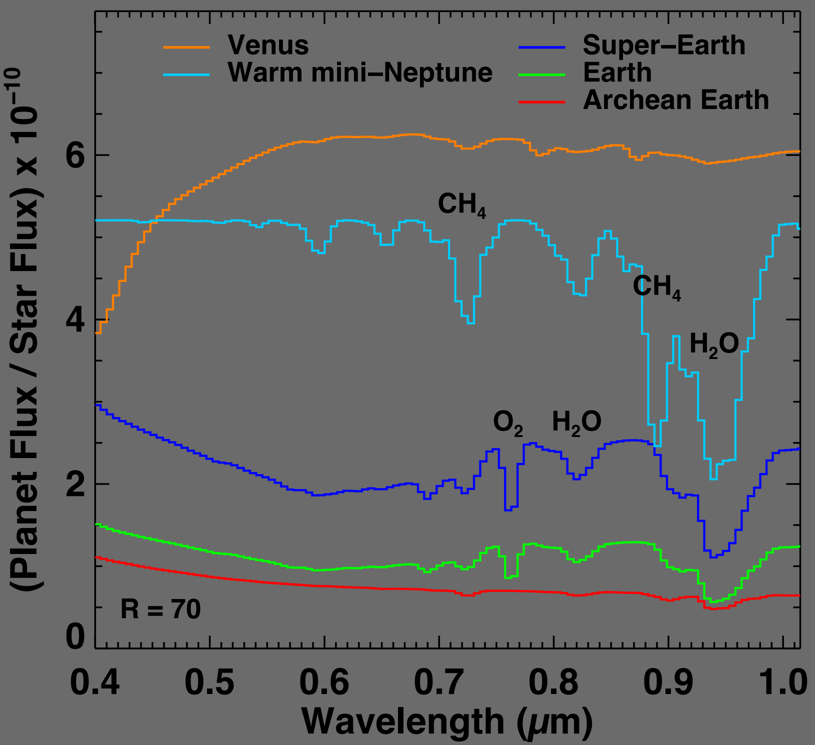


Simulated R=70 planet spectra for the 2.4-m mission, with three representative 10% error bars.

1.1-m mission cannot reach R=70 on small planets.

1. Discover new exoplanets from giants down to Earth size
2. Characterize new planets with R=10 to 70 optical spectra
3. Characterize known giant planets with R=70 spectra and constrain masses
4. Study planetary systems including circumstellar dust
   - Locate dust parent bodies
   - Evidence of unseen planets
   - Exozodi assessment for future missions

Exo-S Science Goals



Above: Simulated spectra of small planets. The Earth, Venus, and super Earth models are from the Virtual Planet Laboratory (VPL; http://depts.washington.edu/naivpl/). The sub-Neptune model is from Renyu Hu (personal communication). The spectra have been convolved to *R*= 70 spectral resolution and re-binned onto a wavelength grid with 11 nanometer bins.

A. Roberge

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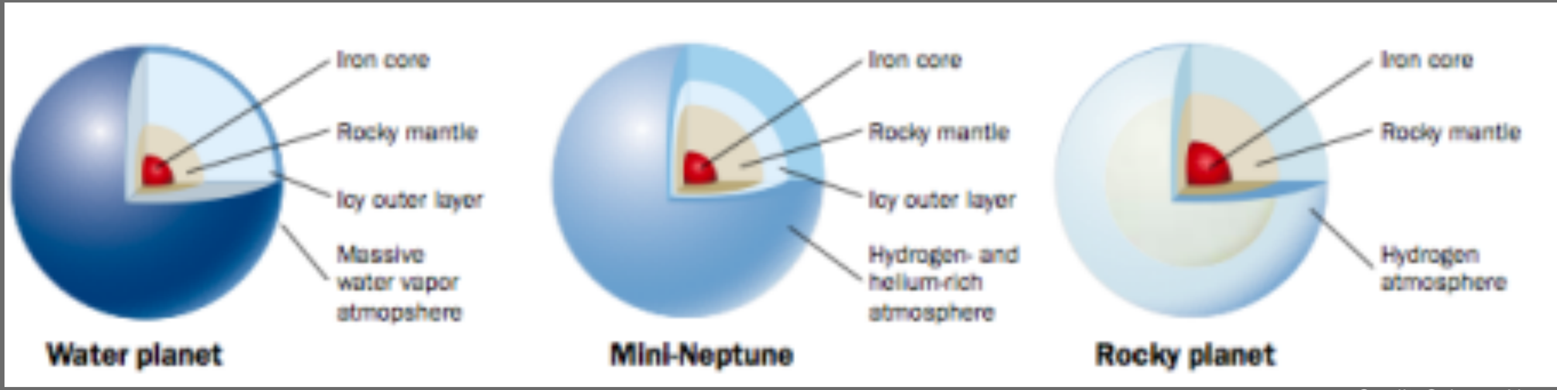
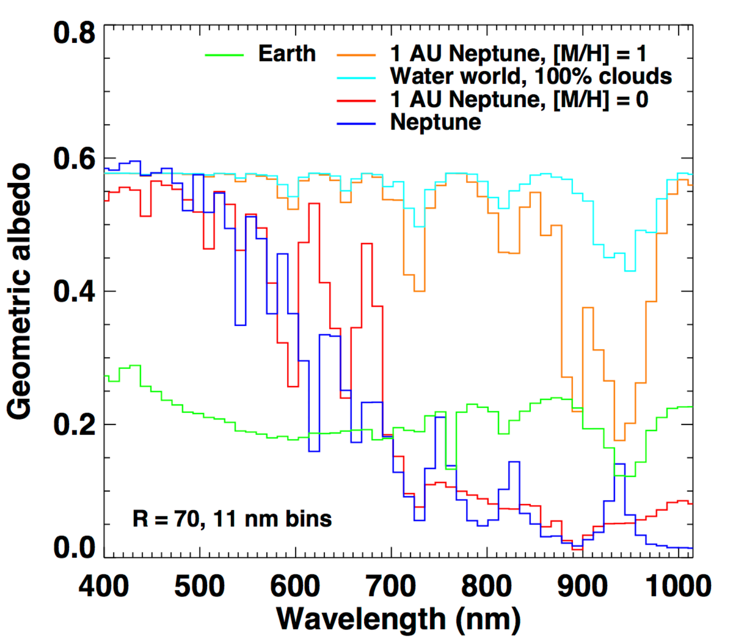


Alternate views of the composition of a mini Neptune

Credit: Science News 2010

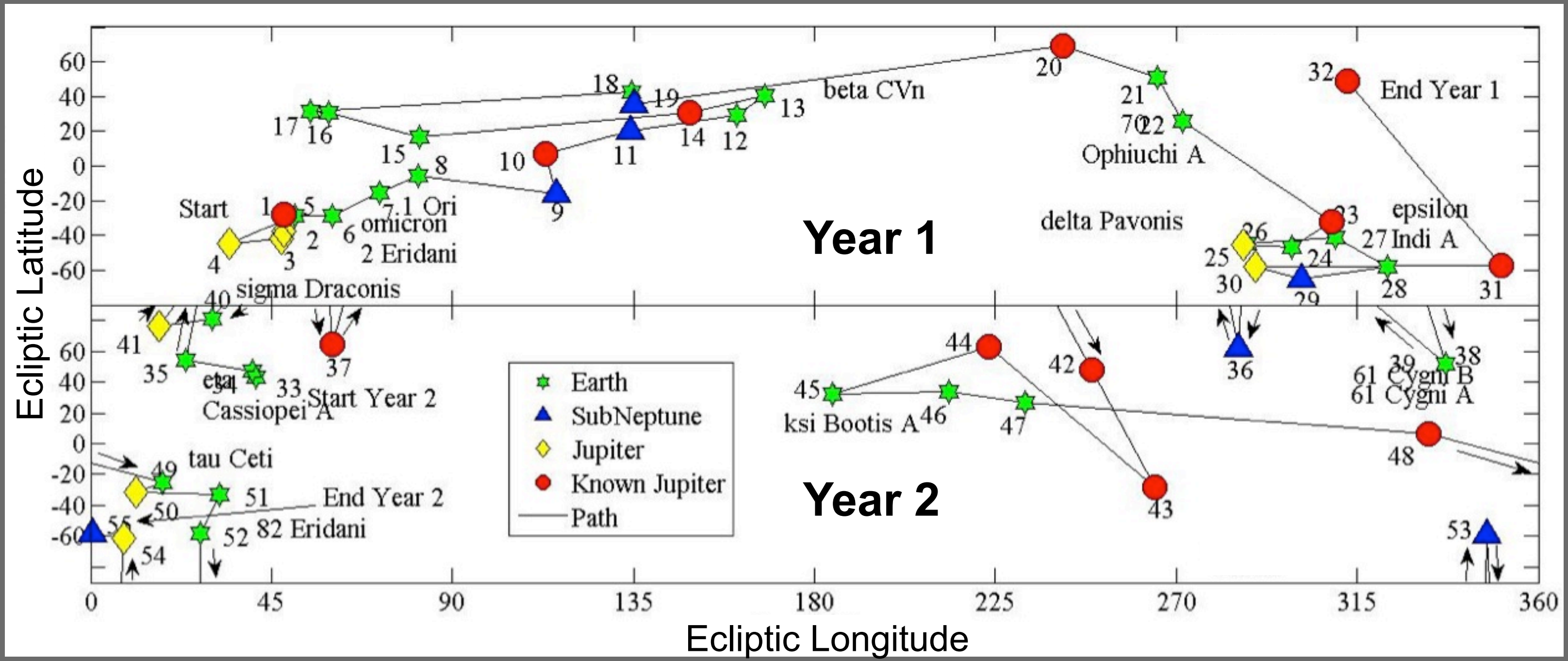
- Comparative exoplanetology for a range of planet types
- Spectra of sub Neptunes to ascertain the very nature of the low-density, extremely common, yet mysterious planets
- Potential for exoEarth discovery (and characterization) for up to 50 target stars (100 mas and limΔmag 26)



Simulated reflected light spectra of exoplanets convolved to R=70

Observing Sequence

1. Schedule known giant planet observations
2. Fill gaps on sky with highest priority blind search target (Earths)
3. Repeat with lower priority targets (sub-Neptunes & Jupiters) until fuel or time limit (2 years) reached. Note: flexibility in schedule.



55 stars visited. Uses ~ 9% of total WFIRST time.

12 known giant planets. Blind search targets: 28 Earths, 7 sub-Neptunes, 8 Jupiters

DRM Yield Summaries

	Completeness		
	Case 1	Case 2	Case 3
HZ Earth	6.3	3.6	10.9
Earth	1.7	2.1	3.7
Sup. Earth	14.9	10.6	27.3
Sub-Neptune	30.3	26.8	52.3
Neptune	43.0	42.7	71.1
Jupiter	63.2	64.4	93.9
Total	159.5	150.2	259.2
	Mean Planet Yields		
	Case 1	Case 2	Case 3
HZ Earth	1.0	0.6	1.7
Earth	0.3	0.3	0.6
Super Earth	1.5	1.1	2.7
SubNeptune	3.0	2.7	5.2
Neptune	4.3	4.3	7.1
Jupiter	6.3	6.4	9.4
Known Jupiters	14	14	12
Total	**30.4**	**29.4**	**38.8**

Completeness is the probability of detecting planet if it's there, summed over all stars

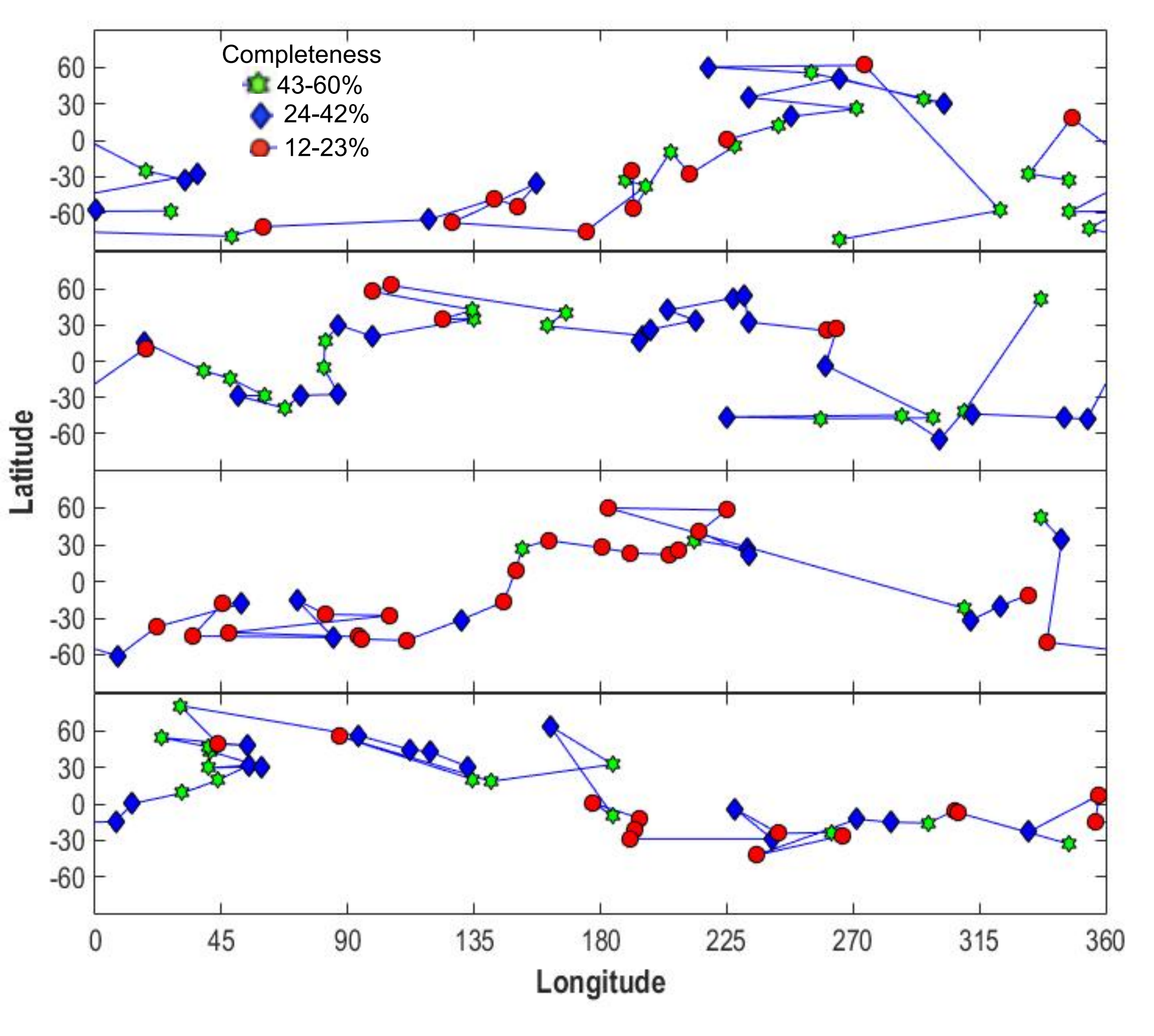
Multiply completeness by planet frequency (η) to get expected yield

Assumed η = 16% for Earths, η = 10% for all other planets

Starshade Rendezvous Earth Finder Mission

- Enhanced concept compared to the Rendezvous Mission (3-year Class C mission)
- A 5-year Class B mission
- A combination of slightly larger starshade and/ or increase in optical throughput with a dedicated instrument
- Focus on habitable zones
- Yields at least 10 exoEarth detections if η_{Earth} is ≥ 20%, plus a much larger number of other planet types.

Starshade Rendezvous Earth Finder Mission



- 158 Target stars
- Summed Completeness
  - Earth: 52
  - Sub-Neptune: 109
  - Jupiter: 135
- Time on Target = 701 days, 46% of mission time
- IWA 55 mas
- 28% throughput

Cost Estimates

- Cost and technology readiness analysis by Exo-S Team, JPL Team X, and Aerospace Corporation
- Estimated 2.4-m mission Phase A – F cost: $627M
  - Includes launch and modifications to WFIRST
- Aerospace Corp. raised no issues with technology schedule

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 Caltech.

Take-Away Message

WFIRST-AFTA can be leveraged for a unique and timely opportunity

- The Starshade Rendezvous Mission with 34-m starshade can access exoEarths in the habitable zone for up to 50 unique target stars
- JPL is now studying a range of mission options that fall under the “Rendezvous” mission umbrella
- Minimal modification to WFIRST needed for starshade readiness