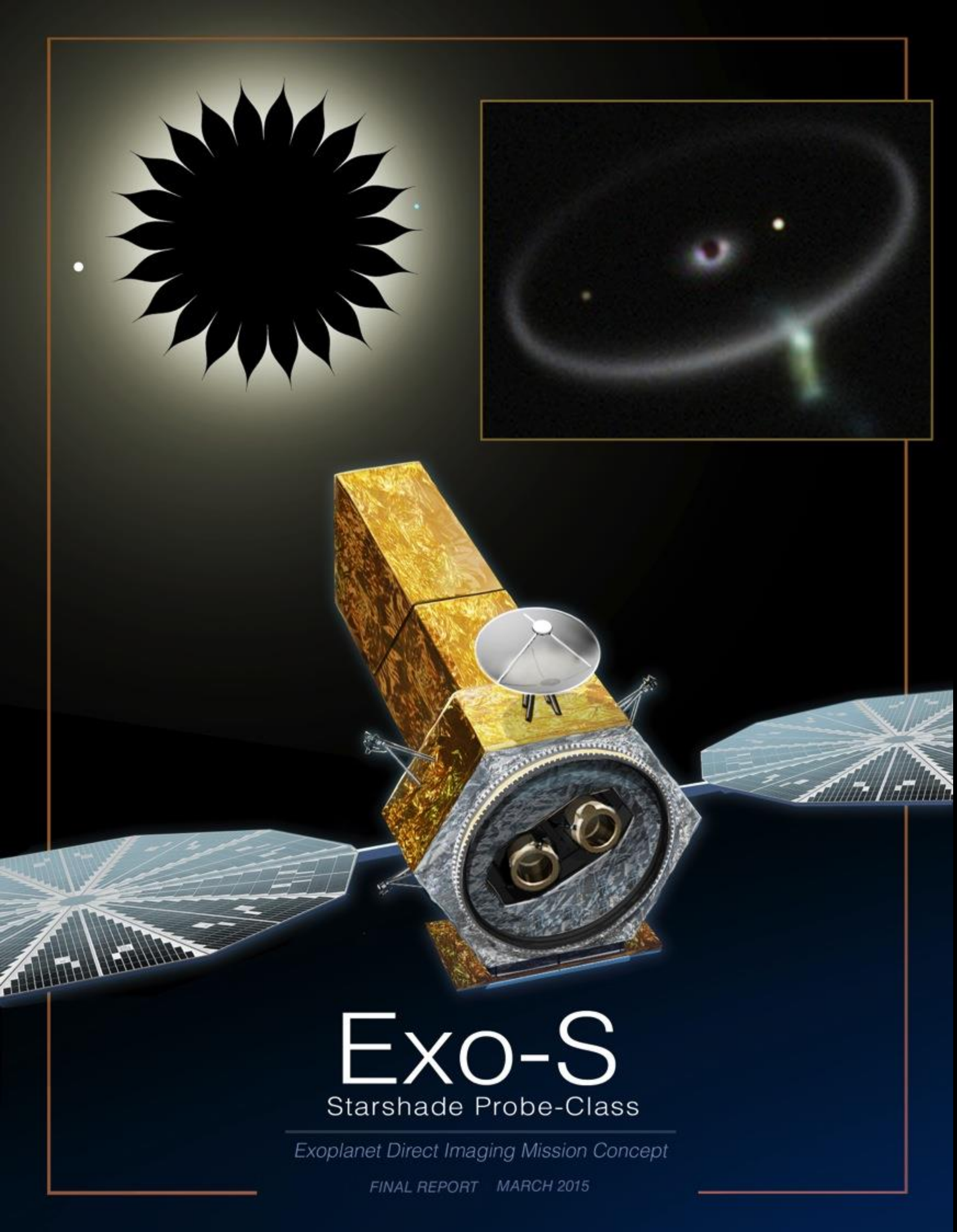

EXO-S: STARSHADE MISSION STUDY FINAL REPORT

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Exoplanet Exploration Program

CL#15-1113
Jet Propulsion Laboratory, California Institute of Technology

Exo-S Study Charter

- The discovery of exoEarths, via a space-based direct imaging mission, is a long-term priority for astrophysics (Astro 2010)
- Exo-S was an 18-month NASA HQ-funded study of a starshade and telescope "probe" space mission (5/2013 to 1/2015)
  - Total mission cost targeted at $1B (FY15 dollars)
  - Technical readiness: TRL-5 by end of Phase A, TRL-6 by end of Phase B
  - New start in 2017
  - Compelling science must be beyond the expected ground capability at the time of mission
- Study also intended as a design input to the exoplanet community to help formulate ideas for the next Decadal Survey

Exo-S Team Members

STDT

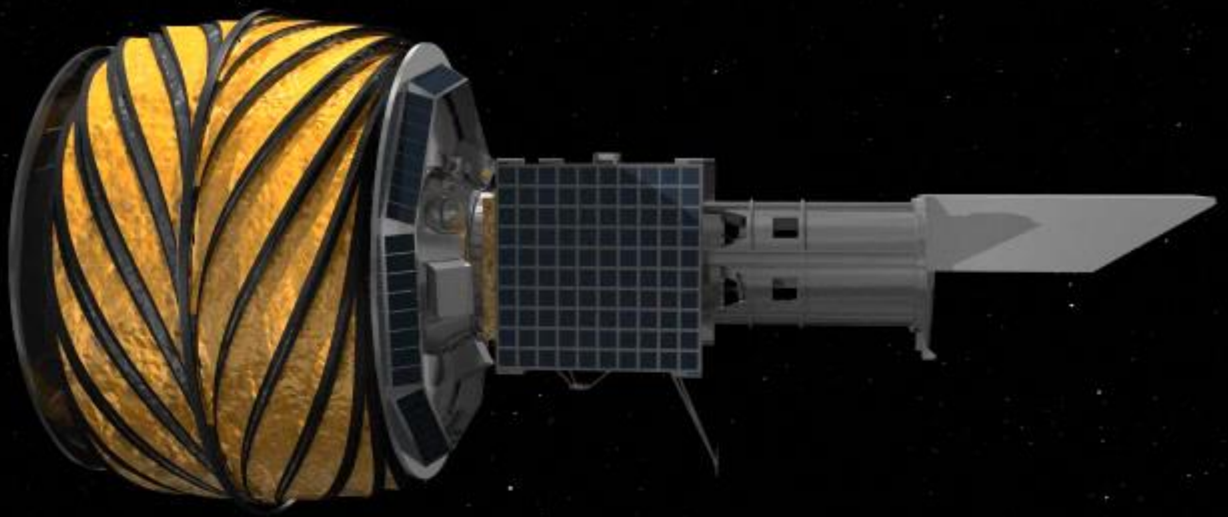
- **S. Seager, Chair (MIT)**
- M. Thomson (NASA-JPL)
- M. Turnbull (GSI)
- W. Sparks (STScI)
- S. Shaklan (NASA-JPL)
- A. Roberge (NASA-GSFC)
- M. Kuchner (NASA-GSFC)
- N. J. Kasdin (Princeton)
- S. Domagal-Goldman (NASA- GSFC)
- W. Cash (Colorado)

JPL Design Team

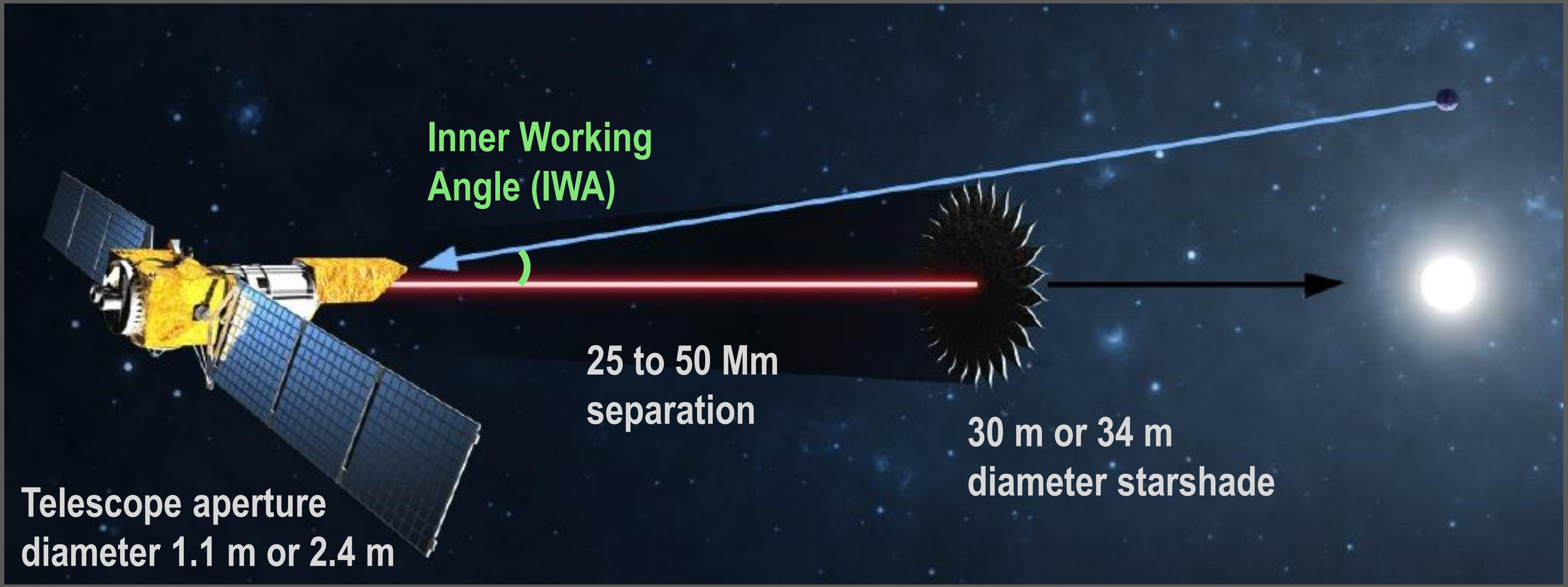
- **K. Warfield, Lead**
- D. Lisman
- C. Heneghan
- S. Martin
- D. Scharf
- R. Trabert
- D. Webb
- E. Cady
- R. Baran
- P. Zarifian
- S. Krach
- B. Hirsch

Two Cost Constrained Exo-S Concepts

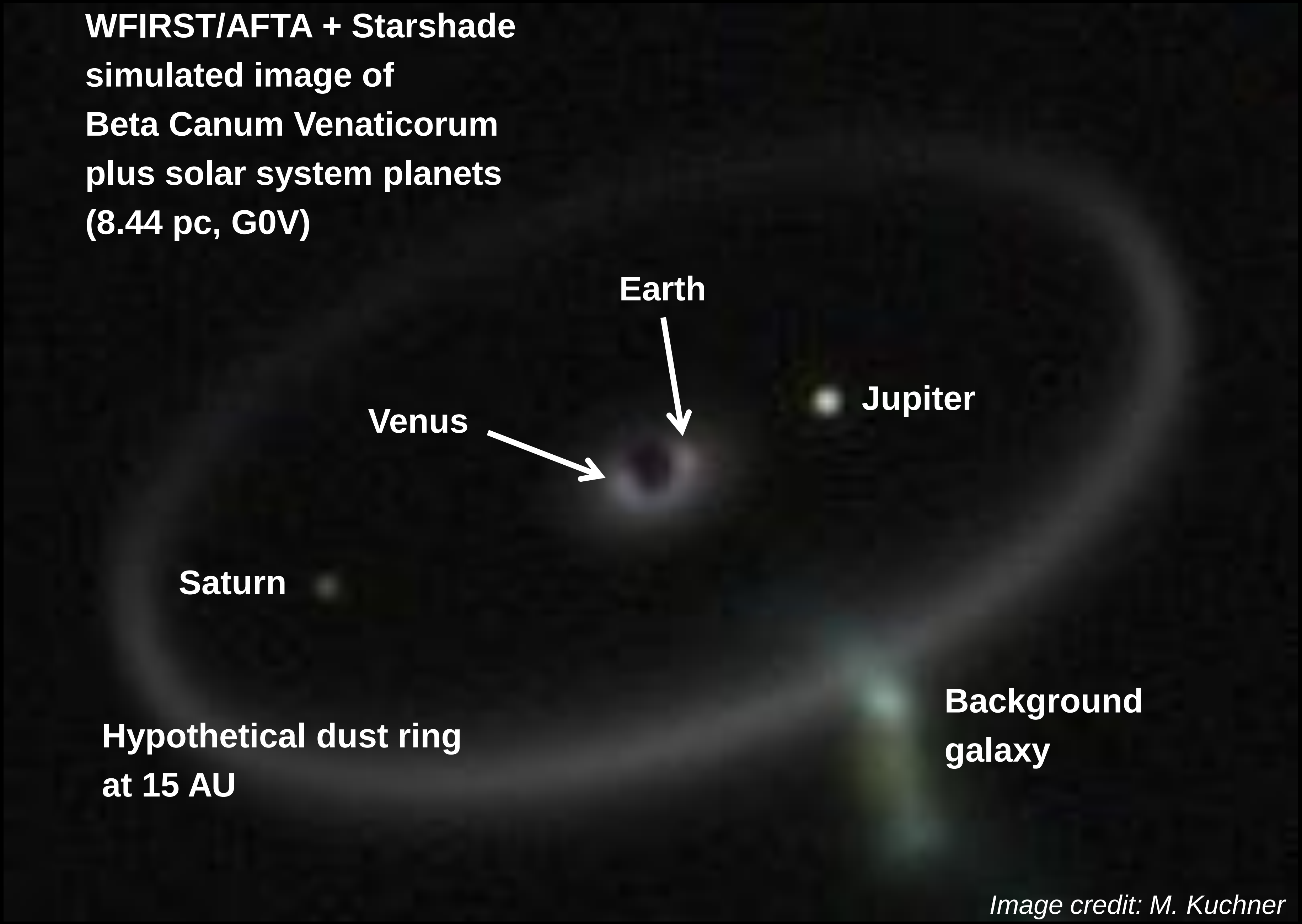
- Exo-S Dedicated Co-Launched Mission
  - Starshade and telescope launch together to conserve cost
  - Telescope: low-cost commercial Earth observer, 1.1 m diameter aperture
  - Starshade: 30 m diameter
  - Orbit: heliocentric, Earth-leading, Earth-drift away
  - Retargeting: by the telescope spacecraft with solar-electric propulstion
  - Three year Class B mission
- Exo-S Rendezvous Mission
  - Starshade launches for a rendezvous with an existing telescope
  - Telescope: WFIRST/AFTA 2.4 m was adopted
  - Starshade: 34 m diameter
  - Orbit: Earth-Sun L2 (assumption for the purposes of the Exo-S study)
  - Retargeting: by the starshade spacecraft with chemical propulsion
  - 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



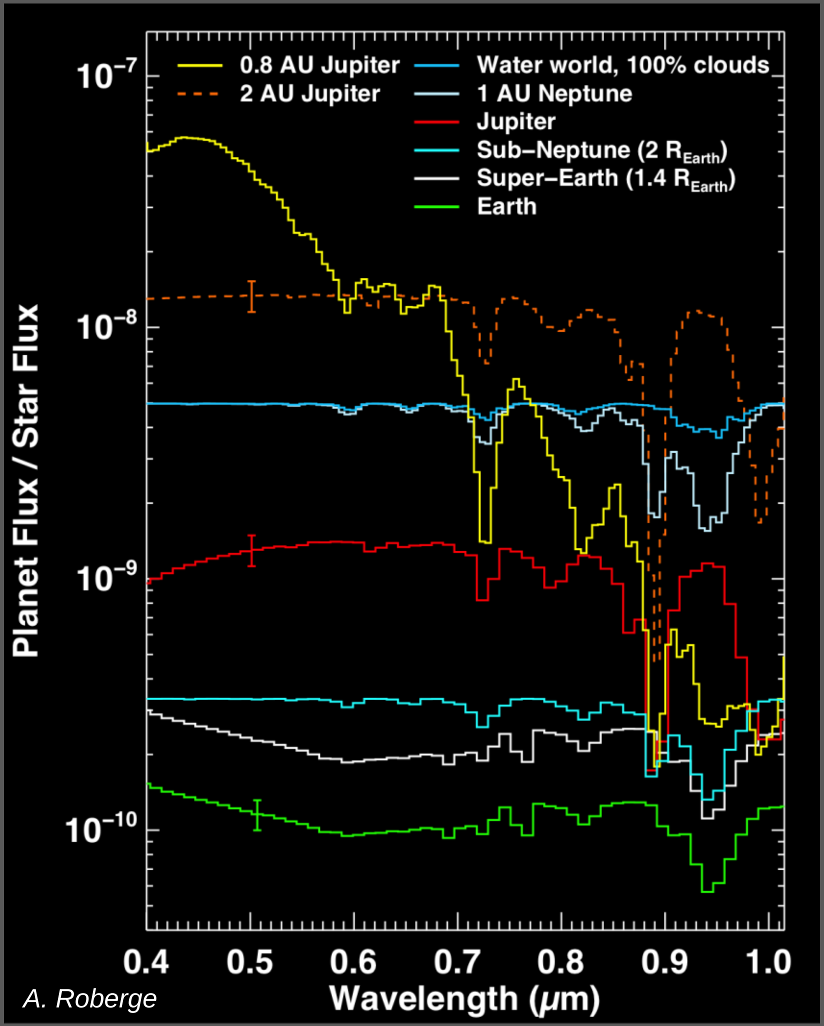
Starshade Basics



- 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)


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 Rendezvous mission, with three representative 10% error bars.

Dedicated 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

Key Capabilities

Instruments: Wide-Field Imager, Integral Field Spectrograph, Guide Camera

Case Study	Parameters	Observing Bands		
		Blue	Green	Red
Rendezvous Mission	Bandpass (nm)	425-602	600-850	706-1000
20m inner disk	IWA (mas)	70	100	118
28 7m petals	Separation (Mm)	50	35	30
Dedicated Mission	Bandpass (nm)	400-647	510-825	618-1000
16m inner disk	IWA (mas)	80	100	124
22 7m petals	Separation (Mm)	39	30	25

FoV (arcsec)	
Imager	IFS
10	2
60	3

Throughput	
Imager	IFS
28%	22%
51%	42%

Contrast at inner working angle consistent w/ error budget

- Dedicated: 5×10^{-10}
- Rendezvous: 1×10^{-10}

Design Reference Mission Strategies

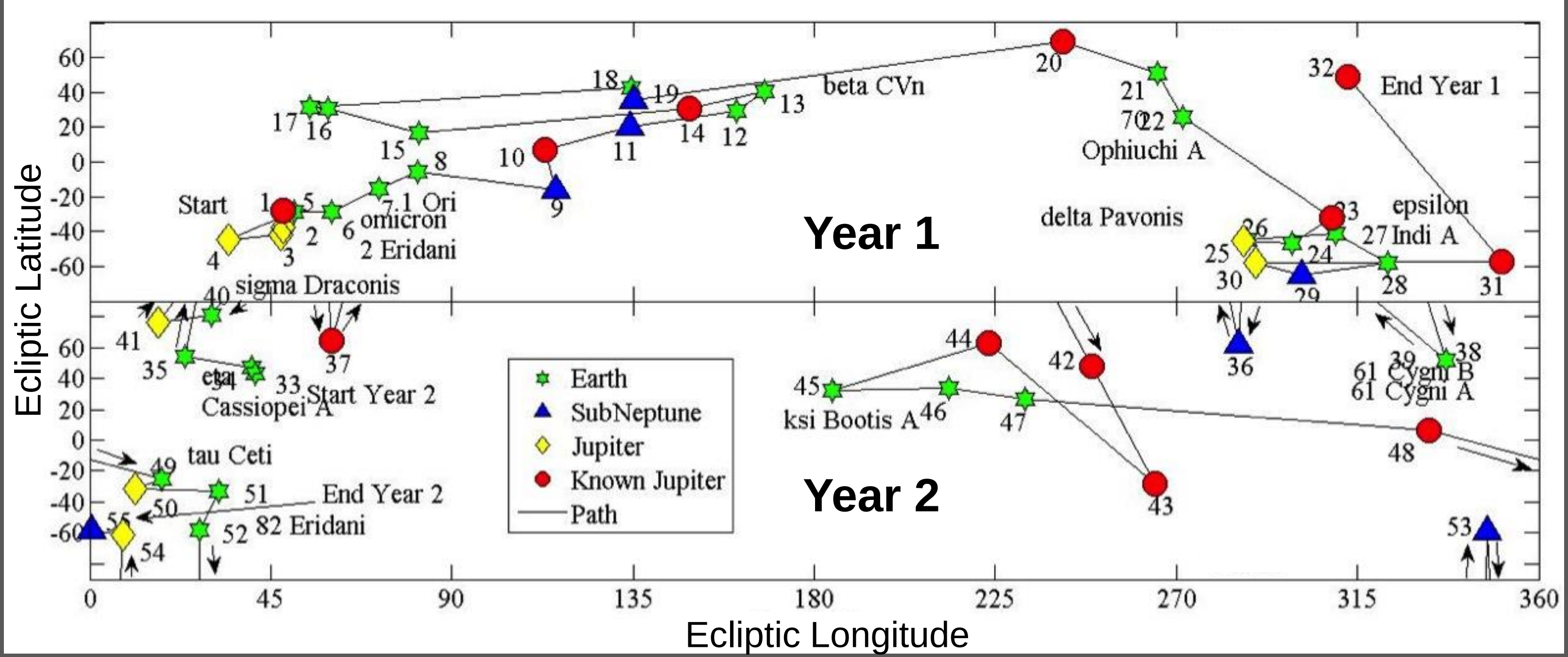
- Planet detection
  - Green band observation with IFS
  - Divided into 3 channels for multi-color imaging
  - SNR = 4 per channel
- Planet characterization
  - SNR = 10, R=10 to 70 per spectral resolution element
- If dust level high, obtain wide-field image then move on

Three target prioritization strategies studied

Study Case	Theme	Mission	Propulsion	Defining Characteristic
Case 1	"Earths in HZ"	1.1 m Dedicated	SEP	Efficient observations based on Stellar Luminosity
Case 2	"Maximum Planet Diversity"	1.1 m Dedicated	SEP	Observe all stars to limiting sensitivity limΔmag=26 (contrast of 4e-11)
Case 3	"Earths in HZ"	2.4 m Rendezvous	Bi-prop	Efficient observations based on Stellar Luminosity

Observing Sequence

1. Schedule known giant planet observations
2. Fill in gaps on sky with highest priority blind search target
3. Repeat with lower priority targets until fuel or time limit reached
4. Reserve 3rd year for follow-up / additional characterization revisits



Rendezvous mission, 2-year sequence, 55 stars visited, Δv = 1266 m/s

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

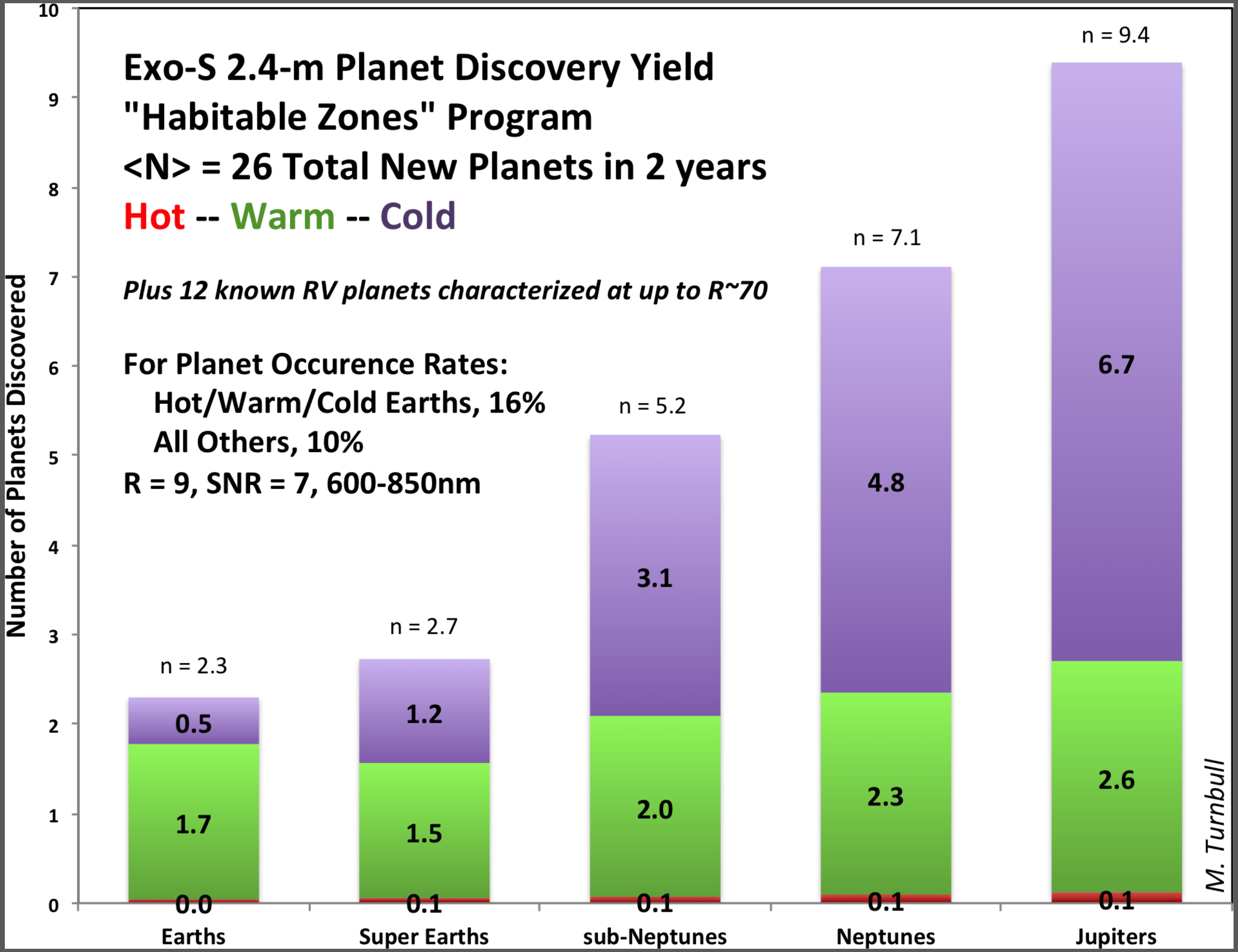
Assumed η = 16% for Earths, η = 10% for all other planets

Large Planet Characterization

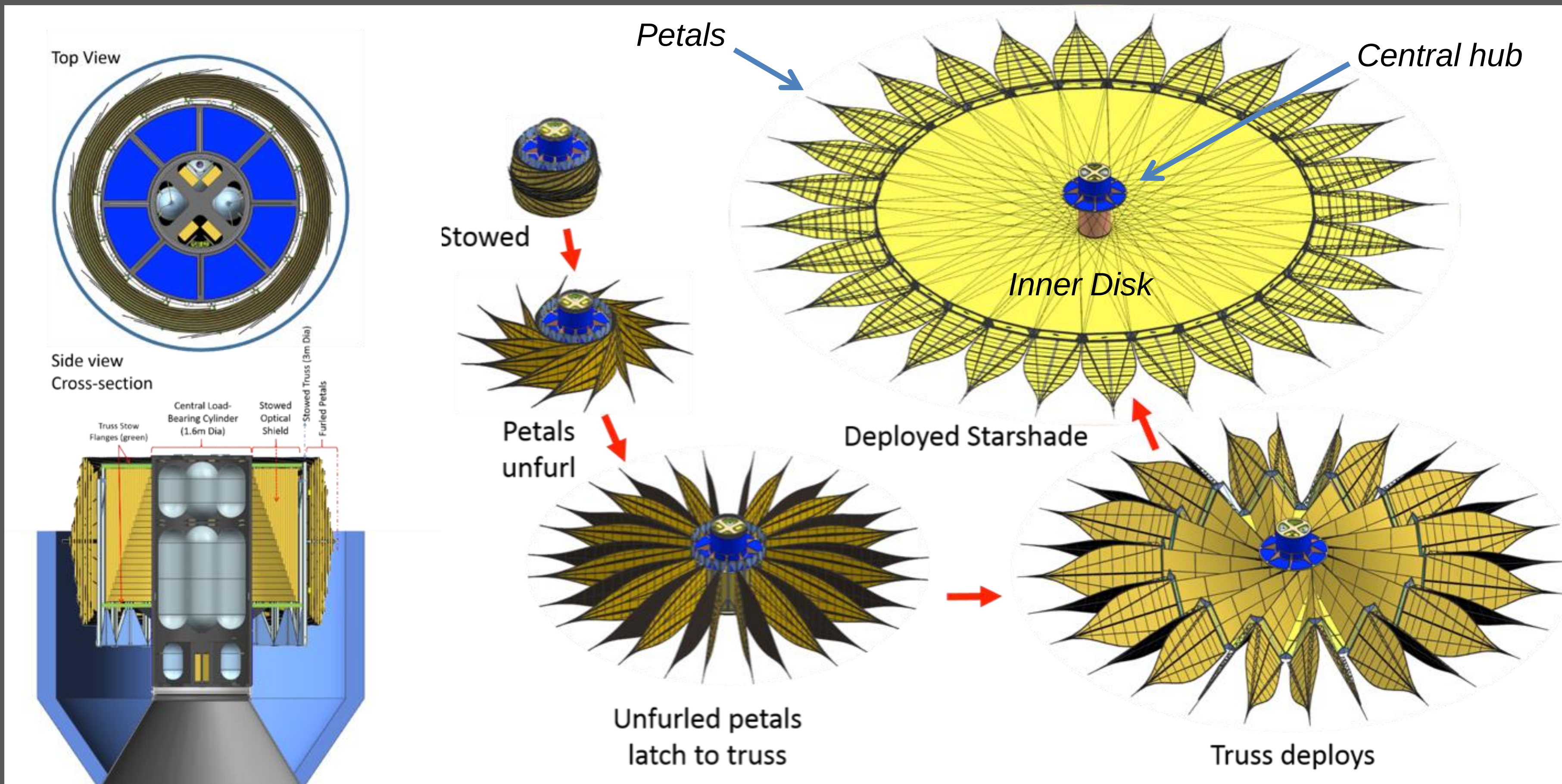
Number of Targets		Case 1	Case 2	Case 3
Jupiter	R > 20	13	25	29
	R = 70	10	24	19
Sub-Neptune	R > 20	0	24	13
	R = 70	0	0	1

Number of stars for which R=X spectra of Jupiters and sub-Neptunes can be acquired

Yield By Planet Type & Temperature



Starshade Mechanical Design Overview



- Starshade stows compactly, fits in 5m launch fairings, can carry a telescope on top, and can carry propellant in central cylinder.
- Inner disk draws heritage from Astromesh Antenna (Thuraya), but is greatly simplified and tailored to accommodate petals.

Starshade Error Budget

Starshade Error Budget (3-sigma)

Error Source	Dedicated Mission (1.1m telescope)		Rendezvous Mission (2.4m telescope)		Demonstrated Performance	Demo
	Tolerance Allocation	Contrast x 10^{-11}	Tolerance Allocation	Contrast x 10^{-11}		
Manufacture						TDEM-09
Petal Segment Shape (Bias)	14 μm	1.4	22 μm	0.4		
Petal Segment Shape (Random)	68 μm	0.3	68 μm	0.1	45 μm	
Petal Segment Placement (Bias)	4 μm	0.7	7 μm	0.1		
Petal Segment Placement (Random)	45 μm	0.6	53 μm	0.5	45 μm	
Pre-Launch Deployment						TDEM-10
Petal Radial Position (Bias)	150 μm	6.0	200 μm	0.15	100 μm	
Petal Radial Position (Random)	450 μm	0.6	450 μm	0.1	300 μm	
Post-Launch Deployment						
Petal Radial Position (Bias)	100 μm	2.7	250 μm	0.23		
Petal Radial Position (Random)	350 μm	0.4	375 μm	0.06		
Thermal						STDT Analysis
Disk-Petal Differential Strain (Bias)	20 ppm	6.0	40 ppm	0.6	12 ppm	
1-5 cycle/petal width (Bias)	10 ppm	1.0	30 ppm	0.2	9×10^{-12} contrast	
Formation Flying						
Lateral Displacement	1 m	2.9	1 m	1.1		
Longitudinal Displacement	250 km	2.5	250 km	0.43		
Total Photometric Error						
Photometric Allocation		50		10		
Total Systematic Error						
Systematic Allocation		4		4		

Full error budget accounts for 200 separate perturbation sources

Will repeat early demos with more flight-like prototypes for TRL-5

32% of total allocation is unallocated reserve

Compliance is demonstrated via TDEMs for several key requirements

Starshade Technology Development Overview

The STDT identified 5 technology gaps.

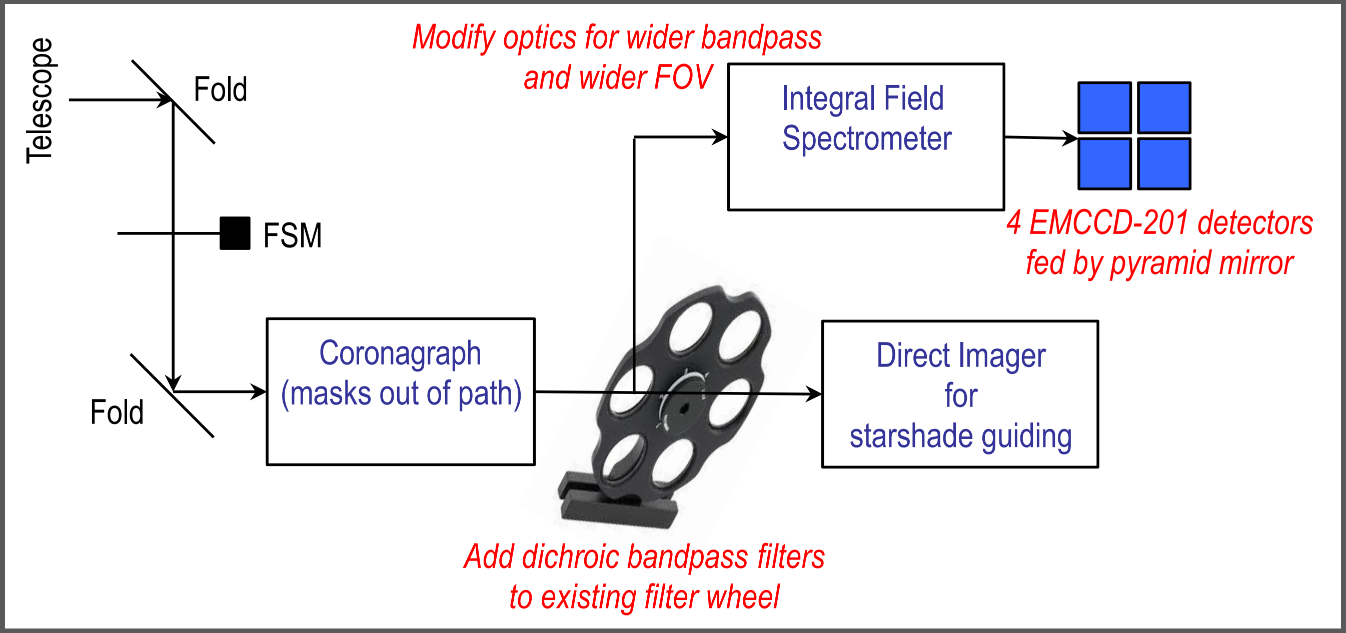
Resolution plans in place to establish TRL-5 by 2017

Technology Gap	Resolution Plan	Funding
1. Control edge scattered Sunlight	Additional modeling	TDEM-12, NGAS
	Testbed	ExEP modeling, infrastructure
	Prototype edge segment	JPL internal R&TD
	Flight-like edges part of TRL-5 petal	TDEM-12, Princeton
2. Verify optical performance at subscale	Modeling	ExEP modeling, infrastructure
	Desert testbed	TDEM-12, NGAS
	Laboratory testbed	TDEM-12, Princeton
3. Demo. formation flying sensing perf.	Design, simulations, algorithm dev.,	TDEM-13, Princeton
	Optical testbed	
4. Mature petal design to TRL-5	Flight-like full-scale petal with: all truss I/Fs, optical edges, optical shield, etc.	TDEM-12, Princeton
5. Mature inner disk design to TRL-5	Flight-like half-scale inner disk with: all petal I/Fs, optical shield, launch restraint	TBD

All efforts to TRL-5 are fully funded, except Gap #5

Starshade-Ready WFIRST/AFTA

- Minimal modifications needed
  - Earth-Sun L2 orbit
  - Use existing coronagraph IFS for science, imager for formation guidance
  - Rotate coronagraph masks out of path, add bandpass filters to existing wheel
  - Add proximity radio with 2-way ranging to bus telecom system
  - IFS FOV reduced to accommodate broader bandpass, but mitigated by adding detectors for bigger focal plane (improves coronagraph FOV as well)



Cost Estimates

- Cost estimates from Exo-S Team, JPL Team X, and Aerospace CATE
- Dedicated mission went slightly over $1B cap
- Rendezvous mission Phase A – F cost: $627M
- Exo-S team estimates close to CATE, except for "threats"
- CATE raised no issues with 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

- Rendezvous Mission can access up to 50 unique target stars for exoEarths in the habitable zone
- Minimal modification needed for starshade readiness
- Starshade technology is on track for TRL-5 by 2017 and for new start by 2018, but not fully funded
- Mission cost ~ $627M