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M. Thomson[2]
M. Turnbull[3]
W. Sparks[4]
S. Shaklan[2]
A. Roberge[5]
B. M. Kuchner[5]
C. N. J. Kasdin[6]
S. Domagal-Goldman[5]

Design Team
K. Warfield, Lead[2]
D. Lisman[2]
S. Martin[2]
R. Trabert[2]
E. Cady[2]
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[6]Princeton University

CL#16-1871

Exo-S-ES Presentation to APD

April, 2016

Study Overview

Sara Seager

Exo-S-ES Study

- Study was a continuation of the Starshade Probe study focusing on a technology development version of the Rendezvous mission concept.
  - Explore a 20 m starshade mission utilizing the WFIRST 2.4 m telescope, at the Earth-Sun L2 point.
- Describe mission concept, driving requirements and estimated cost
- Comparative description of science to the Probe study science
- Technology development progress to date
- A major product is a summary of mission options
- Deliver final briefing including a yield assessment

Exo-S-ES 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 U.)

S. Domagal-Goldman (NASA-GSFC)

JPL Design Team

K. Warfield, Lead

D. Lisman

S. Martin

R. Trabert

E. Cady

S. Krach

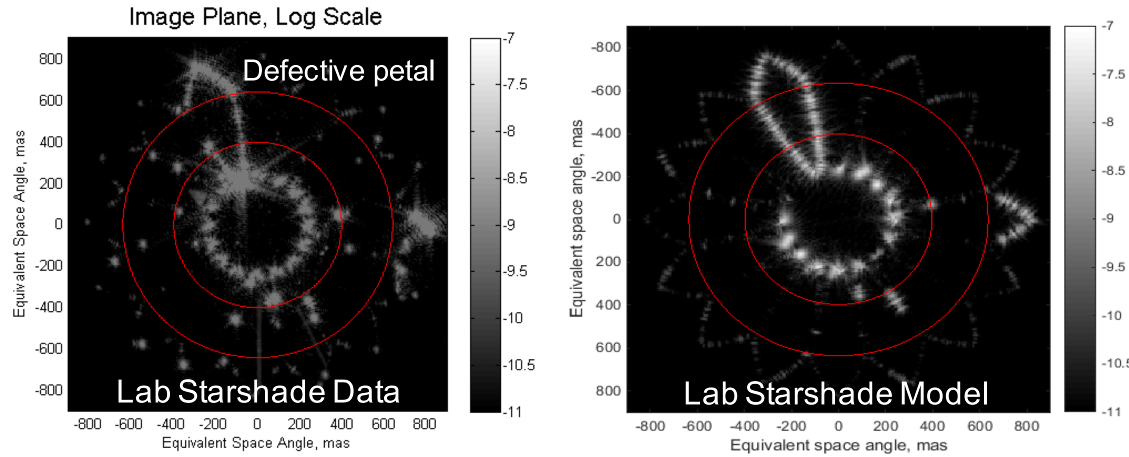
S. Zareh

Community Technical Advances since Exo-S Report
Optical Performance

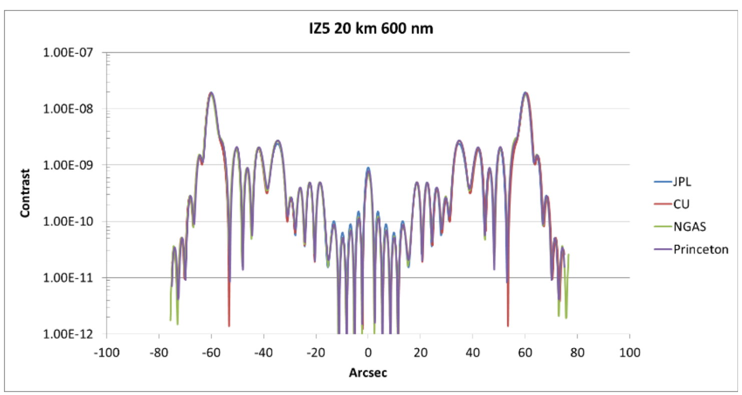
Completed open-air optical testing
(NGAS, Steve Warwick)

and started model validation efforts.

Princeton optical model predicts results from
first generation testbed (30m, not flight #)



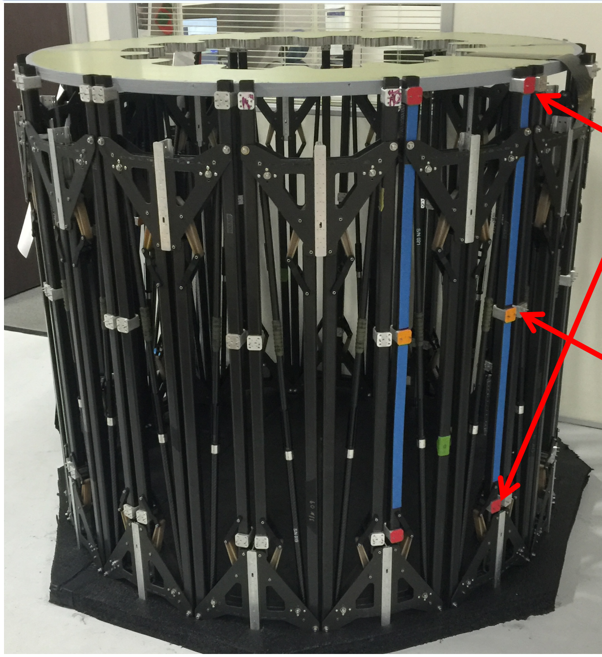
Three independent models are converging
to predict the same phenomenon



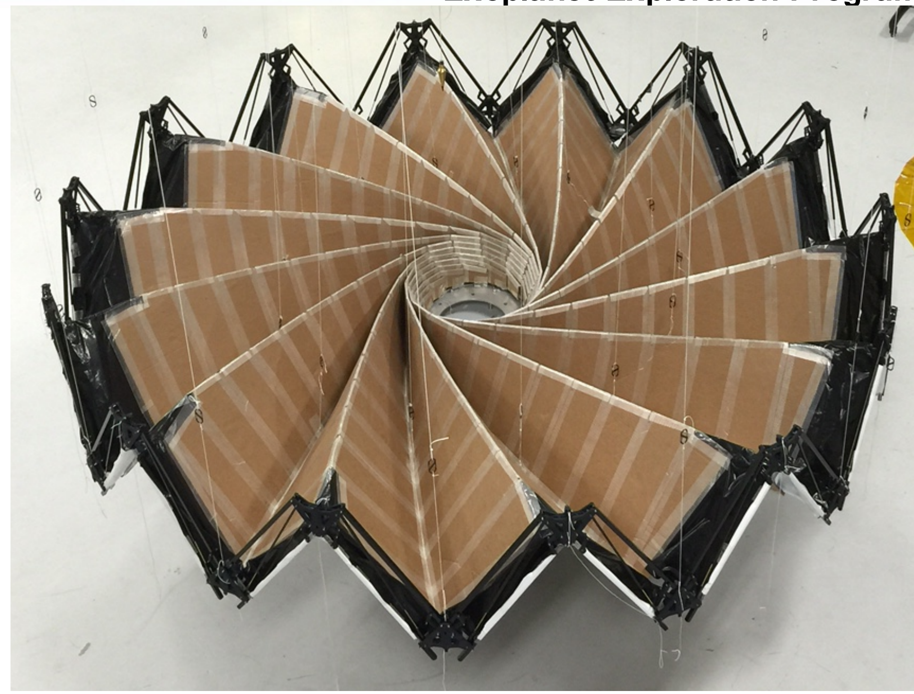
Second generation Princeton optical testbed
(78 m long, near flight Fresnel number)
is nearing completion *(Jeremy Kasdin)*

Community Technical Advances since Exo-S Report

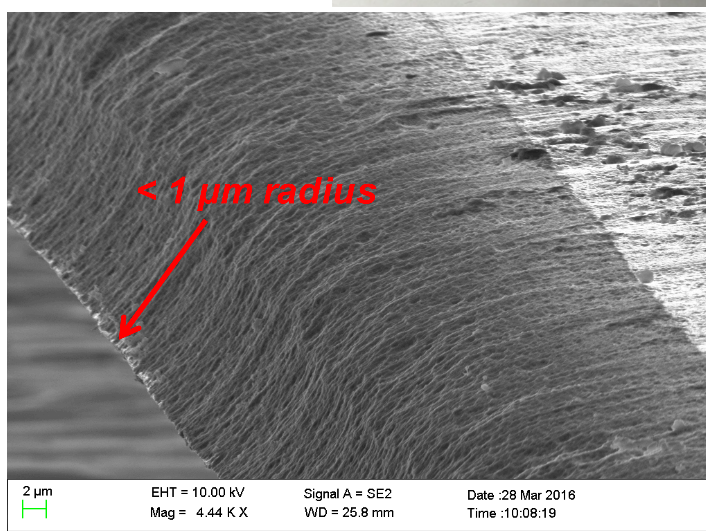
Mechanical Design



Developed second generation inner disk perimeter truss prototype *(Brian Hirsch, JPL)*

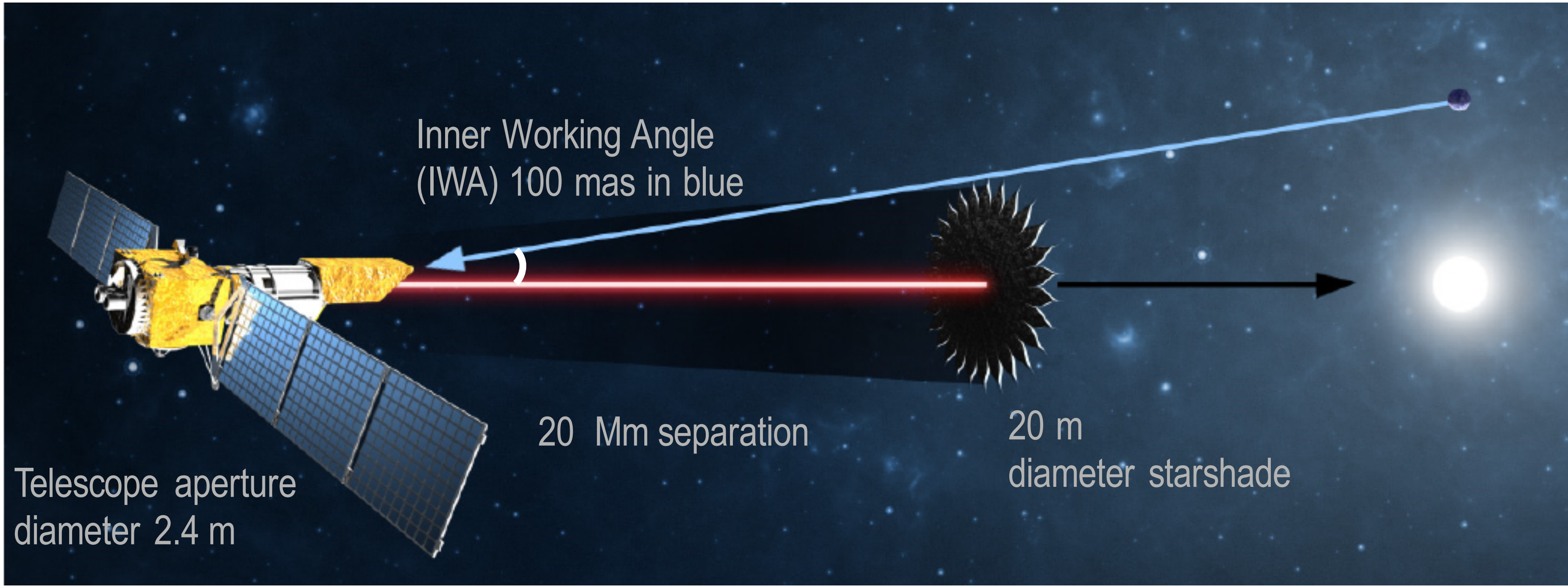


Developed inner disk optical shield concept and rapid prototyped a 5-m-dia. demonstration unit *(David Webb, JPL)*



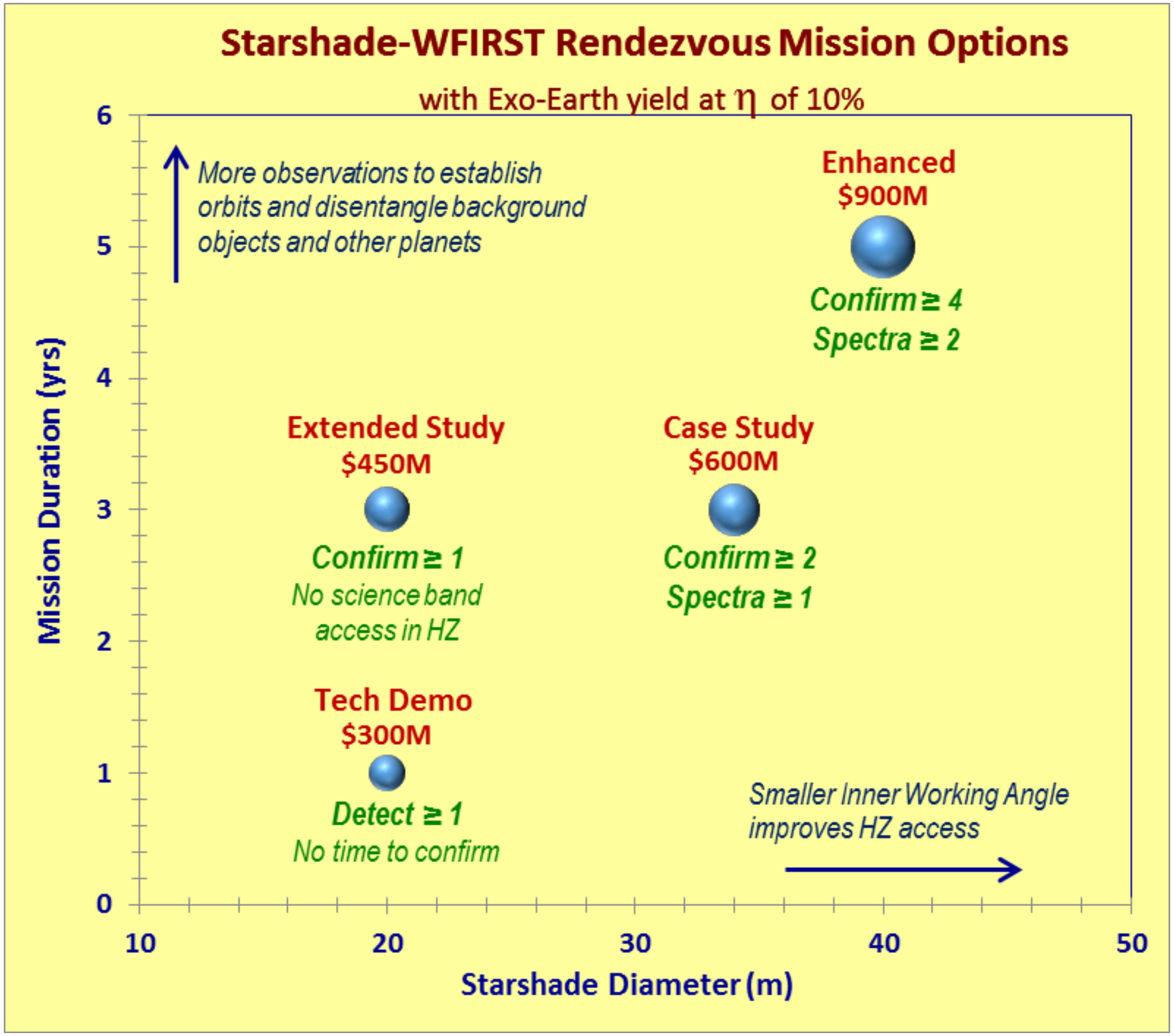
Developed optical edge chemical etching process in amorphous metal without grain structure. *(John Steeves, JPL)*

Exo-S ES Starshade Concept



- Contrast and inner working angle are decoupled from the telescope aperture size
  - A simple space telescope could be used
  - No wavefront correction is needed
- High throughput, broad bandpass
- Outer working angle limited only by detector field of view

Mission Options



Exo-S-ES Presentation to APD

April, 2016

Exo-S-ES Science

Sara Seager

Exo-S-ES Reduced Science

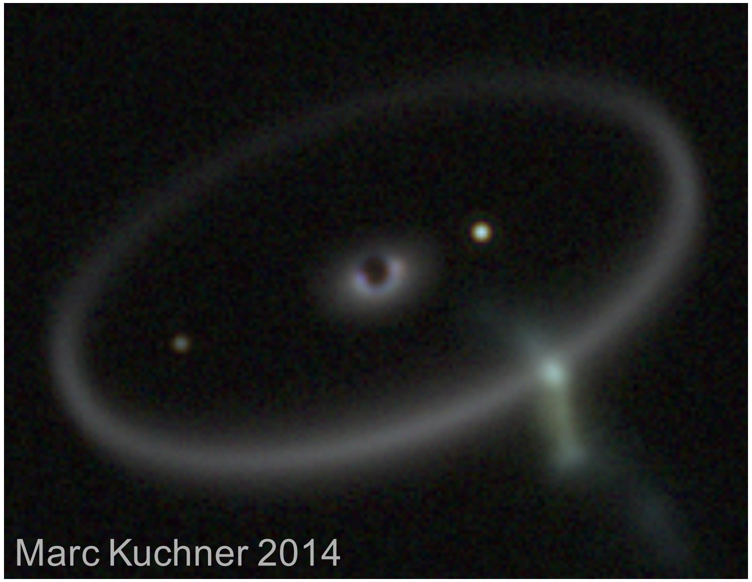


Image: WFIRST + 34m Starshade. Simulated image of Beta Canum Venaticorum (8.44 pc, G0V) plus solar system planets. Hypothetical dust ring at 15 AU

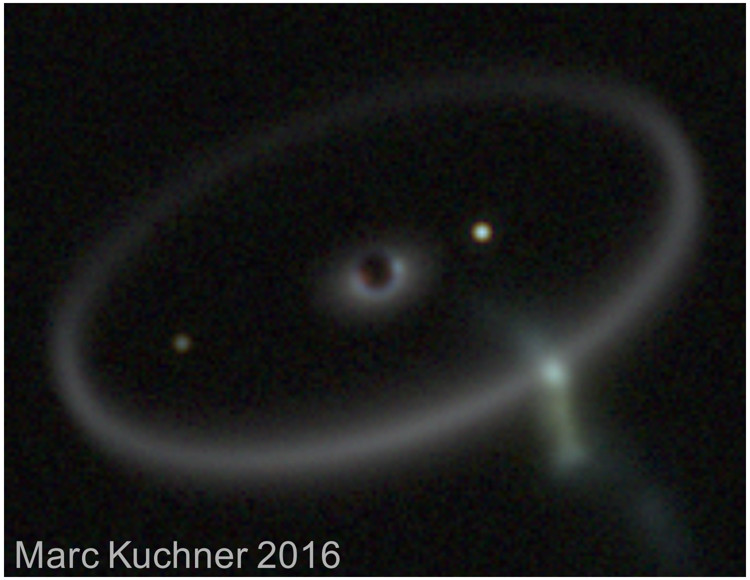


Image: Same simulated image as on the left, but with a 20m Starshade. Except, note the lack of color in inner region

Version	Parameters	Observing Bands		
		Blue	Green	Red
Case Study	Bandpass (nm)	425-602	600-850	706-1000
20m inner disk	IWA (mas)	70	100	118
28 7m petals	Separation (Mm)	50	35	30
Extended study	Bandpass (nm)	425-565	600-800	750-1000
10m inner disk	IWA (mas)	100	140	176
28 5m petals	Separation (Mm)	20.5	15	12

Exo-S ES compared to Exo-S CS

- **Discovery:** Stars that could be searched have the same quality images as before. Fewer targets with desirable IWA
- **Characterization by spectra:** only blue band is accessible for exoEarths
- **Background discrimination:** lack of colors at small IWA hurts for background contamination

Exo-S Rendezvous vs Exo-S ES Science Goals

Exo-S (34 m starshade)	Exo-S ES (20 m starshade)
1) Discover new exoplanets from giant planet down to Earth size	1) Discover exoplanets, focusing on Earth size. Fewer targets available at small IWA
2) Characterize new planets by spectra (R=10 to 70) • Wavelength range from 400–1,000 nm, in three bands	2) Characterization for exo-Earths in the blue band, 425-565 nm
3) Characterize known giant planets by spectra (R=70) and constrain masses • detectable by virtue of extrapolated position in 2024 timeframe	3) Known giant planet characterization is possible for a reduced number
4) Study planetary systems including circumstellar dust in the context of known planets • dust-generating parent bodies • possible detection of unseen planets • assessment of exozodi for future missions	4) Capability for study of exozodial dust and wide field background objects, but in a reduced field

Exo-S-ES Presentation to APD

April, 2016

Observing Strategies and Results

Stuart Shaklan

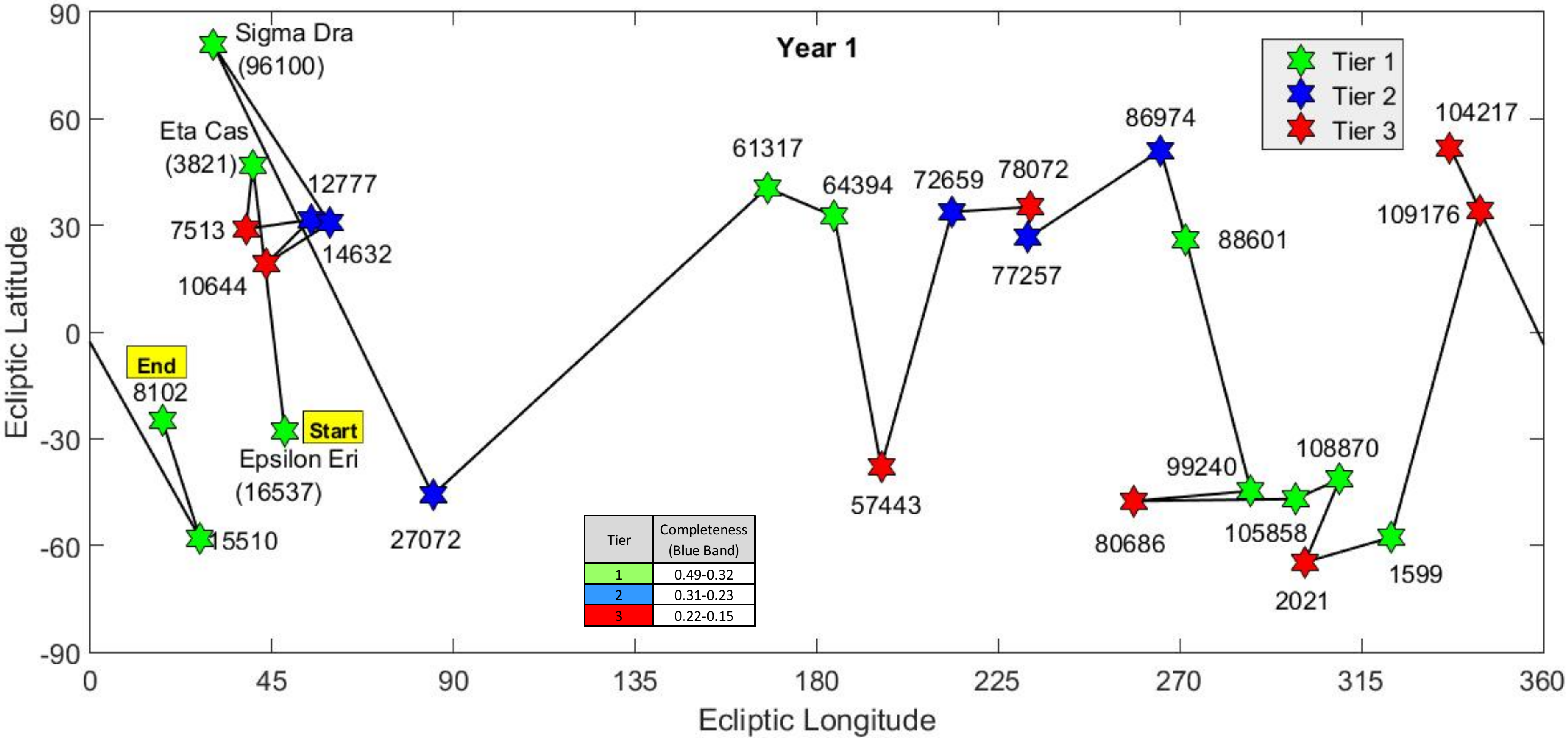
Design Reference Mission

Study	Starshade	Nominal Distance	IWA	Years	Defining Characteristics
Case Study	34m	50,000 km	70 mas	2+1	Known RVs + Exo-Earths
Extended Study	20m	20,000 km	100 mas	2+1	Maximize Exo-Earths in 1 year

- Observation Plan
  - Both studies assume WFIRST at L2 as the observing telescope
  - Case Study was a 2 year sequence. 3rd year left open for revisits.
  - Extended Study is a 1 year sequence, with 2nd and 3rd years left open for revisits.
- Target list drawn from ExoCat (M. Turnbull)
  - Stars to 30 pc
  - Known binaries/multiples removed
- Case Study observes known RVs, then searches for Exo-Earths, followed by searches for mini-Neptunes, and Jupiters.
- Extended Study focused on searching for Exo-Earths, with other planets incidentally observed.

Future cases to study include deeper observations with Rendezvous mission, globally optimized solutions, and 3-year plans.

Observing Sequence: Exo-S ES Study



- Targets prioritized by blue band completeness.
- Sequence assumes detecting planets in first year with follow-up observations and characterizations in the 2nd and 3rd years.

DRM Yield Summary

Expected Number of Detected Planets

Mission	Diam.	Detection	Follow up	HZ Earth	Super Earth			mini-Neptune			Jupiter		
				HZ	Hot	Warm	Cold	Hot	Warm	Cold	Hot	Warm	Cold
Exo-S Tech Demo	20 m	1 yr	--	0.9	0.1	1.3	0.5	0.1	1.5	1.1	0.1	1.5	2.1
Exo-S Extended Study	20 m	2 yr obs	1 yr obs	1.2	0.1	2.0	1.0	0.1	2.3	2.2	0.1	2.4	4.1
Exo-S Case Study*	34 m	2 yr obs	1 yr obs	2.8	0.5	4.6	1.3	0.5	5.5	3.0	0.5	6.1	6.5
Exo-S Enhanced	40 m	3 yr obs	2 yr obs	3.5	0.8	5.7	1.4	0.8	6.8	3.4	0.9	7.6	7.6
Exo-S Enhanced	40 m	5 yr obs	--	4.8	0.6	8.2	2.8	0.7	9.6	6.4	0.7	10.3	12.7

**The DRM for CS reported here has been optimized for exo-Earth detection, more than doubling the exo-Earth observational completeness reported in the Exo-S Final Report.*

- This table shows the expected number of planets detected for five mission scenarios.
- HZ Earths are Earth-like planets in the HZ of their host stars.
- As in the Exo-S Final Report, other planets detections are divided into 3 zones:
  - Hot = 0 – 0.75 AU
  - Warm = 0.75-1.77 AU (HZ)
  - Cold = 1.77 – 10 AU
- The detection numbers assume that the probability of each planet in each zone is 0.1.

The 20 m ES starshade is sensitive to Earths in the HZ and with a 3-yr program could perform follow-up observations to confirm detection. It would also discover super Earths, mini-Neptunes, and Jupiters.

Exo-S-ES Presentation to APD

April, 2016

Mission Options

Doug Lisman

Mission Options

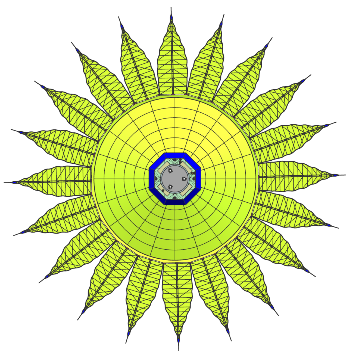
- All options are follow-on missions with WFIRST. All options are designed for operations at the Earth-Sun L2 point.
- Petal optimization for detection in blue band could improve Tech Demo and Extended Study IWA

Mission Option Characteristics							Performance Characteristics				
Option	Starshade Size	Mission Duration	Mission Class	Launch Option	Retarget Propulsion	Ball-Park Mission Cost	Search Mode IWA	Search Mode Bandpass	Telescope Separation	Exo-Earth Detections*	Exo-Earth Character-izations
Exo-S Tech Demo	20 m	1 yr.	D	Antares 3m fairing	Monoprop	\$300M	100 mas	425-565 nm	20 Mm	≥1 candidate	0
Exo-S Extended Study	20 m	3 yr.	C	Falcon 9 5m fairing	Biprop	\$450M	100 mas	425-565 nm	20 Mm	≥1	<1
Exo-S Case Study	34 m	3 yr.	C	Falcon-9 5m fairing	Biprop	\$600M	70 mas	425-602 nm	50 Mm	≥2	≥1
Exo-S Enhanced	40 m	5 yr.	B	Falcon-9 5m fairing	SEP	\$900M	50 mas	425-560 nm	82 Mm	≥4	≥2

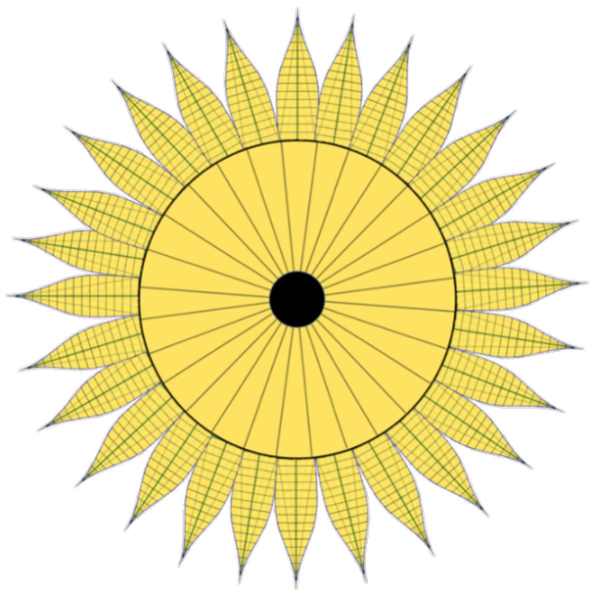
* Confirm in HZ via orbit determination. Assumes 10% frequency of Exo-Earths

Configuration Comparison

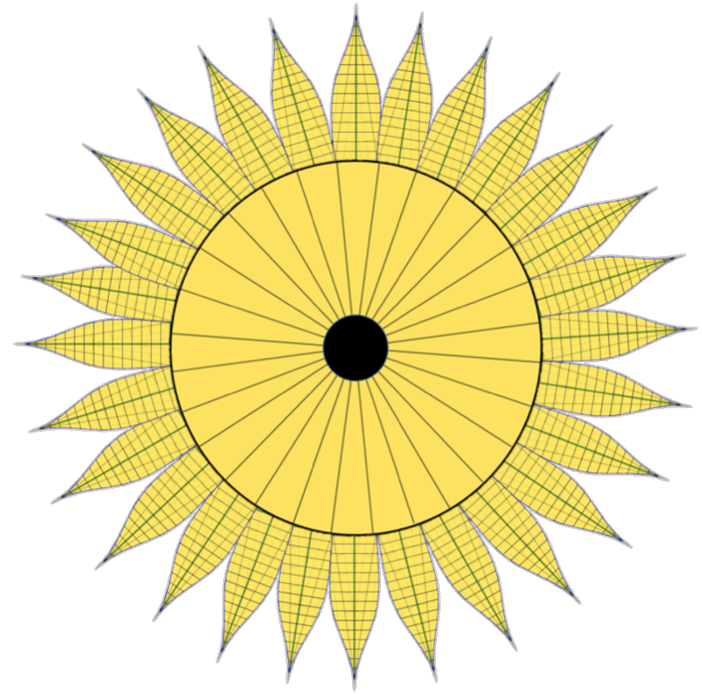
20m Starshade



34m Starshade



40m Starshade



Starshade Spacecraft Characteristics

Option	Starshade Size	Mission Duration	Propulsion Type	Petal Length	Disk Diameter	Petal Count	Starshade Mass	Bus Dry Mass	Spacecraft Dry Mass	Propellant Mass	Spacecraft Wet Mass
Tech Demo	20 m	1 yr.	Monoprop	5 m	10 m	20	300	400	700	400	1100
Exo-S Extended Study	20 m	3 yr.	Bi-prop	5 m	10 m	20	300	450	750	650	1400
Exo-S Case Study	34 m	3 yr.	Bi-prop	7 m	20 m	28	741	715	1456	2021	3477
Exo-S Enhanced	40 m	5 yr.	SEP	8 m	24 m	28	1000	1000	2000	1500	3500

Exo-S Tech Demo and Extended Study

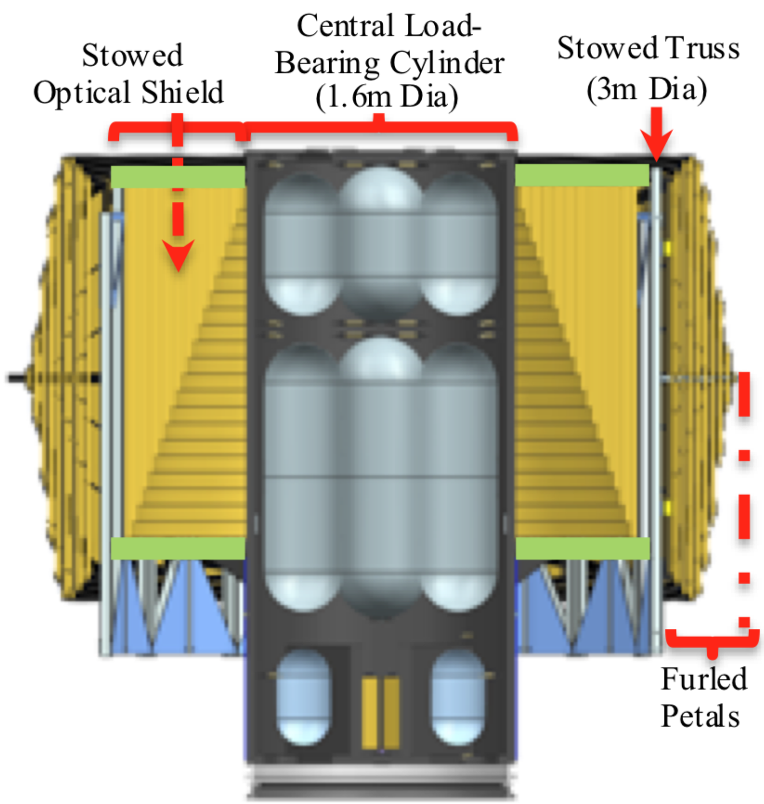
(20m Starshade Mission Options)

- Tech Demo Option
  - 20 m dia. starshade – same as current prototypes
  - Quickest path to flight at the lowest cost
  - 1 year Class D mission with single string avionics
  - Monoprop retargeting propulsion

- Extended Study Option
  - 20 m dia. starshade
  - 3 year Class C mission with select redundancy
  - Biprop retargeting propulsion
  - Compact launch configuration and low mass allow for a possible shared launch on a Falcon 9

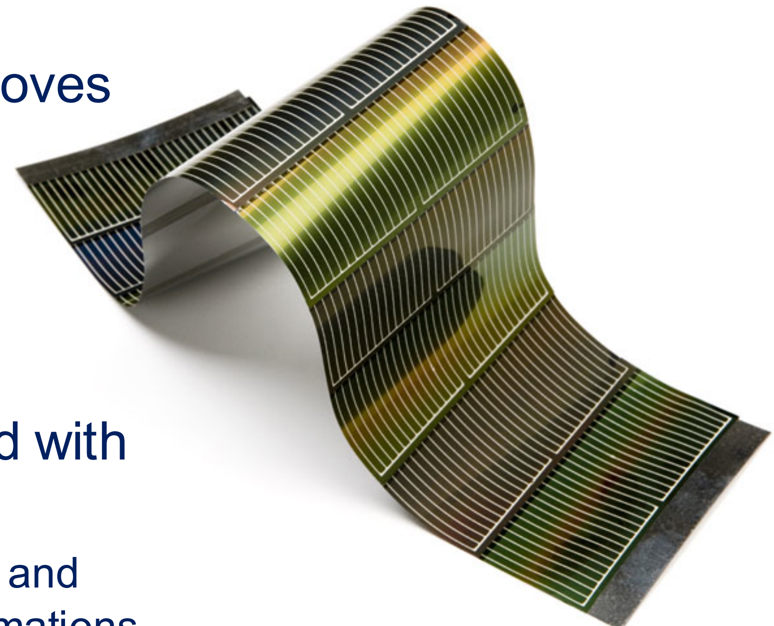
Exo-S Case Study
(34m Option)

- This Rendezvous option is the case study detailed in the Exo-S report
- 3 year Class C mission with select redundancy
- Starshade provides propulsion for retarget maneuvers and formation control
- Biprop propulsion fits in starshade central cylinder



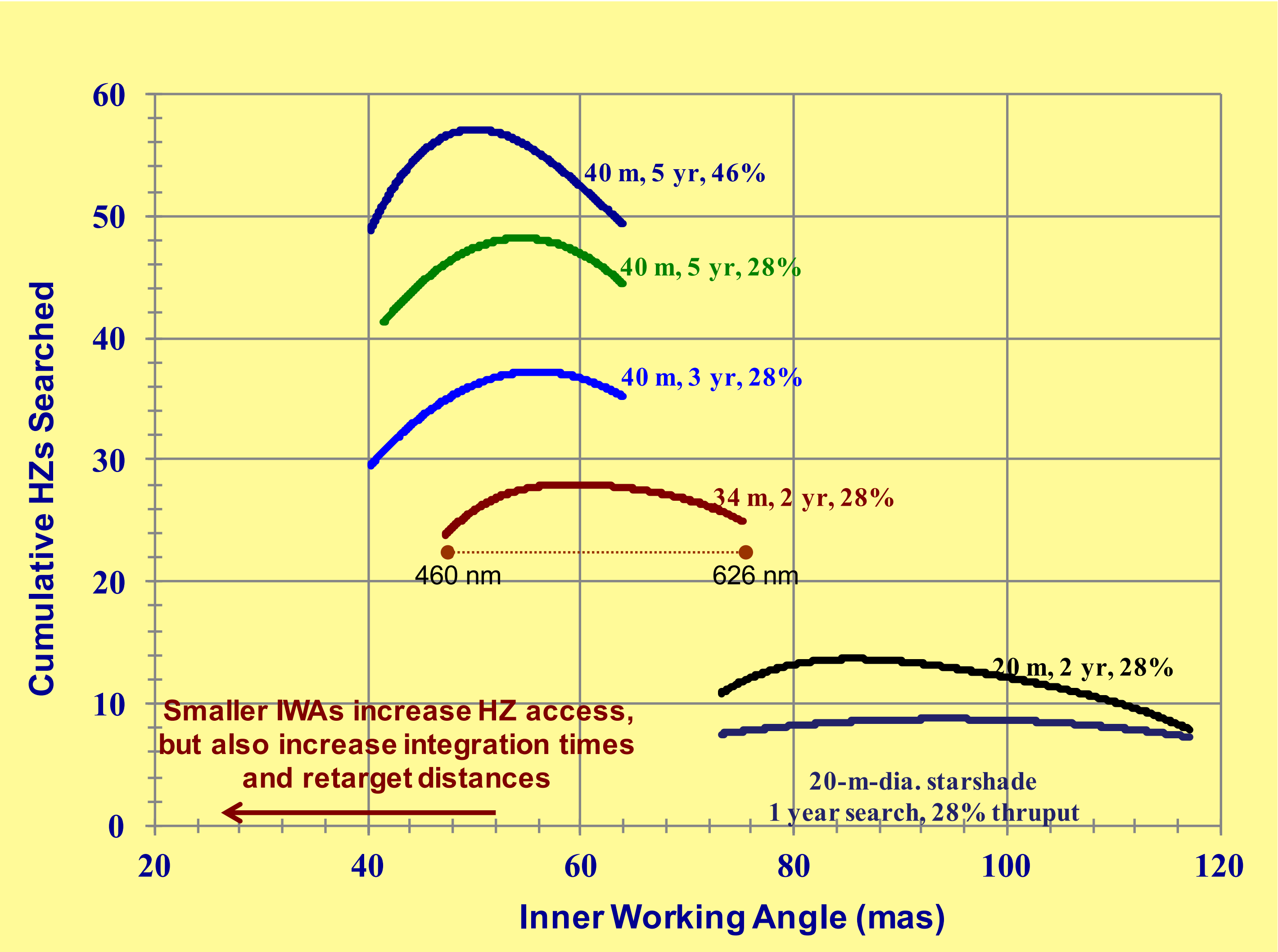
Exo-S Enhanced
(40m Option)

- This Rendezvous option enhances science
- 5 year Class B mission with full redundancy
- Dedicated starshade science instrument improves FOV, throughput and bandpass
- Reduced IWA increases access to HZ
- Heritage SEP thrusters increase retargeting capacity to search available HZs
- Power SEP with thin-film solar cells integrated with the starshades inner disk optical shield
  - A separately deployed array complicates the design and casts shadows on starshade, causing thermal deformations
  - Thin-film solar cells add little mass and stiffness to limit impact to deployment reliability and accuracy



Thin-Film cells are ~ 1μm thick on a Kapton substrate as already included in the optical shield.

Comparative HZ Observational Completeness



Assumptions: optical throughput 46% unless otherwise stated. Minimum time on target = 1 day unless otherwise stated. QE = 0.8, read noise=2.8 e-, dark current=5.5e-4, read time=2000 s, Instrument contrast=1e-10, Sharpness=0.08, Total Zodis = 21.5 mag/sq. arcsec, SNR = 6, minimum wavelength 400 nm, maximum wavelength 460-626 nm, 5 yr mission.

Exo-S-ES Presentation to APD

April, 2016

WFIRST Starshade Readiness

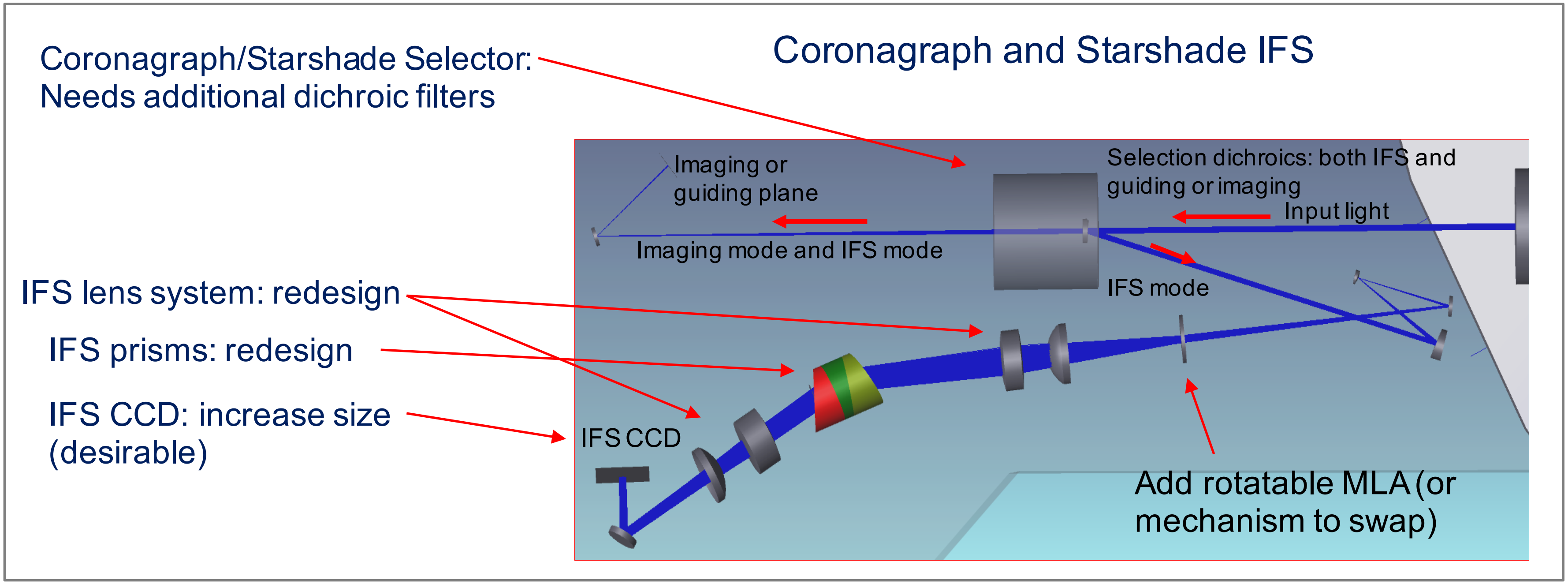
Stefan Martin

WFIRST-Starshade Readiness

- WFIRST could be Starshade Ready with minimal modifications by using the coronagraph optical system for starshade instrumentation and formation guidance
- WFIRST orbit assumed to be Earth-Sun L2
- Perform inter-spacecraft communications and range measurement with radio system added to the bus telecom subsystem (S-band transponder, 2-way ranging, LGA)
- Perform all starshade observations with the existing coronagraph focal plane.
  - Perform starshade guiding with the coronagraph's visible imaging camera
  - Perform spectroscopy with coronagraph-IFS
  - Perform starshade planet imaging with coronagraph's imaging camera
- Add between 4 and 6 dichroics into an existing filter wheel (camera selector wheel).
- Modify IFS prisms, lenses to obtain broader optical bandwidth.

Modifications to WFIRST Coronagraph Instrument

- Starshade utilizes 34% broad-band observations; WFIRST- CGI uses 18%.
  - Possible modifications to accommodate the same product of bandwidth × field of view on IFS, require larger camera (1.6k × 1.6k) or smaller spectral spacing.
- A rotation stage on the microlens array could reduce the intra-spectral spacing.
  - This system would create more cross-talk between spectra.
- IFS would be modified (prism, lenses) to accommodate larger bandwidth.
- System conforms closely to the size of the existing Coronagraph IFS.



WFIRST IFS Design Considerations

The main design difference between the coronagraph and starshade is the wider bandwidth.

Necessary changes

1. Redesign the dispersing prism set
2. Redesign the lenses
3. Microlens array on rotation stage (or swap in a second one)

Lenslet swap options:

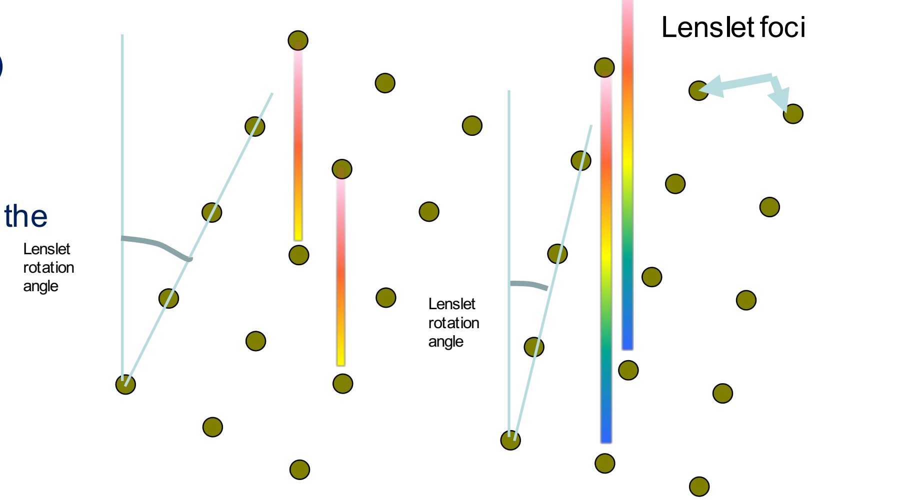
3.1. Increase area and accept reduced FOV

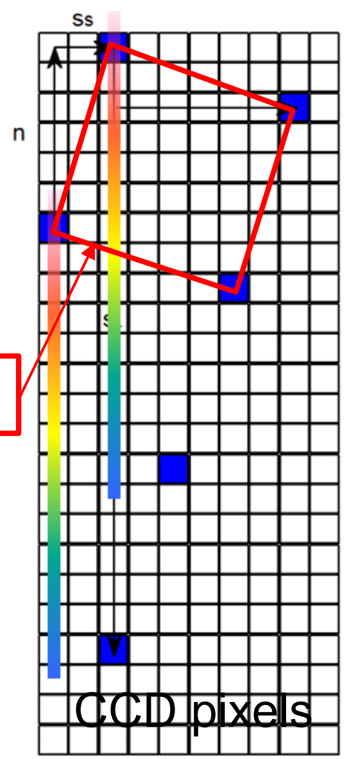
3.2. Maintain area and accept coarser pixel resolution of the FOV (maybe ~3/4)

3.3 Use larger CCD

Coronagraph mode
Shorter spectra
Wider spacing

Starshade mode
Longer spectra
Narrower spacing





Area = M * (N + G)

M = number of spectral gap columns + 1
N = number of pixels in spectrum
G = number of empty pixels at end of spectrum

Using MLA rotation mandates a non-ideal distribution of light on the focal plane

Spectra fall across pairs of columns, affecting the SNR

Therefore, all else being equal, larger arrays are preferred over rotating the MLA

Effect of rotating the MLA is to increase cross-talk between spectra

- Could measure this effect at assembly time (and also on-sky) and deconvolve.
- Cross talk is at the 2% to 5% level rather than 0% to 2% for coronagraph setup.
- Probably okay for Starshade because of relatively limited scene contrast.

Starshade-Coronagraph Option Space

	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Modifications to Coronagraph	Dichroics added to filter wheel	Rotatable MLA Modify IFS CCD 201	Modify IFS Larger EMCCD CCD 207	Modify IFS Largest EMCCD ¼ CCD 282	Dedicated Starshade instrument	Use Wide Field Instrument IFU
Features	Guiding on imager	Wider bandwidth	Wider bandwidth Wider FOV	Wider bandwidth Widest FOV	Widest bandwidth Widest FOV	150 mas fields R = 100
Details	3(+) dichroics MLA fixed	MLA rotates or switches	MLA fixed	MLA fixed	Pickoff mirror Add IR guider Add new design IFS	No guide channel
Notes	Restricted starshade BW 13 um pixels	More spectral crosstalk in SS mode	16 um pixels Coronagraph could also use wider FOV	13 um pixels New design IFS Coronagraph uses part of FOV	Room exists between support structures 4/3 x larger pixel FOV	Could a guide channel be added?
EMCCD	1k x 1k	1k x 1k	1.6k x 1.6k	2k x 2k	2k x 2k	(H2RG)
Throughput	~20%	~20%	~20%	~20%	~36%	36%?
Radial FOV (arcsec)	0.8	0.8	1.2	1.5	2	~1.5
λ Min (nm)	600	425	425	425	425	600?
λ Max (nm)	970	1000	1000	1000	1000	1400?
Bandwidth	18%	34%	34%	34%	50%	50%
Figure of Merit BW*√TP*FOV	6	12	18	23	60	45?
*(√TP ~ SNR)		CCD exists	CCD exists	Full CCD in testing	Add IR guide channel and EMCCD	Add IR guide channel somehow
		Will be qualified	Need to qualify	Need to qualify ¼ CCD	High throughput possible	Yields longer wavelength spectral lines
				Could also use 2x2 EMCCD 201		CO2, O2 and CH4 lines below 1300 nm

Baseline (Opt. 2) and Variants

Exo-S-ES Presentation to APD

April, 2016

Summary Take-away

Sara Seager

Exo-S-ES Take Away

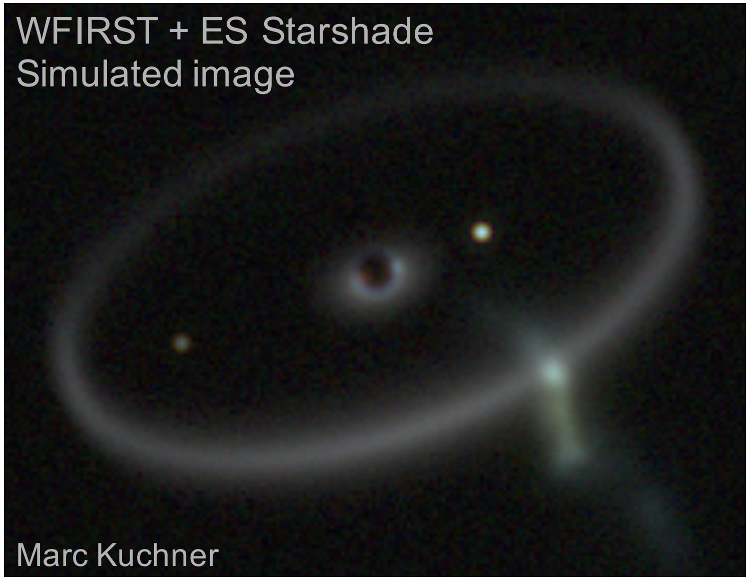
WFIRST/AFTA could be leveraged for a unique and timely opportunity

- There are a range of Starshade Rendezvous Mission options in capability, planet-discovery focus, cost, and risk
- The Exo-S "Extended Study" is a 20 m, 100 mas at blue band starshade as a 3 year class C mission
  - Could access two dozen or more sun-like stars for exoEarths in the HZ (in the blue band)
  - Unique detection space not available to any other method for the near future
  - Would be our first foray into the most interesting detection space: habitable Earth-like planets around sun-like stars
  - A pathfinder for future more capable missions
- The Extended Study cost estimate $ 450 M
- WFIRST/AFTA starshade readiness

requires minimal modification

- Starshade technology is on track for TRL 5

by 2019 for a new start by 2020, but not fully funded

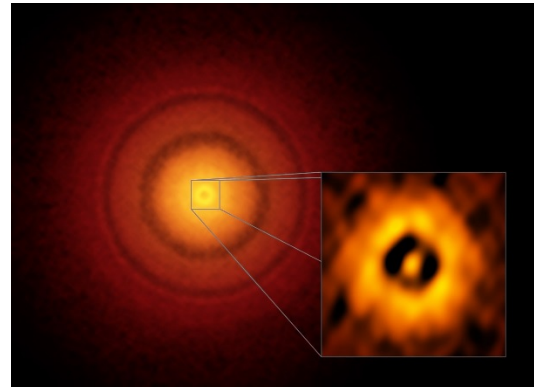


Backup

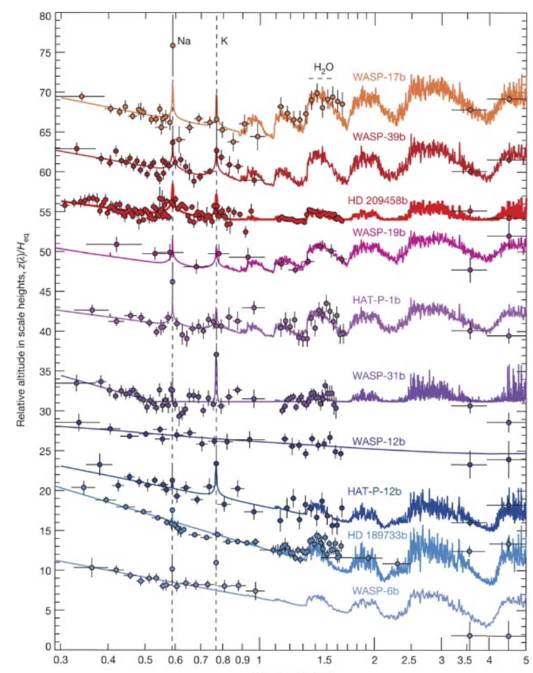
Community Science Advances Since the Exo-S Report

- Kepler K2 continues to make new discoveries
  - > 3 dozen exoplanets with more than 250 candidates awaiting confirmation
- Hubble and Spitzer continue to characterize hot transiting planets
  - Hot Jupiter water vapor from clear to cloudy planets
  - 55 Cnc e very hot day side
- ALMA protoplanetary disks
  - Unprecedented spatial resolution shows cleared gaps

Exoplanets continues to be a fertile field for discovery and characterization. Exo-S Rendezvous will open up new parameter space for discovery

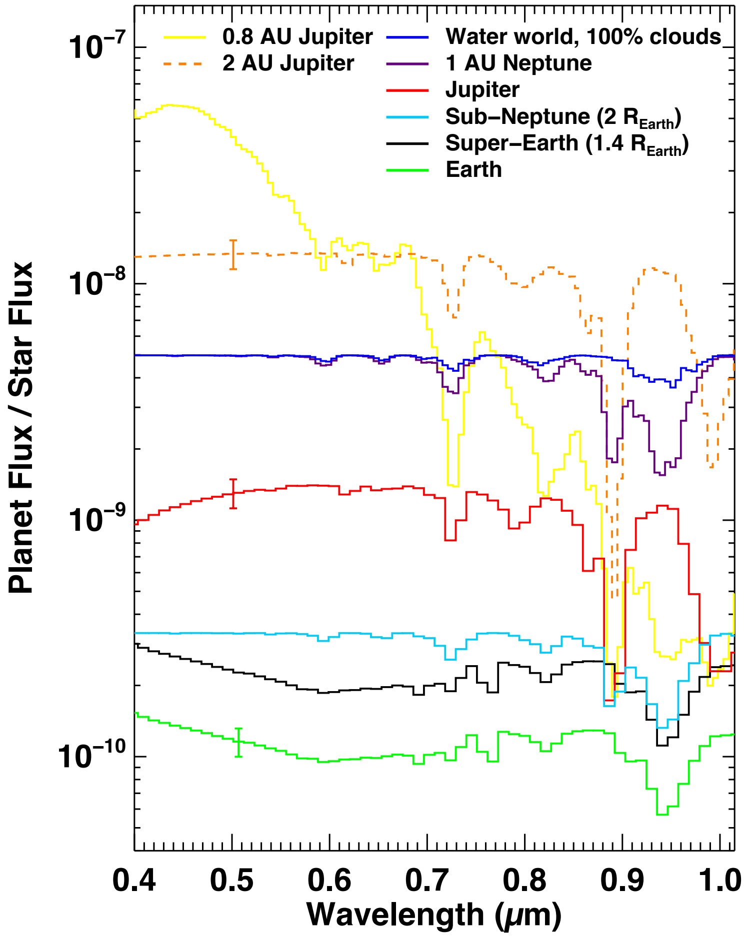


ALMA image of the planet-forming disk around the young, Sun-like star TW Hydrae. Image credit: S. Andrews (Harvard-Smithsonian CfA), ALMA (ESO/NAOJ/NRAO)



Hubble Space Telescope atmosphere comparison for transiting hot Jupiters, showing clear water vapor absorption in the atmospheres of some hot Jupiters but not others. Sing et al. Nature, 2016

Reminder of Exo-S Rendezvous Science Goals



Simulated spectra for the Rendezvous mission, with three representative 10% error bars for SNR=10

1) Discover new exoplanets from giant planet down to Earth size

2) Characterize new planets by spectra (*R*=10 to 70)
   - Wavelength range from 400–1,000 nm, in three bands

3) Characterize known giant planets by spectra (*R*=70) and constrain masses
   - detectable by virtue of extrapolated position in 2024 timeframe

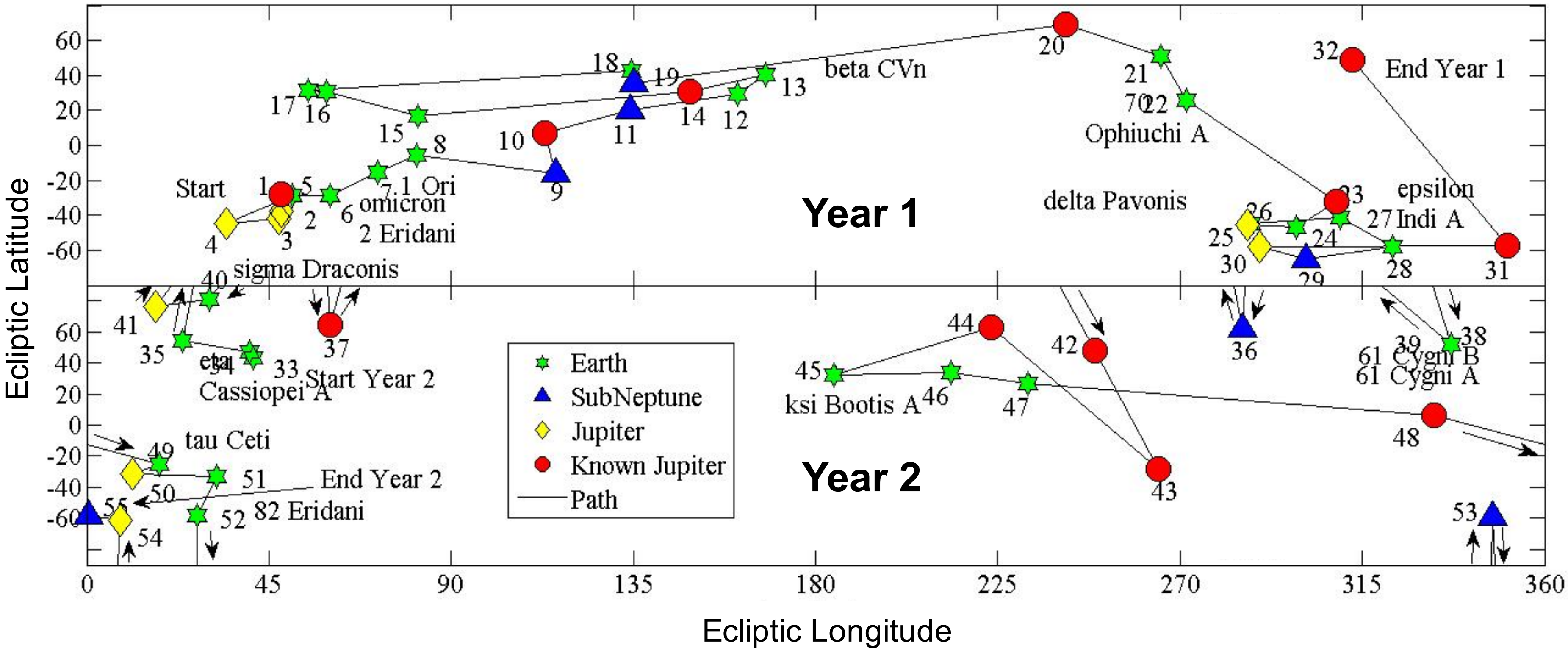
4) Study planetary systems including circumstellar dust in the context of known planets
   - dust-generating parent bodies
   - possible detection of unseen planets
   - assessment of exozodi for future missions

Exo-S ES has limited capabilities in comparison.

Observing Sequence: Exo-S Case Study

This is a 2-year sequence, 55 targets, ΔV = 1266 m/s

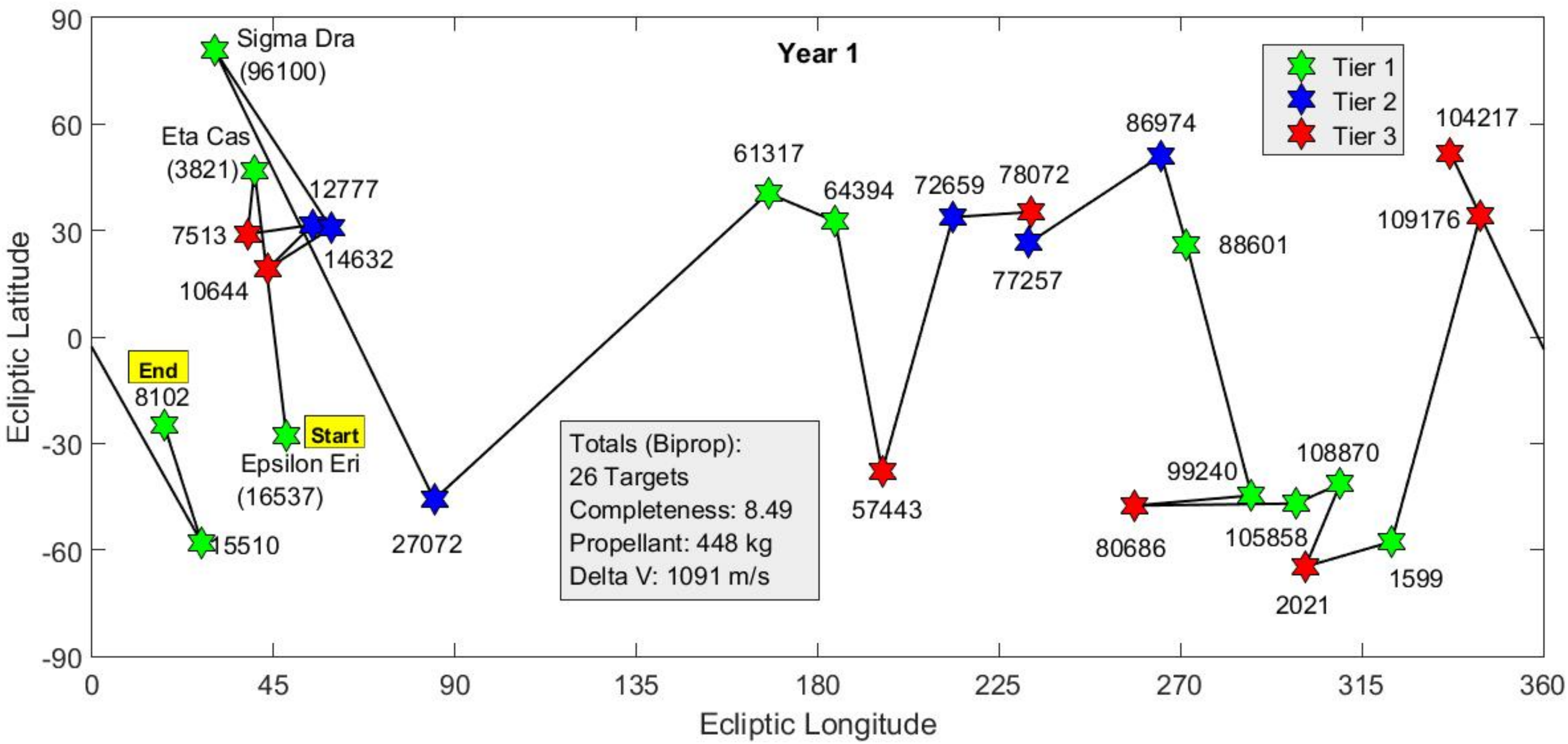
Targets: 12 known RVs, 28 Earth twins, 7 sub-Neptune, 8 Jupiters



Telescope Time Utilized: **9%**. This was a strategic decision to maximize the number of targets while still getting many spectra of giant planets.

This observing program is consistent with low overall utilization of the telescope allowing other science to be performed.

New Figure: Biprop (with insert)



Summary
(Performance Comparison)

Totals	Monopropellant (Isp = 225 s)	Monopropellant (Isp = 225 s)	Bipropellant (Isp = 308 s)
ΔV cap per maneuver (m/s)	Tier 1: 100 Tier 2: 70 Tier 3: 30	Tier 1: 150 Tier 2: 100 Tier 3: 50	
Targets	23	25	26
Completeness	7.87	8.26	8.49
Propellant (kg)	420	507	448
ΔV (m/s)	762.43	930	1091

Earth Detection with Exo-S CS vs. ES

- Exo-S Rendezvous CS reported an exo-Earth observational completeness of 10.9 HZs with a 34 m starshade.
- Exo-S ES, a much smaller starshade of 20 m diameter, has an exo-Earth completeness of 12 HZs.
- How does ES detect more Earths than CS?

Mission	Exo-S CS	Exo-S ES	Comment
Starshade	34 m	20 m	34 m based on TDEM work. 20 m could be rapidly developed.
Duration	2 yr DRM	2 yr DRM	3rd year open for revisits, confirmations
Optical Bandwidth	34%	28%	ES was optimized to balance integration time, IWA, and slew time
IWA	70-100 mas	100 mas	CS was multi-purpose and bounced between blue band and green band
Strategy	RVs and Earths	Earths	RVs are 'guaranteed' science with characterization. Focus on Earth brings ES to CS level of Earth detection
Min. Completeness	25%	10%	ES was optimized to maximize HZ Earth Completeness

Filters, Masks and Science Wavelengths

Mask/filter sets for Coronagraph and Starshade CS

Mask/filter wheel	SPC (Imaging)	SPC (IFS)	HLS (Imaging)	Starshade (IFS and Imaging)	Baseline Filter Wheel Positions Req'd	Starshade-ready Filter Wheel Positions Req'd
Pupil Mask	1	3	open	open	5	5
Focal Plane Mask	2	9	2	open	14	14
Lyot Mask	1	1	1	open	4	4
Field Stop Mask	open	open	2	open	3	3
Color Filters	2	3	2	open	8	8
IFS/Guide select	Dark, mirror, imaging lens, pupil lens, open, focus diversity (x2)			1 to 3	7	7 to 9

Starshade CS and ES require different sets of additional optics in the IFS/Guide select wheel. Exact optics count depends on number of imaging and IFS channels required for science

	Coronagraph	Coronagraph + Starshade CS	Coronagraph + Starshade ES
Coronagraph mode	Dk, M, IL, PL, O, FD1, FD2	Dk, PL, O, FD1, FD2	Dk, M, IL, PL, O, FD1, FD2
		B, C, D	
Starshade mode	N/A	A, B, C, D, E, F	A', B', C', D', E', F'
Total slots	7	9 to 11	10 to 13

Dichroic Filters in IFS Select wheel

	Coronagraph				Starshade-CS						Starshade-ES					
	HLC Imager	SPC IFS	SPC IFS	SPC IFS	IFS	IFS	IFS	Imager	Imager	Imager	IFS	IFS	IFS	Imager	Imager	Imager
Dichroic	D	B	C	C	A	B	C	D	E	F	A'	B'	C'	D'	E'	F'
Min	430	600	700	810	425	600	706	425	600	706	425	600	750	425	600	750
λ Center	515	660	770	890	515	725	855	515	725	855	495	700	875	495	700	875
λ Max	600	720	840	970	600	850	1000	600	850	1000	565	800	1000	565	800	1000
pixels per spectrum		25.2			48.2			N/A			40			N/A		
Instantaneous BW		18%			34%			34%			28%			28%		

Key Parameters and Assumptions

- Conservatively picked a large Exo-Zodi
  - Total zodiacal light contribution is 7 x our own Zodi of 23 mag/sq. arcsec.
- Instrument performance
  - Contrast at Inner Working Angle is 1e-10 for Case Study.
    - This is consistent with the error budget and realistic tolerancing.
  - Additionally, solar glint on the edge of the starshade is included.
- Observing bands:
  - Detections:
    - Case Study: 32% wide band, divided into three channels, SNR = 4 per channel.
    - Extended Study: 28% bandwidth. Optimizes HZ observational completeness.

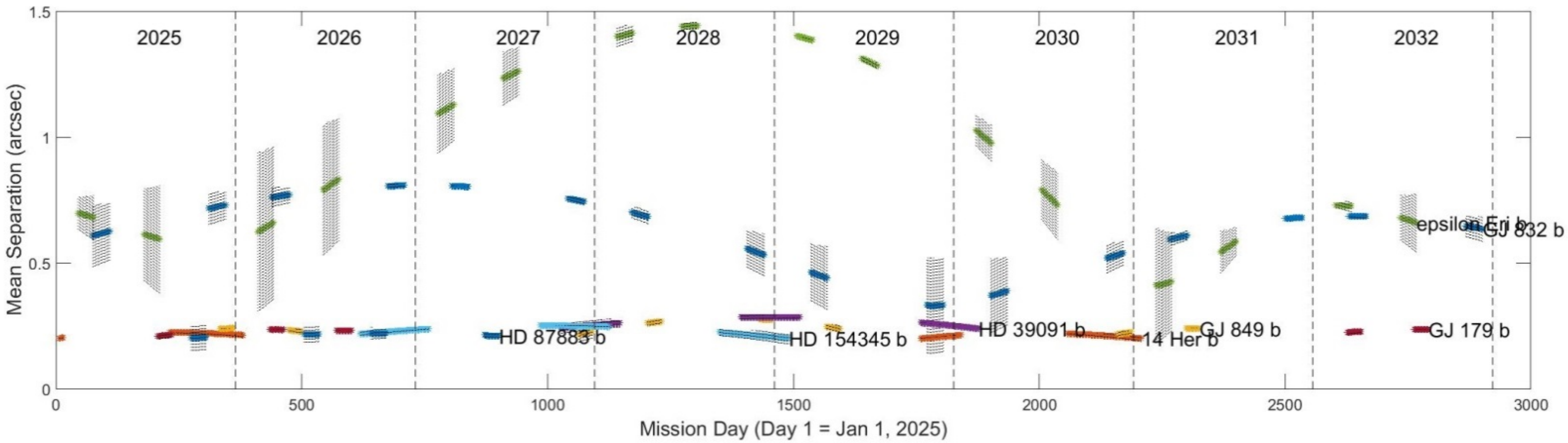
Version	Parameters	Observing Bands		
		Blue	Green	Red
Case Study	Bandpass (nm)	425-602	600-850	706-1000
20m inner disk	IWA (mas)	70	100	118
28 7m petals	Separation (Mm)	50	35	30
Extended study	Bandpass (nm)	425-565	600-800	750-1000
10m inner disk	IWA (mas)	100	140	176
28 5m petals	Separation (Mm)	20.5	15	12

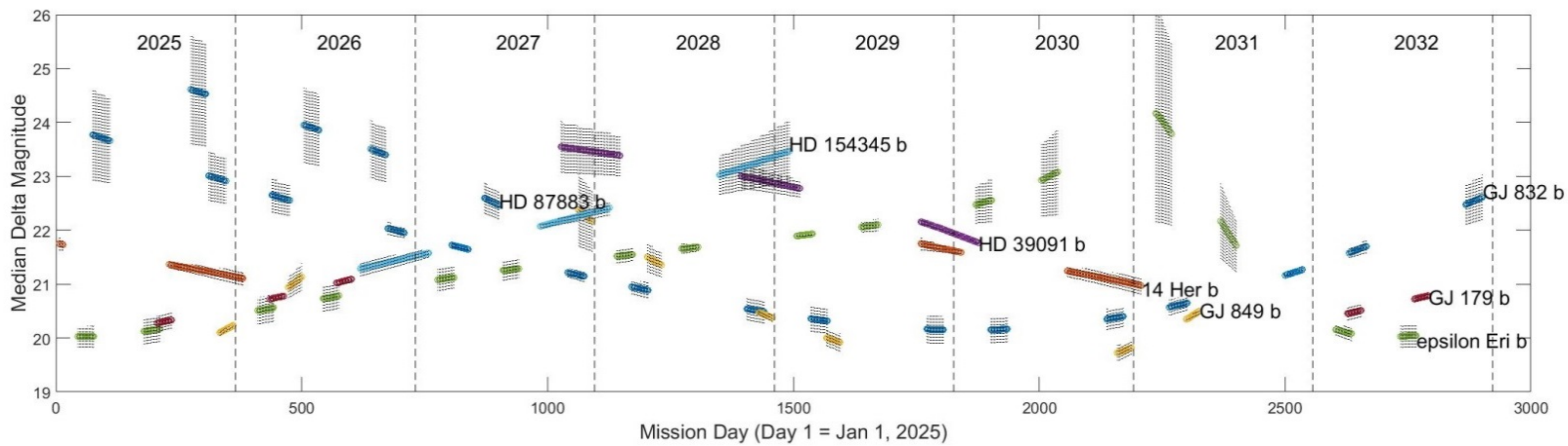
FoV (arcsec)	
Imager	IFS
2.8	0.8

Throughput	
Imager	IFS
28%	22%

Starshades provide high contrast, high throughput, and large bandwidth.

Observability of Known RV Planets with Exo-S ES





This chart shows the known RV planets that are observable with IWA>200 mas at some point in their orbit. The top plot shows the separation based on published orbital data. The possible inclinations account for the range of separations. The bottom plot shows the predicted magnitude relative to the host star, based on a Jupiter-like planet.

Several known RV planets are available for study each year with Exo-S ES.