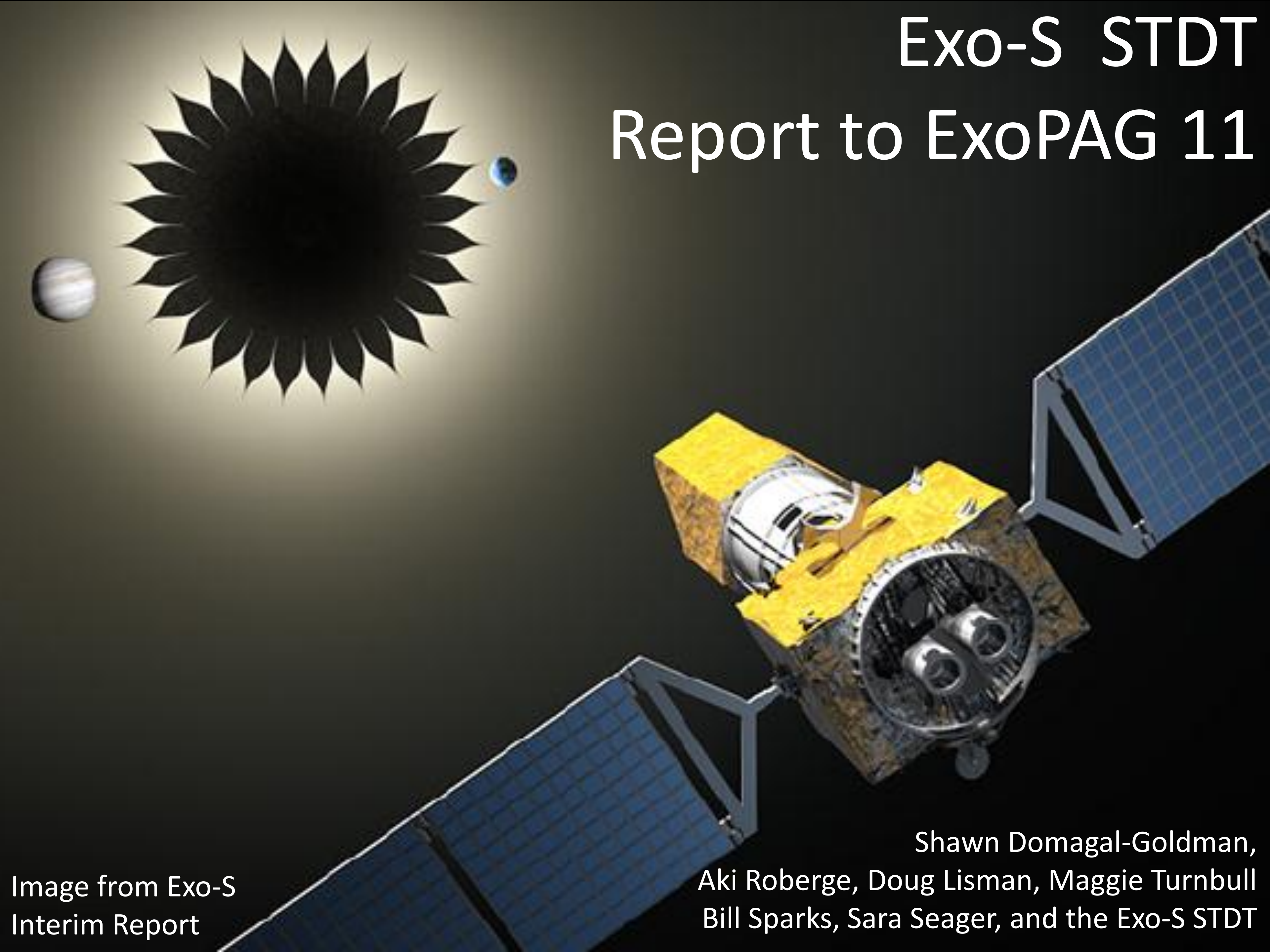
Exo-S STDT
Report to ExoPAG 11



Shawn Domagal-Goldman,
Aki Roberge, Doug Lisman, Maggie Turnbull
Bill Sparks, Sara Seager, and the Exo-S STDT

Image from Exo-S
Interim Report

Exoplanet Probe – Starshade (EXO-S)

Science & Technology Definition Team

Sara Seager (MIT – chair)

Maggie Turnbull (GSI)

N. Jeremy Kasdin (Princeton)

Bill Sparks (STScI)

Shawn Domagal-Goldman (GSFC)

Marc Kuchner (GSFC)

Aki Roberge (GSFC)

Web Cash (Colorado)

Stuart Shaklan (JPL)

Mark Thomson (JPL)

JPL Design Team

Keith Warfield (lead)

Doug Lisman

Rachel Trabert

Stefan Martin

Eric Cady

David Webb

Brian Lim

Cate Heneghan

Daniel Scharf

- Investigating concepts for relatively low-cost missions
- Largely informational studies. No current opportunity to actually execute probe missions

Vol 442|6 July 2006|doi:10.1038/nature04930 nature

LETTERS

Detection of Earth-like planets around nearby stars using a petal-shaped occulter

Webster Cash[1]

Occulting Ozone Observatory Science Overview

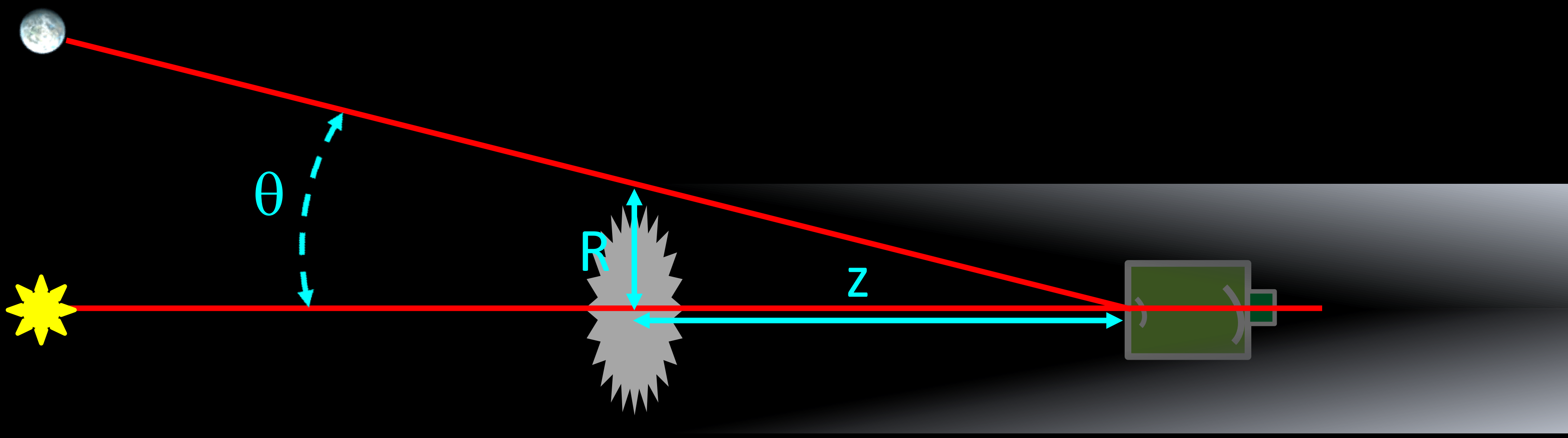
Dmitry Savransky[a], David N. Spergel[a], N. Jeremy Kasdin[a], Eric J. Cady[a], P. Douglas Lisman[b], Steven H. Pravdo[b], Stuart B. Shaklan[b], Yuka Fujii[c]

[a]Princeton University, Princeton, NJ USA
[b]Jet Propulsion Lab and California Institute of Technology, Pasadena, CA USA
[c]The University of Tokyo, Tokyo, Japan

The STDT’s driving question:
What can a starshade mission accomplish with a budget ≤ ~$1bn?

Starshade strengths

- Contrast and inner working angle decoupled from telescope aperture size



IWA ~ angle to edge of starshade

~ R / z

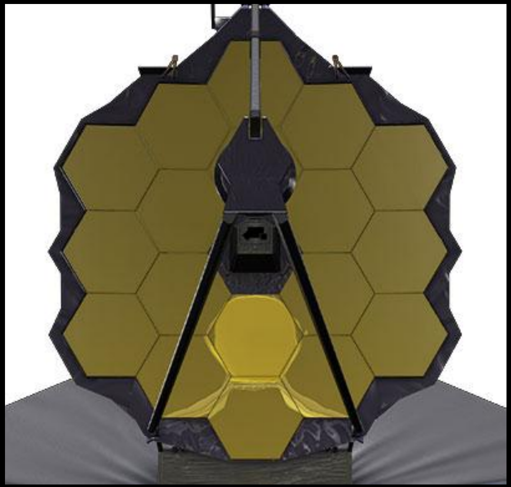
Slides from
Aki Roberge

Starshade strengths

- No outer working angle
- 360 degree suppression
- Broad bandpass, high throughput

W. Cash (Colorado)

- High quality telescope not required
  - Segments & obstructions not a problem
  - Wavefront correction unnecessary



NASA / STScI

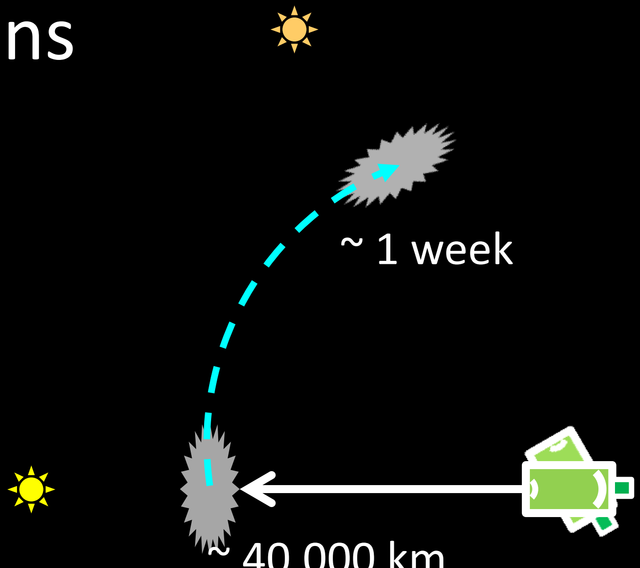
Slides from
Aki Roberge

Starshade drawbacks

- Full-scale end-to-end optical test on ground not possible
  - Sub-scale lab and field tests possible

T. Glassman / NGAS

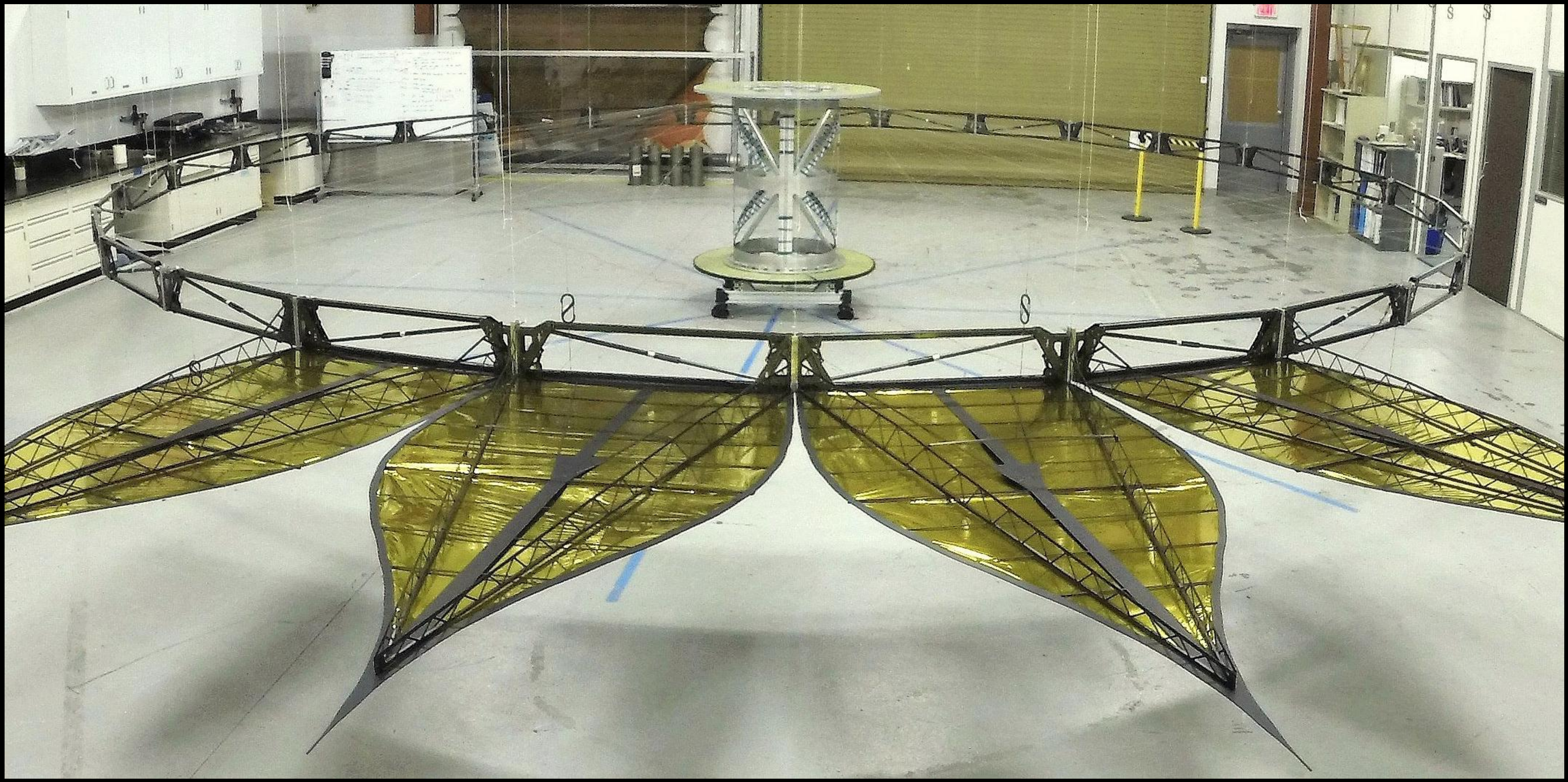
- Long times between observations
- Limited number of starshade movements
- Can't be in Earth orbit



Slides from
Aki Roberge

Exo-S Design and Details

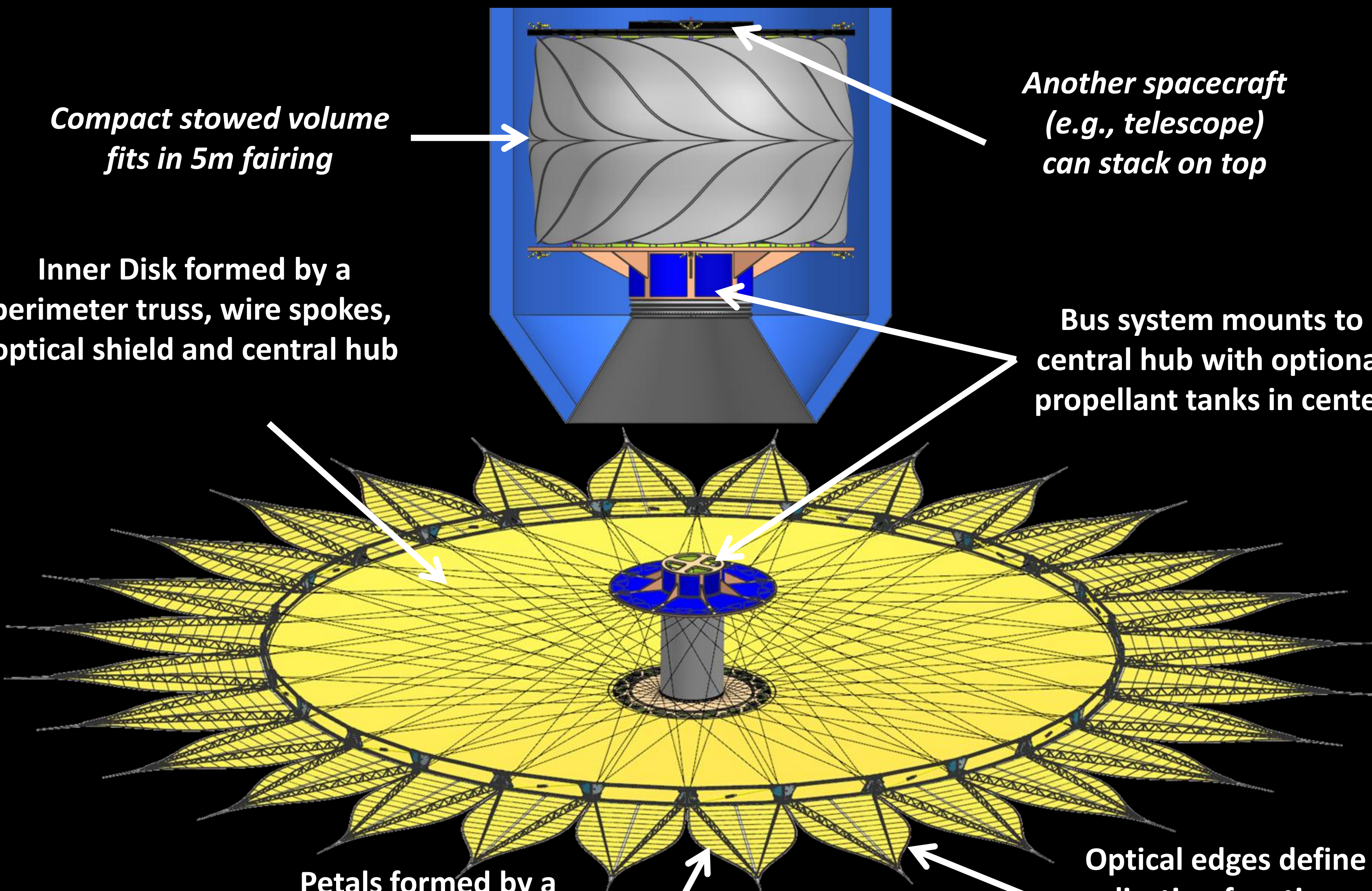
Starshade Deployment Testbed at JPL



10m diameter inner disk and 3.5m long petals assembled by undergraduate students in summer of 2014

Slides from Doug Lisman

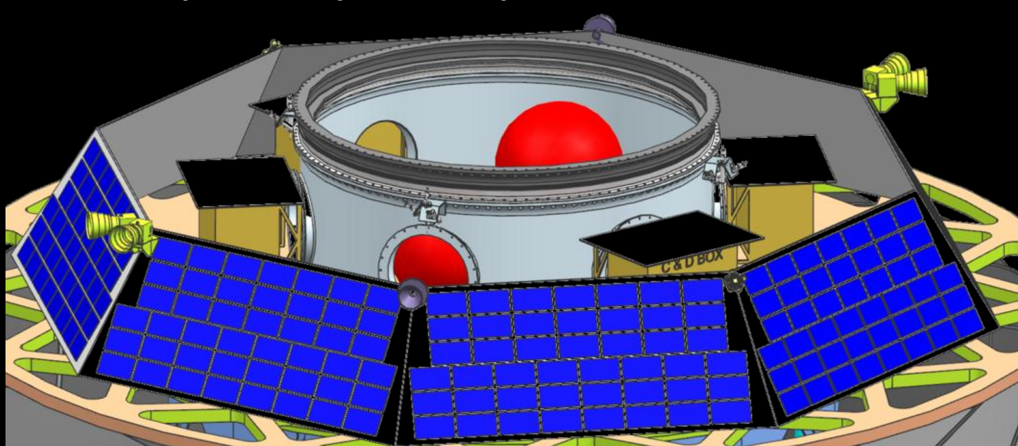
Starshade Spacecraft Architecture

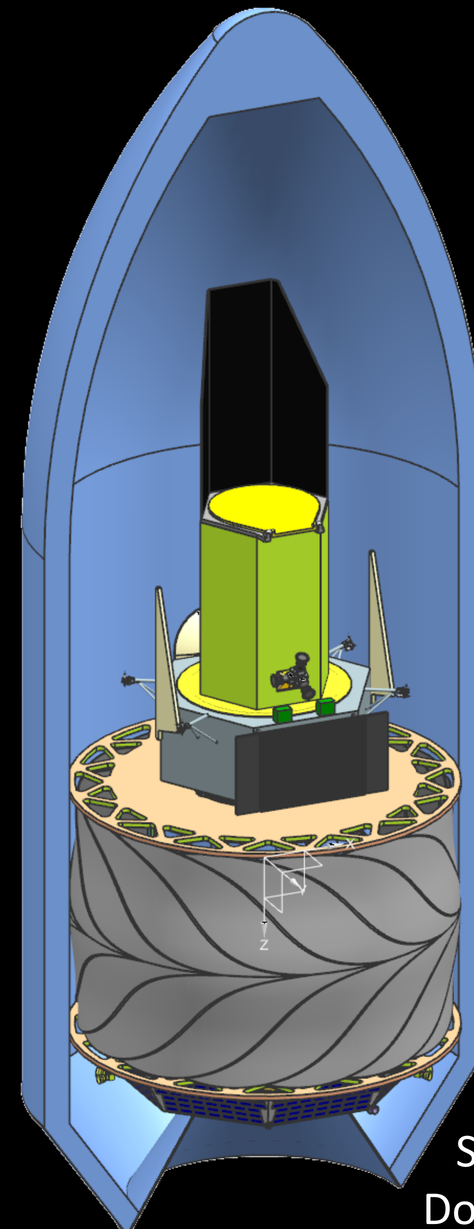


Slides from
Doug Lisman

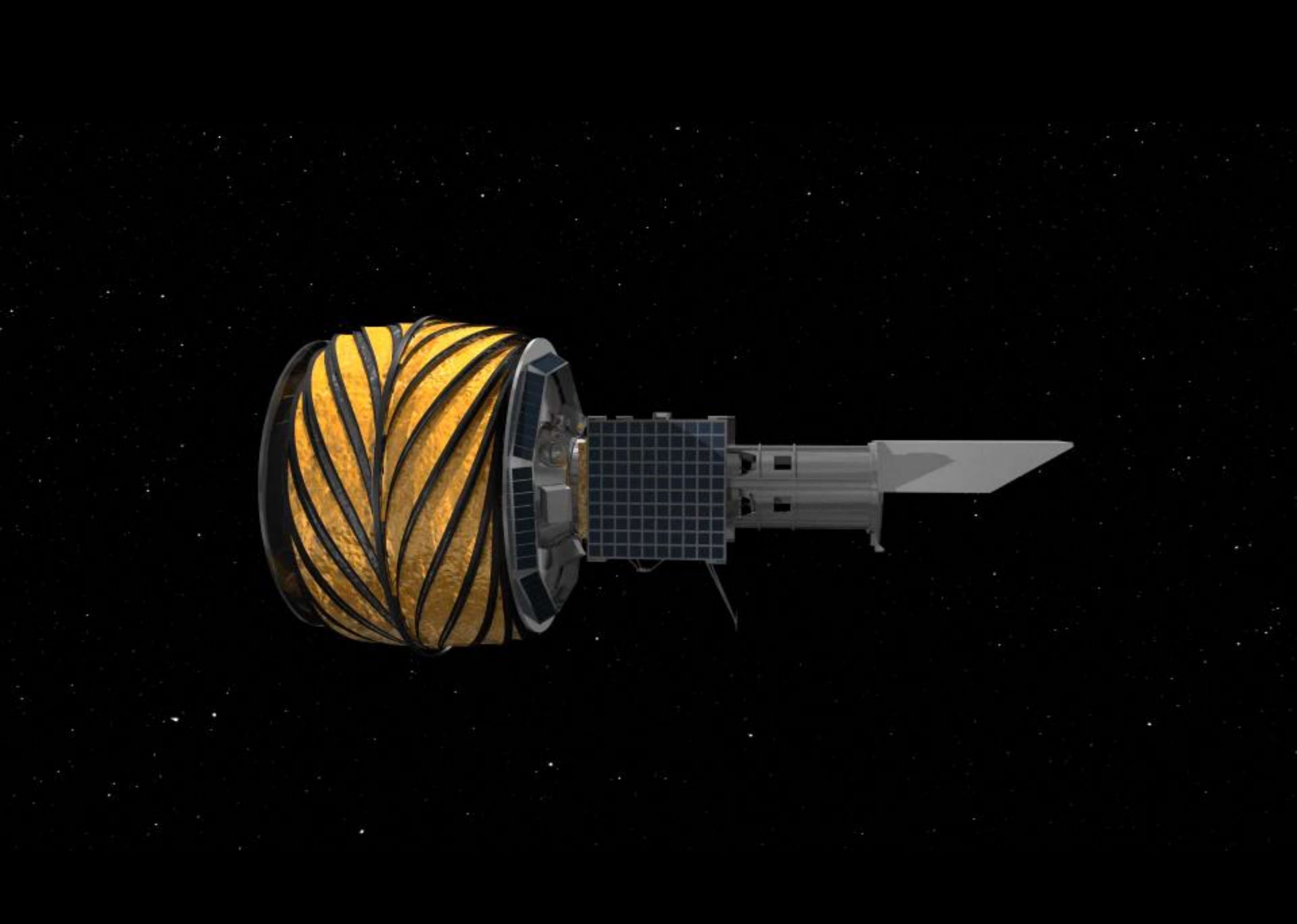
Small Dedicated Telescope Case Study

- 1.1 m telescope stacks on-top starshade at launch
- Falcon-9 launch vehicle with 5 m fairing
- Earth Drift Away orbit for simple navigation and benign environment for formation control
- Telescope provides propulsion for retargeting and formation control
- Telescope carries instrumentation for starshade:
  - Field camera, guide camera and IFS with 3” FOV
- 30 m starshade operates 34,000 km from telescope for primary band of 515-825 nm





Slides from Doug Lisman



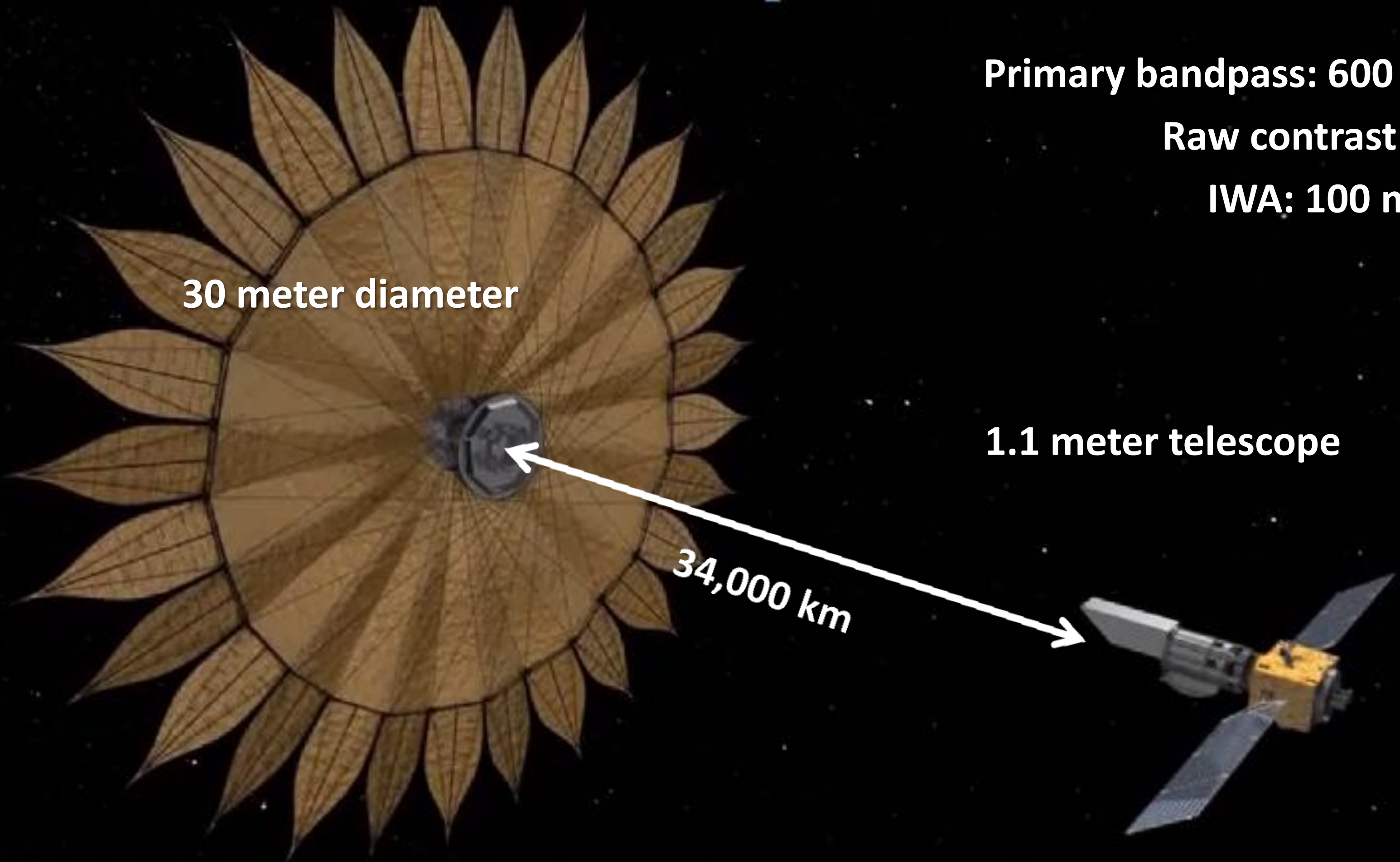
Video from JPL/ExEP

Starshade for a 1.1 meter telescope, co-launched mission

Primary bandpass: 600 – 850 nm

Raw contrast: 1×10^{-10}

IWA: 100 milliarcsec

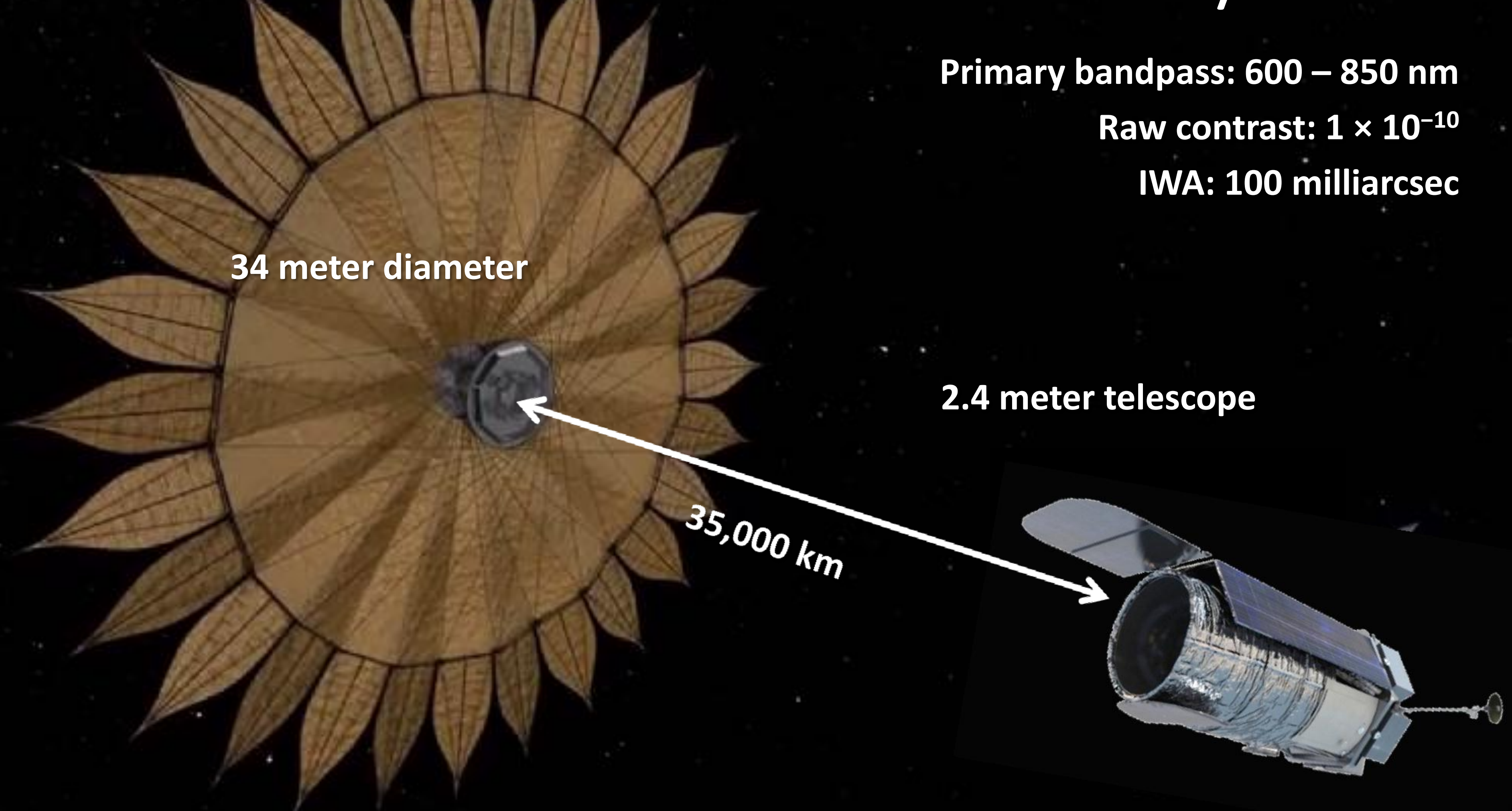


Starshade for a 2.4 meter telescope, rendezvous mission with WFIRST/AFTA

Primary bandpass: 600 – 850 nm

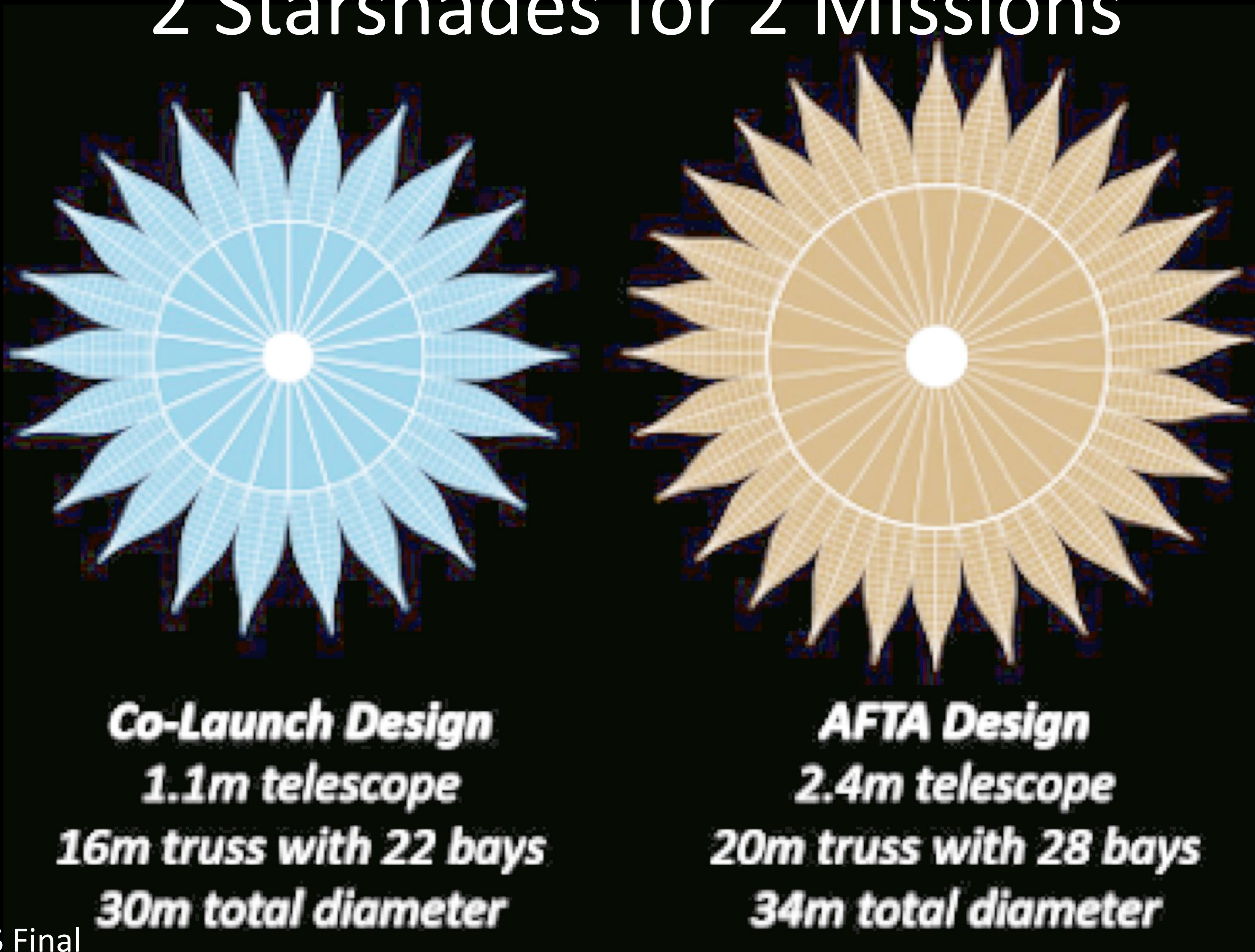
Raw contrast: 1×10^{-10}

IWA: 100 milliarcsec



Assuming use of AFTA coronagraph (slight instrument modification desired)

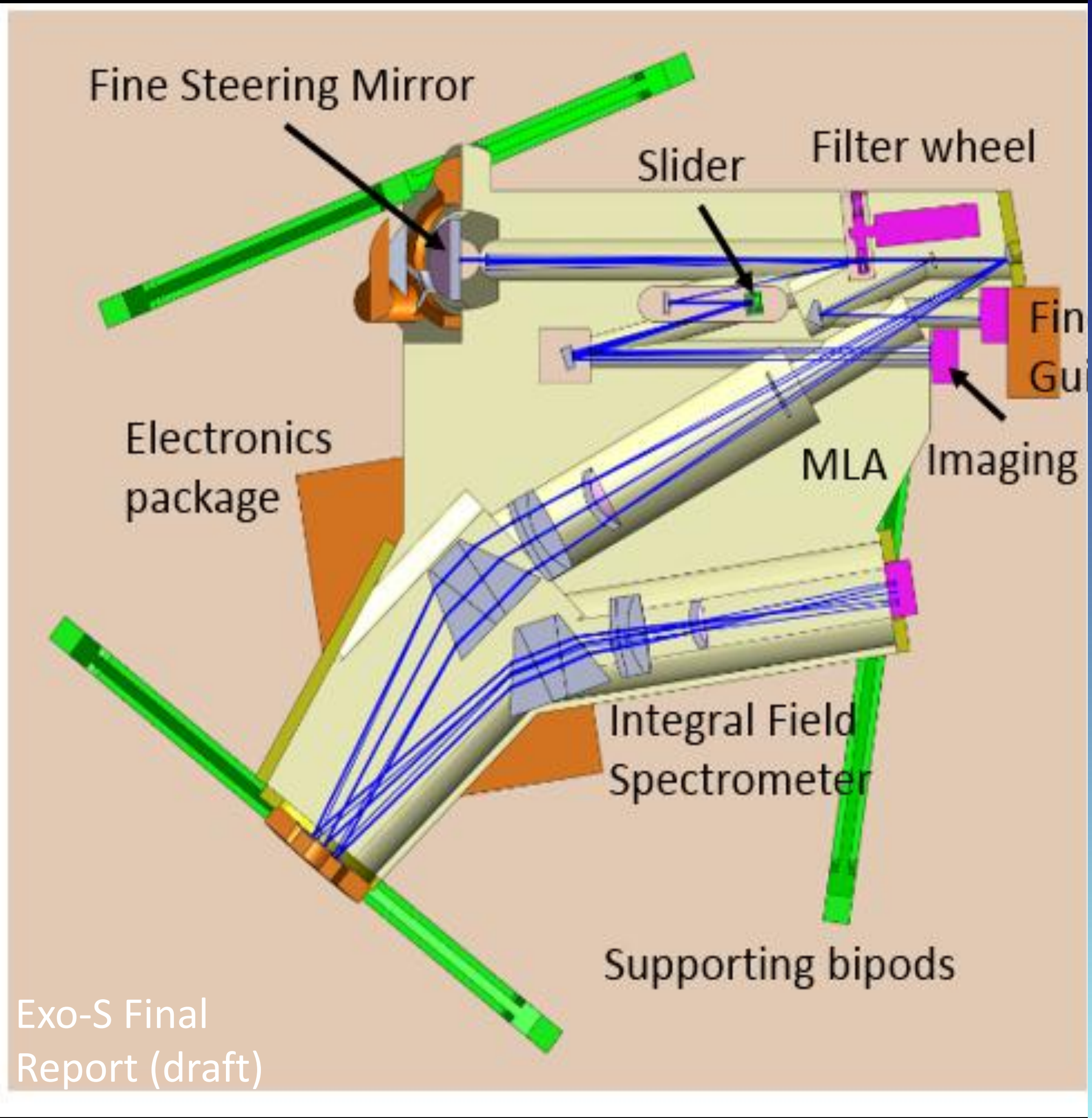
2 Starshades for 2 Missions



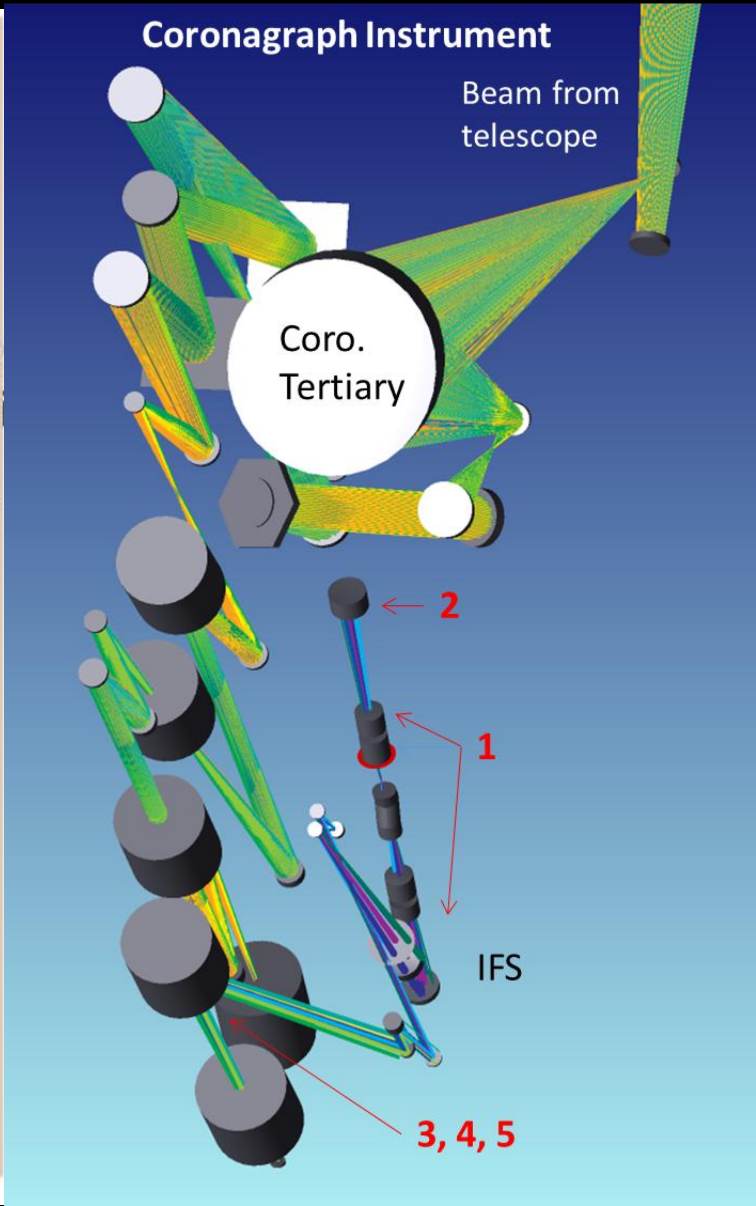
Exo-S Final Report (draft)

Nominal Instrumentation

Telescope co-launched



WFIRST rendezvouz



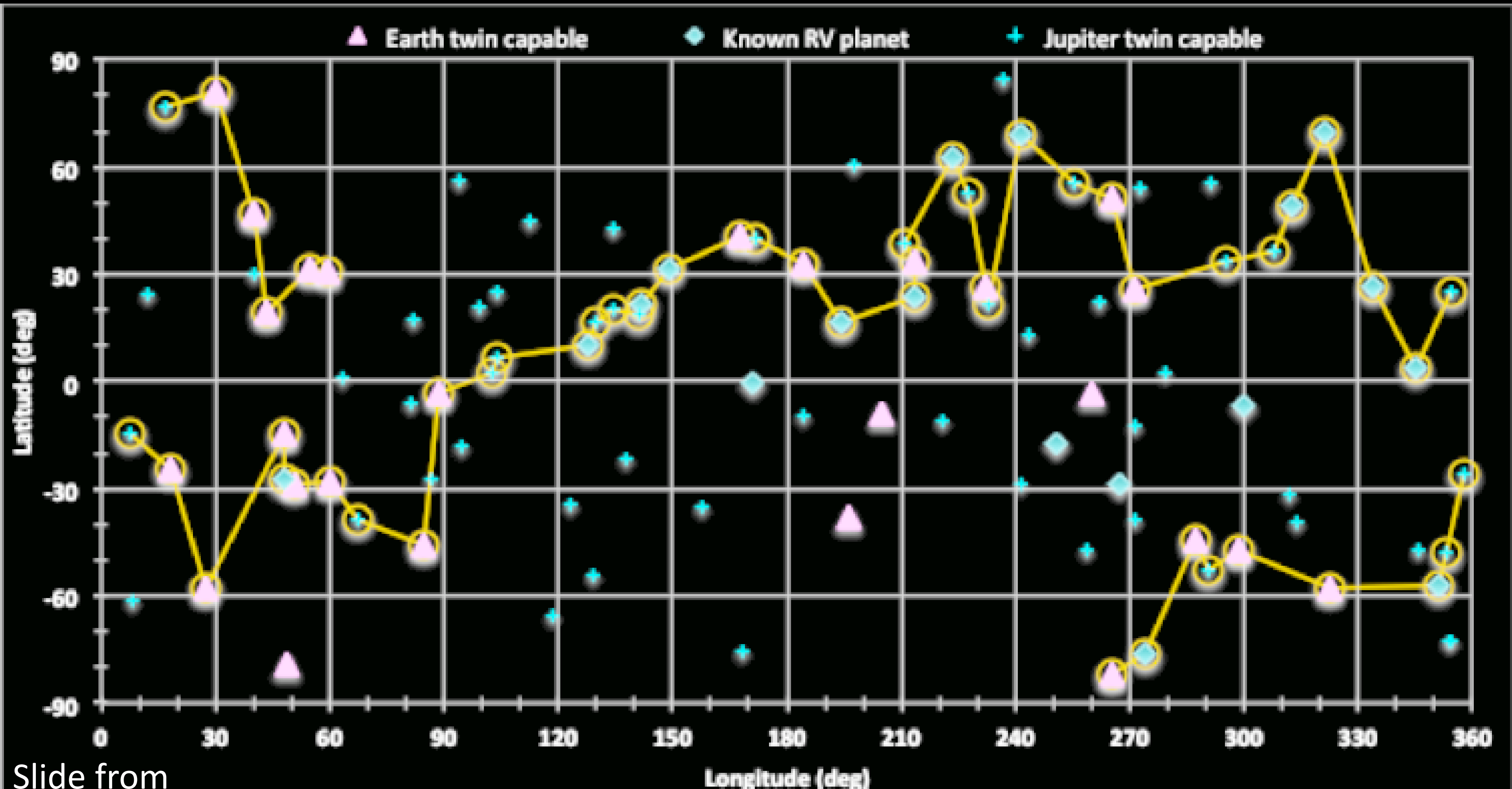
Instrumentation Properties (co-launch mission)

	Imaging camera	**Spectrometer**	**Guide channel**
Array type	e2v CCD 273	e2v CCD 273	Teledyne Hawaii H1RG
Format	2kx2k	2kx2k	1kx1k
Field of view	1 arcmin	3 arcsec	2 arcmin
Pixels/view	1kx1k	105x105	1kx1k
Resolution	60 mas	60 mas	120 mas
Optical throughput	51%	42%	47%
Dark current	0.00055 e-/px/s	0.00055 e-/px/s	<0.05 e-/px/s
Read noise (cds)	3 e- rms	3 e- rms	<30 e- rms
Pixel size	12 μm	12 μm	15 μm
Operating temperature	153K	153K	120K
Quantum efficiency	>70% (425-950 nm)	>70% (425-950 nm)	>70% at 1500 nm

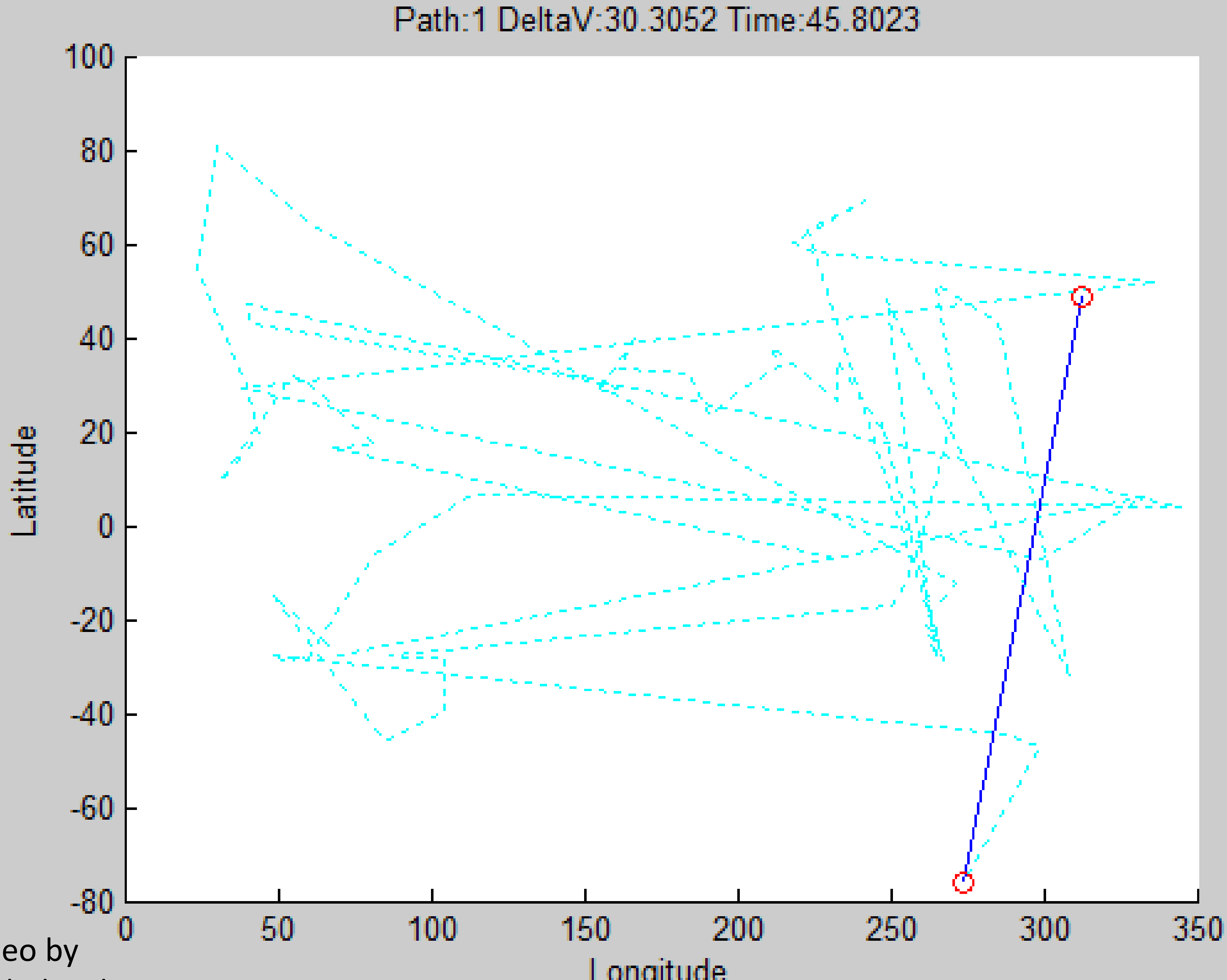
Observation Channels

Mission Scenario	Parameters	Observing Bands		
		Blue	Green	Red
2.4m aperture WFIRST-AFTA	Wavelengths (nm)	425 - 600	600 - 850	710 - 1,000
	Inner Working Angle (mas)	71	100	118
	Separation distance (Mm)	50	35	30
1.1m aperture "co-launch"	Wavelengths (nm)	400 - 630	510 - 825	600 - 1,000
	Inner Working Angle (mas)	75	95	115
	Separation distance (Mm)	x	y	z

Design Reference Mission Example



Slide from
Rachel Trabert



Video by
Rachel Trabert

What kind of science yield will this give the community?

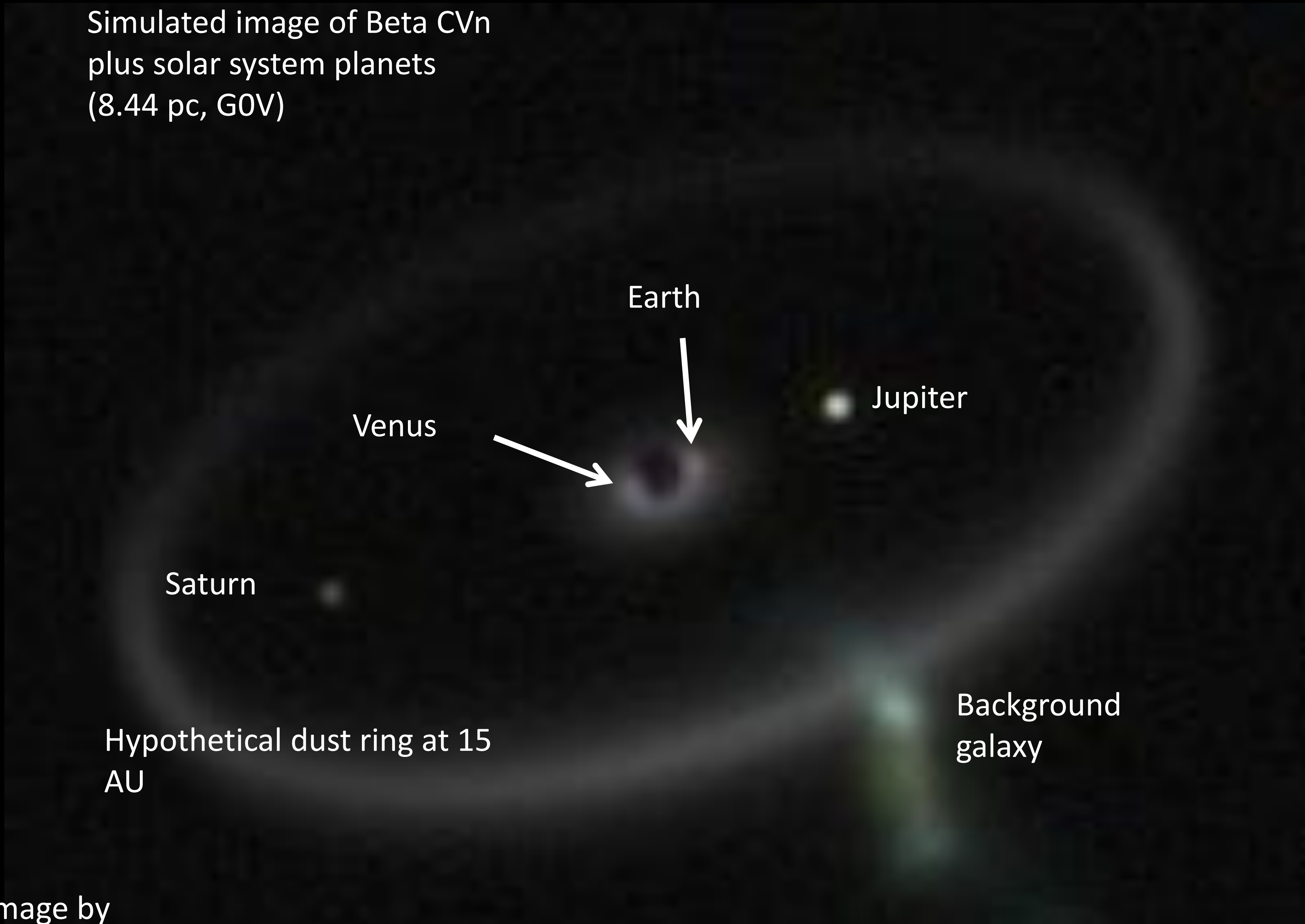
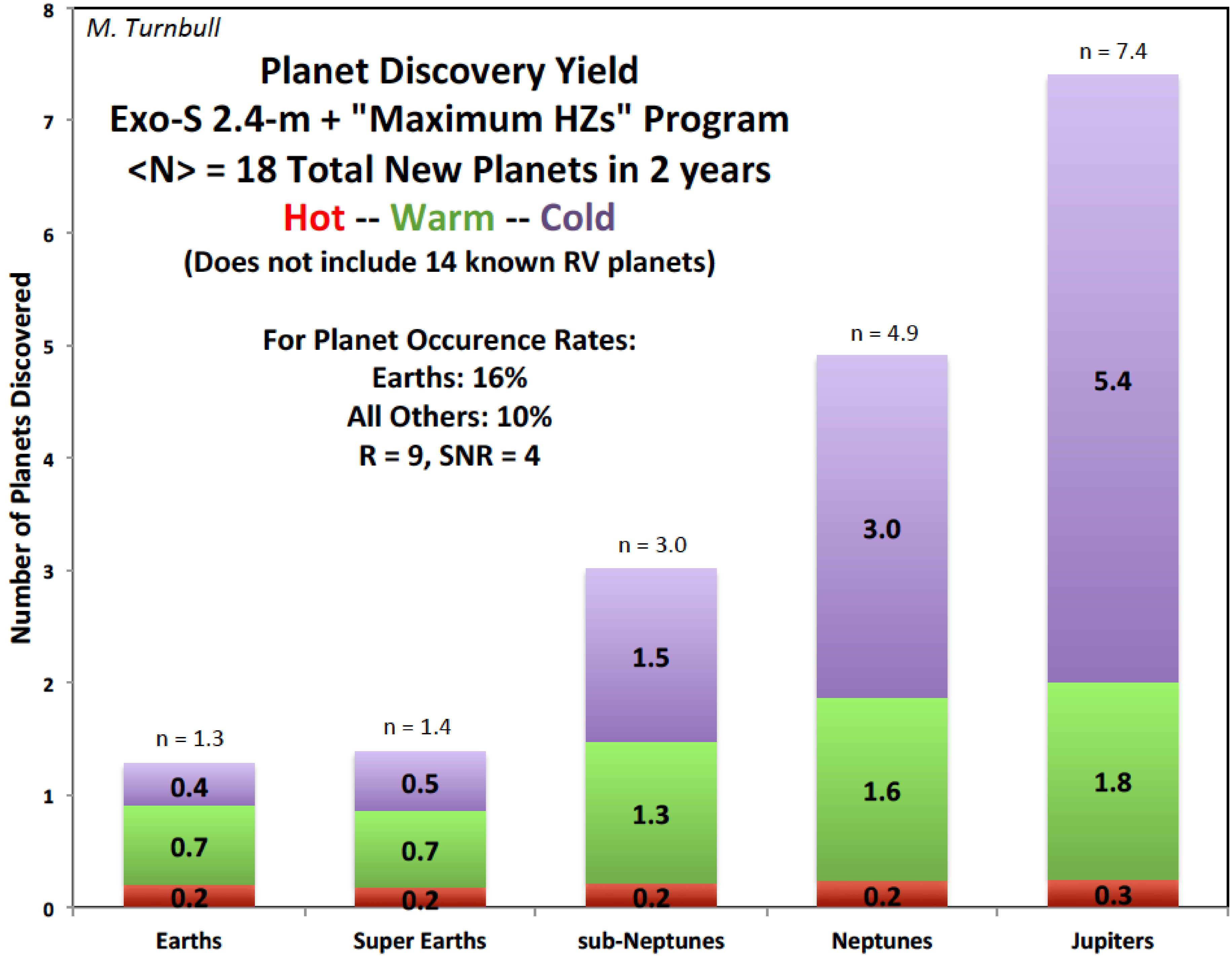
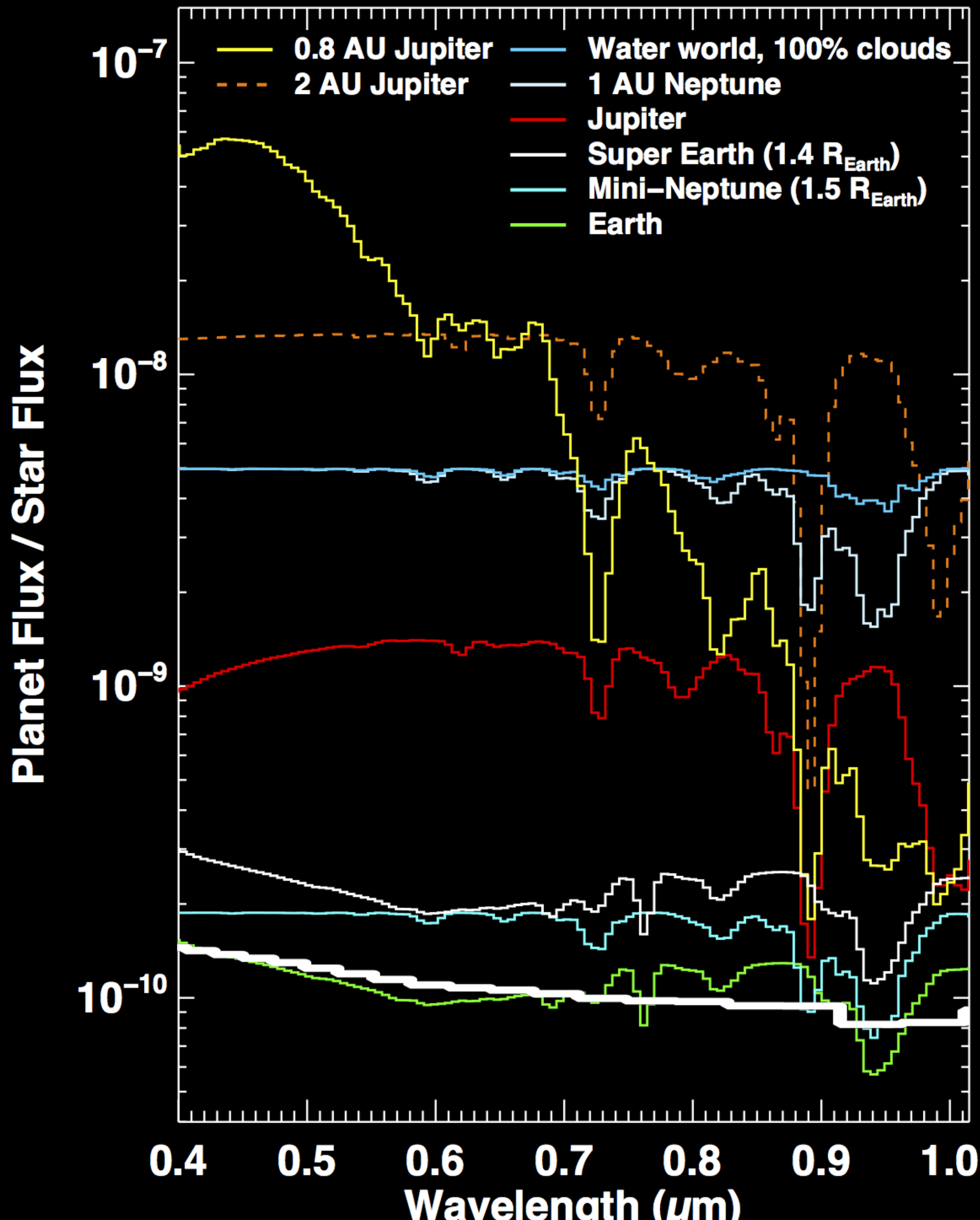


Image by
Marc Kuchner


M. Turnbull
Planet Discovery Yield
Exo-S 2.4-m + "Maximum HZs" Program
<N> = 18 Total New Planets in 2 years
Hot -- Warm -- Cold
(Does not include 14 known RV planets)
For Planet Occurence Rates:
Earths: 16%
All Others: 10%
R = 9, SNR = 4
Number of Planets Discovered
0
1
2
3
4
5
6
7
8
n = 1.3
0.4
0.7
0.2
n = 1.4
0.5
0.7
0.2
n = 3.0
1.5
1.3
0.2
n = 4.9
3.0
1.6
0.2
n = 7.4
5.4
1.8
0.3
Earths
Super Earths
sub-Neptunes
Neptunes
Jupiters



0.8 AU Jupiter
2 AU Jupiter
Water world, 100% clouds
1 AU Neptune
Jupiter
Super Earth (1.4 R_{Earth})
Mini–Neptune (1.5 R_{Earth})
Earth
Planet Flux / Star Flux
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Wavelength (μm)

Technical challenges

- Precise edge profile (~ 50 µm tolerance) required over large structure
- Knife-edge to limit sunlight scattering into telescope
- On-orbit deployment of large structure

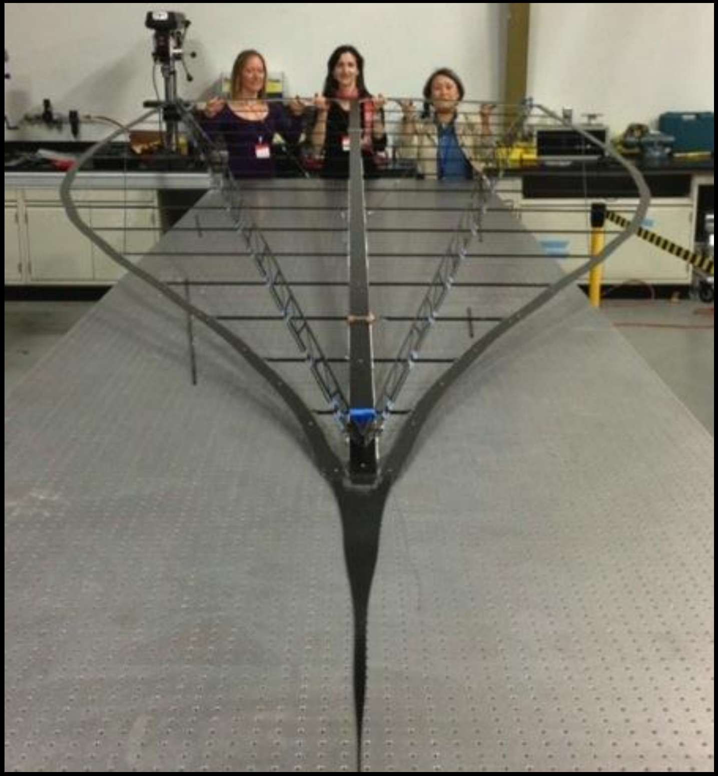
NASA / JPL / Princeton

- Requires lateral alignment between starshade and telescope needed (± 1 meter)

Slides from
Aki Roberge

Precision petal manufacturing

Full-scale petal with edge profile for contrast < 10^{-10}



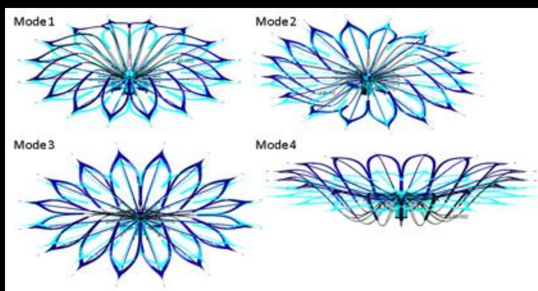
Credit: D. Lisman

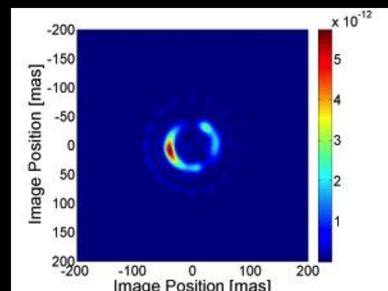
Development of knife-edge to control edge scatter underway

Early Starshade Deployment Trial at JPL (Front View)

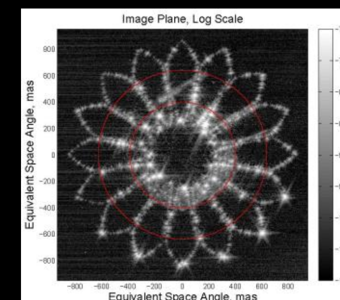
Contrast demonstrations

Optical models with distortions
monochromatic: 10^{-12}



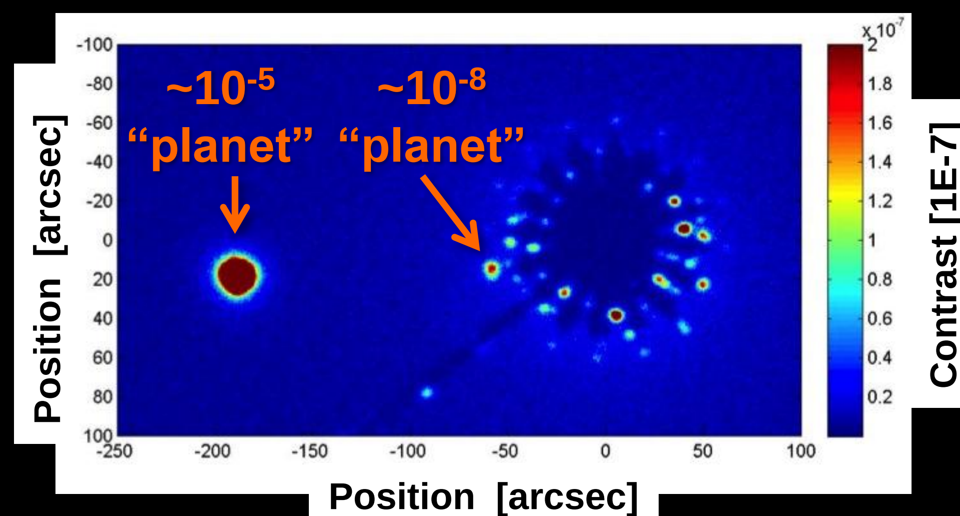


0.1% scale lab testing
monochromatic: 10^{-10}



~ 1% scale field testing
50% bandpass: 10^{-8}

T. Glassman / NGAS



General Exo-S Findings: Starshade General Properties

- “Rendezvous starshades” would likely be < $1B.
- BUT co-launched starshade + telescope missions would likely be > $1B.
- Imaging/spectroscopy would generally NOT be limited by inner working angle (IWA), but by integration time.
- Major progress has been made on 3 of 4 technical tall poles (shape precision, deployment, formation flying). Work is in progress on the 4th (knife edge).

General Exo-S Findings: Mission Yields

- The 1.1m (co-launched telescope) mission would discover ~19 planets and take spectra ($R \geq 70$) of 14 RV planets in the first 2 years.
- The 2.4 m (WFIRST-AFTA) mission would discover ~18 planets including ~3 Earth/super-Earth's (~1 in the HZ), and take spectra ($R \geq 70$) of 14 RV planets in the first two years.
- BOTH missions would take spectra of discovered planets in year 3 of the mission (+ any extended mission).
- The spectra would be limited by integration time. For the 1.1m mission, this would likely limit spectra of Earth-sized worlds to $R \sim 10$. For the 2.4m mission, $R \geq 70$ for most planets would be feasible.

NASA's UV, Visual, & IR Astrophysics Facilities

Adapted from Testimony to Congress Given by J. Grunsfeld (May 5, 2013)