Exo-C coronagraph probe mission study

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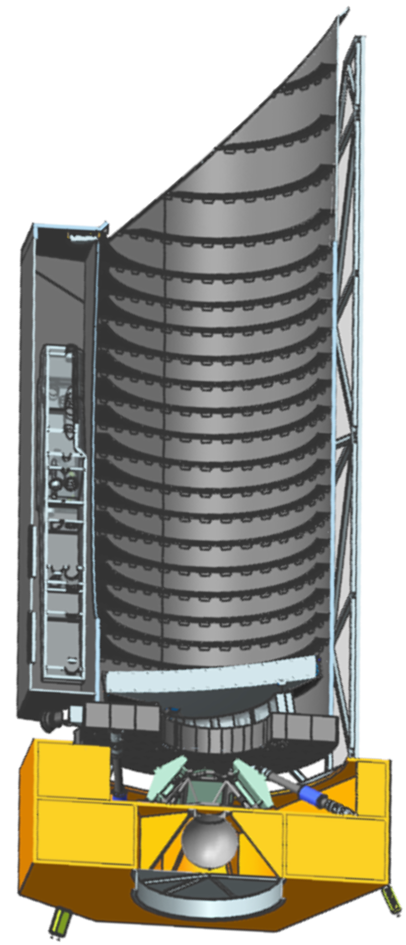
Exo-C Report Findings

- Exo-C uses an internal coronagraph with precision wavefront control to conduct high contrast imaging at visible wavelengths
- Exo-C's science goals are to:
  - Spectrally characterize at least a dozen RV planets
  - Search >100 nearby stars at multiple epochs for planets down to ~3×10^{-10} contrast. Characterize mini-Neptunes, search the α Centauri system.
  - Image hundreds of circumstellar disks
- Even though coronagraph missions have been studies for 20 yr engineering designs evolved significantly to improve performance and risk (cost).
- Exo-C internal costs estimate is $950 M, independent cost estimate is only slightly higher. Study has met its goal of achieving mission with cap of ~$ 1B.



Exo-C Report Findings

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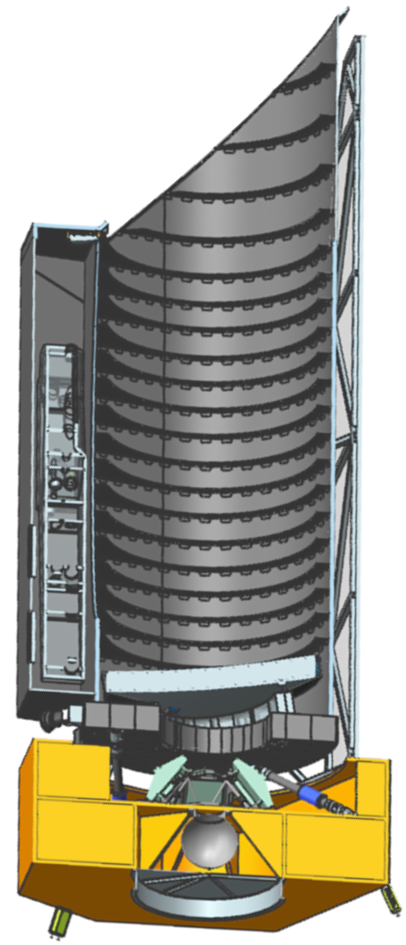
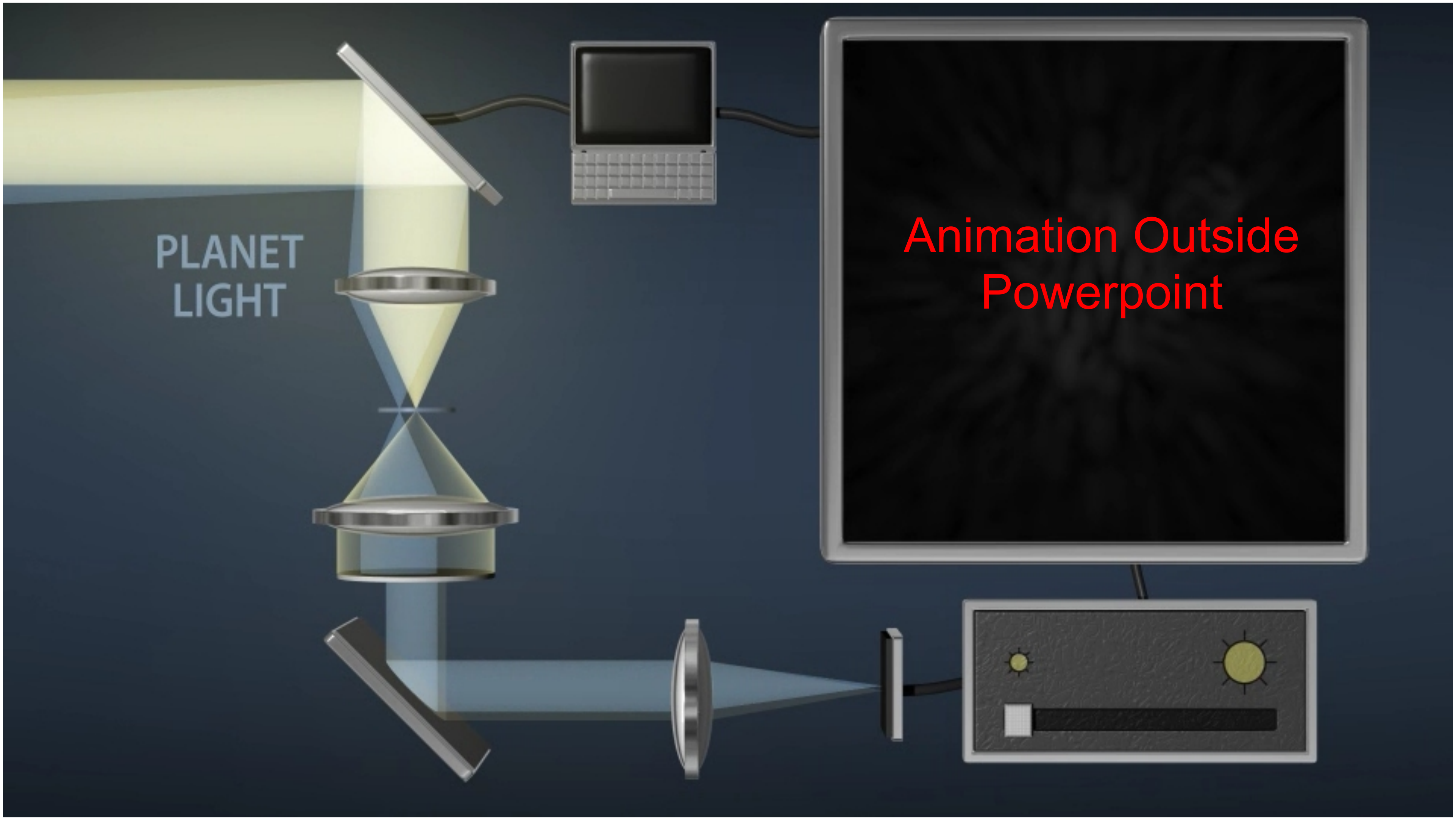


Internal Coronagraph Tutorial



Need for Dedicated Coronagraph Probe Mission

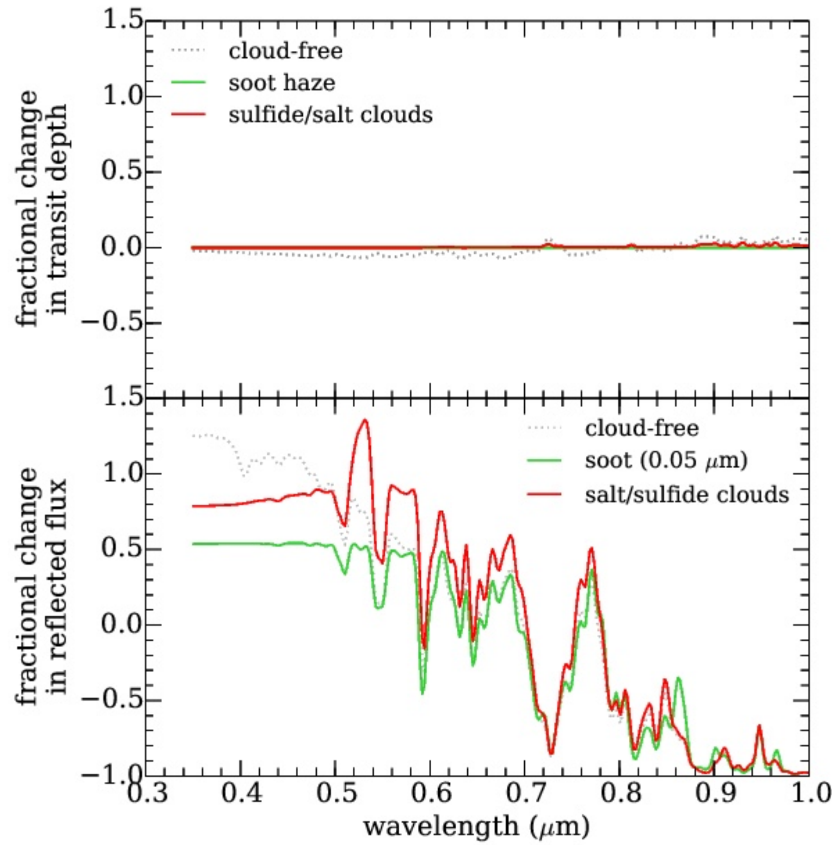
- Radial velocity and transit surveys have shown exoplanets are abundant. Spectral characterization is the natural next step; reflected light planets are unique targets.

<u>Atmospheric features are more readily detected by imaging than by transits</u>

Transit spectra probe only the tenuous upper atmosphere

Curves show spectra relative to mean optical flux level

GJ 1214b model spectra by Caroline Morley and Mark Marley



Need for Dedicated Coronagraph Probe Mission

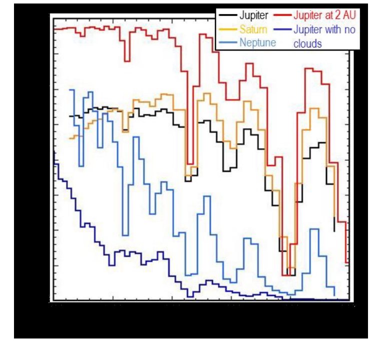
- A ~1.4m aperture can be very effective if corona-graph requirements can drive the mission design
- Community interest in this mission class shown by at least 13 proposals submitted to Mid-Ex, Discovery, Astro 2010 ASMCS, and ESA M class since 1998
- Agility of internal coronagraph allows large number of targets to be observed and at multiple epochs
- Natural technology step to Exo-Earth flagship mission
- Kepler proved stable 1.4m observatory costs < $1B

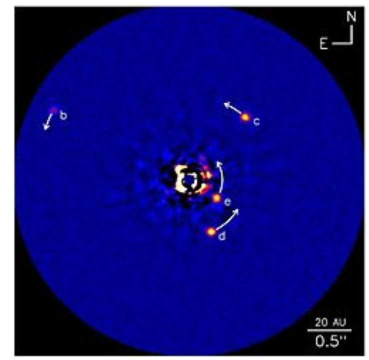
Exoplanet Landscape in 2024

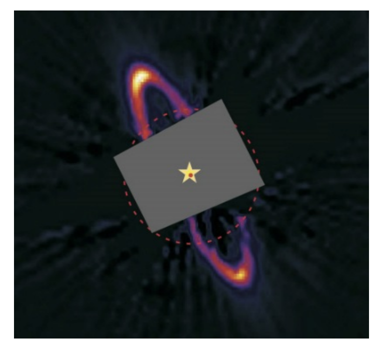
- Indirect detections: RV surveys have detected 10 yr period planets ≥ Saturn mass, 1 yr period planets ≥ Neptune mass around stars F8 & later. Gaia detects short-period Jupiters. Target lists for spectra.
- Transits: TESS has extended Kepler results to brighter stars, defining planet mass-radius relationship. JWST+ELTs get transmission spectra for some of these. PLATO mission begins. All these provide target lists for outer planet imaging searches.
- Exoplanet Direct Imaging: Ground Adaptive Optics (AO) has obtained spectra of dozens of young/massive planets in near-IR thermal emission. Likely contrast limit of $\sim 10^{-8}$ set by atmospheric turbulence. JWST may image cold/wide giant planets around M stars (contrast $\sim 10^{-6}$).
- Disk Imaging: ALMA has redefined knowledge of protoplanetary disks, but cannot map tenuous debris disks at subarcsec resolution. Ground AO imaging polarimetry of brighter disks.

Exo-C Enabling Science

- Obtain optical spectra of nearest RV planets: Measure gas absorbers, fix planet mass.
- Search for planets beyond RV limits (Neptunes, super-Earths) in a nearby star sample. Measure orbits, do spectroscopy of the brightest ones
  - α Centauri system is a very important case
- Image circumstellar disks beyond HST, AO, and ALMA limits
  - Resolve structures driven by planetary perturbations, including dust in nearest habitable zones
  - Time evolution of disk structure & dust properties from protoplanetary to debris disks
- Probe a few systems for exo-Earths, if telescope stability and exozodi are favorable.



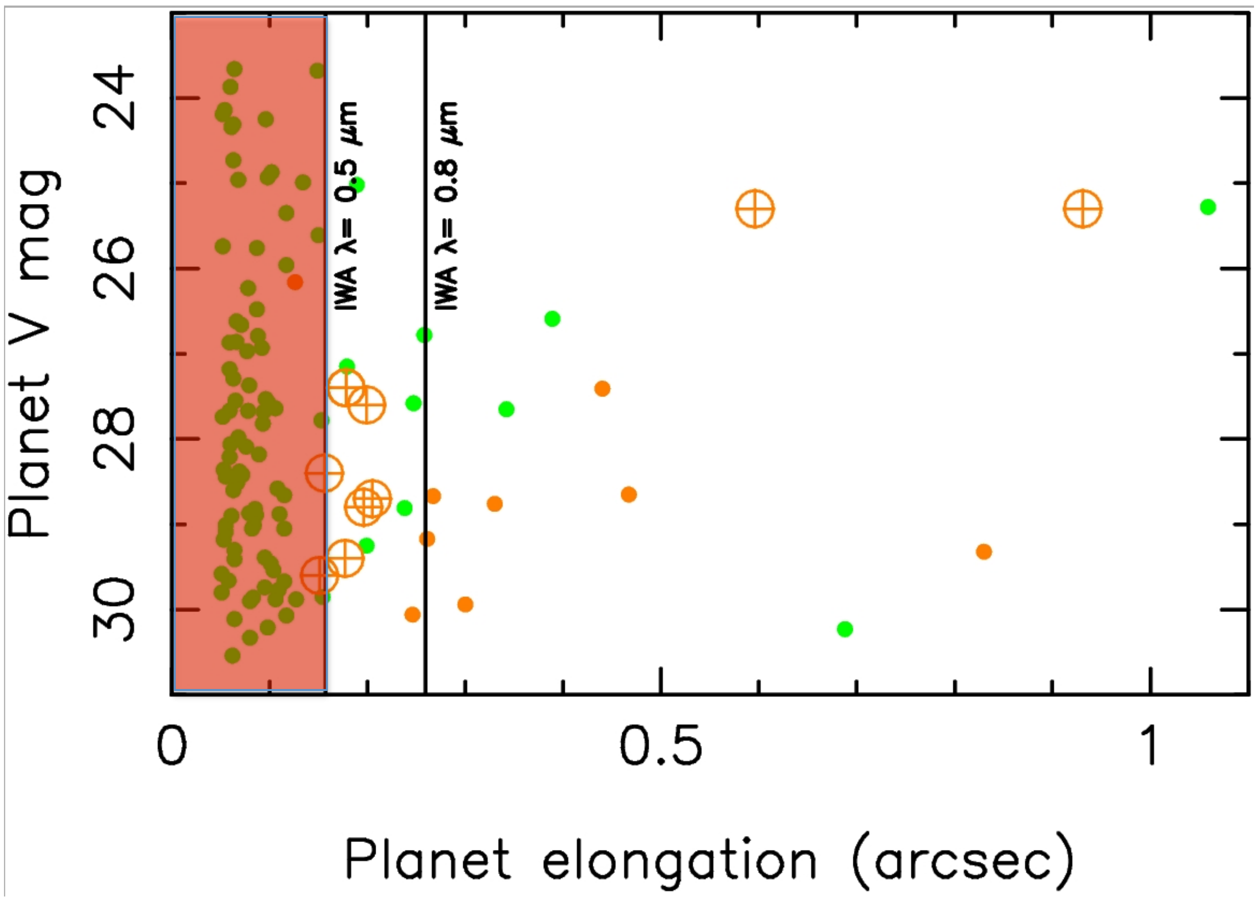




Exo-C Technical Capabilities

Telescope primary mirror	1.4 m diameter
Uncontrolled speckle contrast	1e-09 raw at IWA, better further out
Contrast stability	1e-11 two hours after slew or roll
Spectral coverage	450–1000 nm
Spectral resolution λ > 500 nm	R = 70
Inner Working Angle 2 λ/D	0.16″ @ 500 nm, 0.24″ @ 800 nm
Outer Working Angle > 20 λ/D	2.6″ @ 800 nm
Spillover light from binary companion	3e-8 raw @ 8″, TBD additional reduction from wavefront control
Astrometric precision	< 30 milliarcsec
Fields of view	42″ imager, 2.2″ spectrograph
Mission lifetime	3 years

Exo-C Characterization of Known Exoplanets



Points are known RV planets

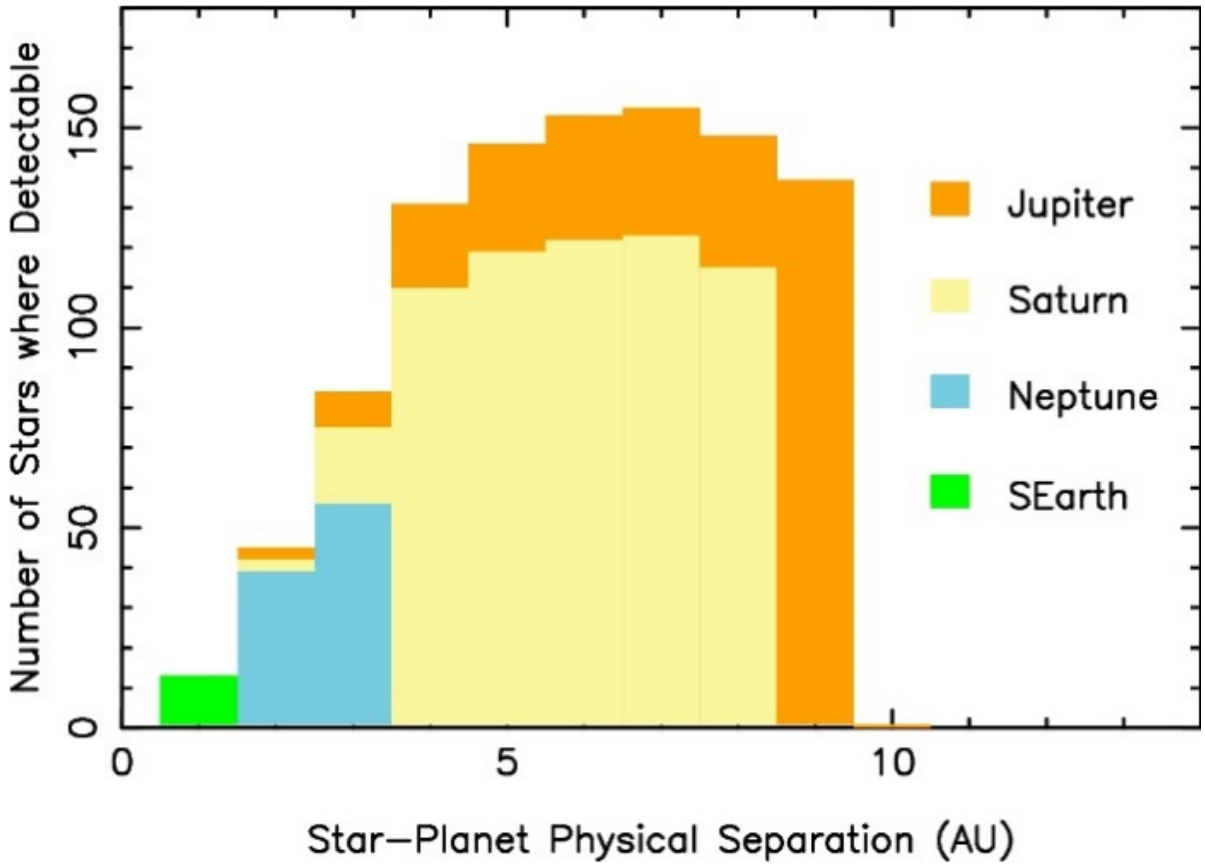
⊕ Earth analog as it would appear in nearby star HZ

Contrast ≥ 10^{-9}

Contrast < 10^{-9}

Vertical lines show 2 λ/D inner working angle for 1.4m telescope at 500 and 800 nm

Exo-C Discovery of New Exoplanets

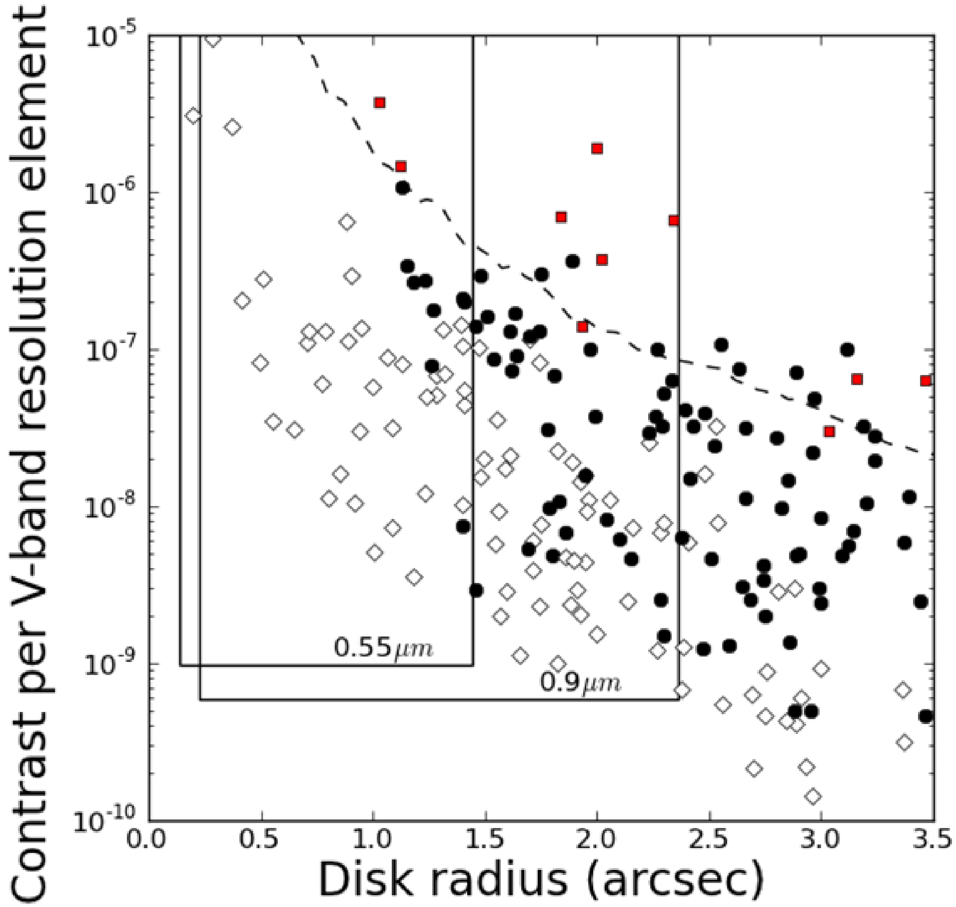


Histogram of detectable planets around nearby stars in total of 1 year of spacecraft time. Search yield of ~> 15 planets is expected

E3xo-C Circumstellar Disk Imaging

Exo-C will discover and characterize circumstellar disks.

- Predicted disk sizes and contrasts for Herschel disks d < 40 pc
- Red points: The small number of disks imaged to date in scattered light.
- Black points: Disks with sizes known from Herschel data (measured at 5” resolution)
- Hollow points: Disks whose sizes can be estimated from far-IR SED and assumed dust properties.



Plot by Geoff Bryden

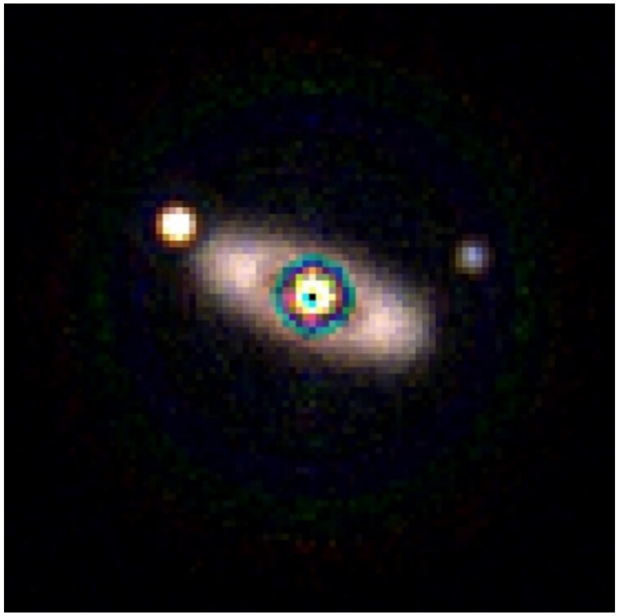
Exo-C Design Reference Mission

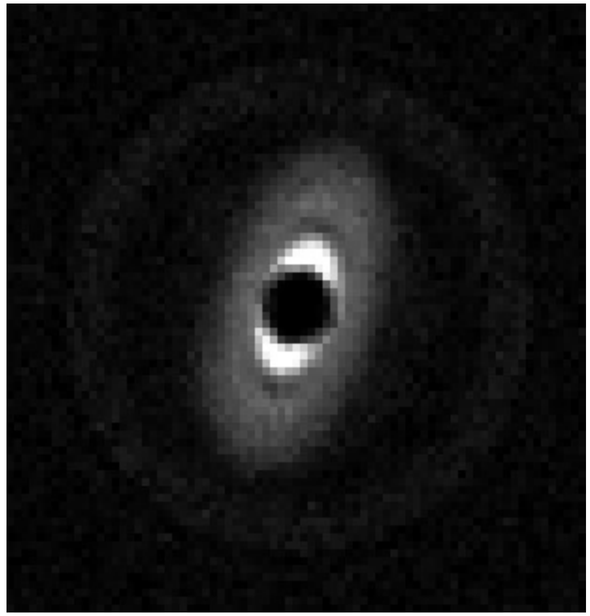
- **Planet characterizations: roughly 1 year of mission time**
  - Take spectra of **~20** exoplanets (both known and mission-discovered)
  - Take multi-color photometry of 20 known RV planets plus an additional **~15** mission-discovered exoplanets
- **Planet discovery surveys: roughly 1.2 years of mission time**
  - Survey **15** nearby stars for super-Earths in the HZ, 6 visits each
  - Survey **135** nearby stars for giant planets, 2-3 visits each

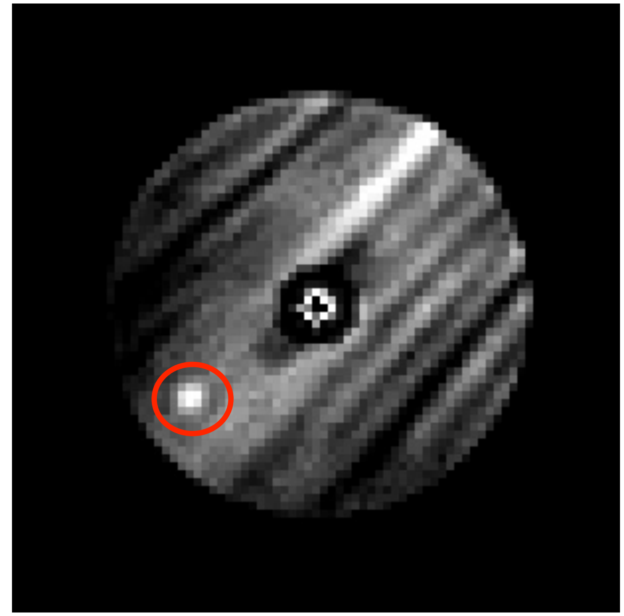
    Provisionally assume 10% yield, or ~15 mission-discovered planets
- **Disk imaging surveys: roughly 0.6 years of mission time**
  - Survey for habitable zone dust in **150** A-K stars
  - Deep search for disks in **60** RV planet systems
  - Resolve structure in **150** known debris disks from Spitzer/Herschel/WISE
  - Resolve structure in **40** protoplanetary disks in nearby molecular clouds

A wide range of science, containing characterizations and surveys

Exo-C Simulated Imagery







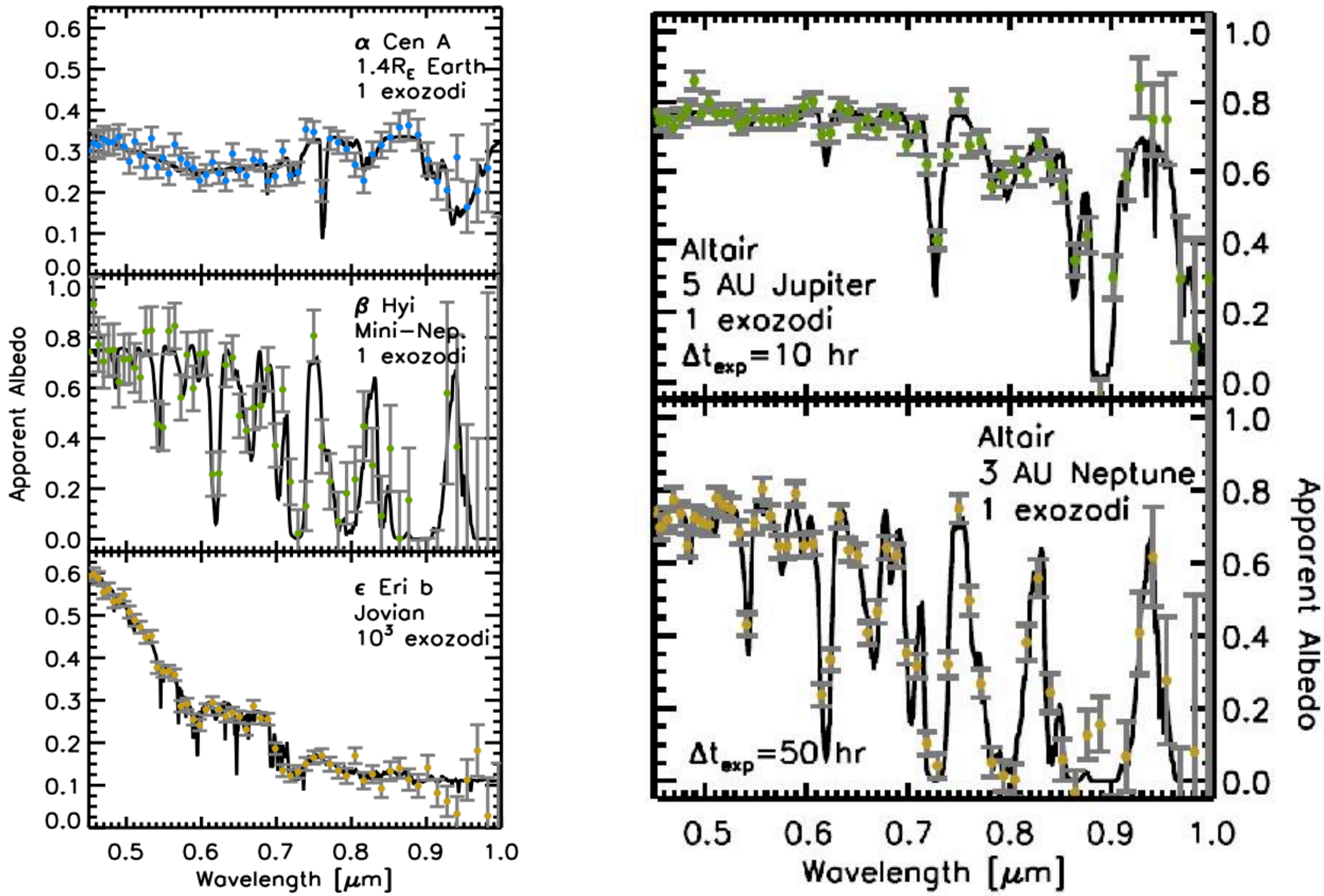
Altair 12 hrs each in V, R, I bands. Jupiter & Saturn analogs detected, 1 zodi dust ring from 2-4 AU

12 hr V band exposure of HIP 85790, a V= 5.6 star at 80 pc with WISE infrared excess. A 50 zodi debris disk extended to 80 AU radius is assumed.

5 day V band exposure of an Earth analog in the HZ of α Cen A (occulted at center). Scattered light from α Cen B is the primary noise source; shown is a 3% residual after calibration.

All simulations use Hybrid Lyot Coronagraph optical models by John Krist

Exo-C Simulated Spectroscopy



Work by Ty Robinson (ORAU / NASA Ames)

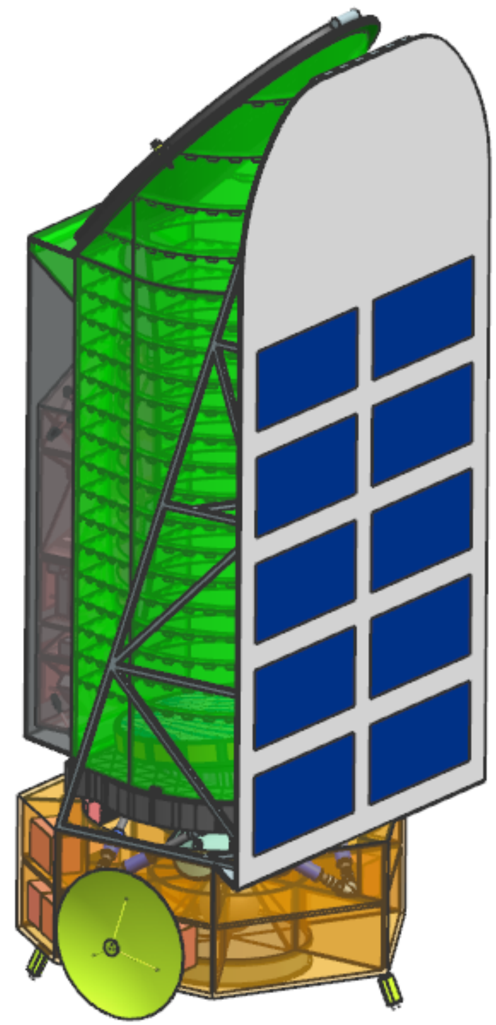
Exo-C General Astrophysics

ExEP

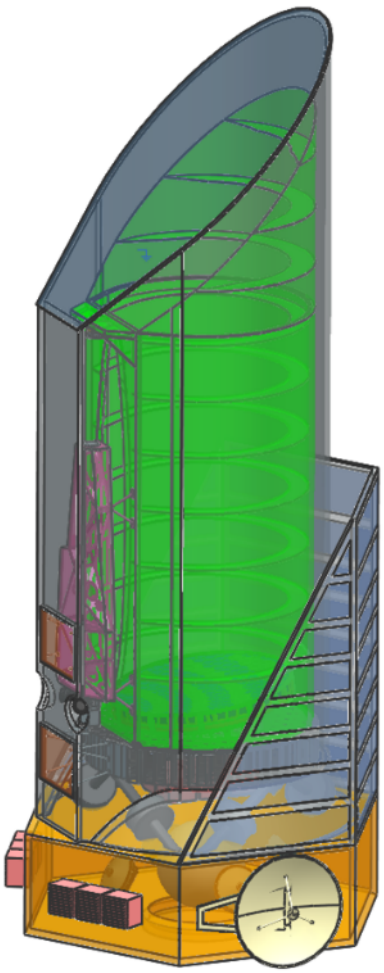
- Exo-C's small fields of view (42 arcsec for imager; 2.2" for imaging spectrograph) will limit general astro applications
- Coronagraph needs stars with V < 13 for pointing system to operate as currently designed
- High contrast science applications for post-main sequence stars and AGN/quasars; see COPAG report
- Use of camera and IFS without coronagraphic spots, or on targets with V≥ 13, would require pointing system redesign
- A second instrument could be accommodated in terms of payload mass/volume, but not within $1B cost cap.
  - Optical/near-IR photometer/spectrometer for transit work can likely be accommodated on instrument bench

Exo-C Baseline Overview

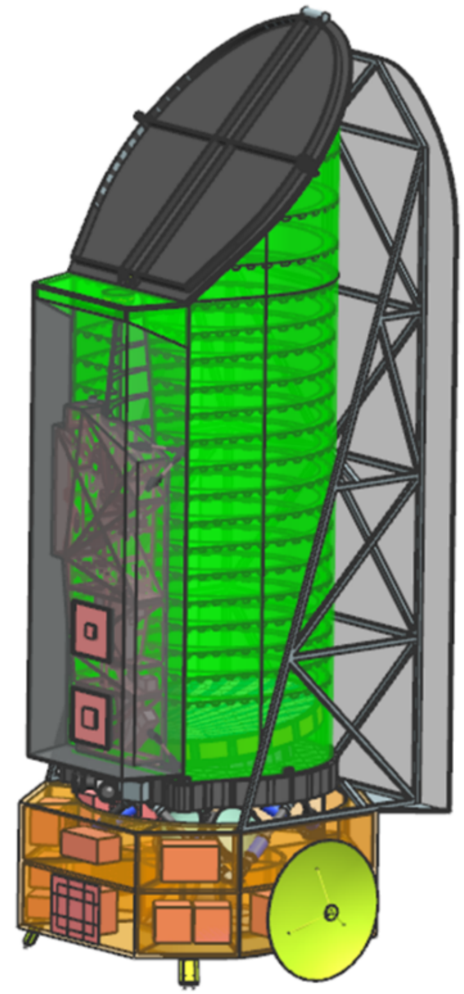
- Earth-trailing orbit as for Kepler
  - Good thermal stability & sky visibility, no propulsion needed
- Unobscured 1.4m Cassegrain telescope
  - Better throughput, spatial resolution, stiffness, coronagraph technical readiness vs. obscured
- Hybrid Lyot coronagraph for 2017 project start; Vector Vortex and PIAA still under consideration for later start
- Active thermal control of telescope & instrument
- Bright science target star is reference for precision pointing and for following low-order wavefront drifts
- ~1000 kg observatory mass, Kepler-like spacecraft bus, Falcon 9 class launch vehicle



Exo-C Design Changes During Study



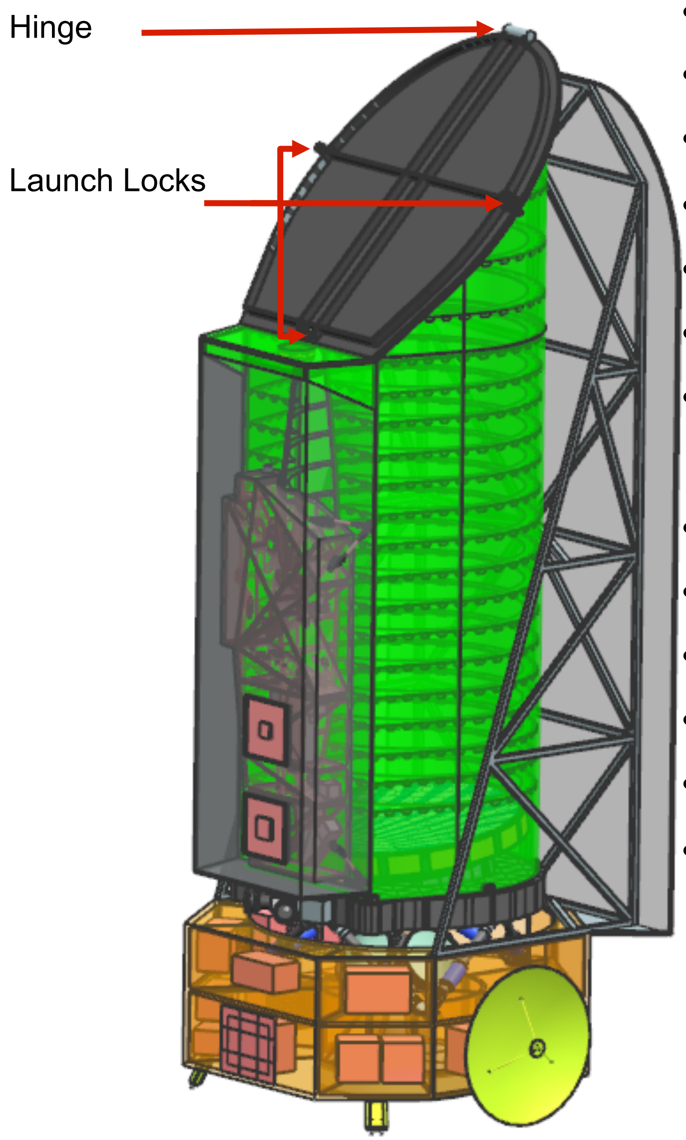
- Reduced telescope aperture from 1.5m to 1.4m (cost ↓)
- Solar array expanded into a sunshield for entire telescope (improves wavefront stability)
- Replaced outer barrel with thermal blankets (mass ↓)
- Lowered stack height (mass ↓)
- Electronics boxes moved inside spacecraft bus (thermal stability)
- Fine pointing requirement relaxed to 0.8 mas (margin +)
- Increased stray light baffling
- Two-layer instrument bench



Interim Design

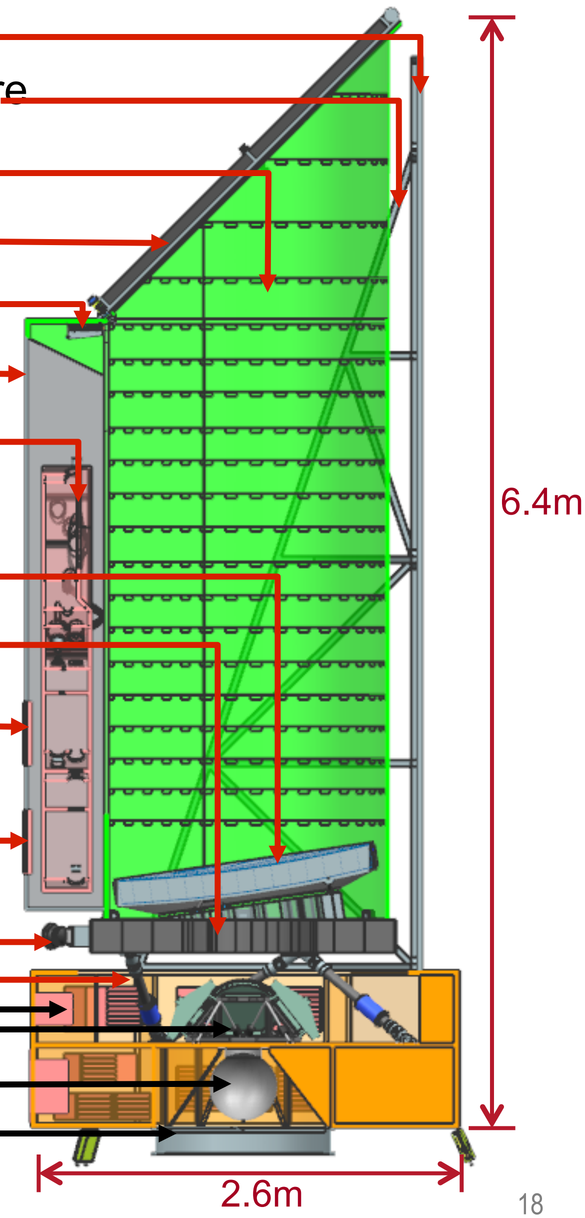
Final Design

Exo-C Subsystem Description



- Solar Array/Sunshade
- SA/Sunshade Support Structure
- Barrel Structure
- Removable Lid
- Secondary Mirror Assy
- Instrument Enclosure
- Instrument Bench Assy

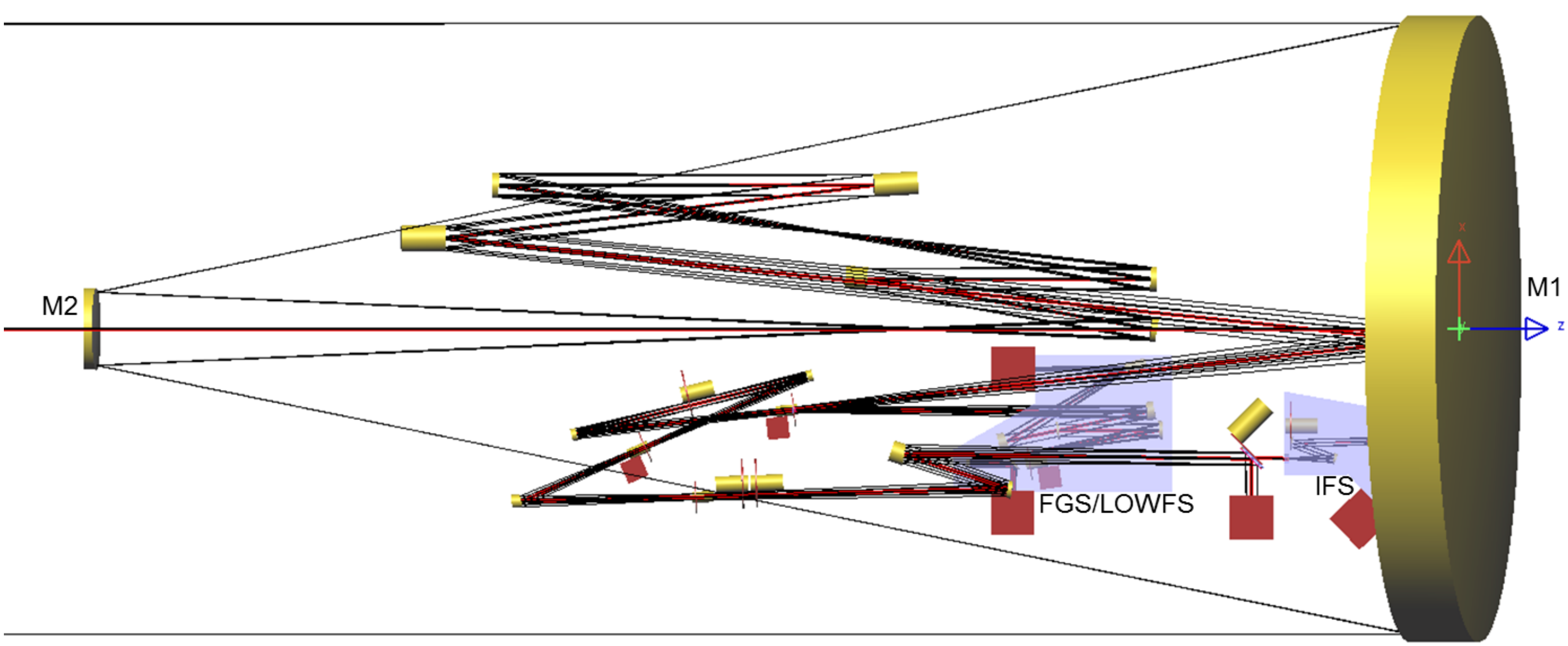
- Primary Mirror Assembly
- Primary Support Structure
- Radiator Panel Assembly
- Star Tracker Assembly
- Isolation Assembly
- Spacecraft Assembly
  - SC and Payload Electronics
  - Reaction Wheel Assy
  - Propulsion Assy
  - LV interface Ring Assy



Exo-C Instrument Configuration

- Imaging camera, integral field spectrograph (IFS), fine guidance sensor (FGS) for pointing, low-order wavefront sensor (LOWFS)
- Wavefront control using two 48x48 Deformable Mirrors (DMs)
- Two-layer optical bench allows Deformable mirror and fine steering mirror to be implemented separately

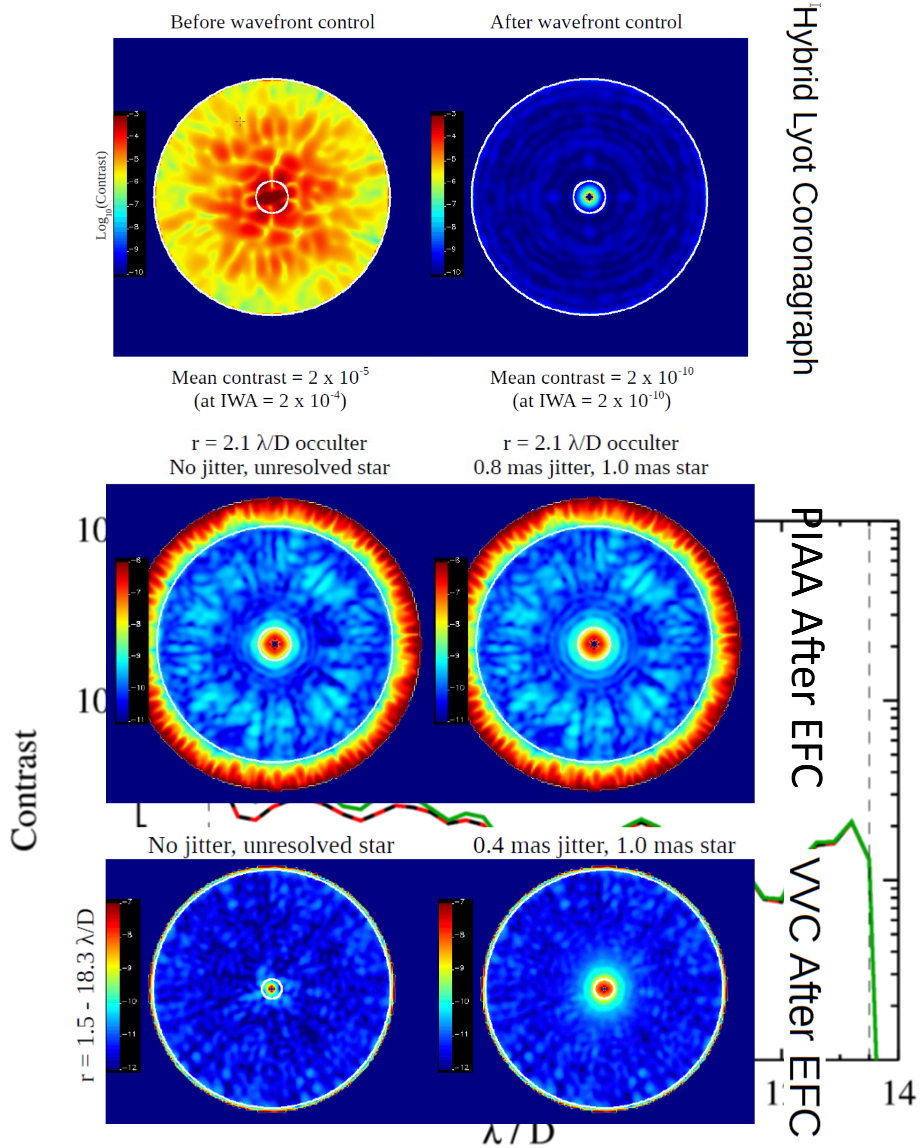
- Lateral instrument configuration on the side of barrel assembly
  - Much larger volume available here than in traditional aft configuration
  - Allows low angle of incidence reflections that minimize instrumental polarization
- kHz fine steering mirror keeps star centered on occulting spot to ~0.8 mas accuracy



Coronagraph (Starlight Suppression) Selection

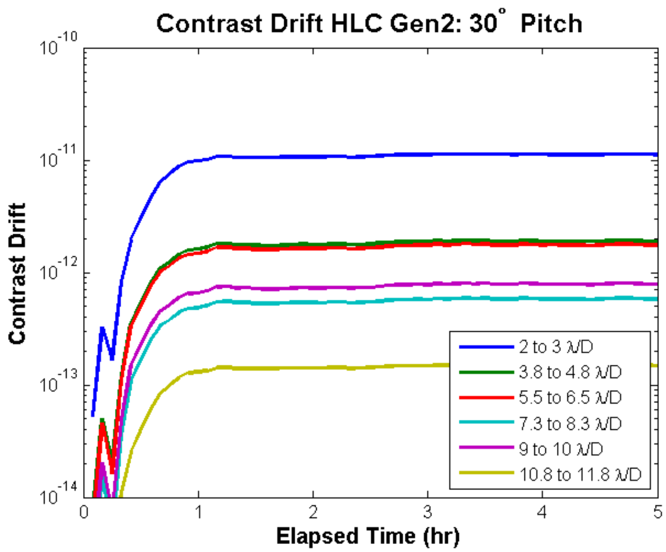
ExEP

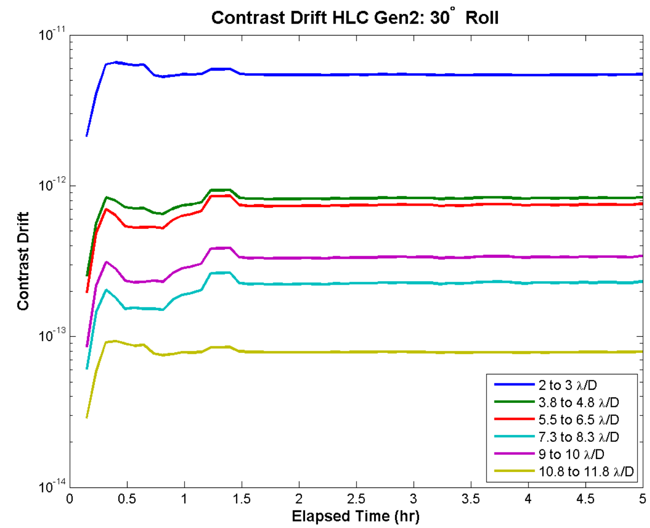
- Five architectures were evaluated: Hybrid Lyot, PIAA, shaped pupil, vector vortex, and the visible nuller
- Realistic optical system models for each with wavefront control and telescope pointing errors
- Contrast maps and individual throughputs used to predict science yield for each. Three met science requirements and have path to readiness, participated in second design cycle
- Summary evaluations result in <u>Hybrid Lyot as baseline</u> for a 2017 project start. Vector Vortex and PIAA remain options for a later start.



Structural Thermal OPtical (STOP) Analysis

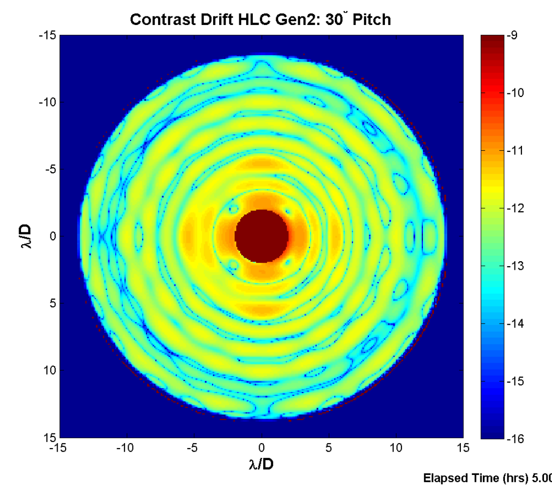
Excellent contrast stability with telescope moves





- Model predictions suggest Exo-C final design will have ~2 hr settling timescale and very small contrast drifts

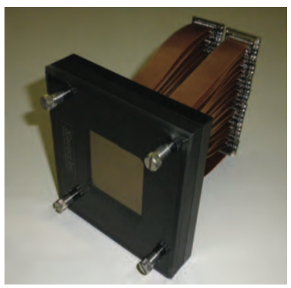
- This would allow low overheads and routine use of two-roll observing strategy



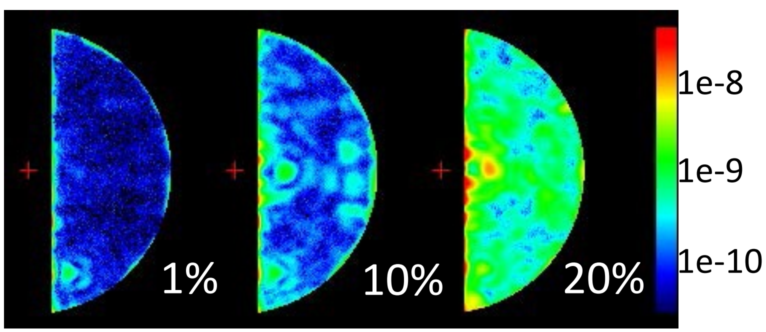
Exo-C Technology Demonstrations

- Exo-C technology is built on years of TPF & TDEM investments and is closely aligned with planned AFTA coronagraph investments and demonstrations.
- Exo-C bandwidth & contrast requirements already met by Hybrid Lyot coronagraph at 3 λ/D inner working angle. 2 λ/D inner working angle requirement met by PIAA & Vector Vortex coronagraphs, but at 10^{-8} contrast and 10% bandwidth.
- Need to demonstrate all the above in a single instrument in the presence of dynamic pointing & wavefront errors → low-order wavefront control.

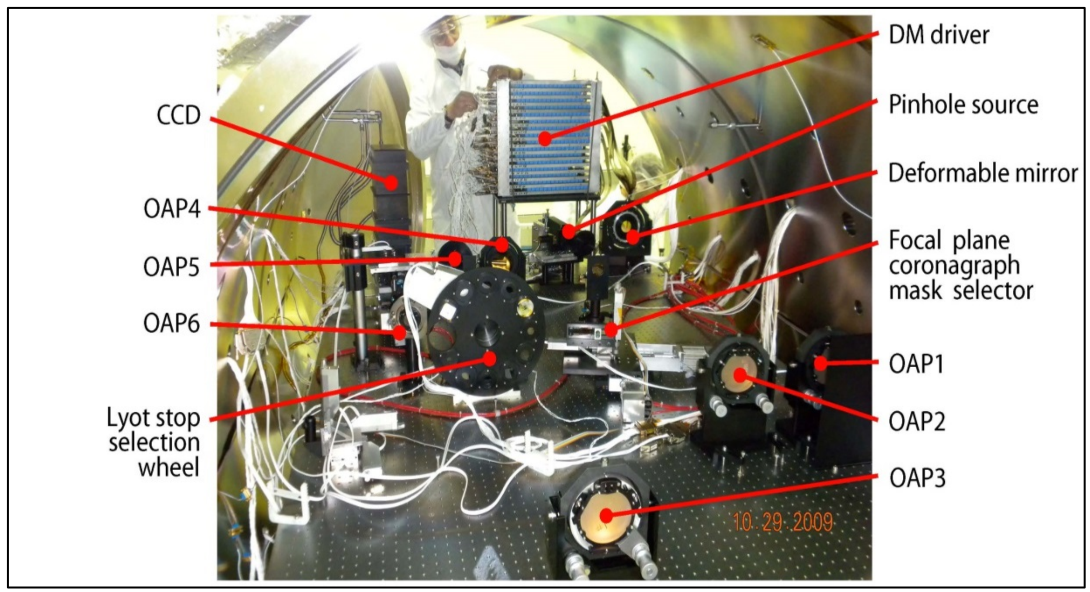
48x48 Xinetics deformable mirror has been shake tested



HCIT Lab contrast demonstration

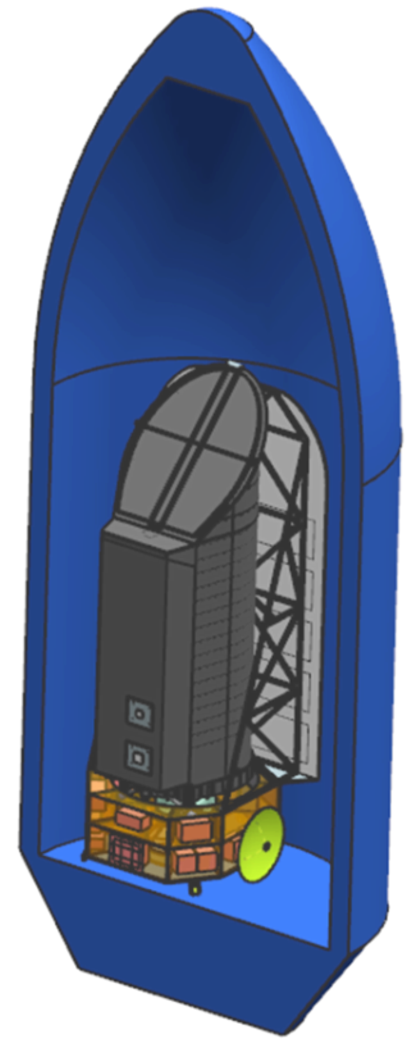


JPL High Contrast Imaging Testbed



Exo-C Estimated Cost and Future Plans

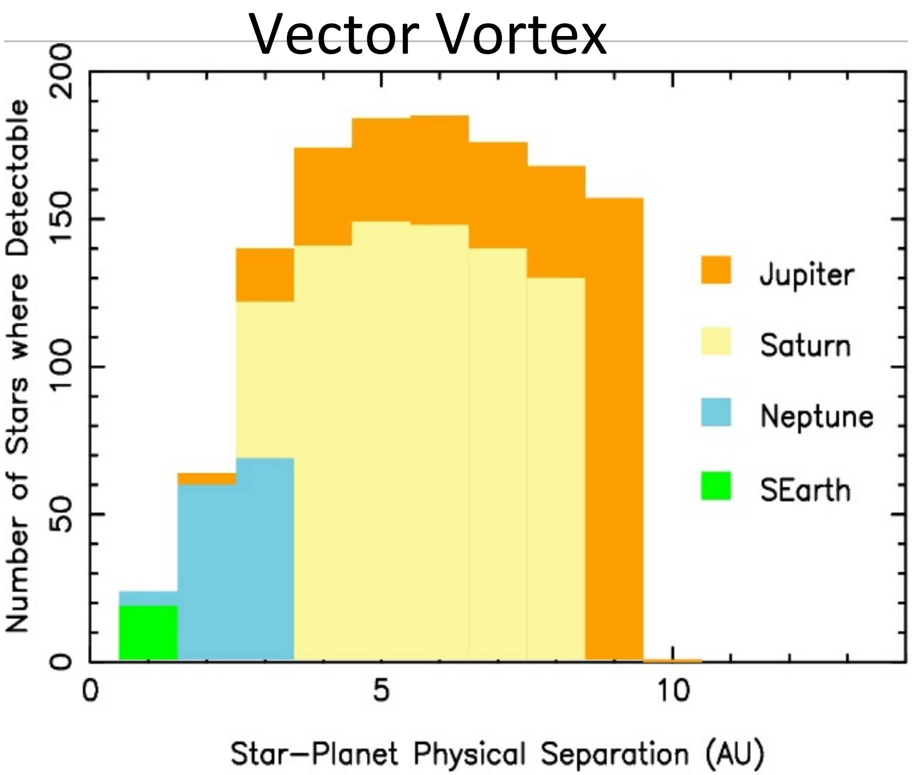
- Exo-C's aperture, orbit, spacecraft, & lifetime are virtually the same as those of the Kepler mission, which at $700M is our cost reference.
- Exo-C's estimated costs are significantly less than those of similar coronagraph mission concepts evaluated by Aerospace for Astro 2010.
- The Exo-C design effort demonstrates that a compelling science mission can be done at the mandated Probe mission cost cap of $1B.
- Final report submitted to NASA HQ on March 10, 2015.
- Exo-C STDT will be studying the science capability of a stand-alone 2.4 m dedicated mission.

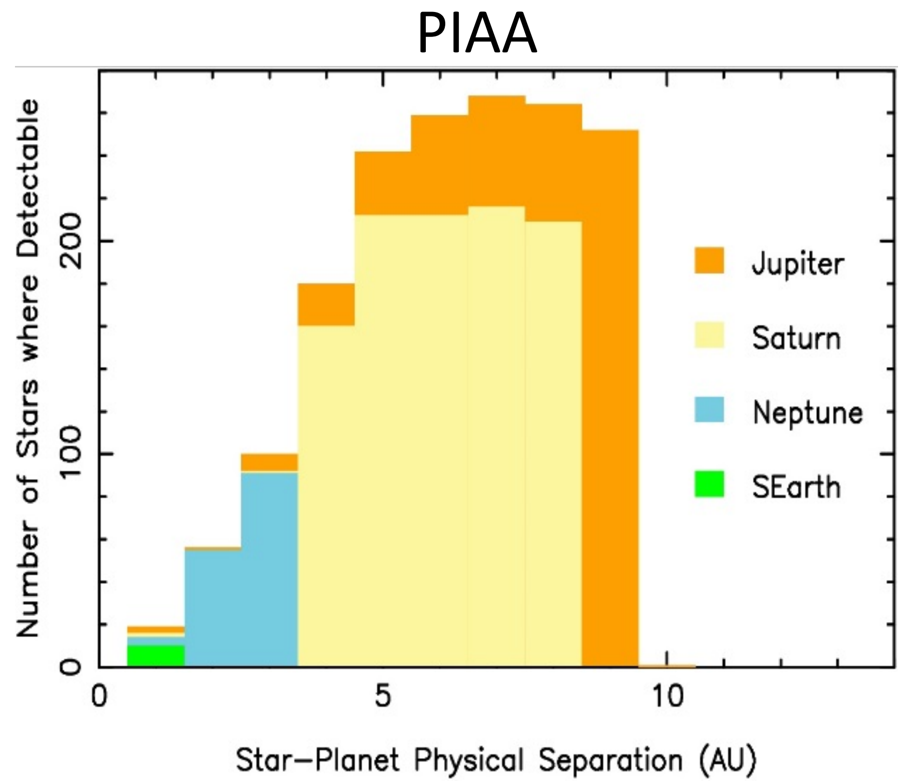


http://exep.jpl.nasa.gov/stdt/exoc/

BACKUP

Possible Improvements to Exo-C Sensitivity





Improved throughputs and inner working angles enable larger exoplanet search space. However, the Vector Vortex and PIAA technologies are less ready and therefore considered alternates.

Exo-C Pointing Control System

ExEP

A robust pointing architecture that leverages flight proven technologies.

Pointing Requirements	
Telescope Pointing (Angle in the sky, RMS per axis)	
Accuracy	2 milliarcsec (Line-of-sight tip/tilt)
	10 arcsec (Line-of-sight roll)
Stability (1000s)	16 milliarcsec (Line-of-sight tip/tilt)
	10 arcsec (Line-of-sight roll)
Coronagraph Pointing (Angle in the sky, RMS per axis):	
Accuracy	0.2 milliarcsec (Line-of-sight tip/tilt)
Stability (1000s)	0.8 milliarcsec (Line-of-sight tip/tilt)

Key Features of the Pointing System	Exo-C	IRIS SmEx (2013)	PICTURE Sounding Rocket (2011)	Kepler Discovery (2009)	Spitzer (2003)	Chandra (1999)	Hubble (1990)	TRACE SmEx (1990)
Fine-guidance sensor (FGS)	X	X	X	X	X	X	X	X
High-bandwidth fast-steering mirror (FSM)	X	X	X					X
Enhanced attitude control system (ACS) using FGS	X	X		X		X	X	X
Passive isolation	X					X	X	
Low-disturbance Earth-trailing orbit	X			X	X			
High-stiffness observatory (no deployables/articulations)	X			X	X			
In-flight pointing stability performance (RMS)		ACS: 250 mas Instrument: 50 mas	ACS: 600 mas Instrument: 5 mas	ACS: 25 mas (<5 Hz) 3 mas (<0.0001 Hz)	ACS: 40 mas	ACS: 250 mas	ACS: 5 mas	ACS: 5 mas Instrument: 100 mas

Exoplanet Probes Linkage to Astro 2010

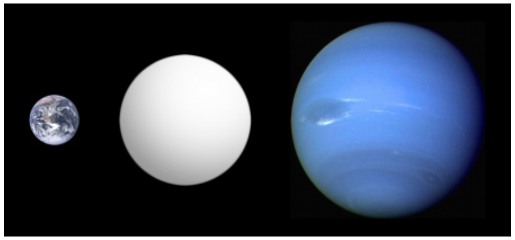
ExEP

"The (EOS) panel did evaluate, and found appealing, several "probe-class" concepts employing ~1.5-m primary mirrors and internal star-light suppression systems, often coronagraphs with advanced wavefront control. Each was judged to be technically feasible after completion of a several year technology development program, and could cost significantly less than a precision astrometry mission like SIM Lite. Such a mission could image about a dozen known (RV) giant planets and search hundreds of other nearby stars for giant planets. Importantly, it could also measure the distribution and amount of exozodiacal disk emission to levels below that in our own solar system (1 zodi) and detect super-Earth planets in the habitable zones of up to two dozen nearby stars. These would be extremely important steps, both technically and scientifically, toward a mission that could find and characterize an Earth-twin."

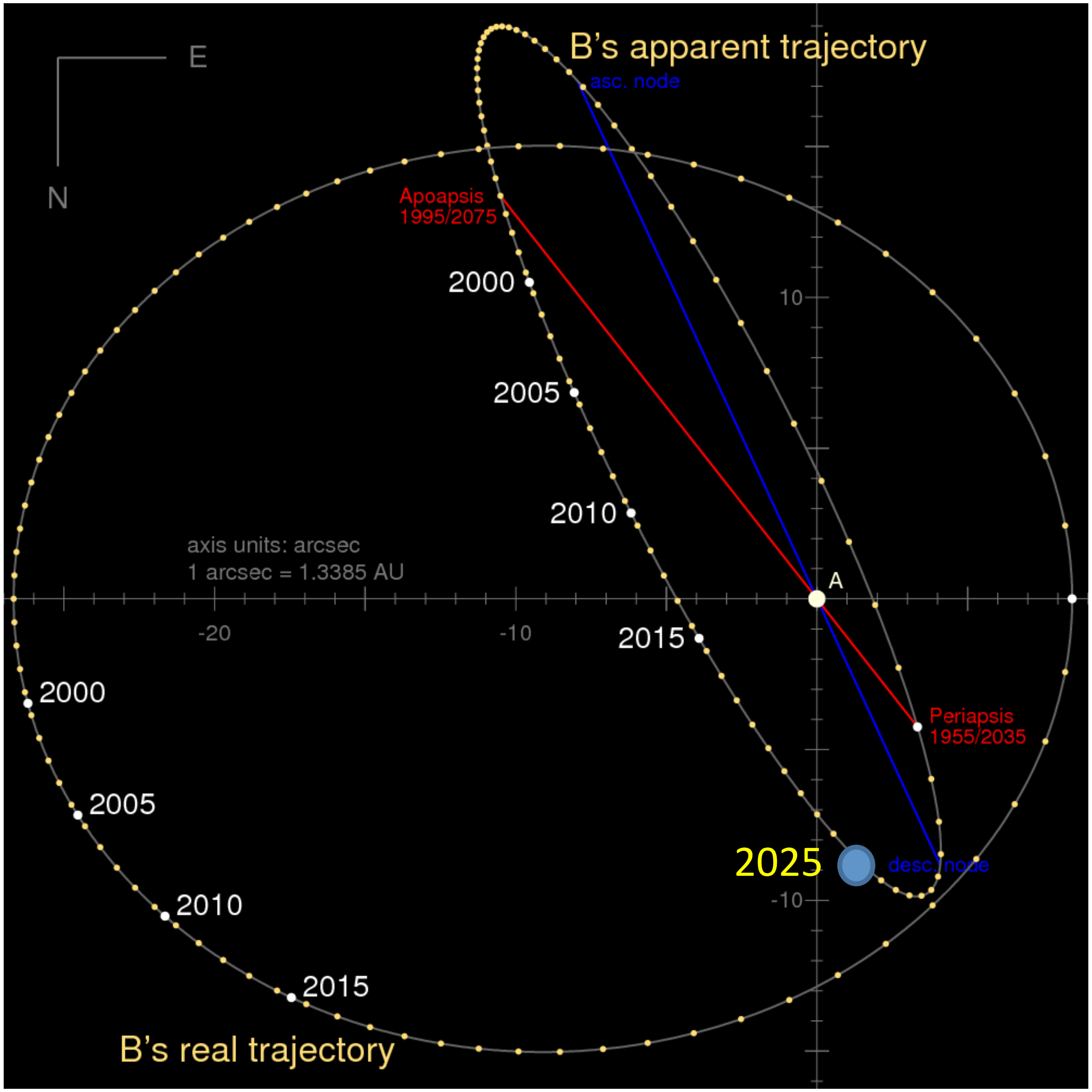
Science frontier discovery areas:

- Identification and characterization of nearby habitable exoplanets
- How diverse are planetary systems ?
- How do circumstellar disks evolve and form planetary systems ?

"… a critical element of the committee's exoplanet strategy is to continue to build the inventory of planetary systems around specific nearby stars"



α Cen Orbit Sets Stray Light Requirement

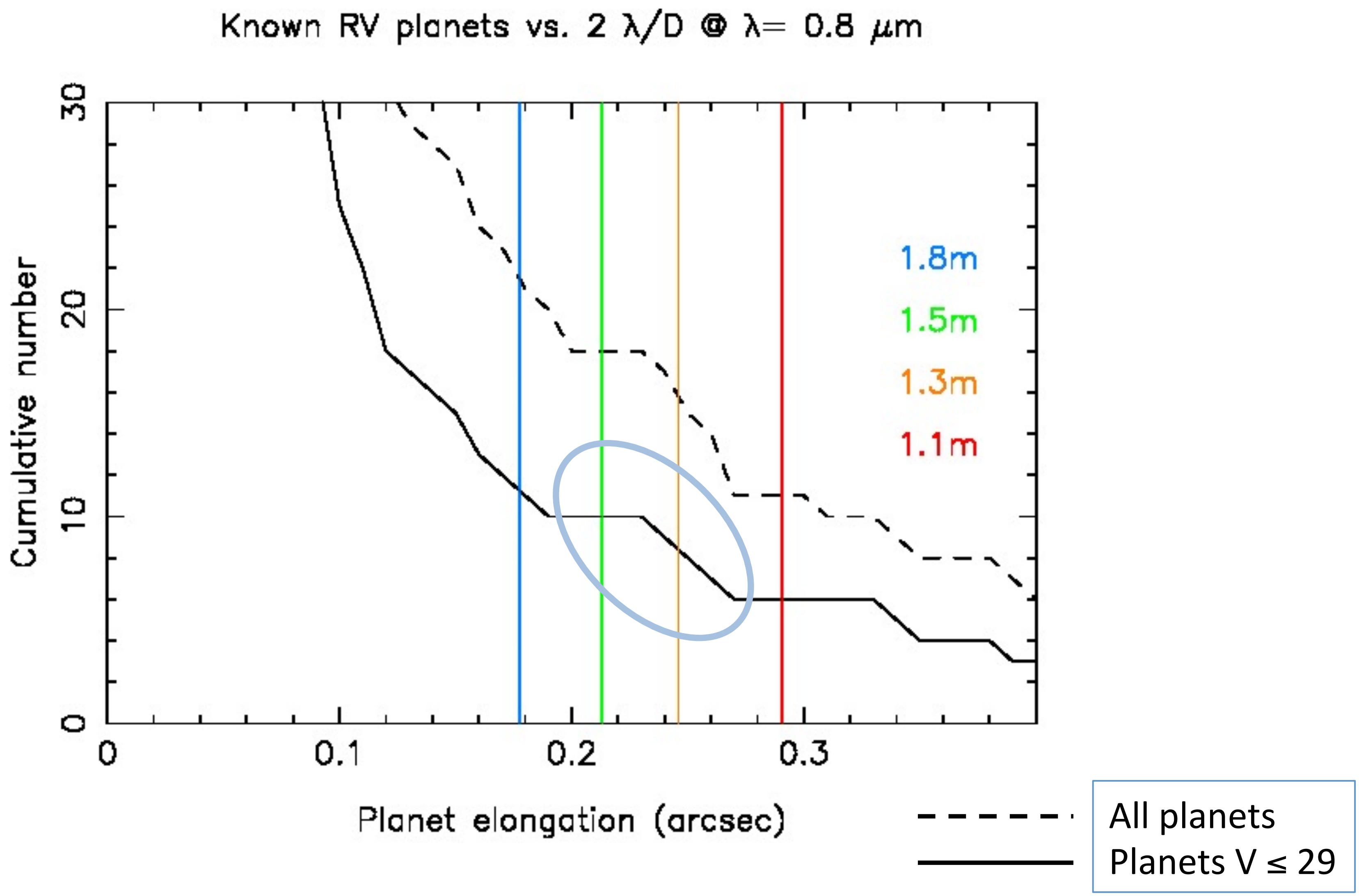


8.5″ separation in 2025, increasing to 10.5″ in 2028.

<u>STEPS FOR CONTROL OF SPILLOVER LIGHT:</u>

- Coronagraph mask concepts to block both stars and accommodate the variable separation
- Primary mirror surface quality specifications at 100 cycles/aperture
- Agile dark hole using deformable mirrors
- Careful baffling and control of internal reflections

Accessible RV Planets vs. Aperture Size



Exo-C Observing Capabilities

Exo-C Working Filter Set	
V band 20%	Photom & blocking
R band 20%	Photom & blocking
I band 20%	Photom & blocking
z band 20%	Photom & blocking
B band 10%	Rayleigh scattering
650 nm 5%	Weak CH_4 band
793 nm 3%	Moderate CH_4 band
835 nm 6%	CH_4 continuum
885 nm 6%	Strong CH_4
940 nm 6%	H_20

Target Category	# Stars	Median V mag
Known RV planets	11	5.7
Search for HZ planets	15	3.7
Searches for larger planets	135	3.8
Survey for HZ dust	150	3.7
Debris disks in RV planet systems	60	5.3
Debris disks detected in far-IR	150	5.3
Protoplanetary disks	40	11.4

Summary of Mission Observing Time

Number of Targets	Mission Time (days with overhead)	Design Reference Mission
35	166	Exoplanet astrometry & multicolor photometry (known and mission-discovered planets)
20	215	Exoplanet spectra (known and mission-discovered planets)
15	113	Search for small exoplanets in nearest star Habitable Zones
150	69	Survey of Habitable Zone dust in A-K stars
135	323	Search for giant planets around nearby stars
60	36	Survey for debris dust in RV planet systems
150	91	Imaging the structure of debris disks identified by Spitzer, Herschel, and WISE
40	24	Structure of nearby protoplanetary disks
	2.8 years	**Total Science Observations** (0.2 years are reserved for in-orbit checkout)

Accessible Earths in HZ

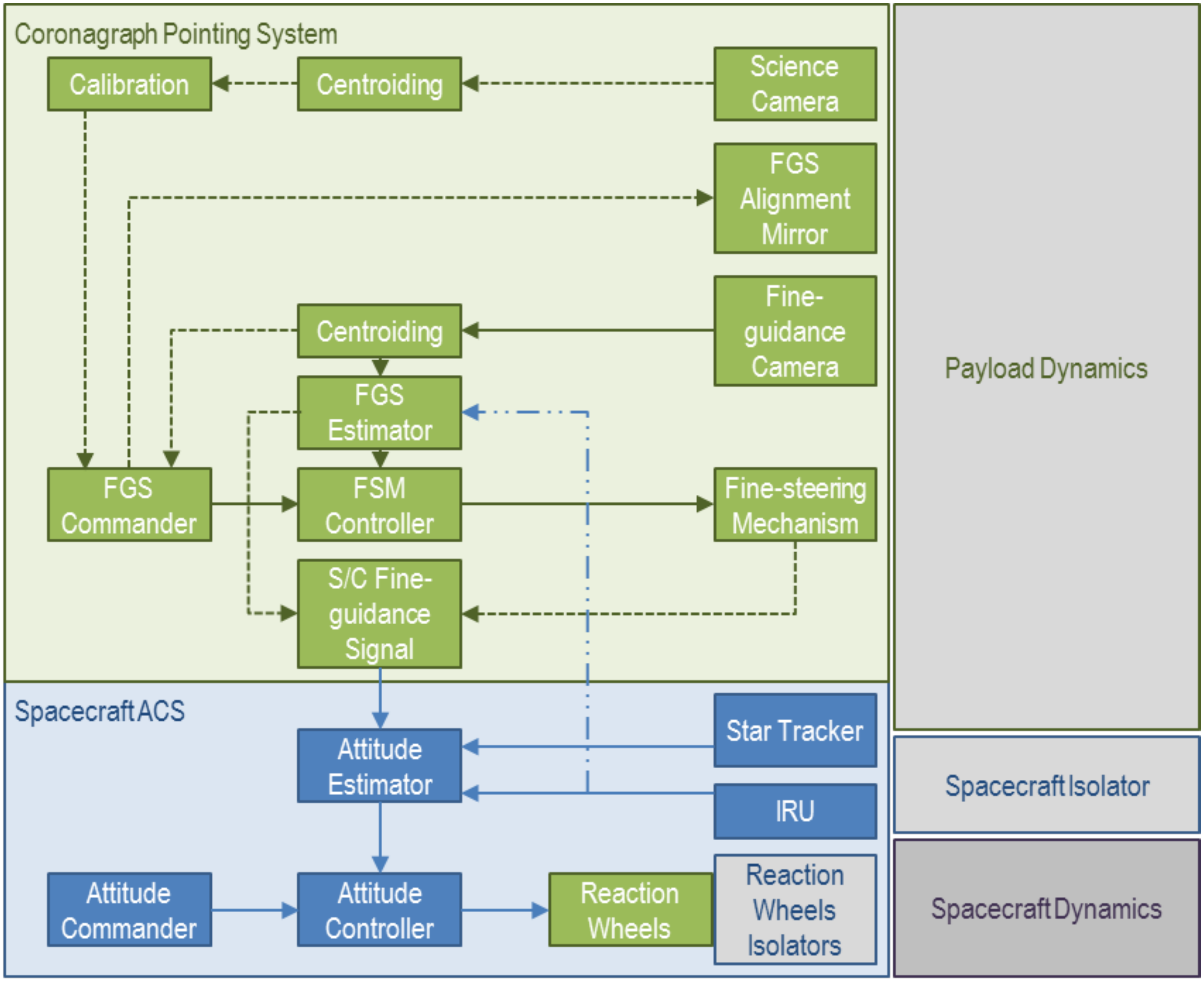
Star	V mag	HZ inner radius (AU)	Elongation (arcsec)	Contrast	Integration time for V band detection (hrs)
alpha Cen A	0.1	1.2	0.93	9×10^{-11}	51
alpha Cen B	1.2	0.8	0.60	2×10^{-10}	99
tau Ceti	3.6	0.7	0.20	3×10^{-10}	99
epsilon Eri	3.7	0.6	0.18	4×10^{-10}	80
eta Cas A	3.6	1.2	0.21	9×10^{-11}	109

For the two components of the alpha Centauri system, scattered light from the companion at 8" has been in included as a noise source. eta Cas is a 12" binary. Exozodiacal light at the minimal 1 zodi level is assumed. tau Ceti and epsilon Eridani both have far-IR excess which may mean high levels of dust in their habitable zones; this is not taken into account for the integration times given here.

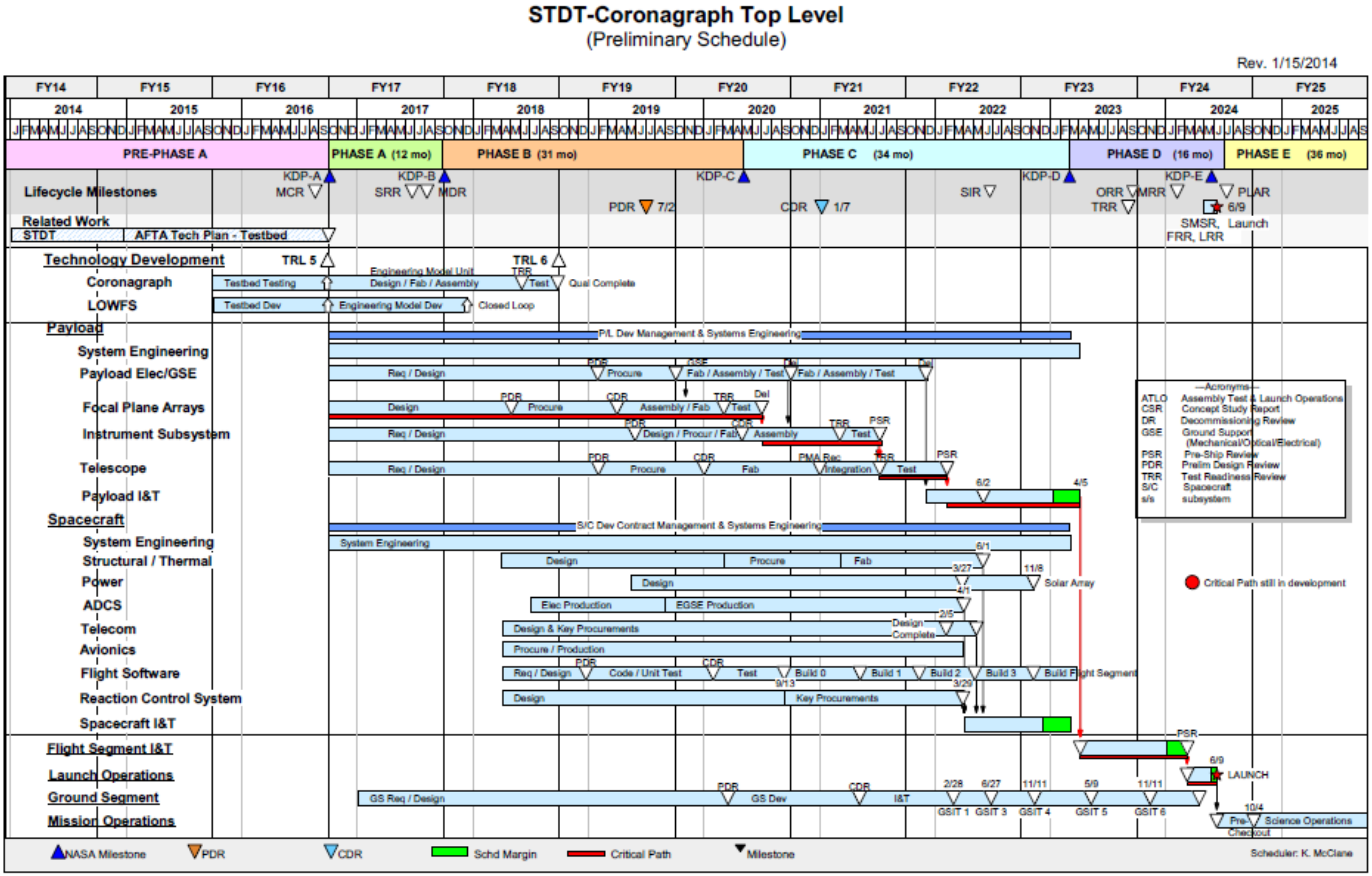
Exo-C Design Trades

Trade	Outcome
Telescope obscured vs. non-obscured	Unobscured aka “off-axis”
Telescope design	Cassegrain
Telescope material: Glass vs. silicon carbide (SiC)	Low CTE glass
Orbit	Earth-training
Aperture size	1.4 m
High-gain antenna (HGA)	Fixed
Isolators: between reaction wheel assembly (RWA) and spacecraft, and again between spacecraft and payload	Two passive layers
Deformable mirrors	Two 48 × 48 devices for 2017, investigate larger formats for later launch
Instrument configuration: Lateral vs. behind primary mirror	Lateral
Mission design	Baseline configuration in §6
Low-order wavefront sensor (LOWFS) design	Zernike WFS, spectral splitting
Spacecraft bus	Kepler type
Solar array configuration	Fixed
Field of regard	Boresight angles of 45-135 degrees w.r.t. the Sun
Mission lifetime	3 years, consumables for 5 years
Pointing architecture	Isolation, flight management system (FMS), payload, and spacecraft interface
Spectrometer architecture	Integrated field spectrometer (IFS): 76x76 lenslet array, R= 70
Telescope stability—thermal architecture	Multizone heater control of telescope barrel and primary mirror; sunshade for telescope
Secondary mirror configuration	Actuated secondary
Telescope metering structure configuration	Integrated with barrel assembly
Instrument architecture	Coronagraph, imaging camera, IFS, fine-guidance sensor (FGS)
Coronagraph architecture	Hybrid Lyot baseline for 2017, Vector Vortex and PIAA still considered for later launch
Science detectors	Science camera and IFS both use 1K x 1K EMCCD for 2017, 2K x 2K for later launch

Pointing System Block Diagram



Preliminary Schedule



Probe studies are directed to be based on a Phase A start at the beginning of FY17, project PDR in FY19 and a launch no later than 12/31/2024. The schedules includes funded schedule reserves per JPL Design Principles.

Exo-C Study Accomplishments

Missions like Exo-C have been proposed/studied several times before. What is new this time?

1. New design independently-costed as a probe-scale mission, providing an existence proof for this mission class
2. Identified lateral instrument bench as optimal for an internal coronagraph mission
3. Modeling showed that Exo-C's combination of orbit, telescope structure, sunshield, and thermal control provides the very high telescope/wavefront stability needed for imaging exoplanets in reflected light
4. Added five years of scientific and technical progress to the case for flying this type of mission