

Probe White Paper #252 “Exo-C”

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Today:

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Exo-C coronagraph probe mission study



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Context for Exo-C Mission Study

- After Astro2010, NASA conducted five “probe” mission studies to investigate astrophysics science available at the ~\$1B cost level.
- *Kepler* mission results strongly motivated the idea of exoplanet direct imaging probes, particularly for mini-Neptunes & super Earths.
- Large mission for spectroscopy of ExoEarths requires 10^{-10} contrast @ 60 mas IWA ($> 10^5$ times beyond HST performance) & aperture size ≥ 4 m. Smaller mission for spectroscopy of larger exoplanets and imaging of disks only needs 10^{-9} contrast & ~1.5 m telescope. A natural first step.
- Coronagraph “Exo-C” and starshade “Exo-S” probe studies initiated in spring 2013 as potential backups to WFIRST, with 2017 readiness required
- There is a rich heritage for small coronagraph mission concepts, with more than a dozen proposed by various PIs since 1999.



Modest-aperture coronagraph mission concepts, 1988-2011

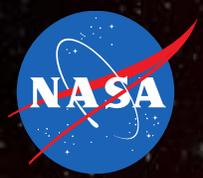
Table F-1. Historic proposals/studies of dedicated internal coronagraph space missions.

Mission	Aperture	Year and AO	Proposal/Study Lead
CIT	1.5 m	1988 JPL study	R. Terrile
CODEX	2.4 m	1997 <i>Hubble</i> instrument proposal	R. Brown
ECLIPSE	1.65 m	1998 MidEx	J. Trauger
ECLIPSE	1.8 m	2000 Discovery	J. Trauger
ESPI	1.5 m	2002 MidEx	G. Melnick
JPF	1.5 m	2002 MidEx	M. Clampin
ECLIPSE	1.5 m	2004 Discovery	J. Trauger
EPIC	1.5 m	2004 Discovery	M. Clampin
ECLIPSE	1.5 m	2006 Discovery	J. Trauger
EPIC	1.5 m	2006 Discovery	M. Clampin
TOPS	1.2 m	2006 Discovery	O. Guyon
SEE-COAST	1.5 m	2007 ESA M1/M2	J. Schneider
ACCESS	1.5 m	2008 ASMCS	J. Trauger
EPIC	1.65 m	2008 ASMCS	M. Clampin
PECO	1.4 m	2008 ASMCS	O. Guyon
SPICES	1.5 m	2010 ESA M3	A. Boccaletti
EXCEDE	0.7 m	2011 MidEx	G. Schneider



Exoplanet Science Landscape in the late 2020s: (1)

- Indirect detections: Around stars mid-F and later, RV surveys will have found 10 yr period planets \geq Saturn mass; 1 yr period planets \geq Neptune mass; and in the quiet stars, perhaps some HZ rocky planets. Gaia detects Jupiters with orbital periods of a few yrs around potentially thousands of stars, including ones unsuitable for sensitive RV measurements. A rich set of targets with known ephemerides for direct spectroscopic follow-up.
- Transits: TESS has extended Kepler results to brighter stars, defining the planet mass-radius relationship. JWST+ELTs get transmission & eclipse spectra for some of these. PLATO mission is returning results. ARIEL mission will be taking spectra of a large sample of hot giant planets. Transiting planets themselves will not be amenable to direct imaging, but mark good target systems for outer planet imaging searches.



Exoplanet Science Landscape in the late 2020s: (2)

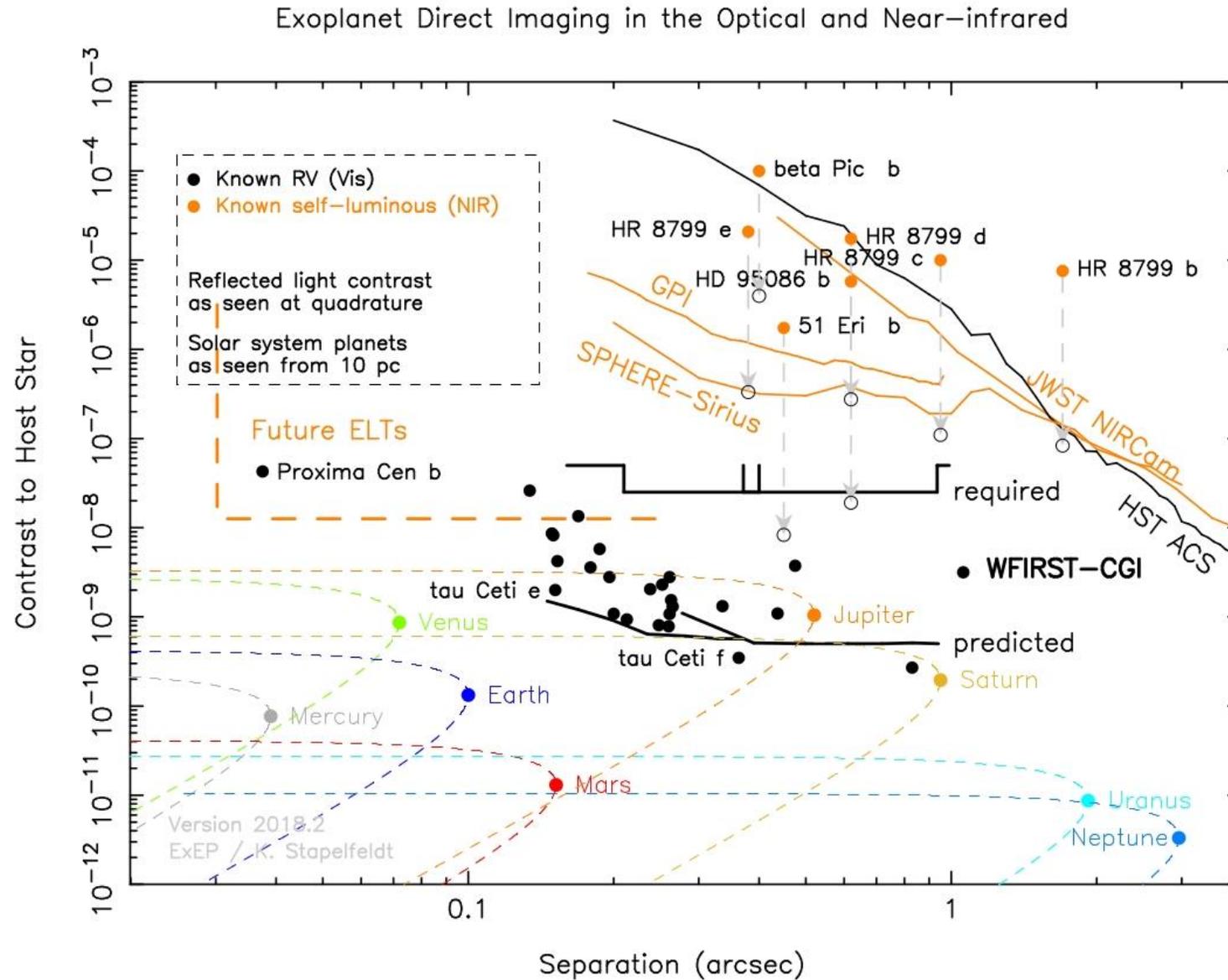
Exoplanet Direct Imaging: Ground AO coronagraphy will have obtained spectra of a few dozen self-luminous giant planets in near-IR or mid-IR thermal emission. Contrast limit of $> 10^{-8}$ set by atmospheric turbulence. A few HZ rocky planets could be detected around red dwarfs when ELTs deploy their extreme AO systems. JWST may image cold/wide giant planets of nearby M stars (mid-IR contrast $\sim 10^{-6}$).

Disk Imaging: ALMA has redefined knowledge of protoplanetary disks, but lacks the sensitivity to study exozodi or map tenuous debris disks at sub-arcsecond resolution. Ground AO imaging polarimetry of brighter disks; JWST imaging informs on disk composition.

The unique domain for small-aperture, space-based high contrast imaging would be contrasts $< 10^{-8}$ at visible wavelengths, studying cool exoplanets & debris disks are seen in reflected light around sun-like stars



Domain of High Contrast Imaging





Exo-C Key Science Questions

- *How does the atmospheric composition of gas and ice giant planets vary with planet mass, orbit, stellar mass & metallicity?*
- *How do clouds affect giant planet atmospheres and vary with the atmospheric temperature and other planetary parameters?*
- *What is the composition of mini-Neptune & super-Earth atmospheres ?*
- *Is the Solar System's architecture of 2 debris belts normal?*
- *How is dust produced and transported in debris disks?*
- *What planets exist in the outer reaches of nearby planetary systems?*
- *How much dust will obscure future images of Earth analogs?*
- *How does the dust component of planetary systems evolve?*



Exo-C Mission Science Objectives

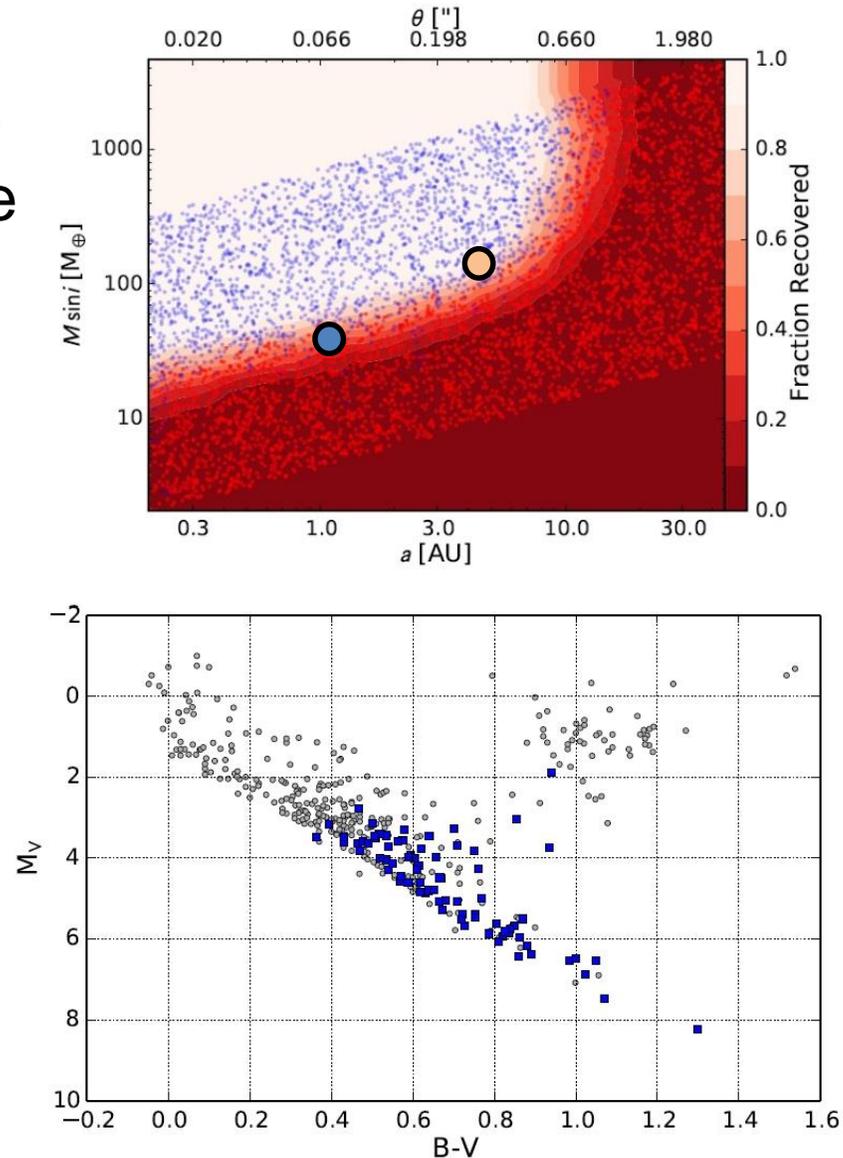
- 1. Discover new planets in the Solar neighborhood:** Exo-C's multi-epoch imaging will search for giant planets beyond the limits of other detection techniques around 150 nearby stars including α Centauri. In subsets of these, mini-Neptune, super-Earth, and perhaps Earth-sized planets will be detectable
- 2. Characterize known and mission-discovered planets:** Exo-C will measure the colors and spectra of at least a dozen known RV and Gaia planets orbiting nearby stars, and of the brightest new planets it discovers - measuring primary atmospheric constituents such as CH_4 and H_2O .
- 3. Structure and evolution of circumstellar disks:** Exo-C will resolve the structure of dust clouds orbiting nearby stars, tracing the gravitational effects of planets too small and remote to detect by any other means, in a sample of hundreds of exo-Kuiper belts around stars of different types and ages.
- 4. Survey of dust in habitable zones:** Exo-C's inner working angle of $0.16''$ at 550 nm will access the habitable zones of around 100 nearby stars.



Science Objective 1: Discover new planets

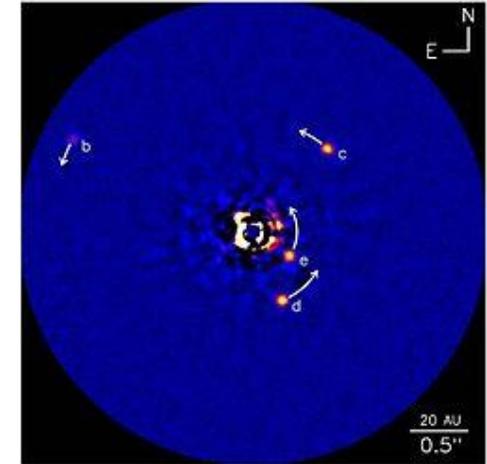
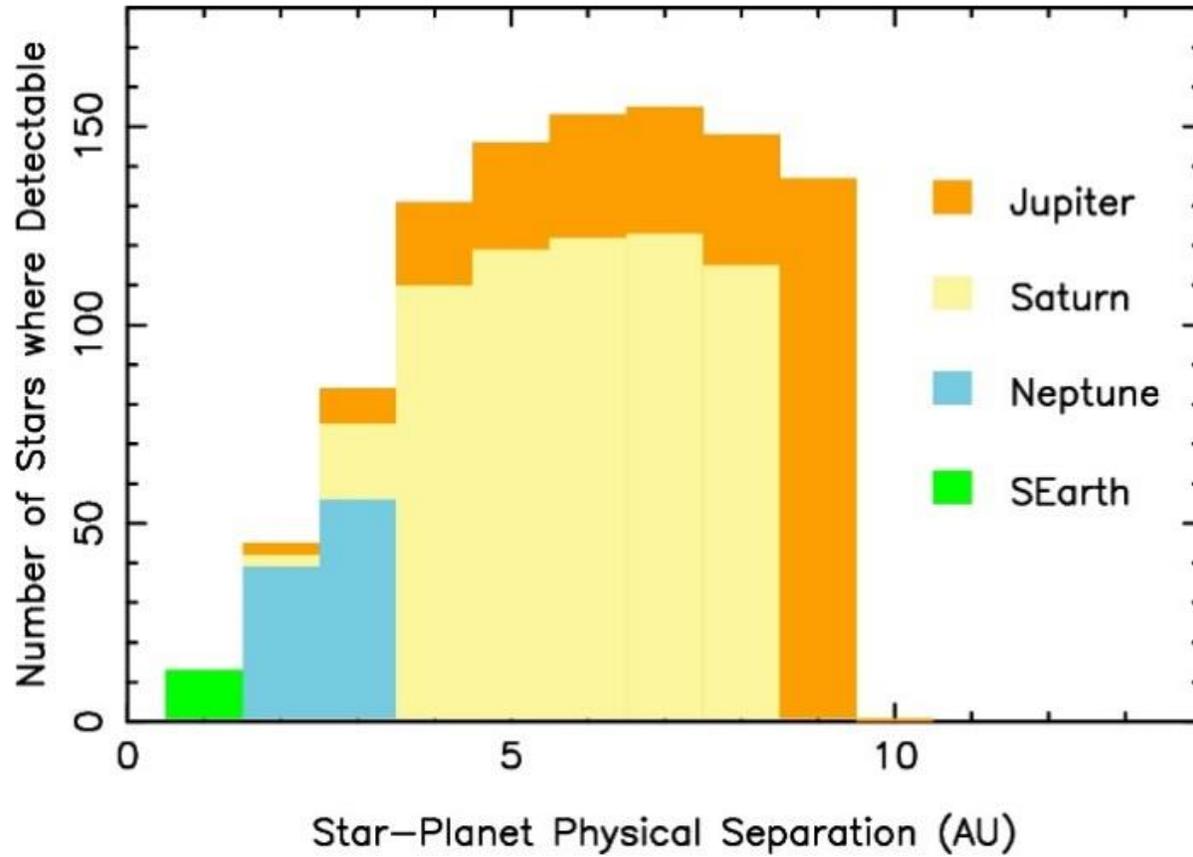
- Search for planets beyond RV limits in a nearby star sample, measure their orbits
 - Mid-F to K stars: New planets would be either small ones (mini Neptunes, super-Earths) unknown in our solar system, or long-period giant planets
 - A to mid-F stars: Any planets would be new vs. today, but Gaia should find some

- Right: HR diagram of the most suitable targets. RV-monitored stars shown in blue. 2/3 of best imaging targets not monitored by RV due to $T_{\text{eff}} > 6000 \text{ K}$
Figures from Howard & Fulton 2016





Exo-C discovery space for new exoplanets



- Histogram of detectable planets around nearby stars in total of 1 year of observing time. A search yield of $\sim > 15$ planets is expected.
- Probes a region not explored by GPI/SPHERE AO imaging surveys.



Today's known exoplanets potentially accessible to Exo-C

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Confirmed Planets

	Host Name	Planet Letter	Discovery Method	Number of Planets in System	Orbit Semi-Major Axis [AU]	Planet Mass or $M^* \sin(i)$ [Jupiter mass]	Distance [pc]	Gaia Distance [pc]	G-band (Gaia) [mag]	Calculated Angular Separation [mas]
<input checked="" type="checkbox"/>	HD 219077	b	Radial Velocity	1	6.22±0.09	10.39±0.09	29.2109957	29.21099578	5.9054804	212.9±3.1
<input checked="" type="checkbox"/>	HD 190360	b	Radial Velocity	2	3.97±0.07	1.54±0.08	16.0142682	16.01426823	5.533628	247.9±4.4
<input checked="" type="checkbox"/>	HD 142	c	Radial Velocity	2	6.8±0.5	5.3±0.7	26.2050915	26.20509151	5.5646787	259.5±19.1
<input checked="" type="checkbox"/>	47 UMa	c	Radial Velocity	3	3.6±0.1	0.540 ±0.066	13.8020833	13.80208330	4.8306003	260.8±7.3
<input checked="" type="checkbox"/>	HD 114613	b	Radial Velocity	1	5.34±0.26	0.357±0.032	20.2947501	20.29475016	4.604076	263.1±12.9
<input checked="" type="checkbox"/>	HD 217107	c	Radial Velocity	2	5.32±0.38	2.60±0.15	20.0734843	20.07348438	5.9545817	265.0±18.9
<input checked="" type="checkbox"/>	HD 160691	c	Radial Velocity	4	5.235	1.814	15.6050896	15.60508964	4.9045525	335.5±0.6
<input checked="" type="checkbox"/>	tau Cet	f	Radial Velocity	4	1.334 ±0.047	0.0124 ±0.0033	3.60339303	3.603393038	3.1336224	370.2±8.5
<input checked="" type="checkbox"/>	51 Eri	b	Imaging	1	12 ±4		29.4±0.3	29.78227303	5.122408	408.2±102.1
<input checked="" type="checkbox"/>	HR 8799	e	Imaging	4	16.4 ±2.1	10 ±7	39.4±0.1	41.29242953	5.898486	416.2±40.6
<input checked="" type="checkbox"/>	55 Cnc	d	Radial Velocity	5	5.503±0.030	3.878±0.068	12.5901130	12.59011303	5.7144375	437.1±2.4
<input checked="" type="checkbox"/>	bet Pic	b	Imaging	2	9.10 ±5.30		19.7538315	19.75383151	3.724775	460.7±146.8
<input checked="" type="checkbox"/>	HD 219134	h	Radial Velocity	6	3.11±0.04	0.34±0.02	6.53249876	6.532498763	5.207887	476.1±6.1
<input checked="" type="checkbox"/>	HD 221420	b	Radial Velocity	1	18.5±2.3	9.70 ±1.00	31.1695199	31.16951994	5.6412215	593.5±73.8
<input type="checkbox"/>	HR 2562	b	Imaging	1	20.3±0.3	30±15	34.0405609	34.04056094	5.988672	596.4±8.9
<input checked="" type="checkbox"/>	HR 8799	d	Imaging	4	24	10±3	39.4±0.1	41.29242953	5.898486	609.1±1.5
<input checked="" type="checkbox"/>	47 UMa	d	Radial Velocity	3	11.6 ±2.9	1.64 ±0.29	13.8020833	13.80208330	4.8306003	840.5±181.1
<input checked="" type="checkbox"/>	HR 8799	c	Imaging	4	38	10±3	39.4±0.1	41.29242953	5.898486	964.5±2.4
<input checked="" type="checkbox"/>	eps Eri	b	Radial Velocity	1	3.39±0.36	1.55±0.24	3.2116±0.0	3.202878581	3.3691404	1056±112
<input checked="" type="checkbox"/>	kap And	b	Imaging	1	55±2	13.616 ±1.04	50.0622794	50.06227946	4.052862	1099±44
<input checked="" type="checkbox"/>	HR 8799	b	Imaging	4	68	7 ±4	39.4±0.1	41.29242953	5.898486	1726±4



Nearby HZs where Exo-C could attempt detection of an Earth-size planet

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 included as a noise source. eta Cas is a 12" binary. Exozodiacal light at the minimal 1 zodi level is assumed.

epsilon Eridani has an LBTI excess indicating a dusty habitable zone; this is not taken into account for the integration time given here.

Finally, detection of an exo-Earth would require that Exo-C exceed its telescope stability requirements (but see chart 34).



Science Objective 2: Exoplanet spectra

- Obtain optical spectra: detect gas absorbers CH_4 , H_2O , constrain abundances and depth of cloud deck.
- Timeseries photometry and astrometry to measure phase curves. Can also determine orbit inclination, resolve $\sin i$ ambiguity in planet mass (but Gaia might do this).

Fig. 4.3-1
model
Jovian planet
Spectra at $R=70$

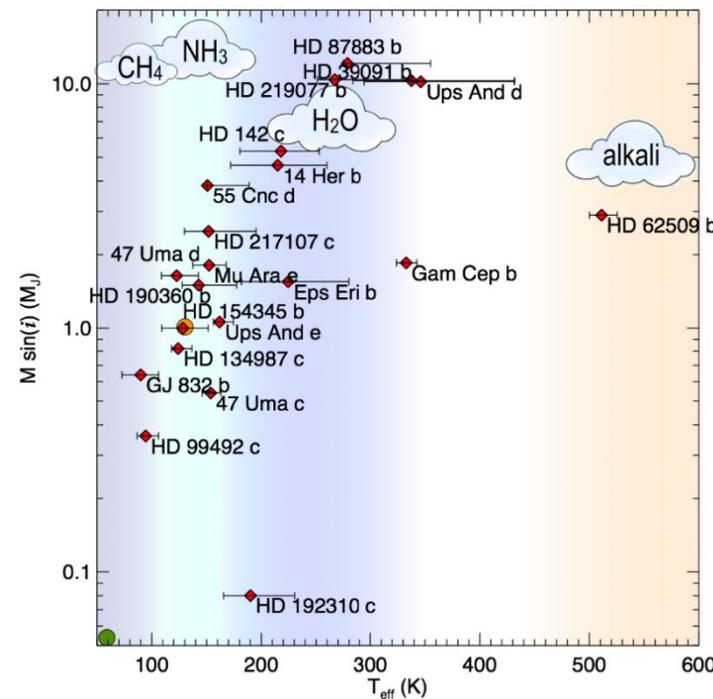
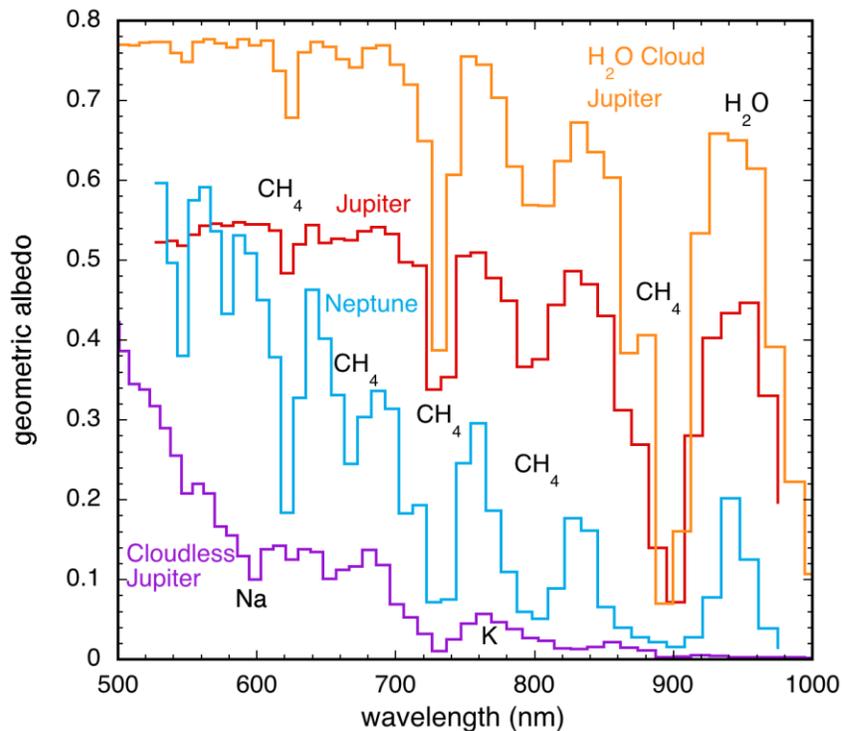
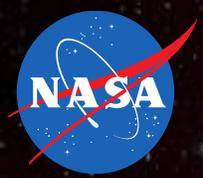


Fig. 4.2-4
Mass-temperature
span of likely
Exo-C targets



Objective 2: Exoplanet spectroscopy requirements

- Spectral resolution $R=70$ required
 - Measures strong & weak CH_4 bands
 - Measures O_2 $0.76 \mu\text{m}$ feature in Earth-like atmospheres
 - Provides clean inter-band continuum
- Wavelength coverage spans optical
 - $0.45 \mu\text{m}$ short wavelength cutoff provides access to Rayleigh scattering continuum
 - $1.0 \mu\text{m}$ long wavelength cutoff covers strong $0.94 \mu\text{m}$ H_2O line & continuum
- $\text{S/N} = 5$ detects the stronger features, 10 detects the weaker ones, 20 needed for abundances.

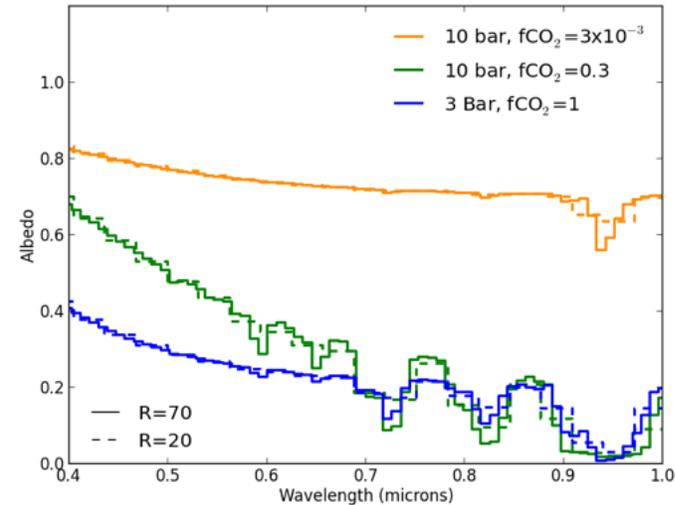
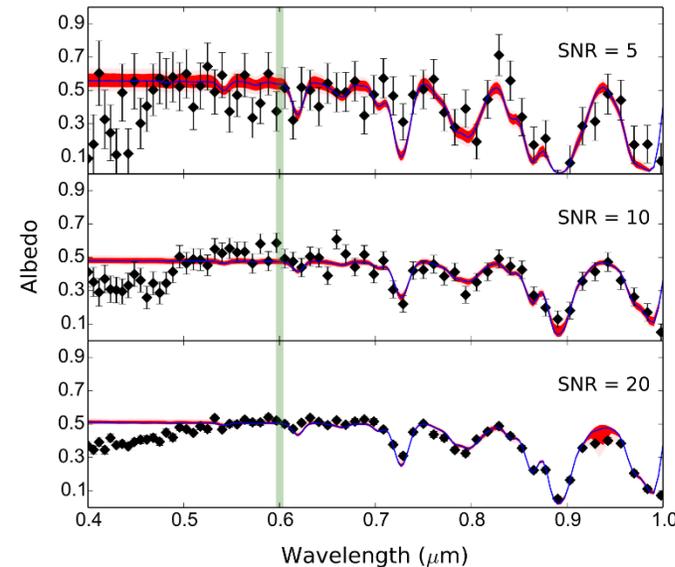


Fig. 4.3-4
model
super-Earth
spectrum



Jupiter
spectrum
measured at
different S/N
ratios



Science Objective 2: Simulated Exo-C spectra

Work by Ty Robinson (at NASA Ames in 2015, now at NAU)

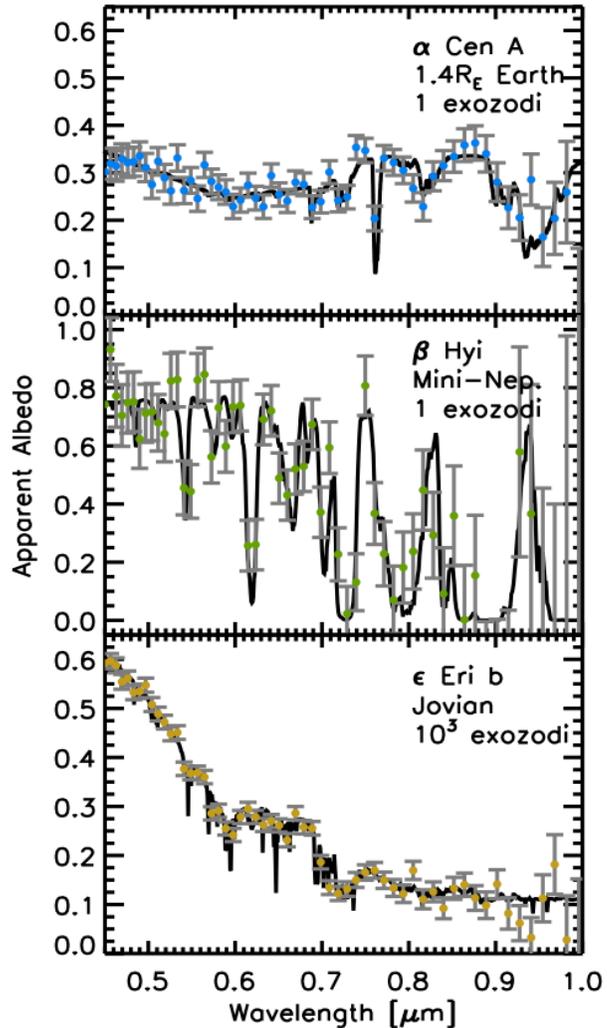


Fig. 4.3-6
Simulated Exo-C spectra putative and real targets. Integration times are a month for the top and middle panels, a week for the bottom panel

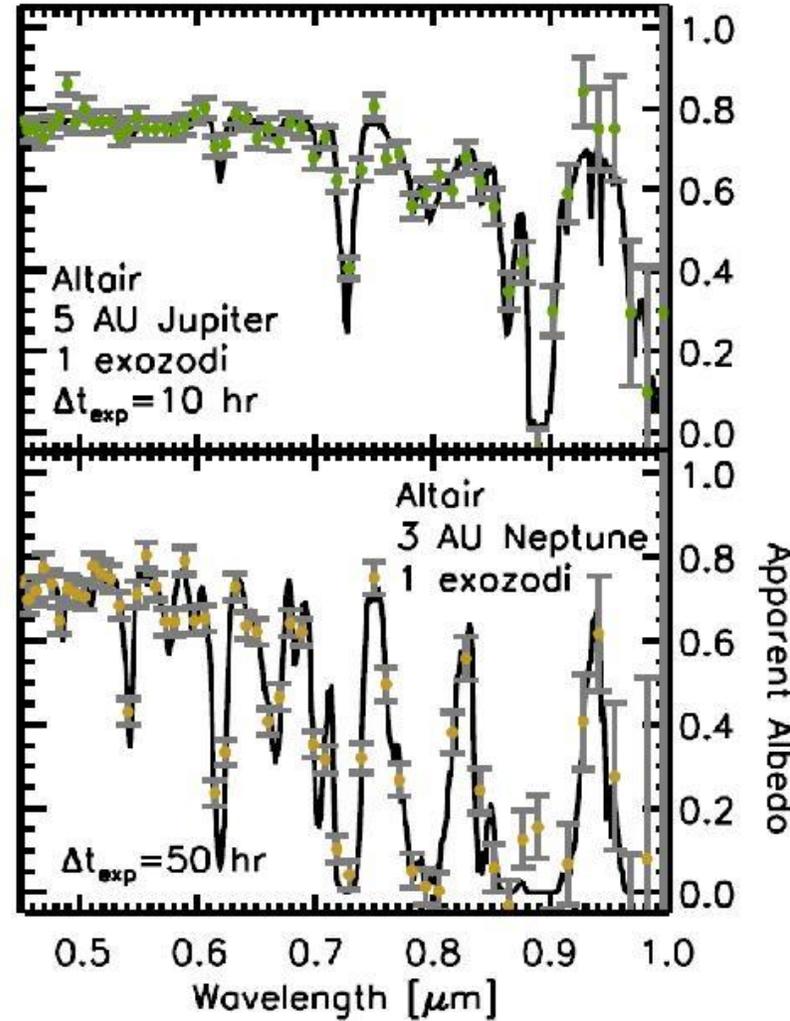
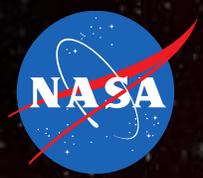


Fig. 4.3-7



Science Objective 3: Circumstellar Disk Imaging

- Debris disks detectable with today's instruments are ~1000 times dustier than the solar system with dynamics dominated by dust-dust collisions.
- Exo-C will image debris dust down to levels near that of the Kuiper Belt, where radiative forces drive dust transport and sort grains.
- Resolved structures in tenuous debris disks will indicate where planets sculpt parent body belts & block the inward flow of grains: indirect planet detections.
- Exo-C will detect the faint scattered light counterparts of protoplanetary disks mapped by ALMA (right).

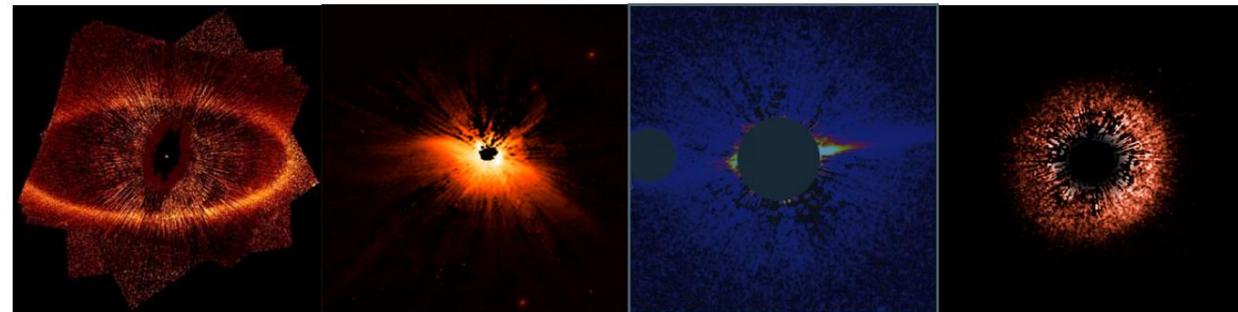
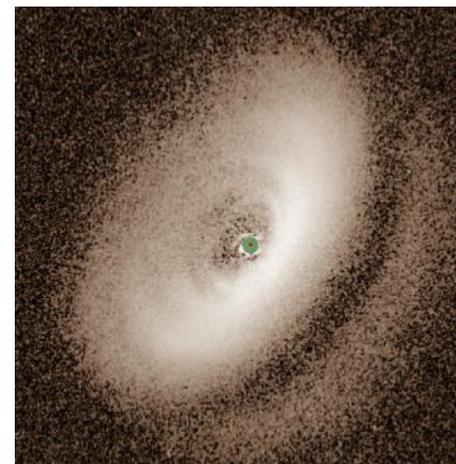
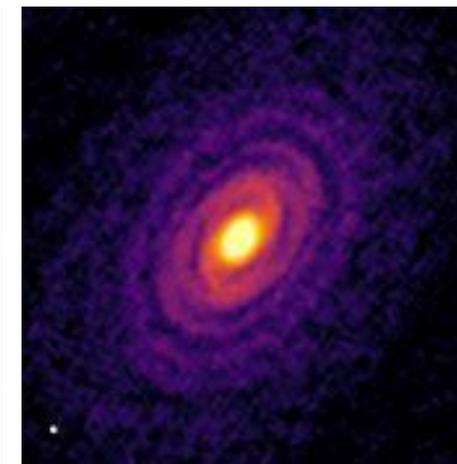


Figure 4.2-10. Optical imaging of debris disks by Hubble reveals a variety of disk structures—from smooth belts to eccentric rings, bow shocks, warps, and other asymmetric structure (Fomalhaut, Kalas et al. 2005; HD 61005, Hines et al. 2007; HD 15115, Kalas et al. 2007; HD 107149, Ardila et al. 2004).

Young star IM Lupi



Avenhaus et al. 2018
VLT SPHERE 1.6 μm



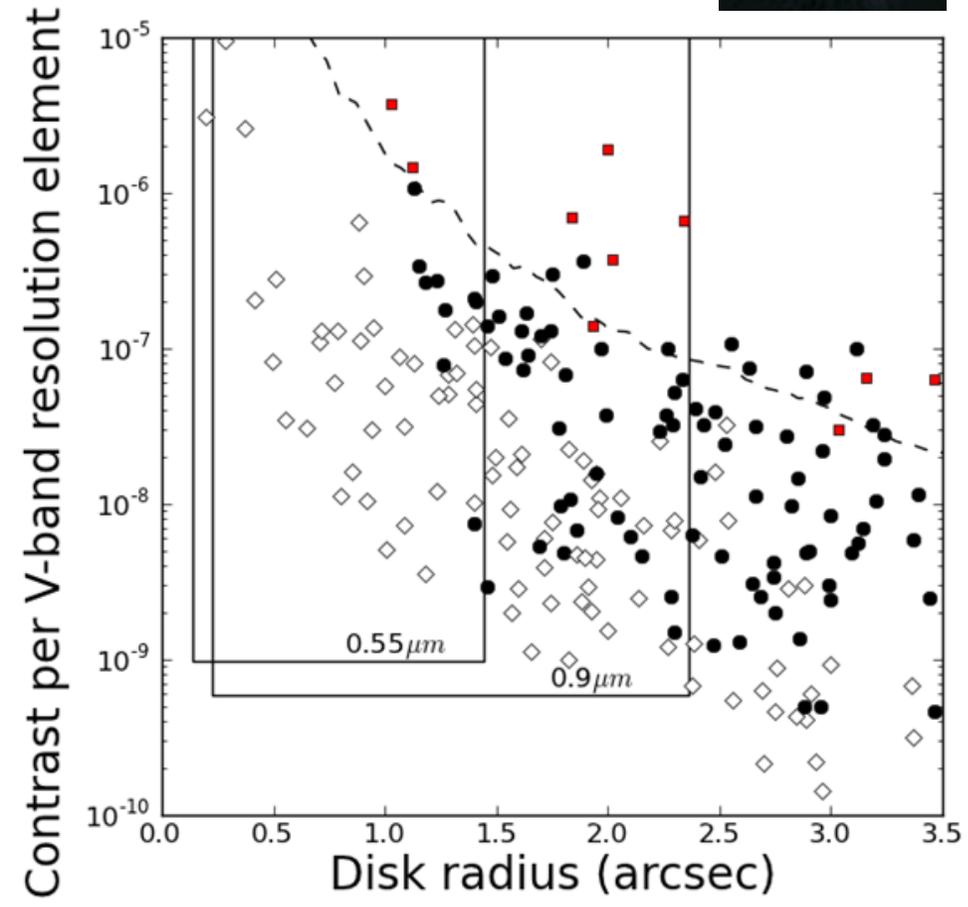
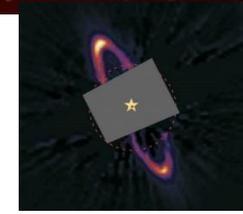
Andrews et al. 2018
ALMA 1.3 mm continuum



Science objective 3: debris disk targets are abundant

Predicted disk sizes and contrasts for Herschel-detected disks within 40 pc

- Boxes show Exo-C dark hole region for imaging detections
- Red points: The small number of debris disks imaged in scattered light up to 2015
- Black points: Disks with sizes known from Herschel data (measured at 5" resolution)
- Hollow points: Disks whose sizes can be estimated from far-Infrared spectrum and assumed dust properties.

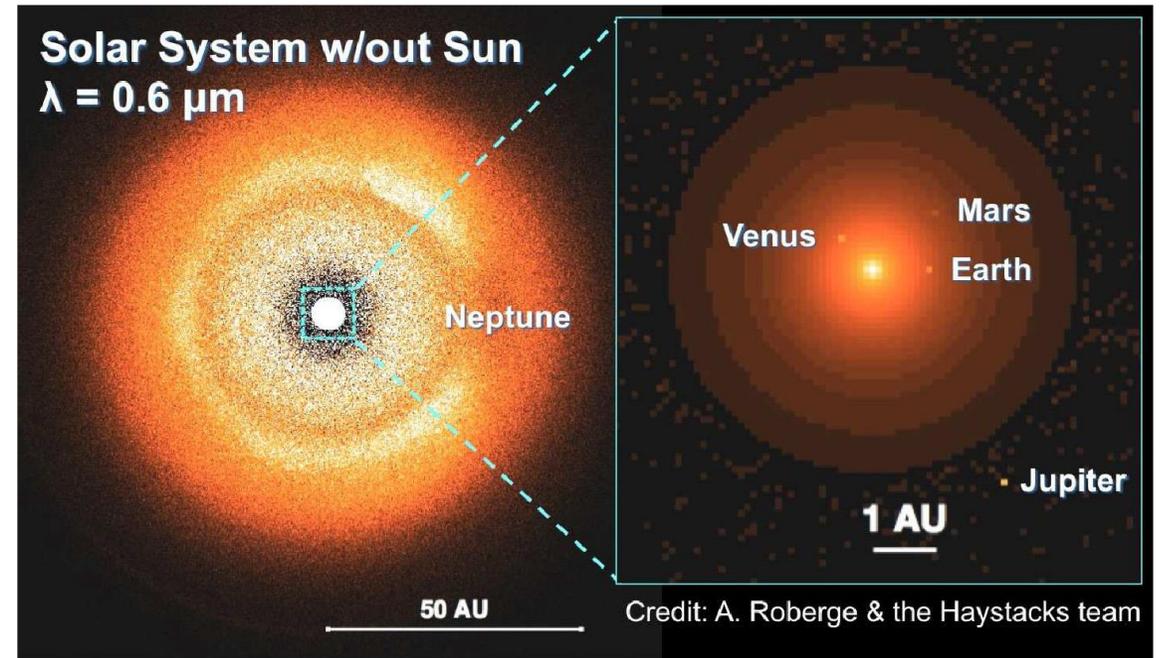


Plot by Geoff Bryden



Science Objective 4: Imaging dust near the HZ , “exozodi”

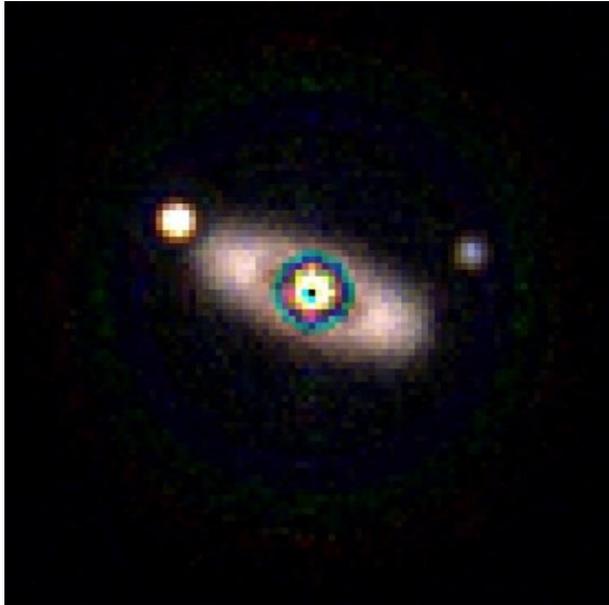
- LBTI “HOSTS” survey of 38 stars has constrained the median level of HZ dust to be $4 +10 / -3$ times the solar system level (Ertel et al. submitted), with the faintest thermal IR detection being 30 zodis.
- Exo-C could detect a few zodis of dust in the outer HZ around roughly 100 nearby stars, in scattered light as for the future flagship.
- For a subset of these exozodi structure might be resolved: gaps & asymmetries that trace presence of planets near the HZ.



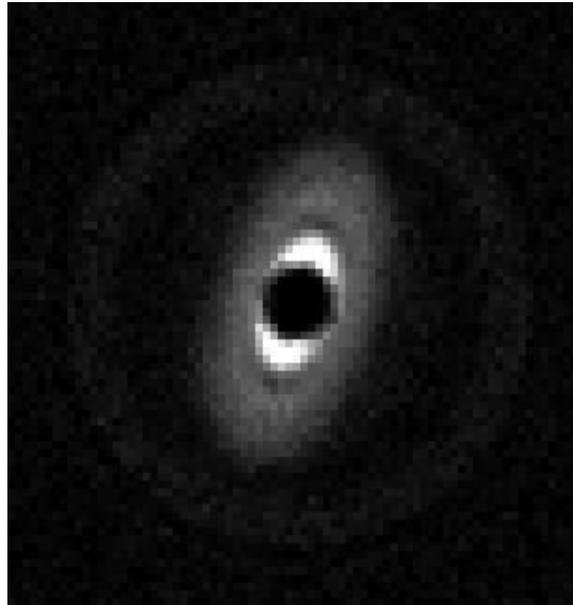
Simulation of structure in the Kuiper Belt and local Zodiacal cloud, with respect to locations of solar system planets



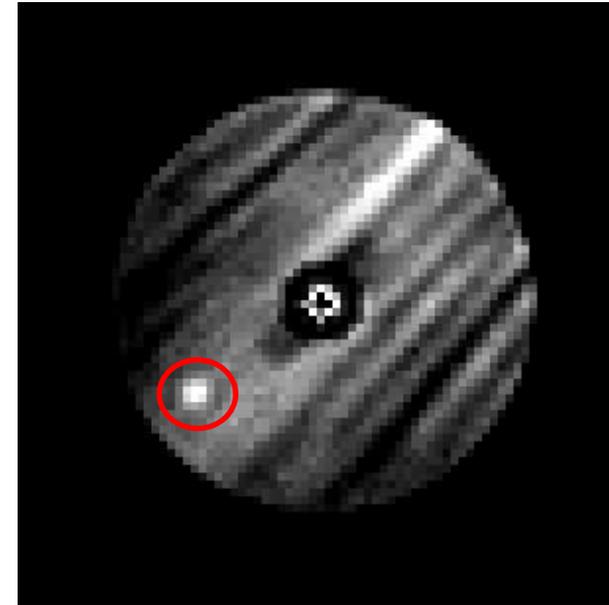
Exo-C Simulated Imagery: Disks & α Centauri



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. Requires better-than-nominal system stability (but see chart 34)

All simulations use Hybrid Lyot Coronagraph optical models by John Krist



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 dust near the habitable zone 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 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 ₂ O

Target Category	# Stars	Median V mag
Known RV planets	12	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

Brightest (best) spectroscopy targets will be the planets discovered through the mission searches



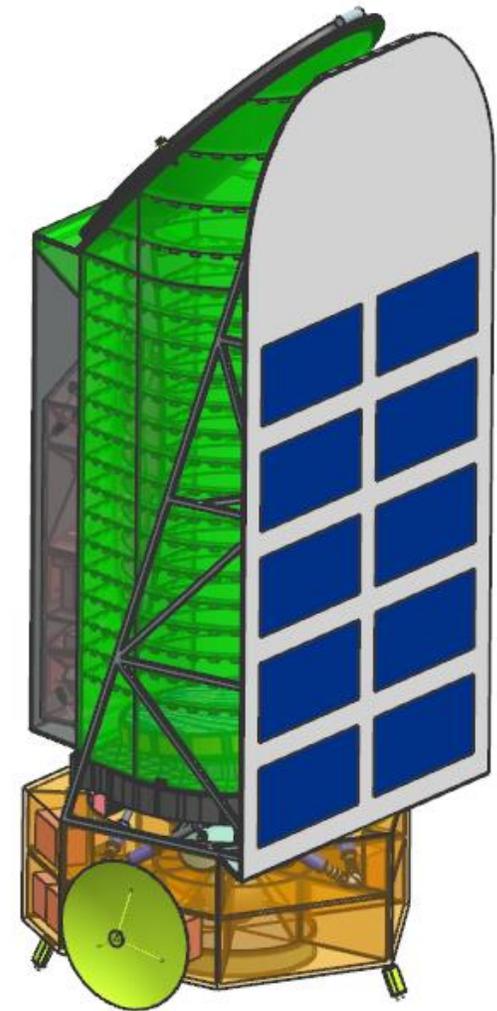
Exo-C Technical Specifications

Telescope primary mirror	1.4 m diameter
Speckle contrast residuals	10^{-9} raw at IWA, better further out
Contrast disturbance due to pitch/roll	10^{-11} @ IWA after 2 hours
Spectral coverage	450–1000 nm
Spectral resolution $\lambda > 500$ nm	$R = 70$
Inner Working Angle (IWA) $2 \lambda/D$	0.16" @ 500 nm, 0.24" @ 800 nm
Outer Working Angle $\sim 20 \lambda/D$	2.6" @ 800 nm
Spillover light from binary companion	3×10^{-8} raw @ 8", TBD additional reduction from wavefront control
Astrometric precision	< 30 milliarcsec (limited by SNR)
Fields of view	42" imager, 2.2" spectrograph
Launch Mass / Vehicle	1656 kg / Falcon 9 or Atlas 501
Mission lifetime	3 years in Earth-trailing orbit



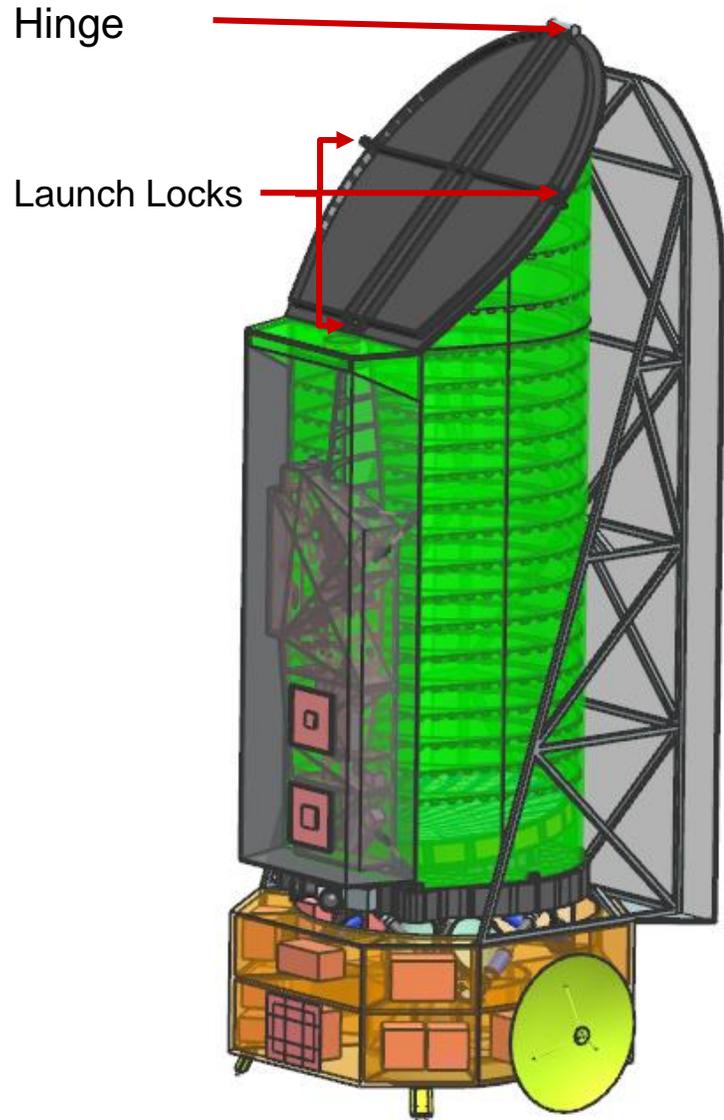
Exo-C Architecture Overview

- 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
 - Same aperture as Kepler's spherical primary
- Hybrid Lyot coronagraph was the 2015 baseline due to best technical readiness
- 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 Subsystem Description

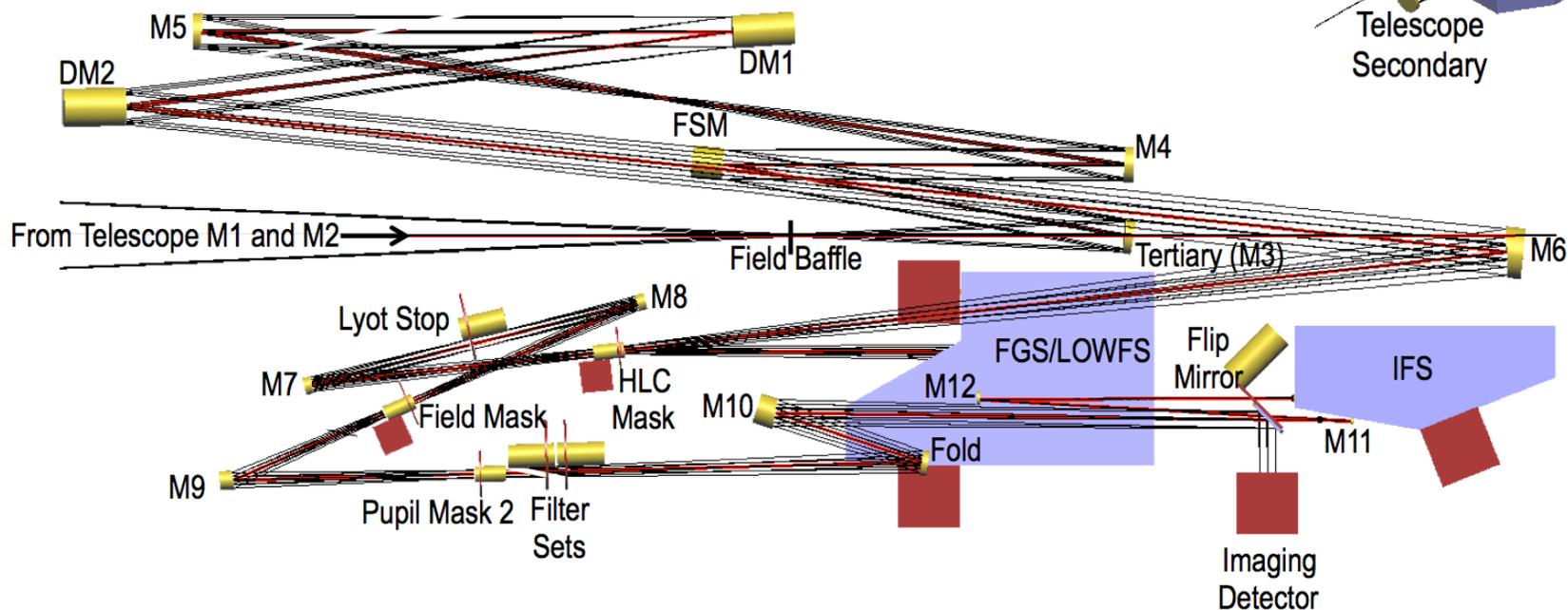
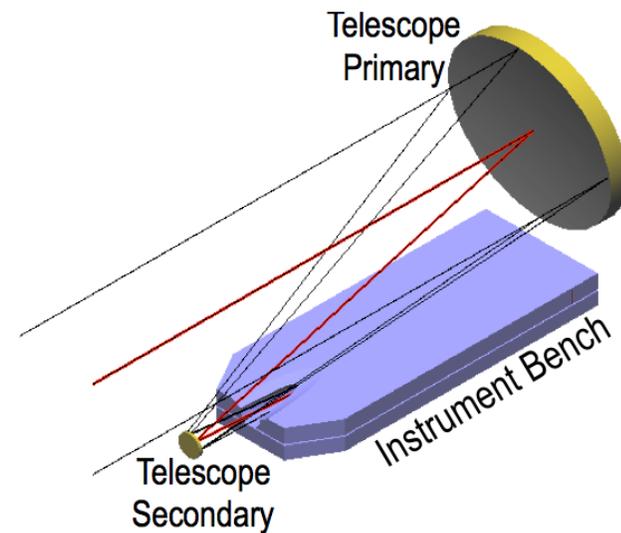


- Solar Array/Sunshade
 - SA/Sunshade Support Structure
 - Barrel Structure
 - Removable Lid
 - Secondary Mirror Assy
 - Instrument Enclosure
 - Instrument Bench Assy
 - Primary Mirror Assembly
 - Primary Support Structure
 - Radiator Panel Assembly
 - Star Tracker Assembly
 - Isolation Assembly
 - Spacecraft Assembly
 - SC and Payload Electronics
 - Reaction Wheel Assy
 - Propulsion Assy
 - LV interface Ring Assy
- 6.4m
- 2.6m



Optical Design Overview

- Lateral instrument bench – instead of aft of primary mirror:
- Allows for lower angle of incidence reflections which reduce induced polarization aberrations on the wavefront
 - Large available volume minimizes the number of fold mirrors needed
 - Lowers overall spacecraft height
- Two 48x48 deformable mirrors are the baseline

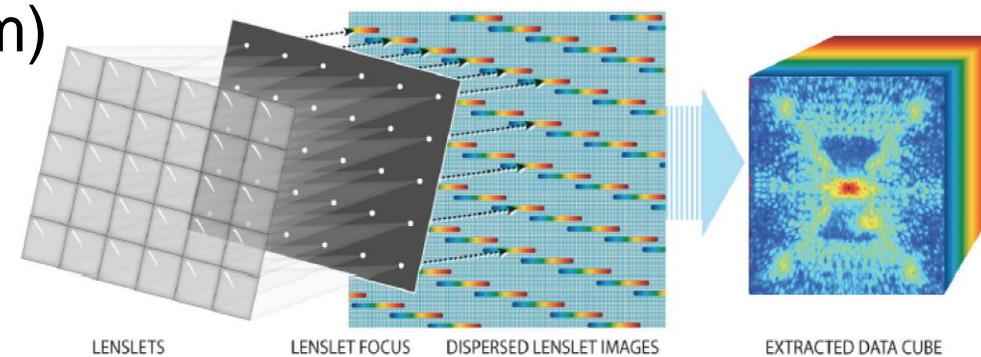




Integral Field Spectrograph (IFS)

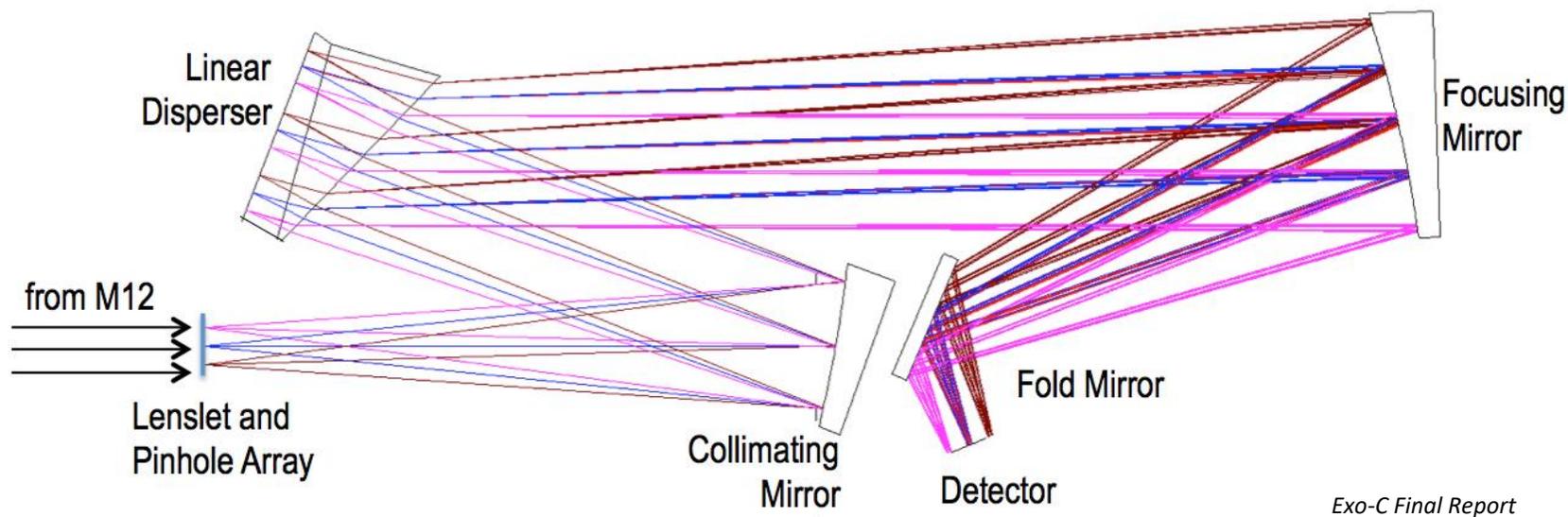
- 1k x 1k EMCCD and 48 x 48 actuator DM
 - Exo-C: 71 x 71 lenslets with 2.3" x 2.3" FOV does not cover OWA (3.5" FOV @ 1 μm)
- 2k x 2k EMCCD for Exo-C:
 - 143 x 143 lenslets, 4.6" x 4.6" FOV

IFS Conceptual Design



McElwain et al, 2012

Compact IFS optical layout with no moving parts



Exo-C Final Report



Observatory stability: Effect of residual pointing jitter on contrast

- Exo-C's benign Earth trailing orbit and lack of articulated or deployable structures minimize environmental and spacecraft disturbances.
- Two stages of passive isolation suppress reaction-wheel disturbance.
- Light from the central star is reflected by the coronagraph mask and used to by the fine-guidance sensor in closed loop with the fast-steering mirror loop to reject LOS jitter.
- Spacecraft body pointing stability 16 mas

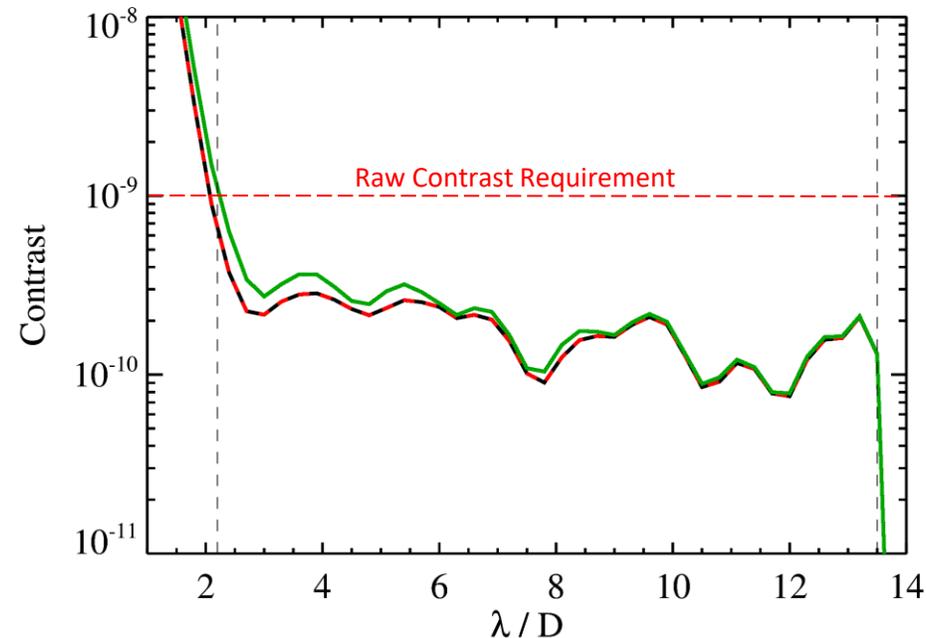


Image contrast achieved by Exo-C using a Hybrid Lyot Coronagraph, including the effects of pointing jitter. The black and red lines show the indistinguishable effects of 0 and 0.4 mas of jitter, while the green line is the Exo-C 0.8 mas performance requirement.

Changes in the reaction wheel speed due to spacecraft maneuvers should not cause excessive jitter induced contrast degradation nor changes in the speckle background.



Observatory stability: Features of thermal design

The secondary mirror and optical bench are highly isolated from solar heating so that the PM-SM de-space is not perturbed by a changing solar load on the sunshade.

MLI isolates optical barrel from space and from the sunshade.

Primary sits in a thermal bath formed by the actively heated barrel, PM shroud, and thermally controlled bipods.

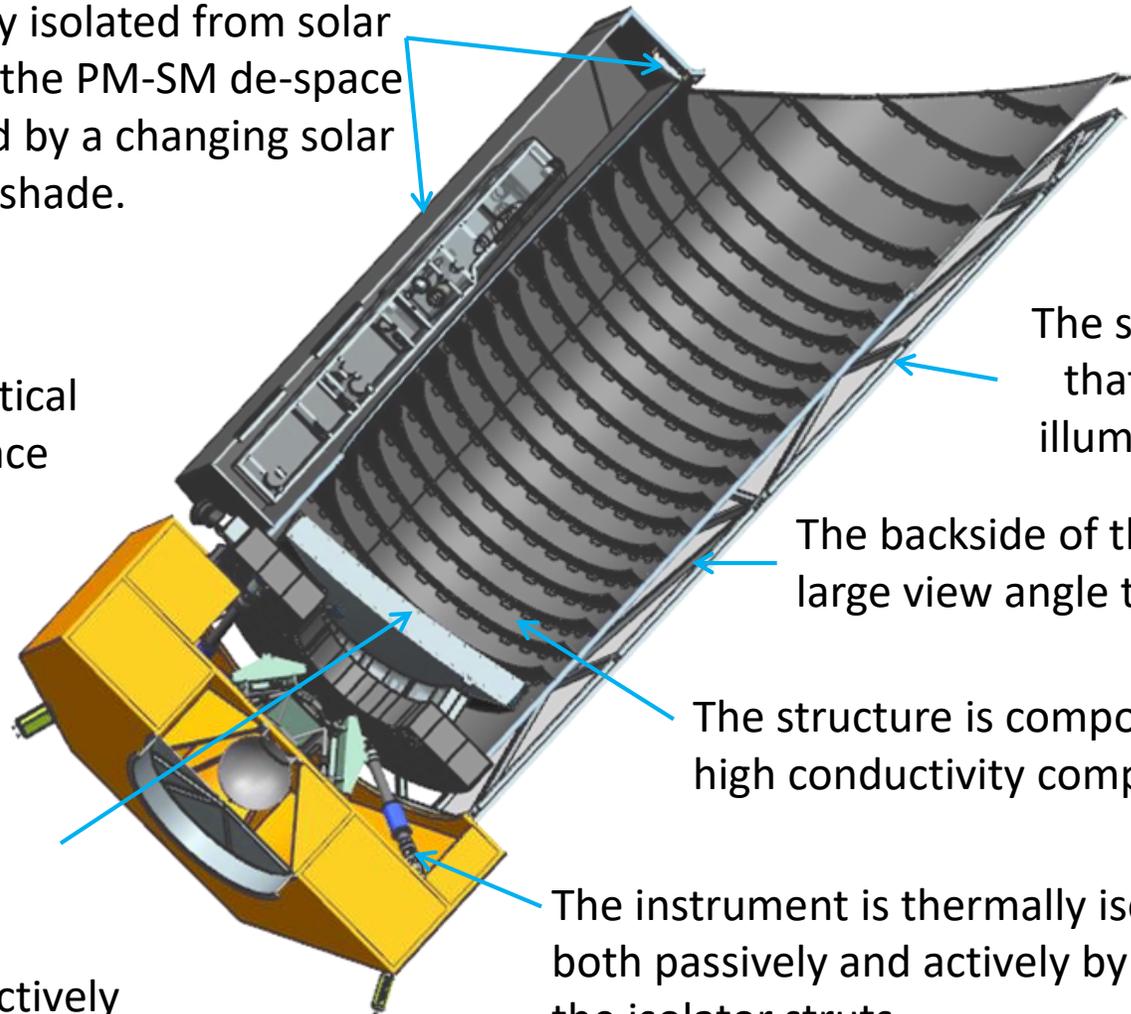
Benign Earth trailing environment

The sunshade ensures that sunlight never illuminates the barrel.

The backside of the sunshade has a large view angle to space.

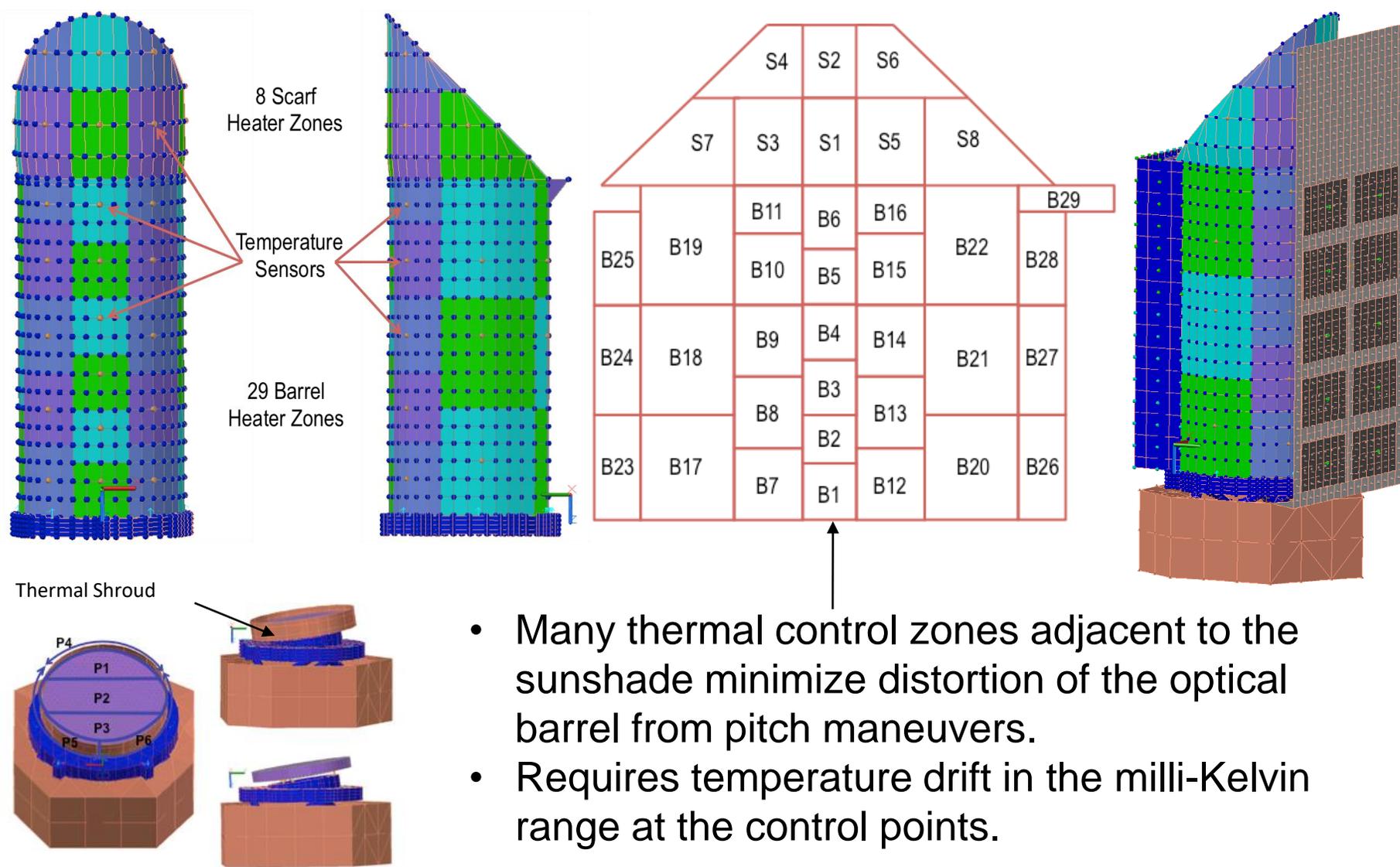
The structure is composed of low CTE high conductivity composite.

The instrument is thermally isolated from the bus both passively and actively by thermal control of the isolator struts.





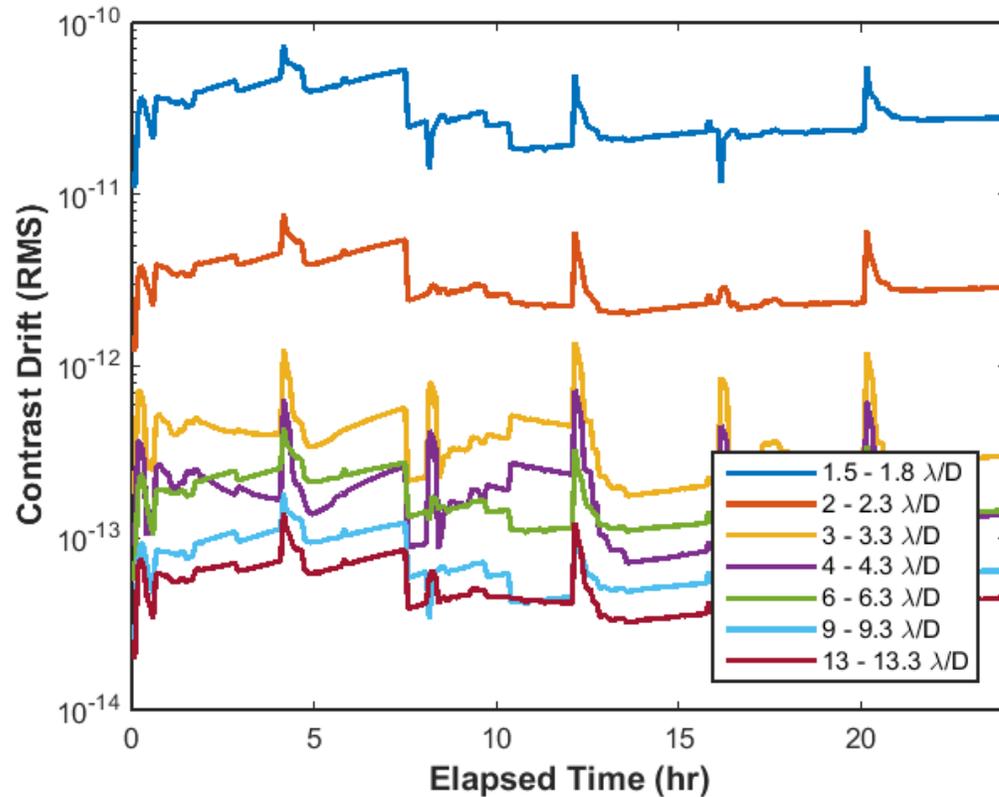
Observatory stability: Structural and control nodes for Exo-C thermal model



The control zone density is highest where the solar heat load is the most variable.



Observatory stability: Effect of spacecraft thermal drift



The spacecraft bus thermal disturbance was modeled as a square wave with an eight hour period and a 1°C peak-to-peak temperature variation of the entire bus.

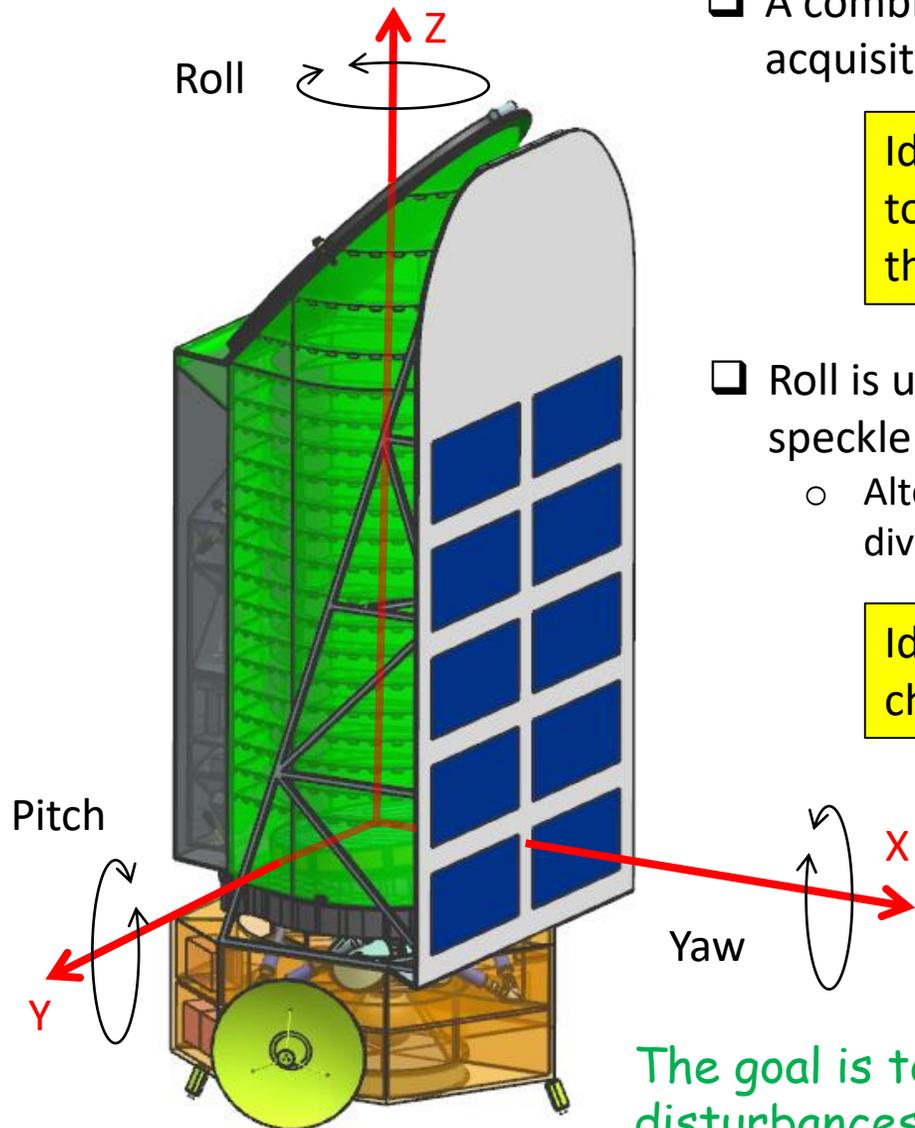
From Kepler's lessons-learned the Exo-C observatory was designed to be thermally isolated from the spacecraft bus. Thermal blankets, low conductivity struts and active thermal control of bipod interfaces nearly eliminate variations in heat transfer across the spacecraft bus / instrument interface.

Simulations by Joel Nissen

The contrast drift is an order of magnitude below the requirement at $2\lambda/D$.



Observatory stability : reference maneuvers



- ❑ A combination of pitch and yaw are used for target acquisition.

Ideally we could maneuver from calibration star to target or target to target without retuning the dark hole.

- ❑ Roll is useful in separating a planetary signal from the speckle background
 - Alternatives are spectral diversity and deformable mirror diversity.

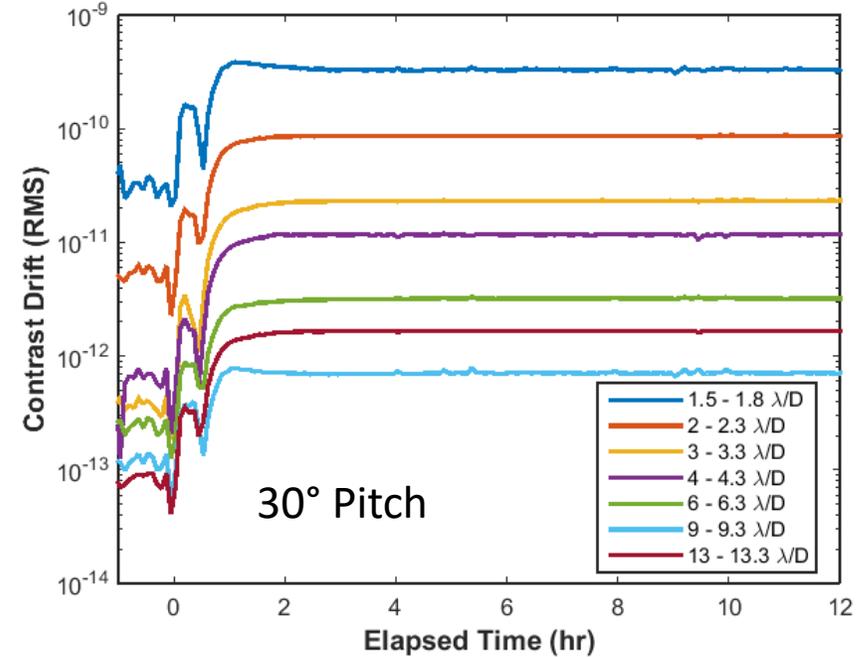
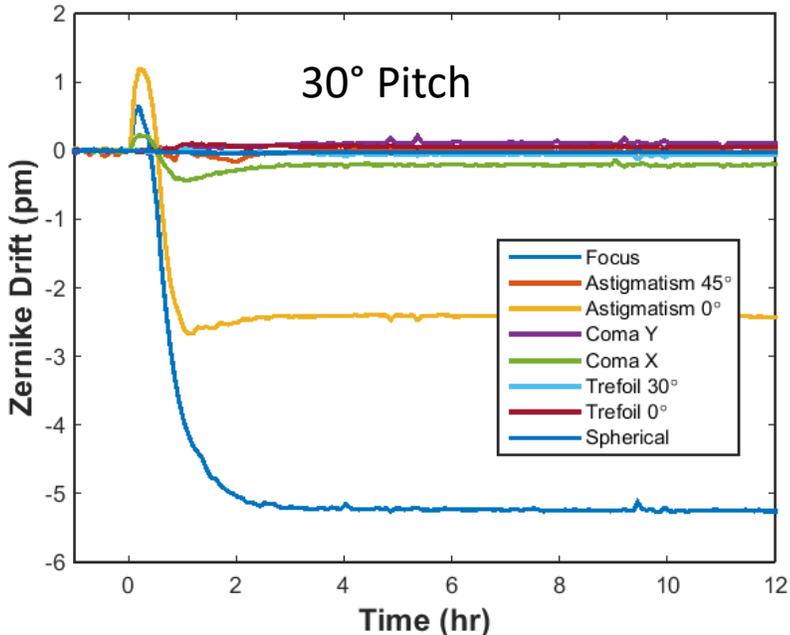
Ideally we could roll the observatory without changing the speckle field.

The goal is to minimize the magnitude of thermal disturbances and the duration of the transients.



Observatory stability: Hybrid Lyot coronagraph

Contrast drift from a 30° pitch maneuver



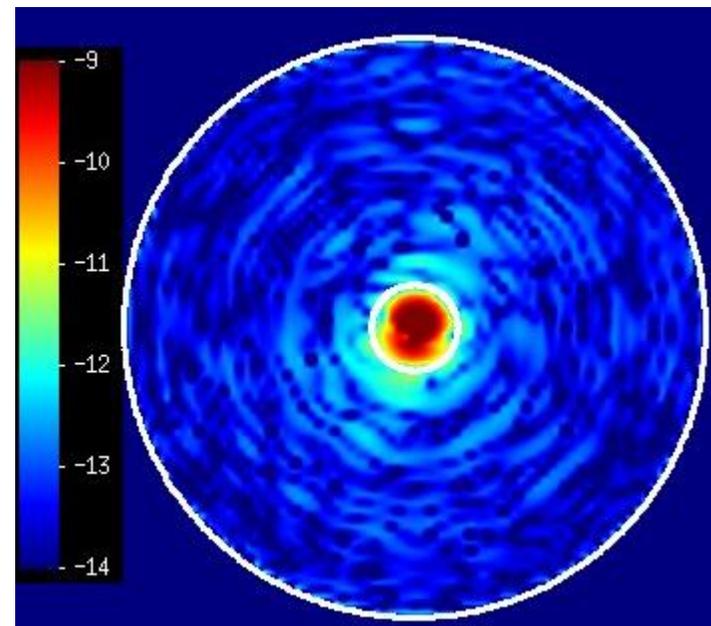
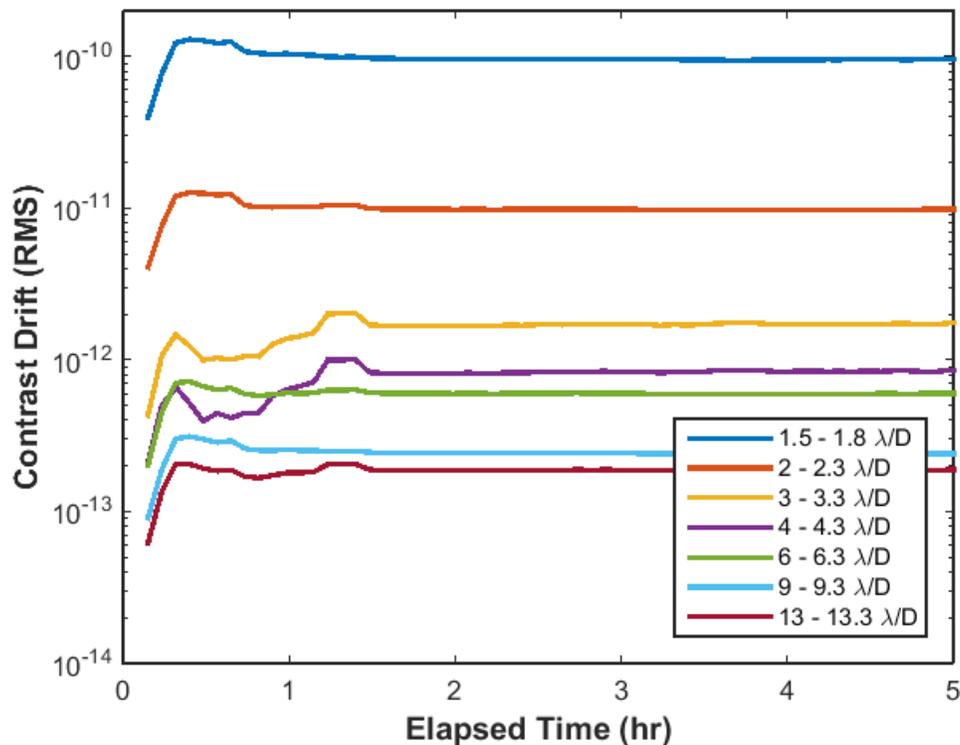
- Pitch maneuver starting at $\beta = 90^\circ$ and ending at $\beta = 120^\circ$.
- picometer WF stability achieves 10^{-10} drift requirement at the IWA = $2\lambda/D$.
- The model suggests that when the dark hole is tuned on a bright calibration star near $\beta = 90^\circ$, the observatory can pitch to a target between $\beta = 60^\circ$ and $\beta = 120^\circ$ without retuning the dark hole.

Contrast Drift is Dominated by Thermally Induced Displacement of the SM



Observatory stability: Hybrid Lyot coronagraph

Contrast drift from a 30° roll maneuver



Contrast drift from rolling the observatory. The small white circle is at IWA = $2\lambda/D$

Rolling the spacecraft from -15° to $+15^\circ$ from the Sun induces very little drift due to symmetric solar loads. This maneuver is a powerful tool in distinguishing a planet from the speckle background.

Simulations by Joel Nissen

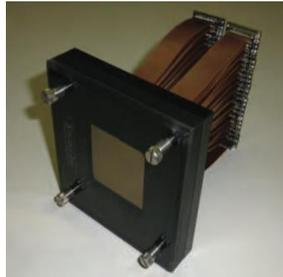
Contrast drift meets the 10^{-10} requirement even at $1.5\lambda/D$.



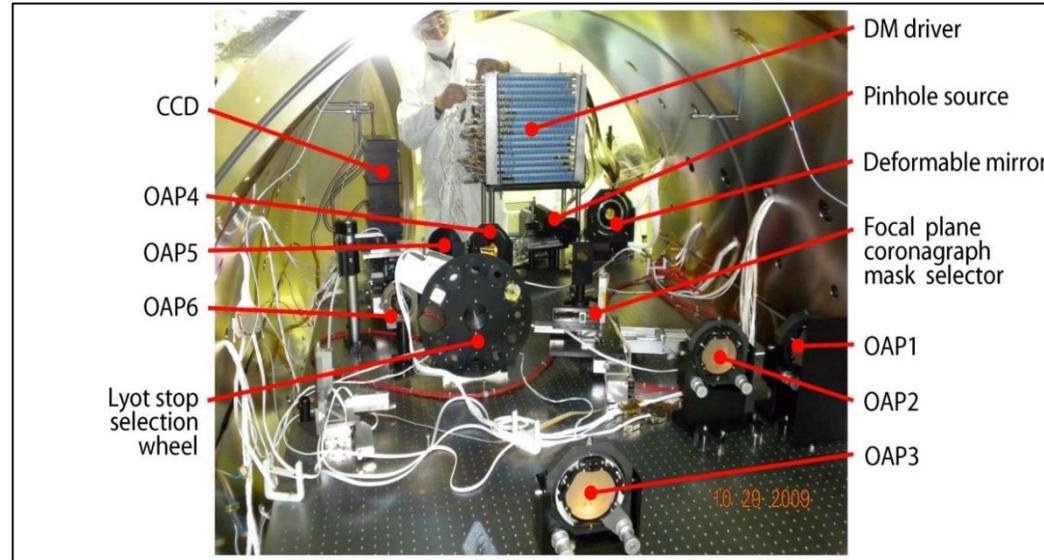
Exo-C coronagraph technology is nearly ready

- Since 2002 NASA has been testing and developing coronagraphs with wavefront control

48x48 Xinetics deformable mirror has been shake tested

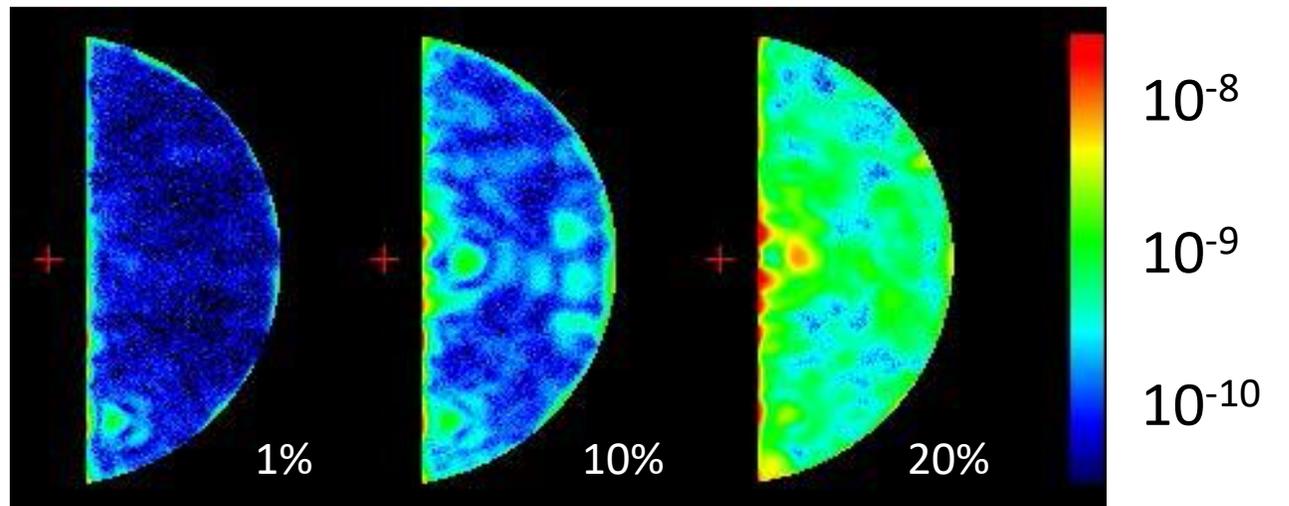


NASA High Contrast Imaging Testbed



- State of the art: Contrast versus spectral bandwidth

Unobscured pupil, single DM, Trauger et al. 2012 with linear version of hybrid Lyot coronagraph





Project cost estimate as updated in 2017

WBS	EXO-C Update Estimate	BOE
Total Project Cost	\$ 971.5	
Technology Development	\$ 4.5	
LOWFS	1.0	Expert judgment
IFS		Expert judgment
Coronagraph	3.5	Expert judgment
Phase A-D Total	\$ 889.2	
01.0 Project Management	64.7	Team X percentages of the total development costs (less L/V and reserves) were used for WBS 1.0, 2.0 and 3.0.
02.0 Project Systems Engineering (incl. Mission Design)		
03.0 Mission Assurance		
04.0 Science	12.7	Kepler actual costs
05.0 Payload System	288.0	NICM V for coronagraph (\$165M), Stahl 2013 Telescope Model (\$104M), Grass roots for vibration isolation (\$5M).
06.0 Flight System	186.8	Based on Kepler actual costs with adjustments for: 1) better reaction wheels (\$0M), 2) improved IRU (\$1.7M), and 3) vibration isolation on reaction wheels (\$1M). Adjustment were estimated using Team X design tools. Procurement burden included.
07.0 Pre-Launch Mission Operations	32.8	Kepler actual costs
08.0 Launch Vehicle	110.0	Specified in guidelines. Based on Team X data
09.0 Ground Data Systems	14.5	Kepler actual costs
10.0 ATLO	inc	Included in WBS 6.0
11.0 Education and Public Outreach	-	Kepler actual costs
Development Reserves	179.8	30% of development costs less launch services (WBS 8.0)
Phase E-F Total	\$ 77.7	
Science and Flight Operations	59.8	Kepler operating costs scaled down to 3 years
Development Reserves	17.9	30% of operations costs

All costs are in \$ FY 15

Further updating to reflect CGI experience up to 2019 would be beneficial

The cost information shown here 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/or Caltech.



Highlights of Exo-C 2015 Aerospace CATE analysis

- Overall technical risk rating was “Medium”. Remaining risks:
 - System engineering development to achieve 0.8 mas pointing
 - Demonstrate $2 \lambda/D$ IWA performance with 10^{-9} raw contrast
- Mass margin ample, power margin adequate
- Low operational risk: Kepler and Spitzer operations experience in Earth-trailing orbit is applicable
- Cost very close to JPL estimate but adds margin for “design threats”
- Inquire at Aerospace Corporation for a copy of the Exo-C CATE report



Exo-C technical readiness has advanced since 2015

- Mass, power, and cost estimates for WFIRST CGI informed a 2017 update to the corresponding estimates for Exo-C's coronagraph
- WFIRST CGI Project technical work directly applicable to Exo-C:
 - Detailed characterization of EMCCD detectors (operating modes, radiation tolerance)
 - Detailed characterization of deformable mirrors (stability & environmental testing)
 - Dynamic laboratory contrast demonstrations with a low-order wavefront sensor driving active tip/tilt and focus correction
 - Progress toward ASIC controllers for the DMs (reduces mass, power, volume required)
 - Improved system throughput budget & understanding of operational overheads
 - Detailed science requirements flowdown up to 2017
- Prototype integral field spectrograph built, tested in HCIT at relevant contrast levels
- Coronagraph mask developments funded by NASA SAT program:
 - Hybrid Lyot (prime) and Vortex, PIAA (backups) all funded over the last few years



Exo-C technical updates for future consideration:

- Coronagraph architecture: Hybrid Lyot was the 2015 baseline
 - Vector vortex charge 6 offers better aberration sensitivity but at the price of a larger inner working angle and operation in only one polarization at a time
 - PIAA offers much higher throughput but with worse aberration sensitivity
 - Should revisit this trade to see if Hybrid Lyot is still the best option
- Assess readiness of larger 2048x2048 detectors for IFS
- Tech demo instrumentation and telemetry needs are better understood now and would need to be incorporated into the Exo-C design
- HabEx's microthruster approach to fine pointing should be evaluated for possible inclusion on Exo-C
- Potential for using Exo-C with a starshade



Programmatic niches for Exo-C

- If cost or schedule issues forced WFIRST to drop its CGI instrument, Exo-C is a backup option that would recover the needed tech demo.
- If Astro2020 prioritizes a large direct imaging mission (e.g. LUVOIR or HabEx) for development in the 2020s & flight in the 2030s, Exo-C might be a distraction. A flagship could do all the Exo-C science, and WFIRST CGI must remain on-track to preserve technical & programmatic momentum.
- If Astro2020 does not prioritize a large direct imaging mission, then it could mean no space-based high contrast science mission until the 2040s.
 - In that scenario, the Exo-C mission would offer an extensive and robust direct imaging science program & technology demonstration during the long wait for a flagship mission

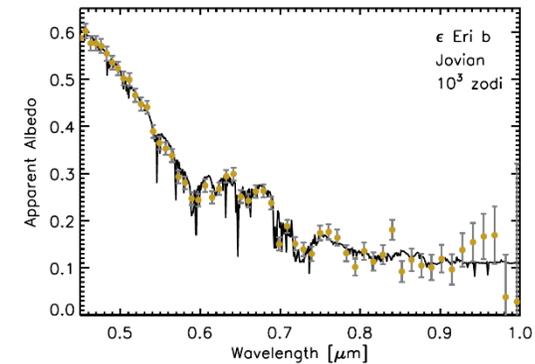


Summary of Exo-C Probe Mission Study

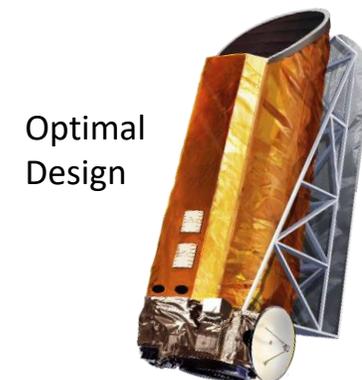
- Exo-C is a study of a Kepler-class space observatory optimized for very high contrast optical imaging and spectroscopy with an internal coronagraph
- The 3 year Design Reference Mission could observe > 400 unique targets to discover and characterize exoplanets and circumstellar disks. Spectra or colors for ~2 dozen planets could be obtained
- Baseline design has excellent modeled contrast stability of $< 10^{-10}$ at its $2 \lambda/D$ inner working angle
- Exo-C's aperture, orbit, spacecraft, & lifetime are virtually the same as those of the Kepler mission
- Launch would be 7 years after Project start
- Exo-C study cost estimate was \$972 M FY 15, independent estimate is only slightly higher
- This is an executable probe mission option for the 2020s



Planet discovery - Altair



RV planet spectrum - ε Eridani b



Optimal Design

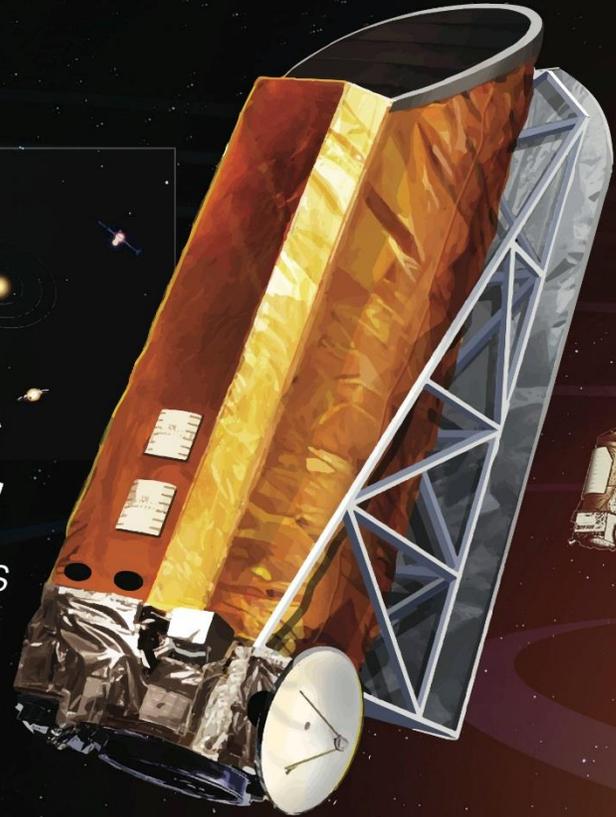
National Aeronautics and Space Administration



Exo-C

Imaging Nearby Worlds

www.nasa.gov



<https://exoplanets.nasa.gov/exep/studies/probe-scale-stdt/>
186 page final report with extensive details, plus Extended Study results



BACKUP



Astro 2010 language on a coronagraph probe mission

“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.”

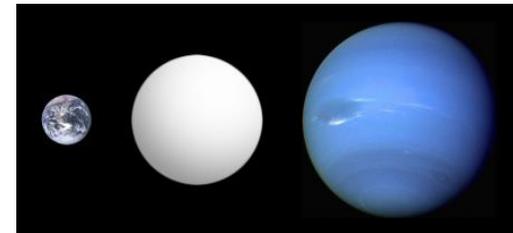
Science frontier discovery areas:

Identification and characterization of nearby habitable exoplanets

How diverse are planetary systems ?

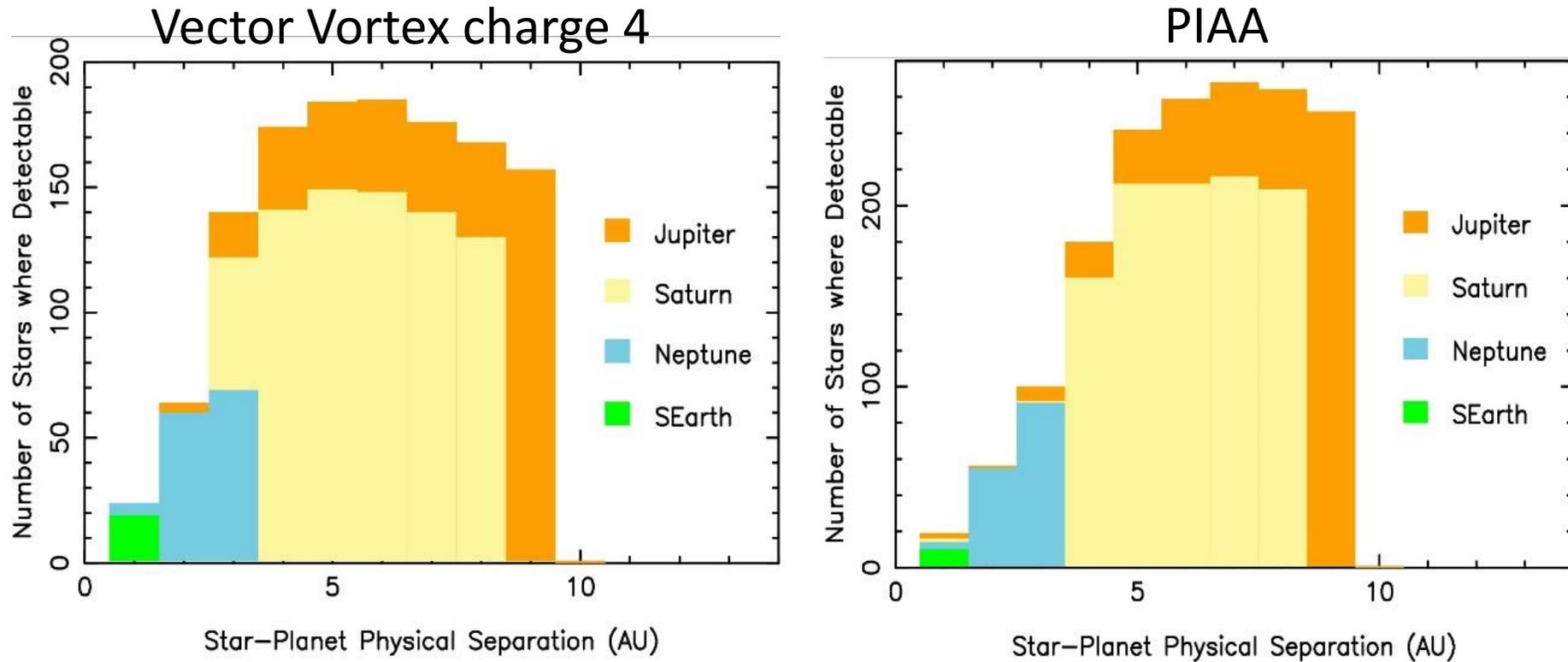
How do circumstellar disks evolve and form planetary systems ?

“... a critical element of the committee’s exoplanet strategy is to continue to build the inventory of planetary systems around specific nearby stars”





Alternate coronagraph architectures expand Exo-C search space



Improved throughputs and inner working angles enable larger exoplanet search space. However, the Vector Vortex and PIAA technologies would need more tech development. Compare to slide 10.

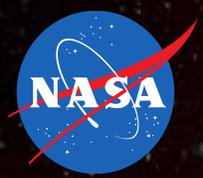


Details of Exo-C Pointing Control System

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



Breakdown 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)



Exo-C Design Trades made

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-trailing
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



Exo-C Extended Study of 2.4m version

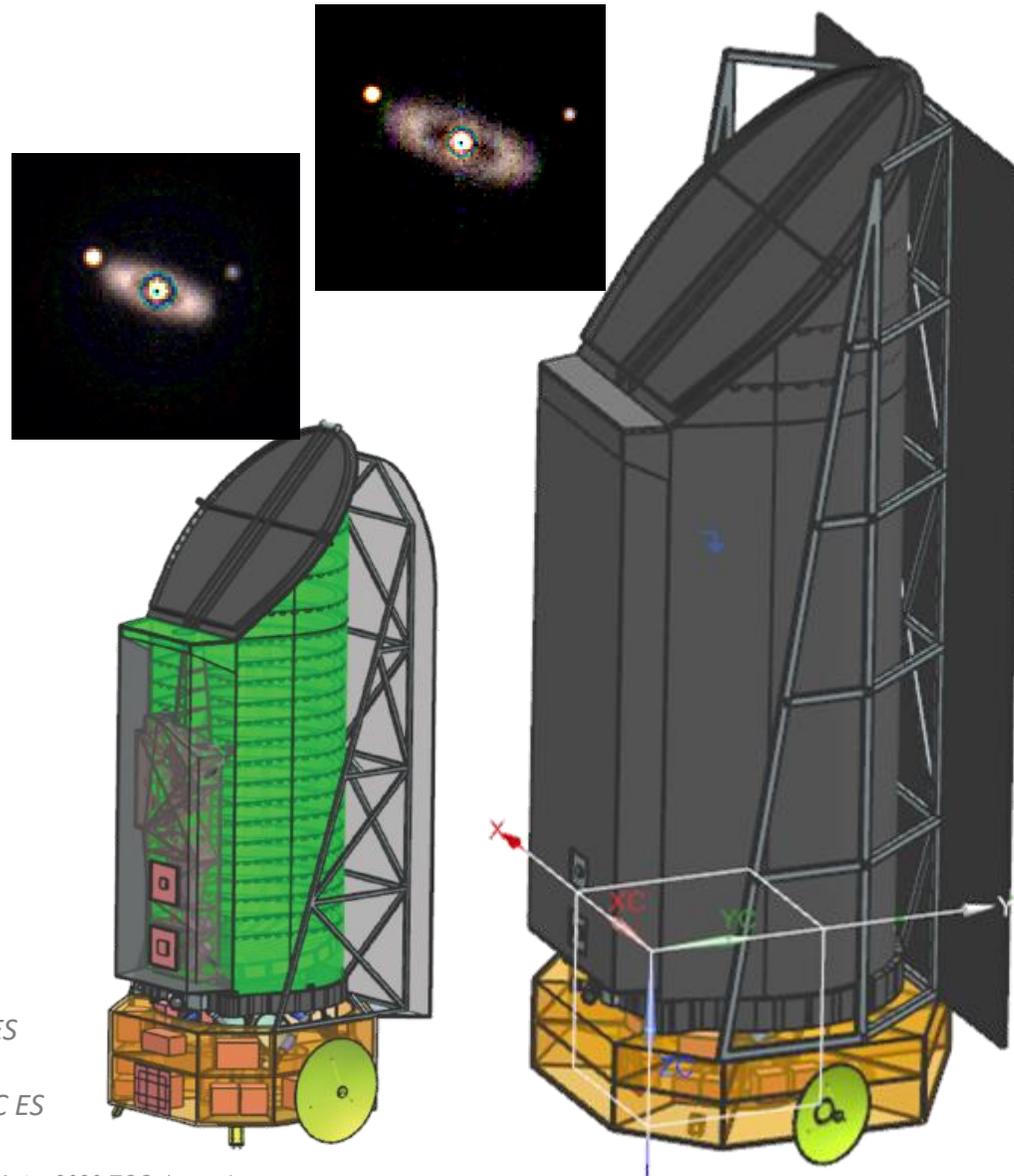
Kerri Cahoy
(MIT), Chair

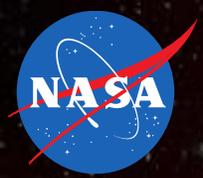
& the Exo-C
study teams

Extended study
presentation
available at ExEP
website

Comparison of 1.4-m Exo-C with 2.4-m Exo-C ES

Drawings, K. Tan and K. Warfield for Exo-C (left) and Exo-C ES (right) [15]. Altair 12 hour composite V, R, I band simulation detecting a Jupiter and Saturn, K. Stapelfeldt for Exo-C, Exo-C ES





Comparing Exo-C & WFIRST CGI

N.B. this reflects the author's current understanding of WFIRST CGI
The CGI Team should be consulted to verify these statements

- Exo-C's coronagraph-optimized mission architecture has numerous advantages vs. WFIRST CGI:
 - Optimal telescope allows for simpler, more efficient coronagraph design
 - 3-4 times better PSF core throughput for planet searches from larger spectral bandwidth, better pupil throughput, fewer reflections in the instrument
 - Raw contrast is ~3x better than CGI best estimates, 50 times better than CGI requirement
 - Full IFS for imaging spectroscopy vs. CGI slit spectrograph
 - Relaxed pointing requirements due to reduced aberration sensitivity
- **3 year high contrast science program vs. < 0.25 yr CGI tech demo**
- WFIRST's tighter PSF provides a 25% smaller IWA
- WFIRST CGI is substantially less costly (~\$350M vs. ~\$1B)