Exoplanet Direct Imaging: Coronagraph Probe Mission Study "Exo-C"

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For the EXO-C STDT and Design Team

Context for Study

- Flagship mission for spectroscopy of ExoEarths is a long-term priority for space astrophysics (Astro2010).

- Requires 10^{-10} contrast at 3 λ/D separation, (>10,000 times beyond HST performance) and large telescope > 4m aperture. Big step.

- An Internal coronagraph mission for spectroscopy of giant planets and imaging of disks requires 10^{-9} contrast at 3 λ/D (already demonstrated in lab) and ~1.5m telescope. Should be much more affordable, good intermediate step.

- Various PIs have proposed many versions of the latter mission 17 times since 1999; no unified approach.

- There is a similar context for a probe starshade mission

NASA HQ Astrophysics Implementation Plan

- New strategic mission expected to start in FY 17. It will be AFTA/WFIRST if budget allows. If not, need less expensive "probe" mission options as backups. Three to choose from: WFIRST, and 2 exoplanet.

- Probe mission terms:
  - cost ~ $1B
  - technical readiness (TRL 5) by 2017
  - Launch in 2024

- Exo-C is an 18 month HQ-funded study of an internal coronagraph probe mission
  - Science & Technology Definition Team (STDT) selected May 2013. _Previous competitors now working together._
  - Engineering Design Team in place at Jet Propulsion Laboratory, July 2013
  - Interim report for March 2014, Final report due January 2015

EXO-C Key People

Science and Technology Definition Team

Karl Stapelfeldt (Chair, GSFC)

Rus Belikov (NASA/Ames)

Geoff Bryden (JPL/Caltech)

Kerri Cahoy (MIT)

Supriya Chakrabarti (UMass Lowell)

Mark Marley (NASA/Ames)

Michael McElwain (NASA/GSFC)

Vikki Meadows (U. Wash)

Gene Serabyn (JPL/Caltech)

John Trauger (JPL/Caltech)

JPL Engineering Design Team

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Keith Warfield	Michael Brenner
Paul Brugarolas	John Krist
Frank Dekens	Jared Lang
Serge Dubovitsky	Joel Nissen
Bobby Effinger	Jeff Oseas
Brian Hirsch	Eric Sunada
Andy Kissil	

ExEP Office

Gary Blackwood	Wes Traub
Peter Lawson	Steve Unwin

Approach to the Study

- Build on previous work (ACCESS, PECO, …)
- Begin with science goals and trade studies of system-level issues: telescope design, orbit selection, pointing control, wavefront stability and control, <u>cost</u>
- Evaluate coronagraph options in the context of achievable system performance
- Engage Aerospace Corp. early in the study for cost feedback
- Innovate
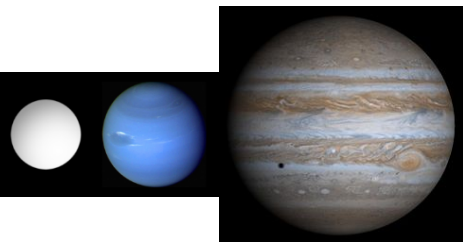
Science Goals
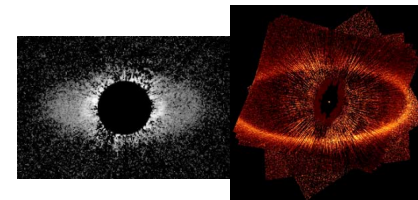
- Obtain optical spectra of the nearest RV planets: measure CH_4, H_2O, Rayleigh scattering. Fix orbit inclination → planet mass.

- Search for planets beyond RV limits (Neptunes, super-Earths) in a TBD nearby star sample. Measure their orbits, carry out follow-on spectroscopy of the brightest ones
  - alpha Centauri system is a particularly important case

- Optical spectra of planets discovered by near-IR ground Adaptive Optics (AO)

- Image circumstellar disks beyond Hubble Space Telescope (HST), AO, and Atacama Large Millimeter/submillimeter Array (ALMA) limits:
  - Resolve disk structures: Size, extent, rings/gaps/asymmetries as evidence for planetary perturbations
  - Dust properties: diagnose via albedo, color, and phase function
  - Time evolution of the above from protoplanetary to debris disks
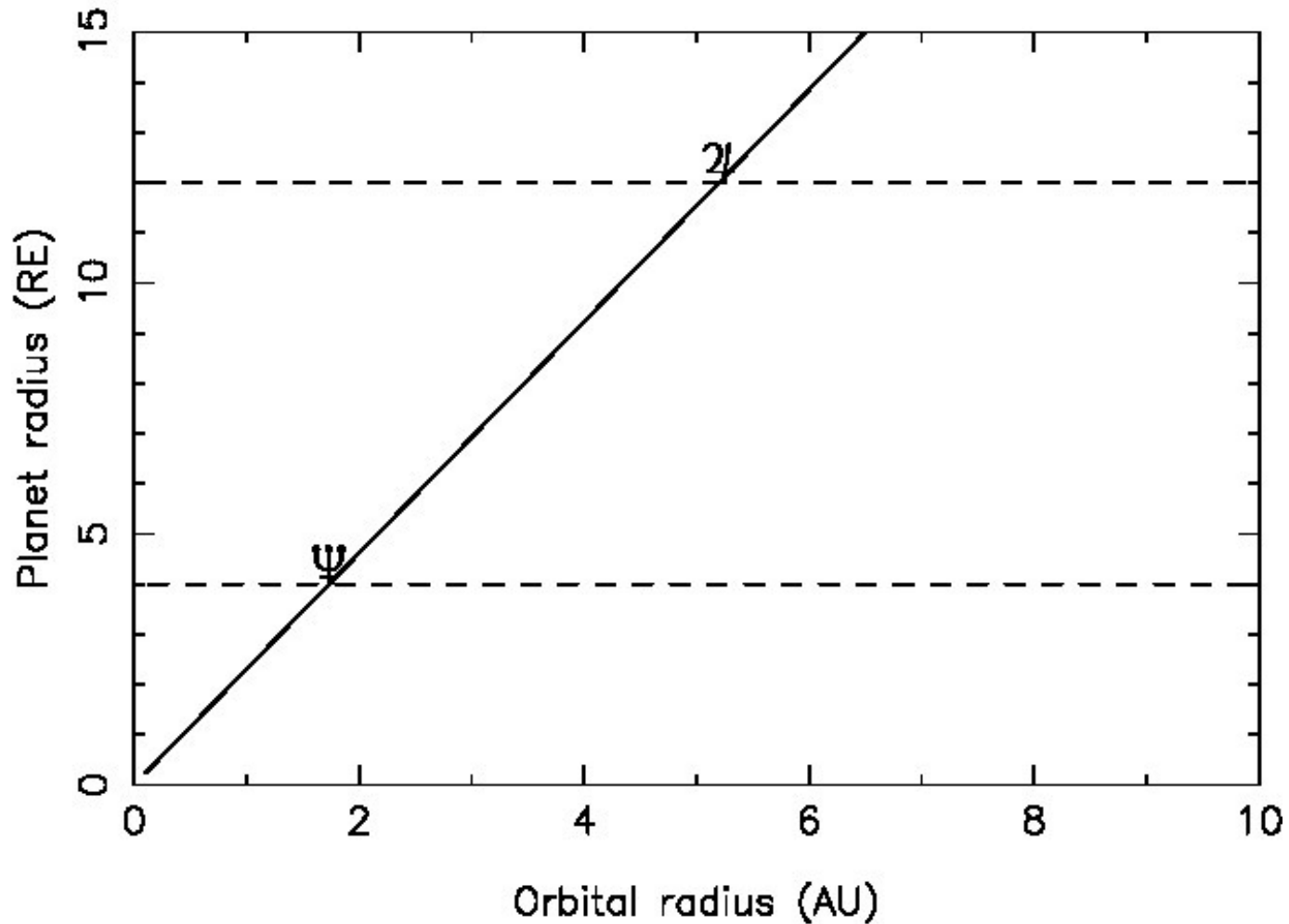 - Assess dust content near HZ in maybe a dozen nearby sunlike stars
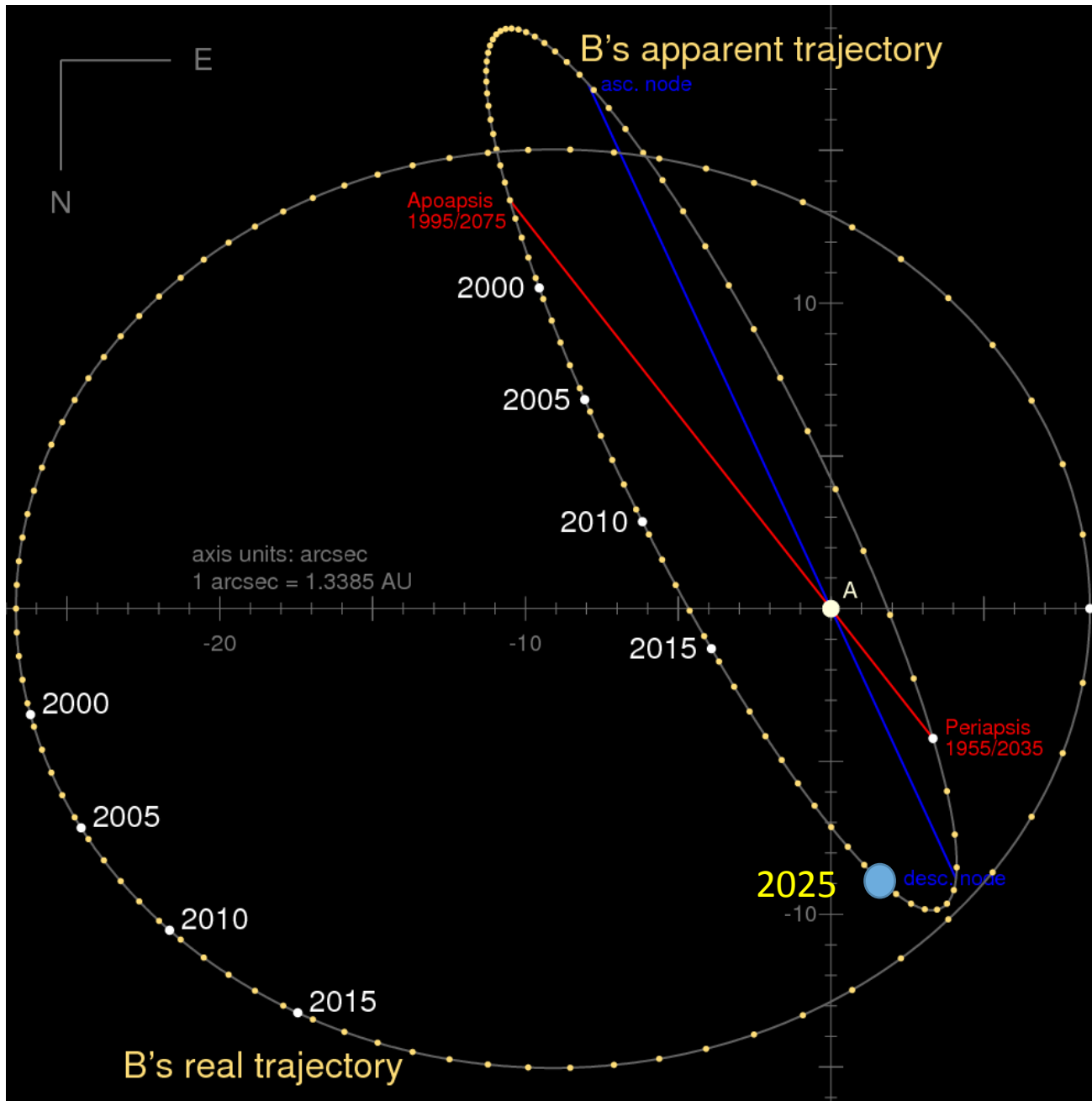
Accessible RV planets

Known RV planets vs. 2 λ/D @ λ= 0.8 μm
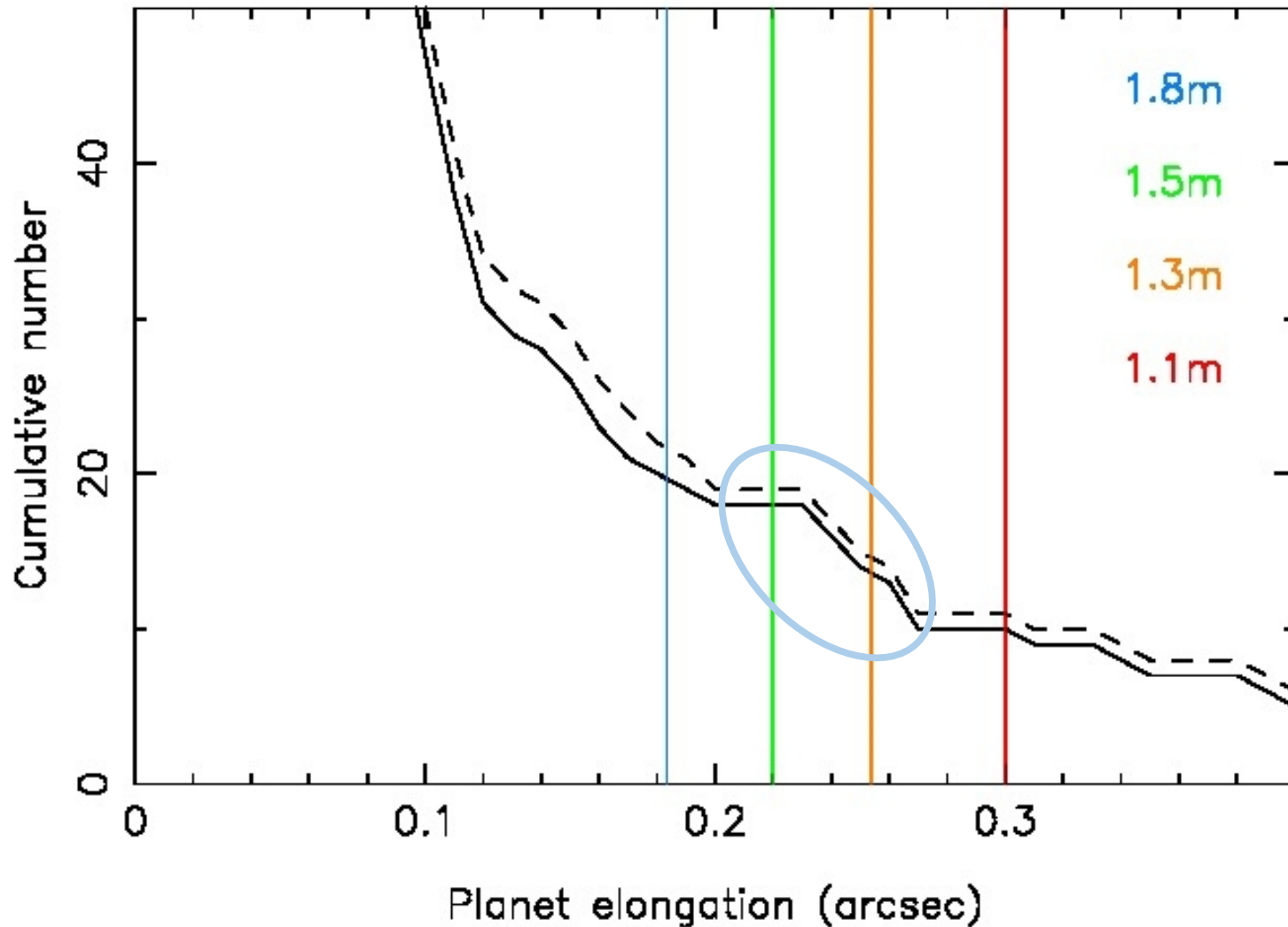
The family of 10⁻⁹ contrast planets

Planet size for 1e−09 contrast at quadrature

alpha Cen orbit:

- 8.5″ separation in 2025, growing to 10.5″ a few years later

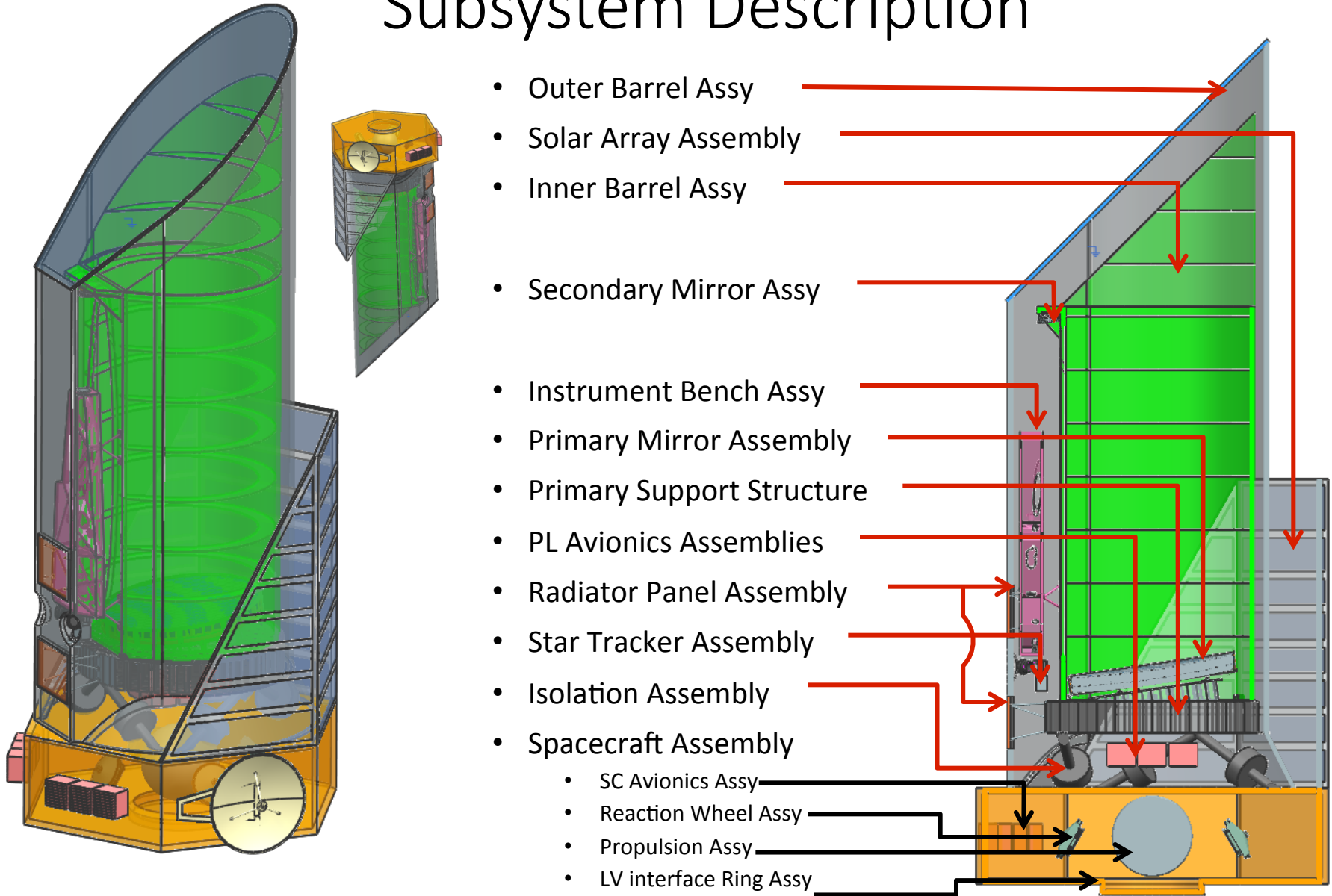- Need corona-graph mask that covers both stars and can accom-modate the vari-able separation

Current Working Science Requirements

|		
Primary diameter	≥ 1.3	m
Uncontrolled speckle contrast	1e-09	raw
Stability over 48 hours	1e-10	
Bandwidth	450-1000	nm
IWA = 2 λ/D @800 nm	0.22	arcsec
OWA = 24 λ/D @ 800 nm	2.8	arcsec
Stray light from binary companion	1e-9	@ 8 arcsec separation
Spectral resolution λ < 630 nm	R > 25	
Spectral resolution λ > 630 nm	R > 50	
Astrometric precision	< 30	milli-arcsec
Mission Life	3+	years

Engineering Trades

- Unanimous decision for unobscured telescope
  - Better throughput, resolution, stiffness, coronagraph TRL. Slightly higher cost

- Telescope aperture of 1.3-1.5m appears to be affordable

- Decided on Earth-trailing orbit
  - Better thermal stability & sky visibility than EO. No propulsion needed. Acceptable data rates.

- Integral Field Spectrograph in addition to filter imaging
  - Simultaneous measurements over ~> 20% bandpass
  - Supports speckle rejection as well as planet spectra

- ~900 kg payload , Kepler-like spacecraft bus, Falcon 9 launch vehicle, JPL cost estimate < $1 B

Subsystem Description

- Outer Barrel Assy
- Solar Array Assembly
- Inner Barrel Assy

- Secondary Mirror Assy

- Instrument Bench Assy
- Primary Mirror Assembly
- Primary Support Structure
- PL Avionics Assemblies
- Radiator Panel Assembly
- Star Tracker Assembly
- Isolation Assembly
- Spacecraft Assembly
  - SC Avionics Assy
  - Reaction Wheel Assy
 - Propulsion Assy
 - LV interface Ring Assy

Instrument Layout

- Unobscured telescope form is baselined
- Cassegrain form baselined: Short Primary-Secondary spacing -> less mass
- Deformable Mirror (DM) 48x48 elements
- Lateral Instrument Configuration along side Inner Barrel Assembly
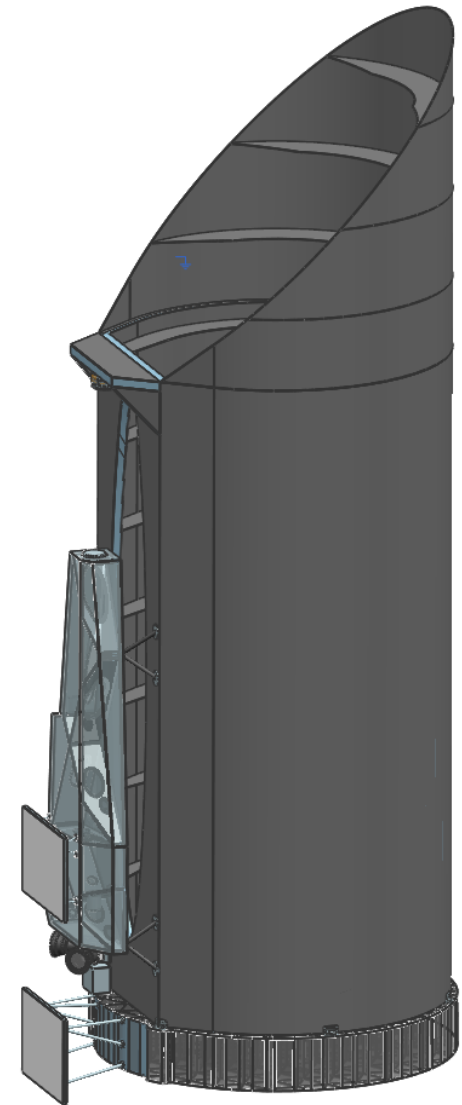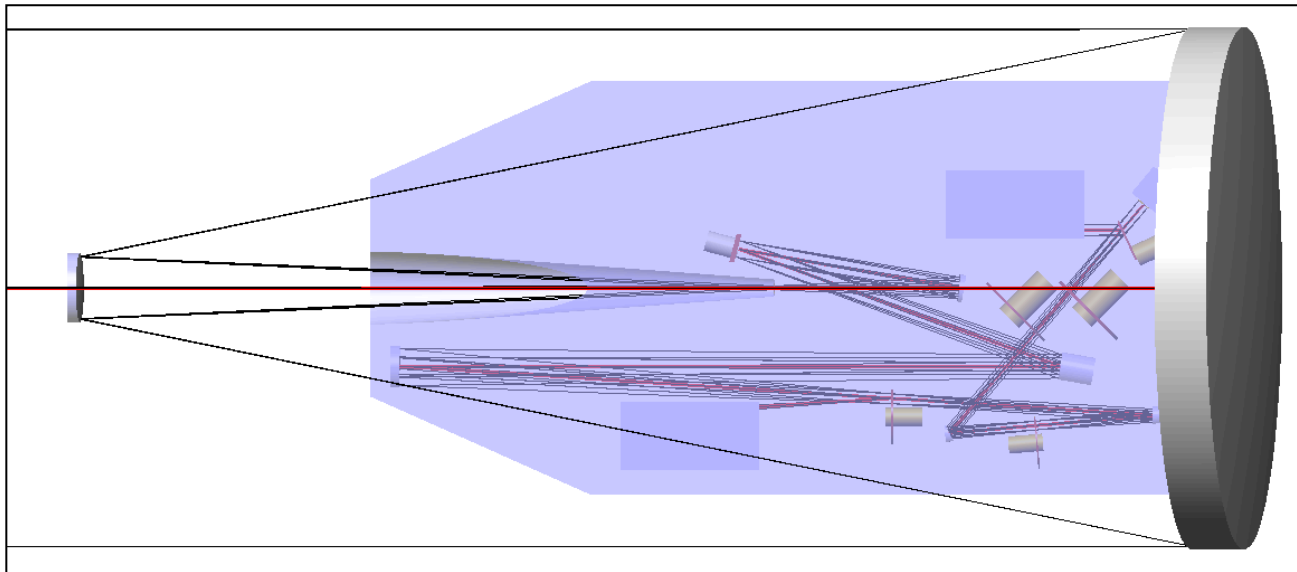
Current Work

- Initial Thermal Performance Modeling
- Initial Structural Modeling for configuration and loads
- Pointing Requirements Generation
- Back end Instrument optical layout including FGS,LOWFS, science camera, and IFS
- Coronagraph trade in progress
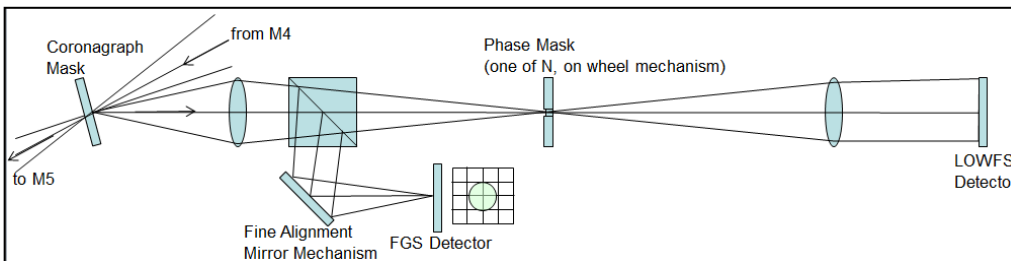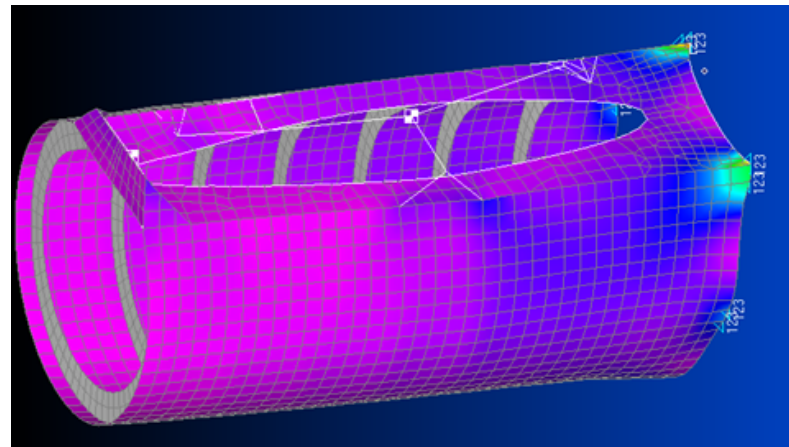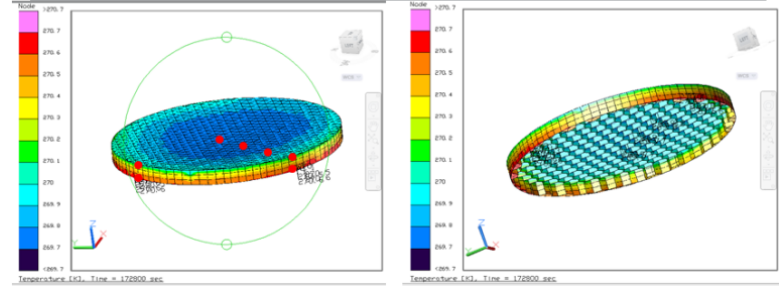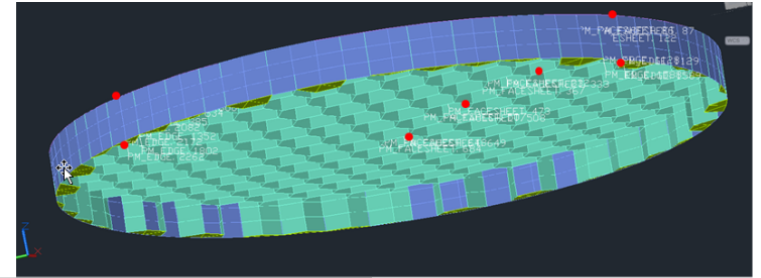
Choosing a coronagraph

- Pre-requisite is having some understanding of likely pointing performance, thermal stability, and control authority over time-variable low order aberrations.

- Six concepts being evaluated: hybrid Lyot, PIAA, shaped pupils, vector vortex, two visible nuller variants.

- Optical simulations flow to science yield estimates. Telescope pointing stability strongly affects science yield. Demonstrated lab performance will be highly weighted.

- EXO-C decision will be totally independent of AFTA choice

Thoughts on 3 year
Design Reference Mission

Science Type	Visits		Science Observation times		Non-observing time between observations		Total Mission Time	Calculated Observation efficiency of each Science Type
	number of targets	Ave number of visits	Average Integration time per visit	Total Observe time per Science Type	Total non-observe time per visit	Total non-observe time per Science Type		
	N_target	N_visit	t_I	T_Obs	$T\_NO= T\_SC+T\_T +T\_IO$			
			(hrs)	(days)	hrs	(days)	(days)	
Spectroscopy of Known Cxoplanets (known from RV and exo-C survey)	30	1	100	125	8	10.0	135	93%
Planet discovery surveys								
Survey nearby stars for super-Earths within the habitable zone	20	6	20	100	8	40	140	71%
Seach for giant planets around nearby stars	150	3	20	375	8	150	525	71%
Disk Imaging Surveys								
Detection survey in RV planet systems	200	1	12	100	3	25.0	125	80%
Known debris disks within 40 pc	80	1	6	20	3	10.0	30	67%
Young debris disks from WISE	120	1	6	30	3	15.0	45	67%
Nearby protoplanetary disks	80	1	6	20	3	10.0	30	67%
Total on-orbit ops time				770		260	1030	
Initial On-Orbit Checkout (days)							60	
Total (days)							1090	71%
Total (years)							3.0	

General Astrophysics Capability

- High contrast science on post-main sequence stars, AGN/quasars, …

- Imaging camera will have 1 arcmin FOV with small filter set; IFS will have ~2.8" FOV.

- Camera and IFS useable without coronagraphic spots

- Pointing performance for targets other than bright stars is still TBD. Support for moving targets doable but not in baseline cost.

- Not currently planning for UV capability (cost)

- A second instrument could be accommodated in terms of payload mass/volume, but not in terms of cost.

Conclusions

- Exo-C Study is well underway. We will show what an affordable, optimal, high TRL exoplanet imaging mission can do.

- We are eager to get our first Structural-Thermal-OPtical models to assess telescope stability

- Capability to search alpha Cen system may be key to selling the mission

- Please see me here, or send me your suggestions for things we should look into or how you'd like to help: karl.r.stapelfeldt@nasa.gov.