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

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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)

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JPL Engineering Design Team

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Serge Dubovitsky

Bobby Effinger

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Michael Brenner

John Krist

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Joel Nissen

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ExEP Office

Gary Blackwood

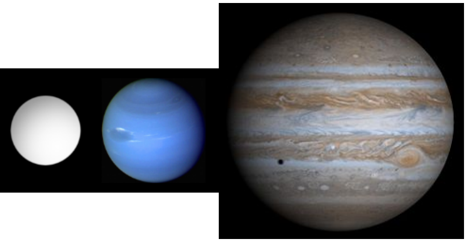
Peter Lawson

Wes Traub

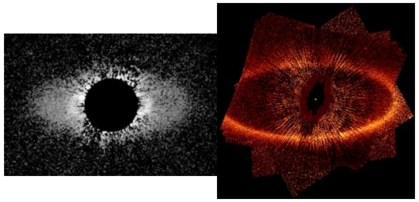
Steve Unwin

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

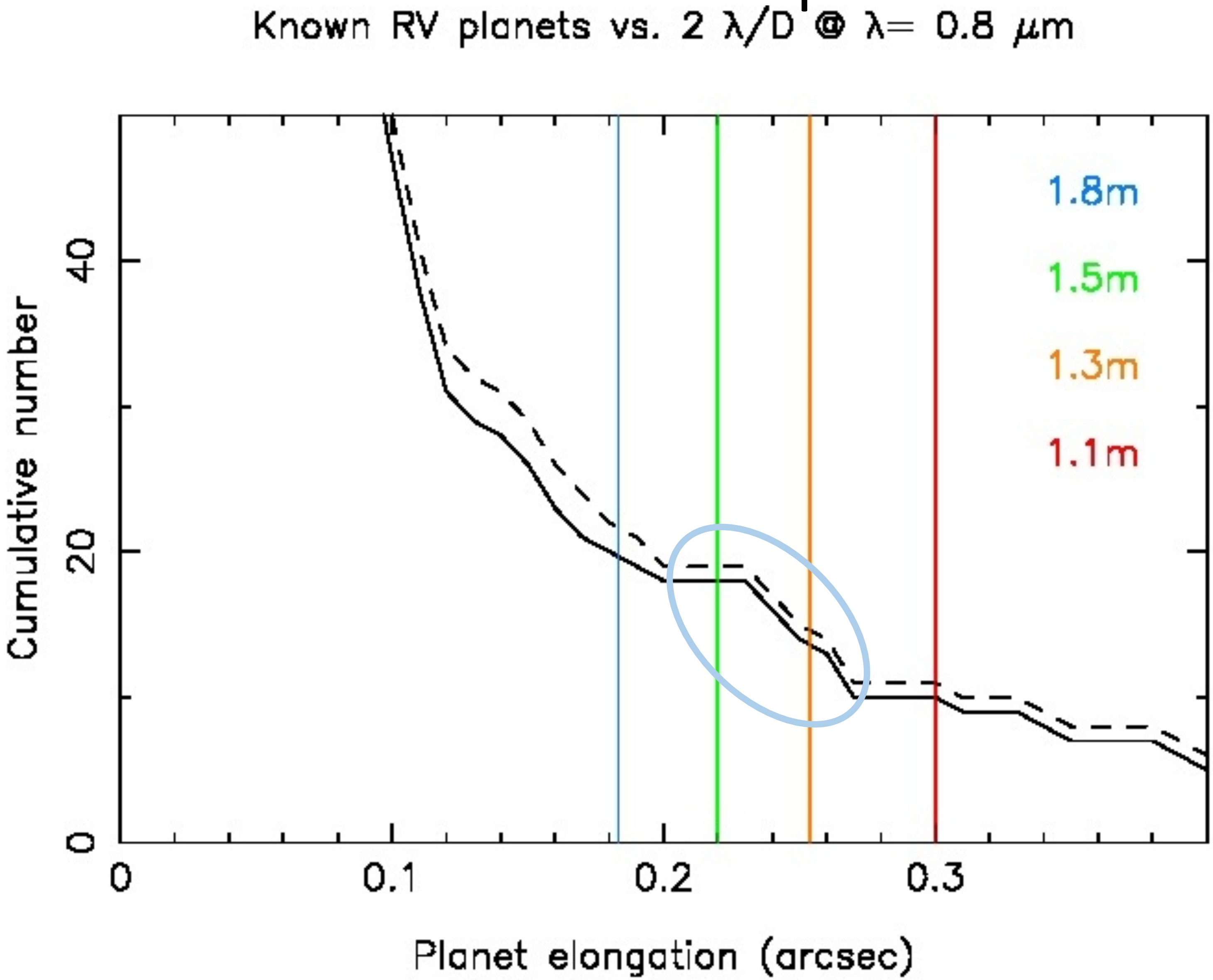


Science Goals

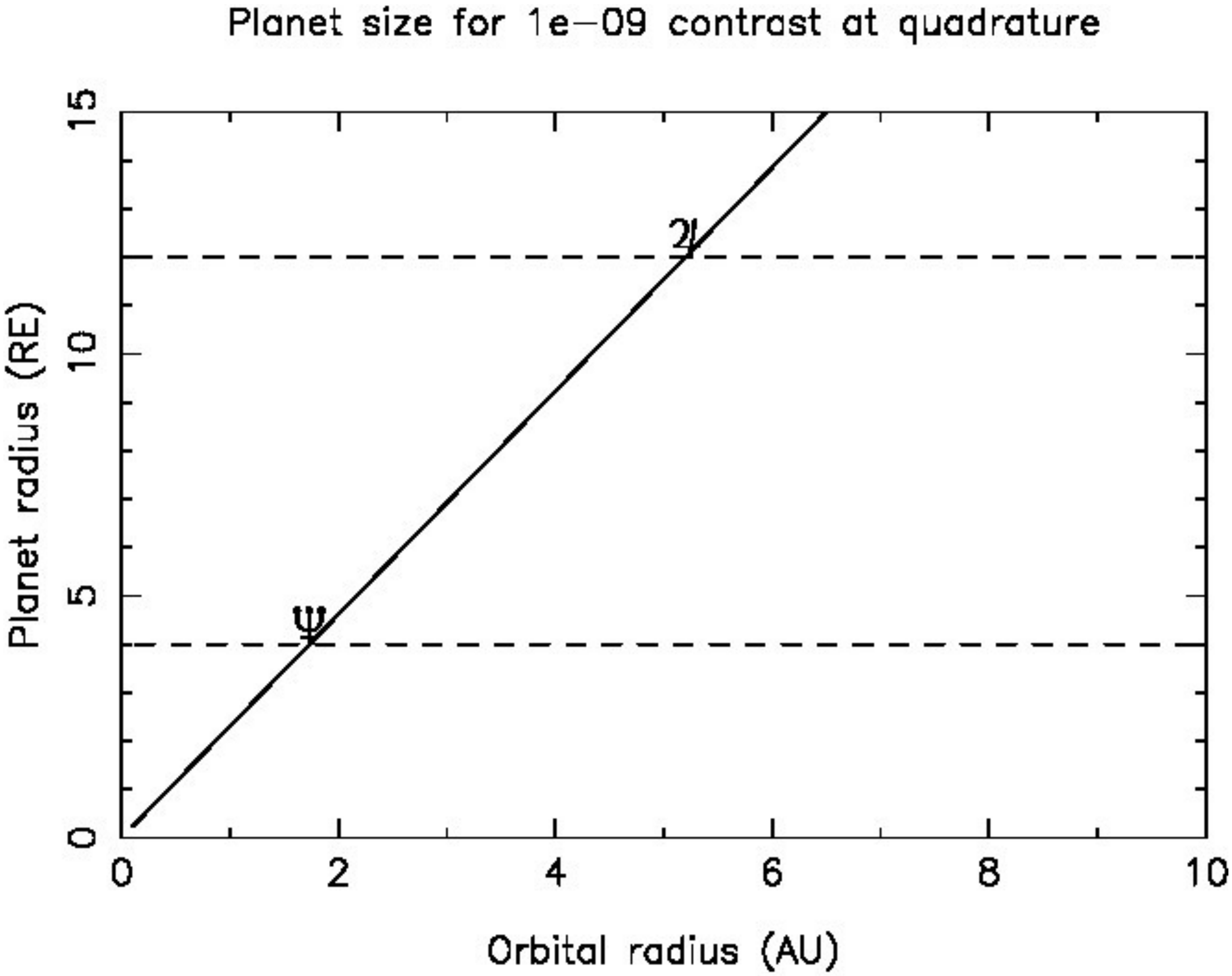


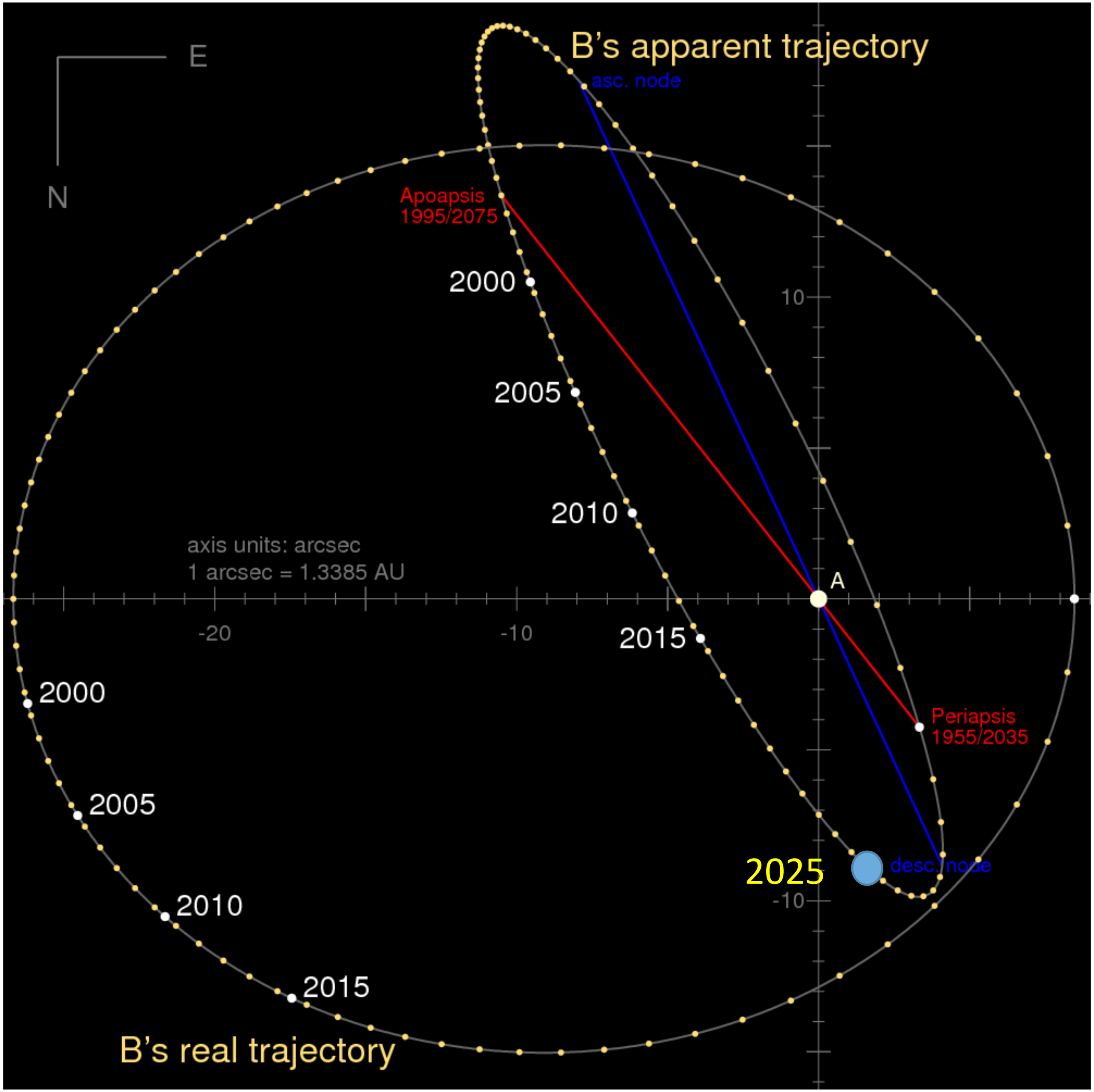
- Obtain optical spectra of the nearest RV planets: measure CH_4, H_2O, Rayleigh scattering. Fix orbit inclination → planet mass.
- Search for planets beyond RV limits (Neptunes, super-Earths) in a TBD nearby star sample. Measure their orbits, carry out follow-on spectroscopy of the brightest ones
  - 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



The family of 10^{-9} contrast planets





alpha Cen orbit:

- 8.5″ separation in 2025, growing to 10.5″ a few years later
- Need coronagraph mask that covers both stars and can accommodate the variable separation

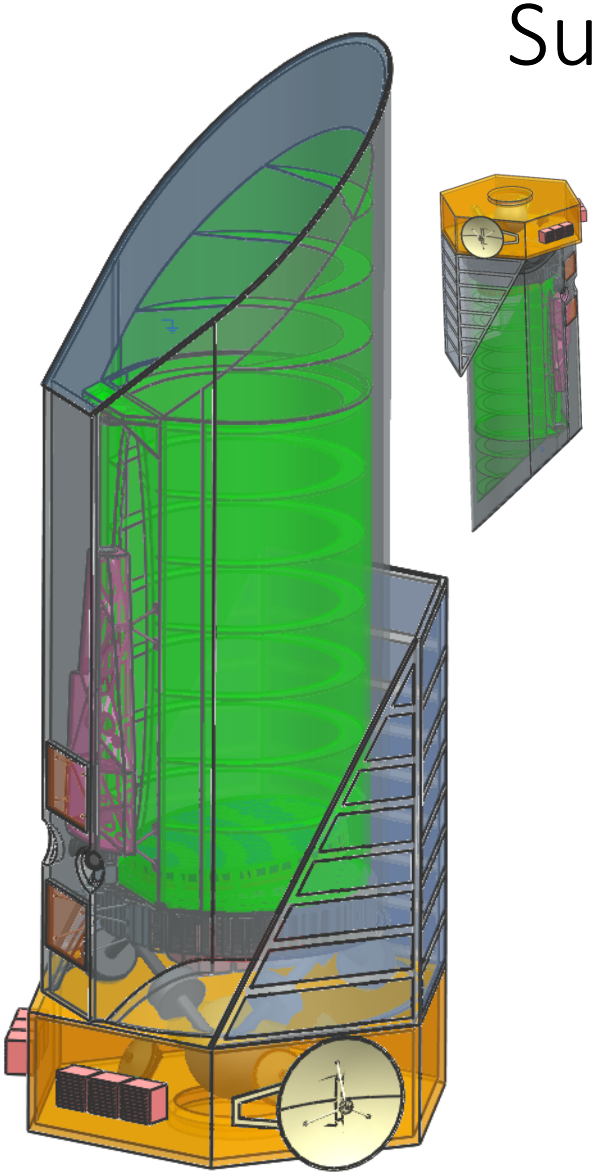
Current Working Science Requirements

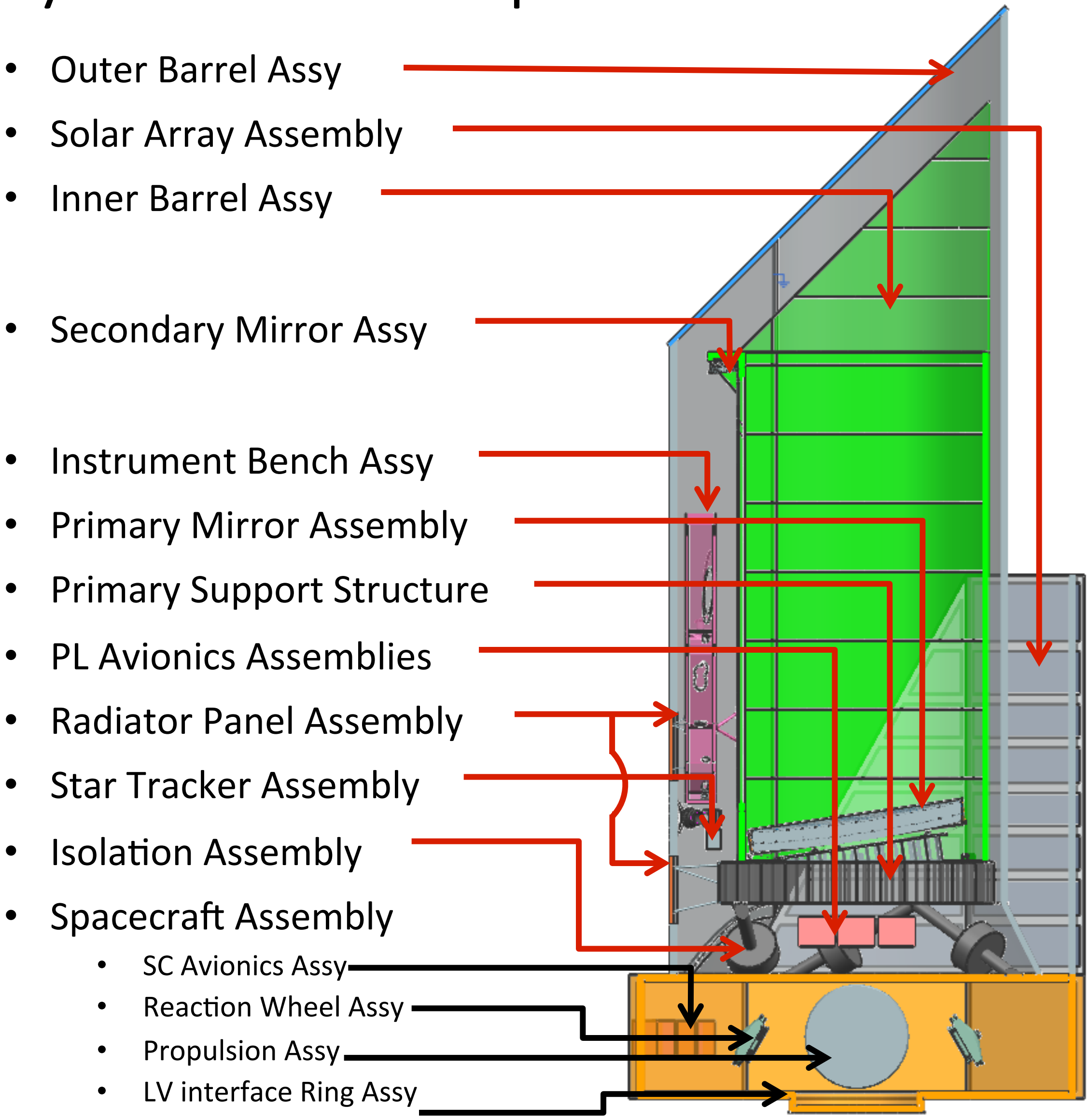
Primary diameter	≥ 1.3	m
Uncontrolled speckle contrast	1e-09	raw
Stability over 48 hours	1e-10	
Bandwidth	450-1000	nm
IWA = 2 λ/D @800 nm	0.22	arcsec
OWA = 24 λ/D @ 800 nm	2.8	arcsec
Stray light from binary companion	1e-9	@ 8 arcsec separation
Spectral resolution $\lambda < 630$ nm	R > 25	
Spectral resolution $\lambda > 630$ 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

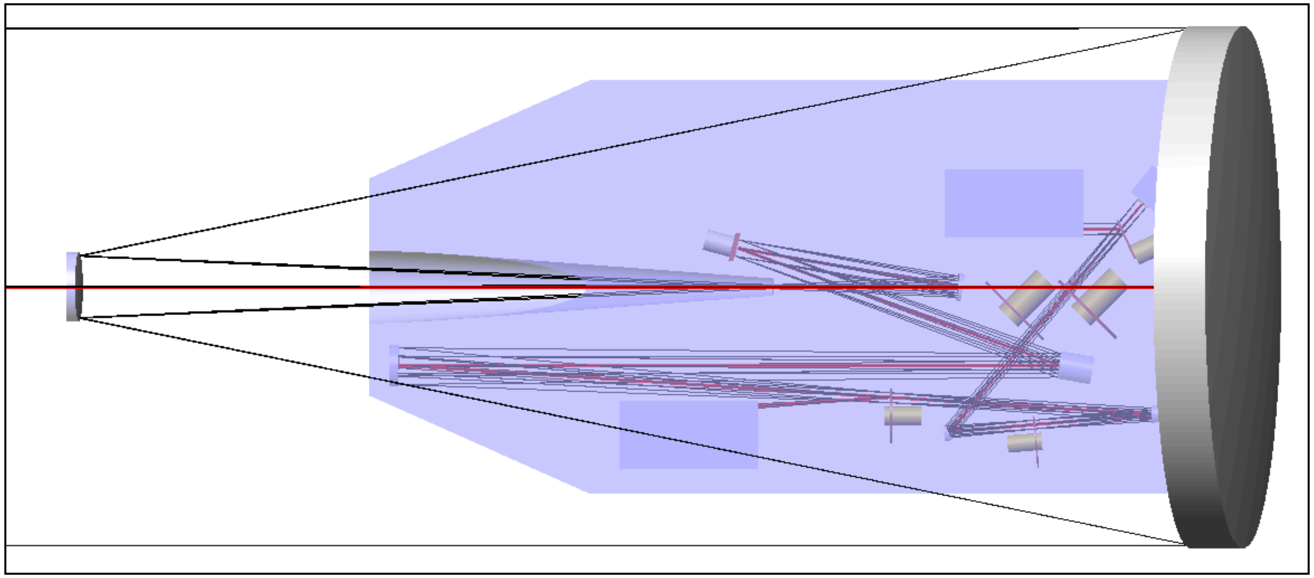


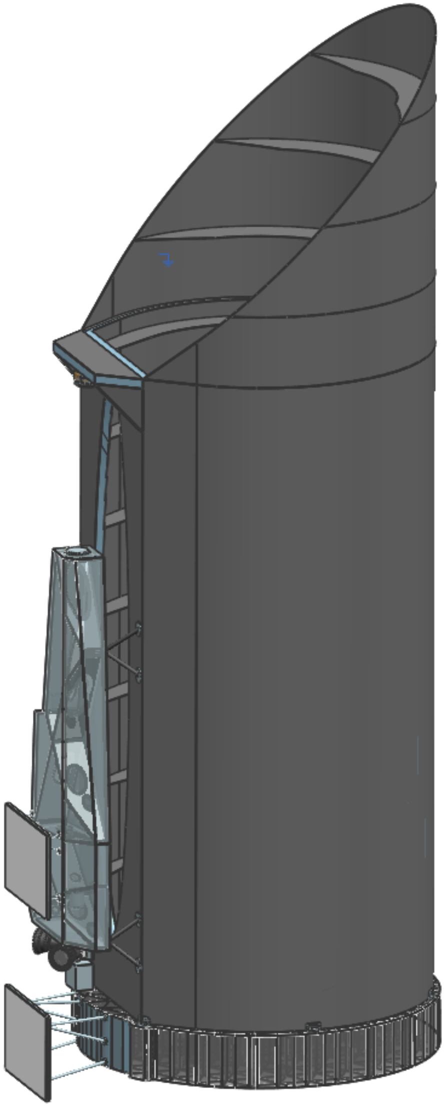


- Outer Barrel Assy
- Solar Array Assembly
- Inner Barrel Assy
- Secondary Mirror Assy
- Instrument Bench Assy
- Primary Mirror Assembly
- Primary Support Structure
- PL Avionics Assemblies
- Radiator Panel Assembly
- Star Tracker Assembly
- Isolation Assembly
- Spacecraft Assembly
    - SC Avionics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

Instrument Layout

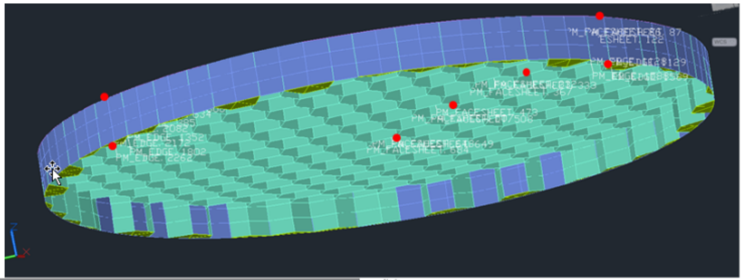
- Unobscured telescope form is baselined
- Cassegrain form baselined: Short Primary-Secondary spacing -> less mass
- Deformable Mirror (DM) 48x48 elements
- Lateral Instrument Configuration along side Inner Barrel Assembly

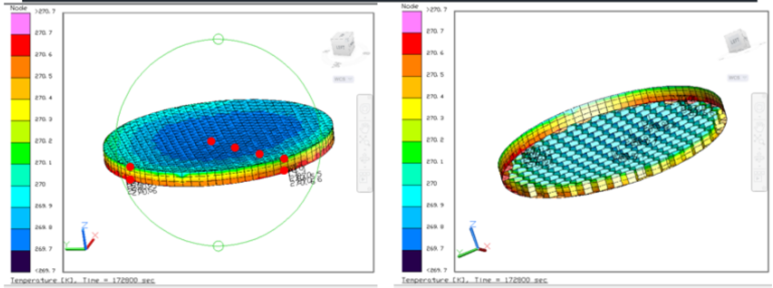


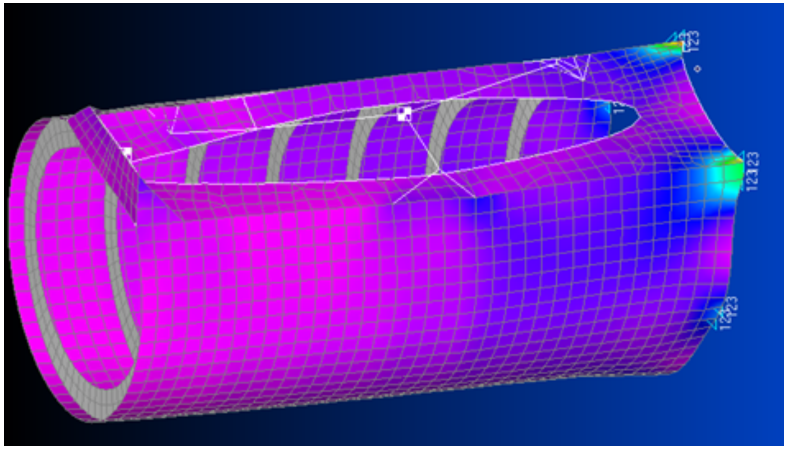


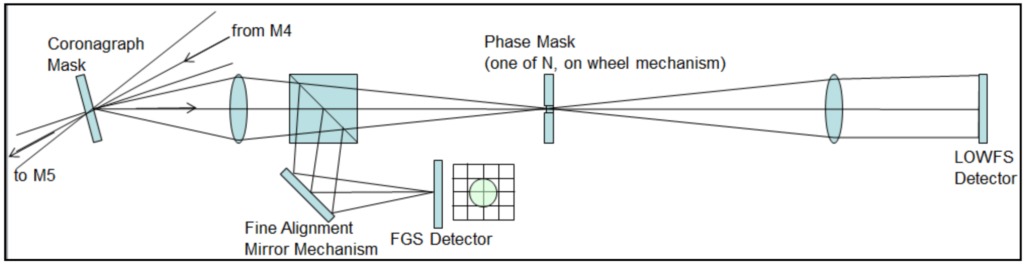
Current Work

- 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





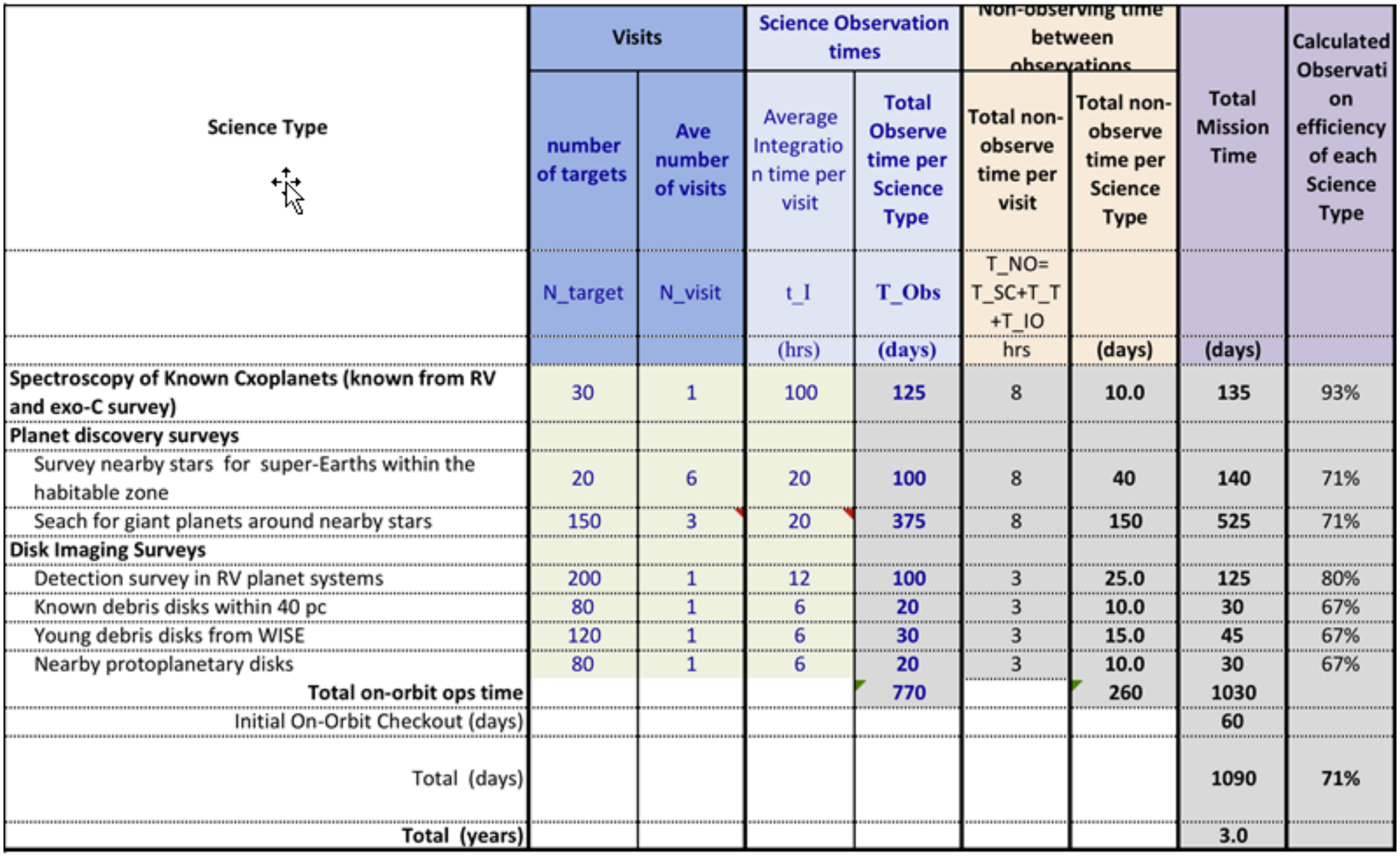




Choosing a coronagraph

- 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			
	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	Total Mission Time	Calculated Observation efficiency of each 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.