ExO: The Exoplanet Observatory

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and the ExO community team
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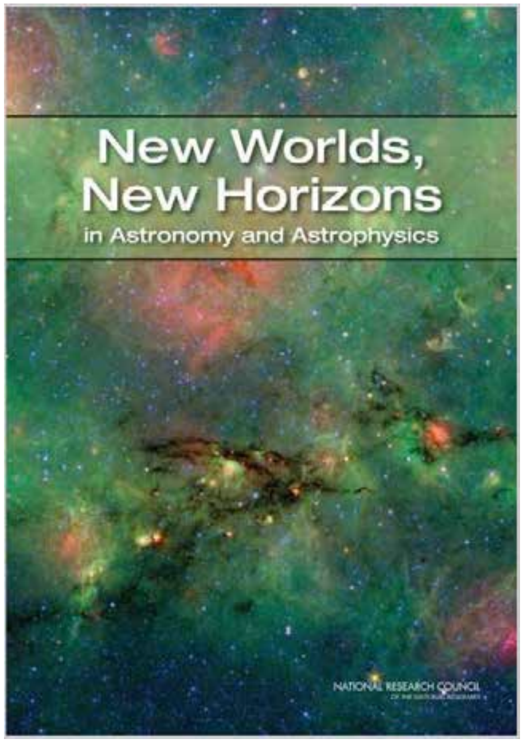
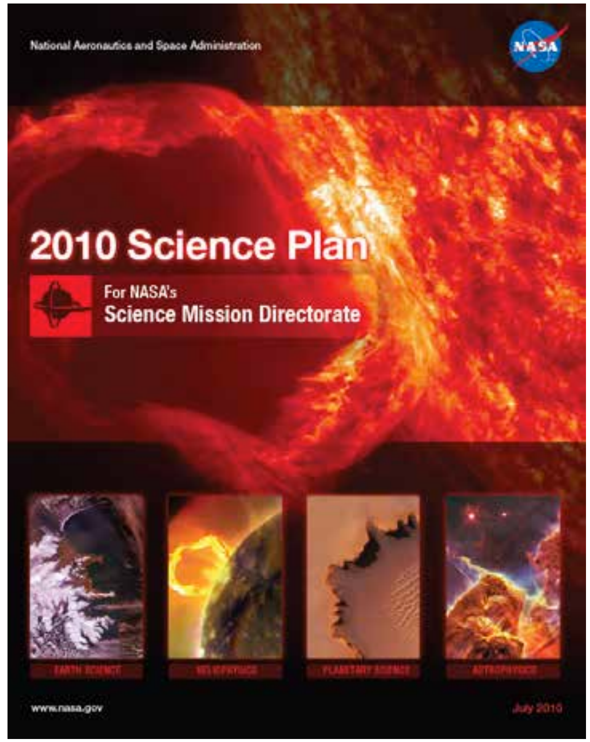
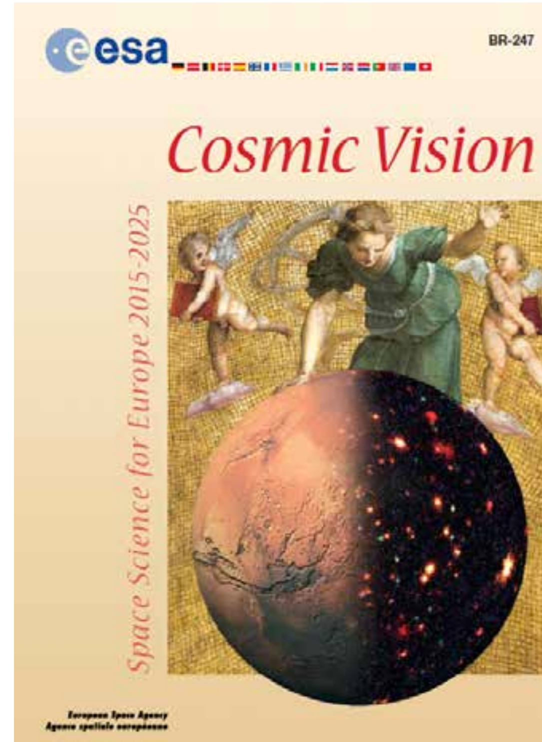
SALSO Workshop, Huntsville, AL, Feb 5-6, 2013

Alignment with National and International Science Goals and Priorities

Prepares for a future mission to image Earth-like planets and search for signs of life.







Directly aligned with NASA SMD Astrophysics objectives and Roadmaps. Will address the key question: “Are we alone?”

Directly aligned with ESA’s Cosmic Vision for 2015-2025.

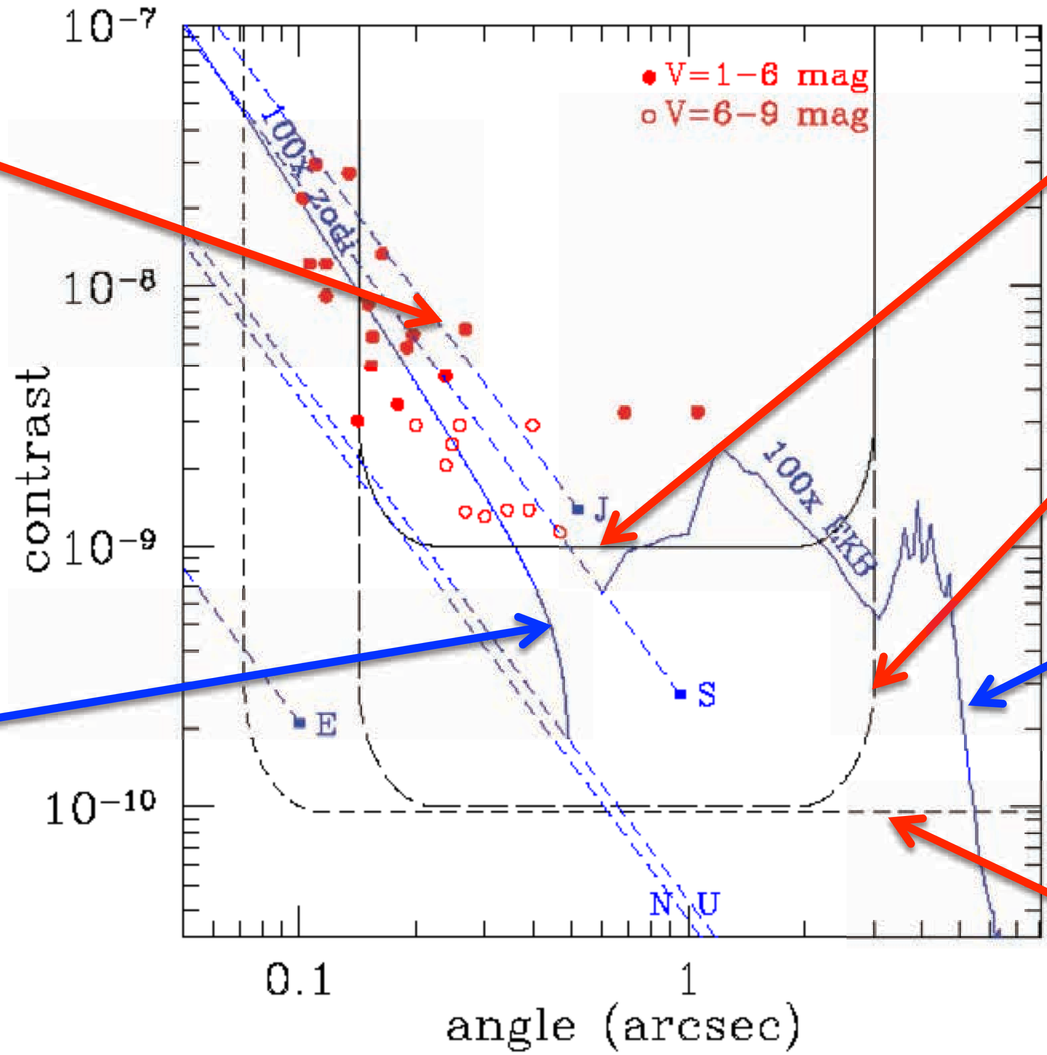
2. ExO Science Goals

- Exoplanet key programs 50%; General Observer programs 50%

- Image & characterize planetary systems, around 100 nearby stars
  - Measure brightness of planets (Super-Earths to Jupiters)
  - Measure masses of planets
  - Measure orbits of planets
  - Measure colors & spectra of planets, in visible region
  - Measure brightness & colors of dust belts (zodi & Kuiper)
  - Measure spectra of transiting planets, in near-infrared region

- GO program (Cosmic Origins, Planetary, other exoplanet projects)
  - Spectral images of outer planets, moons, asteroids for clouds, chemistry …
  - Circumstellar science of young stars, evolved stars, AGNs …
  - Orbits of near-Earth objects
  - Galactic dynamics via tidal tails & rotation curves
  - Stellar masses from microlensing events

3a. ExO Science Discovery Space



Stars with known planets (from RV)

Exo-Zodiacal belt (100x our Solar System at 10pc)

ExO baseline performance

ExO goal performance

Exo-Kuiper belt (100x our Solar System at 10pc)

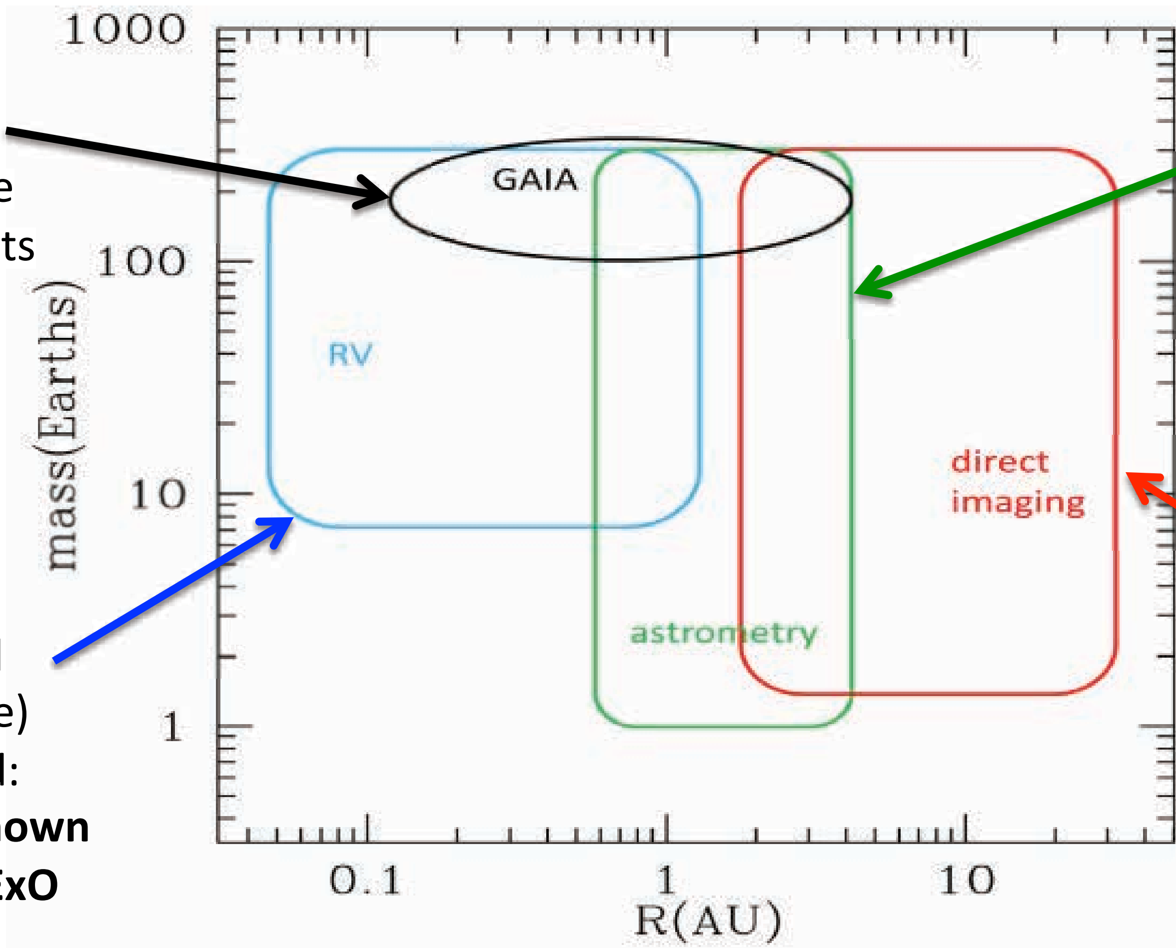
ExO with external occulter

3b. ExO Science Discovery Space

- *ExO greatly extends the accessible discovery space, to much lower masses*

GAIA-detected planets (black): more known targets

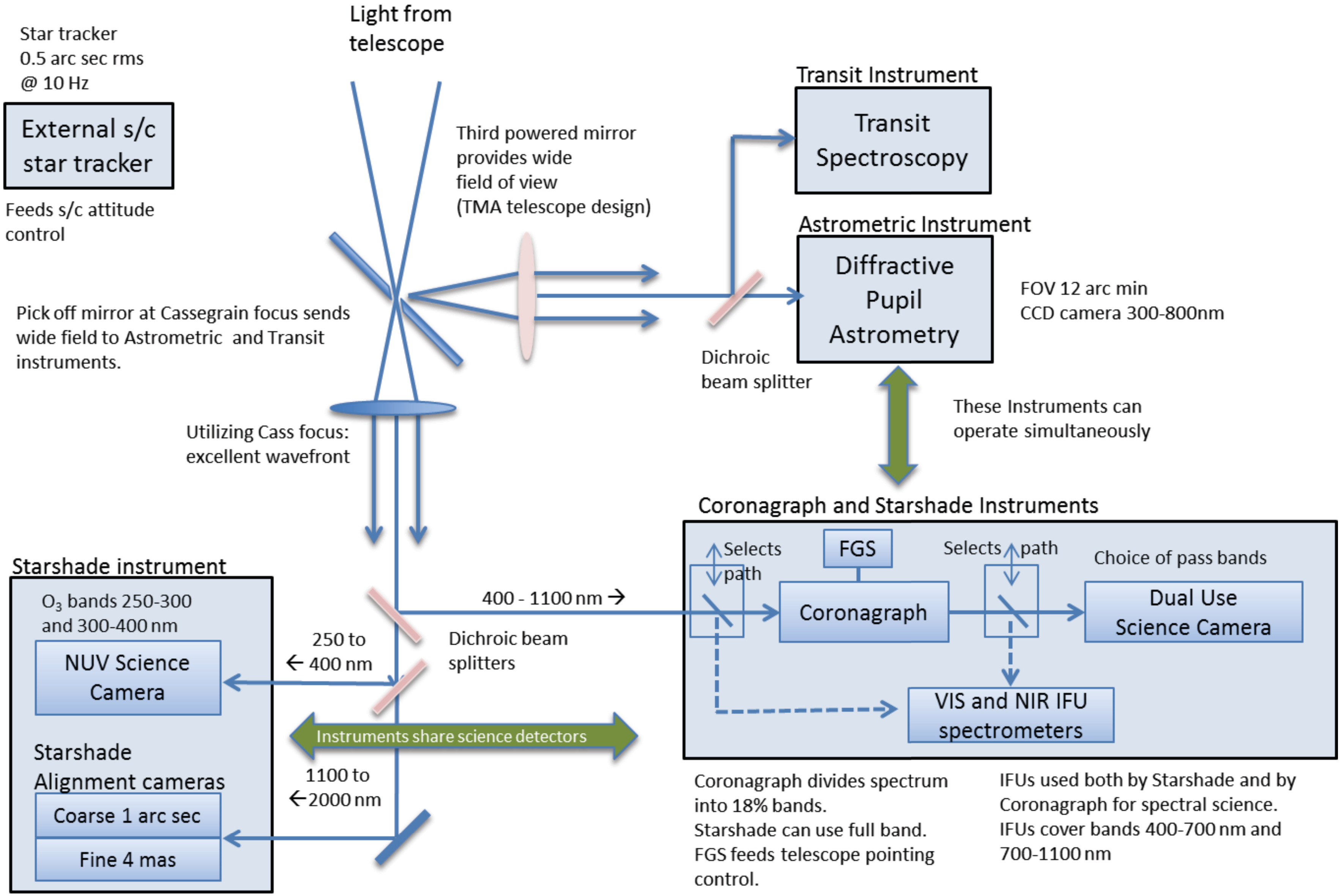
RV-detected planets (blue) from ground: these are **known targets for ExO**



ExO astrometry (green) finds planets out to ~3 AU, down to Earth mass

ExO imaging & spectra (red) finds orbits & atmospheric chemistry for orbits out to 30 AU

4. ExO Instrument Suite



Coronagraph divides spectrum into 18% bands.
Starshade can use full band.
FGS feeds telescope pointing control.

IFUs used both by Starshade and by Coronagraph for spectral science.
IFUs cover bands 400-700 nm and 700-1100 nm

Astrometry Instrument Concept

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 200:11 (22pp), 2012 June GUYON ET AL.

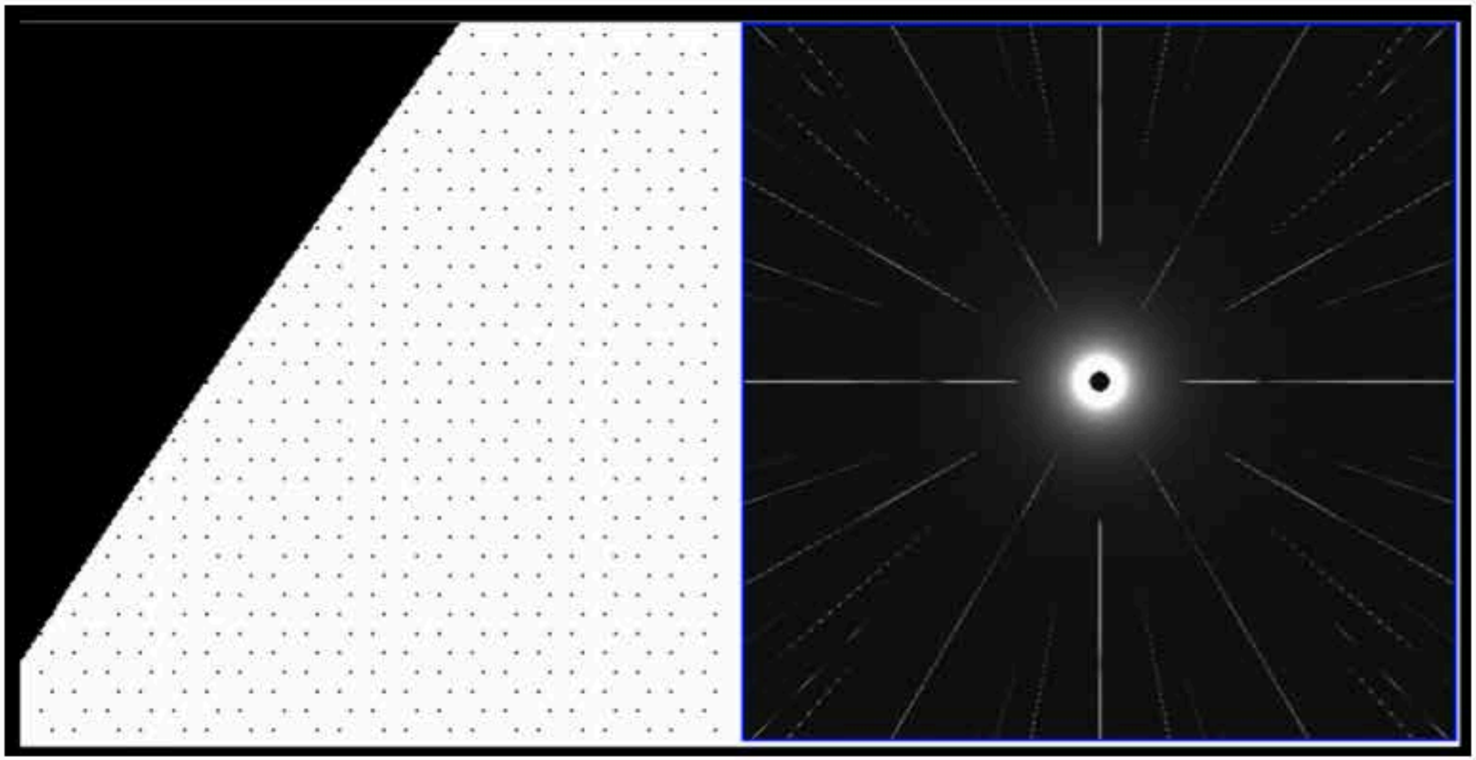
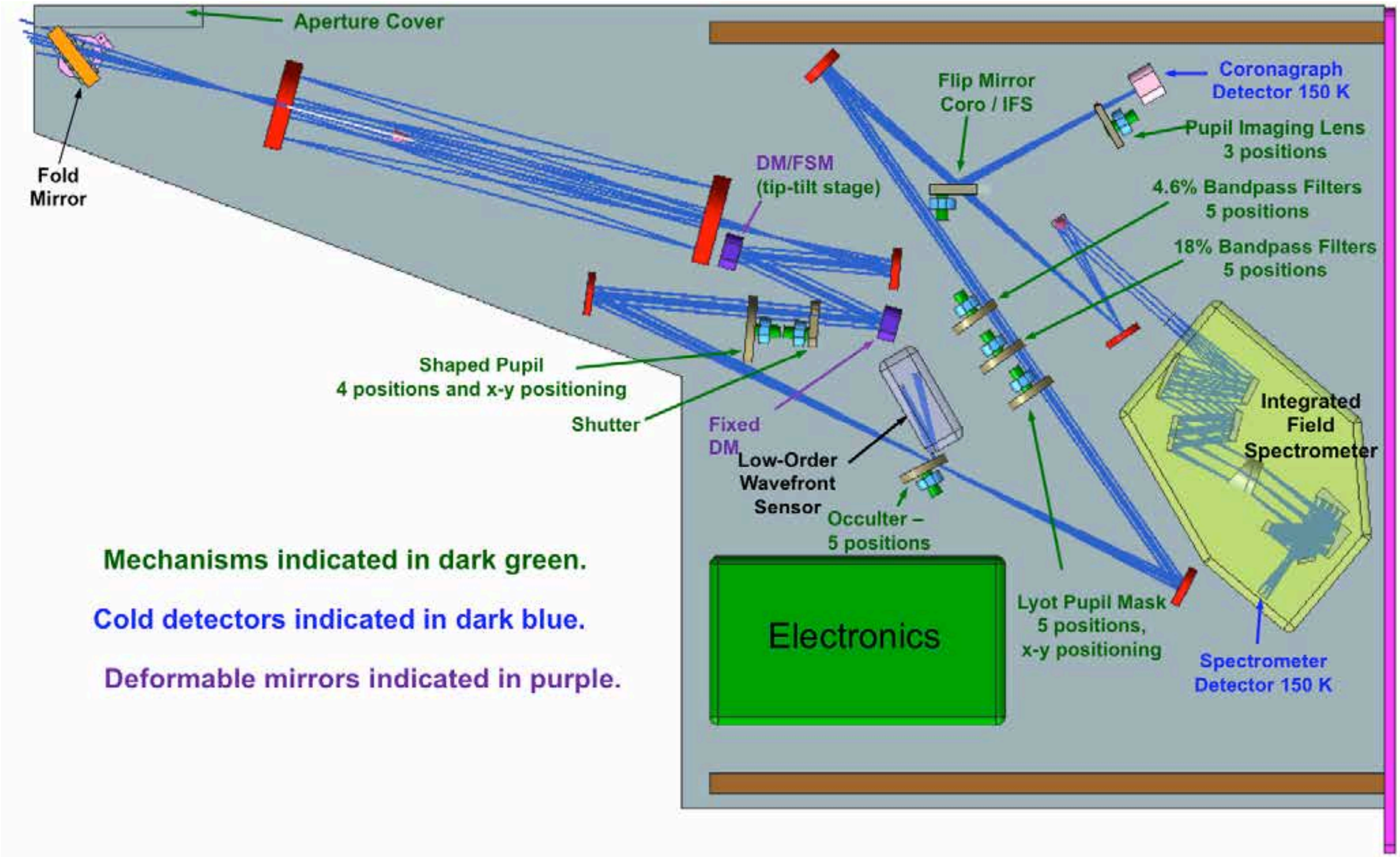


Figure 2. Dots on the telescope primary mirror (left) and corresponding on-axis PSF in the wide-field astrometric camera (right). The primary mirror area shown is 3% of the pupil diameter across and is located at the edge of the pupil. The spacing between the diffraction spikes, their extent in the focal plane, and their overall luminosity can be chosen by appropriate design of the dot pattern on the pupil.

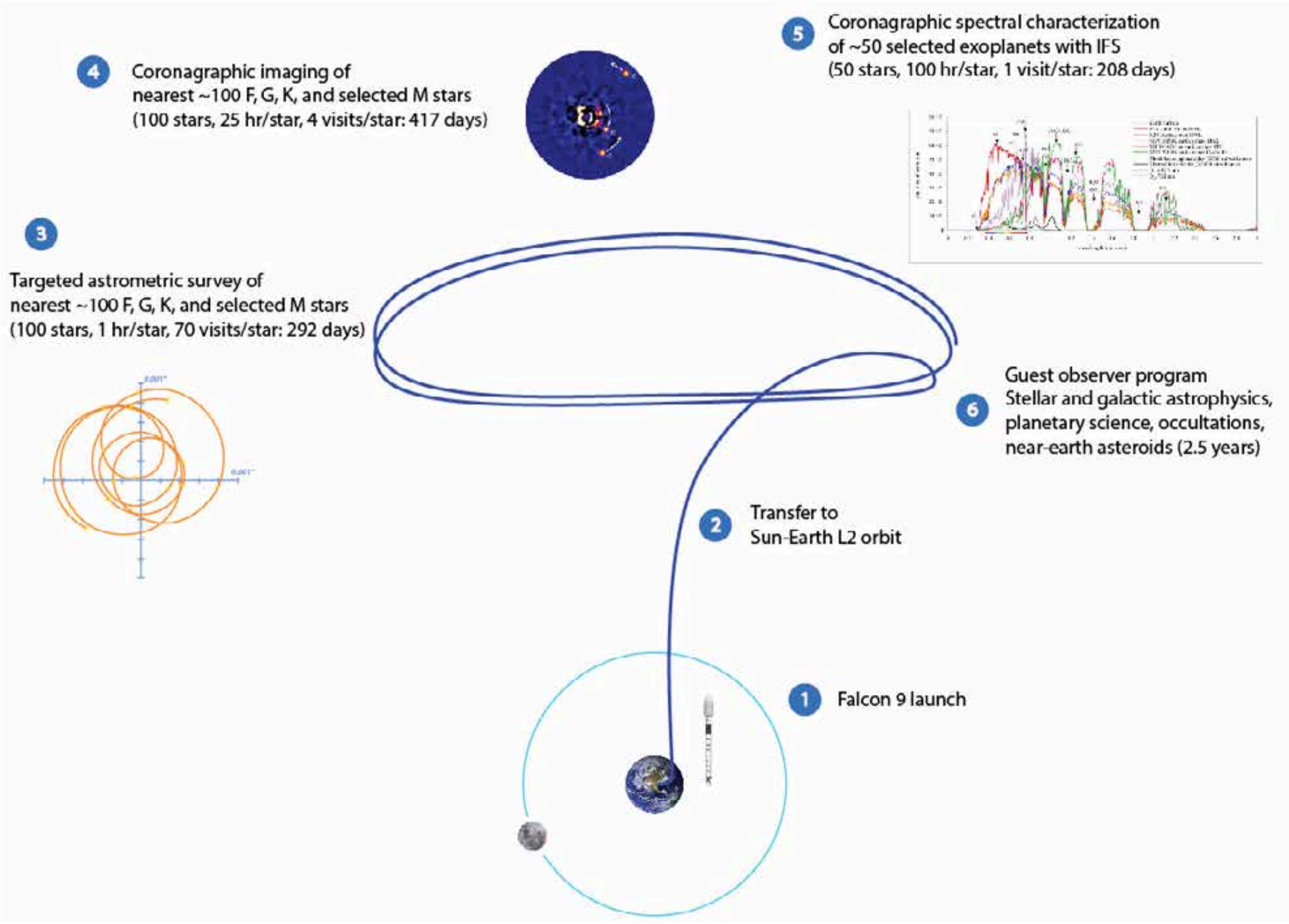
For further details see the presentation by Guyon et al.

Coronagraph Instrument Concept



For comparable concept see the presentation by Trauger et al.

5. ExO Operations Concept



ExO Time Allocation: 50% to exoplanets, 50% to astrophysics and planetary science

Method	Instrument	# stars	# hr/visit	# visits/ star	# hr/star	Allocation (hr)
astrometry	astro. cam.	100 stars	1 hr	70 visit/ star	70 hr	7,000 hr
image	coron. cam.	100 stars	25 hr	4 visit/star	100 hr	10,000 hr
spectrum	coron. IFS	50 stars	100 hr	1 visit/star	100 hr	5,000 hr
					sub-total:	**22,000 hr**
GO program	Above plus time-resolved spectrometer	tbd	tbd	tbd	tbd	22,000 hr
					grand total:	**44,000 hr = 5 yr**

Exoplanet science objectives:

- Astrometry: Search 100 stars for mass and orbit, from Earth to Jupiter, at 0.1 to 4 AU
- Imaging: Search 100 stars for brightness and orbit, from Earth to Jupiter, at 2 to 30 AU
- Spectrum: Planet spectra around 50 stars, from Super-Earth to Jupiter, at 2 to 30 AU

6. ExO Innovations

Innovative use of NASA capabilities and/or commercial services

- Makes full use of diameter of 2.4-m telescope to achieve required angular resolution needed for exoplanet imaging
- Makes full use of collecting area of 2.4-m telescope to achieve imaging of faint exoplanets and dust discs at contrast levels of 0.1 - 1.0 x 10^{-9} (e.g., 25^{th} magnitude objects)
- Potential "stretch" market for commercial servicing at Sun-Earth L2 point

Innovative use of processes or partnerships

- Potential for ESA & JAXA instrument contributions & science collaborations

7. ExO Addresses Multiple Objectives

- Advances frontier science, as #1 medium recommendation by Astrophysics Decadal Survey
- Advances technology, in line with STMD goals, including “wave-front sensing and control”, which is applicable to all telescopes and imaging systems, civilian and military
- Advances public awareness of STEM goals, in an understandable context of using a telescope to search for very faint planets
- Near-Earth Object tracking, a long-term NASA goal
- Engages science community currently using ground-based (mainly radial velocity), and soon with JWST (transiting planets) and WFIRST (gravitational microlensing)
- Huge potential for public interest in following the progress of mission, as it searches for planets around nearby, recognizable stars, and starts on the road to finding Earths, including the search for life

8. ExO is "Doable"

- Telescope already exists, is "ready to go", saving years of development work & cost uncertainty
- The L2 destination is well-understood, with excellent properties for this mission
- Spacecraft and mission architecture understood, with no major challenges
- Operations, navigation, data storage and downlink all understood, with no major challenges
- The instrument suite has been well-studied & demonstrated in the lab, and could be brought to TRL-6 within 3 years, at reasonable cost

Technical Feasibility

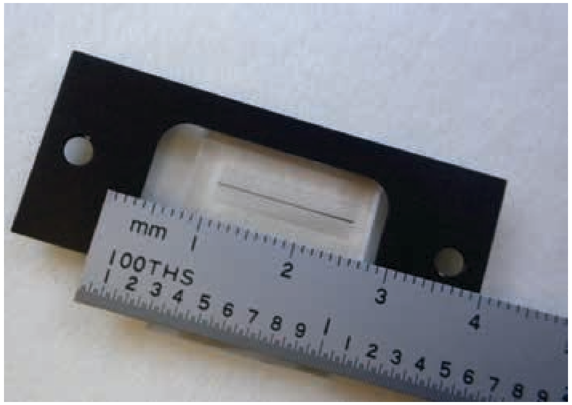


Image Plane Amplitude & Phase
Mask (Trauger, JPL)

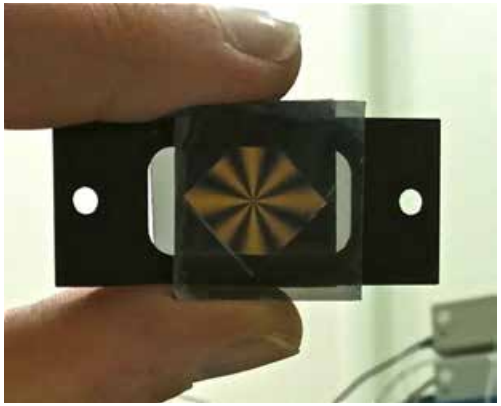
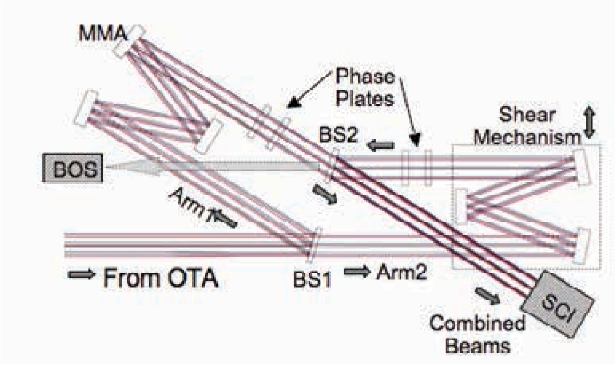
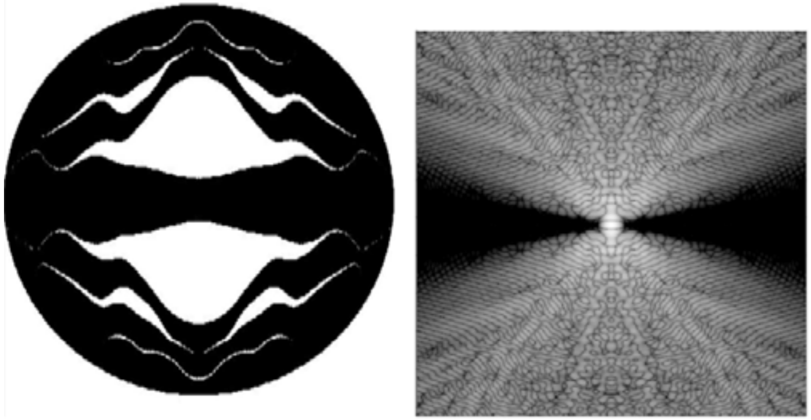


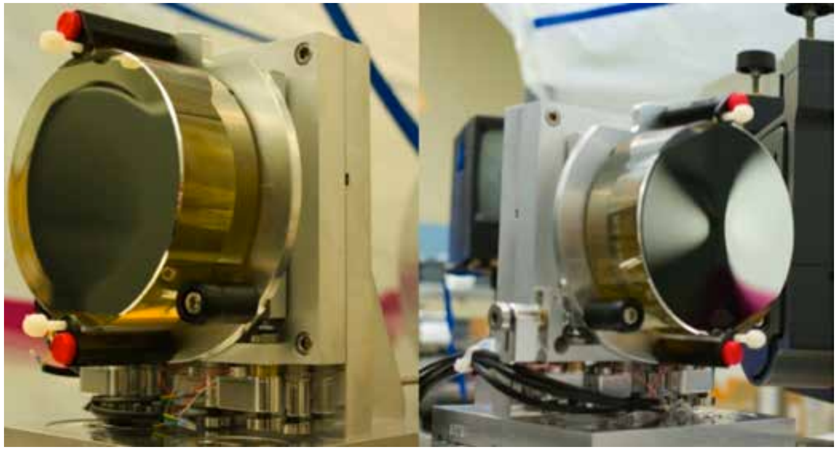
Image Plane
Phase Mask (Serabyn, JPL)



Pupil Shearing
(Clampin, NASA GSFC)

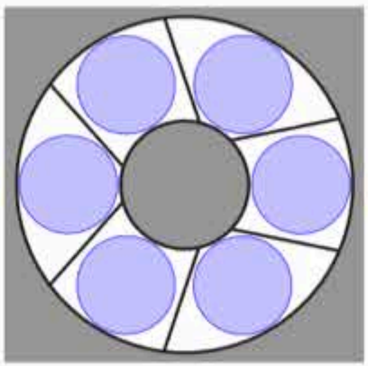


Pupil Masking (Vanderbei, Univ. Princeton)

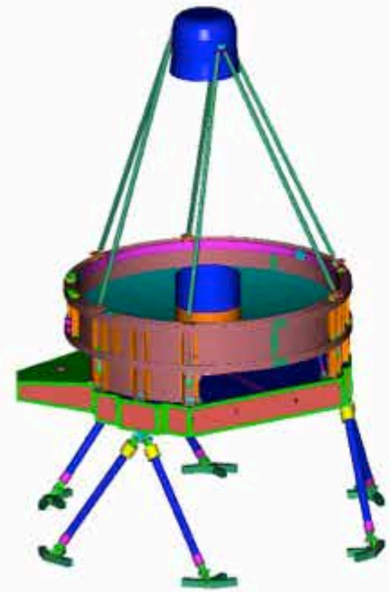


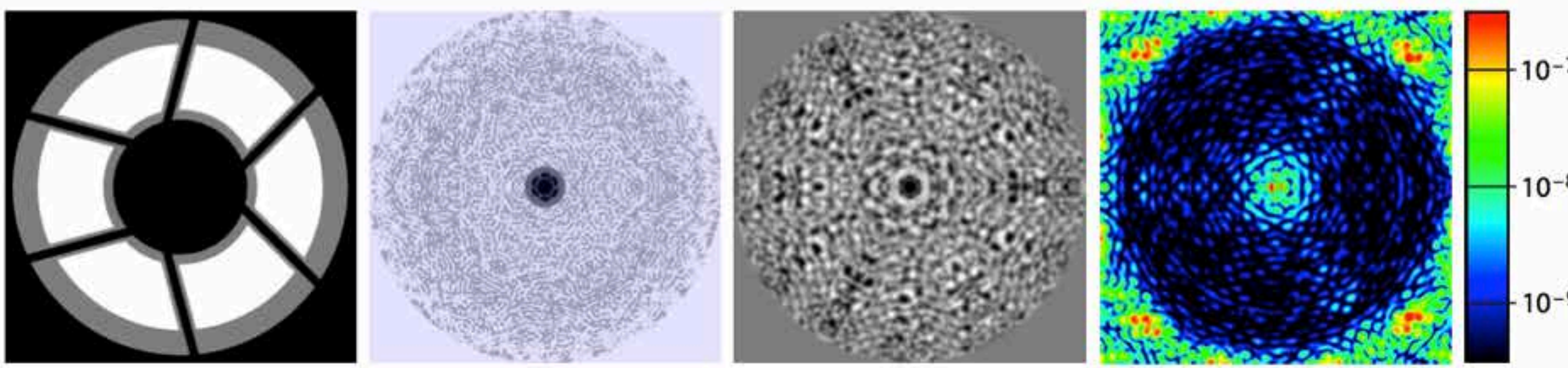
Pupil Mapping (Guyon, Univ. Arizona)

Designs for partly obscured apertures



Hybrid Lyot Masks
Vector Vortex
Visible Nulling Coronagraph
Pupil Masks
Phase Induced Amplitude Apodization





TELESCOPE APERTURE & LYOT MASK — LYOT FOCAL PLANE MASK (TRANSMITTANCE) — LYOT FOCAL PLANE MASK (PHASE SHIFT) — HIGH CONTRAST DARK FIELD

Courtesy of John Trauger (JPL/Caltech)

9. ExO Cost & Risk

- ExO lowers risk by using existing systems and technology:
  - Telescope, ground system, operational infrastructure, data analysis
  - Instrument technology requirements understood: clear path to TRL 6 by PDR (2019)
- Cost estimate by analogy at the subsystem level
  - Life cycle total estimated cost (including LV): $1.5B
  - Instrument suite estimated cost $350M

10. ExO is aligned with NASA goals

Astrophysics Division Goals

- NWNH-2010, #1 medium-scale recommendation is

"preparation for a planet-imaging mission beyond 2020"

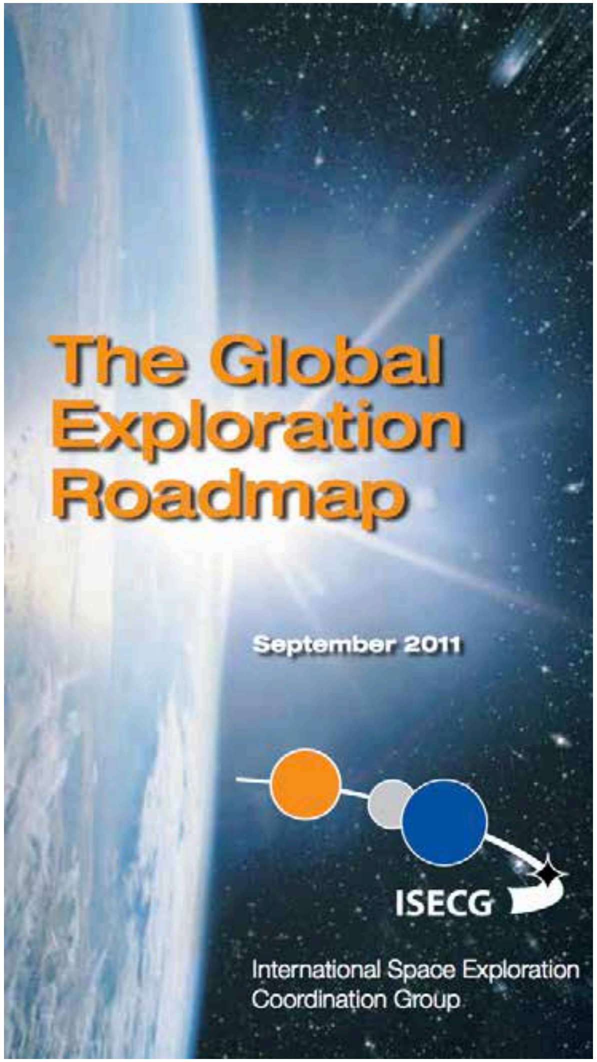
- NWNH-2010, small-scale recommendation is

"understanding the birth of galaxies, stars, and planets"

Technology Directorate Goals

- Advances technology of high-contrast imaging & spectroscopy
- Prepares for a later mission to image Earths & search for signs of life

Alignment with NASA Goals and Priorities



Space Technology Mission Directorate

– "High-contrast imaging and spectroscopy" ranked amongst the top 16 NASA Technologies to be pursued within STMD (OCT)

Human Exploration and Operations Directorate

- Advanced Technology Development
- Use ISS for demonstrations of technology, operation concepts and techniques
- Develop a new generation of space systems and infrastructure

Backup:

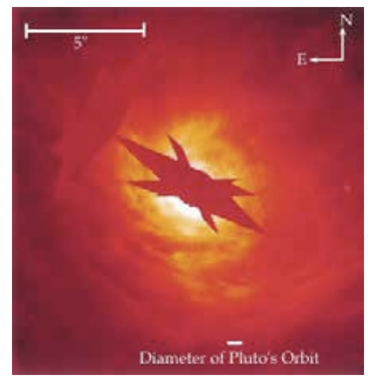
Science Objectives
Instrument Suite
Mission Design
Operations Concept

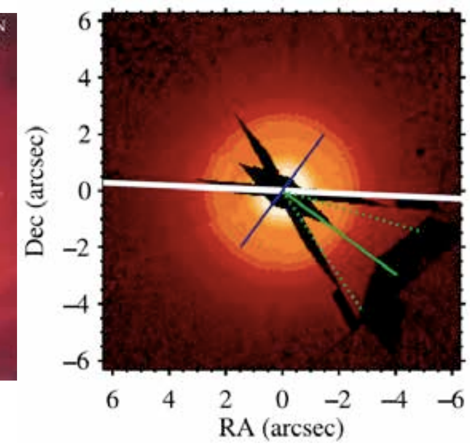
Coronagraph Science: Circumstellar Disks (1)

- **ExO's Key Features for Disks Science: CONTRAST and IWA !!**
  - HST has imaged virtually all bright debris disks with fractional luminosity Ld/L* > 10^{-4}.
  - ExO's niche is to extend this work to much lower contrast (Ld/L* ~ 10^{-6}) and closer in (dark hole: 0.1 to 2.5")
  - Shall concentrate on nearby stars (provides enough photons for wavefront control, and best physical spatial resolution)
  - Can sample of variety of states across planetary systems evolution, from YSO's to young PMS to mature stars

- **Direct Spectro Imaging of Young Planets embedded in Bright ProtoPlanetary Disks:**
  - Constrain Planet Formation Mechanisms in the first 10 Myr.

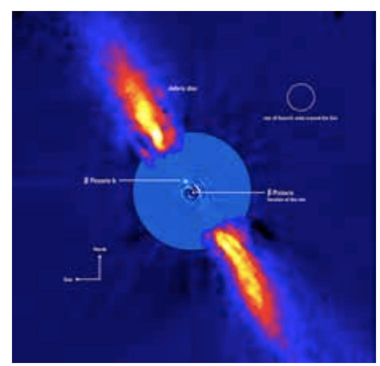
  Examples: HST /STIS images of AB Aur (Grady et al. 1999) and TW Hya (Roberge et al. 2005):

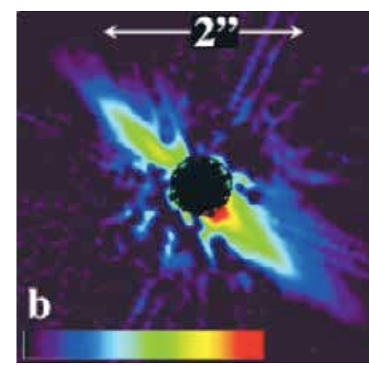




- **Direct Imaging of Planets and (Transitional) Disks around Pre Main Sequence Stars:**
  - Directly study the correlation between the presence of disk asymmetries, rings, gaps and other dynamical structures, and the existence of planets

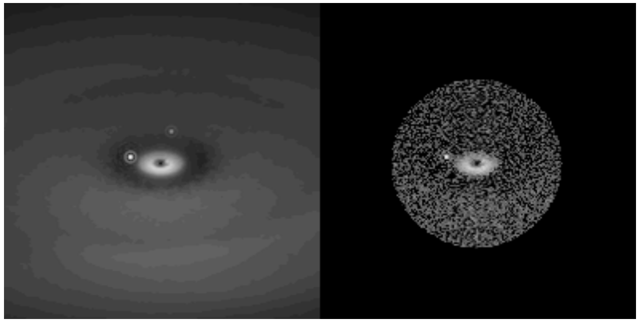
  Examples: wrapped disks around bet Pic (Lagrange et al. 2010) and HD 32297 (Schneider et al. 2005)





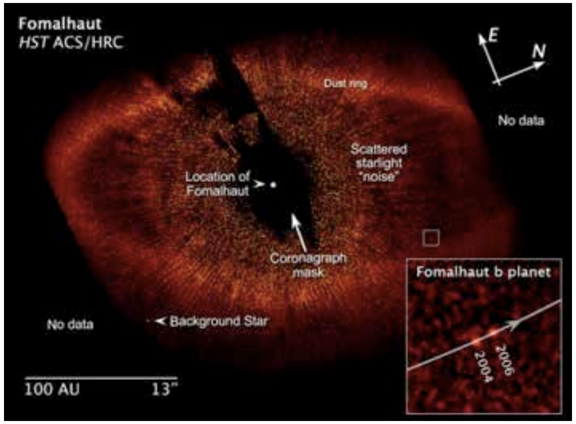
Coronagraph Science: Circumstellar Disks (2)

- **Observations of Faint Debris Disks in the HZ of Mature Stars**
  - ExO allows to get down to exo-zodi and exo-Kuiper Belt levels much fainter than HST.
  - Level of scattered exo-zodi visible light is key information for the proper design of future Earthlike-exoplanet direct imaging missions



Simulation of Solar System as seen from 20 pc with ExO Coronagraph (courtesy of J. Krist). Jupiter and zodi cloud are clearly visible

- **Obtain Spatially Resolved Scattered Light Spectra of Circumstellar Disks**
  - Examine the composition (and compositional spatial gradient) of grains and parent planetesimals across debris disks,
  - Important as a source of biogenic material that can be delivered to terrestrial planet surfaces.



Fomalhaut's debris disk observations with HST/ STIS (Kalas et al. 2005)

Science with Time-Resolved Spectrometer

- High-contrast (2-5 PPM in 1 hr on α Cen) spectra
- Large SALSO mirror and extreme instrument stability allows *photometric detection of non-transiting planets*
- For nearest super-Earths, exo-Neptunes, exo-giant planets, we get:
  - Eclipse-mapped images (if transiting)
  - Spectroscopic phase curves (if not transiting)
- Nearest giants: atmospheric comp. and *T(p)* in 3D!
- [Estimates of number of transit spectra] ?
- [Simulated spectra from spectrometer] ?
- First space-based 1-2.5 μm solar-system occultations (? check NICMOS)

Time-Resolved Spectrometer

- Key instrument parameters
  - 0.4 – 2.5 μm single order
  - Resolving power R=2000
  - >10 Hz full-frame (faster subarray)
  - Fast steering mirror keeps PSF stable to 0.01 pix
  - 1 ms absolute, 1 μs relative timing accuracy (occultations)
  - Storage for few-days' stare, downloadable while obs.
- Design heritage
  - Uses Moon Mineralogy Mapper optics: already flown successfully
  - Adopt results from trades studies and from the FINESSE and EChO phase-A concept studies

Synergy with JWST

- Both ExO coronagraph and JWST NIRCam will directly image mature giant planets
  - JWST mid-IR (~4μm) *emission* spectra
  - ExO visible *reflection* spectra
  - Together, they will constrain abundances, temperatures, scattering, albedos, clouds
- Both missions can observe many of the same nearby (d < ~30 pc) AFG stars
- Small overlap in the actual detected planets
  - because of the larger JWST IWA (~600 mas = 4 to 6 λ/D at 4 μm)
  - falloff at r^{-2} of visible planet brightness with distance from the star

Opportunities with ExO in Astrophysics and Planetary Science

(Nancy will format next 5 slides as tables)

Astrophysics using Coronagraph IFU

Straight-through to IFU (no coronagraph) improves the spectral & spatial resolution of current *Hubble* programs of narrow-field imaging with broadband photometry

Resolved solar-system objects (Orton)	Image Uranus and Neptune 0.4–1.0 @ 0.05 arcsec/pixel	measure the long-term variability of clouds and the distribution of methane, and their dependence on insolation
		investigate short-term variations, such as those determined in 2009–2012 for Uranus and continuing for Neptune
	Image Titan at 0.4–1.0 microns @ 0.05 arcsec/pixel	determine variability of clouds and composition to test alternative global-climate models of the atmosphere
	Image Io at 0.4-1.0 microns	characterize and differentiate between various volcanic plumes
	Imaging of Enceladus at 0.4–1.0 microns	characterize the time dependence of its south polar plumes (Sufficient sensitivity? Radius = 0.04 arcsec: coronagraph?)
	Spatially resolved spectroscopic imaging of comets.	determine the distribution of dust and gas vs. insolation and composition of nucleus
Circumstellar science with faint central star not requiring coronagraph (Sahai)	obscured dying stars in sample of ~50	explore near-stellar environment of AGB and post-AGB objects to reveal disks, jets, and multiplicity, using 0.4-1 micron imaging
	young stars in radiation-dominated environments (Sahai)	study free-floating evaporating gas globules (frEGGs) and photo-evaporating disks (proplyds) to better understand their evolutionary relationship
Resolved AGN (Zlatan)		

Astrophysics using Coronagraph IFU

The coronagraph would be inserted for programs impeded by bright, unresolved, central sources.

Unresolved solar-system objects (Orton)	minor asteroids, small satellites, KBOs, unresolved comets	discovery of multiple systems
		characterization of 0.4-1.0 micron spectra
Circumstellar science with bright star requiring coronagraph	Thousands of known YSO dust structures and gas jets < 500 pc as yet unstudied because of blinding light of central. (Stapelfeldt)	trace dust dispersal process with age; look for radial zones cleared by protoplanets;
	unobscured dying stars in larger sample of several hundred (Sahai)	explore near-stellar environment of AGB and post-AGB objects to reveal disks, jets, and multiplicity, using 0.4-1
		search RGBs for analogs of the Kuiper Belt and Oort Cloud, indirect evidence of giant planets or brown dwarfs in those regions, and the beginnings of the dust-driven mass-loss process controlling late stellar evolution
		search faint, high-latitude carbon stars for companions and circumstellar disks predicted by mass-transfer
	young stars in radiation-dominated environments (Sahai)	study free-floating evaporating gas globules
Unresolved AGN (Zlatan)		

Astrophysics using Astrometric Camera

Near-earth objects (Bendek).	track and survey potentially hazardous objects (NEOs)	determine orbits
“Missing dwarf galaxy problem” (Spergel)	observe tidal tails of globular clusters in the Galactic halo to seek evidence for lumps of orbiting dark matter with no or very few stars attached	test of cold dark matter theory
Clusters (Bendek)	clusters of galaxies	membership determination
Galactic dynamics (Bendek)	e.g. Westerlund 1, NGC3603, R136…	proving galactic dynamics efficiently using local starbust templates in low extinction areas to enable visible bands observation.
	external galaxies within 1 Mpc.	direct extragalactic dynamics and rotation curves
Extragalactic parallaxes (Bendek)	Measure giant K0 stars and Cepheids in external galaxies	Improved distance scale for determination of H_0 (?).
Stellar mass estimation at 1% level (Makarov, Gaudi)	measure deflections of anonymous background stars microlensed by known, passing, foreground, bright, high-proper-motion stars.	fundamental stellar data, including perhaps for exoplanet search targets using coronagraph.
Lens mass estimation (5%) for photometric microlensing events. (Gaudi)	Observe the curved trajectory of source star during event.	fundamental stellar data, perhaps on stars with planetary microlensing perturbations, in which case the true planetary mass is determined.
		mass function of isolated remnants (BH, NS, and WD).
Test Newton’s Law of Gravity in the weak-field regime. (Makarov).	observe relative acceleration of known, extremely wide pairs of common proper motion stars	test of fundamental physics
Constrain the accuracy of the radio/optical reference-frame link. (Makarov)	determine if the quasars defining the International Celestial Reference Frame (ICRF) are point sources at the sub-mas scale of the well characterized ExO PSF	if the quasars are resolved by ExO, it will cast doubt on the ability of Gaia to connect the ICRF and the Geocentric Celestial Reference Frame at the microarcsec level

Astrophysics using Time-Resolved Spectrometer (R = 2000, λ= 0.4–2.5 μm)

Resolved solar-system objects (Orton)	slit-scan spectral imaging of Jupiter using 0.8-2.5 micron spectrometer	search for seasonal influences on clouds and gas compo
		investigate variations on rapid time scales (days to weeks), such as the whitening and re-darkening of major bands
		search for seasonal influences on clouds and gas composition
		characterize the behavior of the atmosphere between *Juno* and JUICE missions (c. 2017-2030)
	slit-scan spectral imaging of Saturn using 0.4-2.5 micron spectrometer	determine the full extent of strong seasonal influences on clouds and gas composition
		compare with *Cassini* observations to determine differences
		examine rapidly evolving events (e.g. the great northern hemisphere storm of 2010)
	slit-scan spectral imaging of Uranus using 0.4-2.5 micron spectrometer	
Stellar occultations (Harrington)	rapid-cadence spectra for up to several days, with accurate per-pixel timing, even using very faint (and therefore abundant) stars	atmospheres: determine high-resolution vertical thermal and compositional profiles, study wave propagation and energy transport to the stratosphere
		rings: map ringlet and gap locations, density and particle sizes, with km resolution
		map the column density and composition of comet comae with km resolution
		directly measure sizes of KBOs, comet nuclei, and asteroids

ExO Mission Timeline

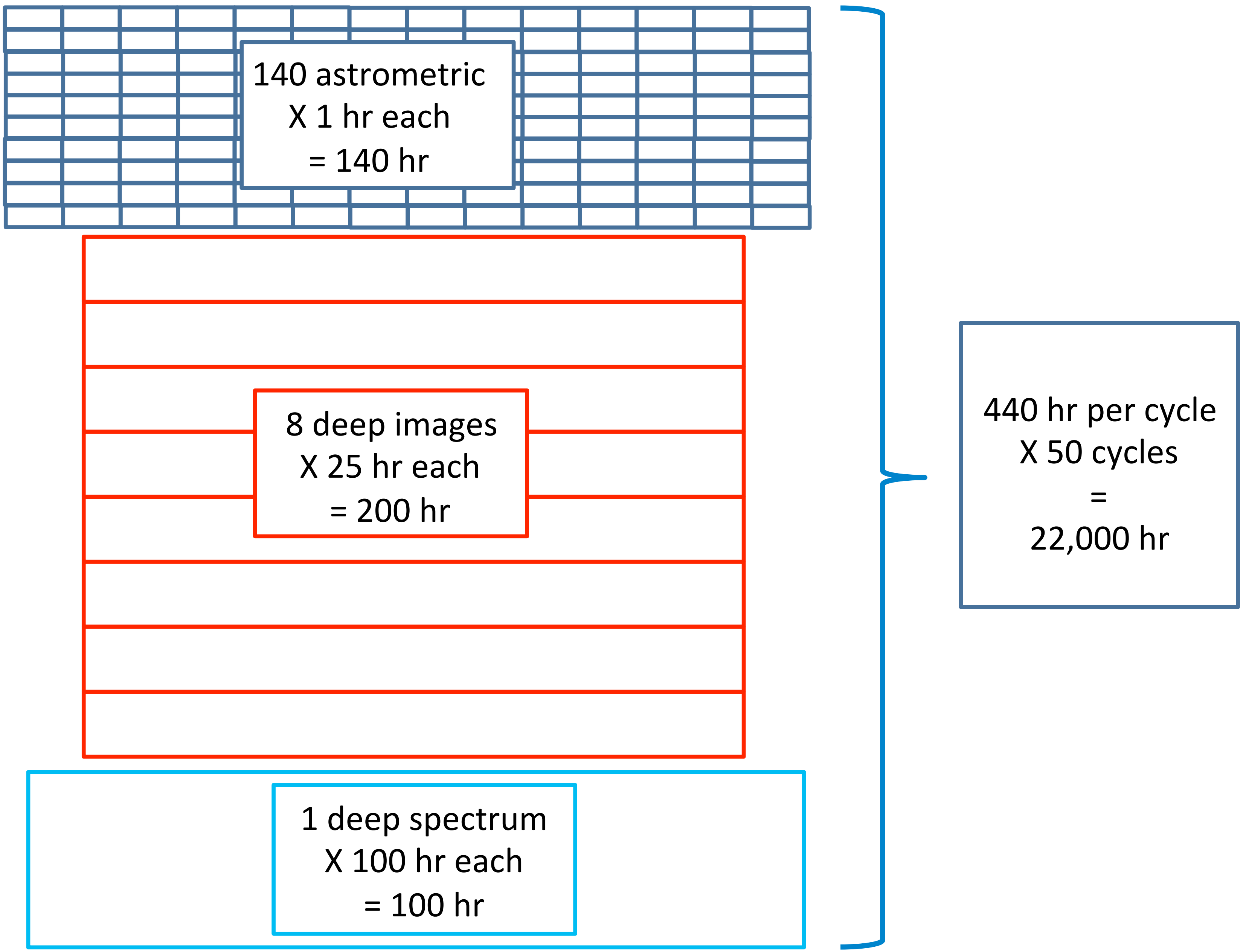
- 5 year mission lifetime
- Exoplanet science objectives can be met in 50% of available time
- Remaining 50% open to any topic in astrophysics and planetary science
- Scheduling is flexible: any combination of
  - Key Projects
  - Legacy Programs
  - Guest Observer Programs, etc.
- Example: could structure the observing in a series of ‘cycles’

Observing cycles: an example

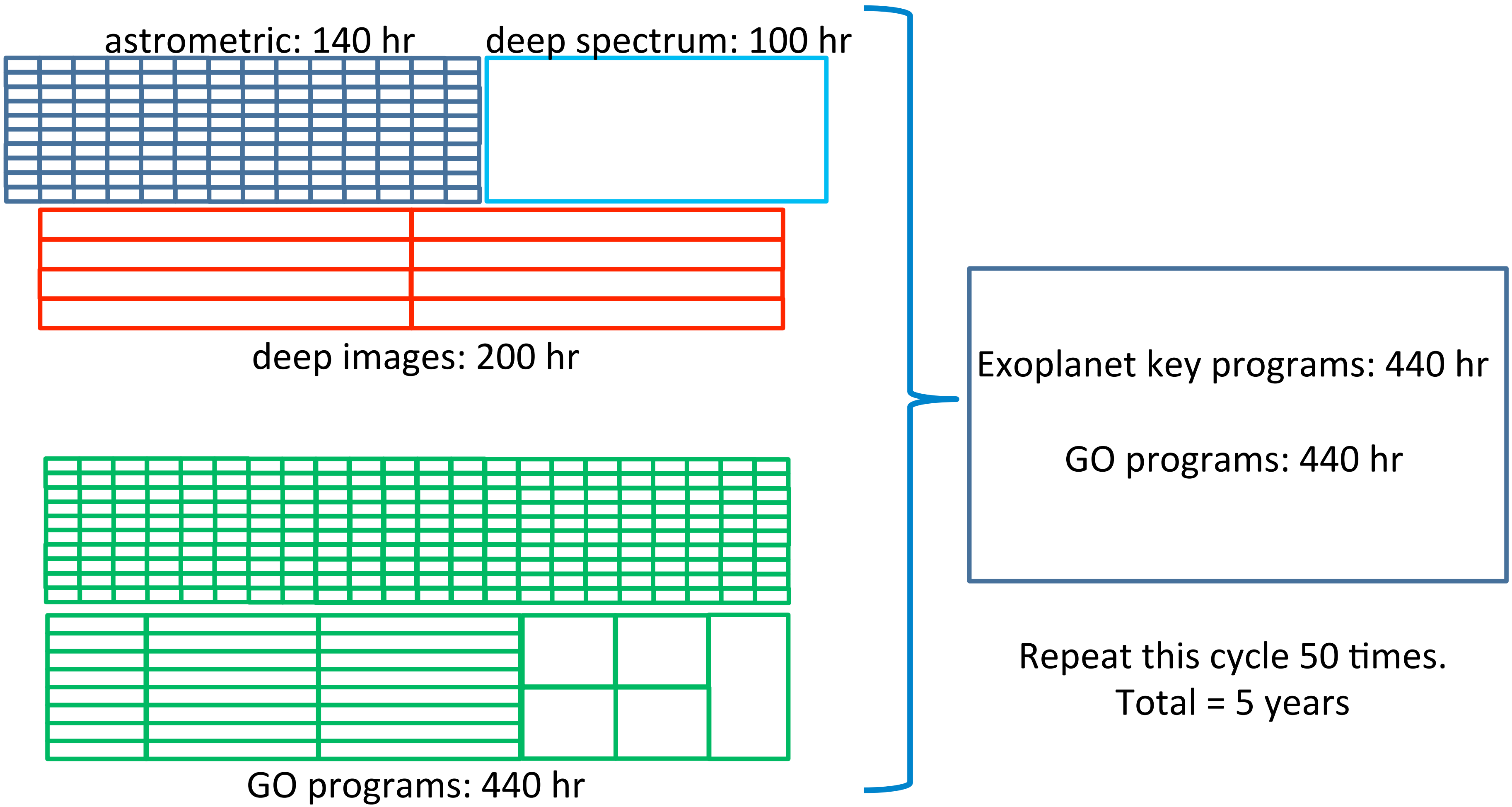
- One observing cycle:
- ~18days on exoplanet science
  - 140 astrometric measurements, 1 hr each, time = 140x1hr = 140 hr
  - 8 imaging measurements, 25 hr each, time = 8x25hr = 200 hr
  - 1 spectrum measurement, 100 hr each, time = 1x100hr = 100 hr
  - Total time = 440 hr (=18 days)
- ~18 days on General Observer science
  - Interleave exoplanet key program with GO program

- Repeat cycle for 5 years:
  - 50 repeats of above cycle, 2x50x440 hr = 44,000 hr

Illustration of the 18-day observing cycle



36-day cycle illustrated



Repeat this cycle 50 times.
Total = 5 years