Precision Radial Velocities and the NASA Exoplanet Exploration Program

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Jet Propulsion Laboratory/California Institute of Technology

August 17, 2017

3rd Workshop on Extremely Precise Radial Velocities (EPRV) – State College

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Artist concept of Kepler-16b
Credit: NASA/JPL-Caltech/T. Pyle

NASA Exoplanet Exploration Program

Astrophysics Division, NASA Science Mission Directorate

NASA's search for habitable planets and life beyond our solar system

Program purpose described in
2014 NASA Science Plan

1. **Discover planets around other stars**
2. **Characterize their properties**
3. **Identify candidates that could harbor life**

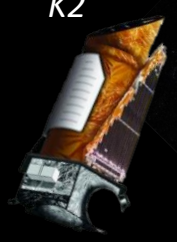
ExEP serves the science community and NASA by implementing NASA's space science vision for exoplanets

https://exoplanets.nasa.gov

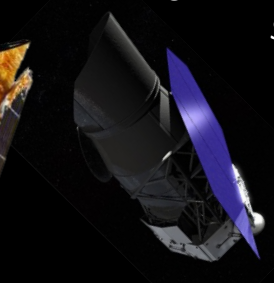
NASA Exoplanet Exploration Program

Space Missions and Mission Studies

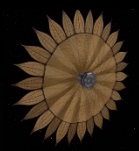
Kepler, K2



WFIRST



Starshade



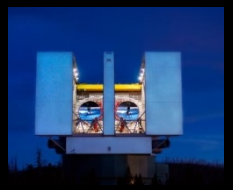
Decadal Studies

Coronagraph

Communications

Supporting Research & Technology

Key Sustaining Research

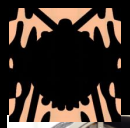


Large Binocular Telescope Interferometer

Keck Single Aperture Imaging and RV

NN-EXPLORE

Technology Development



Coronagraph Masks

High-Contrast Imaging

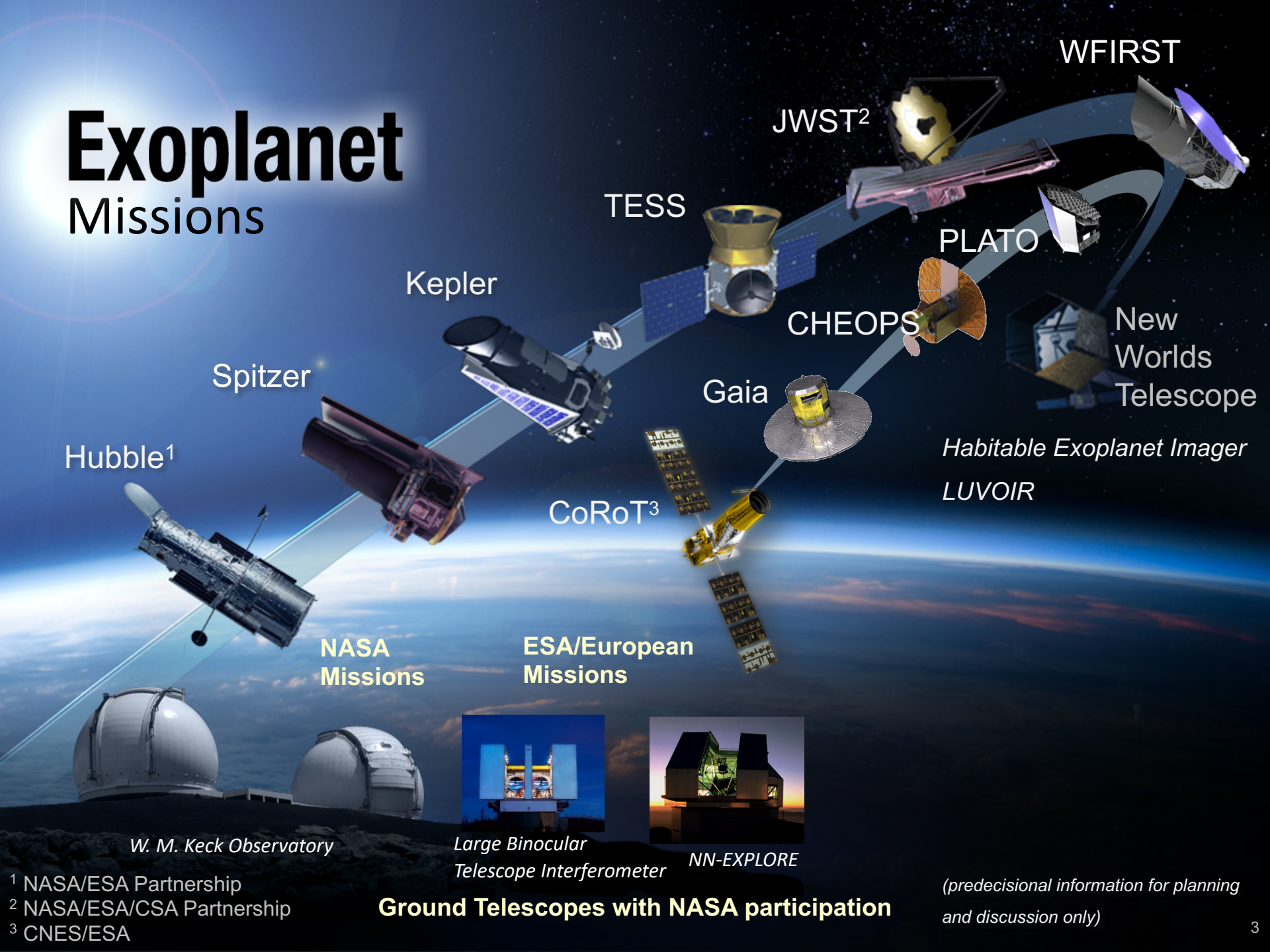
Deployable Starshades

NASA Exoplanet Science Institute

Archives, Tools, Sagan Fellowships, Professional Engagement

https://exoplanets.nasa.gov

Exoplanet Missions



Ground Telescopes with NASA participation

[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA

(predecisional information for planning and discussion only)

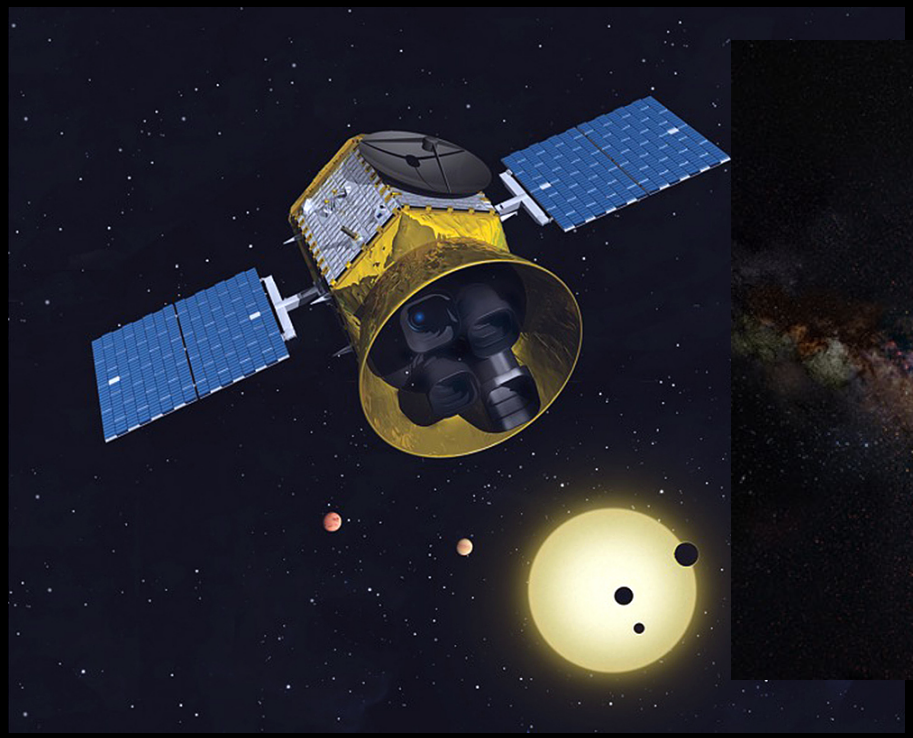
Exoplanet research within *other* NASA Projects & Programs

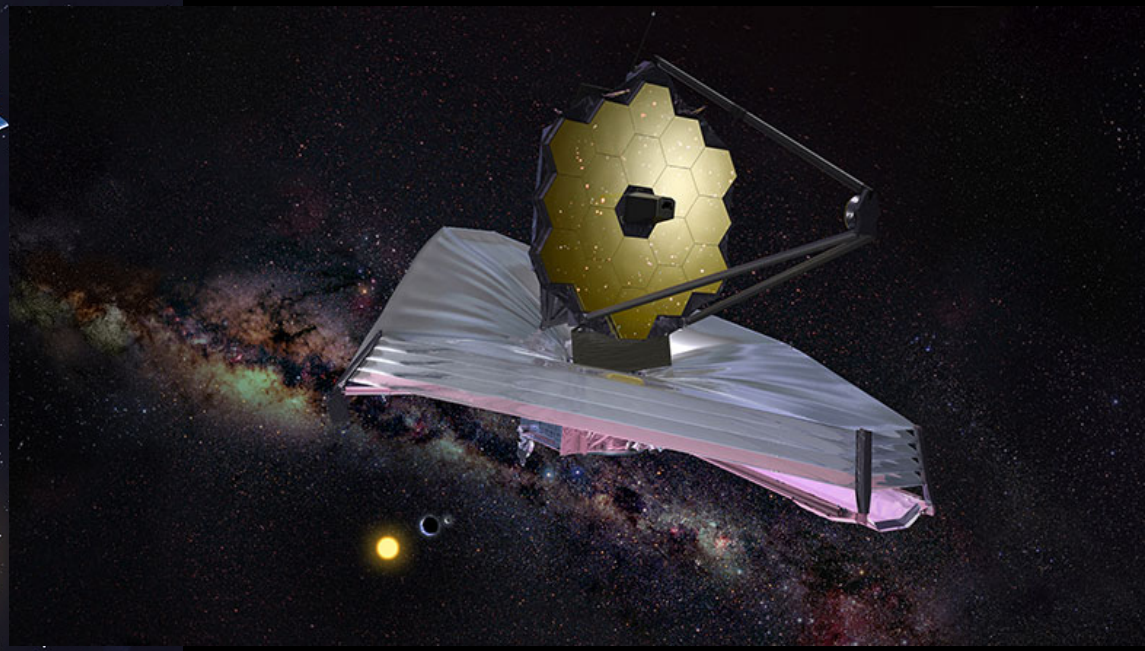
(General-purpose activities managed *outside* of ExEP)

- Hubble Space Telescope general observer (STScI)
- Spitzer Space Telescope general observer (SSC/IPAC)
- Research & Analysis grant programs (NASA HQ)
  - Exoplanet Research (**XRP**), Habitable Worlds, Emerging Worlds
  - NASA Astrobiology Institute (**NAI**)
  - Nexus for Exoplanet System Science (**NExSS**)
- **JWST** (NASA HQ & STScI; in dev. for 10/18 launch)
- **TESS** (NASA Explorer Program; in dev. for 3/18 launch)
- Explorer Program concept studies (selected 8/2017): FINESSE, Contribution to ESA ARIEL mission

TESS
launch: Mar 2018

JWST
launch: Oct 2018





(not to scale!)

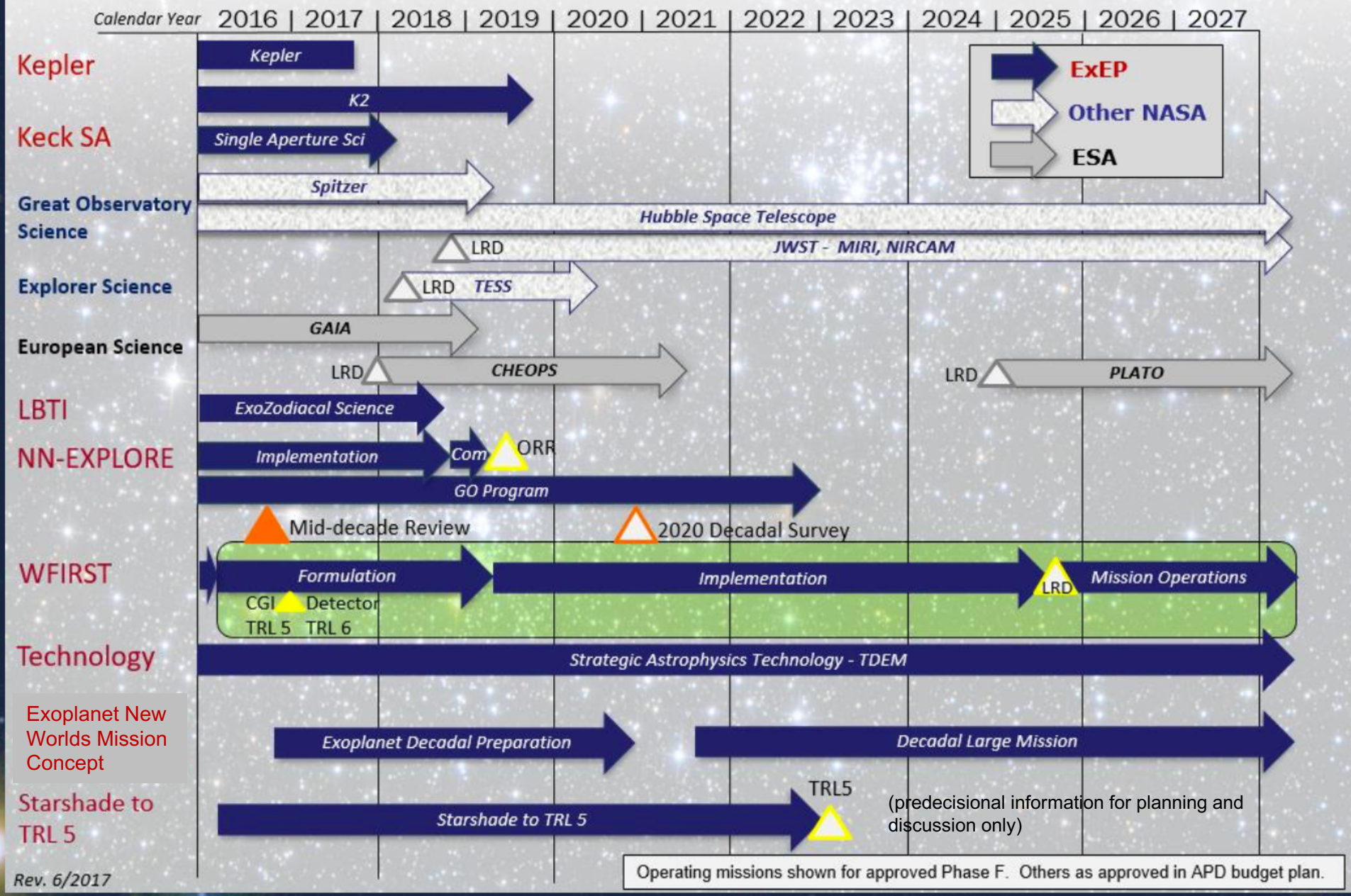
(https://tess.gsfc.nasa.gov/overview.html, NASA)

(https://jwst.stsci.edu/science, NASA)

Exoplanet Exploration: A Decade Horizon

NASA and ESA efforts

ExoPlanet Exploration Program



Important reminder:

NASA doesn't invest in ground-based astronomy for the sake of doing good science; NASA invests in ground-based astronomy because there is a compelling mission need to do so.

ExoPAG SAG8 report (Plavchan, Latham, et al., 2015) summarized how PRV provides NASA mission support: target identification for mission science yield optimization, follow-up validation & characterization of low-mass transiting exoplanets, determination of exoplanet masses and orbits

New Worlds, New Horizons (2010 Decadal)

"One of the fastest-growing and most exciting fields in astrophysics is the study of planets beyond our solar system. The ultimate goal is to image rocky planets that lie in the habitable zone—at a distance from their central star where water can exist in liquid form—and to characterize their atmospheres. To prepare for this endeavor, the committee recommends a program to lay the technical and scientific foundations for a future space imaging and spectroscopy mission. ***NASA and NSF should support an aggressive program of ground-based high-precision radial velocity surveys of nearby stars to identify potential candidates.*** *In the first part of the decade NASA should support competed technology development to advance multiple possible technologies for a next-decade planet imager, and should accelerate measurements of exozodiacal light levels that will determine the size and complexity of such missions." (NWNH)*

*"****Improve radial velocity measurements on existing ground-based telescopes to discover planets within a few times the mass of Earth as potential targets for future space-based direct-detection missions****." (NWNH)*

"Is the typical outcome of planet formation gas-giant worlds with panoplies of satellites, like Jupiter and Saturn, or rocky worlds like Earth with atmospheres and surface liquids stabilized by being suitably near to stable parent stars like the Sun, or some completely different kind of object that is not represented in our solar system? ***The answer to this question will require a complete census of planetary systems in the nearby portion of our galaxy. By compiling the statistics of planetary sizes, masses, and orbits for a range of planetary systems around stars of different masses, compositions, and ages, it will be possible to gain deep insight into the processes by which worlds such as our own come into being****." (NWNH)*

Science Questions and Required Data for Direct Imaging Exoplanet Missions

	Science Questions	Targets	Data Type and Quality
Planetary Sys. Properties	A1 Planetary System Diversity	Statistical Studies of Planetary Systems	1) Multi-epoch Imaging: Planetary Orbits 2) Phot/Spec/RV/Astrom: Planet Masses
	A2 Planetsimal Belts, Exo-Zodi Disks, Formation of Planetary Systems?		1) O/IR Imaging: Locations of Dust Belts 2) Planet masses and orbits (RV, Astrom.)
Planet Properties	B1 Rotation and Obliquitiy	Studies of Individual Planets	1) Time-Resolved Phot/Spec 2) High-Res Spec. for Rotational Period 3) Lightcurves at Multiple Orb. Phases: Obliquity
	B2 Which Rocky Planets have Surface Liquid Water?		1) Time-Resolved Obs: Ocean Glint 2) Rotational Mapping: Oceans 3) Water Line Spectroscopy
	B3 Aerosols and Composition in Giant Planets		1) Low-res., broad range spectroscopy 2) Time-resolved Phot. for Cloud Mapping 3) Optical/Near-IR Colors
	B4 Terrestrial Planets Atmospheric Composition		1) Low-res., broad range spectroscopy 2) Optical/Near-IR colors 3) Planet masses and orbits
Planetary Processes	C1 What Processes/Properties Influence Atmospheric Circulation?	Statistical Studies of Groups of Planets	1) Multi-epoch, moderate to high-res. NIR spectroscopy
	C2 Key evolutionary pathways for rocky planets?		1) Atmospheric Characterization (B4) 2) Planet Mass
	C3 Geological Activity/Interior Processes		1) Atmospheric Characterization (B4) AND 2) Surface mapping (B2) 3) Planet Mass (RV or astrom.)

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NASA support of precision radial velocity work

- Development of NN-Explore instrument NEID (collaboration w/NSF). This will lead to community access to state-of-the-art PRV spectrograph on northern 4-m class telescope, and pipeline/data archiving at NExScI
- Community access to Keck HIRES (managed through Keck Cooperative Agreement for NASA time). KPF will be available 2020. Support by NExScI.
- IRTF/iSHELL observations (NASA telescope, managed by Planetary Sciences; astrophysics limited to 50%)
- EarthFinder probe study – develop case for precision RV from space
- R&A Programs (e.g. XRP), Astrobiology, NExSS
- Recent past:
  - Seed funding for CHIRON (CTIO 1.5-m, PI Fischer), iLocator (LBT, PI Crepp), MINERVA-Red (PI: Blake)
  - Technology grant to develop laser frequency comb (MIT, testing HARPS-N)

NN·EXPLORE

Partnership for Exoplanet Discovery and Characterization

- Motivation
  - 2010 Decadal Survey called for precise ground-based spectrometer for exoplanet discovery and characterization
  - Follow-up & precursor science for current missions (K2, TESS, JWST, WFIRST)
  - Inform design/operation of future missions
- Scope:
  - Extreme precision radial velocity spectrometer (<0.5 m/s) with 40% of time on WIYN telescope
    - Penn State NEID proposal selected in March 2016
    - Instrument to be commissioned spring 2019
    - R= 100,000; 380-930 nm wavelength coverage
  - Ongoing Guest Observer program using NOAO share of telescope time for exoplanet research

NN-Explore Exoplanet Investigations with Doppler Spectroscopy

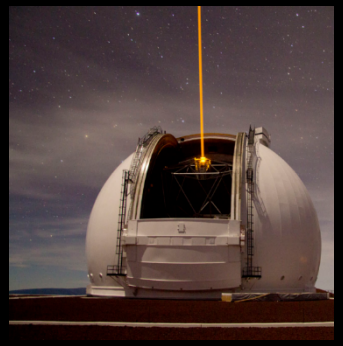
PennState

PI: S. Mahadevan

3.5m WIYN Telescope
Kitt Peak National Observatory
Arizona

Ground-Based Support for Space Missions

The twin 10m Keck telecopes at Mauna Kea, Hawaii



- NASA is 1/6th partner
- Key Projects and smaller general observer Investigations
- Proposals for 2018A due on 9/14
- HIRES (now), KPF (2020-)

Astrophysics Probe Mission Concepts

Announced by NASA March 20

- 10 proposals selected for mission concept studies
  - PI-led science team
  - NASA mission design labs at JPL and GSFC.
  - Results will be provided to 2020 Decadal Committee

PI	Affiliation	Title
Camp, J.	NASA's Goddard Space Flight Center	Transient Astrophysics Probe Concept Study
Cooray, A.	Univ. California, Irvine	Cosmic Dawn Intensity Mapper
Danchi, W.	NASA's Goddard Space Flight Center	Cosmic Evolution through UV spectroscopy (CETUS)
Glenn, J.	Univ. of Colorado	Galaxy Evolution Probe
Hanany, S.	Univ. of Minnesota	Inflation Probe Mission Concept Study
Mushotzky, R.	Univ. of Maryland	AXIS: A High Spatial Resolution X-ray Probe Satellite
Olinto, A.	Univ. of Chicago	Concept Study of the Probe Of Extreme Multi Messenger Astrophysics (POEMMA)
Plavchan, P.	Missouri State Univ.	EarthFinder: A Diffraction-Limited Precise Radial Velocity Observatory in Space (*Partial selection)*
Ray, P.	Naval Research Laboratory	STROBE-X: X-ray Timing and Spectroscopy on Dynamical Timescales from Microseconds to Years
Seager, S.	Massachusetts Institute of Technology	Starshade Rendezvous (*Partial selection)*

- 2 exoplanet studies were "partially" selected:
  - Peter Plavchan: develop the science case for space PRV mission.
  - Sara Seager: update starshade rendezvous mission concept.

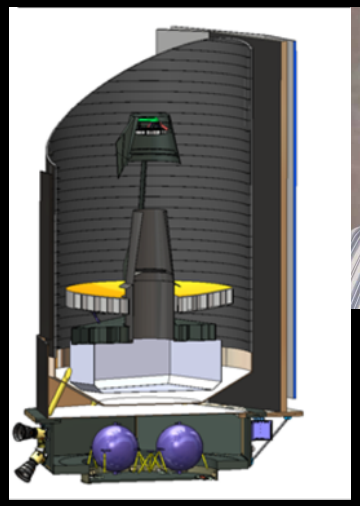
- The ExEP and PCOS / COR programs are facilitating all ten studies by supporting the PIs throughout the study and more specifically assisting the PIs in executing their design lab studies.

TEAMX Jet Propulsion Laboratory

Goddard SPACE FLIGHT CENTER Integrated Design Center

EarthFinder Probe Mission Concept

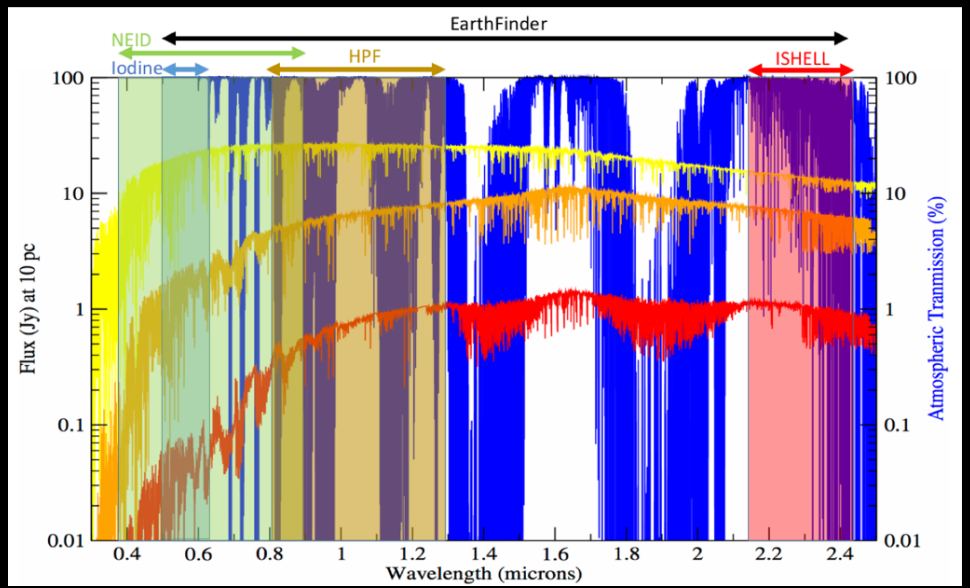
- Going to space removes some error budget terms
  - Tellurics, Sky, Scattered sunlight, wind, temporal and wavelength-dependent variable atmospheric transmission
  - All benefits of diffraction-limited, single mode fiber compact spectrographs
- Quantify advantages of going to space vs. a ground global network of super-CARMENES with R>150k and 1 cm/s stability for mitigating stellar activity
  - Uninterrupted cadence (no 1.0 day alias)
  - Uninterrupted spectral grasp from visible through NIR
  - No tellurics
  - Can we do 1 cm/s from the ground or not?



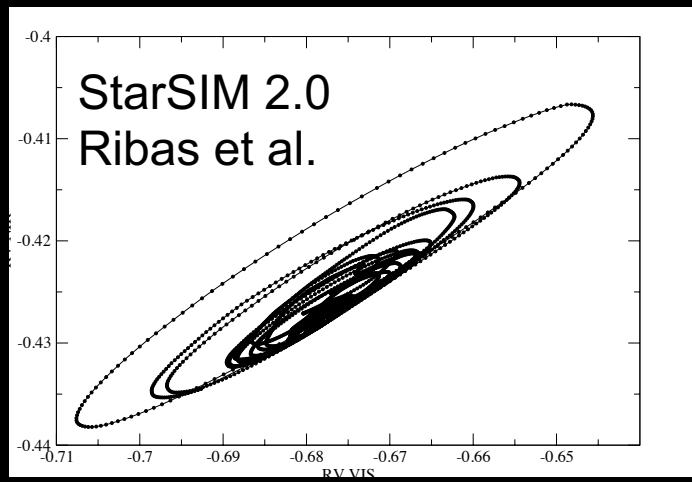
D~1-1.5m
Not to scale

Earth-trailing like Kepler or L2

Want to help? pplavcha@gmu.edu



NIR RVs



Vis RVs

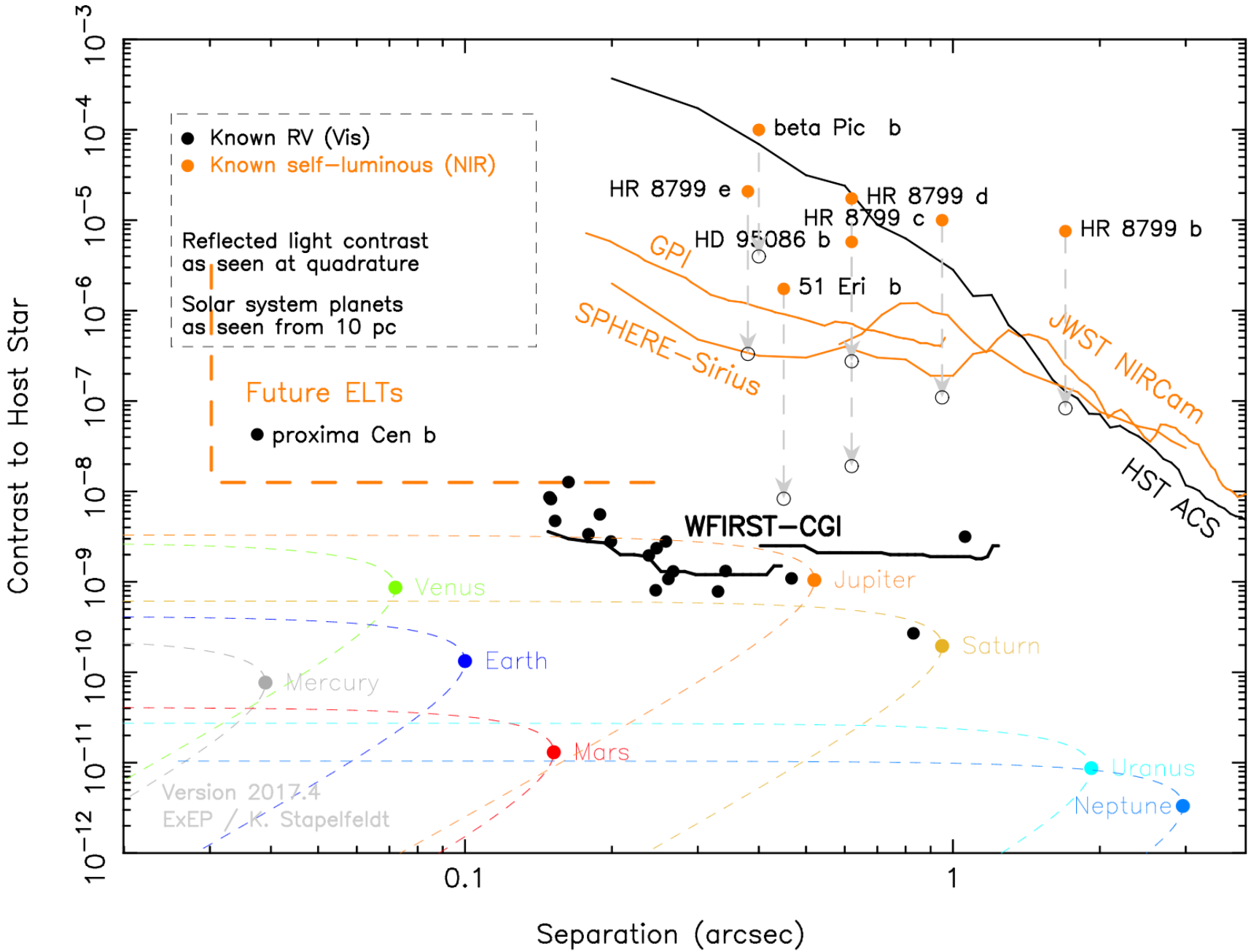
Wide Field Infrared Survey Telescope (WFIRST)

Dark Energy, Exoplanets via two main methods

- WFIRST in Phase A
- All technology milestones were met on time
  - Five for IR Detector, now at TRL 6
  - Nine for Coronagraph, now at TRL 5
- Actively studying making WFIRST starshade-ready (not baseline).
- Reviews for SRR/MDR: delayed to allow independent external review
- https://www.nasa.gov/feature/nasa-taking-a-fresh-look-at-next-generation-space-telescope-plans

Credit: NASA/GSFC

Exoplanet Direct Imaging in the Optical and Near–infrared



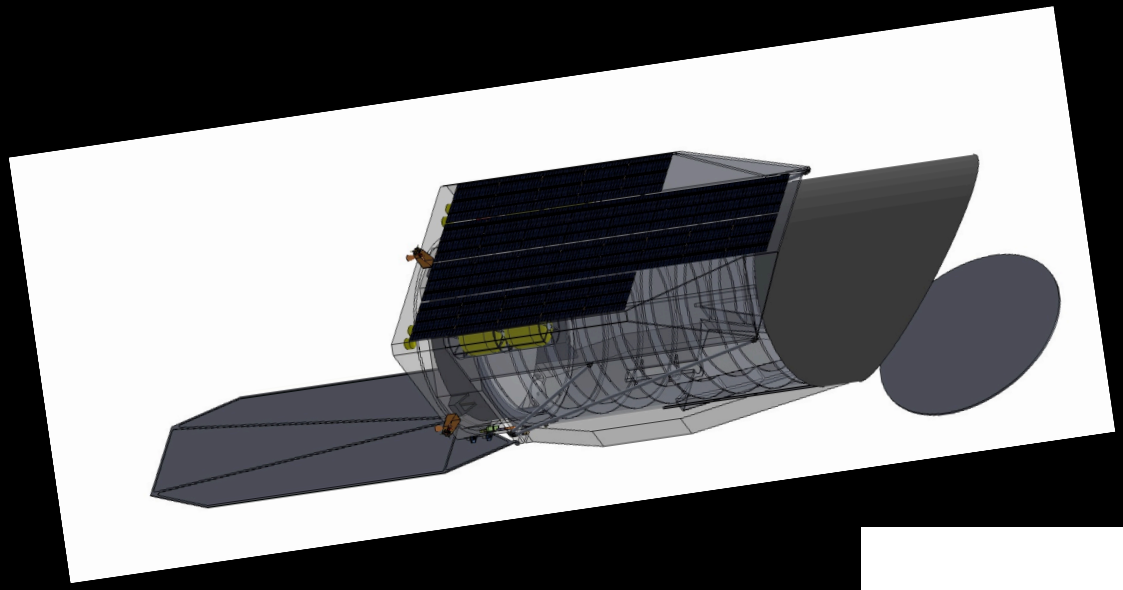
Possible New Worlds Exoplanet Telescopes

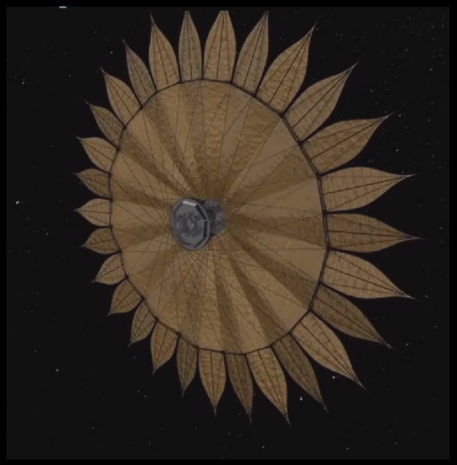
(if selected by 2020 decadal -> launch ~mid-2030s)

- **Large Ultra-Violet Optical InfraRed Telescope (LUVOIR)**
  - Coronagraphic imaging with deployed/segmented primary mirror
  - Large apertures & exoplanet survey samples
  - 5 instruments, equal weighting to exoplanets & general astrophysics
- **Habitable Exoplanet Mission (HabEx)**
  - Coronagraph & starshade imaging with monolithic, off-axis telescope
  - Smaller apertures & exoplanet survey samples
  - 3 instruments, including UV spectrometer & general astrophysics camera
- **Origins Space Telescope (OST)**
  - mid/far-infrared flagship concept
  - Primary exoplanet science case is transit spectroscopy
  - New exoplanet working group co-Chaired by Lisa Kaltenegger (Cornell) & Kevin Stevenson (STScI)

Progress in HabEx and LUVOIR designs

(work outside of ExEP)

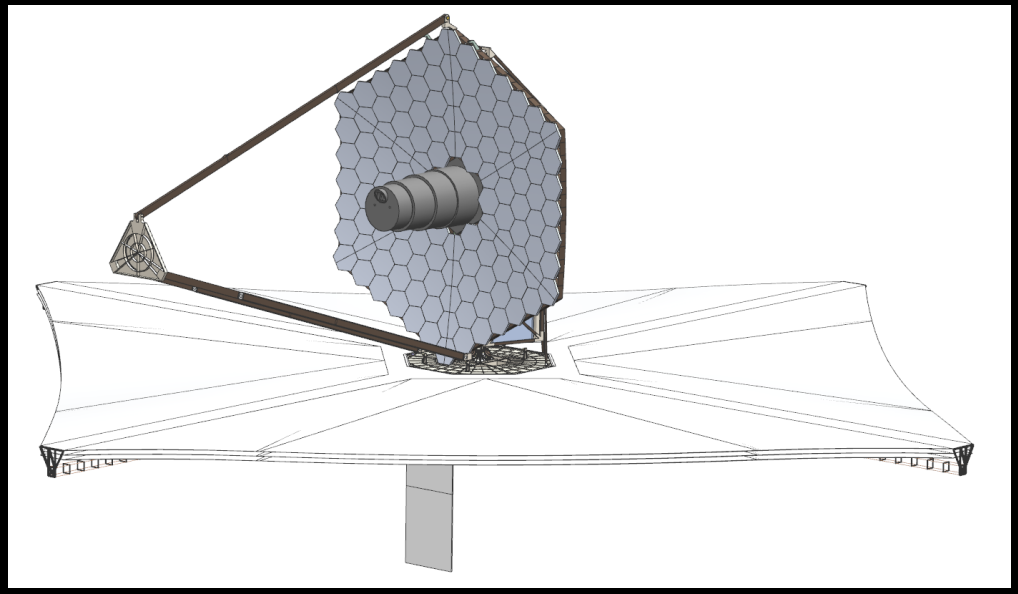




Above: HabEx 4m telescope with lateral optical bench, solar pressure paddle & starshade

Right: LUVOIR 15m telescope, 6 ring hex, deployed sunshade

ExEP supports technology needs



Two community studies of potential future missions to find/characterize ExoEarths : Habitable Exoplanet Mission (HabEx) and Large UltraViolet Optical near-IR (LUVOIR) surveyor

- Both have goal of studying Earthlike planets in reflected light; they differ in levels of ambition, cost, and technical readiness
  - HabEx to "*search for*" signs of habitability and biosignatures
  - LUVOIR to "*constrain the frequency of*" habitability and biosignatures = larger statistical survey of exoEarths, larger aperture
- HabEx to focus on exoplanets, "best effort" on general astrophysics. Starshade. Study led by JPL/Caltech
- LUVOIR gives equal priority to exoplanets and cosmic origins science, is HST-like, an expansive vision. Study led by NASA Goddard.
- Interim reports late 2017; final reports early 2019. Next Astrophysics Decadal Survey to decide if one of them might go forward

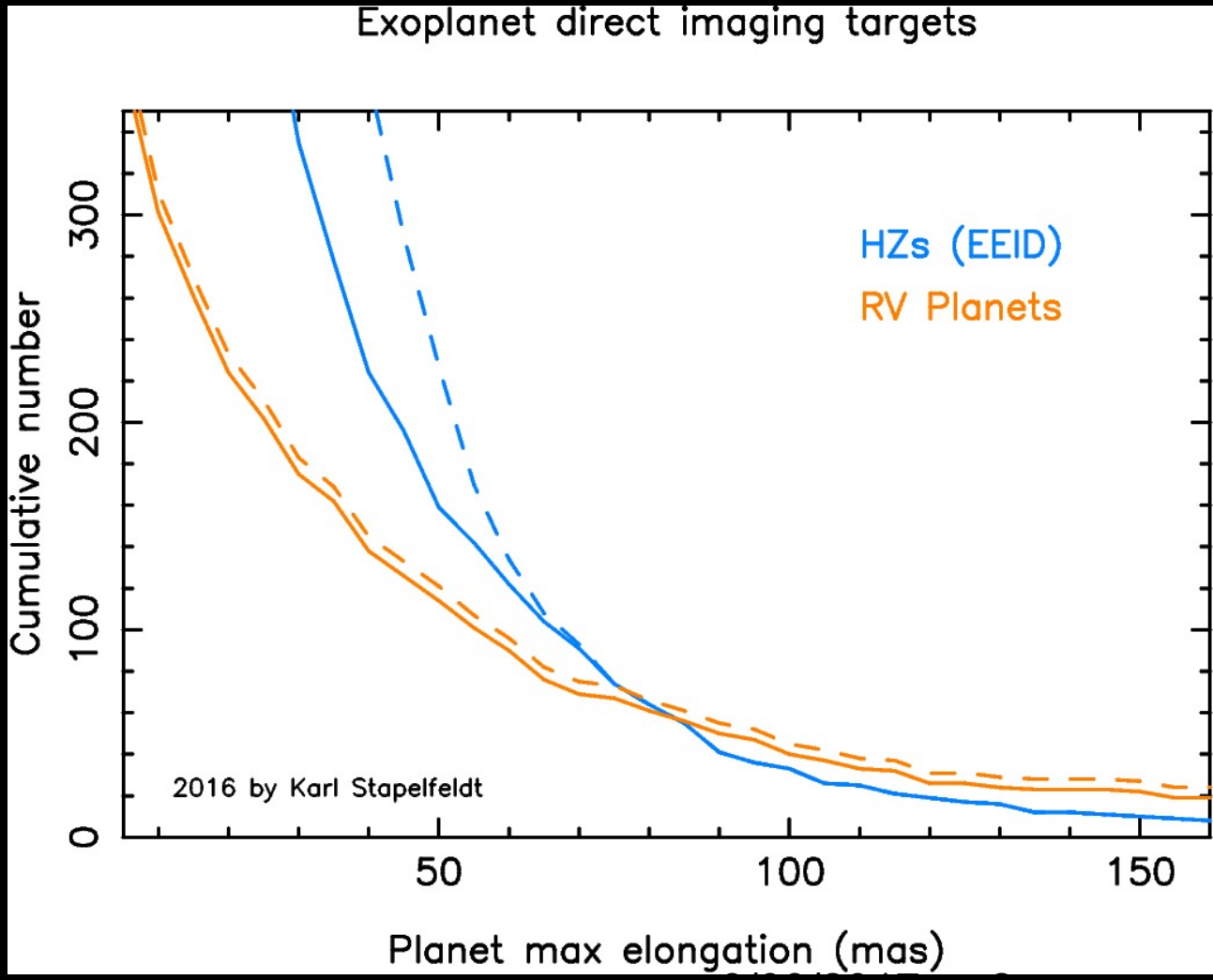
(predecisional information for planning and discussion only)

Capabilities of future space telescopes for exoplanet imaging characterization - target samples

Cumulative number of known RV planets and HZs that can potentially be accessed, as a function of how close to the star one can look.

Values reflect local distribution of star types & their distances from the Sun

Accessing 100 HZs will require looking as close as 70 mas, which at 0.55 μm could require a ~5 m telescope



NASA Auth Bill S.442

SEC. 508. EXTRASOLAR PLANET EXPLORATION STRATEGY.

(a) STRATEGY.—

(1) IN GENERAL.—The Administrator shall enter into an arrangement with the National Academies to develop a science strategy for the study and exploration of extrasolar planets, including the use of the Transiting Exoplanet Survey Satellite, the James Webb Space Telescope, a potential Wide-Field Infrared Survey Telescope mission, or any other telescope, spacecraft, or instrument, as appropriate.

(2) REQUIREMENTS.—The strategy shall—

(A) outline key scientific questions;

(B) identify the most promising research in the field;

(C) indicate the extent to which the mission priorities in existing decadal surveys address the key extrasolar planet research and exploration goals;

(D) identify opportunities for coordination with international partners, commercial partners, and not-for-profit partners; and

(E) make recommendations regarding the activities under subparagraphs (A) through (D), as appropriate.

(b) USE OF STRATEGY.—The Administrator shall use the strategy—

(1) to inform roadmaps, strategic plans, and other activities of the Administration as they relate to extrasolar planet research and exploration; and

(2) to provide a foundation for future activities and initiatives related to extrasolar planet research and exploration.

(c) REPORT TO CONGRESS.—Not later than 18 months after the date of enactment of this Act, the National Academies shall submit to the Administrator and to the appropriate committees of Congress a report containing the strategy developed under subsection (a).

NASA Needs for PRV for next decade and beyond

- Masses and orbits necessary for interpreting exoplanet spectra, constraining composition of transiting and imaged exoplanets. Doppler spectroscopy provides Critical to achieving NASA mission science goals -> needed ground-based work
- TESS follow-up -> masses -> targets for JWST transit spectroscopy to characterize exoplanet atmospheres
- Monitor RVs of nearby FGK stars for targets for WFIRST imaging (large planets, wide orbits) in late 2020s and future mission(s) in 2030s; e.g. NEID on WIYN, Keck HIRES (eventually KPF), etc.
- Masses and orbits of planets in hab zones of nearby FGK stars (TBD by 2020 Decadal: perhaps either WFIRST + Starshade Rendezvous imaging exoEarths by end of 2020s, or future flagship (e.g. LUVOIR, HabEx) in mid-2030s).
- Pay special attention to “mission stars”, see target lists at: https://exoplanetarchive.ipac.caltech.edu/docs/MissionStellar.html

Total NEID instrumental error budget: 27.0 cm/s

(Halverson+ 2016)

Instrument (uncalibratable): 15.1 cm/s (30.6%)

Fiber & illumination: 8.7 cm/s

Calibration source modal noise	2.5 cm/s
Continuum modal noise	2.5 cm/s
Near-field scrambling	3.5 cm/s
Far-field scrambling	5.0 cm/s
Stray light	5.0 cm/s
Polarization	2.0 cm/s

Detector effects: 7.1 cm/s

Readout thermal change	5.0 cm/s
Charge transfer inefficiency	5.0 cm/s

Barycentric correction: 1.7 cm/s

Algorithms	1.0 cm/s
Exposure midpoint time	1.0 cm/s
Coordinates and proper motion	1.0 cm/s

Reduction pipeline: 10 cm/s

Software algorithms	10 cm/s

25%

Instrument (calibratable): 11.2 cm/s (1.1%)

Thermo-mechanical: 7.8 cm/s

Thermal stability (grating)	3.5 cm/s
Thermal stability (cross-disp.)	3.0 cm/s
Thermal stability (bench)	3.0 cm/s
Vibrational stability	2.0 cm/s
Pressure stability	<0.1 cm/s
LN2 fill transient	1.0 cm/s
Zerodur phase change	5.0 cm/s

Detector effects: 8.1 cm/s

Pixel inhomogeneities	1.0 cm/s
Electronics noise	1.0 cm/s
Stitching error	3.0 cm/s
CCD thermal expansion	2.0 cm/s
Readout thermal change	5.0 cm/s
Charge transfer inefficiency	5.0 cm/s

Calibration source (uncalibratable): 11.5 cm/s (18.7%)

Calibration accuracy: 5.7 cm/s

Stability	4.0 cm/s
Photon noise	4.0 cm/s

External errors (uncalibratable): 18.7 cm/s (49.6%)

Calibration process: 10 cm/s

Software algorithms	10 cm/s

Telescope: 12.2 cm/s

Guiding	scrambling
ADC	6.9 cm/s
Focus	5.0 cm/s
Windshake	8.0 cm/s

Atmospheric effects: 14.1 cm/s

Micro-telluric contamination	10 cm/s
Sky fiber subtraction	10 cm/s

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov