Jet Propulsion Laboratory
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NASA's Technology Investments Towards an Exo-Earth Imaging and Characterization Mission

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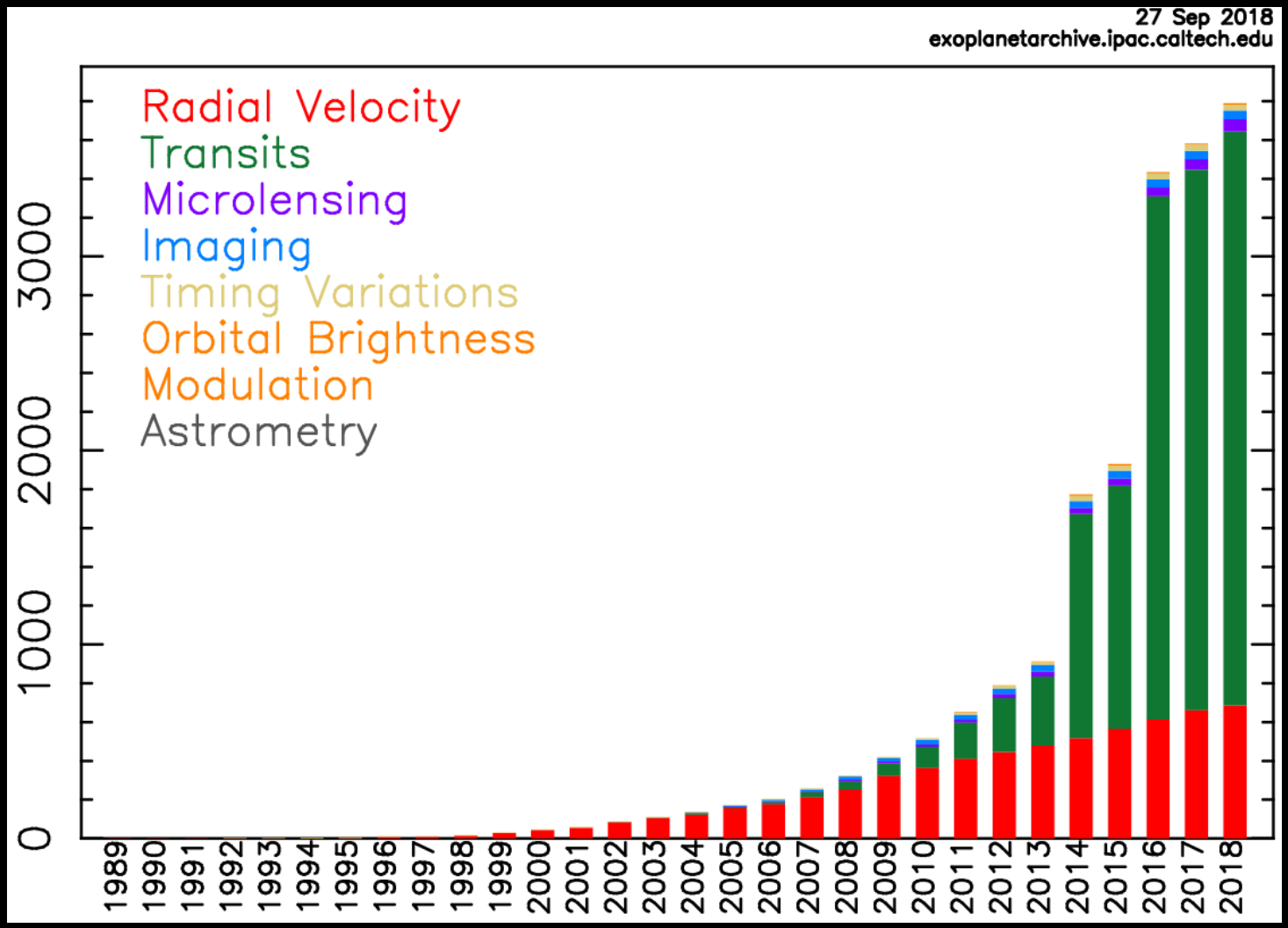
Mirror Technology Days
El Segundo, CA
November 5, 2018

3791 Confirmed Exoplanets

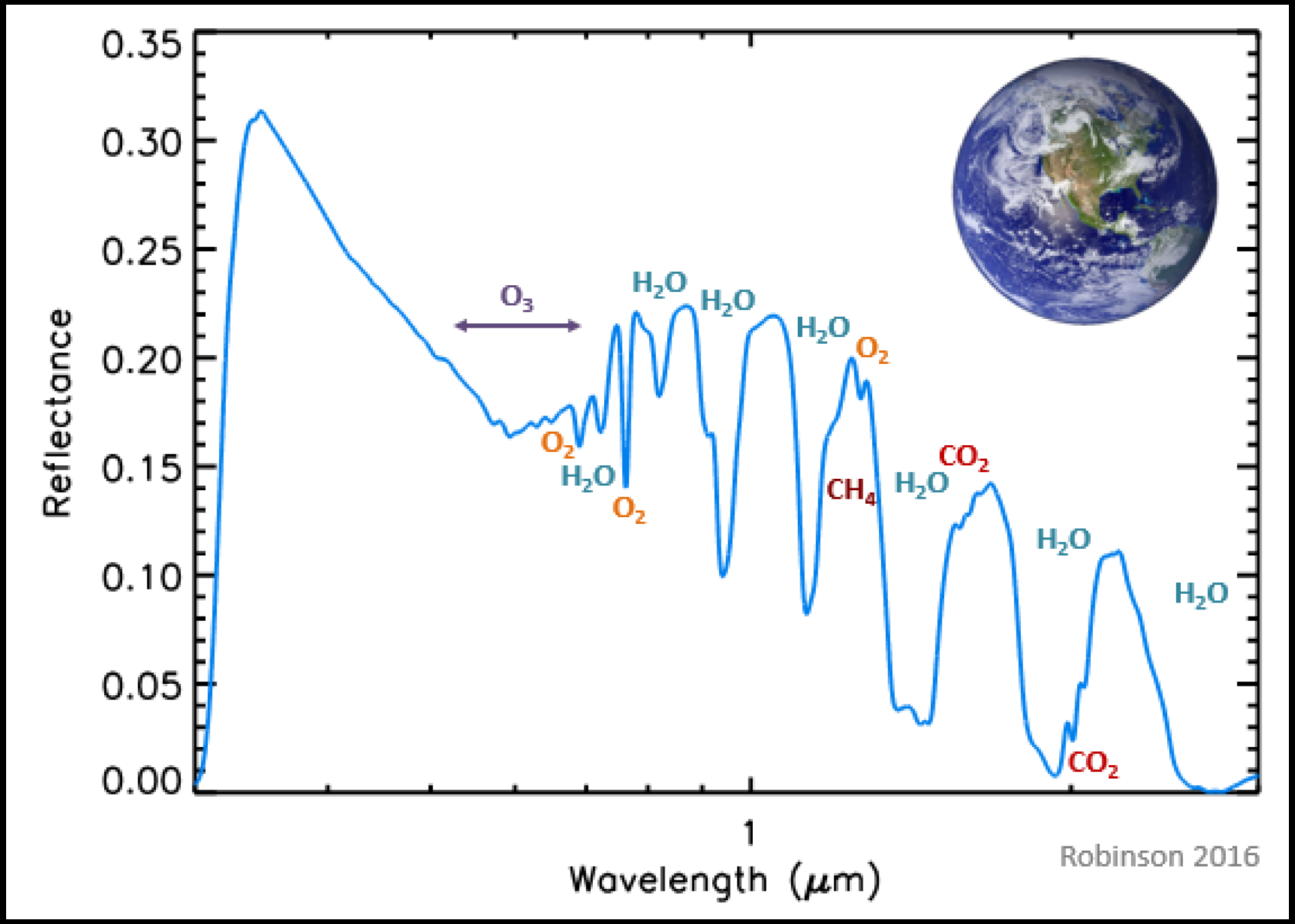


Number of Planets

Discovery Year

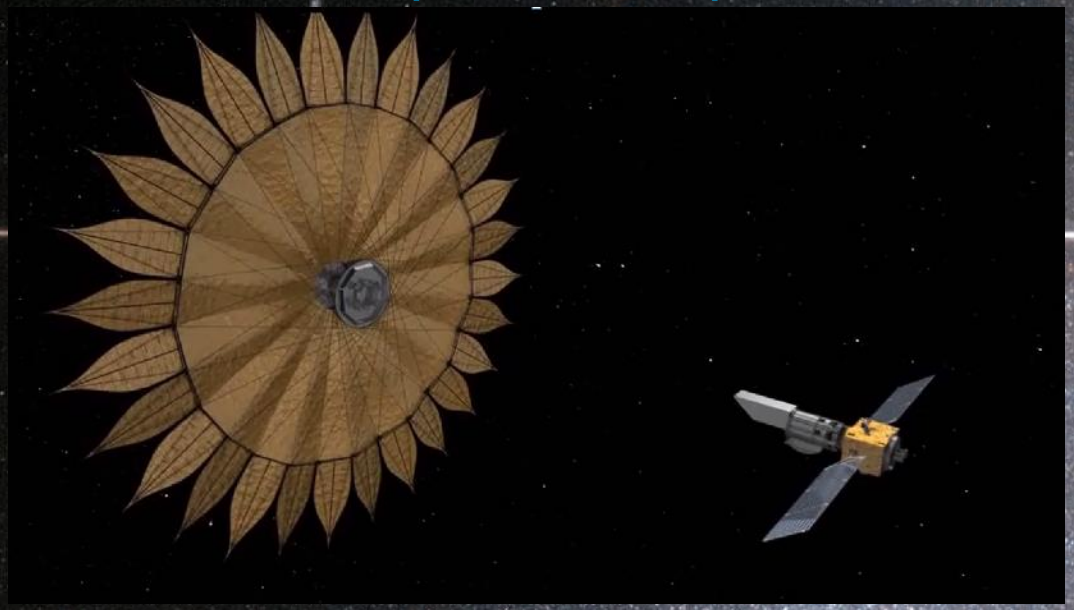
The Evidence for Life on Exoplanets

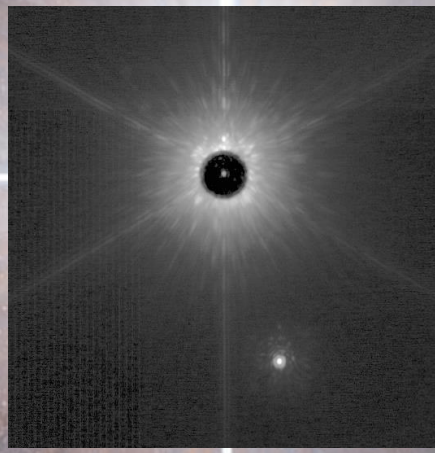
--reflected light spectroscopy



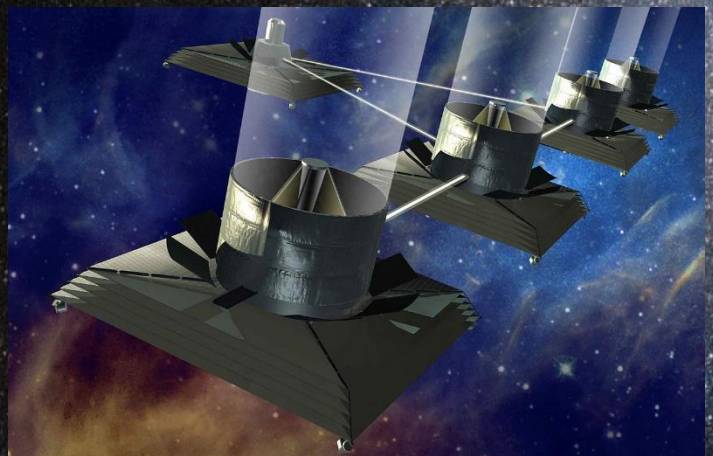
Starlight Suppression is the Key Technology in the Search for Earth-Size Exoplanets and Life

External Occulter (Starshade)

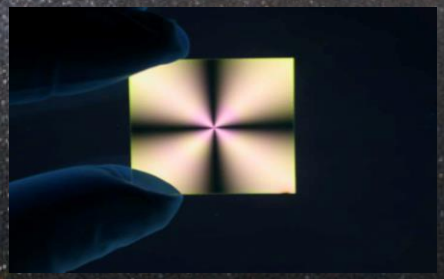




Nulling Interferometry



Internal Occulter (Coronagraph)



2010 Decadal Survey Recommendation

Medium-scale

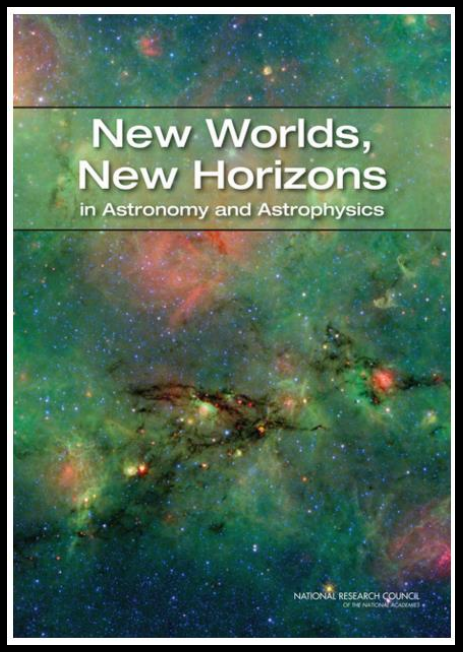


TABLE ES.4 Space: Recommended Activities—Medium-Scale (Priority Order)

Recommendation	Science	Appraisal of Costs[a]
1. New Worlds Technology Development Program	Preparation for a planet-imaging mission beyond 2020, including precursor science activities	$100M to $200M
2. Inflation Probe Technology Development Program	Cosmic microwave background (CMB)/ inflation technology development and preparation for a possible mission beyond 2020	$60M to $200M

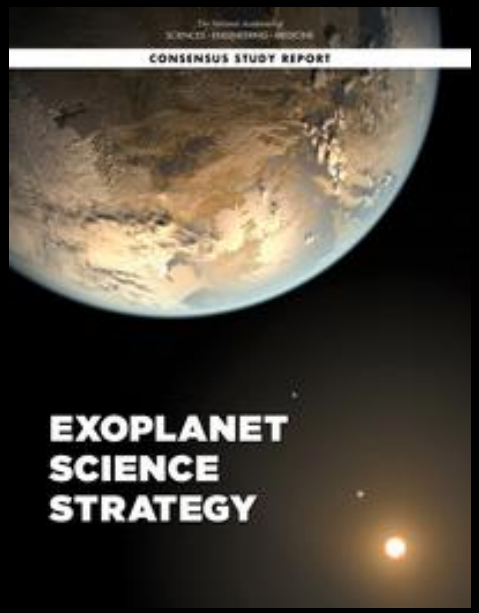
"…high-priority science areas for which mid-term investments are needed beginning early in the decade, including development of a variety of technologies for exoplanet imaging, such as coronagraphs, interferometers, and starshades, leading to possible late-decade down-selecting."

Exoplanet Science Strategy

Released by National Academies in September 2018

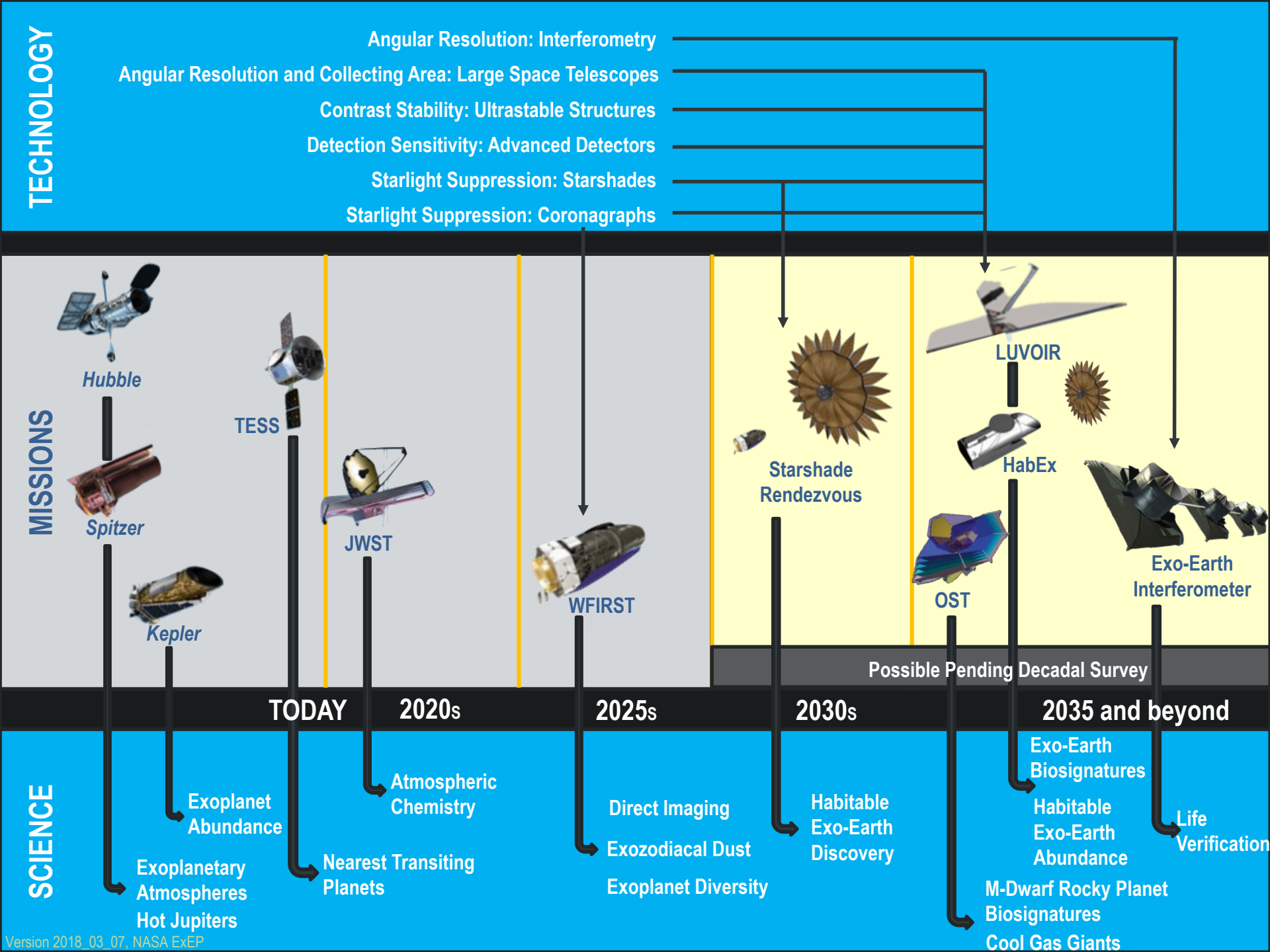
David Charbonneau (Harvard)

Scott Gaudi (Ohio State University)



Featured 7 recommendations, including:

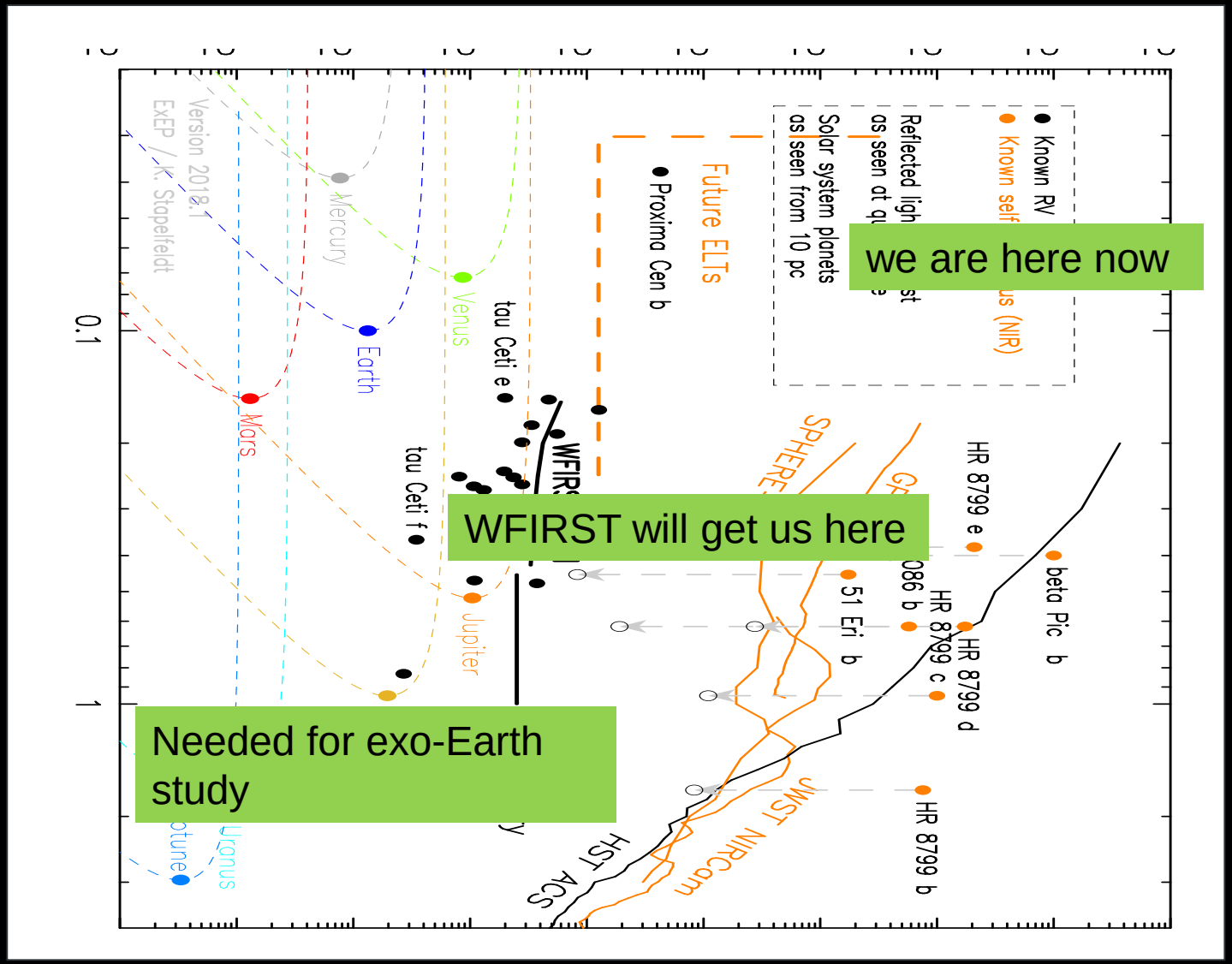
Recommendation: NASA should lead a large strategic direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars.



Version 2018_03_07, NASA ExEP

WFIRST Coronagraph

A key stepping stone

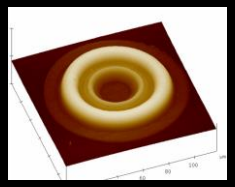


WFIRST Coronagraph Tech Development

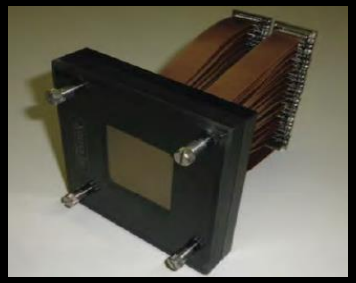
Achieved technology milestones to TRL 5

(see J. Trauger talk 8:00 Wednesday)

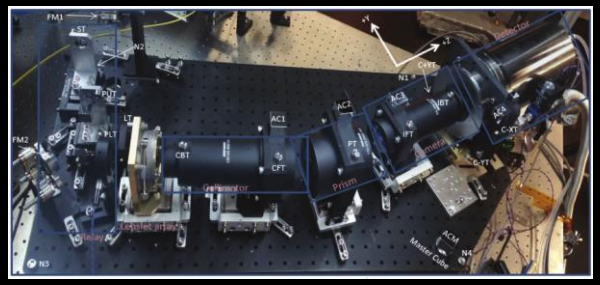
High-contrast coronagraph masks with a highly obscured pupil



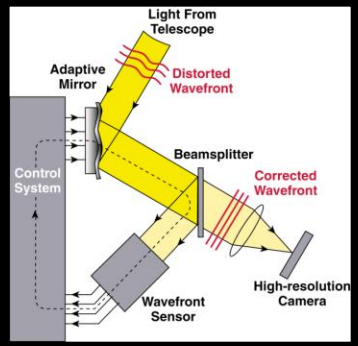
Deformable mirrors



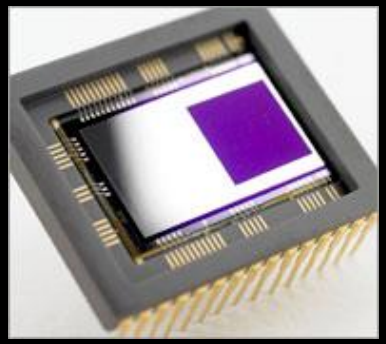
Integral field spectrograph + coronagraph



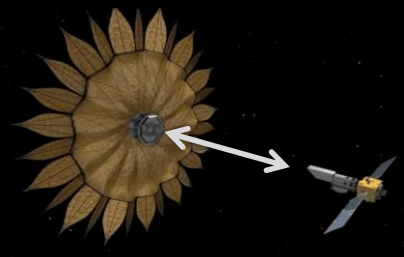
Low order wavefront sense / control



Ultra-low noise EMCCD for space



Compatibility with a starshade for possible rendezvous mission pending 2020 Decadal Survey

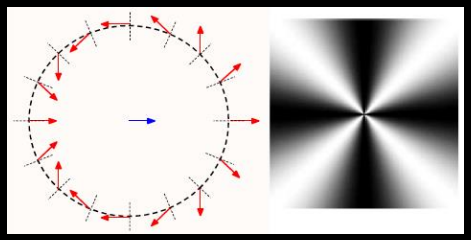


Segmented Coronagraph Design & Analysis (SCDA) Study

- ExEP-led study to evaluate coronagraph designs for a segmented/obscured telescope
  - Stuart Shaklan, Brendan Crill (JPL) are Study Leads, five teams
  - Ensure that there is at least one coronagraph architecture that can meet the contrast requirements of future large segmented space telescopes to directly image and characterize exo-Earths.
- Promising designs delivered of APLC (STScI/GSFC), Vortex (Caltech/JPL), HLC (JPL)
- Lessons Learned (see SPIE papers for details)
  - Big dropoff in throughput when secondary mirror obscuration exceeds 30%
  - Maximize inscribed diameter of primary
  - Segmentation gaps are not a problem (if small)
- Next Steps
  - Test New apodization masks in testbeds
  - Test robustness of designs to wavefront errors and tolerancing: Do these coronagraphs put constraints on the telescopes that are unrealistic?

NASA TDEM Awards

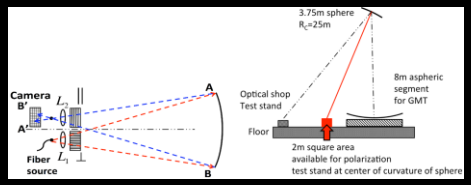
- Annually competed awards solicited to meet NASA's priorities
- Active awards are advancing exoplanet direct-imaging technology and yields
- Coronagraphy
  - Vector Vortex (PI Serabyn/NASA-JPL)
  - Visible Nulling Coronagraph (PI Hicks/NASA-GSFC)
  - Deformable mirrors (PI Bierden/BMC, PI Helmbrecht/Iris AO)
  - Polarization (PI Breckenridge/UA)
  - Lyot Coronagraph (PI Trauger/NASA-JPL)
  - Phase-Induced Amplitude Apodization-Complex Mask Coronagraph (PI Belikov/NASA-Ames)
  - Apodized Pupil Lyot Coronagraph (PI Soummer/STScI)
  - Wavefront control techniques (PI Guyon/UA)
- Starshade
  - Re-directed to starshade technology activity



TDEM-14 Serabyn

TDEM-13 Hicks

TDEM-17 Soummer

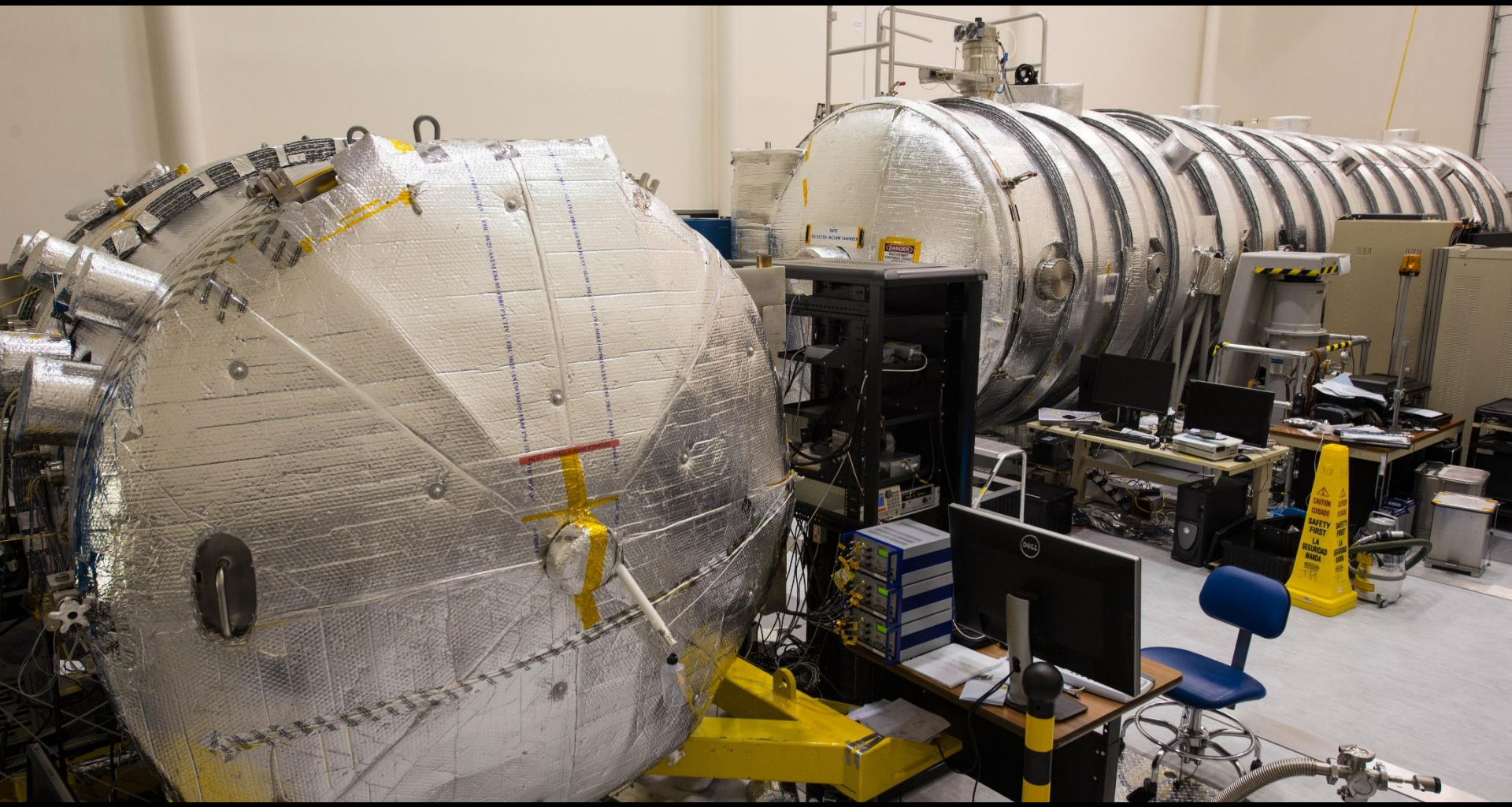


TDEM-15 Breckinridge

TDEM-10 Bierden

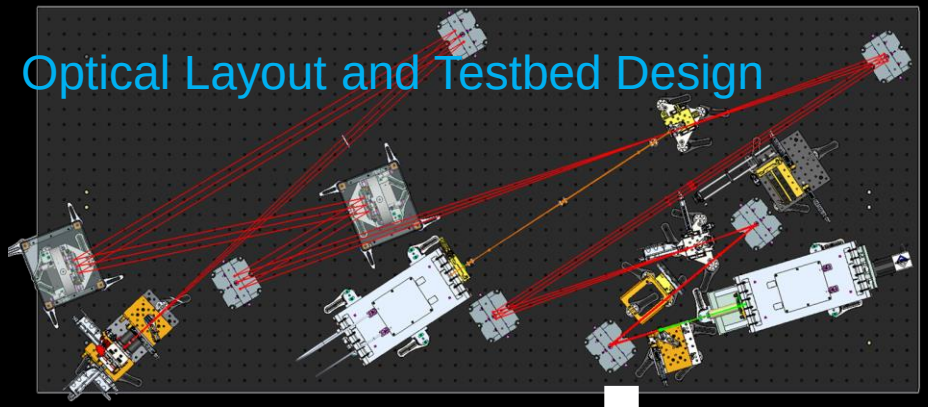
High Contrast Imaging Testbed Facility (JPL)

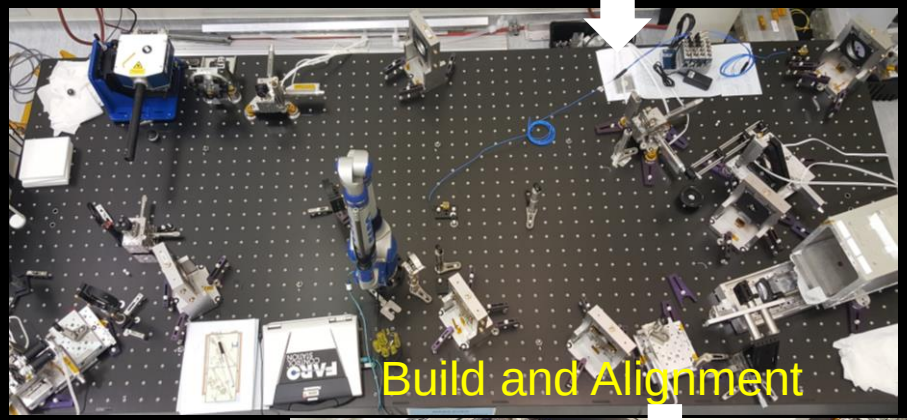
Advancing space coronagraph technology



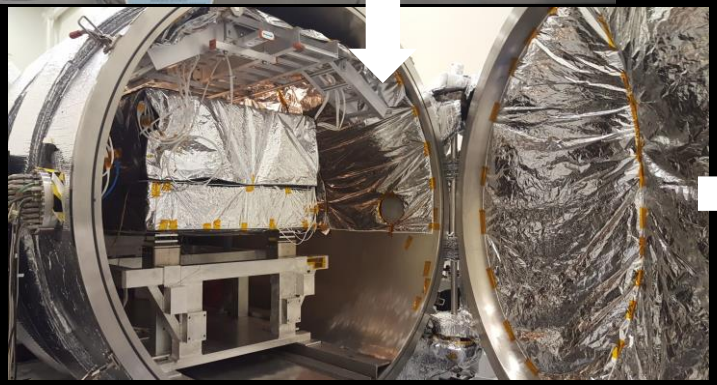
High-Contrast Imaging Testbed (HCIT)

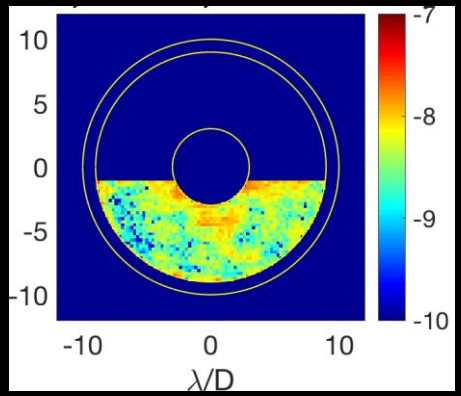
Decadal Survey Testbed





In Vacuum Chamber (June 2018)





<u>Decadal Survey Testbed</u>

Phase I: aiming to meet 10^{-10} contrast with 10% band and a clear aperture in 2018

Phase II: replace clear pupil with a segmented/obscured (static) aperture in 2019

Phase III: replace static aperture with a dynamic segmented/obscured telescope simulator in 2020

As of Oct 15: 4×10^{-9} contrast

550 nm 10% band

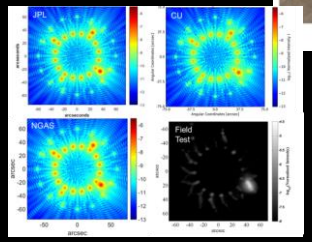
Starshade Technologies

Maturing to TRL 5

(see P. Willems talk, Wednesday a.m.)

Starlight Suppression

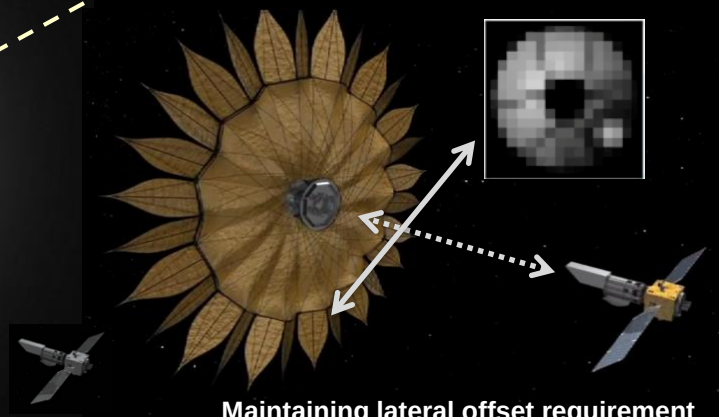
Suppressing scattered light off petal edges from off-axis Sunlight



Model Validation & suppressing diffracted light from on-axis starlight

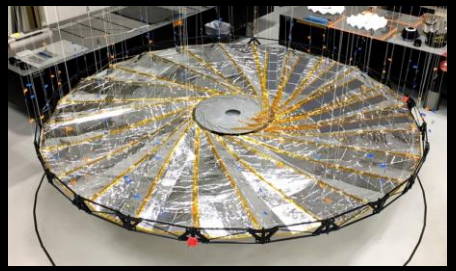
(see A. Harness talk, Wedesday a.m.)

Formation Sensing

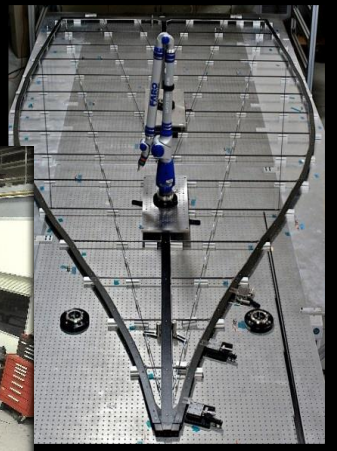


Maintaining lateral offset requirement between the spacecraft

Deployment Accuracy and Shape Stability



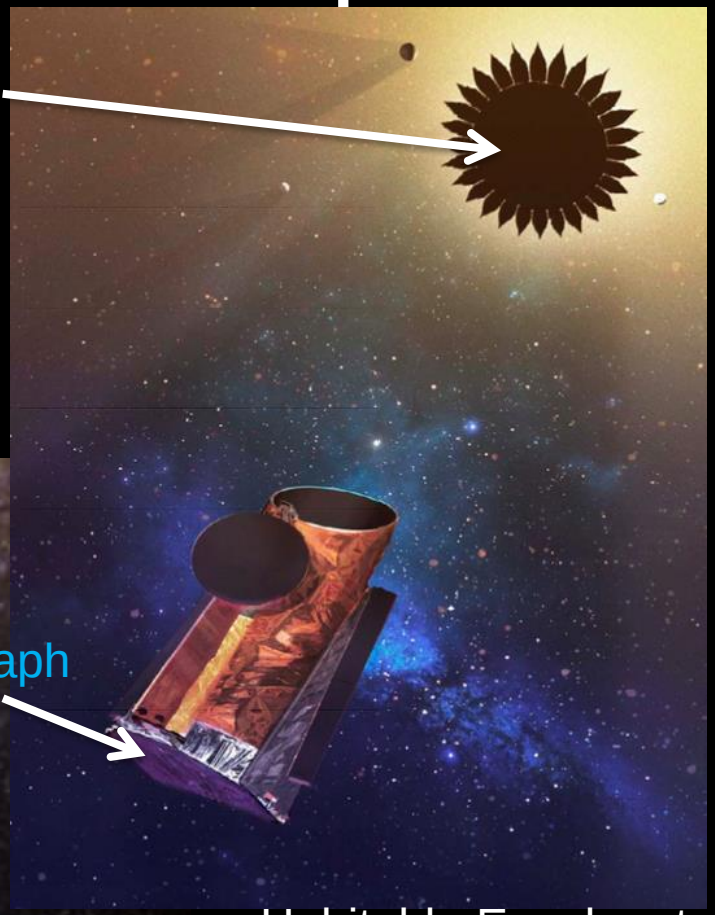
Positioning the petals to high accuracy, blocking on-axis starlight, maintaining overall shape on a highly stable structure



Fabricating the petals to high accuracy

(see Tendeg talks, Wedesday a.m.)

Possible New Worlds Exoplanet Telescopes
(mid-2030s)



Habitable Exoplanet Imaging Mission (HabEx)

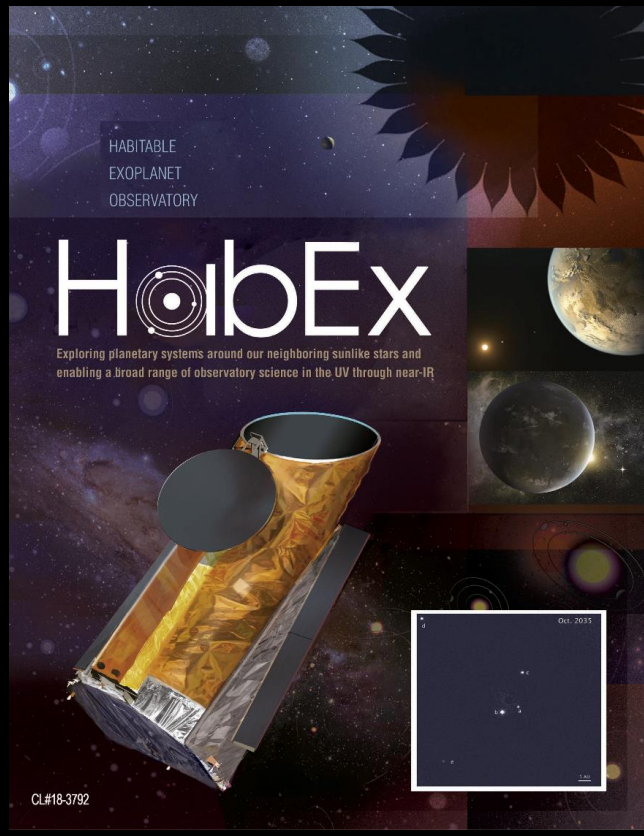
Large Ultra-Violet Optical Infrared Telescope (LUVOIR)

HabEx Mission Concept

(see R. Morgan talk, next)

- Off-axis 4 m monolith telescope primary equipped with both a starshade and a coronagraph for starlight suppression

- **Key technologies:**
  - 52 m diameter starshade
    - architecture goes beyond WFIRST rendezvous architecture
  - 4 m glass monolith for space with 1 nm stability
    - Largest monolith ever flown
  - Microthrusters replacing reaction wheels for fine pointing
    - Successfully flight qualified as part of LISA Pathfinder
  - ultra-low noise near-infrared detectors



LUVOIR Mission Concept

(see talk this morning)

15m on-axis mirror (120 ~1.5m segments) space telescope using a coronagraph

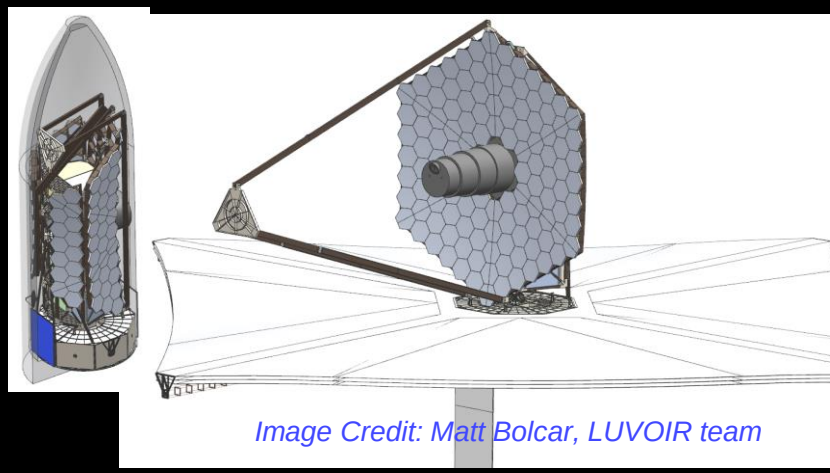
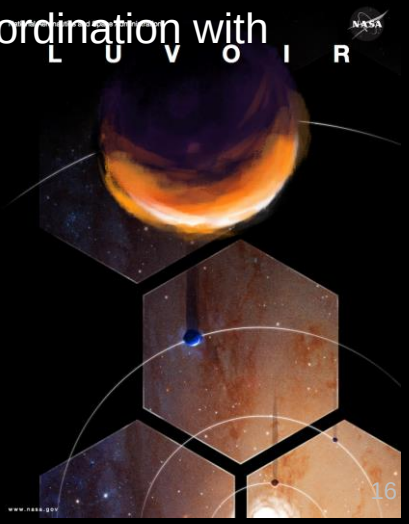


Image Credit: Matt Bolcar, LUVOIR team

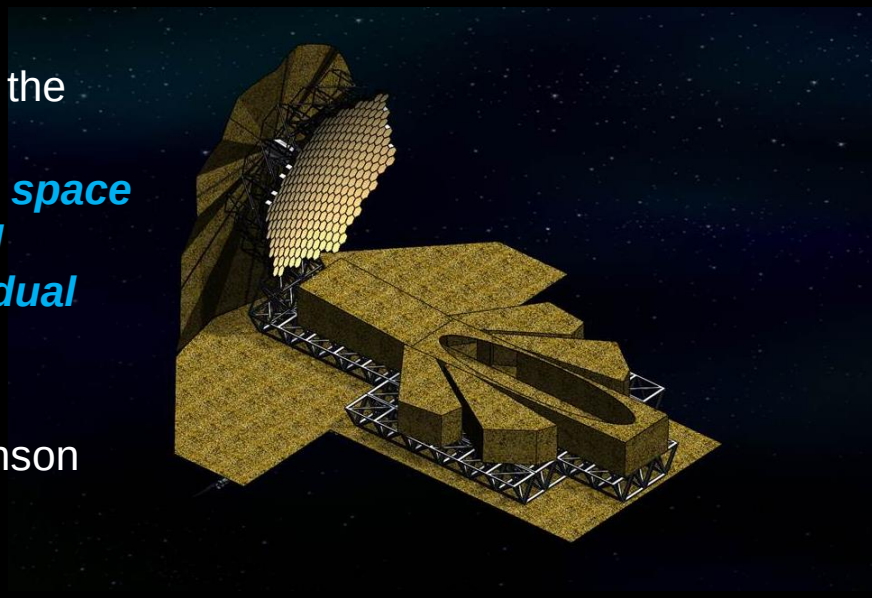
Key Technologies:

- An ultra-stable opto-mechanical structure enabling 10 pm rms wavefront stability
  - isolation stages, laser metrology, capacitive edge sensors, thermal control
- Segmented-aperture coronagraphy at 10^{-10} contrast, ≥ 10% band
  - APLC design is the leading candidate – work being done in coordination with SCDA
  - needs to be demonstrated in the lab
- Meter-class segmented mirrors with SFE < 5 nm rms
- ultra-low noise near-infrared detectors



In-Space Assembled Telescope (iSAT) Study

- Chartered by NASA SMD and APD to answer the question
  When is it worth assembling telescopes in space rather than building them on the Earth and deploying them autonomously from individual launch vehicles?



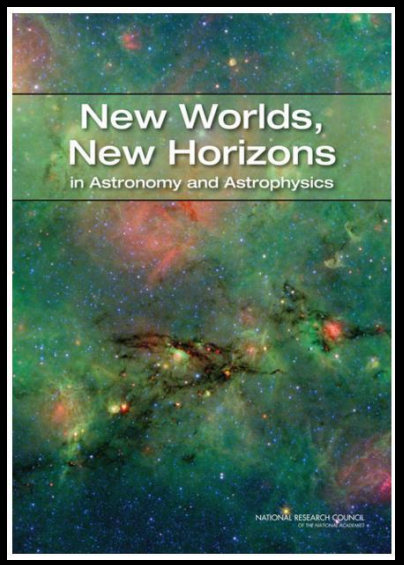
- Study Leads: Nick Siegler (JPL), Harley Thronson (GSFC), Rudra Mukherjee (JPL)
- Final deliverable is a White Paper to the Decadal Survey Committee in Spring 2019
- Activity 1a: Modularizing a 20 m space telescope
  - Reference concept completed
- Activity 1b: Assembling and testing the 20 m modularized telescope in space
  - Meeting held at LaRC October 2-4
  - Currently examining assembly at cis-Lunar and SE-L2

Measuring Mass of Earth-Like Exoplanets

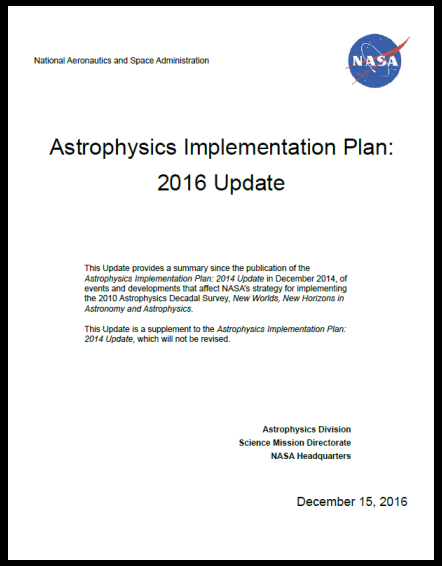
Mass measurement needed to interpret spectral measurements and evaluate habitability.

- Radial Velocity
  - Use a spectrograph to measure Doppler shift in a star's spectral lines from reflex motion due to an orbiting planet
  - 1 cm/s level needed to characterize Earth-like planets
  - Currently limited by stellar jitter at the 50-100 cm/s level typically, but removal of stellar jitter has been demonstrated with higher cadence measurements over a broader band.
  - New instruments coming on line in 2019, such as NN-EXPLORE's NEID, will reach ~30 cm/s
  - Possible technology needs both for space- and ground-based measurements include: precision wavelength calibration, detector metrology, stable environments, broad wavelength coverage.
  - **Exoplanet Science Strategy recommended a major initiative led by NASA in this area**
- Astrometry
  - Use precise (few microarcsecond) angular position measurements of stars to measure reflex motion of stars due to orbiting planets; SOA is Gaia which has achieved 10 μas
  - Exoplanet Science Strategy notes that this is a backup to Radial Velocity
  - Possible technology needs: detector metrology, precise optical field distortion calibration (e.g. diffractive pupils)

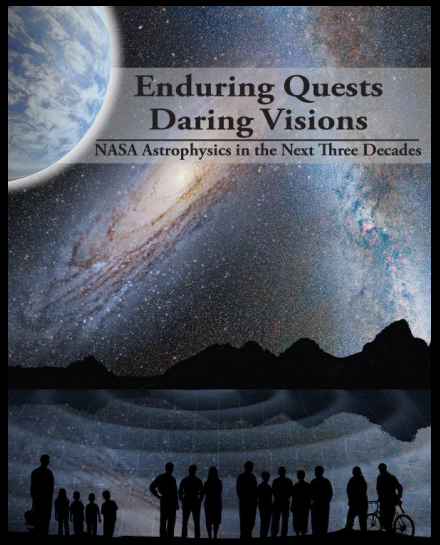
Towards an exo-Earth imaging and characterization mission



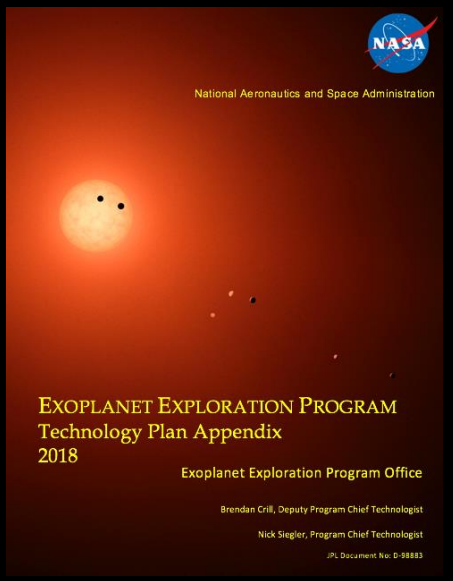
2010 Decadal Survey



APD Implementation Plan (2012, 2014, 2016)



NASA APD
30 year vision (2013)



ExEP Technology Plan Appendix (2018): updated annually

- STDT final reports (2019)
- 2020 Decadal Survey final report (December 2020)
  - will set the nation's science priorities, including recommendations for NASA astrophysics missions

Acknowledgements

This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration