Jet Propulsion Laboratory
California Institute of Technology

The NASA Exoplanet Exploration Program: *Recent Results and Future Directions*

Dr. Gary H. Blackwood
Manager, NASA Exoplanet Exploration Program
Jet Propulsion Laboratory
California Institute of Technology

February 7, 2019
Giant Magellan Telescope Project Office
Pasadena, CA

Artist concept of Kepler-16b

Program Overview

Recent Results

Future Directions

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

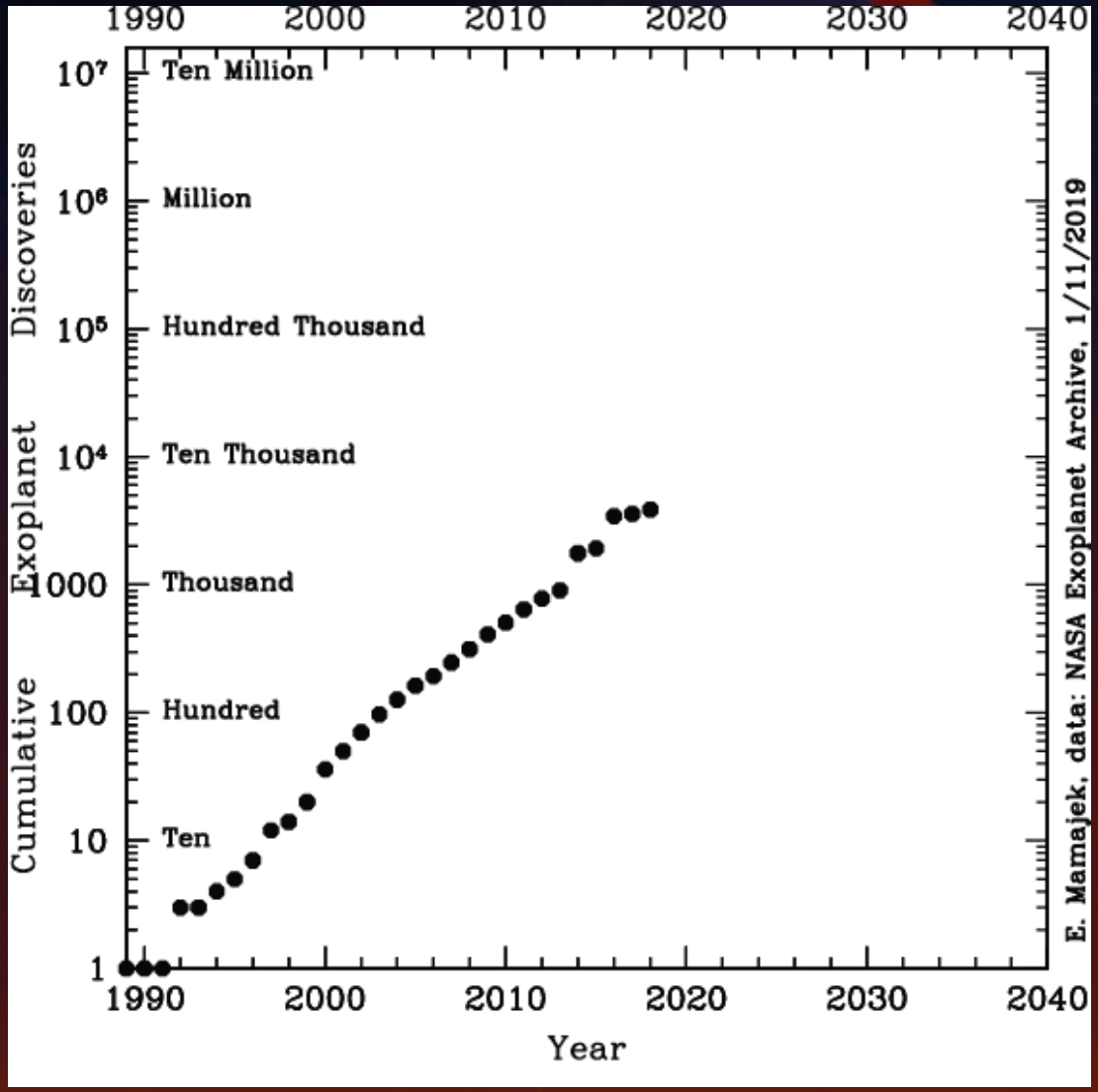
ExEP serves the Science Community and NASA:

- Focal point for exoplanet science and technology
- Integration of cohesive strategy for future discoveries

https://exoplanets.nasa.gov

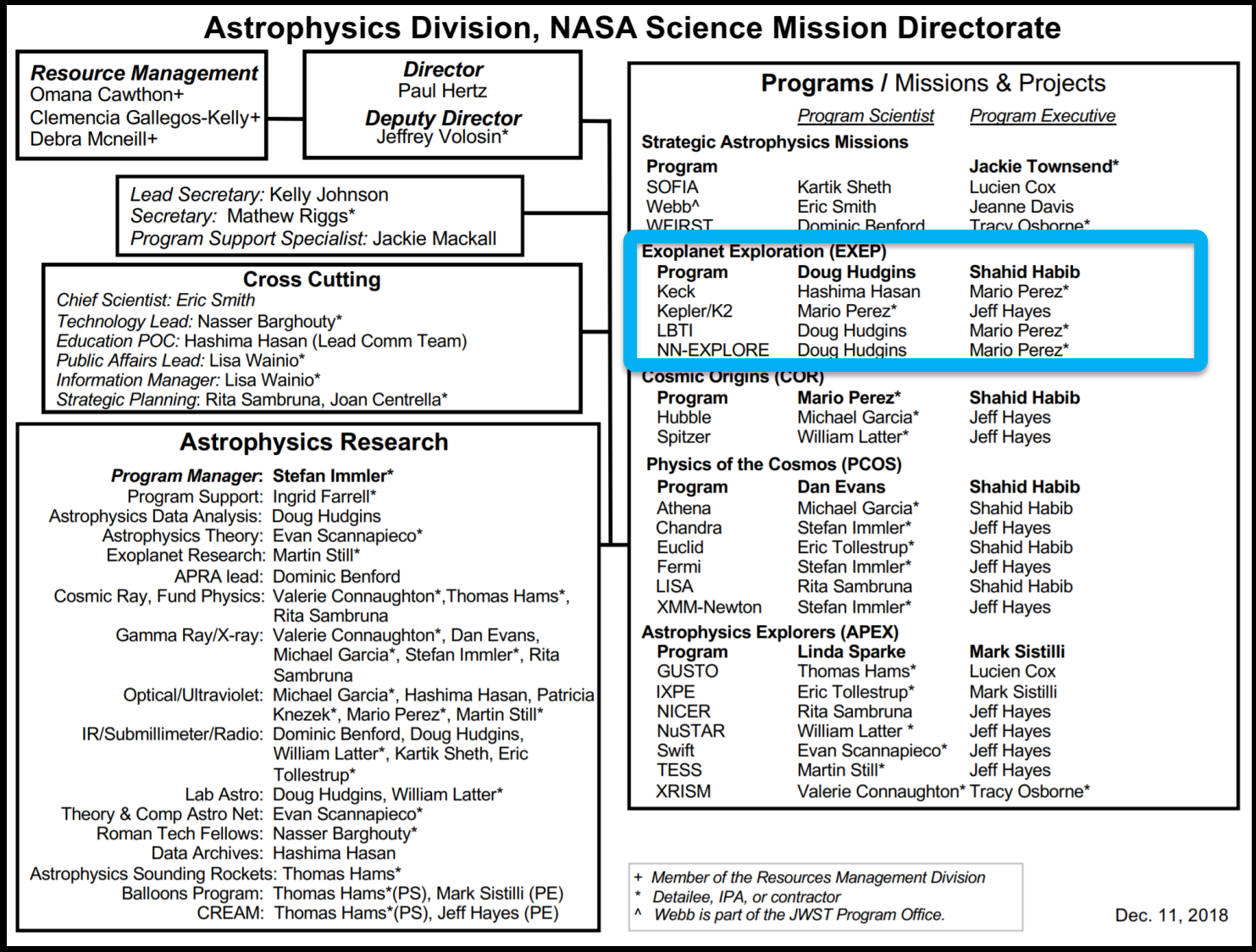
Mamajek's Law

Doubling Time for Confirmed Exoplanets

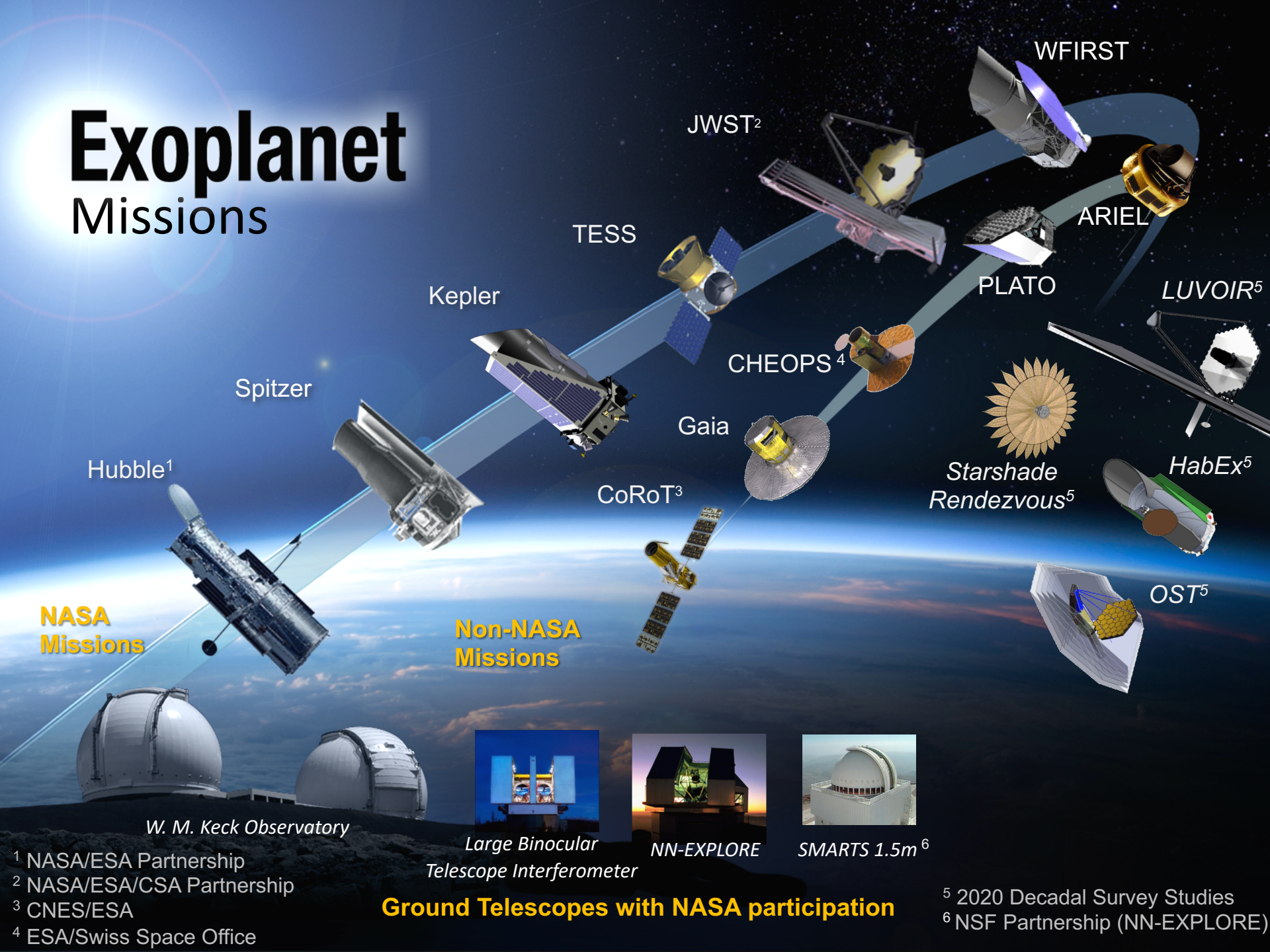


Credit: NASA/JPL
Eric Mamajek

ExEP: a NASA Program within Astrophysics



Exoplanet Missions

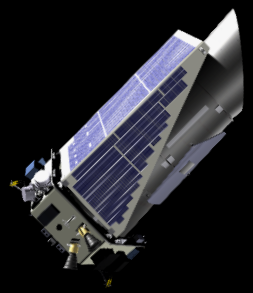


[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA
[4] ESA/Swiss Space Office
[5] 2020 Decadal Survey Studies
[6] NSF Partnership (NN-EXPLORE)

NASA Exoplanet Exploration Program

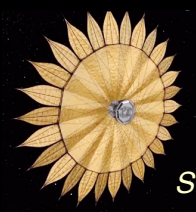
Space Missions and Concept Studies

Kepler K2



Large- and Probe-Scale Mission Concepts

Coronagraph



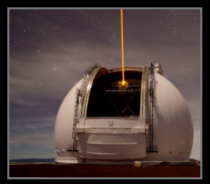
Starshade

Exoplanet Communications

Science Research & Technology

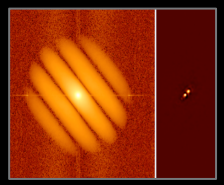
Key Sustaining Research

NN-EXPLORE



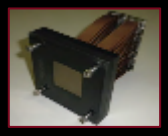
Keck Observatory

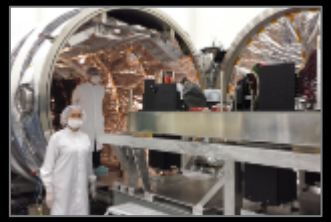
Large Binocular Telescope Interferometer



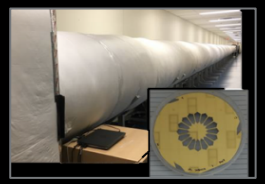
High Resolution Imaging

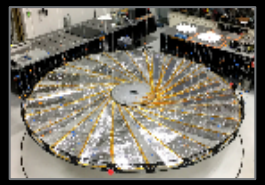
Technology Development





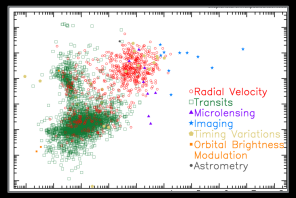
Coronagraph Technology Development





Starshade Technology Development (S5)

NASA Exoplanet Science Institute (NExScI)



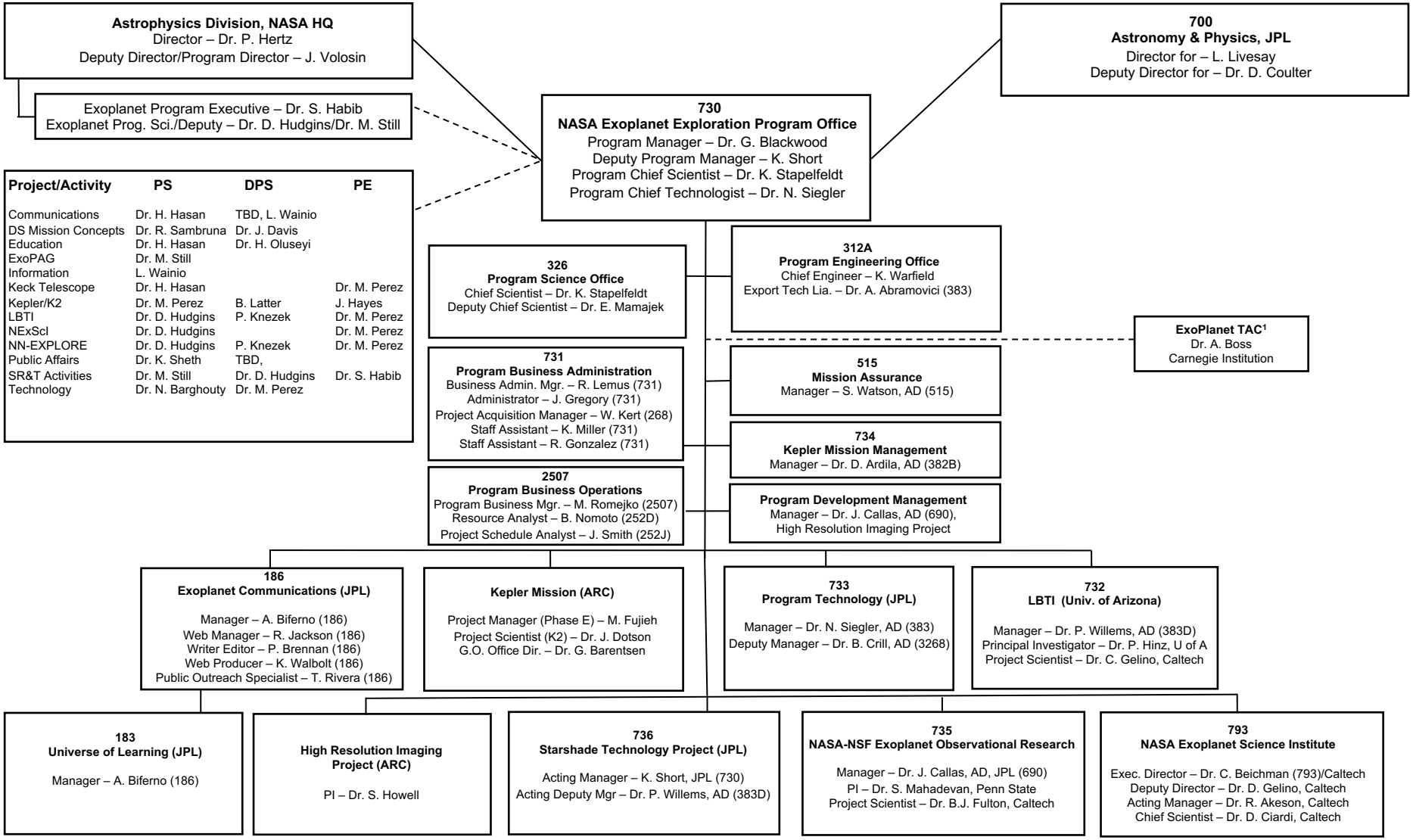
Archives, Tools, Sagan Program, Professional Engagement

Exoplanet Travel Bureau

Latest Poster

Webby Award for Exoplanet Exploration – People's Voice in Weird Category

NASA Exoplanet Exploration Program Organization Chart



[1]Reports to NASA HQs APD

DOC ID: 1261719

February 5, 2019
R. Lemus
NASA Exoplanet Exploration Program

Legend:
Programmatic lines of authority
Interface

Other Services Provided by ExEPO

As chartered by NASA Astrophysics Division

- Recommend to APD strategies to advance NASA's exoplanet science and technology objectives
  - Informed by missions, academy reports, and ExoPAG
- Conduct mission studies and trades
- Capture and maintain technology roadmaps
- Technology: identify, prioritize, manage, and certify TRL
- Engage in non-APD and non-NASA partnerships
- Facilitate the ExoPAG

- In all cases: Decisions guided by science priorities

Increased Observation Opportunities

And Community Access to Data

- WIYN / NEID: call for 2019B semester will be part of upcoming NOAO call (~March 2019)
- CHIRON on SMARTS 1.5m telescope: US access to Southern Hemisphere radial velocity
  - 40 nights/semester
  - Complements Keck / HIRES and WIYN / NEID
- Keck Strategic Mission Projects included in 2019B call
- Community access to High Resolution Imaging – Speckle Interferometry. PI Steve Howell (NASA ARC)
  - Three instruments available through NOAO: WIYN/NESSI (39 mas), Gemini-N/'Alopeke and Gemini-S/DSSI (17 mas)
  - Data processed by PI team and posted at NExScI exoplanet archive
- Community Access to HIRES PRV data reduction pipeline
- K2 (re) processed data available at MAST

Kepler K2

- End of Flight due to fuel exhaustion
- Goodnight command sent on Nov. 15th, anniversary of Johannes Kepler's death
- C19 (partial) data downlinked
- Data Processing
  - C0 to C18 data at MAST. C19 data processing underway. Raw cadence online.
- Data reprocessing: C0, C2, C3, C13. Next is C11
- Kepler/K2 SciCon V
  March 4-8, 2019; Glendale CA

Program Implementation Highlights

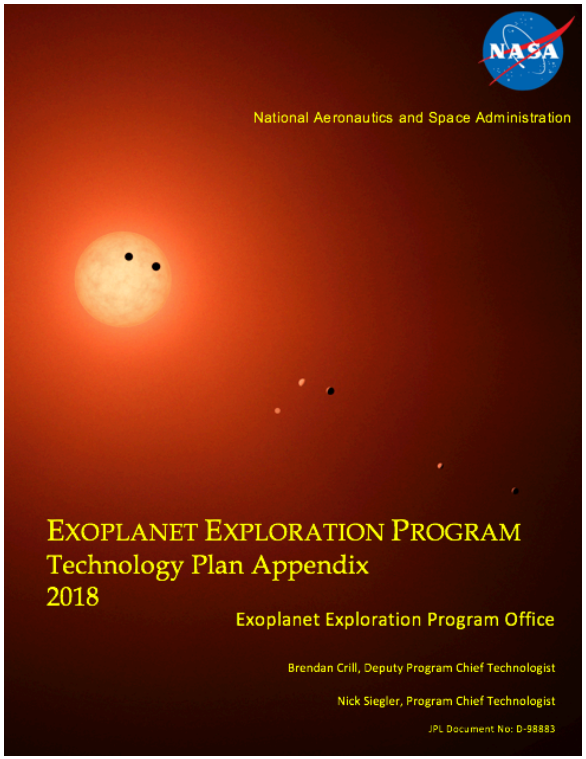
- LBTI: completed survey, studying instrument upgrades
- Technology:
  - Coordination of prioritization, investment with PCOS/COR
  - Decadal Survey Testbed: Lyot coronagraph <5e-10 contrast
  - Segmented Coronagraph Design: results adopted by LUVOIR
- Support to WFIRST: MEMs deformable mirrors, coronagraph testing, starshade interface
- Support to Large Mission Studies and Probe Studies
- Follow-up Observing site provide to TESS by NExScI
- ExoComm: Exoplanet Travel Bureau immersive experience
- NEID: final integration and test underway at Penn State
- ExEP Postdoc position created
- Starshade Technology and NExScI – following pages

ExEP Science Gap List as of Fall 2018
(grouped by topic, no implied priority in ordering)

Spectral characterization of small exoplanets
Modeling exoplanet atmospheres
Spectral signature retrieval
Planetary system architectures
Occurrence rates for HZ exoplanets (e.g. $\eta_{\oplus}$)
Yield estimates for exoplanet direct imaging missions
Improve target lists and stellar parameters for exoplanet missions
Mitigate stellar jitter as a limitation to exoplanet dynamical measurements
Dynamical confirmation of exoplanet candidates, determination of their masses & orbits
Precursor surveys of direct imaging targets
Understand the abundance and substructure of exozodiacal dust
Measurement of accurate radii for transiting exoplanets

ExEP Technology List

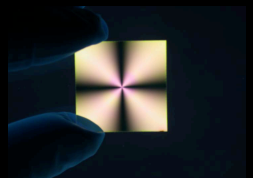
ID	Technology	Technology Gap	Technology Description	Current Capabilities	Needed Capabilities
S-1	**Controlling Scattered Sunlight**	Starshade Contrast	Limit edge-scattered sunlight and diffracted starlight with optical petal edges that also handle stowed bending strain.	Machined graphite edges meet all specs but edge radius (≥ 10 µm); etched metal edges meet all specs but in-plane shape tolerance (Exo-S design).	Integrated petal optical edges maintaining precision in-plane shape requirements after deployment trials and limit solar glint contributing < 10^{-10} contrast at petal edges.



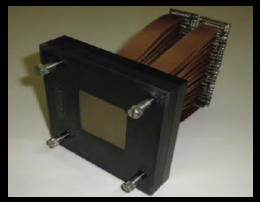
- **24 technologies currently tracked**
- **Technology List posted here:** https://exoplanets.nasa.gov/exep/technology/gap-lists/
- **More detail coming soon in the Technology Plan Appendix**

V-NIR Coronagraph/Telescope Technology Gaps

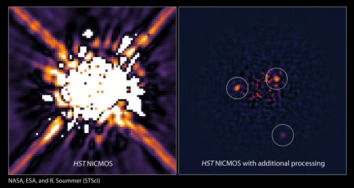
Contrast



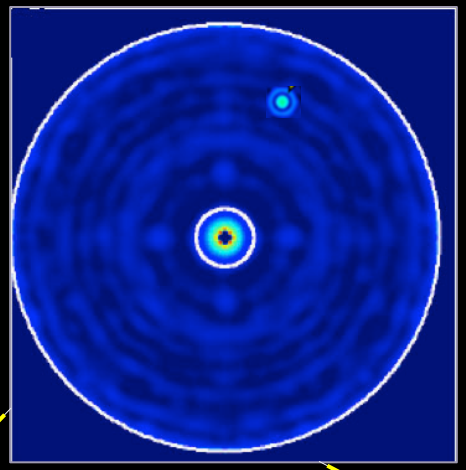
CG-2: Coronagraph Architecture



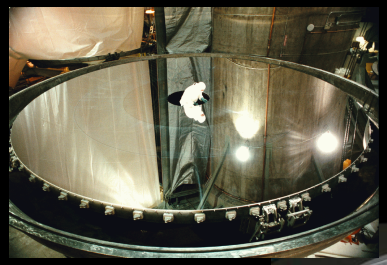
CG-3: Deformable Mirrors



CG-4: Data Post-Processing



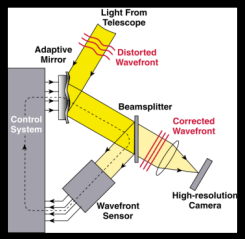
Angular Resolution



CG-1: Large Monolith Mirrors

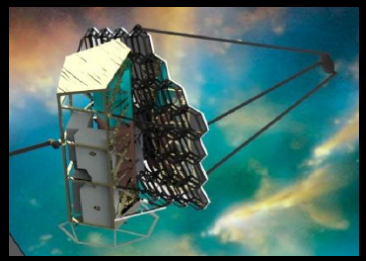
CG-1: Segmented Mirrors

Contrast Stability



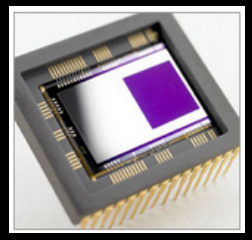
CG-5: Wavefront Sensing and Control

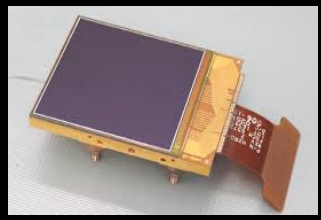
CG-6: Mirror Segment Phasing



CG-7: Telescope Vibration Sensing and Control or Reduction

Detection Sensitivity

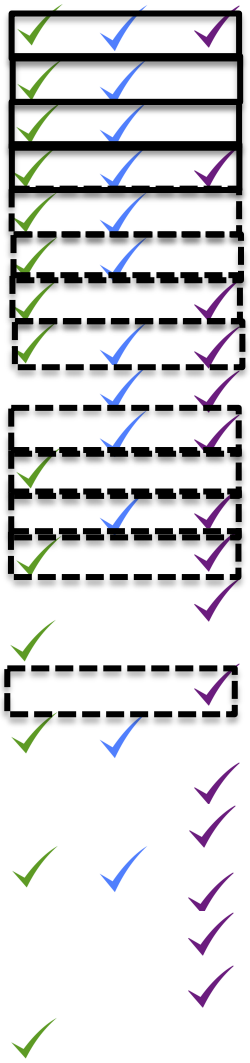




Ultra-low Noise Visible (CG-8) and Infrared (CG-9) Detectors

Investments in ExEP Technologies

Tech. ID	Technology Title
CG-2	Coronagraph Architecture
S-2	Starlight Suppression and Model Validation
S-1	Controlling Scattered Sunlight
S-3	Lateral Formation Sensing
S-5	Petal Positioning Accuracy and Opaque Structure
S-4	Petal Shape and Stability
CG-3	Deformable Mirrors
CG-1	Large Aperture Primary Mirrors
CG-6	Mirror Segment Phasing
CG-7	Telescope Vibration Sense/Control or Reduction
CG-9	Ultra-Low Noise Near-Infrared Detectors
CG-5	Wavefront Sensing and Control
CG-8	Ultra-Low Noise Visible Detectors
M-4	Ultra-Stable Mid-IR detector
M-3	Astrometry
CG-4	Data Post-Processing Algorithms and Techniques
CG-10	Mirror Coatings for UV/NIR/Vis
M-2	Space-based Laser Frequency Combs
CG-13	Ultra Low-noise Mid-IR detectors
M-1	Extreme Precision Ground-based Radial Velocity
CG-14	Mid-IR Large Aperture Telescopes
CG-15	Mid-IR Coronagraph Optics and Architecture
CG-16	Cryogenic Deformable mirror
CG-12	Ultra-Low Noise UV Detectors



✓ SAT / APRA

✓ directed

✓ mission or mission concept

funded to TRL 5 *

funded to TRL 5 * for some mission architectures

Carried over from 2017

New to list in 2018

* for an exo-Earth imaging mission

Recent Results

LBT Interferometer at Mt. Graham, Arizona

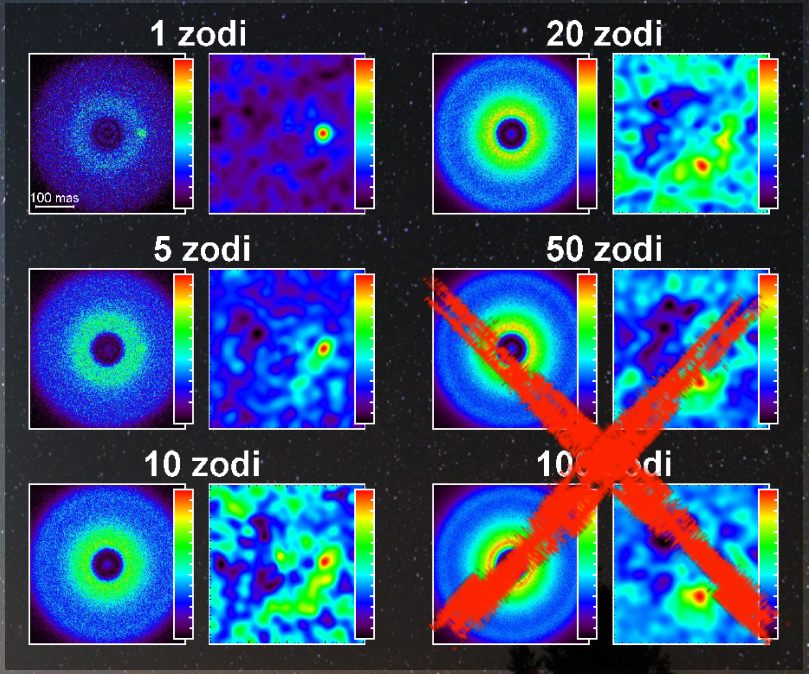
- Two 8m telescope on common mount, LBTI instrument integral to telescope design
- NASA-funded key science project "Hunt for Observable Signatures of Terrestrial Systems" (HOSTS)

- Unbiased survey of 38 stars is now complete. 10 detections, 4 new, and first detections of 10 μm excess around Sun-like stars.

Interim survey results for 30 stars appear in Ertel et al. 2018 A.J. 155 194

Overall limits to median exozodi level

- ~ 80% of the stars surveyed lack detectable extended emission at 10 μm, and thus are not very dusty.
- Upper limits on median zodi level for stars without cold dust (95% confidence, assuming lognormal distribution):
  - 13 zodis for all stars,
  - 26 zodis for FGK stars
- The median exozodi level could still be lower
- These limits depend on the assumed distribution function, will be detailed in Ertel et al. 2019



Simulations for 4m telescope, Defrère et al. (2012)

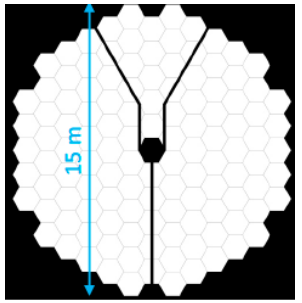
Segmented Coronagraph Design and Analysis

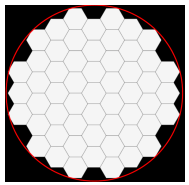
- **Designs from APLC (STScI/GSFC) and Vortex (Caltech/JPL) teams, HLC team (JPL/Caltech) is catching up: visit website for list of publications**

- **Head-to-head comparison of APLC/HLC/VC designs w/ PROPER**
  - Results from PROPER agreed very well with SCDA team results.
  - Evaluated sensitivity to stellar diameter and low order wavefront errors

- **Provided input to a Stark et al. paper (JATIS submitted) on science yields**

- **Focus for 2019**
  - Another iteration of designs including optimization for robustness
  - Further science yield calculations
  - Evaluation of robustness to telescope stability
  - Reporting to the community prior to Astro2020

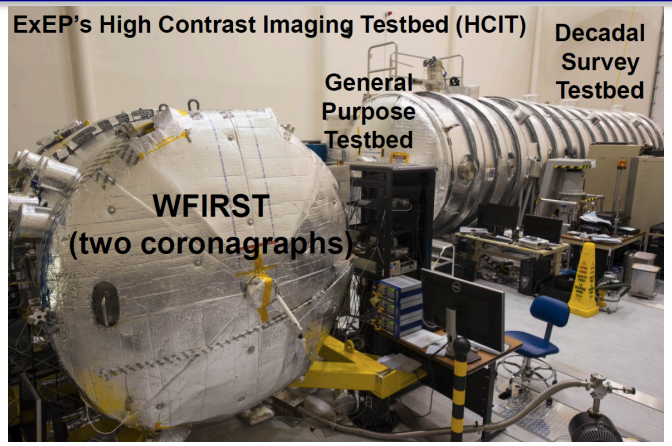




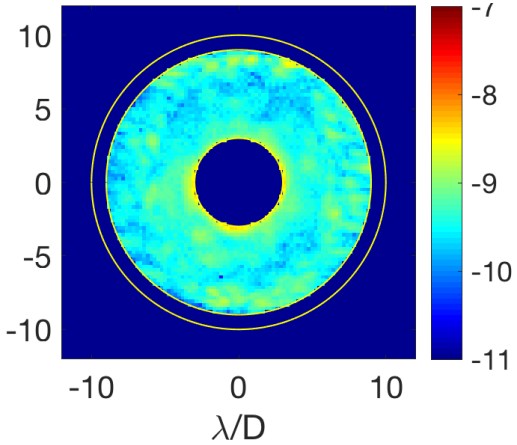
https://exoplanets.nasa.gov/exep/technology/SCDA/

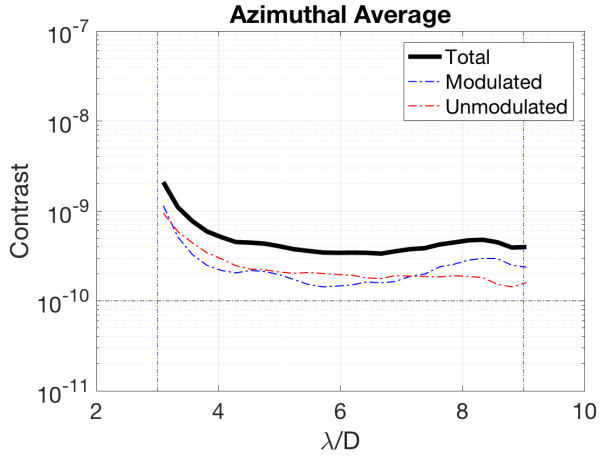
Decadal Survey Testbed

- **Phase I underway: commissioning the new testbed with a Lyot coronagraph: aiming to demonstrate 10^{-10} contrast performance with a clear pupil**



- **As of December 2018, contrast 4.6×10^{-10} achieved for 9% bandwidth around 550 nm and a 360 degree dark hole; working angle 3-9 λ/D**



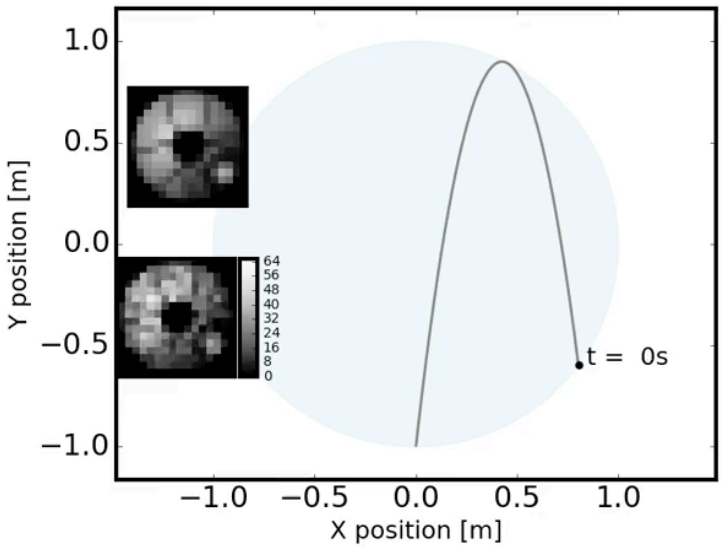


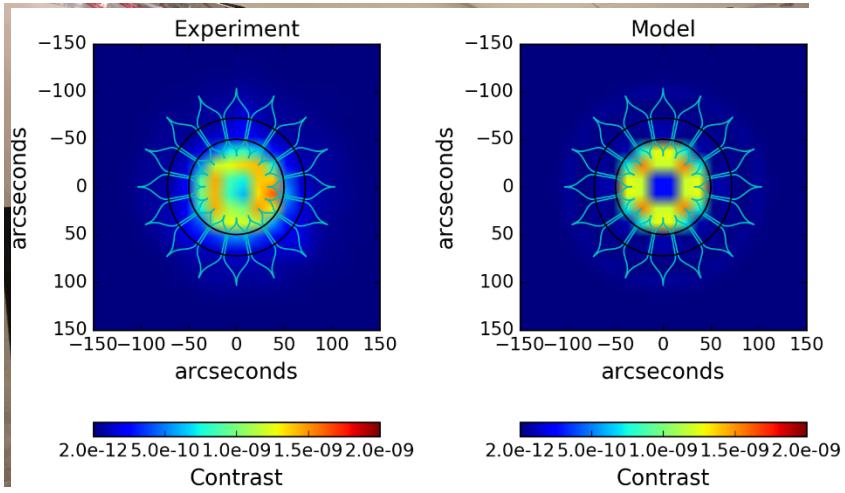
- **Phase 2: add a free-standing pupil mask with a segmented pattern, repeat demo**

- **Phase 3: add a High-Order WaveFront Sensor (HOWFS) and simulated dynamic wavefront errors from segment-segment piston/tip/tilt**

Starshade Technology Development Activity (S5)

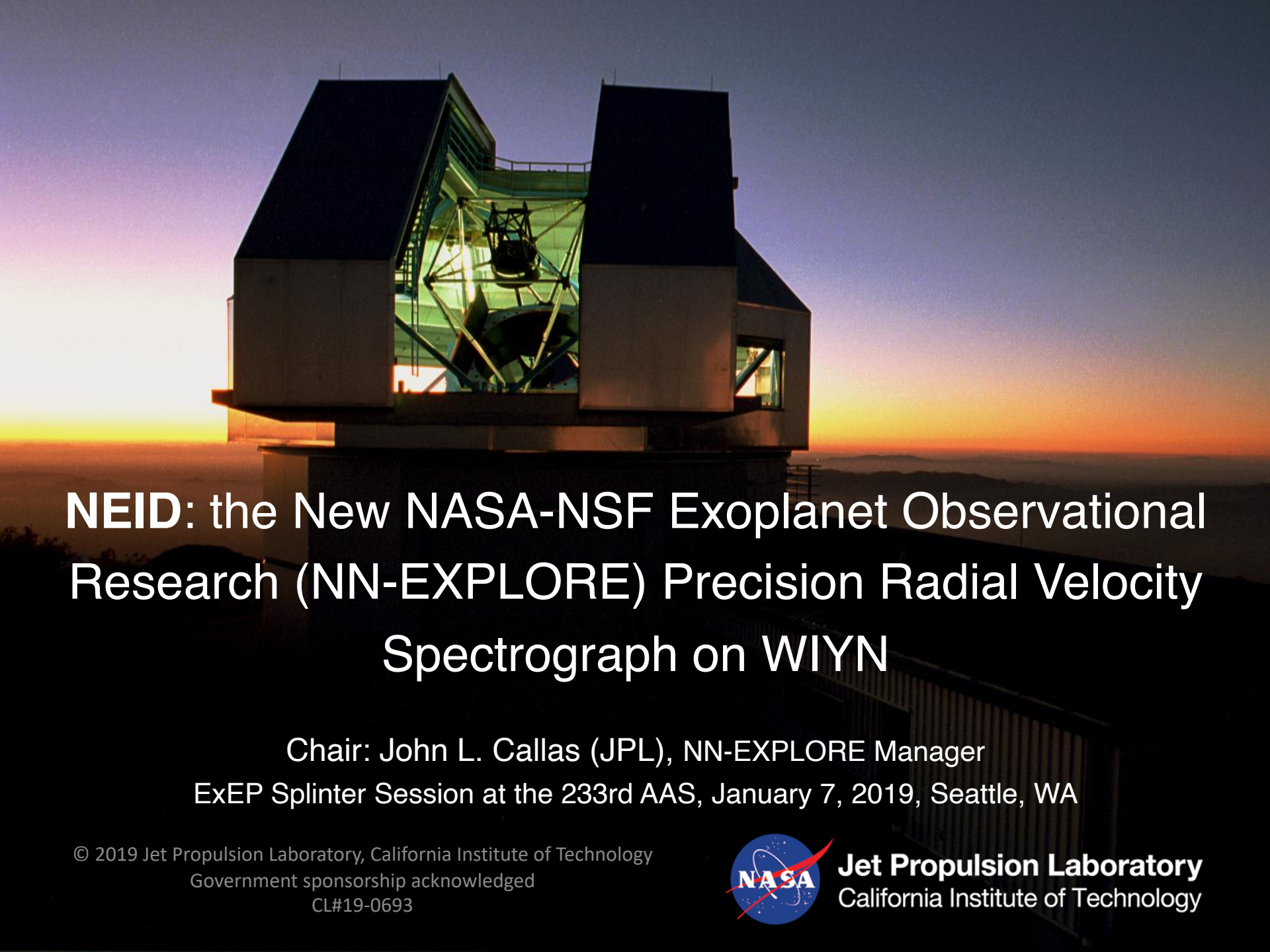
- **Technology Development Plan approved, team is now implementing the plan**
  - to mature Starshade technology to TRL 5 by 2023 in 15 milestones
  - retiring as much risk as possible prior to Astro2020
- **Starshade Science and Industry Partnership (SIP) convened to build community involvement: <u>you</u> can participate!**
- **Major progress on:**
  - **Formation Sensing** Technology Gap nearly complete: subscale demo of sensing at ~cm precision
    - milestone documentation submitted to ExoTAC: final review in January
  - **Starlight Suppression and Model Validation**:
    subscale demonstration of 4.3×10^{-11} mean contrast performance at flight Fresnel number





https://exoplanets.nasa.gov/exep/technology/starshade/

Future Directions



NEID: the New NASA-NSF Exoplanet Observational Research (NN-EXPLORE) Precision Radial Velocity Spectrograph on WIYN

Chair: John L. Callas (JPL), NN-EXPLORE Manager

ExEP Splinter Session at the 233rd AAS, January 7, 2019, Seattle, WA

Jet Propulsion Laboratory
California Institute of Technology

The NEID Team

PennState

Suvrath Mahadevan (PI)
Fred Hearty (PM)
Jason Wright (PS)
Andy Monson (SE)
Larry Ramsey (PA)
Eric Levi (ME)
Scott Blakeslee (ME)
Colin Nitroy (ME)
Tyler Anderson (EE)
Joe Ninan
Gudmundur Stefansson
Emily Lubar
Shubham Kanodia
Eric Ford
Fabienne Bastien
Thomas Beatty
Rebekah Dawson
Sree Prasumarthi

THE UNIVERSITY OF ARIZONA

Chad Bender (IS)
Kyle Kaplan

MACQUARIE University

Christian Schwab (OS)

UC Irvine

Paul Robertson

WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

Marsha Wolf
Jeff Percival
Michael Smith
Kurt Jaehnig

NExScI
NASA Exoplanet Science Institute

Rachel Akeson
BJ Fulton
Russ Laher

Penn
University of Pennsylvania

Cullen Blake (IS)

Caltech

Arpita Roy

JPL

John Callas
Phil Willems
Rich Capps

NOAO

Lori Allen
Jayadev Rajagopal
Rob Christensen
Emily Hunting
Bob Marshall
Erik Timmerman

Goddard
SPACE FLIGHT CENTER

Michael McElwain (IS)
Qian Gong
Sarah Logsdon
Ravi Kopparapu

NIST

Scott Diddams

Carleton

Ryan Terrien

भौतिक अनुसंधान प्रयोगशाला
Physical Research Laboratory

Abhijit Chakraborty

Massachusetts Institute of Technology

Sam Halverson

NASA

NSF

Overview & Capabilities

Telescope: 3.5m WIYN Telescope @ KPNO

Waveband & Resolution: 380 – 930 nm, complete coverage, R ~90K

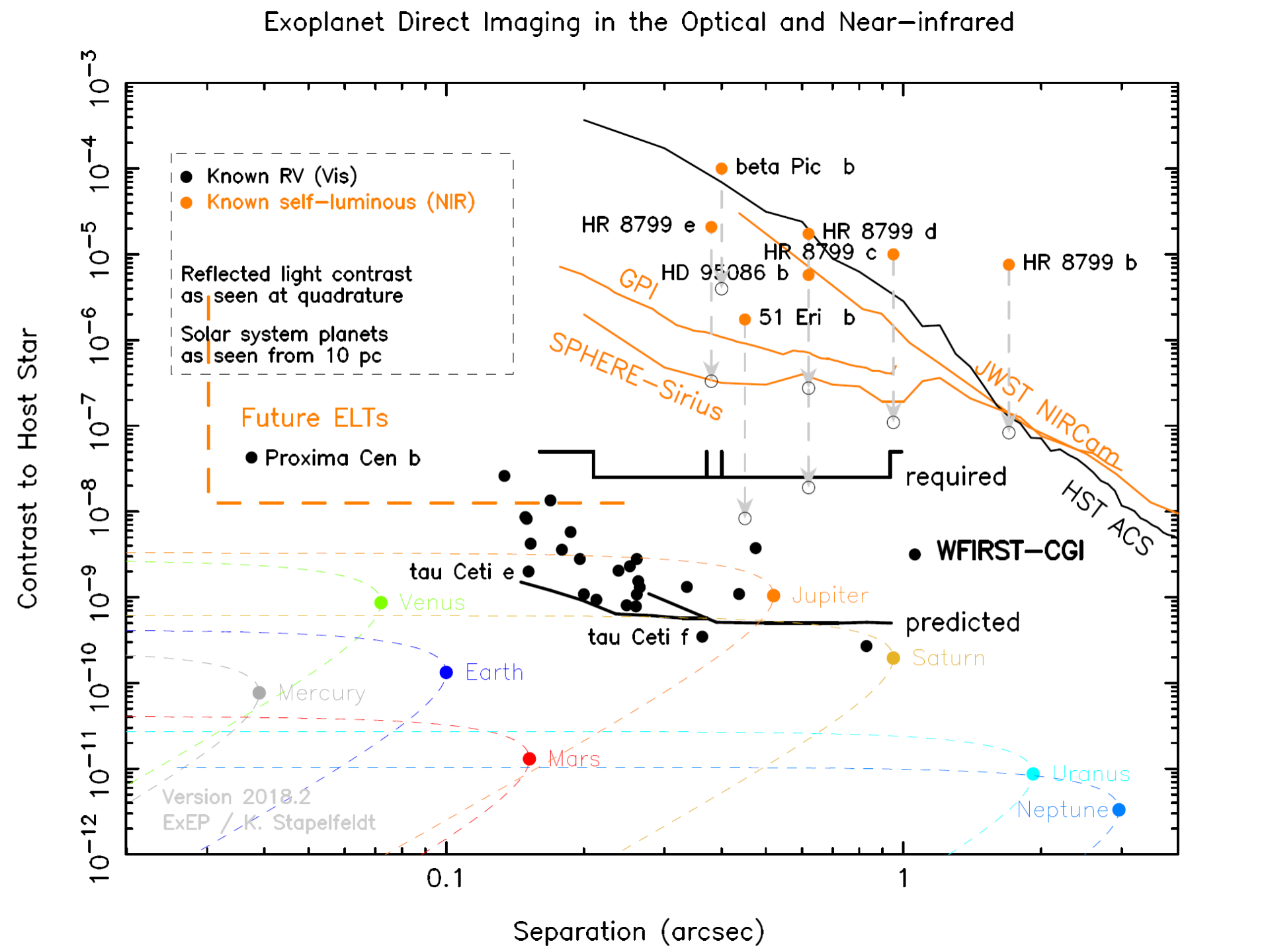
Expected Precision: 30 cm/s (instrumental) initial w/ path to 10 cm/s

Expected On Sky: mid-late 2019

Available to the Public!

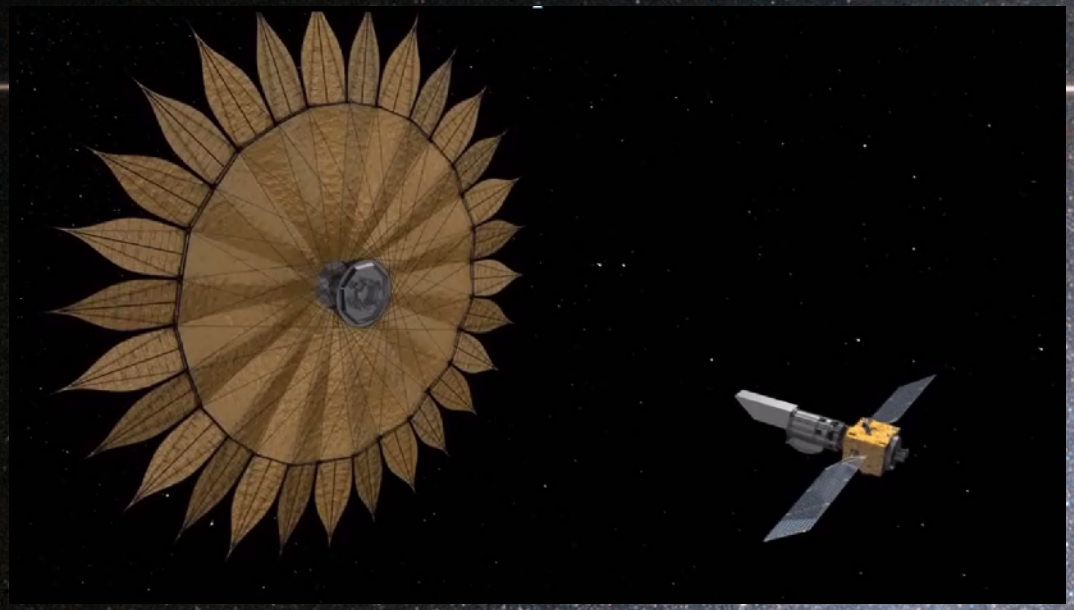
Two Observing Modes:

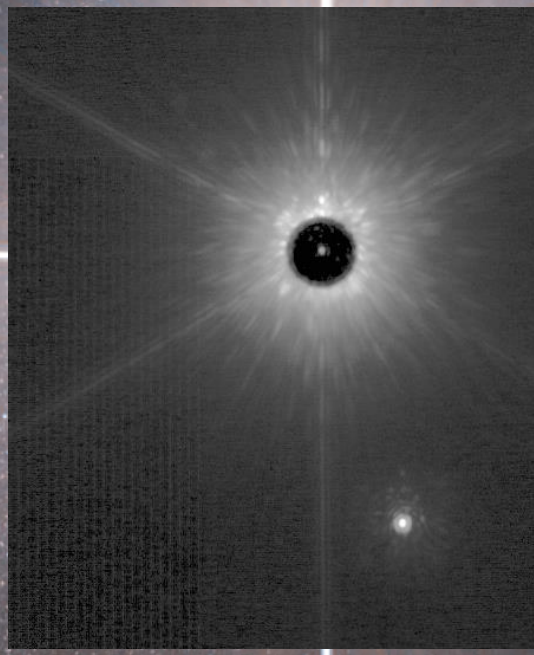
- HR (R~90,000)
  - Highest precision RVs on bright targets (V<12, e.g. TESS)
  - Simultaneous Cal
- HE (R~60,000) (subject to de-scope)
  - Faint targets (V<16)
  - Poor weather
  - e.g. K2


Exoplanet Direct Imaging in the Optical and Near−infrared
Contrast to Host Star
Separation (arcsec)
Known RV (Vis)
Known self−luminous (NIR)
Reflected light contrast as seen at quadrature
Solar system planets as seen from 10 pc
Future ELTs
Proxima Cen b
beta Pic b
HR 8799 e
HR 8799 d
HR 8799 c
HR 8799 b
HD 95086 b
51 Eri b
GPI
SPHERE−Sirius
JWST NIRCam
HST ACS
required
WFIRST−CGI
predicted
tau Ceti e
tau Ceti f
Venus
Earth
Mercury
Mars
Jupiter
Saturn
Uranus
Neptune
Version 2018.2
ExEP / K. Stapelfeldt
0.1
1

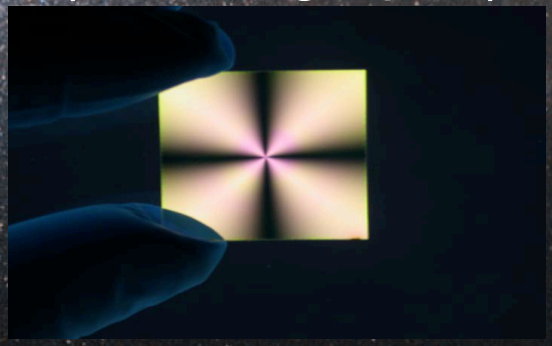
Starlight Suppression

External Occulters
(Starshades)

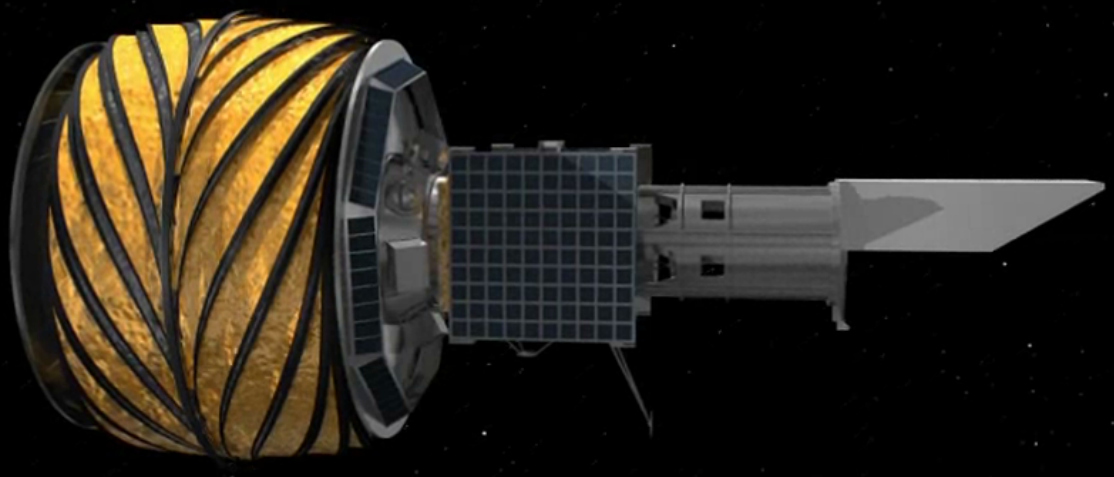




Internal Occulters
(Coronagraphs)

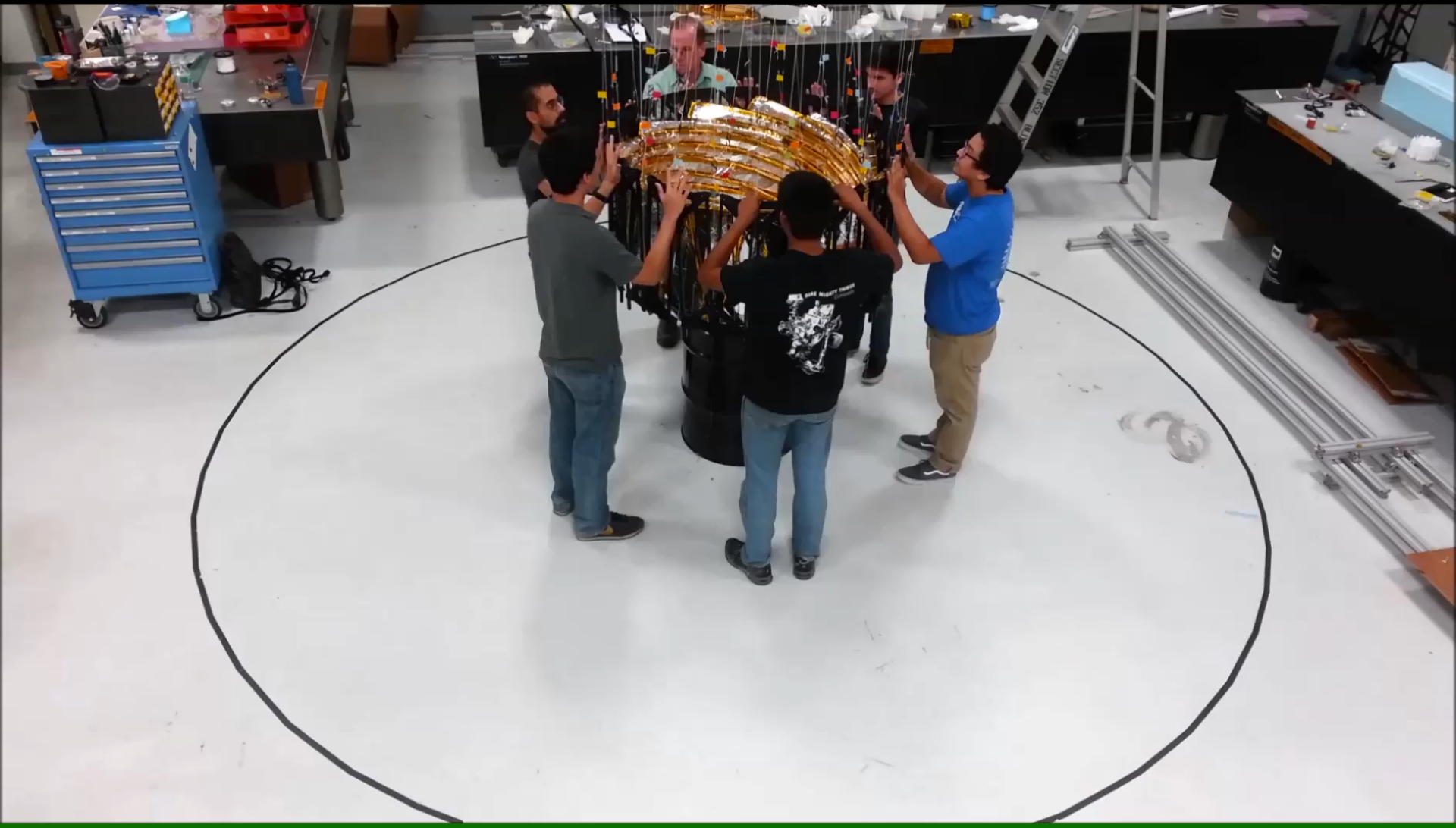


Starshade (External Occulter)

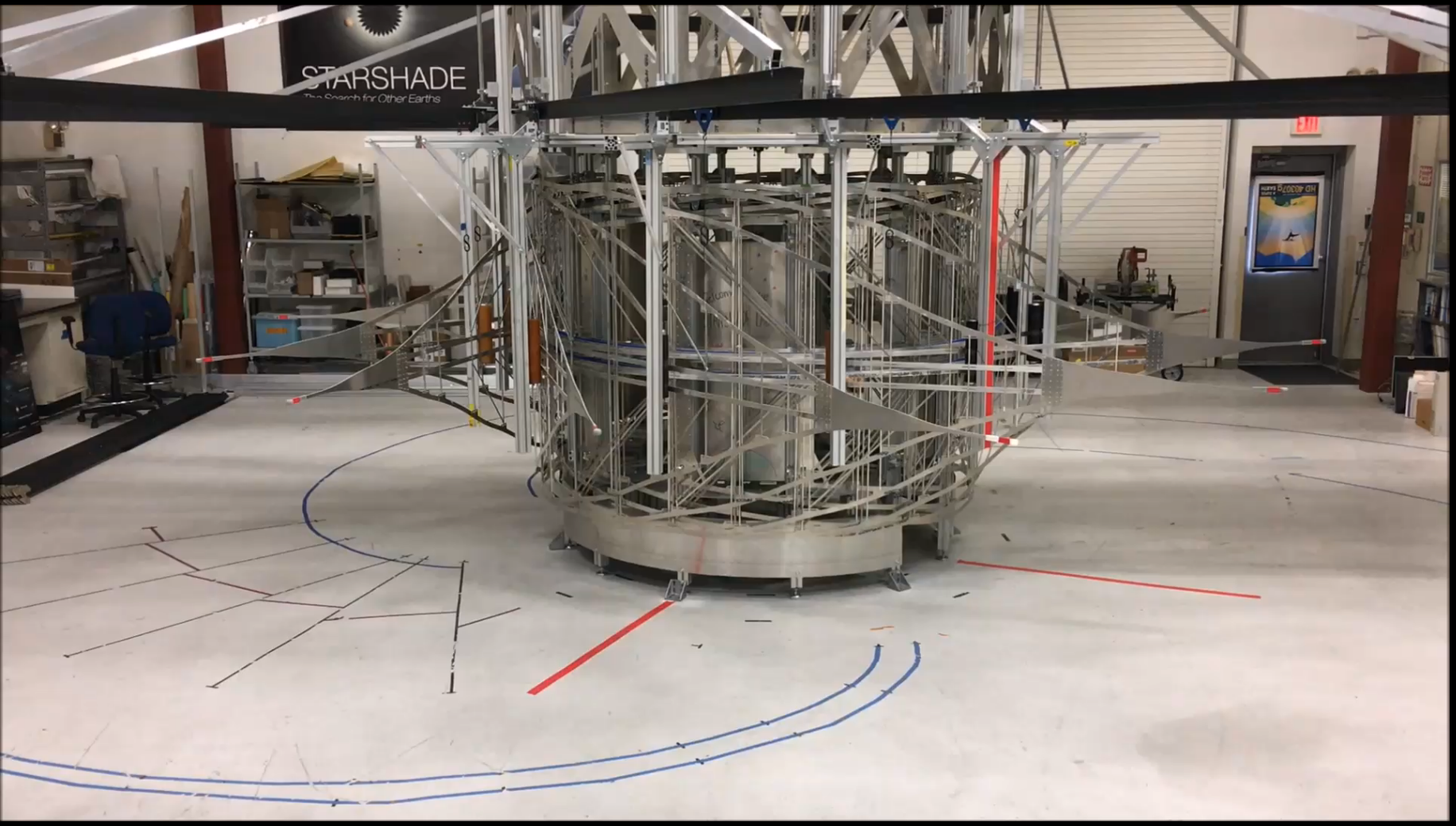


Starshade Inner Disk Deployment

Starshade Optical Shield

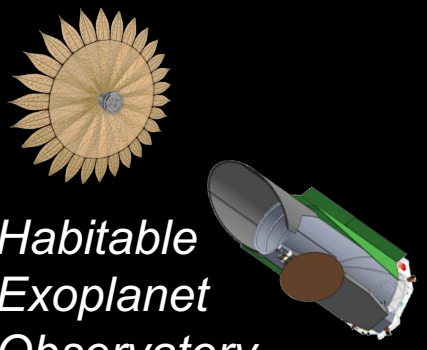


Petal Deployment Testbed



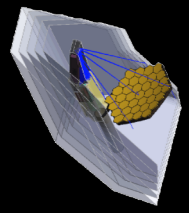
Exoplanet Mission Concepts

Large Scale



Habitable Exoplanet Observatory

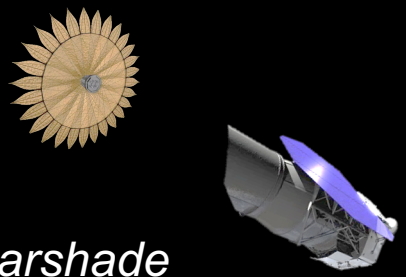
LUVOIR



Origins Space Telescope

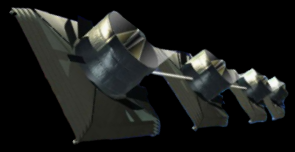
Medium Scale Concepts

EarthFinder



Starshade Rendezvous

Visionary



Life-Finder Interferometer

https://science.nasa.gov/astrophysics

Future Directions / Discussion

- NAS Exoplanet Science Strategy Report calls for a precision radial velocity initiative to reach ~1cm/sec
  - Will begin a community working group leading to a recommendation to NASA APD
- NAS Astrobiology Science Strategy Report calls for "NASA [to] implement high-contrast starlight suppression technologies in near-term space- and ground-based direct imaging missions"
  - NASA involvement in near-IR or thermal-IR high contrast imaging (HCI) on ELTs
  - Complementary Science
  - Technology relevance

Jet Propulsion Laboratory
California Institute of Technology

---

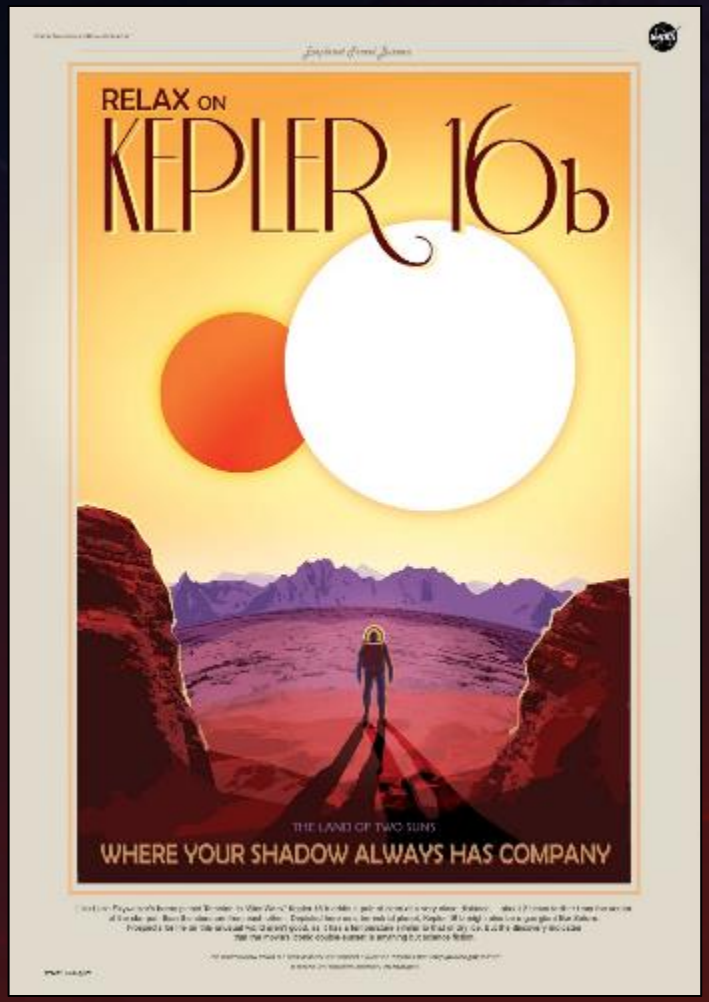
exoplanets.nasa.gov

Acknowledgements

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

ExoComm

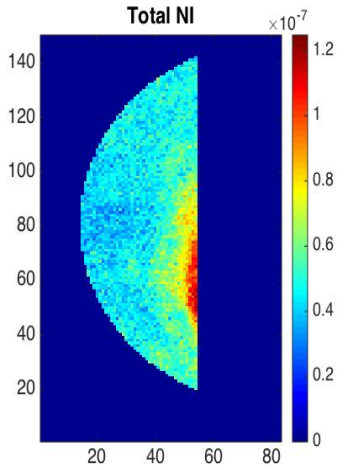
Exploring a Galaxy of Worlds While Inspiring our Own



“Exoplanet Earth” Edition

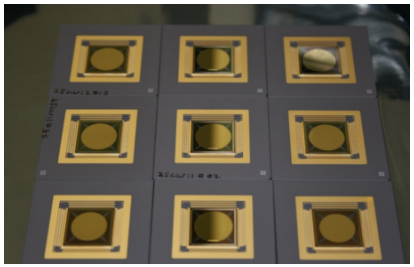
We are a Leo Sun from Trappist-1

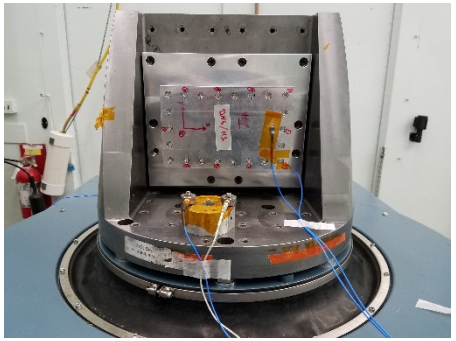
TDEM News



- **TDEM-14 PI Gene Serabyn charge-6 and -8 vortex coronagraph achieved vortex record 5.1×10^{-8} contrast at 2% band 550 nm. tests resume in HCIT in January. Goal: 10^{-9} contrast 10% band**

- **TDEM-10 PI Paul Bierden. MEMS DMs exposed to random vibe at GSFC; post-environmental characterization underway**



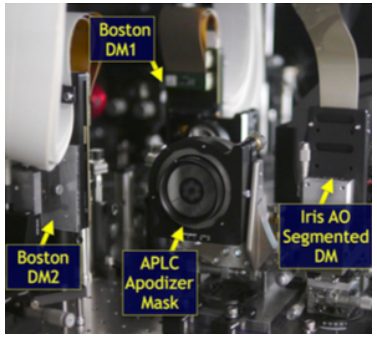


https://exoplanets.nasa.gov/exep/technology/TDEM-awards/

New TDEM awards this year (TDEM-17)

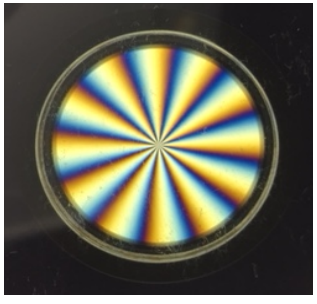
Rémi Soummer

First System-level Demonstration of High-Contrast for Future Segmented Space Telescopes



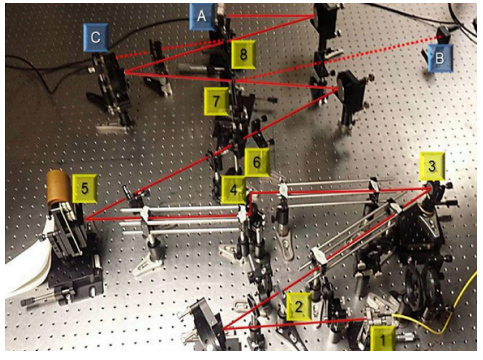
Gene Serabyn

Vortex Coronagraph High Contrast Demonstrations



Olivier Guyon

Linear Wavefront Control for High Contrast Imaging



Implications of HOSTS results (2)

- Larger space telescopes can cope better with higher levels of exozodi. At the HOSTS exozodi upper limit, R= 70 spectroscopy of a fiducial Earth analog around a solar analog at 10 pc is
  - Robustly possible with the LUVOIR 8 & 15 m architectures
  - Viable for the HabEx 4m architecture
  - Very difficult for the WFIRST 2.4m architecture. Success would be possible only in the closer and less dusty targets, and by observing at lower spectral resolution.
- Remaining uncertainty in exozodi level implies that integration times needed for detection & spectroscopy will remain uncertain by a factor of ~2
- For New Worlds mission architectures that are observing time limited, tighter exozodi limits could enable the use of a smaller space telescope.

Technology: TecLooking Ahead

- **Technology Plan Appendix: 2019 edition (February)**
- **Support for Large Mission STDTs: LUVOIR, HabEx, Origins**
  - Technology Readiness Level assessment in early 2019
- **Directed work package on Exoplanet Spectroscopy kicking off at GSFC (lead: McElwain)**
  - Parabolic DMs (Groff), Lenslet/pinhole array coupling coronagraph to IFS (Zimmerman), Hole-multiplying CCDs (Rauscher), Exoplanet Spectral Retrieval (Mandell)
- **Starshade technology milestones : S5**
  - Review of Formation Sensing milestone in January
  - Starlight suppression / model validation milestone coming soon
- **TDEM**
  - Coronagraph demos scheduled for HCIT: Vortex, PIAACMC, Hybrid Lyot
  - Final Reports on 1. polarization (Breckinridge), 2. MEMS DMs (Bierden)
  - TDEM-17 whitepapers: next-generation Vortex Coronagraphy, APLC Coronagraphy, Linear Wavefront Control early 2019
- **SCDA reports: whitepaper, further publications**
- **iSAT whitepaper**
- **Decadal Survey Testbed**
  - Phase 1 progressing towards 10^{-10} contrast demo; Phase 2 segmented pupil coming soon..
- **Technology Gap prioritization in coordination with PCOS/COR: summer 2019**