



# Exoplanet Exploration Program Update

**Dr. Gary H. Blackwood, Program Manager**

NASA Exoplanet Exploration Program

Jet Propulsion Laboratory

California Institute of Technology

CL#17-2593

**June 06, 2017**

230<sup>th</sup> Meeting of the American Astronomical Society

Austin, Texas

Program Overview

Program Purpose

Discover / Characterize

Identify Habitable Worlds

Serving the Community

ExoComm

# NASA Exoplanet Exploration Program

Astrophysics Division, NASA Science Mission Directorate

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



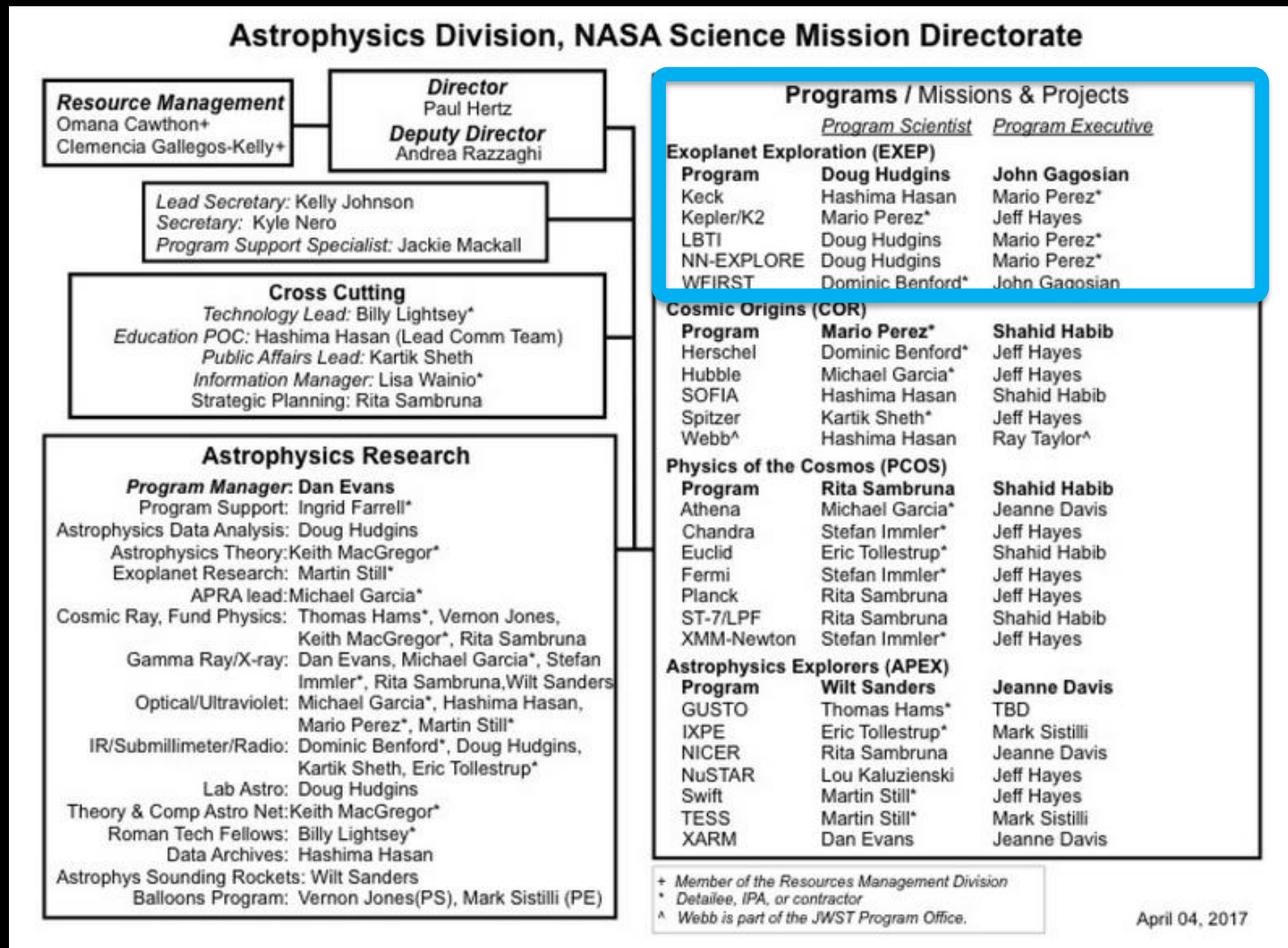
Program purpose described in  
**2014 NASA Science Plan**

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



# ExEP is a Program Office within the NASA Astrophysics Division



# Exoplanet Missions



W. M. Keck Observatory



Large Binocular Telescope Interferometer



NN-EXPLORE

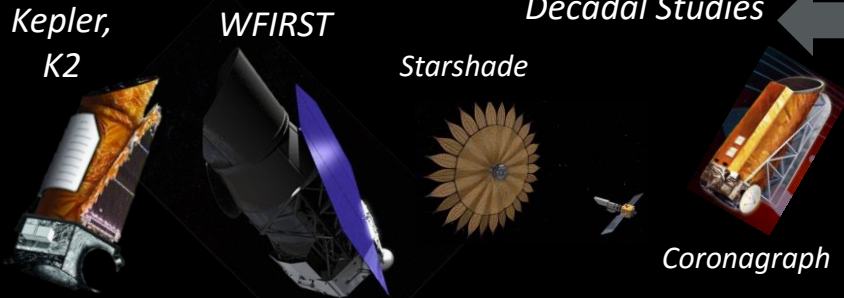
## Ground Telescopes with NASA participation

- <sup>1</sup> NASA/ESA Partnership
- <sup>2</sup> NASA/ESA/CSA Partnership
- <sup>3</sup> CNES/ESA



# NASA Exoplanet Exploration Program

## Space Missions and Mission Studies



## Communications



## Supporting Research & Technology

### Key Sustaining Research



Large Binocular Telescope Interferometer



Keck Single Aperture Imaging and RV



NN-EXPLORE

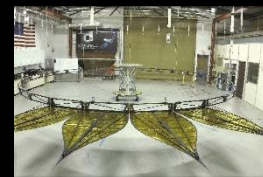
### Technology Development



Coronagraph Masks



High-Contrast Imaging



Deployable Starshades

### NASA Exoplanet Science Institute

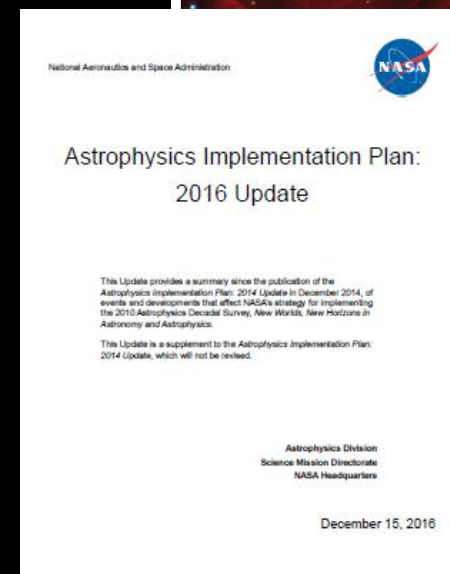
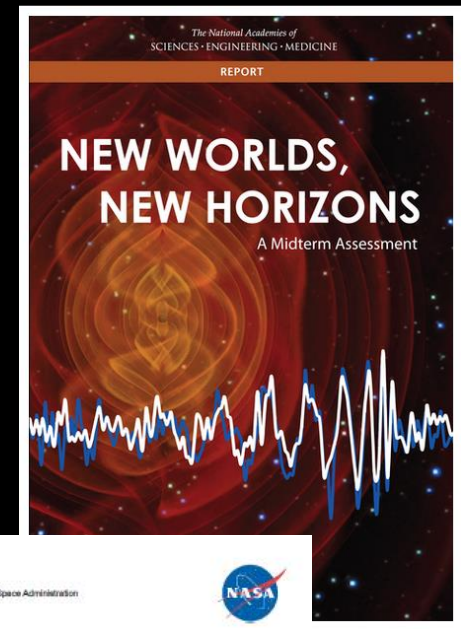
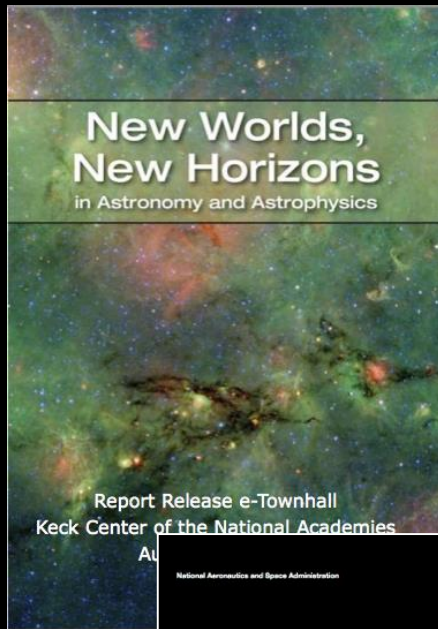


<https://exoplanets.nasa.gov>

# Astrophysics Division: Driving Documents

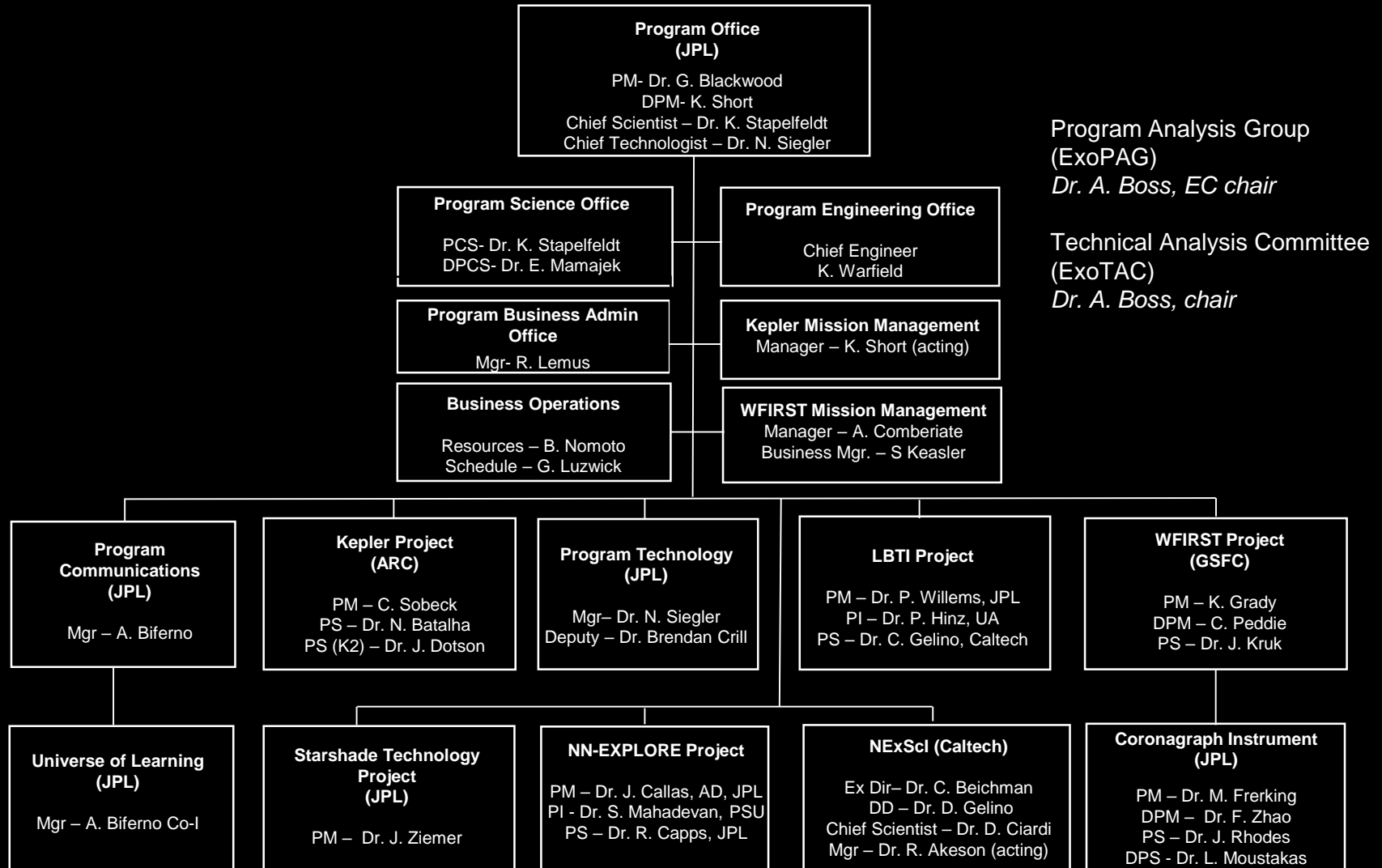
## Results of NWNH:

- **WFIRST** is top large-scale recommended activity
- **NWNH technology program** is top medium-scale recommended activity



# Exoplanet Exploration Program

Astrophysics Division, Science Mission Directorate





# Exoplanet Exploration Program

Serving the exoplanet science community by implementing NASA's space science vision for exoplanets

	Today	Enabled Science	Future	Enabled Science
Discover	<b>Show Me the Planets!</b>			
Characterize				
Identify Worlds that Could Harbor Life				
Community Support				

# Purposes: Discover and Characterize

## Enabling Science Today

	Today	Enabled Science
Discover	<ul style="list-style-type: none"><li>• Kepler</li><li>• K2</li></ul>	<ul style="list-style-type: none"><li>• Occurrence rates for science and design of future missions</li><li>• Discoveries via photometry and microlensing, potential JWST Targets</li></ul>
Characterize	<ul style="list-style-type: none"><li>• NASA Keck time</li><li>• NNEXPLORE GO, including NESSI</li><li>• NASA Exoplanet Archive</li></ul>	<ul style="list-style-type: none"><li>• SMD Science, Exoplanet follow up and precursor science</li><li>• Exoplanet Science</li><li>• Orbit prediction and observability for space missions for all exoplanets and user targets.</li><li>• Table of transmission spectroscopy data including from HST and Spitzer.</li></ul>
<i>Space Missions Not in the ExEP</i>	<ul style="list-style-type: none"><li>• HST, Spitzer</li></ul>	<ul style="list-style-type: none"><li>• Atmospheres, microlensing discoveries</li></ul>

# Kepler Close-Out

Delivering Kepler's Legacy

- Kepler closeout and final data processing continues steadily within overall schedule margin
- SOC 9.3 **Final Occurrence Rate** Products planned for June 2017



**KEPLER&K2**  
2017 **SciConIV**

**JUNE 19-23 2017**

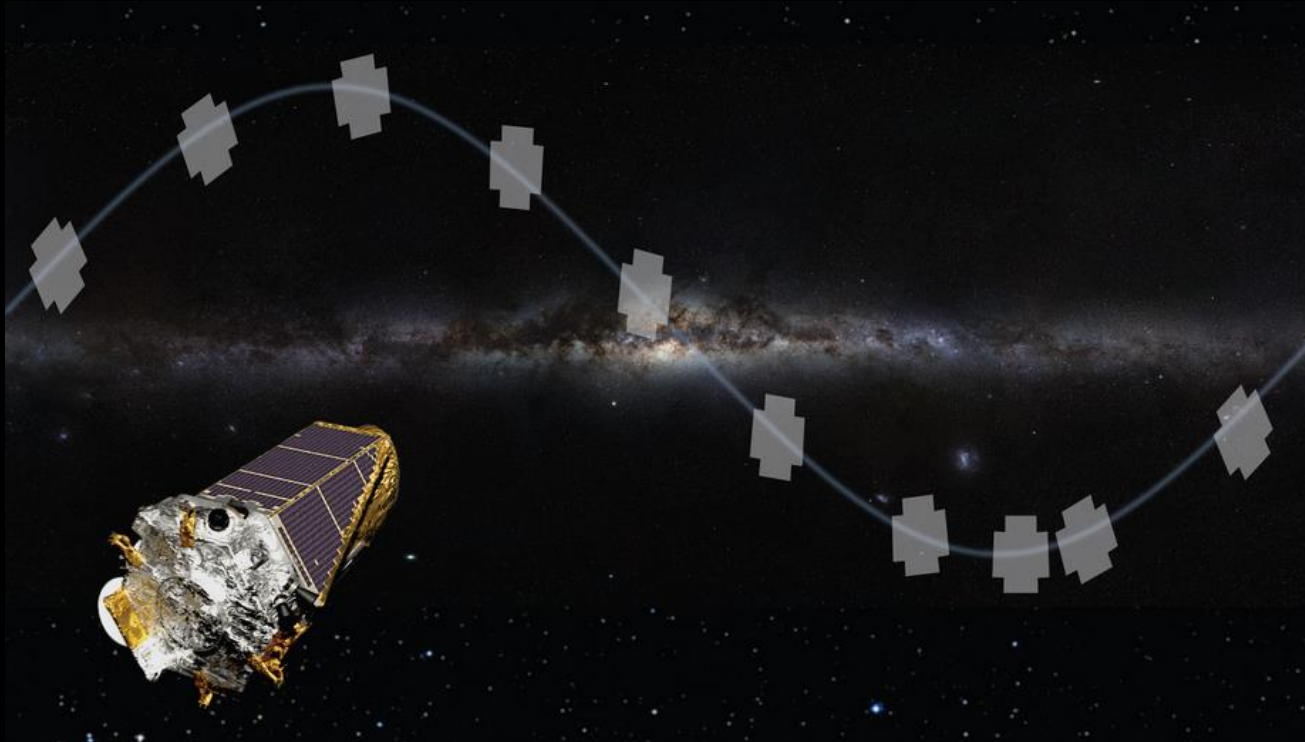
• NASA Ames Research Center •  
Moffett Field, CA





# Kepler K2

Extending the Power of Kepler to the Ecliptic



Recently completed Campaign 13 (Taurus); now in Campaign 14 (Leo)

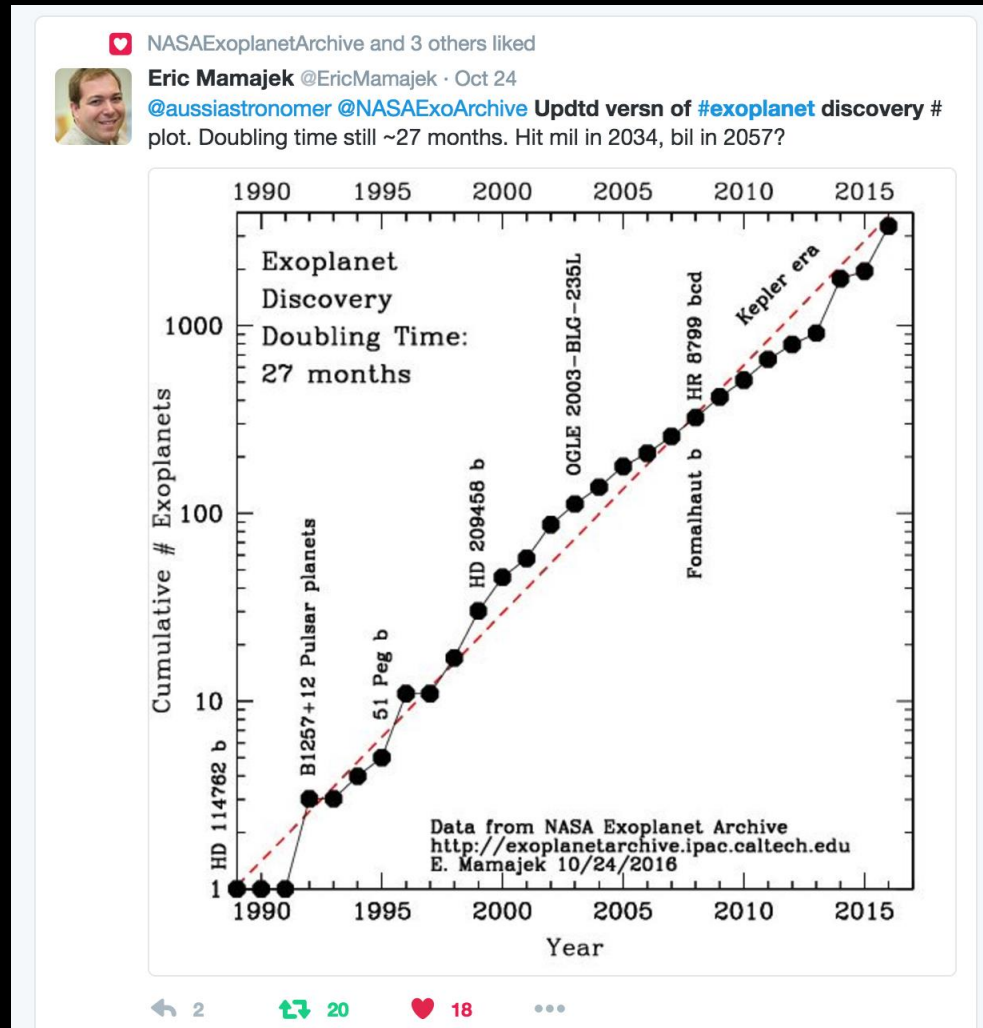
Upcoming:

- Changed the position of the field for Campaign 16 – Kepler will observe in the forward-facing direction; emphasis on supernova science

<https://exoplanets.nasa.gov/k2>

# “Mamajek’s Law”

## Exoplanet Discovery Doubling Time



Credit: J. Christenson

# Exoplanet Exploration Program

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	Today	Enabled Science	Future	Enabled Science
Discover				
Characterize				
Identify Worlds that Could Harbor Life				
Community Support				

**Show Me the Planets!**



# Purposes: Discover and Characterize

Enabling Science in the *Future*

	Future	Enabled Science
Discover	<ul style="list-style-type: none"><li>• <b>WFIRST Microlensing Survey</b></li></ul>	<ul style="list-style-type: none"><li>• Census for long period planets</li></ul>
Characterize	<ul style="list-style-type: none"><li>• <b>NEID GO</b></li><li>• <b>WFIRST Coronagraph</b></li><li>• Original Probe Studies (Coronagraph, Starshade)</li><li>• OST</li></ul>	<ul style="list-style-type: none"><li>• Exoplanet Mass</li><li>• Reflected Light Spectroscopy</li><li>• Reflected Light Spectroscopy</li><li>• Reflected Light Spectroscopy</li></ul>
<i>Space Missions Not in the ExEP</i>	<ul style="list-style-type: none"><li>• <b>TESS, JWST</b></li></ul>	<ul style="list-style-type: none"><li>• Discoveries via photometry, atmospheres via transmission spectroscopy</li></ul>

# WFIRST Microlensing Census for Exoplanets

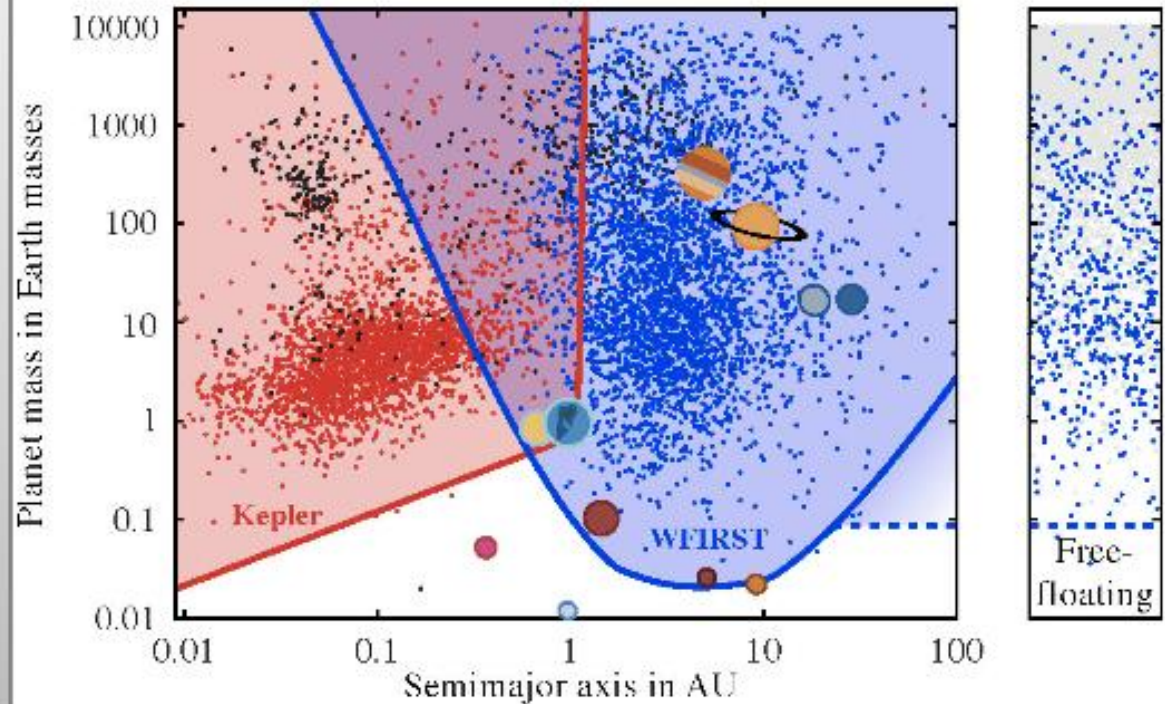


Together, Kepler and WFIRST-AFTA complete the statistical census of planetary systems in the Galaxy.



## WFIRST-AFTA will:

- Detect 2800 planets, with orbits from the habitable zone outward, and masses down to a few times the mass of the Moon.
- Be sensitive to analogs of all the solar system's planets except Mercury.
- Measure the abundance of free-floating planets in the Galaxy with masses down to the mass of Mars

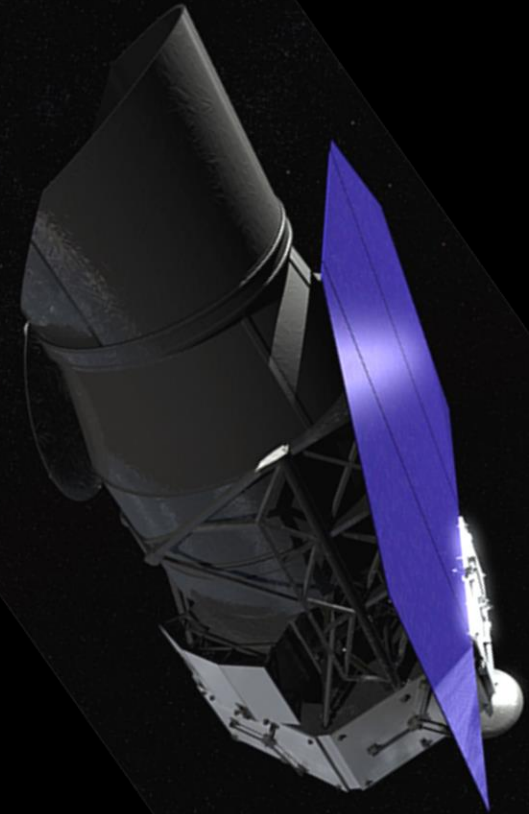


*Credit: D. Bennett, M. Penny*

# Wide Field Infrared Survey Telescope (WFIRST)

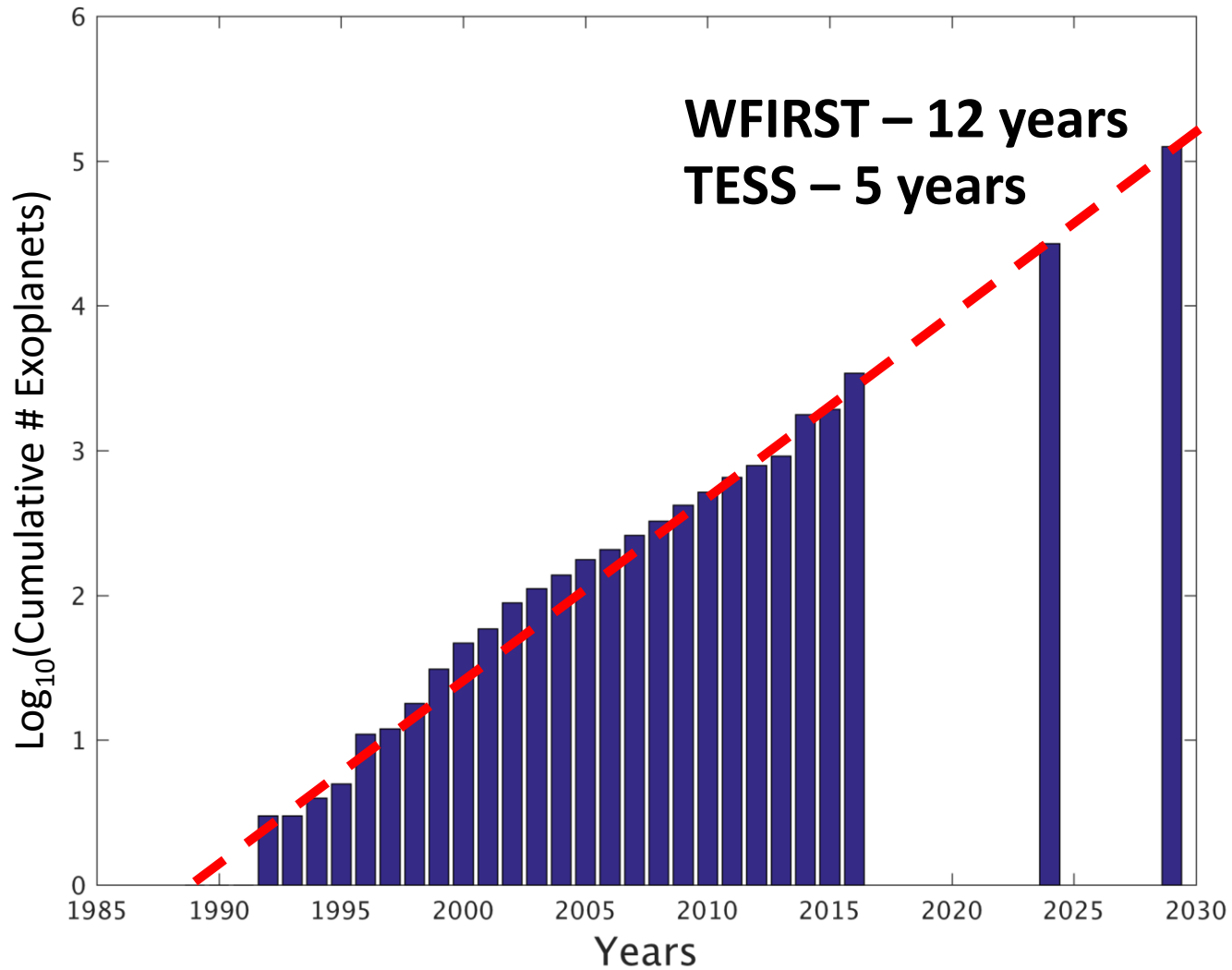
Dark Energy, Infrared Survey... and Alien Worlds

- 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.
- 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>





# How Much Longer Can Mamajek's Law Last?





- Extreme precision radial velocity spectrometer ( $<0.5$  m/s) for WIYN telescope
- Laser frequency comb reference
- Plan for instrument commissioning: August 2019
- Ongoing Guest Observer program using NOAO share of telescope time for exoplanet research
- Please propose!



NN-Explore Exoplanet Investigations with Doppler Spectroscopy



*PI: S. Mahadevan*

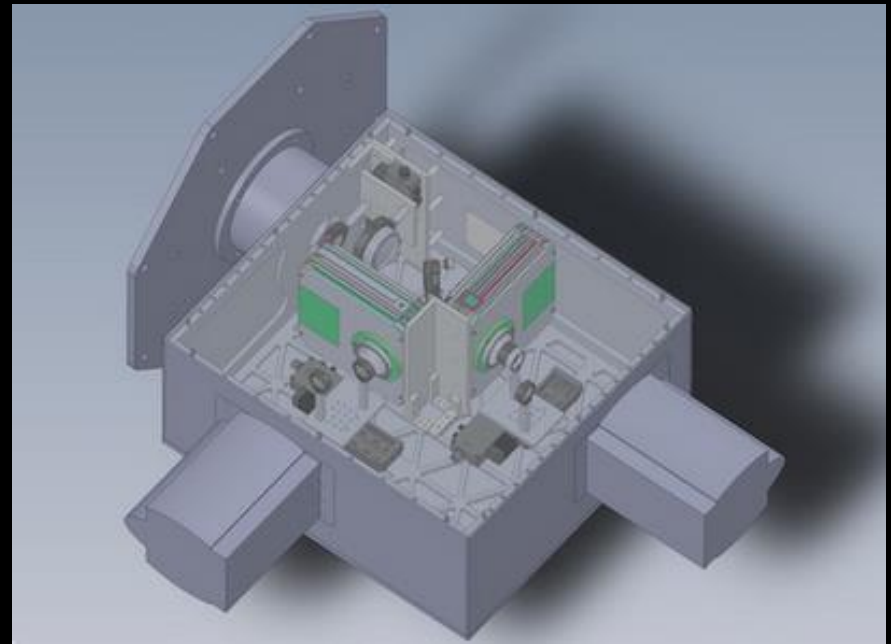


NOAO 3.5-m WIYN Telescope, Kitt Peak National Observatory, Arizona

# NESSI on WIYN 3.5m Observatory, Kitt Peak

The NASA Exoplanet Star (and) Speckle Imager

- Speckle images in two simultaneous colors
- Resolution at or near diffraction limit
- Companion detection and characterization to delta magnitudes of  $\sim 5$
- PI: Steve Howell, NASA ARC



<http://www.wiyn.org/Instruments/>

# A Familiar Habitable Zone



*Credit: Luc Forsyth*



# Exoplanet Exploration Program

Serving the exoplanet science community by implementing NASA's space science vision for exoplanets

	Today	<i>Enabled Science</i>	Future	<i>Enabled Science</i>
Discover				
Characterize				
Identify Worlds that Could Harbor Life	<b>You Had Me at Habitable</b>			
Community Support				

# Purpose: Identify Habitable Worlds

Enabling Science Today

	Today	Enabled Science
Identify Worlds that Could Harbor Life	<ul style="list-style-type: none"><li>• Large Binocular Telescope Interferometer</li><li>• Technology - Competed</li><li>• Starshade Technology Development</li><li>• Starshade Readiness Working Group</li><li>• Segmented Coronagraph Design and Analysis</li><li>• Telescope Stability Workshop</li></ul>	<ul style="list-style-type: none"><li>• Exozodiacal Dust survey</li><li>• Increasing TRL feasibility</li><li>• Decreasing inner working angle</li><li>• Increasing outer working angle</li><li>• Increasing starshade suppression</li><li>• Minimizing segmented mirror edge diffraction</li><li>• Increasing coronagraph contrast</li></ul>

# Ground-Based Support for Space Missions

Partnering to Enable Key Projects for Strategic Reasons



Keck Observatory: (1/6 partner)  
Key SMD Project and GO  
Investigations



Large Binocular Telescope Interferometer:  
Exozodiacal Dust Survey  
University of Arizona



NN-EXPLORE using WIYN Telescope  
NEID Precision Radial Velocity Instrument

# Large Binocular Telescope Interferometer

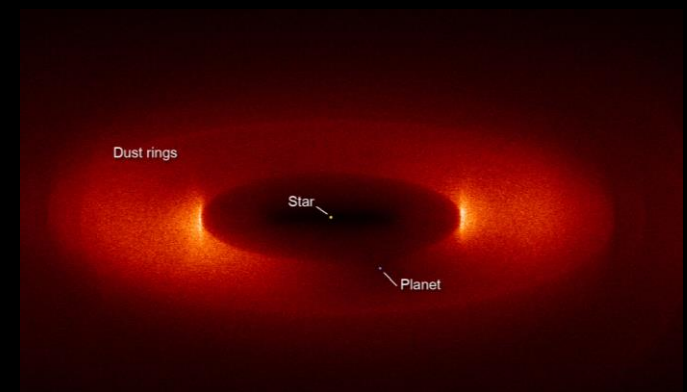
Measuring HZ Exozodiacal Dust to Inform Designs of Future Missions



Credit: ESO/Y. Beletsky

- 35-star survey, September 2018
- Progress: 26 stars observed
- Measurement Precision: ~12 zodi, one star one sigma

*Phil Hinz, PI*

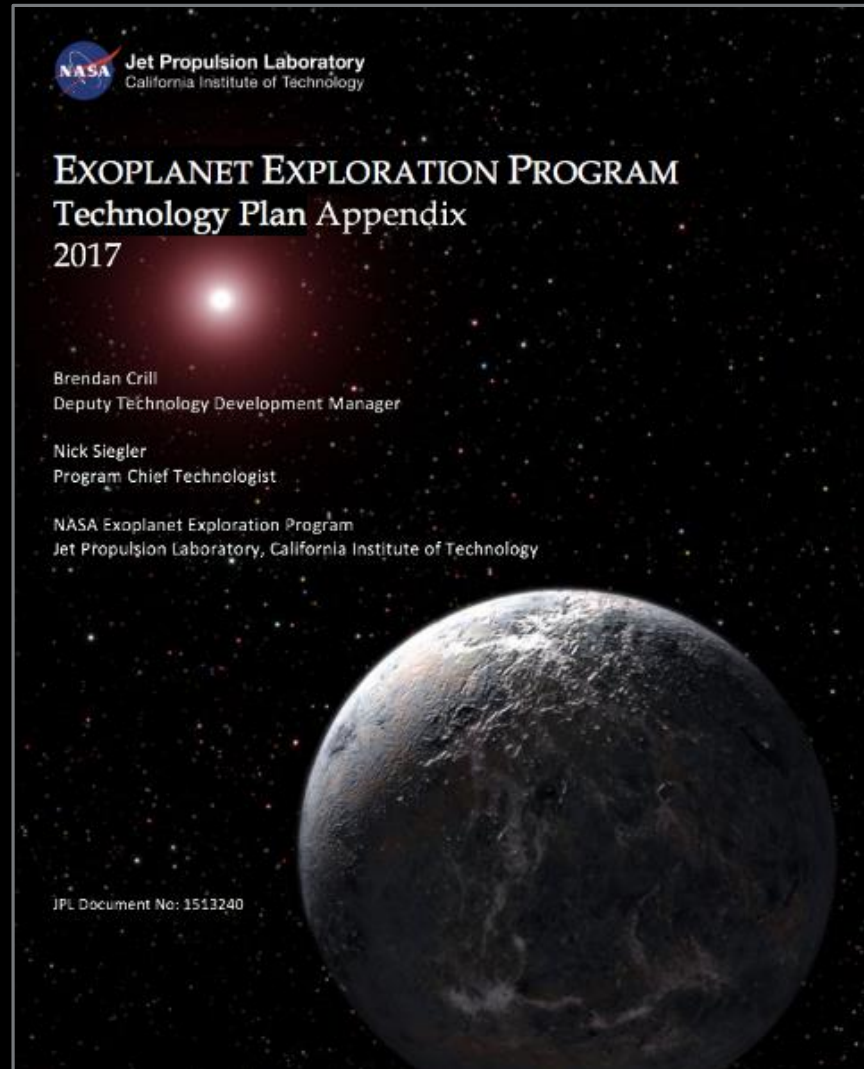


Credit: NASA/GSFC



# Strategic Astrophysics Technology – TDEM

Advancing Technology Readiness towards next Decadal Survey



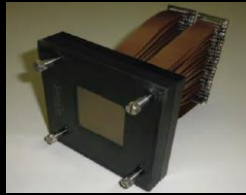
*Appendix revision  
published January 2017*

# Coronagraph/Telescope Technology Needs

## Contrast



Coronagraph architectures



Deformable mirrors

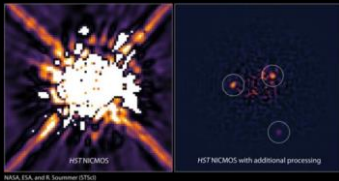
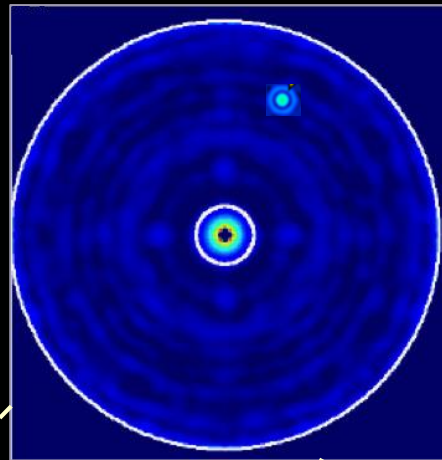
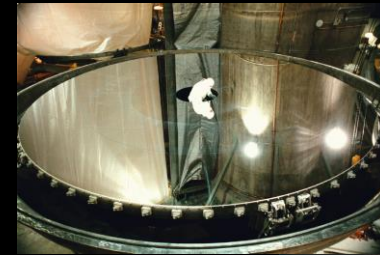


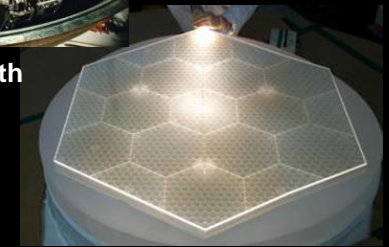
Image post-processing



## Angular Resolution

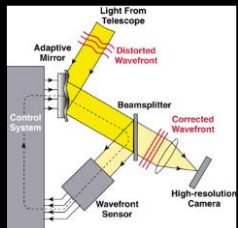


Large monolith



Segmented

## Contrast Stability



Wavefront sensing and control

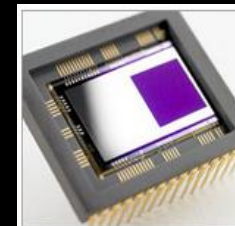


Segment phasing and rigid body sensing and control

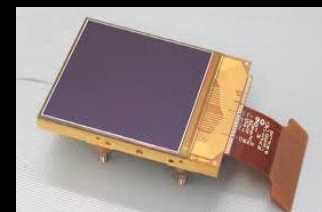


Telescope vibration sensing and control

## Detection Sensitivity



Ultra-low noise visible and infrared detectors



# Starshade Technology Needs

## Starlight Suppression



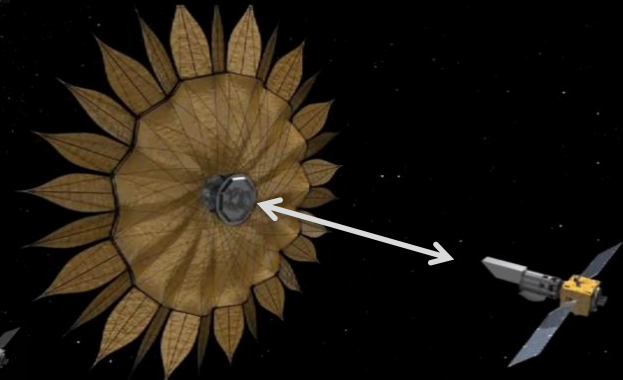
Suppressing scattered light off petal edges from off-axis Sunlight (S-2)



Suppressing diffracted light from on-axis starlight (S-1)



## Formation Sensing and Control

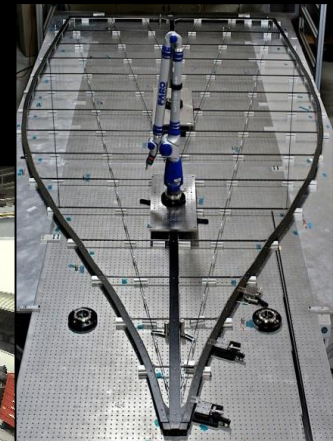


Maintaining lateral offset requirement between the spacecrafts (S-3)

## Deployment Accuracy and Shape Stability



Positioning the petals to high accuracy, blocking on-axis starlight, maintaining overall shape on a highly stable structure (S-5)



Fabricating the petals to high accuracy (S-4)

S-# corresponds to ExEP  
Starshade Technology Gap number  
<http://exoplanets.nasa.gov/exep/technology/gap-lists>

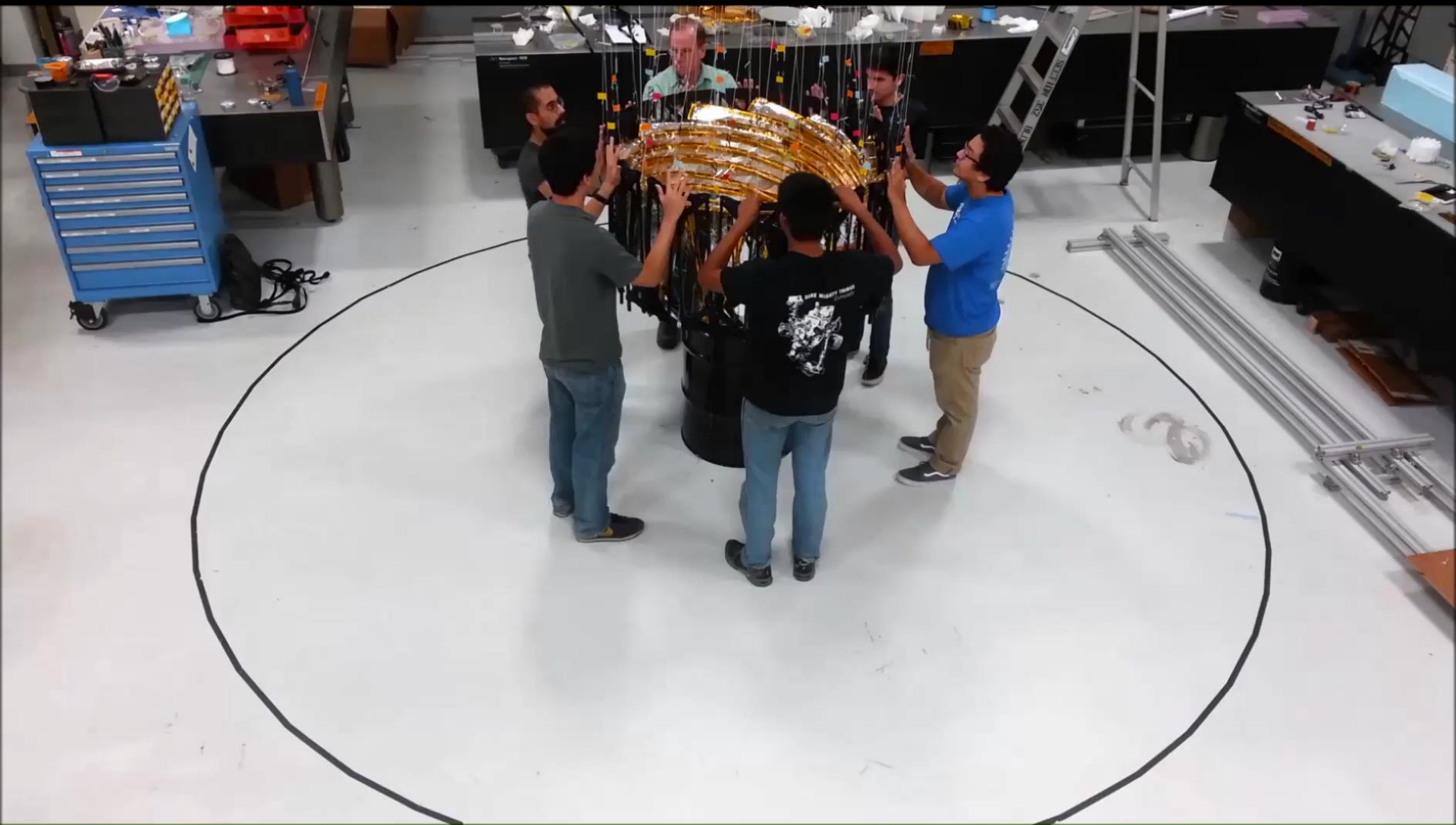


# Early Inner Disk Deployment Trials at JPL





# Starshade Optical Shield



# Exoplanet Exploration Program

Serving the exoplanet science community by implementing NASA's space science vision for exoplanets

	Today	<i>Enabled Science</i>	Future	<i>Enabled Science</i>
Discover				
Characterize				
Identify Worlds that Could Harbor Life	<b>You Had Me at Habitable</b>			
Community Support				

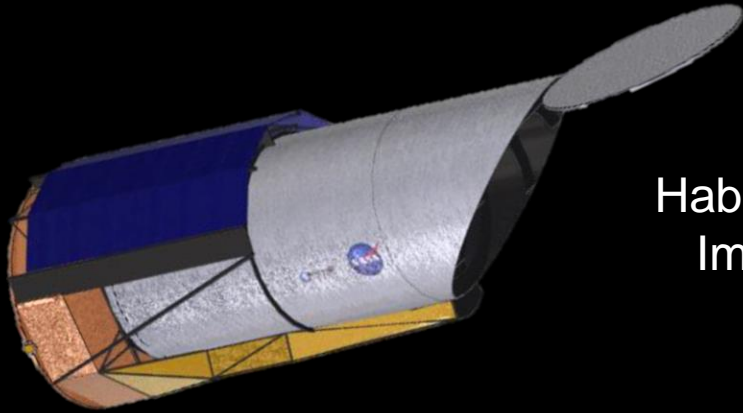
# Purpose: Identify Habitable Worlds

Enabling Science in Future

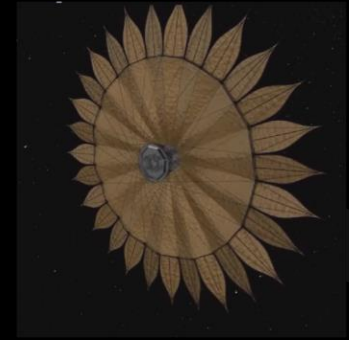
	Future	Enabled Science
<b>Identify Worlds that Could Harbor Life</b>	<ul style="list-style-type: none"><li>• Current Probe Starshade - WFIRST Rendezvous (Seager, Kasdin)</li><li>• LUVOIR</li><li>• HabEx</li><li>• OST</li><li>• Current Probe Precision RV in Space (Plavchan)</li><li>• Standard Definitions and Evaluation Team</li></ul>	<ul style="list-style-type: none"><li>• Reflected Light Spectroscopy</li><li>• Reflected Light Spectroscopy</li><li>• Reflected Light Spectroscopy</li><li>• Reflected Light, Transmission Spectroscopy</li><li>• Mass Measurements</li></ul>

# Possible New Worlds Exoplanet Telescopes

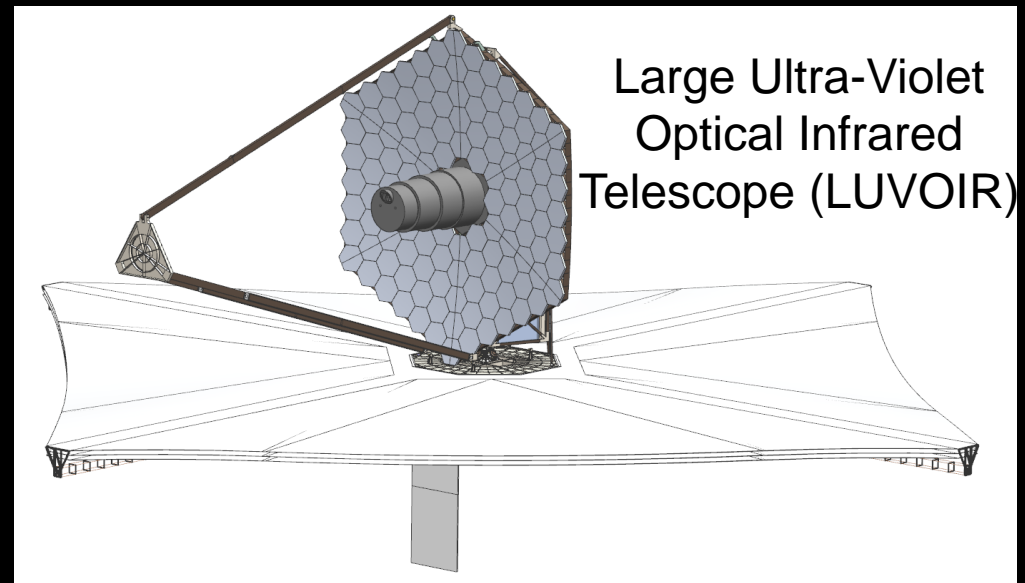
(mid 2030s)



Habitable Exoplanet  
Imaging Mission  
(HabEx)





Origins Space  
Telescope (OST)



Large Ultra-Violet  
Optical Infrared  
Telescope (LUVOIR)

# Medium-Scale Space Mission Concepts

Announced by NASA March 20

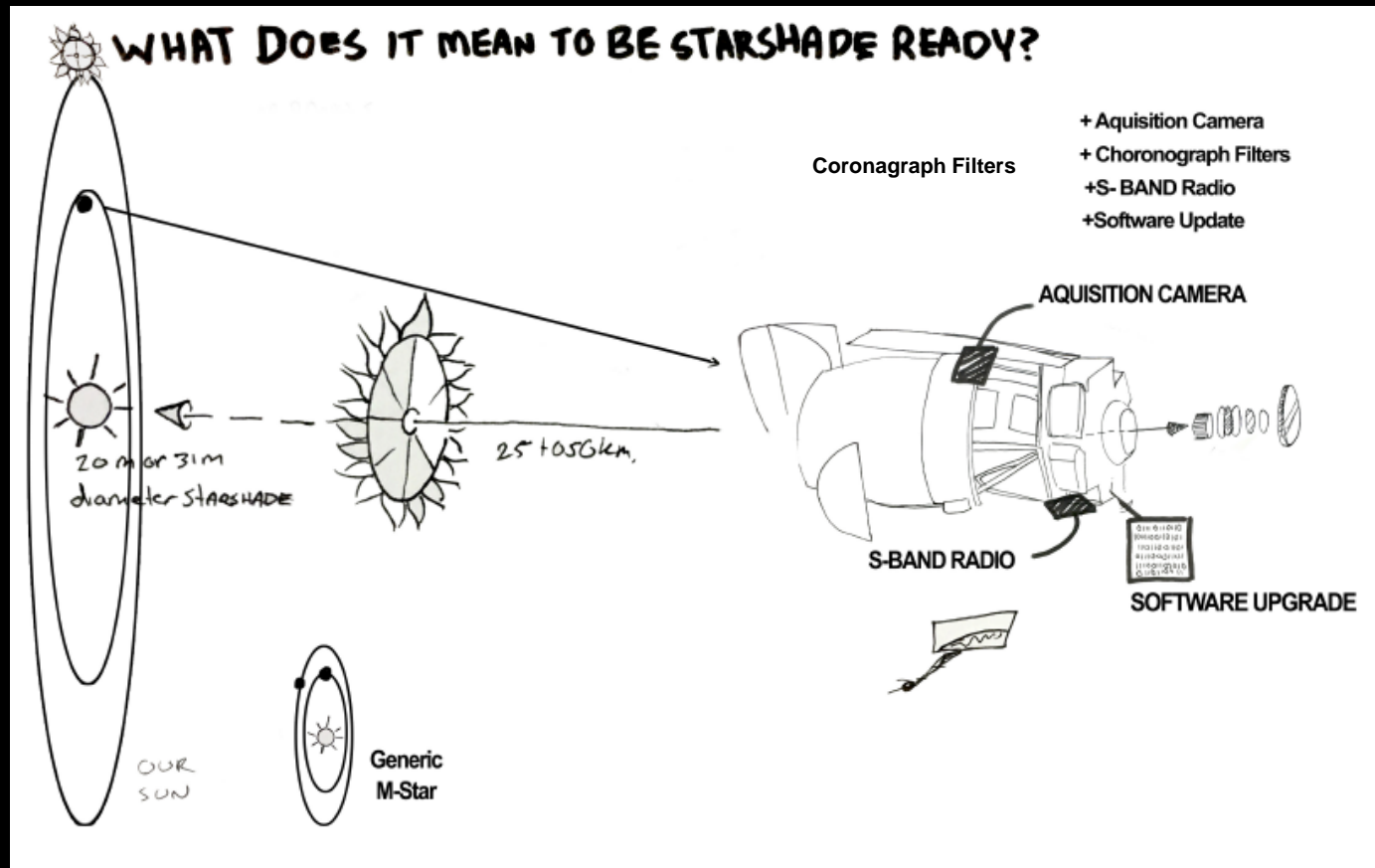
PI	Affiliation	Title
Camp, J.	NASA's Goddard Space Flight Center	Transient Astrophysics Probe Concept Study
<u>Cooray</u> , A.	Univ. California, Irvine	Cosmic Dawn Intensity Mapper
Danchi, W.	NASA's Goddard Space Flight Center	Cosmic Evolution through UV spectroscopy (CETUS)
Glenn, J.	Univ. of Colorado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



# WFIRST Starshade-Ready

Accommodation Study to Enable a Rendezvous at L2

- WFIRST Starshade could directly image habitable-zone exo-earths in late 2020s



# Exoplanet Exploration Program

Serving the exoplanet science community by implementing NASA's space science vision for exoplanets

	Today	<i>Enabled Science</i>	Future	<i>Enabled Science</i>
Discover				
Characterize				
Identify Worlds that Could Harbor Life				
Community Support	<b>Serving the Science Community</b>			

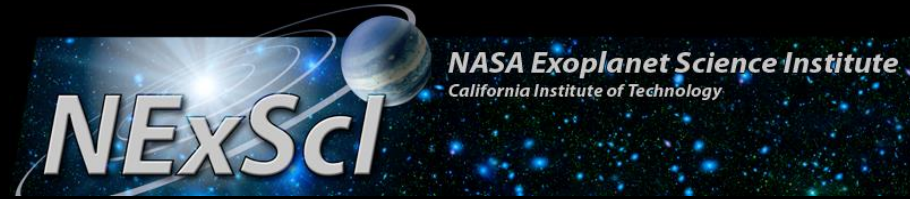
# Serving the Exoplanet Science Community

## Community Support

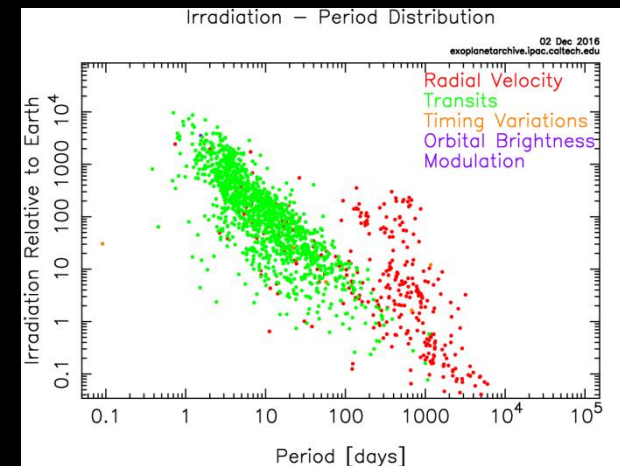
### NExSci:

- NASA Exoplanet Archive
- Exoplanet Follow-up Observing Program - Kepler/K2/TESS
- NASA Keck Time - GO
- NN-EXPLORE - GO
- Sagan Summer Workshop
- Sagan Fellowships
- Community support (workshops, conferences)
- Support to ExoPAG and SAGs
- Communication Products
- Education Products
- People Resources: Program Scientists, Technologists, Managers, Communications, Education
- Archive provides the ability to do orbit prediction and observability for space missions on all of the confirmed planets and candidates as well as the users own targets.
- ExoFOP supports Kepler, K2, TESS
- GO serves current observers
- Sagan trains next generation of scientists
- Scientific Community support
- SOC members, workshop members, review boards, technology strategy, engineering troubleshooters, Invited speakers, communication and education resources

# NASA Exoplanet Science Institute



- **Sagan Summer School**, August 2017  
“Microlensing in the Era of WFIRST”
- **NASA/Keck time** (90 nights/yr) supports Exoplanets, Cosmic Origins, Physics of the Cosmos and Solar System Science
- **Exoplanet Archive** tracks exoplanet population and Kepler pipeline products
- **Exoplanet Follow-up Observing Program** supports Kepler & K2 sources follow-up

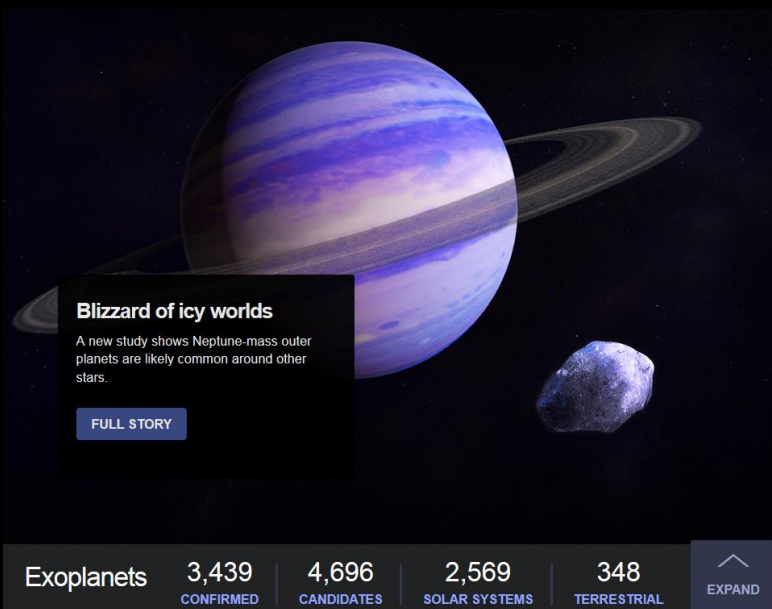




# Exoplanet Communications

Data Visualization Tools and New Thematic Exoplanet Hub

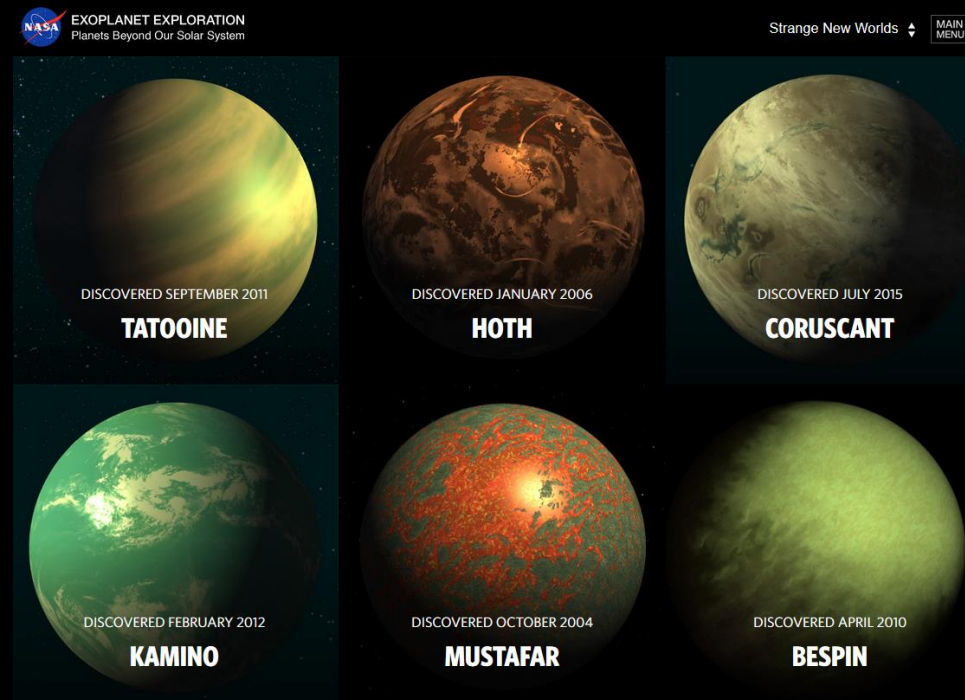
# exoplanets.nasa.gov



**Blizzard of icy worlds**  
A new study shows Neptune-mass outer planets are likely common around other stars.







FULL STORY

Exoplanets	3,439	4,696	2,569	348	EXPAND
	CONFIRMED	CANDIDATES	SOLAR SYSTEMS	TERRESTRIAL	



EXOPLANET EXPLORATION  
Planets Beyond Our Solar System

Strange New Worlds | MAIN MENU

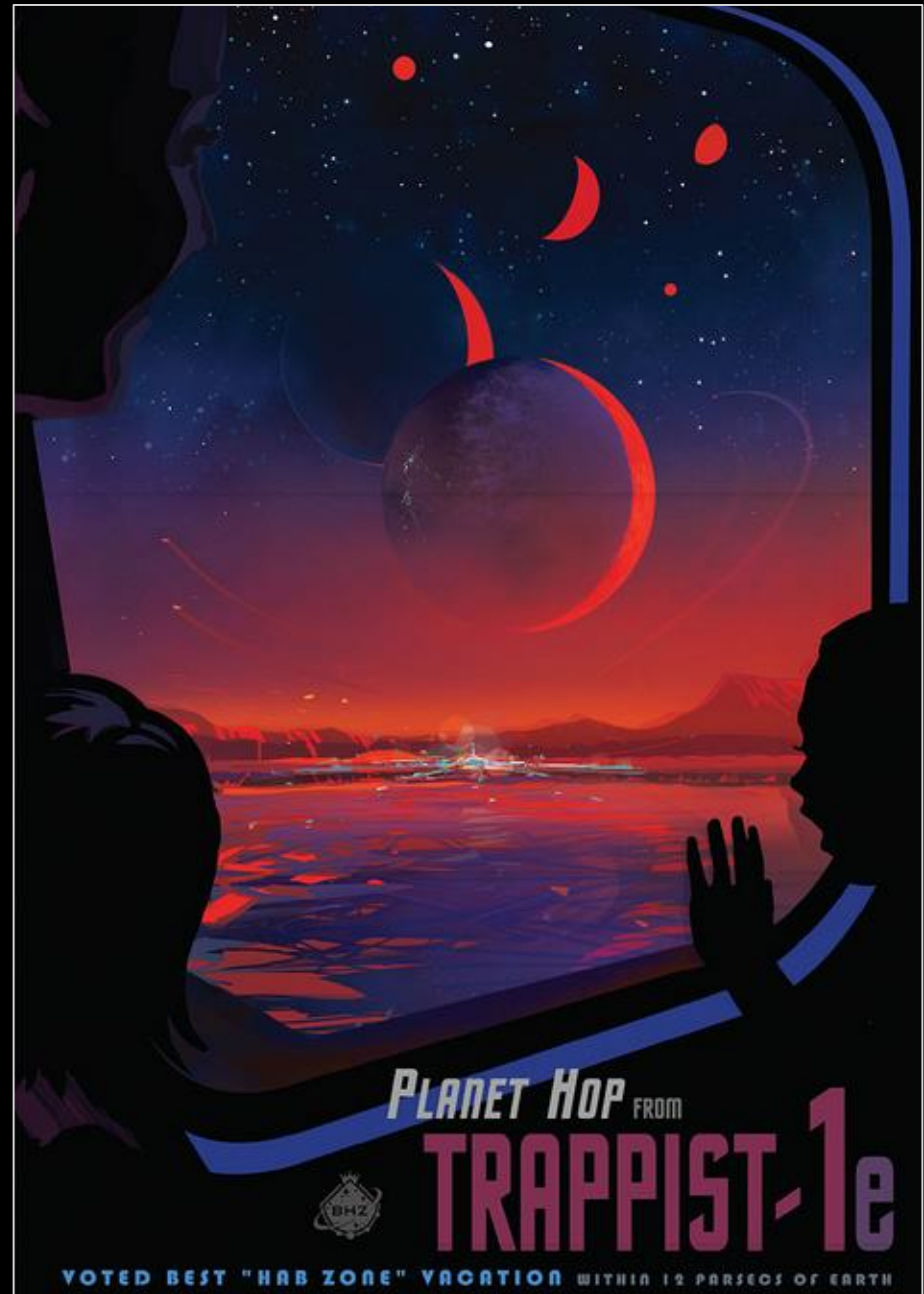
 <p>DISCOVERED SEPTEMBER 2011 <b>TATOOINE</b></p>	 <p>DISCOVERED JANUARY 2006 <b>HOTH</b></p>	 <p>DISCOVERED JULY 2015 <b>CORUSCANT</b></p>
 <p>DISCOVERED FEBRUARY 2012 <b>KAMINO</b></p>	 <p>DISCOVERED OCTOBER 2004 <b>MUSTAFAR</b></p>	 <p>DISCOVERED APRIL 2010 <b>BESPIN</b></p>

Replaced exoplanets.jpl.nasa.gov  
Exoplanet-thematic content featuring  
content across NASA.

3D, interactive planet renderings  
Custom planet textures can be created  
for press releases.  
(contact the Comm team in advance)

# Serving the Community

## *The Exoplanet Travel Bureau*



# The Exoplanet Exploration Program

## Summary

### Delivering upon these Purposes:

- Show Me the Planets!
- You Had Me at Habitable
- Serving the Science Community

Stay connected with us through newsletter and website: [exoplanets.nasa.gov](https://exoplanets.nasa.gov)

### Contacts:

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Chief Engineer

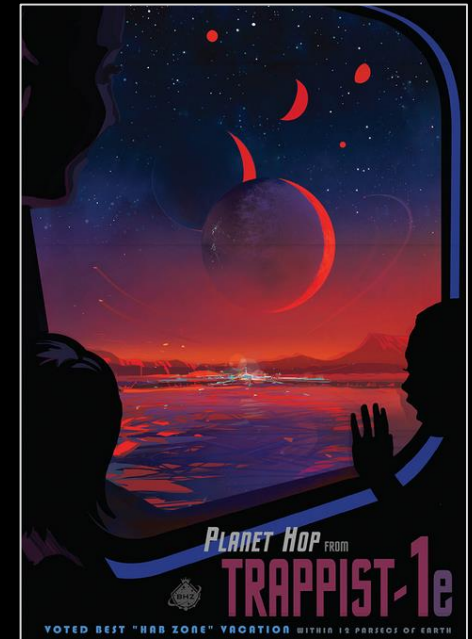
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**Jet Propulsion Laboratory**  
California Institute of Technology

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[jpl.nasa.gov](http://jpl.nasa.gov)



National Aeronautics and  
Space Administration

Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California

# Acknowledgements

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- Work was also carried out at NASA's
  - Goddard Space Flight Center
  - Ames Research Center
- Work was carried out as well under contracts with the National Aeronautics and Space Administration and
  - Princeton University
  - University of Arizona
  - Northrop Grumman Aerospace Systems
  - National Optical Astronomy Observatory (NOAO)
  - Massachusetts Institute of Technology
  - Pennsylvania State University
- Contributions from ExEP program leadership and staff gratefully acknowledged