



**Jet Propulsion Laboratory**  
California Institute of Technology

# NASA Exoplanet Exploration Program Overview and Status

**Dr. Gary H. Blackwood**

Program Manager

Jet Propulsion Laboratory

California Institute of Technology

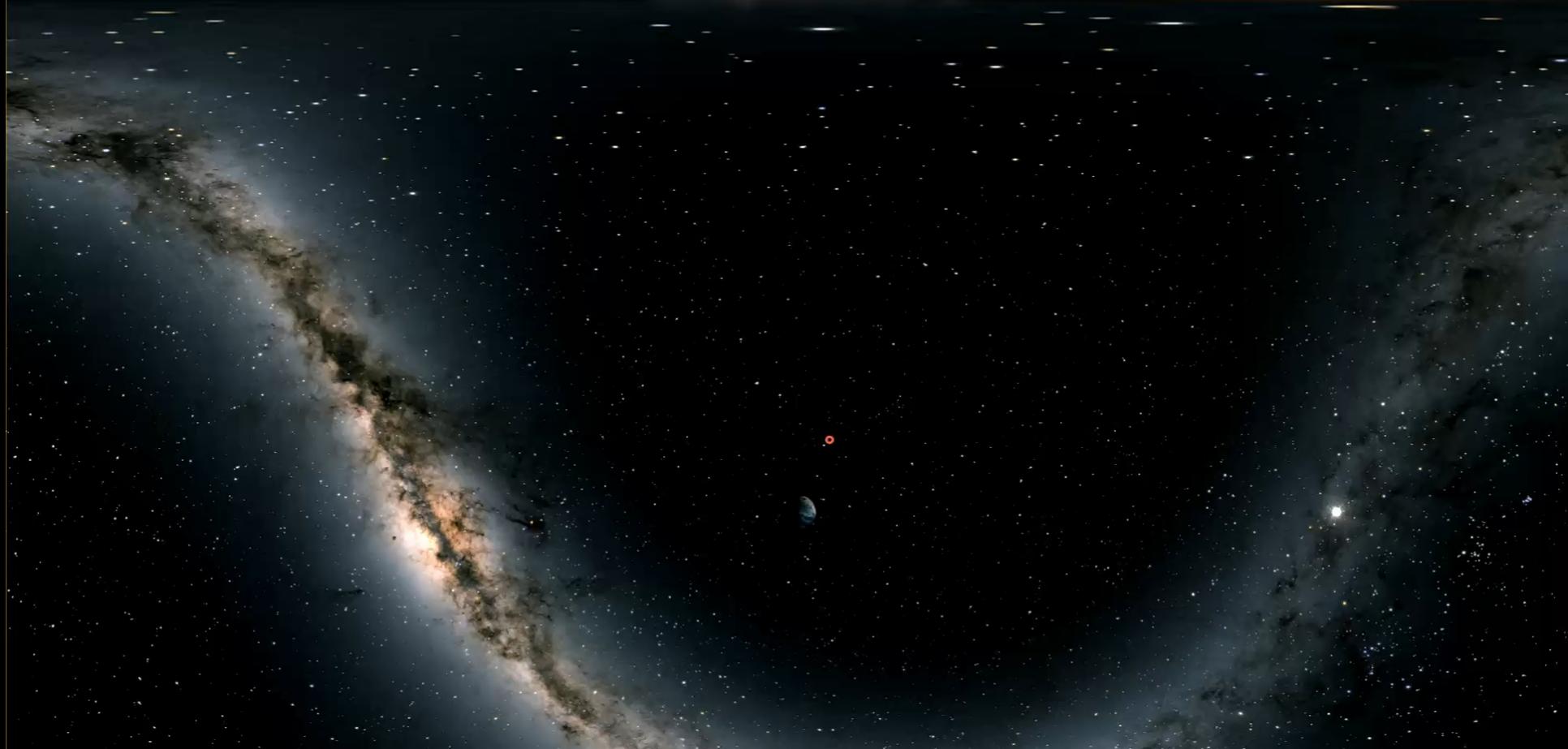
**June 25, 2019**

Astrobiology Science Conference

Bellevue WA

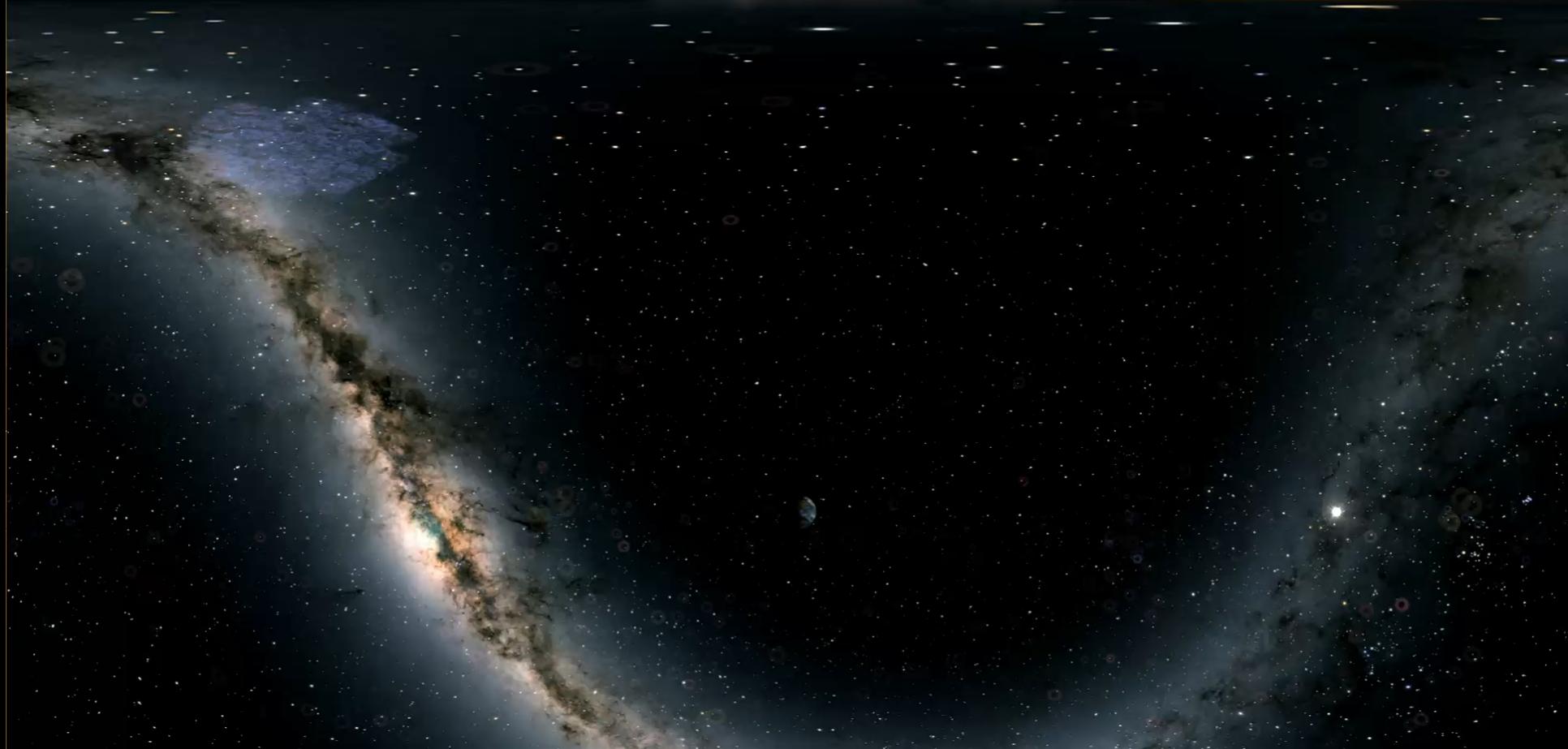


Year: 1995  
Exoplanets: 3



Credit: SYSTEM Sounds (Russo, Santaguida)

Year: 2019  
Exoplanets: 4003



Credit: SYSTEM Sounds (Russo, Santaguida)

# There Are More Planets Than Stars



Program Overview



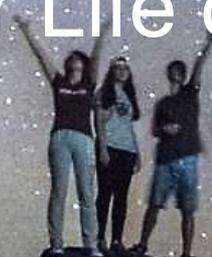
Discover, Characterize



Search for Life on Exoplanets



Engage!





# Program Overview

# 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

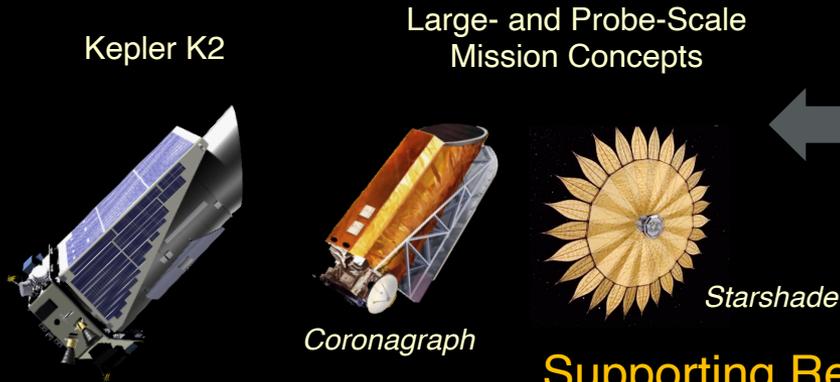
ExEP serves the Science Community and NASA:

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

<https://exoplanets.nasa.gov>

# NASA Exoplanet Exploration Program

## Space Missions and Concept Studies



## Exoplanet Communications

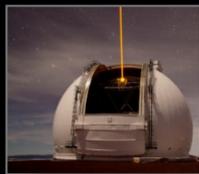


## Supporting Research & Technology

### Key Sustaining Research



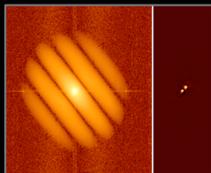
NN-EXPLORE



Keck Observatory



Large Binocular Telescope Interferometer

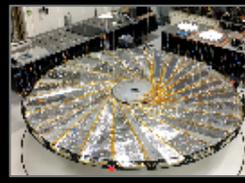
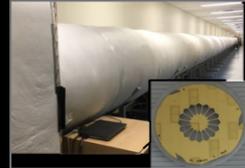


High Resolution Imaging

### Technology Development

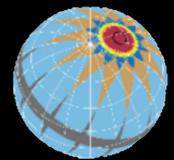
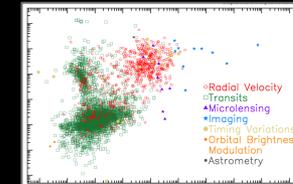


Coronagraph Technology Development



Starshade Technology Development (S5)

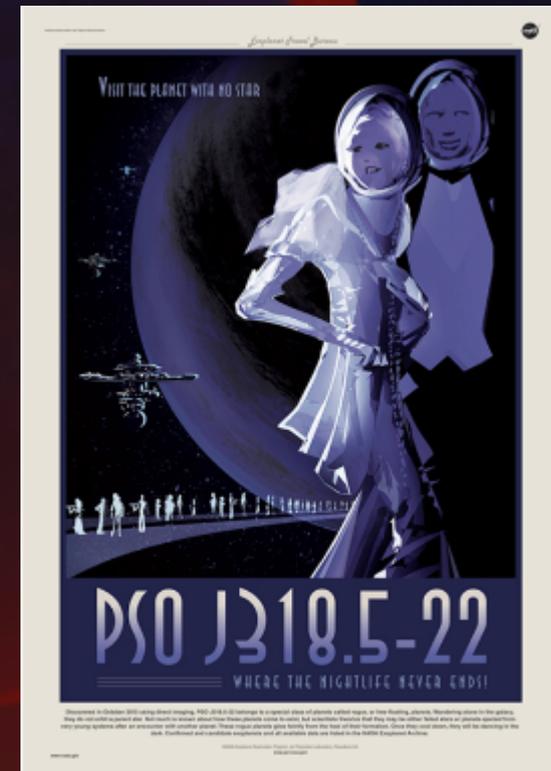
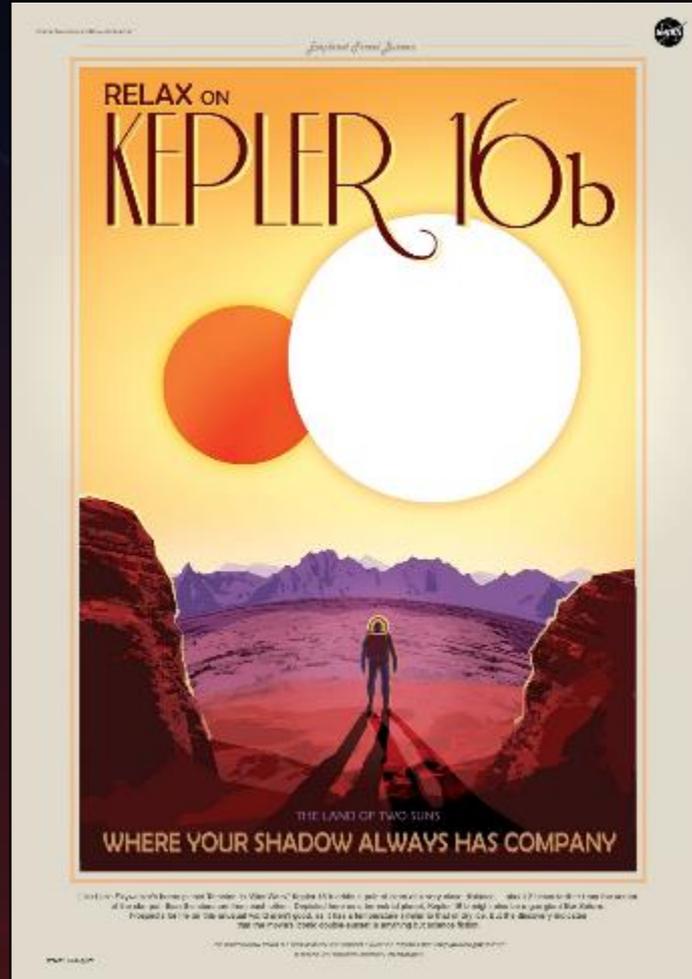
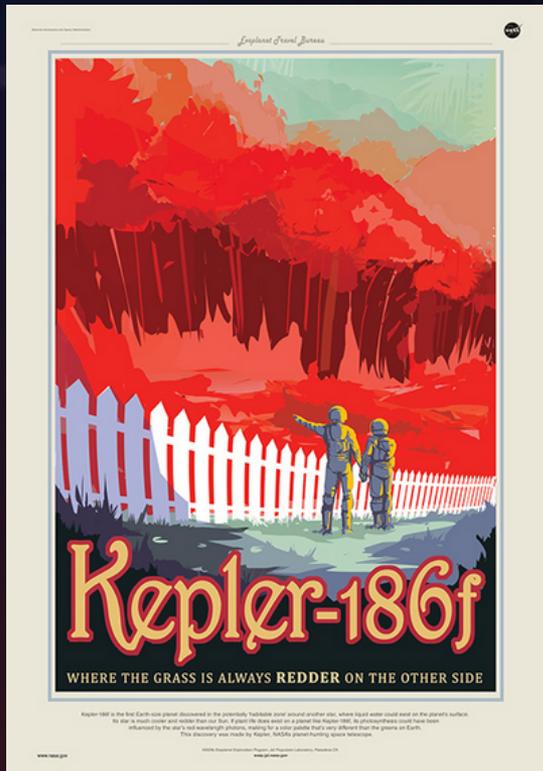
### NASA Exoplanet Science Institute (NExSci)



Archives, Tools, Sagan Program, Professional Engagement

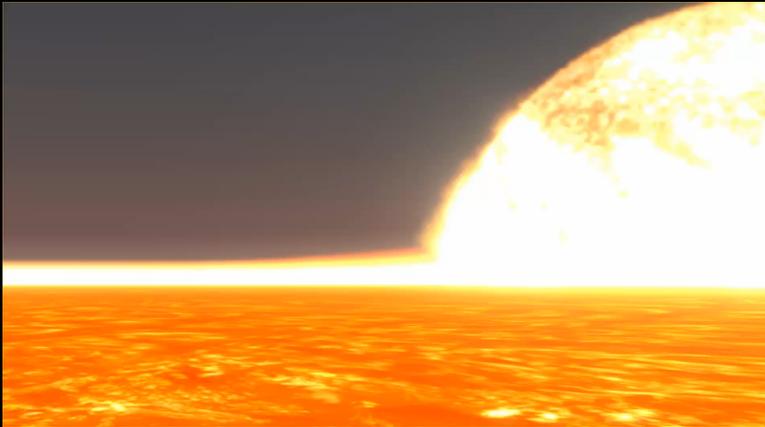
# ExoComm

## Exploring a Galaxy of Worlds While Inspiring our Own



# Exoplanet Travel Bureau

Series of Exoplanet Products



National Aeronautics and Space Administration

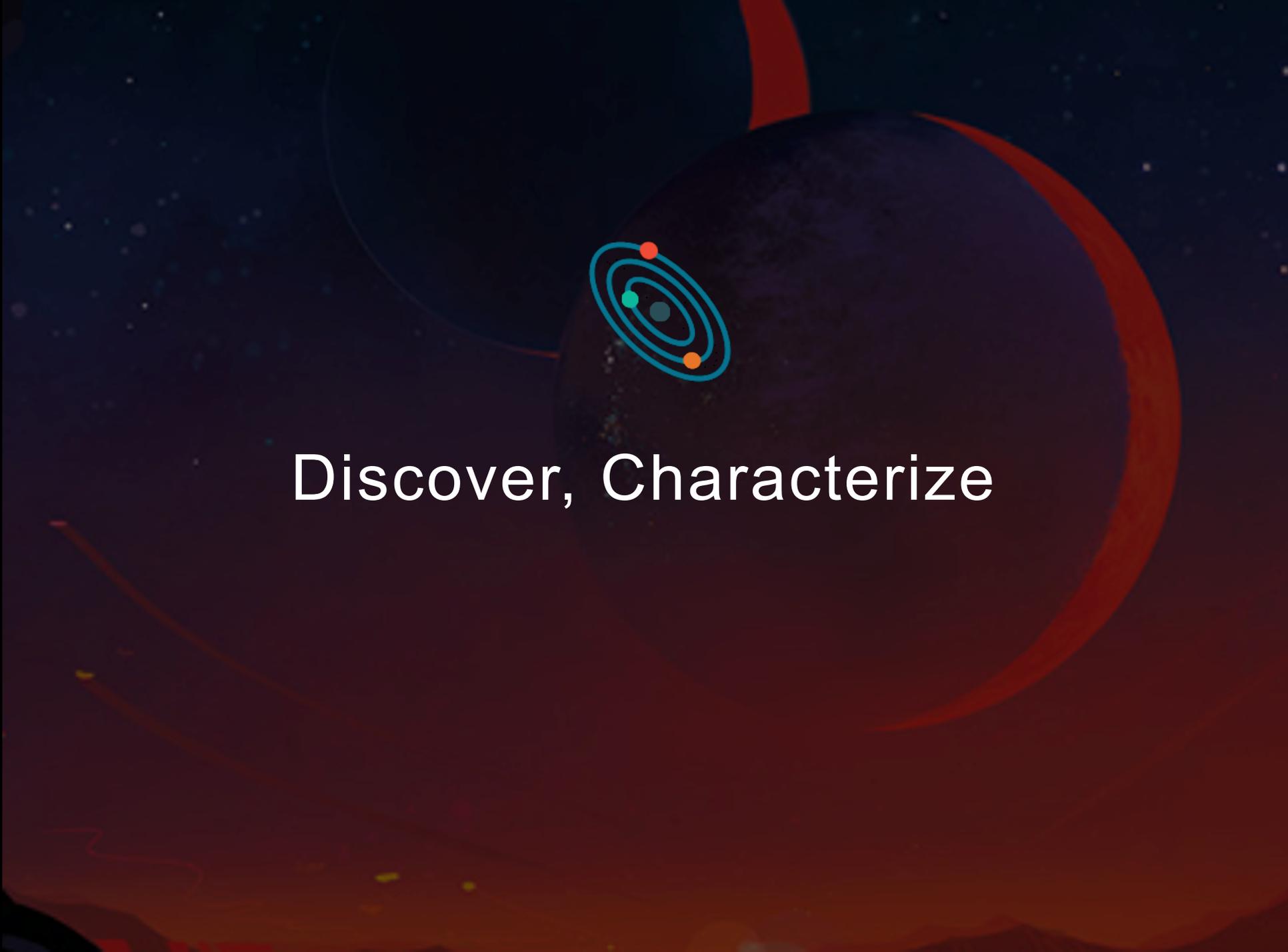
Exoplanet Travel Bureau

55 Cancri e  
lava life

*Skies sparkle above a never-ending ocean of lava*

A global ocean of lava under sparkling, silicate skies reflecting the lava below: what better choice for an extreme vacation? Planet Janssen, or 55 Cancri e, orbits a star called Copernicus only 41 light years away. The molten surface is completely uninhabitable, but you'll ride safely above, taking in breathtaking views: the burning horizon, Janssen's sister planet Galileo hanging in a dark sky, and curtains of glowing particles as you glide across the terminator to Janssen's dark side. Book your travel now to the hottest vacation spot in the galaxy, 55 Cancri e.

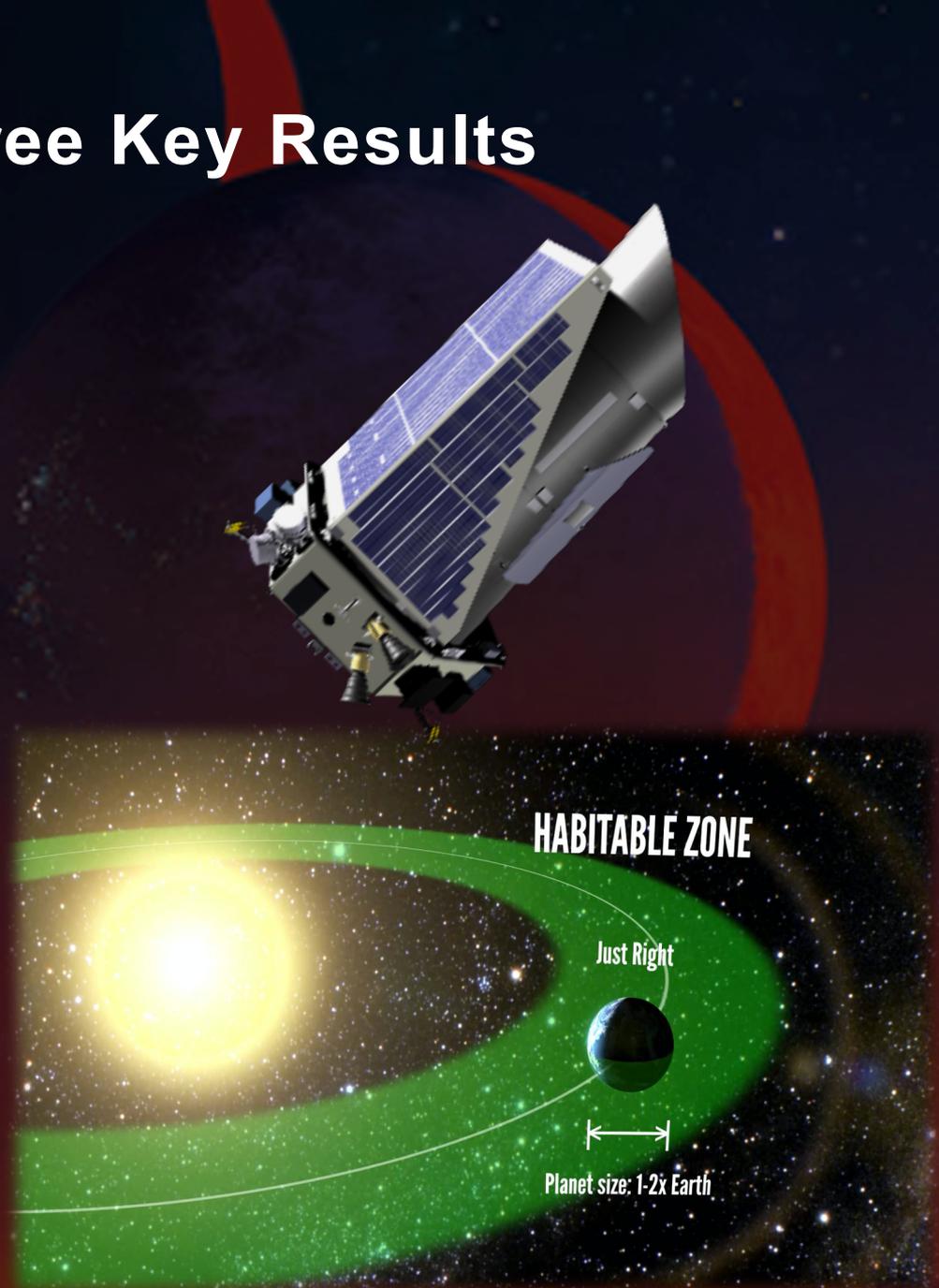
NASA's Exoplanet Exploration Program, Jet Propulsion Laboratory, Pasadena, CA  
www.nasa.gov exoplanets.nasa.gov



Discover, Characterize

# Kepler Mission: Three Key Results

1. There are more planets than stars in the galaxy
2. Small planets are common
3. Small planets in the Habitable Zone are common



# A Familiar Habitable Zone



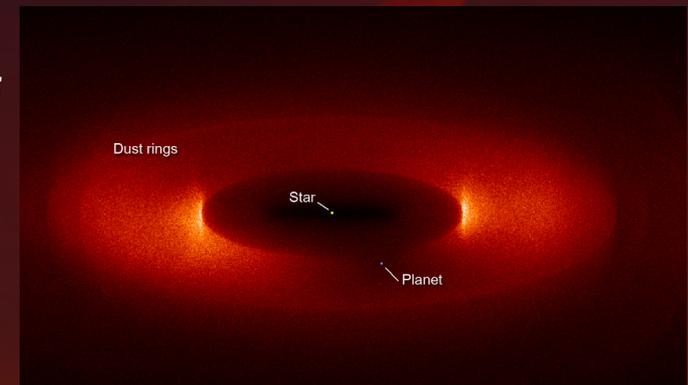
Credit: Luc Forsyth

# Large Binocular Telescope Interferometer

Measuring HZ Exozodiacal Dust to Inform Designs of Future Missions

- 35-stars observed
- NASA survey planned to complete June 2018
- Paper by S. Ertel accepted by ApJ on first 30 stars
- Result: majority of stars in survey are *not dusty*

*Phil Hinz, PI*

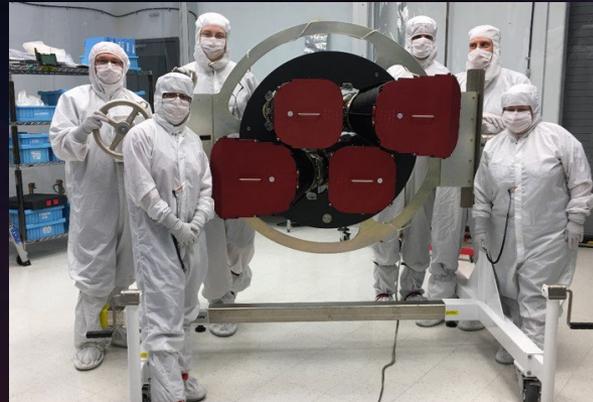


Credit: ESO/Y. Beletsky

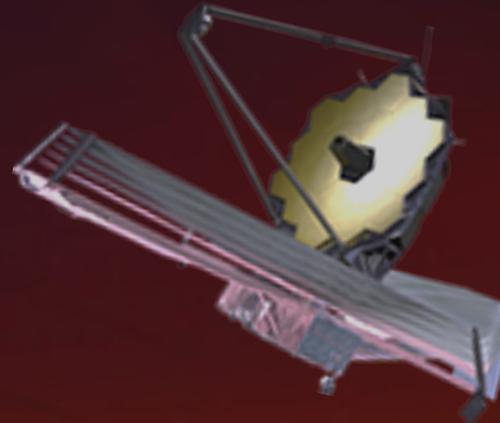
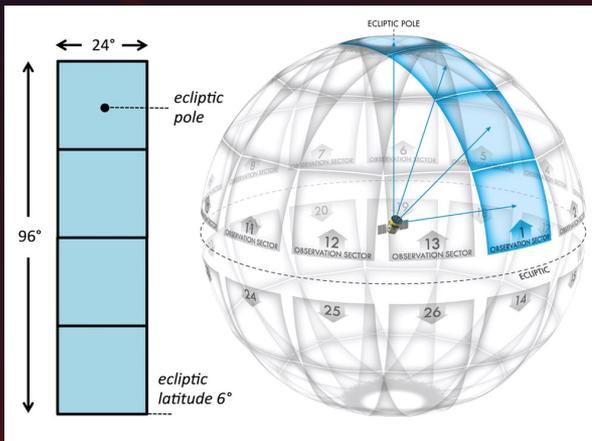
Credit: NASA/GSFC

# Transiting Exoplanet Survey Satellite

Provides targets for JWST transit spectroscopy



- Designed to find transiting planets around nearby stars
- Will survey the entire sky
- Order of magnitude more planets than Kepler



Credit: MIT/G. Ricker

# NASA ExEP Science Gap List (2018)

(grouped by topic, no implied priority in ordering)

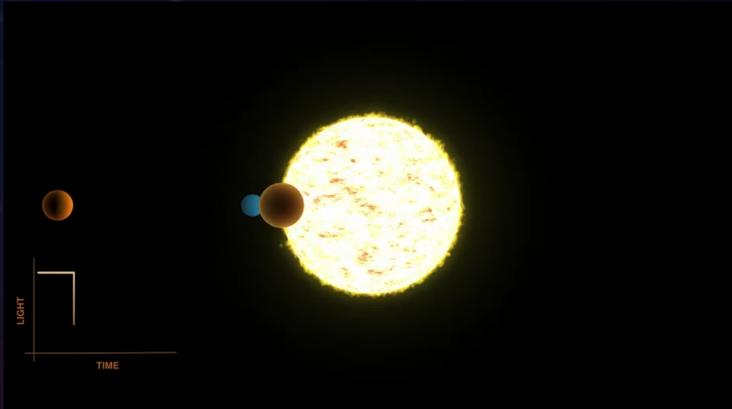
- Spectral characterization of small exoplanets
  - Modeling exoplanet atmospheres
  - Spectral signature retrieval
  - Understand the abundance and substructure of exozodiacal dust
  - Measurement of accurate radii for transiting exoplanets
- Need Planet Mass**
- Planetary system architectures
  - Occurrence 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

ExEP Science Plan Gap List & Appendix:

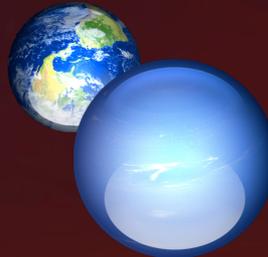
<https://exoplanets.nasa.gov/exep/science-overview/>

Credit: E. Mamajek

# Making the Planets Count!



Transit



Doppler Spectroscopy  
(Radial Velocity)



# NN-EXPLORE

## NASA-NSF Exoplanet Observational Research

- Extreme precision radial velocity spectrometer ( $<0.5$  m/s) at the WIYN Telescope on Kitt Peak
- On track for late 2019 commissioning
- Guest Observer program:
  - Starting 2019B: 90 nights per year





# 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
- Recently additional time purchased on SMARTS 1.5-m (**CHIRON**) and AAT (**VELOCE**) to help w/TESS followup (through NOAO proposal calls)
- Community access to Keck **HIRES** (managed through Keck Cooperative Agreement for NASA time)
- **KPF** on Keck will be available for science mid-2021. Support by NExScI.
- IRTF/**iSHELL** observations (NASA telescope, managed by Planetary Sciences Division; astrophysics limited to 50%)
- EarthFinder probe study – develop case for precision RV from space
- R&A Programs (e.g. XRP)
- Other examples: 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)

# Exoplanet Missions

**NASA Missions**

**Non-NASA Missions**

Hubble<sup>1</sup>

Spitzer

Kepler

TESS

JWST<sup>2</sup>

WFIRST

PLATO

CHEOPS<sup>4</sup>

Gaia

CoRoT<sup>3</sup>

Starshade  
Rendezvous<sup>5</sup>

LUVOIR<sup>5</sup>

HabEx<sup>5</sup>

OST<sup>5</sup>



W. M. Keck Observatory



Large Binocular  
Telescope



WIYN<sup>6</sup>



SMARTS 1.5m<sup>6</sup>

**Ground Telescopes with NASA participation**

<sup>5</sup> 2020 Decadal Survey Studies

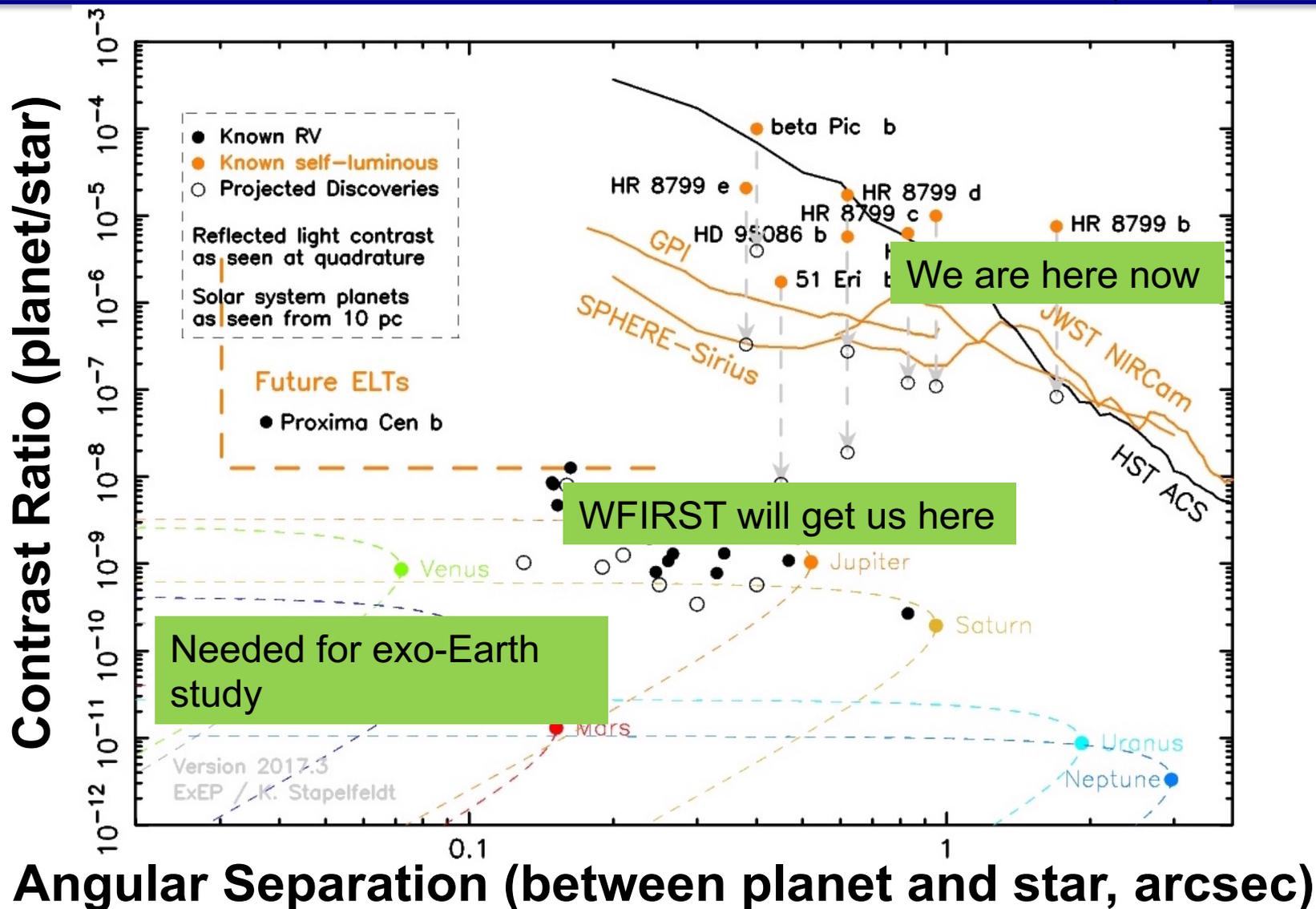
<sup>6</sup> NSF Partnership (NN-EXPLORE)

- <sup>1</sup> NASA/ESA Partnership
- <sup>2</sup> NASA/ESA/CSA Partnership
- <sup>3</sup> CNES/ESA
- <sup>4</sup> ESA/Swiss Space Office



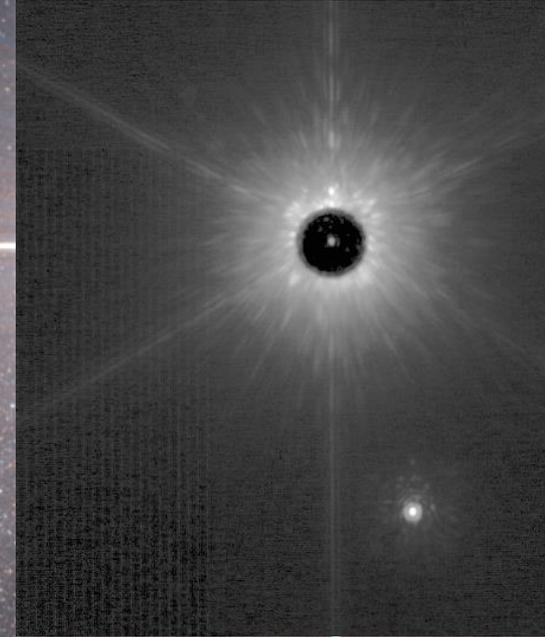
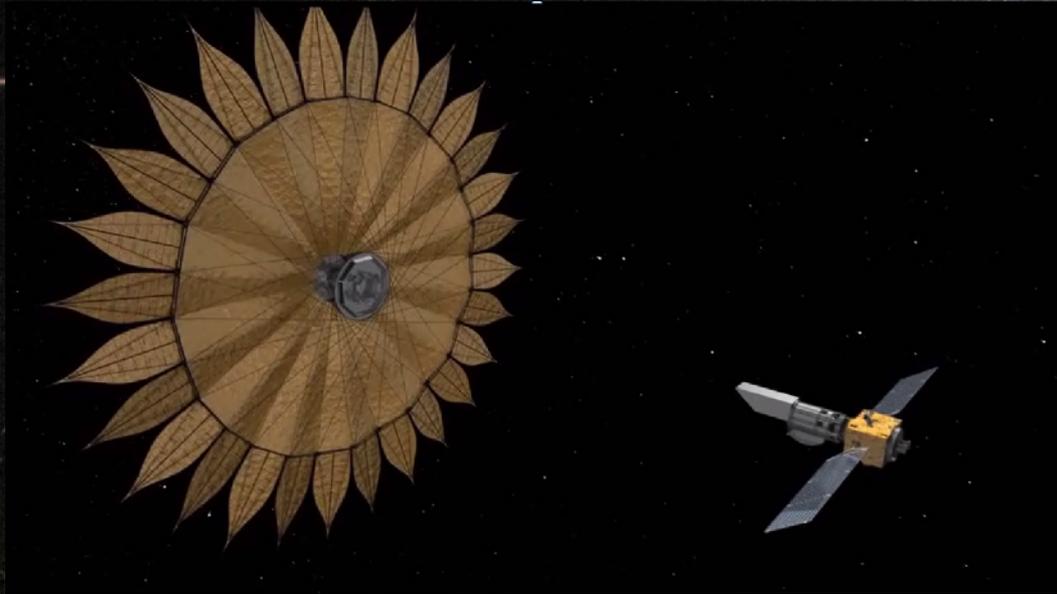
# The Search for Life on Exoplanets

# Still a Way to go to Imaging Exo-Earths

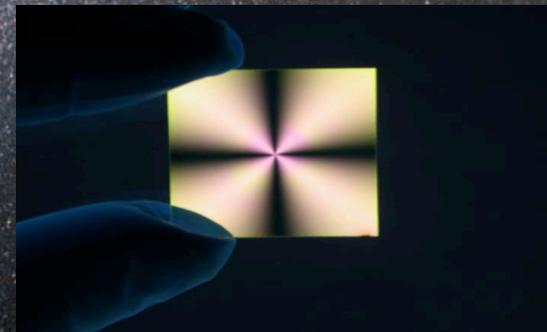


# Starlight Suppression

External Occulters  
(Starshades)



Internal Occulters  
(Coronagraphs)

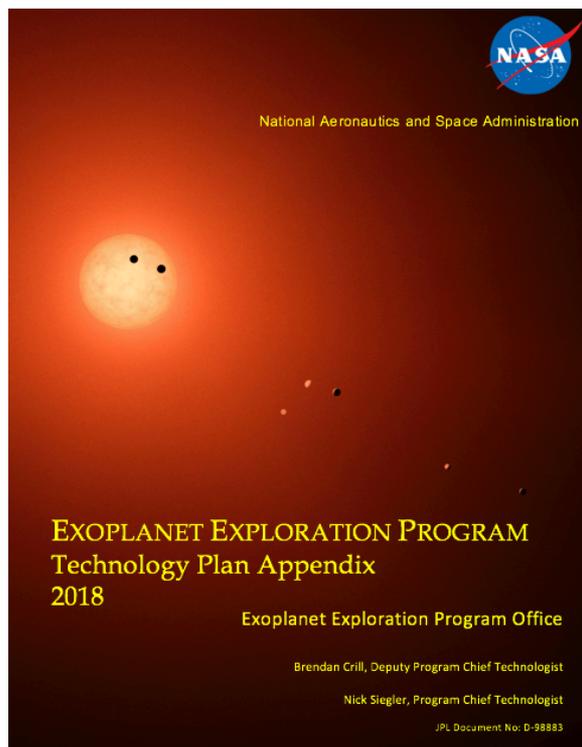


# ExEP Technology List



Exoplanet Exploration Program

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 ( $\geq 10 \mu\text{m}$ ); 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

# ExEP's Decadal Survey Testbed



Exoplanet Exploration Program



Credit: N. Siegler

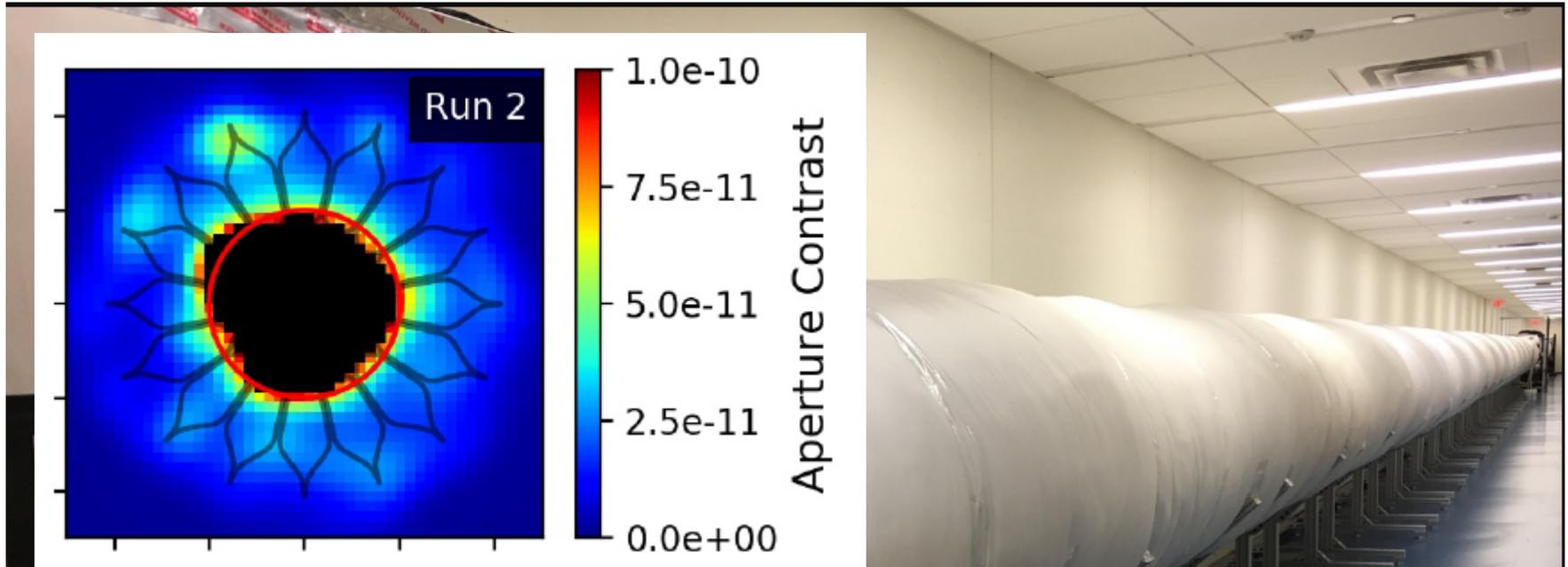
The DST established a new record  $3.8 \times 10^{-10}$  contrast using a classic Lyot coronagraph mask: 550 nm, 10% bandpass, 3-8  $\lambda/D$

# Starshade Technology Development

Starlight Suppression and Model Validation



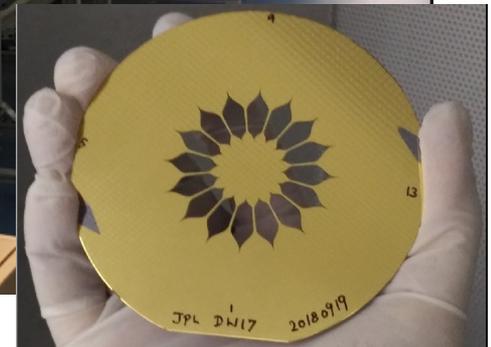
Exoplanet Exploration Program



Met  $< 10^{-10}$  contrast goal at the inner working angle,  
640-725 nm

Frick Testbed, Princeton University

Lead: Anthony Harness



Credit: N. Siegler

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

1 cm/s ?

Calibration Challenges

Detectors

10 cm/s

Telluric Contamination

Observational Strategies

30 cm/s

Stellar Oscillations and Granulation

RV Pipelines

Computation and Statistical Methods

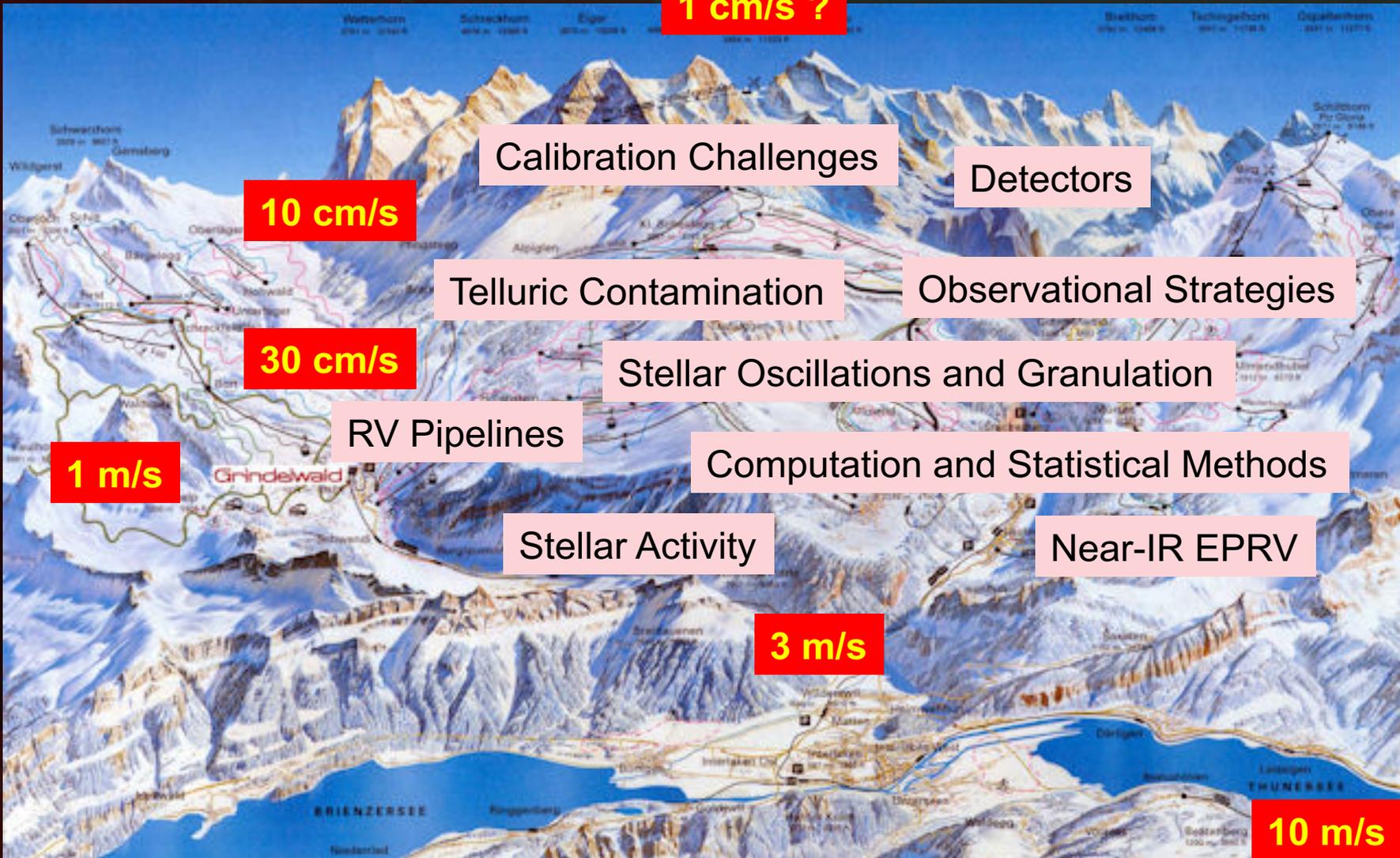
1 m/s

Stellar Activity

Near-IR EPRV

3 m/s

10 m/s



Credit: <http://www.swisswintersports.co.uk>

# From P. Hertz' CAA Presentation, March 2019

## Exoplanet Science Strategy Extreme Precision Radial Velocity Initiative

Exoplanet Science Strategy Recommendation:

“NASA and NSF should establish a strategic initiative in extremely precise radial velocities (EPRVs) to develop methods and facilities for measuring the masses of temperate terrestrial planets orbiting Sun-like stars”

- Combine efforts in instrumentation, survey execution, and data analysis techniques involving stellar astrophysics and heliophysics
- Undertake the coordinated, sustained effort to tackle the myriad of error terms that currently limit RV precision.
- Assess ultimate goal to control systematics at  $\sim 1$  cm/s, accounting for stellar variability and tellurics

Response: NASA and NSF are jointly commissioning a community-based “Extreme Precision Radial Velocity (EPRV) Working Group” (EPRV-WG) to develop a blueprint for a strategic EPRV initiative.

- Working Group forming now, first in-person workshop  $\sim$ June 2019
- EPRV-WG to submit a candidate program architecture by Feb 2020 for consideration by Agencies during annual budget formulation process



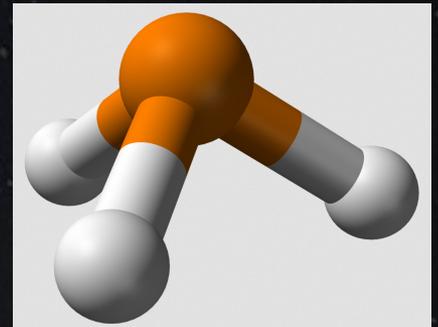
**Engage!**

# For Astrobiology Community:

## Ways to Engage NASA Exoplanet Program and Community

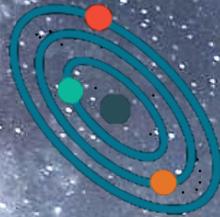
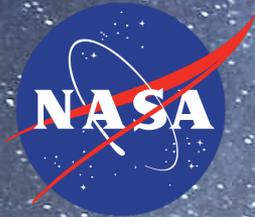
- Be relevant to Agency goals: reference science and technology gap lists during proposals
- Participate in EPRV Initiative – interdisciplinary
- Engage through NExSci: archive, Sagan summer workshops
- Attend ExoPAG – student travel support
  - <https://exoplanets.nasa.gov/exep/exopag/>
- Show us what to measure, what technologies we need to develop

Credit: Clara Sousa-Silva  
Curious Case of Phospine



"All these worlds are yours"

- Arthur C. Clarke





**Jet Propulsion Laboratory**  
California Institute of Technology

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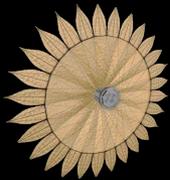
[jpl.nasa.gov](http://jpl.nasa.gov)

# Acknowledgements

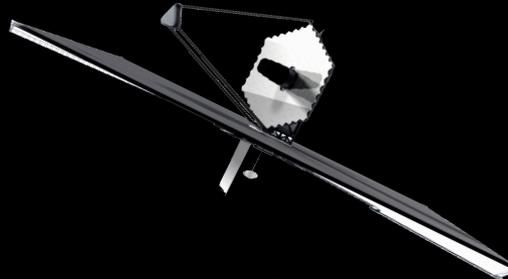
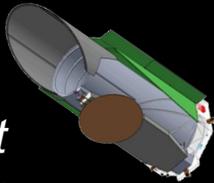
This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration. © 2019 All rights reserved.

# Exoplanet Mission Concepts

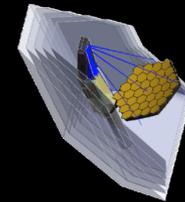
## Large Scale



*Habitable  
Exoplanet  
Observatory*



*LUVOIR*

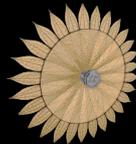


*Origins Space  
Telescope*

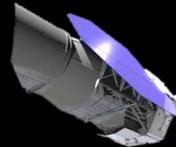
## Medium Scale Concepts



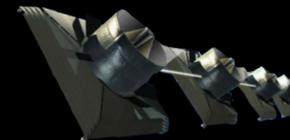
*EarthFinder*



*Starshade  
Rendezvous*



## Visionary



*Life-Finder  
Interferometer*