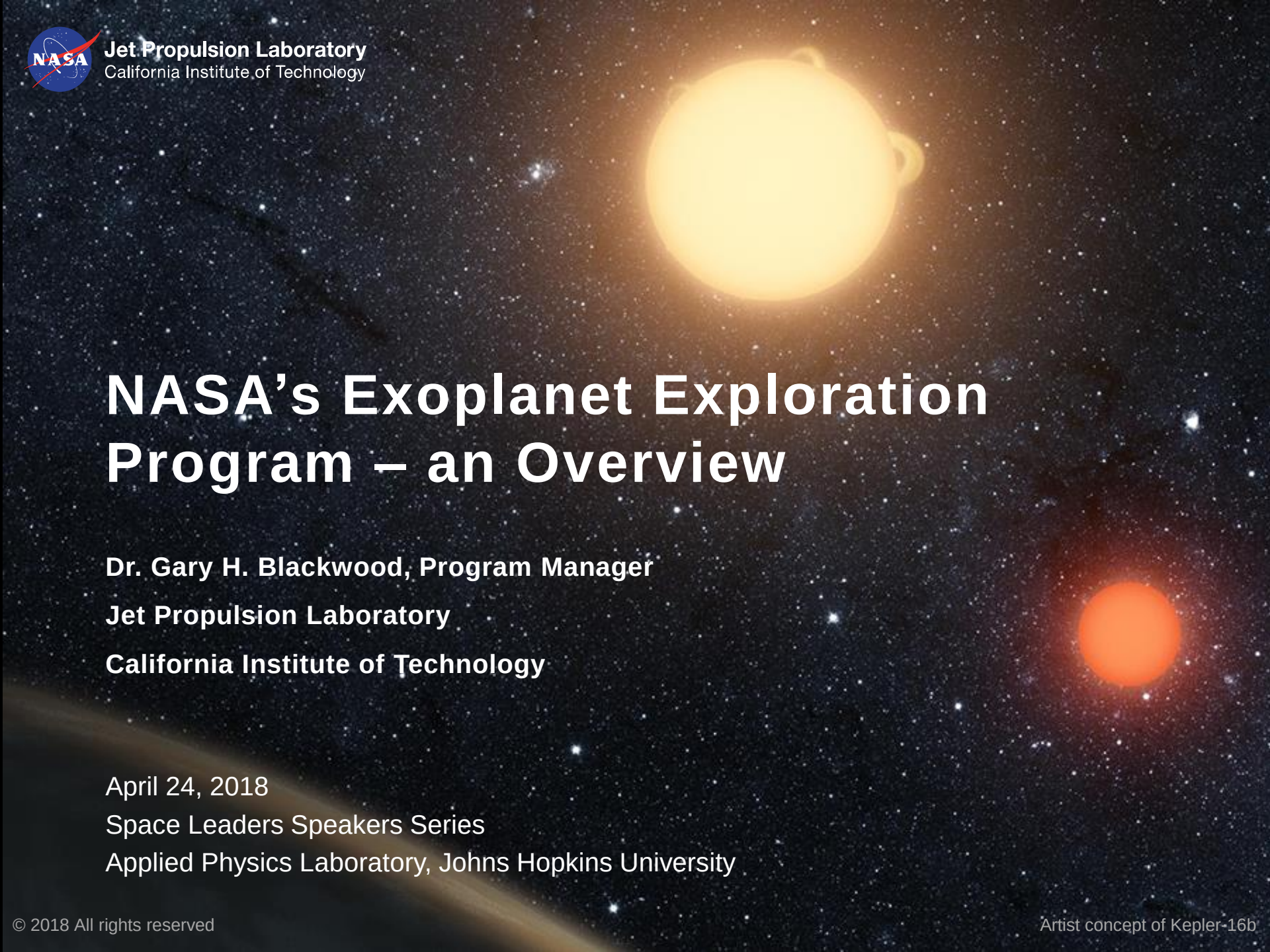


Jet Propulsion Laboratory
California Institute of Technology

NASA's Exoplanet Exploration Program – an Overview

Dr. Gary H. Blackwood, Program Manager

Jet Propulsion Laboratory

California Institute of Technology

April 24, 2018
Space Leaders Speakers Series
Applied Physics Laboratory, Johns Hopkins University

Artist concept of Kepler-16b

Program Overview

Current Investments and Results

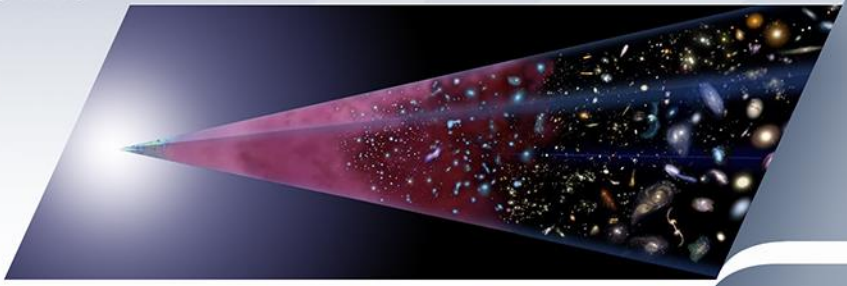
Communicating Exoplanets

Exoplanet Forward Strategy

Why Astrophysics?

Astrophysics is humankind's scientific endeavor to understand the universe and our place in it.

How did our universe begin and evolve?

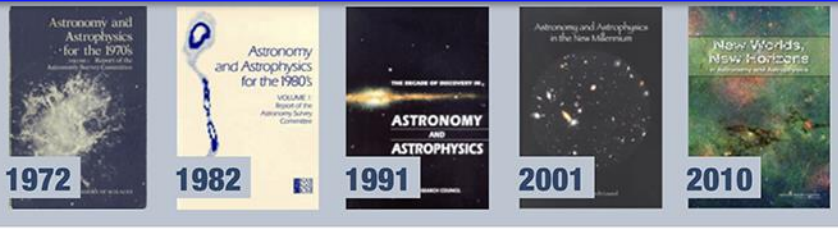


How did galaxies, stars, and planets come to be?

Are we alone?

ExEP

Enduring National Strategic Drivers




Transiting Exoplanet Survey Satellite
April 18, 2018

NASA Exoplanet Exploration Program

Astrophysics Division, NASA Science Mission Directorate

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

Program purpose described in 2014 NASA Science Plan

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

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

https://exoplanets.nasa.gov

Exoplanet Missions

WFIRST

JWST[2]

ARIEL

TESS

PLATO

LUVOIR[5]

Kepler

CHEOPS[4]

Spitzer

Gaia

Hubble[1]

Starshade Rendezvous[5]

HabEx[5]

CoRoT[3]

OST[5]

NASA Missions

Non-NASA Missions

W. M. Keck Observatory

Large Binocular Telescope Interferometer

NN-EXPLORE

Ground Telescopes with NASA participation

[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA
[4] ESA/Swiss Space Office

[5] 2020 Decadal Survey Studies

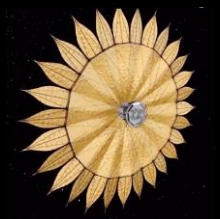
NASA Exoplanet Exploration Program

Space Missions and Mission Studies

Kepler & K2

Probe-Scale Studies

Starshade



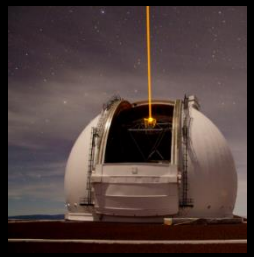
Coronagraph

Communications

Supporting Research & Technology

Key Sustaining Research

NN-EXPLORE



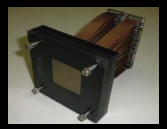
Keck Single Aperture Imaging & RV

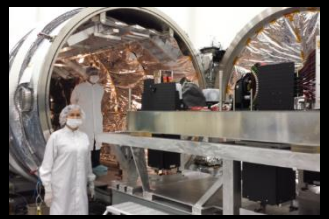
Large Binocular Telescope Interferometer

Technology Development

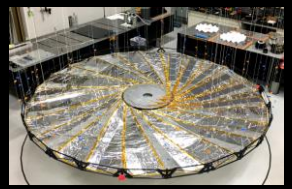
Occulting Masks

Deformable Mirrors



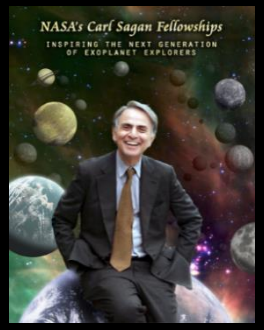


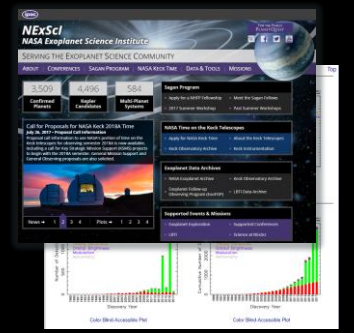
High-Contrast Imaging



Deployable Starshades

NASA Exoplanet Science Institute

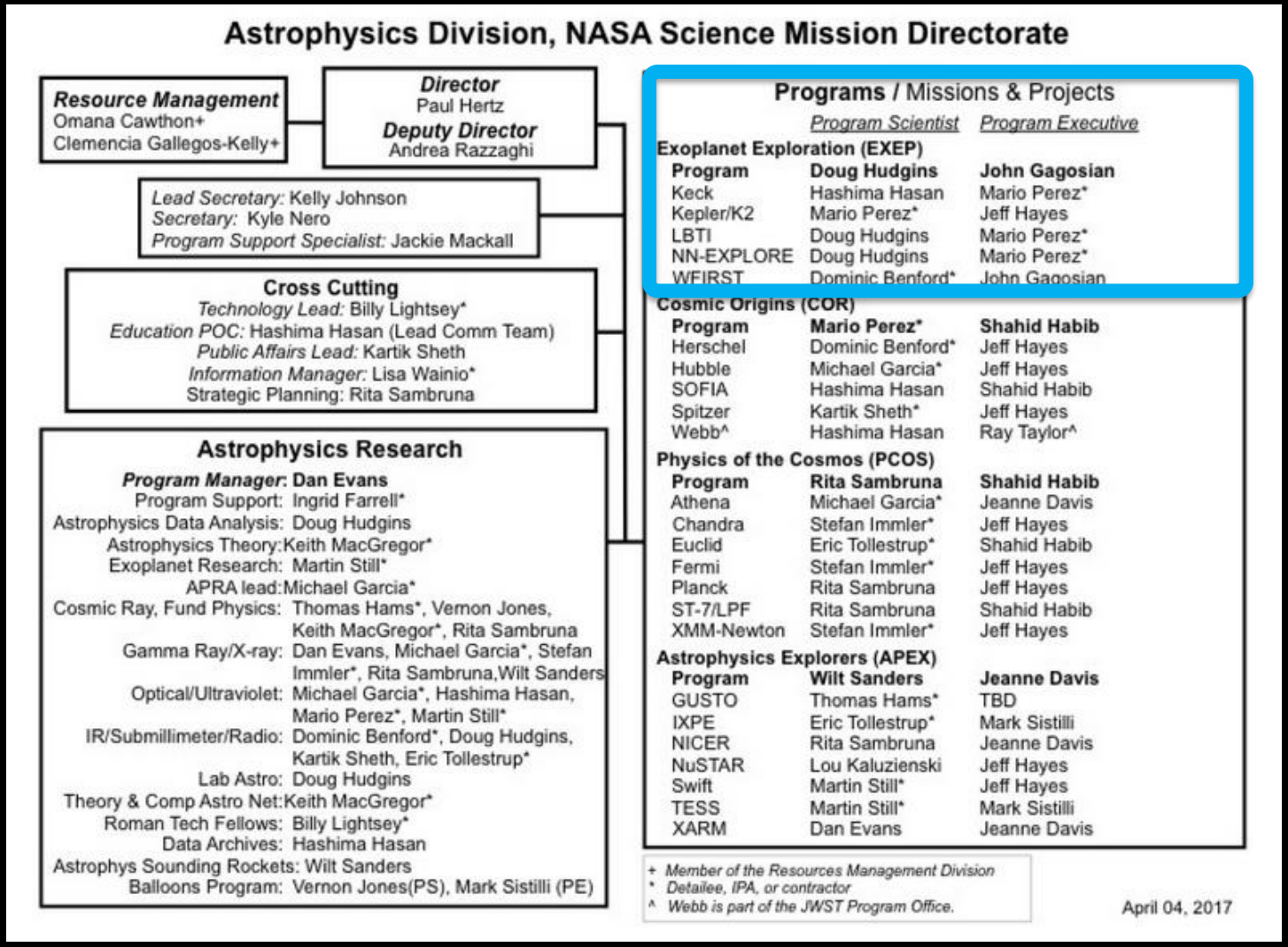




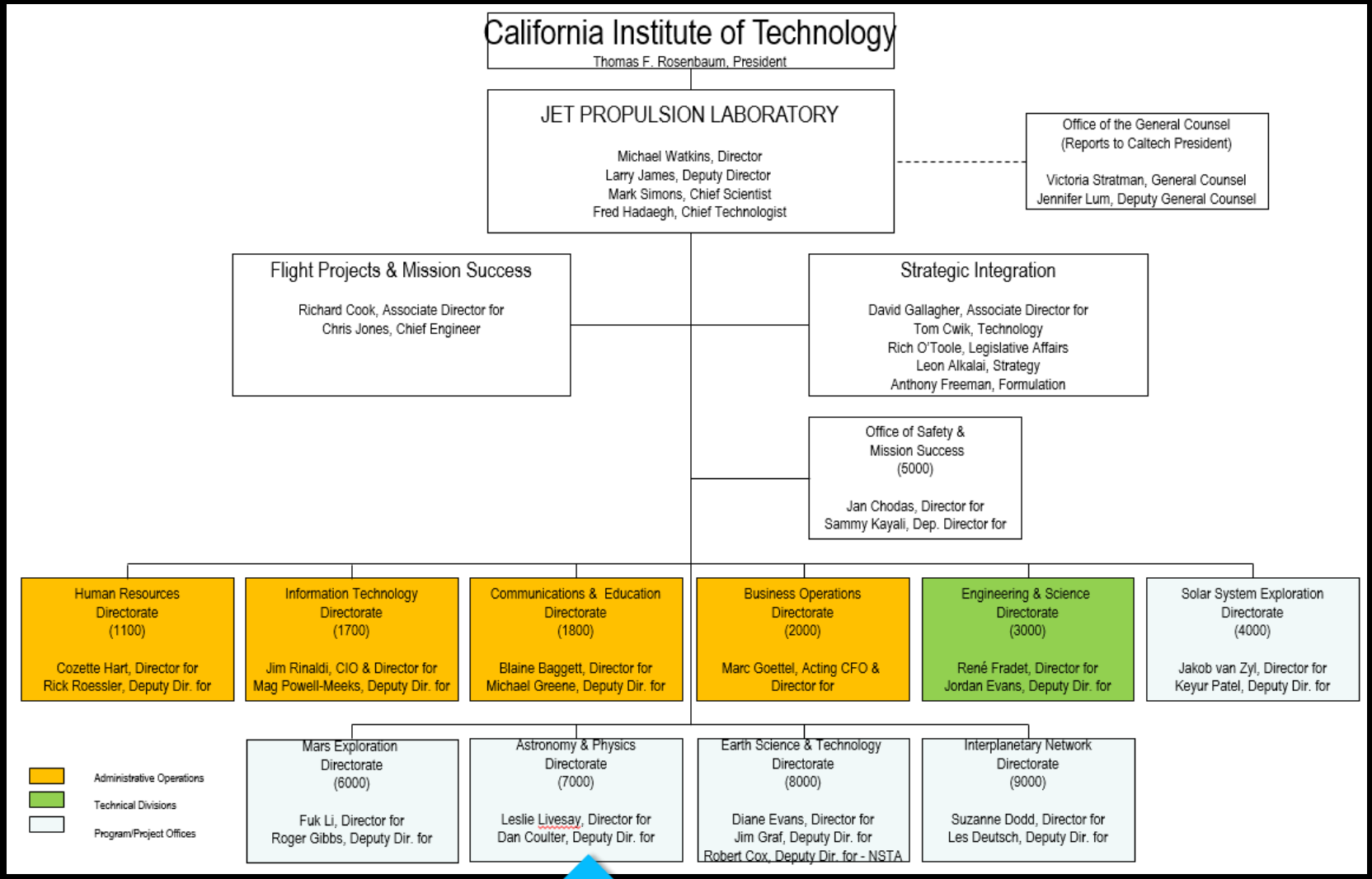
Archives, Tools, Sagan Fellowships, Professional Engagement

https://exoplanets.nasa.gov

ExEP is a Program within the Astrophysics Division, Science Mission Directorate



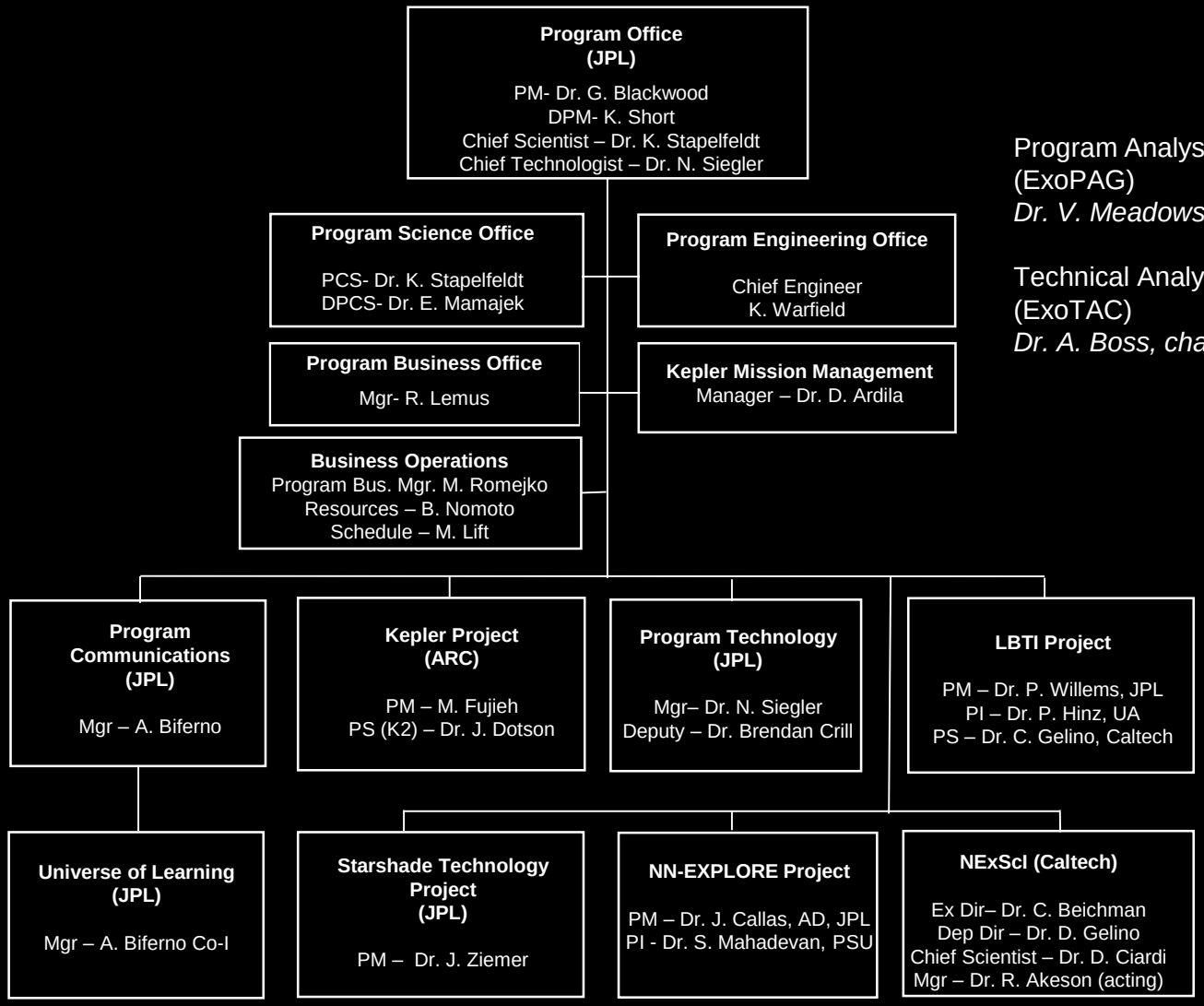
JPL Directorate 700 Manages ExEP for APD



ExEP (Office 730) within Astronomy and Physics Directorate

NASA Exoplanet Exploration Program

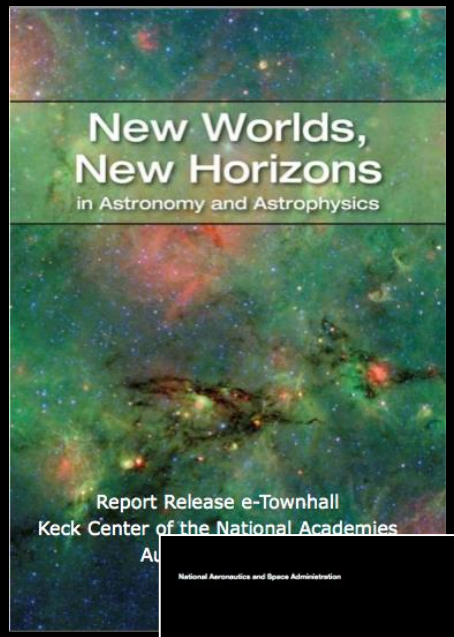
Astrophysics Division, Science Mission Directorate



Program Analysis Group (ExoPAG)
Dr. V. Meadows, EC chair

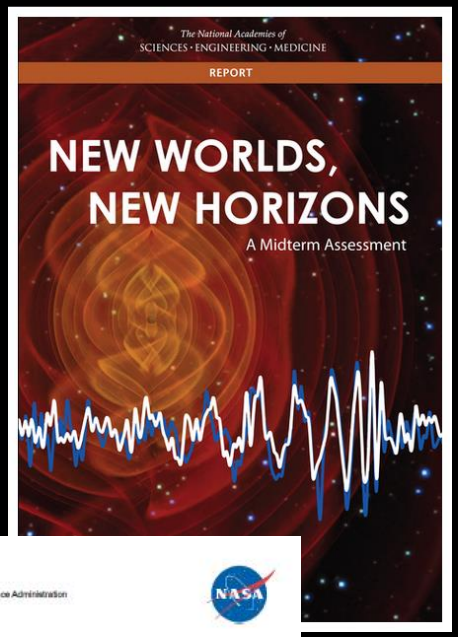
Technical Analysis Committee (ExoTAC)
Dr. A. Boss, chair

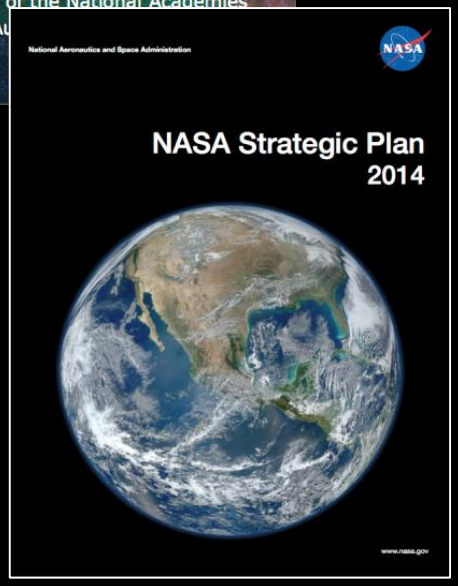
ExEP Implements per NASA Driving Documents

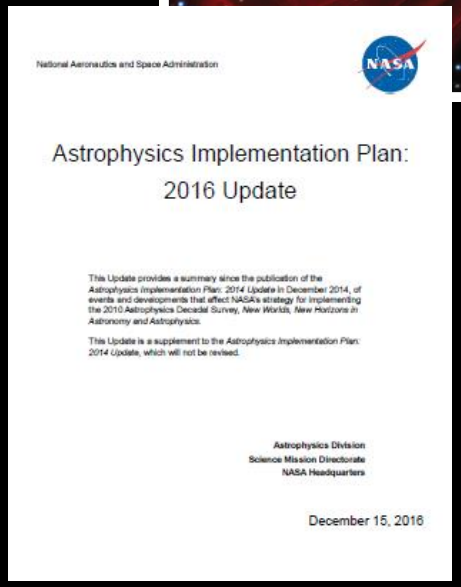


Results of NWNH:

- WFIRST is top large-scale recommended activity
- New Worlds Technology Development Program is top medium-scale recommended activity



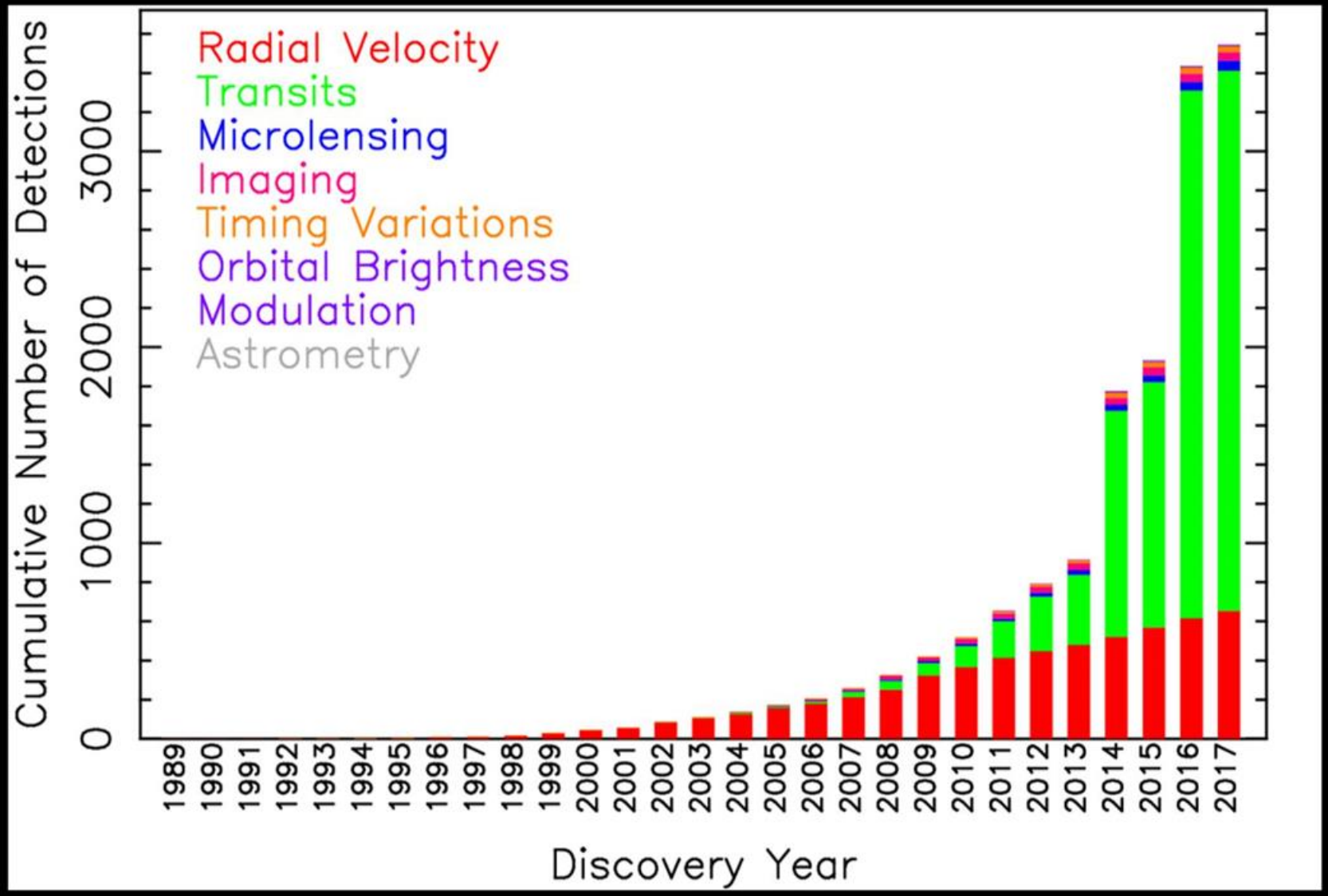




http://science.nasa.gov/astrophysics/documents

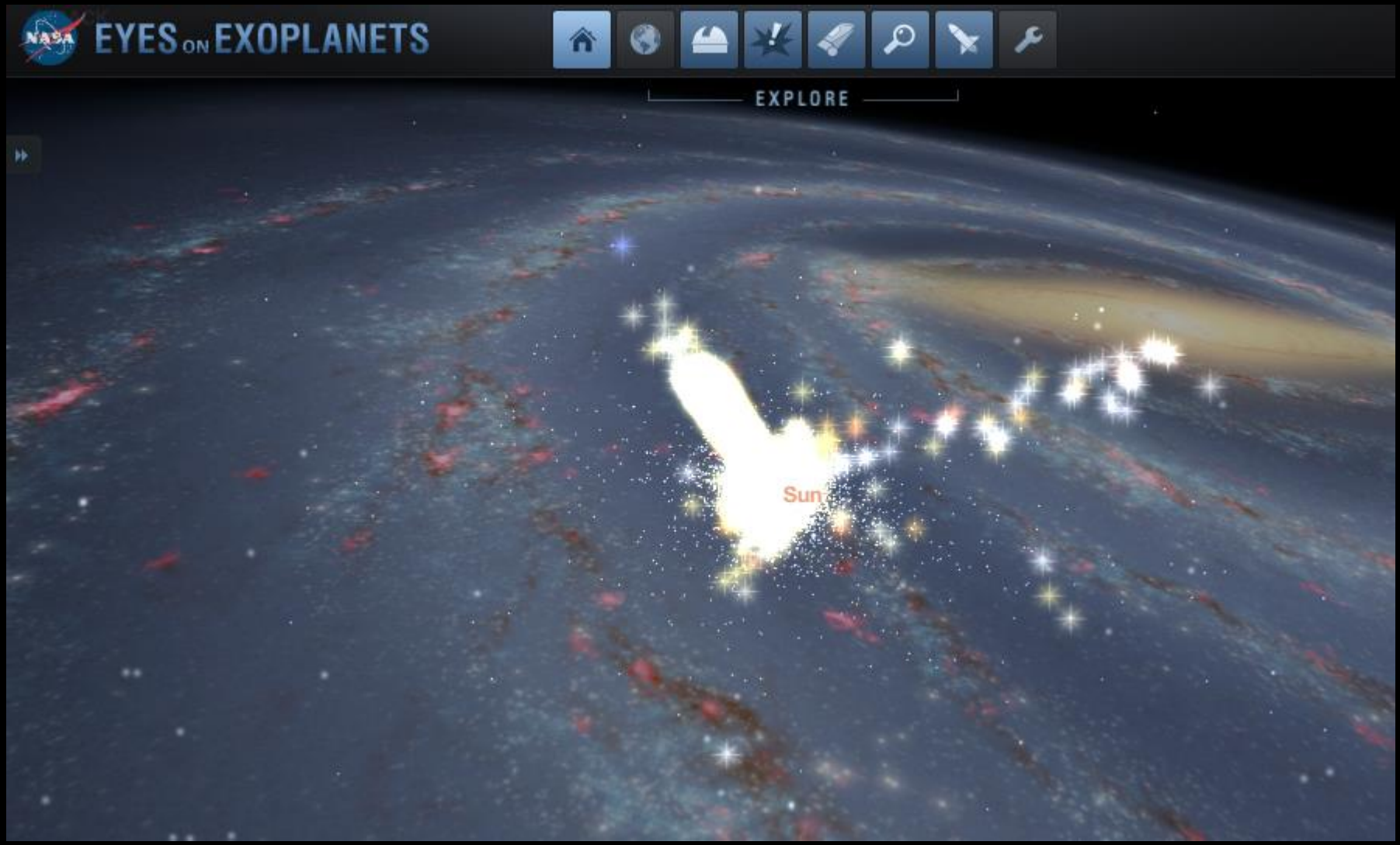
Thousands of Exoplanets

Number doubles every ~26 months. "Mamajek's Law"



Where are the Exoplanets?

Visualization from *Eyes on Exoplanets*

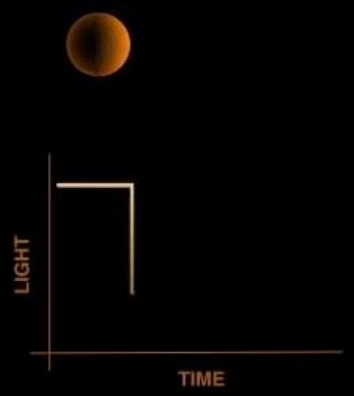


How Do We Find Exoplanets?

Doppler Spectroscopy or Radial Velocity Method

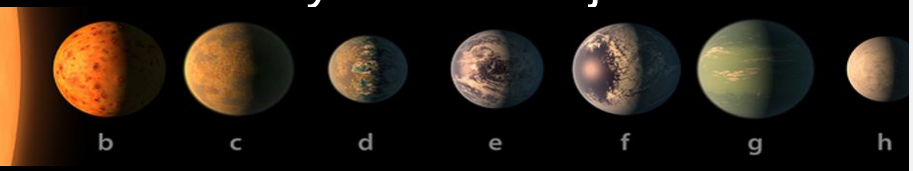
How Do We Find Exoplanets?

Transit Method

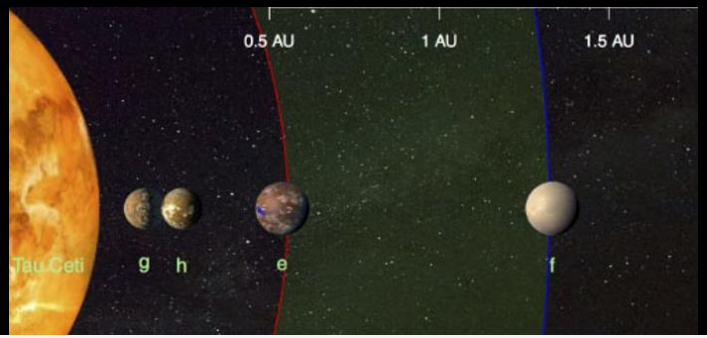


Exoplanet Science News

Courtesy: E. Mamajek

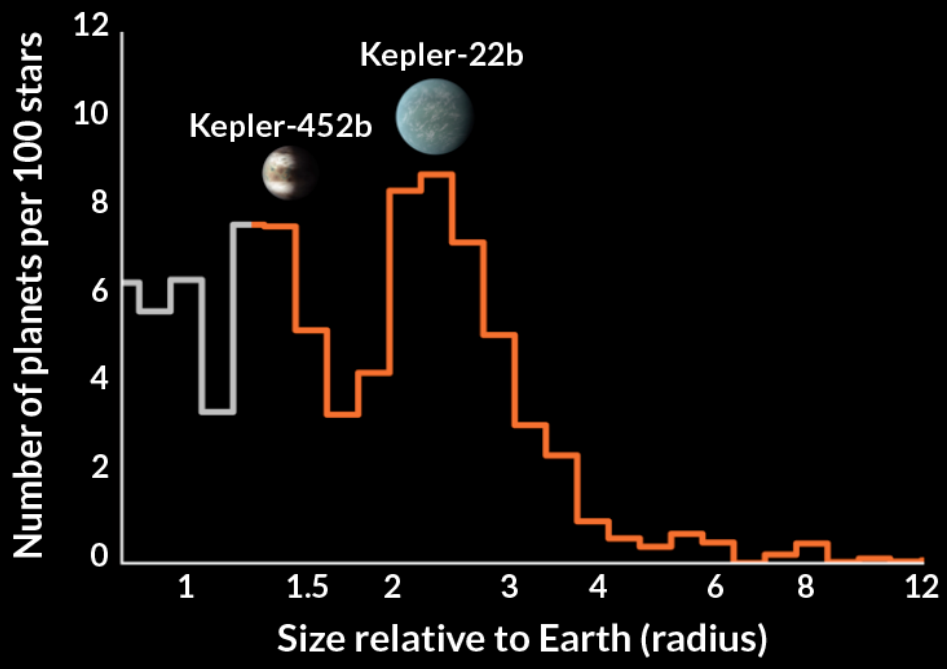


- Gillon et al. (2017, Nature) reported discovery w/Spitzer that the nearby ultra cool dwarf TRAPPIST-1 has 7 transiting Earth-sized exoplanets.



- Feng et al. 2017 found evidence for four planets in new HARPS data of the nearby star τ Ceti.

- Fulton et al. (2017) reported strong evidence for gap between "super-Earth" and "sub-Neptune" exoplanets using Kepler data + spectroscopic data for stars from Keck.



Program Overview

Current Investments and Results

Communicating Exoplanets

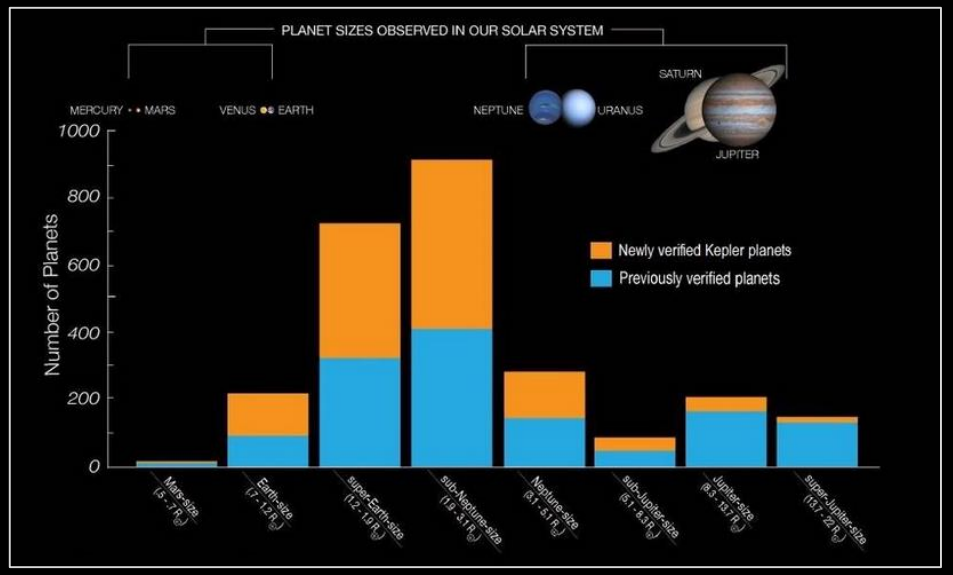
Exoplanet Forward Strategy

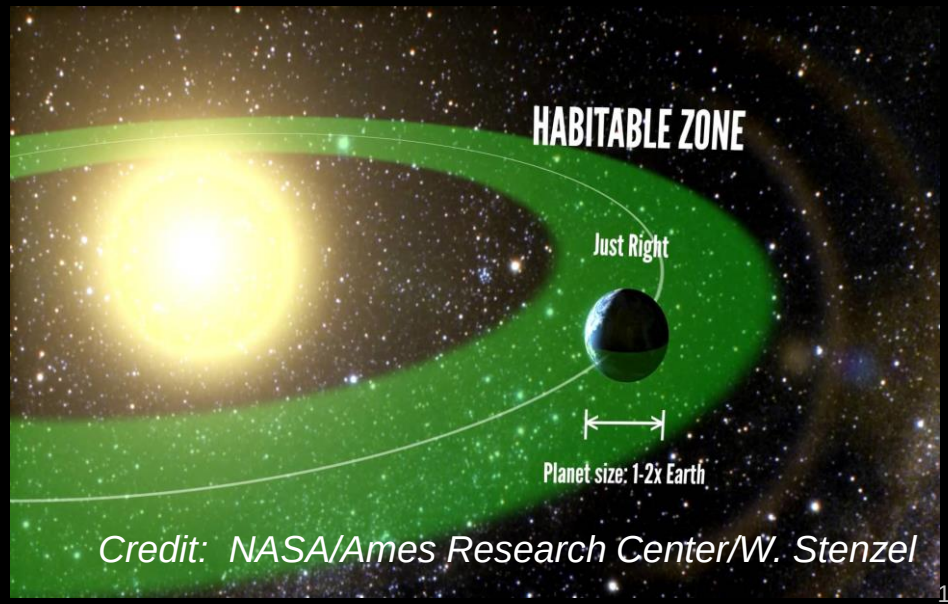
Three Key Kepler Results

1. On average there is at least one planet for each of the stars in the night sky

2. Small planets are the most common type in the Galaxy

3. Earth-sized (0.5 to 2 Earth radii) planets in the Habitable Zone are common



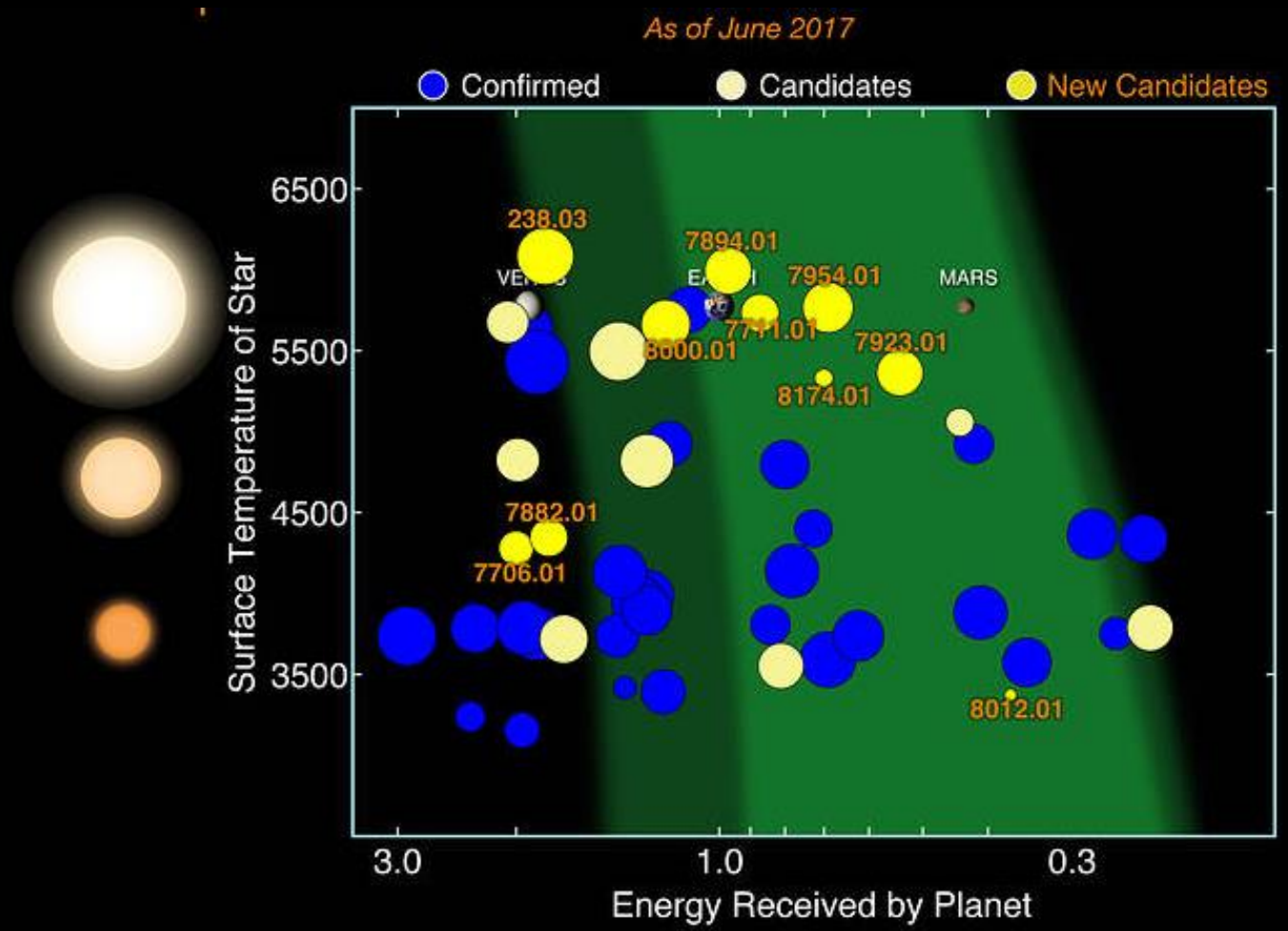


Credit: NASA/Ames Research Center/W. Stenzel

A Familiar Habitable Zone

Credit: Luc Forsyth

Kepler Habitable Zone Planets



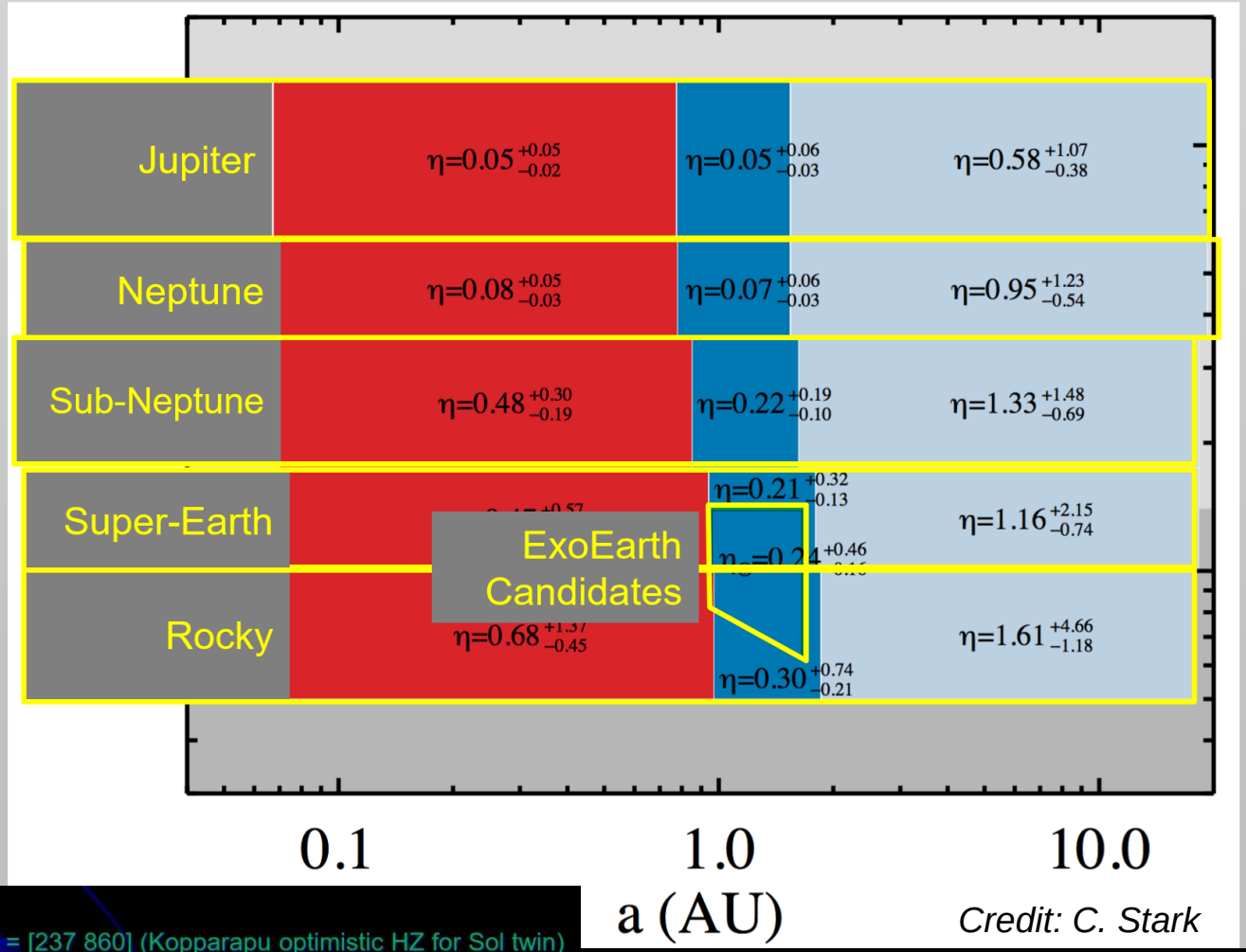
Recent DR 25 identifies additional HZ candidates and their reliability, S. Thompson et al.

Credit: NASA/Ames Research Center/W. Stenzel

Frequency of ExoEarths in Habitable Zone

Per Exoplanet Program Analysis Group

We use the SAG13 continuous distribution, but adopt coarse grid to communicate results:



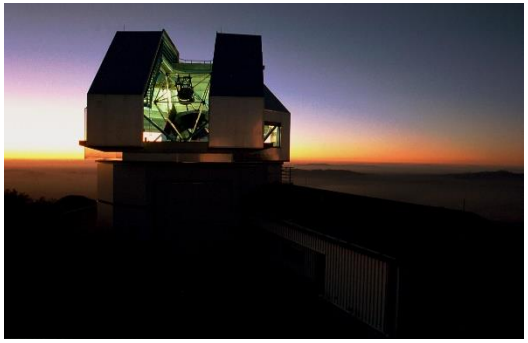
$\eta_{habSol,SAG13}$

- R = [0.5 – 1.5], P = [237 860] (Kopparapu optimistic HZ for Sol twin)

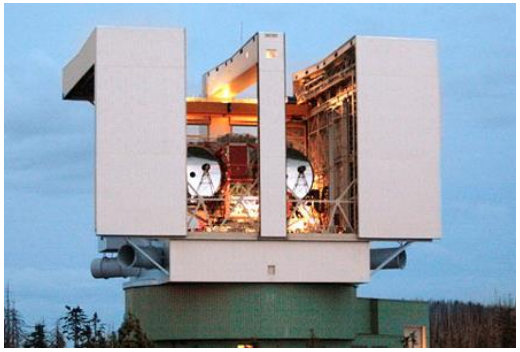
20

Additional Technology Activities in Support of 2010 Decadal Recommendations

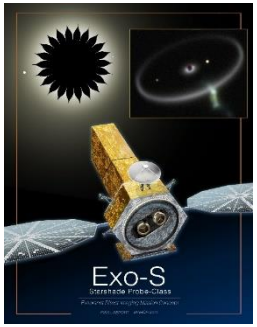
- NASA is developing an Extreme Precision Doppler Spectrometer (EPDS) to be installed as a facility-class instrument on the WIYN telescope; the EPDS instrument is scheduled for commissioning in 2019.

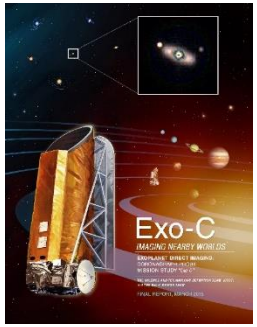


- NASA invested in the LBTI and the associated survey of exozodiacal dust levels around a set of nearby stars reached its target of 35 stars in 2018.



- APD chartered the Exo-C and Exo-S studies to study the feasibility of possible medium-size missions (total mission cost less than $1B) for direct imaging of exoplanets.





Large Binocular Telescope Interferometer

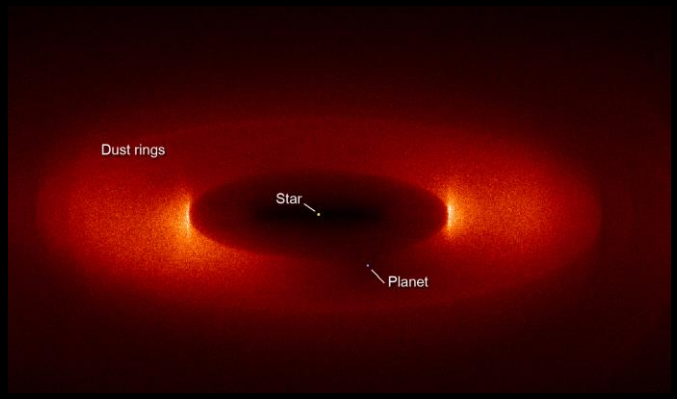
Measuring HZ Exozodiacal Dust to Inform Designs of Future Missions

Credit: ESO/Y. Beletsky

- 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

THE UNIVERSITY OF ARIZONA



Credit: NASA/GSFC

NN-EXPLORE

NASA-NSF Exoplanet Observational Research

PennState

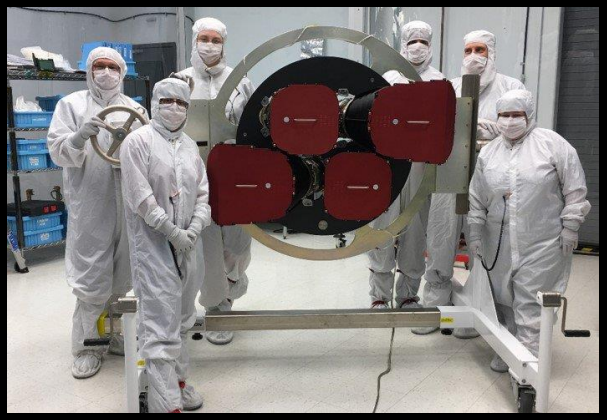
PI: S. Mahadevan

- Extreme precision radial velocity spectrometer (<0.5 m/s) at the WIYN Telescope on Kitt Peak
- On track for August 2019 commissioning
- Guest Observer program:
  - Starting 2019B: 90 nights per year
  - Current: Guest Observer program using NOAO share of telescope time for exoplanet research

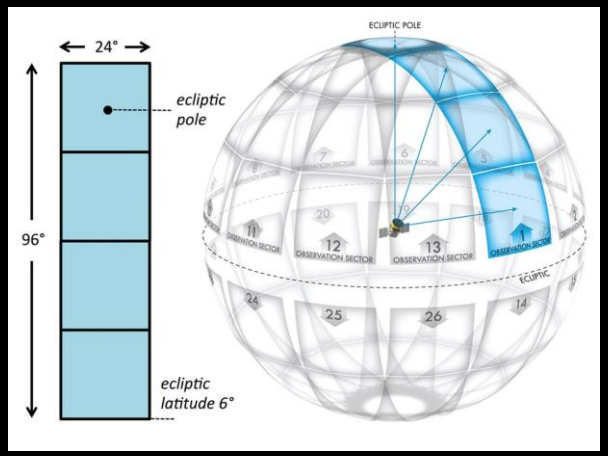
NEOS Camera

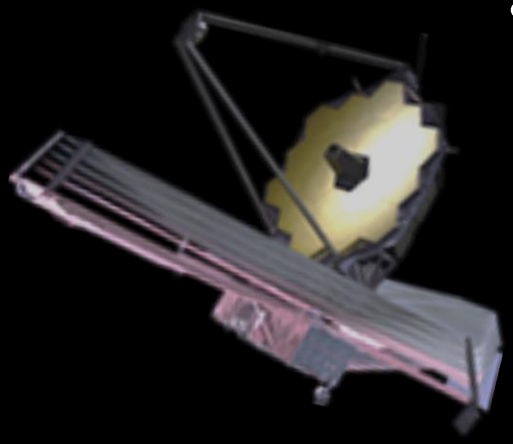
Transiting Exoplanet Survey Satellite

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

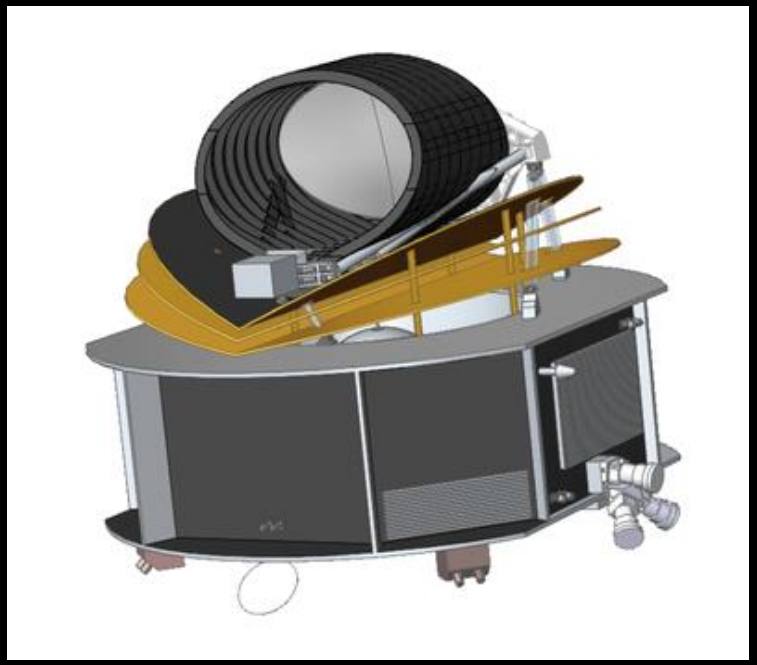




ARIEL

Near- and mid-IR transit spectroscopy

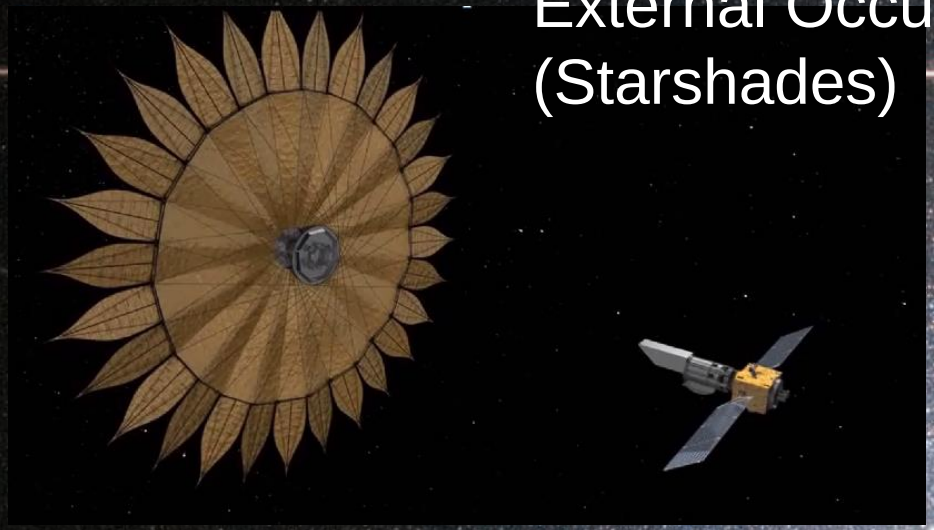
- ESA approved ARIEL as M4 science mission and 2028 launch.
- ARIEL will conduct near- and mid-IR transit spectroscopy of hundreds of planets Neptune-sized and larger.
- ARIEL is led by G. Tinetti of Univ. College London

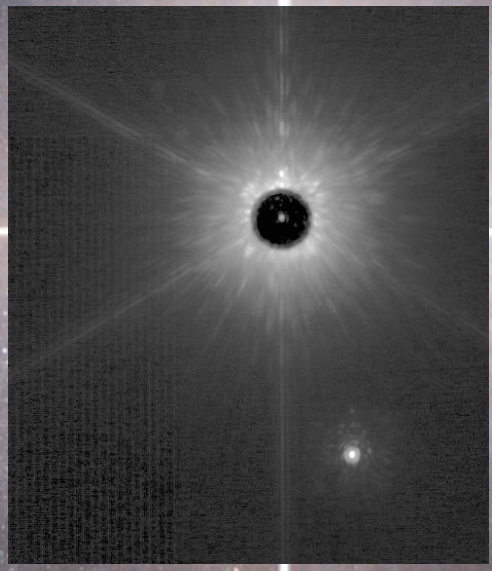


Starlight Suppression

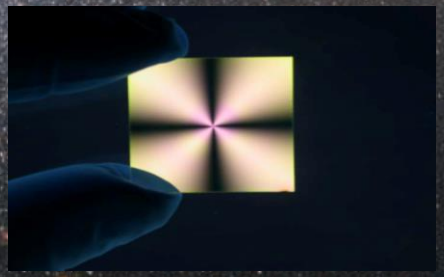
The Key to the Search for Life on Earth-sized Exoplanets

External Occulters
(Starshades)

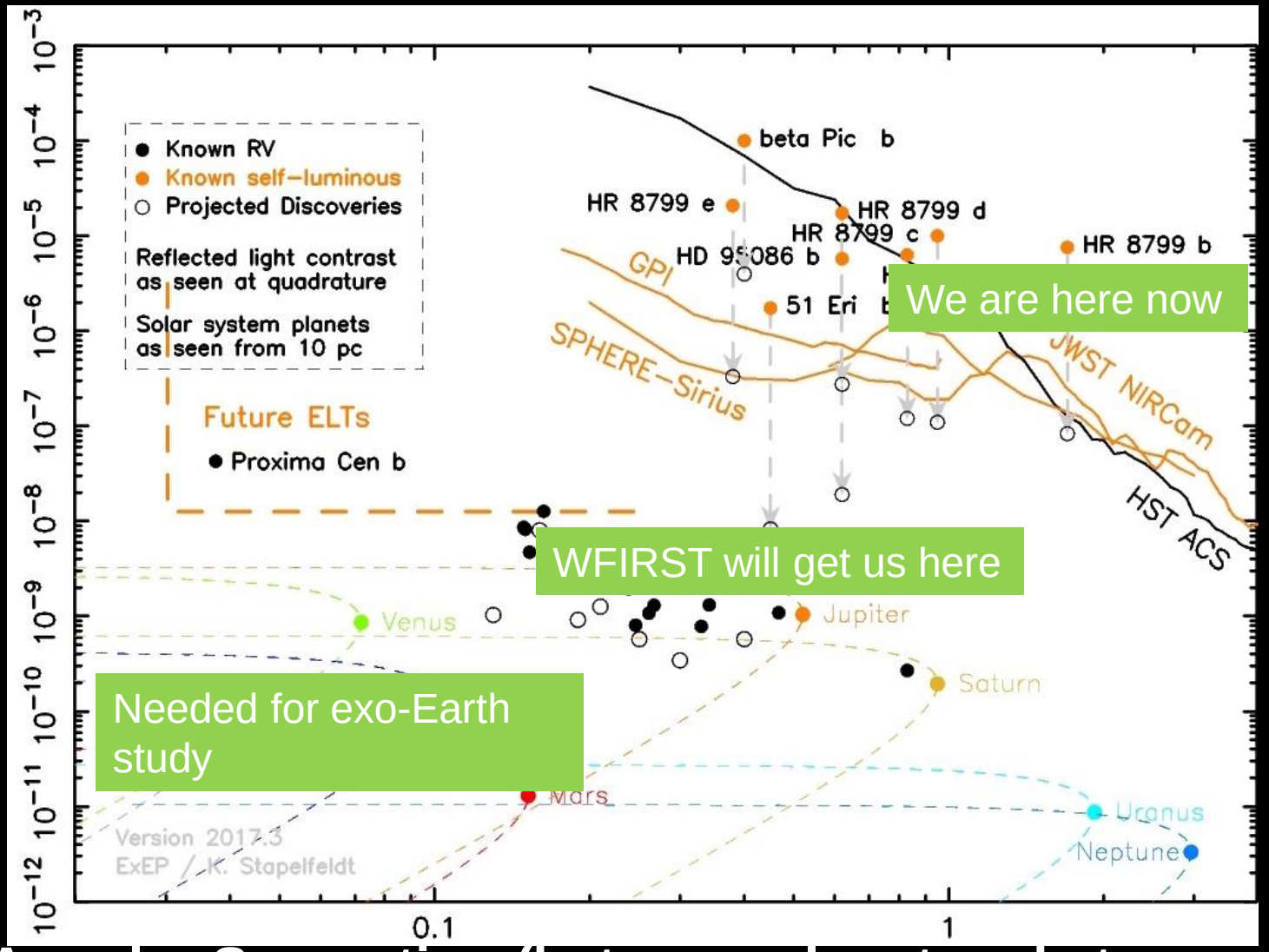




Internal Occulters
(Coronagraphs)

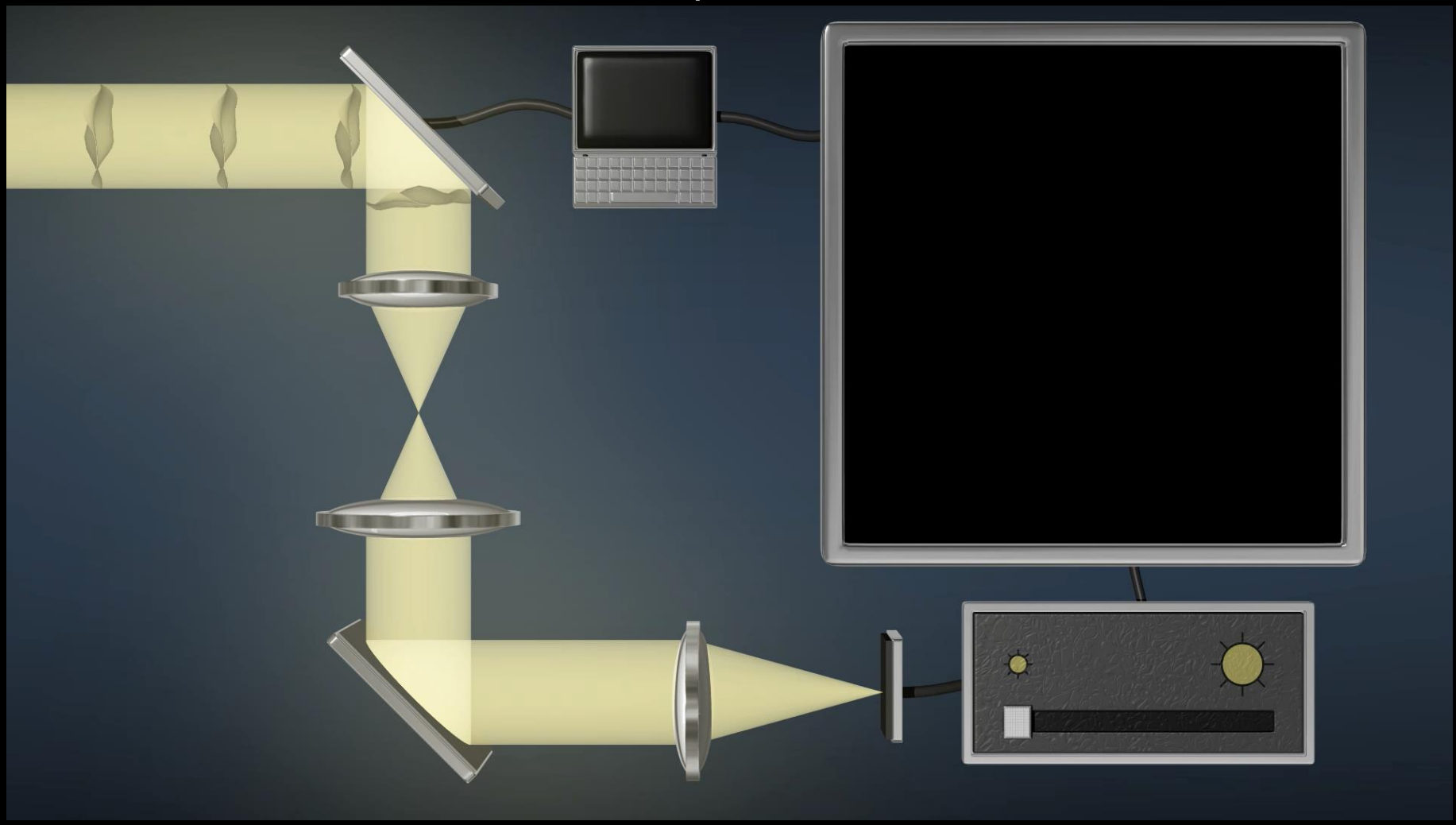


Challenge to Directly Image Exo-Earths



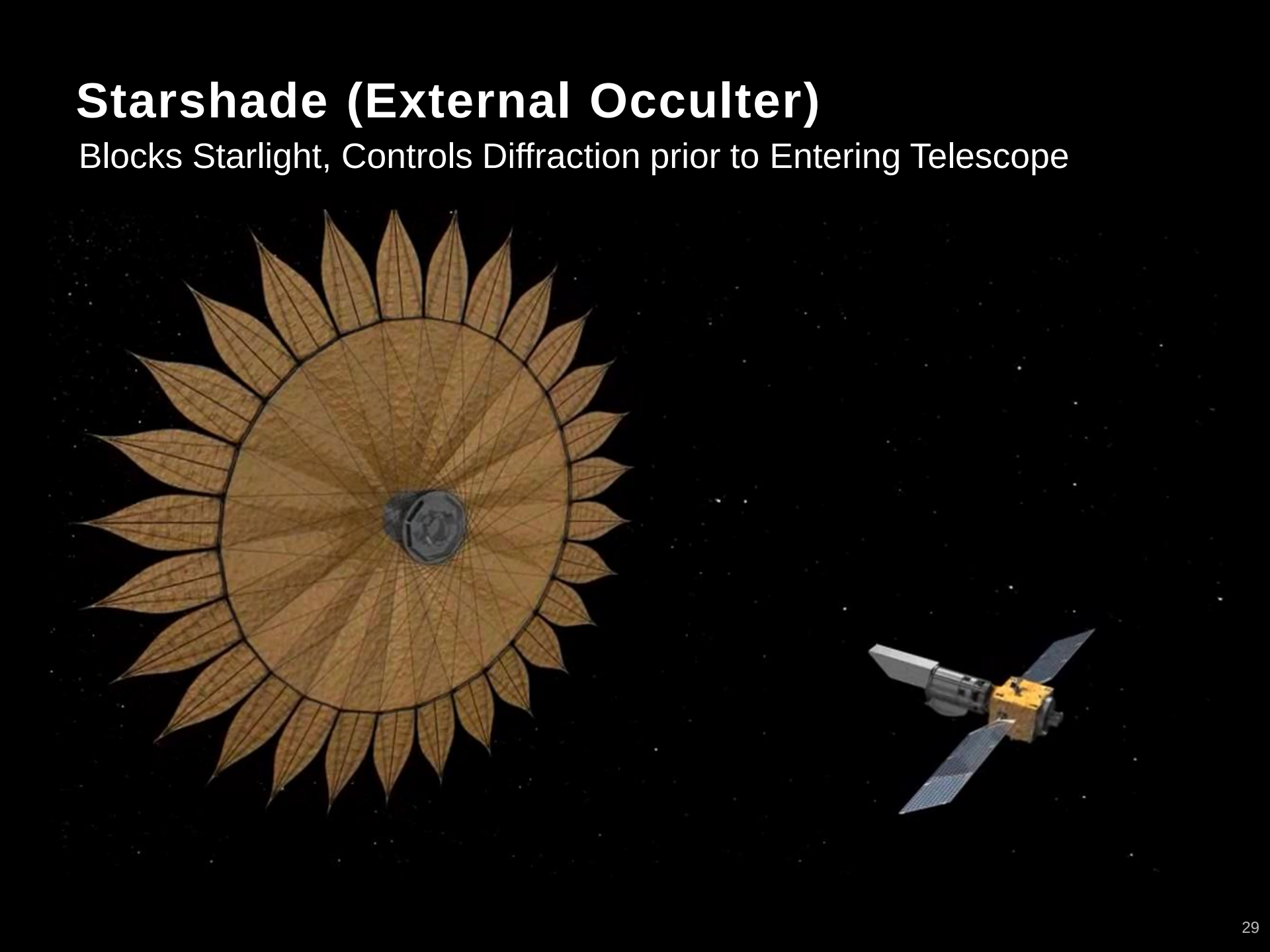
Internal Coronagraph

Controls Diffraction to Reveal Exoplanets in “Dark Hole”



Starshade (External Occulter)

Blocks Starlight, Controls Diffraction prior to Entering Telescope

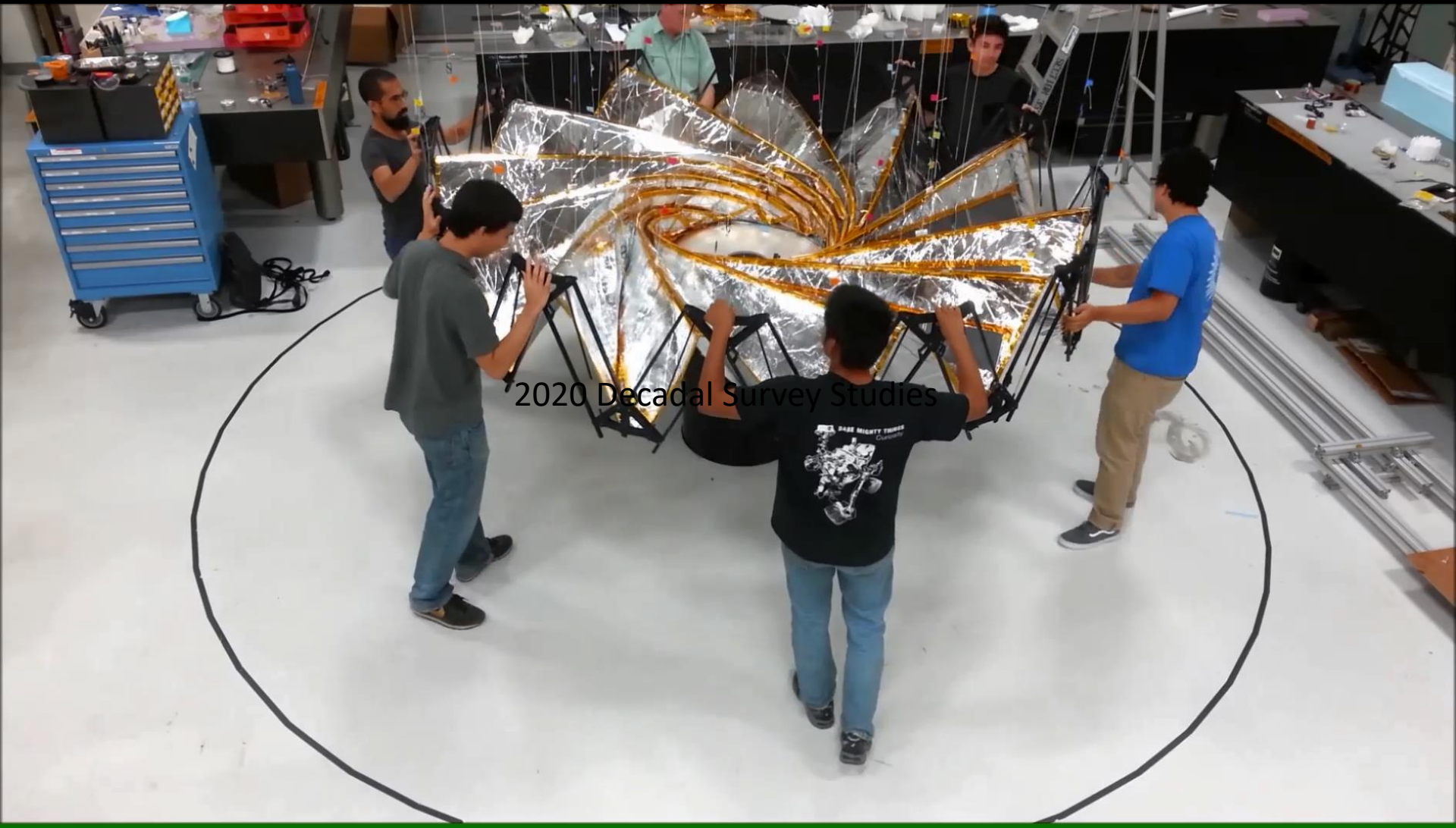


STARSHADE TECHNOLOGY PROGRESS

Automatic Deployment of Wrapped Petals

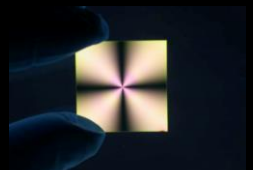
Inner Disk Deployment Trials

Starshade Optical Shield

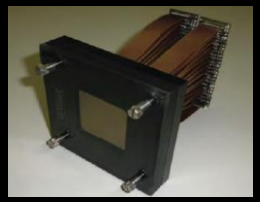


V-NIR Coronagraph/Telescope Technology Gaps

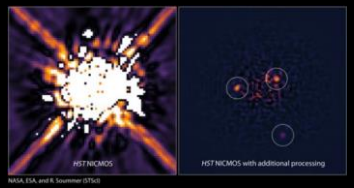
Contrast



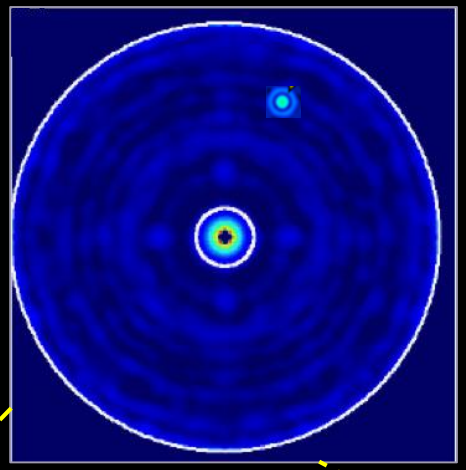
CG-2: Coronagraph Architecture



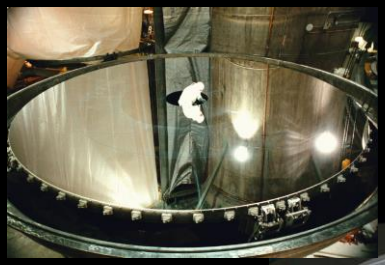
CG-3: Deformable Mirrors



CG-4: Data Post-Processing



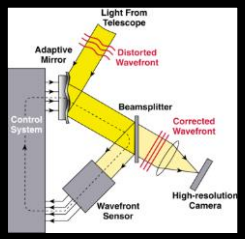
Angular Resolution



CG-1: Large Monolith Mirrors

CG-1: Segmented Mirrors

Contrast Stability

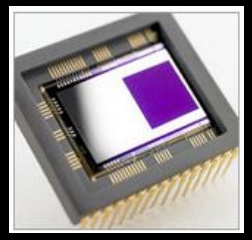


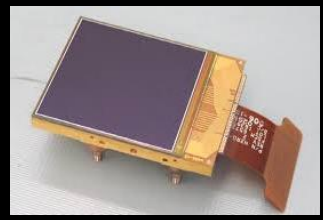
CG-5: Wavefront Sensing and Control

CG-6: Mirror Segment Phasing

CG-7: Telescope Vibration Sensing and Control or Reduction

Detection Sensitivity

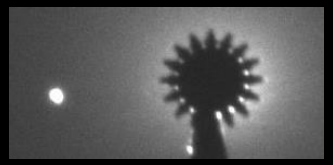




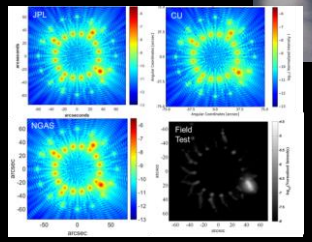
Ultra-low Noise Visible (CG-8) and Infrared (CG-9) Detectors

Starshade Technology Gaps

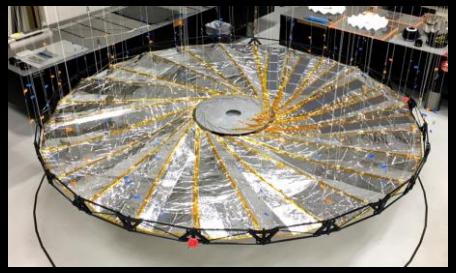
Starlight Suppression



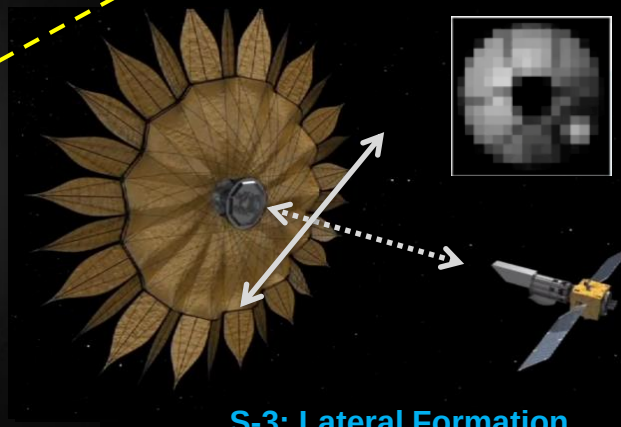
S-1: Controlling Scattered Sunlight



S-2: Starlight Suppression and Model Validation

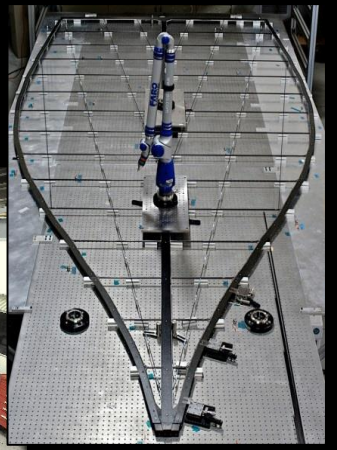


Formation Sensing



S-3: Lateral Formation Sensing

Deployment Accuracy and Shape Stability



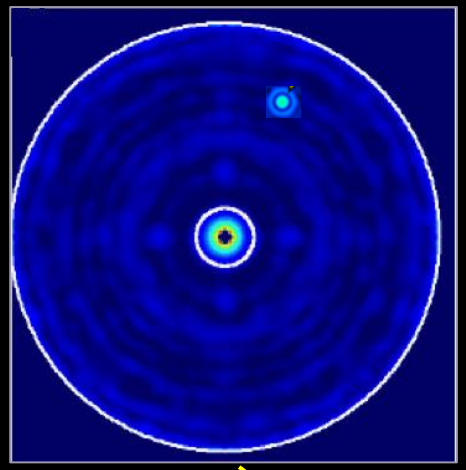
S-4: Petal Shape And Stability

S-5: Petal Positioning Accuracy and Opaque Structure

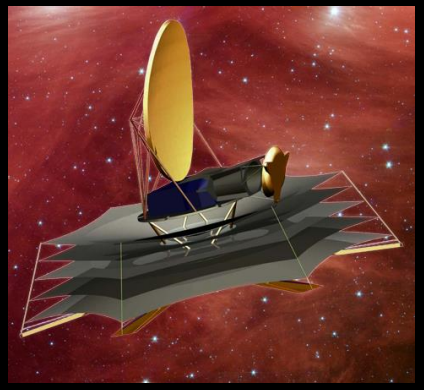
Mid-IR Coronagraph/Telescope Technology Gaps

Contrast

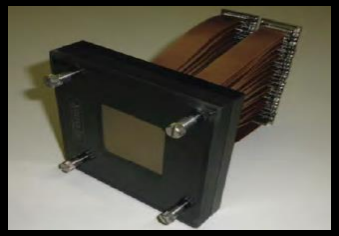
G-15: Mid-IR Coronagraph Optics and Architecture



Angular Resolution

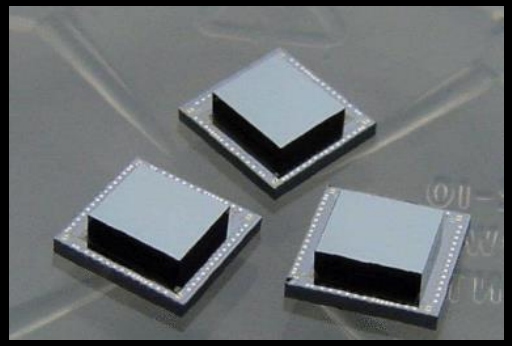


CG-14: Mid-IR Large Aperture Telescopes



CG-16: Cryogenic Deformable Mirror

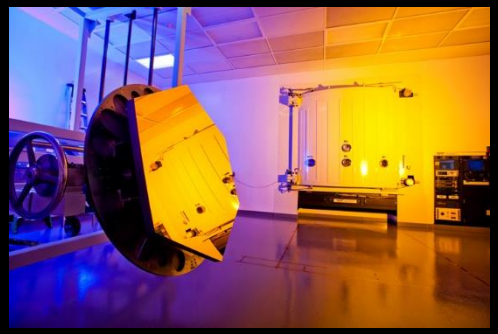
Detection Sensitivity



CG-13: Low-Noise Mid-IR Detectors

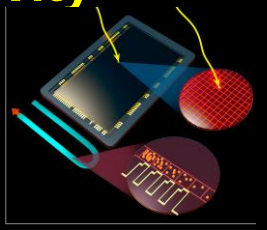
Other Technology Gaps

UV Contrast

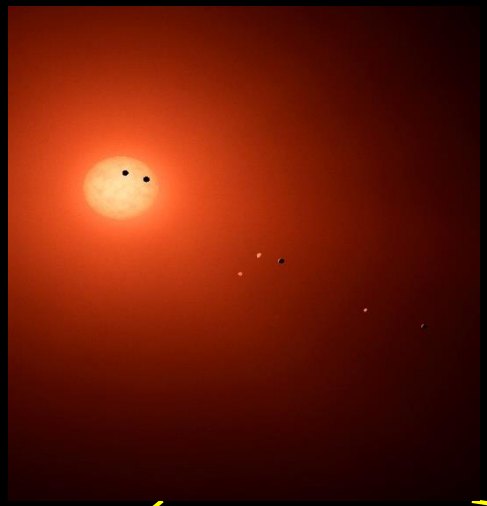


CG-10 UV/V/NIR Mirror Coatings

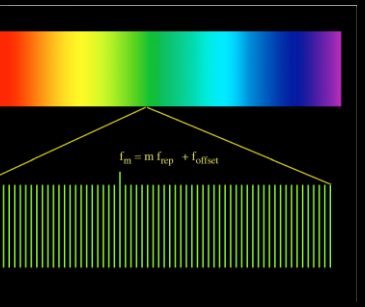
UV Detection Sensitivity



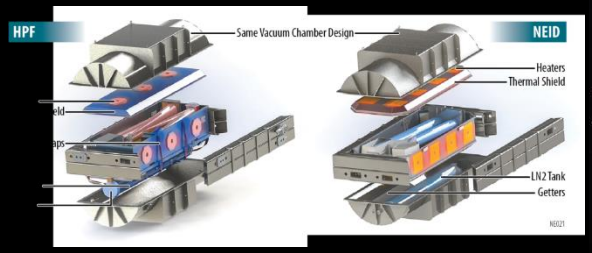
CG-12: Ultra-low Noise UV Detectors



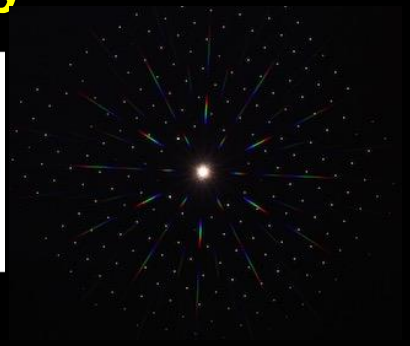
Stellar Reflex Motion Sensitivity



2: Laser Frequency Combs for Space-based EPRV

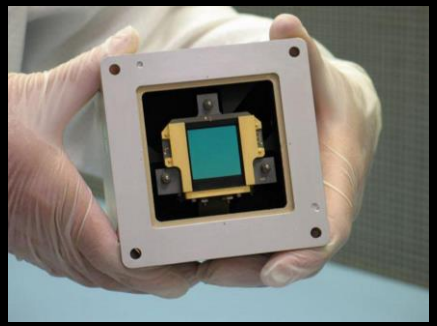


M-1: Ground-based Ultra-high Precision Radial Velocity



M-3: Astrometry

Transit Spectroscopy Sensitivity



M-4: Ultra-stable Mid-IR Detectors for Transit Spectroscopy

Program Overview

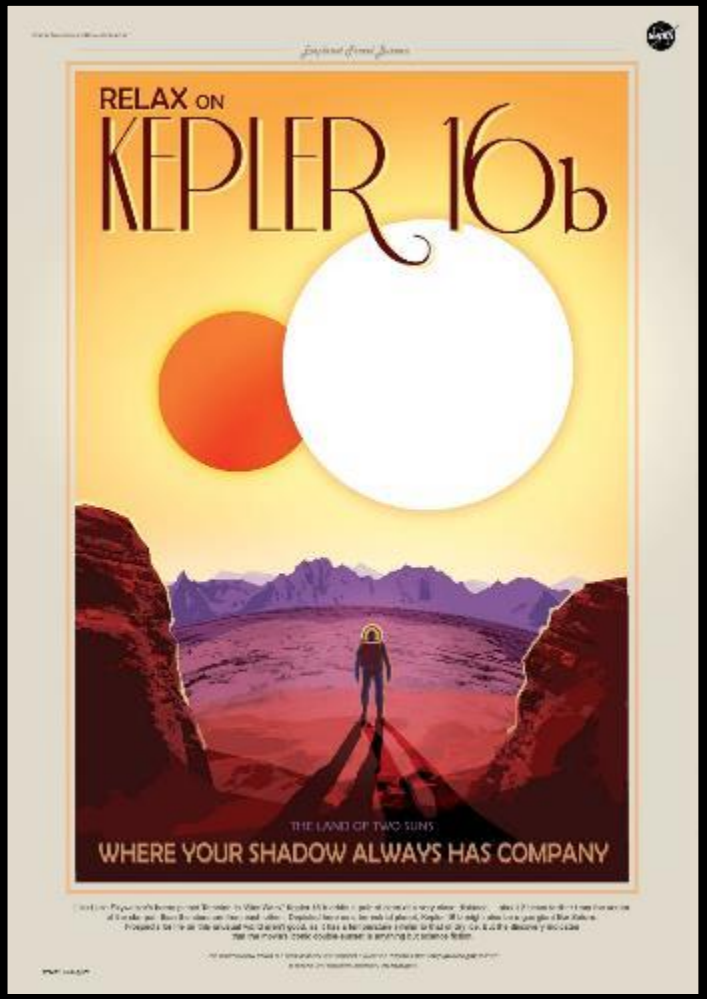
Current Investments and Results

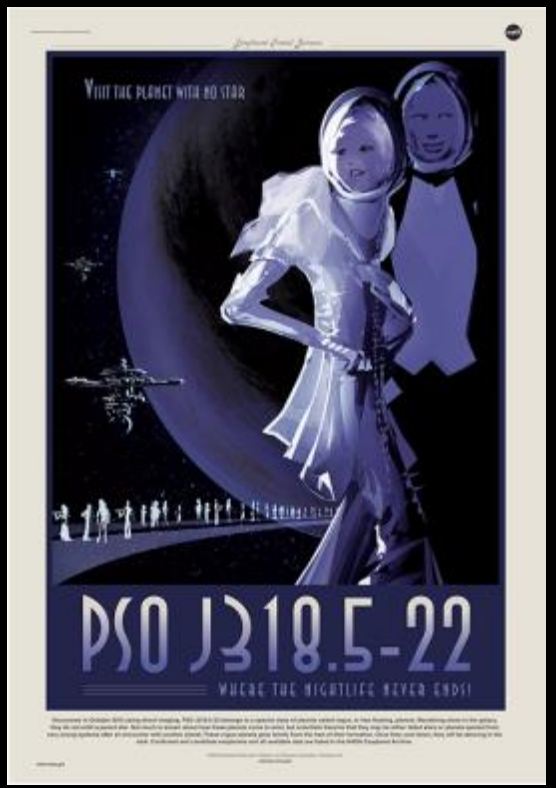
Communicating Exoplanets

Exoplanet Forward Strategy

Exoplanet Communications

Explore a Galaxy of Worlds, Inspiring our Own





Exoplanet Travel Bureau

"All the News That's Fit to Print"

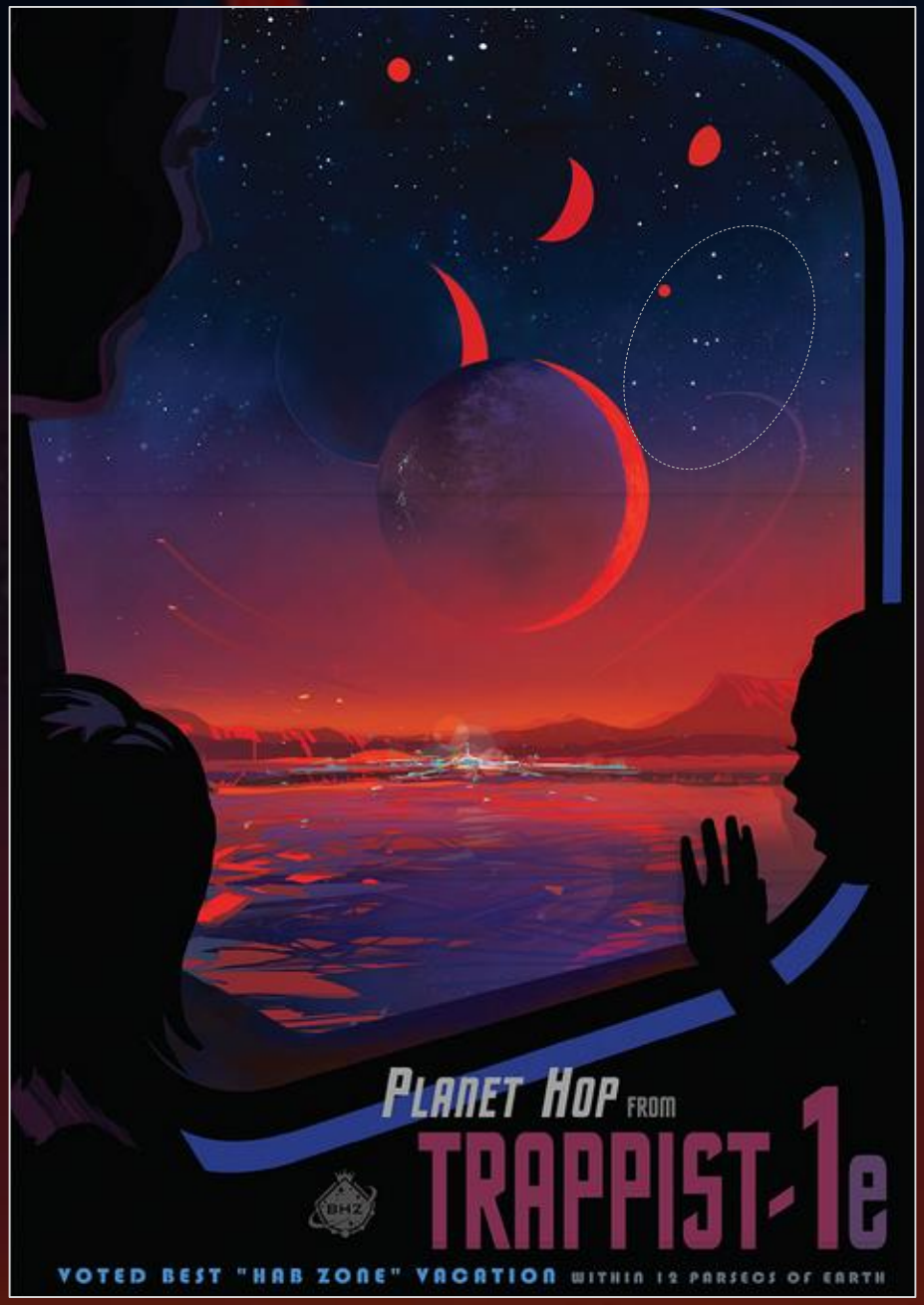
The New York Times

Late Edition

Today, patchy morning fog, partly sunny, warm, high 64. Tonight, mostly cloudy, mild, low 52. Tomorrow, clouds and sunshine, showers, high 66. Weather map is on Page B8.

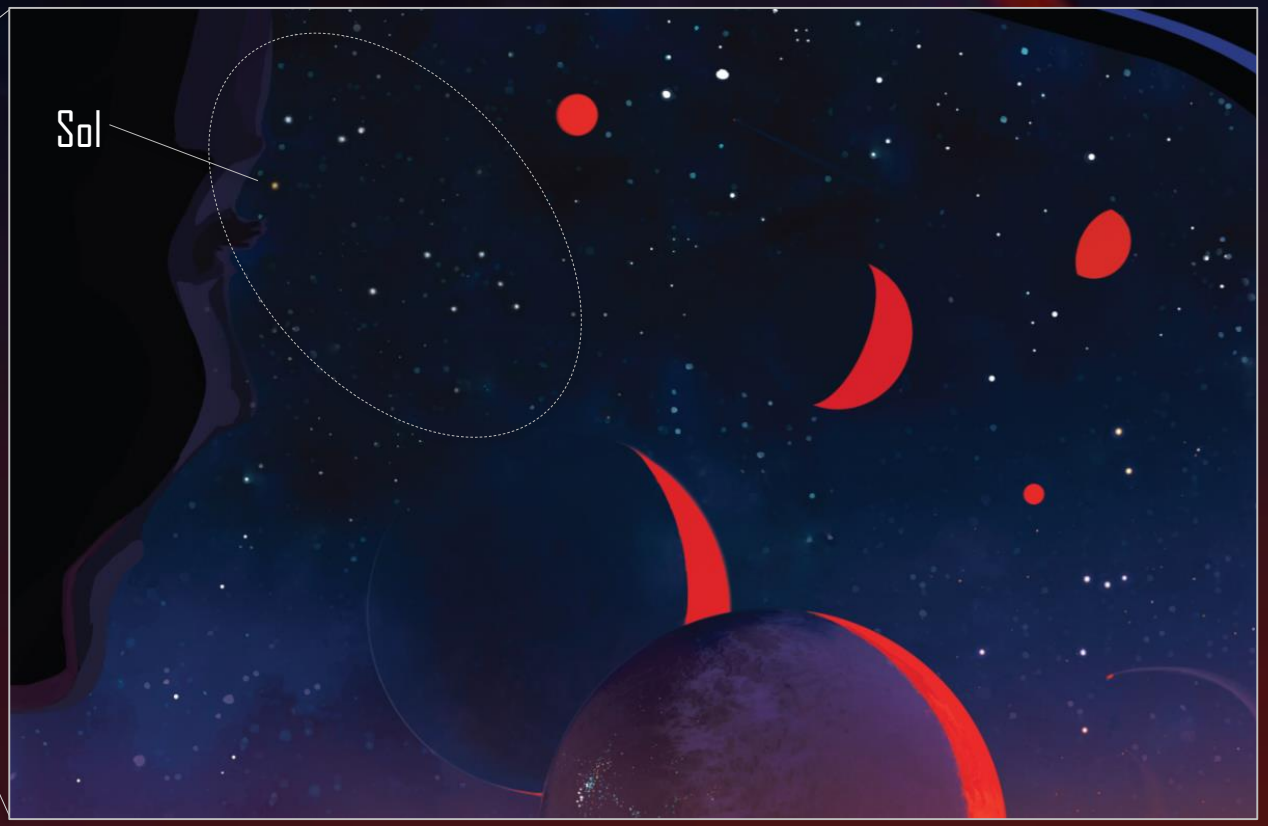
VOL. CLXVI . . . No. 57,517 © 2017 The New York Times Company NEW YORK, THURSDAY, FEBRUARY 23, 2017 $2.50

A rendering of newly discovered Earth-size planets orbiting a dwarf star named Trappist-1 about 40 light-years from Earth. Some of them could have surface water.



“EXOPLANET EARTH” EDITION OF TRAPPIST-1

Connecting exoplanet Science Enthusiasm to our own World



Our Star appears as a Leo Sun as seen from Trappist-1

Program Overview

Current Investments and Results

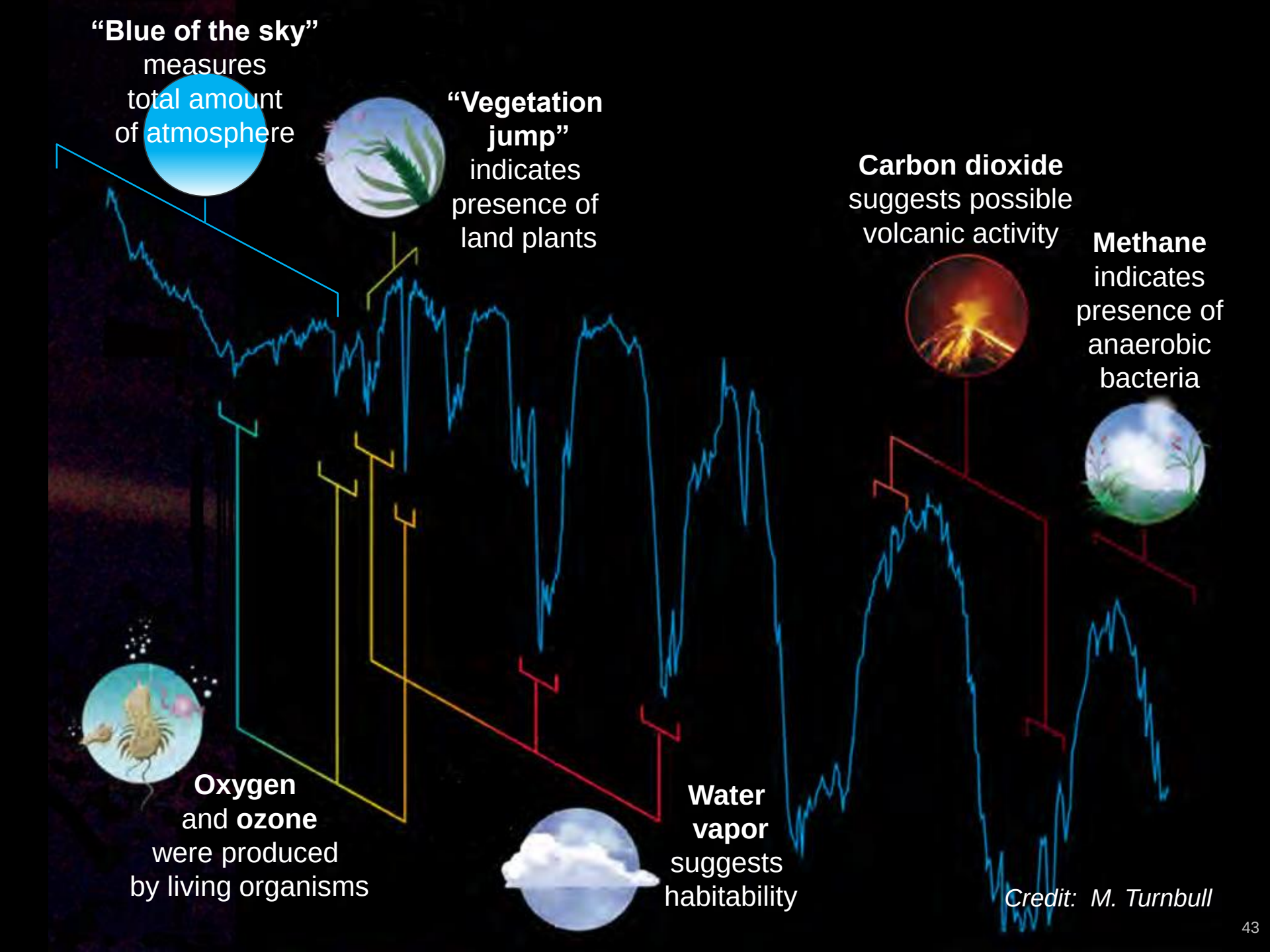
Communicating Exoplanets

Exoplanet Forward Strategy

Snapshot of ExEP Science Gap List

Grouped by topic, no priority implied

Spectra of small planets
Modeling exoplanet atmospheres
Spectral signature retrieval
Combining exoplanet demographics from multiple methods
Occurrence rates for small planets (e.g. $\eta_{\oplus}$)
Quantified science yield comparison between flagships, probes & WFIRST
Systematic strategy for prioritizing flagship mission targets
Nearby star catalog
Achieving RV sensitivity to Earth-like planets: mitigating RV jitter
Community RV facilities for Kepler, K2, TESS follow-up
Search completeness of current prec. RV surveys for direct imaging targets
Dedicated WFIRST/CGI RV precursor programs
Achieving astrometric sensitivity to Earth-like planets
Exozodi as a noise source for flagship imaging of exoplanets
Exozodi substructure as a noise source for exoplanet imaging (flagship)
High resolution imaging in bulk to validate TESS candidates
Projected state of ground-based direct imaging capability
Generation of light curves for TESS full frame images


"Blue of the sky" measures total amount of atmosphere
"Vegetation jump" indicates presence of land plants
Carbon dioxide suggests possible volcanic activity
Methane indicates presence of anaerobic bacteria
Oxygen and ozone were produced by living organisms
Water vapor suggests habitability
Credit: M. Turnbull

Exoplanet Roadmap

From 2013 Enduring Quests, Daring Visions

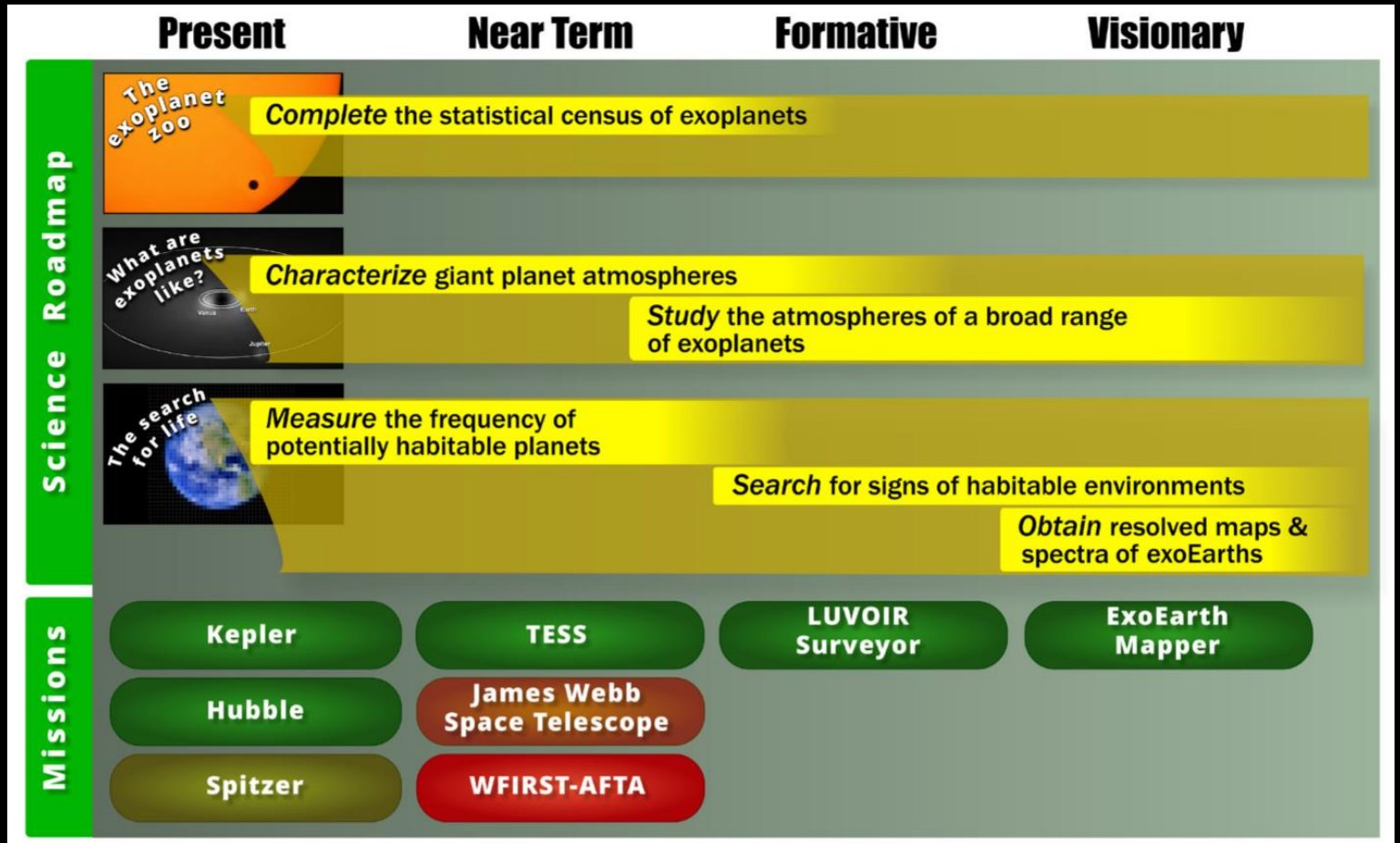


Figure 2.16 *Schematic of the Exoplanets Roadmap, with science themes along the top and a possible mission sequence across the bottom.* ***Credit: F. Reddy (NASA GSFC)***

TECHNOLOGY

- Angular Resolution: Interferometry
- Angular Resolution and Collecting Area: Large Space Telescopes
- Contrast Stability: Ultrastable Structures
- Detection Sensitivity: Advanced Detectors
- Starlight Suppression: Starshades
- Starlight Suppression: Coronagraphs

MISSIONS


Hubble


Spitzer


Kepler


TESS

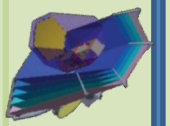

JWST

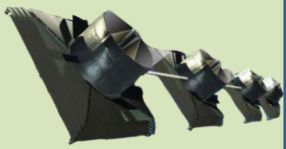

WFIRST


Starshade Rendezvous


LUVOIR


HabEx


OST


Exo-Earth Interferometer

Possible Pending Decadal Survey

TODAY	2020s	2025s	2030s	2035 and beyond

SCIENCE

- Exoplanetary Atmospheres
- Hot Jupiters
- Exoplanet Abundance
- Nearest Transiting Planets
- Atmospheric Chemistry
- Direct Imaging
- Exozodiacal Dust
- Exoplanet Diversity
- Habitable Exo-Earth Discovery
- M-Dwarf Rocky Planet Biosignatures
- Cool Gas Giants
- Exo-Earth Biosignatures
- Habitable Exo-Earth Abundance
- Life Verification

Version 2018_03_07, NASA ExEP

Exoplanet Missions

WFIRST

JWST[2]

ARIEL

TESS

PLATO

LUVOIR[5]

Kepler

CHEOPS[4]

Spitzer

Gaia

Hubble[1]

Starshade Rendezvous[5]

HabEx[5]

CoRoT[3]

OST[5]

NASA Missions

Non-NASA Missions

W. M. Keck Observatory

Large Binocular Telescope Interferometer

NN-EXPLORE

Ground Telescopes with NASA participation

[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA
[4] ESA/Swiss Space Office

[5] 2020 Decadal Survey Studies

Jet Propulsion Laboratory
California Institute of Technology

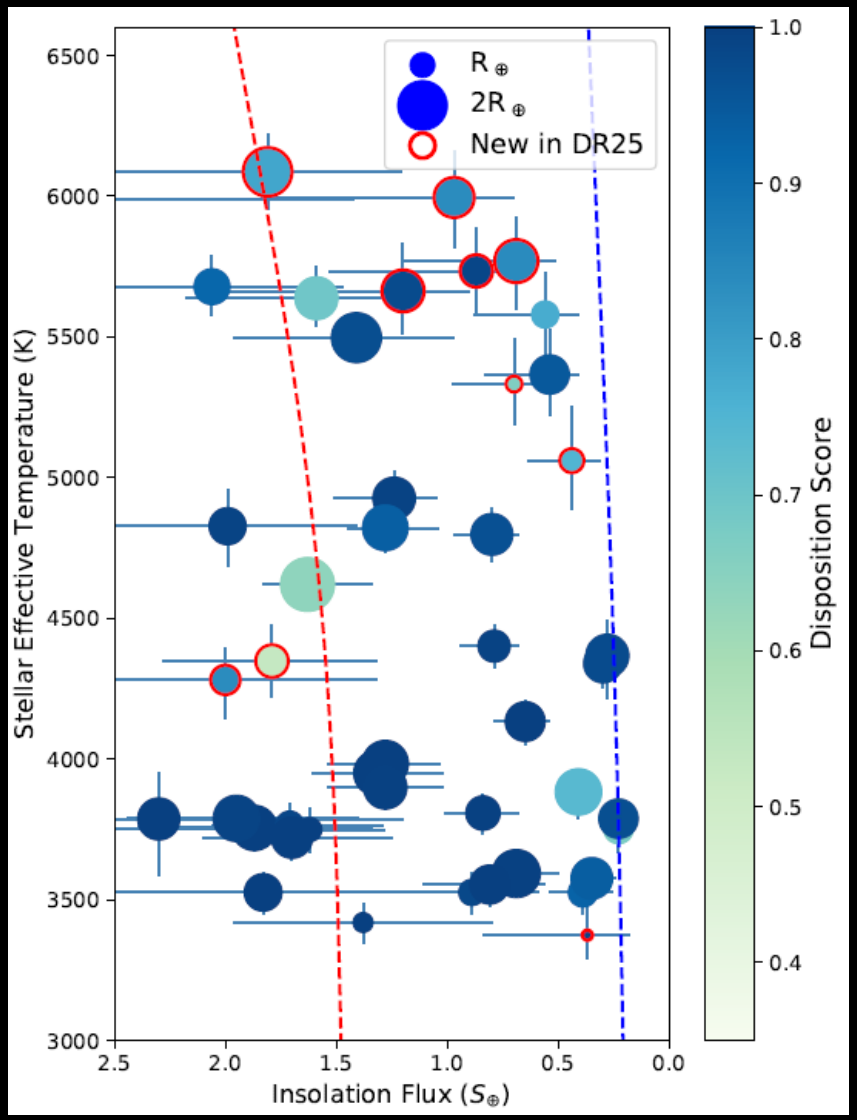
exoplanets.nasa.gov

Backup

Science Highlight #1: KOI catalog from Kepler DR 25

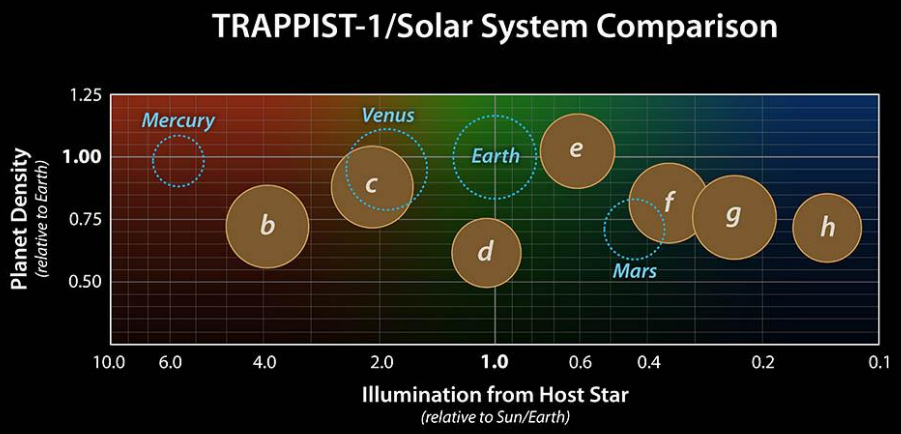
S. Thompson et al. arXiv:1710.06758. Submitted and under review

- Produced by fully automated detection pipelines
- 4034 candidates, 219 new
- 10 new super-⊕-sized in HZs
- Includes completeness and reliability estimates derived from signal injection & recovery experiments
- Key support document of the Kepler final data delivery
- Right: HZ candidates with their estimated reliability
- Others will use this catalog as starting point for $\eta_\oplus$ estimates



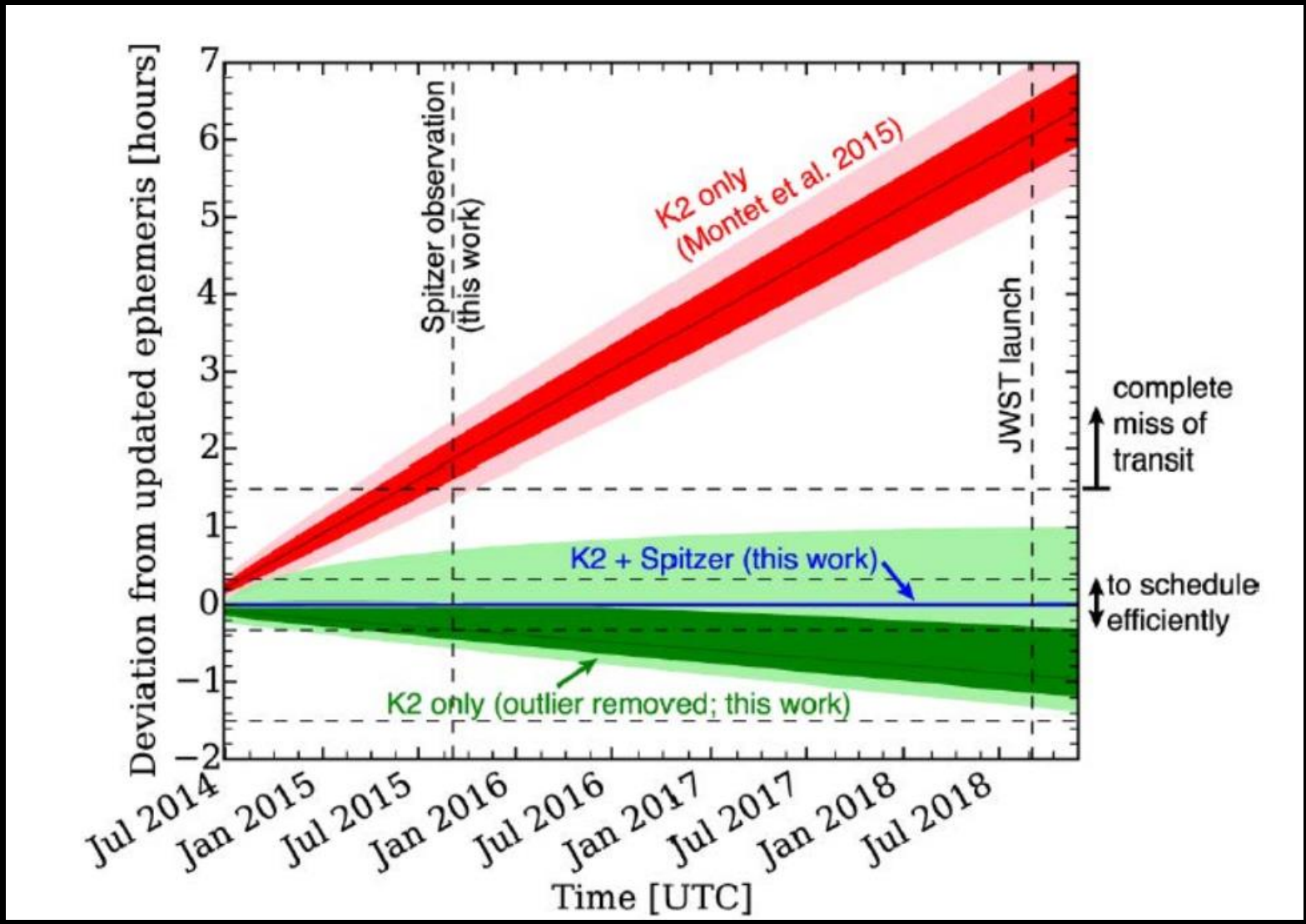
Program Science News

- De Wit et al. 2018 https://arxiv.org/abs/1802.02250 have analyzed additional Spitzer data on the Trappist-1 system and find that these Earth-sized planets are generally less dense than Earth. This suggest a bulk composition with more volatiles (deep atmospheres, water layers) than Earth



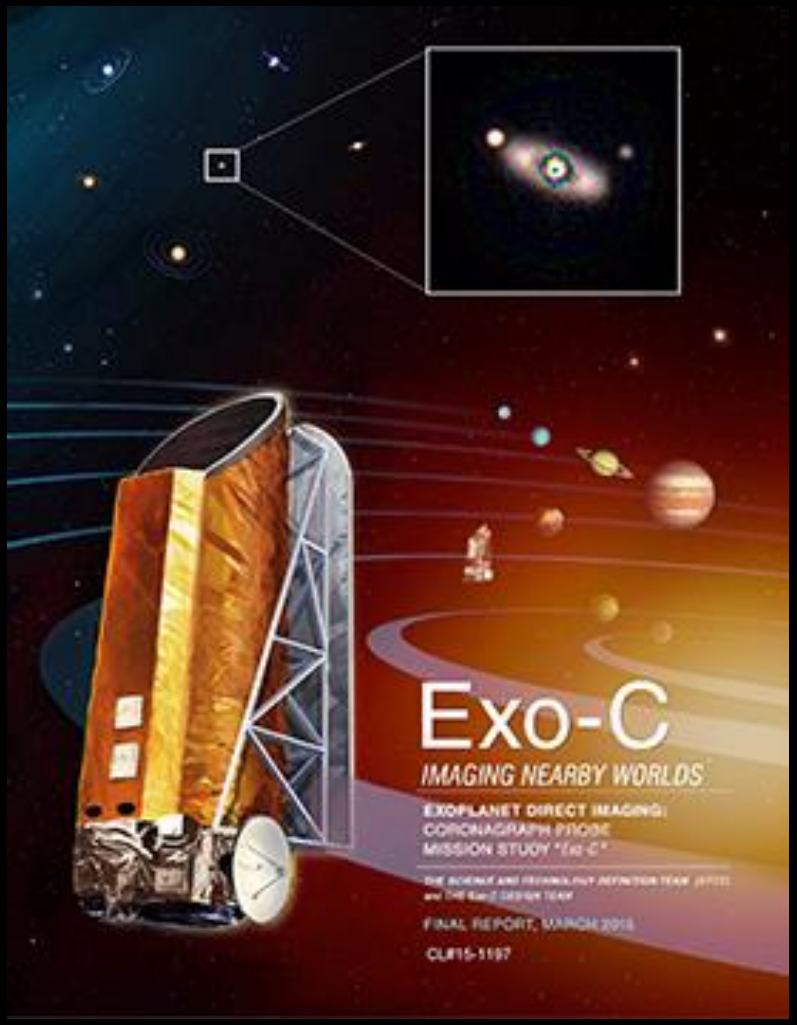
- ESA approves ARIEL as M4 science mission and 2028 launch. ARIEL will conduct near- and mid-IR transit spectroscopy of hundreds of planets Neptune-sized and larger. ARIEL is led by G. Tinetti of Univ. College London

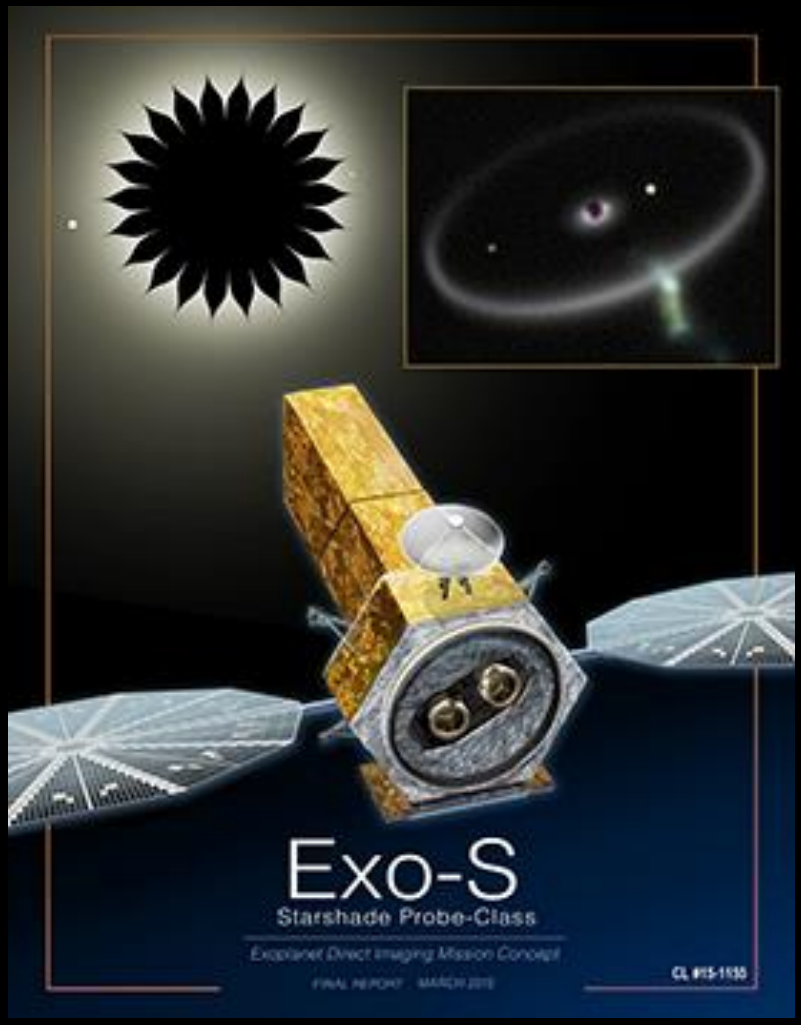
SPITZER TELLS **JWST** "WHEN" TO LOOK FOR EXOPLANET TRANSIT



Updates to 2015 Exoplanet Probe Studies

Short white papers requested by NASA HQ June 2017, delivered Nov. 2017; led by Stapelfeldt & Mamajek with inputs from STDT alumni





Acknowledgements

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

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