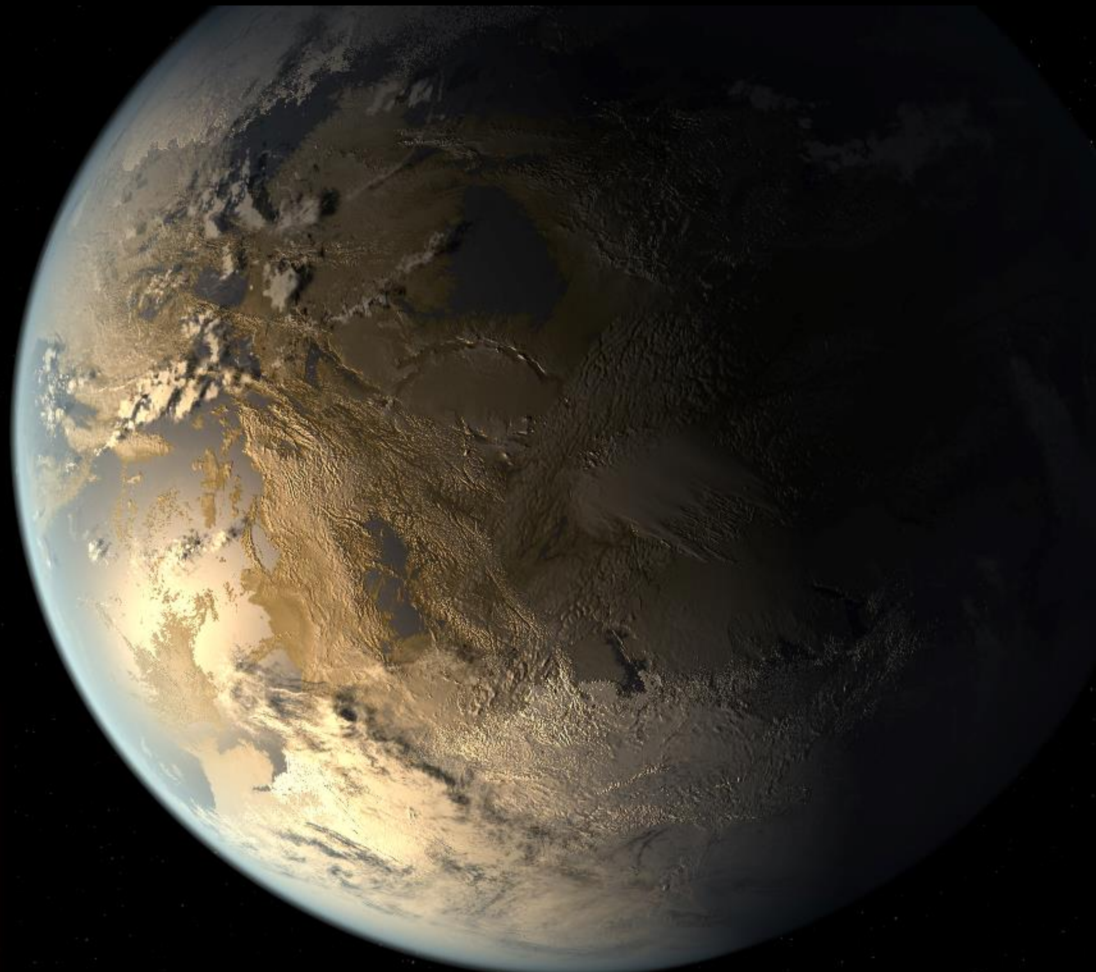
National Aeronautics and Space Administration

# NASA and the Search for Life on Planets around Other Stars

A presentation to the

National Academies Committee on Exoplanet Science Strategy

6 March 2018

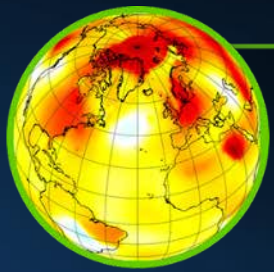


*Astrophysics*

**Paul Hertz**
Director, Astrophysics Division

**Douglas Hudgins**
Program Scientist, Exoplanet Exploration Program

# Key NASA/SMD Science Themes



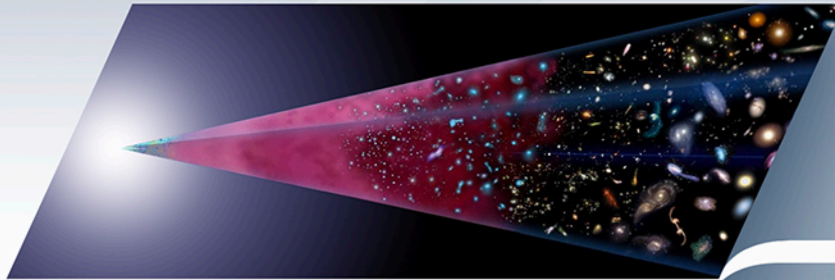
Protect and Improve
Life on Earth

Search for
Life Elsewhere

Discover the Secrets
of the Universe

# 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?

**Enduring National Strategic Drivers**


1972 1982 1991 2001 2010

# NASA's Exoplanet Exploration Program

## Space Missions and Mission Studies

Kepler, K2

WFIRST

Starshade

Decadal Studies

Coronagraph

## Public Communications


## Supporting Research & Technology

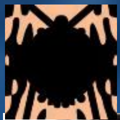
### *Key Sustaining Research*

Large Binocular Telescope Interferometer

Keck Single Aperture Imaging and RV

NN-EXPLORE

### *Technology Development*

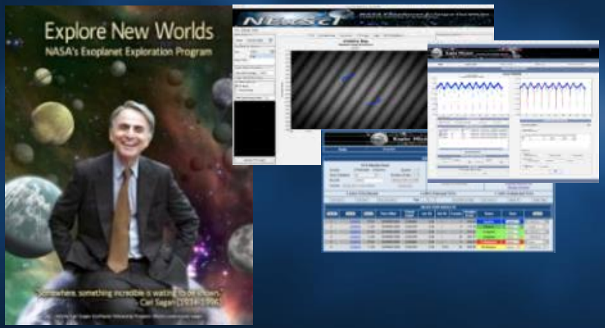


Coronagraph Masks

High-Contrast Imaging

Deployable Starshades

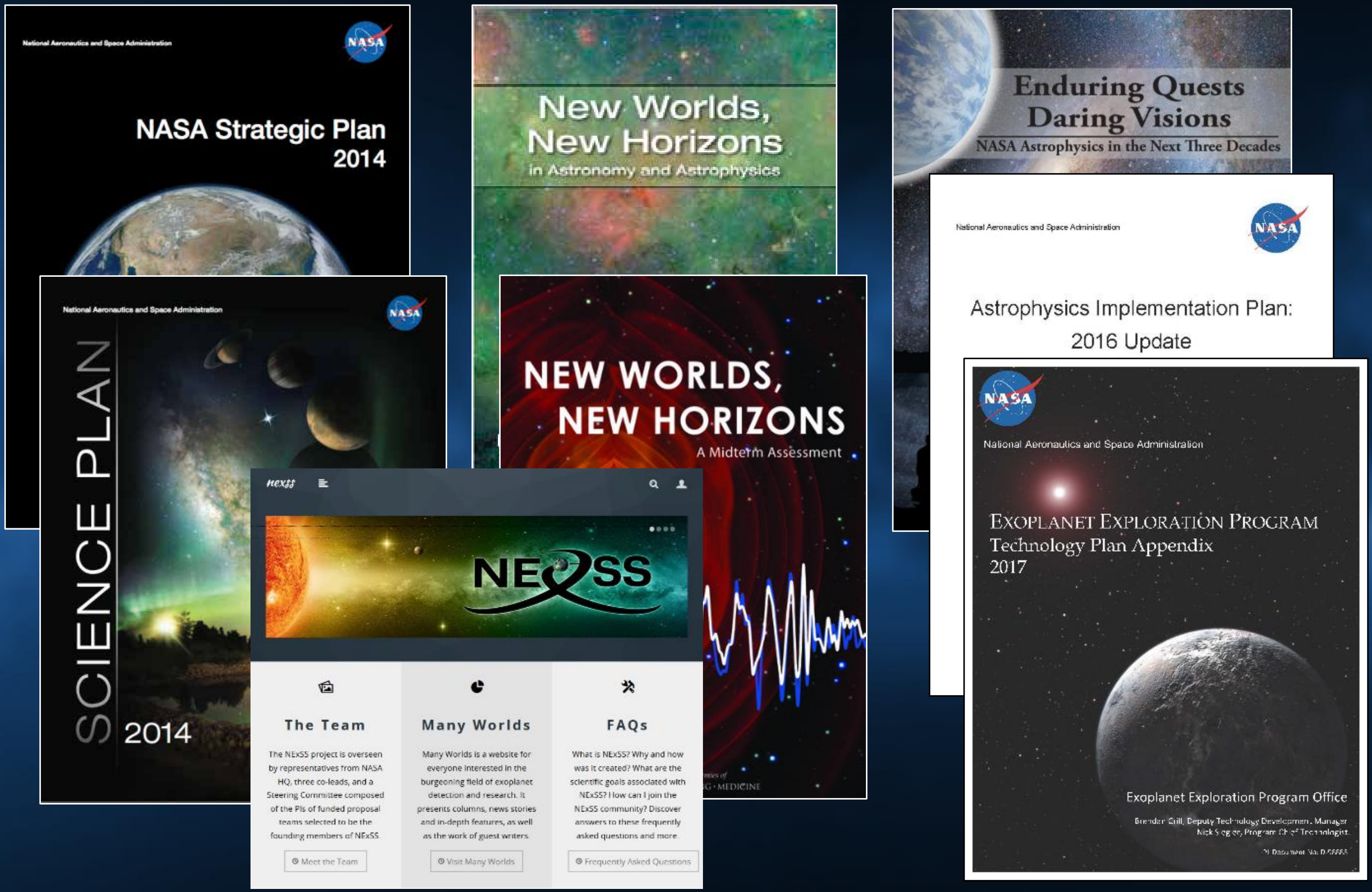
### *NASA Exoplanet Science Institute*




Archives, Tools, Sagan Fellowships, Professional Engagement

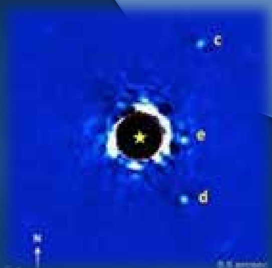
https://exoplanets.nasa.gov

# Foundational Documents for the NASA's Astrophysics Division

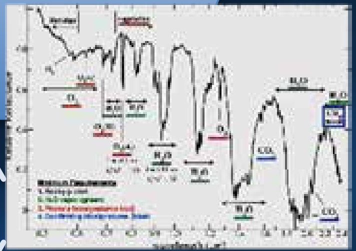


# NASA's cross-divisional Search for Life Elsewhere

## ASTROPHYSICS
- Exoplanet detection and characterization
- Stellar characterization
- Mission data analysis
  *Hubble, Spitzer, Kepler, TESS, JWST, WFIRST, etc.*



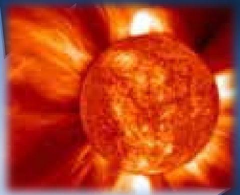
## Planetary SCIENCE/ ASTROBIOLOGY
- Comparative planetology
- Planetary atmospheres
- Assessment of observable biosignatures
- Habitability



## EARTH SCIENCES
- GCM
- Planets as systems

## PLANETARY SCIENCE RESEARCH
- Exoplanet characterization
- Protoplanetary disks
- Planet formation
- Comparative planetology

## HELIOPHYSICS
- Stellar characterization
- Stellar winds
- Detection of planetary magnetospheres



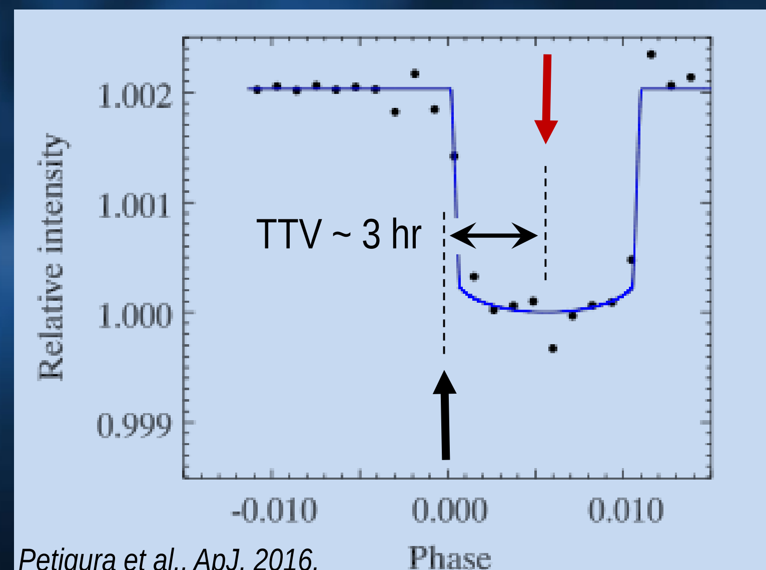
# Exoplanet Exploration at NASA
# 2007 - present

# The Spitzer Space Telescope

For the last decade, the Spitzer Space Telescope has used both spectroscopic and photometric measurements in the mid-IR to probe exoplanets and exoplanetary systems.

- Spitzer follow up observations of known transiting systems have revealed additional, new planets and helped refine measurements of the size and orbital dynamics of known planets as small as the Earth.


A 20-day long Spitzer observation of the TRAPPIST-1 system revealed 7 earth-sized planets, four of which were previously unknown. *Gillon et al., Nature, 2017*.



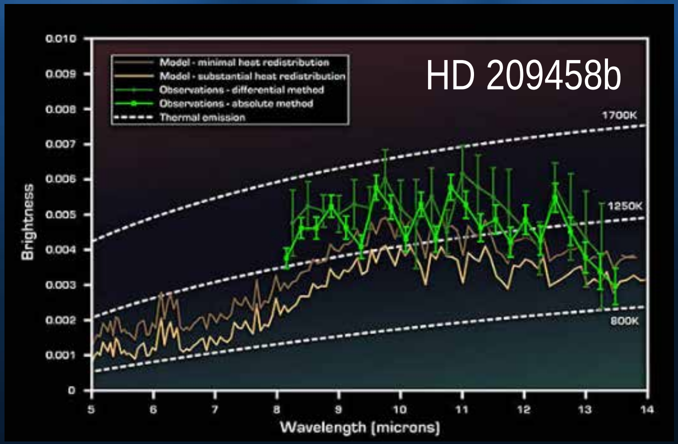

*Petigura et al., ApJ, 2016.*

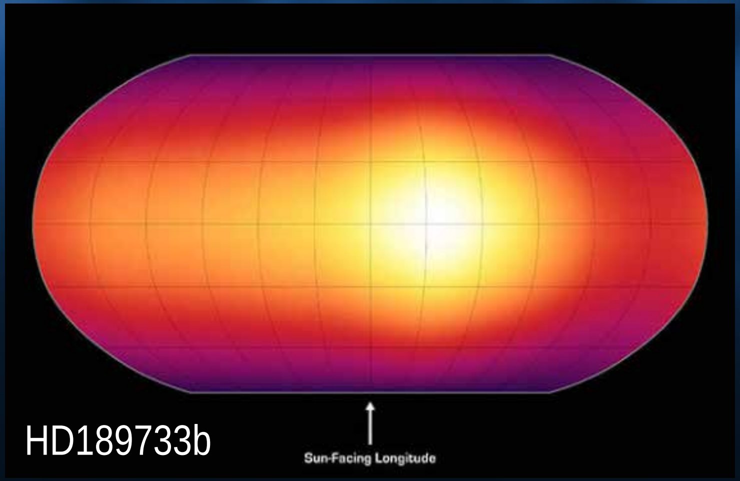
Transit-timing variation in the planet K2-24b cause by gravitational interaction with K2-24c

# The Spitzer Space Telescope

For the last decade, the Spitzer Space Telescope has used both spectroscopic and photometric measurements in the mid-IR to probe exoplanets and exoplanetary systems.

- Spitzer follow up observations of known transiting systems have revealed additional, new planets and helped refine measurements of the size and orbital dynamics of known planets as small as the Earth.
- Spitzer measurements of the IR emission spectra from “hot Jupiter” exoplanets have been used to constrain the atmospheric composition of those planets, and thermal maps generated by photometric monitoring of such planets during their orbits provides insight into their atmospheric dynamics.

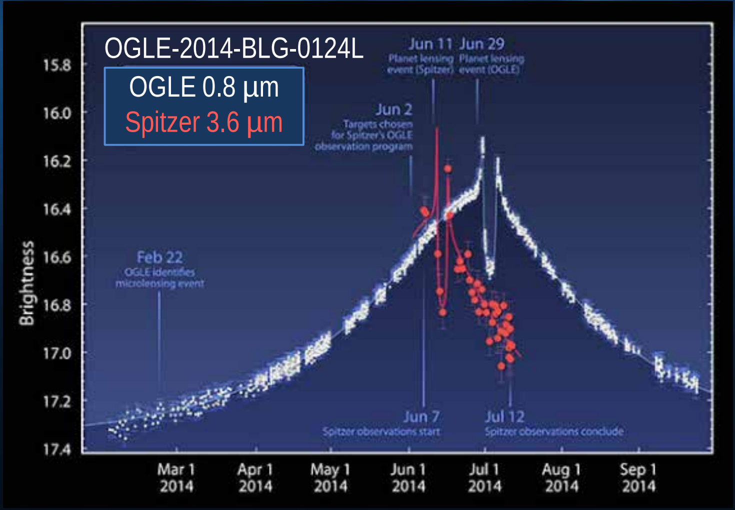


# The Spitzer Space Telescope

For the last decade, the Spitzer Space Telescope has used both spectroscopic and photometric measurements in the mid-IR to probe exoplanets and exoplanetary systems.

- Spitzer follow up observations of known transiting systems have revealed additional, new planets and helped refine measurements of the size and orbital dynamics of known planets as small as the Earth.
- Spitzer measurements of the IR emission spectra from “hot Jupiter” exoplanets have been used to constrain the atmospheric composition of those planets, and thermal maps generated by photometric monitoring of such planets during their orbits provides insight into their atmospheric dynamics.
- Gravitational microlensing observations combining measurements from Spitzer and those from ground-based observatories can break degeneracies and allow complete characterization of planets orbiting distant lensing stars.

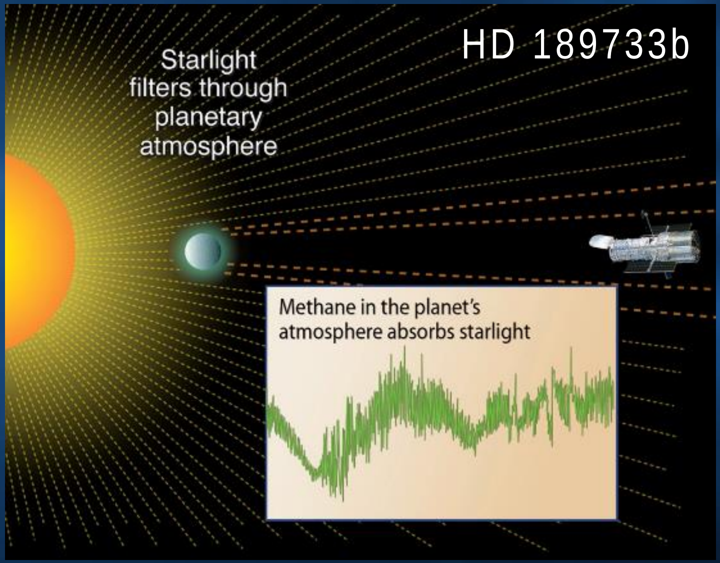



*Udalski et al., ApJ, 2015.*

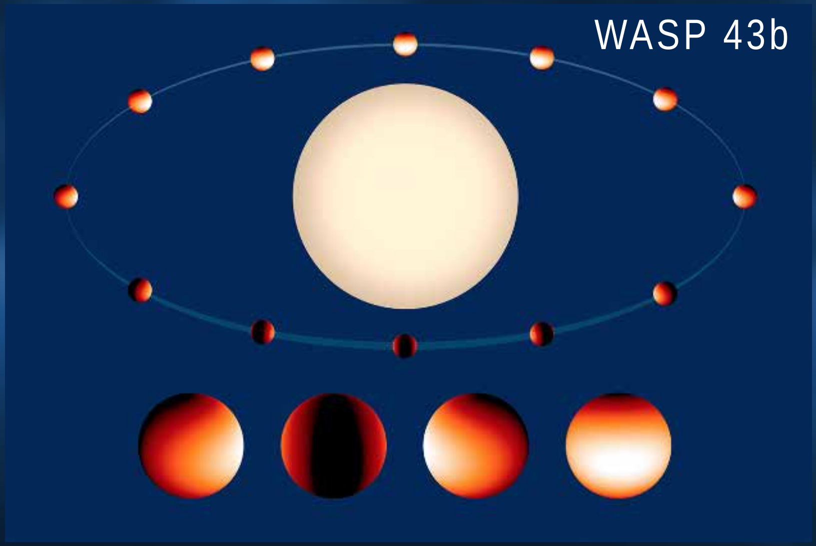
# The Hubble Space Telescope

Hubble has made important contributions to our understanding of exoplanets and exoplanetary systems by both indirect and direct observations.

- Hubble has revealed the absorption of such species as H, C, O, $CO_2$, $H_2O$, and $CH_4$ in the upper atmospheres of transiting hot Jupiters, and measured the temperature distribution and water abundance at varying depths into their atmospheres.




Hubble/NICMOS measurement of the absorption of methane in the atmosphere of HD189733b. *Swain et al., Nature, 2008*.

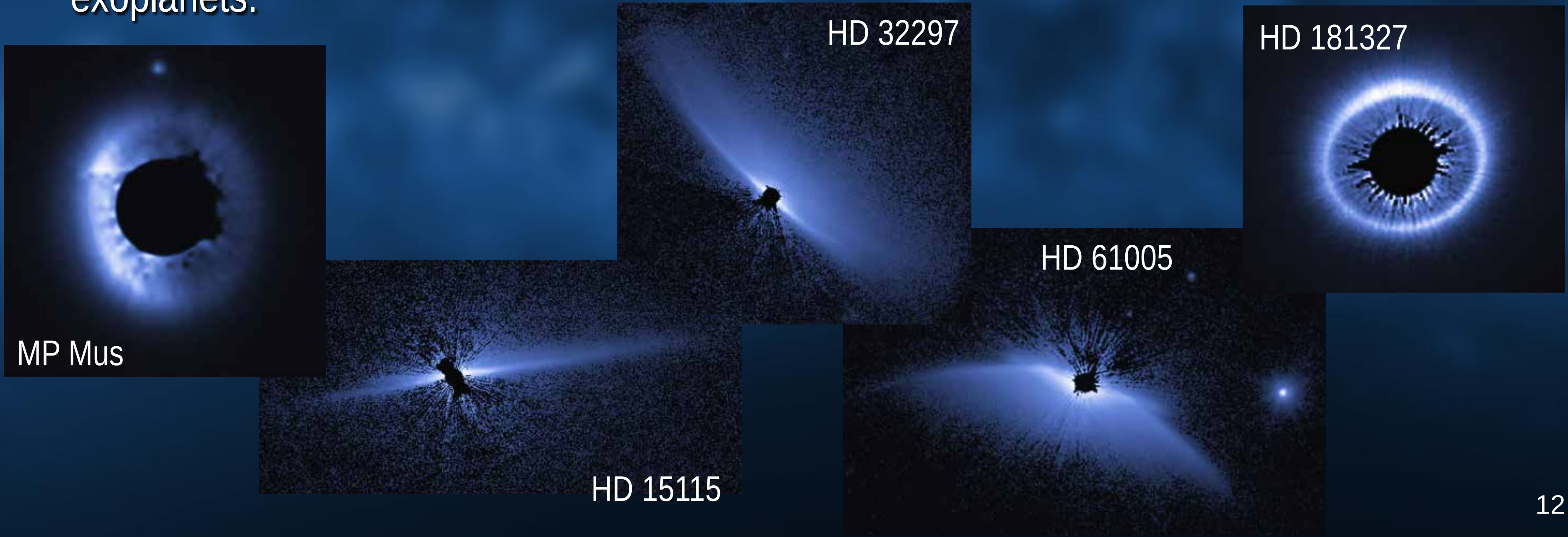



The temperature map of exoplanet WASP-43b reveals a steep temperature gradient from 2800ºF on the day side to 1000ºF on the night side. *Stevenson et al., Science, 2014*.

# The Hubble Space Telescope

Hubble has made important contributions to our understanding of exoplanets and exoplanetary systems by both indirect and direct observations.

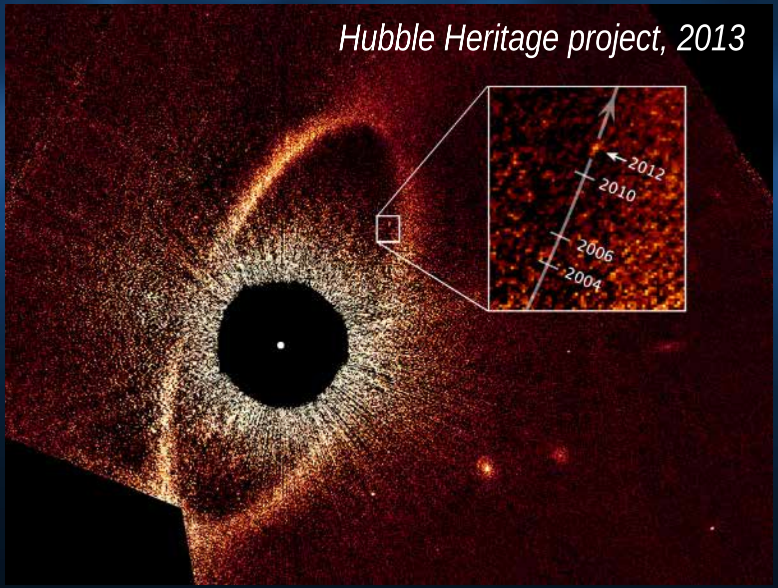
- Hubble has revealed the absorption of such species as H, C, O, $CO_2$, $H_2O$, and $CH_4$ in the upper atmospheres of transiting hot Jupiters, and measured the temperature distribution and water abundance at varying depths into their atmospheres.
- Hubble has also been used to directly image debris disks in nearby, nascent planetary systems and study how they are sculpted by the influence of (seen and unseen) exoplanets.



# The Hubble Space Telescope

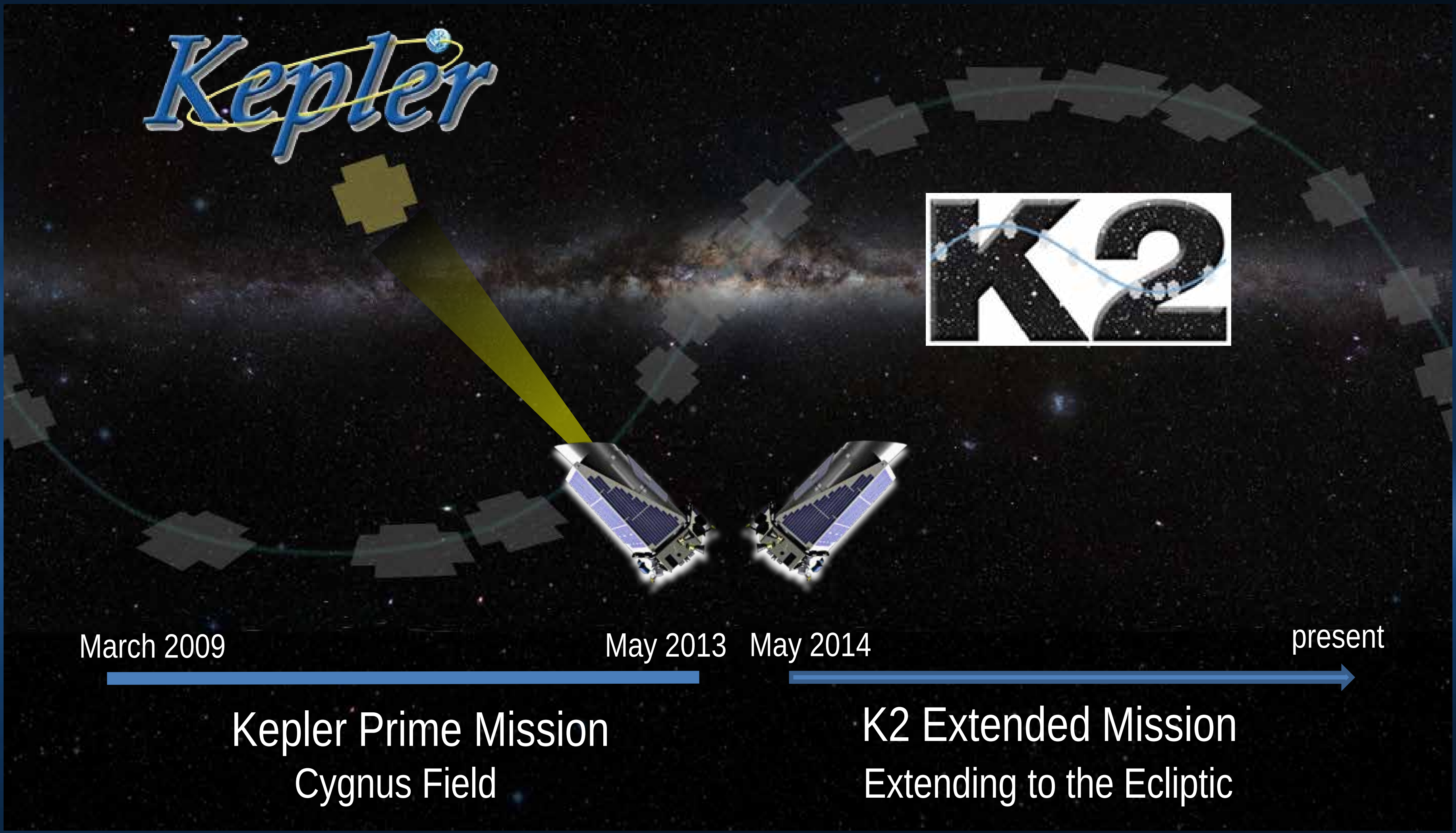
Hubble has made important contributions to our understanding of exoplanets and exoplanetary systems by both indirect and direct observations.

- Hubble has revealed the absorption of such species as H, C, O, $CO_2$, $H_2O$, and $CH_4$ in the upper atmospheres of transiting hot Jupiters, and measured the temperature distribution and water abundance at varying depths into their atmospheres.
- Hubble has also been used to directly image debris disks in nearby, nascent planetary systems and study how they are sculpted by the influence of (seen and unseen) exoplanets.
- Hubble has directly imaged several young "Super-Jupiter" (M ~ a few times $M_{Jup}$) exoplanets on large (~tens to hundreds of AU) orbits around their star.




Hubble image showing the planet Fomalhaut b. Fomalhaut b is less than 500 Myr old and has a highly elliptical orbit that carries it between 50 to 300 AU from its parent star over a period of nearly 2000 years.

# The Kepler Revolution



# The Kepler Revolution

## Kepler mission Take Away #1:

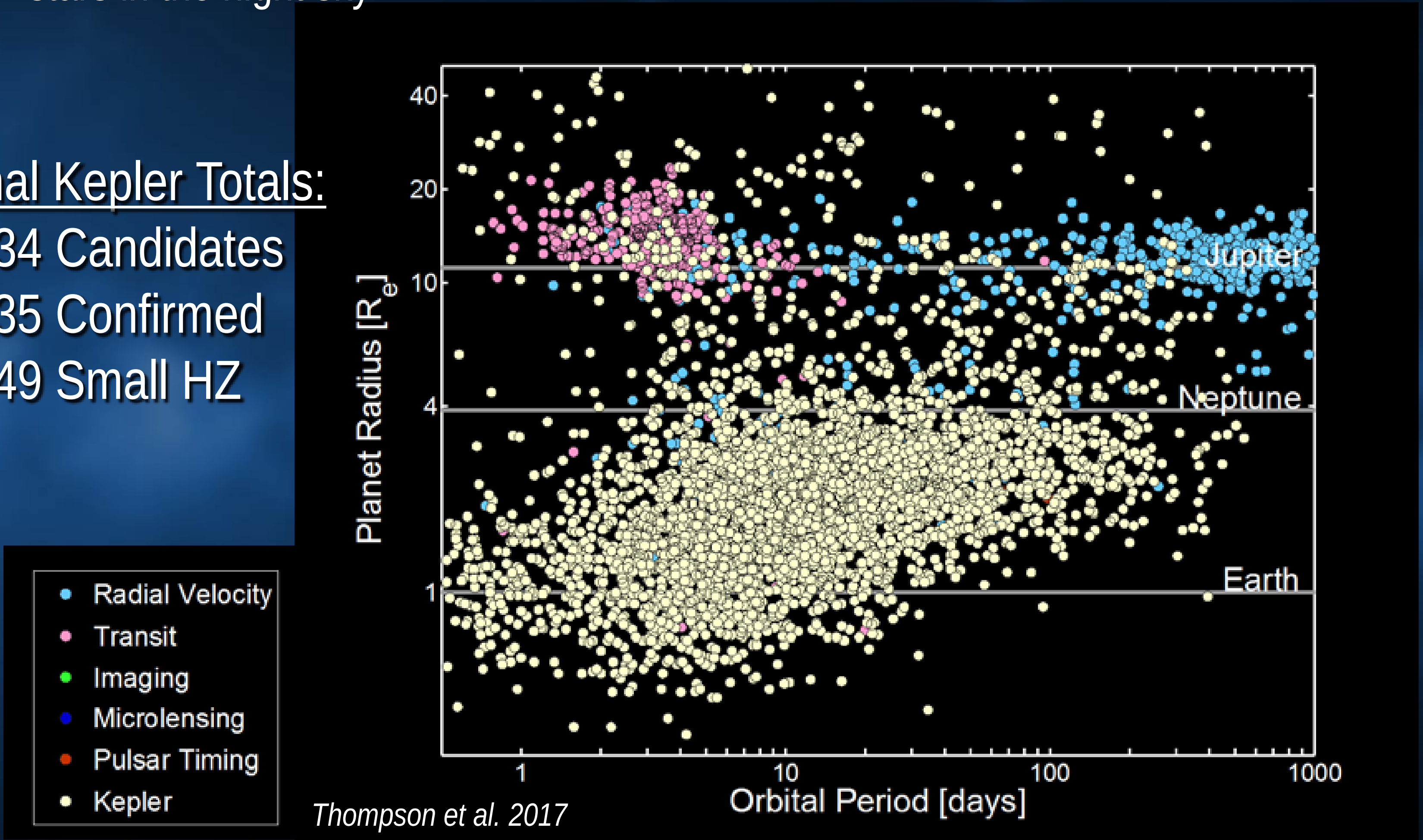
Planets are abundant. On average there is at least one planet for each of the stars in the night sky

<u>Final Kepler Totals:</u>

4034 Candidates

2335 Confirmed

49 Small HZ

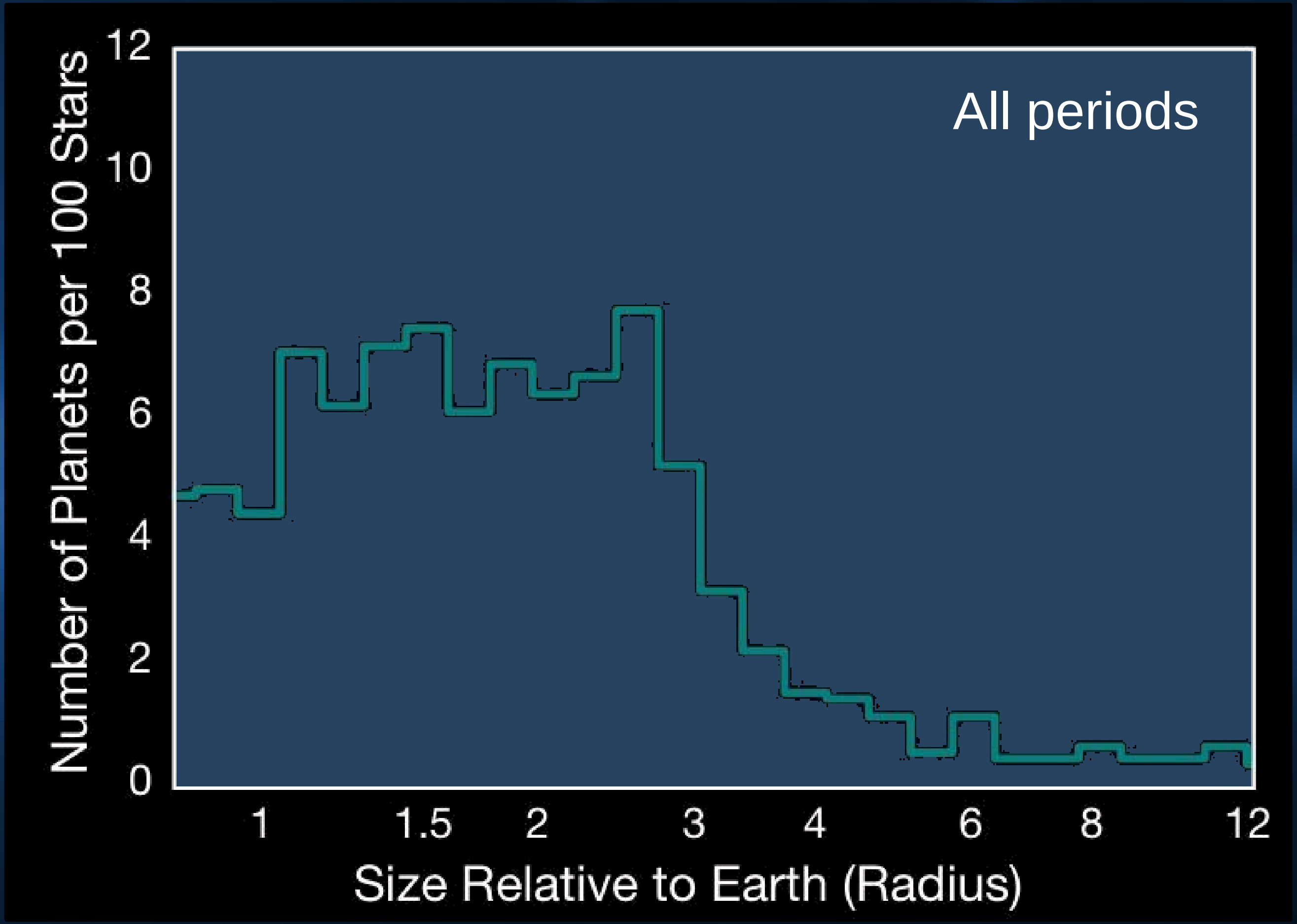



*Thompson et al. 2017*

# The Kepler Revolution

## Kepler mission Take Away #2:

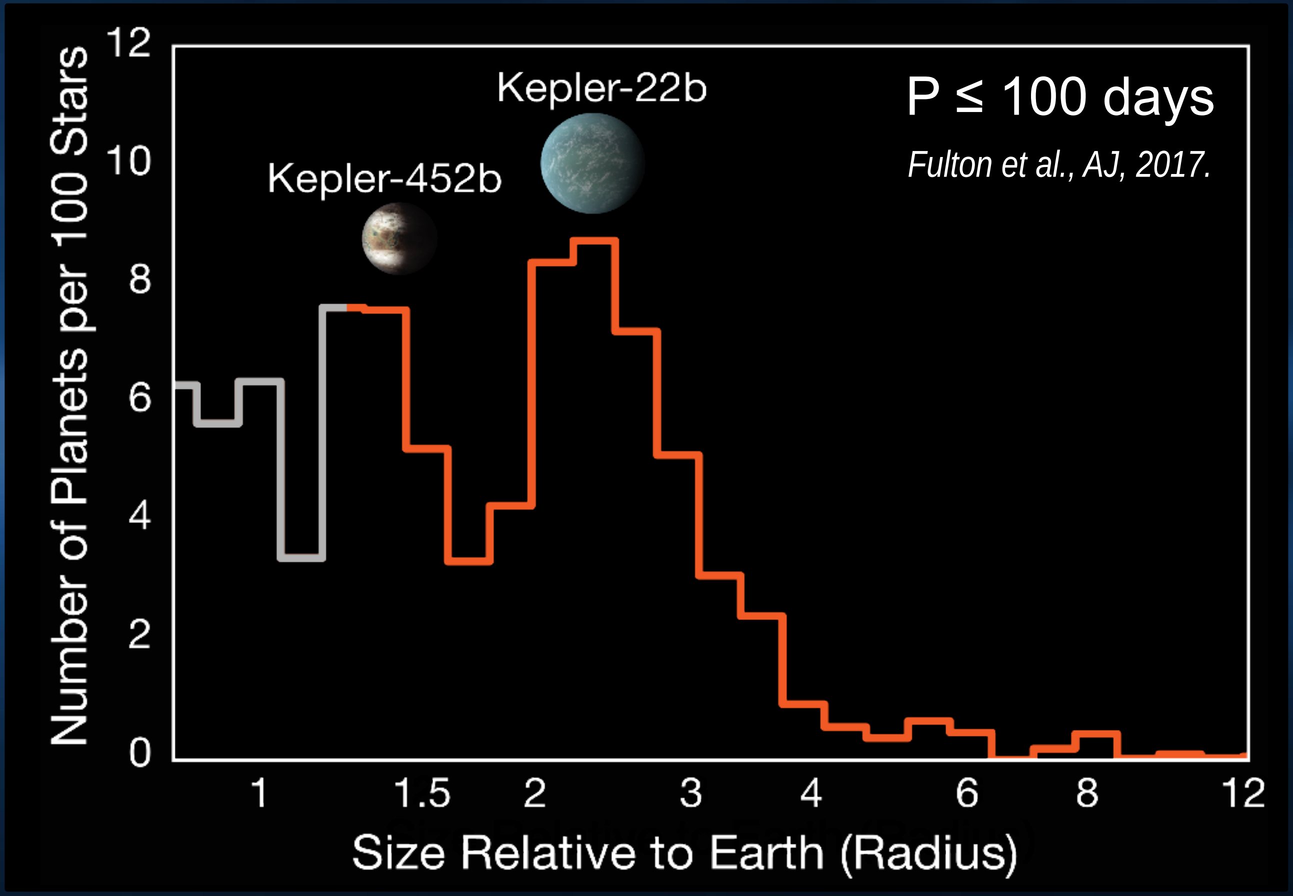
Small Planets ($R \leq 4\ R_{Earth}$) are by far the most abundant



# Kepler Revolution

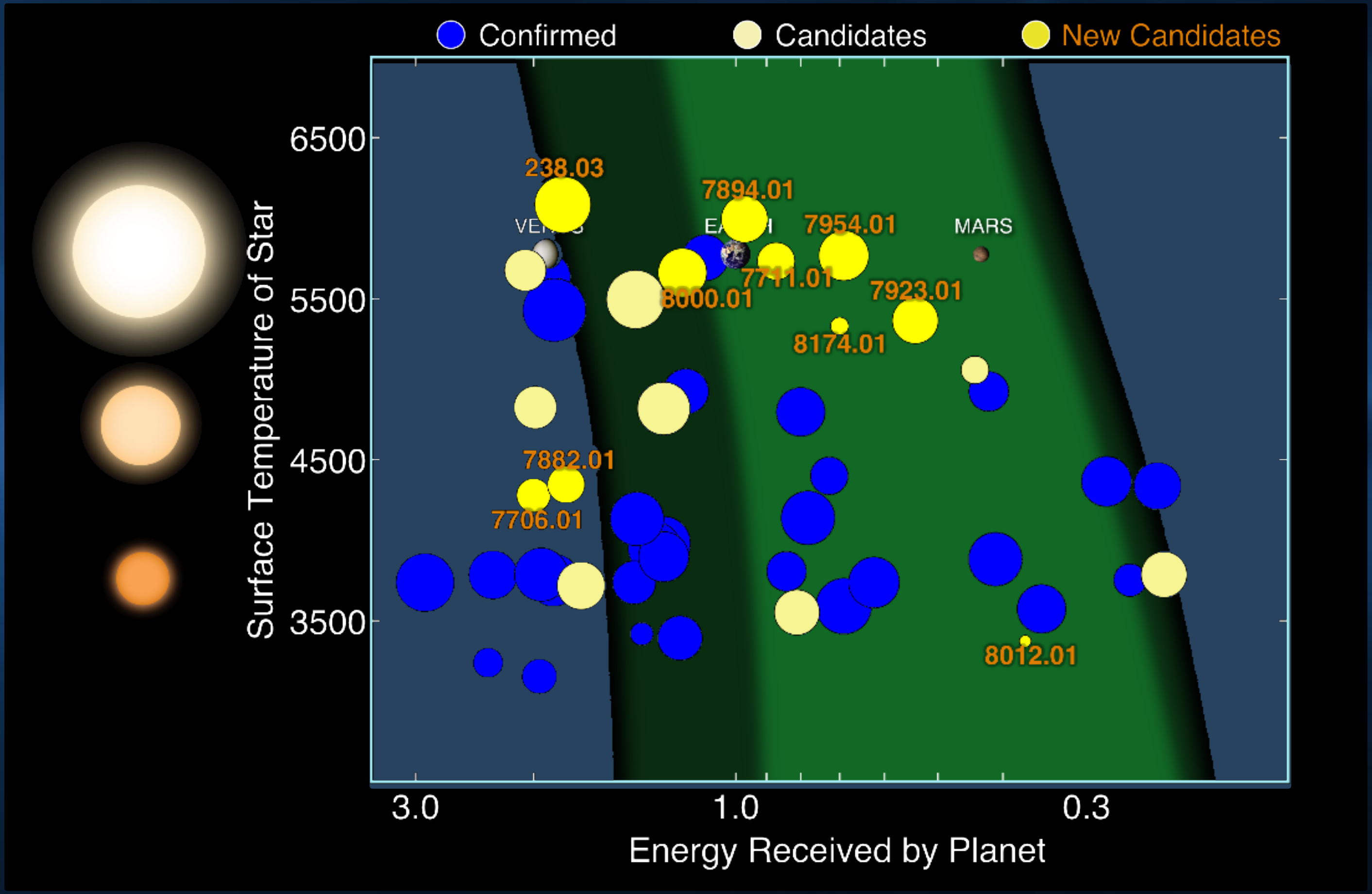
## Kepler mission Take Away #3:

Small Planets ($R \leq 4\ R_{Earth}$) are by far the most abundant
and they fall into two distinct size bins: $R \leq 1.5\ R_{Earth}$, $R \geq 2\ R_{Earth}$



# Kepler mission Take Away #4:

Planets with $R \leq 2\ R_{Earth}$ are common in the habitable zones of F, G, K, and M dwarfs.



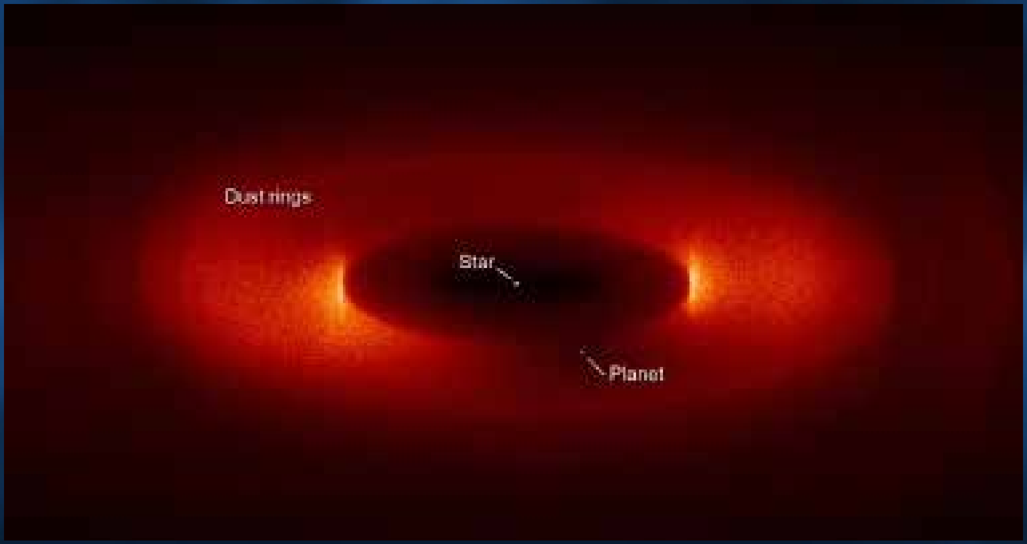
# NASA-sponsored Ground Based Projects

## Large Binocular Telescope Interferometer

Measuring average levels of exozodiacal dust in the habitable zone to inform the design of future exoplanet direct detection missions.

- Survey of zodiacal dust levels around 35 stars scheduled for completion is Sept. 2018
- Precision: 12 zodi single star one sigma; ensemble mean uncertainty better than 2 zodi
- Responds to Astro 2010 call for exoplanet precursor science

*LBTI instrument (green structure) mounted between the two LBT primary mirrors*



# NASA-sponsored Ground Based Projects

## Large Binocular Telescope Interferometer

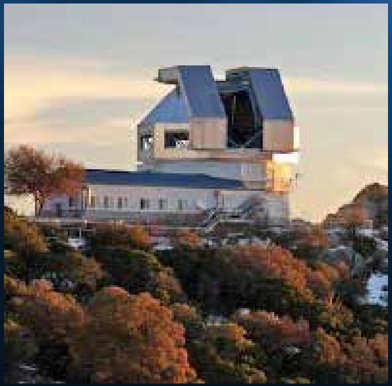
Measuring average levels of exozodiacal dust in the habitable zone to inform the design of future exoplanet direct detection missions.

- Survey of zodiacal dust levels around 35 stars scheduled for completion is Sept. 2018
- Precision: 12 zodi single star one sigma; ensemble mean uncertainty better than 2 zodi
- Responds to Astro 2010 call for exoplanet precursor science

## NASA-NSF EXoPLanet Observational REsearch (NN_EXPLORE)

Partnership to use the NOAO share of the 3.5-m WIYN telescope on Kitt Peak to provide the community with the access and cutting-edge tools to conduct ground-based observations that advance exoplanet science

- Responds to Astro2010 call for investment in ground-based precision radial-velocity capabilities
- Emphasis on community follow-up of K2 and TESS targets & precursor science in support of future missions (Webb, WFIRST)

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

# NASA-sponsored Ground Based Projects

## Large Binocular Telescope Interferometer

Measuring average levels of exozodiacal dust in the habitable zone to inform the design of future exoplanet direct detection missions.

- Survey of zodiacal dust levels around 35 stars scheduled for completion is Sept. 2018
- Precision: 12 zodi single star one sigma; ensemble mean uncertainty better than 2 zodi
- Responds to Astro 2010 call for exoplanet precursor science

## NASA-NSF EXoPLanet Observational REsearch (NN_EXPLORE)

Partnership to use the NOAO share of the 3.5-m WIYN telescope on Kitt Peak to provide the community with the access and cutting-edge tools to conduct ground-based observations that advance exoplanet science

- Responds to Astro2010 call for investment in ground-based precision radial-velocity capabilities
- Emphasis on community follow-up of K2 and TESS targets & precursor science in support of future missions (JWST, WFIRST)

## W. M. Keck Observatory

Strategic observing in support of NASA Astrophysics and Planetary Science flight missions.

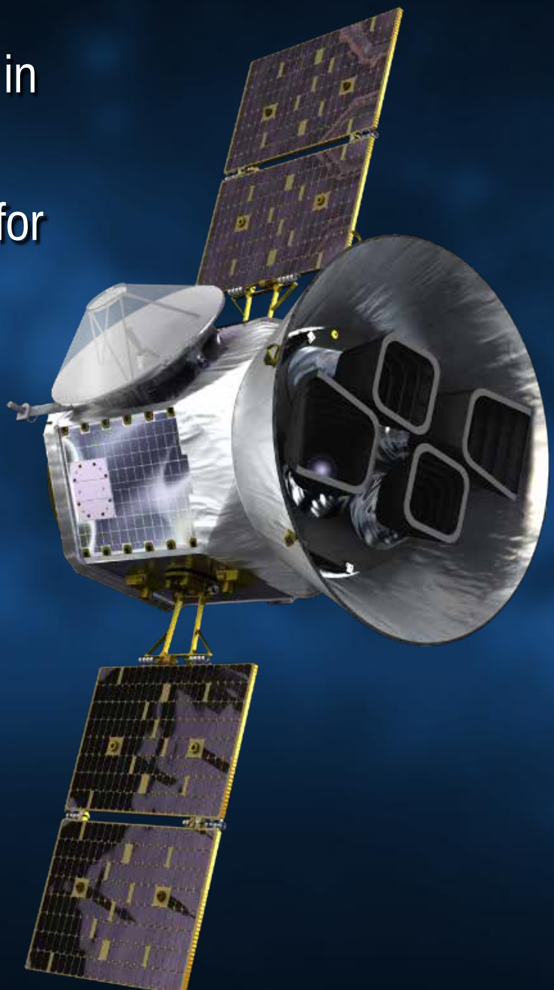
- Advancing mission science through key strategic mission support observing programs, e.g. Kepler/K2, Hubble, WFIRST/Euclid, Webb, Europa Clipper.

# Exoplanet Exploration at NASA 2018 - 2025

# The TESS Mission

**The Transiting Exoplanet Survey Satellite (TESS) – NASA's next mission dedicated to exoplanet exploration.**

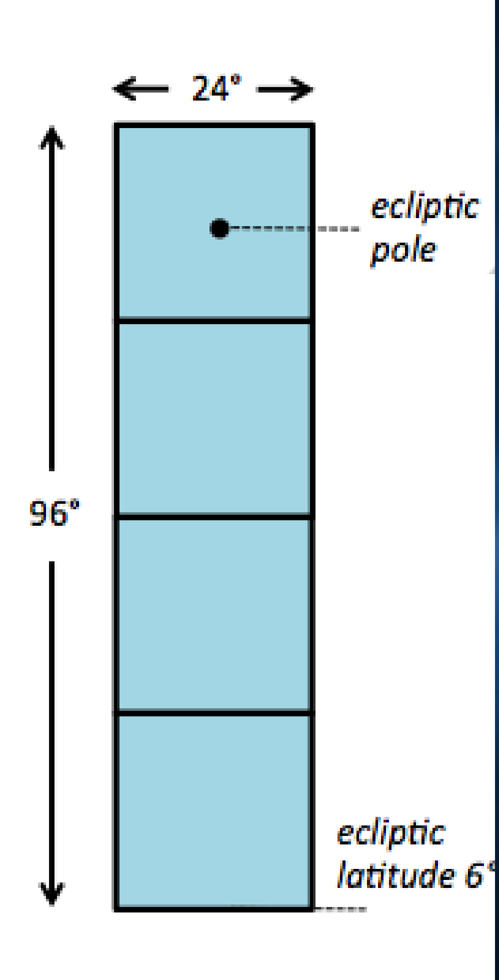
- Selected under NASA's Astrophysics Explorers Program in 2013.
- TESS is a two-year mission to provide an all-sky survey for transiting exoplanets around the nearest and brightest stars.



# The TESS Mission

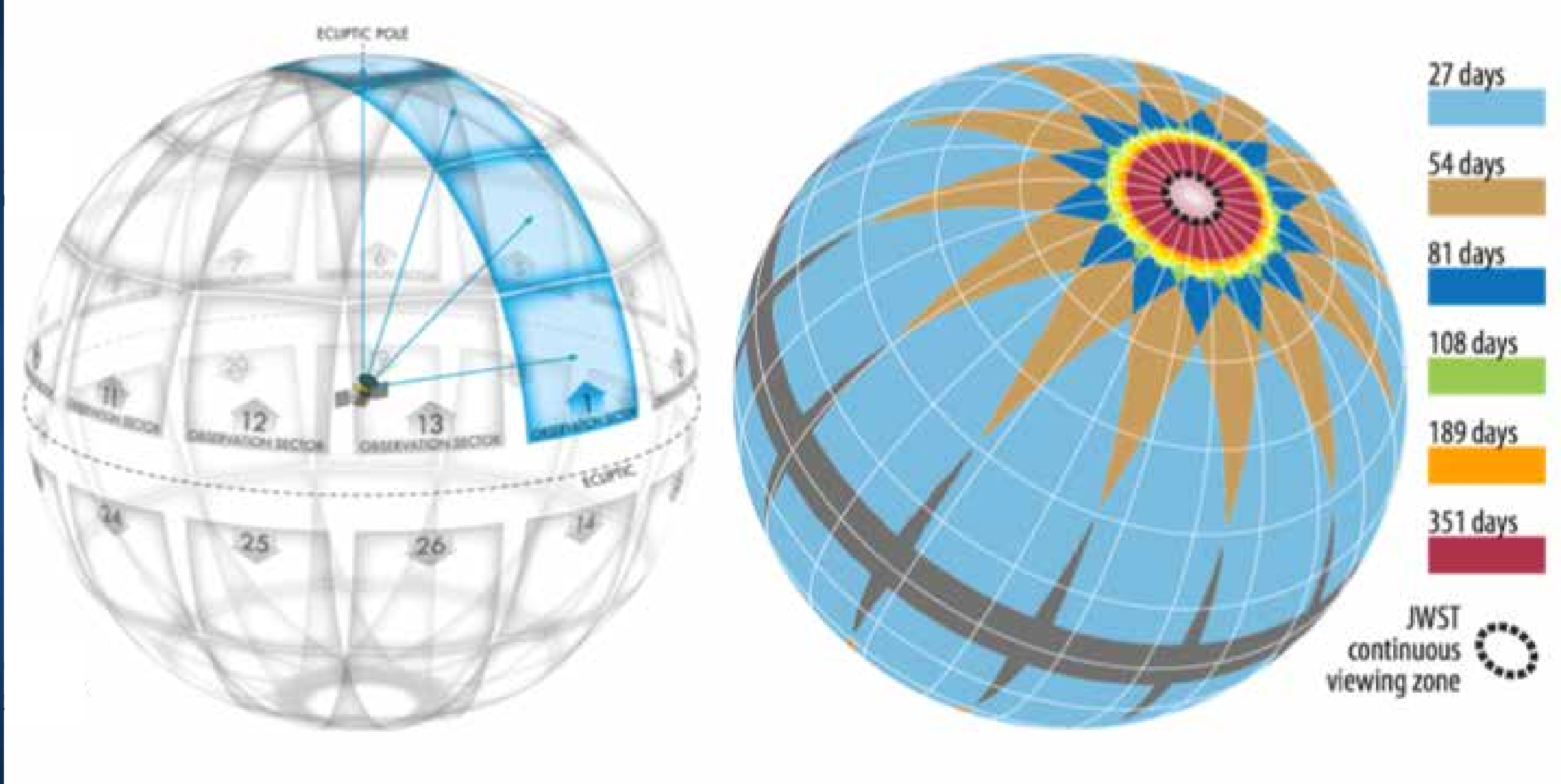
**The Transiting Exoplanet Survey Satellite (TESS) – NASA's next mission dedicated to exoplanet exploration.**

- Selected under NASA's Astrophysics Explorers Program in 2013.
- TESS is a two-year mission to provide an all-sky survey for transiting exoplanets around the nearest and brightest stars.
- TESS is made up of 4 wide-field cameras that together provide a 24º x 96º field of view.
- TESS is an MIT-led NASA mission scheduled to launch in April 2018.
- By surveying the nearest and brightest stars, TESS will provide ideal targets for exoplanet characterization observations by Webb and perhaps other future exoplanet characterization missions.



# The TESS Mission

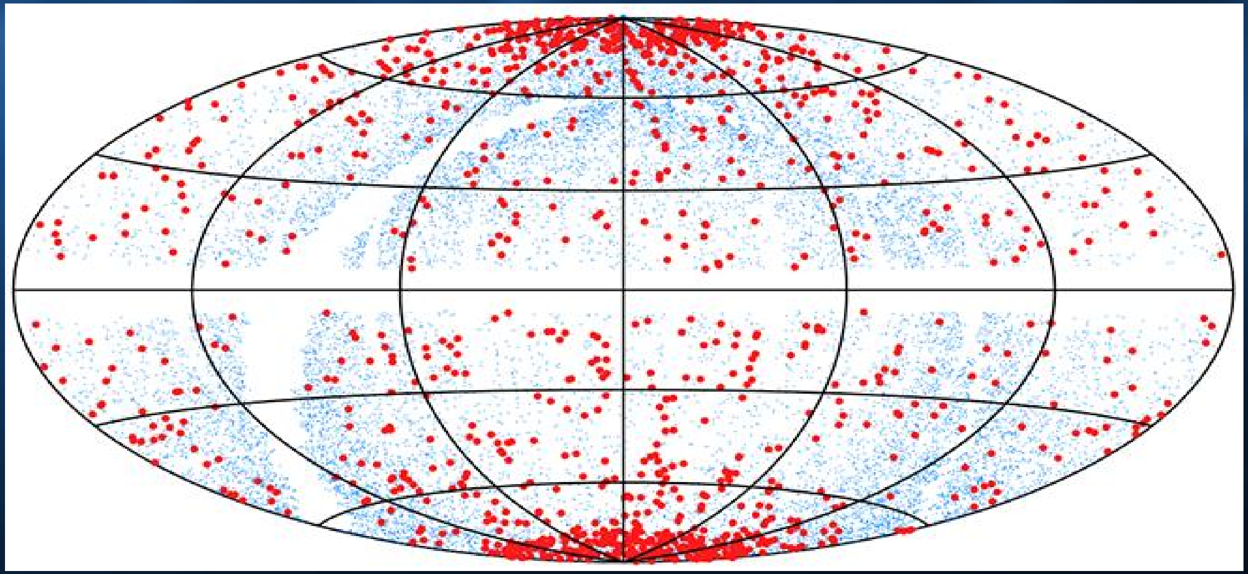
- TESS will survey the sky in a series of 26 27-day observing campaigns, beginning with the southern hemisphere sky.




Ricker et al. (2014)
Sullivan et al. (2015)

# The TESS Mission

- TESS will survey the sky in a series of 26 27-day observing campaigns, beginning with the southern hemisphere sky.
- TESS will not only monitor the brightness of some 200,000 pre-selected target stars across the sky every 2 min, but it will also collect full-frame images (FFIs) of the entire TESS FOV every 30 min.
- It is predicted that the TESS targets will yield ~1600 new exoplanets, while the FFIs may yield as many as 20,000 more.

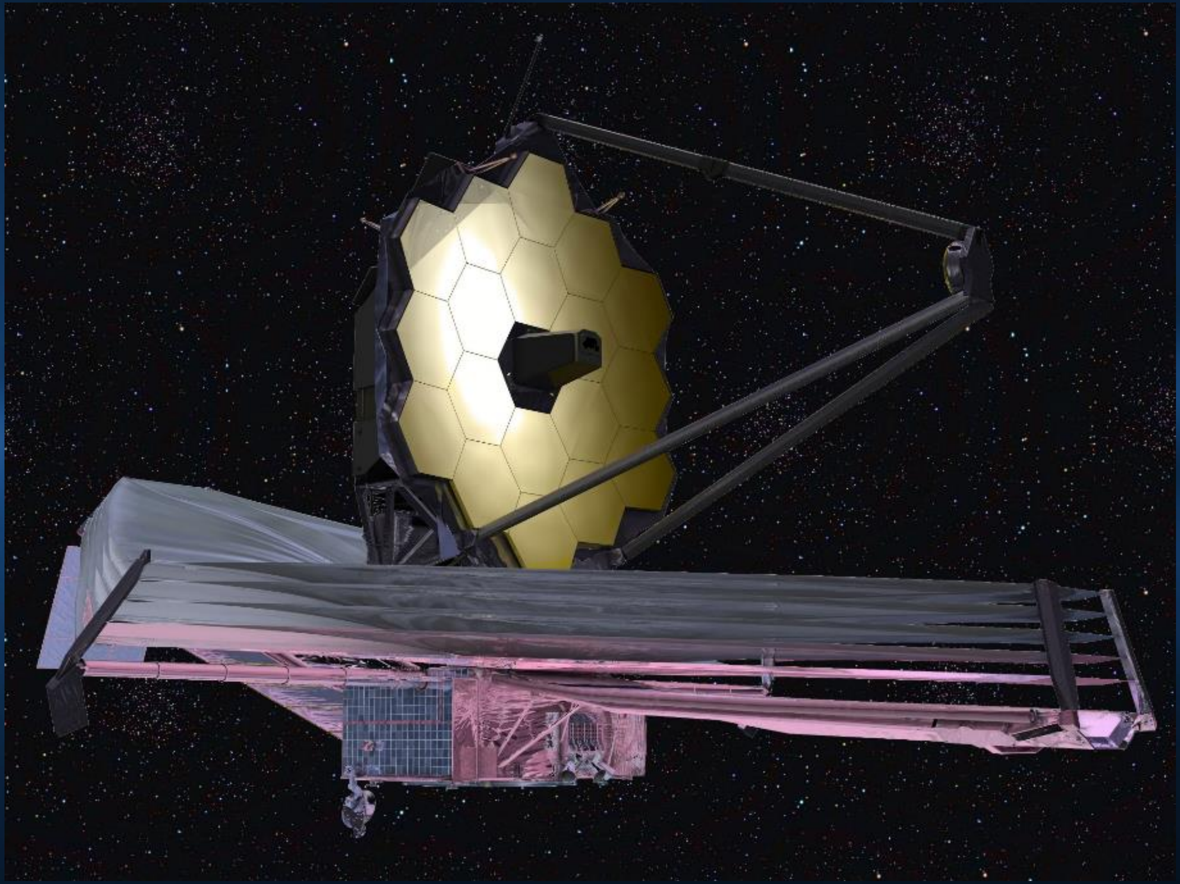


- Detectable planets around 200,000 target stars
- Detectable planets around 2,000,000 stars in FFIs

Ricker et al. (2014)
Sullivan et al. (2015)

# James Webb Space Telescope

The James Webb Space Telescope, NASA's next Great Observatory, is a 6.5-m space telescope operating at near- and mid-infrared wavelengths and scheduled to launch in 2019.

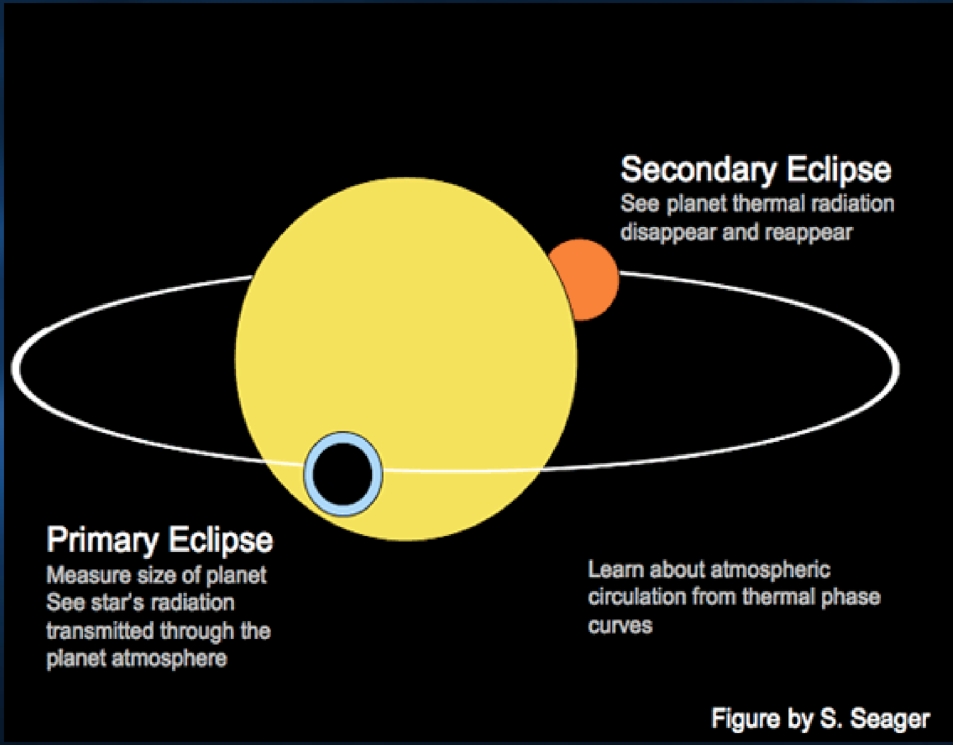


# James Webb Space Telescope

The James Webb Space Telescope, NASA's next Great Observatory, is a 6.5-m space telescope operating at near- and mid-infrared wavelengths and scheduled to launch in 2019.

Webb will make important contributions to exoplanet science in two ways:

1) Transit/eclipse spectroscopy. By measuring the spectrum of light filtering through the atmosphere of a transiting exoplanet, or that emitted from the exoplanet, Webb will be able to probe the atmospheric composition and climatic characteristics of smaller planets on larger orbits than ever before.



# James Webb Space Telescope

The James Webb Space Telescope, NASA's next Great Observatory, is a 6.5-m space telescope operating at near- and mid-infrared wavelengths and scheduled to launch in 2019.

Webb will make important contributions to exoplanet science in two ways:

2) Direct Imaging of large, young planets on large orbits (~10s of

# James Webb Space Telescope

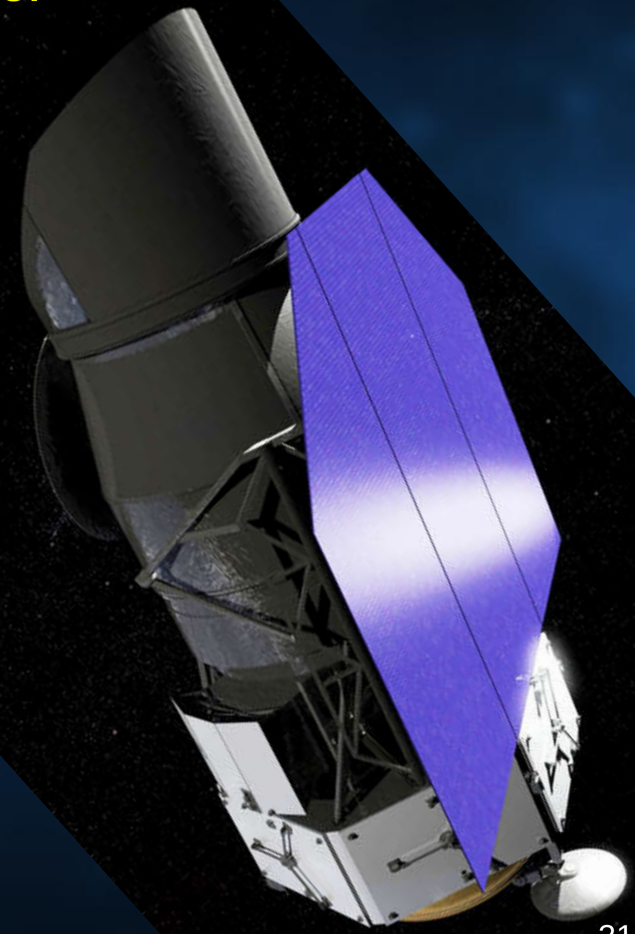
## Cycle 1 Webb observations of Exoplanets and Exoplanetary systems (includes both Guaranteed Time and Early Release Science observations).

| Program | Title | PI | Allocation (hrs) |
|---|---|---|---|
| GTO 1177 | MIRI observations of transiting exoplanets | Greene | 75 |
| GTO 1185 | Transit Spectroscopy of Mature Planets | Greene | 154 |
| GTO 1188 | Spectroscopy of Young, Widely Separated Exoplanets | Hodapp | 23.8 |
| GTO 1193 | Coronagraphic Imaging of Young Planets - Part 1 - Moonshots | Beichman | 46 |
| GTO 1194 | Characterization of the HR 8799 planetary system and planet search | Beichman | 15 |
| GTO 1195 | Coronagraphic Imaging of Young Planets - Part 3 | Beichman | 10 |
| GTO 1200 | Architecture of Directly-Imaged Extrasolar Planetary Systems | Rameau | 7.5 |
| GTO 1201 | NIRISS Exploration of the Atmospheric diversity of Transiting exoplanets (NEAT) | Lafreniere | 200 |
| GTO 1224 | Transiting exoplanet characterization with JWST/NIRSPEC | Birkmann | 50 |
| GTO 1241 | MIRI Coronagraphic Imaging of exoplanets | Ressler | 19 |
| GTO 1270 | Characterizing the TWA 27 system | Birkmann | 8.3 |
| GTO 1274 | Extrasolar Planet Science with JWST | Lunine | 74.3 |
| GTO 1277 | Coronographic Observations of Young Exoplanets | Lagage | 15.2 |
| GTO 1279 | Thermal emission from Trappist1-b | Lagage | 25.1 |
| GTO 1280 | MIRI Transiting Observation of WASP-107b | Lagage | 10.1 |
| GTO 1281 | MIRI and NIRSPEC Transit Observations of HAT-P-12 b | Lagage | 32.1 |
| ERS 1366 | The Transiting Exoplanet Community Early Release Science Program | Batalha | 78.1 |
| ERS 1386 | High Contrast Imaging of Exoplanets and Exoplanetary Systems with JWST | Hinkley | 38.8 |
| | | TOTAL | 882.3 |

# WFIRST*

The Wide-Field InfraRed Survey Telescope (WFIRST) - a space observatory designed to settle fundamental questions in the areas of dark energy, exoplanets, and near-infrared astrophysics.

- 2.4-m space telescope, same size as the Hubble space telescope but with 100x larger field of view.
- 5-year mission planned for launch in mid-2020s.
- Equipped with two instruments:
  - Wide-Field Instrument (WFI) – a 288 megapixel camera operating in the near-infrared (0.7 - 2.0 μm).
  - Coronagraph Instrument (CGI) – a technology demonstration instrument designed to demonstrate key coronagraph technologies required for a future exoplanet direct detection mission.



*Proposed for termination in FY 19 President's Budget

# WFIRST Exoplanet Science – gravitational microlensing exoplanet survey.

When a foreground star passes in front of a more distant star, its gravitational attraction focuses the light causing it to appear to brighten.

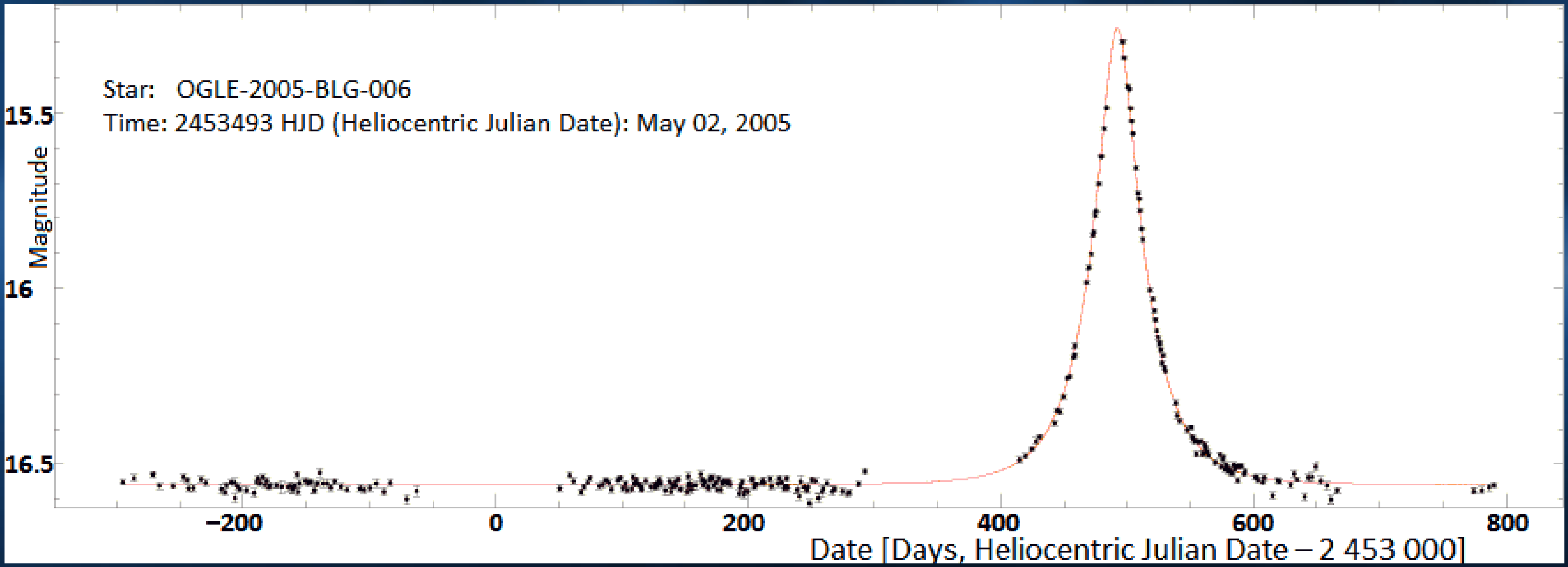



*Figure by J. Skowron, 2006*

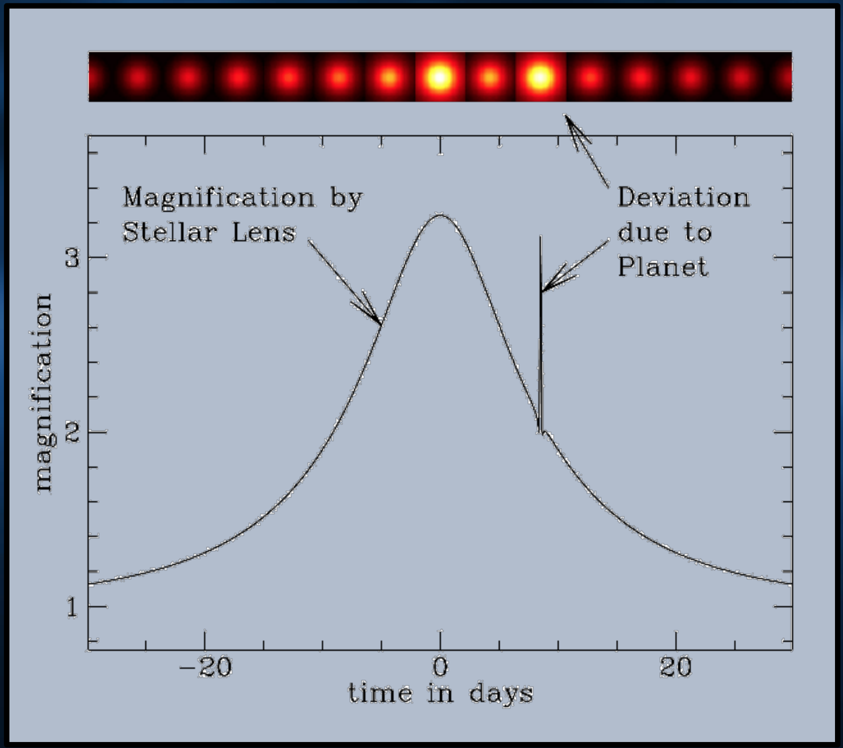
WFIRST

# WFIRST Exoplanet Science – gravitational microlensing exoplanet survey.

When a foreground star passes in front of a more distant star, its gravitational attraction focuses the light causing it to appear to brighten.

If the lensing star happens to have a planet around it, the gravitational attraction of the planet will give rise to an observable “blip” in the light curve

Gravitational microlensing is sensitive to planets as small as Earth on orbits larger than ~1 AU, so it will be a perfect compliment to Kepler and RV surveys

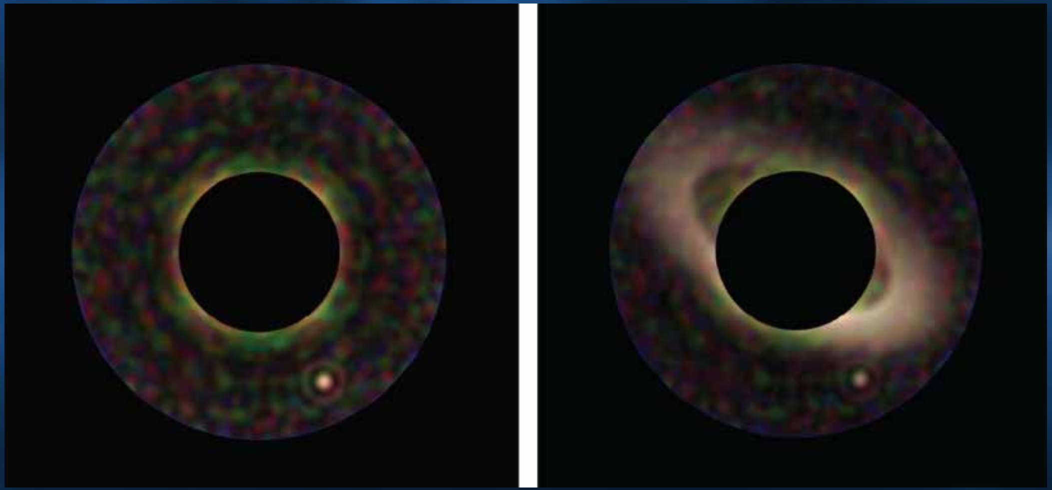



*Courtesy D. Bennett*

# WFIRST Exoplanet Science – exoplanet direct imaging.

As a technology demonstration, WFIRST will carry into space the first coronagraph designed for exoplanet direct imaging.

- A coronagraph is an instrument designed to efficiently block the light from a star, allowing scientists to detect and study much fainter objects lying close by.
- If the technology demonstration is fully successful, the WFIRST CGI will allow the first direct images of Jupiter, Saturn, and Neptune-sized exoplanets orbiting a few AU from their star.



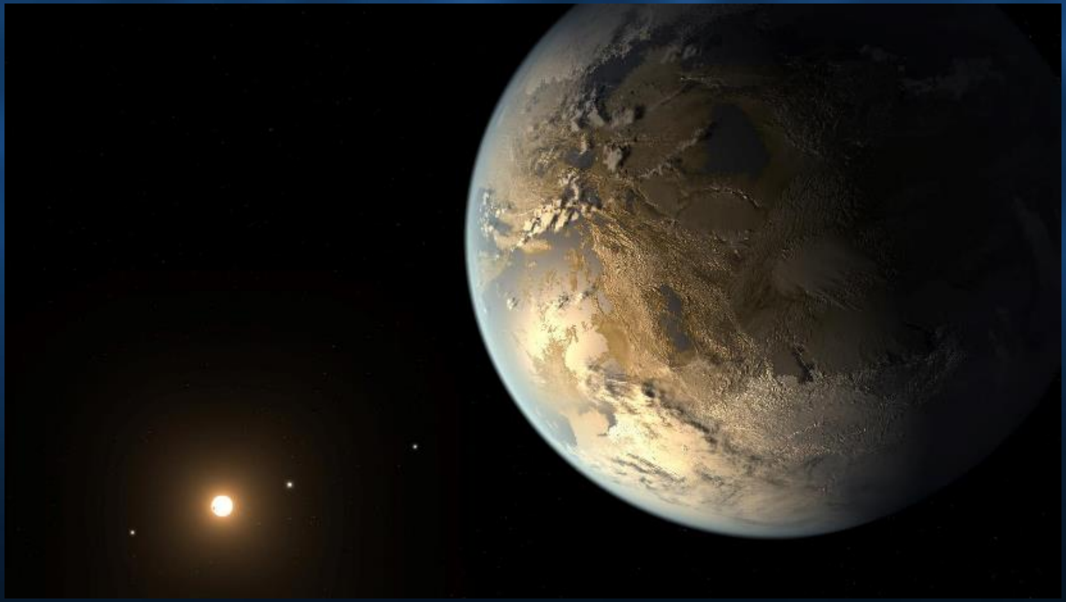
Simulation of expected image with CGI on WFIRST of a planet (at about 5 o'clock) with no zodiacal dust cloud (left) and with a zodiacal dust cloud (right).

# Exoplanet Exploration at NASA Beyond 2025

# Exoplanet Exploration Beyond WFIRST

The ultimate goal of Astro2010's New Worlds Technology Development Program and NASA's Exoplanet Exploration Program is the characterization of habitable, rocky planets capable of supporting life.

- NASA's Exoplanet Exploration program is currently working to develop the technology that will be needed to fly a future "New Worlds Mission"—a space mission capable of imaging Earth-sized, rocky planets in the habitable zones of their stars and determining their characteristics.



# Exoplanet Exploration Beyond WFIRST

The ultimate goal of Astro2010's New Worlds Technology Development Program and NASA's Exoplanet Exploration Program is the characterization of habitable, rocky planets capable of supporting life.

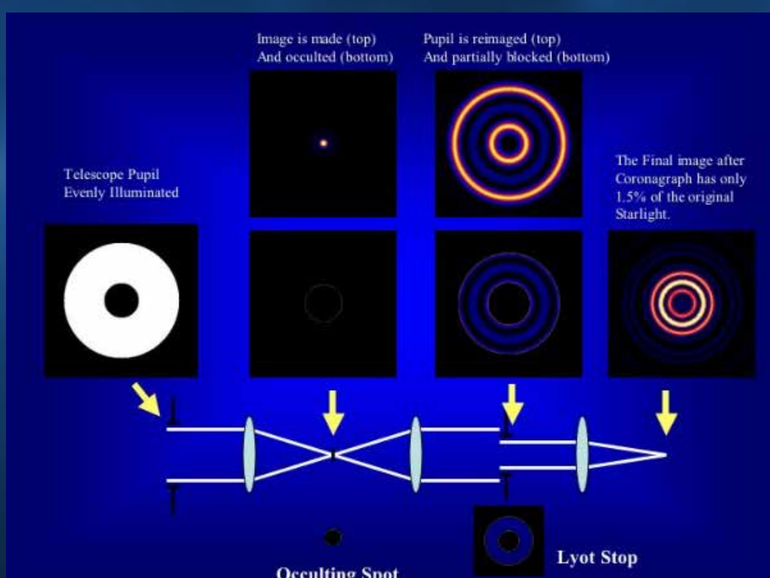
- NASA's Exoplanet Exploration program is currently working to develop the technology that will be needed to fly a future "New Worlds Mission"—a space mission capable of imaging Earth-sized, rocky planets in the habitable zones of their stars and determining their characteristics.
- The biggest challenge is "starlight suppression." The New Worlds Mission will need to be able to efficiently block the light from a star and allow us to detect the feeble reflected light from a planet 10 billion times fainter orbiting nearby.
- NASA is currently developing two candidate technologies that will allow us to achieve this demanding goal: (1) coronagraphs, and (2) starshades.

# Exoplanet Exploration Beyond WFIRST

## Coronagraphs (Internal Occulters)

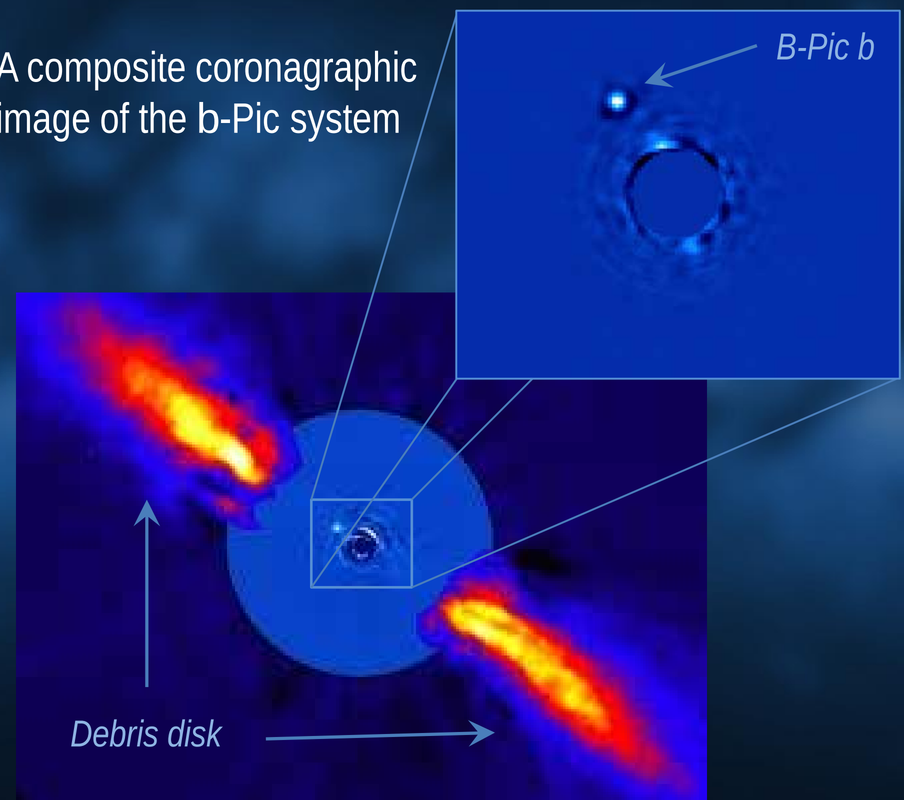
A coronagraph uses a complex array of advanced optics and field stops to “condition” the light from the telescope, correcting for aberrations and removing the light from a star while passing the light from a planet only a tiny distance away.

A schematic illustration of the Lyot Coronagraph




*Images from the Lyot Project*

A composite coronagraphic image of the b-Pic system




*Images courtesy of ESO*

# Exoplanet Exploration Beyond WFIRST

## Starshades (External Occulters)

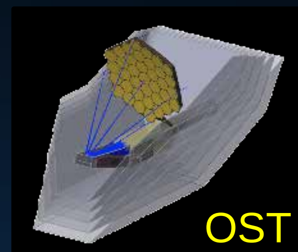
- A starshade makes use of a “sunflower” shaped mask that is tens of meters in diameter and flies tens or hundreds of thousands of kilometers in front of a normal space telescope and blocks the light from the star.
- Precise control of the shape of the petals is crucial to the performance of the starlight suppression system.

Desert testing of a starshade prototype.

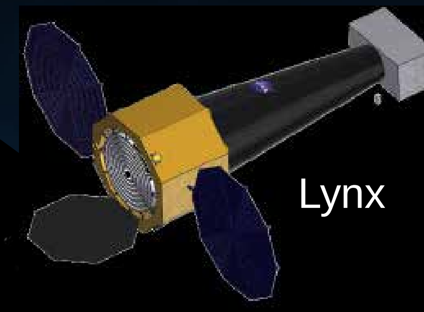
*Images courtesy S. Warwick/Northrop-Grumman Space Technologies*

# Preparing for the 2020 Decadal Survey

- Large Mission Concept Studies






- Competed Probe Concept Studies
  - Cosmic Dawn Intensity Mapper (A. Cooray)
  - Cosmic Evolution through UV Spectroscopy Probe (W. Danchi)
  - Galaxy Evolution Probe (J. Glenn)
  - High Spatial Resolution X-ray Probe (R. Mushotzky)
  - Inflation Probe (S. Hanany)
  - Multi-Messenger Astrophysics Probe (A. Olinto)
  - Precise Radial Velocity Observatory (P. Plavchan)
  - Starshade Rendezvous Mission (S. Seager)
  - Transient Astrophysics Probe (J. Camp)
  - X-ray Timing and Spectroscopy Probe (P. Ray)

- NASA Managed Exoplanet Probe Studies
  - Exo-C (probe-class coronagraphic mission)
  - Exo-S (probe-class starshade mission)


# Exoplanet Technology Gap List

NASA's technology development activities also extend to include technologies that enable or enhance the capabilities of future exoplanet missions.

NASA tracks the network of interdependent technologies through a technology gap list that is revised and updated with community input on an annual basis.

## 2017 ExEP Technology Gap List

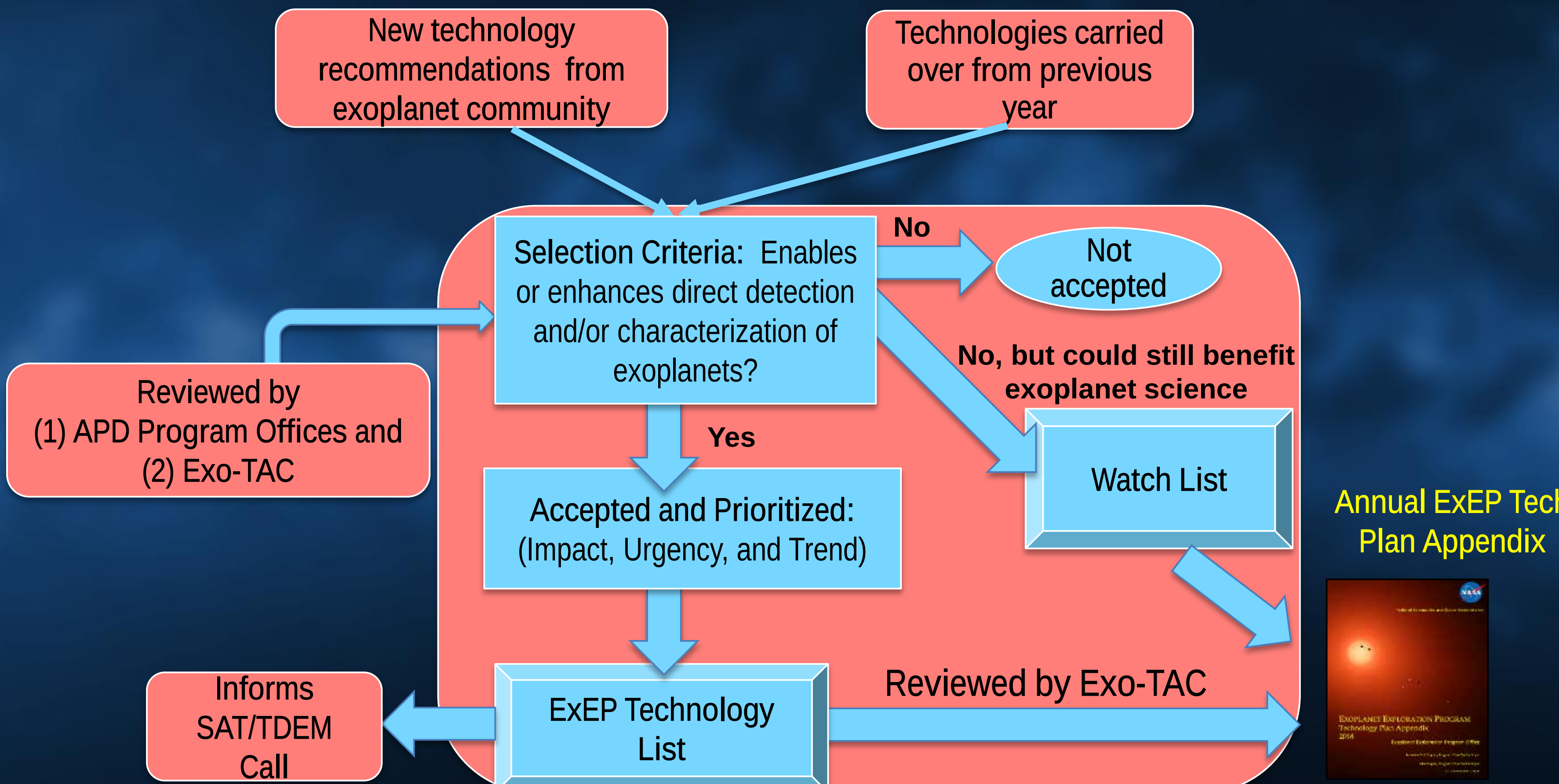
| Tech. ID | Technology Title |
|---|---|
| CG-1 | Large Aperture Primary Mirrors |
| CG-2 | Coronagraph Architecture |
| CG-3 | Deformable Mirrors |
| CG-4 | Data Post-Processing Algorithms and Techniques |
| CG-5 | Wavefront Sensing and Control |
| CG-6 | Mirror Segment Phasing |
| CG-7 | Telescope Vibration Sense/Control or Reduction |
| CG-8 | Ultra-Low Noise Visible Detectors |
| CG-9 | Ultra-Low Noise Near-Infrared Detectors |
| CG-10 | Mirror Coatings for UV/NIR/Vis |
| CG-12 | Ultra-Low Noise UV Detectors |
| CG-13 | Ultra Low-noise Mid-IR detectors |

| Tech. ID | Technology Title |
|---|---|
| CG-14 | Mid-IR Large Aperture Telescopes |
| CG-15 | Mid-IR Coronagraph Optics and Architecture |
| CG-16 | Cryogenic Deformable mirror |
| S-1 | Controlling Scattered Sunlight |
| S-2 | Starlight Suppression and Model Validation |
| S-3 | Lateral Formation Sensing |
| S-4 | Petal Shape and Stability |
| S-5 | Petal Positioning Accuracy and Opaque Structure |
| M-1 | Extreme Precision Ground-based Radial Velocity |
| M-2 | Space-based Laser Frequency Combs |
| M-3 | Astrometry |
| M-4 | Ultra-Stable Mid-IR detector |

| |
|---|
| Carried over from 2017 |
| New to list in 2018 |

# Exoplanet Technology Gap List

The technologies on the gap list are prioritized through a rigorous process involving review by an independent Exoplanet Technology Assessment Committee (ExoTAC). The resulting prioritization is published in an annual appendix to the ExEP Tech Plan and informs technology investments (both competed and directed) during the following year.



# Technology Development Supporting Potential Future Large Astrophysics Missions

### HabEx

- 12 of 12 gaps being addressed
- mirror coatings, starshade starlight suppression, starshade controlling scattered sunlight, starshade lateral formation sensing, starshade petal position accuracy, starshade petal shape and stability, *telescope vibration control*, deformable mirrors, **visible detectors**, *large aperture primary mirror*, **wavefront sensing and control**, ***coronagraph optics and architecture***

### LUVOIR

- 7 of 9 gaps being addressed
- closed-loop segment phasing, *vibration isolation*, ***wavefront sensing and control***, *mirror segments*, ***high-contrast segmented-aperture coronagraphy***, deformable mirrors, near infrared detectors, **visible detectors**, mirror coatings

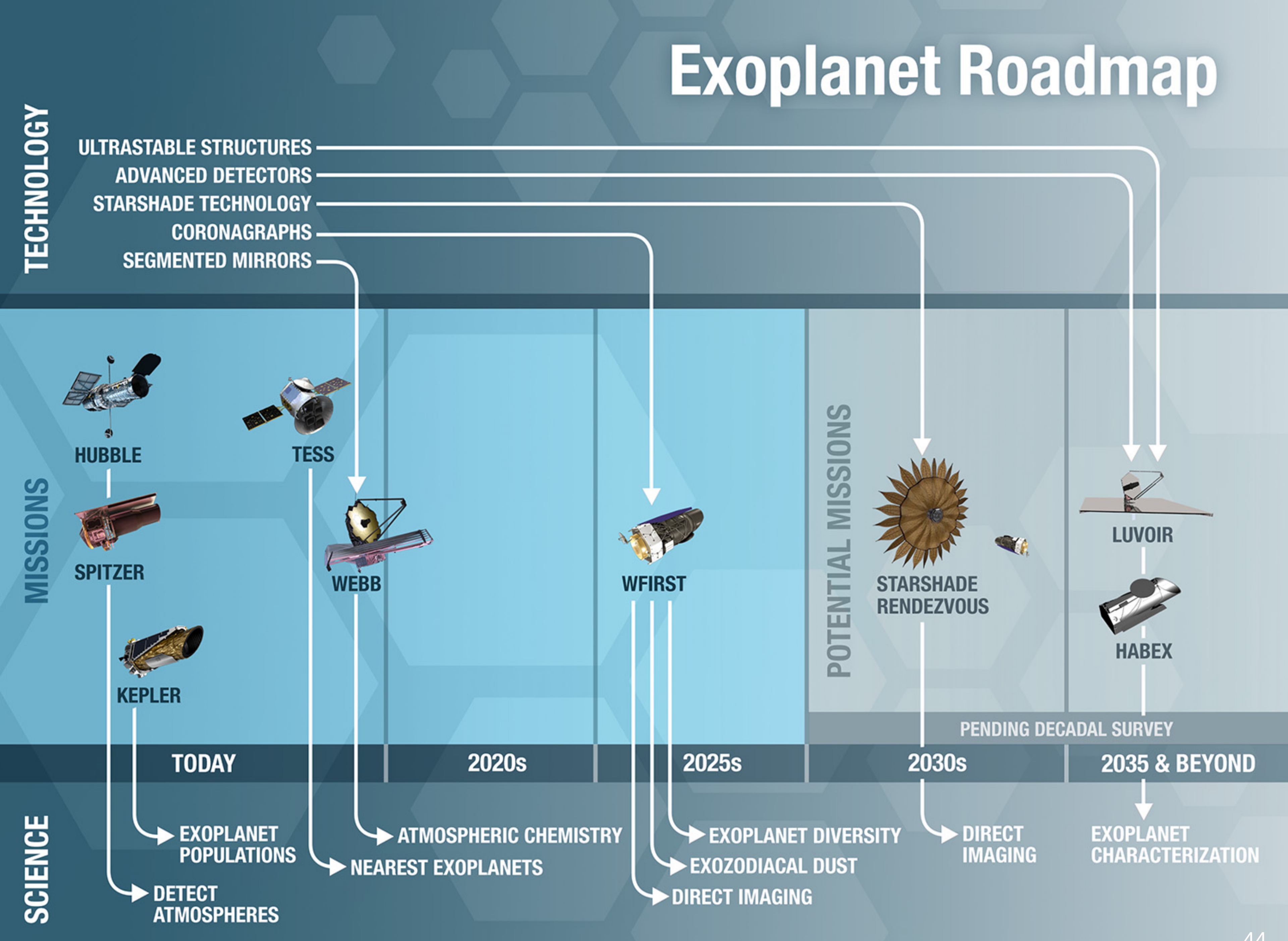
### Lynx X-ray Surveyor

- 4 of 5 gaps being addressed
- high-resolution lightweight X-ray optics, non-deforming X-ray reflecting coatings, megapixel X-ray imaging detectors, **large-format, high resolution X-ray detectors**, X-ray grating arrays

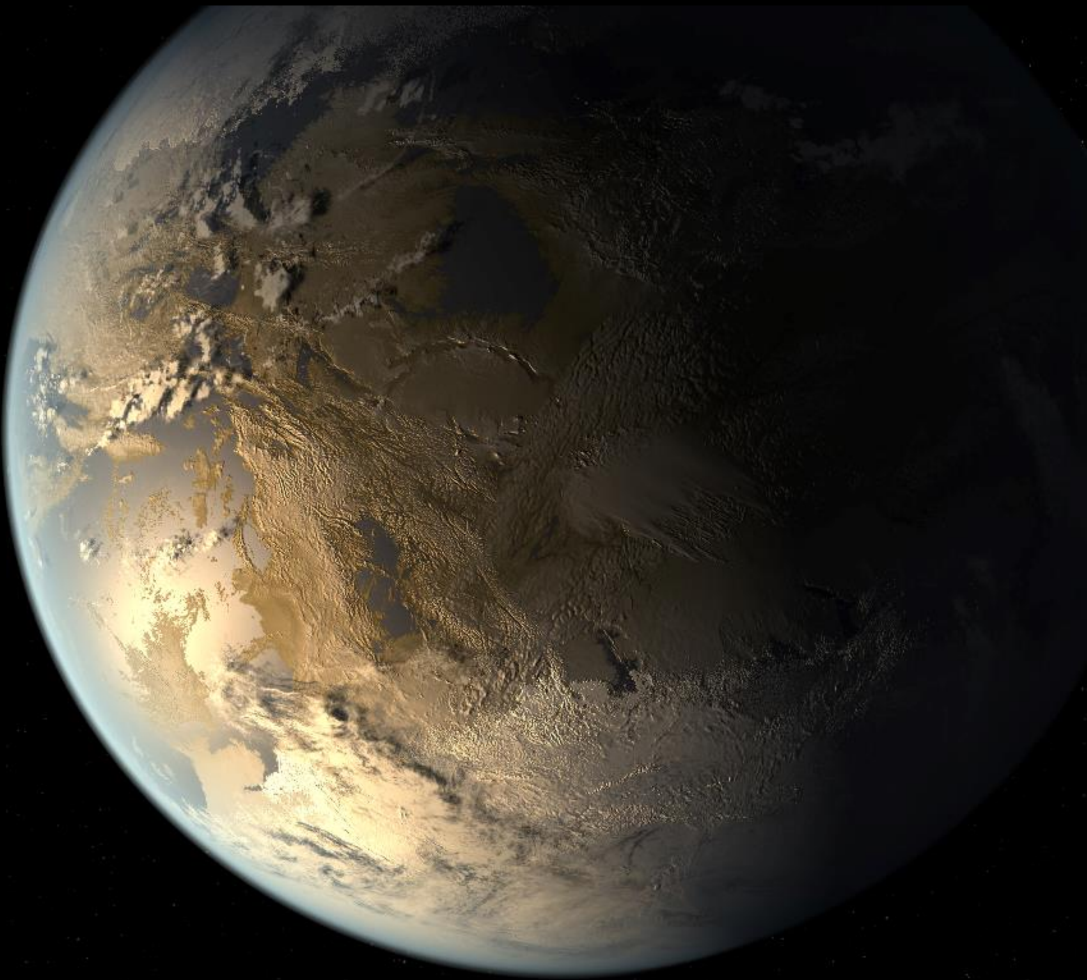
### Origins Space Telescope

- 2 of 5 gaps being addressed
- far-infrared (FIR) detectors, cryogenic readouts for large-format FIR detectors, warm readout electronics for large-format FIR detectors, sub-Kelvin Coolers, cryogenic FIR mirror segments

- Purple: technologies being advanced through SAT or directed development,
- **Bold**: technologies being advanced by WFIRST or ATHENA
- *Italics*: technologies being worked on through the STDT's design studies
- Additional gaps being addressed through APRA but not tallied here


Exoplanet Roadmap
TECHNOLOGY
ULTRASTABLE STRUCTURES
ADVANCED DETECTORS
STARSHADE TECHNOLOGY
CORONAGRAPHS
SEGMENTED MIRRORS
MISSIONS
HUBBLE
TESS
SPITZER
WEBB
KEPLER
WFIRST
POTENTIAL MISSIONS
STARSHADE RENDEZVOUS
LUVOIR
HABEX
PENDING DECADAL SURVEY
TODAY
2020s
2025s
2030s
2035 & BEYOND
SCIENCE
EXOPLANET POPULATIONS
DETECT ATMOSPHERES
ATMOSPHERIC CHEMISTRY
NEAREST EXOPLANETS
EXOPLANET DIVERSITY
EXOZODIACAL DUST
DIRECT IMAGING
DIRECT IMAGING
EXOPLANET CHARACTERIZATION

*Searching for life elsewhere*



# *Astrophysics*