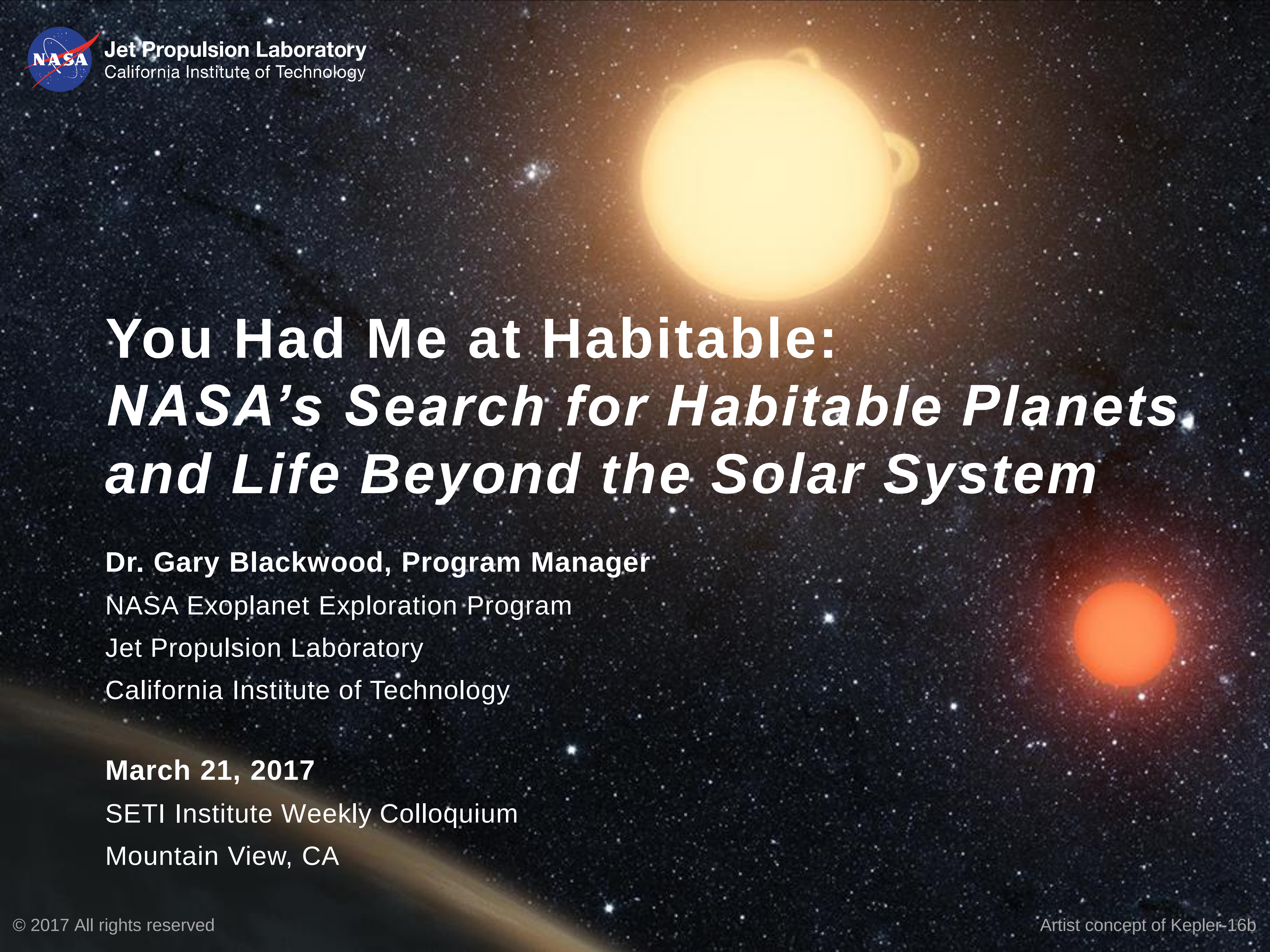

Jet Propulsion Laboratory
California Institute of Technology

You Had Me at Habitable: *NASA's Search for Habitable Planets and Life Beyond the Solar System*

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

March 21, 2017
SETI Institute Weekly Colloquium
Mountain View, CA

Artist concept of Kepler-16b

Program Overview

Science Updates

How Do We Discover & Characterize Exoplanets?

Progress towards 2010 Decadal Survey Priorities

Plan Forward: Science and Technology

You Had Me at Habitable

Program Overview

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You Had Me at Habitable

NASA Exoplanet Exploration Program

Astrophysics Division, NASA Science Mission Directorate

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

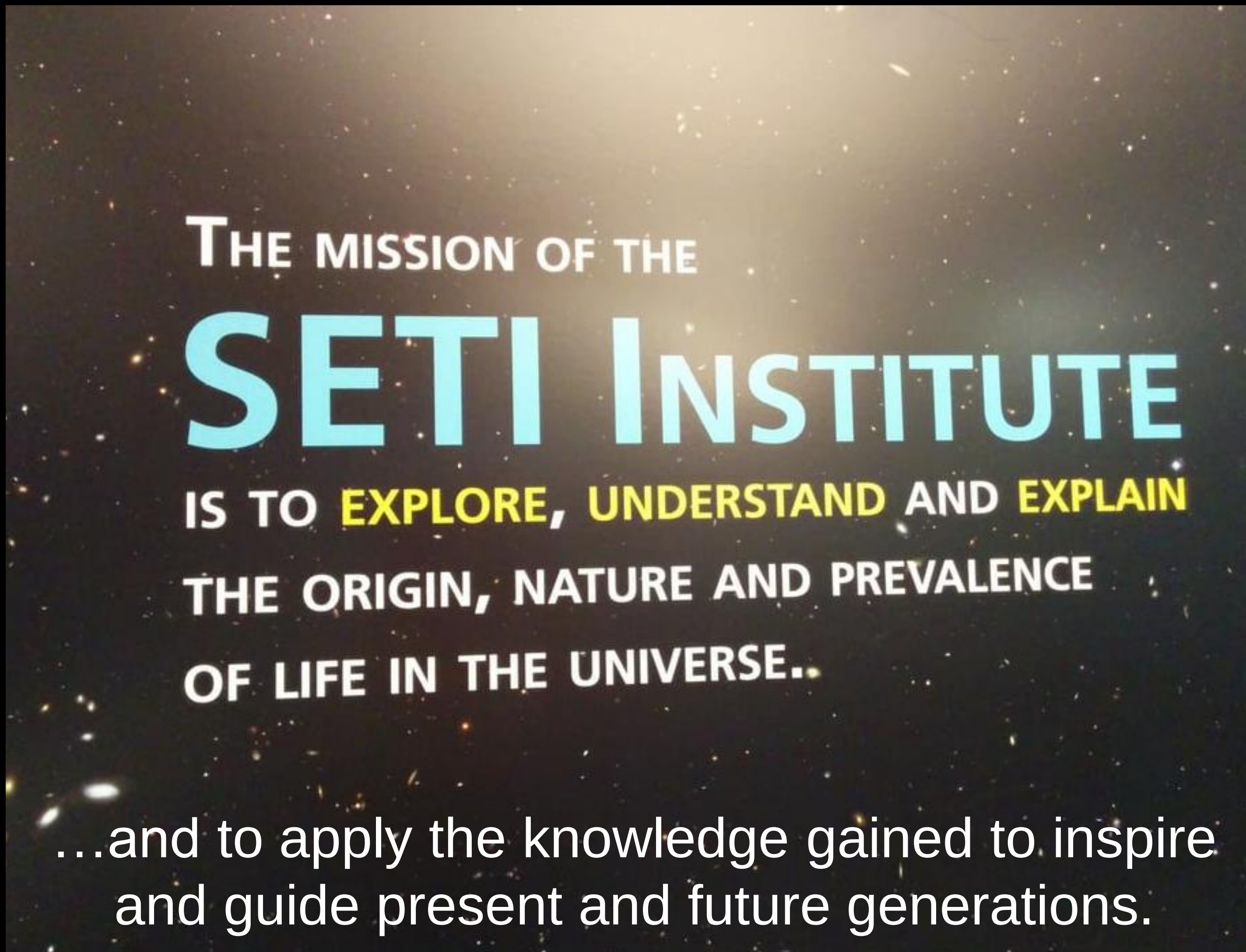
Program purpose described in
2014 NASA Science Plan

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

SETI Mission Statement



…and to apply the knowledge gained to inspire and guide present and future generations.

NASA Exoplanet Exploration Program

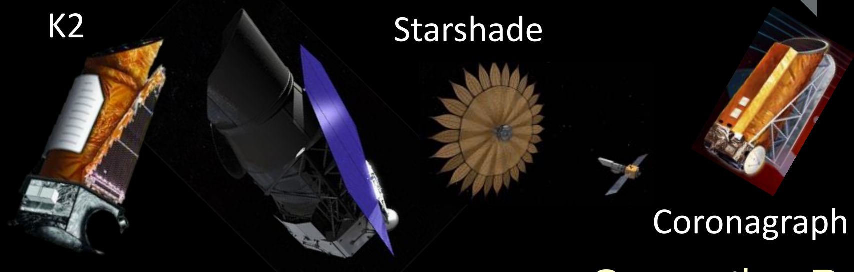
Space Missions and Mission Studies

Kepler, K2

WFIRST

Starshade

Decadal Studies



Coronagraph

Public Communications

Supporting Research & Technology

Key Sustaining Research

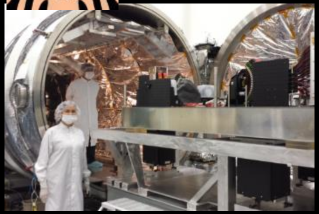
Large Binocular Telescope Interferometer

Keck Single Aperture Imaging and RV

NN-EXPLORE

Technology Development

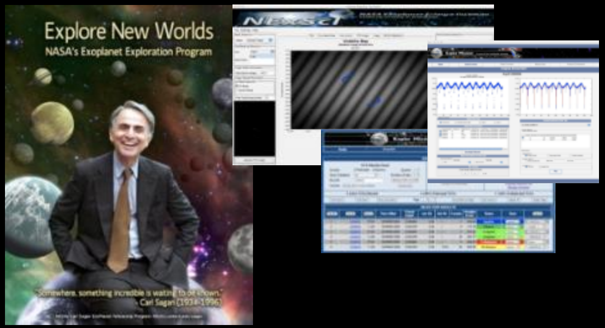
Coronagraph Masks



High-Contrast Imaging

Deployable Starshades

NASA Exoplanet Science Institute



Archives, Tools, Sagan Fellowships, Professional Engagement

https://exoplanets.nasa.gov

ExEP is a Program Office within the NASA Astrophysics Division

Astrophysics Division, NASA Science Mission Directorate

Resource Management
Omana Cawthon+
Clemencia Gallegos-Kelly+

Director
Paul Hertz
Deputy Director
Andrea Razzaghi

Lead Secretary: Kelly Johnson
Secretary: Kyle Nero
Program Support Specialist: Jackie Mackall

Cross Cutting
Technology Lead: Billy Lightsey*
Education POC: Hashima Hasan (Lead Comm Team)
Public Affairs Lead: Kartik Sheth
Information Manager: Lisa Wainio*
Strategic Planning: Rita Sambruna

Astrophysics Research
Program Manager: Linda Sparke
Program Support: Ingrid Farrell*
Astrophysics Data Analysis: Doug Hudgins
Astrophysics Theory: Keith MacGregor*, Theresa Brandt*
Exoplanet Research: Martin Still*
APRA lead: Michael Garcia*
Cosmic Ray, Fund Physics: Thomas Hams*, Vernon Jones, Keith MacGregor*, Rita Sambruna
Gamma Ray/X-ray: Dan Evans, Michael Garcia*, Stefan Immler*, Lou Kaluzienski, Rita Sambruna, Wilt Sanders
Optical/Ultraviolet: Michael Garcia*, Hashima Hasan, Mario Perez*, Martin Still*
IR/Submillimeter/Radio: Dominic Benford*, Doug Hudgins, Kartik Sheth, Eric Tollestrup*
Lab Astro: Doug Hudgins
Theory & Comp Astro Net: Keith MacGregor*
Roman Tech Fellows: Billy Lightsey*
Data Archives: Hashima Hasan
Astrophysics Sounding Rockets: Wilt Sanders
Balloons Program: Vernon Jones(PS), Mark Sistilli (PE)

Programs / Missions & Projects

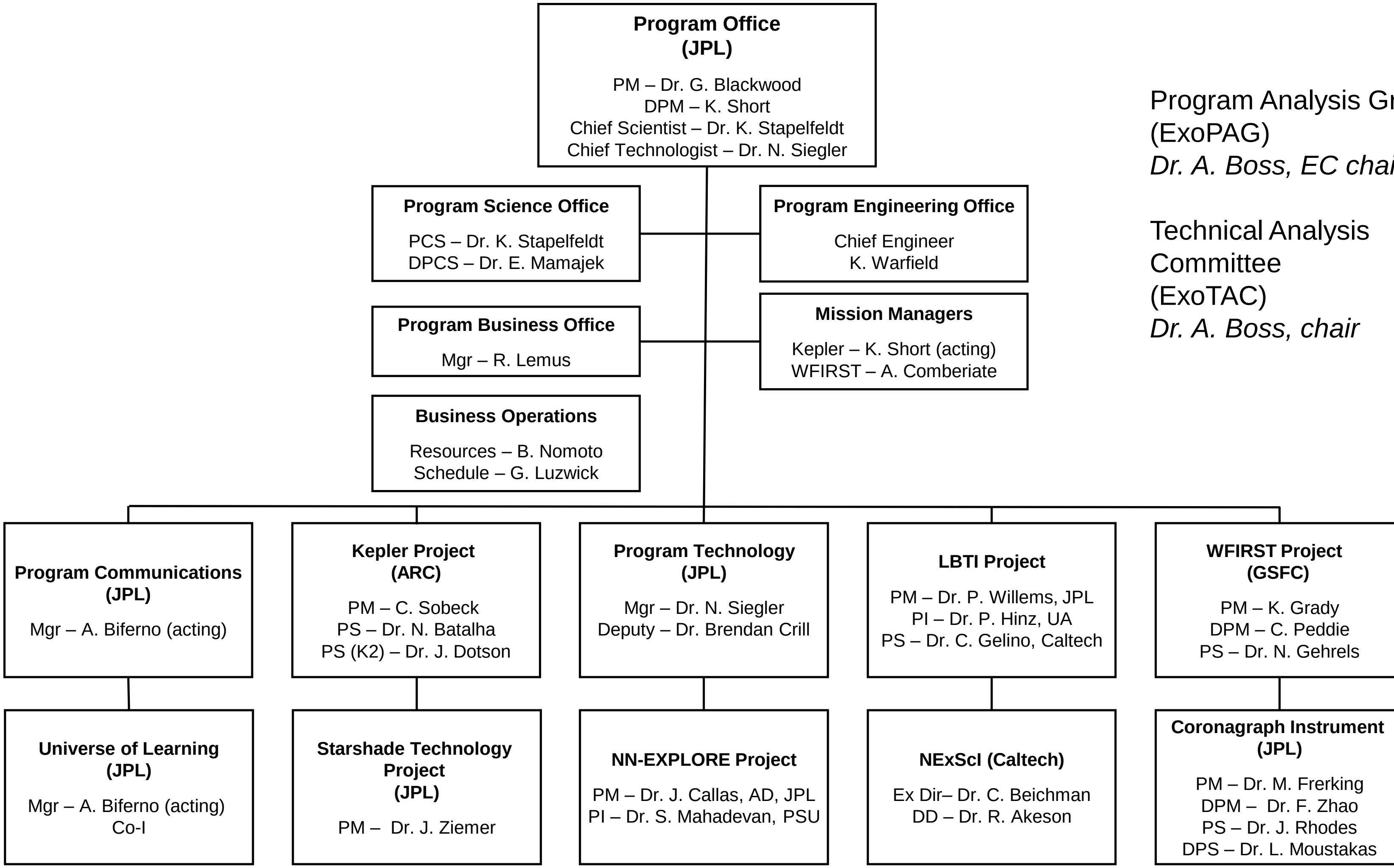
	Program Scientist	*Program Executive*
Exoplanet Exploration (EXEP)		
Program	**Doug Hudgins**	**John Gagosian**
Keck	Hashima Hasan	Mario Perez*
Kepler/K2	Mario Perez*	Jeff Hayes
LBTI	Doug Hudgins	Mario Perez*
NN-EXPLORE	Doug Hudgins	John Gagosian
WFIRST	Dominic Benford*	John Gagosian
Cosmic Origins (COR)		
Program	**Mario Perez***	**Shahid Habib***
Herschel	Dominic Benford*	Jeff Hayes
Hubble	Michael Garcia*	Jeff Hayes
James Webb^	Hashima Hasan	Ray Taylor^
SOFIA	Hashima Hasan	Shahid Habib*
Spitzer	Kartik Sheth*	Jeff Hayes
Physics of the Cosmos (PCOS)		
Program	**Rita Sambruna**	**Shahid Habib***
Athena	Michael Garcia*	Jeanne Davis
Chandra	Stefan Immler*	Jeff Hayes
Euclid	Linda Sparke	Shahid Habib*
Fermi	Stefan Immler*	Jeff Hayes
Planck	Rita Sambruna	Jeff Hayes
ST-7/LPF	Rita Sambruna	Shahid Habib*
XMM-Newton	Stefan Immler*	Jeff Hayes
Astrophysics Explorers (APEX)		
Program	**Wilt Sanders**	**Jeanne Davis**
Hitomi	Lou Kaluzienski	Jeanne Davis
NICER	Rita Sambruna	Jeanne Davis
NuSTAR	Lou Kaluzienski	Jeff Hayes
Swift	Martin Still*	Jeff Hayes
TESS	Doug Hudgins	Mark Sistilli

+ Member of the Resources Management Division
** Detailee, IPA, or contractor*
^ James Webb is part of the JWST Program Office.

Dec, 06 2016

ExEP Resides within NASA JPL Directorate

Astrophysics Division, Science Mission Directorate



Program Analysis Group (ExoPAG)
Dr. A. Boss, EC chair

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

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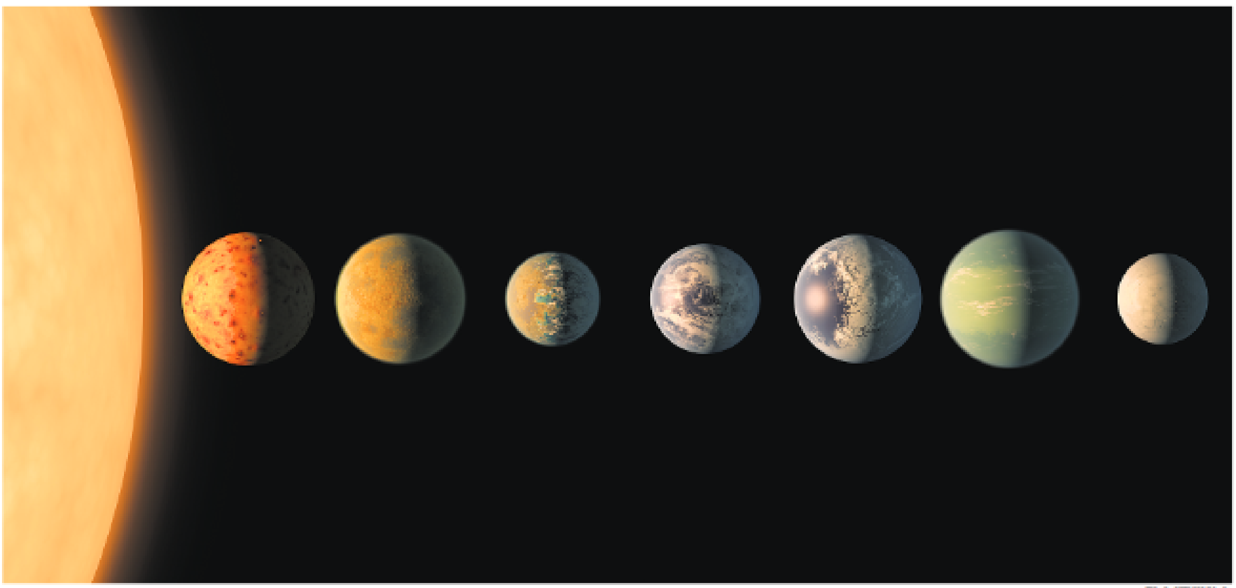
Seven ExoPlanets Above the Fold

"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 B9.

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



JPL-CALTECH/NASA

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.

TRUMP RESCINDS OBAMA DIRECTIVE ON BATHROOM USE

ENTERING CULTURE WARS

Question of Transgender Rights Splits DeVos and Sessions

This article is by Jeremy W. Peters, Jo Becker and Julie Hirschfeld Davis.

WASHINGTON — President Trump on Wednesday rescinded protections for transgender students that had allowed them to use bathrooms corresponding with their gender identity, overruling his own education secretary and placing his administration firmly in the middle of the culture wars that many Republicans have tried to leave behind.

In a joint letter, the top civil rights officials from the Justice Department and the Education Department rejected the Obama administration's position that nondiscrimination laws require schools to allow transgender students to use the bathrooms of their choice.

That directive, they said, was improperly and arbitrarily devised, "without due regard for the primary role of the states and lo-

Circling a Star Not Far Away, 7 Shots at Life

By KENNETH CHANG

Uber's Culture Of Gutsiness Under Review

By MIKE ISAAC

Migrants Hide, Fearing Capture on 'Any Corner'

By VIVIAN YEE

No going to church, no going to the store. No doctor's appointments for some, no school for others. No driving, period — not

IMMIGRATION A police department worries a crackdown will harm work to fight gangs. PAGE A14

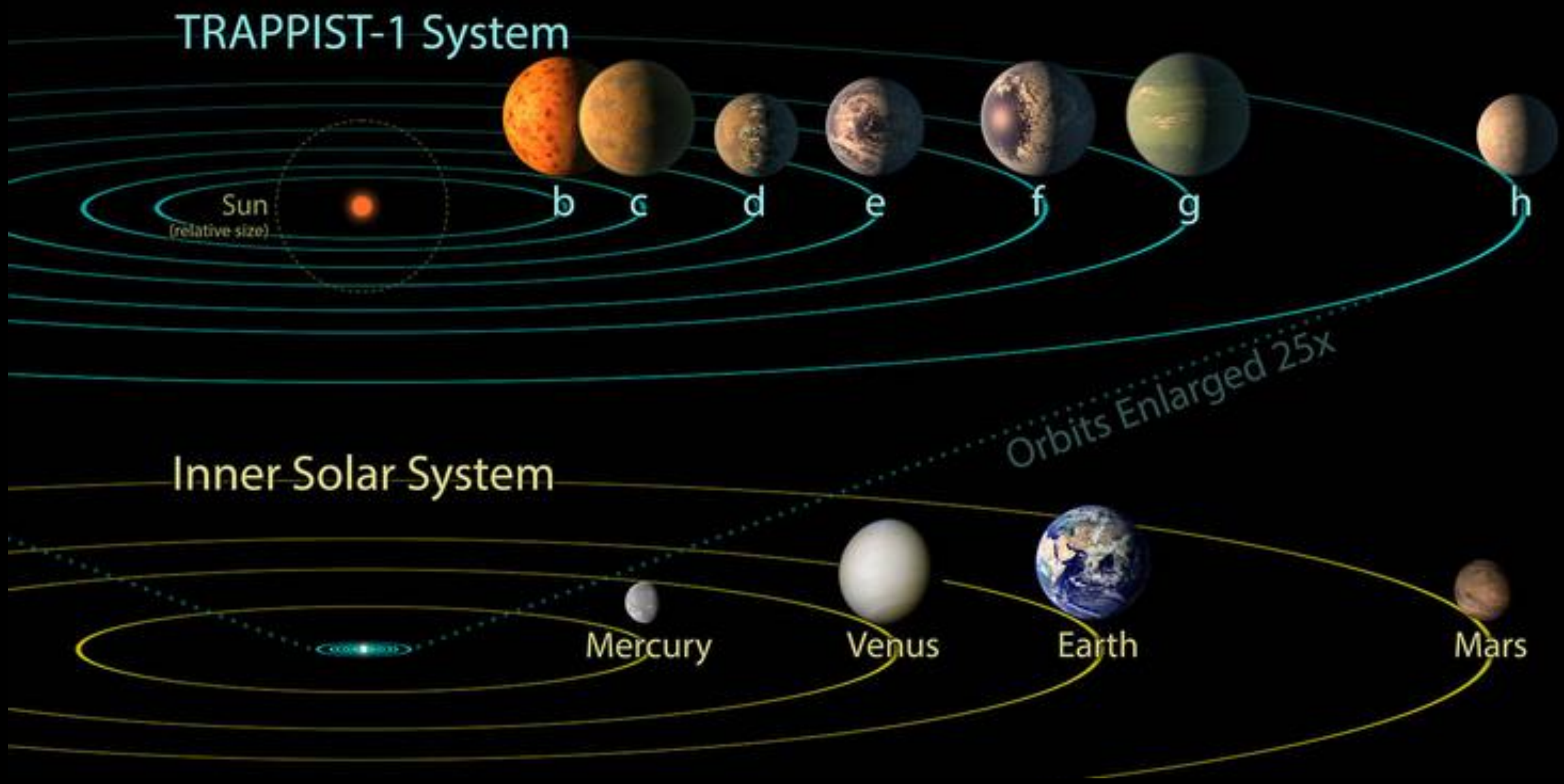
MEXICO The secretary of state pays a visit at a time of rising

duras.

If deportation has always been a threat on paper for the 11 million people living in the country illegally, it rarely imperiled those who did not commit serious crimes. But with the Trump ad-

Trappist-1 Discovery

The Richest Set of Earth-sized Planets Ever Found

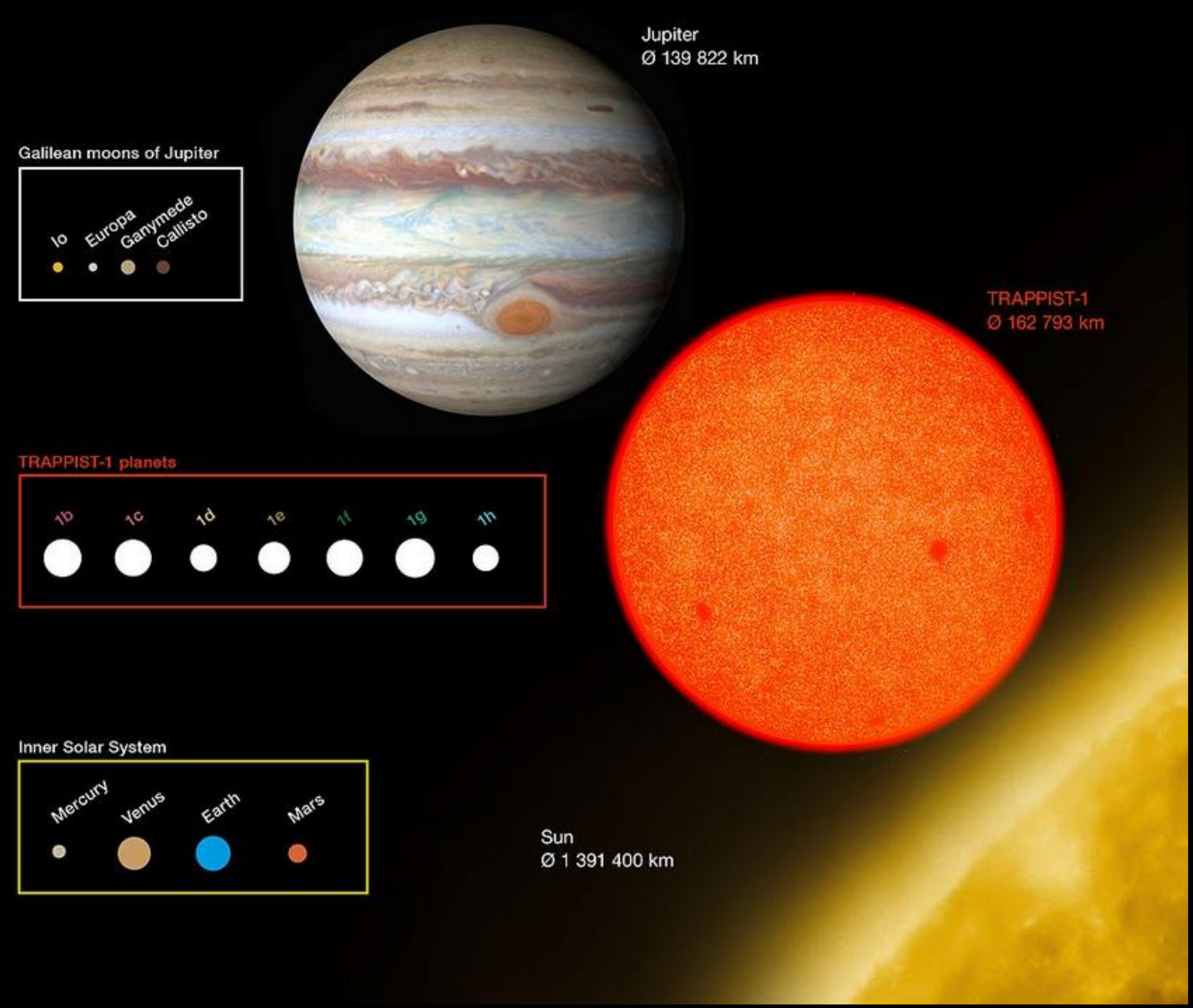


Credit: NASA/JPL

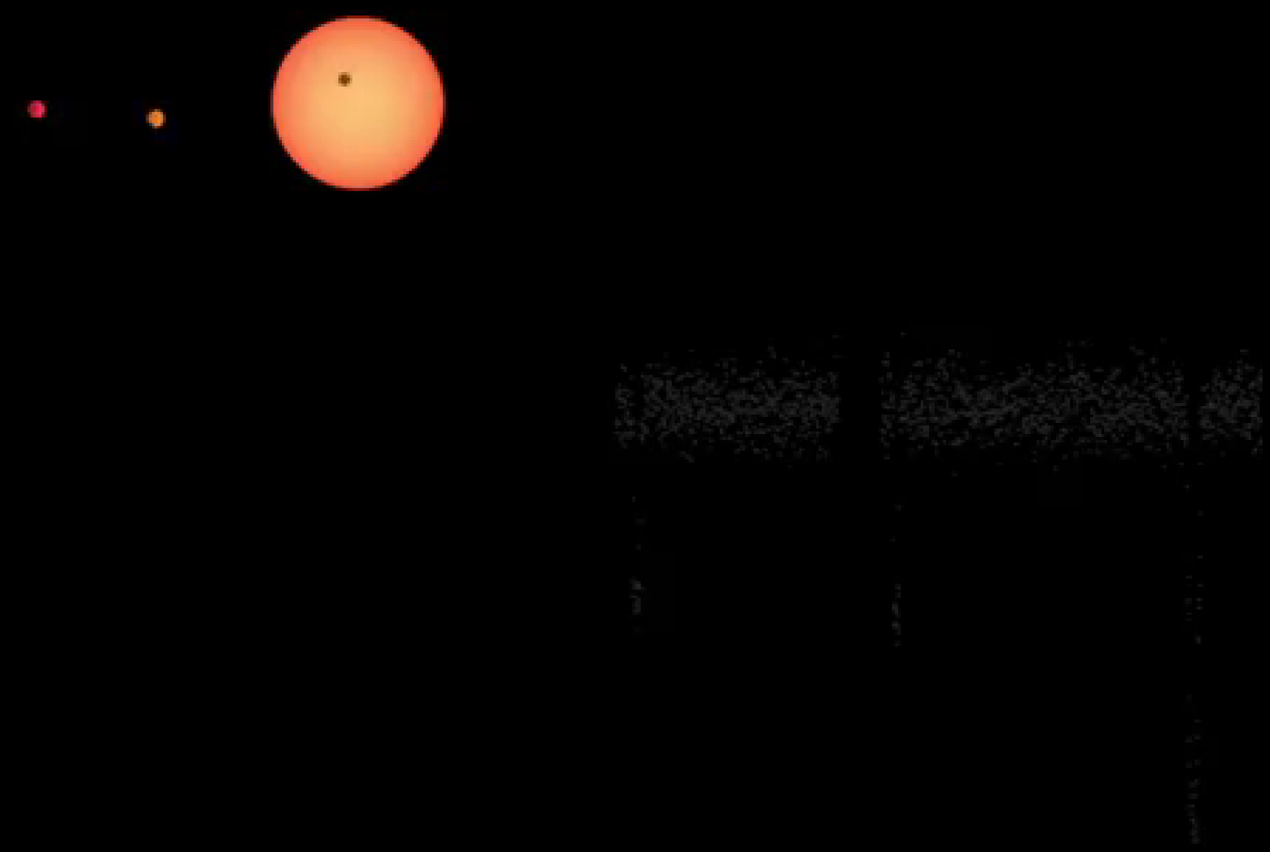
A Familiar Habitable Zone

Credit: Luc Forsyth

Trappist-1: a Relatively Small Star



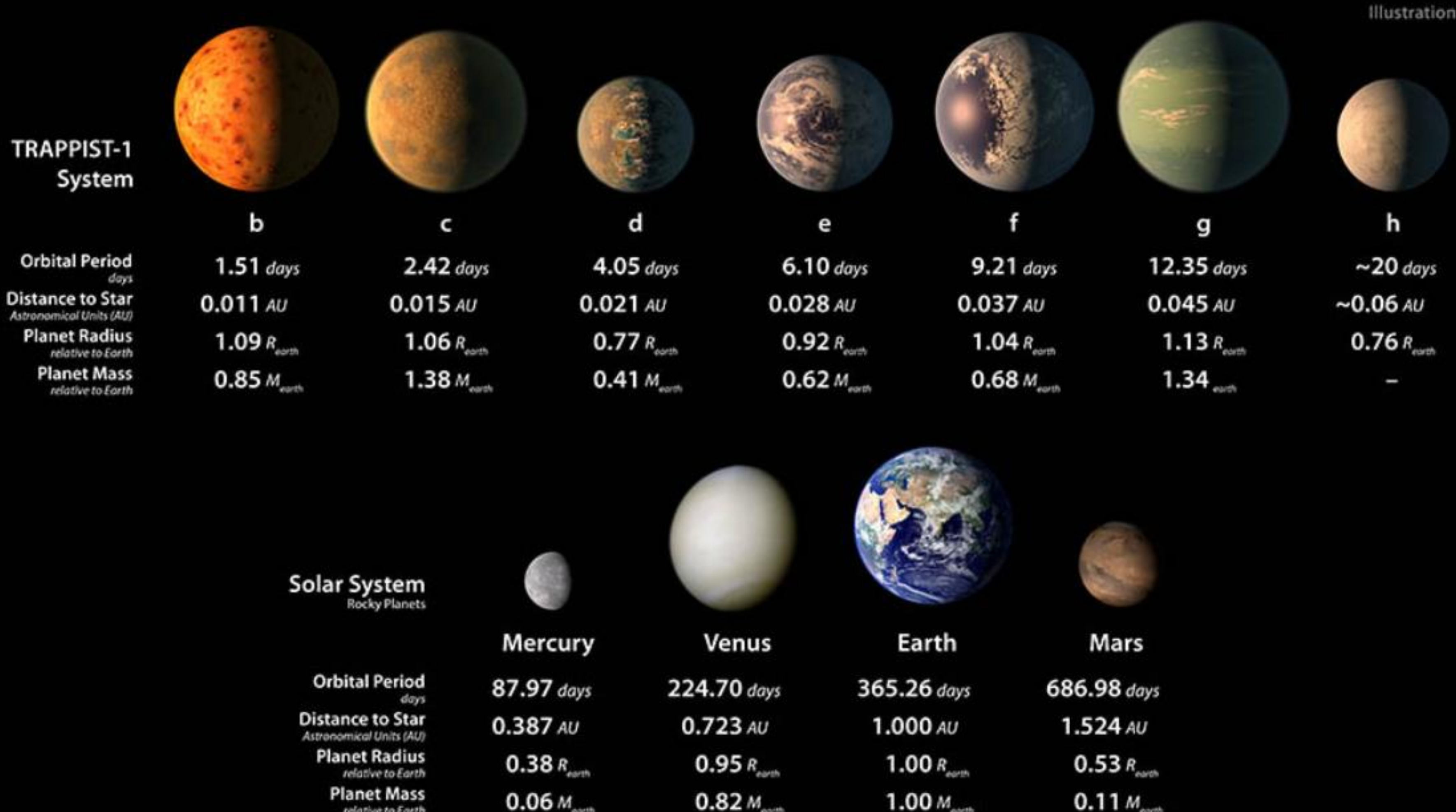
How Spitzer Observed the Trappist-1 System



Credit: NASA/JPL

Spitzer Measures Planet Size & Transit Timing

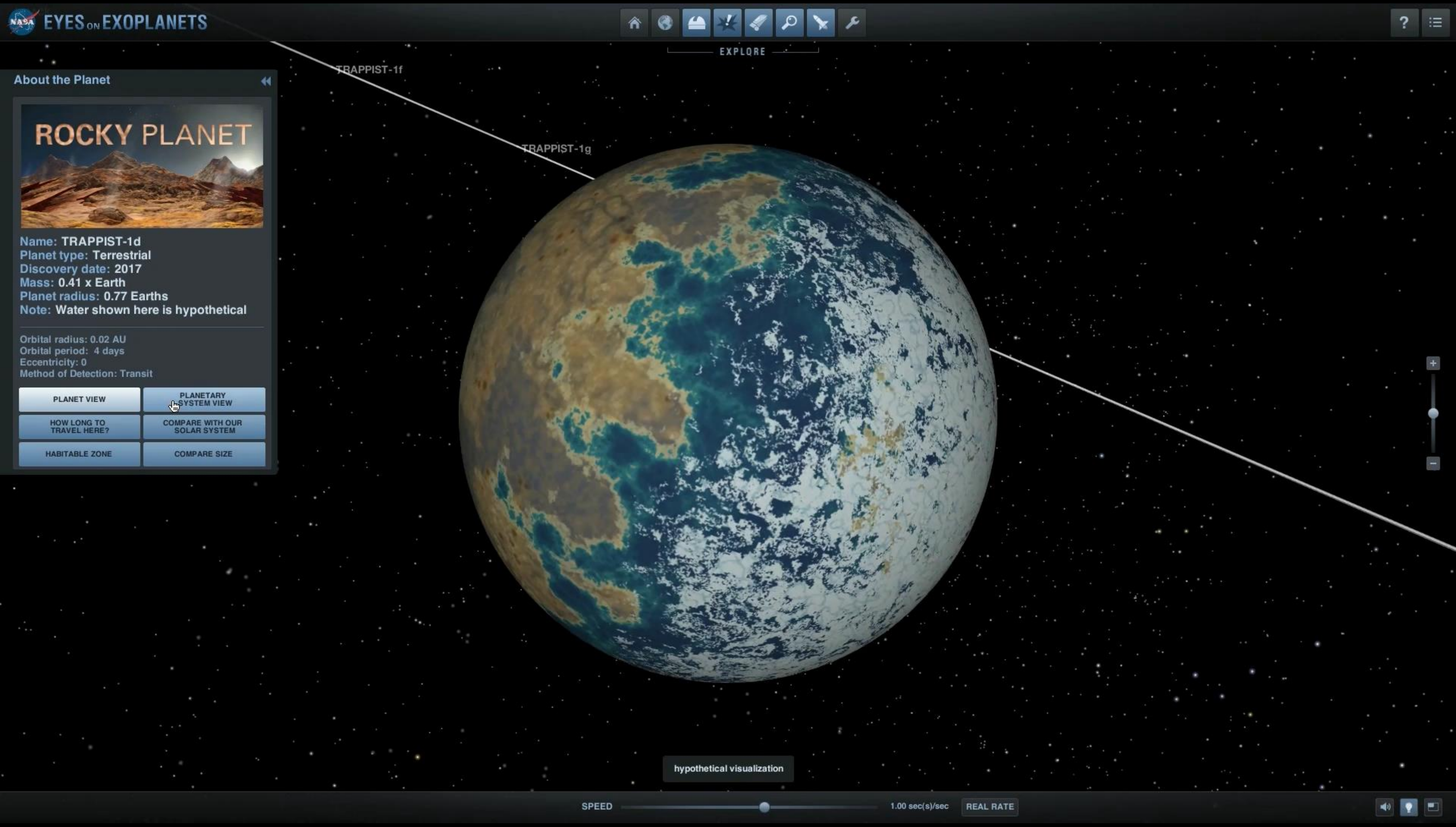
Orbital mechanics used to deduce mass from transit timing variations



TRAPPIST-1 System	b	c	d	e	f	g	h
Orbital Period (days)	1.51 days	2.42 days	4.05 days	6.10 days	9.21 days	12.35 days	~20 days
Distance to Star (Astronomical Units (AU))	0.011 AU	0.015 AU	0.021 AU	0.028 AU	0.037 AU	0.045 AU	~0.06 AU
Planet Radius (relative to Earth)	1.09 R_{earth}	1.06 R_{earth}	0.77 R_{earth}	0.92 R_{earth}	1.04 R_{earth}	1.13 R_{earth}	0.76 R_{earth}
Planet Mass (relative to Earth)	0.85 M_{earth}	1.38 M_{earth}	0.41 M_{earth}	0.62 M_{earth}	0.68 M_{earth}	1.34 $_{earth}$	–

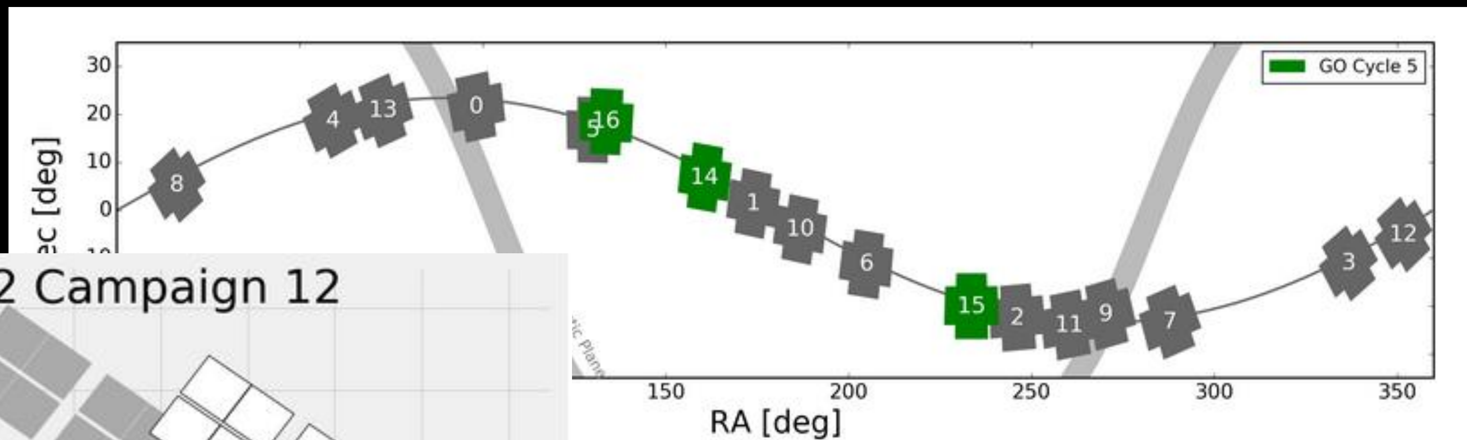
Solar System (Rocky Planets)	Mercury	Venus	Earth	Mars
Orbital Period (days)	87.97 days	224.70 days	365.26 days	686.98 days
Distance to Star (Astronomical Units (AU))	0.387 AU	0.723 AU	1.000 AU	1.524 AU
Planet Radius (relative to Earth)	0.38 R_{earth}	0.95 R_{earth}	1.00 R_{earth}	0.53 R_{earth}
Planet Mass (relative to Earth)	0.06 M_{earth}	0.82 M_{earth}	1.00 M_{earth}	0.11 M_{earth}

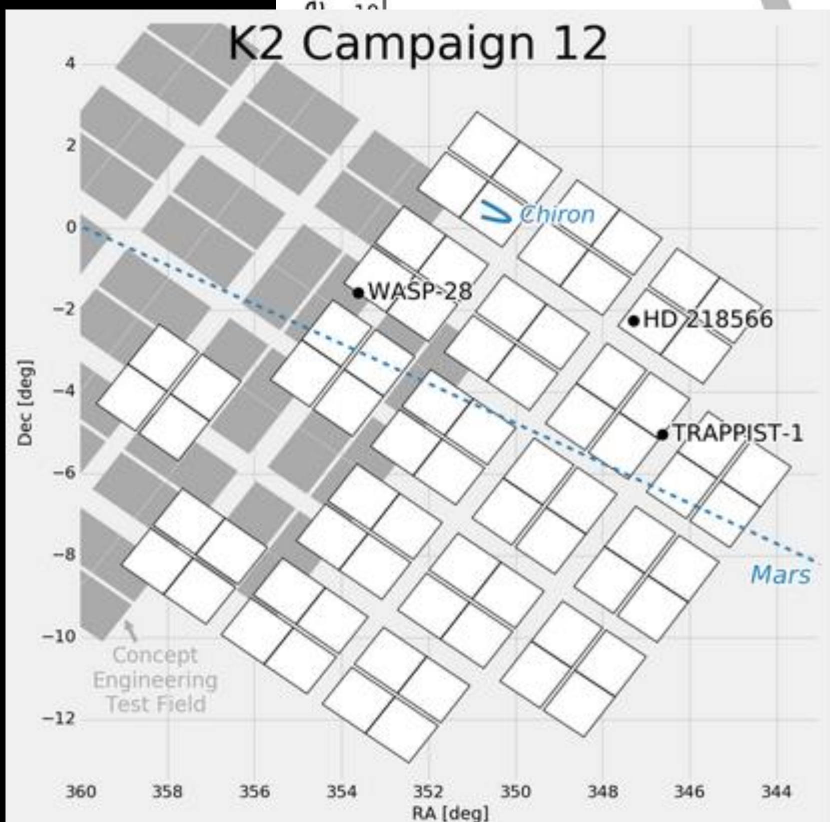
Credit: NASA/JPL


EYES ON EXOPLANETS
EXPLORE
TRAPPIST-1f
TRAPPIST-1g
About the Planet
ROCKY PLANET
Name: TRAPPIST-1d
Planet type: Terrestrial
Discovery date: 2017
Mass: 0.41 x Earth
Planet radius: 0.77 Earths
Note: Water shown here is hypothetical
Orbital radius: 0.02 AU
Orbital period: 4 days
Eccentricity: 0
Method of Detection: Transit
PLANET VIEW
PLANETARY SYSTEM VIEW
HOW LONG TO TRAVEL HERE?
COMPARE WITH OUR SOLAR SYSTEM
HABITABLE ZONE
COMPARE SIZE
hypothetical visualization
SPEED
1.00 sec(s)/sec
REAL RATE

Kepler K2: 80 days on Trappist-1

Campaign 12 ended March 4





- Expect 200–500 ppm photometry on Trappist-1
- Published Trappist transits are a couple of %

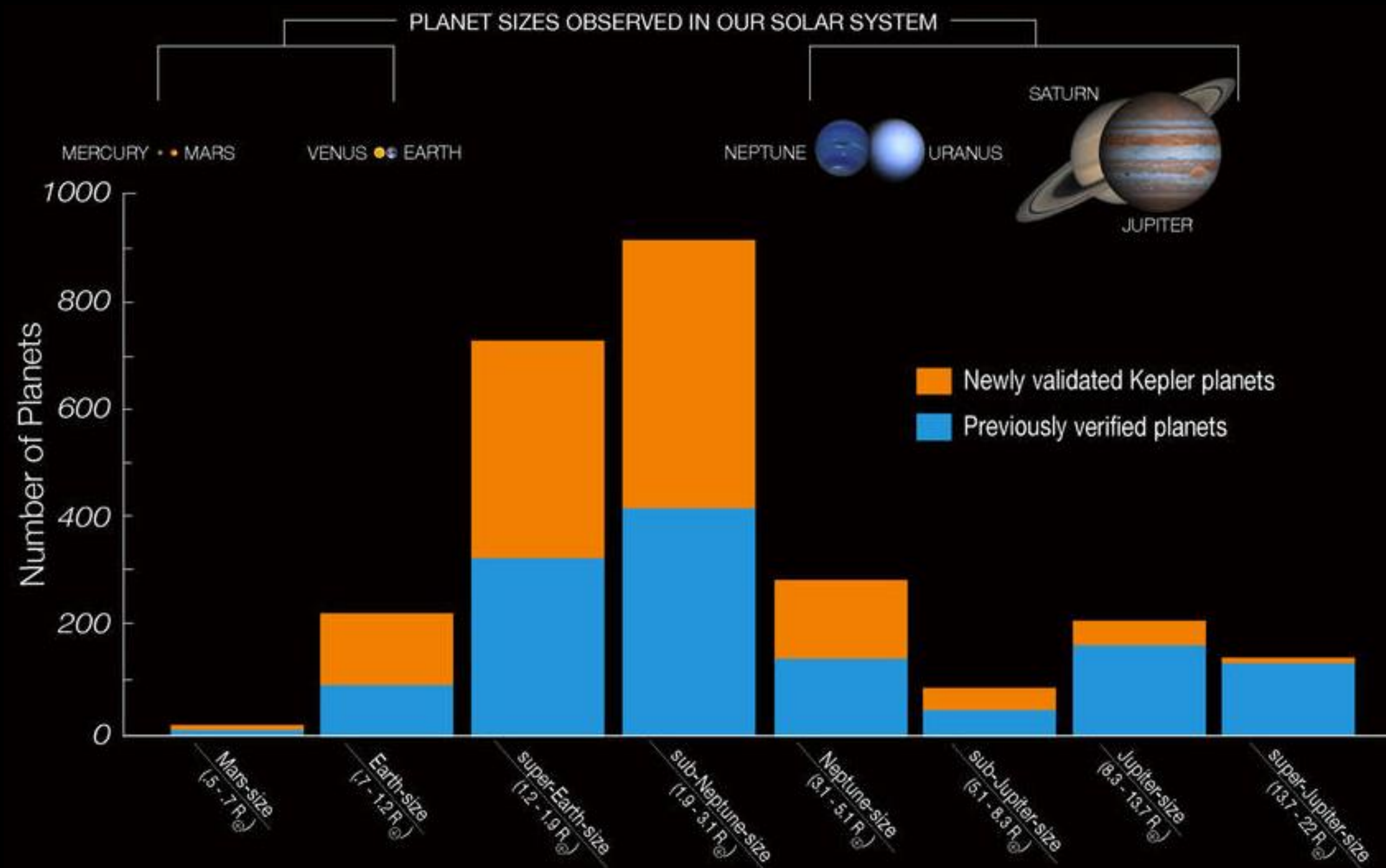
Key Takeaways from Trappist Discovery

- This is the richest set of Earth-sized exoplanets ever found orbiting a single star, with 3 in the habitable zone.
- It shows that red dwarf stars, the most common type of star, can host rich planetary systems. More discoveries like this can be expected
- The Trappist exoplanets will be top targets for future observations with the James Webb Space Telescope. The presence and composition of an atmosphere can be measured through infrared spectra taken during transit; but the observations will be difficult.
- Most exoplanets do not transit their star. For the general case, direct imaging remains essential for measuring atmospheres and possible biosignatures.

Kepler’s Verified Planets, by Size

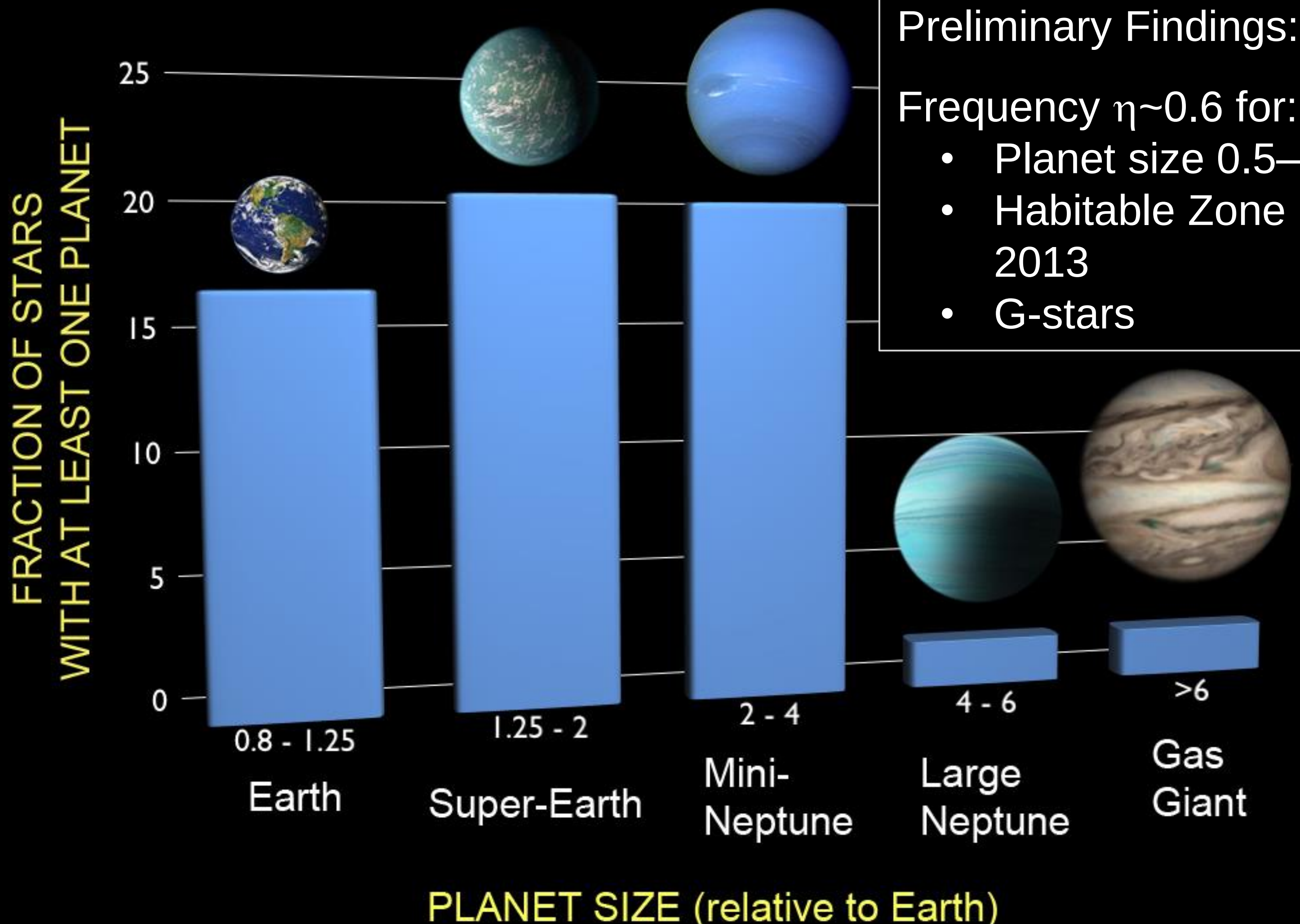
As of May 10, 2016

Final data release: spring 2017



Credit: NASA/ARC

Exoplanetary Occurrence Rates



ExoPAG SAG13 (Belikov 2017): Preliminary Findings:

Frequency η~0.6 for:

- Planet size 0.5–1.5 R_e
- Habitable Zone per Kopparapu 2013
- G-stars

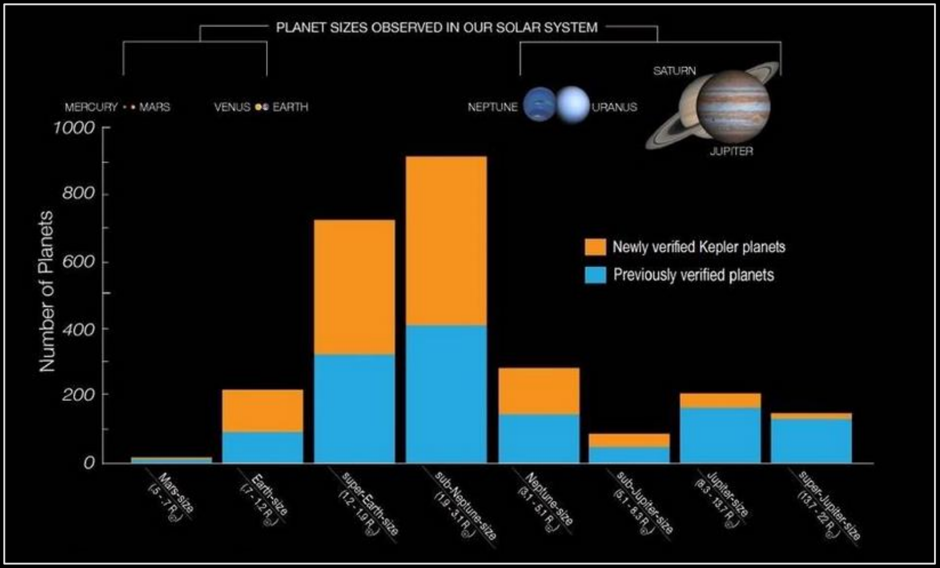
Credit: NASA/Kepler/F. Fressin

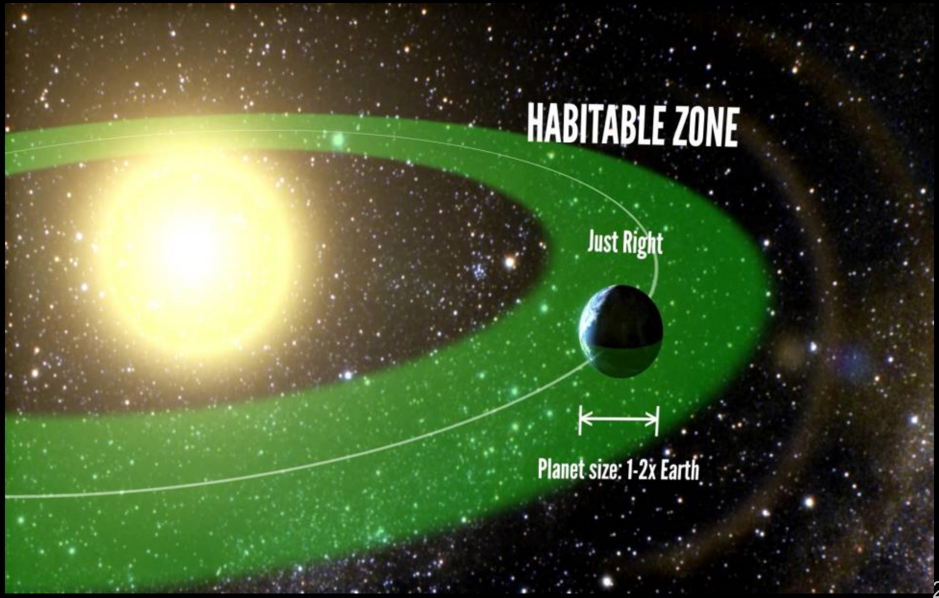
Three Key Kepler Results

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

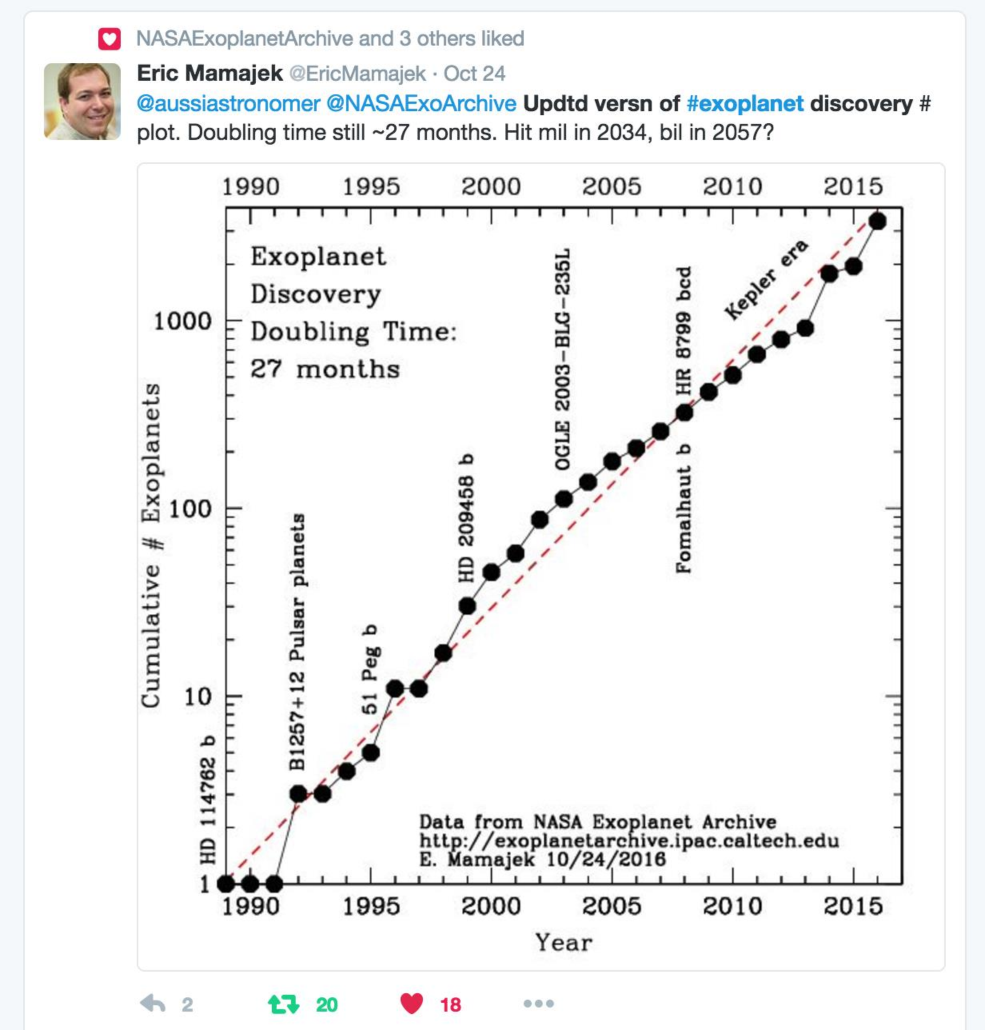
3. Earth-sized (0.5 to 2 Earth radii) planets in the Habitable Zone are common





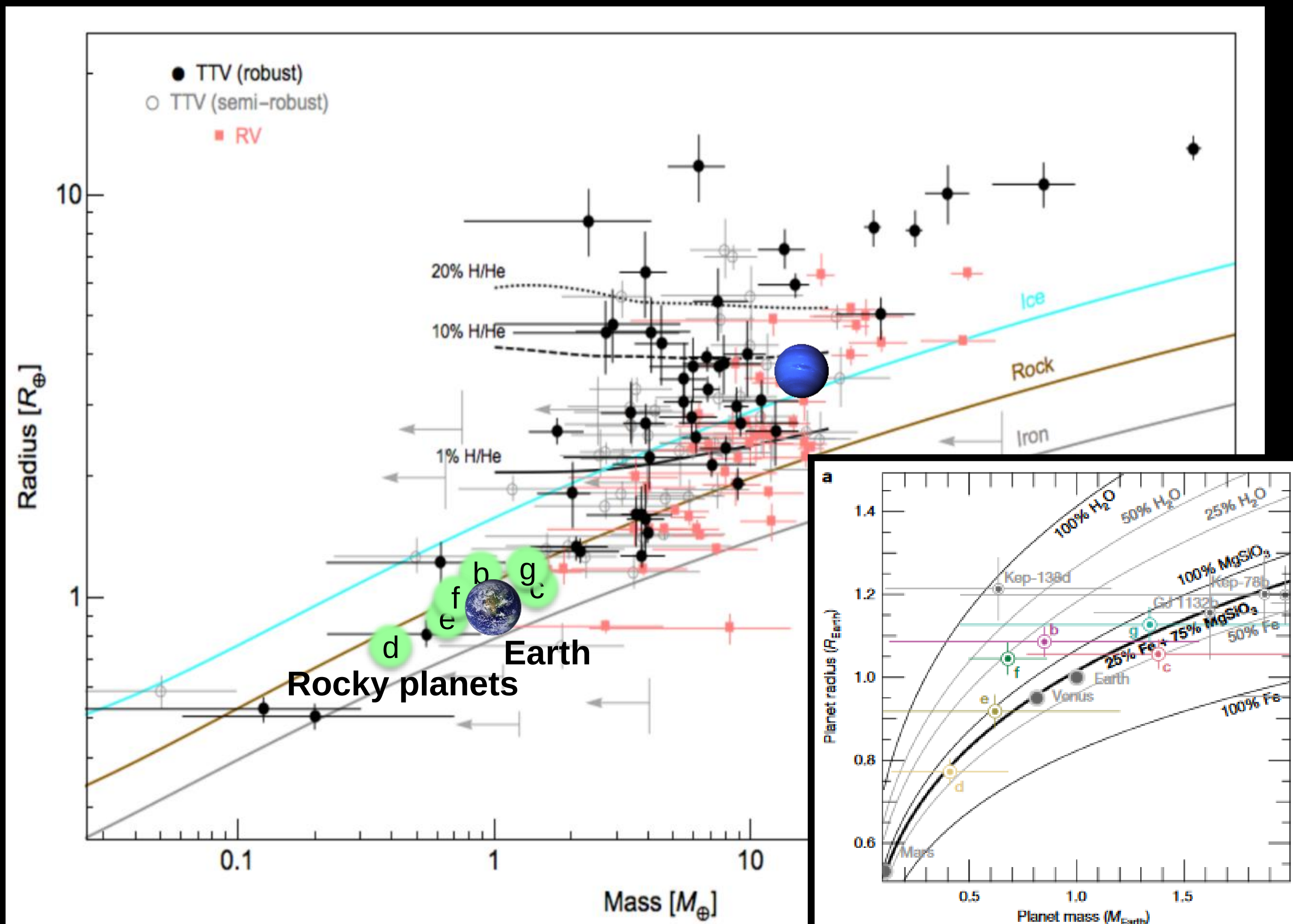
"Mamajek's Law"

Exoplanet Discovery Doubling Time



Credit: J. Christenson

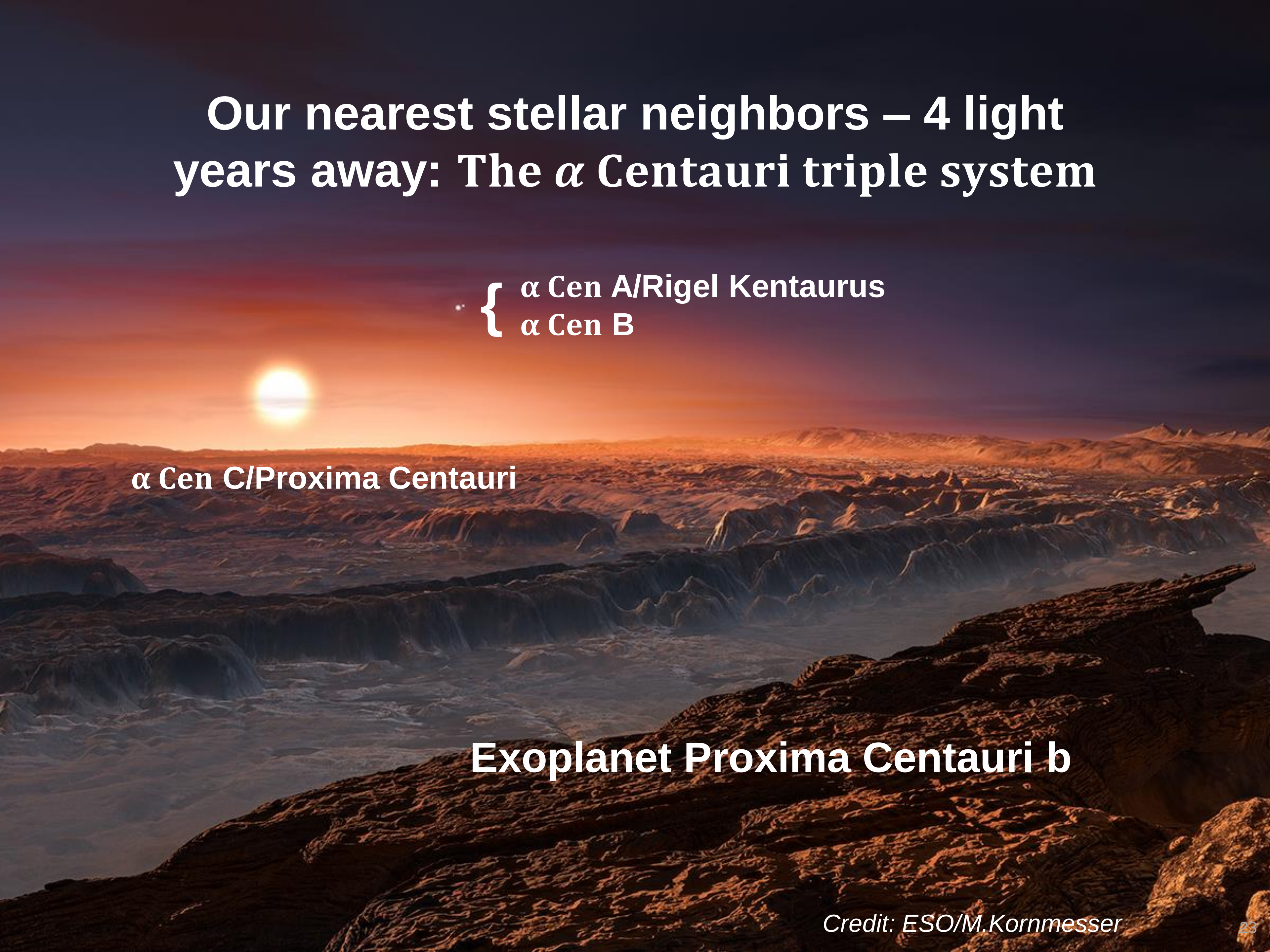
Where are the Rocky Planets?



Credit: Hadden & Lithwick 2016

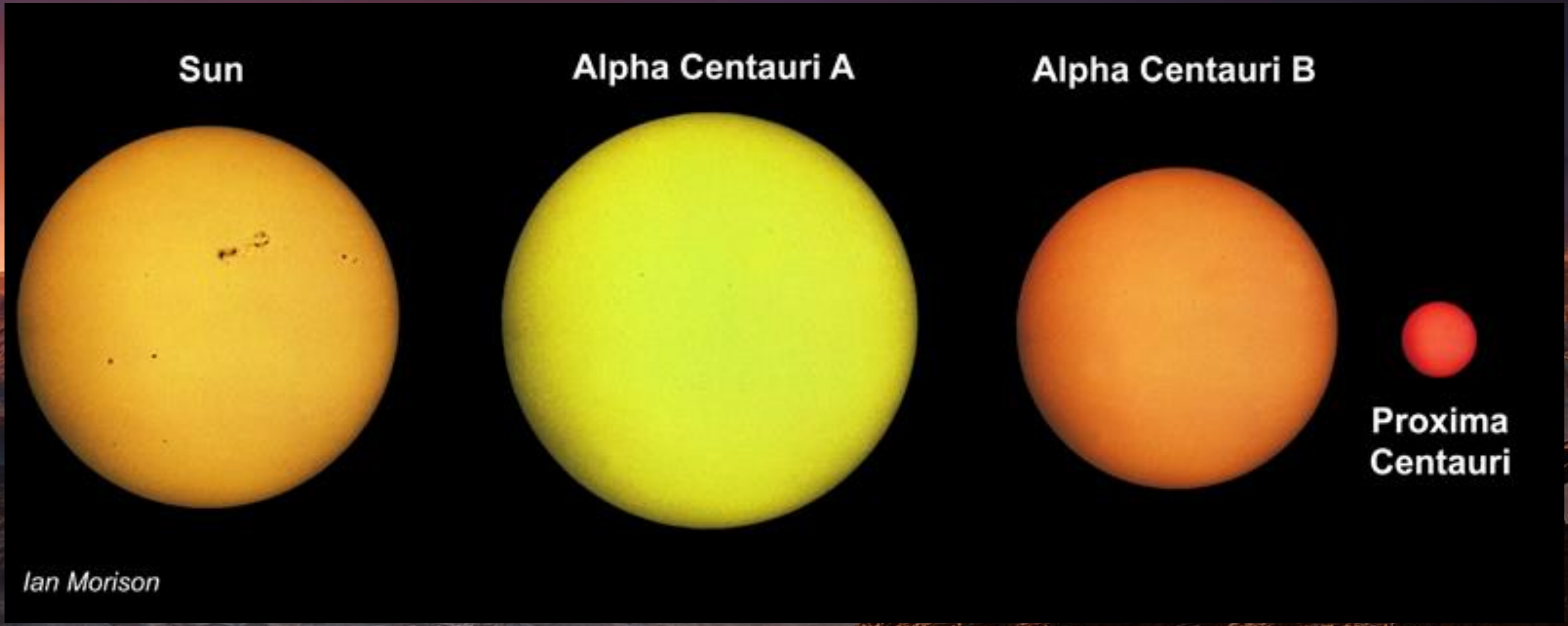
Credit: Gillon et al. 2017

Our nearest stellar neighbors – 4 light years away: The α Centauri triple system



Credit: ESO/M.Kornmesser

The α Centauri triple system

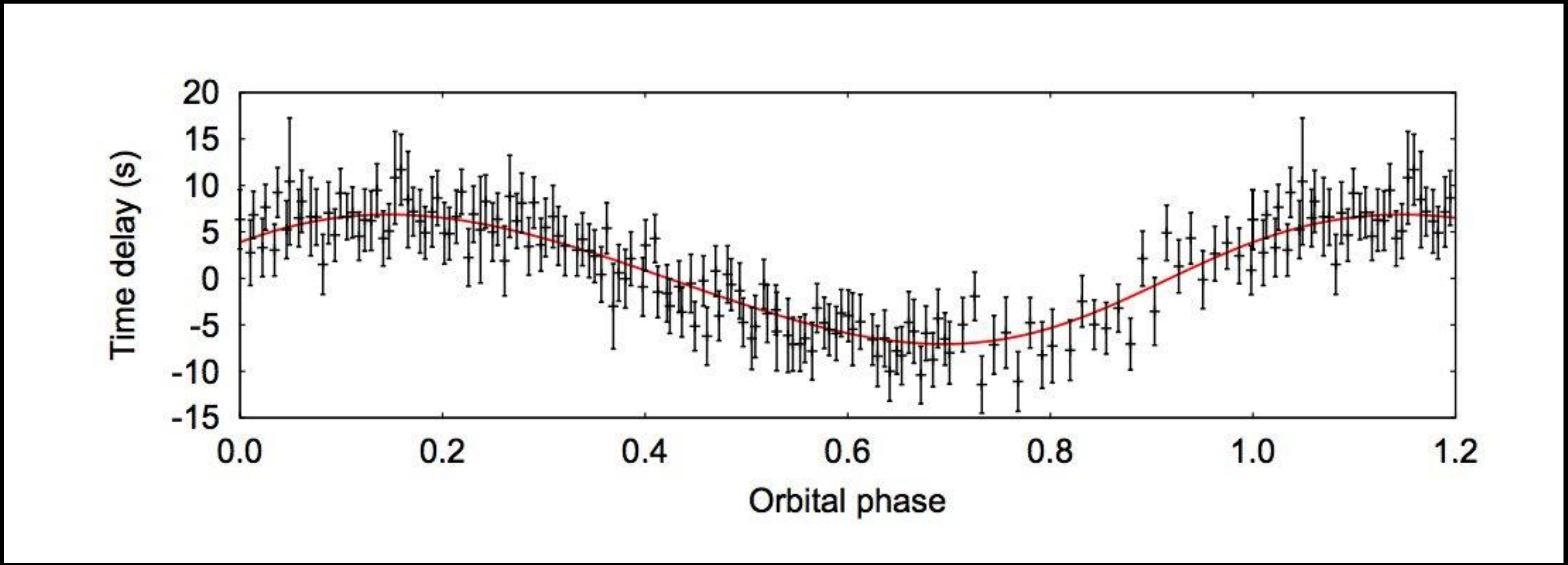


Credit: ESO/M.Kornmesser

Credit: ESO/M.Kornmesser/G. Coleman

Planet Orbiting A-type Main Sequence Star

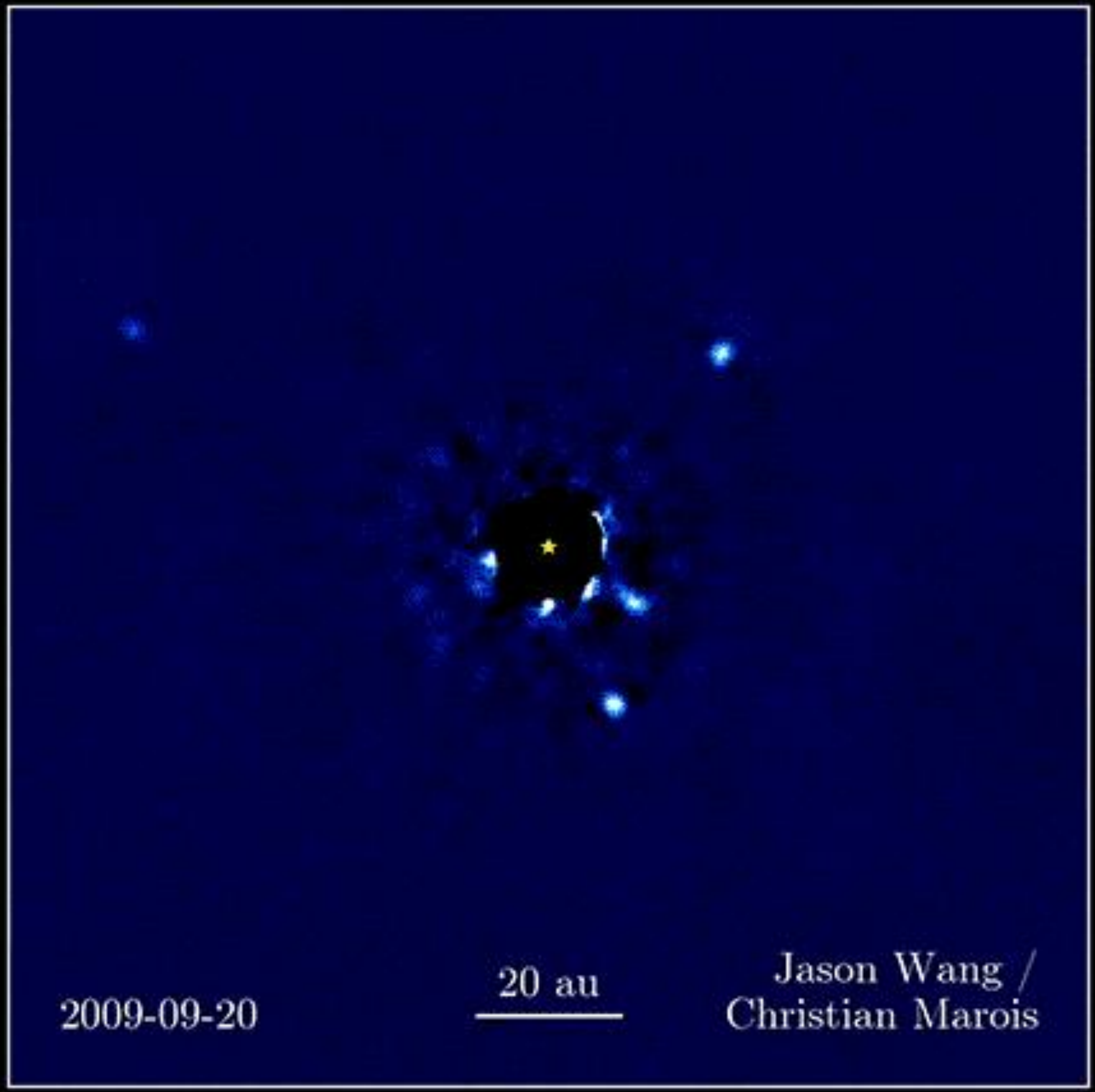
Murphy & Bedding 2016, arXiv:1608.02945 (accepted)



Planets orbiting A stars are hard to find via RV and transits due to rapid rotation, larger stellar radii, and pulsations.

This planet was identified via phase modulation of the stellar pulsations.

HR 8799: Orbital Motion of Four Giant Planets



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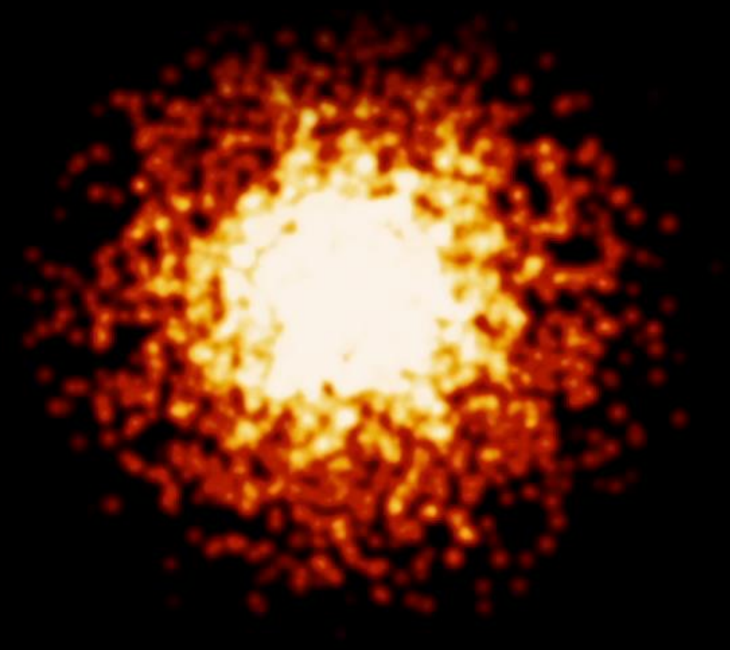
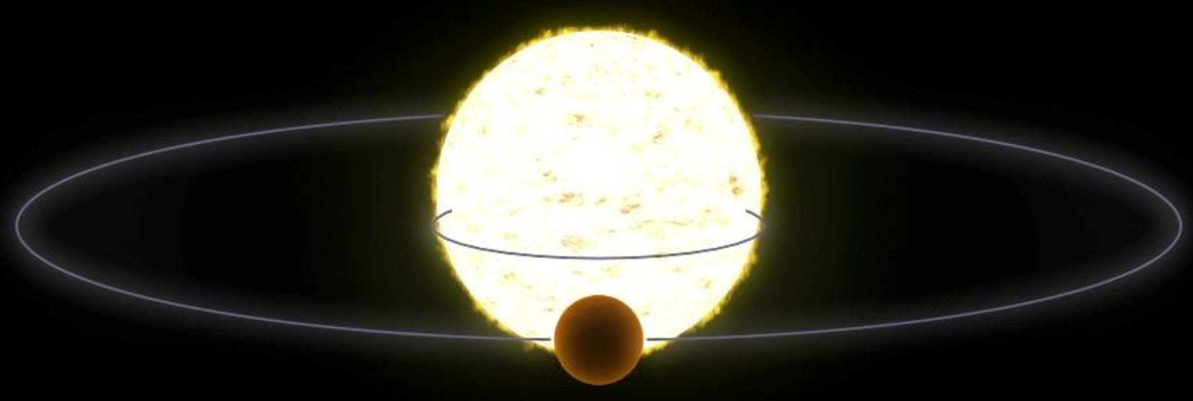
Techniques to Detect Exoplanets

Direct Imaging



Techniques to Detect Exoplanets

Astrometric Method



Techniques to Detect Exoplanets

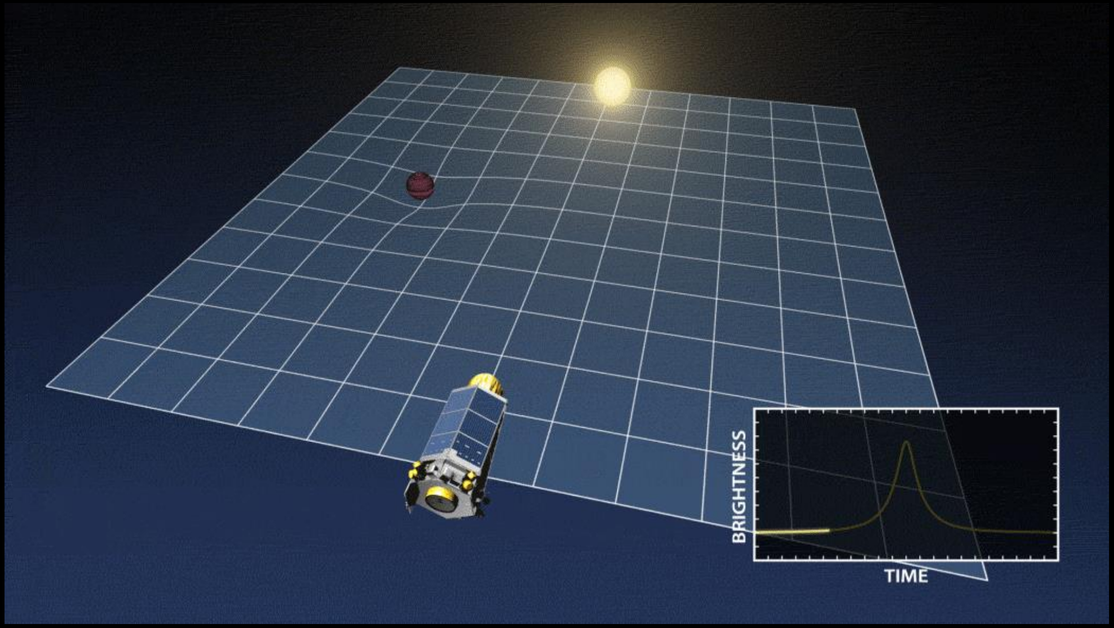
Doppler Spectroscopy or Radial Velocity Method

Techniques to Detect Exoplanets

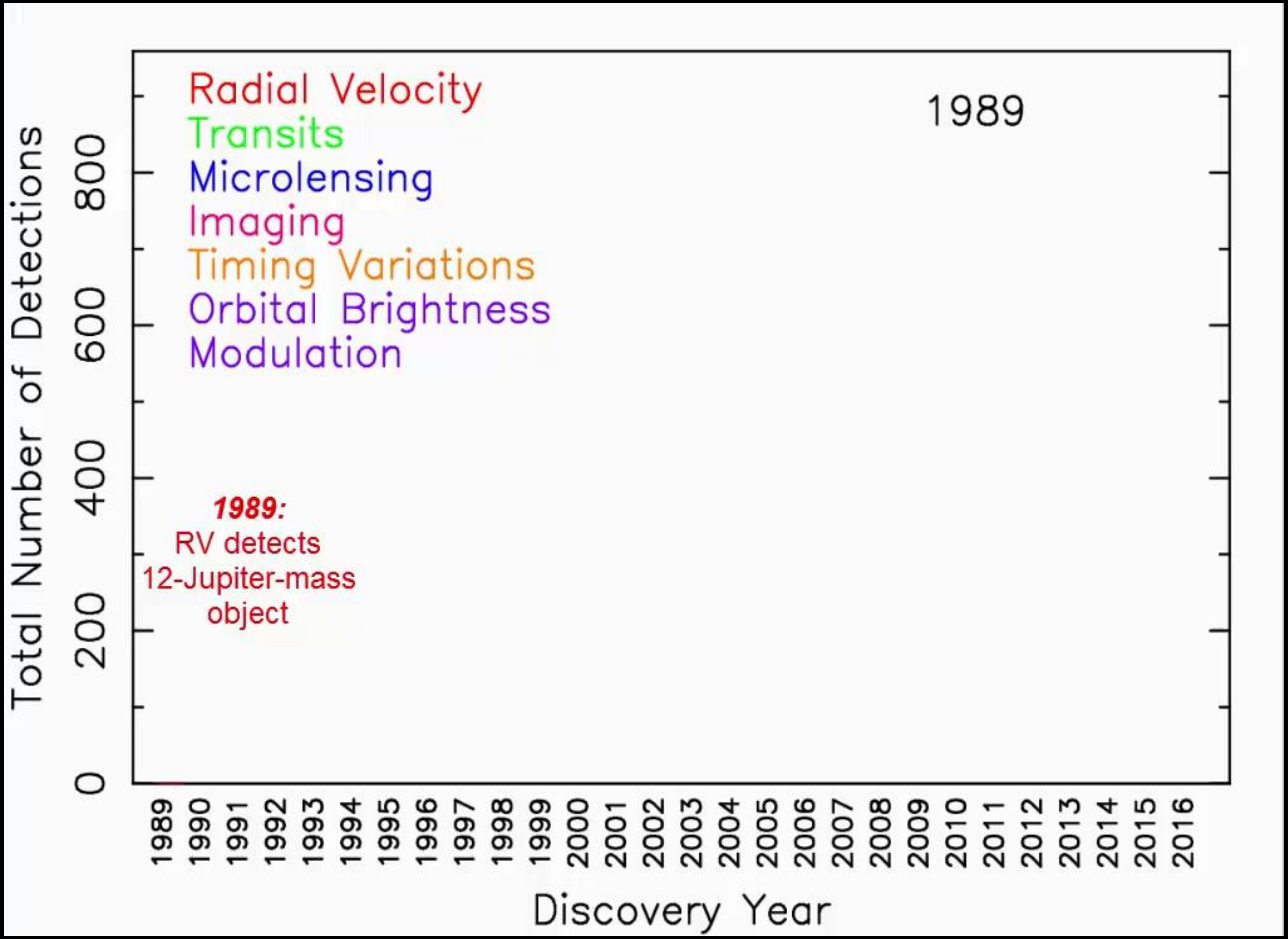
Transit Method

Techniques to Detect Exoplanets

Microlensing Method



Confirmed Exoplanets versus Time



Confirmed Exoplanets by Technique

Technique	Number as of 15 Feb 2017
Astrometry	1
Eclipse timing	8
Transit timing	15
Imaging	44
Microlensing	44
Orbital brightness modulation	6
Pulsar timing / pulsation	7
Stellar radial velocity	621
Transit	2732

Exoplanet Science by Technique

Sample	Planet Radius	Planet Mass	Planet Orbit	Characterize Atmosphere	System context view
Radial Velocity	No	Lower limit	Yes	No	Planets within ~< 5 AU
Transit	Yes	Yes if RV, or if TT varies	Yes if RV	Yes for larger planets & scale heights	Coplanar & short orbital period planets
µLensing	No	Yes	partially	No	Usually no
Imaging of self-luminous planets	Estimate from radiometry	Yes, estimate from theory and age	Yes	Yes	Hot planets plus all dust
Imaging of reflected light planets	Rough estimate only	No	Yes	Yes	All but the closest planets & dust
Stellar Astrometry	No	Yes	Yes	No	All but the closest planets

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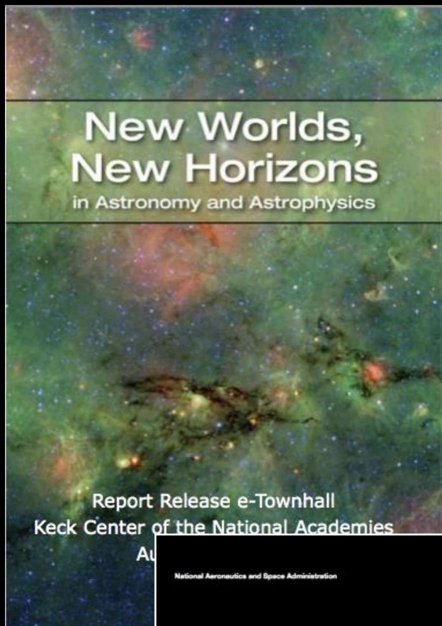
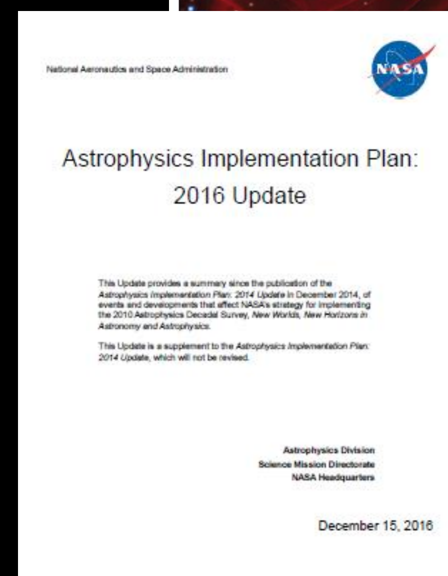
Astrophysics Division: Driving Documents



Results of NWNH:

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



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

Kepler Close-Out

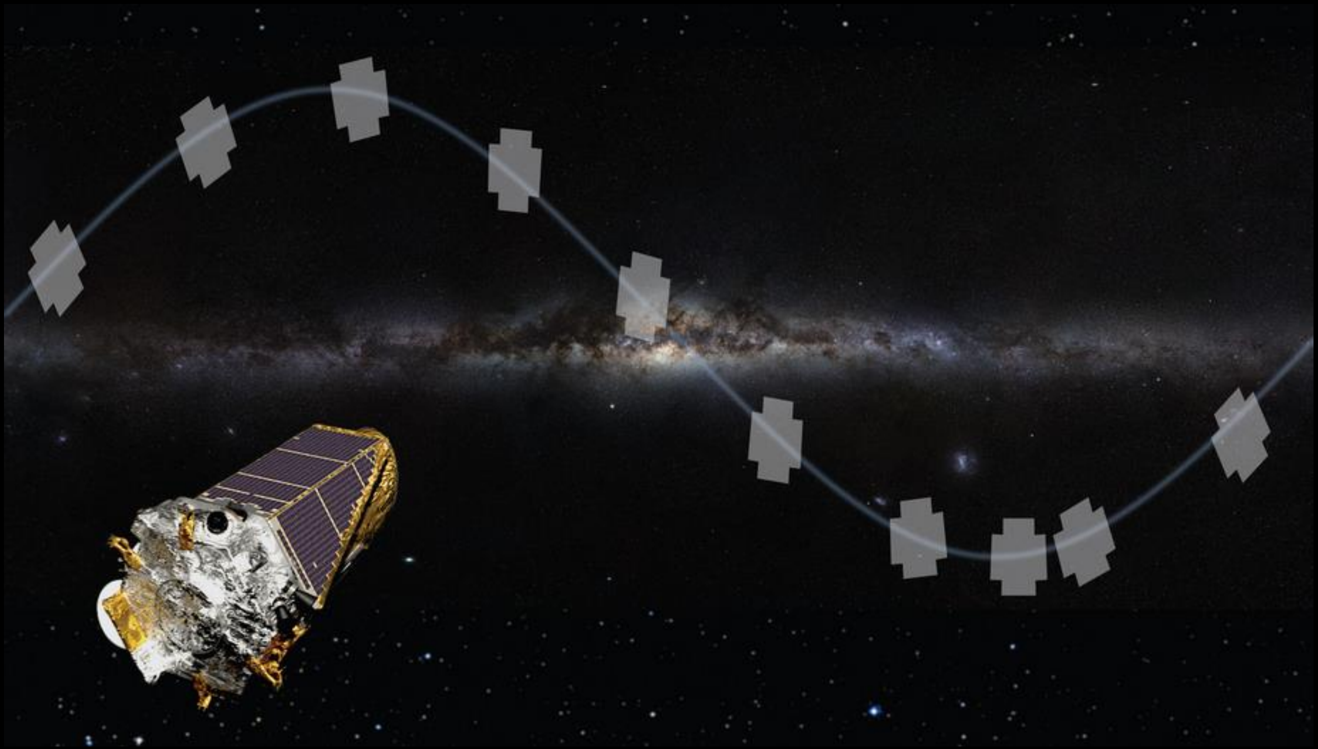
Delivering Kepler's Legacy

- Kepler closeout and final data processing continues steadily within overall schedule margin
  - The final reprocessing of the Kepler Q0–Q17 short cadence light curves has been completed, and the files are online at MAST (Mikulski Archive)
  - Held successful Documentation Completeness Review
  - SOC 9.3 Final Occurrence Rate Products planned for Spring 2017

Credit: NASA/ARC

Kepler K2

Extending the Power of Kepler to the Ecliptic



Upcoming

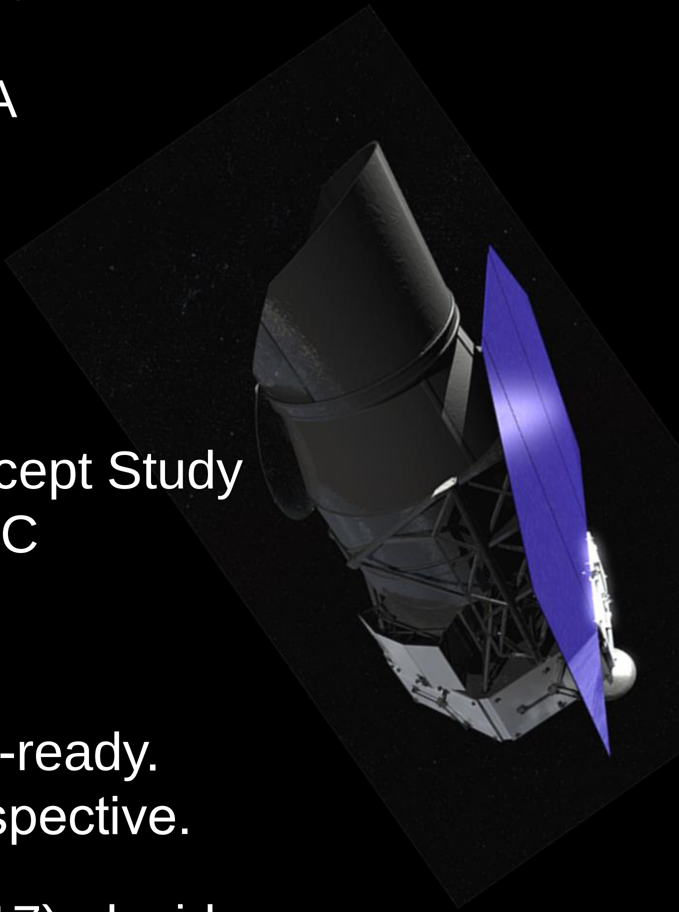
- Changed the position of the field for Campaign 16 – Kepler will observe in the forward-facing direction; emphasis on supernova science
- Release of Microlensing results from Campaign 9

https://exoplanets.nasa.gov/k2

Wide Field Infrared Survey Telescope (WFIRST)

Dark Energy, Infrared Survey… and Alien Worlds

- WFIRST is making great progress 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
- Wide Field Instrument Industry 6-month Concept Study with Ball Aerospace and Lockheed Martin ATC
- Reviews for SRR/MDR: July 2017
- Actively studying making WFIRST starshade-ready. First look: it's feasible from cost and risk perspective.
  - NASA Key Decision Point B (October 2017); decide whether WFIRST should remain starshade-compatible



Credit: NASA/GSFC

Large Binocular Telescope Interferometer

Measuring HZ Exozodiacal Dust, Informing Designs of Future Missions

- 35-star HOSTS survey delivery planned for September 2018
- 2016B Progress: HOSTS total now at 15 stars
- Precision: 12 zodi, one star one sigma, Gives better than 2 zodi mean uncty (one sigma of ensemble).
- Will inform design of exoplanet large mission studies for 2020 Decadal Study

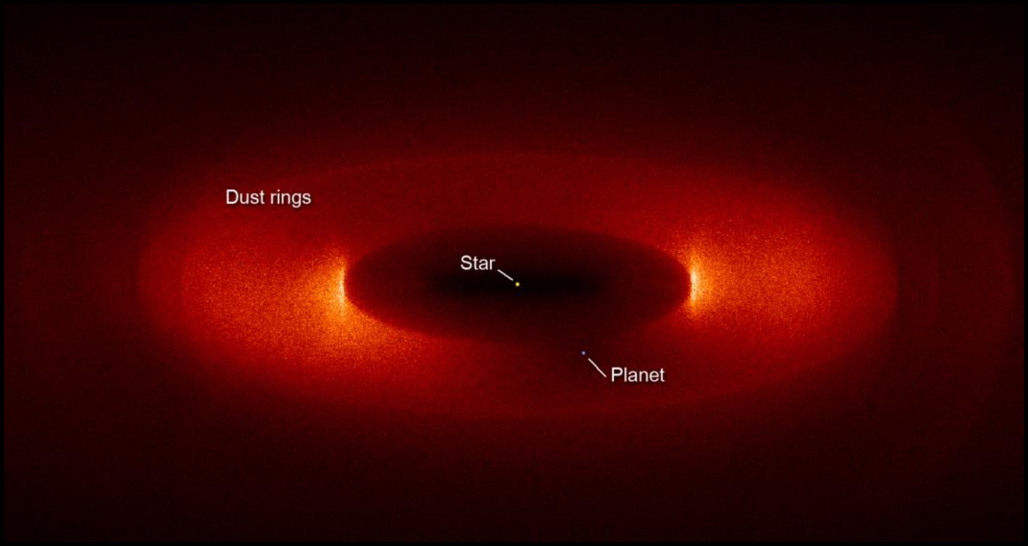
Phil Hinz, PI

THE UNIVERSITY OF ARIZONA

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

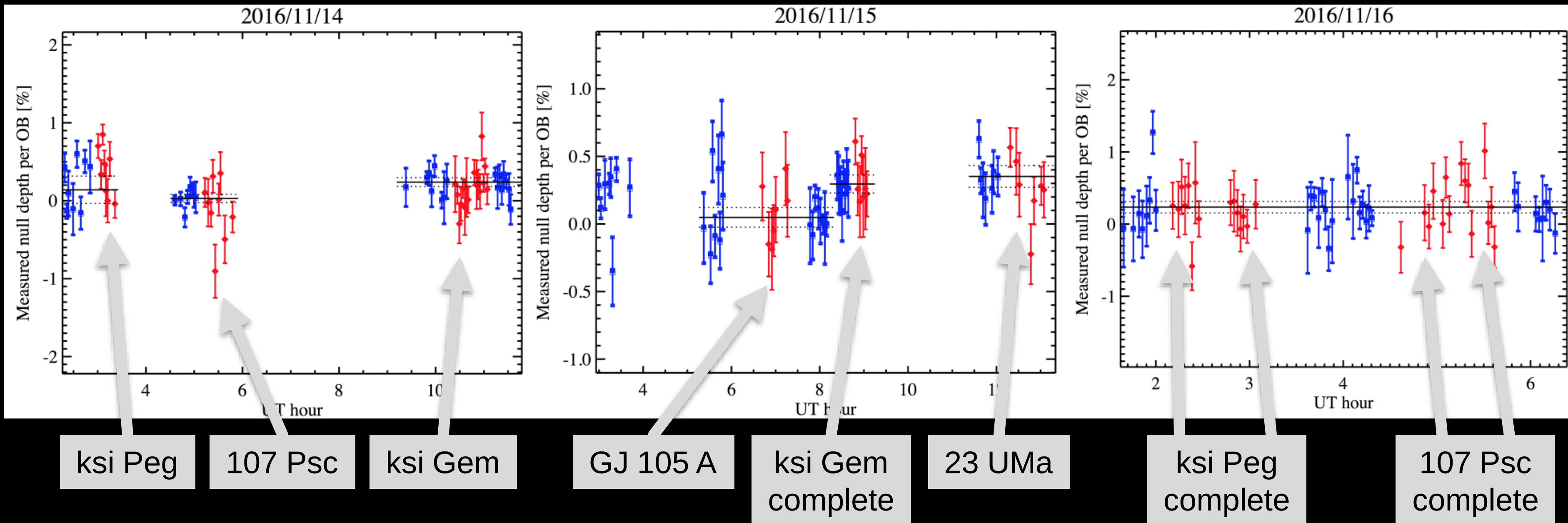
(Exo) Zodiacal Dust

Credit: ESO/Y. Beletsky

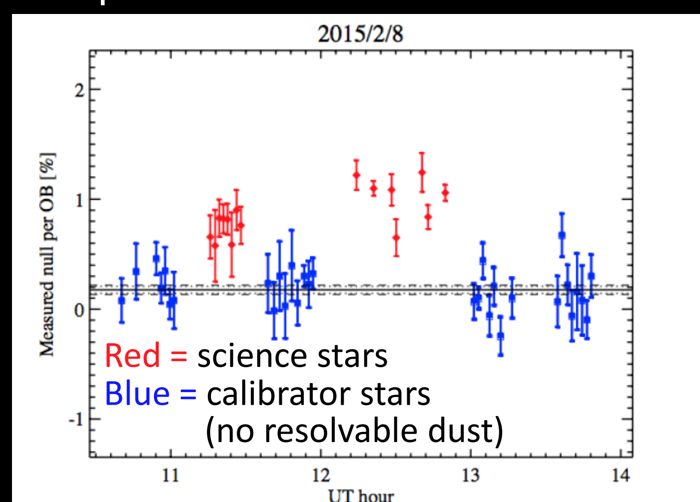


Credit: NASA/GSFC

Preliminary November 2016 HOSTS Data



Sample dust detection: beta Leo



The dust disk surrounding beta Leo (red data) emits 10 micron radiation not seen around calibrator stars (blue data). Measured dust brightness is 90±8 zodis.

NN-EXPLORE

Partnership for Exoplanet Discovery and Characterization

- Motivation
  - 2010 Decadal Survey calls for precise ground-based radial-velocity spectrometer for exoplanet discovery and characterization
  - Follow-up & precursor science for current missions (K2, TESS, JWST, WFIRST)
- Scope
  - Extreme precision radial velocity spectrometer (<0.5 m/s) for WIYN telescope development is underway
  - Instrument planned to be commissioned by August 2019
  - Ongoing Guest Observer program using NOAO share of telescope time for exoplanet research. Please propose!
- Status
  - Held Instrument Detailed Design Review, and PDR for port adapter
  - Next steps: DDR for port adapter

NEID

NN-Explore Exoplanet Investigations with Doppler Spectroscopy

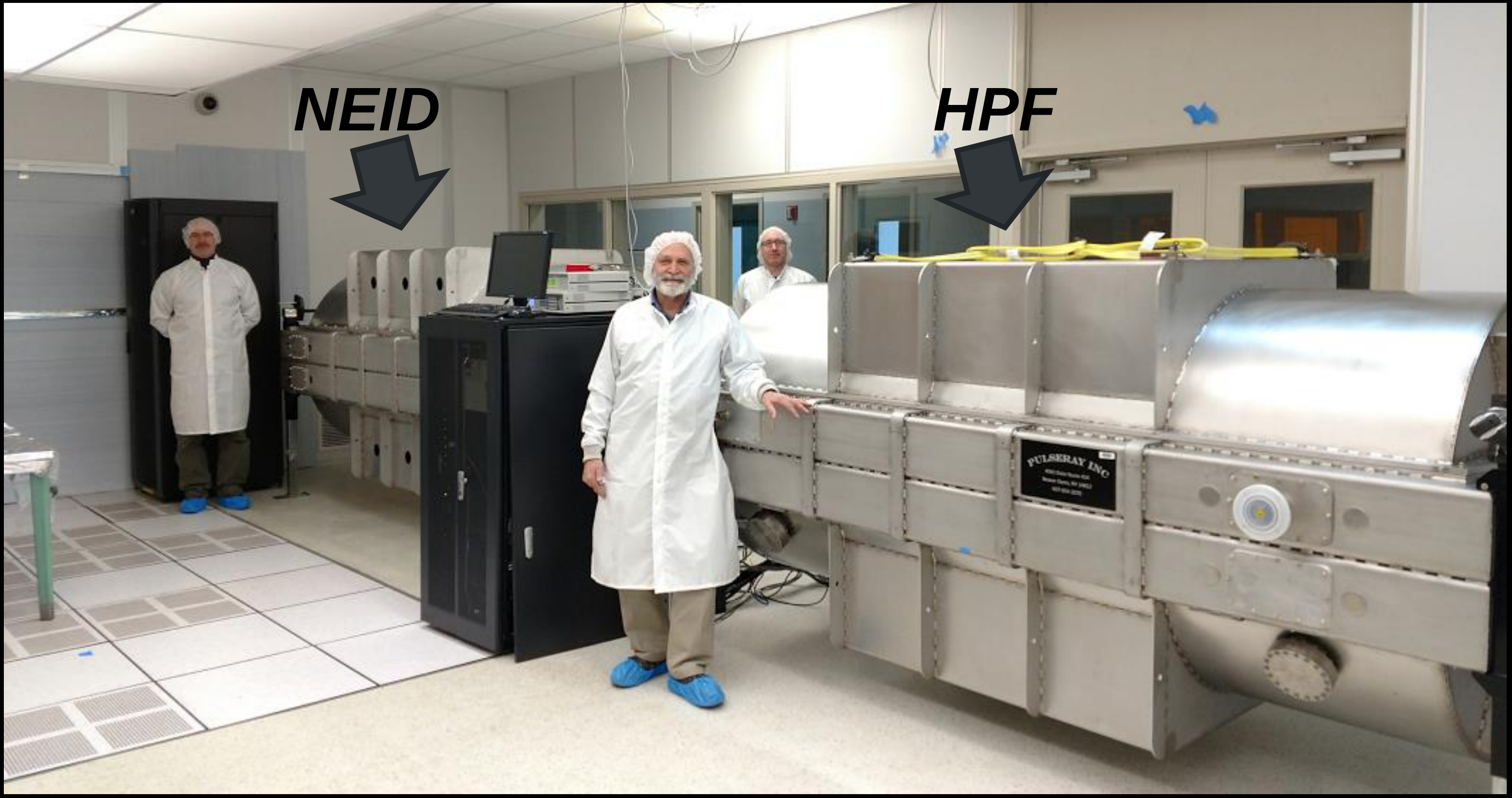
PennState

PI: S. Mahadevan

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

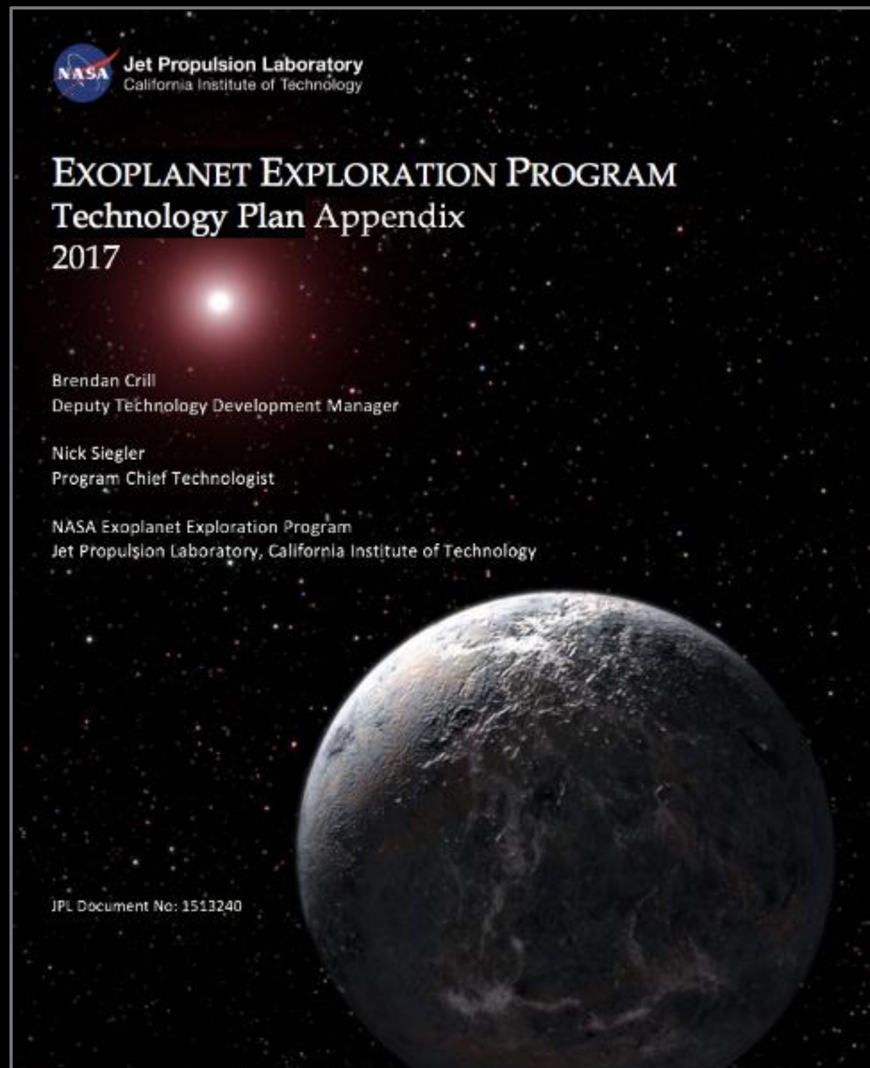
NEID Cryostat at Penn State

Cryostat built and integrated in upstate New York



Strategic Astrophysics Technology – TDEM

Advancing Technology Readiness towards next Decadal Survey


Jet Propulsion Laboratory
California Institute of Technology

EXOPLANET EXPLORATION PROGRAM
Technology Plan Appendix
2017

Brendan Crill
Deputy Technology Development Manager

Nick Siegler
Program Chief Technologist

NASA Exoplanet Exploration Program
Jet Propulsion Laboratory, California Institute of Technology

JPL Document No: 1513240

Appendix revision published January 2017

NASA Exoplanet Science Institute

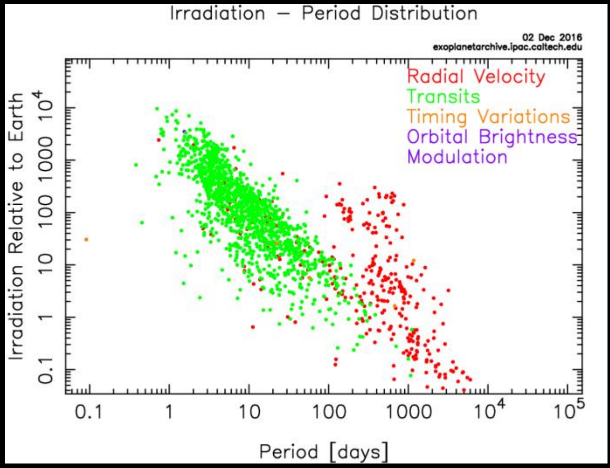
- Sagan Summer School, July 2016
  "Is there a Planet in my Data?"

- Sagan Summer School, August 2017
  "Microlensing in the Era of WFIRST"

- NASA/Keck times (90 nights/yr) supports Exoplanets, Cosmic Origins, Physics of the Cosmos and Solar System Science

- Exoplanet Archive tracks exoplanet population and Kepler pipeline products

- ExoFOP supports Kepler & K2 sources follow-up



Program Overview

Science Updates

How Do We Discover & Characterize Exoplanets?

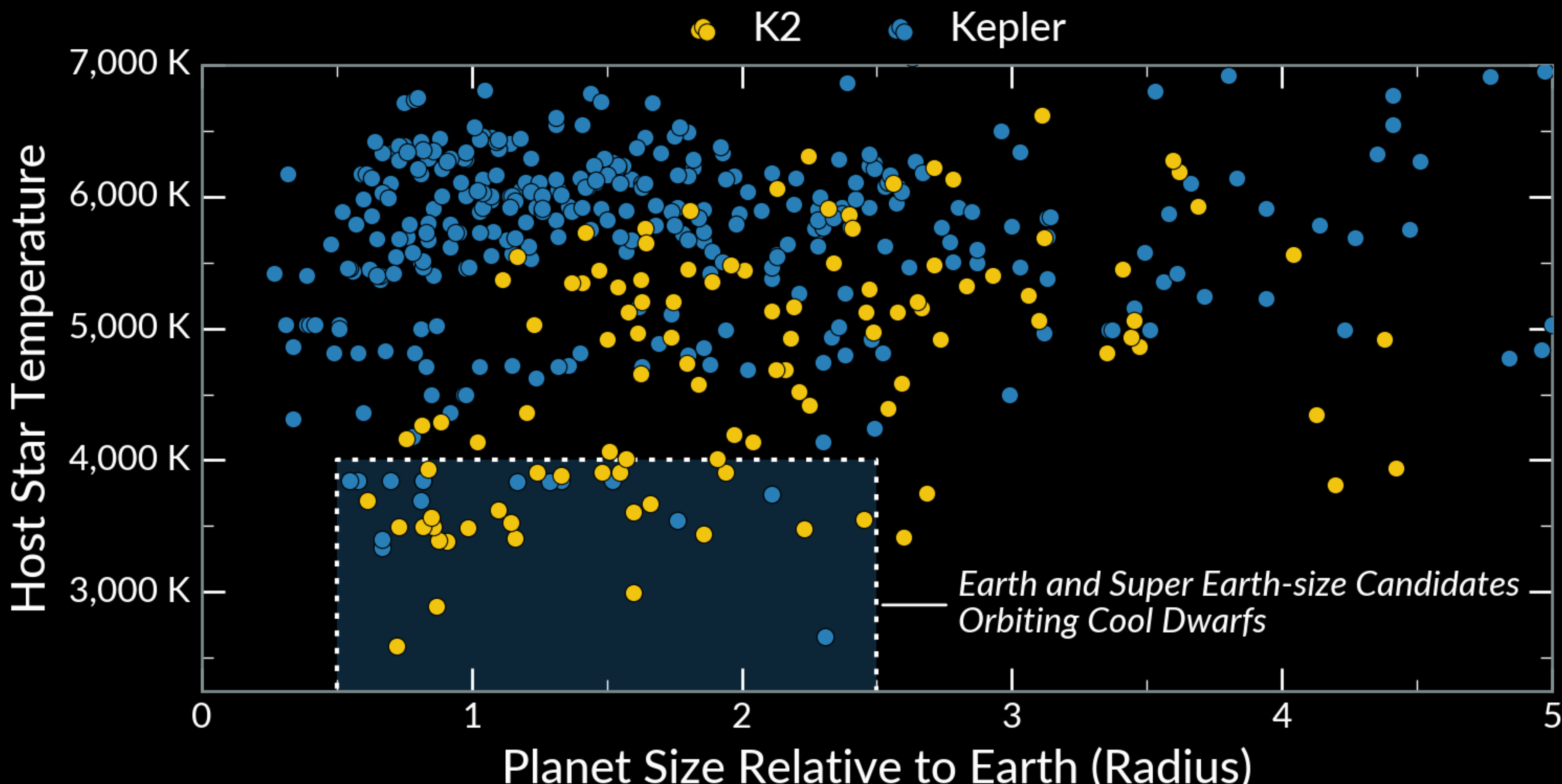
Progress towards 2010 Decadal Survey Priorities

Plan Forward: Science and Technology

You Had Me at Habitable

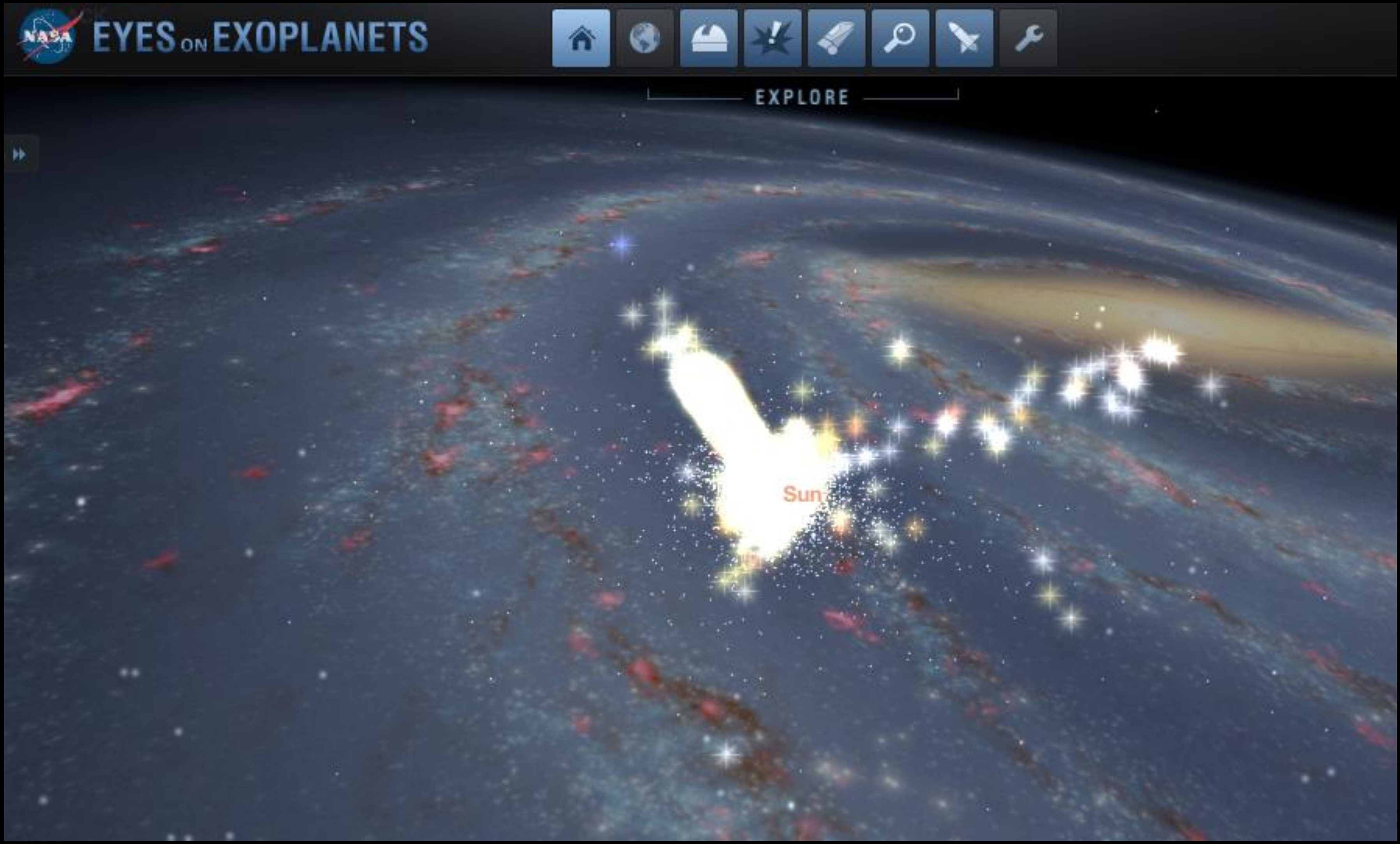

Exoplanet
Missions
WFIRST
JWST[2]
TESS
PLATO
Kepler
CHEOPS
New
Worlds
Telescope
Spitzer
Gaia
Hubble[1]
Habitable Exoplanet Imager
CoRoT[3]
LUVOIR
NASA
Missions
ESA/European
Missions
W. M. Keck Observatory
Large Binocular
Telescope Interferometer
NN-EXPLORE
Ground Telescopes with NASA participation
1 NASA/ESA Partnership
2 NASA/ESA/CSA Partnership
3 CNES/ESA

Planet Candidates for Atmospheric Characterization (Ks < 11)



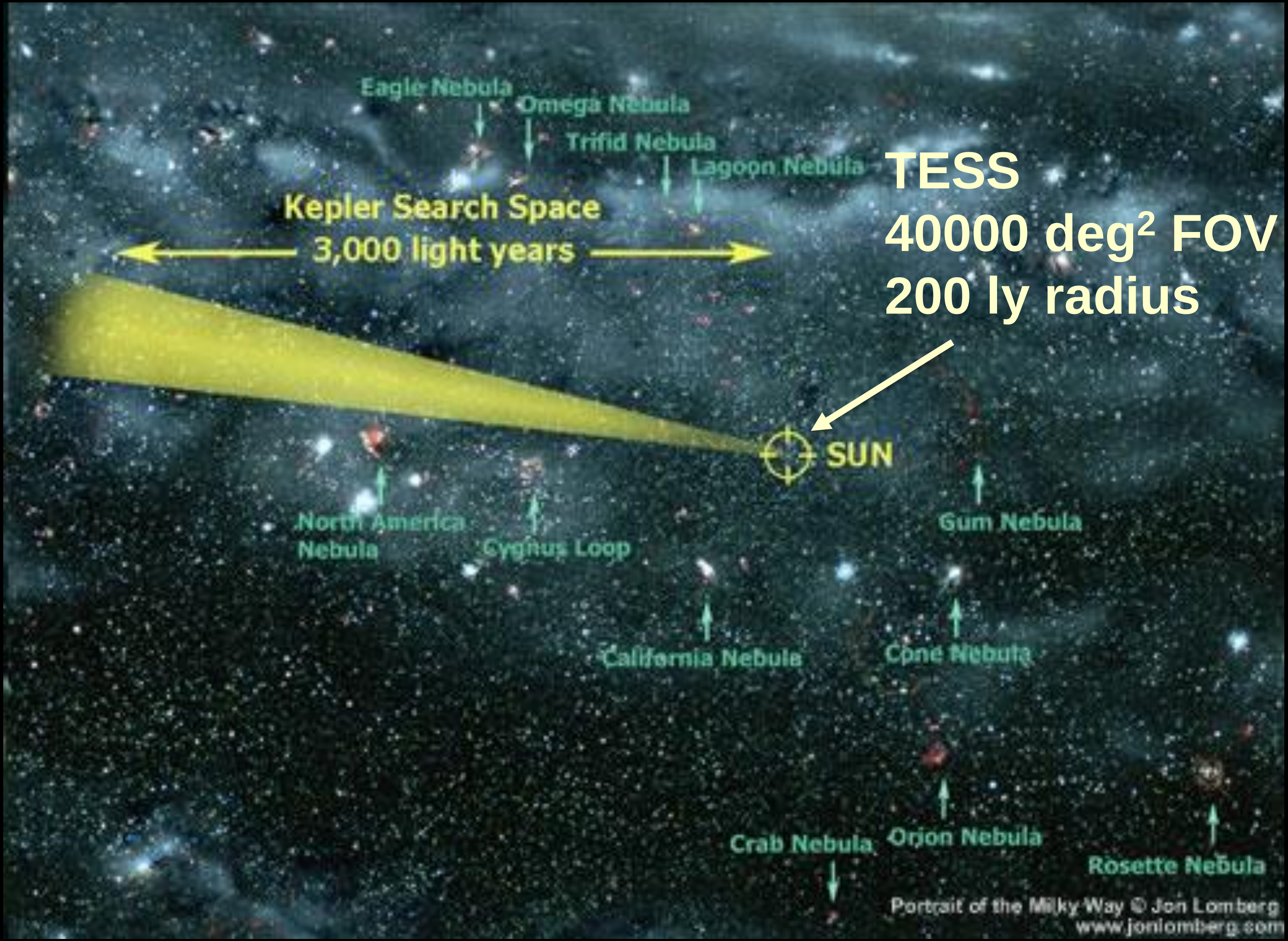
Exoplanet: Confirmed and Candidates

Visualization from *Eyes on Exoplanets*



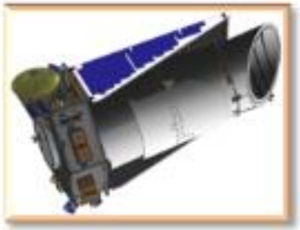
TESS Will Survey Nearby Stars

Provides Bright Targets for JWST Transit Spectroscopy



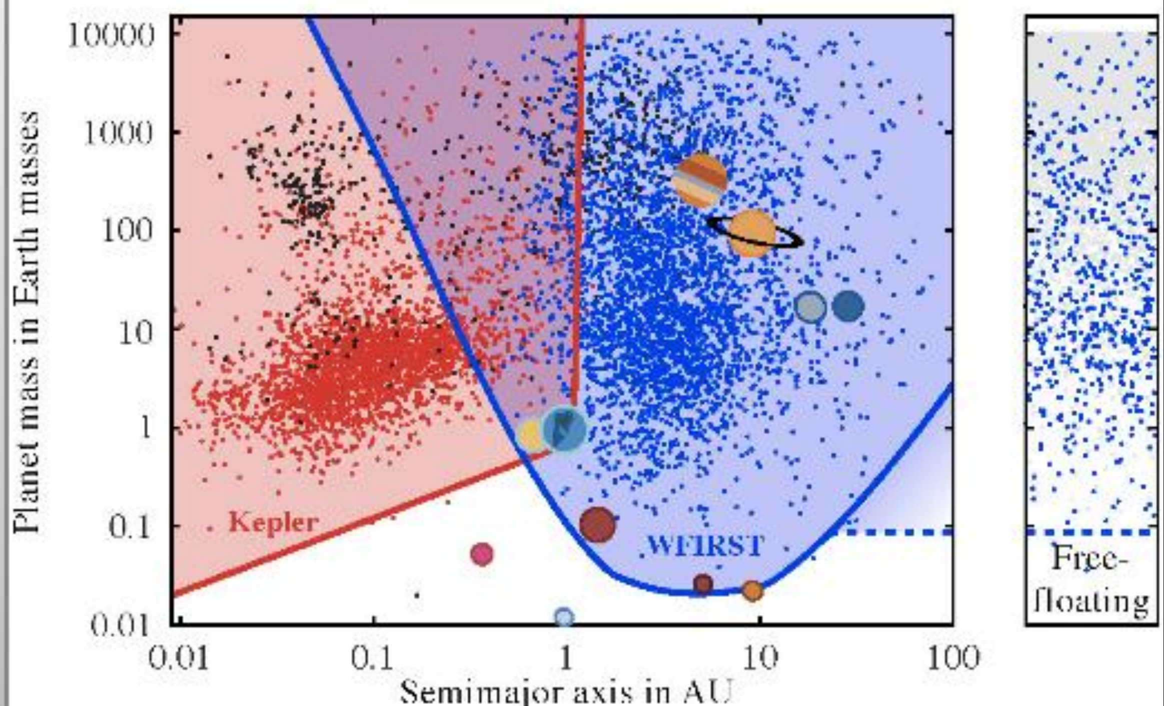
WFIRST Microlensing Census for Exoplanets

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



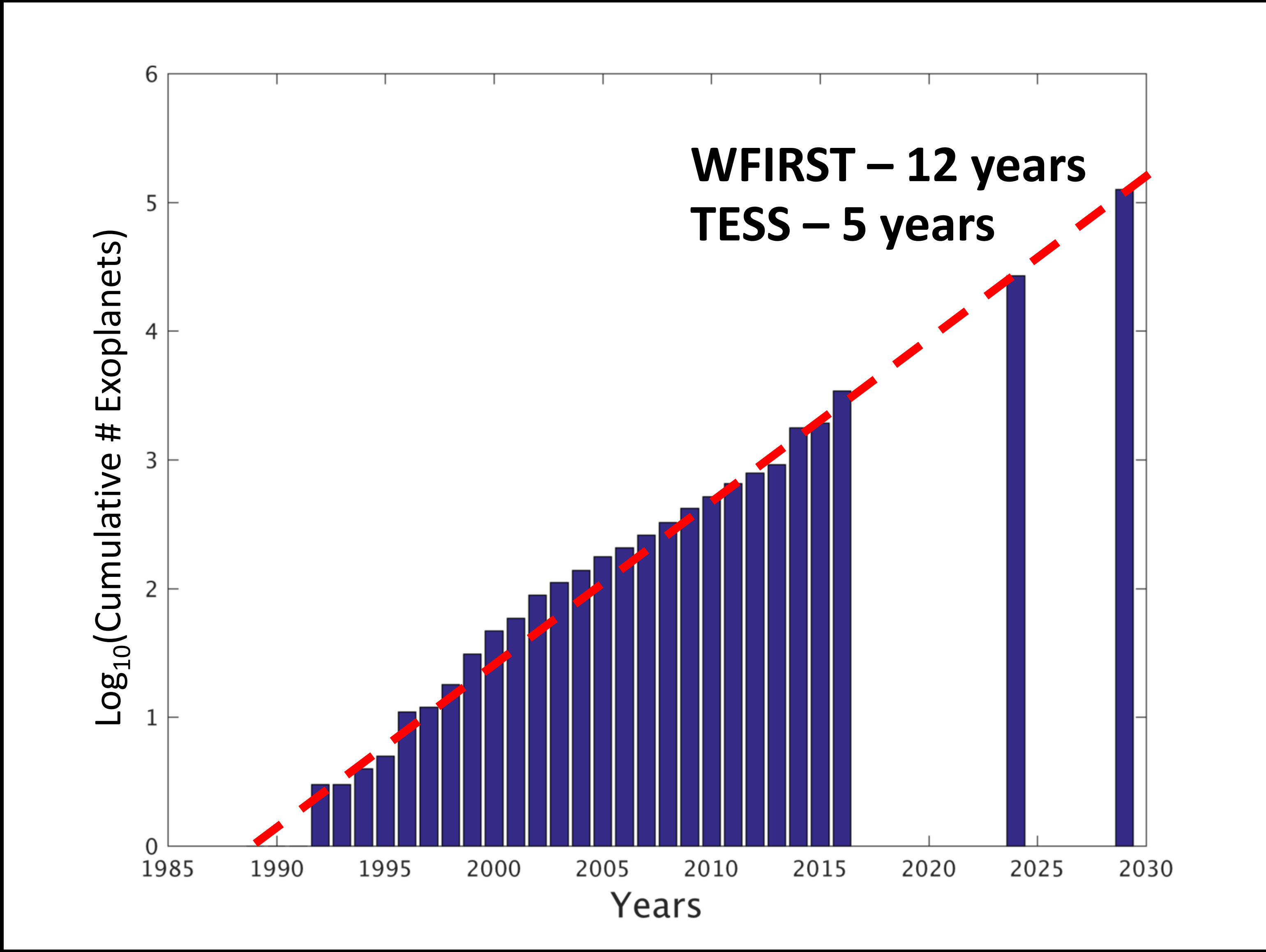
WFIRST-AFTA will:

- 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



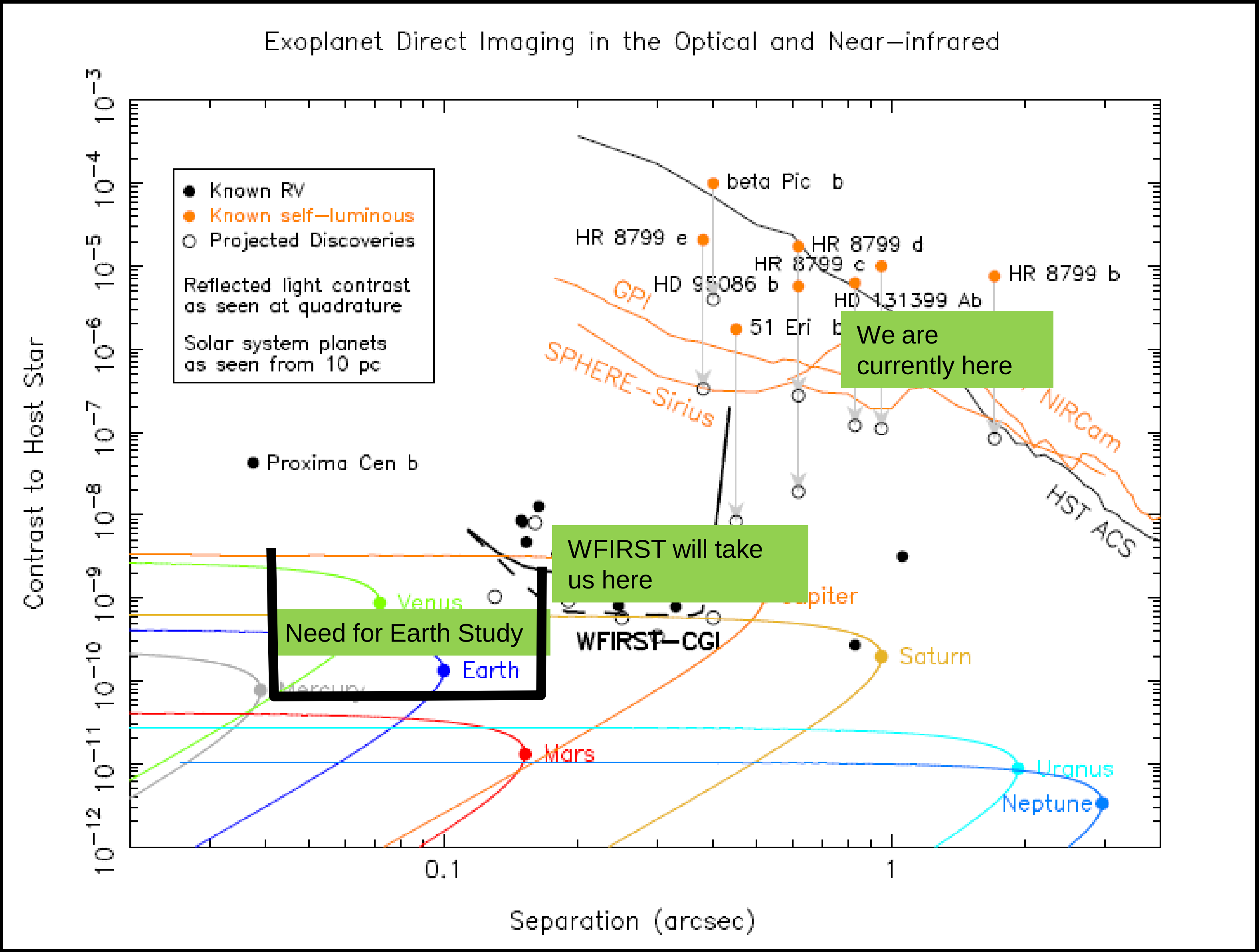
Credit: D. Bennett, M. Penny

How Much Longer Can Mamajek's Law Last?

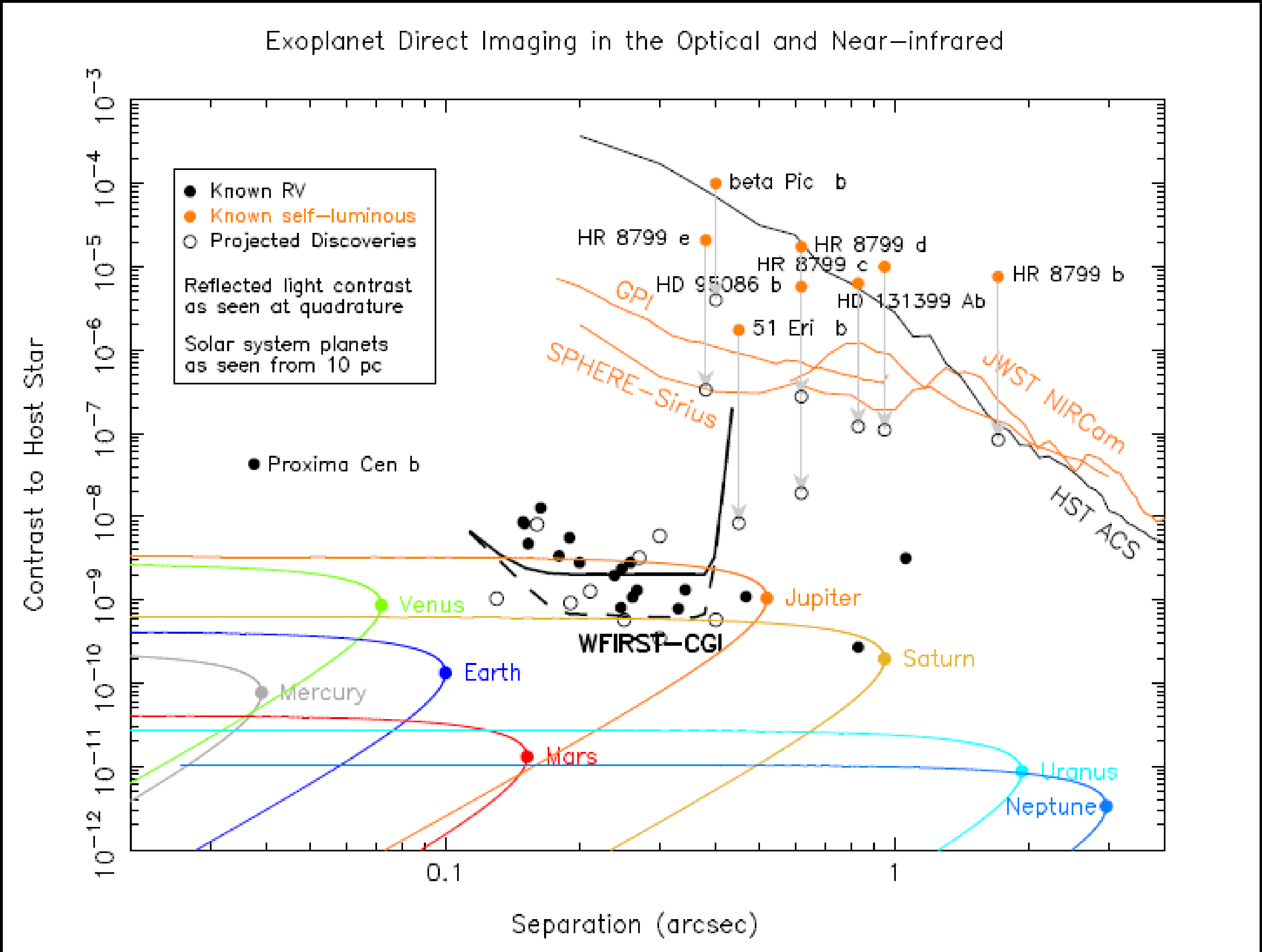


Credit: J. Christiansen

Exoplanet Direct Imaging

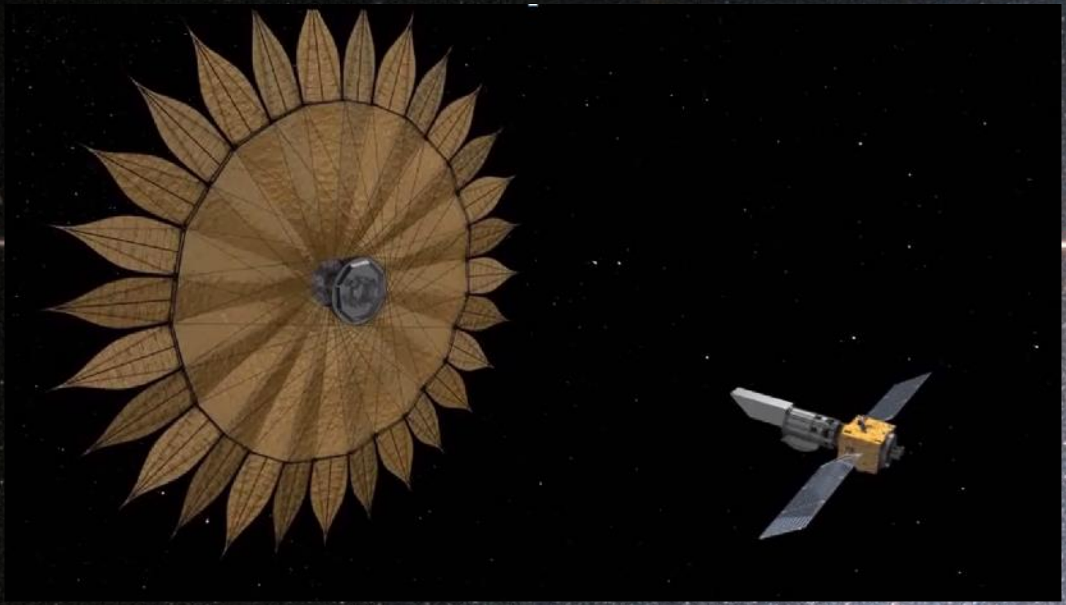


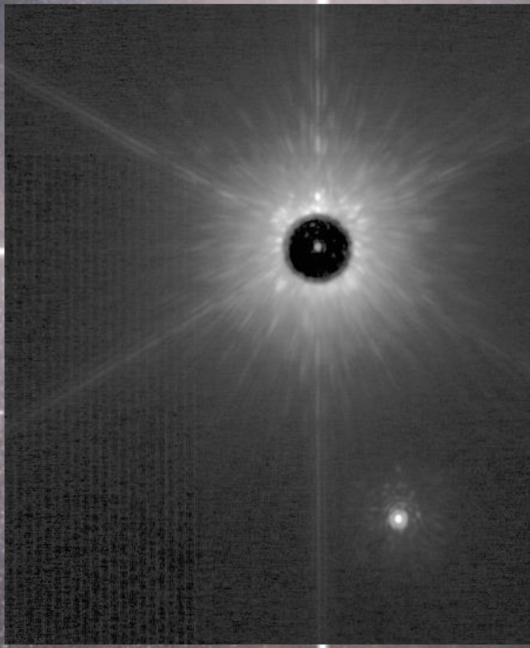
Exoplanet Direct Imaging



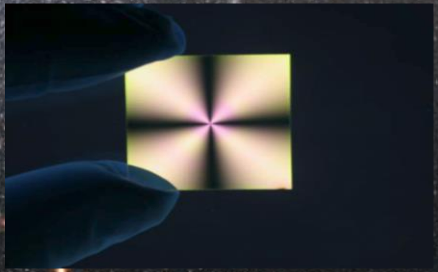
Starlight Suppression is <u>the</u> Key Technology in the Search for Life on Earth-Size Exoplanets

External Occulters (Starshades)



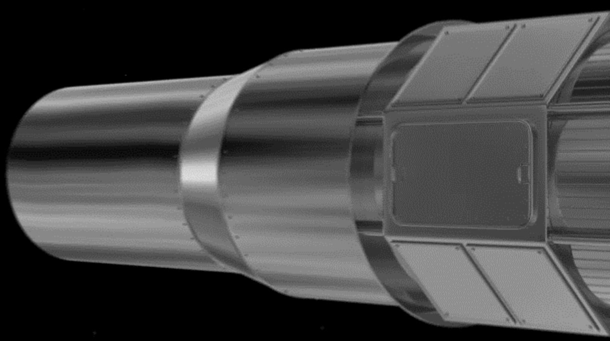


Internal Occulters (Coronagraphs)



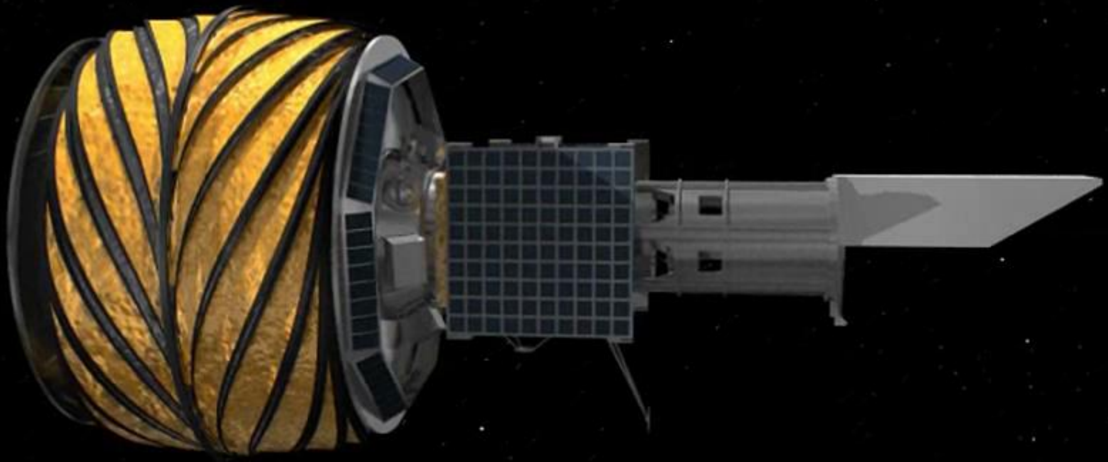
Internal Coronagraph

Controls Diffraction to Reveal Exoplanets in “Dark Hole”



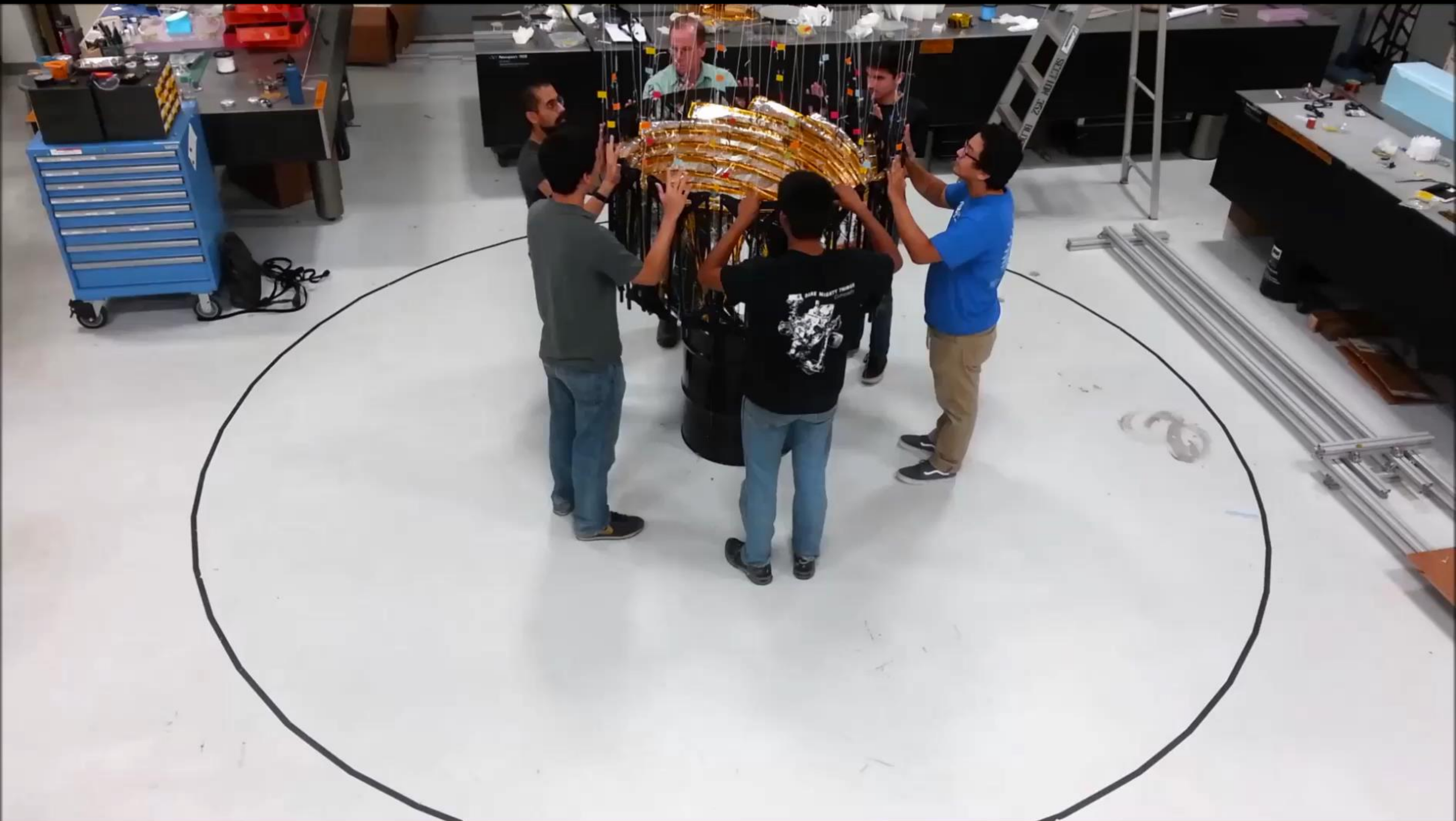
Starshade (External Occulter)

Blocks Starlight, Controls Diffraction prior to Entering Telescope



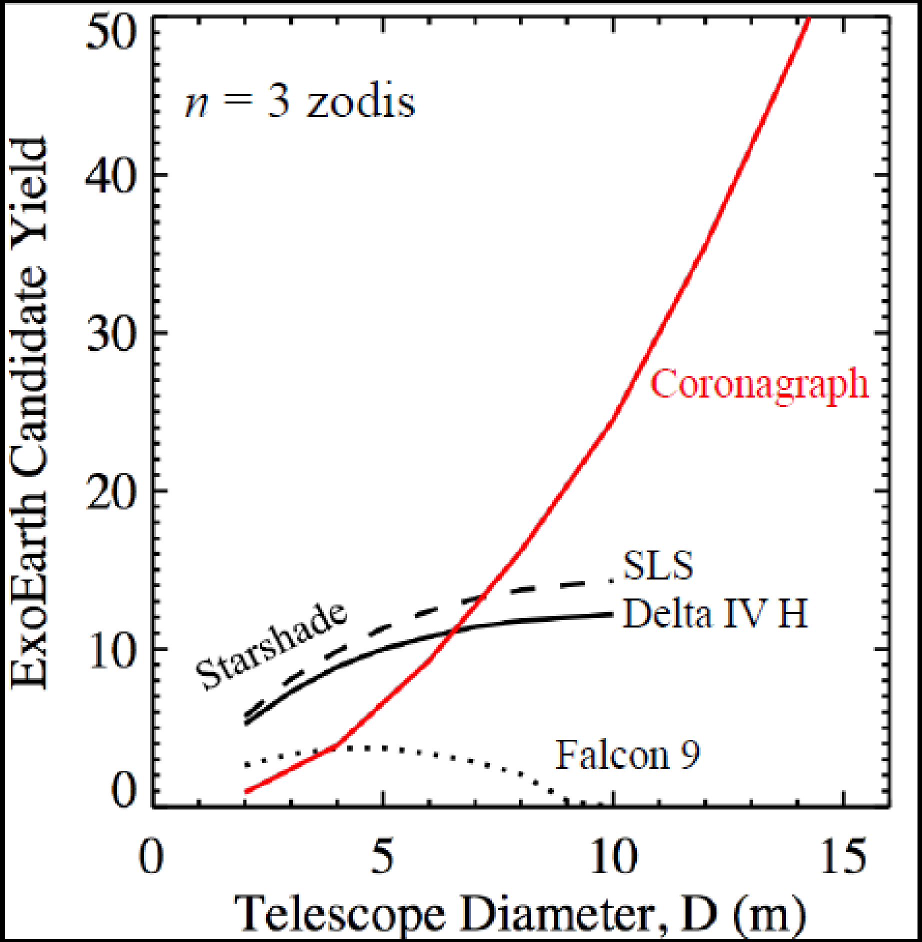
Early Inner Disk Deployment Trials at JPL

Starshade Optical Shield



Starshade and Coronagraph: Relative Yield

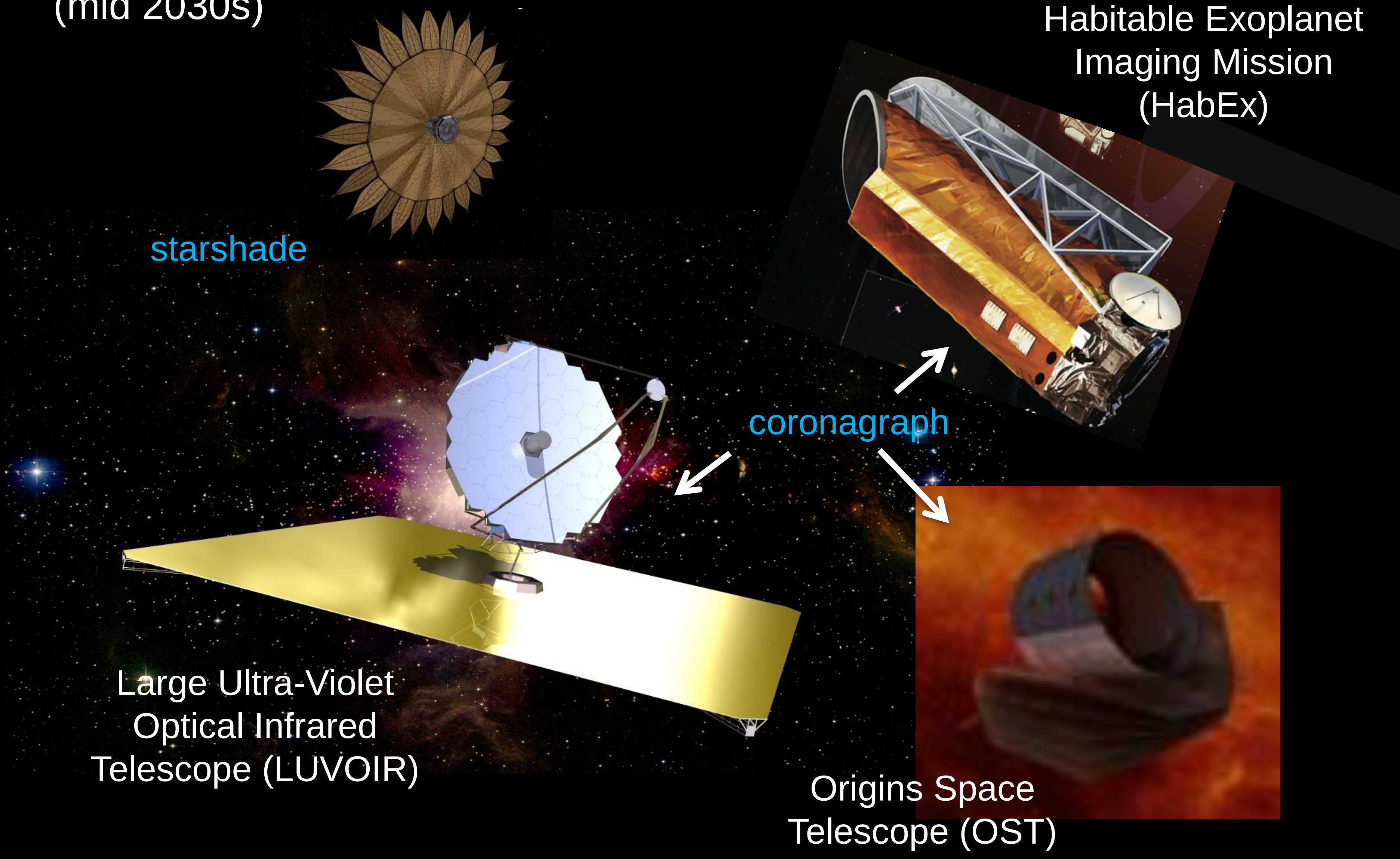
- Starshades appear to provide greater yield for telescope apertures less than ~6 m (depending upon launch vehicle and exozodi)

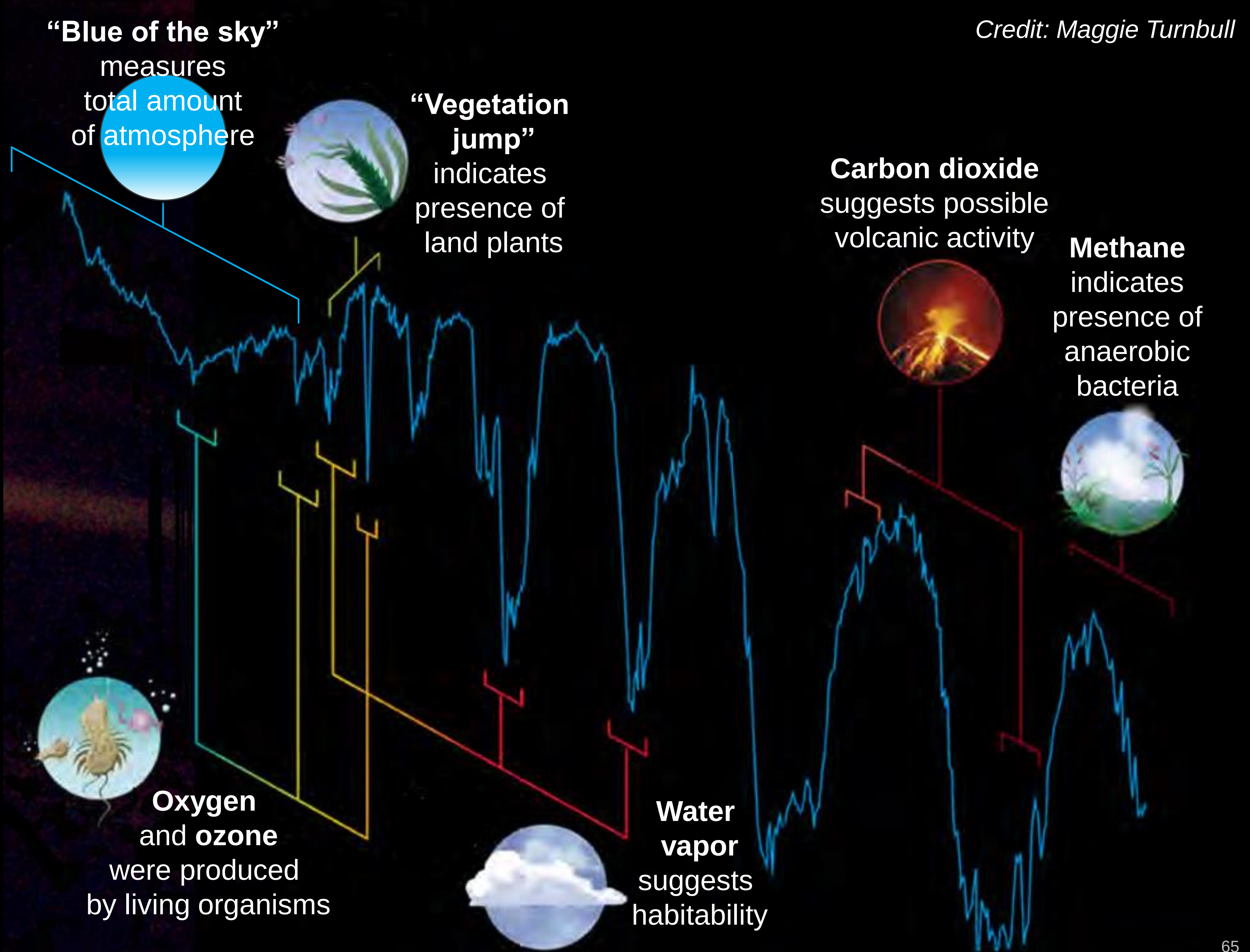


Credit: C. Stark et al 2016

Possible New Worlds Exoplanet Telescopes

(mid 2030s)





Credit: Maggie Turnbull
"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

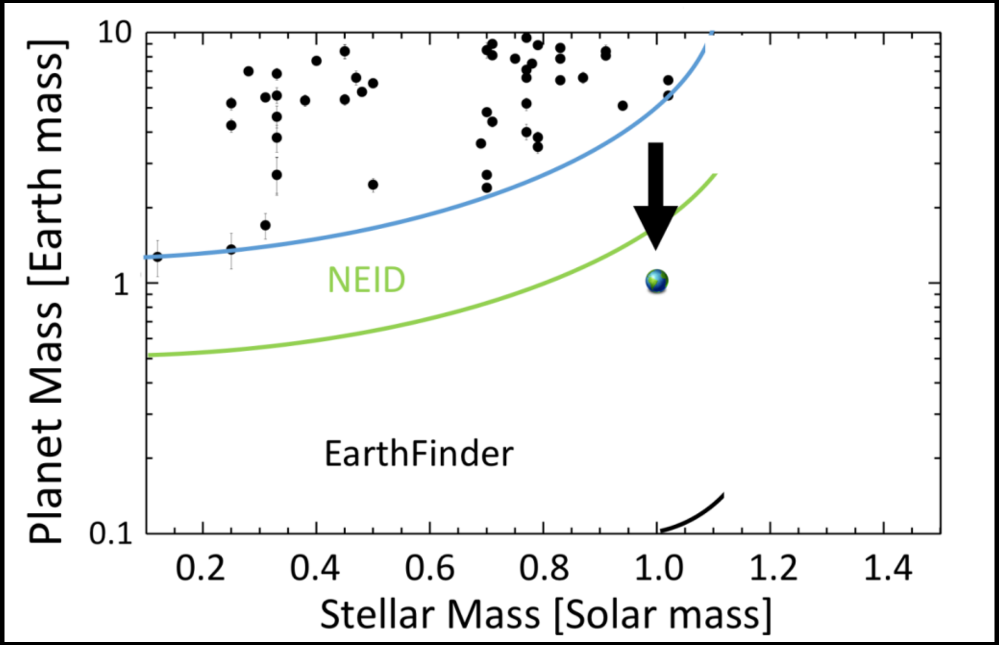
Medium-Scale Space Mission Concepts

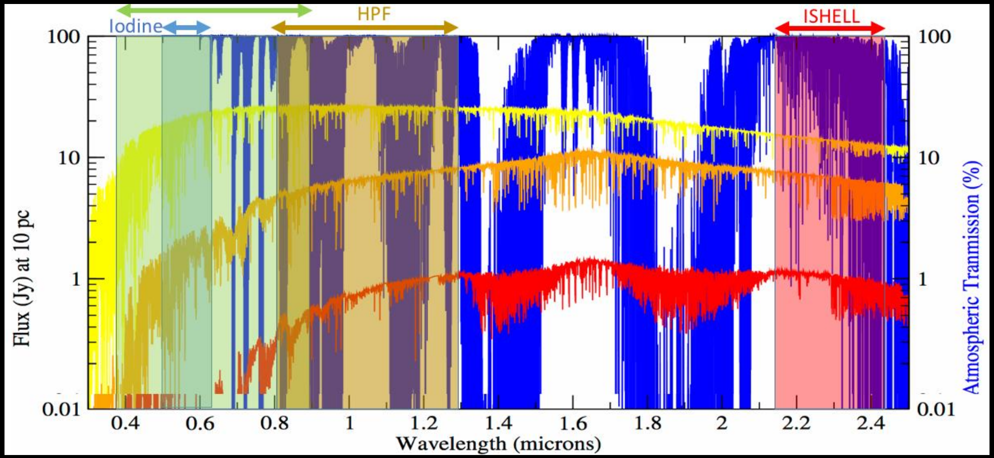
Announced by NASA March 20

PI	Affiliation	Title
Camp, J.	NASA's Goddard Space Flight Center	Transient Astrophysics Probe Concept Study
Cooray, 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
Hanany, S.	Univ. of Minnesota	Inflation Probe Mission Concept Study
Mushotzky, R.	Univ. of Maryland	AXIS: A High Spatial Resolution X-ray Probe Satellite
Olinto, A.	Univ. of Chicago	Concept Study of the Probe Of Extreme Multi Messenger Astrophysics (POEMMA)
Plavchan, P.	Missouri State Univ.	EarthFinder: A Diffraction-Limited Precise Radial Velocity Observatory in Space (*Partial selection)*
Ray, P.	Naval Research Laboratory	STROBE-X: X-ray Timing and Spectroscopy on Dynamical Timescales from Microseconds to Years
Seager, S.	Massachusetts Institute of Technology	Starshade Rendezvous (*Partial selection)*

Precision Radial Velocity from Orbit

Avoid the Telluric Lines



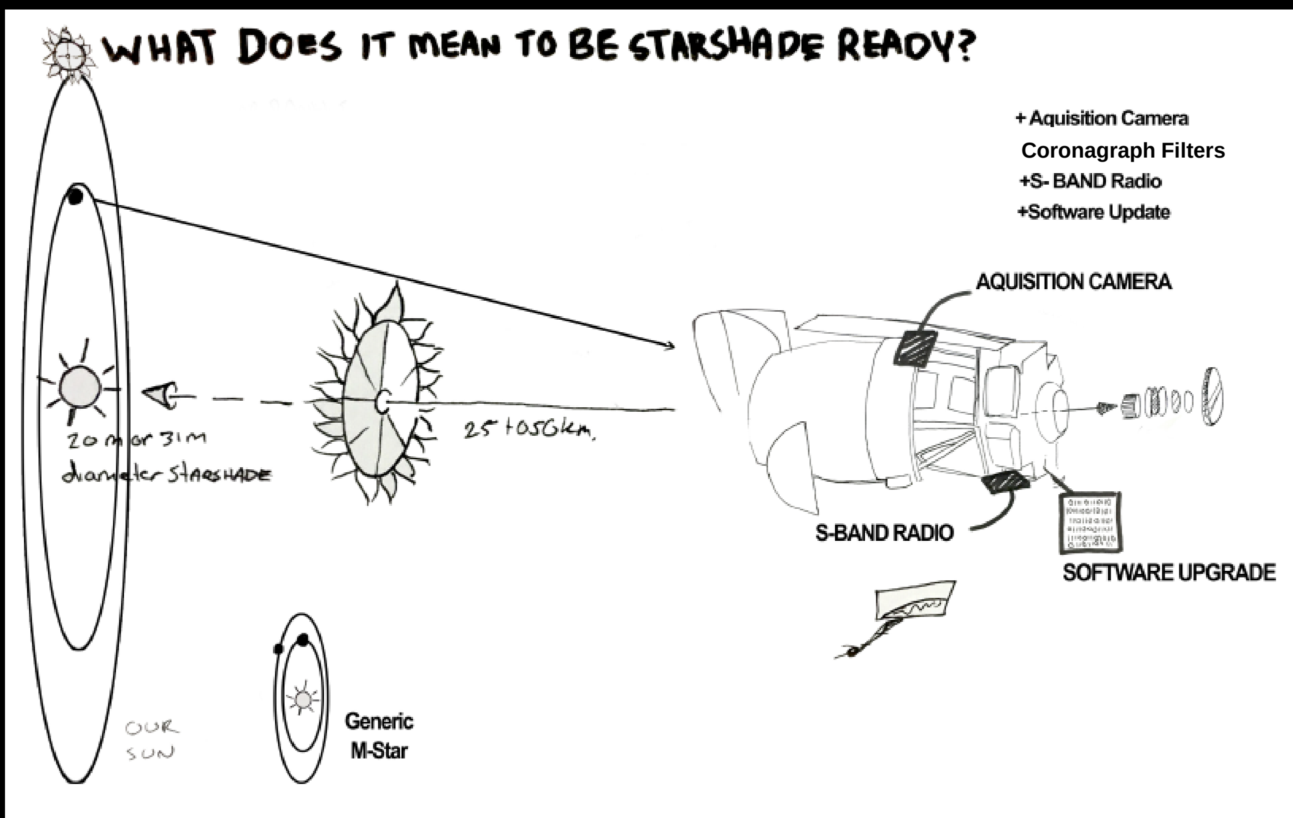


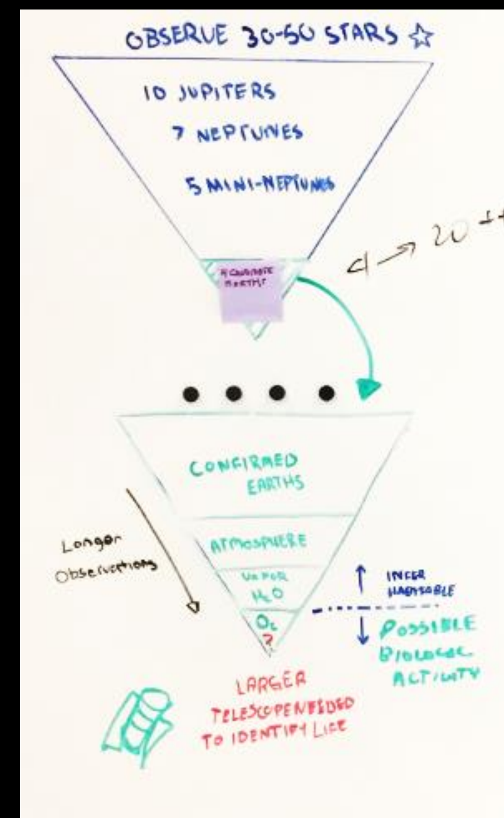
Credit: P. Plavchen

WFIRST Starshade-Ready

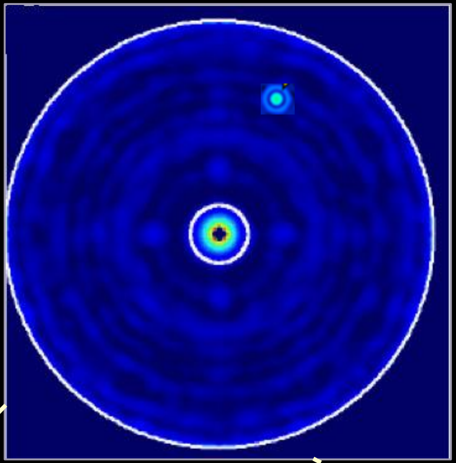
Accommodation Study to Enable a Rendezvous at L2

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

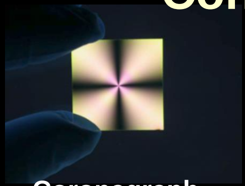




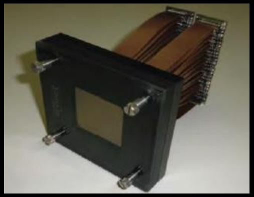
Coronagraph/Telescope Technology Needs



Contrast



Coronagraph architectures



Deformable mirrors

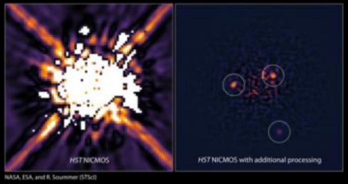
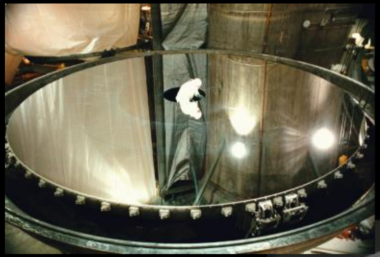
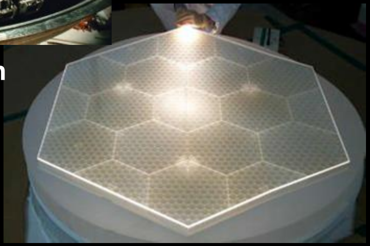


Image post-processing

Angular Resolution

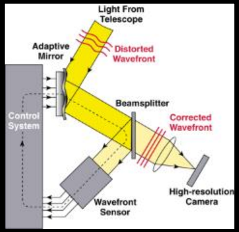


Large monolith

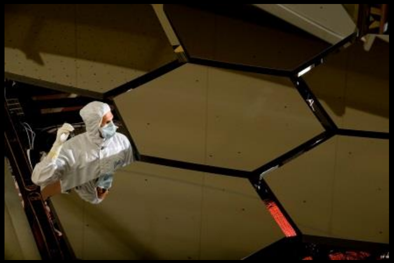


Segmented

Contrast Stability



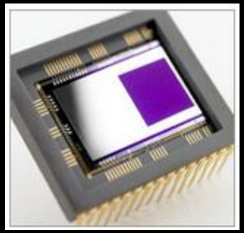
Wavefront sensing and control

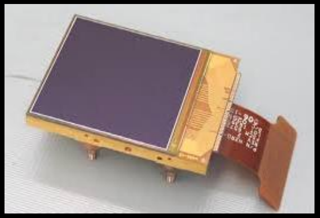


Segment phasing and rigid body sensing and control

Telescope vibration sensing and control

Detection Sensitivity



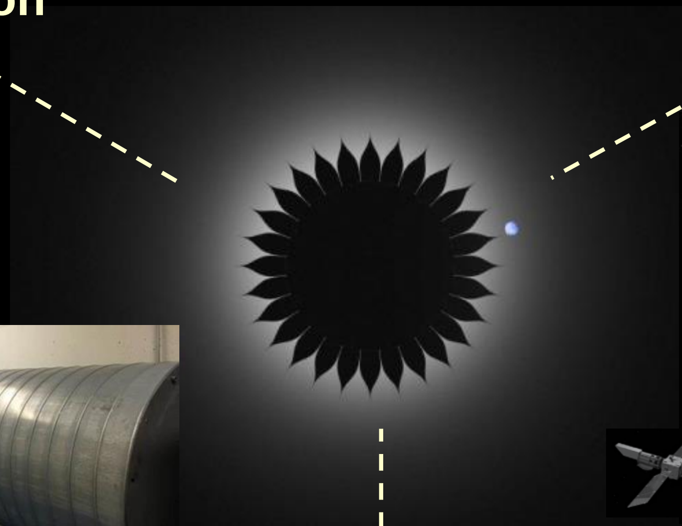


Ultra-low noise visible and infrared detectors

Starshade Technology Needs

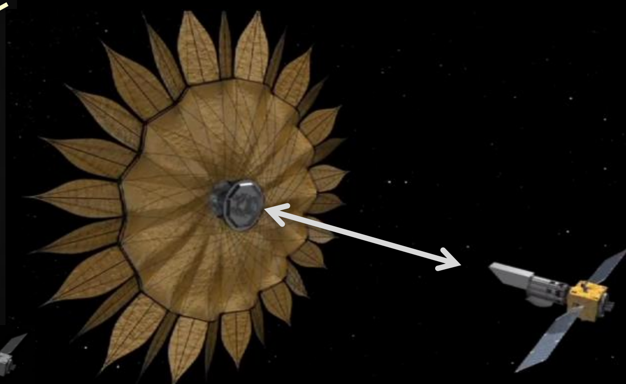
1) Starlight Suppression

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



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

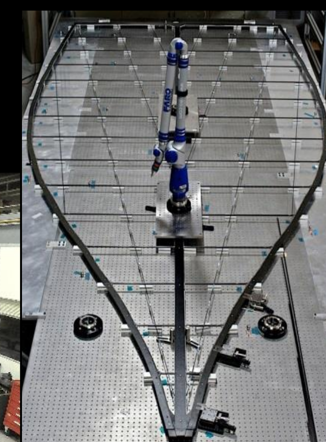
2) Formation Sensing and Control



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

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

Program Overview

Science Updates

How Do We Discover & Characterize Exoplanets?

Progress towards 2010 Decadal Survey Priorities

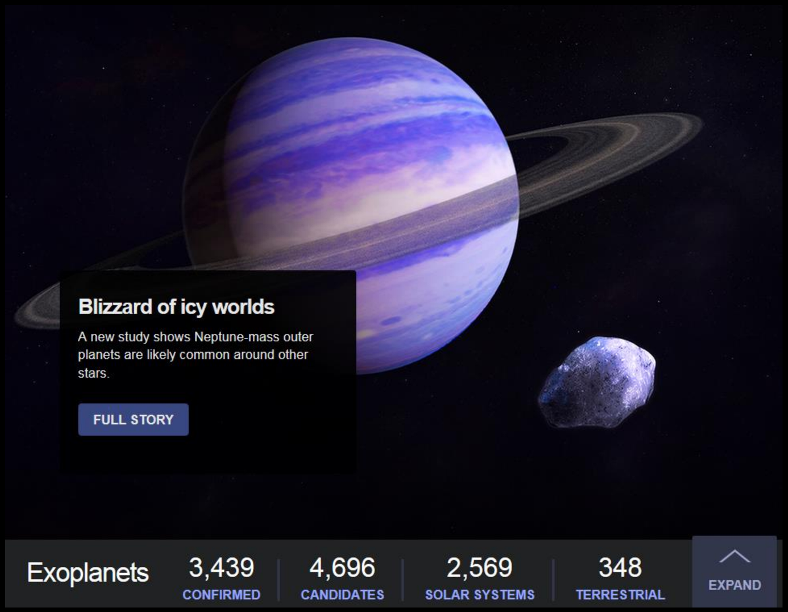
Plan Forward: Science and Technology

You Had Me at Habitable

Exoplanet Communications

Data Visualization Tools and New Thematic Exoplanet Hub

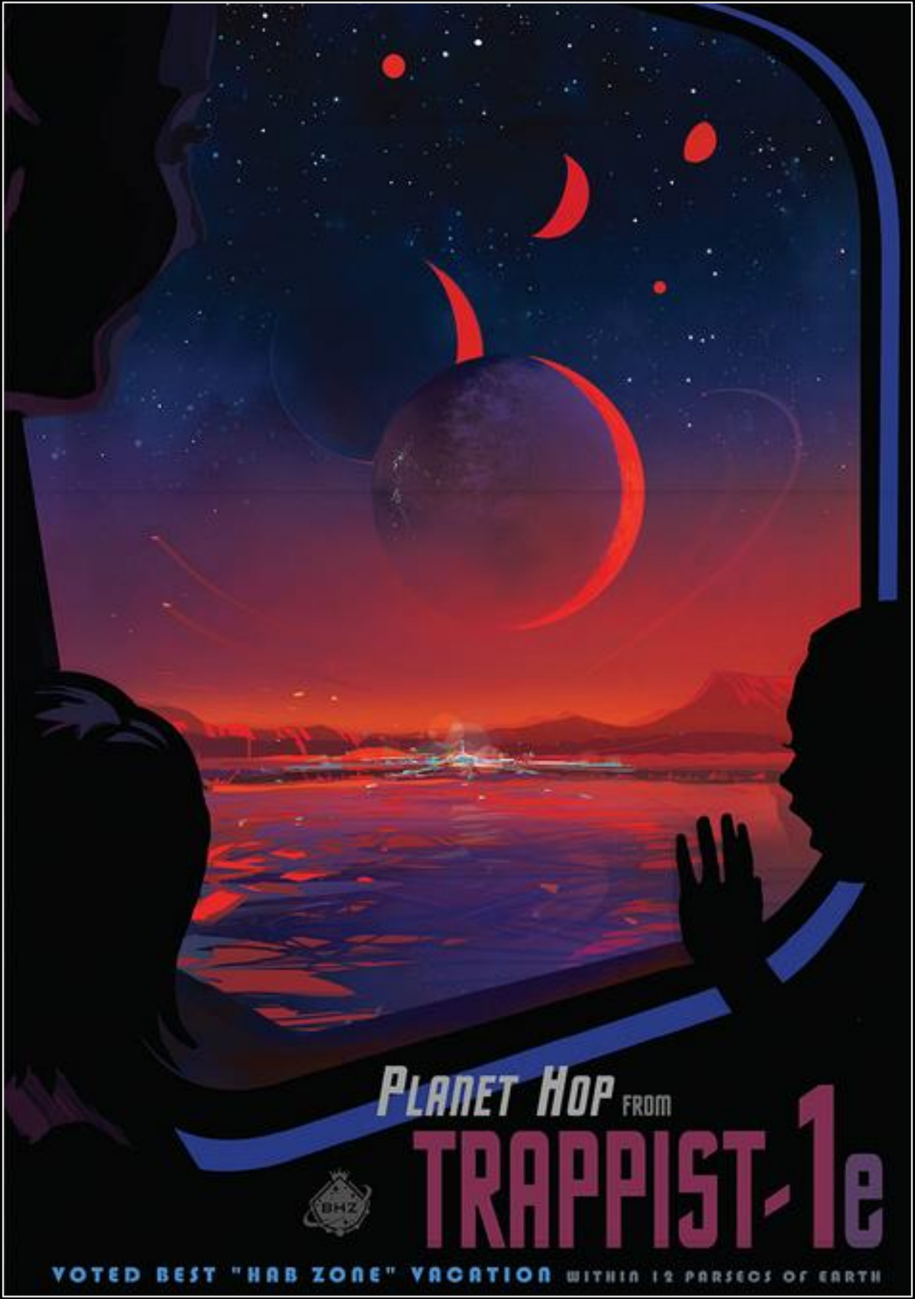
exoplanets.nasa.gov



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

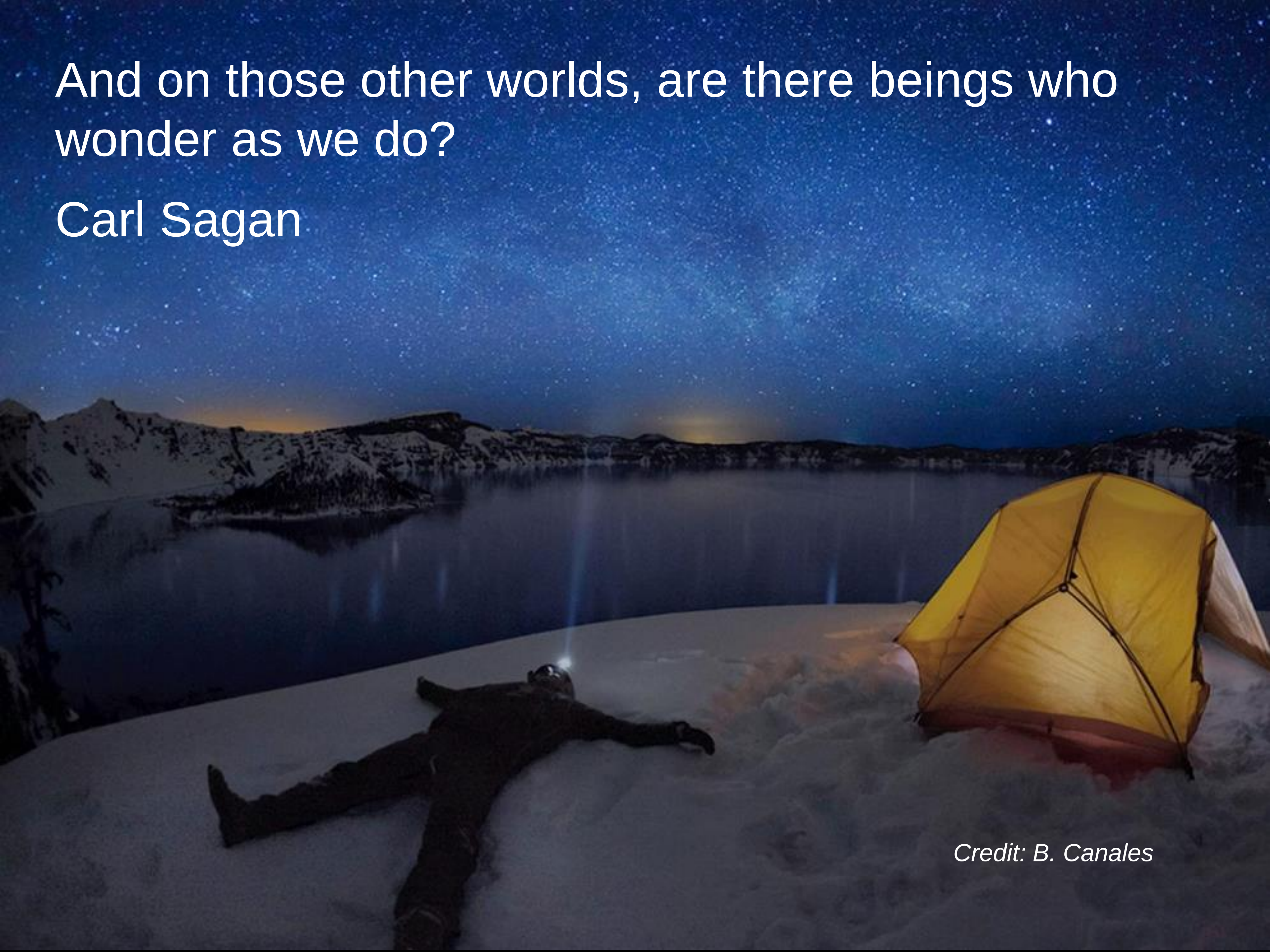
3D, interactive planet renderings
Custom planet textures can be created for press releases.
(contact the Comm team in advance)

Exoplanet Travel Bureau

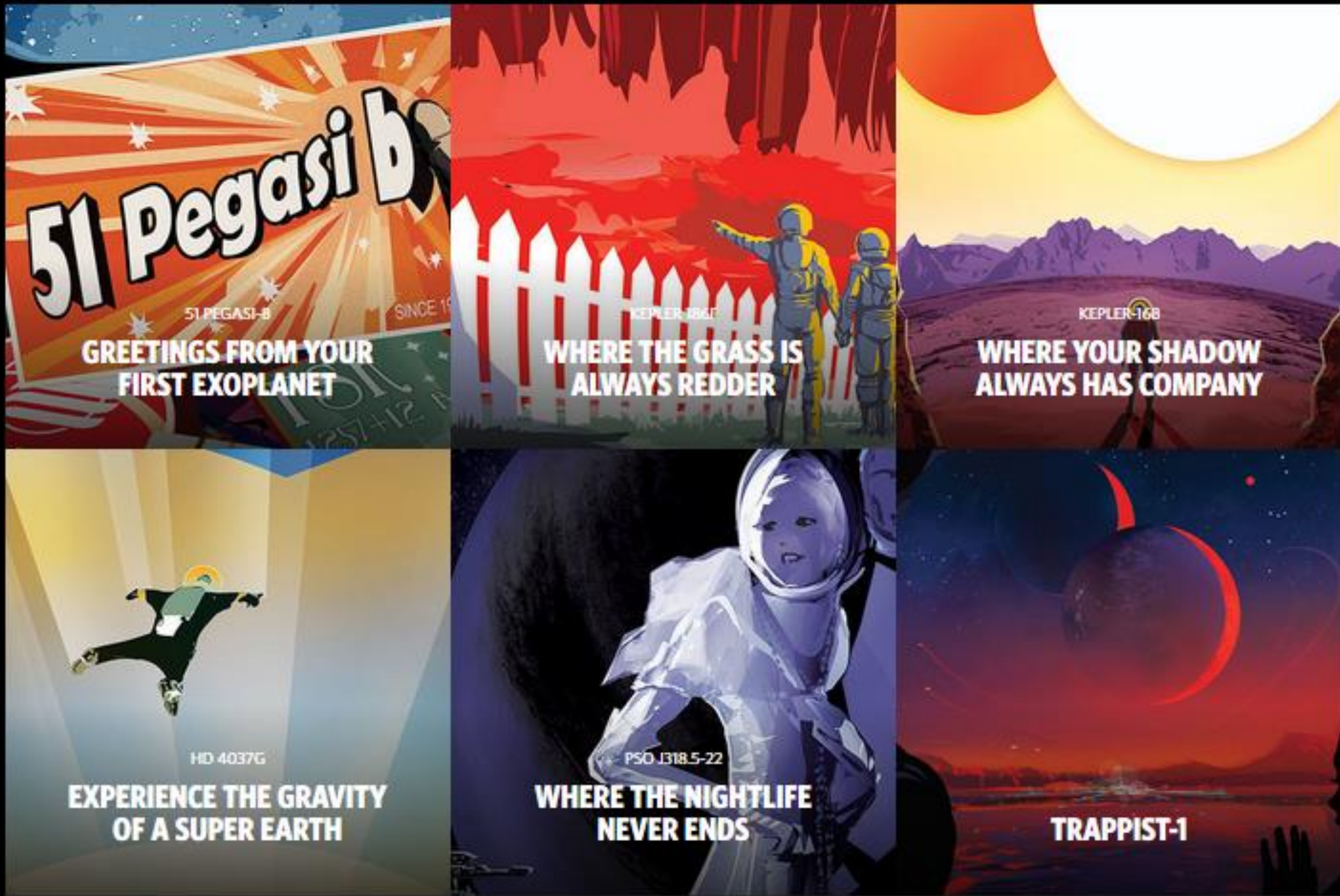


My Story

Credit: London Mint Office


And on those other worlds, are there beings who wonder as we do?
Carl Sagan
Credit: B. Canales

Exoplanet Travel Bureau



Exploring a Galaxy of Worlds while Inspiring Our Own

Introducing Baby Kepler! (Cloutier)

You Had Me at Habitable

DOB 2/6/16 • Age on Earth – 1 • Kepler 16b – 1.5 • Proxima b – 33 • Trappist-1b – 243

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

Acknowledgements

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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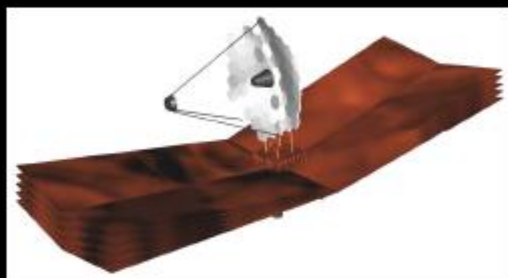
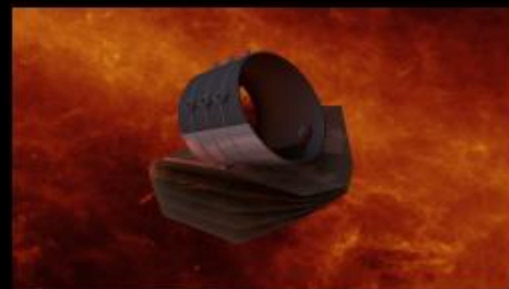
- Work was also carried out at NASA's
  - Goddard Space Flight Center
  - Ames Research Center
- Work was carried out as well under contracts with the National Aeronautics and Space Administration and
  - Princeton University
  - University of Arizona
  - Northrop Grumman Aerospace Systems
  - National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

Origins Space Telescope

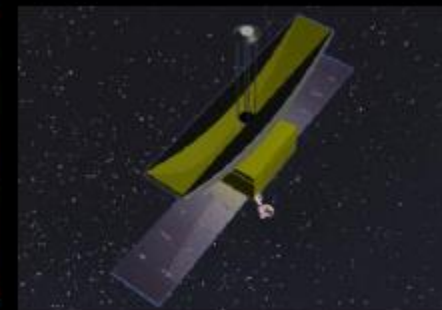
Credit: A. Cooray



JWST-like?



Spitzer-like?



Rotating aperture?

- 8–13 m single aperture
- 5–600 μm
- 4.5 K active-cooled
- Exoplanets
  - Transit/secondary eclipse spectroscopy
  - Direct imaging via a mid-IR coronagraph