Jet Propulsion Laboratory
California Institute of Technology

Exoplanet Exploration Program Updates

Dr. Gary H. Blackwood, Program Manager

Dr. Karl R. Stapelfeldt, Program Chief Scientist

Jet Propulsion Laboratory

California Institute of Technology

January 7, 2018
ExoPAG 17, National Harbor, Maryland

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Artist concept of Kepler-16b

Kepler / K2

Program Progress vs 2010 Decadal Priorities

Program Science Updates

NASA Exoplanet Exploration Program

Astrophysics Division, NASA Science Mission Directorate

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

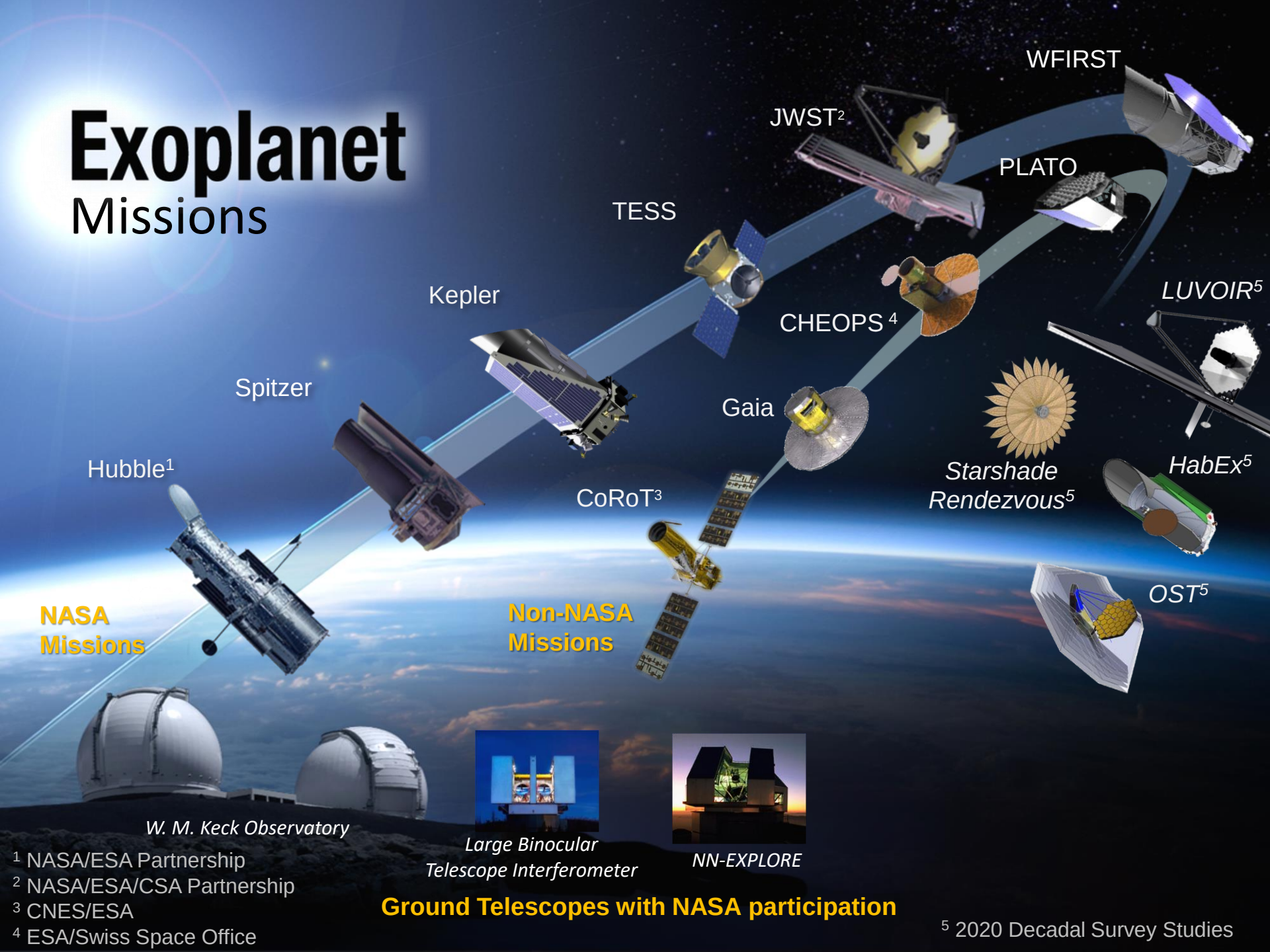
Program purpose described in 2014 NASA Science Plan

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



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

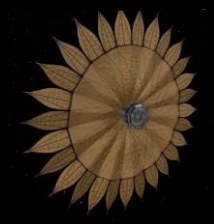
NASA Exoplanet Exploration Program

Space Missions and Mission Studies

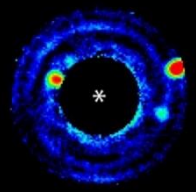
Kepler & K2

Probe-Scale Studies

Starshade



Coronagraph

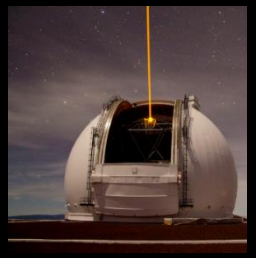


Communications

Supporting Research & Technology

Key Sustaining Research

NN-EXPLORE



Keck Single Aperture Imaging & RV

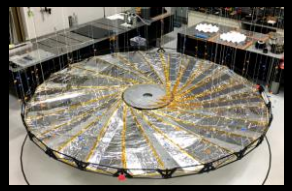
Large Binocular Telescope Interferometer

Technology Development

Occulting Masks

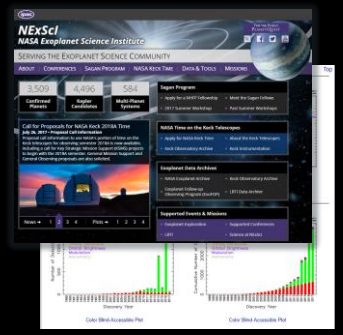
Deformable Mirrors

High-Contrast Imaging



Deployable Starshades

NASA Exoplanet Science Institute

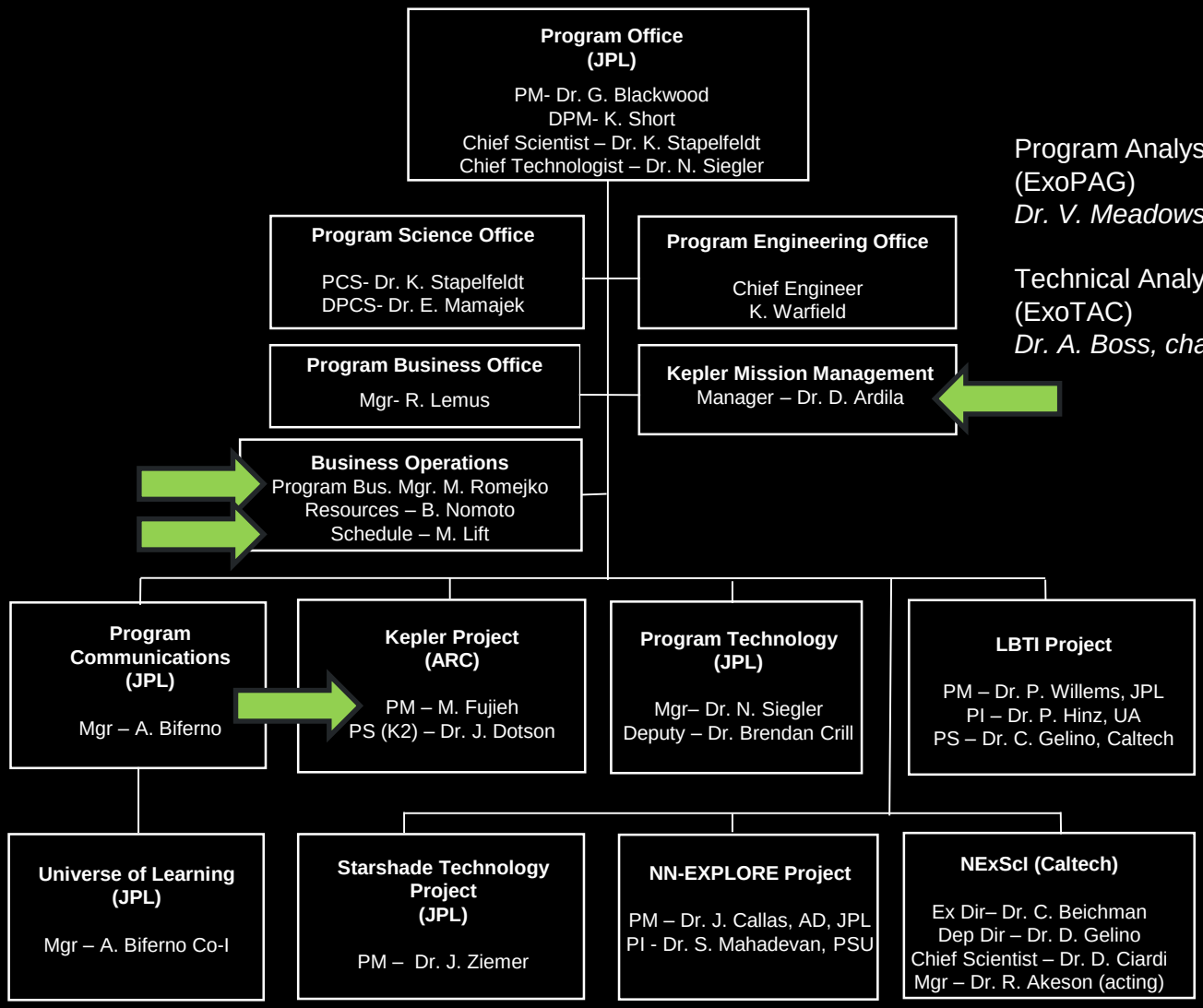


Archives, Tools, Sagan Fellowships, Professional Engagement

https://exoplanets.nasa.gov

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

New Leadership in ExEP Projects

Kepler K2

Maura Fujieh
Kepler K2 Project Manager
NASA Ames Research Center

Dr. Jessie Dotson
Kepler K2 Project Scientist
NASA Ames Research Center

Dr. David Ardila
Kepler K2 Mission Manager
Exoplanet Exploration Program
Jet Propulsion Laboratory

Kepler / K2

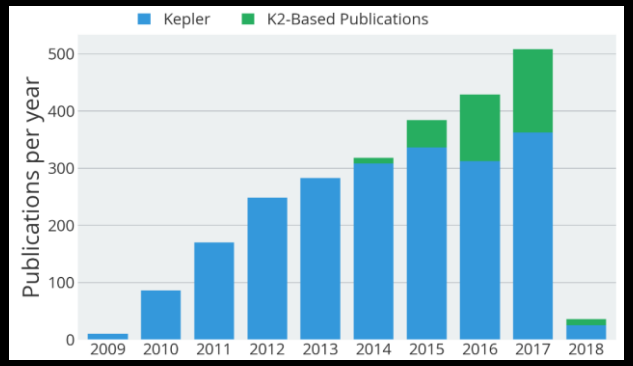
Program Progress vs 2010 Decadal Priorities

Program Science Updates

Kepler Close Out

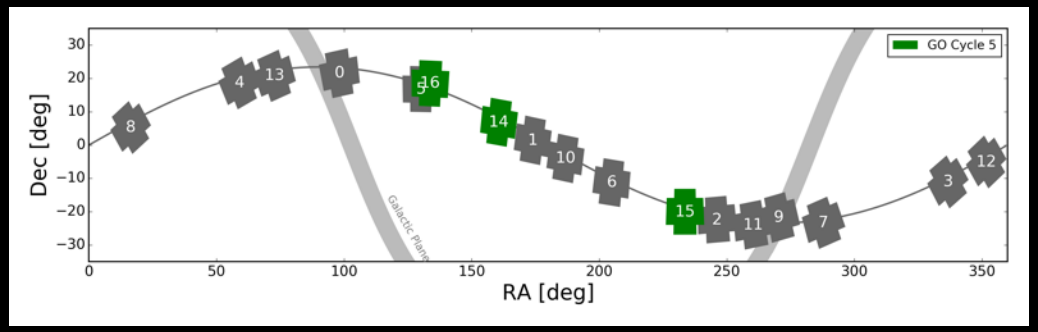
Delivering Kepler's Legacy

- Primary mission phase is complete
  - Final DR25 data products are live at the NExScI & MAST archives
  - All Level 1 milestones are delivered
- Mission paper describing DR25 planet catalog by Thompson et al. is submitted
- Kepler/K2: >500 publications in 2017
- Kepler mission celebrations held at Ames, Caltech and Ball Aerospace



Kepler K2

Extending the Power of Kepler to the Ecliptic



- Positive community response to K2 Cycle 6 proposal call (Campaigns 17-18-19)
- Campaign 16 (current) and Campaign 17 are forward-facing to facilitate simultaneous ground-based observations
- Spacecraft performance remains healthy. Fuel estimates range from Spring-Summer of 2018
- Proposal to perform best-effort uniform K2 data reprocessing before mission closeout is under review
- Tuesday evening session (7:30-9:00): K2 & TESS Missions and Science Opportunities

Kepler / K2

Program Progress vs 2010 Decadal Priorities

Program Science Updates

Large Binocular Telescope Interferometer

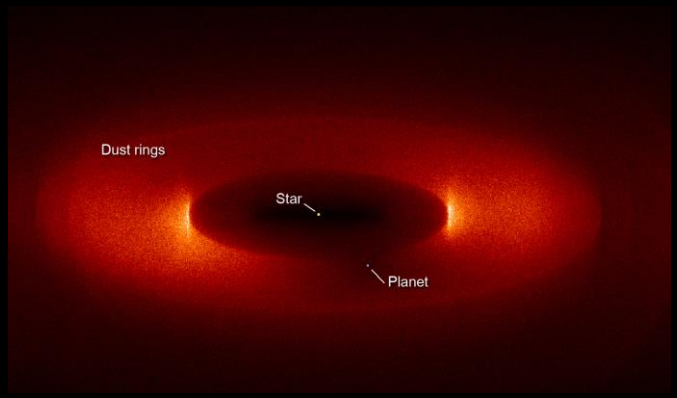
Measuring HZ Exozodiacal Dust to Inform Designs of Future Missions

Credit: ESO/Y. Beletsky

- 35-star survey, 30 observed
- NASA survey planned to complete June 2018
- Paper submitted to ApJ by S. Ertel
- See Thursday talk by Phil Hinz at: Ground Based Support for NASA Exoplanet Missions, 2:00 – 3:30 pm

Phil Hinz, PI

THE UNIVERSITY OF ARIZONA



Credit: NASA/GSFC

NN-EXPLORE

NASA-NSF Exoplanet Observational Research

PI: S. Mahadevan

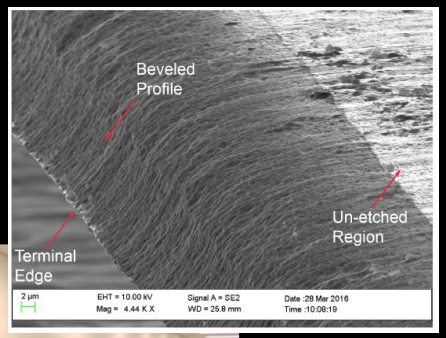
- Extreme precision radial velocity spectrometer (<0.5 m/s) at the WIYN Telescope on Kitt Peak
- NEID Instrument build underway
  - Subsystems delivered to Penn State
  - U. Wisconsin building port adapter
- WIYN facility construction underway
- On track for August 2019 commissioning
- Guest Observer program:
  - Starting 2019B: 90 nights per year
  - Current: Guest Observer program using NOAO share of telescope time for exoplanet research
- See Thursday talk by John Callas at: Ground Based Support for NASA Exoplanet Missions, 2:00 – 3:30 pm

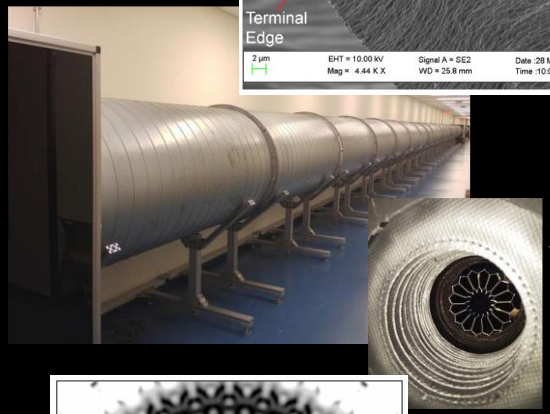
NEOS Camera

Starshade Technology Development (S5)

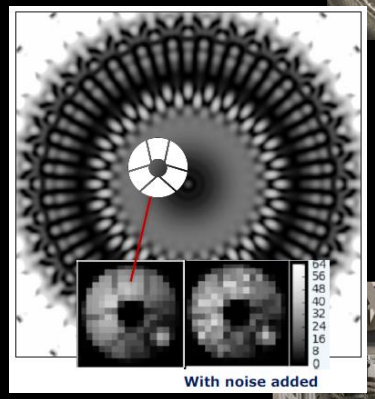
- December Status Review and peer reviews concluded that S5 progress is on track
- Technology plan will be delivered Spring 2018
- Technical progress continues in suppression, edge scattering and formation flying sensor model/algorithms, Petal Launch restraint and Unfurling System (PLUS)
- Mechanical architecture trade is well underway – NGAS on contract and Trade Evaluation Team active

Etched amorphous metal edge segment

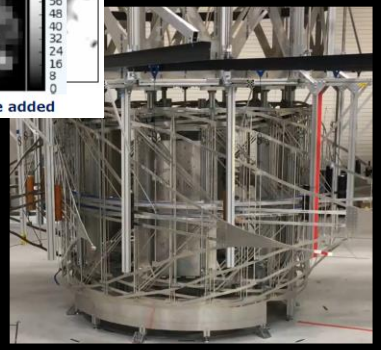




Princeton starlight suppression testbed



Lateral position sensing



PLUS system for wrapped petals

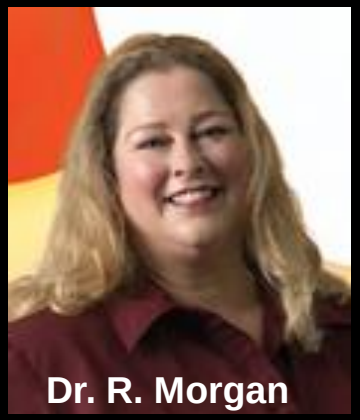
Standard Definitions and Evaluation Team

Supporting the Large Mission Studies for Exoplanet Direct Imaging

- Chartered to provide a consistent, transparent yield analysis using common input parameters
  - https://exoplanets.nasa.gov/exep/resources/documents/
- Strawman apples-to-apples (Jan) for LUVOIR and HabEx mission concepts
- Next deliverable (June) following the interim reports
- Yield analysis: EXOSIMS and Starks' AYO
  - https://github.com/dsavransky/EXOSIMS
  - https://asd.gsfc.nasa.gov/luvoirdev/tools/
- Input parameters adopted for occurrence rates, HZ, planet radius, albedo, etc.
- Contact Rhonda Morgan or go to
  - EXOSIMS: Wed. 5:30 pm, posters 264.04, 246.06, 246.11
  - AYO: Tues. 5:30 poster 148.42 AYO, Tues. 6:30 pm HabEx Splinter, Wed 2:00 pm LUVOIR Tools

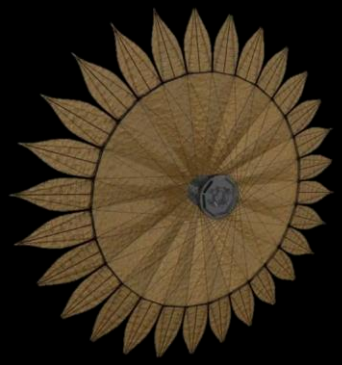
Rhonda Morgan
Bruce Macintosh
Dmitry Savransky
Chris Stark
Avi Mandell
Ruslan Belikov
John Krist
Eric Nielson

STDT Liaisons:
Courtney Dressing
Karl Stapelfeldt
Klaus Pontoppidan


Dr. R. Morgan

Ongoing ExEP Support to WFIRST

- Provide the High Contrast Imaging Testbed for WFIRST Coronagraph (CGI) testing
- Backup deformable mirror technology
- Starshade accommodation support
- Polarization studies: confirmed software accuracy
- NExScI archive for UKIRT microlensing survey of galactic bulge
- The ExoPAG is one of the forums that the community can become engaged with WFIRST development



Additional ExEP Service

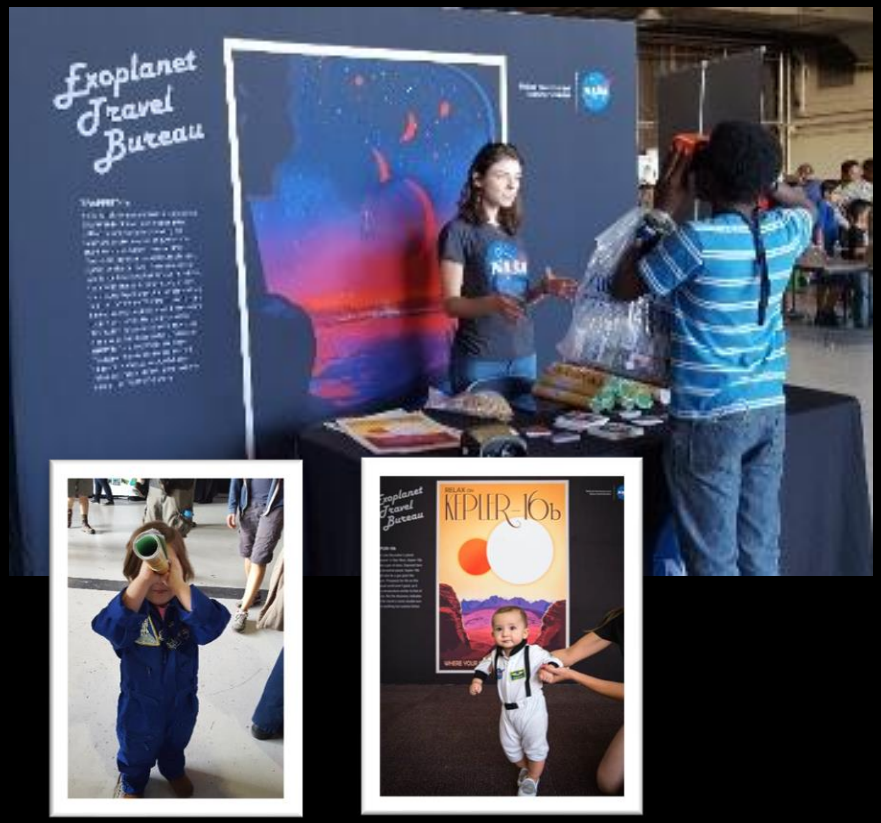
To APD and to the Science Community

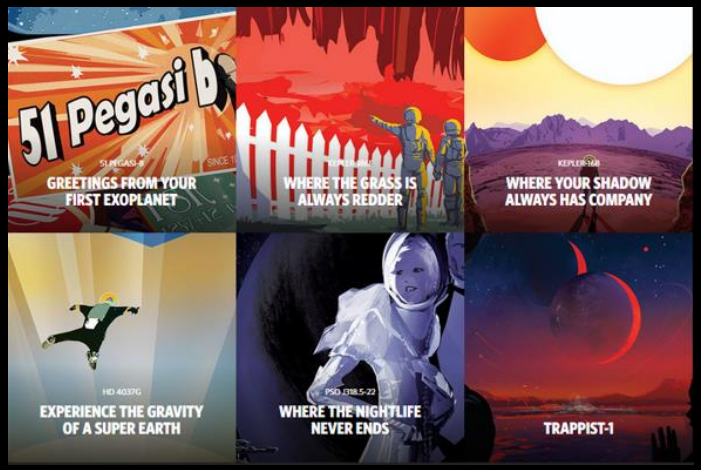
2017 Sagan Fellows Symposium

- Community / Science
  - NExScI - archive, Keck Single Aperture, Follow-up program, NHFP fellowships (Beichman)
  - Science participation on LUVOIR, HabEx, and OST (Stapelfeldt and Mamajek)
  - Telescope stability workshop (Stapelfeldt)
  - Support to ExoPAG support (e.g., student travel)
- Technology
  - Technology Gap Prioritization and Investment (Siegler, Crill)
  - Technology Web Colloquium Series (Crill)
  - Decadal Survey Testbed upgrade to HCIT (Siegler)
  - Segmented Coronagraph Design and Analysis (Shaklan)
  - In-Space Servicing and Assembly study (Siegler)

Exoplanet Communications

Inspiring Our World while we Explore a Galaxy of Others





- See Thursday Talk by Anya Biferno at ExEP Splinter Session, January 11 from 10:00 -11:30 am
- Stop by the ExEP booth

Kepler / K2

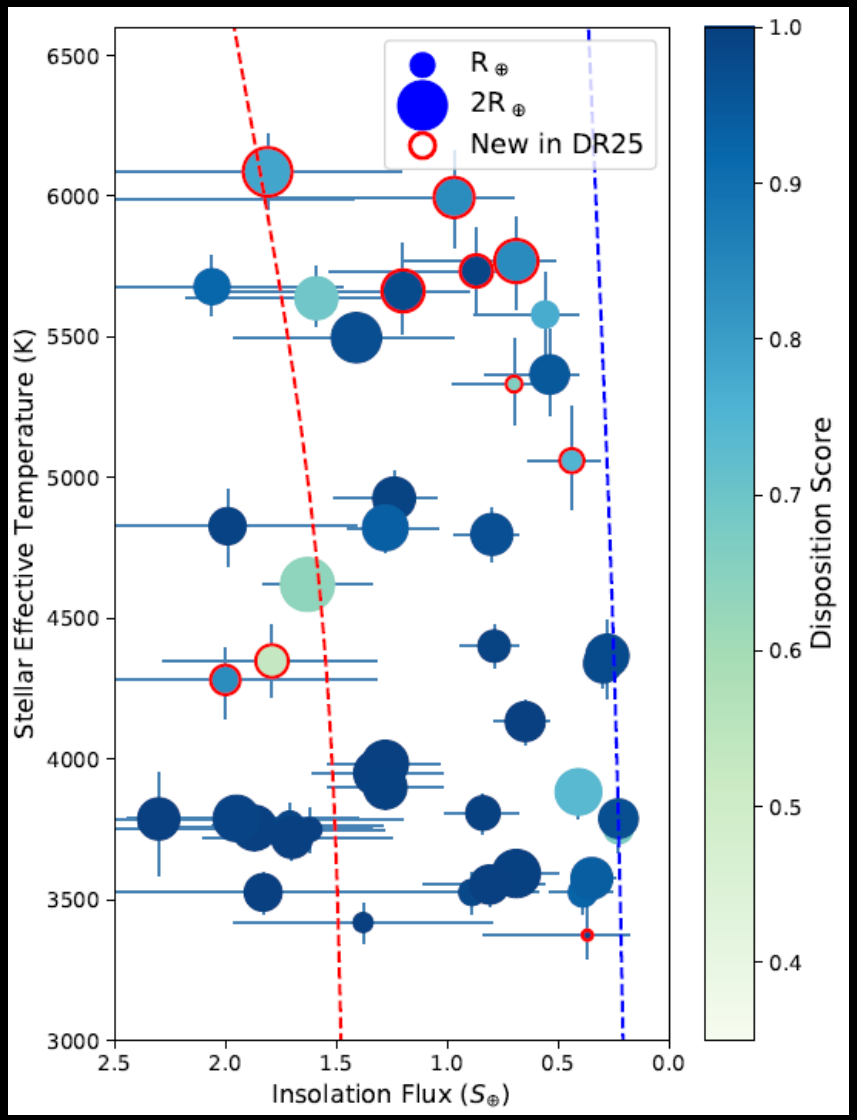
Progress vs 2010 Decadal Priorities

Program Science Updates

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



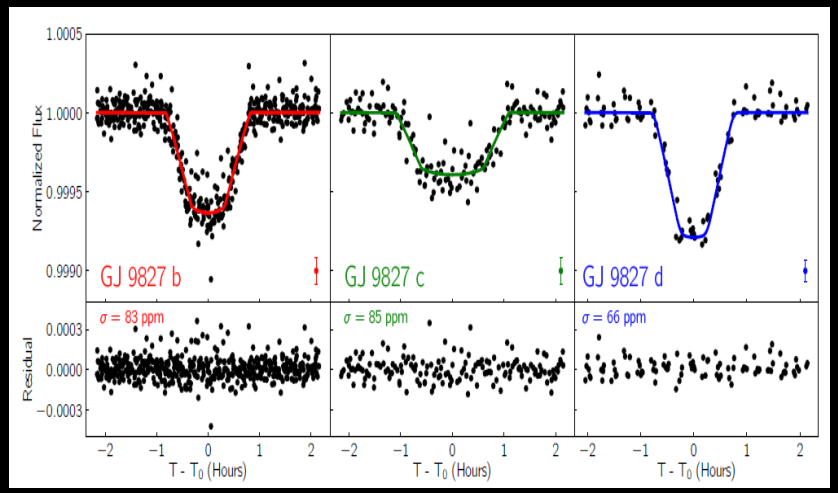
Science Highlight #2: LBTI HOSTS interim results

S. Ertel et al. submitted and under review

- 10 μm nulling interferometry partial results for 30 stars
- Sample combines Sun-like & early-type stars
- Median exozodi < 13 zodis overall, < 29 zodis in Sun-like subsample, for an assumed log-normal distribution
- 2 stars have 4σ LBTI detections & no prior IR excess. Roughly 200 zodis each. HZ dust but not Kuiper Belt dust ?
- Implications for future missions left for final results paper
- See Phil Hinz's talk Thursday

Science Highlight #3: K2 finding JWST targets

- GJ 9827: K6 dwarf at 30 pc
- System of 3 transiting super-Earths found in K2 Campaign 12 data
- Closest Kepler planets to Earth !
- The two largest (1.8 & 2.1 $R_\oplus$) are in the top 10-best JWST transit spectroscopy targets identified to date (bright star K= 7)



Above: Niraula et al. 2017 A.J. 154 266
Below: Rodriguez et al. 2017 arXiv:1709.01957

THE BEST CONFIRMED PLANETS FOR TRANSMISSION SPECTROSCOPY WITH $R_P < 3 R_\oplus$

Planet	$R_P(R_\oplus)$	S/N[a]	Reference
GJ 1214 b	2.85±0.20	1.00	Charbonneau et al. (2009)
55 Cnc e[b]	1.91±0.08	0.41	Dawson & Fabrycky (2010)
HD 97658 b	$2.34^{+0.17}_{-0.15}$	0.36	Dragomir et al. (2013)
TRAPPIST-1f	1.045±0.038	0.24	(Gillon et al. 2017)
GJ 9827 b	$1.62 \pm 0.11\ R_\oplus$	**0.14**	**this work**
HD 3167 c	$2.85^{+0.24}_{-0.15}$	0.14	Vanderburg et al. (2016c); Christiansen et al. (2017)
HIP 41378 b	2.90±0.44	0.14	Vanderburg et al. (2016a)
GJ 9827 d	$2.07 \pm 0.14\ R_\oplus$	**0.13**	**this work**
K2-28 b	2.32±0.24	0.12	Hirano et al. (2016)
HD 106315 b	2.5±0.1	0.10	(Crossfield et al. 2017; Rodriguez et al. 2017)

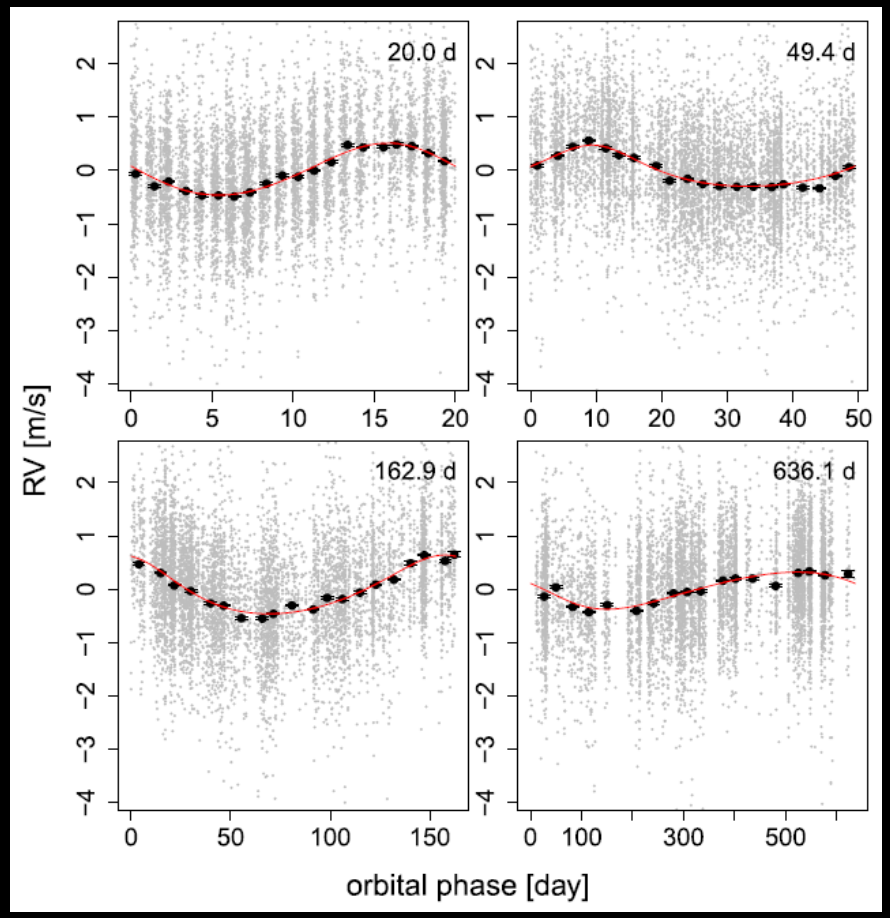
Discoveries by K2

Science Highlight #4: tau Ceti RV planets

- Using new techniques to mitigate stellar RV jitter, Feng et al. 2017 found evidence for four super-Earths in new HARPS data of the nearby star τ Ceti. The RV semi-amplitudes of ~0.4 m/sec <u>are the smallest currently claimed detections with the RV method.</u>

- The two outermost planets lie at the inner & outer edges of the HZ. <u>The 3rd planet may be detectable with WFIRST CGI</u> at V band if the exozodi is low: contrast ~2×10^{-9} at 0.15″ max elongation.

<u>Quiet</u> G8 V star, V= 3.5, d= 3.7 pc

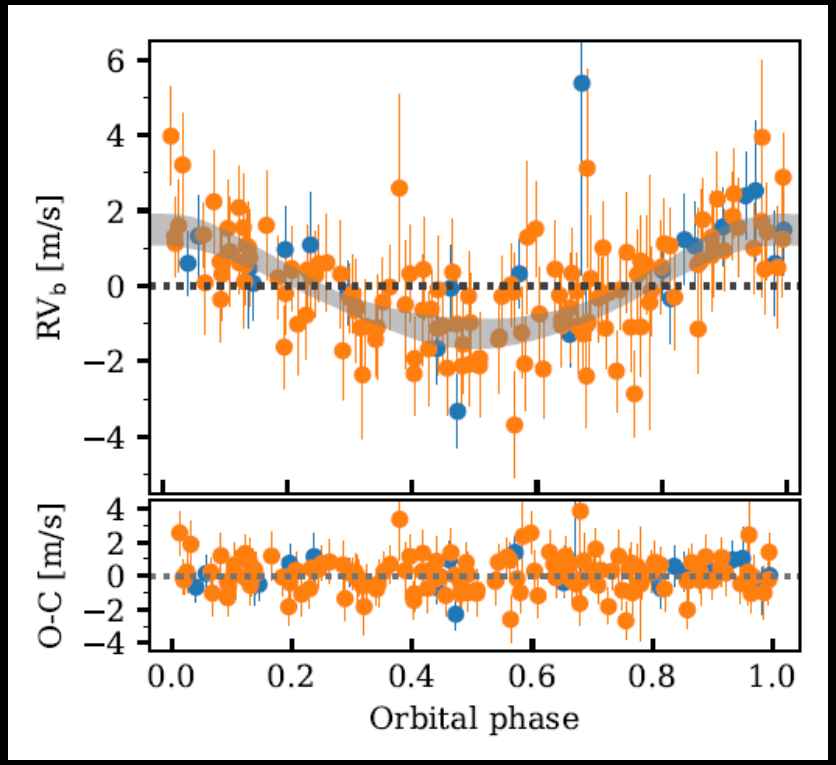


Feng et al. 2017 A.J. 154 135

Result exemplifies goal of using improved RV to characterize imaging targets

Science Highlight #5: RV finds an ELT target

- Ross 128 is an old, quiet M4 dwarf @ 3.4 pc distance
- Earth-mass planet at inner edge of HZ (Msini= 1.35 $M_\oplus$, 1.38x stellar flux at Earth)
- K2 Campaign 1 found no transits
- At $2x10^{-8}$ contrast & 15 mas max elongation, Ross 128 b is a potential target for correlation spectroscopy on future ELTs
- Will be roughly twice as hard as proxima Cen b. For a 3 λ/D IWA coronagraph, E-ELT could only image Ross 128 at $\lambda < 1\ \mu m$
- Even at only 3 pc, ELT imaging of M dwarf HZs will be hard !

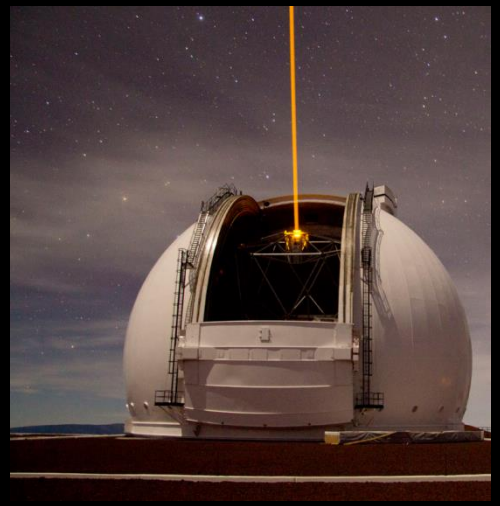


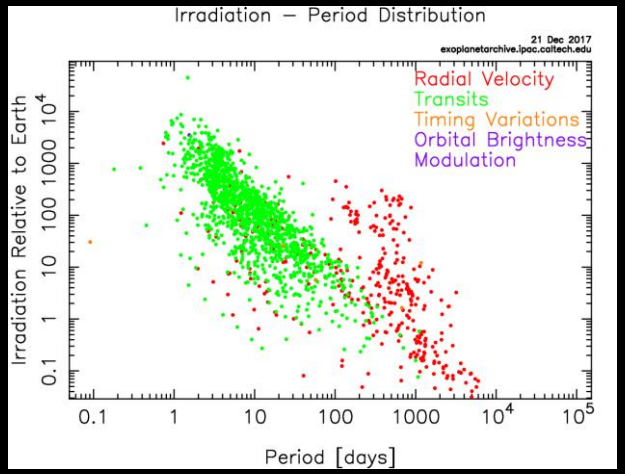
Bonfils et al. 2017 arXiv: 1711.06177
data from HARPS spectrograph

NASA Exoplanet Science Institute (NExScI) Update

- Sagan Summer Workshop August 2017: "Microlensing in the Era of WFIRST" had more than 90 participants
- Sagan Summer Workshop July 2018: "Did I Really Just Find an Exoplanet?" SOC Chair is Ian Crossfield (MIT)

- Keck news: 1) NASA cooperative agreement extended for 5 more years. 2) 2018A selections include 4 key projects (3 in exoplanets). 3) New community HIRES pipeline coming for 2019A !
- Exoplanet Archive tracks exoplanet population and Kepler pipeline products
- ExoFOP supports Kepler & K2 sources follow-up, gearing up for TESS





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Telescope Stability workshop session afternoon of October 4 @ Ball Aerospace

- The performance of internal coronagraphs is limited by wavefront stability of the instrument and host telescope
- At the site of the fall LUVOIR meeting, 55 attendees heard presentations on stability aspects of Kepler, JWST, and WFIRST, and held a lengthy discussion of how WFIRST might serve as a stability tech demo
- Key points that emerged:
  - Telescope STOP models are usually verified using ground test data taken in controlled conditions
  - The use of on-orbit data to validate STOP models wasn't really done for Kepler, isn't planned for JWST, but could be a valuable part of the WFIRST CGI tech demo
  - Plans for WFIRST telemetry need to be better defined, in order to assess whether additional telemetry to support STOP model comparisons would be worth the added cost

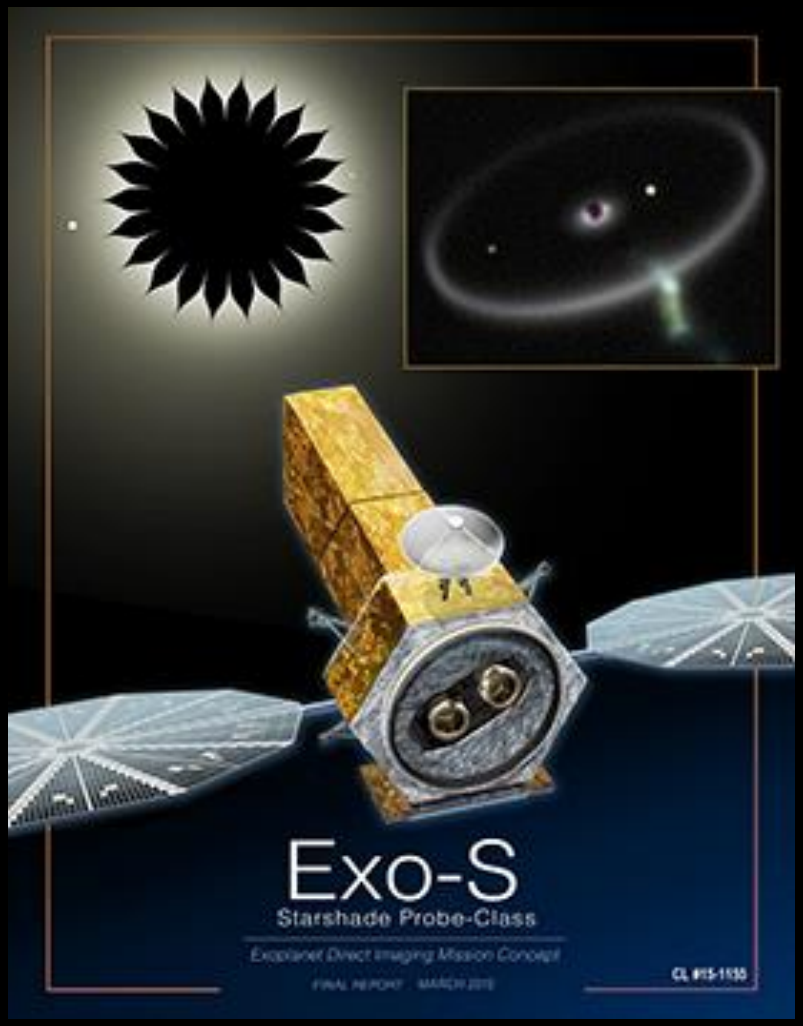
"STOP"≡ Structural/ Thermal/OPtical

Inputs to WFIRST CGI technical requirements

- WFIRST CGI is now a pure tech demo with no science requirements. Baseline technical requirements (BTRs) are now being established that did not previously exist.
- ExEP, LUVOIR, and HabEx are customers for the CGI tech demo. In late October we jointly developed a set of recommendations that were presented to the November meeting of the WFIRST FSWG. These contributed to the Project's decision to retain CGI's Integral Field Spectrometer
- Revision of CGI requirements is nearing completion, we await the final version to see how far the Project can go towards our recommendations. Requirements review is scheduled for the end of February.

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



Executive Summary of Exo-S Dedicated Mission Concept Update

- Exo-S dedicated mission is 1.1-m telescope + starshade, Earth-leading orbit
- Recent discoveries are showing richer landscape and improved modeling among smaller planets – especially “sub-Neptunes” & “super-Earths” not represented in our solar system. Exo-S can characterize temperate & cold examples of both new types among nearby stars.
- Yields updated using EXOSIMS w/new SAG13 occurrence rates:
  - ~50% increase in # of detected exoplanets, and detections of rocky planets in habitable zones increases from ~1 to 3+-2
- Smaller starshade adopted (26m vs. 30m originally)
  - Utilizes current “*S5*” tech program work; identical S5 TRL5 truss
  - Mass reduction in starshade put into added fuel for more retargets & science
  - After 2 yrs 30-m starshade has 1/2 fuel, but 26-m starshade has 2/3rd fuel remaining for follow-up observations & possible extended mission
- Tech advances allow small cost savings compared to original study
- Current cost estimate **$1.1B (FY18$)***
- Current schedule estimate: 7 $^{3/4}$ years from KDP-A (start FY23) to launch in late 2030

* The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

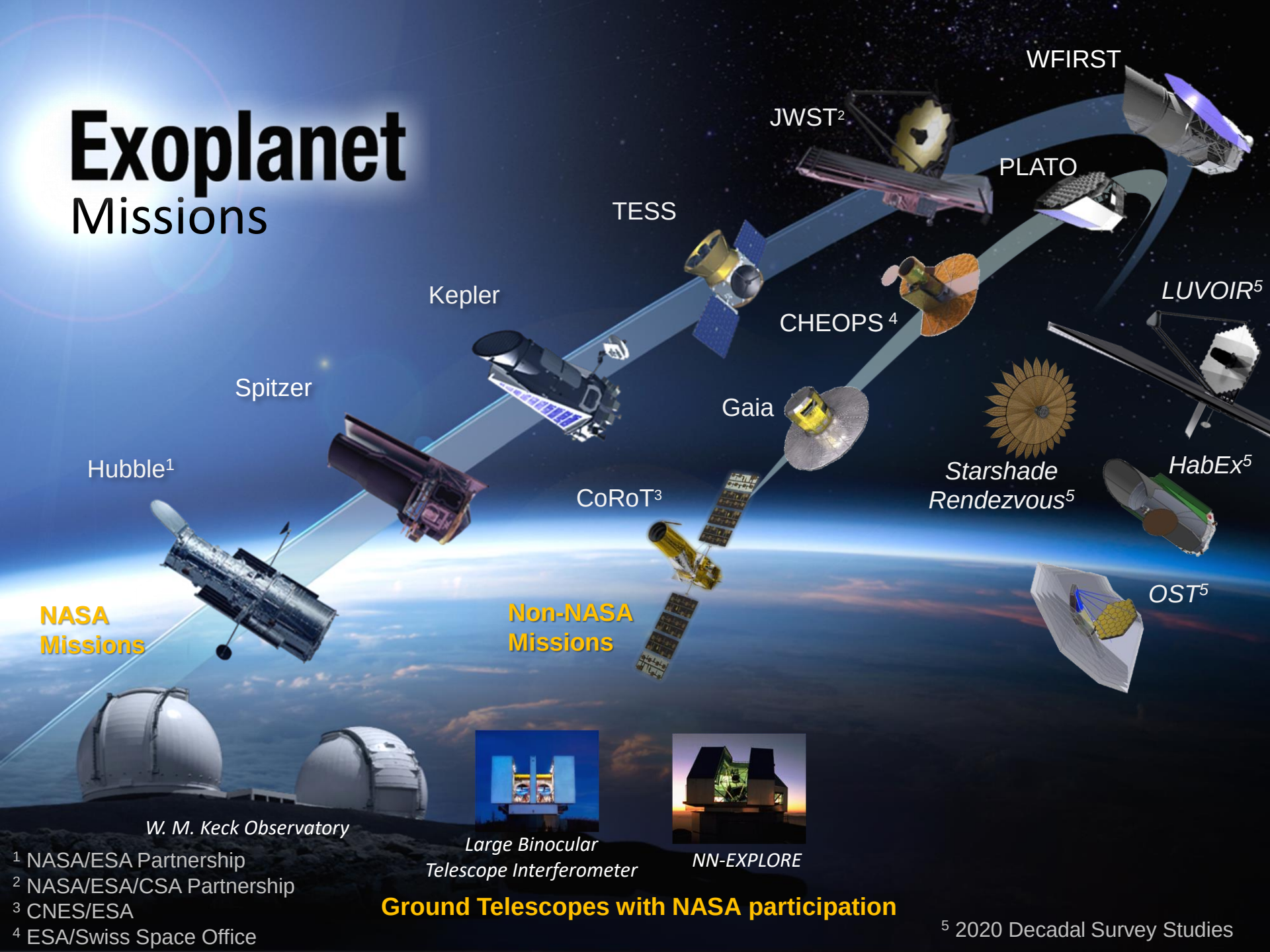
Predecisional information, for planning and discussion only (CL#18-0018). © 2018 California Institute of Technology. Government sponsorship acknowledged

Executive Summary of Exo-C Probe Study Update

- Exo-C is a 1.4m unobscured telescope on a commercial spacecraft bus in Earth-trailing orbit, w/ coronagraph instrument similar to WFIRST CGI
- Prime science goals remain characterization of known giant planets & circumstellar disks, searches for exozodi & new planets beyond RV limits
- Since 2015 a few new/accessible exoplanet targets are identified by RV surveys; dozens of new debris disk targets identified in *Herschel* datasets
- WFIRST/CGI study work has improved understanding and reduced risk for the Exo-C coronagraph:
  - 40% increase in HLC system throughput relative to 2015 instrument design
  - Testbed demonstrations of Low-Order WaveFront Sensing & control and high contrast integral field spectrograph
  - Performance & qualification of low-noise EMCCD detectors
  - Higher fidelity mass and power estimates
- **Exo-C cost now $1.07 B FY 18***, a 10% increase largely due to inflation
- FY 20 start would result in FY 27 launch
- Option to fly starshade with Exo-C would require further study

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only.
It does not constitute a commitment on the part of JPL and/or Caltech.

Exoplanet Missions



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

[5] 2020 Decadal Survey Studies

Jet Propulsion Laboratory
California Institute of Technology

exoplanets.nasa.gov

Acknowledgements

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration. © 2018 All rights reserved.

- 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