Jet Propulsion Laboratory
California Institute of Technology

NASA Exoplanet Exploration Program Updates and Technology Challenges

(CL#16-4657)

Session Introduction

Dr. Gary Blackwood

Manager, NASA Exoplanet Exploration Program

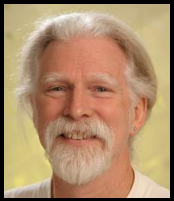
Jet Propulsion Laboratory, California Institute of Technology

September 15, 2016

AIAA Space 2016, SPSC-03, Long Beach CA

Session Speakers

- **The NASA K2 Mission: (Exo)planets to Dark Energy**
  Dr. Steve B. Howell, NASA Ames Research Center



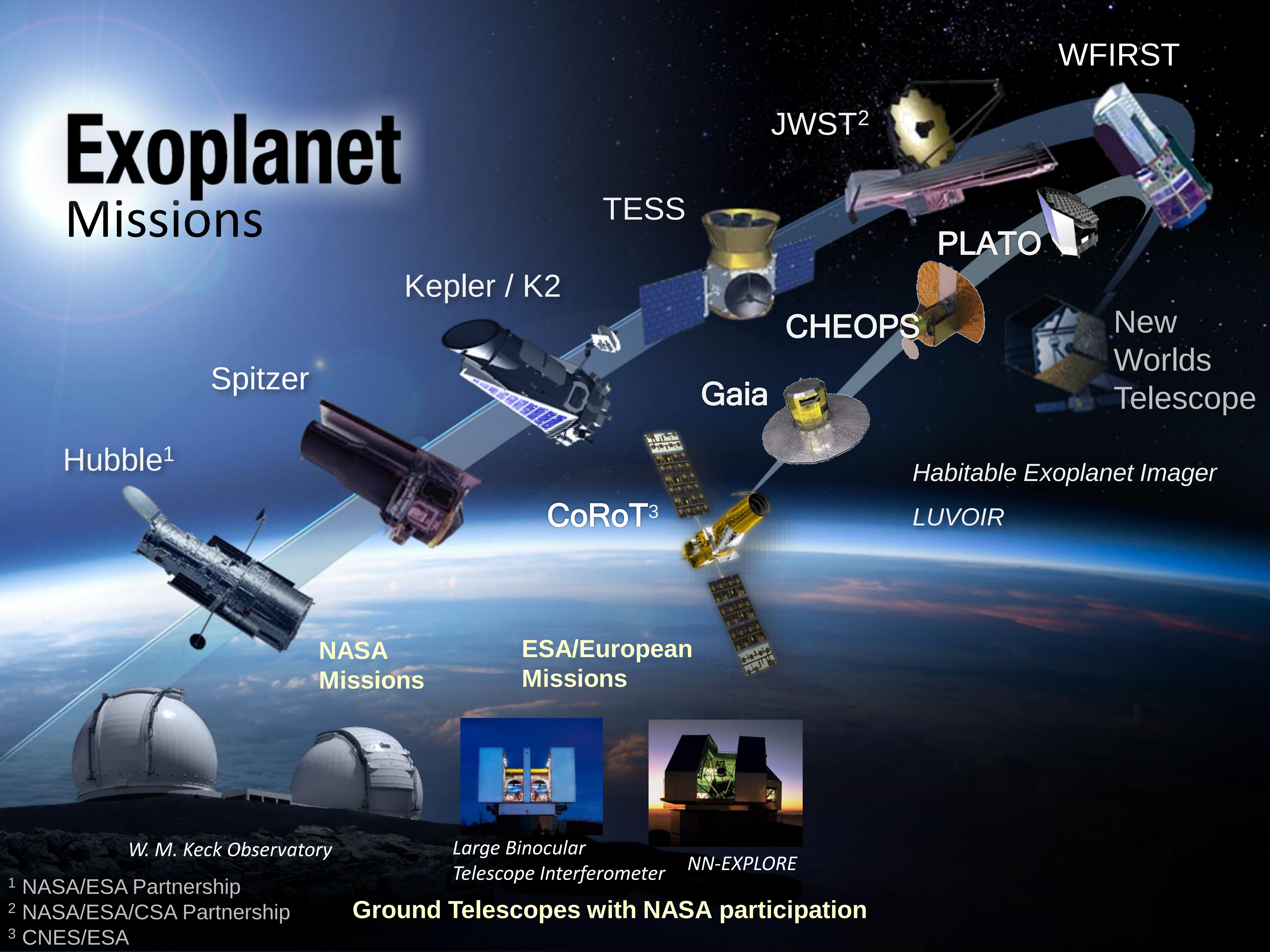
- **The NASA Exoplanet Exploration Program Overview**
  Dr. Karl Stapelfeldt, Program Chief Scientist, NASA Exoplanet Exploration Program, Jet Propulsion Laboratory, California Institute of Technology

- **The Habitable Exoplanet Imaging Mission - Science and Technology Drivers**
  Dr. B. Scott Gaudi, The Ohio State University and Jet Propulsion Laboratory

- **LUVOIR - Science Cases and Technology Drivers**
  Dr. Shawn Domagal-Goldman, NASA Goddard Space Flight Center

- **Technology Needs to Discover Earth 2.0**
  Dr. Nick Siegler, NASA Exoplanet Exploration Program, Jet Propulsion Laboratory, California Institute of Technology

- **Exploring New and Known Exoplanets with the WFIRST Coronagraph and Starshade**
  Dr. Margaret Turnbull, SETI Institute


Exoplanet
Missions
WFIRST
JWST[2]
TESS
PLATO
Kepler / K2
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
[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA
Ground Telescopes with NASA participation

Kepler and K2 – NASA's Exoplanet Missions

Dr. Steve B. Howell
Project Scientist, NASA Ames Research Center

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The Kepler and K2 Missions

The Kepler space telescope's primary goal was to detect Earth-size exo-planets orbiting solar-like stars.

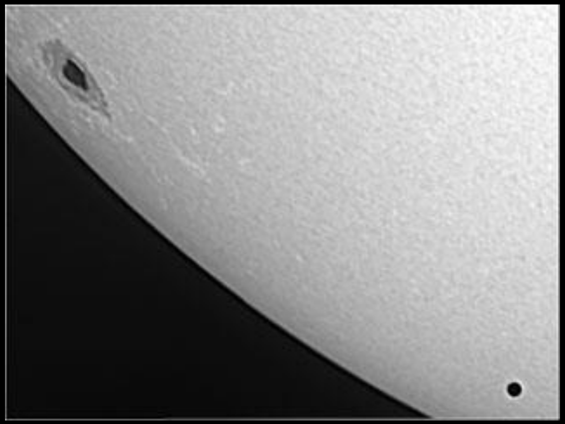
The K2 mission has broader science goals including the discovery of High-Value Exoplanets

Kepler and K2 observations have provided paradigm changing Exoplanet and Stellar Astrophysics science!

Drawing and Reality

Kepler was launched in 2009 It simultaneously monitored >150,000 stars in a 100 sq. degree region of the sky.

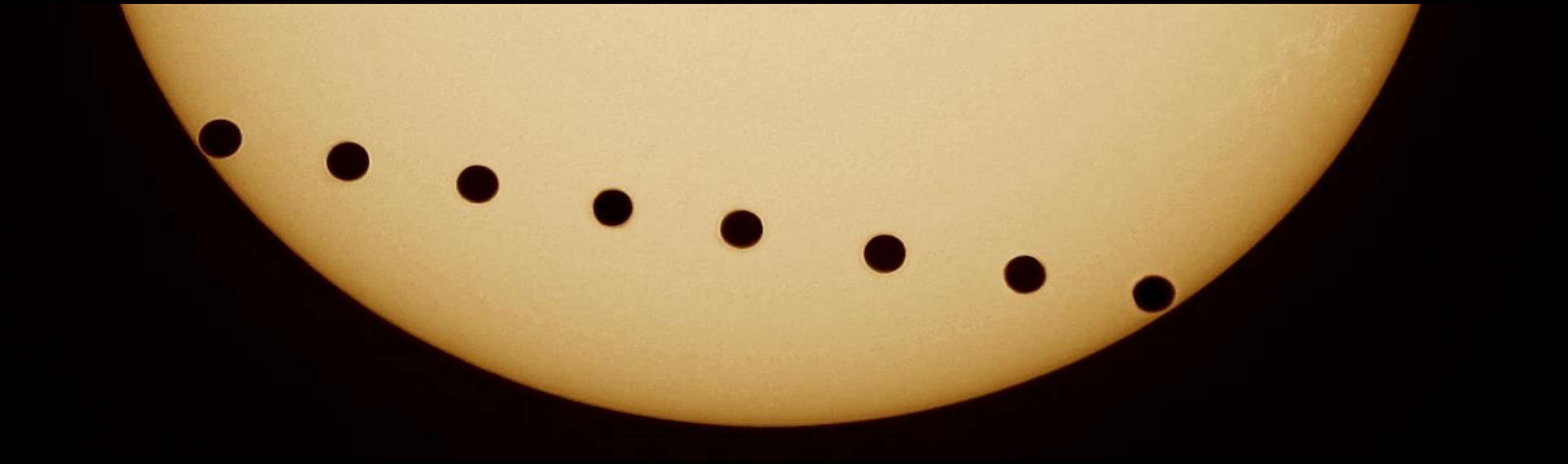
Planetary Transits



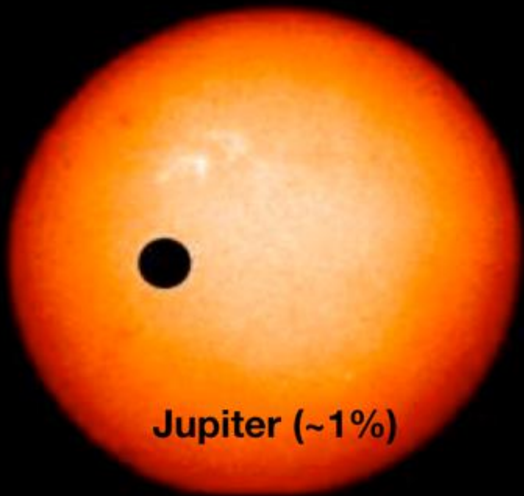
Mercury
Transit
2006

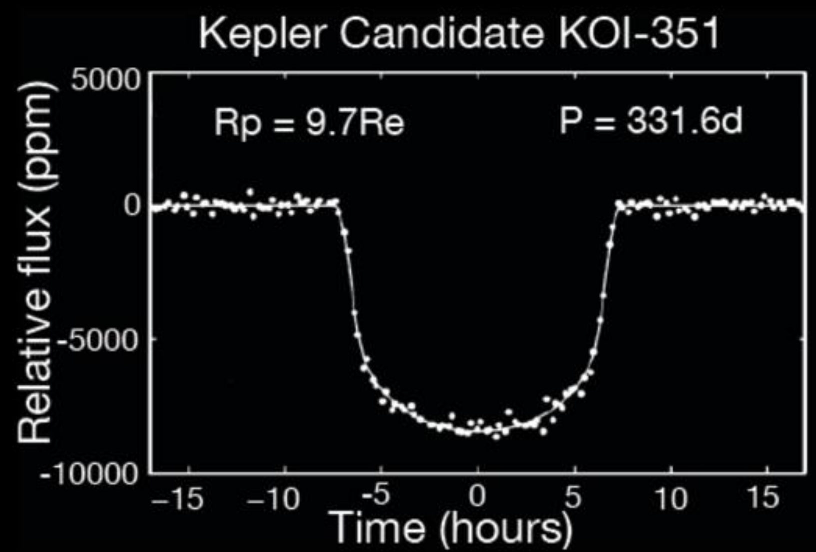
We can observe transits of Mercury and Venus from the Earth

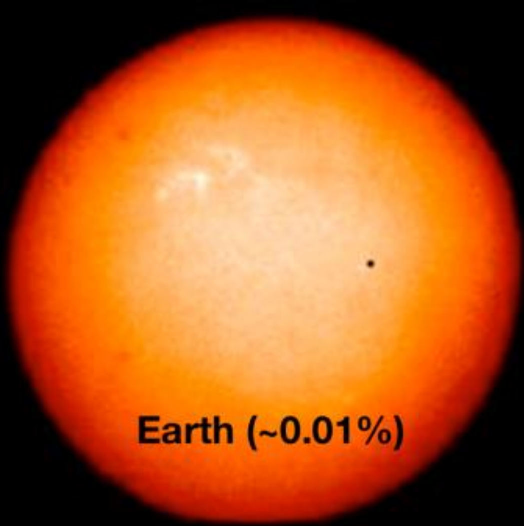
Venus transit 2004 – 5 June 2012, -> 2117, 2125
They have been observed in 1639, 1761, 1769, 1874, 1882

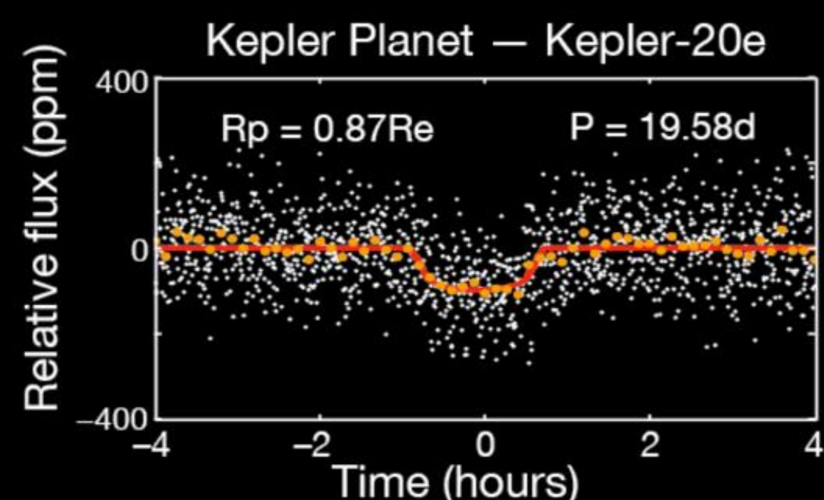


Kepler Earth-size Planets: Detection Method

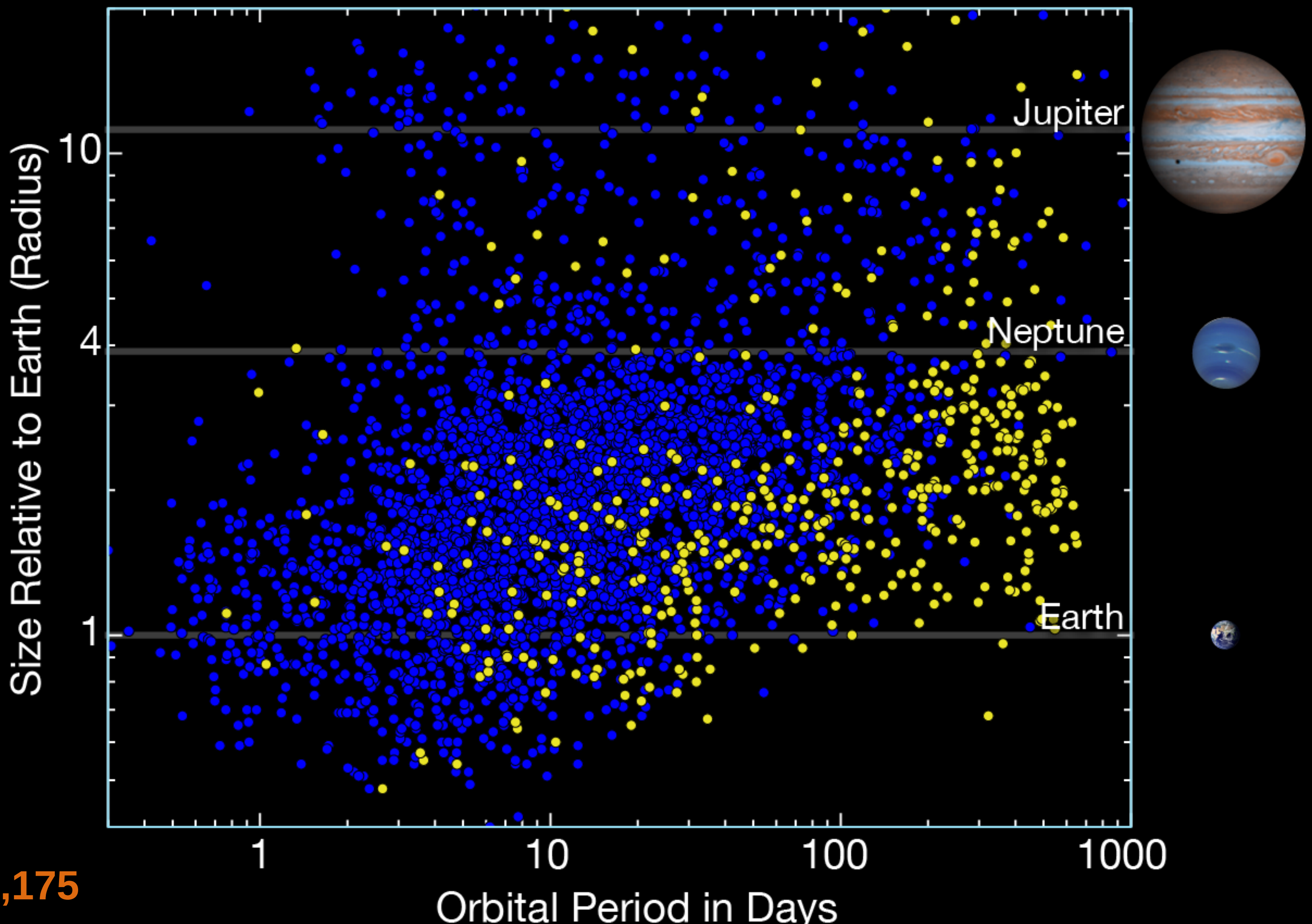






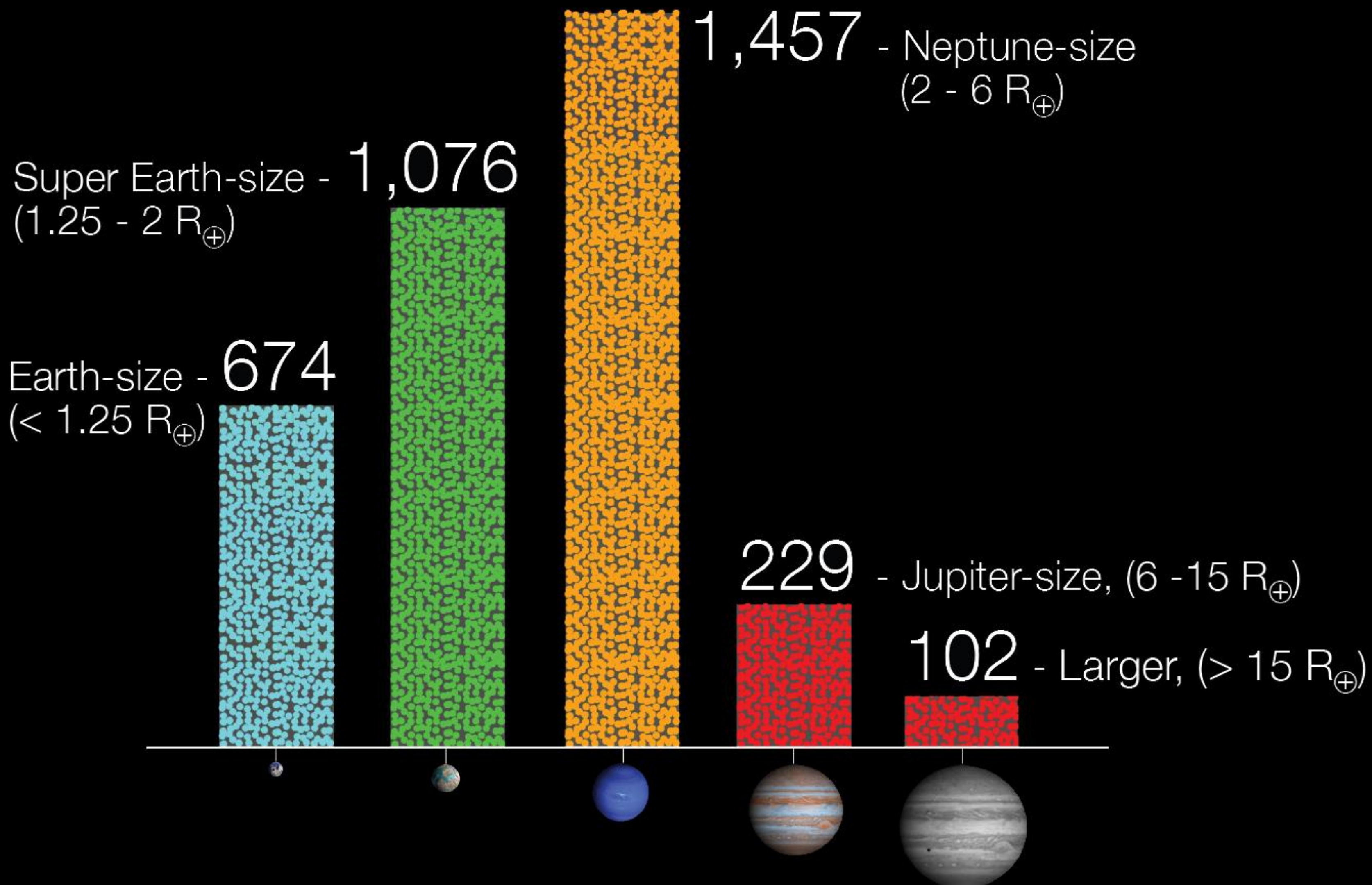


Kepler Planet Candidates

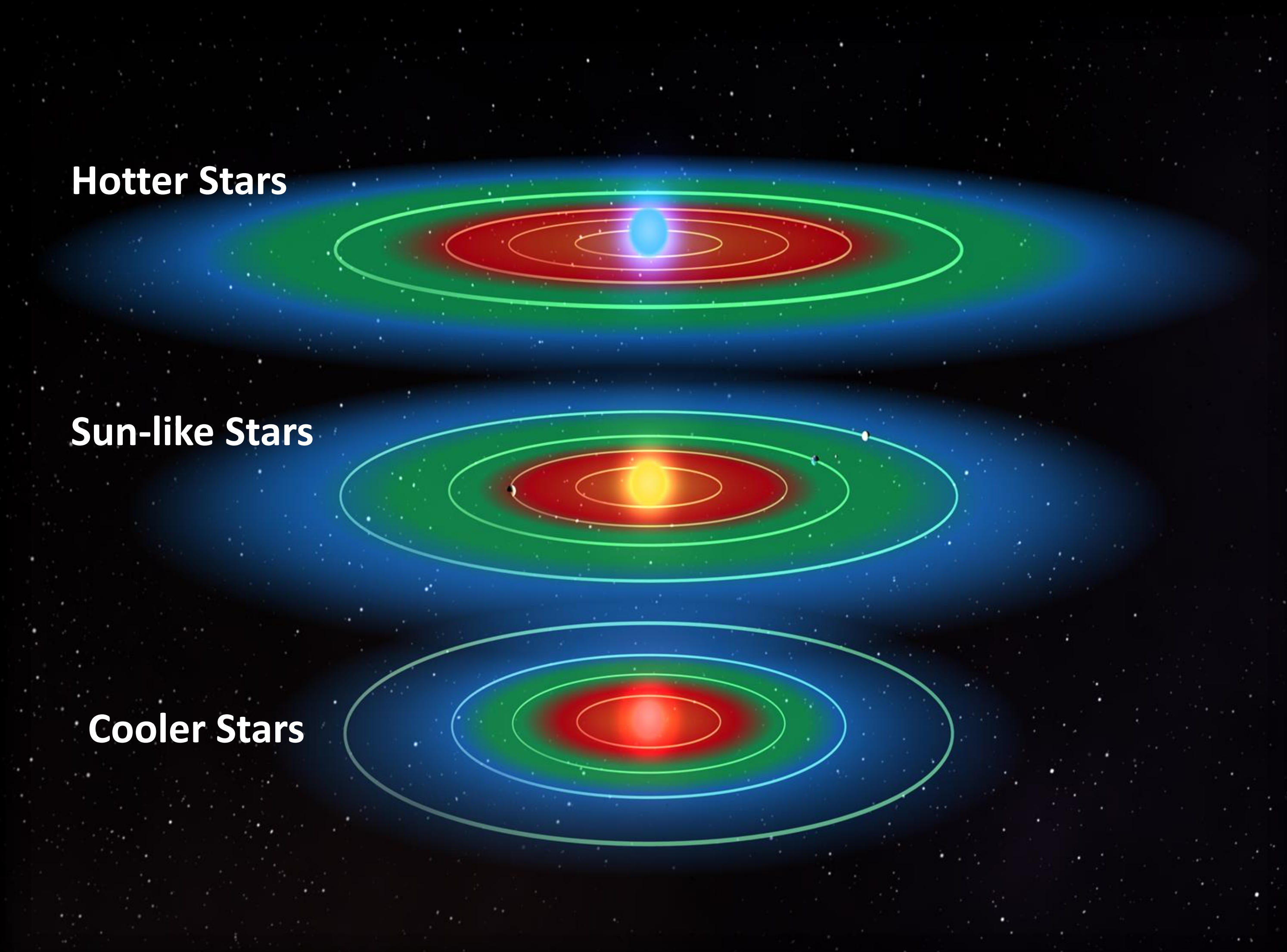


Total = 4,175

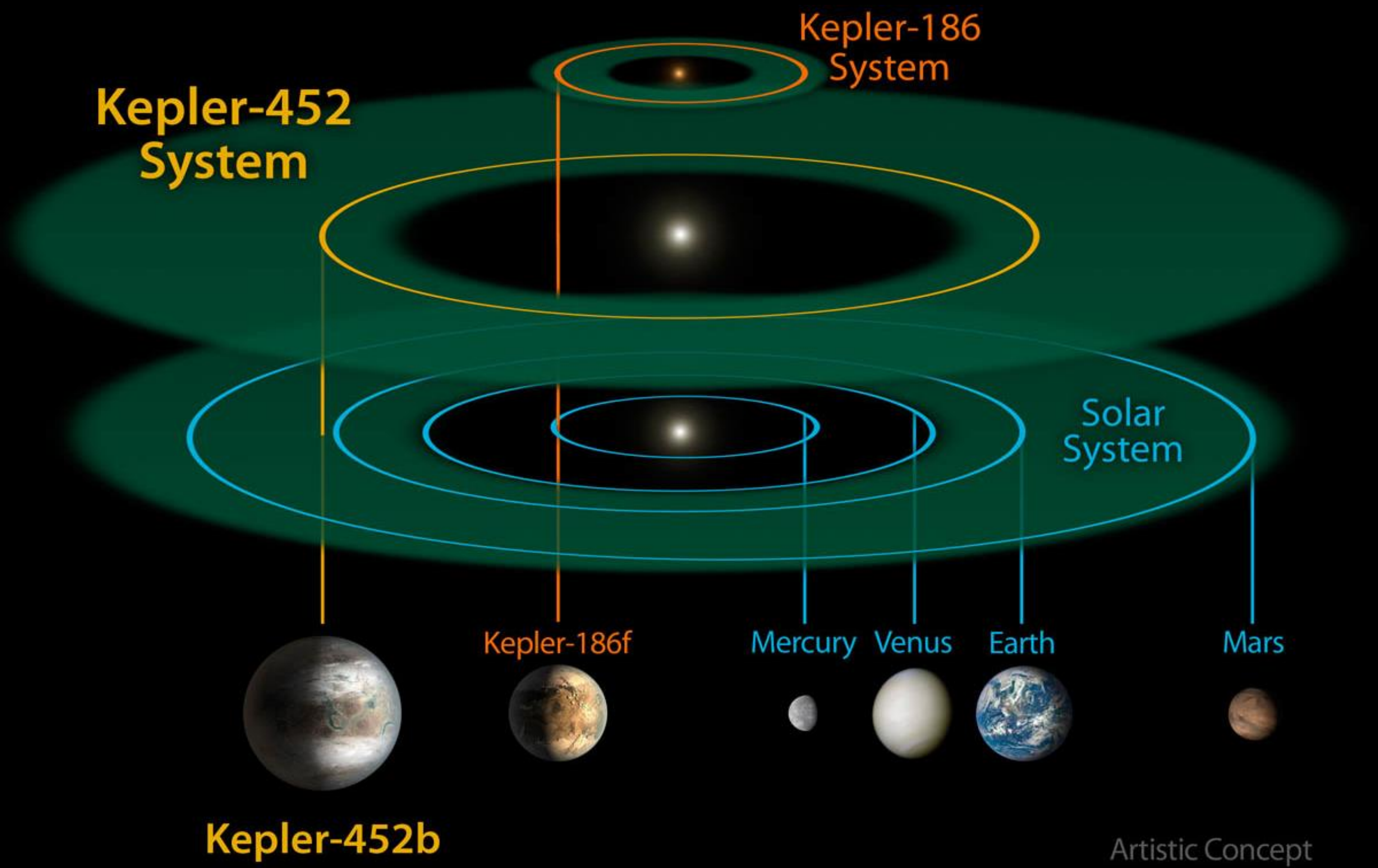
Sizes of Discovered Exoplanet Candidates



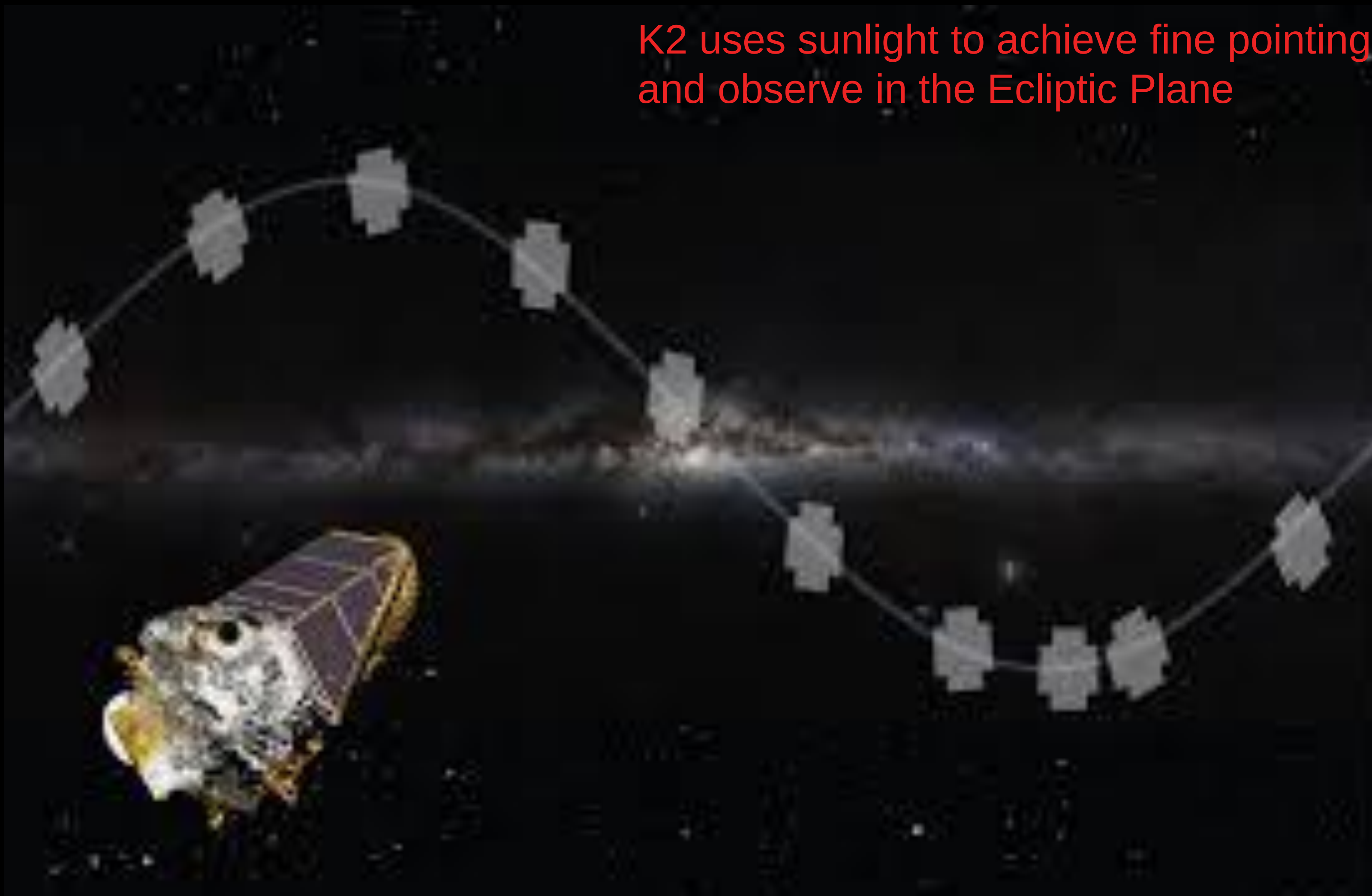
Habitable Zone
Liquid Water on Surface



Kepler's Two Most "Earth-Like" Exoplanets

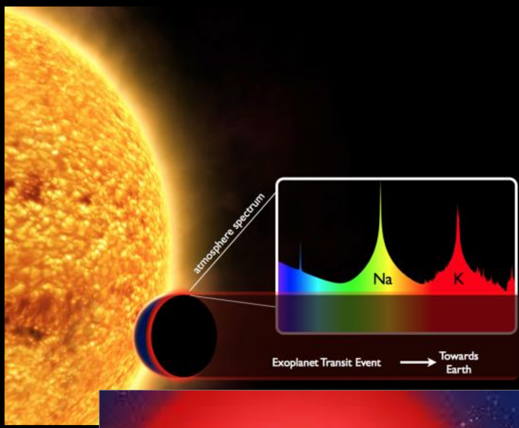


K2: Ecliptic Viewing



K2: Investigates Broad Science Areas

Discover high value exoplanets



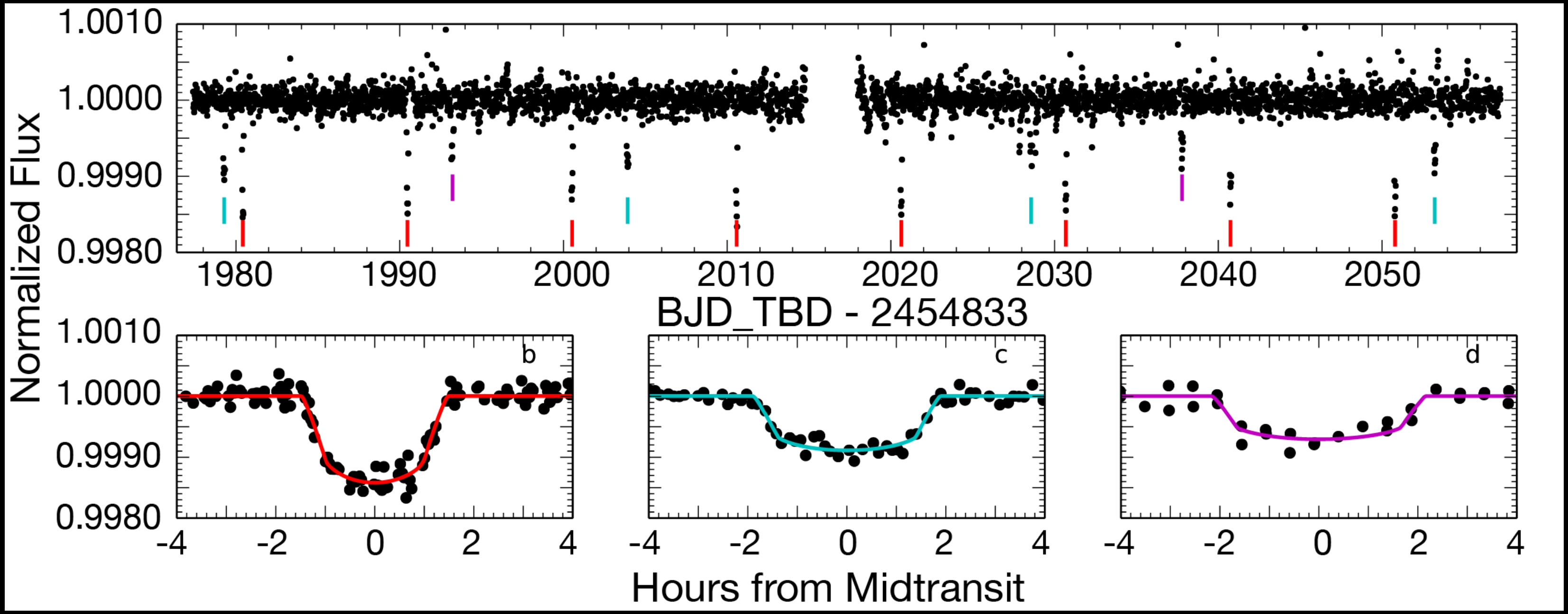
Study of protoplanetary disks & migration limit

Explore accretion physics and supernovae

Examine astrophysics over a range of stellar properties

K2–3 Planetary System: High Value Planets

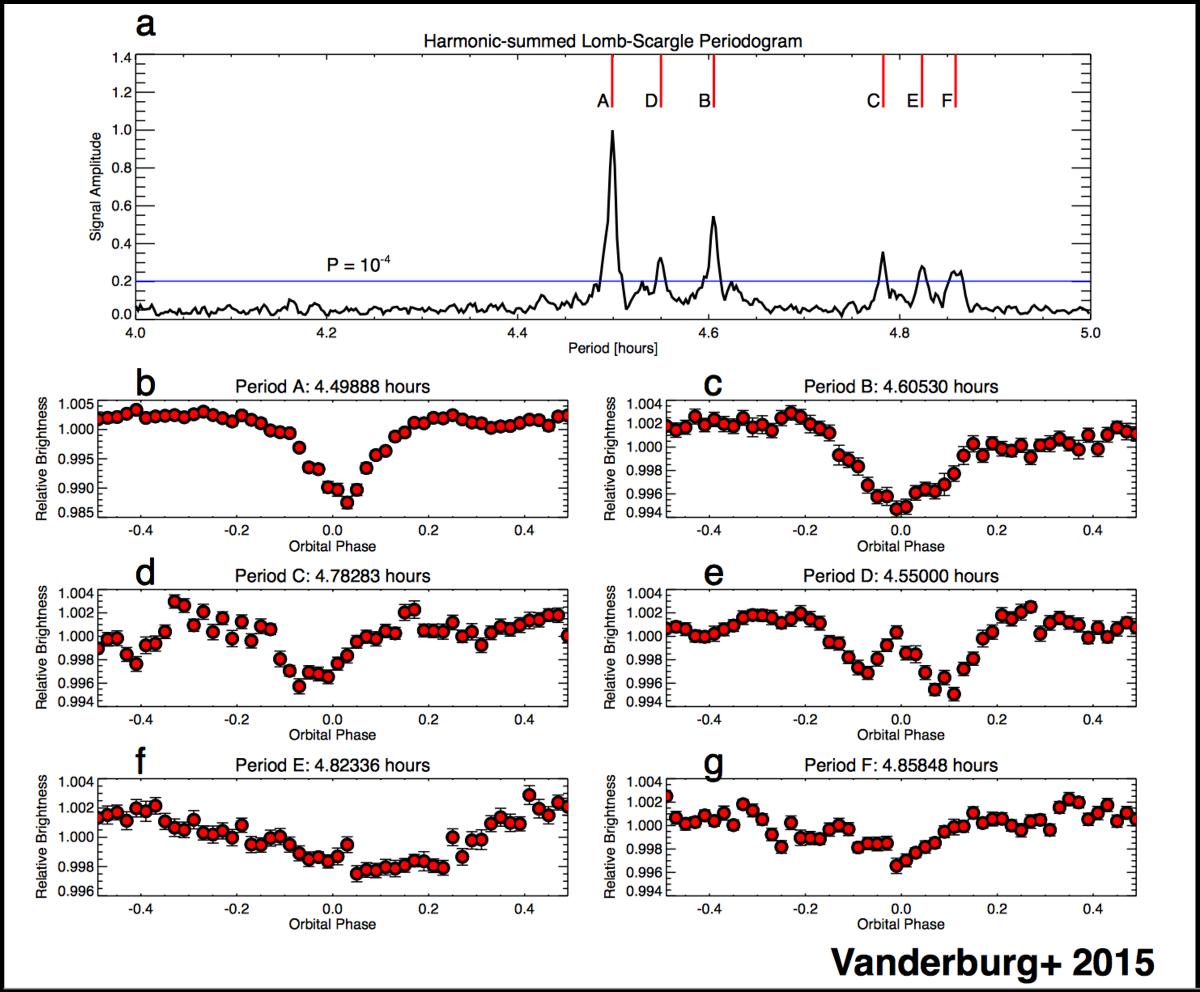
Three Super-Earths, K2-3d in the Habitable Zone, M0 dwarf, distance = 42 pc



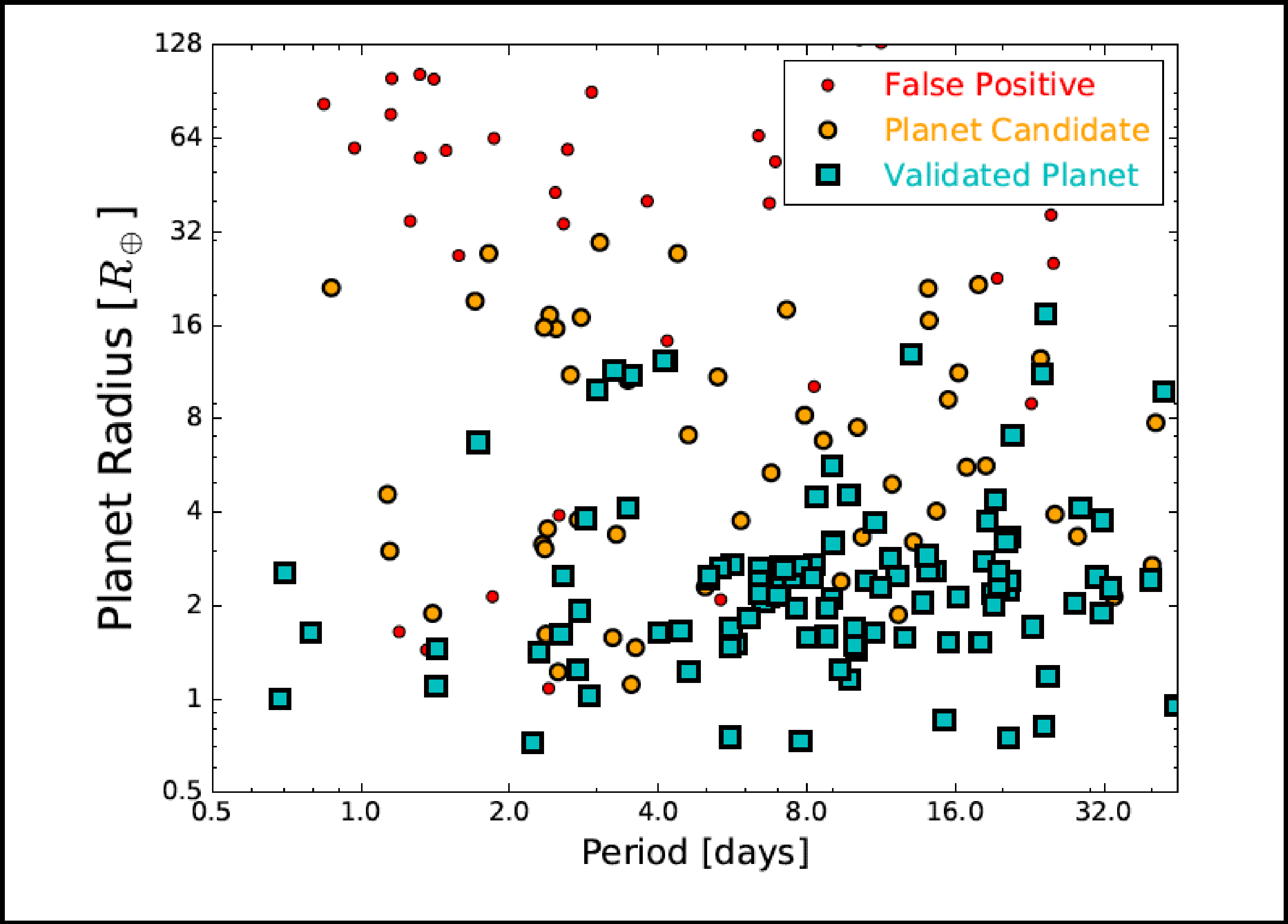
K2: Disintegrating Planets around White Dwarfs

WD 1145+017
Disintegrating planets or planetesimals

Four known disintegrating transiting systems.

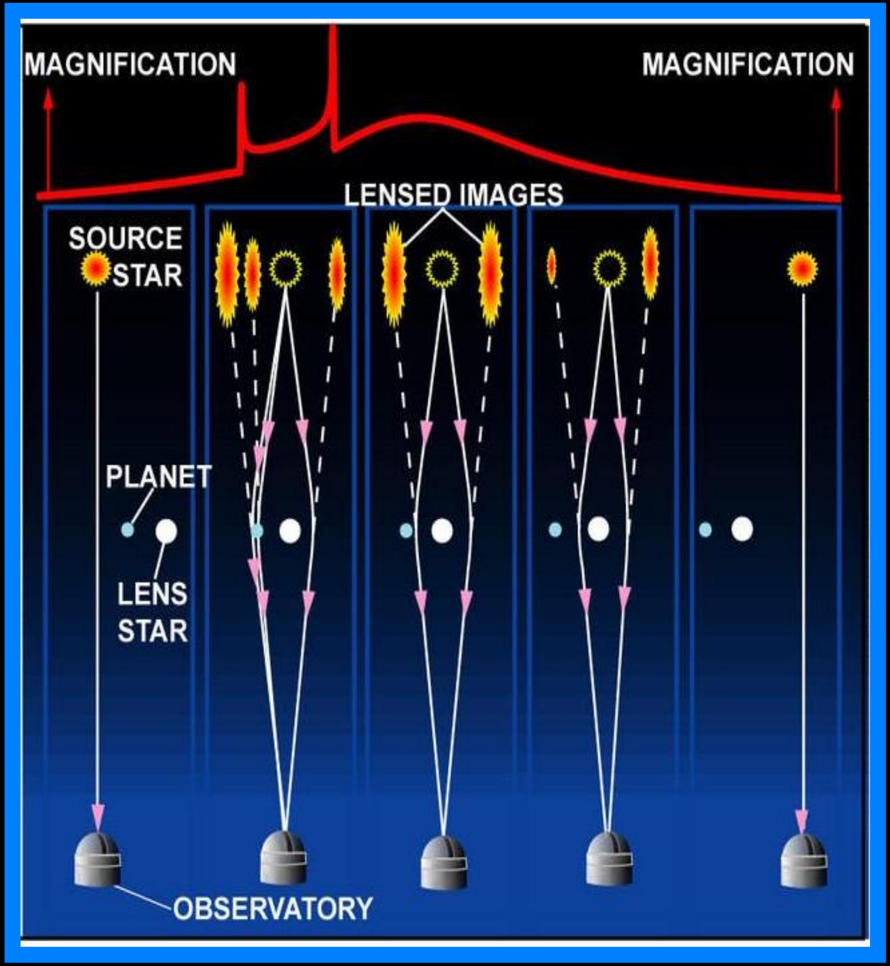


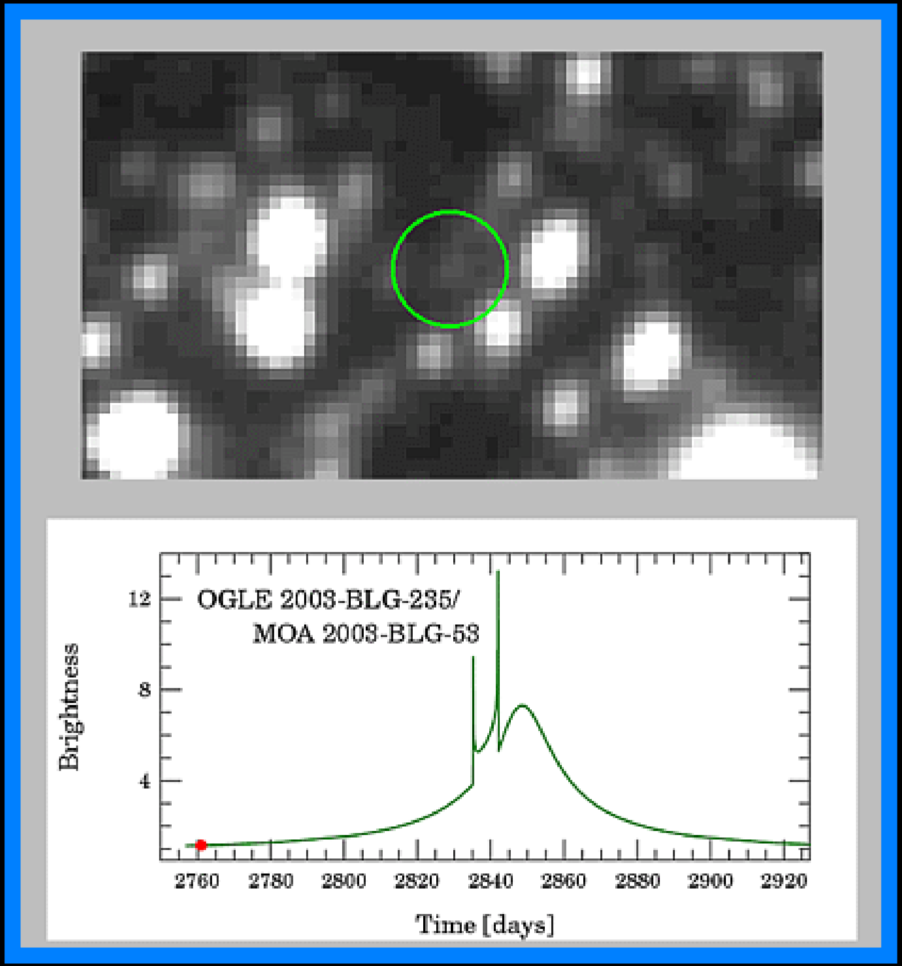
K2 Planetary Systems:
Bright, Nearby stars, Rocky planets,
Habitable Zone Planets

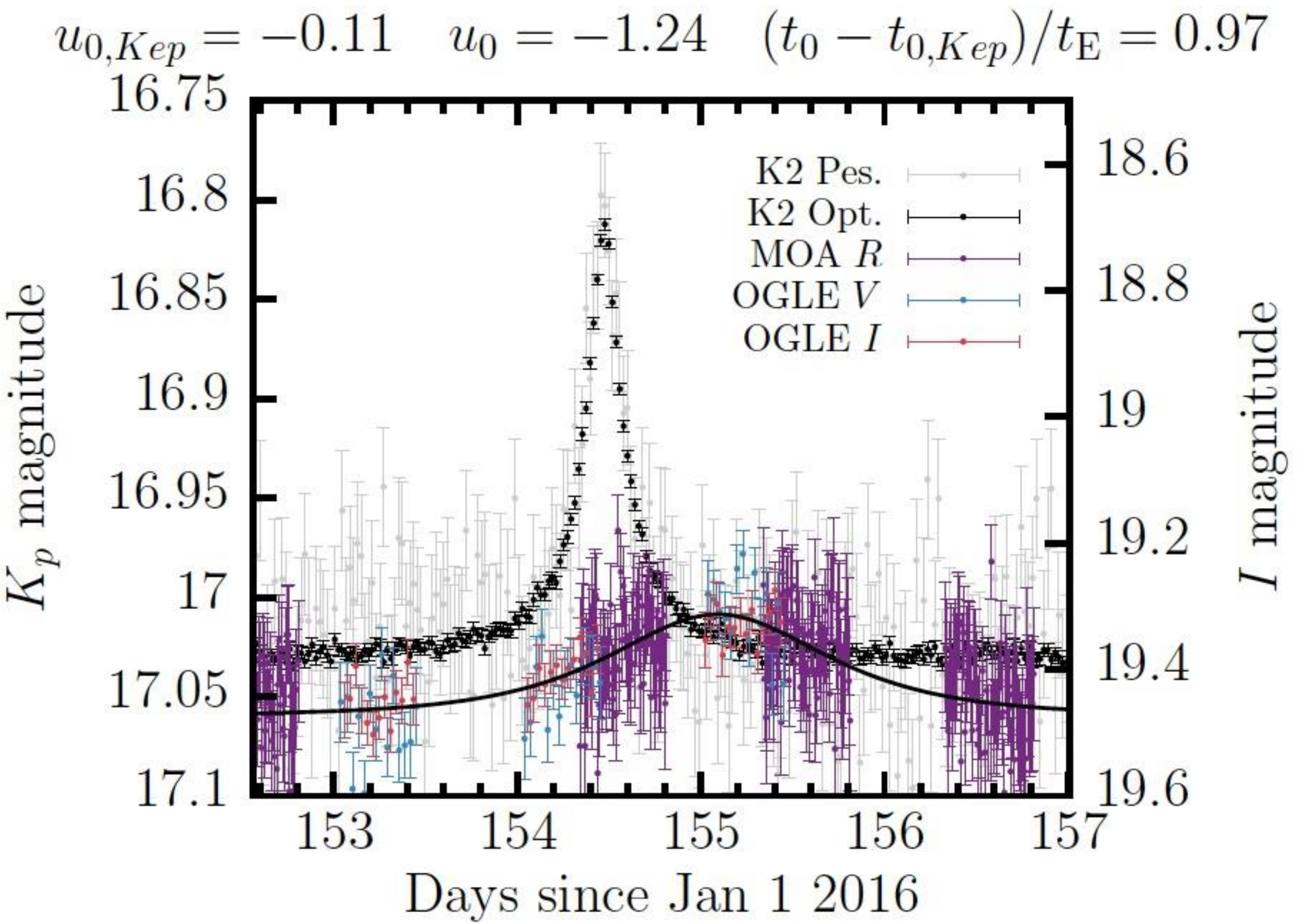


Characterizing the rocky, to ice, to gaseous boundaries

Another Method to Find Exoplanets: Microlensing

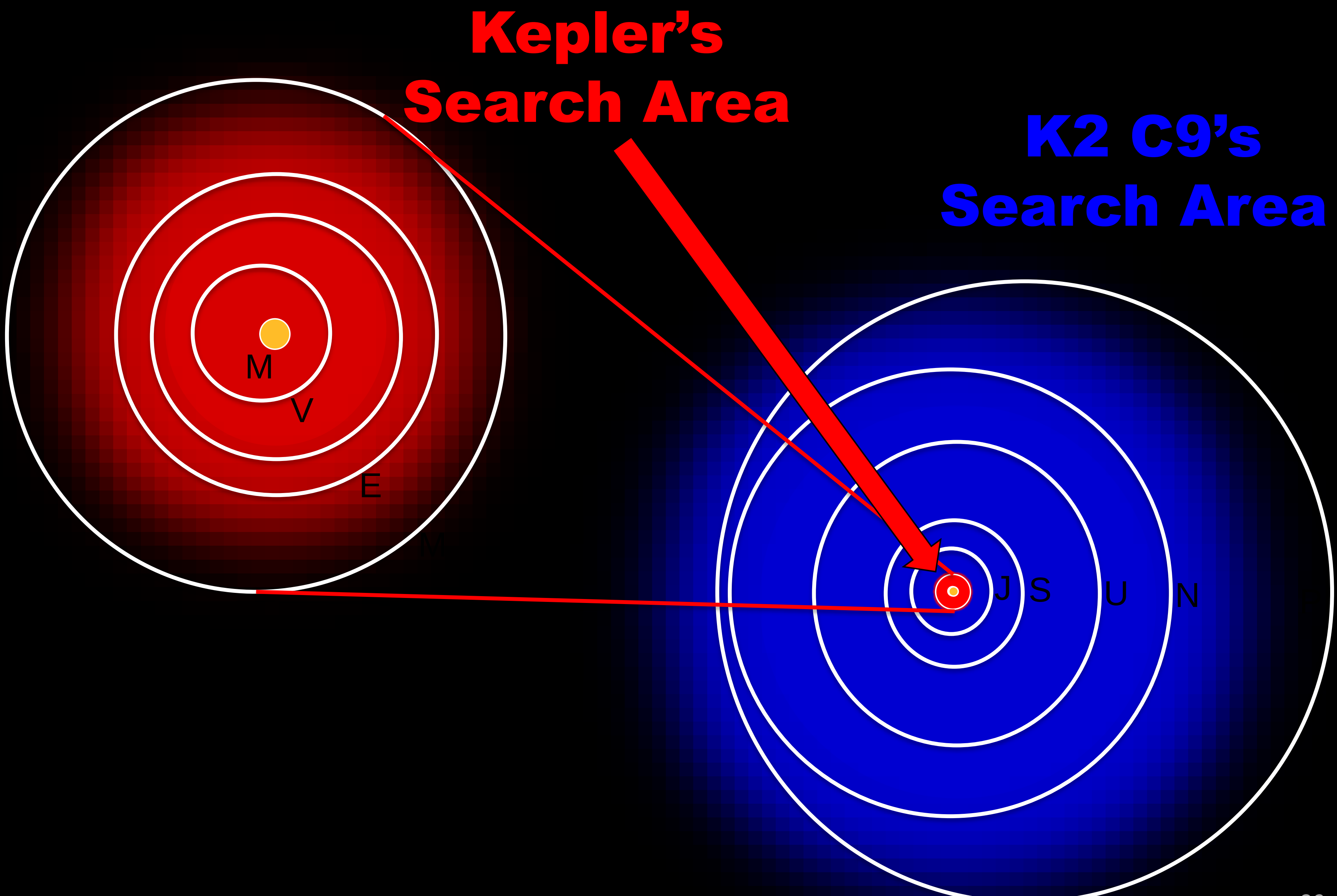




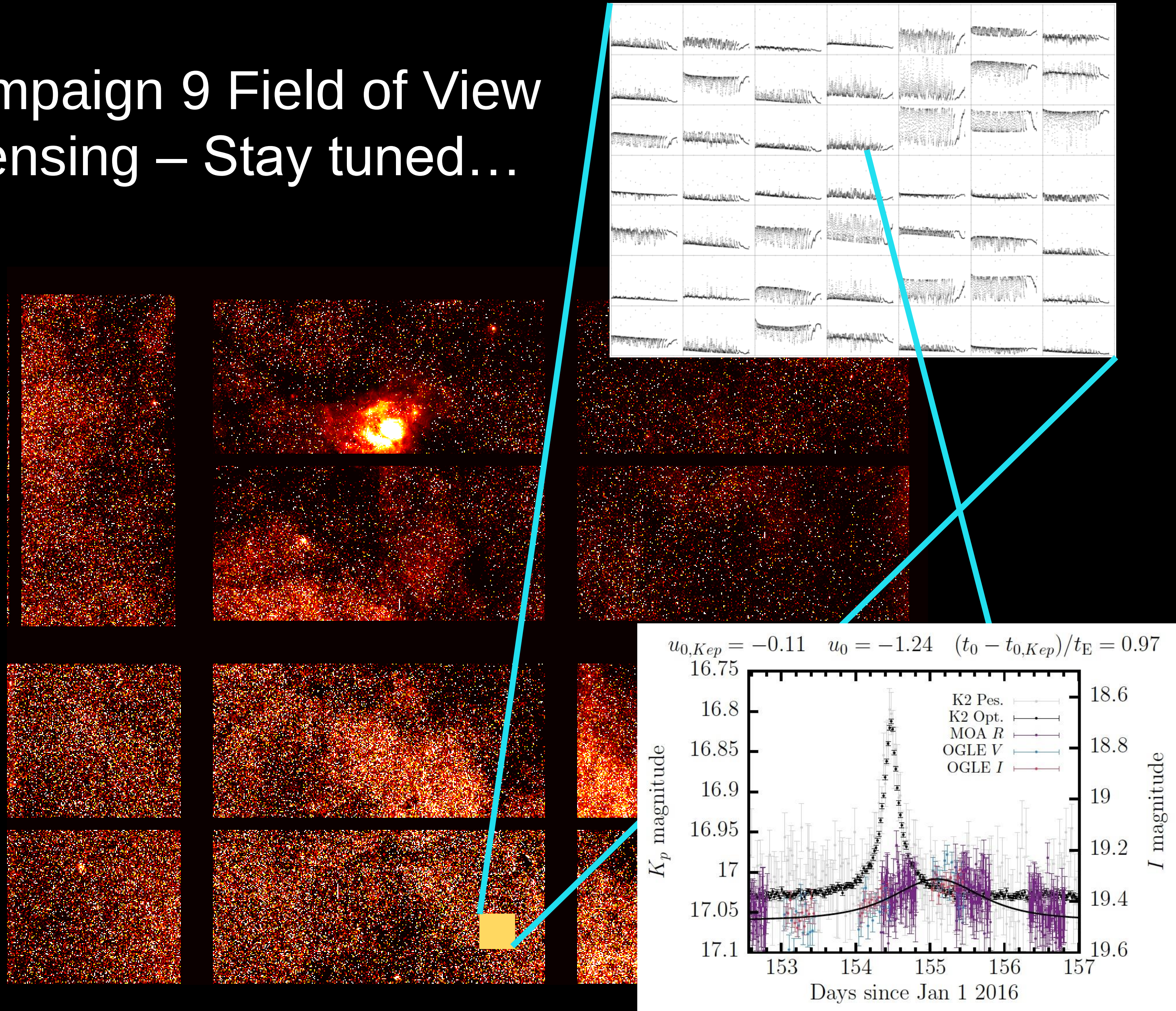


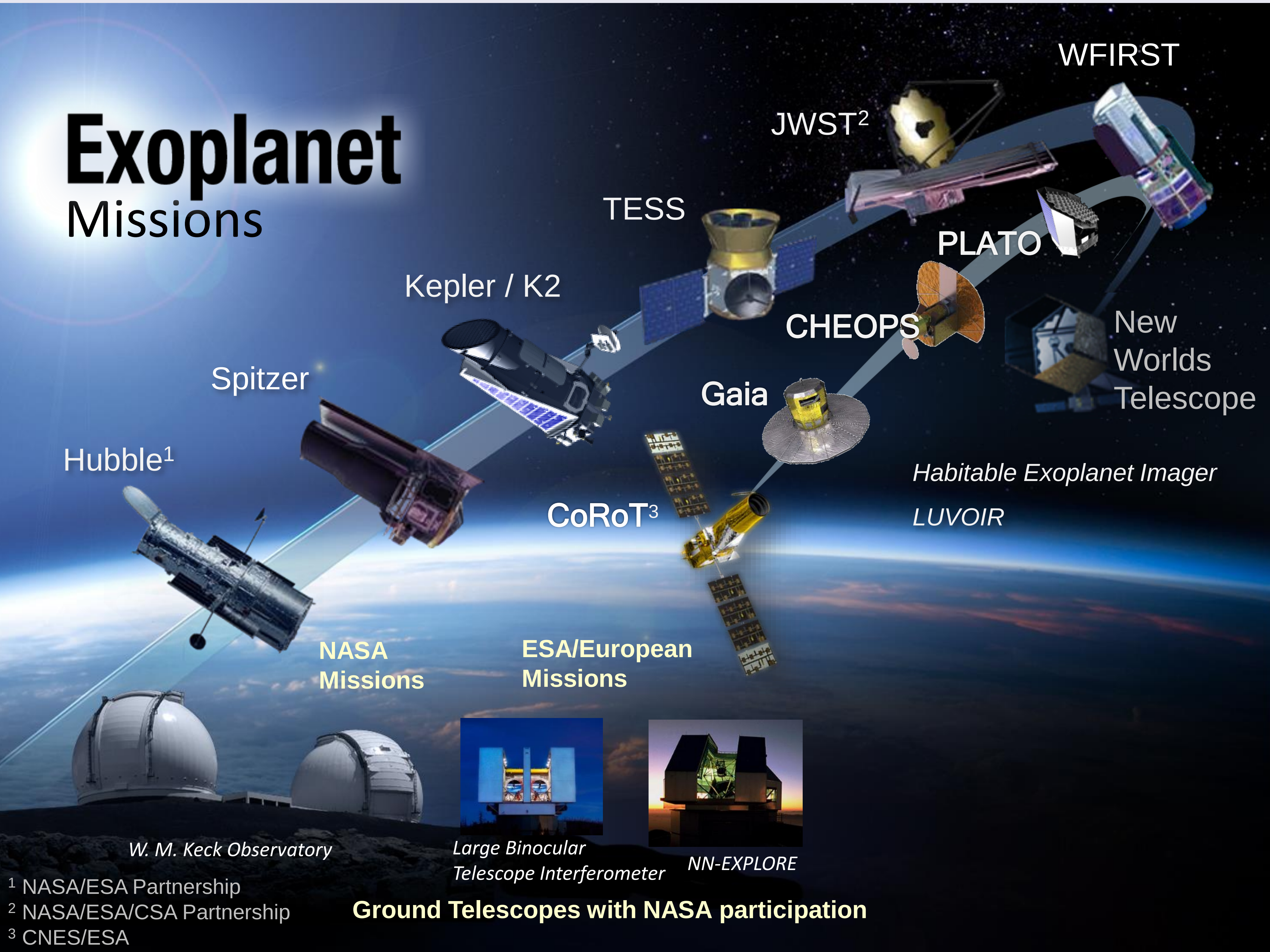
Penny et al. 2016

K2's Campaign 9; A Joint Ground+Space Microlensing Survey



K2 Campaign 9 Field of View
Microlensing – Stay tuned…




Exoplanet Missions
WFIRST
JWST2
TESS
PLATO
Kepler / K2
CHEOPS
New Worlds Telescope
Spitzer
Gaia
Hubble1
Habitable Exoplanet Imager
CoRoT3
LUVOIR
NASA Missions
ESA/European Missions
W. M. Keck Observatory
Large Binocular Telescope Interferometer
NN-EXPLORE
1 NASA/ESA Partnership
2 NASA/ESA/CSA Partnership
3 CNES/ESA
Ground Telescopes with NASA participation

Jet Propulsion Laboratory
California Institute of Technology

The NASA Exoplanet Exploration Program

(CL#16-4813)

Dr. Karl Stapelfeldt, Program Chief Scientist
Jet Propulsion Laboratory, California Institute of Technology

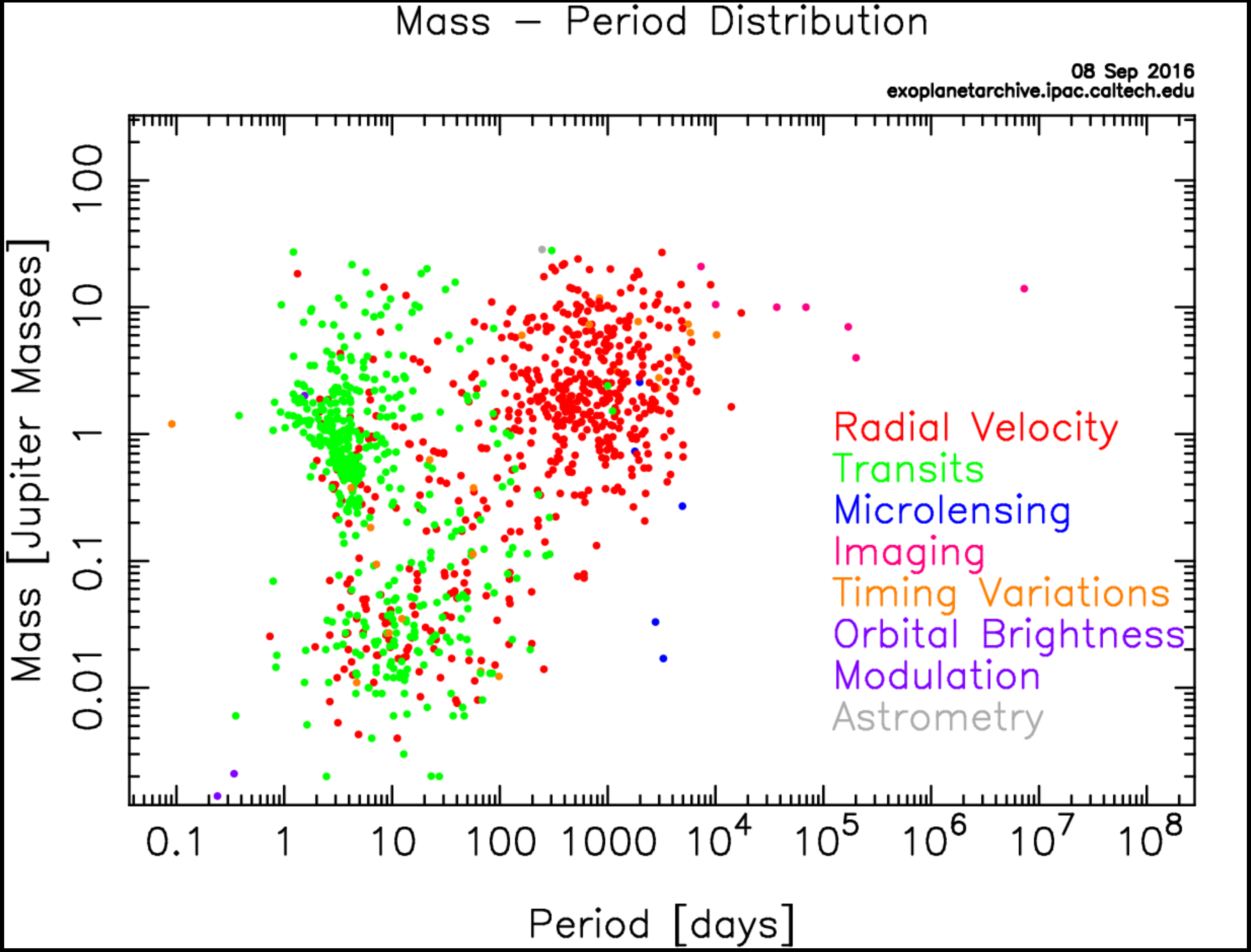
Sept 15, 2016

AIAA Space 2016

Long Beach, CA

Artist concept of Kepler-16b

Known exoplanets by Discovery method

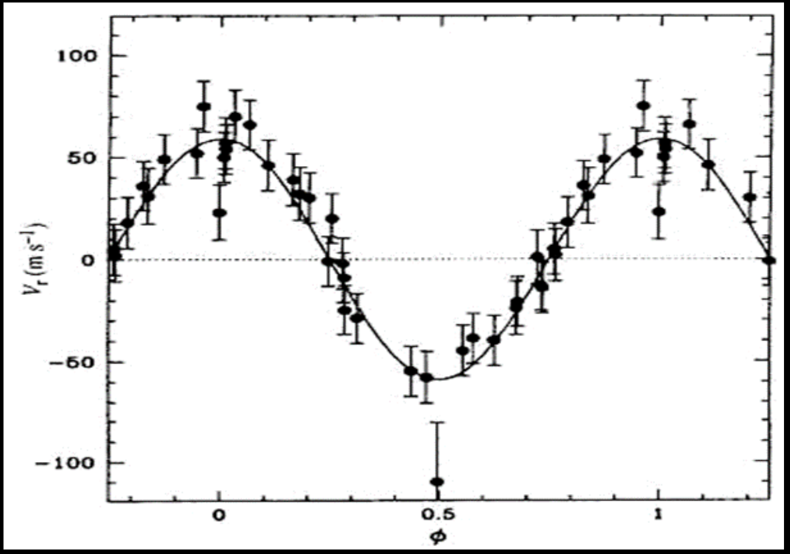


Known exoplanets by Discovery method

Measurement Technique	Number as of 14 Sep 2016
Transit (Kepler, …)	2671
Stellar radial velocity (Keck, ESO, …)	597
Imaging (ground adaptive optics, …)	43
Microlensing (ground surveys)	39
Other (timing variations, phase curves, astrometry)	37
Total	3387

Radial Velocity (RV) technique: measures dynamical disturbance of host star due planet’s gravity and orbit

- First planet (“hot Jupiter”) discovered in 1995
- Measures planet orbital period and lower limit on planet mass
- Method identifies targets for follow-up imaging to study planet atmosphere



51 Pegasi
Mayor & Queloz 1995

Important RV Discovery in August 2016: A potentially Habitable planet orbits Proxima Centuari, the nearest star !

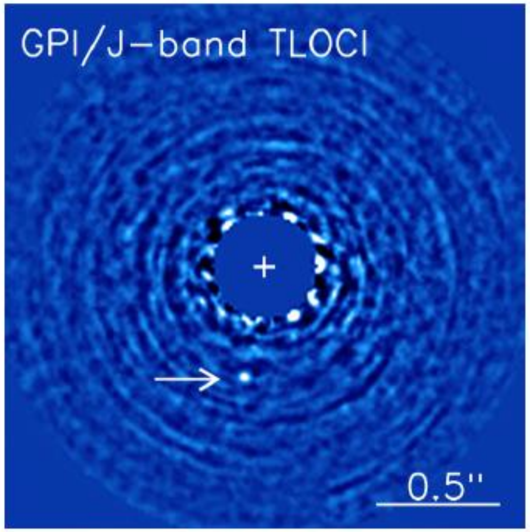
Anglada-Escudé et al. 2016

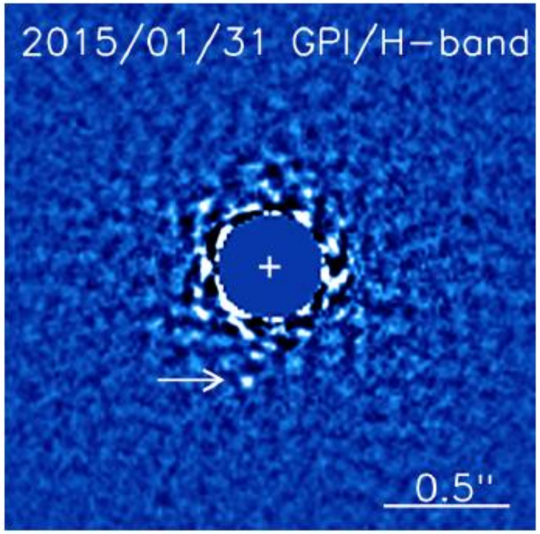
Art by European Southern Observatory

What we know about Proxima Centauri b:

- The system lies 4 light years away
- The host star is a red dwarf with high stellar activity
- Planet mass is at least 1.3 x that of Earth
- The planet's orbital period is 11.2 days, or an orbital distance of 0.05 AU from the star.
- At this distance the planet receives enough heat& light from its star for water to exist as a liquid on its surface, so the planet is *Potentially Habitable*
- Cannot say yet if it is Earthlike or not: does it have a solid surface, an atmosphere, and liquid water ?
- Do other nearby stars have potentially habitable planets ? We don't yet have the ability to answer this.

State of the art for Exoplanet imaging today: Gemini Planet Imager





- Gemini Planet Imager detection of hot young planet "51 Eridani b" (Macintosh et al. 2015)
- <u>Contrast to star is 2x10^{-6} at 0.5″ separation</u>
- Planet is glowing from its own heat, T= 700 K
- Mass is roughly twice that of Jupiter
- Spectrum below shows methane & some water)

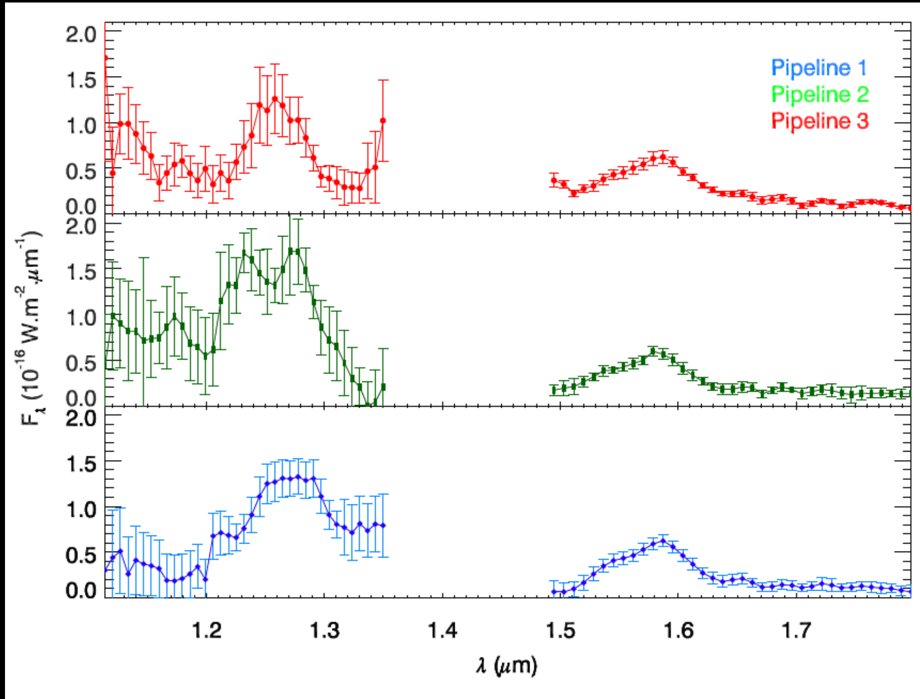


Figure S2: 51 Eri b spectra from the three different pipelines. The *H*-band spectra

NASA Exoplanet Exploration Program

NASA Astrophysics Division, Science Mission Directorate

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

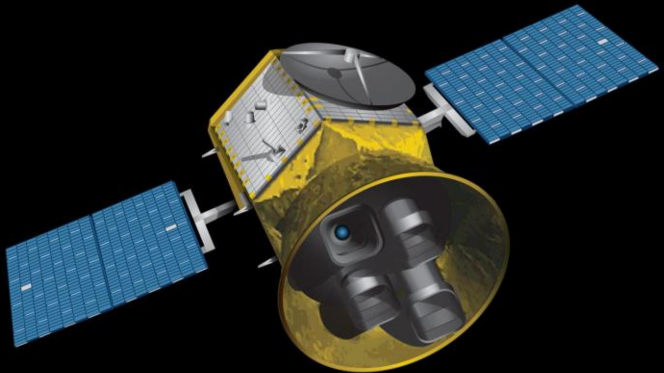
http://exoplanets.nasa.gov/exep

Landscape of NASA exoplanet activities

Work going on outside of ExEP

- General-purpose space telescopes do important work
  - Hubble Space Telescope
  - Spitzer Space Telescope
  - James Webb Space Telescope (late 2018 launch)

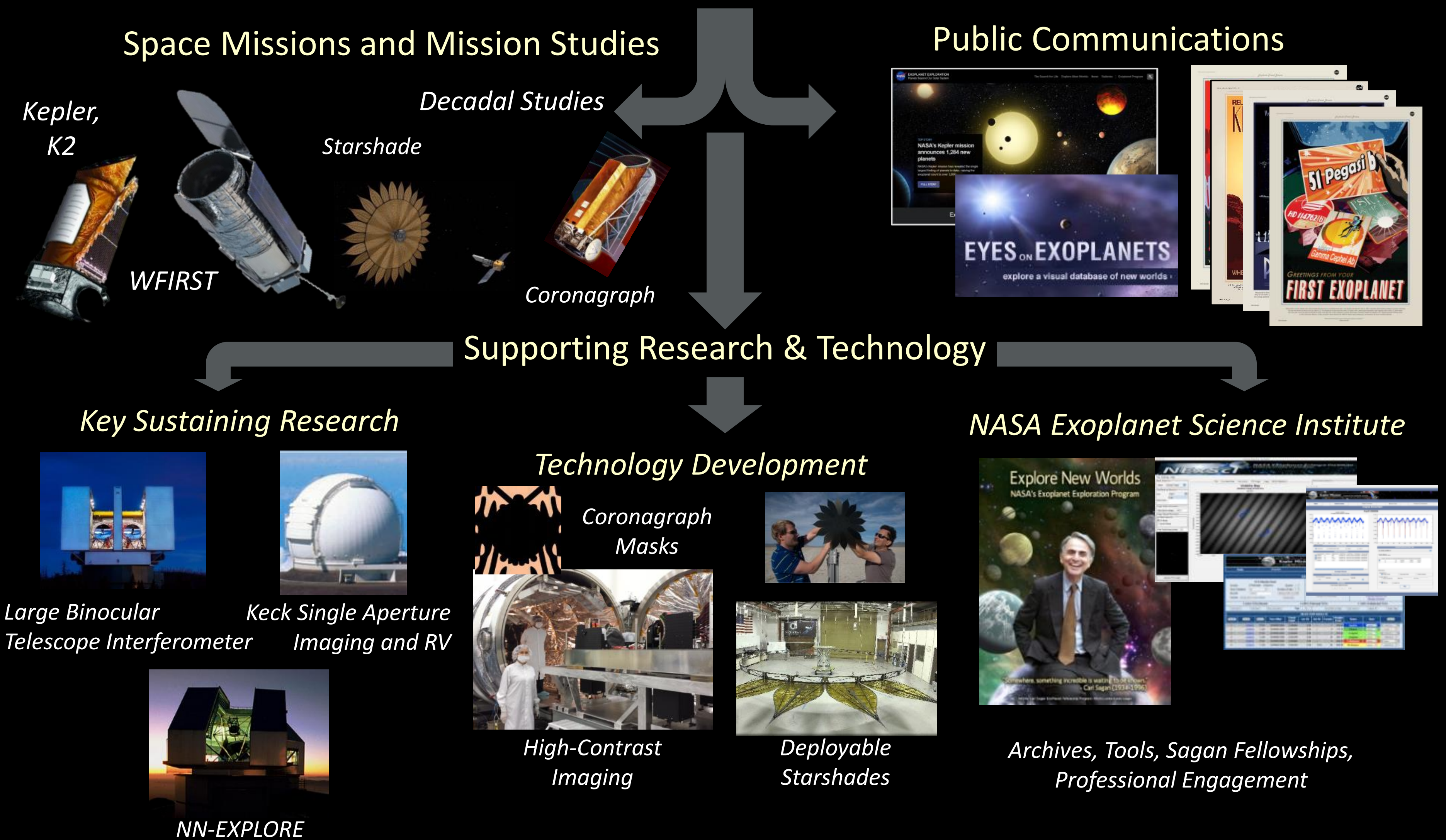
- NASA Explorer Program
  - TESS all-sky transit survey launches in late 2017



TRANSITING EXOPLANET SURVEY SATELLITE
DISCOVERING NEW EARTHS AND SUPER-EARTHS IN THE SOLAR NEIGHBORHOOD

NASA Exoplanet Exploration Program

ExoPlanet Exploration Program



http://exoplanets.nasa.gov

Mission studies: Direct imaging mission concepts

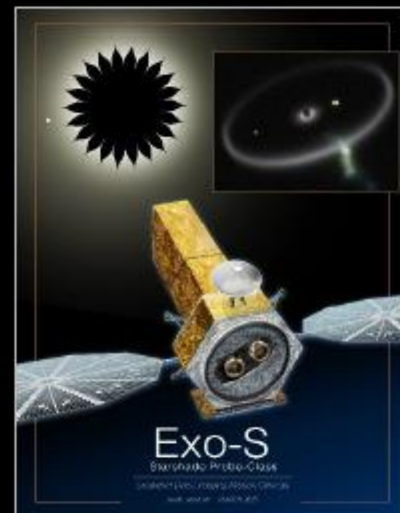
Carried out 2013-2015; directed at cost point < $ 1 B

Exo-C:

Internal Occulter (Coronagraph)

K. Stapelfeldt, STDT Chair, GSFC

- 1.4 m unobscured telescope
- Kepler-like mission in Earth-trailing orbit
- RV planets, dust disks, mini-Neptunes, super-Earths ?



Exo-S:

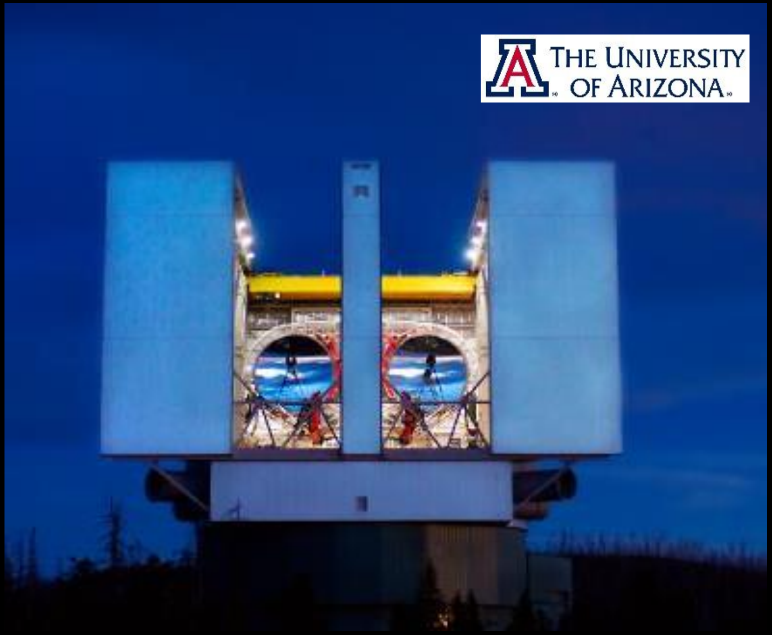
External Occulter (Starshade)

S. Seager, STDT Chair, MIT

- Studied 2 spacecraft mission and starshade to rendezvous with WFIRST
- RV planet, dust disks, small planets down to Earth analogs in a few systems

Large Binocular Telescope Interferometer (LBTI)

Measure background light from dust orbiting nearby stars



- Light scattered off dust in our solar system is brighter than any of the planets
- Brightness of this "zodiacal light" in other planetary systems could limit our ability to image small planets

- LBTI is a specialized instrument designed to measure this light
- Deployed to LBT on Mt. Graham in Arizona. Measurement limits to date are 15x dust level in our solar system
- Survey continues this fall

NASA/NSF partnership “NN-Explore”

Extreme Precision Doppler Spectrometer

NN-Explore Exoplanet Investigations with Doppler Spectroscopy

PI: S. Mahadevan

- Motivation:
  - 2010 Astronomy Decadal Survey called for precise ground-based spectrometer for exoplanet discovery and characterization
  - Needed for follow-up & precursor science for NASA missions (K2, TESS, JWST, WFIRST)
  - Results inform design/operation of future missions
- Instrument is now being built
  - Will use 40% of time on WIYN telescope in AZ
    - Penn State NEID proposal selected in March 2016
    - Instrument to be commissioned spring 2019
    - R= 100,000; 380-930 nm wavelength coverage; measurement precision better than 0.5 m/sec
  - Observing time will be open to the scientific community through peer-reviewed proposal process, just as NASA/Keck time is now.

3.5m WIYN Telescope
Kitt Peak National Observatory
Arizona

Community Support

NASA Exoplanet Science Institute at Caltech campus

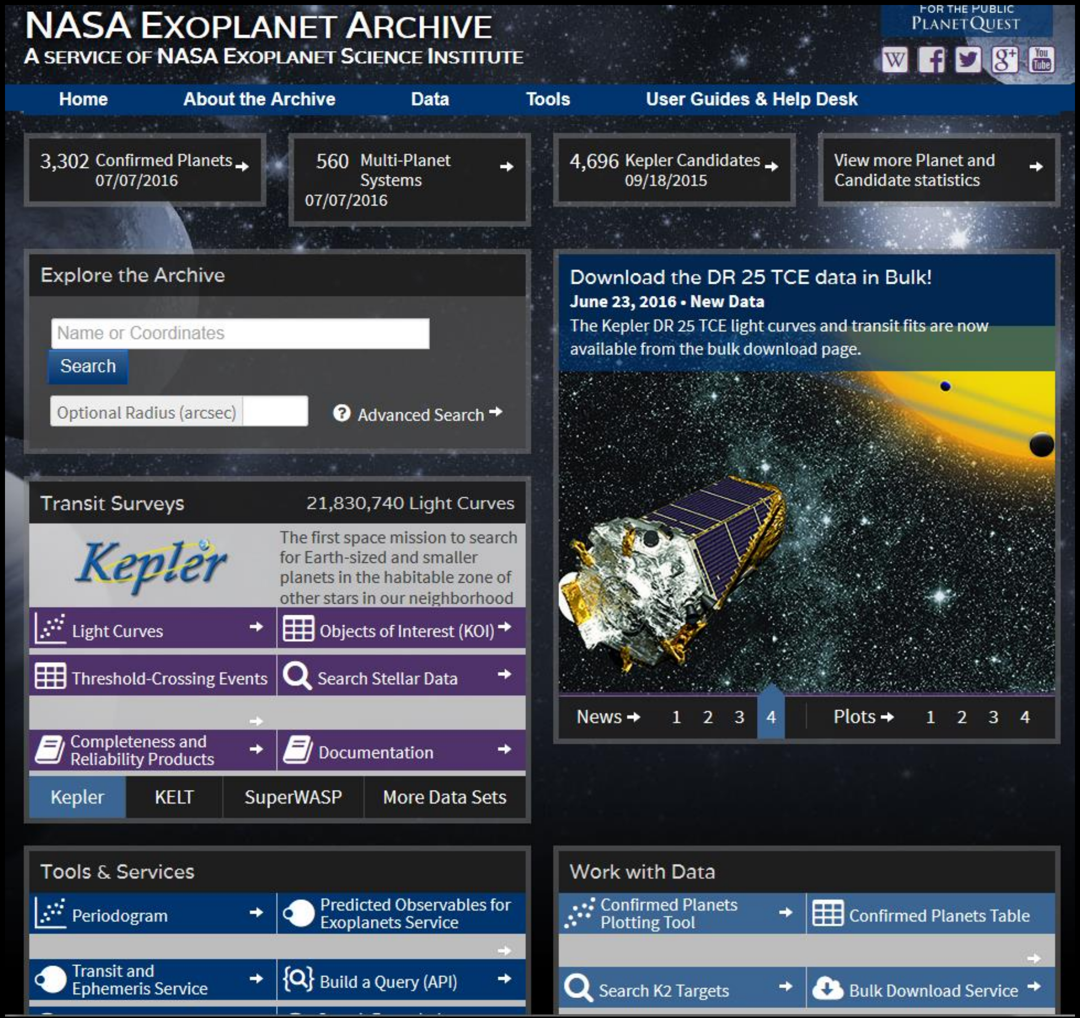
Exoplanet Archive

- Planet tables
- Light curves
- Analysis tools
- Regularly updated

Followup Program

- Data sharing infrastructure for community followup of Kepler, K2, TESS

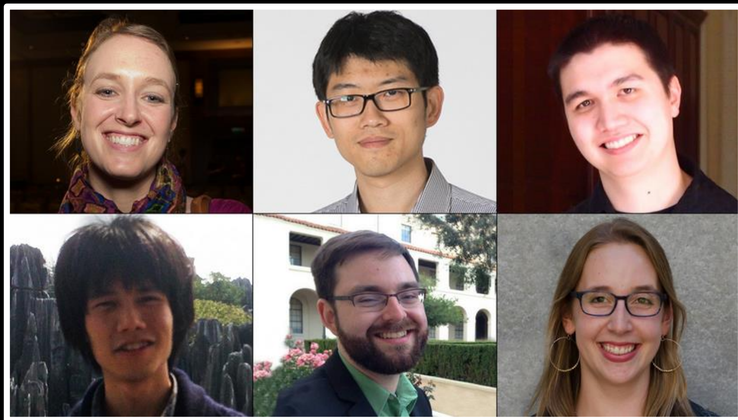
http://exoplanetarchive.ipac.caltech.edu



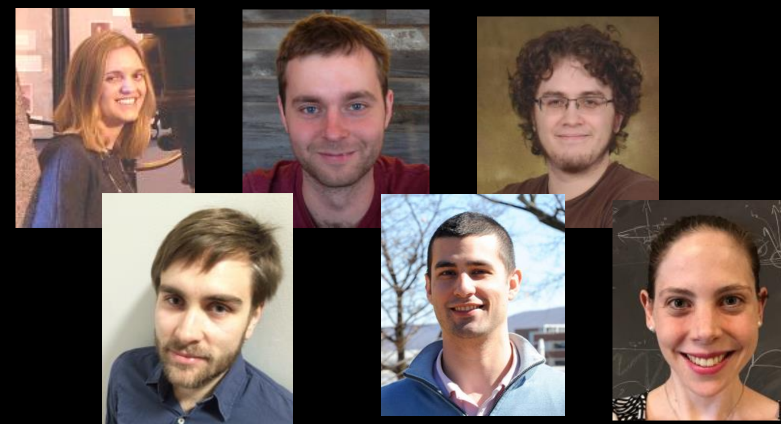
Sagan Postdoctoral Fellowship Program

supports exoplanet research by outstanding early career scientists

2016



2015



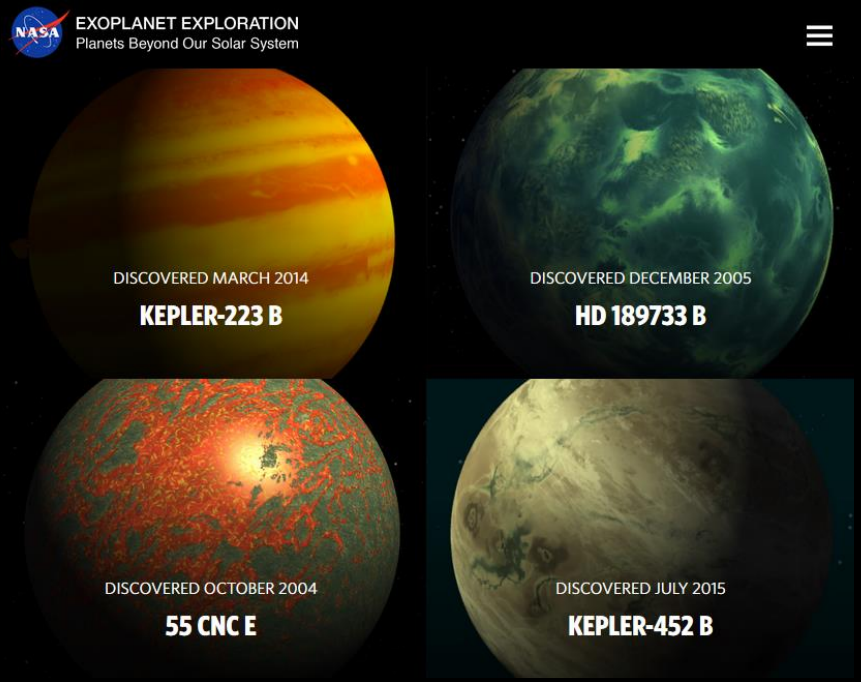
2013

2014

Annual Sagan Summer School in Pasadena provides training in exoplanet research techniques for students

New public website for NASA Exoplanet Exploration:

exoplanets.nasa.gov



Replaces planetquest.jpl.nasa.gov
New content, compatibility with mobile devices,
some features of “eyes on exoplanets” incorporated

Important NASA Exoplanet websites and dates

Main Exoplanet Program website:
    http://exoplanets.nasa.gov

Exoplanet science archive:
    http://exoplanetarchive.ipac.caltech.edu

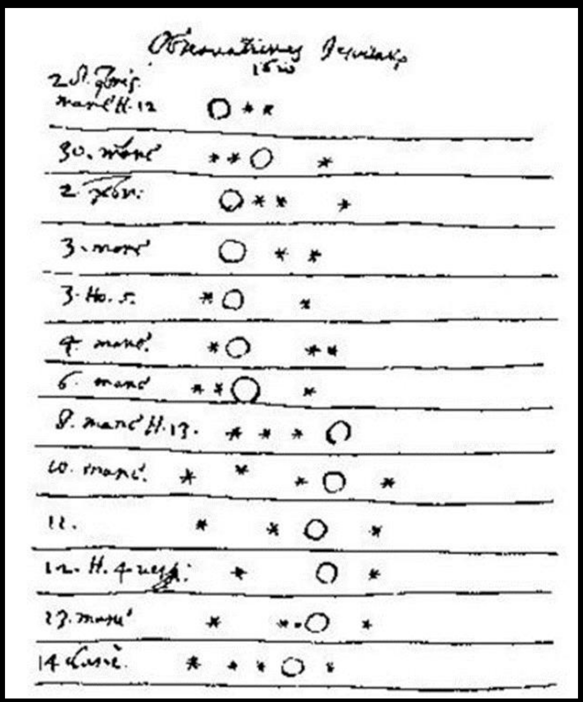
ExoPAG 15 meeting at winter meeting of the American Astronomical Society: Jan 2-3 2017, Dallas TX

Kepler and K2 Science Conference IV:
    June 19-23 2017, NASA Ames Research Center

WFIRST Community Science Conference:
    June 26-30 2017, Space Telescope Science Institute

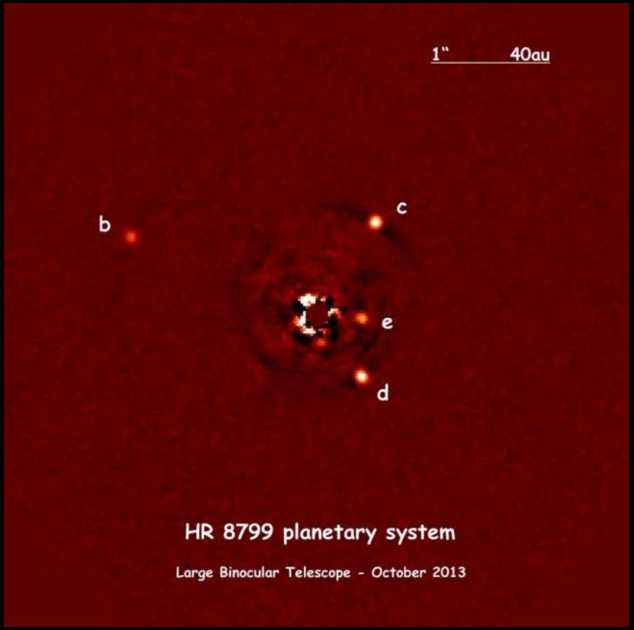
Epilog: Discovering Planetary Systems:

1610



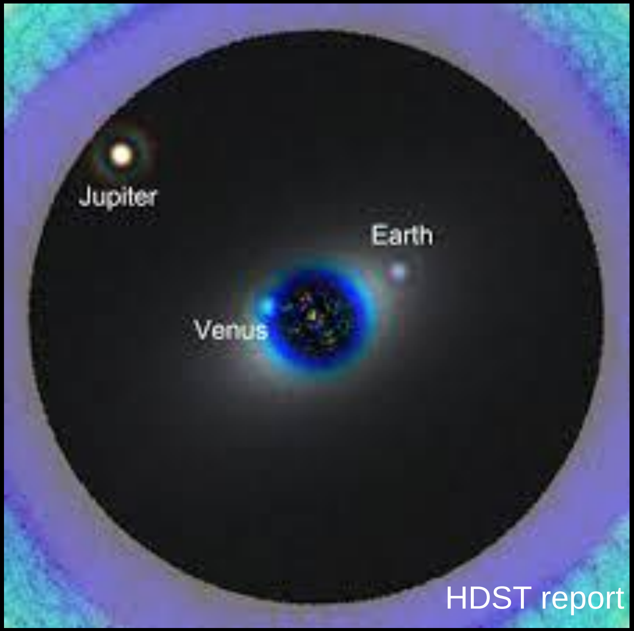
Galileo discovers
Jovian satellite system

2008



Marois et al. discover
HR 8799 planetary system

2035 ?



Future space
telescopes confirm first
habitable exoplanet

Jet Propulsion Laboratory
California Institute of Technology

Exoplanet Exploration Program Organization Chart

Astrophysics Division, NASA HQ
Director – Dr. P. Hertz
Deputy Director/Program Director – A. Razzaghi

Astronomy Physics & Space Technology Directorate, JPL
Director for – L. Livesay
Deputy Director for – Dr. D. Coulter

Exoplanet Program Executive – J. Gagosian
Exoplanet Prog. Sci./Deputy – Dr. D. Hudgins/Dr. M. Still

730
Exoplanet Exploration Program Office
Program Manager – Dr. G. Blackwood
Deputy Program Manager – K. Short
Program Chief Scientist – Dr. K. Stapelfeldt
Program Chief Technologist – Dr. N. Siegler

WFIRST Program Executive – J. Gagosian
WFIRST Program Scientist / Deputy – Dr. D. Benford / Dr. L. Sparke
Kepler / Closeout Program Exec – K. Chamberlin
Kepler / K2 Program Executive – J. Hayes
Kepler / K2 Program Scientist / Deputy – Dr. M. Perez / Dr. D. Hudgins
NExScI Program Executive – Dr. M. Perez
NExScI Prog. Scientist – Dr. D. Hudgins
LBTI Program Executive – Dr. M. Perez
LBTI Prog. Scientist – Dr. D. Hudgins
Keck Telescope Program Executive – Dr. M. Perez
Keck Telescope Program Scientist – Dr. H. Hasan
Sagan Fellows – Dr. K. Sheth
NN-EXPLORE Program Executive - J. Gagosian
NN-EXPLORE Program Scientist / Deputy - Dr. D. Hudgins / Dr. M Perez
SR&T Activities Program Executive – J. Gagosian
SR&T Activities Program Scientist / Deputy – Dr. D. Hudgins / Dr. M. Still
ExoPAG Program Scientist – Dr. M. Still
ExEP Technology Lead – Dr. W. Lightsey
Program Office Communications – Dr. H. Hasan

ExoPlanet TAC[1]
Dr. A. Boss
Carnegie Institution

7301
Program Science Office
Chief Scientist – Dr. K. Stapelfeldt
Deputy Chief Scientist – Dr. E. Mamajek
Dr. N. Gautier (326)
Dr. G. Bryden (326)

7303
Program Engineering Office
Program Chief Engineer – K. Warfield
Export Tech Lia. – Dr. A. Abramovici (383)
Mission Assurance Manager – J. Mehta

7311
Program Business Office
Business Admin. Mgr. – R. Lemus (731)
Administrator – O. Pananyan (731)
Project Acquisition Manager – W. Kert (268)
Staff Assistant – K. Miller (731)
Staff Assistant – J. Gregory (731)

Mission Managers
Kepler Mission Mgr. – I. Heinrichsen (734)
WFIRST Mission Mgr. – I. Heinrichsen (730)

7312
Business Operations
Resource Analyst – B. Nomoto (252)
Project Schedule Analyst – G. Luzwick (252)

7302
Program/Project Communications and Public Engagement (JPL)
Manager – M. Greene (183)
Web Manager – R. Jackson
Engagement Specialist – A. Biferno
Writer Editor – P. Brennan
Internet Communications – A. Samuelson

Kepler (ARC)
Project Manager (Phase E) – C. Sobeck
Project Scientist (Phase E) – Dr. N. Batalha
Project Scientist (K2) – Dr. J. Dotson
Guest Observer Office Dir. – Dr. T. Barclay

733
Program Technology (JPL)
Manager – Dr. N. Siegler, AD (383)

732
LBTI (Univ. of Arizona)
Manager – Dr. P. Willems, AD (383D)
Principal Investigator – Dr. P. Hinz, U of A
Project Scientist – Dr. C. Gelino, Caltech

WFIRST Project Office (GSFC)
Project Manager – K. Grady
Deputy Project Manager – C. Peddie
Project Scientist – Dr. N. Gehrels

WFIRST Formulation Science Working Group
Project Scientist – Dr. N. Gehrels, GSFC
Dr. D. Spergel[1], Princeton
Dr. J. Kasdin[1], Princeton

Universe of Learning (JPL)
Manager – M. Greene (183)
Engagement Spec. – A. Biferno
Public Outreach Spec. – S. Edberg

Starshade Technology Project (JPL)
Manager – Dr. J. Ziemer, AD, JPL (3830)

735
NASA-NSF Exoplanet Observational Research
Manager – Dr. J. Callas, AD, JPL (383D)
Principal Investigator – Dr. S. Mahadevan, Penn State

790
NASA Exoplanet Science Institute (Caltech)
Exec. Director – Dr. C. Beichman (790)
Deputy Director – Dr. R. Akeson
Manager – Dr. D. Imel

706
WFIRST Project Office (JPL)
Project Manager, P. Barela
Dep Proj Mgr.– B. Parvin (706)
Project Scientist: Dr W. Traub
Deputy Proj. Scientist: Dr. J. Rhodes
Coronagraph – Dr. F. Zhao (383)
Technology - Dr. I. Poberezhskiy (383)
Dr. R. Demers (383)
Science Center – Dr. R. Cutri (Caltech)

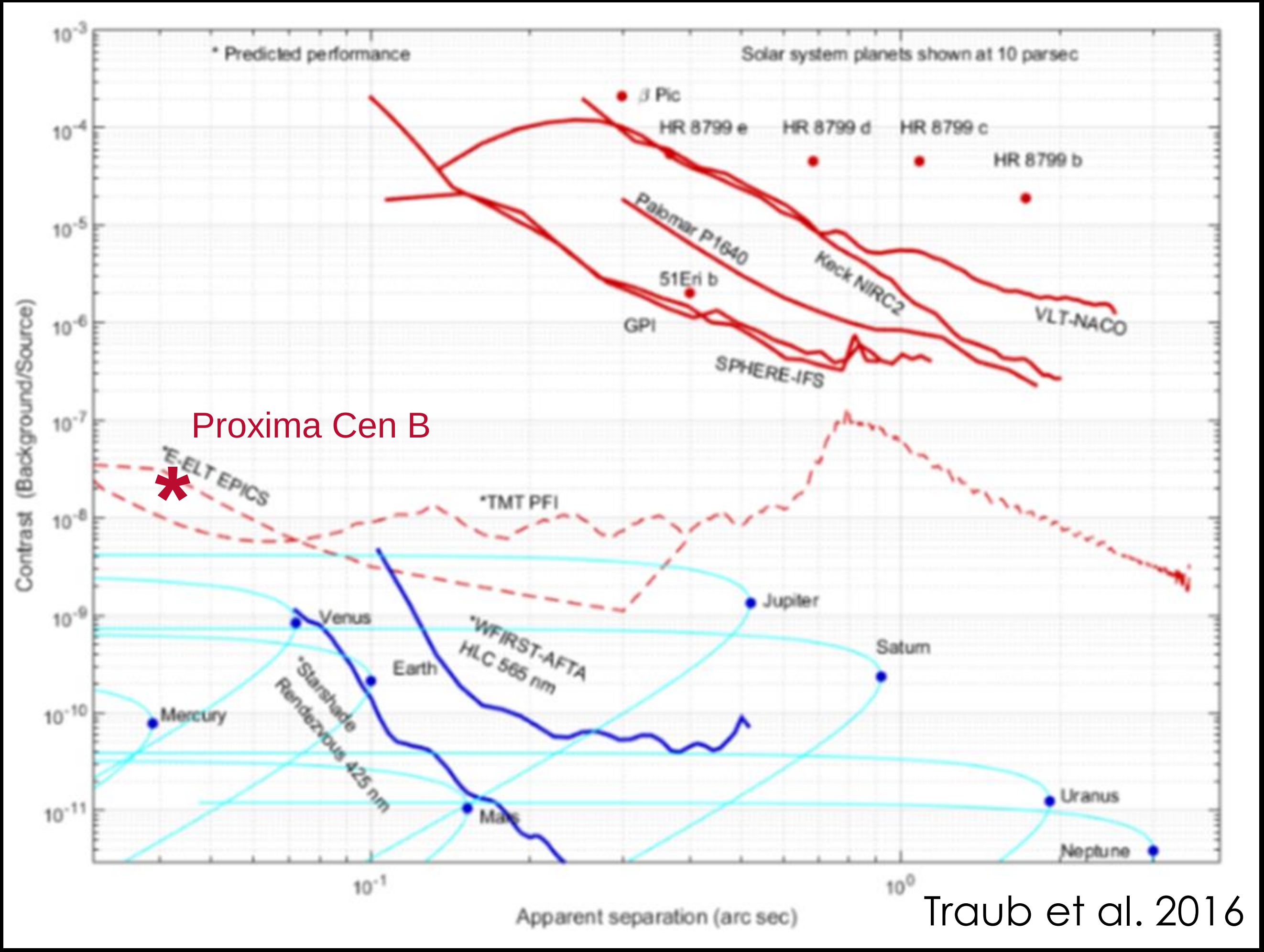
WFIRST TAC[1]
Dr. A. Boss
Carnegie Institution

[1]Reports to NASA HQs APD

Legend:
Programmatic lines of authority ———
Interface – – – – – –

September 8, 2016
R. Lemus
NASA Exoplanet Exploration Program

FUTURE EXOPLANET SPECTROSCOPY: Extremely LARGE GROUND Telescopes, 2024+ solar system analogs out of reach

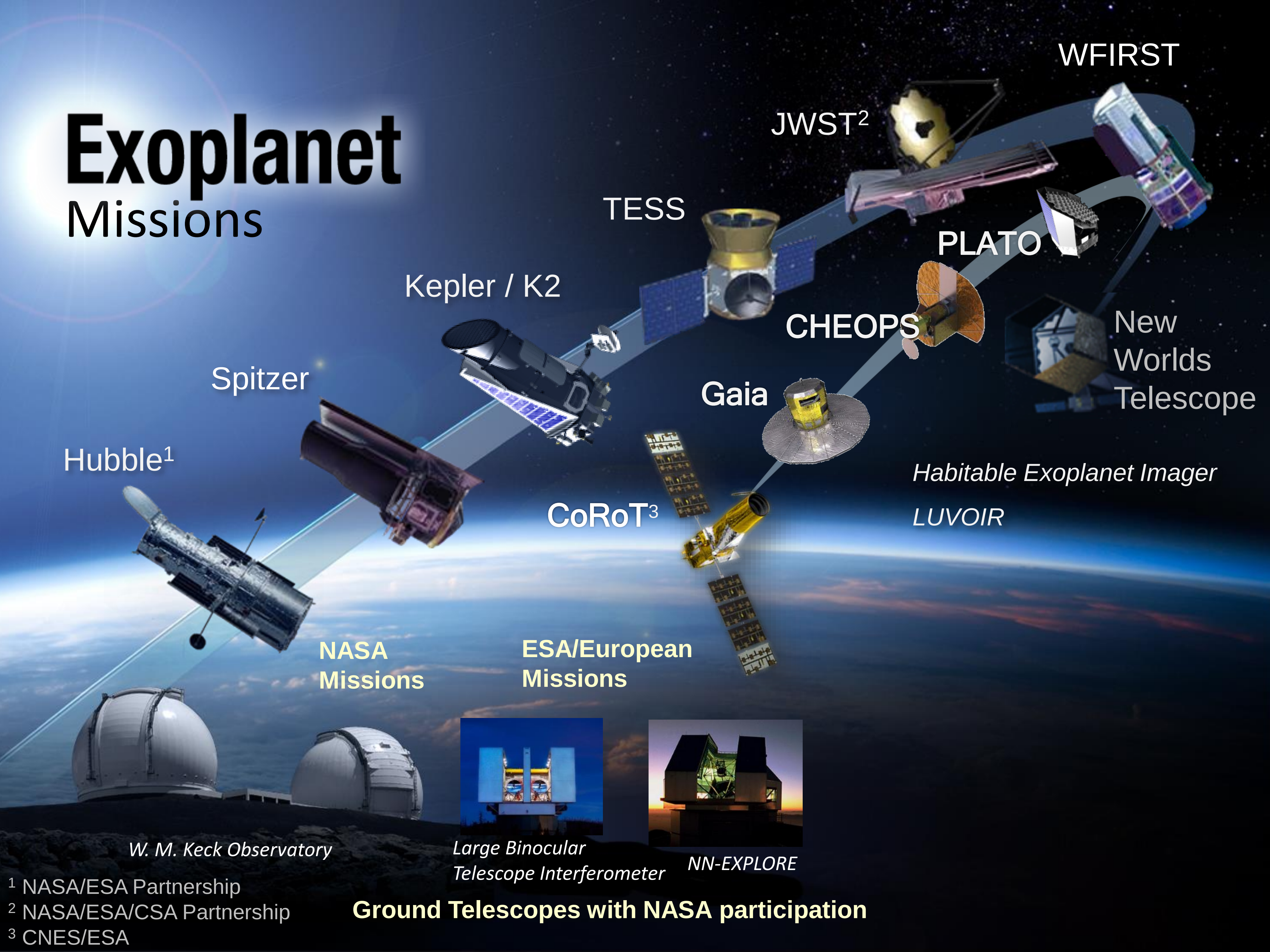


Traub et al. 2016

38, 25, and 30 m telescope projects are underway

Instruments for high contrast imaging not available until end of the 2020s

Favorable contrast of 10^{-8} in M4+ star HZs; a dozen targets may be doable


Exoplanet
Missions
WFIRST
JWST2
TESS
PLATO
Kepler / K2
CHEOPS
New
Worlds
Telescope
Spitzer
Gaia
Hubble1
Habitable Exoplanet Imager
CoRoT3
LUVOIR
NASA
Missions
ESA/European
Missions
W. M. Keck Observatory
Large Binocular
Telescope Interferometer
NN-EXPLORE
1 NASA/ESA Partnership
2 NASA/ESA/CSA Partnership
3 CNES/ESA
Ground Telescopes with NASA participation

Jet Propulsion Laboratory
California Institute of Technology

The Habitable Exoplanet Imaging Mission: Science and Technology Drivers

Scott Gaudi

Thomas Jefferson Chair, The Ohio State University

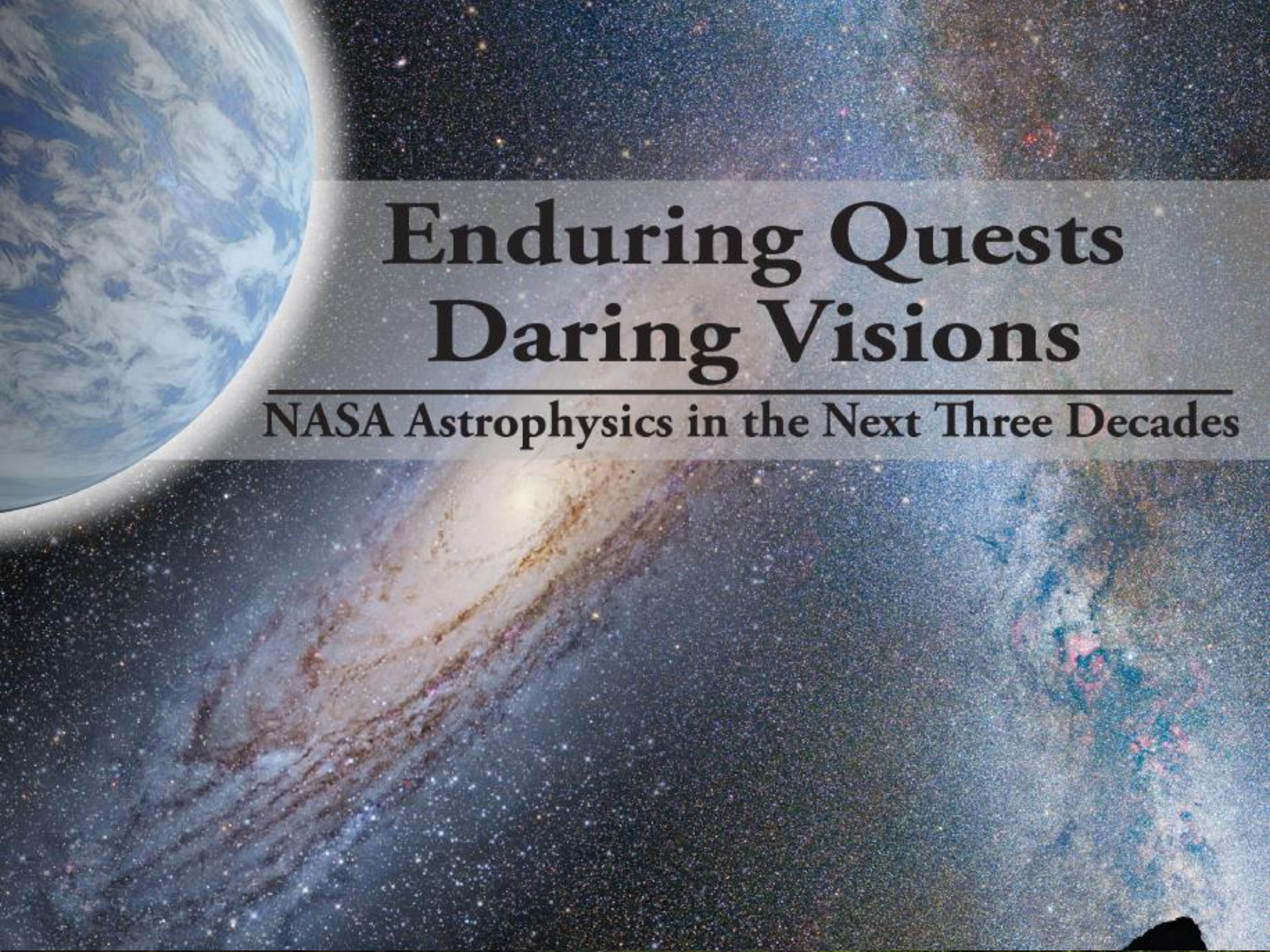
Distinguished Visiting Scientist, Jet Propulsion Laboratory

September 15, 2016

NASA Exoplanet Exploration Program Updates and Technology Challenges

AIAA Space 2016, SPSC-03, Long Beach CA

Are we alone?

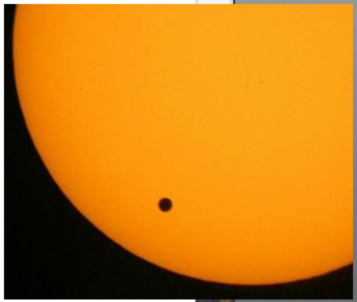

Enduring Quests
Daring Visions
NASA Astrophysics in the Next Three Decades

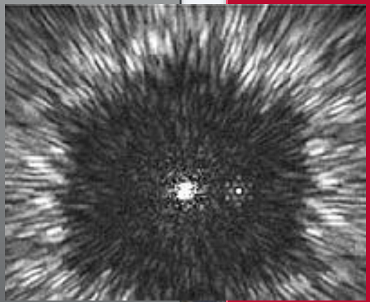
Stage 0 (current)	Stage 1 (2020-2030)	Stage 2 (2030-2040)	Stage 3 (>2040)

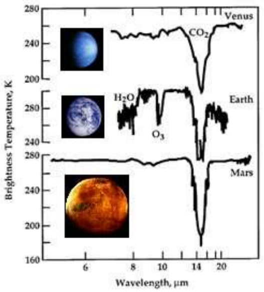
A Complete Exoplanet Census

The Search for Habitable Climates and Life.

Characterizing Atmospheres of Other Worlds







TESS

JWST

HST

Spitzer

Kepler

WFIRST+C (+S?)

Transit Characterization Mission?

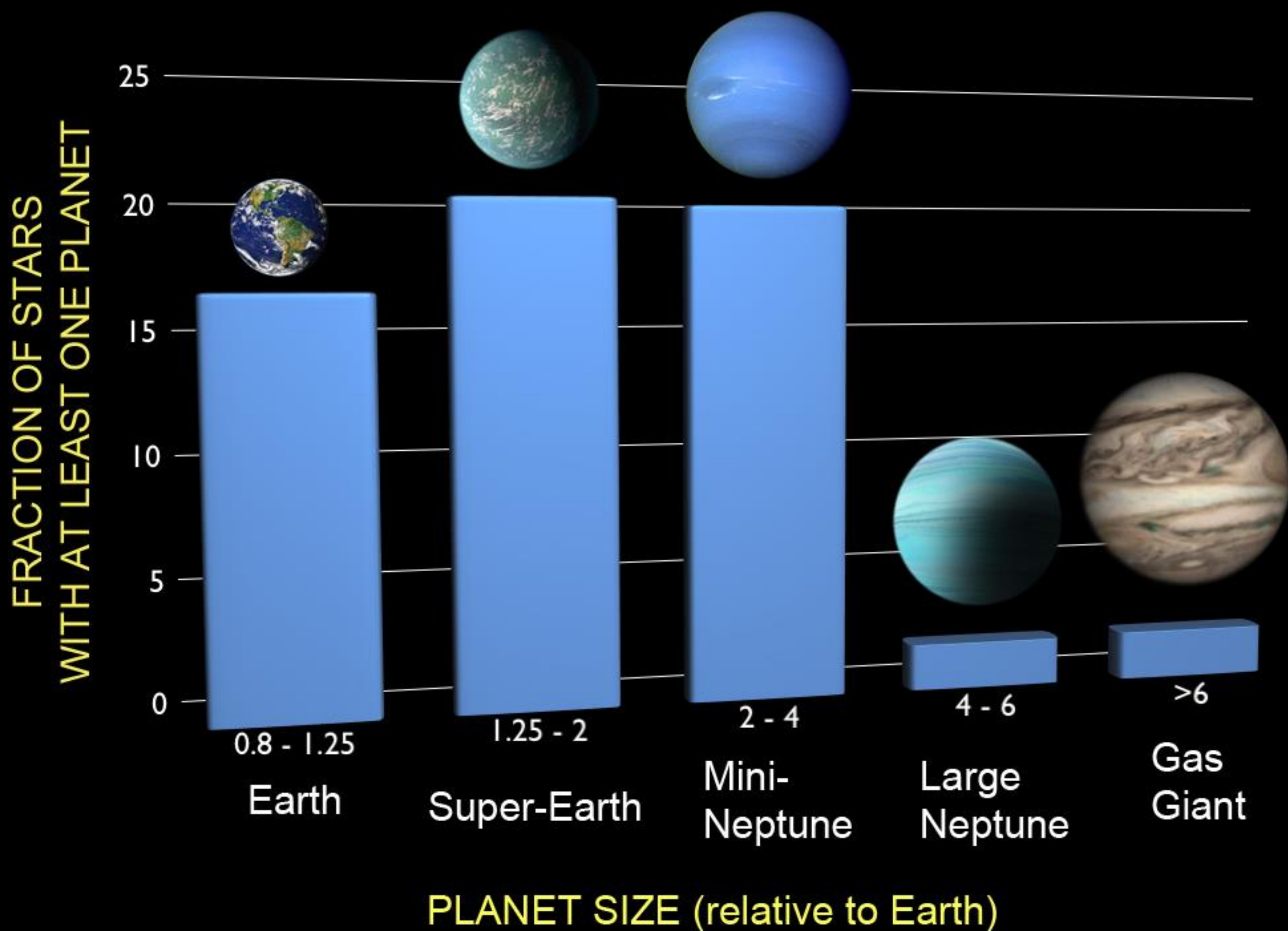
w Worlds Telescope

Astrometry Mission?

Earth Mapper

Mid-IR Interferometer

NASA's Kepler Space Telescope



FRACTION OF STARS
WITH AT LEAST ONE PLANET
25
20
15
10
5
0
0.8 - 1.25
Earth
1.25 - 2
Super-Earth
2 - 4
Mini-
Neptune
4 - 6
Large
Neptune
>6
Gas
Giant
PLANET SIZE (relative to Earth)

NASA’s Wide Field Infrared Survey Telescope (WFIRST)

WFIRST+C Exoplanet Science

The combination of microlensing and direct imaging will dramatically expand our knowledge of other solar systems and will provide a first glimpse at the planetary families of our nearest neighbor stars

Microlensing Survey

Monitor 200 million Galactic bulge stars every 15 minutes for 1.2 years

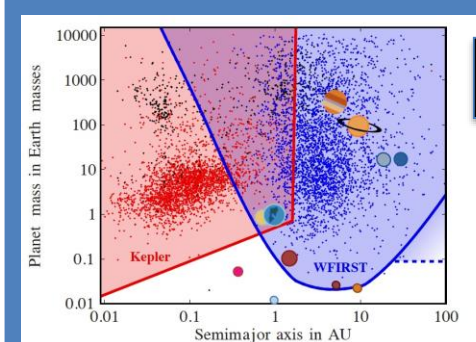
2800 cold exoplanets
300 Earth-mass planets
40 Mars-mass or smaller planets
40 free-floating Earth-mass planets

High Contrast Imaging

Survey up to 200 nearby stars for planets and debris disks at contrast levels of 10^{-9} on angular scales > 0.2”
R=70 spectra and polarization between 400-900 nm

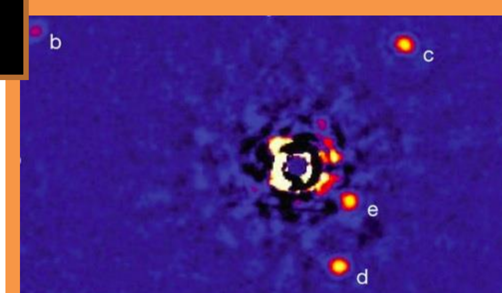
Detailed characterization of up to a dozen giant planets.
Discovery and characterization of several Neptunes
Detection of massive debris disks.

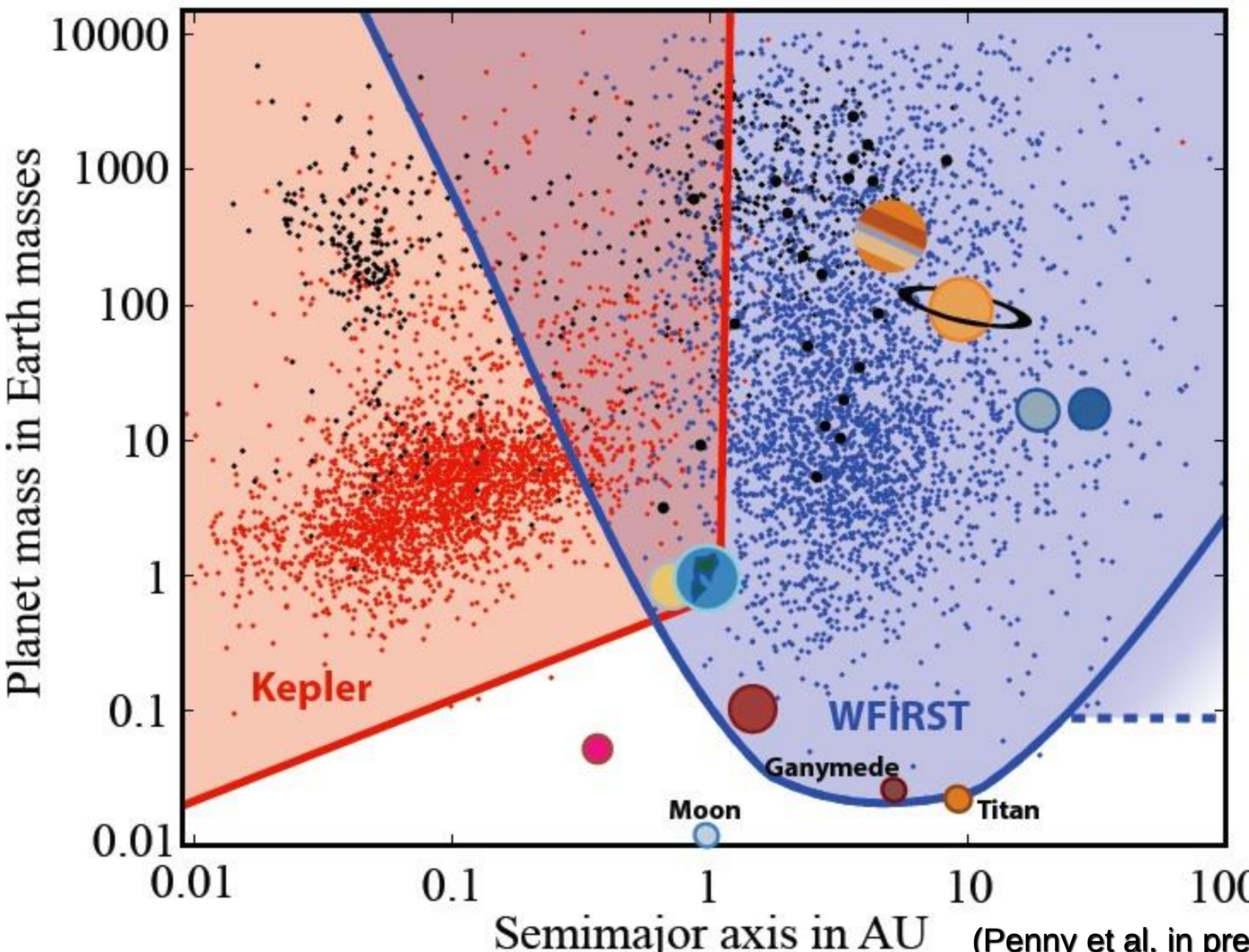
Complete the Exoplanet Census



- **How do planetary systems form and evolve?**
- **What are the constituents and dominant physical processes in planetary atmospheres?**
- **What kinds of unexpected systems inhabit the outer regions of planetary systems?**
- **What are the masses, compositions, and structure of nearby circumstellar disks?**
- **Do small planets in the habitable zone have heavy hydrogen/helium atmospheres?**

Discover and Characterize Nearby Worlds





(Penny et al. in prep)

Toward the "Pale Blue Dot"

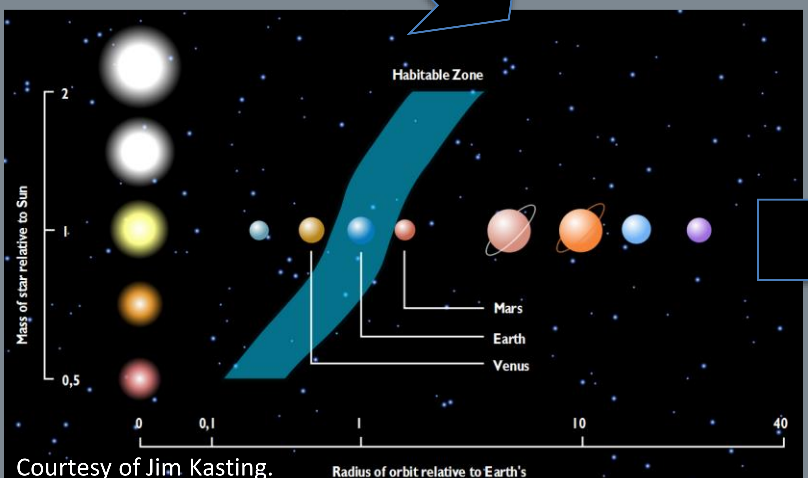
WFIRST will lay the foundation for a future flagship direct imaging mission capable of detection and characterization of Earthlike planets

Microlensing Survey

- Inventory the outer parts of planetary systems, potentially the source of the water for habitable planets.
- Quantify the frequency of solar systems like our own.
- Confirm and improve Kepler's estimate of the frequency of potentially habitable planets.
- When combined with Kepler, provide statistical constraints on the densities and heavy atmospheres of potentially habitable planets.

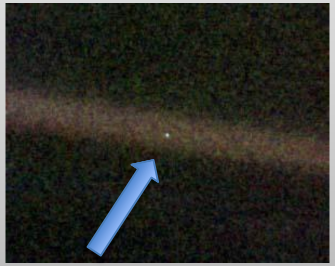
High Contrast Imaging

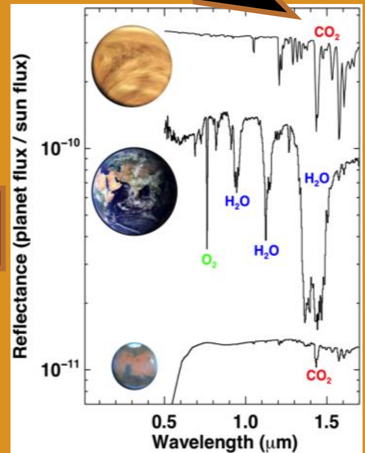
- Provide the first direct images of planets around our nearest neighbors similar to our own giant planets.
- Provide important insights about the physics of planetary atmospheres through comparative planetology.
- Assay the population of massive debris disks that will serve as sources of noise and confusion for a flagship mission.
- Develop crucial technologies for a future mission, and provide practical demonstration of these technologies *in flight.*

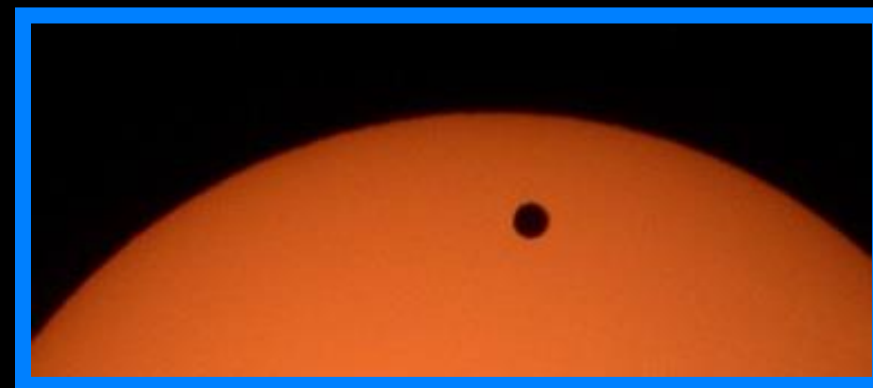


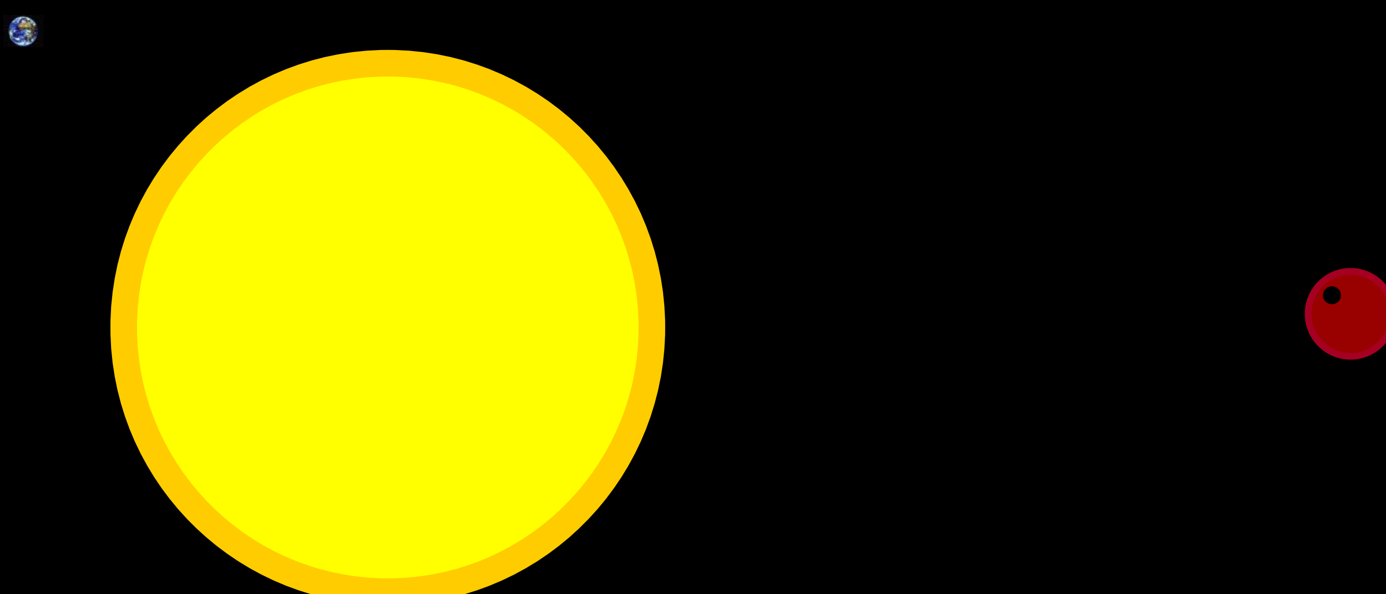
Courtesy of Jim Kasting.

Science and technology foundation for the New Worlds Mission.



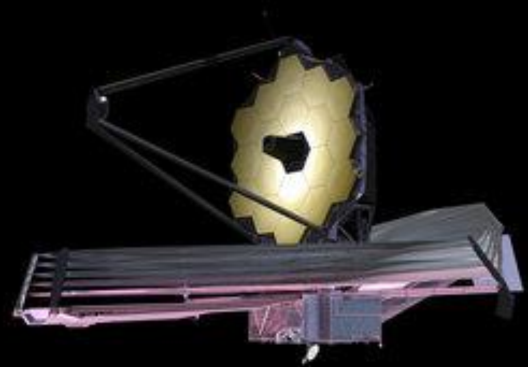


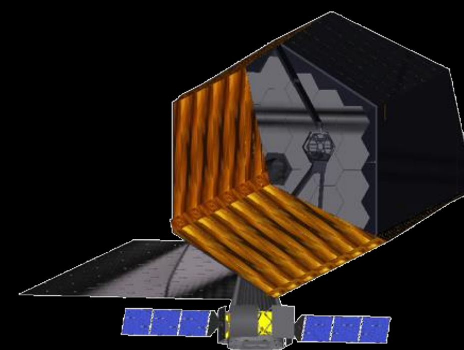


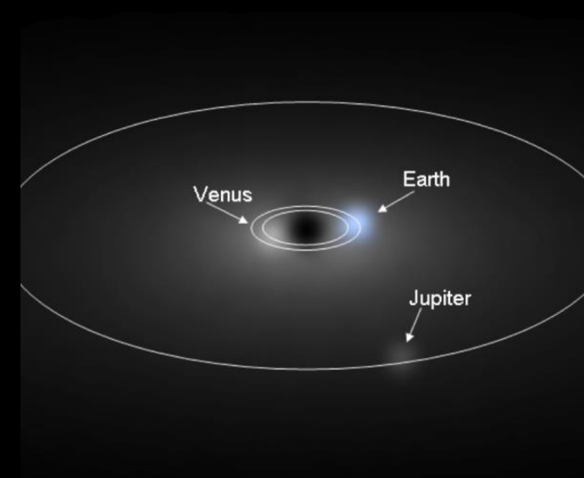


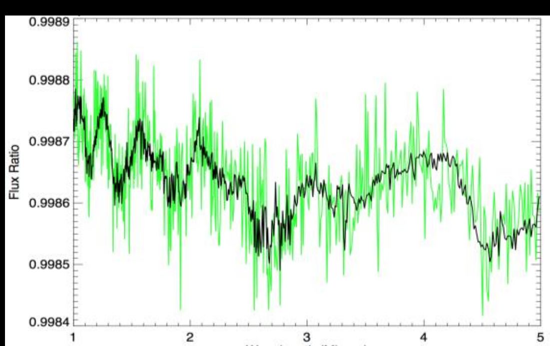
TESS+JWST:
Transit spectroscopy

HabEx/LUVOIR:
Direct Imaging



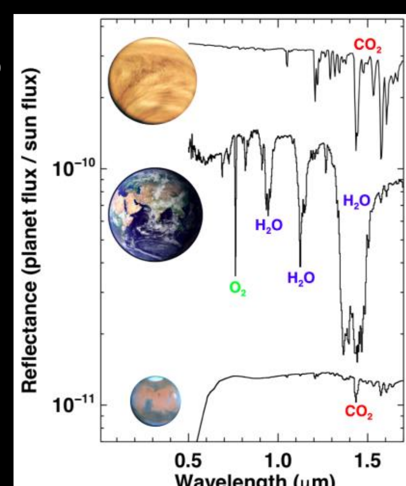




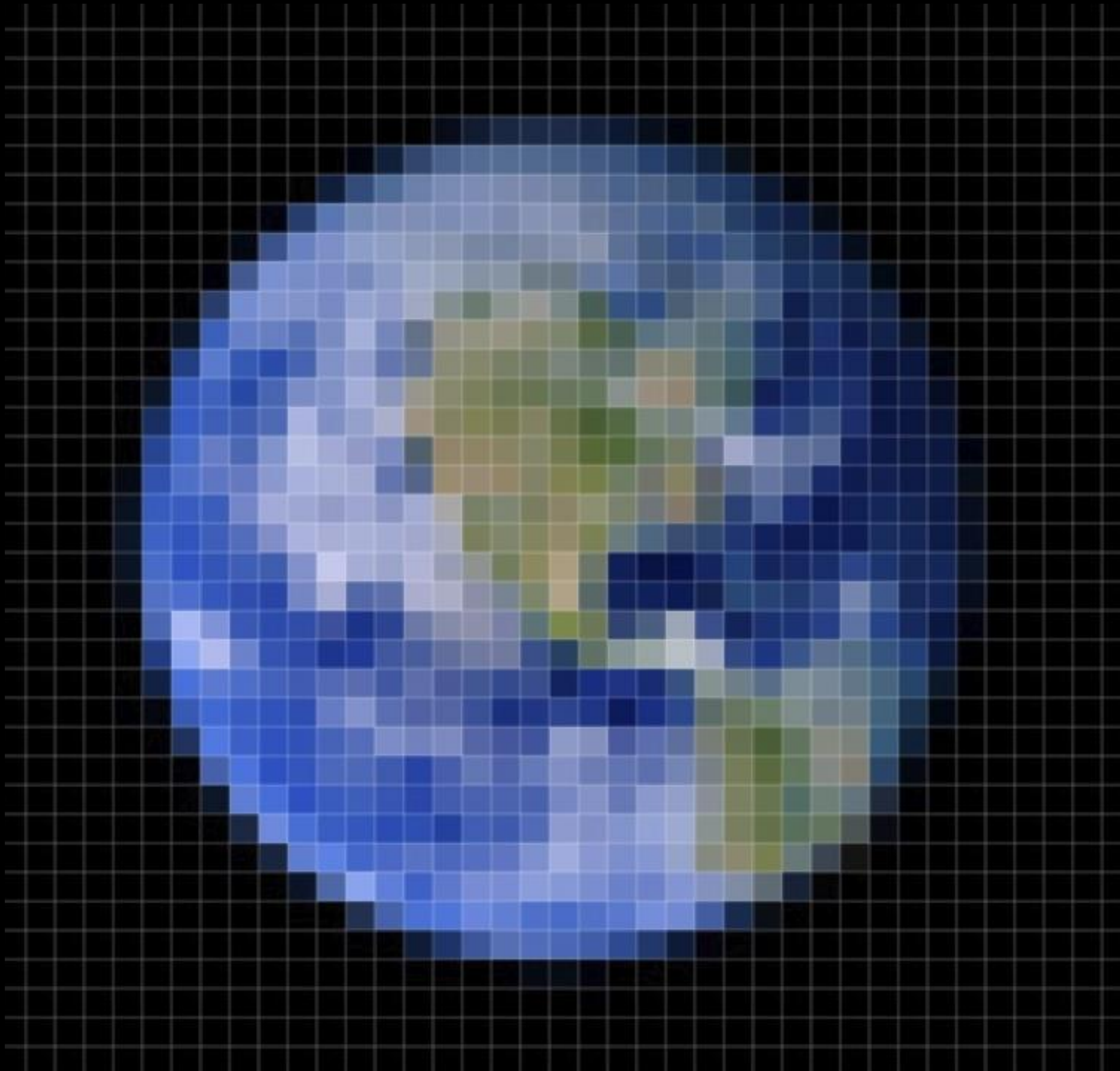


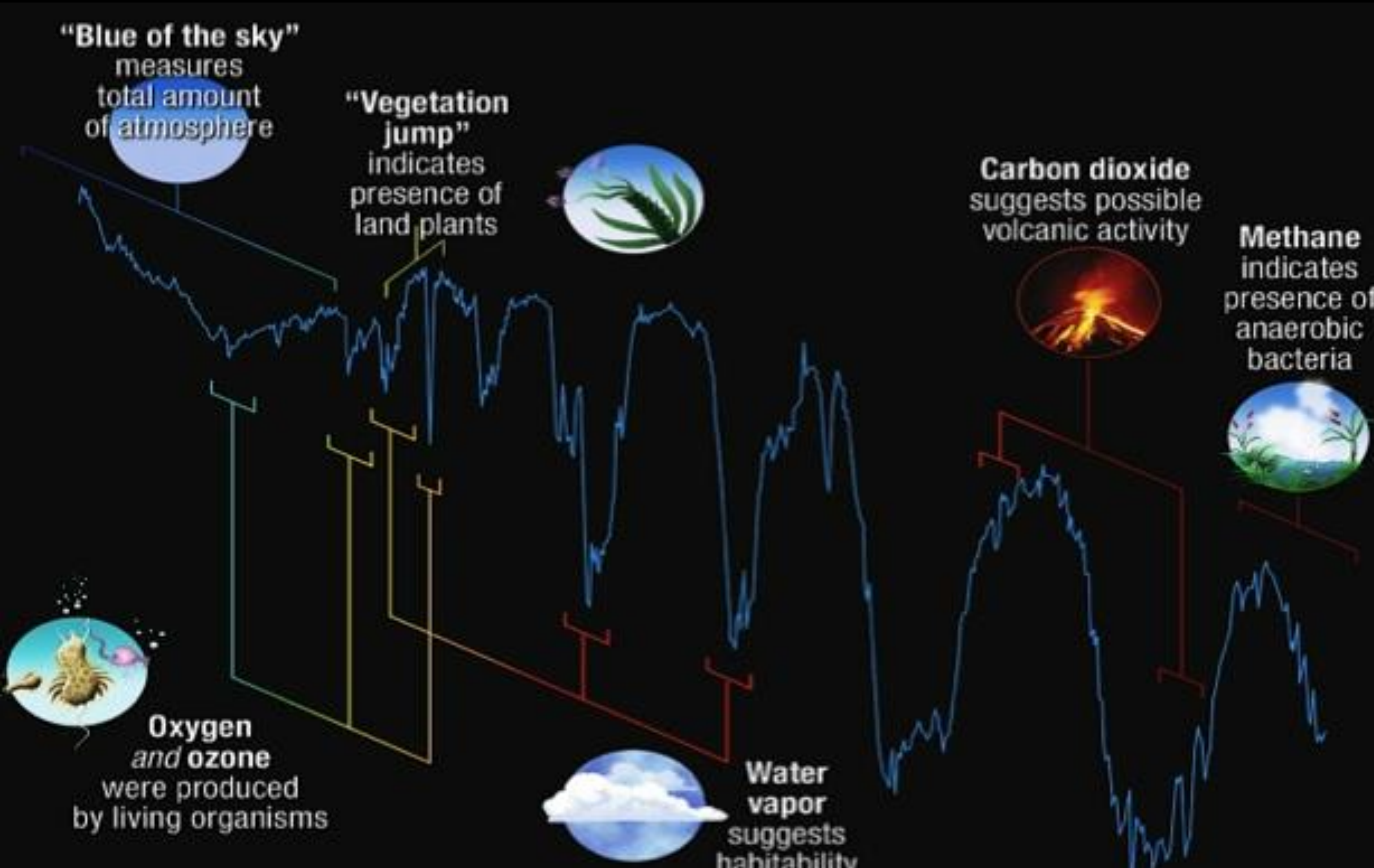
Batalha et al. 2015

V. Meadows and A. Roberge



W. Cash





"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

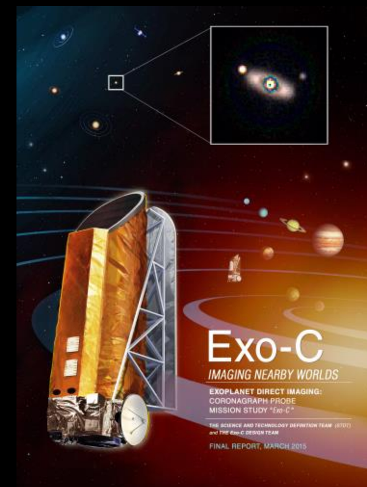
Key Requirements and Challenges for Imaging and Characterization

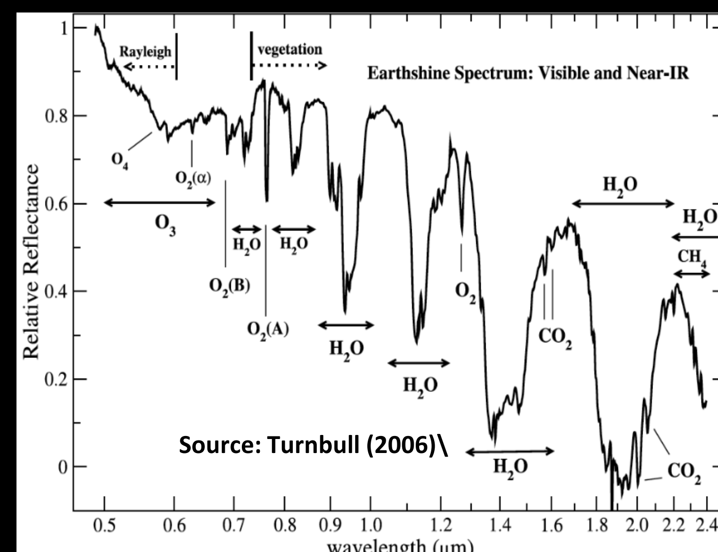
- Required regardless of architecture:
  - Very high contrast observations: >10^{10} dynamic range.
  - At very high spatial resolution (~50 mas) : that is 2*l/D at 0.5mm for a 4m telescope.
  - Over a broad wavelength range: At least from 400nm (250nm) to 1000nm (1700nm).
  - With very low noise/ high QE detectors over that range.

- Large aperture: HabEx considering ~4m to 8m

Key Architecture Trades and Open Questions for Exoplanet Science

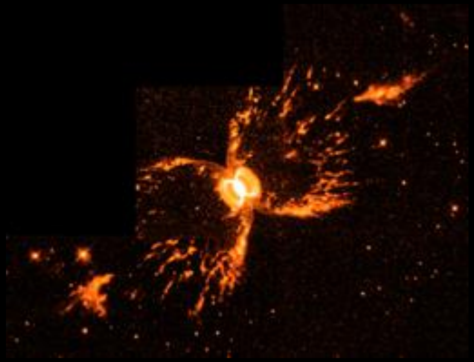
- High Contrast Imaging Concept is open !
  - Many design options are *a priori* possible
  - On or off-axis telescope?
  - Segmented or monolith?
  - Internal coronagraph, external starshade, both?
  - Low R IFS vs high R low SN cross-correlation?
  - All to be defined by STDT and science community, with support from JPL study office





HabEx Science Goals and Concept

- Primary Goal Requires a large (4m+) ultra-stable space telescope with a unique combination of
  - Very high spatial resolution (< 30 mas) and dynamic range (~10^{10})
  - High sensitivity / exquisite detectors in the optical (possibly UV and NIR)
  - HabEx currently considering 4m and 6.5m point designs.
- Such a facility will necessarily also provide exceptional capabilities for
  - Characterizing *full* planetary systems, including rocky planets, “water worlds”, gas giants, ice giants, inner and outer dust belts
  - Conducting planet formation and evolution studies
  - Star formation and evolution studies
  - Studying the formation and evolution of galaxies
  - Other general Astrophysics applications

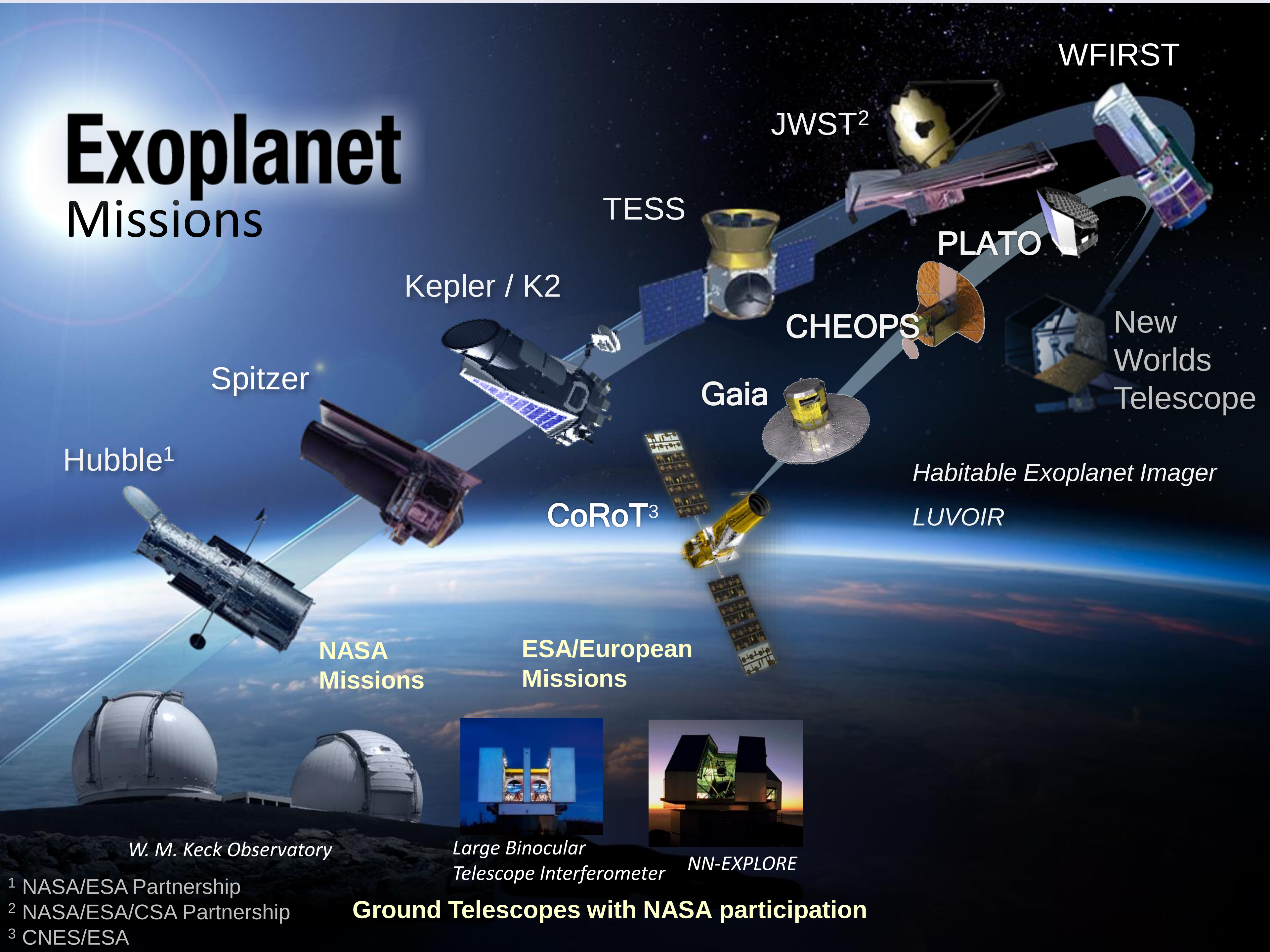


- Overall Concept is open and to be defined by STDT and science community, with support from the study office
  - Many design options a priori possible (on/off axis telescope, segmented or not, internal coronagraph and/or external starshade)
- Science and Technology Definition Team will direct design team to explore key trades (l, D, FoV, R)
  - For the primary science goal and for non exoplanet studies

HabEx STDT

- Face-to-face meetings are open to the public.
- Next meeting: November 10-11 at New Haven, joint w/ the LUVOIR STDT
- http://www.jpl.nasa.gov/habex/

HabEx STDT Meeting, May 16-17 2016, Washington, DC. Team members from left to right: Rachel Somerville, David Mouillet, Shawn Domagal-Goldman, Leslie Rogers, Martin Still, Olivier Guyon, Paul Scowen, Kerri Cahoy, Daniel Stern, Scott Gaudi, Bertrand Mennesson, Lee Feinberg, Karl Stapelfeldt, Sara Seager, Dimitri Mawet. Missing STDT members (unable to attend meeting in person): Jeremy Kasdin, Tyler Robinson and Margaret Turnbull.


Exoplanet
Missions
WFIRST
JWST[2]
TESS
PLATO
Kepler / K2
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

Jet Propulsion Laboratory
California Institute of Technology

LUVOIR:
Exoplanet Science Drivers and Technology Needs

Shawn Domagal-Goldman
NASA Goddard Space Flight Center

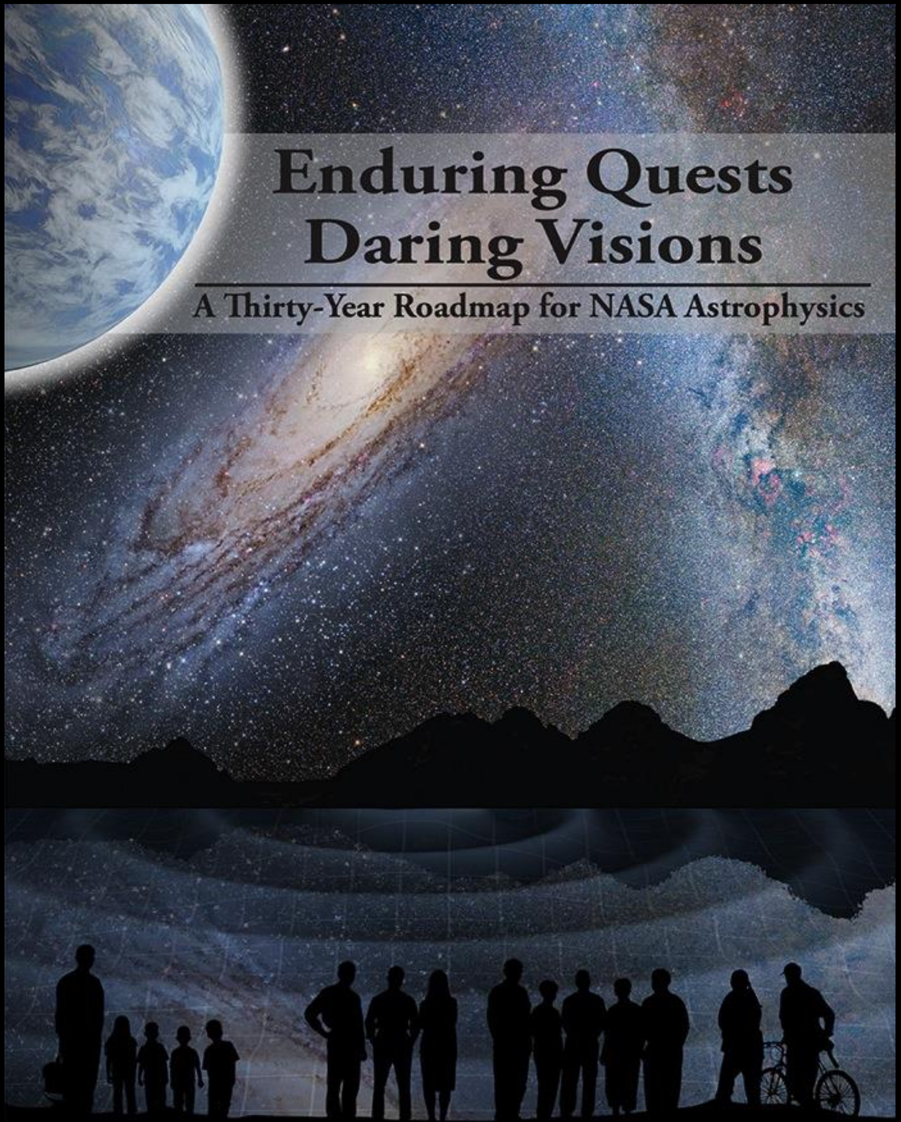
September 15, 2016
AIAA Space 2016, SPSC-03, Long Beach CA

What is the Large UV/Optical/Infrared Surveyor?

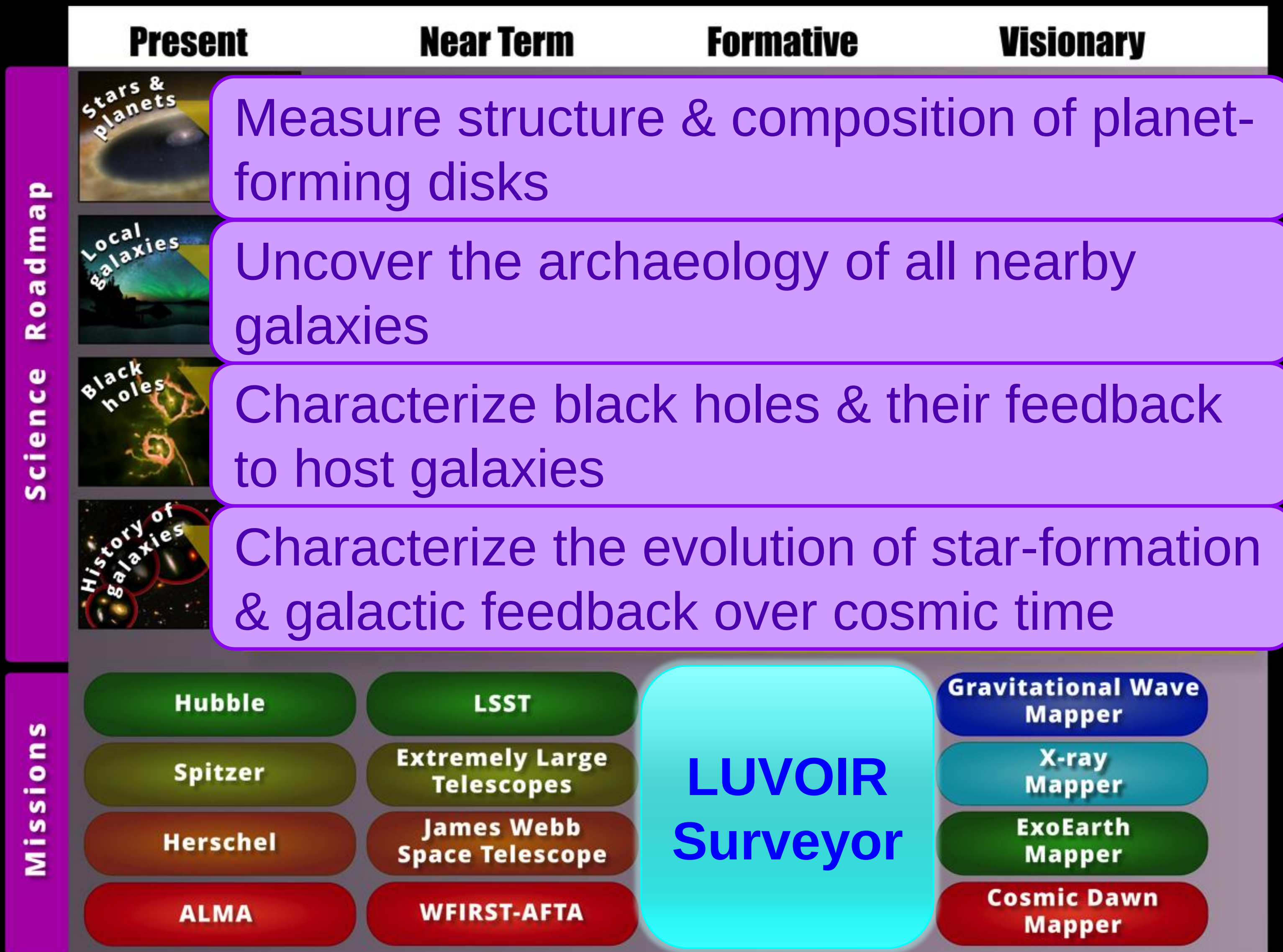
General purpose, multi-wavelength observatory with broad science capabilities

Roots in previous studies over last decade(s)

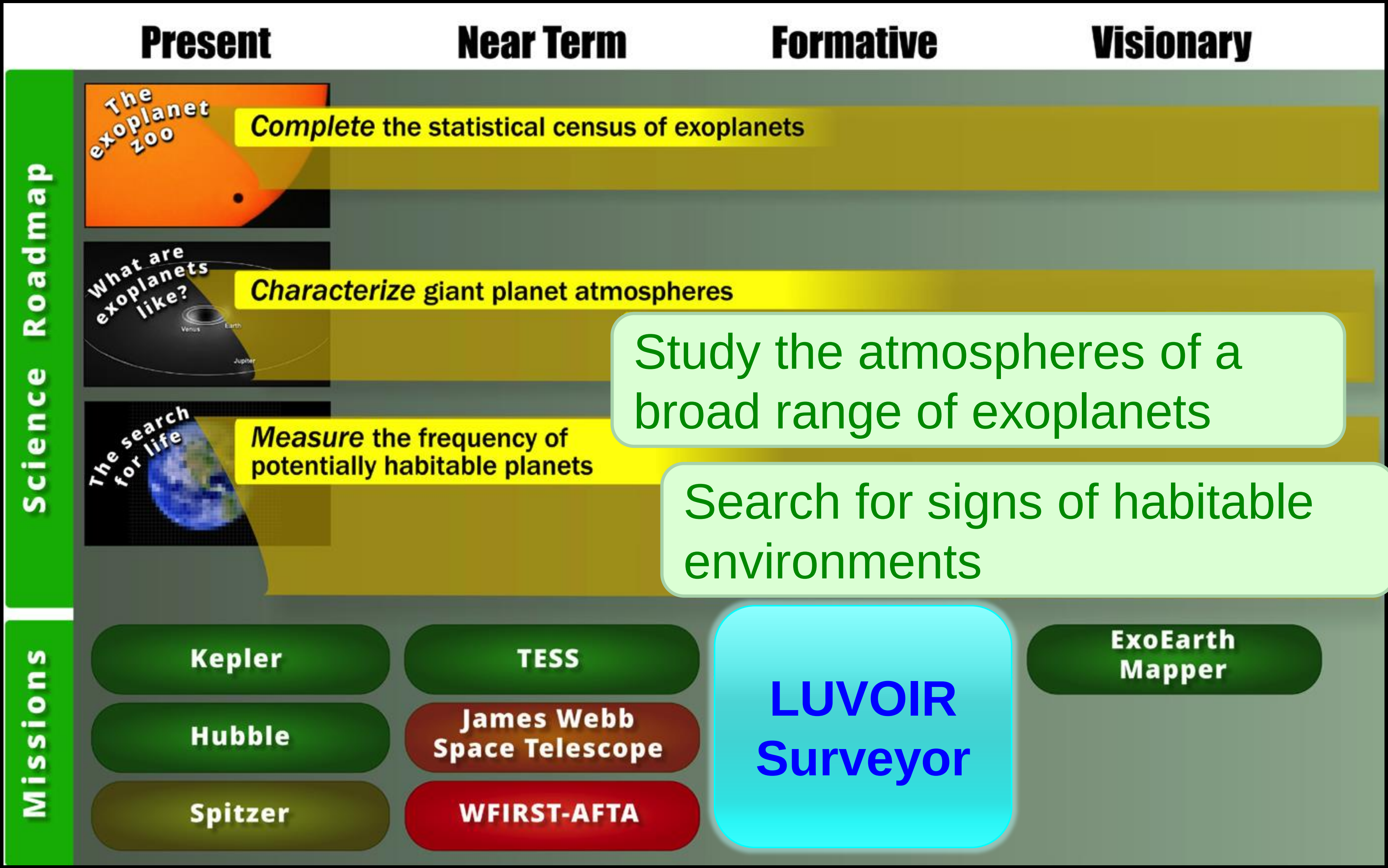
Acronym comes from 2013 Astrophysics Visionary Roadmap



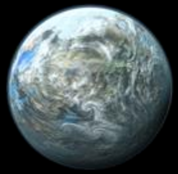
Cosmic origins science goals in Roadmap



Exoplanet science goals in Roadmap



Difference between LUVOIR and HabEx?



Both LUVOIR and HabEx have two primary science goals

- Habitable exoplanets & biosignatures
- Broad range of general astrophysics

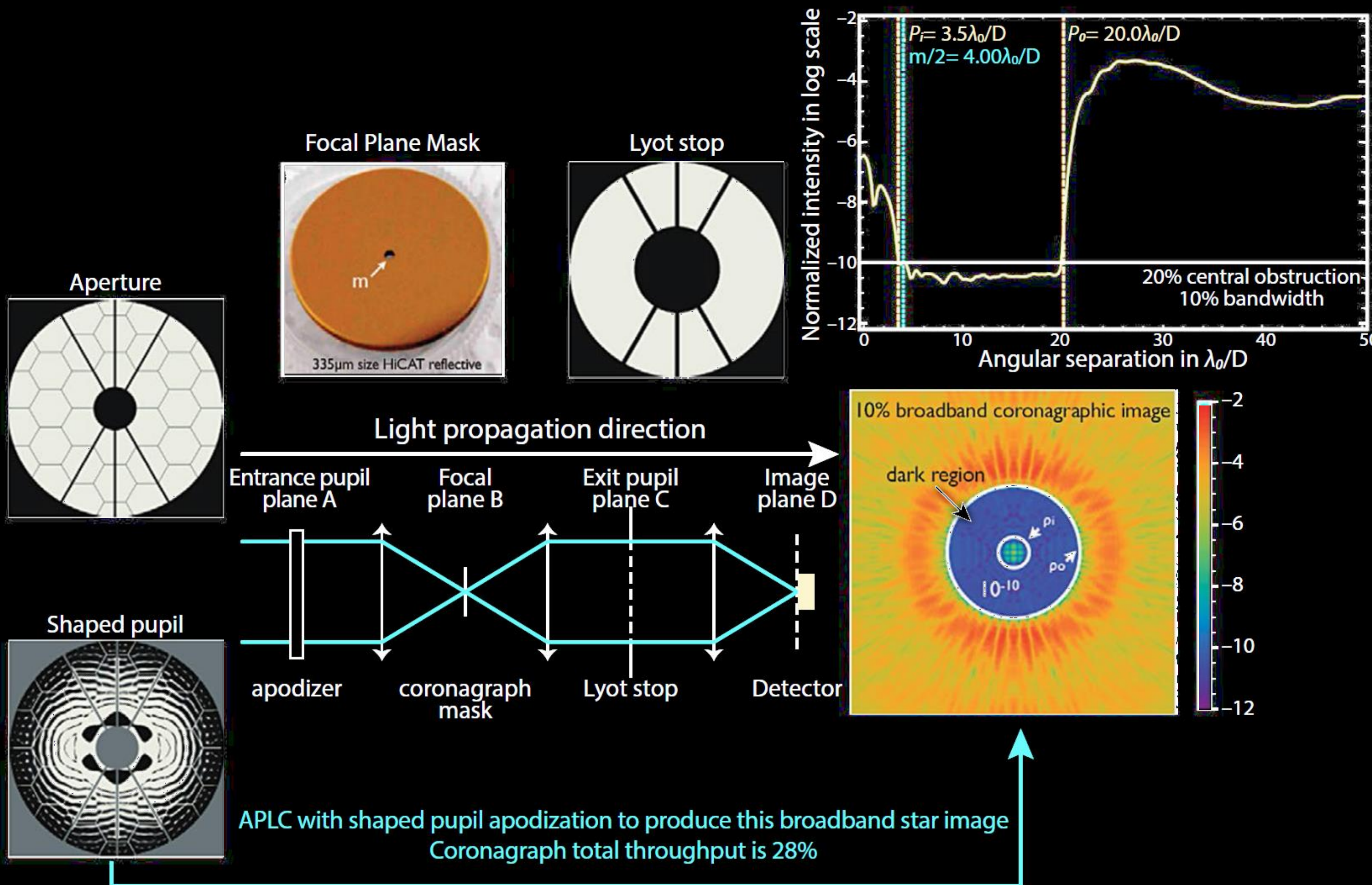
The two architectures will be driven by difference in focus

- For LUVOIR, both goals are on equal footing. LUVOIR will be a general purpose "great observatory", a successor to HST and JWST in the ~ 8 – 16 m class
- HabEx will be optimized for exoplanet imaging, but also enable a range of general astrophysics. It is a more focused mission in the ~ 4 – 8 m class

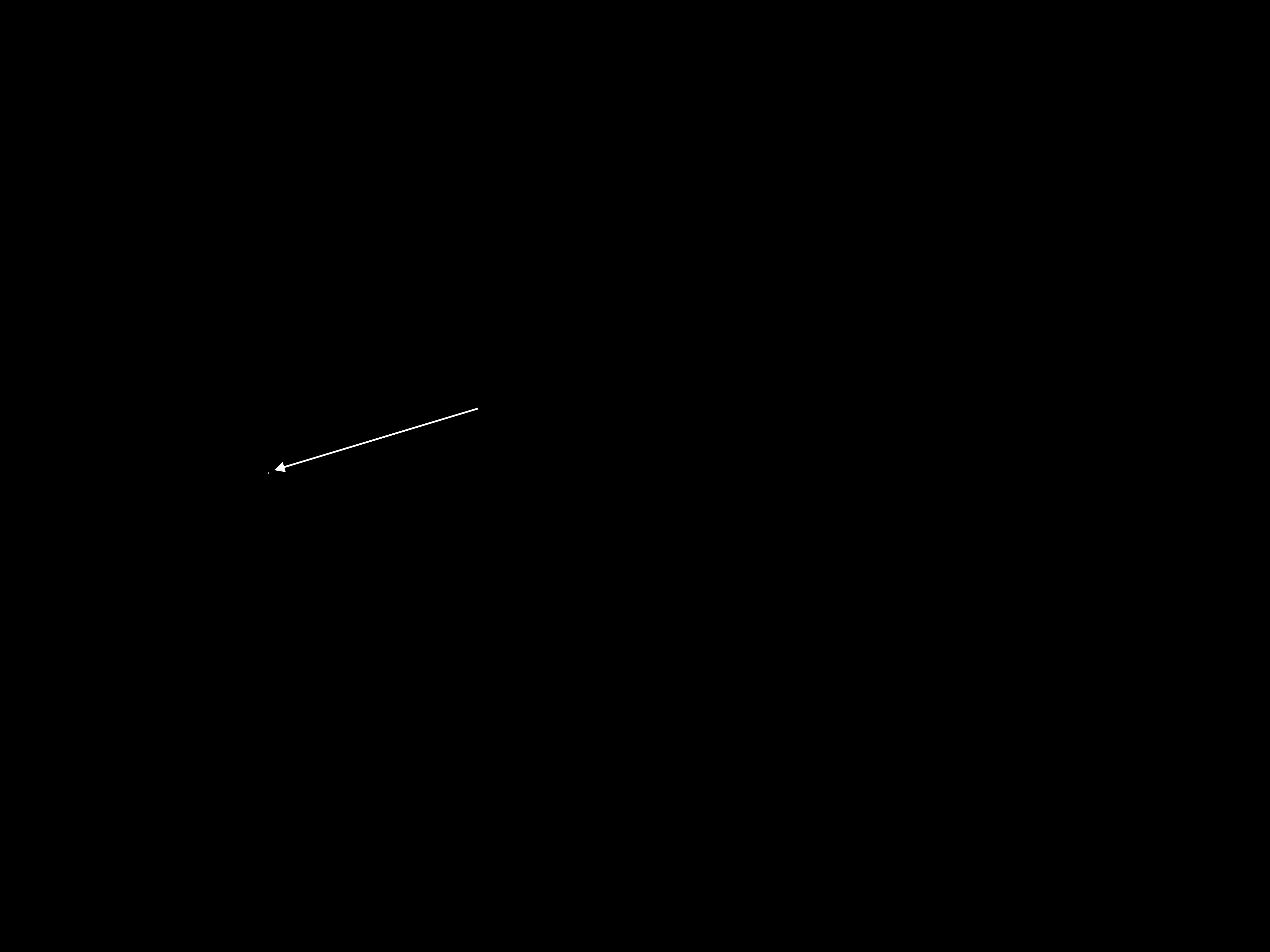
Similar exoplanet goals, differing in quantitative levels of ambition

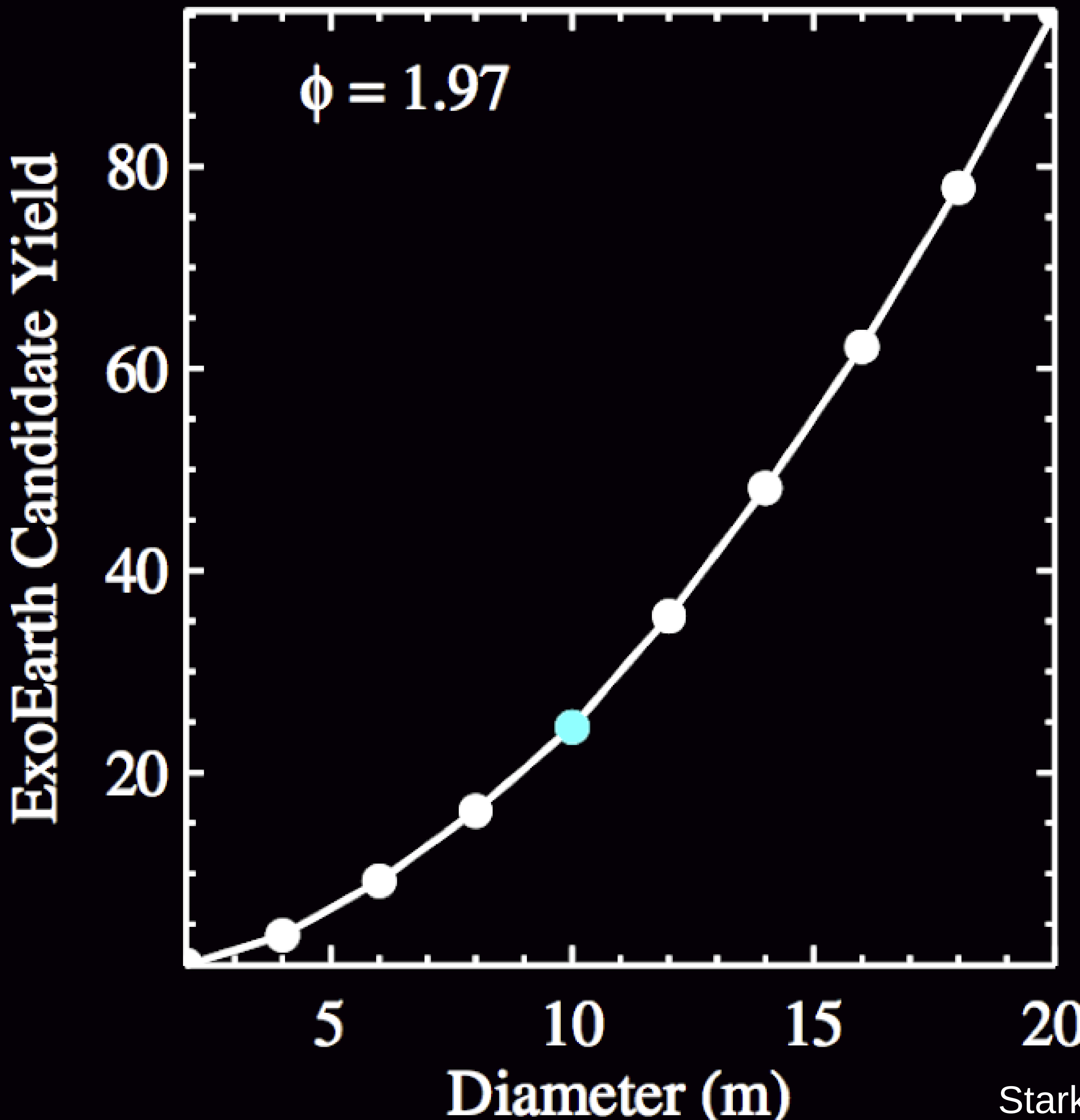
- HabEx will *explore* the nearest stars to "search for" signs of habitability & biosignatures via direct detection of reflected light
- LUVOIR will *survey* more stars to "constrain the frequency" of habitability & biosignatures and produce a statistically meaningful sample of exoEarths

The two studies will provide a continuum of options for a range of futures

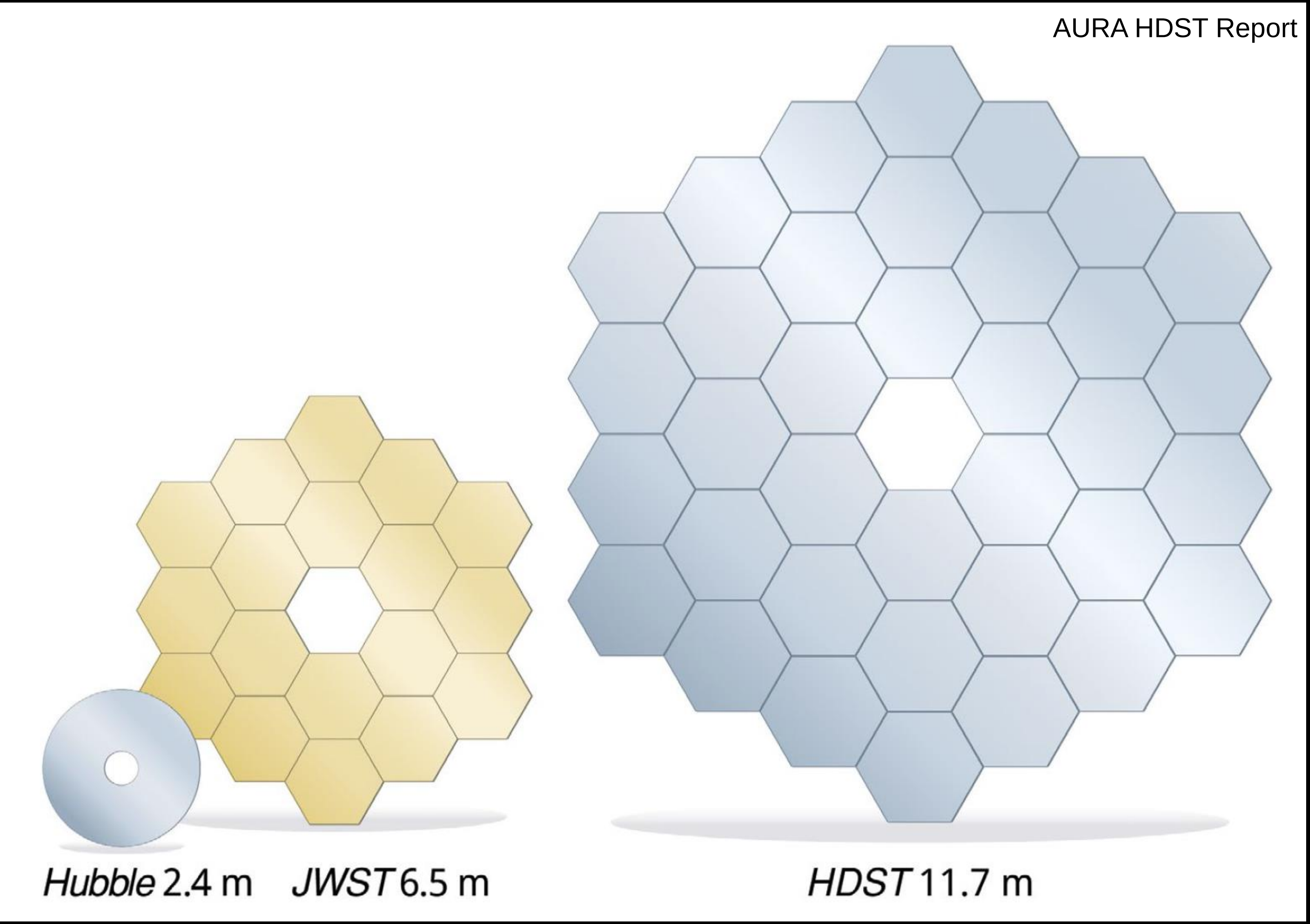


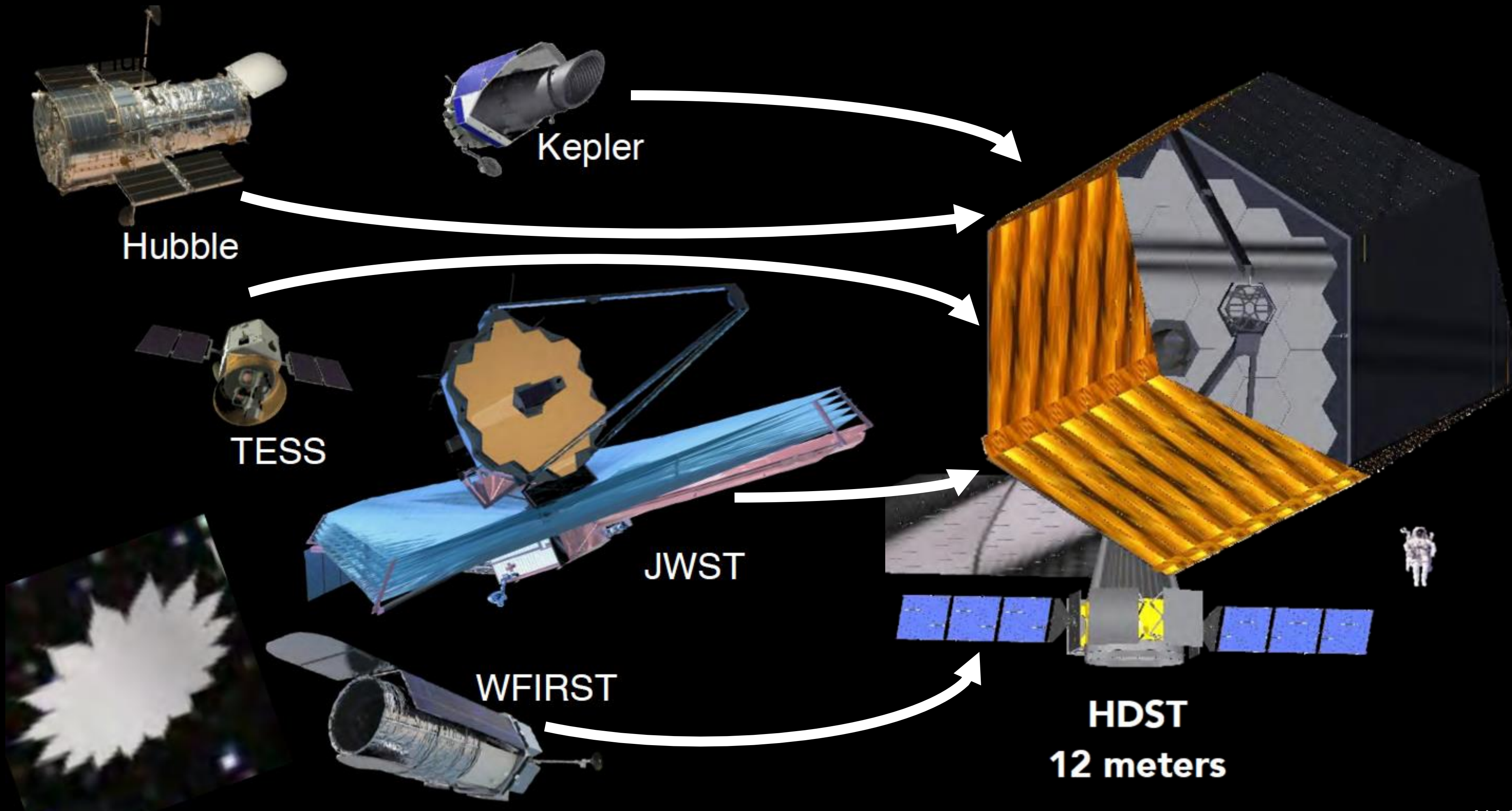
N’Diaye et al., 2016





Stark, et al., 2015


AURA HDST Report
Hubble 2.4 m
JWST 6.5 m
HDST 11.7 m



NASA

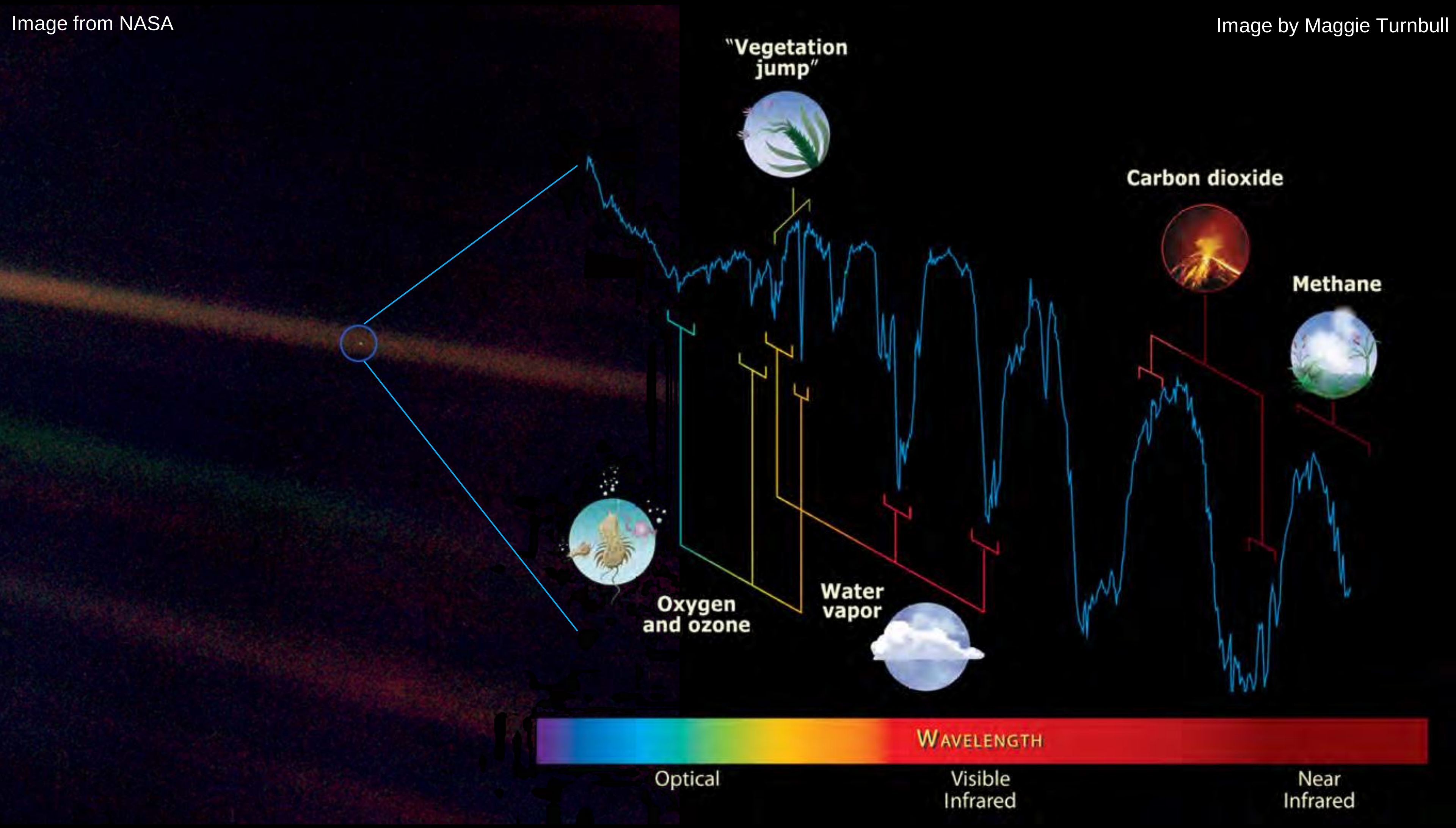


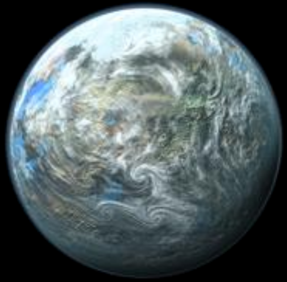
Image from NASA
Image by Maggie Turnbull
"Vegetation jump"
Carbon dioxide
Methane
Oxygen and ozone
Water vapor
Wavelength
Optical
Visible Infrared
Near Infrared

LUVOIR as currently envisaged

All to be determined by the STDT

Capabilities

- FUV to NIR wavelength sensitivity
- Suite of imagers and spectrographs
- High-contrast capability (~ 10^{-10})
- Aperture diameter of order 8 – 16 m
- Serviceable (astronaut or robot)
- "Space Observatory for the 21st Century" – decades of science, instrument upgrades (like Hubble), capability to answer questions we have not yet conceived



Current LUVOIR instrument suite

High-contrast instrument – *Lead: Laurent Pueyo (STScI)*

- Imaging and low-resolution spectroscopy

UV instrument – *Lead: Kevin France (U of Colorado)*

- Imaging (> 1 arcmin field-of-view)
- High-resolution point-source spectroscopy and medium-resolution multi-object spectroscopy

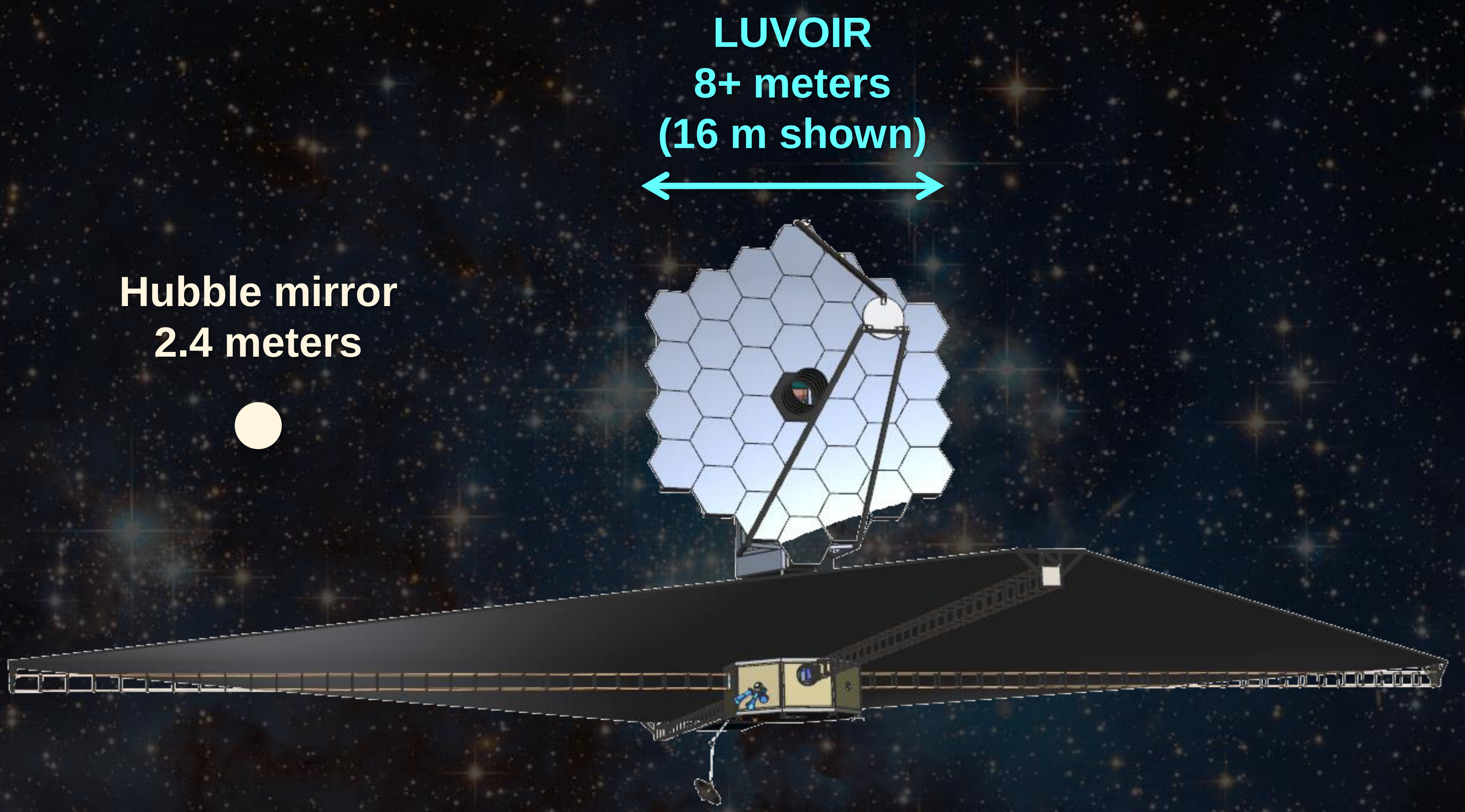
Wide-field imager – *Lead: Marc Postman (STScI)*

- Imaging (4 – 6 arcmin field-of-view)

Optical / NIR spectrograph – *Lead: Courtney Dressing (Caltech)*

- Multiple resolution modes up to R ~ 10^5

A possible LUVOIR architecture



Technology Area	Difficulty	Urgency
High-Contrast Segmented-Aperture Coronagraphy	CRITICAL	CRITICAL
Ultra-Stable Opto-mechanical Systems (includes Sensing, Control, Mirrors, and Structures)	CRITICAL	CRITICAL
Large Format, High Sensitivity, High-Dynamic Range UV Detectors	HIGH	HIGH
Vis/NIR Exoplanet Detectors	HIGH	MED
Starshade	HIGH	MED
Mirror Coatings	MED	MED
MIR (3–5 μm) Detectors	LOW	LOW

STDT voting members

Debra Fischer
(Yale)

Brad Peterson
(Ohio State / STScI)

Jacob Bean
(Chicago)

Daniela Calzetti
(U Mass)

Rebekah Dawson
(Penn State)

Courtney Dressing
(Caltech)

Lee Feinberg
(NASA GSFC)

Kevin France
(Colorado)

Jay Gallagher
(Wisconsin)

Olivier Guyon
(Arizona)

Walt Harris
(Arizona / LPL)

Mark Marley
(NASA Ames)

Leonidas Moustakas
(JPL)

John O'Meara
(St. Michael's)

Vikki Meadows
(Washington)

Ilaria Pascucci
(Arizona)

Marc Postman
(STScI)

Laurent Pueyo
(STScI)

David Redding
(JPL)

Jane Rigby
(NASA GSFC)

Aki Roberge
(NASA GSFC)

David Schiminovich
(Columbia)

Britney Schmidt
(Georgia Tech)

Karl Stapelfeldt
(JPL)

Face-to-face meetings

3rd meeting Nov 9 – 10, 2016 @ Yale University, joint w/ the HabEx team

Observers welcome at all LUVOIR meetings

LUVOIR community working groups

Exoplanets

- Leads: Mark Marley (Ames), Avi Mandell (GSFC)

Cosmic Origins

- Leads: John O'Meara (St. Michael's), Jane Rigby (GSFC)

Solar System

- Leads: Walt Harris (LPL), Geronimo Villanueva (GSFC)

Simulations

- Leads: Jason Tumlinson (STScI), Aki Roberge (GSFC)

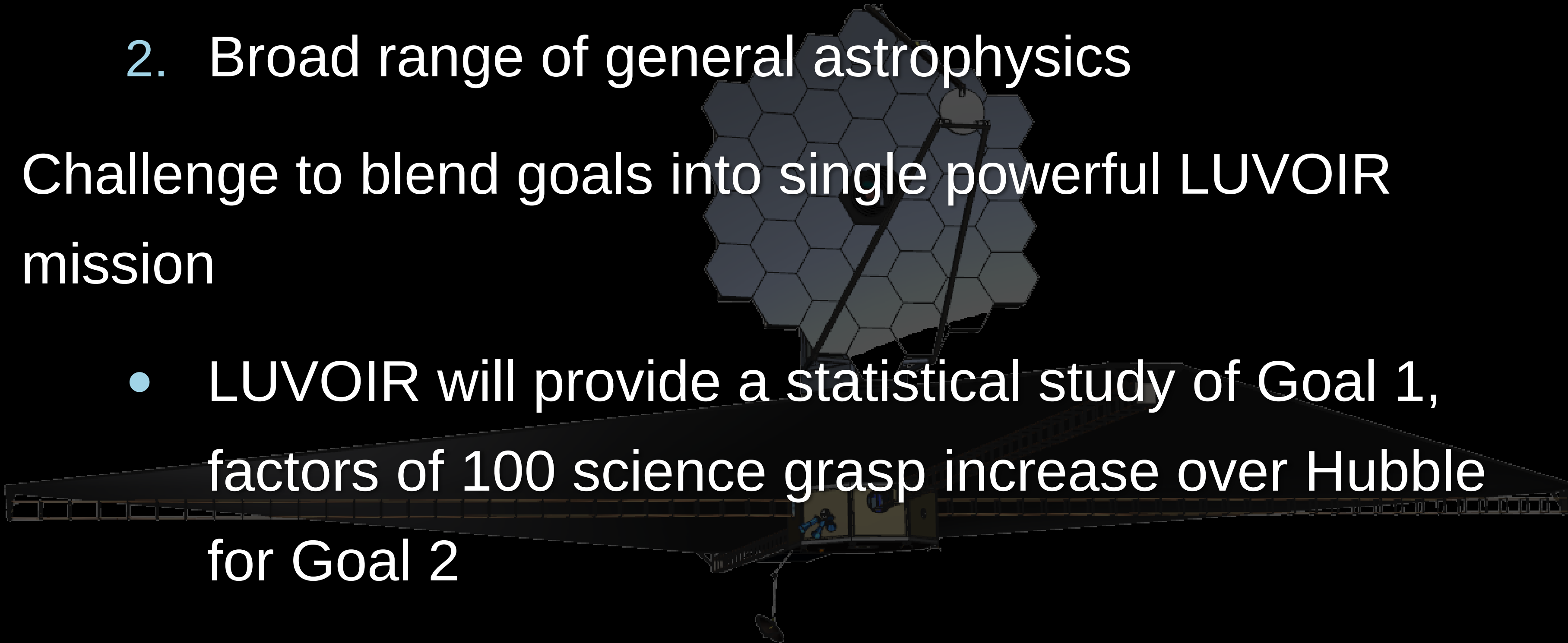
Technology

- Leads: David Redding (JPL), Matt Bolcar (GSFC)

Summary

LUVOIR has dual primary science goals

1. Habitable exoplanets & biosignatures
2. Broad range of general astrophysics



Challenge to blend goals into single powerful LUVOIR mission

- LUVOIR will provide a statistical study of Goal 1, factors of 100 science grasp increase over Hubble for Goal 2

Provide wide range of capabilities to enable decades of future investigations and unexpected discoveries

Get Involved with LUVOIR and HabEx

Websites:

http://asd.gsfc.nasa.gov/luvoir/

http://www.jpl.nasa.gov/habex/

Contact us!

LUVOIR Study Chairs

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LUVOIR Study Scientist

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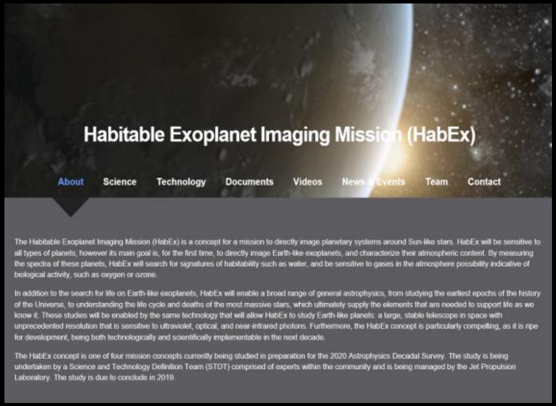

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HabEx Study Scientist

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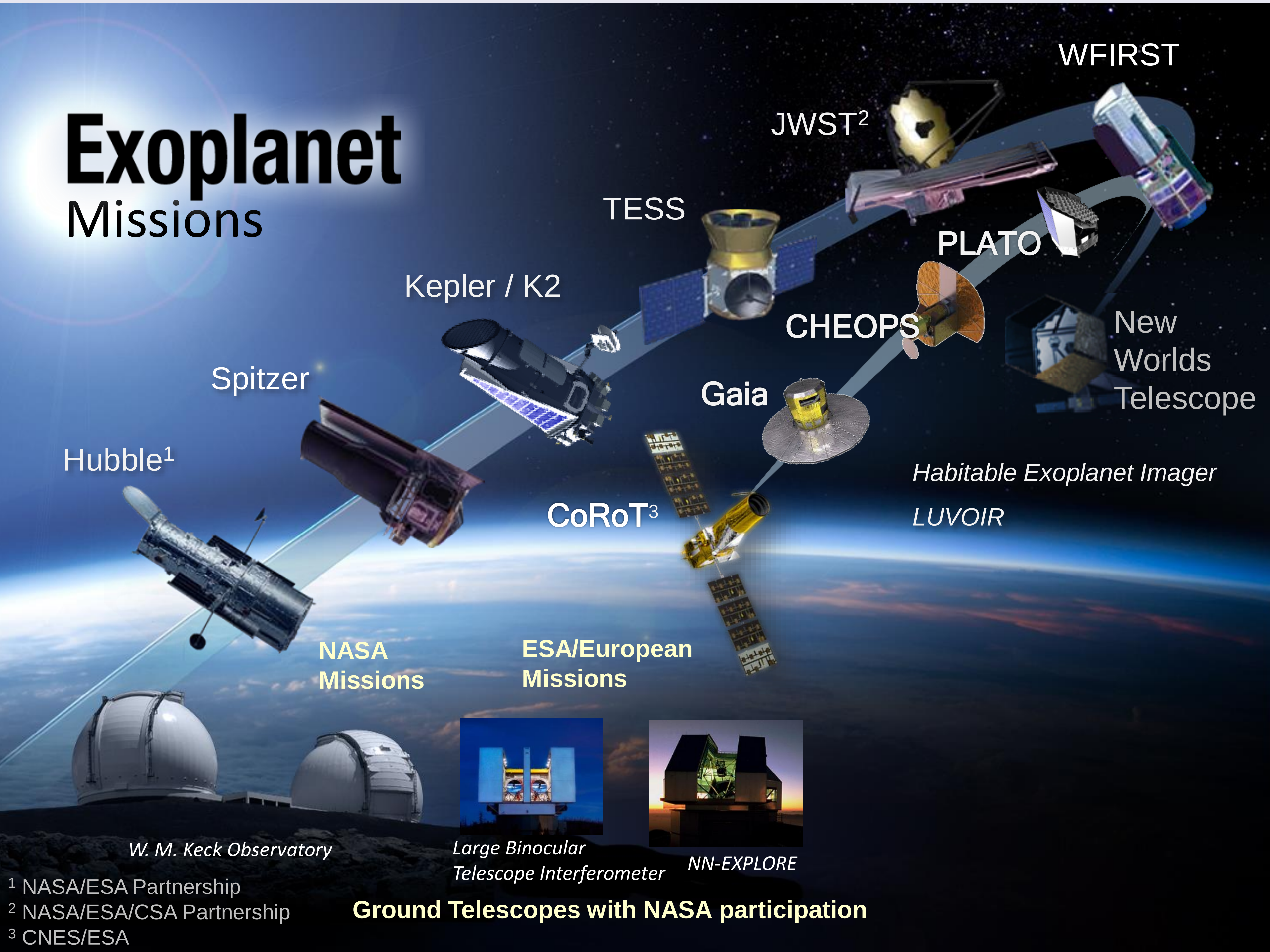

Exoplanet
Missions
WFIRST
JWST2
TESS
PLATO
Kepler / K2
CHEOPS
New
Worlds
Telescope
Spitzer
Gaia
Hubble1
Habitable Exoplanet Imager
CoRoT3
LUVOIR
NASA
Missions
ESA/European
Missions
W. M. Keck Observatory
Large Binocular
Telescope Interferometer
NN-EXPLORE
1 NASA/ESA Partnership
2 NASA/ESA/CSA Partnership
3 CNES/ESA
Ground Telescopes with NASA participation

Jet Propulsion Laboratory
California Institute of Technology

Technology Needs to Discover Earth 2.0

(CL#16-4258)

Dr. Nick Siegler

NASA Exoplanet Exploration Program

Program Chief Technologist

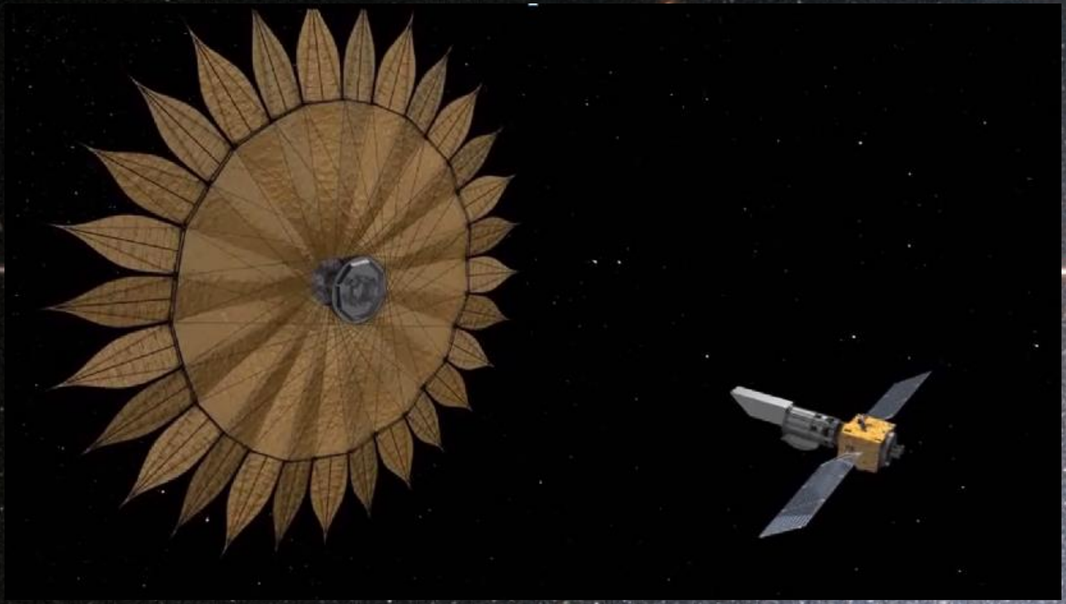
Jet Propulsion Laboratory / Caltech

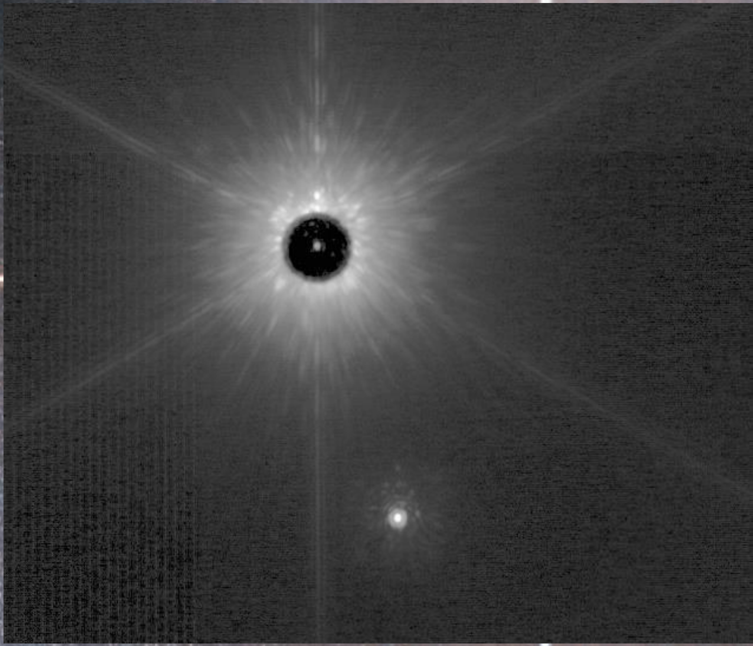
September 15, 2016

NASA Exoplanet Exploration Program Updates and Technology Challenges

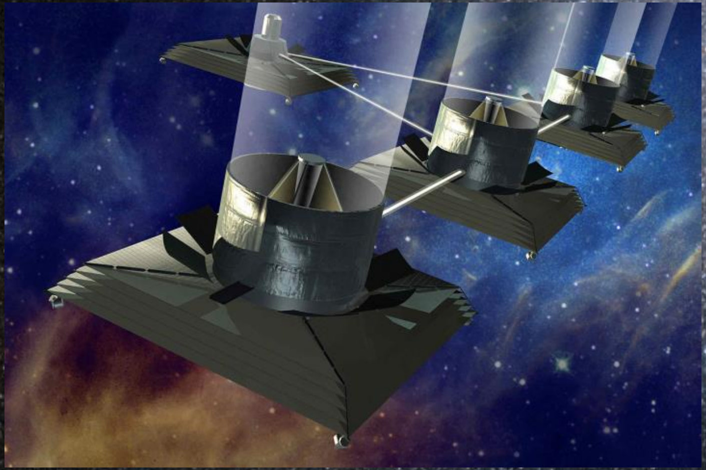
AIAA Space 2016, SPSC-03, Long Beach CA

External Occulters (Starshades)

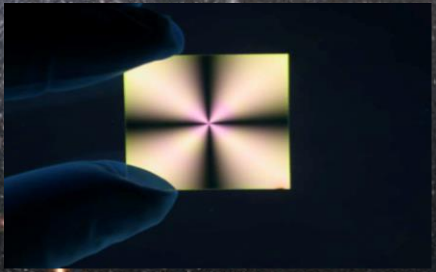


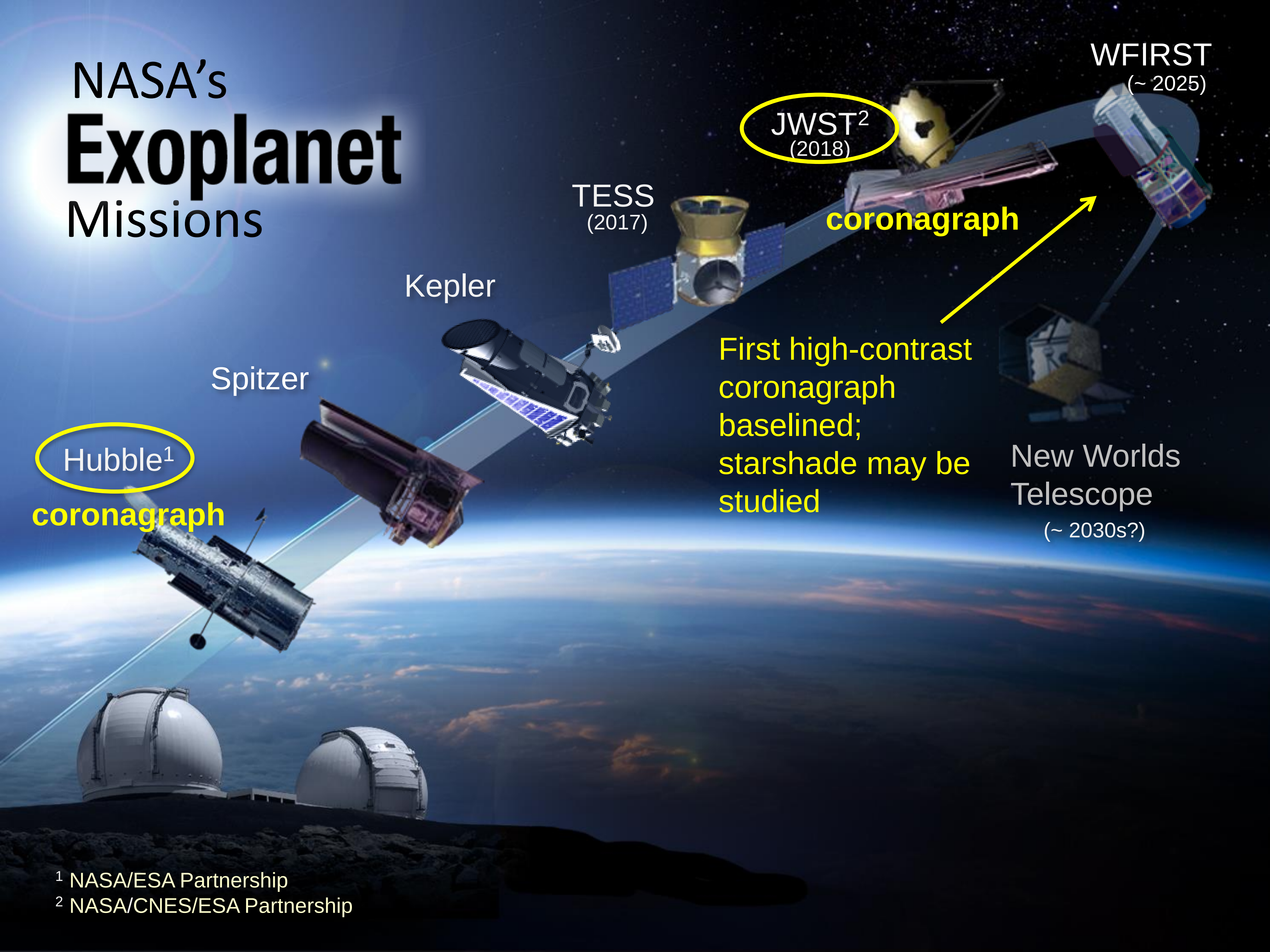


Nulling Interferometry



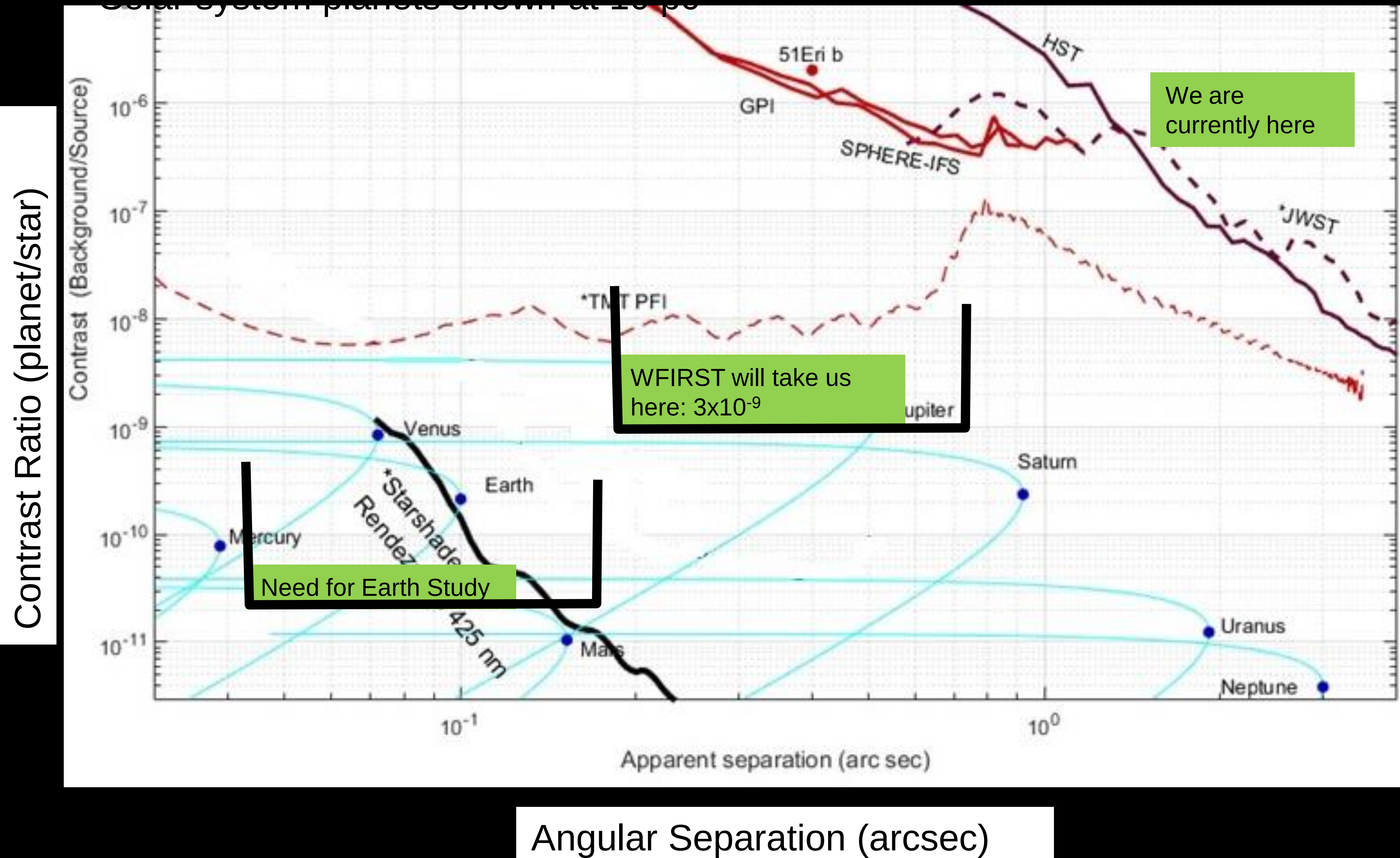
Internal Occulters (Coronagraphs)





NASA's
Exoplanet
Missions
WFIRST
(~ 2025)
JWST[2]
(2018)
coronagraph
TESS
(2017)
Kepler
Spitzer
Hubble[1]
coronagraph
First high-contrast coronagraph baselined; starshade may be studied
New Worlds Telescope
(~ 2030s?)
[1] NASA/ESA Partnership
[2] NASA/CNES/ESA Partnership

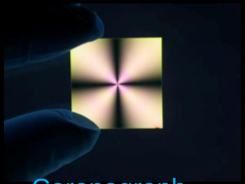
Towards the Detection of Exo-Earths



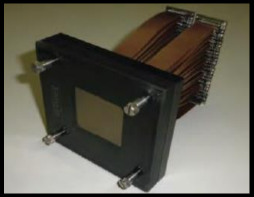
How a Coronagraph Works

Coronagraph/Telescope Technology Needs

Contrast



Coronagraph architectures



Deformable mirrors

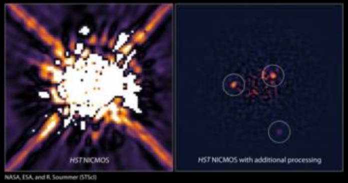
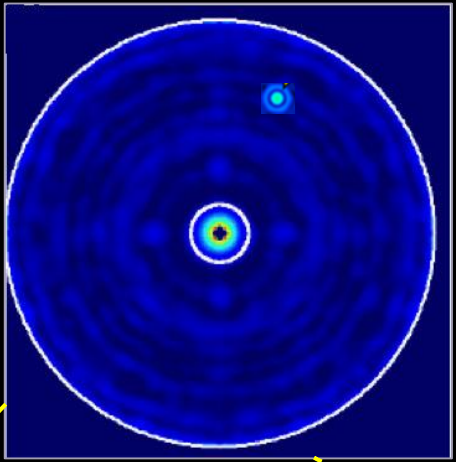
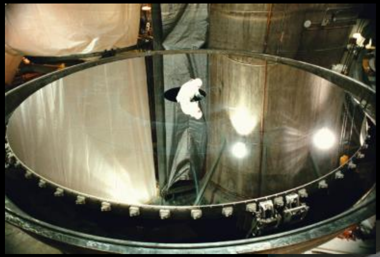


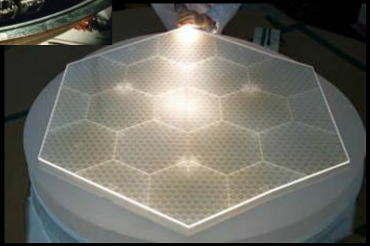
Image post-processing



Angular Resolution

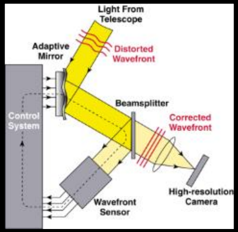


Large monolith

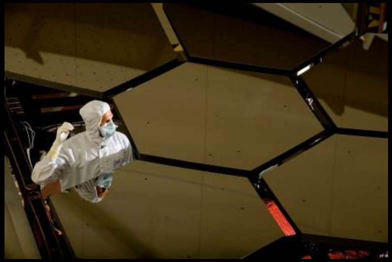


Segmented

Contrast Stability



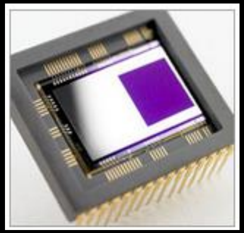
Wavefront sensing and control

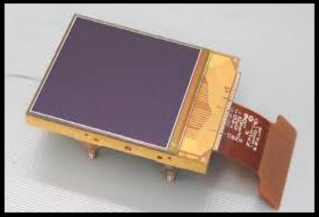


Segment phasing and rigid body sensing and control

Telescope vibration sensing and control

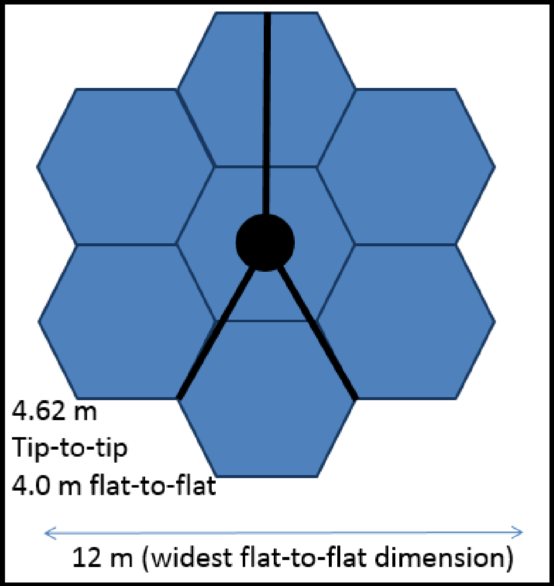
Detection Sensitivity

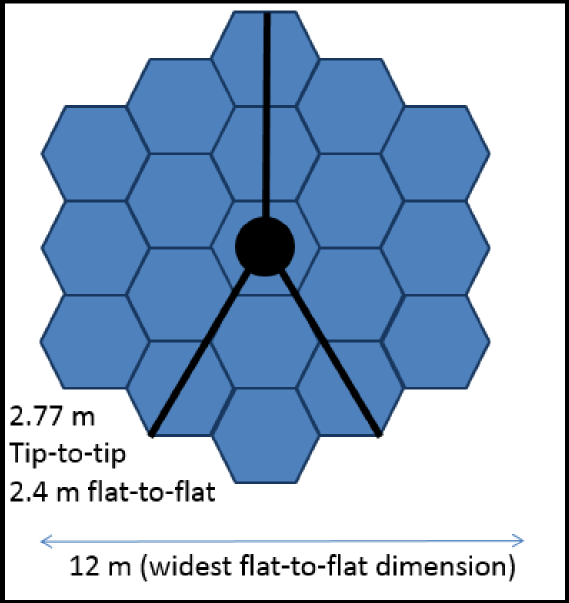


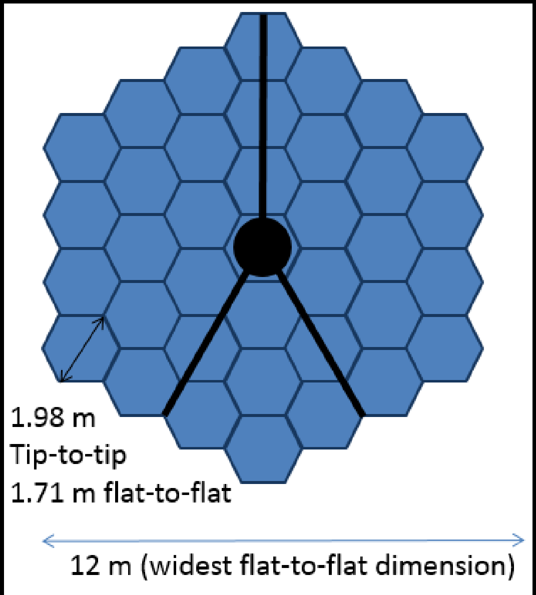


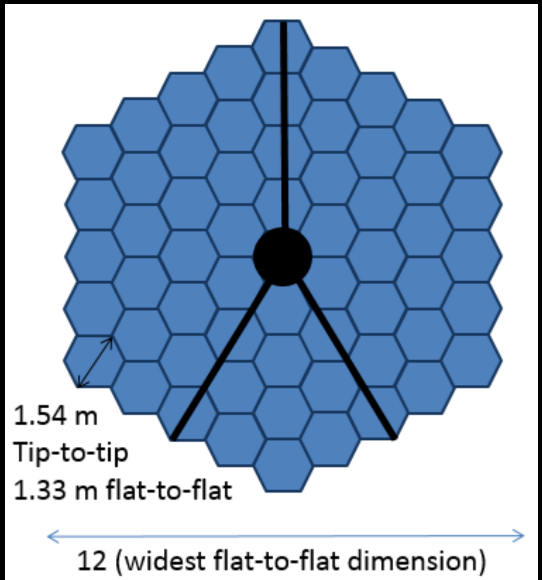
Ultra-low noise visible and infrared detectors

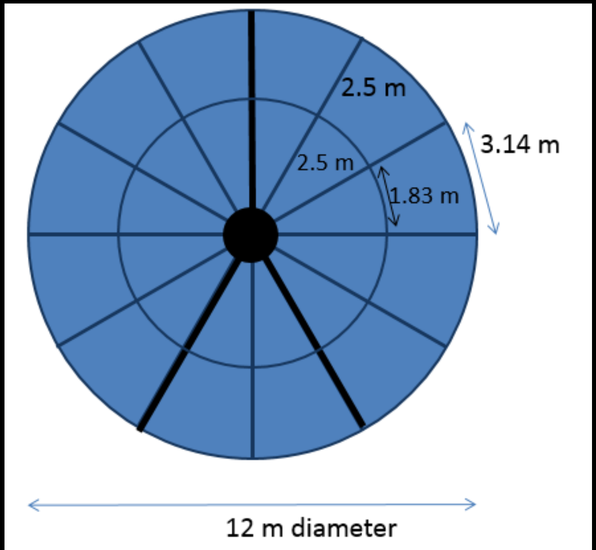
Segmented Coronagraph Design Analysis

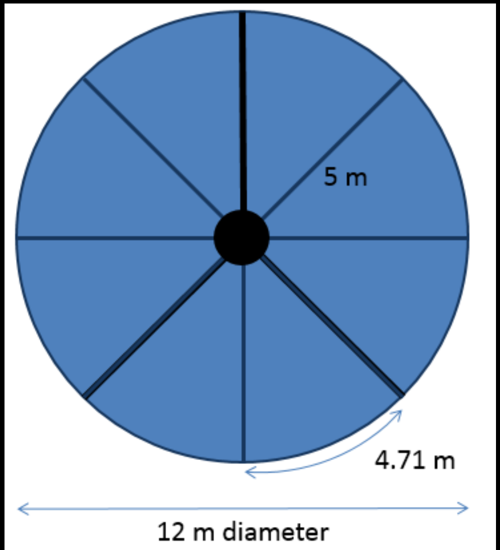




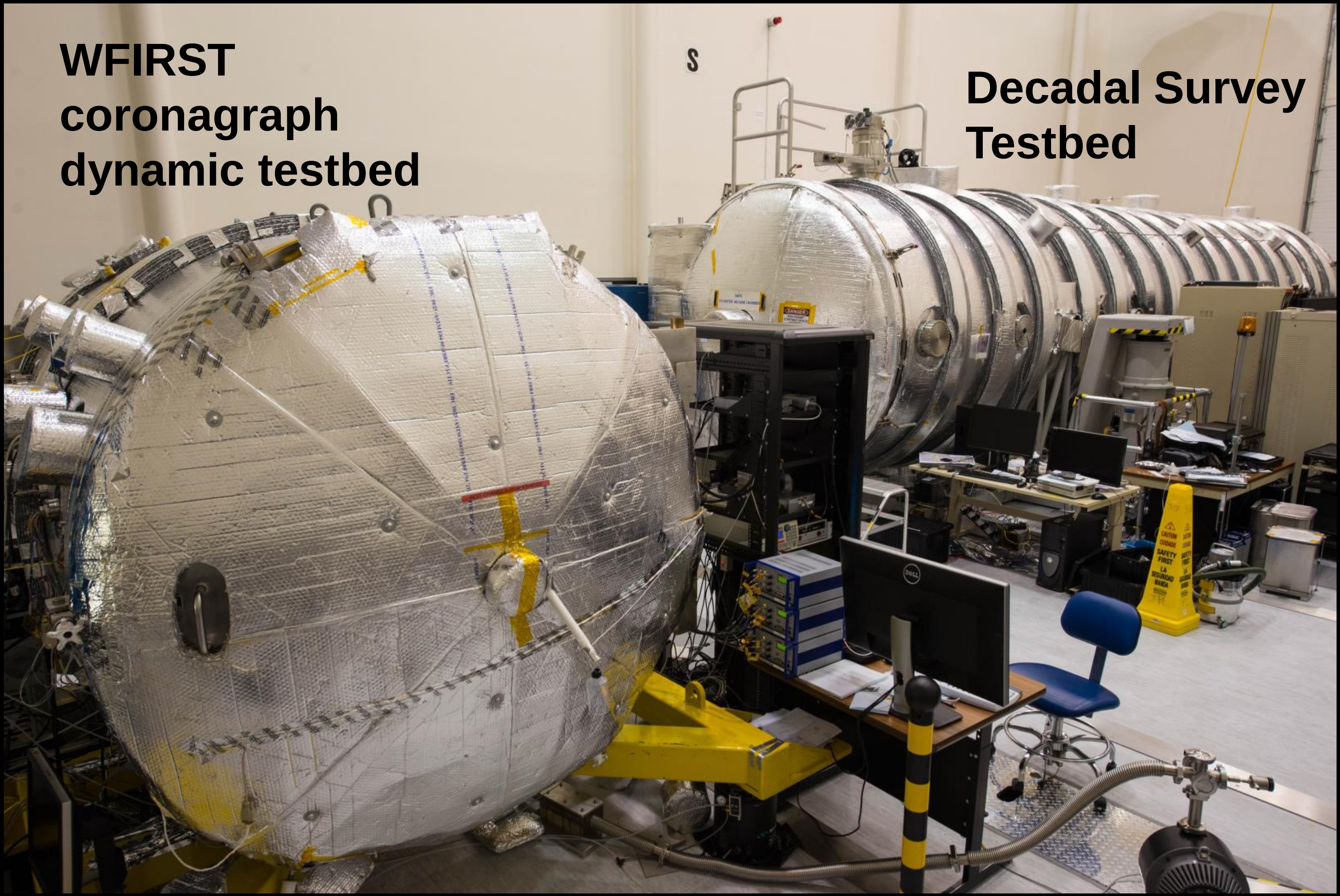




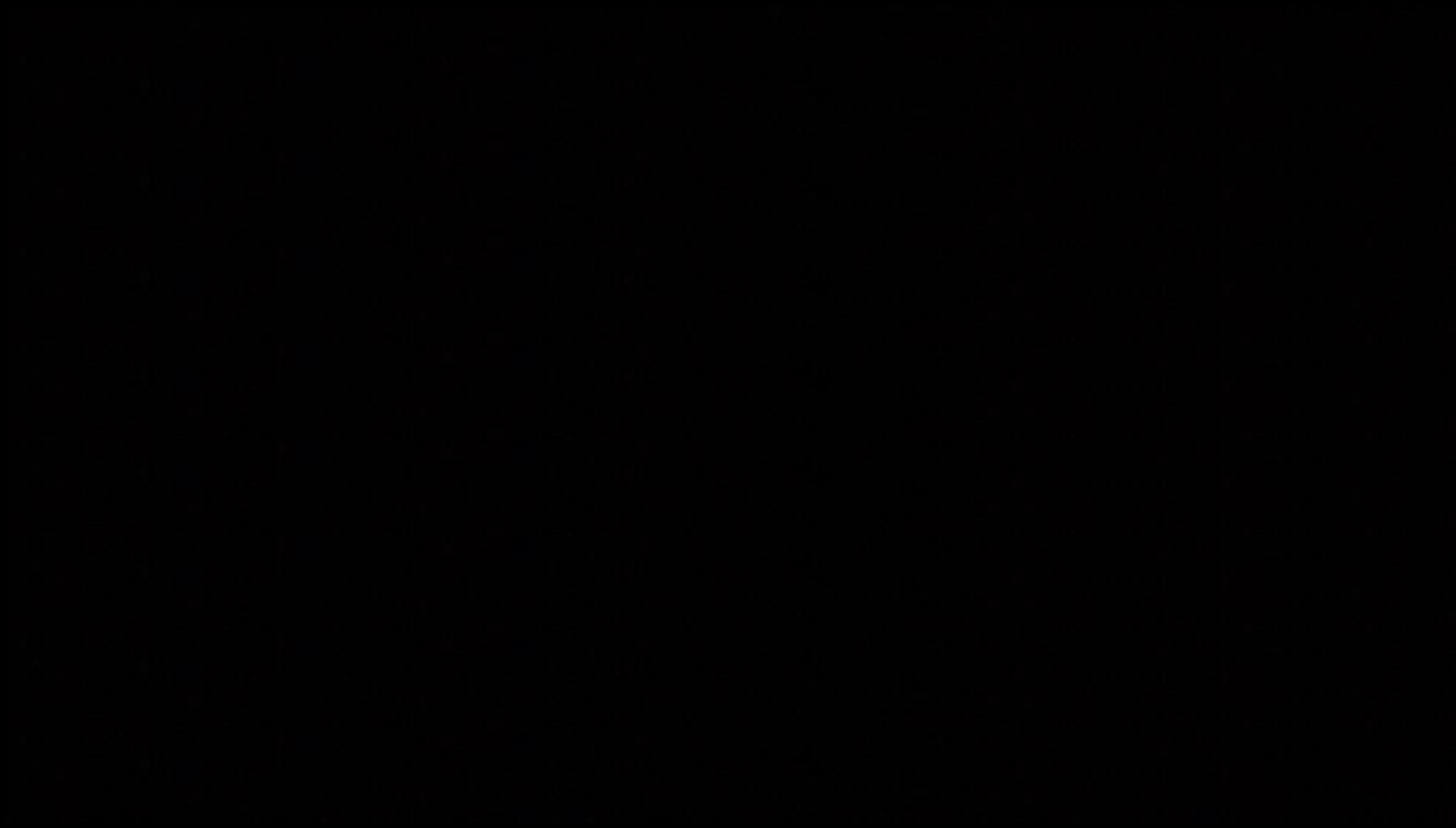


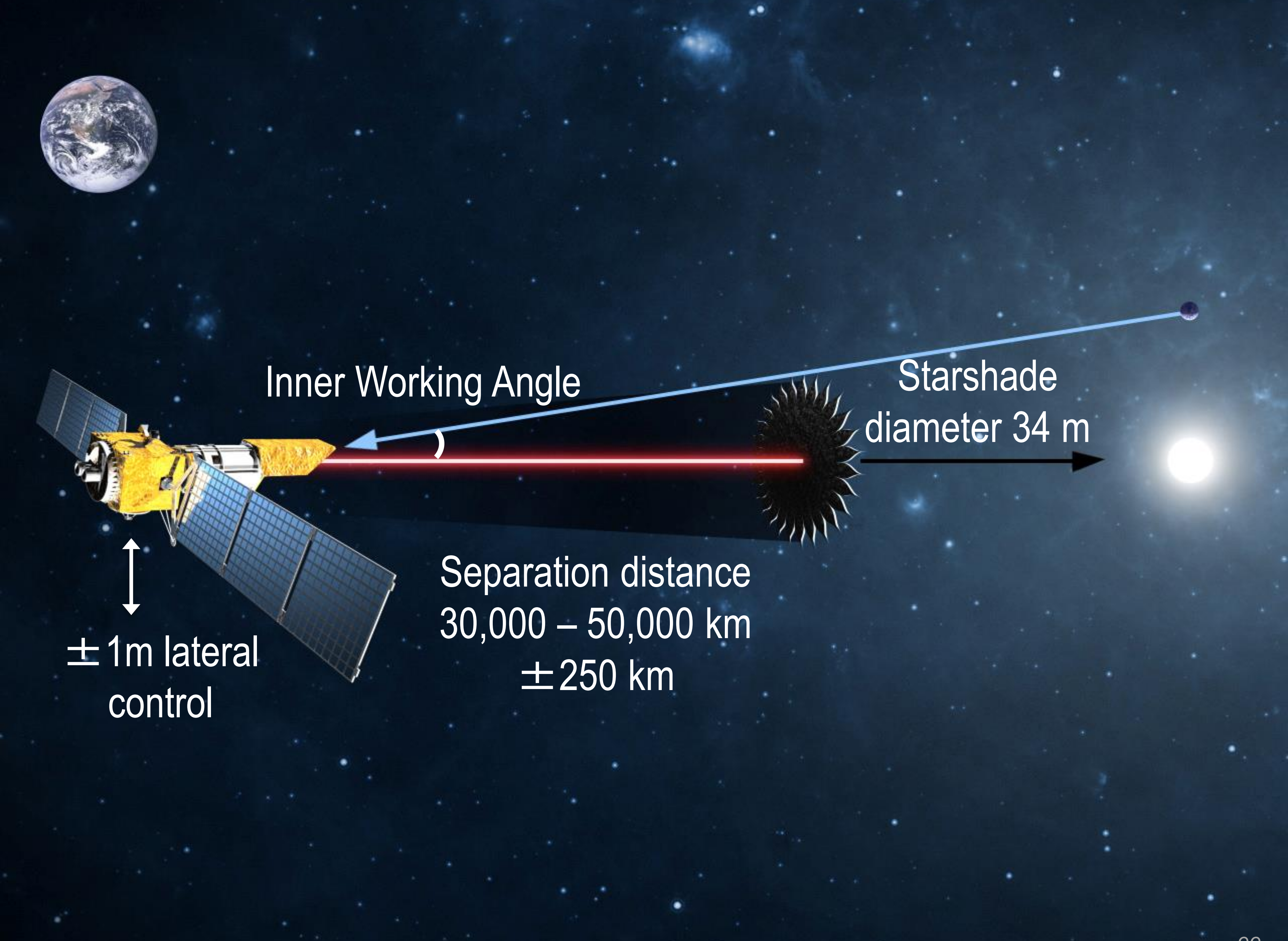


NASA's High Contrast Imaging Testbeds (JPL)



Starshade Concept



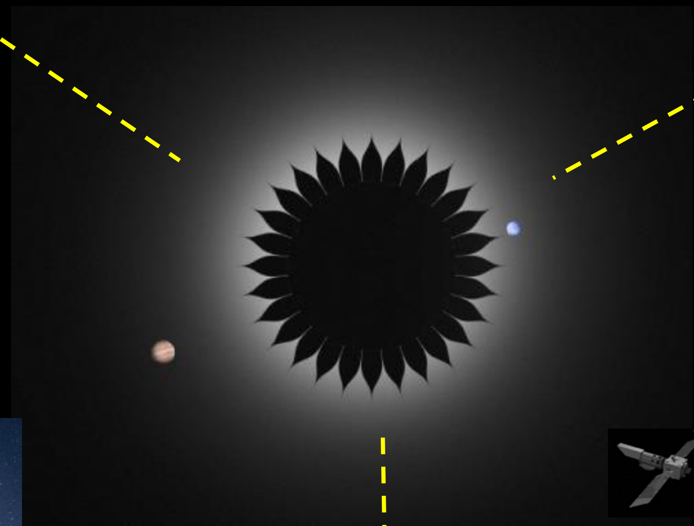


Inner Working Angle
Starshade
diameter 34 m
±1m lateral
control
Separation distance
30,000 – 50,000 km
±250 km

Starshade Technology Needs

Light Suppression

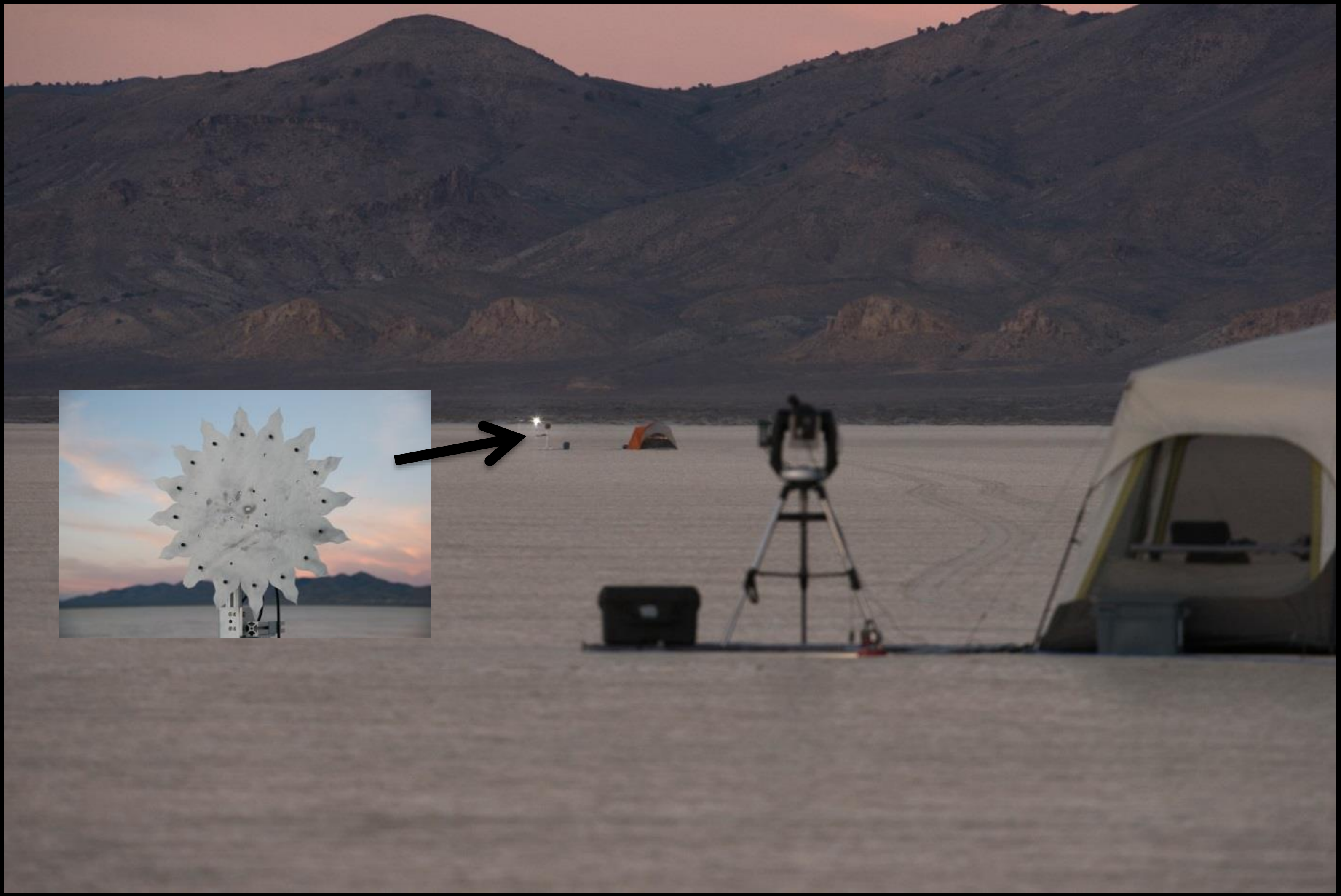
Formation Sensing and Control



Deployment Accuracy and Shape Stability

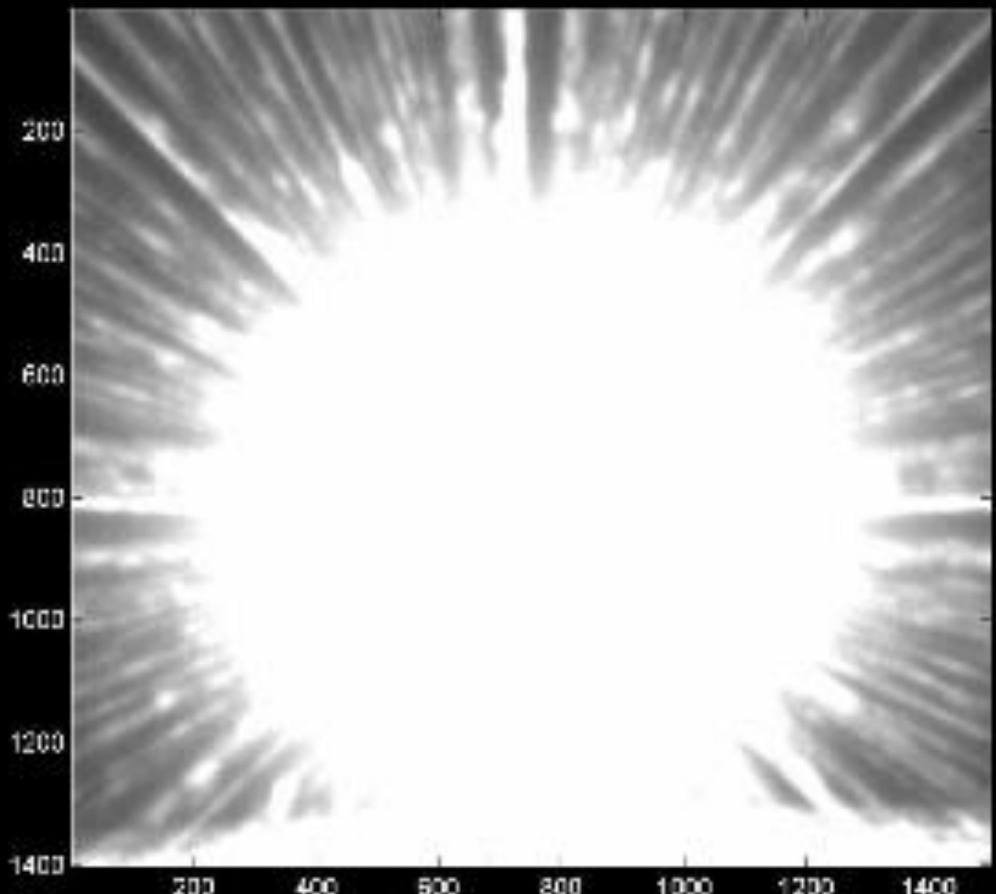
Suppressing diffracted light from on-axis starlight

Desert Testing of the Starshade



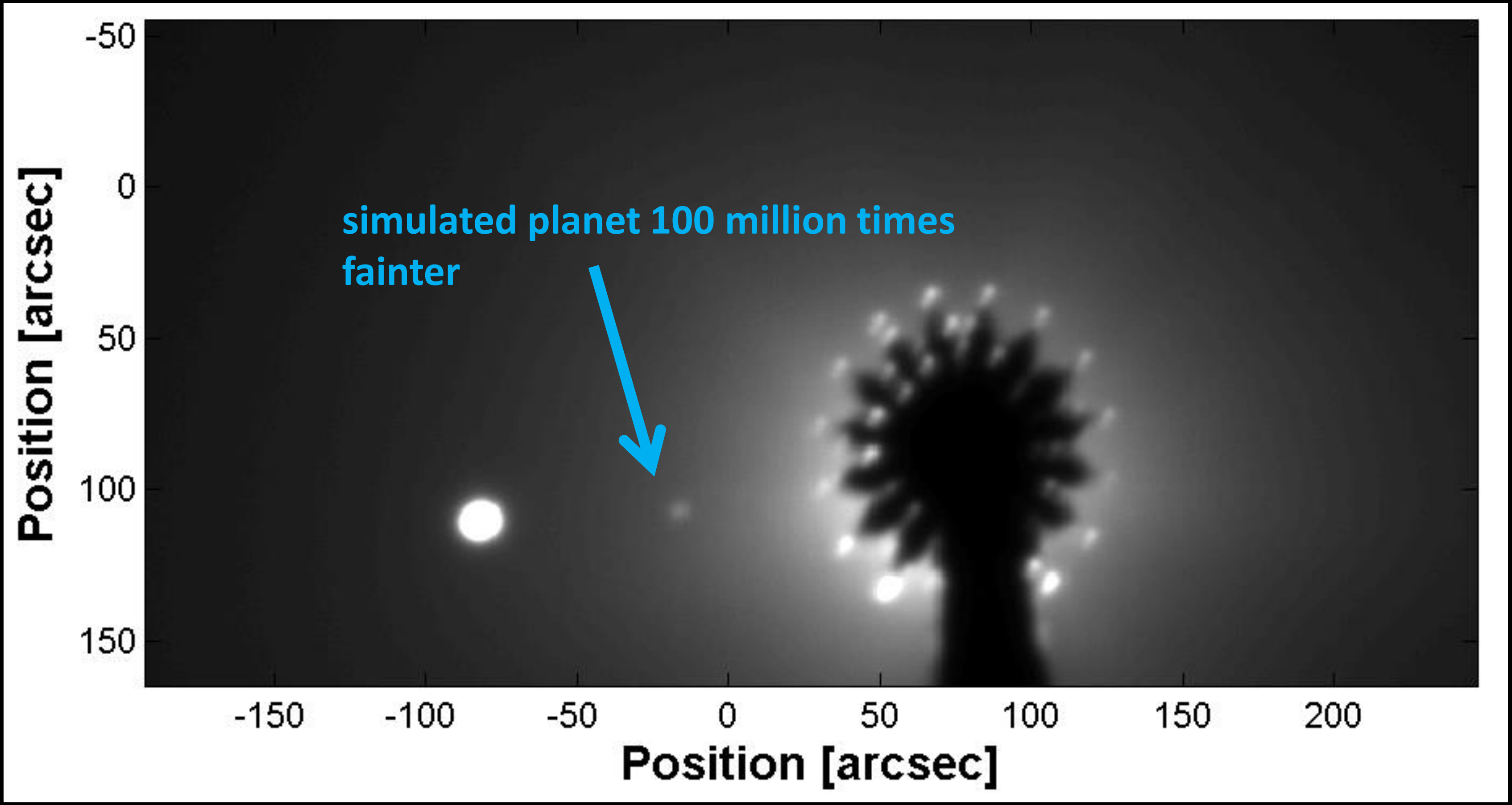
Northrop Grumman Aerospace Systems

Desert Testing of the Starshade



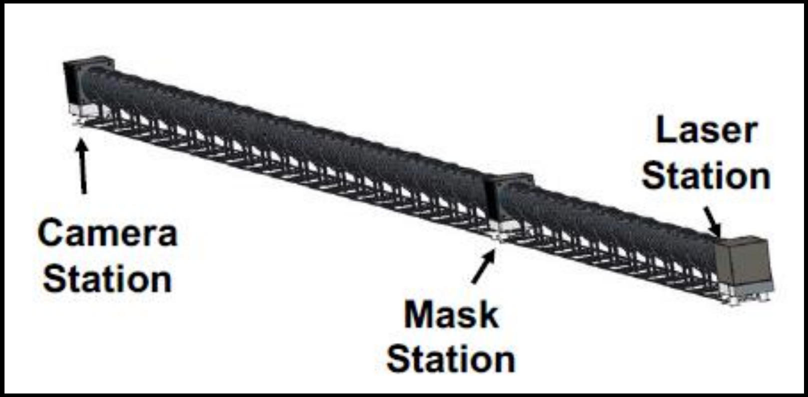
Northrop Grumman Aerospace Systems

Desert Testing of the Starshade



Northrop Grumman Aerospace Systems

Optical Demonstrations at Princeton University

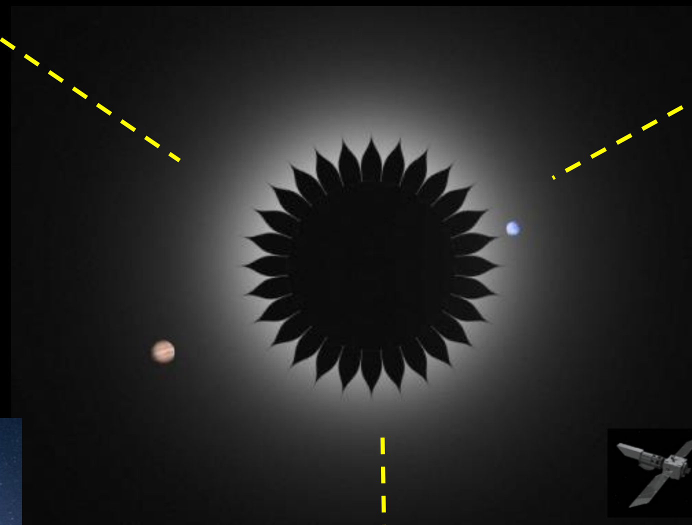


Jeremy Kasdin (Princeton)

Starshade Technology Needs

Light Suppression

Suppressing scatted light off petal edges from off-axis Sunlight

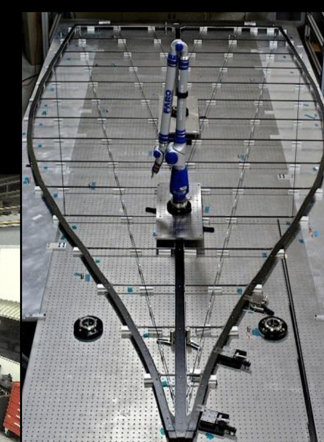


Formation Sensing and Control

Suppressing diffracted light from on-axis starlight

Deployment Accuracy and Shape Stability

Positioning the petals to high precision, blocking on-axis starlight, maintaining overall shape on a highly stable structure



Fabricating the petal to high precision

Inner Disk Prototype Deployment Trial at JPL

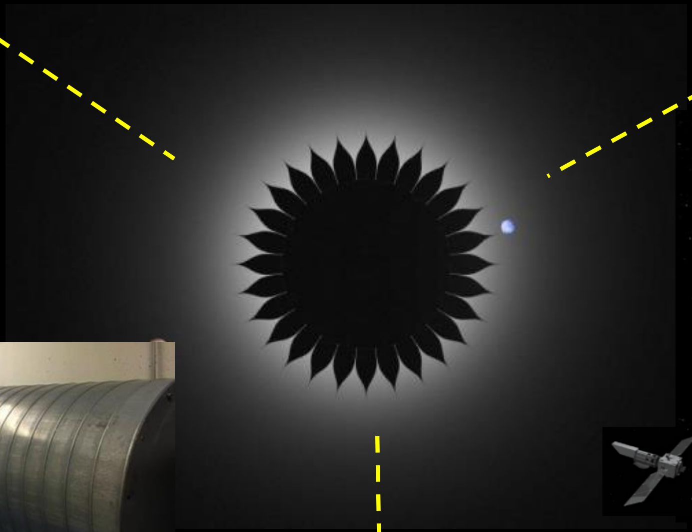
2 m Optical Shield Prototype Deployment Trial at JPL

5 m Origami Optical Shield Deployment Trial at JPL

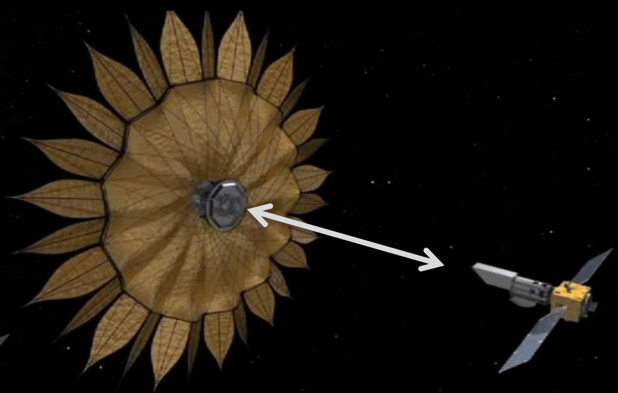
Starshade Technology Needs

Starlight Suppression

Suppressing scatted light off petal edges from off-axis Sunlight



Formation Sensing and Control

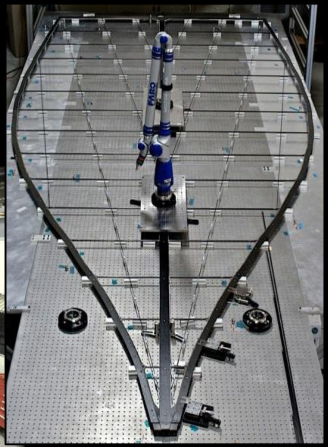


Maintaining lateral offset requirement between the spacecrafts

Suppressing diffracted light from on-axis starlight

Deployment Accuracy and Shape Stability

Positioning the petals to high precision, blocking on-axis starlight, maintaining overall shape on a highly stable structure



Fabricating the petal to high precision

Recent Starshade Technology News

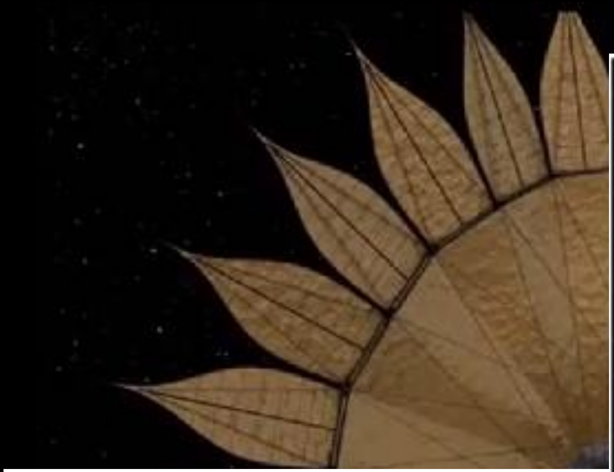
- NASA-chartered starshade technology activity in March
  - *Starshade Technology Project advances technology to TRL-5*

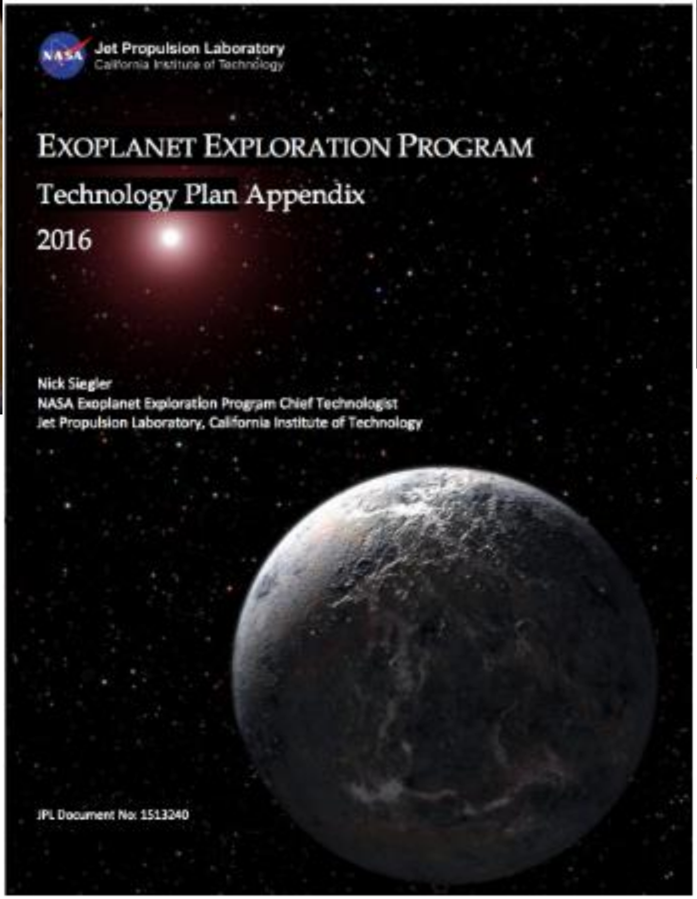
- Starshade Readiness Working Group commenced in January to identify the recommended path to flight for a starshade mission.
  - *Multi-institutional working group and participation*
  - *Report out to NASA HQ by October 2016*

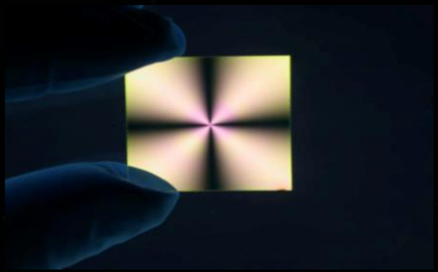
- WFIRST is assessing the impact of accommodating a potential future starshade mission
  - *Final decision will be made no later than summer of 2017.*

This is our reality...

ExEP Technology Gap Lists







Starshade Technology Gap List

Table A.4 Starshade Technology Gap List

ID	Title	Description	Current	Required
S-1	Control Edge-Scattered Sunlight	Limit edge-scattered sunlight with optical petal edges that also handle stowed bending strain.	Graphite edges meet all specs except sharpness, with edge radius ≥10 μm.	Optical petal edges manufactured of high flexural strength material with edge radius ≤ 1 μm and reflectivity ≲ 10%.
S-2	Contrast Performance Demonstration ar Optical Model Validation	Experimentally validate the equations that predict the contrasts achievable with a starshade.	Experiments have validated optical diffraction models at Fresnel number of ~500 to contrasts of 3×10^{-10} at 632 nm.	Experimentally validate models of starlight suppression to ≤ 3×10^{-11} at Fresnel numbers ≤ 50 over 510-825 nm bandpass.
S-3	Lateral Formation Flying Sensing Accuracy	Demonstrate lateral formation flying sensing accuracy consistent with keeping telescope in starshade's dark shadow.	Centroid accuracy ≥ 1% is common. Simulations have shown that sensing and GN&C is tractable, though sensing demonstration of lateral control has not yet been performed.	Demonstrate sensing lateral errors ≤ 0.20m at scaled flight separations and estimated centroid positions ≤ 0.3% of optical resolution. Control algorithms demonstrated with lateral control errors ≤ 1m.
S-4	Flight-Like Petal Fabrication and Deployment	Demonstrate a high-fidelity, flight-like starshade petal and its unfurling mechanism.	Prototype petal that meets optical edge position tolerances has been demonstrated.	Demonstrate a fully integrated petal, including blankets, edges, and deployment control interfaces. Demonstrate a flight-like unfurling mechanism.
S-5	Inner Disk Deployment	Demonstrate that a starshade can be autonomously deployed to within the budgeted tolerances.	Demonstrated deployment tolerances with 12m heritage Astromesh antenna with four petals, no blankets, no outrigger struts, and no launch restraint.	Demonstrate deployment tolerances with flight-like, minimum half-scale inner disk, with simulated petals, blankets, and interfaces to launch restraint.

Coronagraph/Telescope Technology Gap List

able A.3 Coronagraph Technology Gap List.

ID	Title	Description	Current	Required
C-1	Specialized Coronagraph Optics	Masks, apodizers, or beam-shaping optics to provide starlight suppression and planet detection capability.	A linear mask design has yielded 3.2×10^{-10} mean raw contrast from 3–16 λ/D with 10% bandwidth using an unobscured pupil in a static lab demonstration.	Circularly symmetric masks achieving ≤ 1×10^{-10} contrast with IWA ≤ 3λ/D and ≥ 10% bandwidth on obscured or segmented pupils.
C-2*	Low-Order Wavefront Sensing & Control	Beam jitter and slowly varying large-scale (low-order) optical aberrations may obscure the detection of an exoplanet.	Tip/tilt errors have been sensed and corrected in a stable vacuum environment with a stability of 10^{-3} λ rms at sub-Hz frequencies.	Tip/tilt, focus, astigmatism, and coma sensed and corrected simultaneously to 10^{-4} λ (~10's of pm) rms to maintain raw contrasts of ≤ 1×10^{-10} in a simulated dynamic testing environment.
C-3*	Large-Format Ultra-Low Noise Visible Detectors	Low-noise visible detectors for faint exoplanet characterization with an Integral Field Spectrograph.	Read noise of < 1 e^-/pixel has been demonstrated with EMCCDs in a 1k × 1k format with standard read-out electronics	Read noise < 0.1e^-/pixel in a ≥ 4k × 4k format validated for a space radiation environment and flight-accepted electronics.
C-4*	Large-Format Deformable Mirrors	Maturation of deformable mirror technology toward flight readiness.	Electrostrictive 64x64 DMs have been demonstrated to meet ≤ 10^{-9} contrasts in a vacuum environment and 10% bandwidth.	≥ 64x64 DMs with flight-like electronics capable of wavefront correction to ≤ 10^{-10} contrasts. Full environmental testing validation.
C-5	Efficient Contrast Convergence	Rate at which wavefront control methods achieve 10^{-10} contrast.	Model and measurement uncertainties limit wavefront control convergence and require many tens to hundreds of iterations to get to 10^{-10} contrast from an arbitrary initial wavefront.	Wavefront control methods that enable convergence to 10^{-10} contrast ratios in fewer iterations (10-20).
C-6*	Post-Data Processing	Techniques are needed to characterize exoplanet spectra from residual speckle noise for typical targets.	Few 100x speckle suppression has been achieved by HST and by ground-based AO telescopes in the NIR and in contrast regimes of 10-5 to 10^{-6}, dominated by phase errors.	A 10-fold improvement over the raw contrast of ~10^{-9} in the visible where amplitude errors are expected to no longer be negligible with respect to phase errors.

*Topic being addressed by directed-technology development for the WFIRST/AFTA coronagraph. Consequently, coronagraph technologies that will be substantially advanced under the WFIRST/AFTA technology development are not eligible for TDEMs.

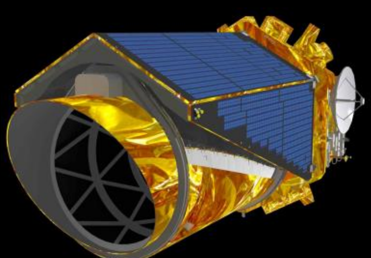
https://exoplanets.nasa.gov/

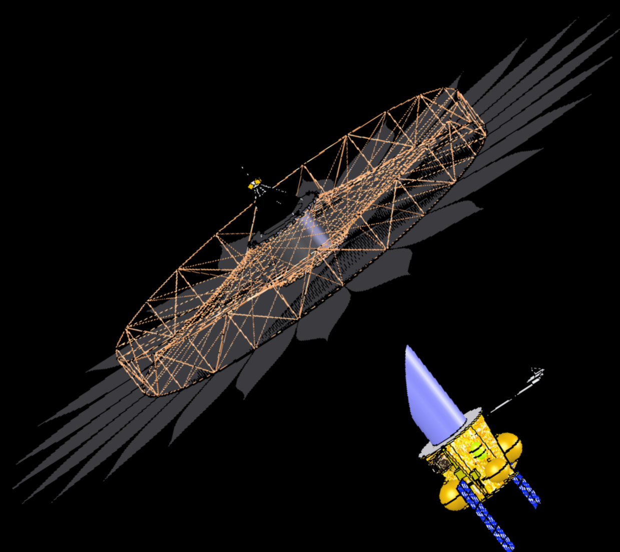
Opportunities to Participate

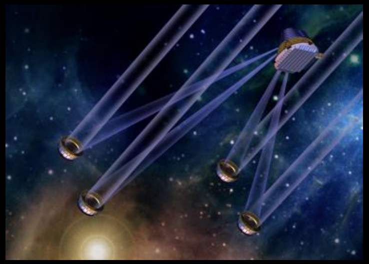
- Propose for a NASA Strategic Astrophysics Technology (SAT)
  - for TRL 3-5 (http://nspires.nasaprs.com/external/)
- Propose for an NASA Astrophysics Research and Analysis (APRA) grant
  - TRL 1-2 (http://nspires.nasaprs.com/external/)
- Propose for a NASA Small Business Innovation Research (SBIR) grant
  - All ExEP technology gaps are mapped to the 2015 NASA Technology Roadmaps
    - http://www.nasa.gov/offices/oct/home/roadmaps/index.html
- Opportunity for involvement in the Starshade Technology Project
  - Workshop date to be announced (to be scheduled before end of CY16)
- Visit the Exoplanet Exploration Program (ExEP) technology website
  - https://exoplanets.nasa.gov/exep/technology/technology-overview/

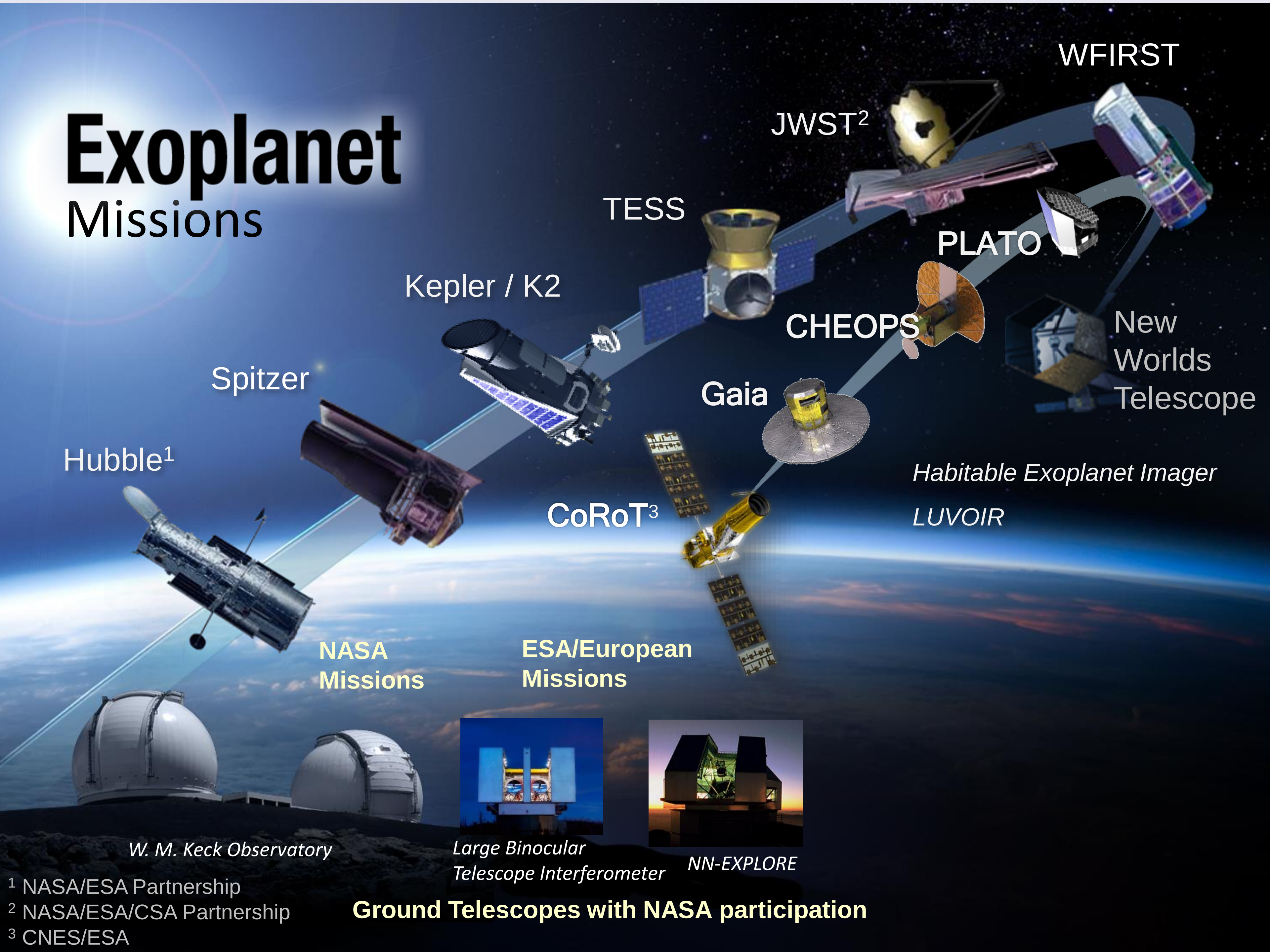
Acknowledgements

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









Exoplanet
Missions
WFIRST
JWST[2]
TESS
PLATO
Kepler / K2
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
[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA
Ground Telescopes with NASA participation

Jet Propulsion Laboratory
California Institute of Technology

Exploring Exoplanets with WFIRST Coronagraph and Starshade

Dr. Margaret Turnbull
Carl Sagan Center for the Study of Life in the Universe
SETI Institute

September 15, 2016
AIAA Space 2016, SPSC-03, Long Beach CA

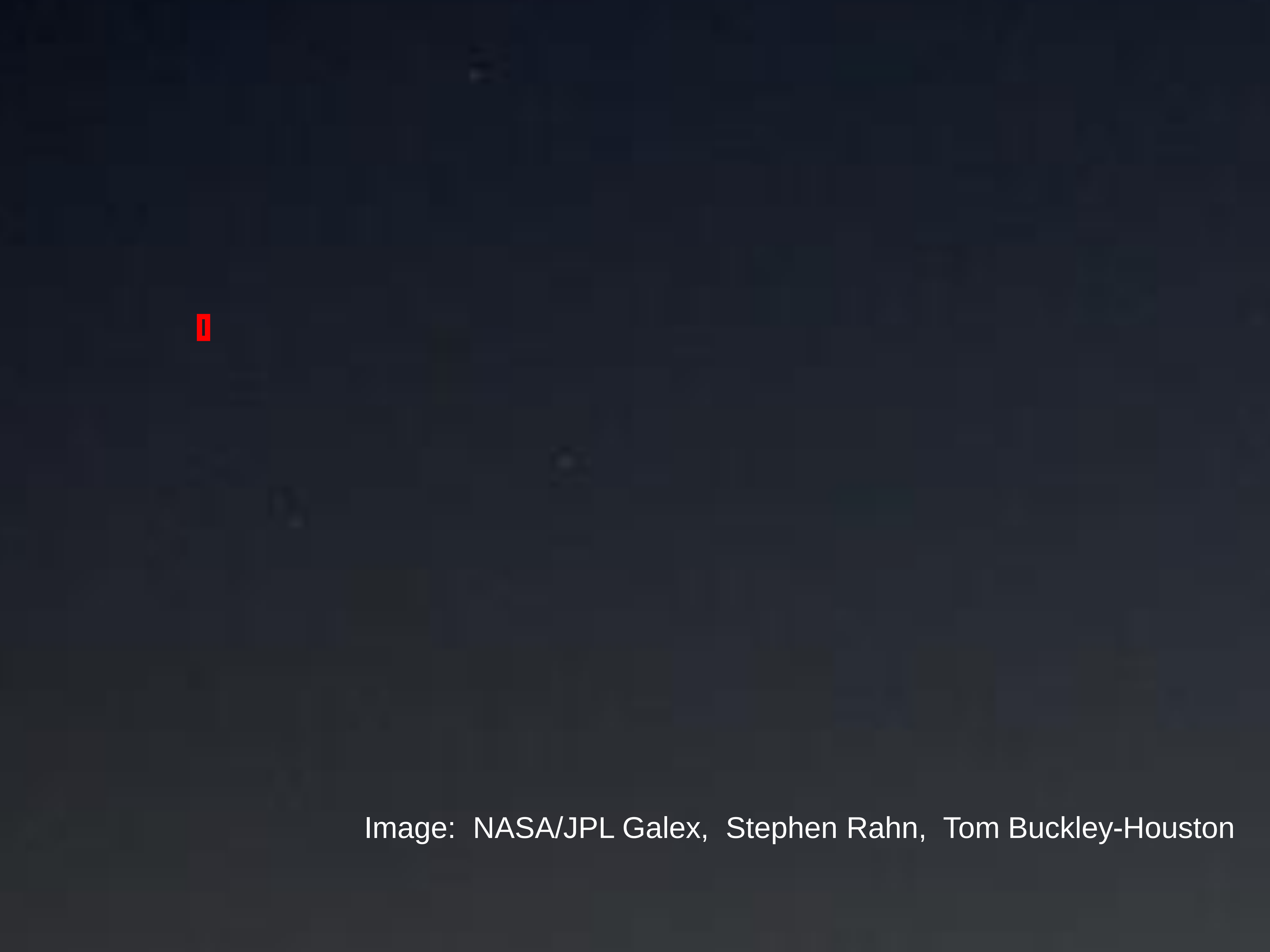


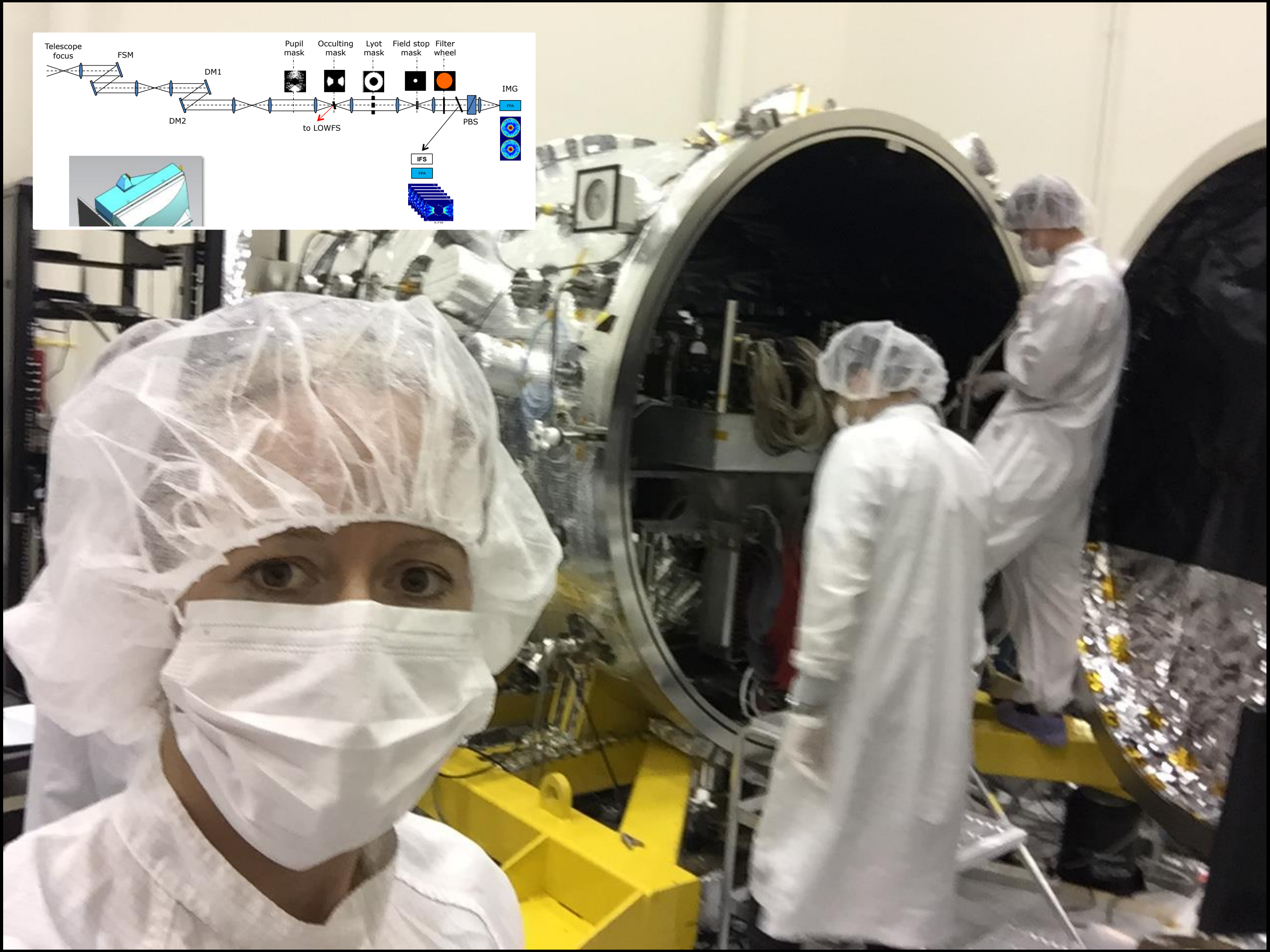
Image: NASA/JPL Galex, Stephen Rahn, Tom Buckley-Houston

Where to begin?

Image: NASA/JPL Galex, Stephen Rahn, Tom Buckley-Houston

<u>WFIRST: Where the rubber meets the road.</u>

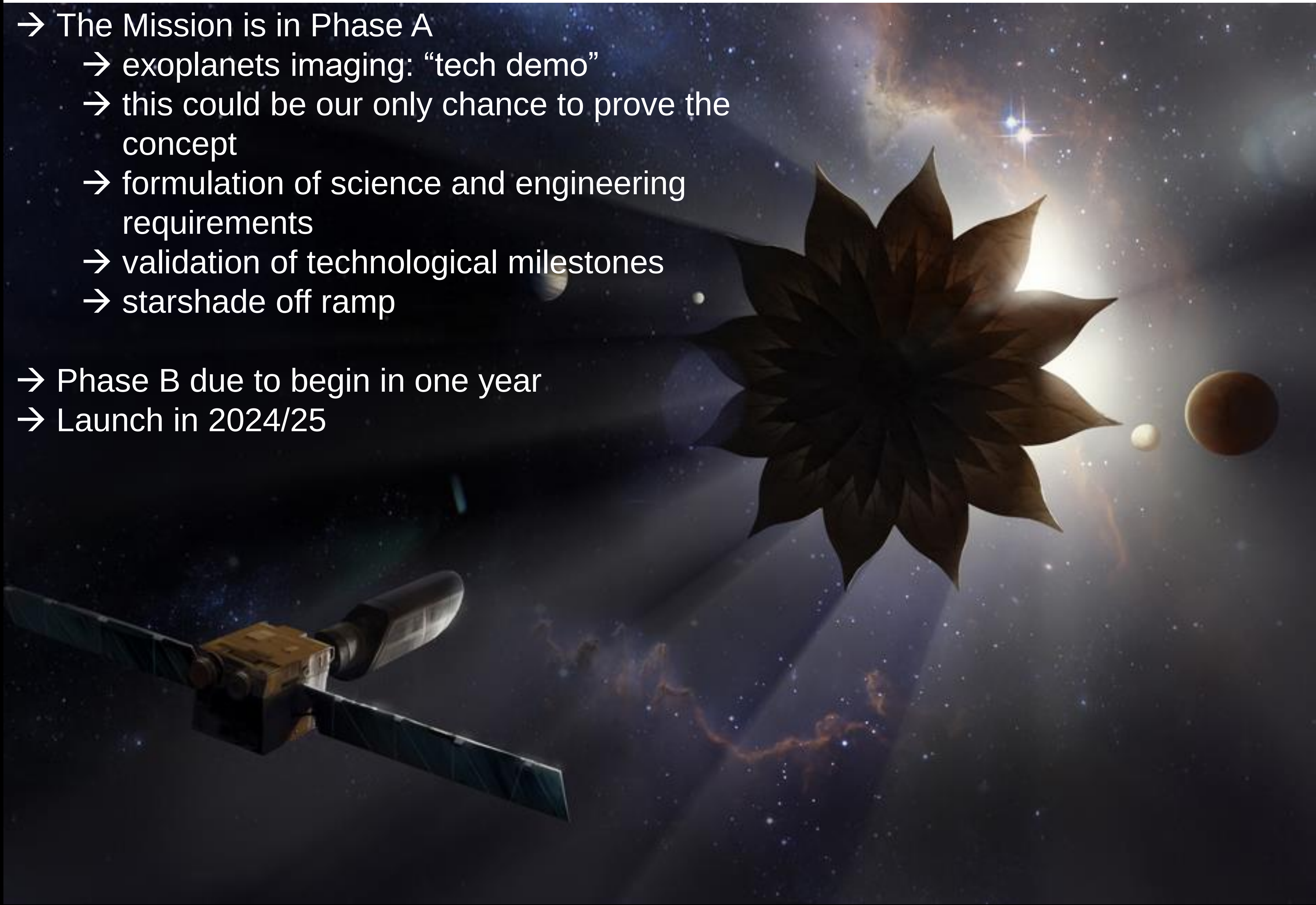
Three Coronagraphs (Hybrid Lyot, Shaped Pupil, and PIAA)
and an IFS in testing under vaccuum at JPL



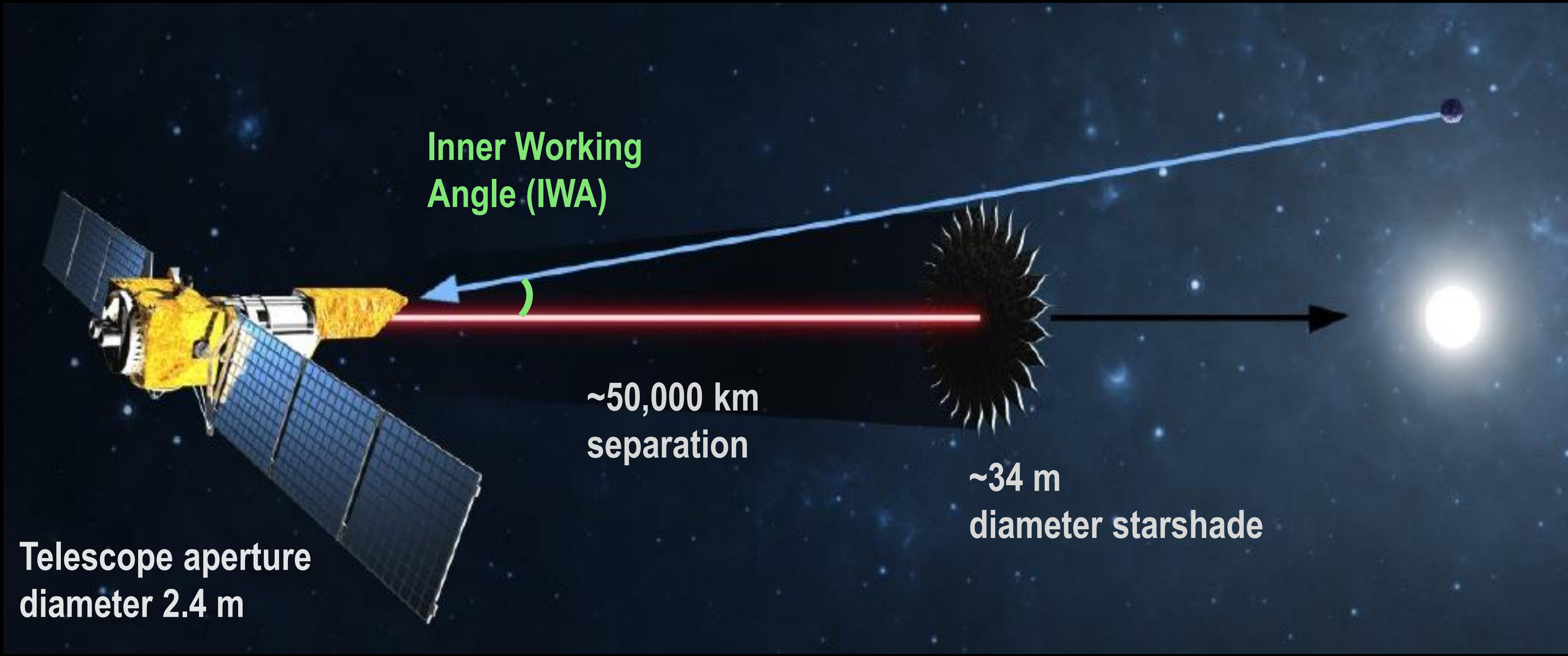
WFIRST Baseline: L2, starshade ready

- → The Mission is in Phase A
  - → exoplanets imaging: “tech demo”
  - → this could be our only chance to prove the concept
  - → formulation of science and engineering requirements
  - → validation of technological milestones
  - → starshade off ramp

- → Phase B due to begin in one year
- → Launch in 2024/25

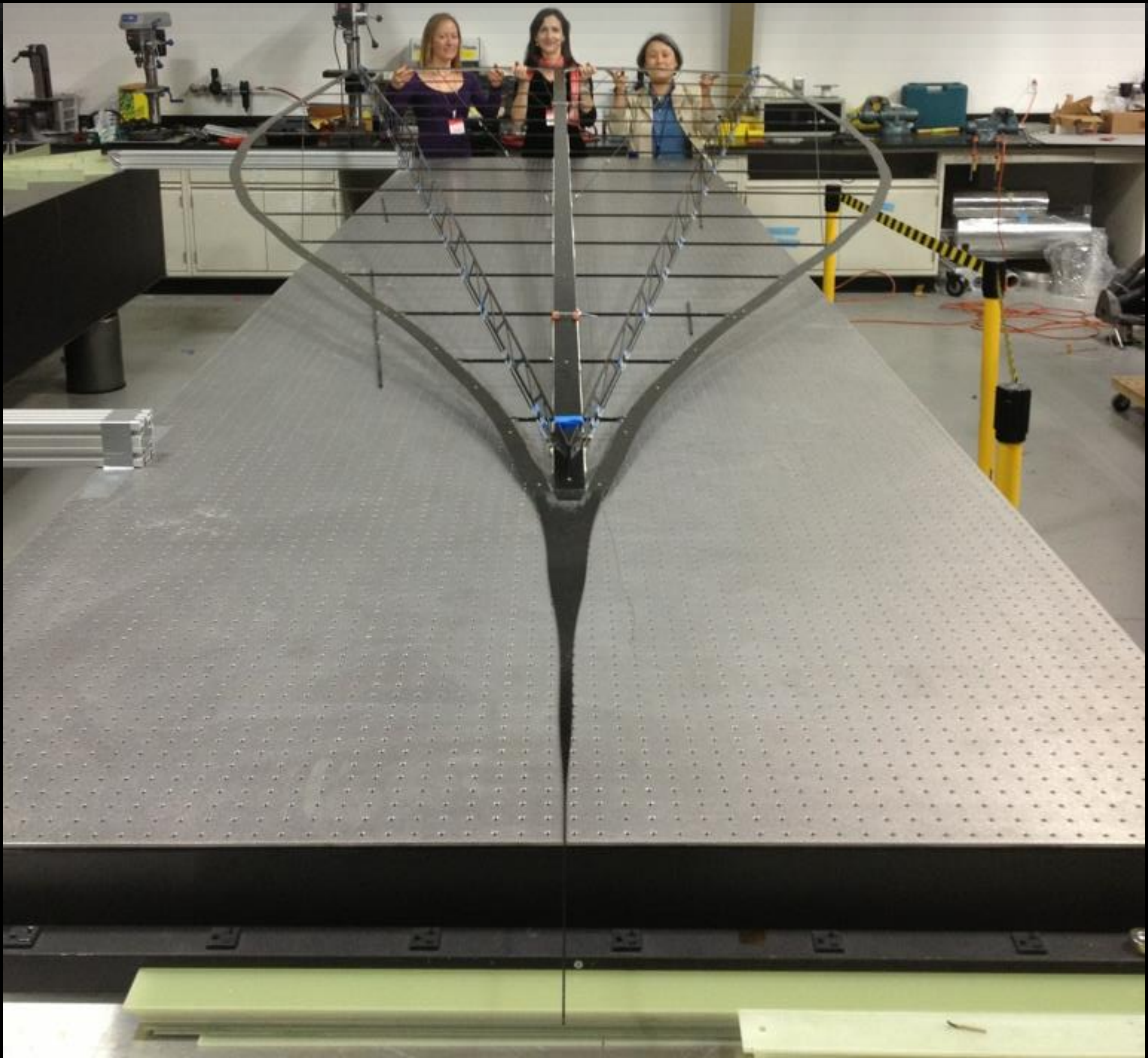


Starshade Basics

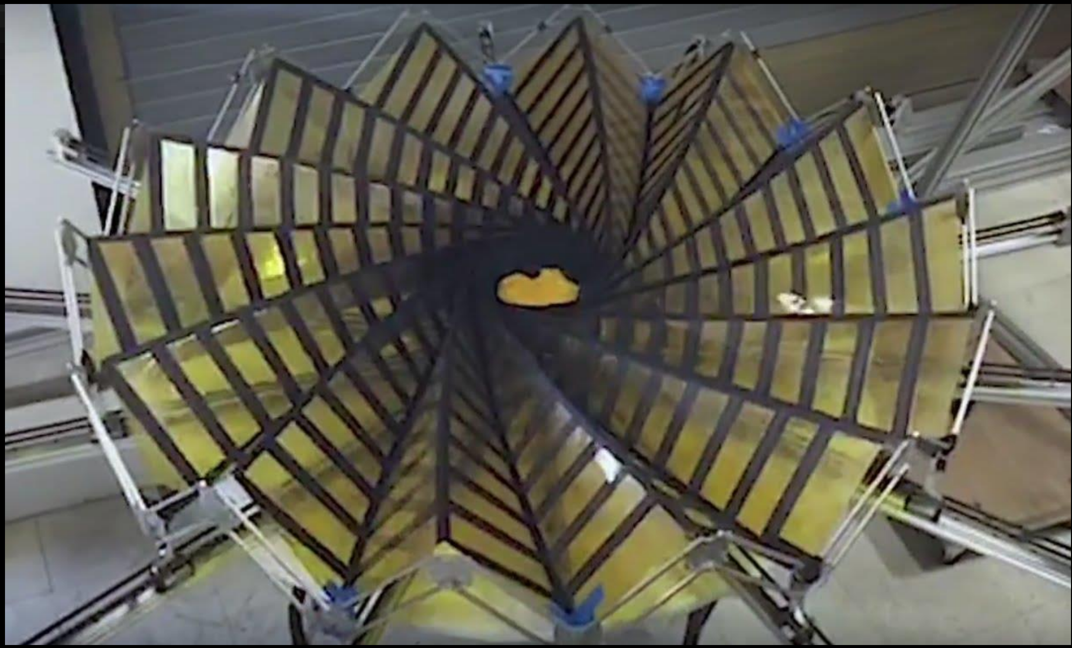


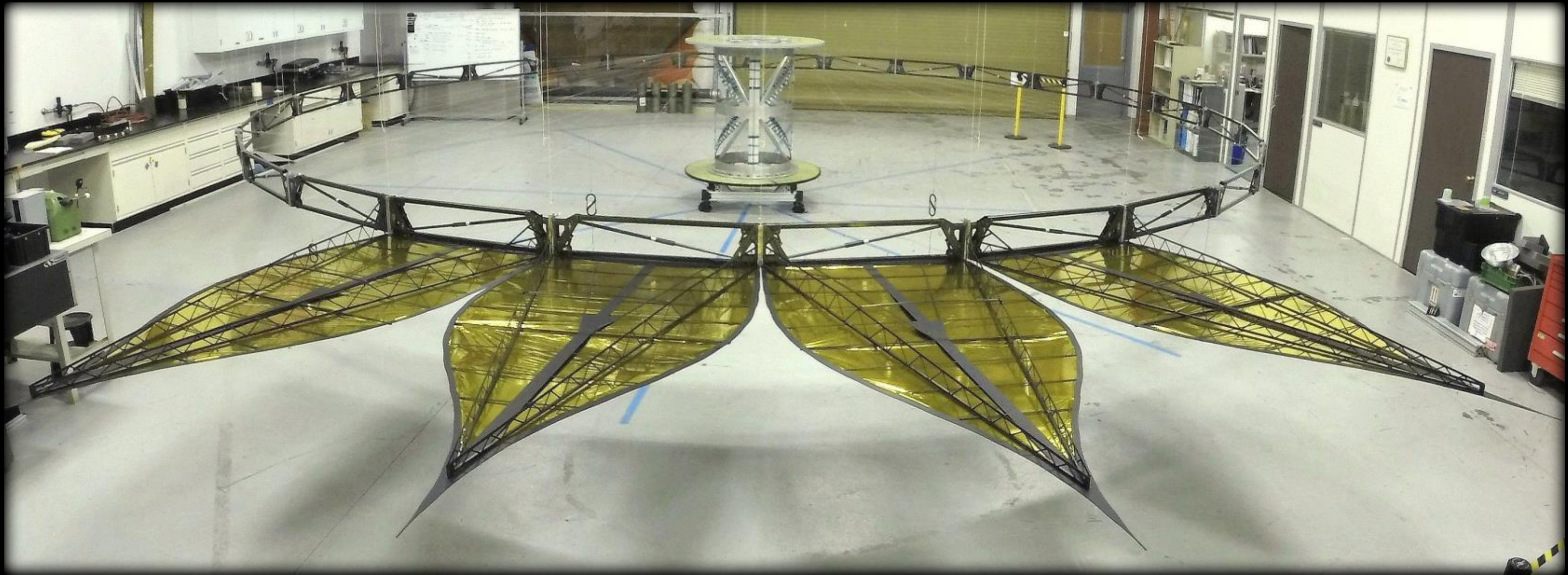
- PRO: Contrast and IWA decoupled from telescope aperture size
- PRO: No outer working angle
- PRO: Few reflections = high throughput, broad wavelength bandpass
- PRO: Starlight does NOT enter telescope
  - High quality telescope not required, wavefront correction unnecessary
- CON? Retargeting requires long starshade slews (days to weeks)

Starshade Lab at JPL



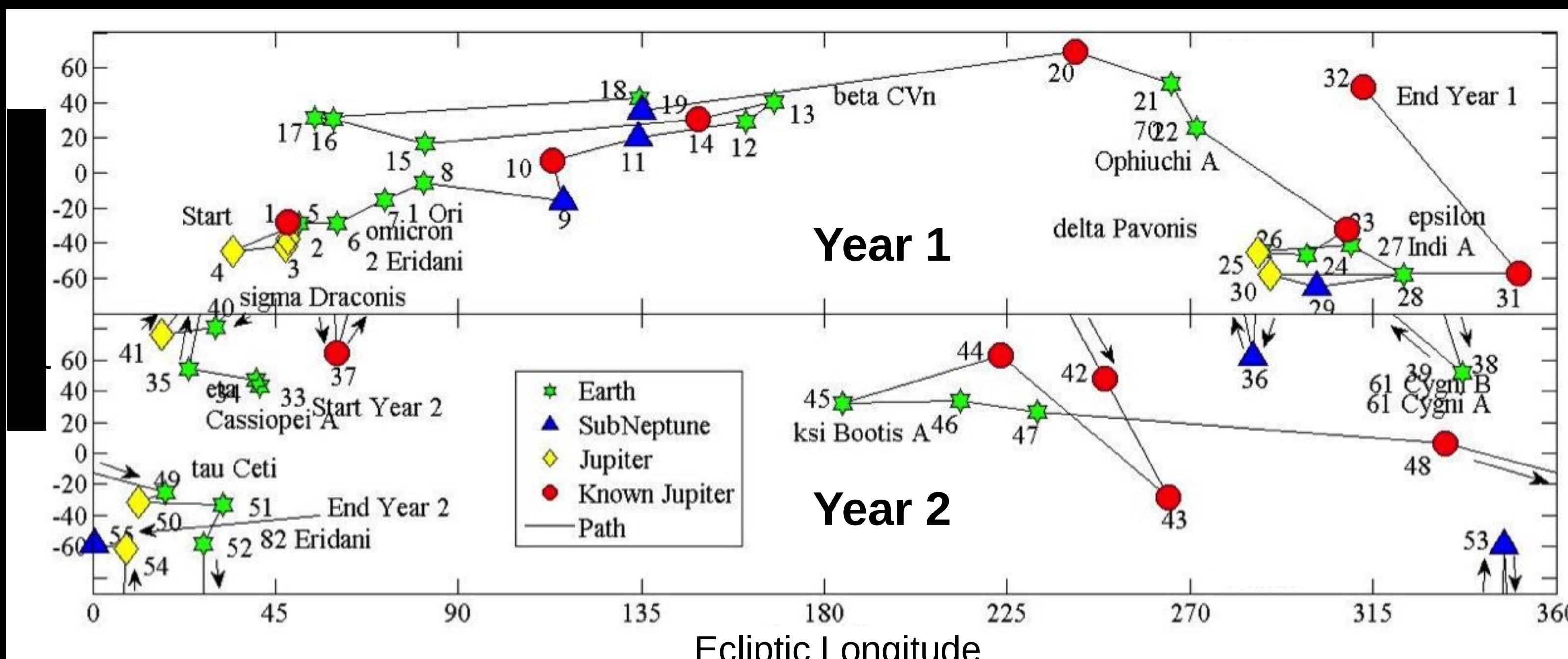
Starshade Lab at JPL





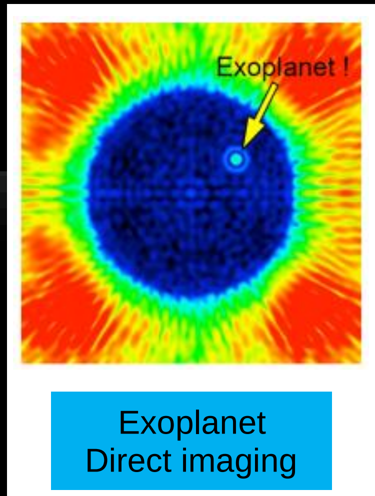
Observing Sequence

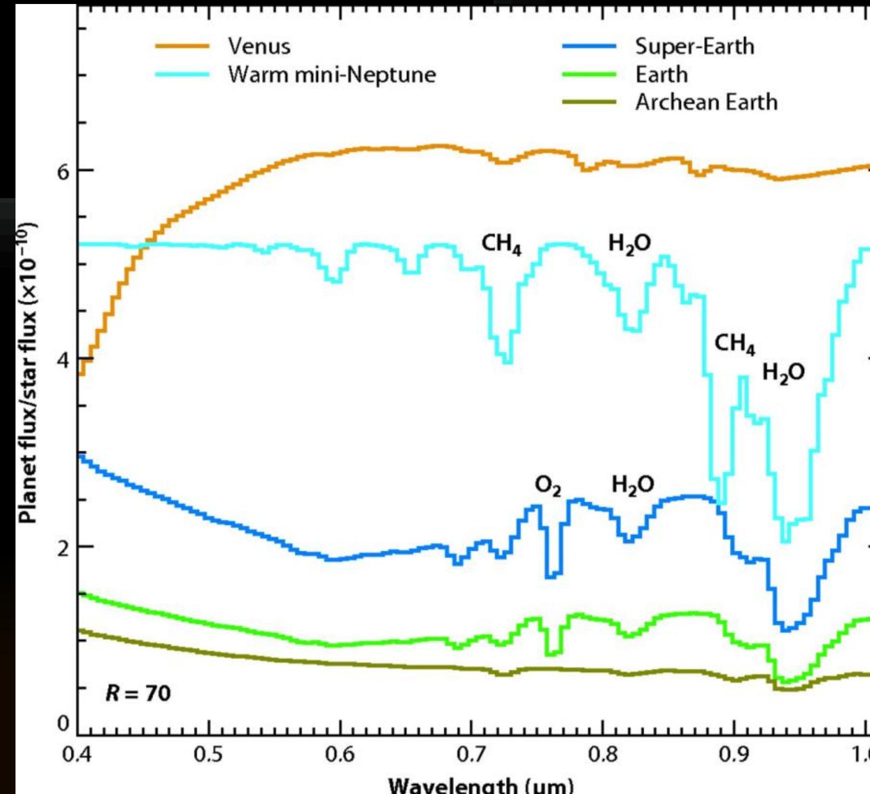
1. Schedule known giant planet observations
2. Fill in gaps on sky with highest priority blind search target
3. Repeat with lower priority targets until fuel or time limit reached
4. Reserve 3rd year for follow-up / additional characterization revisits

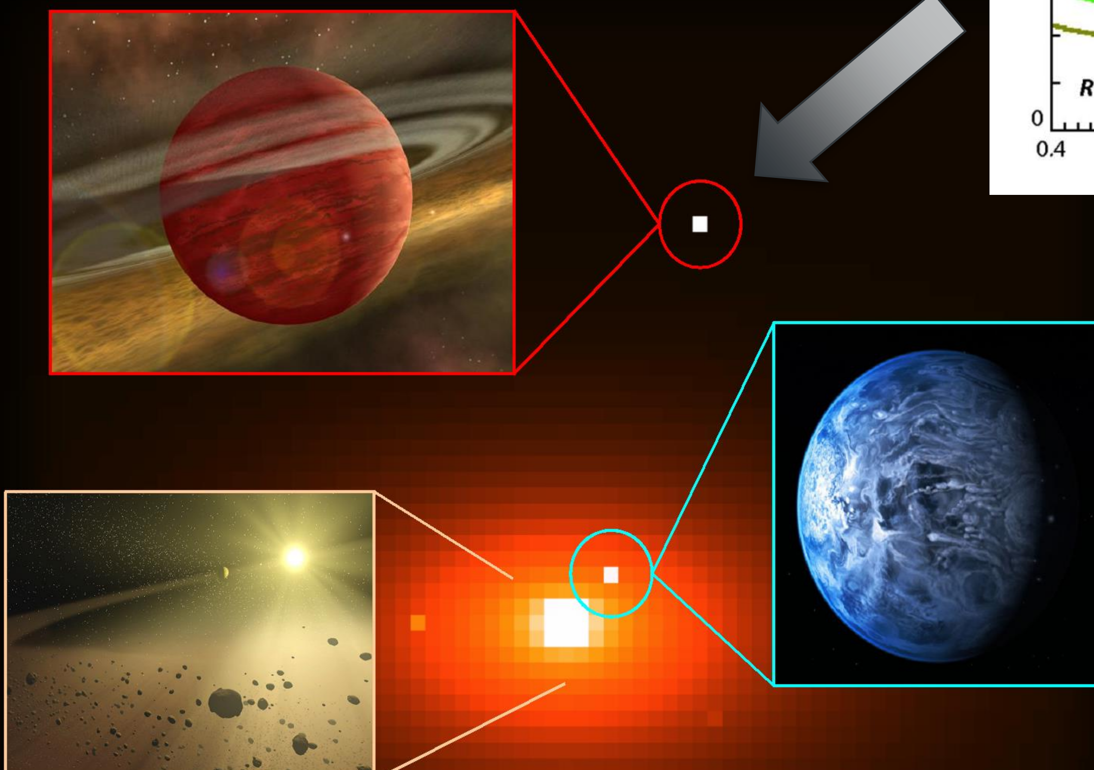


Rendezvous mission, 2-year sequence, 55 stars visited, Δv = 1266 m/s

12 known giant planets. Blind search targets: 28 Earths, 7 sub-Neptunes, 8 Jupiters



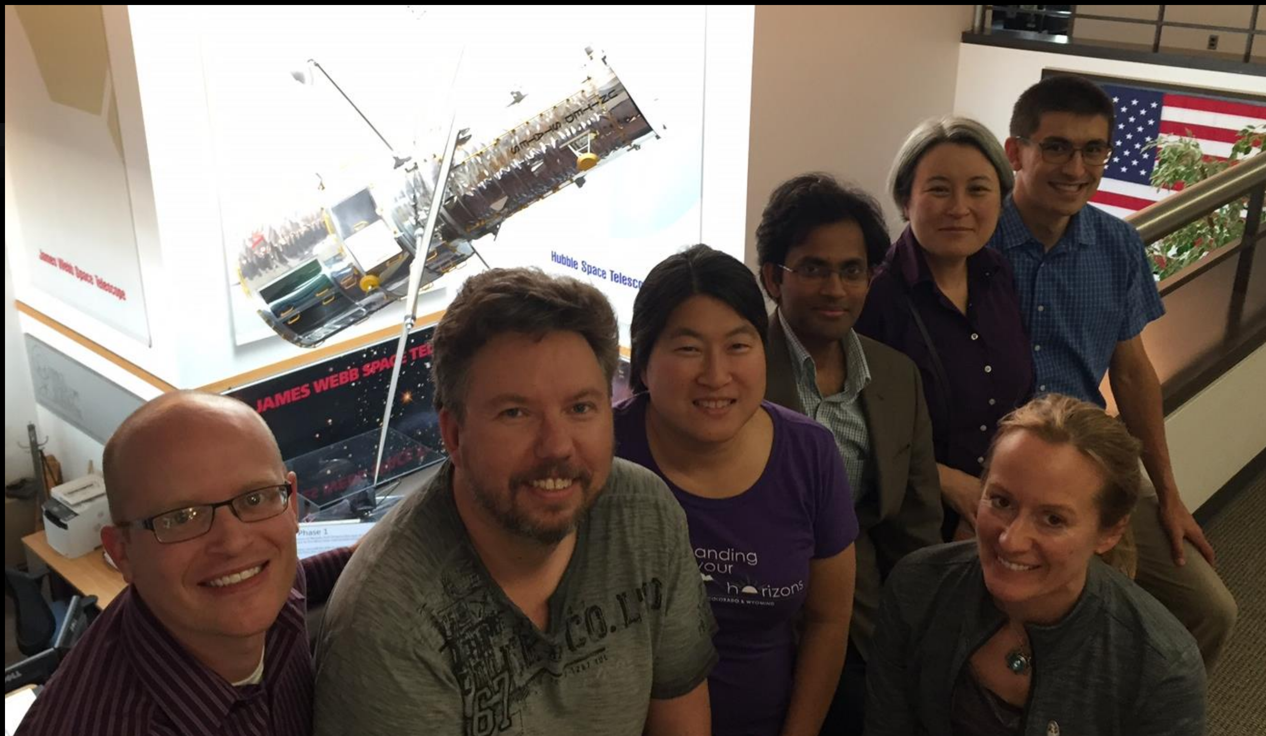




GOAL

Detect known and new planets and ask: What are they like?

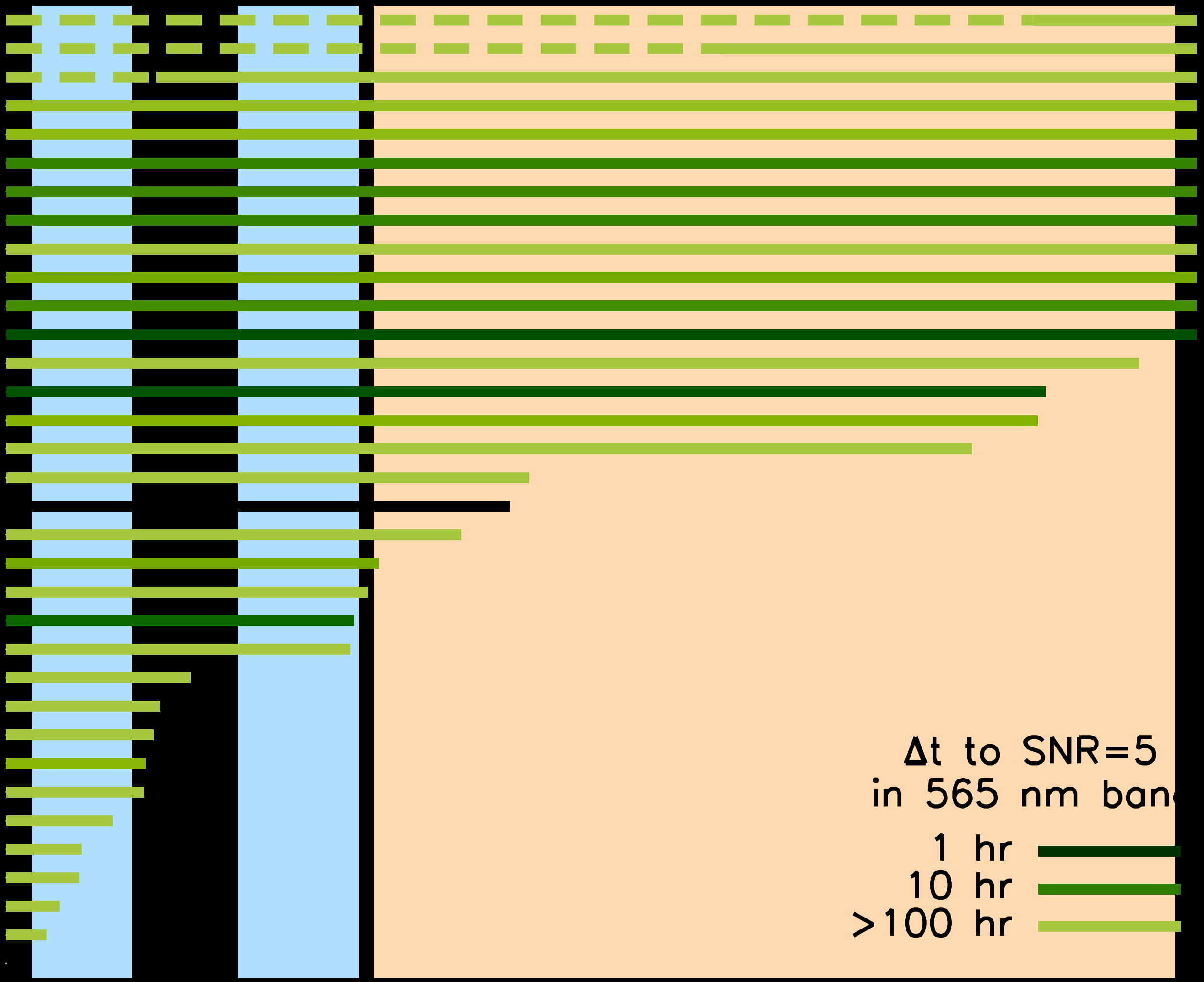
WFIRST Exoplanet Scientists



Disks, Super-Earths(?), Known and New Giants, Background, Binaries, Calibration, Operations, Post-processing, Retrieval, Requirements, Starshade Readiness

→ Targets WG co-chaired w/Andrew Howard
→ Retrieval Challenge led by Turnbull team
→ NExSS participation:
Kane, Jang-Condell, Roberge, Turnbull

High Priority Known Planets: What can we learn from real data?



Registration: WFIRST Exoplanets Data Challenge

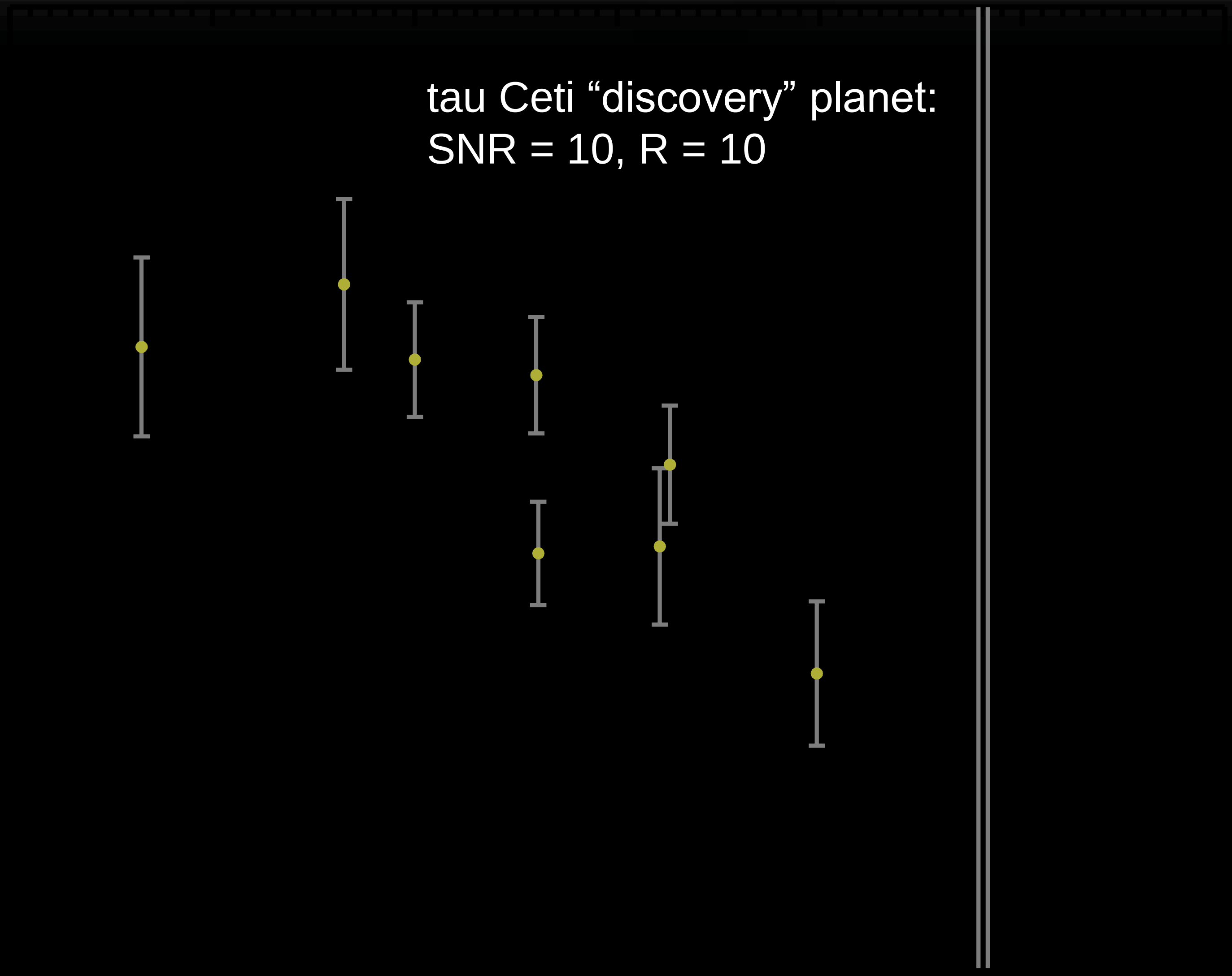
Welcome to the WFIRST Exoplanets Data Challenge! The WFIRST mission is currently in Phase A, during which time the science and instrument performance requirements will be defined for exoplanets imaging and spectroscopy. In order to provide the project with the best possible inputs before the end of Phase A in 2017, we are seeking participation from teams with spectral retrieval expertise through the WFIRST Exoplanets Data Challenge.

The Challenge will run from August 15th to November 15th, 2016. The 2016 Challenge consists of a blind spectral retrieval exercise using simulated extracted spectra for several "known RV" and/or hypothetical "discovery" exoplanets. The spectra will NOT need to be extracted from simulated IFS data, but we will explore the impact of signal-to-noise ratio and spectral resolution on the detection/measurement of atmospheric abundances and other planet properties. Even with that relatively "simple" goal, we expect the Challenge to be non-trivial!

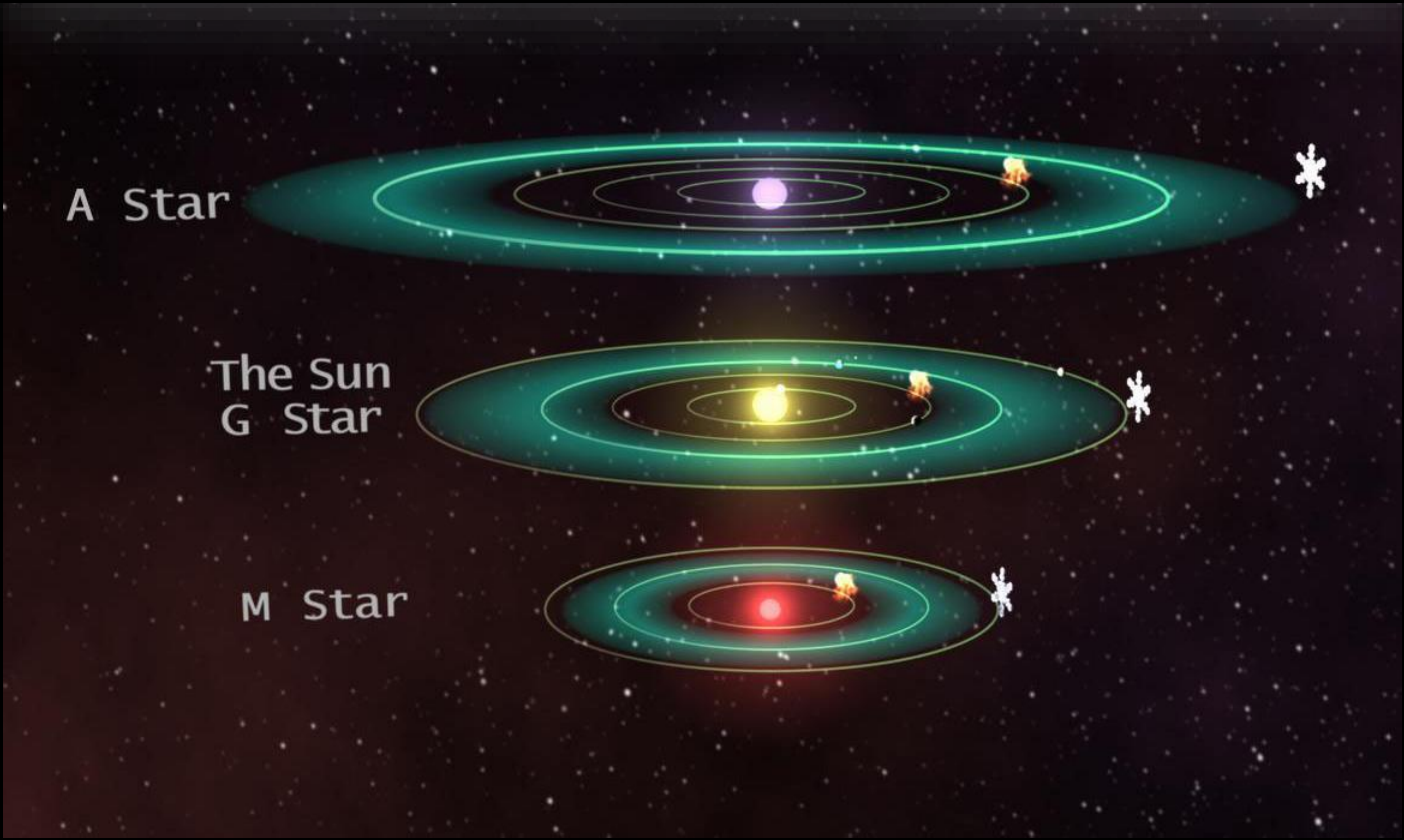
Incentive to Participate: While defining the first space-borne exoplanet imaging mission is hopefully its own compelling reason for doing this, to make this a little more fun we are offering travel expenses and registration costs for one person on each team which fully completes the challenge (all four planets, all SNR and R, all requested retrieval outputs) to attend the 2017 WFIRST Science Meeting, or another exoplanets meeting of your choice (up to $2000).

Data Challenges

Data Challenges



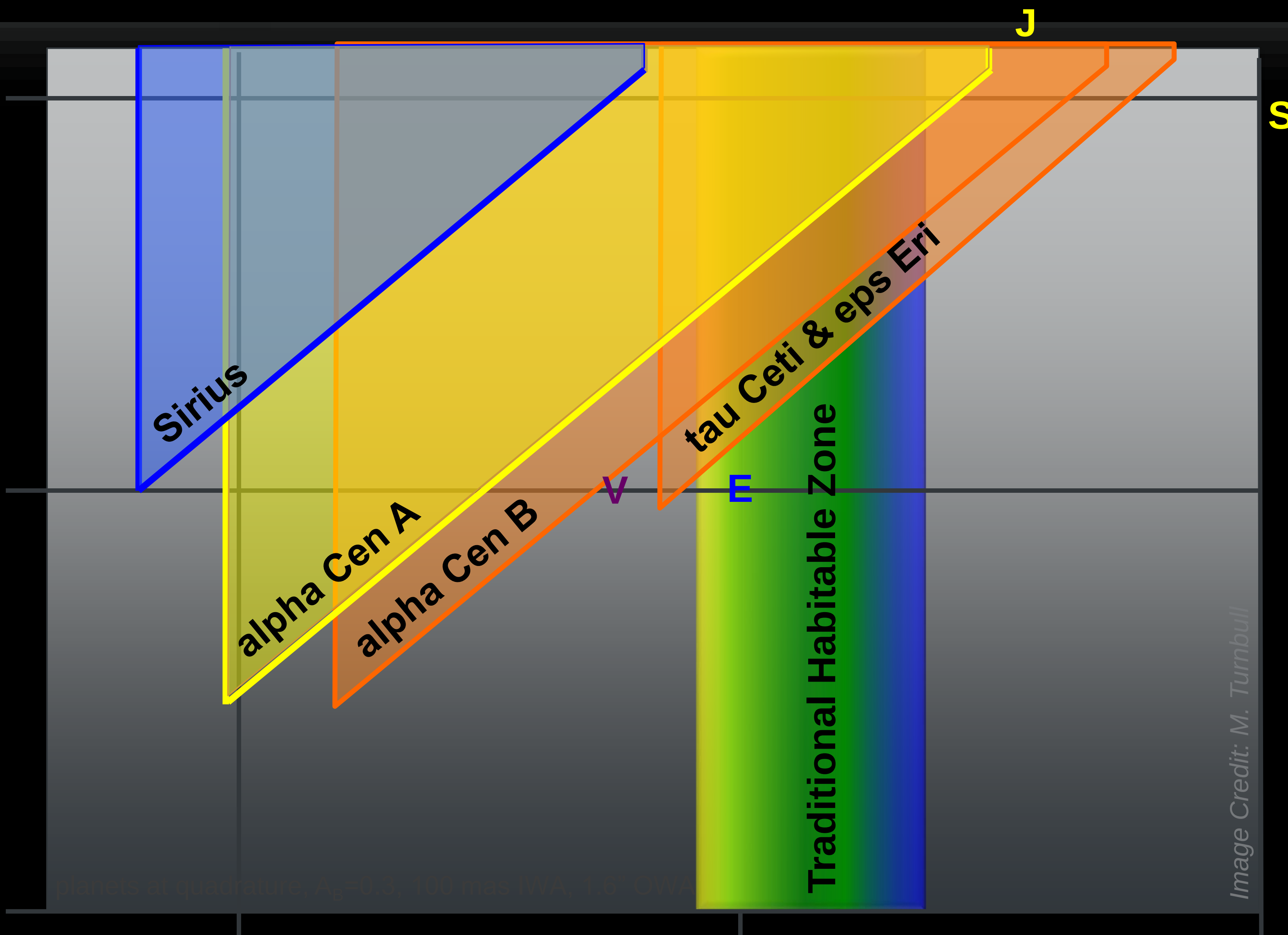
Discovery: What Other Planets Can We Find?



Let’s Talk About Stars

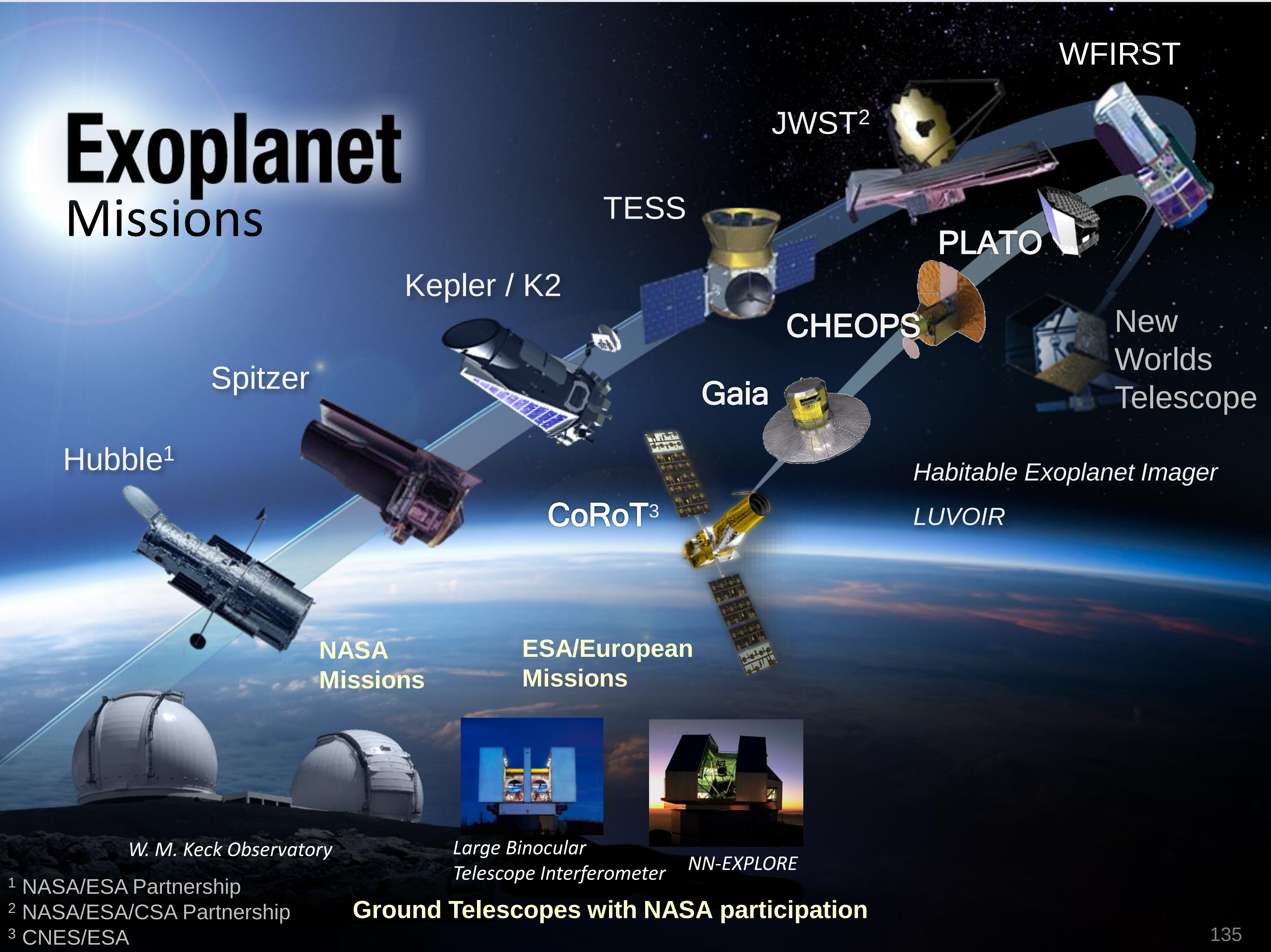
	Exo-S Targets (in order of planet brightness)					Temperature Regime of Planets brighter than V = 30 ("priority zero" targets in bold)				
Target	HIP	IWA(AU)	IHZ(mas)	OHZ(mas)	min R_p (Re)	1 Re	1.5 Re	2 Re	4 Re	11 Re
Sirius A	32349	0.26	1574	3714	0.2	hot-warm	hot	hot	hot	hot
Vega	91262	0.77	763	1800	0.5	hot	hot	hot	hot	hot-warm
Procyon A	37279	0.35	571	1347	0.2	hot	hot-warm	hot-warm	hot-warm	hot-warm
Altair	97649	0.51	478	1129	0.3	hot	hot-warm	hot-warm	hot-cold	hot-cold
Fomalhaut	113368	0.77	395	932	0.5	hot	hot	hot-warm	hot-warm	hot-cold
beta Leo	57632	1.10	260	614	0.6	hot	hot	hot-warm	hot-cold	hot-cold
beta Cas	746	1.68	241	569	1.0	hot	hot	hot	hot-warm	hot-cold
alpha Cep	105199	1.50	223	526	0.9	hot	hot	hot-warm	hot-warm	hot-cold
eta Boo	67927	1.14	204	481	0.7	hot	hot-warm	hot-warm	hot-cold	hot-cold
beta TrA	77952	1.24	186	439	0.7	hot	hot-warm	hot-warm	hot-cold	hot-cold
beta Hyi	2021	0.75	193	457	0.4	hot-warm	hot-warm	hot-cold	hot-cold	hot-cold
delta Cap	107556	1.19	183	432	0.7	hot	hot-warm	hot-warm	hot-cold	hot-cold
iota UMa	44127	1.45	165	389	0.9	hot	hot-warm	hot-warm	hot-cold	hot-cold
alpha Cir	71908	1.66	160	378	1.0	hot	hot	hot-warm	hot-cold	hot-cold
tet UMa	46853	1.35	162	382	0.8	hot	hot-warm	hot-warm	hot-cold	hot-cold
Tabit	22449	0.81	161	380	0.5	hot-warm	hot-warm	hot-cold	hot-cold	hot-cold
gamma Cep	116727	1.41	183	432	0.8	hot	hot	hot-warm	hot-cold	hot-cold
detla Aql	95501	1.55	145	342	0.9	hot	hot-warm	hot-warm	hot-cold	hot-cold
mu Her	86974	0.83	150	355	0.5	hot-warm	hot-warm	hot-cold	hot-cold	hot-cold
eta Cep	102422	1.43	161	380	0.8	hot	hot-warm	hot-warm	hot-cold	hot-cold
eta Cassiope	3821	0.59	144	341	0.3	hot-warm	hot-cold	hot-cold	hot-cold	hot-cold
tau Ceti	8102	0.37	148	349	0.2	hot-cold	hot-cold	hot-cold	hot-cold	hot-cold
delta Eridani	17378	0.90	152	360	0.5	hot-warm	hot-warm	hot-cold	hot-cold	hot-cold
delta Pavoni:	99240	0.61	142	334	0.4	hot-warm	hot-cold	hot-cold	hot-cold	hot-cold
beta Vir	57757	1.09	134	315	0.6	hot-warm	hot-warm	hot-cold	hot-cold	hot-cold
gamma Lep	27072	0.89	133	314	0.5	hot-warm	hot-warm	hot-cold	hot-cold	hot-cold
eta Lep	28103	1.49	124	292	0.9	hot	hot-warm	hot-warm	hot-cold	hot-cold
beta Aql	98036	1.37	137	324	0.8	hot	hot-warm	hot-warm	hot-cold	hot-cold
epsilon Erida	16537	0.32	138	326	0.2	hot-cold	hot-cold	hot-cold	hot-cold	hot-cold
iota Peg	109176	1.17	122	288	0.7	hot-warm	hot-warm	hot-cold	hot-cold	hot-cold
alpha Fornac	14879	1.42	121	286	0.8	hot	hot-warm	hot-warm	hot-cold	hot-cold
gam Ser	78072	1.13	118	278	0.7	hot-warm	hot-warm	hot-cold	hot-cold	hot-cold
I Car	50954	1.62	110	259	1.0	hot	hot-warm	hot-warm	hot-cold	hot-cold

Discovery: What Other Planets Can We Find?



"Once we lose our fear of being tiny, we find ourselves on the threshold of a vast and awesome universe..."

-Carl Sagan



Exoplanet
Missions
WFIRST
JWST[2]
TESS
PLATO
Kepler / K2
CHEOPS
New
Worlds
Telescope
Spitzer
Gaia
Hubble[1]
Habitable Exoplanet Imager
CoRoT[3]
LUVOIR
NASA
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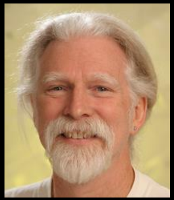
ESA/European
Missions
W. M. Keck Observatory
Large Binocular
Telescope Interferometer
NN-EXPLORE
[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA
Ground Telescopes with NASA participation

Panel Discussion

- **The NASA K2 Mission: (Exo)planets to Dark Energy**
  Dr. Steve B. Howell, NASA Ames Research Center



- **The NASA Exoplanet Exploration Program Overview**
  Dr. Karl Stapelfeldt, Program Chief Scientist, NASA Exoplanet Exploration Program, Jet Propulsion Laboratory, California Institute of Technology

- **The Habitable Exoplanet Imaging Mission - Science and Technology Drivers**
  Dr. B. Scott Gaudi, The Ohio State University and Jet Propulsion Laboratory

- **LUVOIR - Science Cases and Technology Drivers**
  Dr. Shawn Domagal-Goldman, NASA Goddard Space Flight Center

- **Technology Needs to Discover Earth 2.0**
  Dr. Nick Siegler, NASA Exoplanet Exploration Program, Jet Propulsion Laboratory, California Institute of Technology

- **Exploring New and Known Exoplanets with the WFIRST Coronagraph and Starshade**
  Dr. Margaret Turnbull, SETI Institute