Jet Propulsion Laboratory
California Institute of Technology

The NASA Exoplanet Exploration Program

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Sept 15, 2016
AIAA Space 2016
Long Beach, CA

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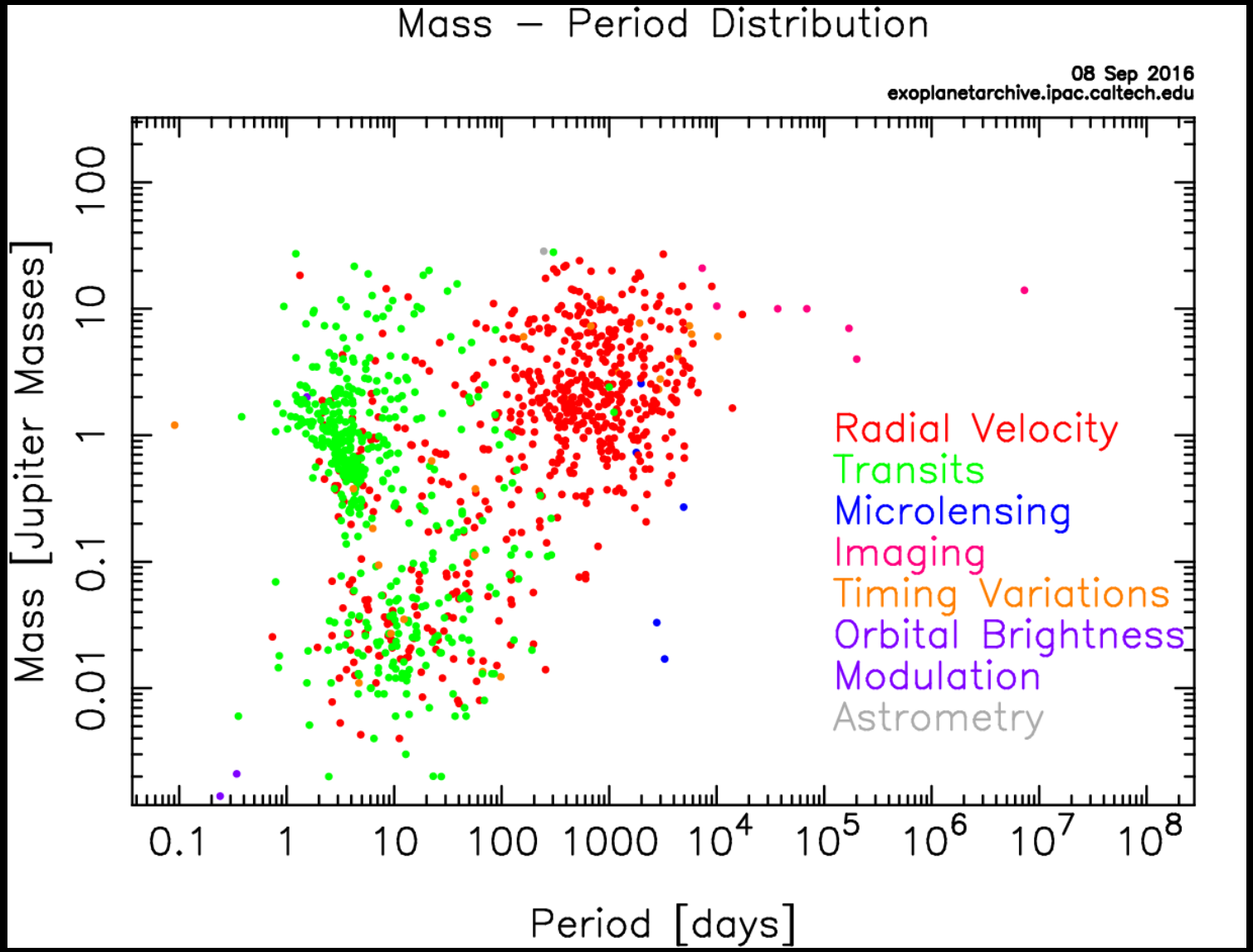
Artist concept of Kepler-16b

Known exoplanets by Discovery method

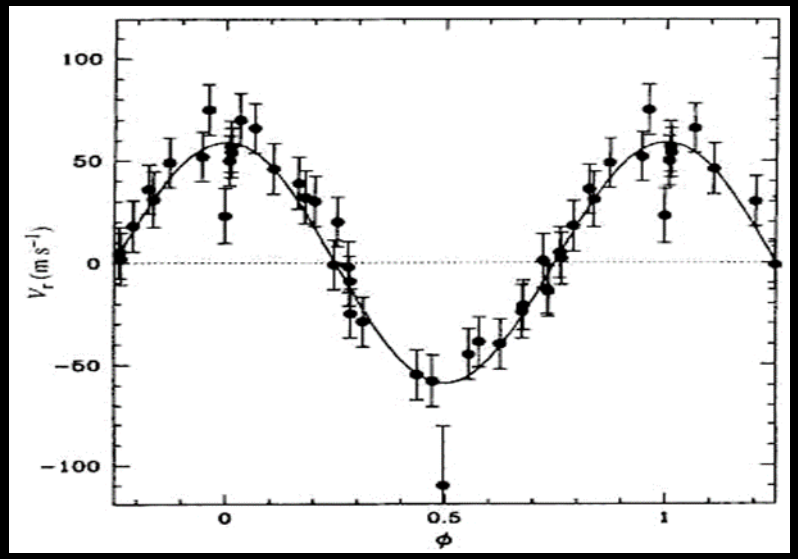


Known exoplanets by Discovery method

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

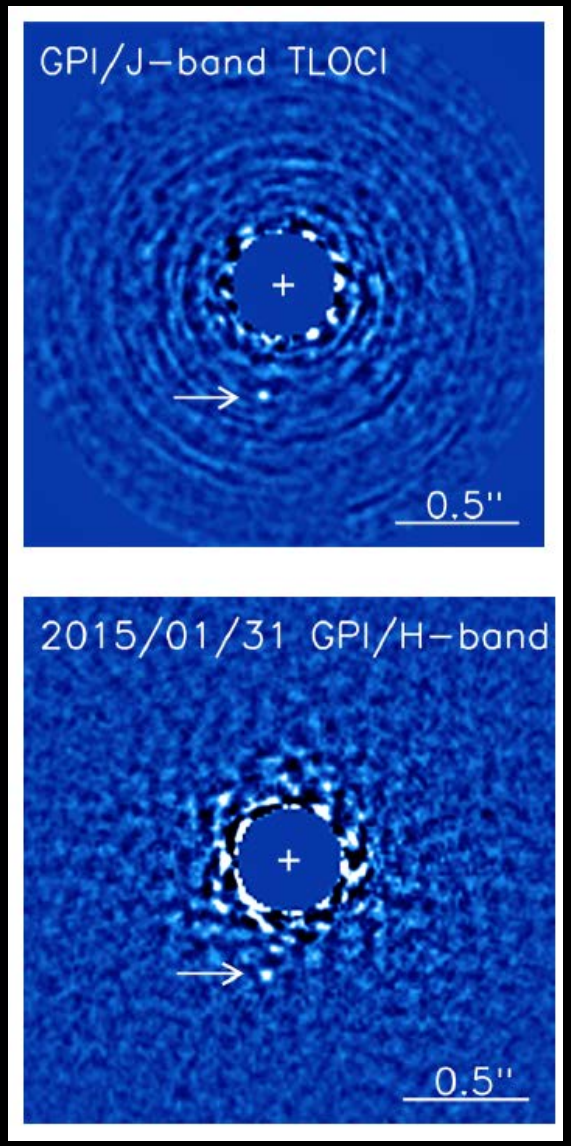
Important RV Discovery in August 2016: A potentially Habitable planet orbits Proxima Centuari, the nearest star !

Anglada-Escudé et al. 2016

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)
- Contrast to star is 2×10^{-6} at 0.5″ separation
- Planet is glowing from its own heat, T= 700 K
- Mass is roughly twice that of Jupiter
- Spectrum below shows methane & some water)

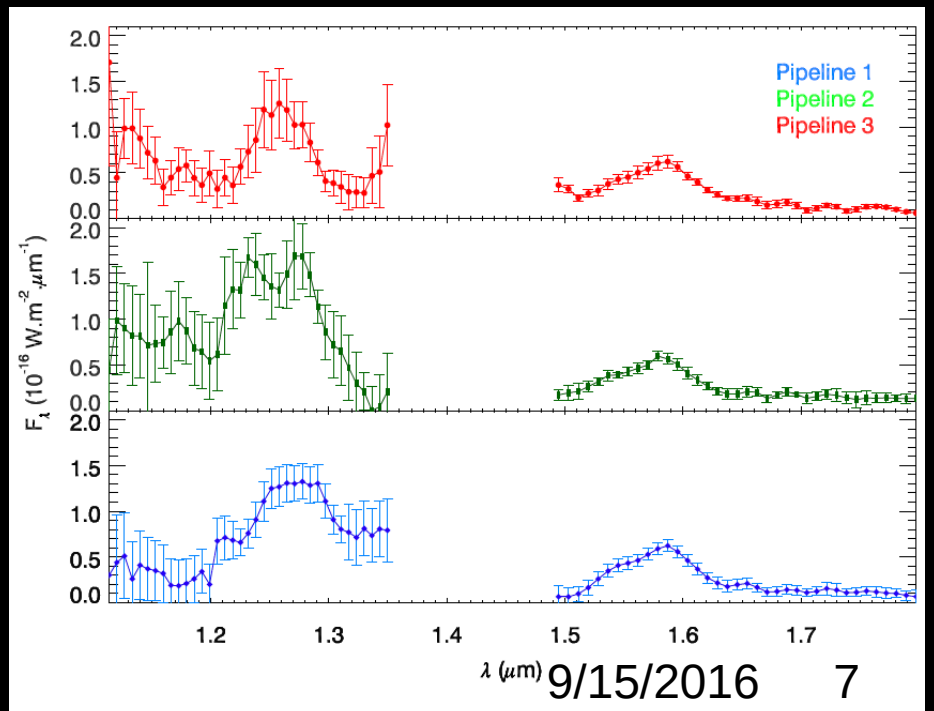


Figure S2: 51 Eri b spectra from the three different pipelines. The *H*-band spectra

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

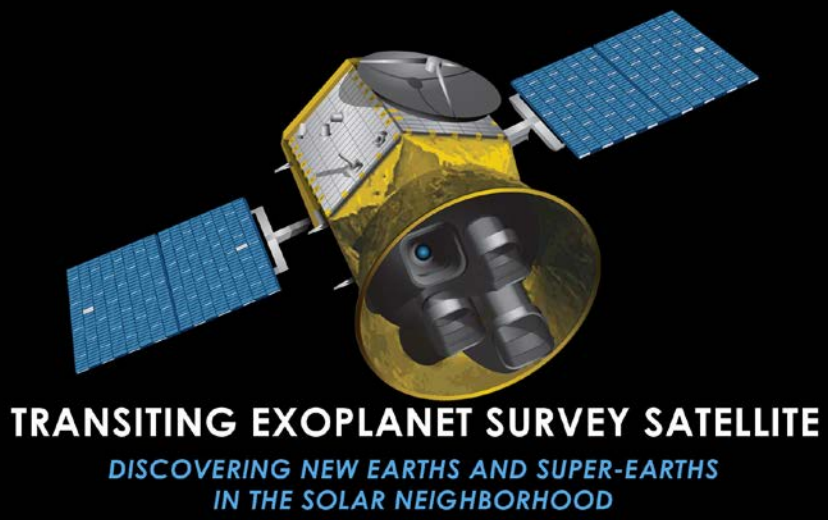
http://exoplanets.nasa.gov/exep

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

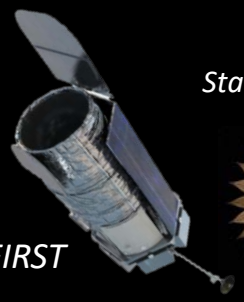


NASA Exoplanet Exploration Program

Space Missions and Mission Studies

Kepler, K2

WFIRST



Starshade

Decadal Studies

Coronagraph

Public Communications

Supporting Research & Technology

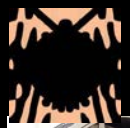
Key Sustaining Research

Large Binocular Telescope Interferometer

Keck Single Aperture Imaging and RV

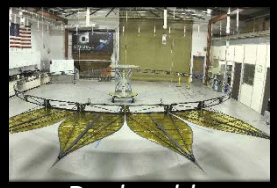
NN-EXPLORE

Technology Development



Coronagraph Masks

High-Contrast Imaging



Deployable Starshades

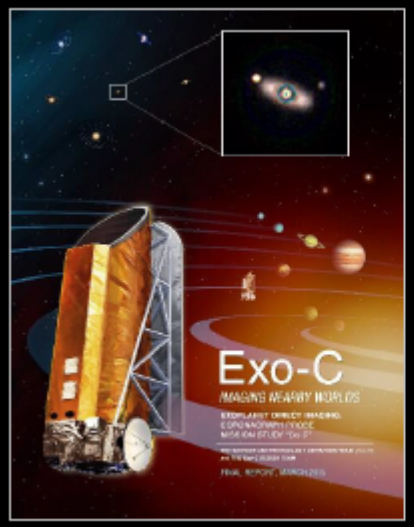
NASA Exoplanet Science Institute

Archives, Tools, Sagan Fellowships, Professional Engagement

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

Exo-S:

External Occulter (Starshade)

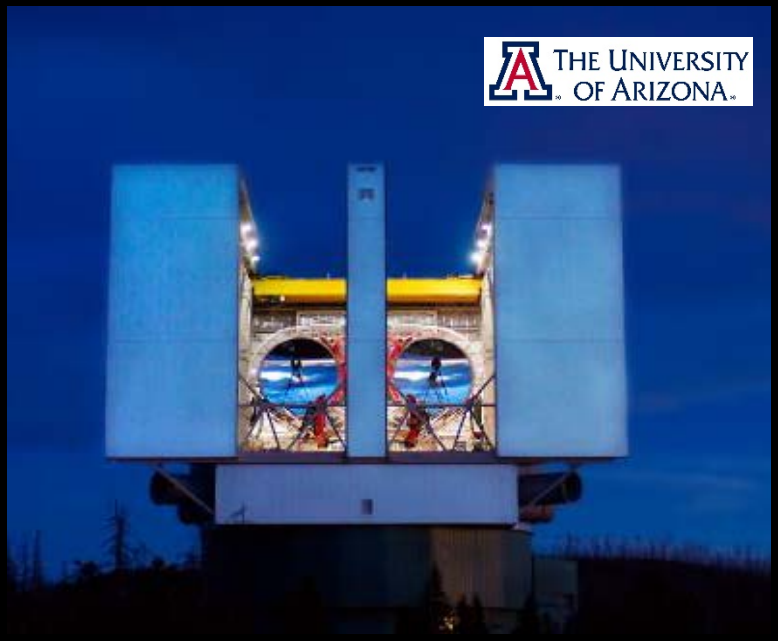
S. Seager, STDT Chair, MIT

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

- 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

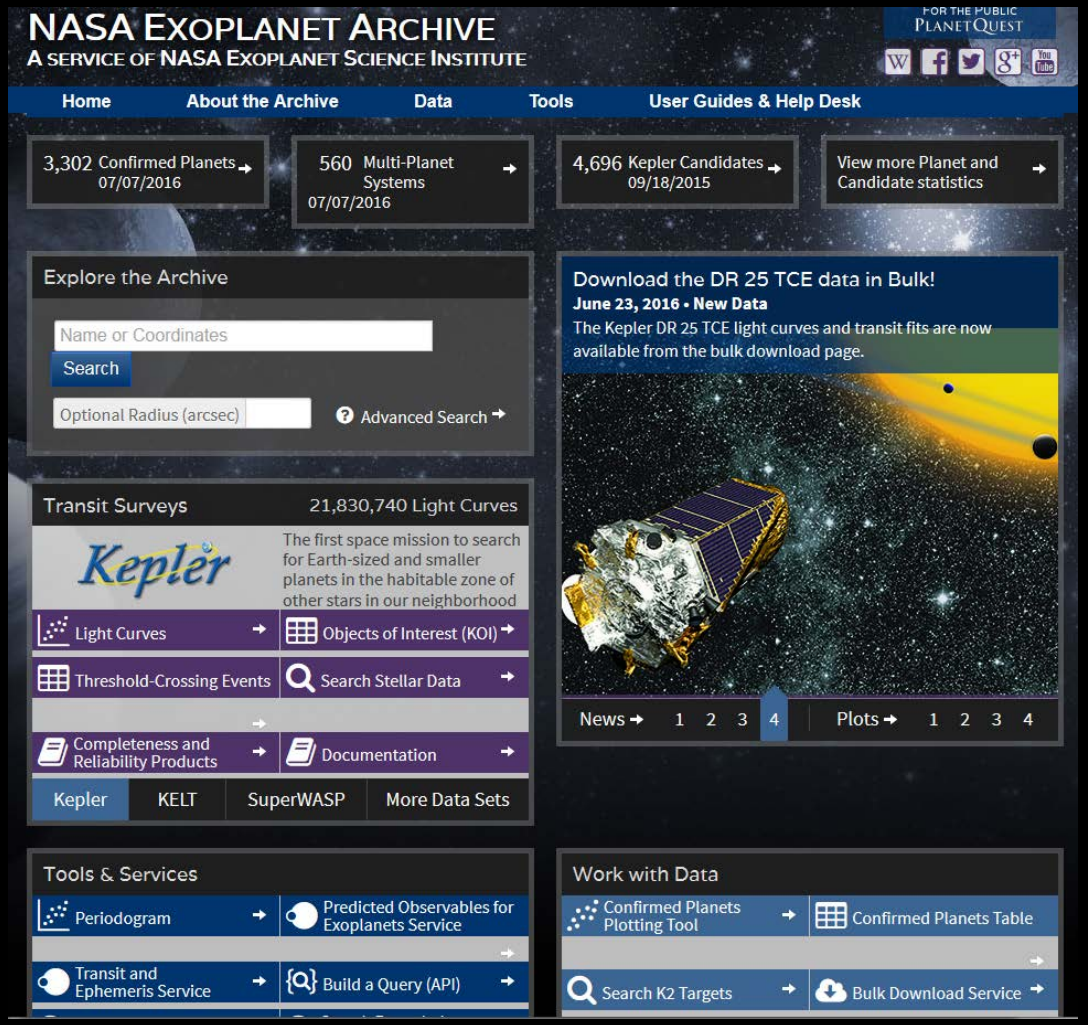
Exoplanet Archive

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

Followup Program

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

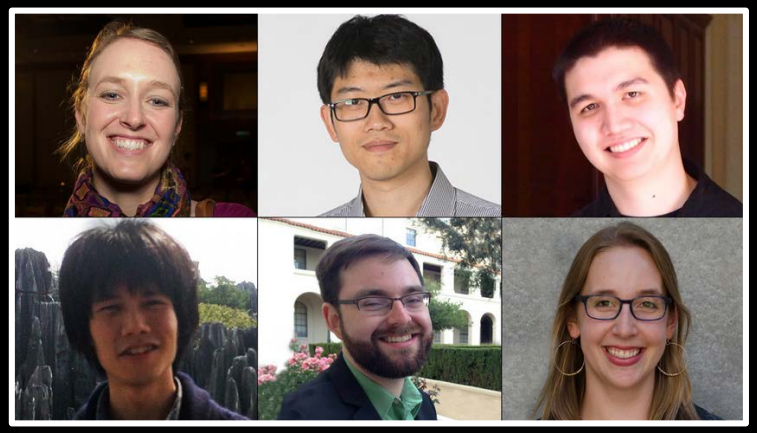
http://exoplanetarchive.ipac.caltech.edu



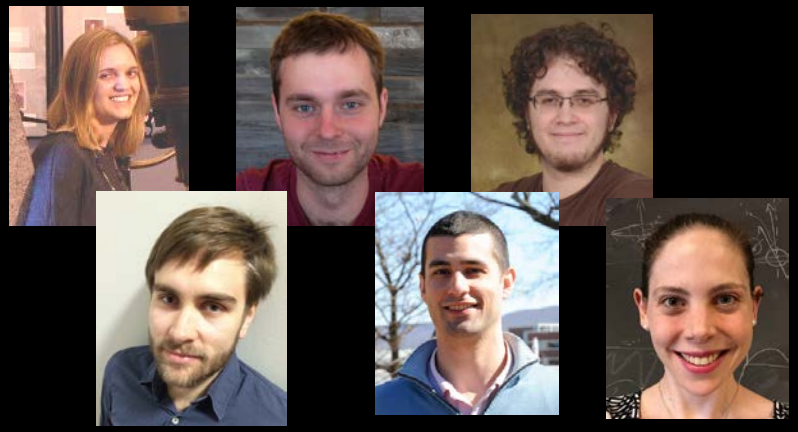
Sagan Postdoctoral Fellowship Program

supports exoplanet research by outstanding early career scientists

2016

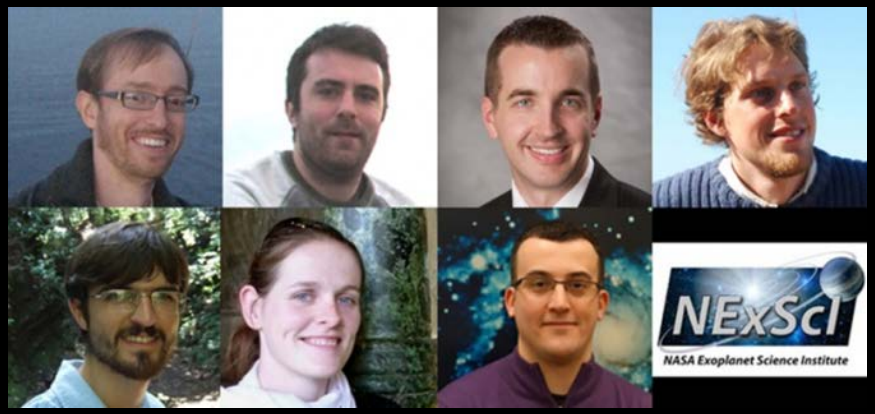


2015



2013

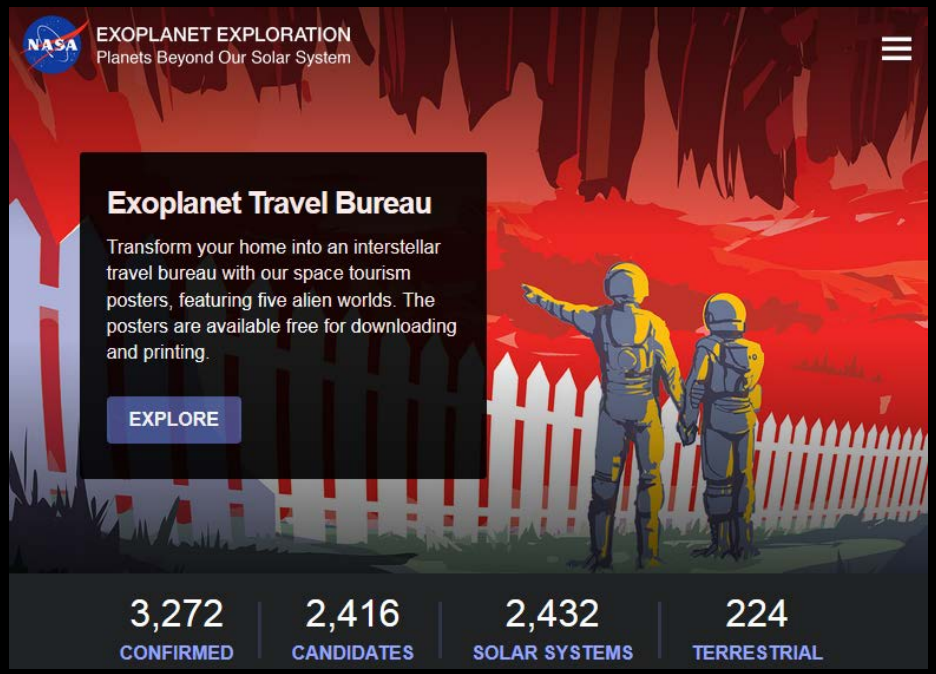
2014

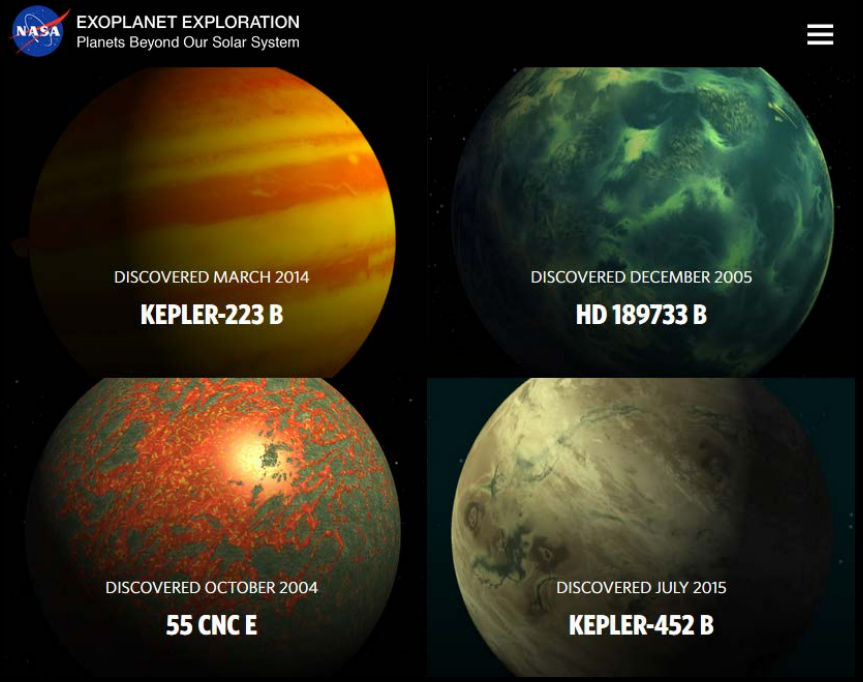


Annual Sagan Summer School in Pasadena provides training in exoplanet research techniques for students

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

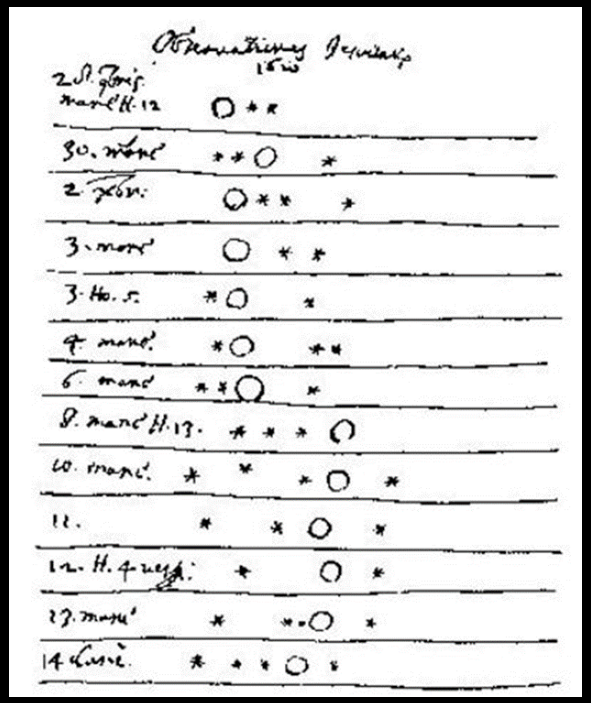
ExoPAG 15 meeting at winter meeting of the American Astronomical Society: Jan 2-3 2017, Dallas TX

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

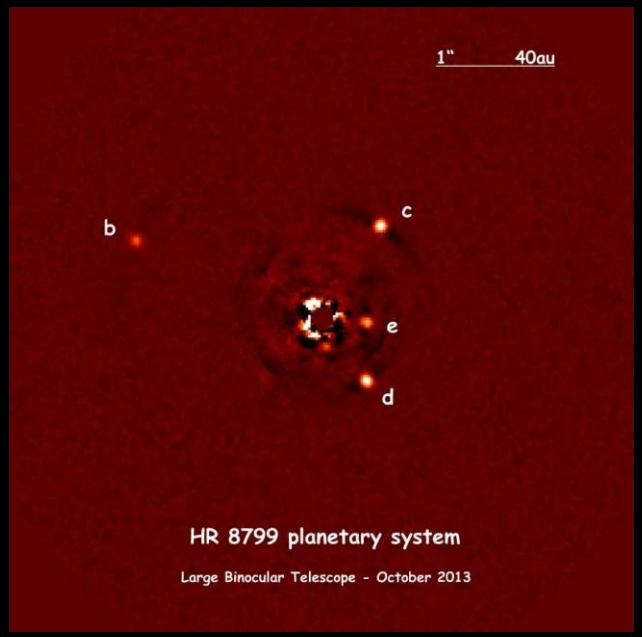
Epilog: Discovering Planetary Systems:

1610



Galileo discovers
Jovian satellite system

2008



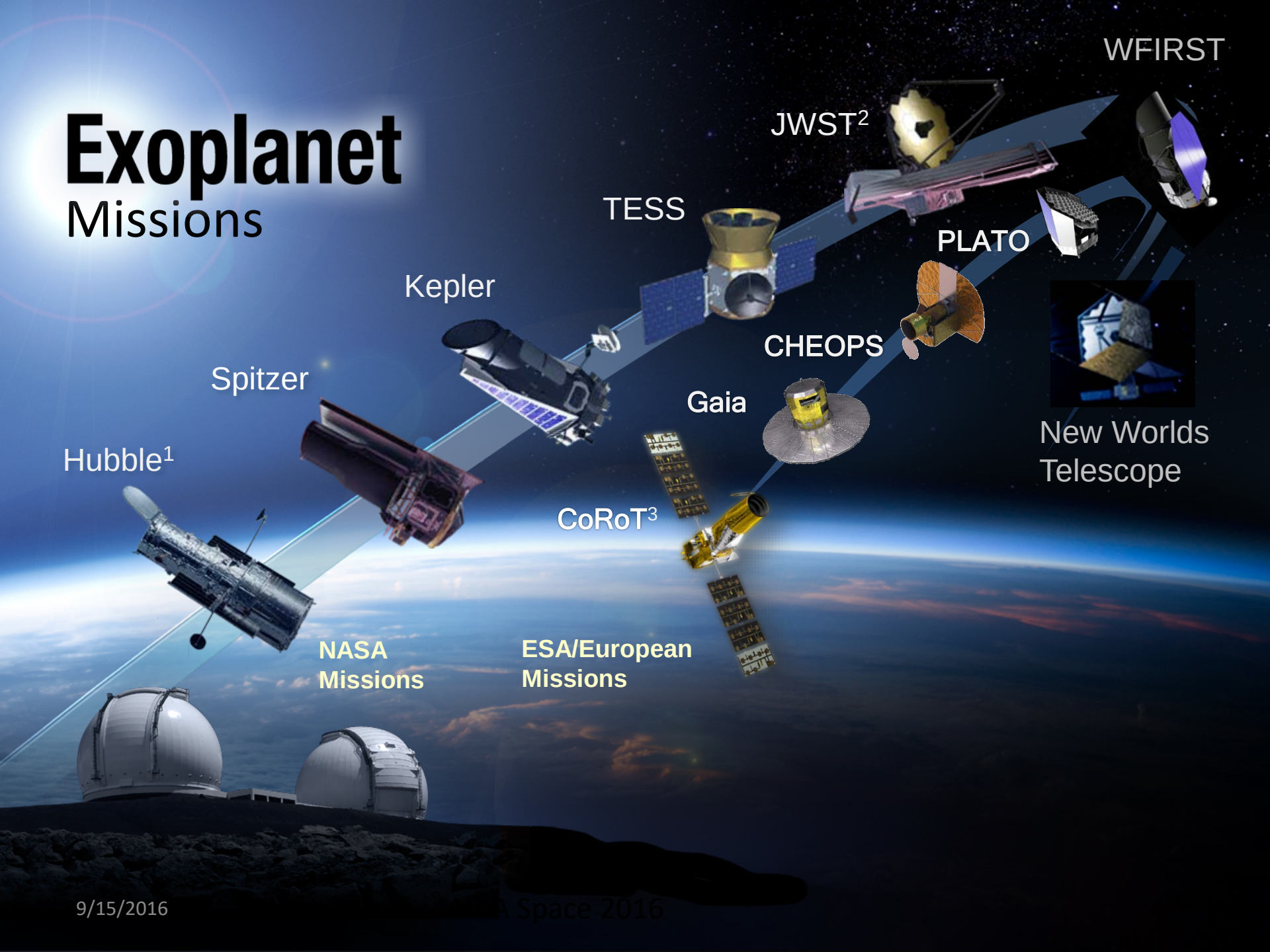
Marois et al. discover
HR 8799 planetary system

2035 ?

Future space
telescopes confirm first
habitable exoplanet

Jet Propulsion Laboratory
California Institute of Technology

Exoplanet Missions



Exoplanet Exploration Program Organization Chart

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

Exoplanet Prog. Exec. – J. Gagosian
Exoplanet Prog. Sci. – Dr. D. Hudgins

WFIRST Program Executive – J. Gagosian
WFIRST Program Scientist – Dr. D. Benford
Kepler / Closeout Program Exec – K. Chamberlin
Kepler / K2 Program Executive – J. Hayes
Kepler / K2 Program Scientist – Dr. M. Perez
NExScI, Keck, LBTI Prog. Exec. – Dr. M. Perez
NExScI, Keck, LBTI Prog. Sci. – Dr. H. Hasan
NExScI, Keck, LBTI Deputy Prog. Sci – Dr. K. Sheth
NN-EXPLORE Program Exec/Sci.- Dr. D. Hudgins

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

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

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

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

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

7310
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)

Exoplanet Probe STDT - Starshade[1]
Dr. S. Seager, MIT

Exoplanet Probe Extended Study Office
K. Warfield (312)

Exoplanet Probe STDT - Coronagraph[1]
Dr. K. Cahoy, MIT

7312
Business Operations
Resource Analyst – L. Scott (252)
Project Schedule Analyst – G. Luzwick (252)

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

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

Kepler (ARC)
Project Manager (Phase E) – C. Sobeck
Project Scientist (Phase E) – Dr. S. Howell
Mission Scientist – Dr. N. Batalha
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. R. Millan-Gabet, 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

Ground Observatories & Suborbital Activity (Caltech)
Manager – Dr. D. Imel
Keck Project Scientist –
Dr. R. Akeson

Starshade Technology Project (JPL)
Manager – TBD

735
NASA-NSF Exoplanet Observational Research
Manager – Dr. P. Willems, AD, JPL (383D)
Pennsylvania State University Team

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

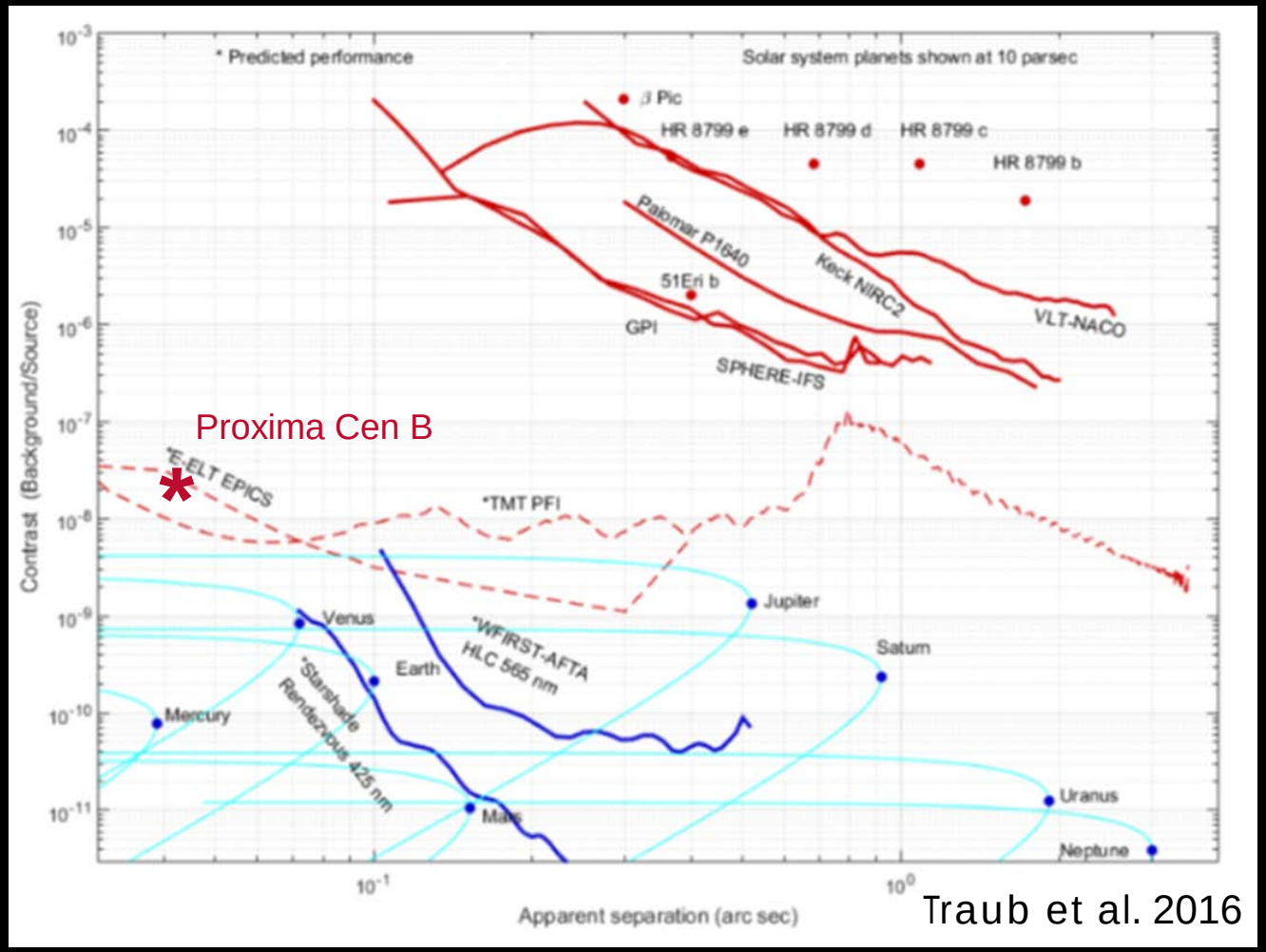
706
WFIRST Project Office (JPL)
Project Manager, P. Barela
Project Scientist: Dr W. Traub
Deputy Proj. Scientist: Dr. J. Rhodes
Telescope – B. Parvin (706)
Coronagraph – Dr. F. Zhao (383)
Technology -
Dr. I. Poberezhskiy (383)
Dr. R. Demers (383)
Science Center –
Dr. R. Cutri (Caltech)

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

[1]Reports to NASA HQs APD

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

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