European Geosciences Union
General Assembly 2014

The Future of NASA's Exoplanet Exploration Program

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29 April, 2014

The Exoplanet Exploration Program: Exploring New Worlds

Exploring *How the Universe Works*
Discovering *and Characterizing Exoplanets*
Searching *for Signs of Life in the Galaxy*

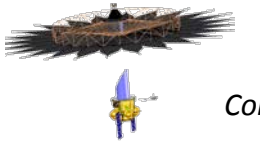
Space Missions and Mission Studies

Kepler

AFTA

Probe-Scale:

External Occulter (Starshade)



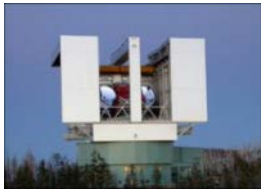
Coronagraph

Public Engagement

Supporting Research & Technology

Key Sustaining Research

Keck Single Aperture Imaging and RV



Large Binocular Telescope Interferometer

Technology Development

High Contrast Imaging

Deployable Star Shades

Archives, Tools & Professional Education

NASA Exoplanet Science Institute

Exoplanet Missions

JWST

AFTA

TESS

Kepler

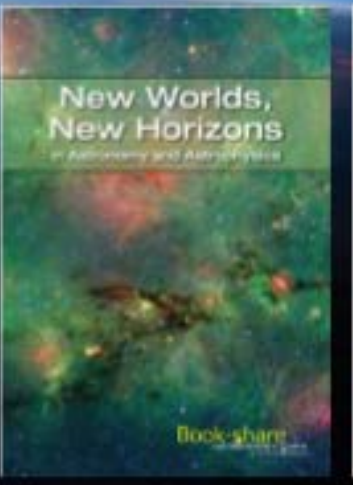
New Worlds Telescope

Spitzer

Hubble

Ground-based Observatories

2001 Decadal Survey



2010 Decadal Survey

The Search for Life in the Universe Requires η_{Earth}

Complete the census

- Kepler (warm planets)
- WFIRST microlensing (cool planets)

Find nearby transiting planets

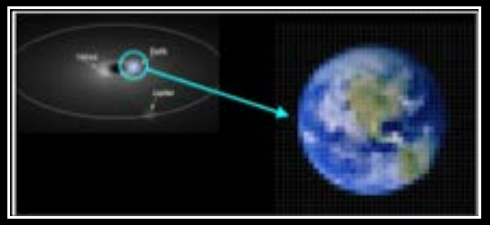
- TESS

Characterize super-earth/mini-Neptunes

- JWST

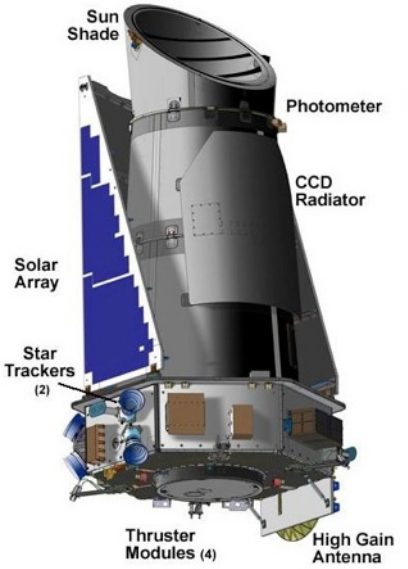
Imaging and Spectroscopy of planets

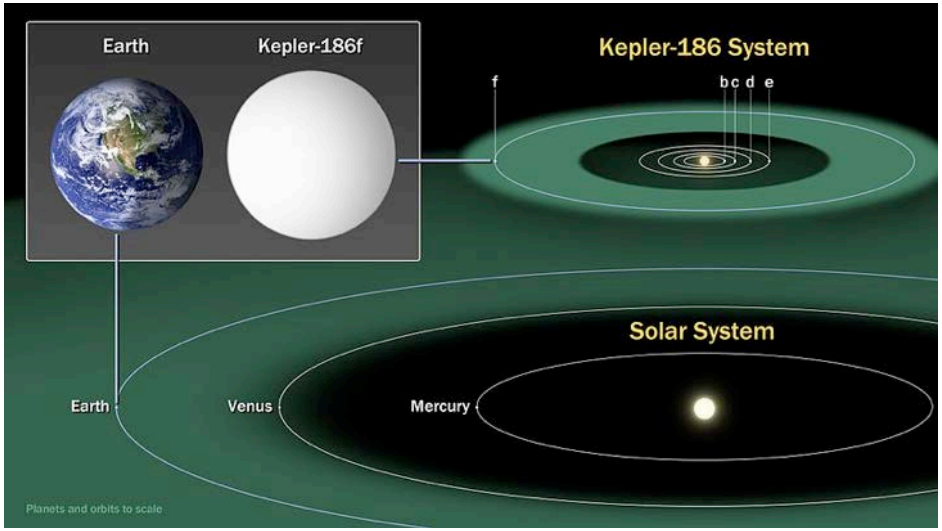
- WFIRST-AFTA coronagraph
  - Jupiters, Neptunes, Super-Earths
- New Worlds Mission ('Earth 2.0')



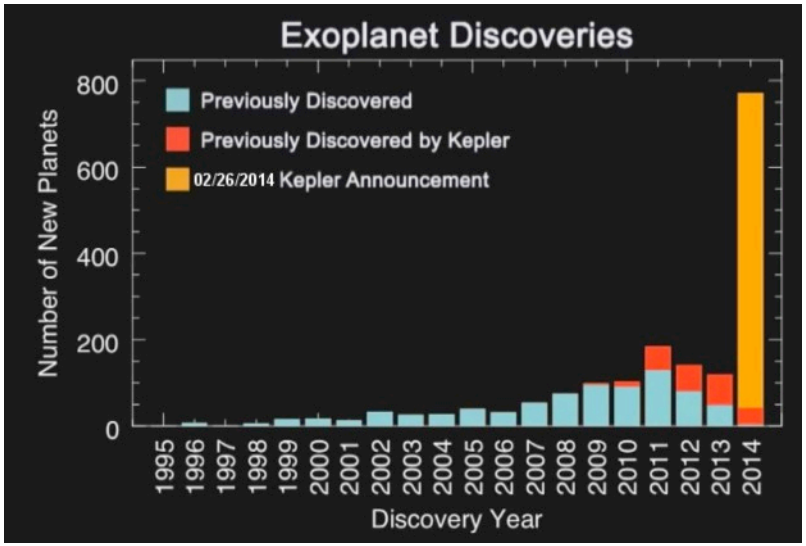
Kepler Mission

- Kepler Mission ended in May 2013 after a second reaction wheel failed
- Analysis of Kepler data continue
- Data from Quarter 0-17 (May 2009 – May 2013) are archived





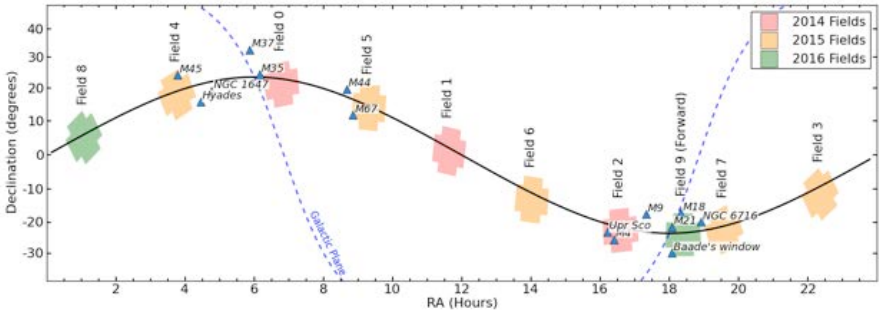
April 17: Kepler team announced discovery of Kepler-186f, the first nearly Earth-sized planet located in the habitable zone of an M1 dwarf



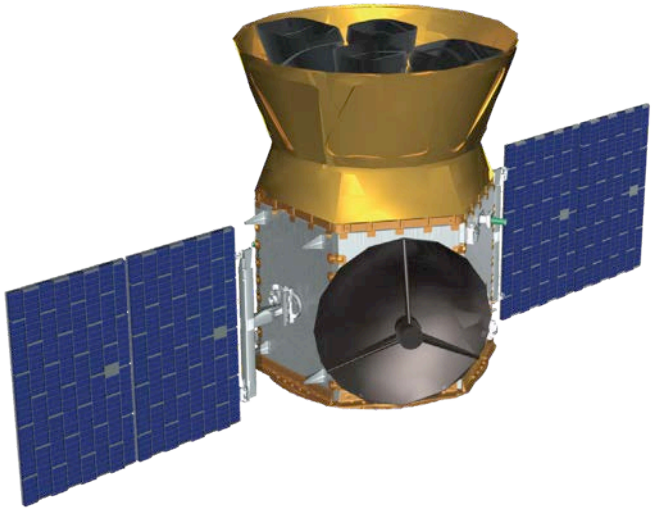
February 26: announced Kepler confirms the existence of **715** new exoplanets using "verification by multiplicity"

Kepler's 'Second Light' – the Proposed K-2 Mission

- A series of engineering demonstrations of 2-wheel performance on the spacecraft were performed in 2013
- With only two reaction wheels, operations are possible only in certain orientations (balancing solar pressure)
- Photometry possible at reduced precision (~60 ppm in 6 hours on V-12 G-star)
- In Feb 2104 a second detector module failed (40 of the original 44 operational)
- A Call for White Papers resulted in 42 submitted papers covering exoplanets, asteroseismology, open cluster studies, NEOs, and more.
- Kepler Project received permission in Dec 2013 to submit a proposal to the 2014 Astrophysics Senior Review of Operating Missions
  - Under review: Hubble, Chandra, Fermi, NuSTAR, Spitzer, Suzaku, Swift, XMM-Newton, and WISE
- If approved, K-2 will observe a series of ecliptic plane fields



TESS
Transiting Exoplanet Survey Satellite



- Mission PI: George Ricker, MIT
- Selection occurred April 5, 2013
- SRR held February 2014
- Development progressing on plan
- Tentative launch date August 2017

Mission: All-Sky, two-year photometric exoplanet mapping mission.

Instruments: Four WFOV CCD cameras with overlapping FOV of 23x90deg.
Passively-cooled 600-1000nm 4096x4096 pixel FPA

Science goal: *Identify transiting planets around the brightest stars in the sky*

- Planets with periods up to 1 month in the ecliptic (~HZ for M stars)
- Can find up to 1 year orbits in continuous viewing zones at ecliptic poles

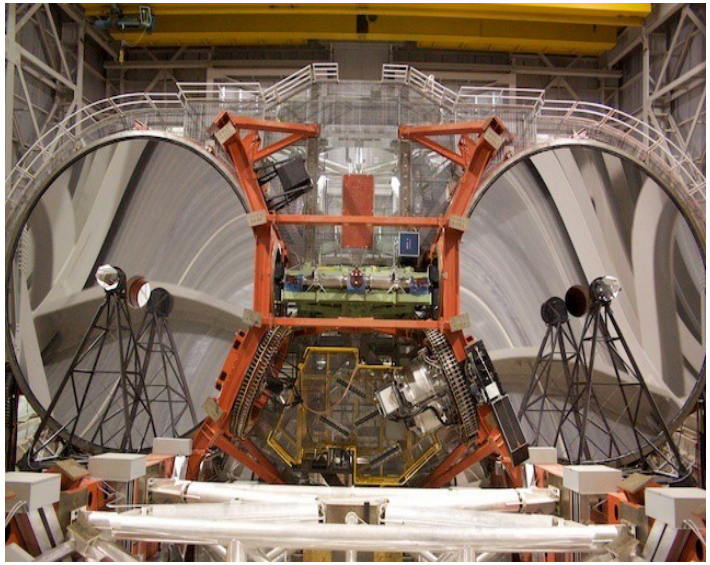
A subset of the resulting planets will have their atmospheres characterized by:

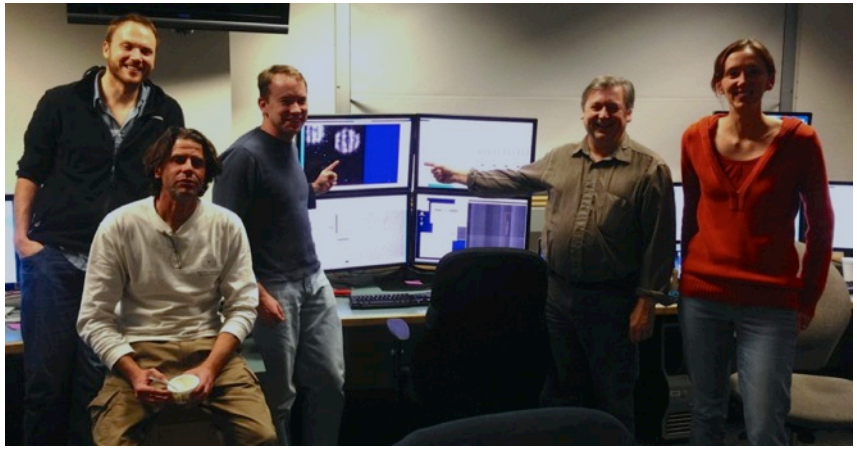
- JWST
- Extremely Large Telescopes (ELTs)
- Future Exoplanet Explorers, Probes, and Large Missions

Large Binocular Telescope Interferometer (LBTI)
University of Arizona

Commissioning Status:

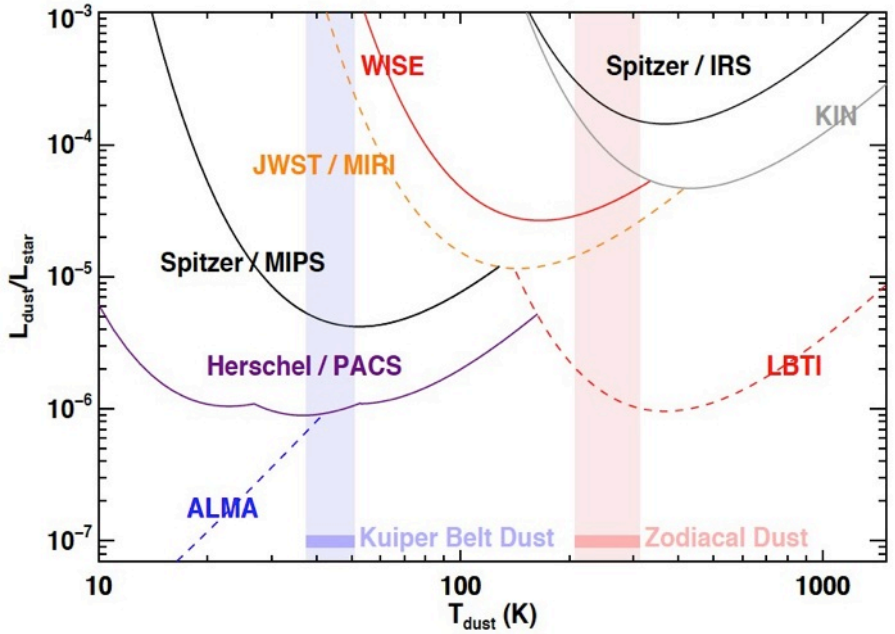
- All subsystems finalized and demonstrated on–sky
- Achieved closed-loop nulls on the sky (in Dec 2013)





Science Capabilities:

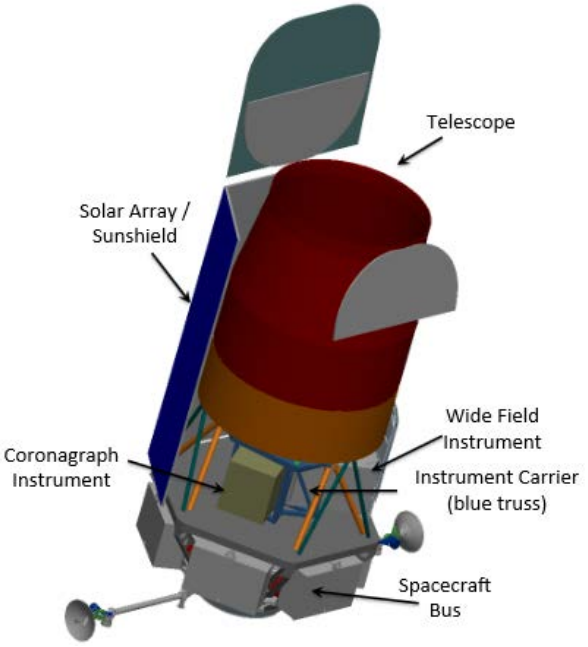
- LBTI will enable characterization of exo-solar planetary systems
- Survey 50 nearby stars for exozodiacal dust, at levels of 3-6 times (1σ) the dust in our own planetary system



WFIRST-AFTA

- 2.4m aperture on-axis obscured telescope, 270K
- 28.5 degree inclination geosynchronous orbit, Atlas V 541 launch vehicle
- Two-channel widefield instrument with IFU channel 0.6 to 2.0 µm for Dark Energy, NIR Surveys, and Exoplanet Microlensing
- FPA: 6x3 4k x 4k HgCdTe detectors, 0.76 to 2.0 µm
- Coronagraph instrument for Exoplanet Direct Imaging and Characterization
- Mission life 6 years with coronagraph

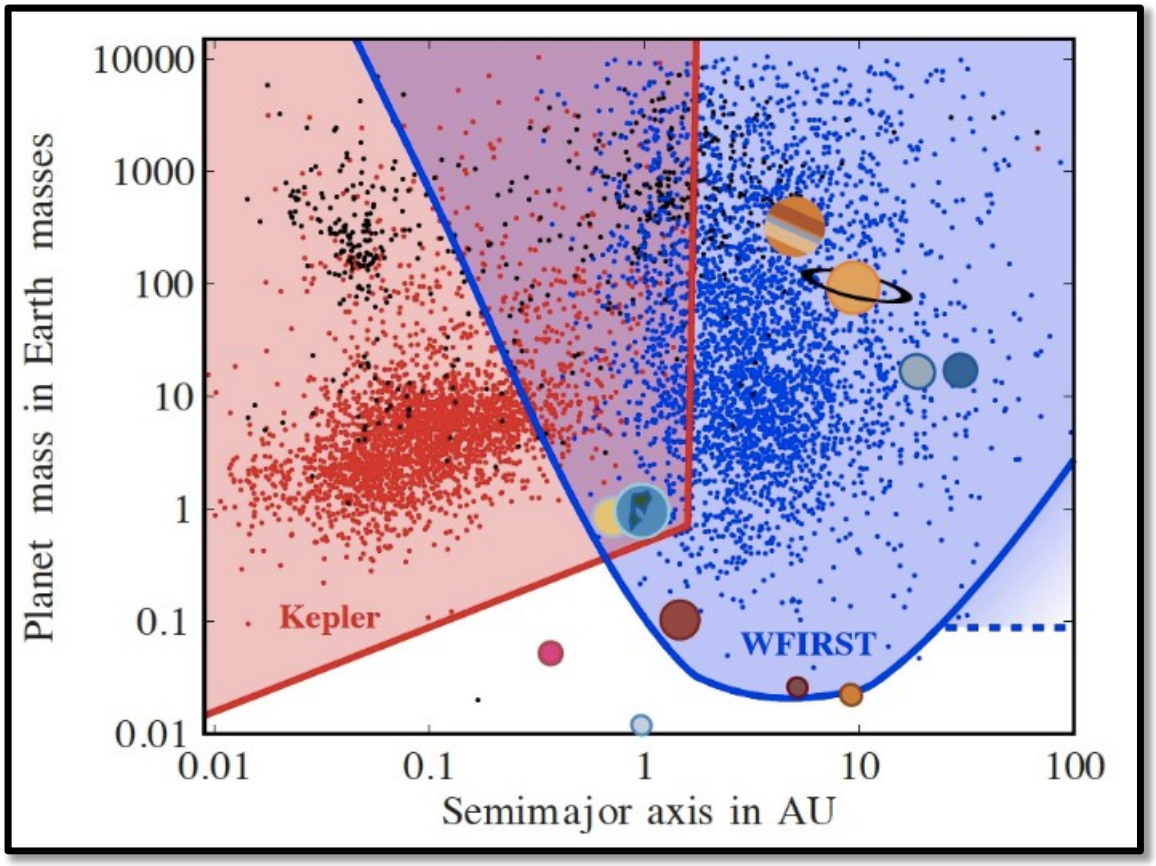
- *Science Definition Team (SDT):*
  - *SDT Interim Report* due in May 2014
  - *SDT Final Report* due in Jan 2015



WFIRST final report May 23, 2013
http://wfirst.gsfc.nasa.gov/

Exoplanet detection by AFTA Microlensing

- Search field towards galactic bulge
- Sensitive to ~3000 bound planets
- Sensitive to hundreds of unbound, free-floating planets to ~Mars mass
- Complements the census begun by Kepler



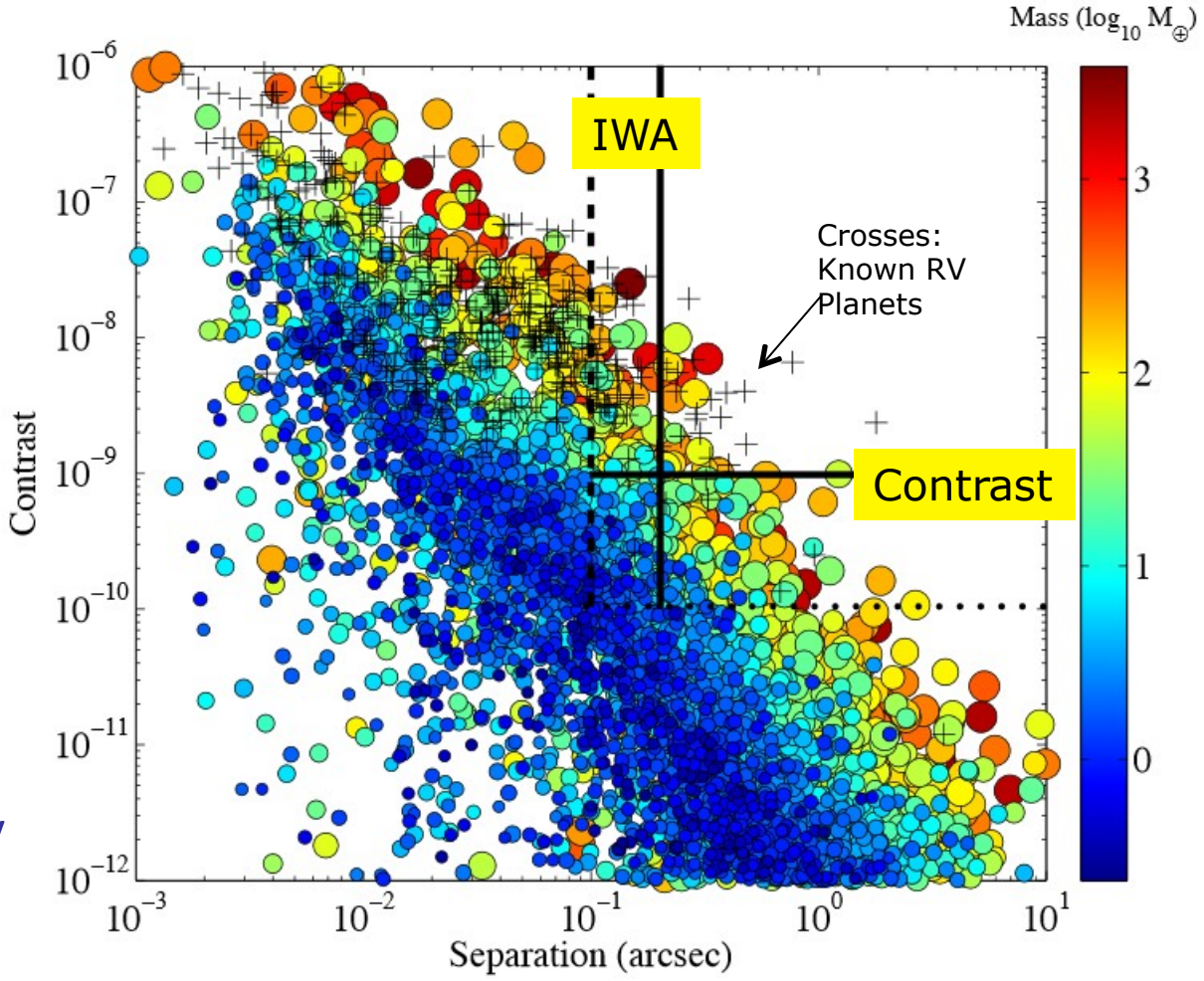
Sensitivity of AFTA Coronagraph for Imaging Exoplanets

- Model planets are shown:
  - Gas giants: red, yellow
  - Ice giants: blue-green
  - Terrestrial: blue

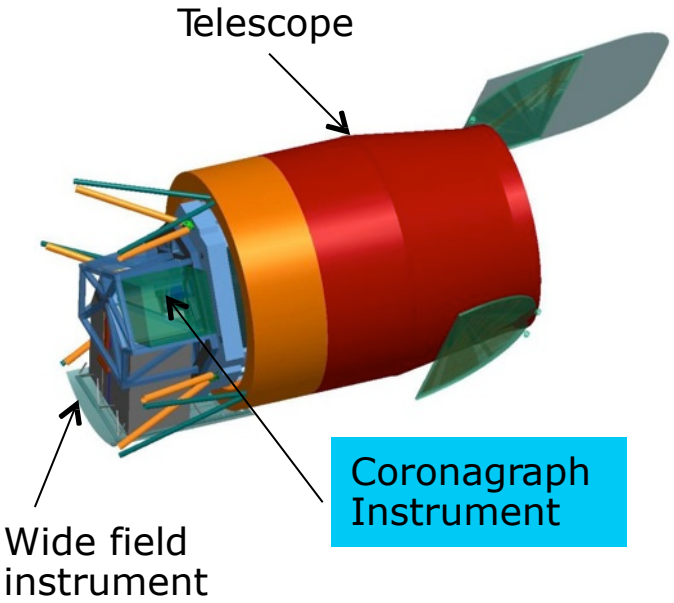
- Measurement goal is to measure the brightness of reflected light of each planet, across the spectrum

- Science goal is to determine atmospheric gases, clouds, clues regarding origin & evolution of planet, and history of planet system

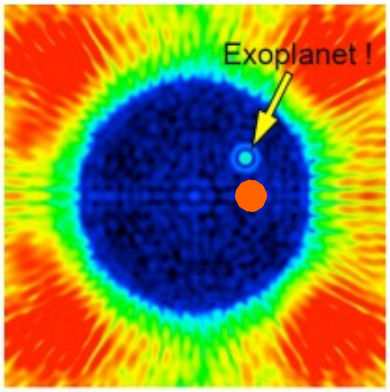
- Debris Disks (exozodiacal dust)



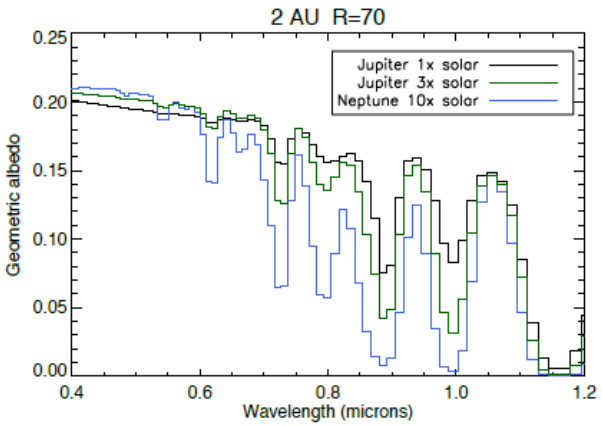
AFTA Coronagraph Instrument



Coronagraph Instrument



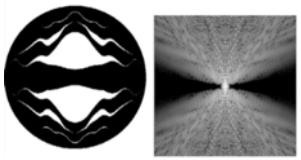
Exo-planet Direct imaging



Exo-planet Spectroscopy

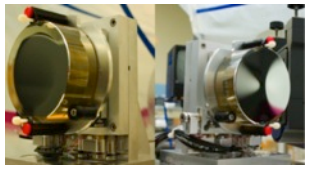
- Characterize the spectra of over a dozen radial velocity planets
- Discover and characterize up to a dozen more ice and gas giants
- Provide crucial information on the physics of planetary atmospheres and clues to planet formation
- Respond to Decadal Survey to mature coronagraph technologies, leading to first images of a nearby Earth

Several Potential Technologies for High-Contrast Imaging

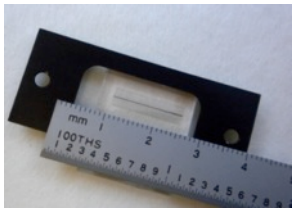


Shaped Pupil Mask Pupil Masking (Vanderbei & Kasdin, Princeton Univ.)

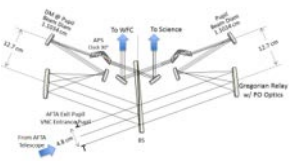
Vector Vortex Mask Image Plane (Serabyn, JPL)



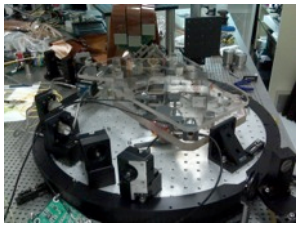
Phase Induced Amplitude Apodization (PIAA) Pupil Re-Mapping (Guyon, Univ. Arizona)



Hybrid / Band-Limited Lyot Mask Image Plane Amplitude & Phase (Trauger, JPL)



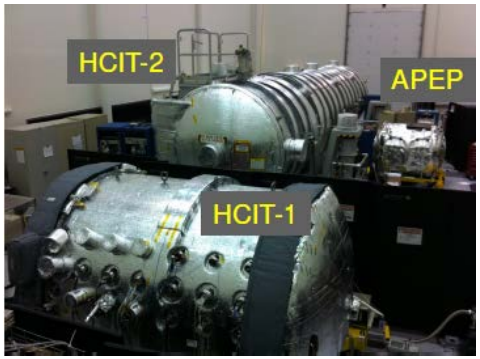
Visible Nuller Coronagraph: Phase-Occulting (Lyon, GSFC)



Visible Nuller Coronagraph: DaVinci (Shao, JPL)

Primary Approach (combined on filter wheel)	**Back-up approach**
• Hybrid Lyot Coronagraph • Shaped Pupil	• PIAA-CMC (Phase-Induced Amplitude Apodization Complex Mask Coronagraph)

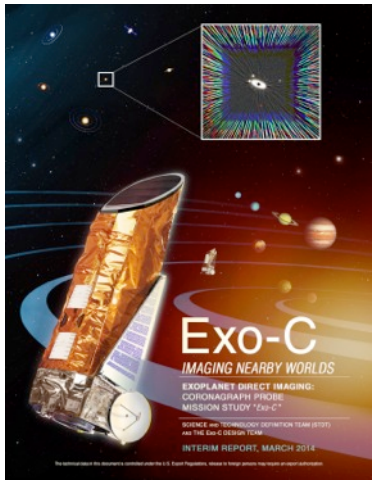
Downselection in Jan 2014



- TRL-5 at start of Phase A (Oct 2016)
- TRL-6 at PDR (Oct 2018)

Exoplanet Probe Studies

- In 2013 NASA began studies for two 'probe-scale' exoplanet missions
  - For consideration by 2020 Decadal Survey
  - To guide technology investment for remainder of decade
  - Candidate for 2017 new start if AFTA cannot be started this decade
- Two Science and Technology Definition Teams (STDTs) selected
  - Exo-C: Probe coronagraph
  - Exo-S: Probe starshade (external occulter)
- Success criteria include:
  - Compelling science, viable technology, $1B life cycle cost



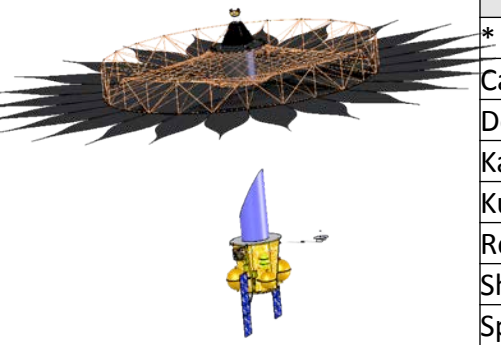
- Both teams have written *Interim Reports* (May 2014)
- *Final Mission Concept Reports* due in January 2015
- *Independent* cost estimates due in February 2015

STDT Membership

Probe Coronagraph

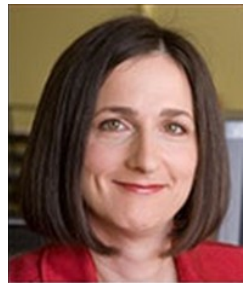
Last	First	Organization
* Stapelfeldt	Karl	NASA Goddard Space Flight Center
Belikov	Rus	NASA Ames Research Center
Bryden	Geoff	Jet Propulsion Laboratory
Cahoy	Kerri	Massachusens Inst. of Technology
Chakrabarti	Supriya	Univ. of Massachusetts, Lowell
Marley	Mark	NASA Ames Research Center
McElwain	Michael	NASA Goddard Space Flight Center
Meadows	Vikki	Univ. of Washington
Serabyn	Gene	Jet Propulsion Laboratory
Trauger	John	Jet Propulsion Laboratory
* Chair		

Karl Stapelfeldt
GSFC
Chairperson



Probe Starshade

Last	First	Organization
* Seager	Sara	Massachusetts Inst. of Technology
Cash	Webster	Univ. of Colorado
Domagal-Goldman	Shawn	NASA Goddard Space Flight Center
Kasdin	Jeremy	Princeton Univ.
Kuchner	Marc	NASA Goddard Space Flight Center
Roberge	Aki	NASA Goddard Space Flight Center
Shaklan	Stuart	Jet Propulsion Laboratory
Sparks	William	Space Telescope Science Institute
Thomson	Mark	Jet Propulsion Laboratory
Turnbull	Margaret	Global Science Institute
* Chair		



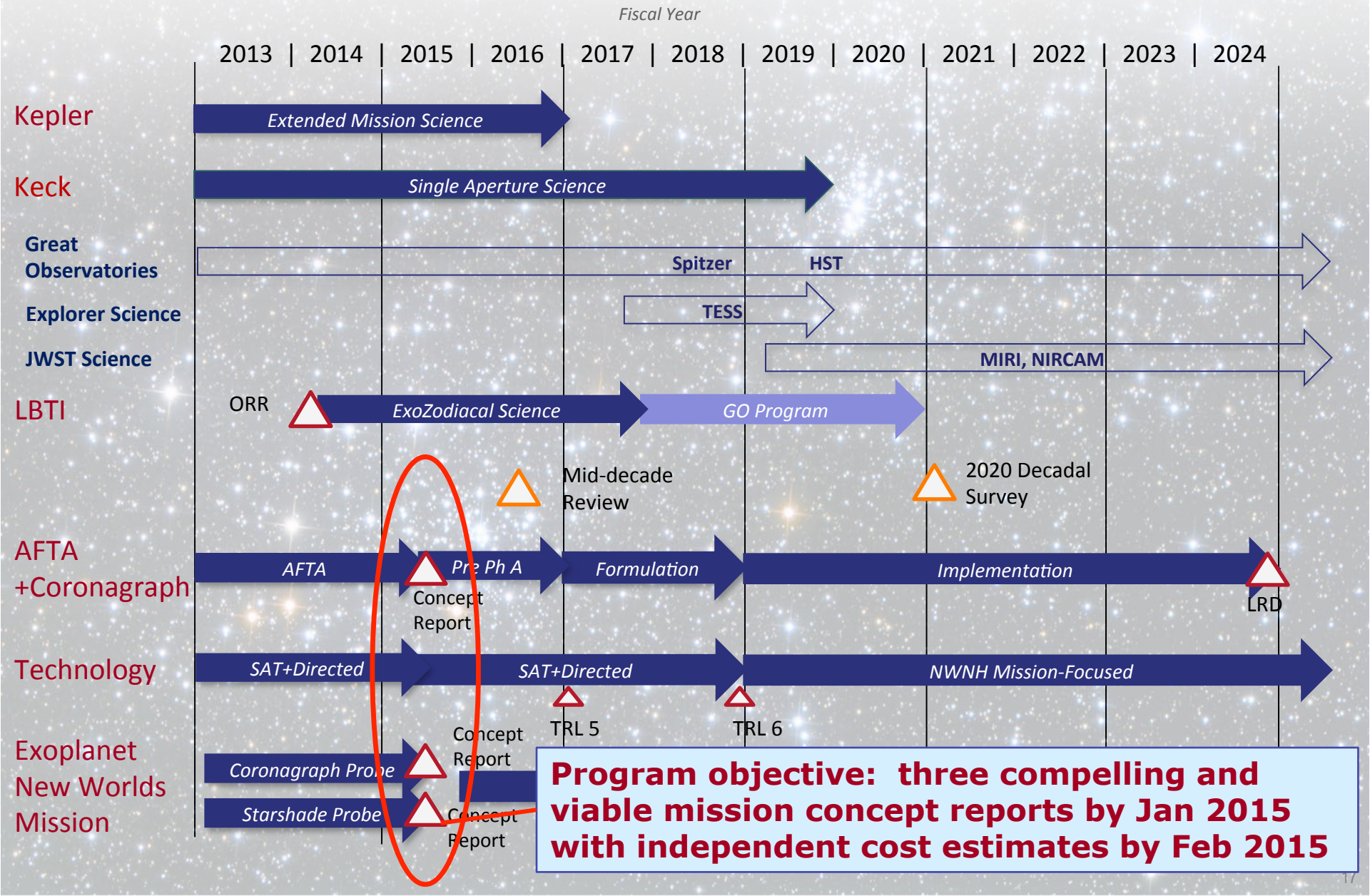
Sara Seager
MIT
Chairperson

Starshade Deployment

at Northrop Grumman's Goleta Facility

Exoplanet Exploration: A Decade Horizon

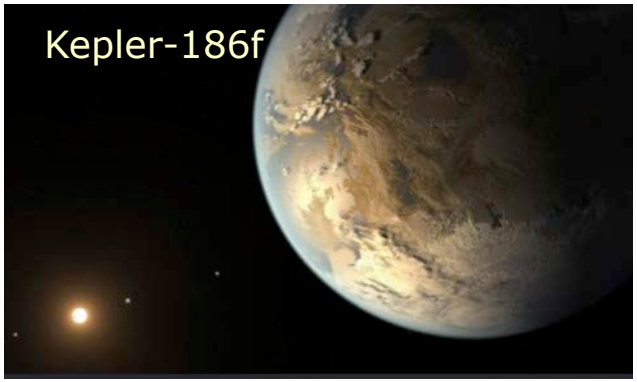
NASA-sponsored efforts



ExEP: Recent Progress and a Look Ahead

Great Progress!

- Significant recent scientific discoveries:
  - Kepler current totals: confirmed (964), candidates (3845)
  - Kepler-186f: rocky planet in Habitable Zone of an M star
- Kepler demonstrated two-wheel science observations
- LBTI: reached sensitivity of 36x Solar System zodi level
- Downselected coronagraph technologies for AFTA
- Delivered 3 interim reports: AFTA and two Probes
- Technology: steady progress in high-contrast imaging, starshade deployment demonstrations

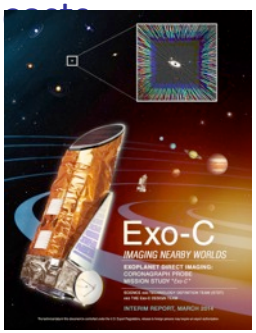


AFTA Coronagraph Technology Downselect

Probe and AFTA interim Reports

Looking Ahead:

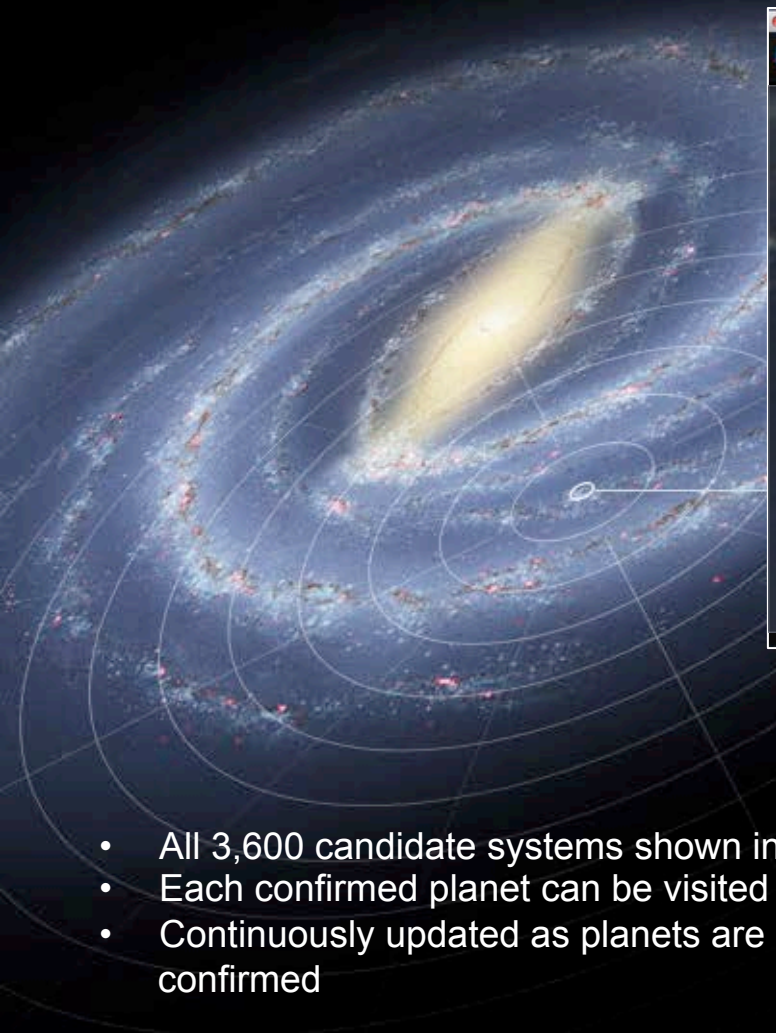
- LBTI: final steps to commissioning
- WFIRST-AFTA: technology progress, final report and [illegible]
- Probe studies: final reports and *independent* costs
- Sagan Summer Workshop "Imaging Planets & Disks"
- *Exoplanet Program Analysis Group* very active

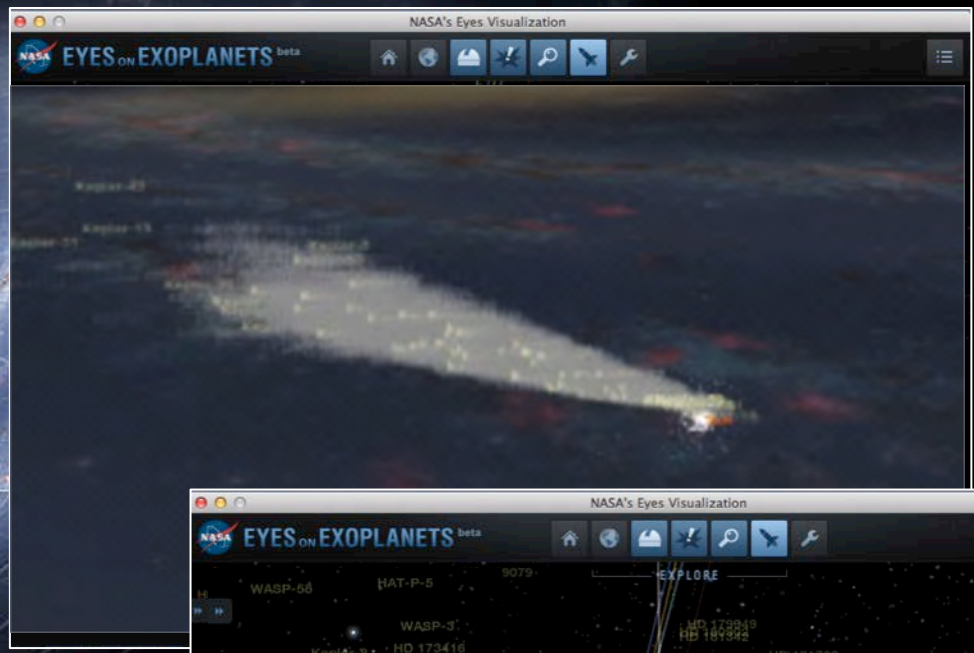


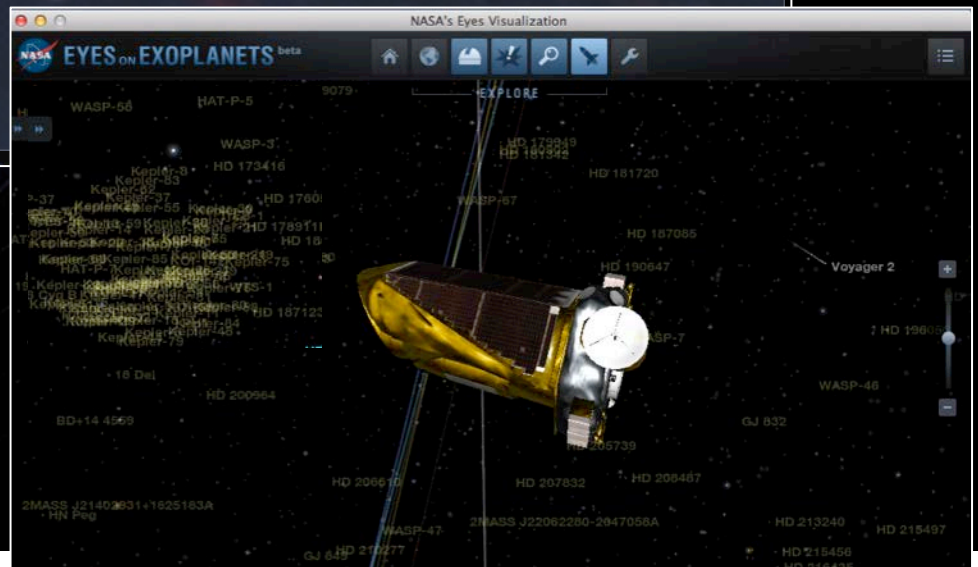
‘Eyes on Exoplanets’: Interactive Tour

EYES ON EXOPLANETS

http://eyes.jpl.nasa.gov/exoplanets







- All 3,600 candidate systems shown in FOV
- Each confirmed planet can be visited
- Continuously updated as planets are confirmed

- For more information on NASA exoplanet missions:

http://exep.jpl.nasa.gov