Jet Propulsion Laboratory
California Institute of Technology

The NASA Exoplanet Exploration Program:

The Search for Planets, Habitability, and Life in our Galaxy

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Jet Propulsion Laboratory, California Institute of Technology

Deputy Program Scientist

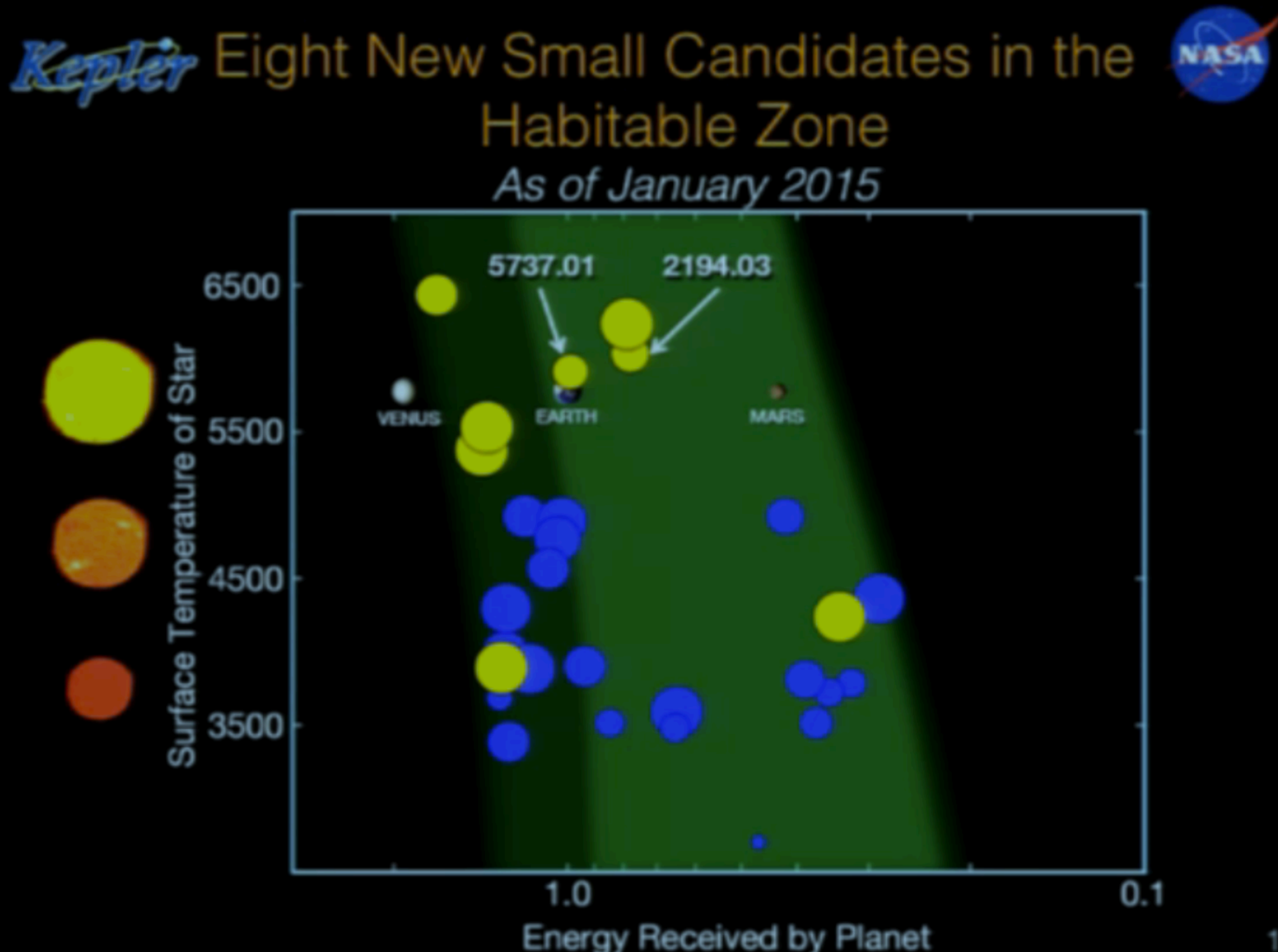
NASA Exoplanet Exploration Program

January 19-21, 2015

19th Annual International Conference on Gravitational Microlensing

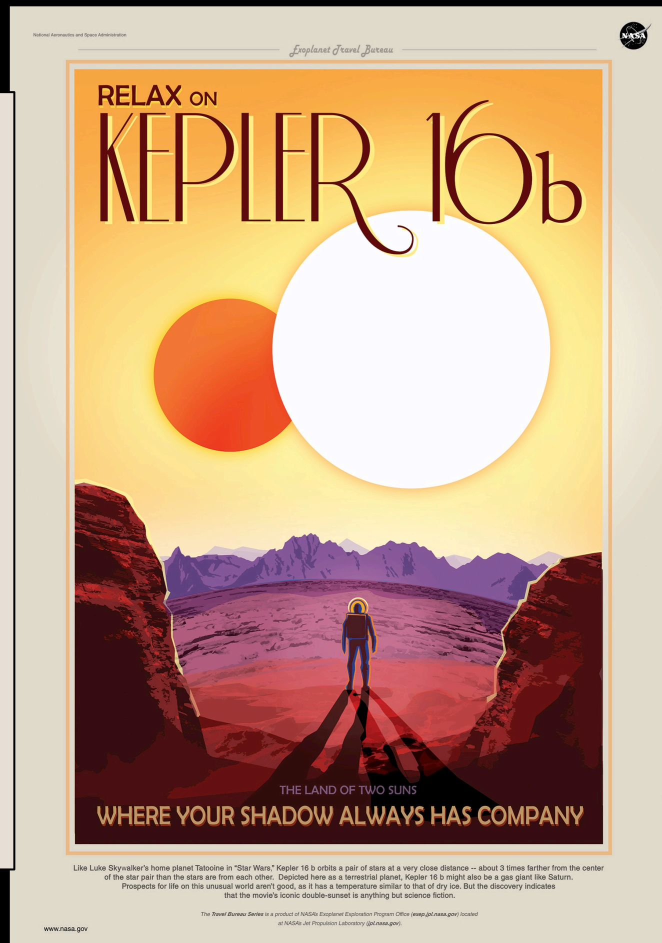
Annapolis MD

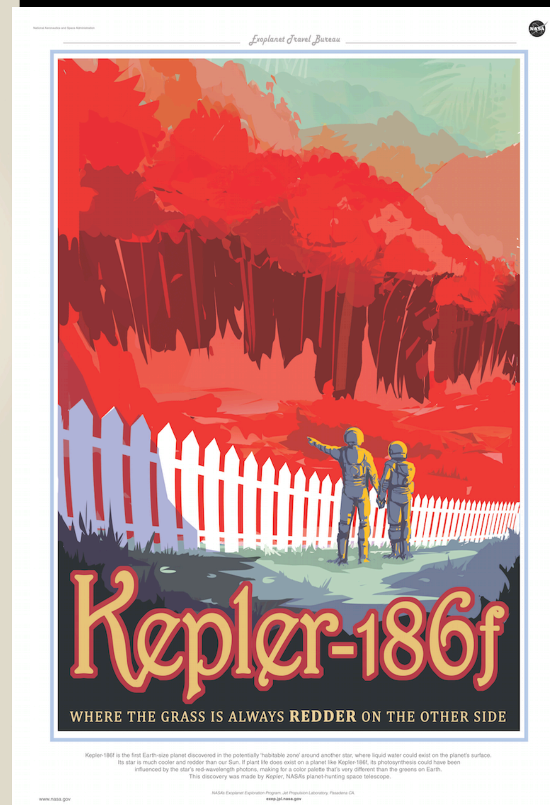
We are particularly interested in those in the *Habitable Zone*



Doug Caldwell, AAS 225 Meeting, Seattle, Jan 2015

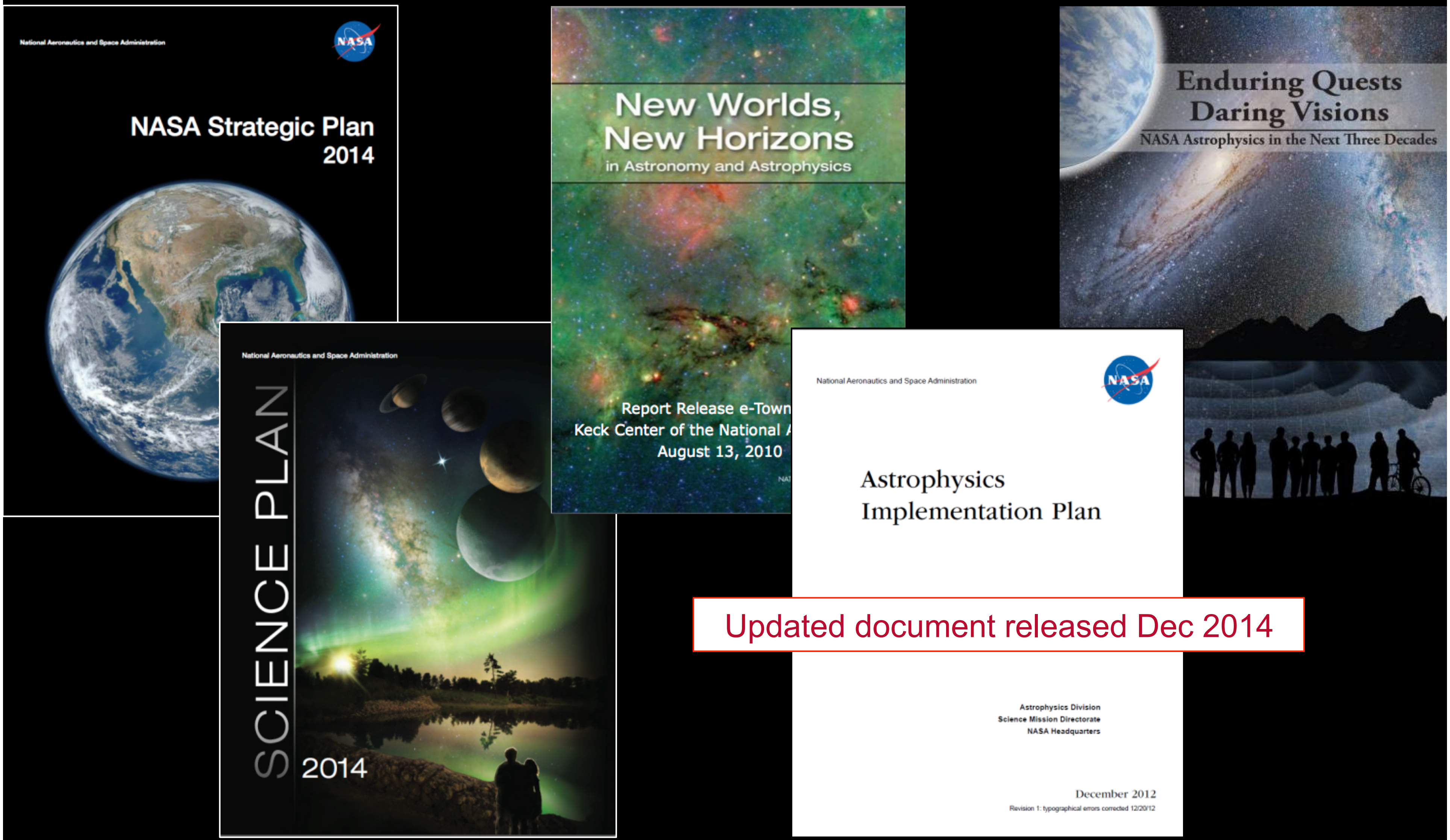
Where will exploration take us in 100 years?
Introducing the ***Exoplanet Travel Bureau***





The Exoplanet Exploration Program

NASA Astrophysics Documents



Updated document released Dec 2014

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

What is the Purpose of the Program?

Described in 2014 NASA Science Plan

Exoplanet Exploration Program

1. Discovering planets around other stars
2. Characterizing their properties
3. Identifying candidates that could harbor life

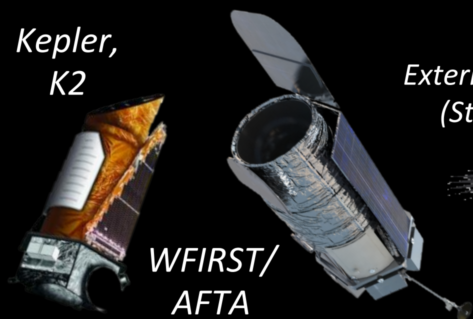
Interdisciplinary Studies of **Exoplanets:**

Crosscutting Work Between the Astrophysics and Planetary Science Divisions

The Exoplanet Exploration Program

Space Missions and Mission Studies

Kepler, K2



WFIRST/ AFTA

Probe-Scale:

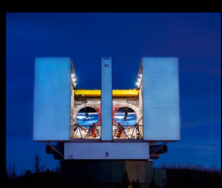
External Occulter (Starshade)

Coronagraph

Public Engagement

Supporting Research & Technology

Key Sustaining Research

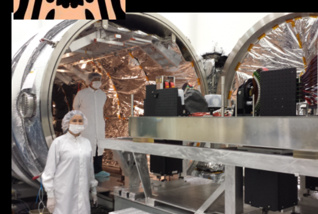


Large Binocular Telescope Interferometer

Keck Single Aperture Imaging and RV

Technology Development

Coronagraph Masks



High Contrast Imaging

Deployable Star Shades

NASA Exoplanet Science Institute

The Program relies on the Scientific Community

Active teams and committees:

- ExoTAC (Technology Assessment Committee)
  Chair: A. Boss, Carnegie Institution
- WFIRST/AFTA SDT (Science Definition Team)
  Chair: D. Spergel, Princeton University
- STDTs (Science and Technology Definition Team)
  One each for:
  - Exo-C (Probe Coronagraph) Chair: K. Stapelfeldt, GSFC
  - Exo-S (Probe Starshade) Chair: S. Seager, MIT
- ExoPAG (Program Analysis Group)
  Chair: S. Gaudi, Ohio State University

Key Exoplanet Science Questions

1. Discovering Planets: How abundant are exoplanets in our Galaxy?
   - Radial Velocity — <1 m/s
   - Transit Photometry — < 10 parts per million
   - Microlensing — Exoplanet populations and demographics
2. Characterizing Planets: What are the (large) exoplanets like?
   - Transit Spectroscopy — < 100 parts per million
   - Direct Imaging
     - High Contrast — < 1E-9 (after post-processing)
     - Small Inner Working Angle — < 500 mas (<200 mas)
     - Spectroscopy — R~40 in visible, near infrared (water lines)
3. "Pale Blue Dots": Are the planets habitable? Are there signs of life?
   - Transit Spectroscopy — < 1 part per million
   - Direct Imaging
     - High Contrast — < 1E-10 (after post-processing)
     - Small Inner Working Angle — < 100 mas (<40mas)
     - Spectroscopy — R~70 in visible, near infrared (biosignature gases)
     - η_{Earth} — Quantify, for mission design
     - Exozodiacal Dust — Quantify, for mission design
     - Yield — Ideally: dozens of rocky planets

Current Exoplanet Science Missions

Kepler Space Telescope

- **PI:** W. Borucki, NASA Ames Research Center
- **Launch Date:** March 6, 2009
- **Science Data Collection through May 2013**
- **Final processing of full data set underway**

Kepler Closeout

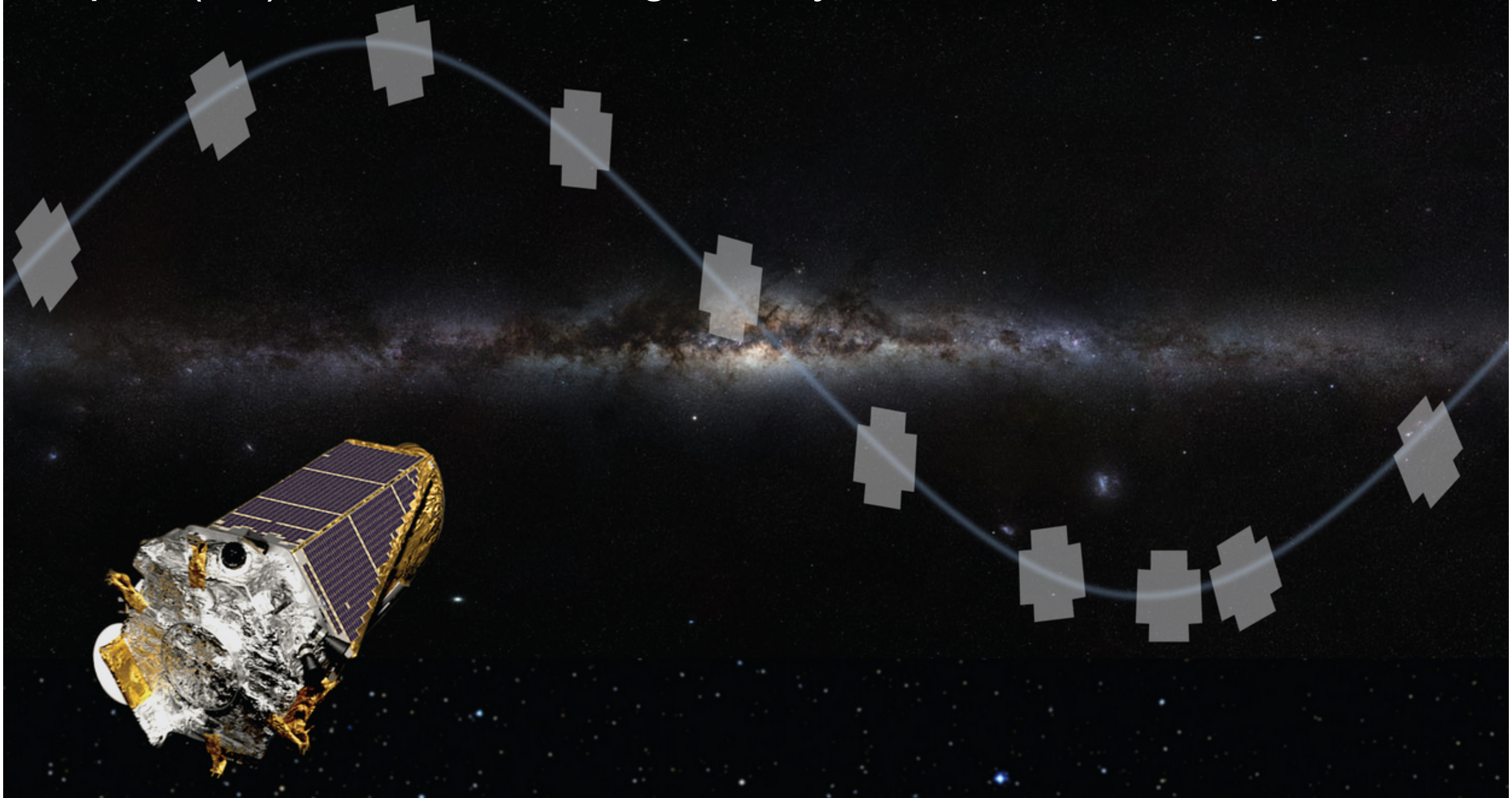
Harvesting the exoplanet yield from the mission

- Already available to Community: Q0-Q16

- Uniform Processing: Q0-Q17 (9.2)
  - Long cadence light curves — Dec 2014
  - Short cadence light curves — Mar 2015
  - Release notes — Jul 2015

- Final Data processing: Q0-Q17 (9.3)
  - Light curves — Jan 2016
  - Release notes — Aug 2016

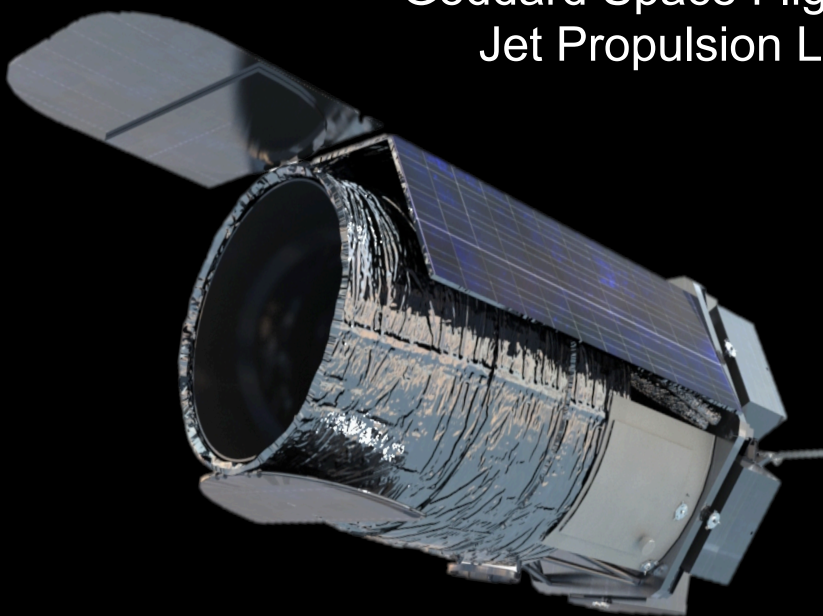
Kepler (K2) is now observing 80-day windows in the ecliptic



WFIRST / AFTA

Wide-Field Infrared Survey Telescope (WFIRST)
Astrophysics Focused Telescope Assets (AFTA)

Goddard Space Flight Center
Jet Propulsion Laboratory
STScI
NExScI



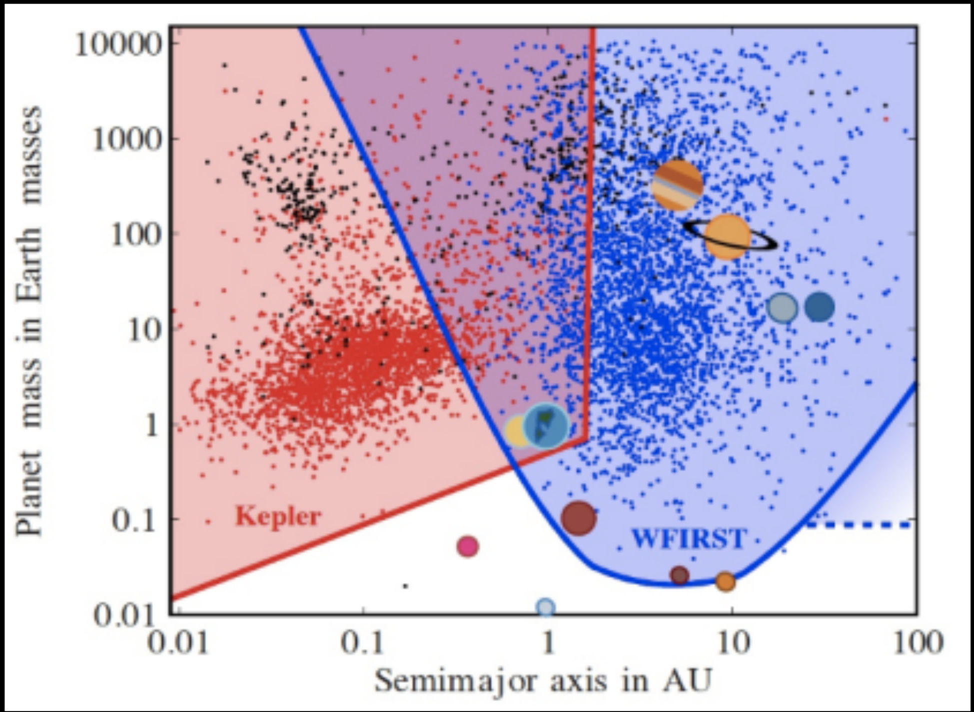
Wide-field Instrument

— H4RG detectors (Qty 18)
— Wavelength: 0.6 to 2.0 micron
— FOV: 0.28 deg^2

Wide-field Instrument Science

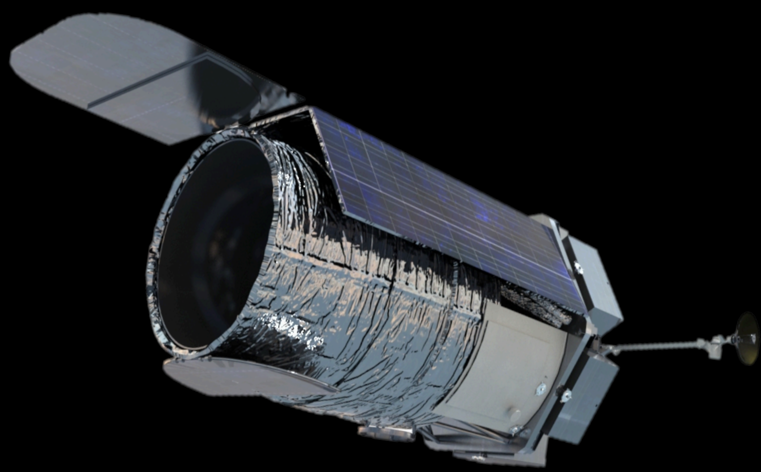
— Dark Energy
— Infrared Survey
— Microlensing survey for exoplanets

WFIRST / AFTA
Microlensing survey completes the census begun by Kepler



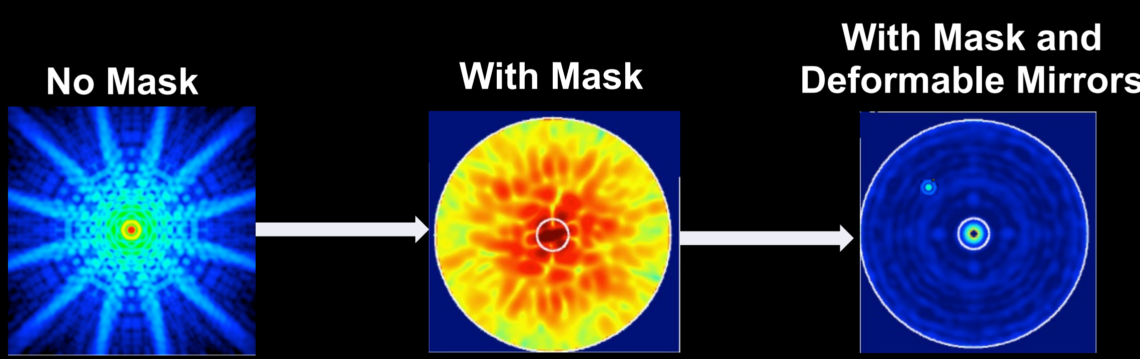
WFIRST / AFTA Coronagraph

Direct Imaging of Exoplanet Nearest Neighbors



Coronagraph Instrument
- Imaging and spectra channels
- 0.4 – 1 μm bandpass
- ≤ 10^{-9} detection contrast
- 100 mas inner working angle at 0.4 μm
- R ~ 70

Coronagraph Science
- Imaging and spectroscopy of exoplanet atmospheres down to a few Earth masses
- Study populations of debris disks



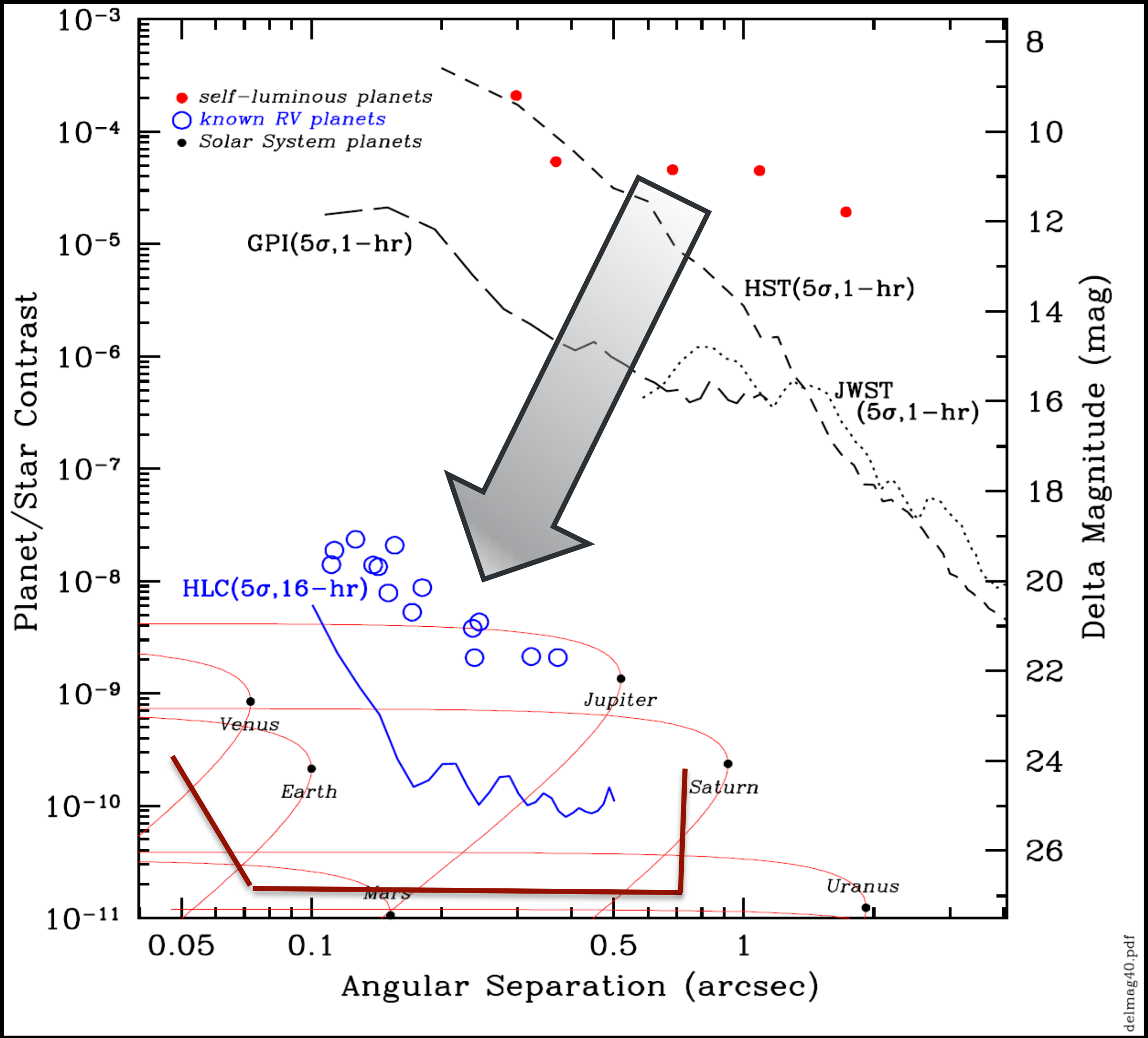
Coronagraph will develop the technologies for a future exo-Earth mission

WFIRST Coronagraph images cool gas and ice giants

GPI

WFIRST

New Worlds Telescope



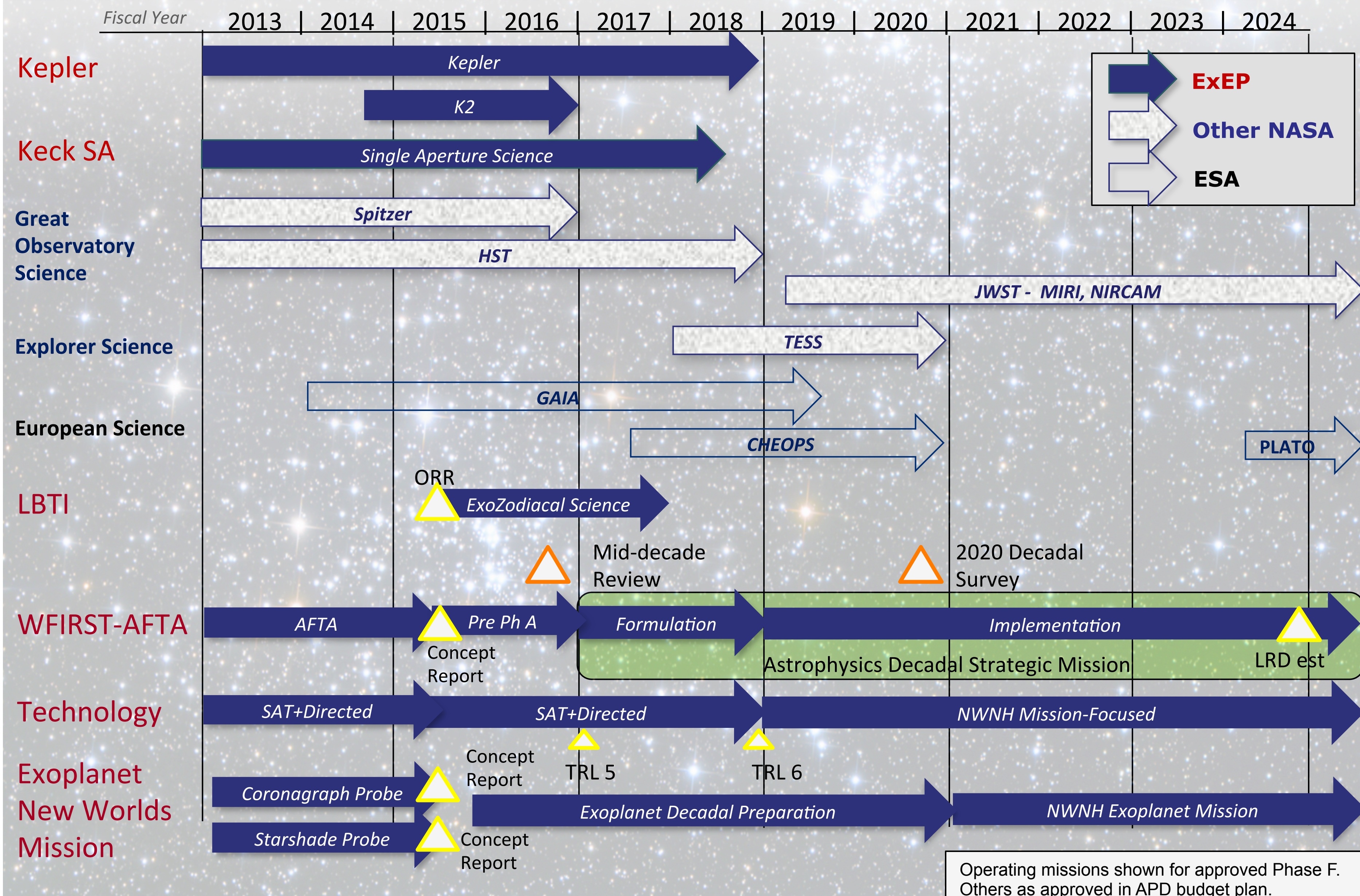
HST

JWST

W. Traub

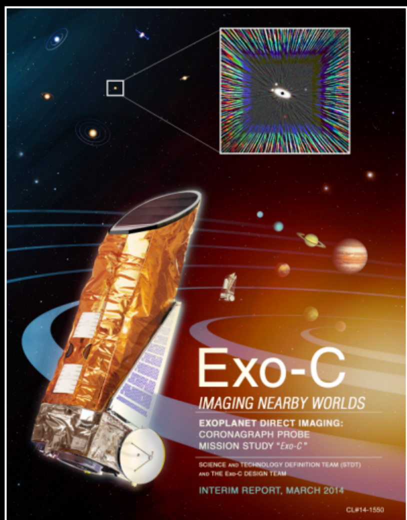
Exoplanet Exploration: A Decade Horizon

NASA and ESA efforts



Operating missions shown for approved Phase F. Others as approved in APD budget plan.

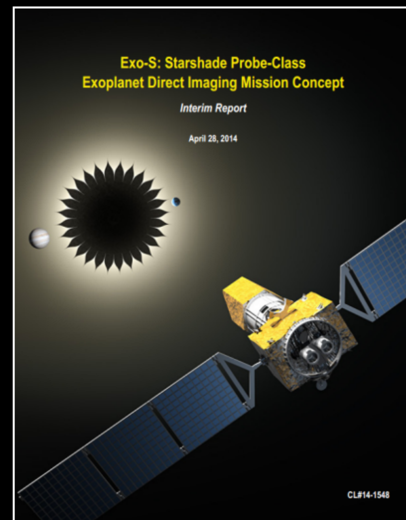
Probe-Scale studies: High-Contrast Imaging



Exo-C:

Internal Occulter (Coronagraph)

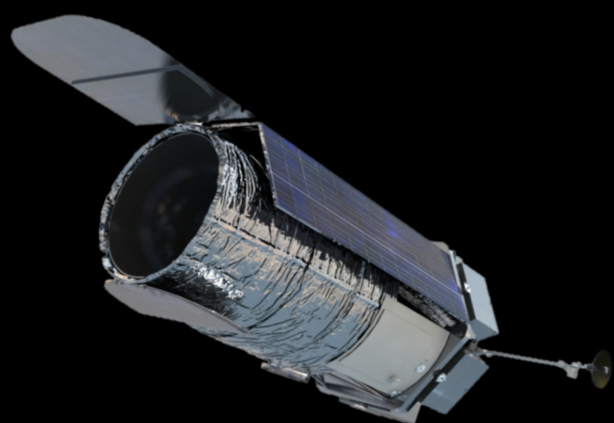
K. Stapelfeldt,
STDT Chair, GSFC

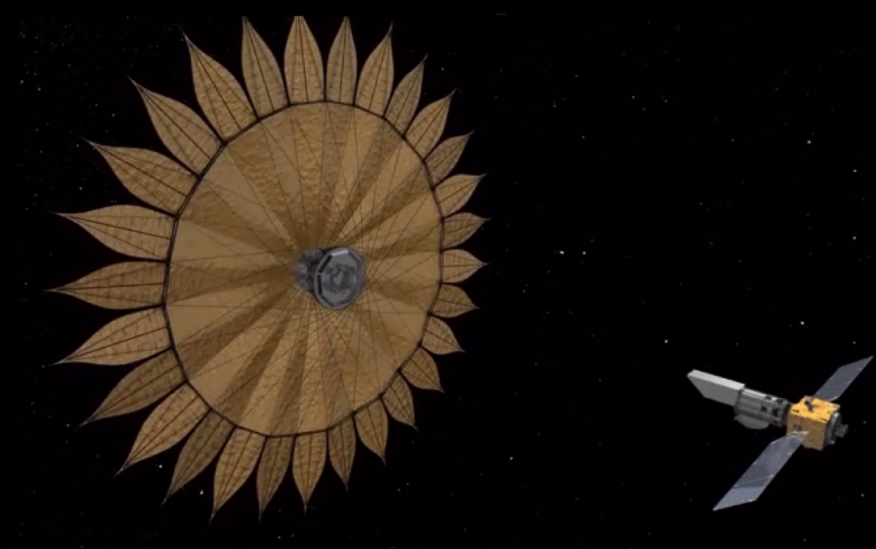


Exo-S:

External Occulter (Starshade)

S. Seager,
STDT Chair, MIT

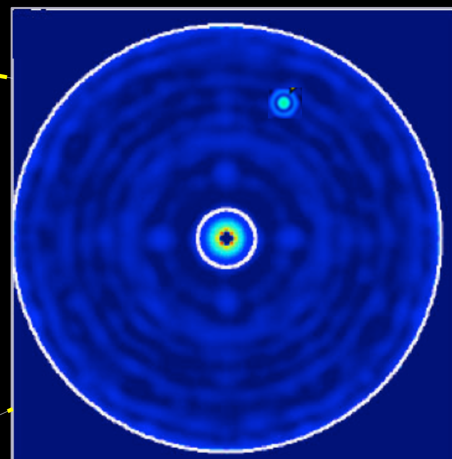




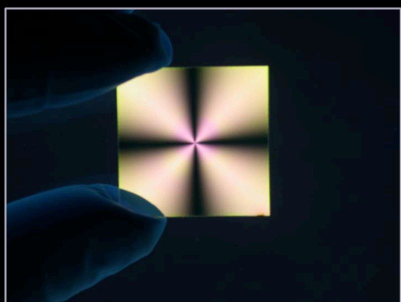
Enabling the Exo-Future:

Technology Development

Technology Development for Coronagraphs

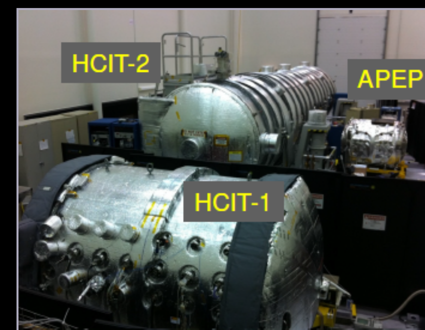


Occulting Masks/
Apodizers



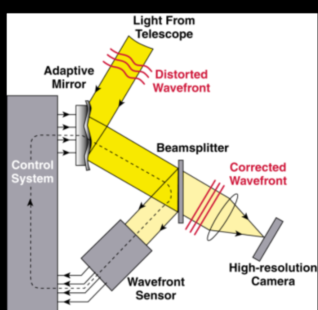
Serabyn – Vector Vortex Mask

System Demonstration

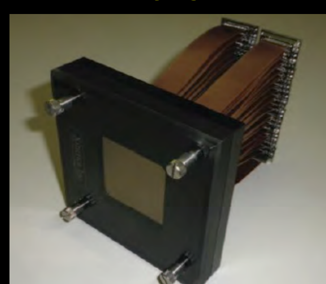


Jet Propulsion Laboratory

Low Order Wavefront
Sensing and Control

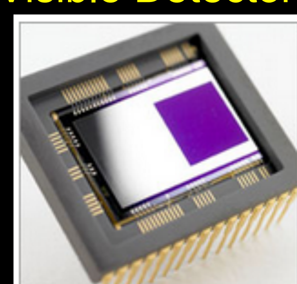


Deformable
Mirrors



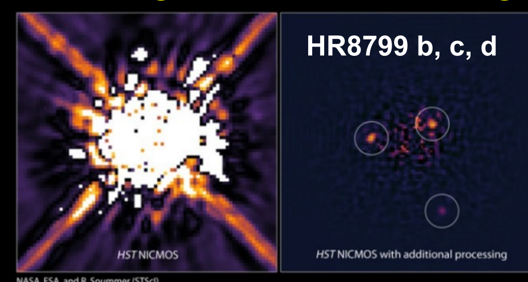
Xinetics

Ultra-Low-Noise
Visible Detectors



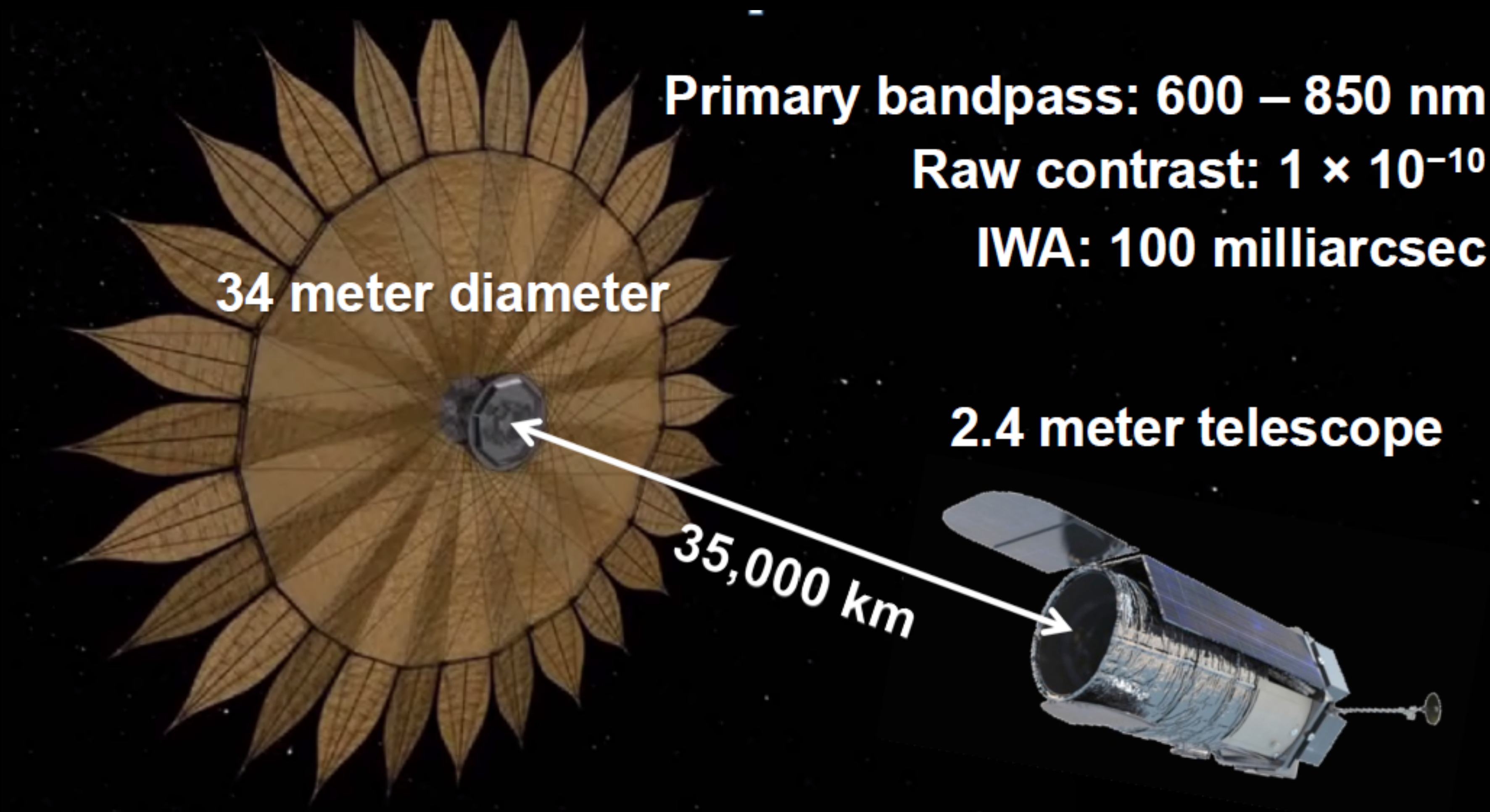
e2v Electron Multiplying CCD

Image Post Processing



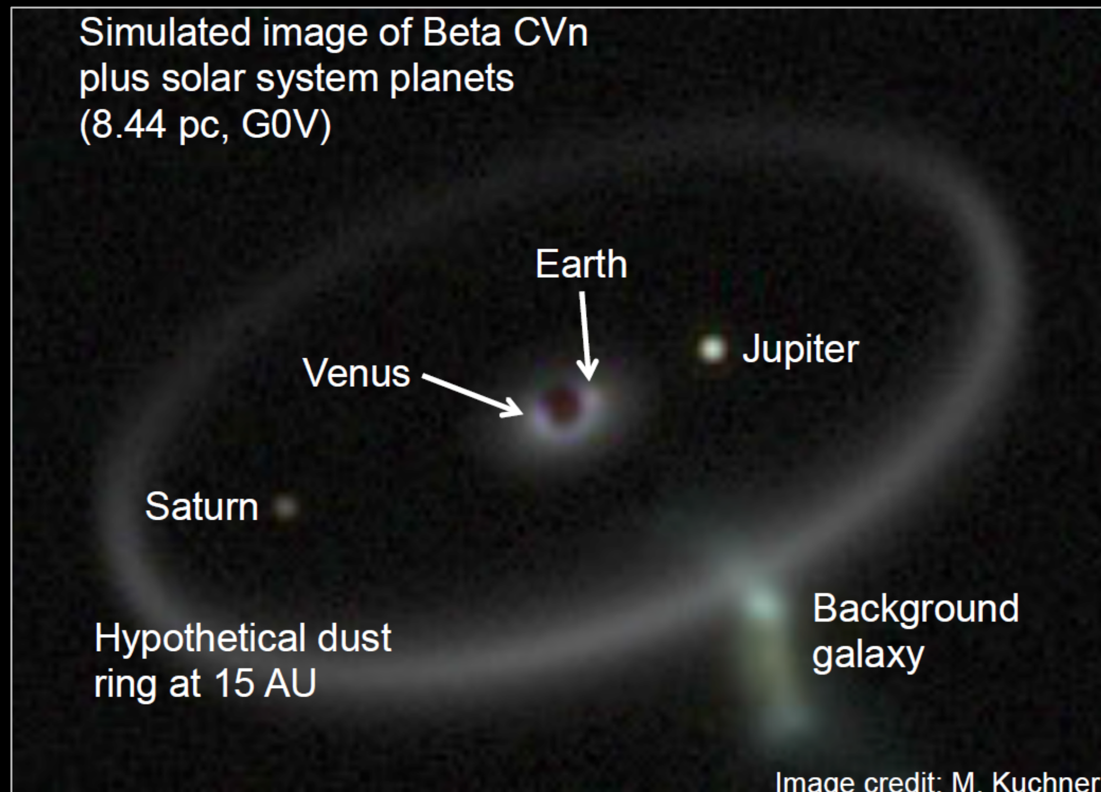
Soummer et al. 2011

Starshade for a 2.4m telescope



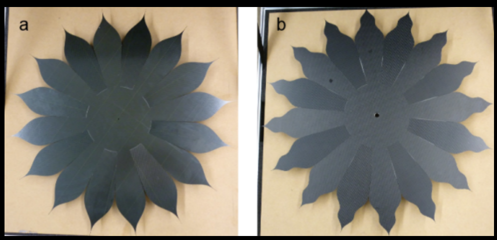
Example of Science from Starshade with 2.4m telescope

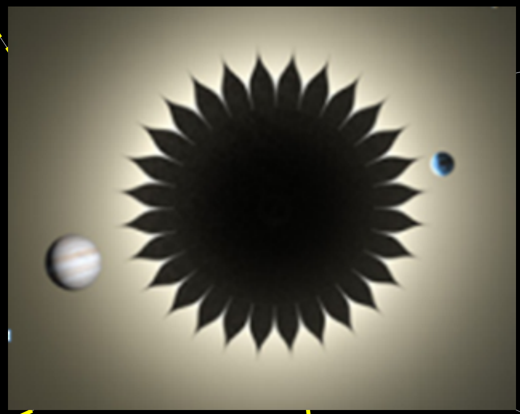
- Observe 52 stars in 2 years
- 13 known exoplanets
- 19 HZ targets. Expect ~ 2 Earths or Super-Earths
- Can detect sub-Neptunes to Jupiters around all HZ targets and 20 additional stars



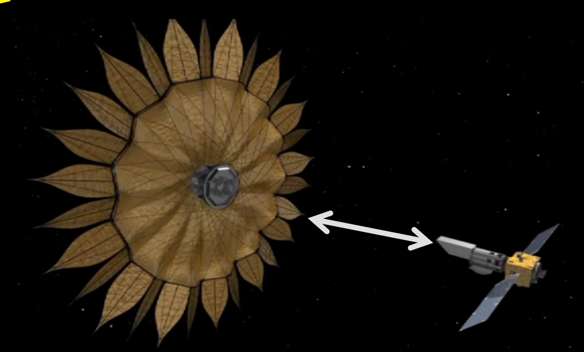
Technology Development for Starshades (External Occulters)

Control of Scattered Light





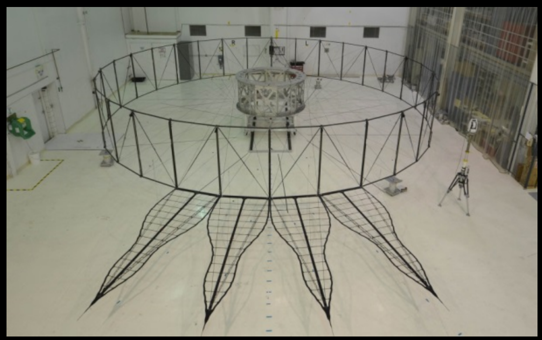
Formation Flying



Validation of Optical Models

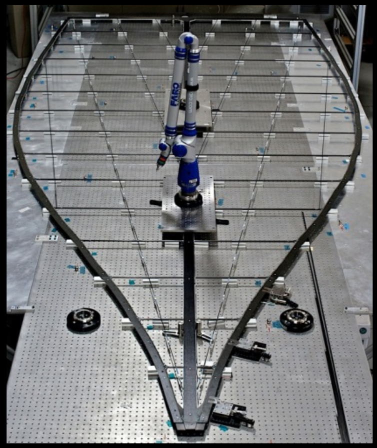
NGAS

Starshade Deployment



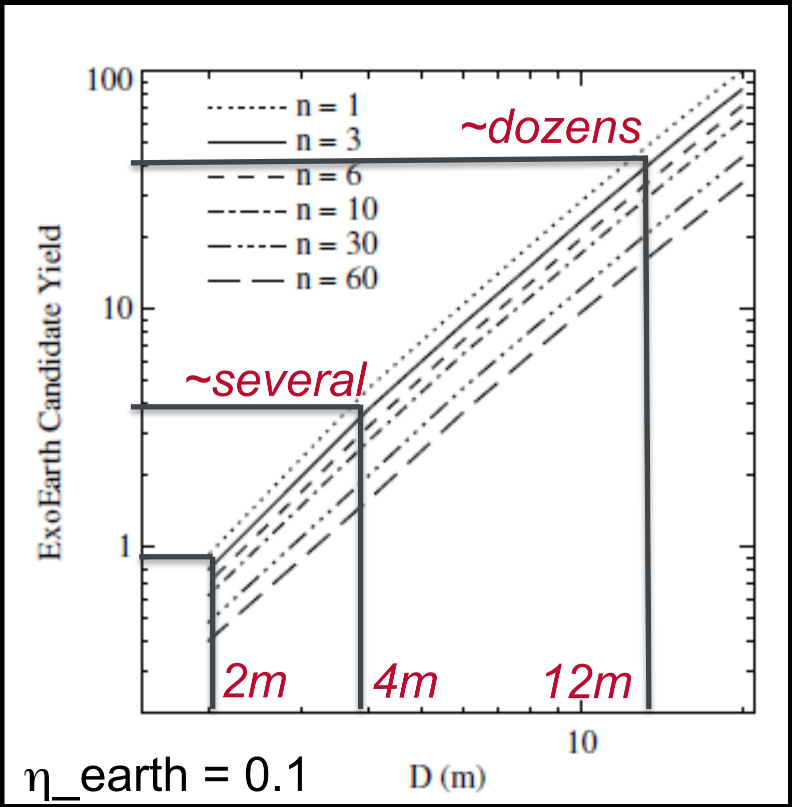
NGAS, Princeton, JPL

Petal Prototype



Princeton, JPL

Exo-Earths require large telescopes



Stark et al, 2014
For Coronagraphs

- Yield most sensitive to (in order):
  - Telescope diameter
  - Coronagraph inner working angle
  - Coronagraph contrast
  - Coronagraph noise floor

- Also sensitive to η_earth (strong) and exozodical dust (relatively weak)

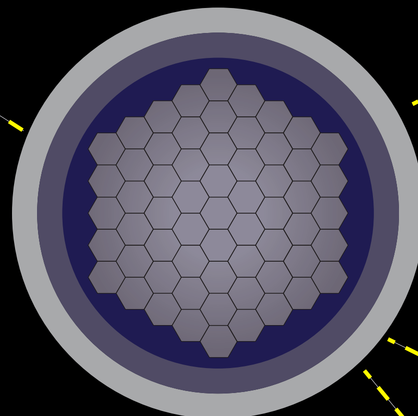
Formative Era: Large UV-Optical-IR Telescope (LUVOIR)

Optics Deployment and Assy

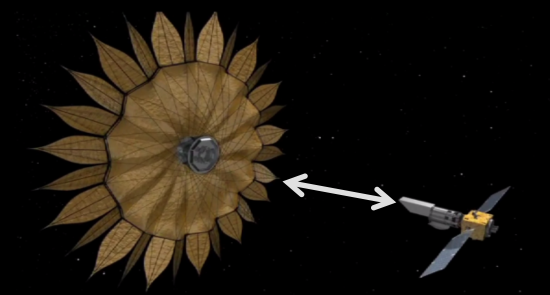
SiC Active Hybrid Mirror, Xinetics

MOIRE, BATC

Lightweight ULE, ITT



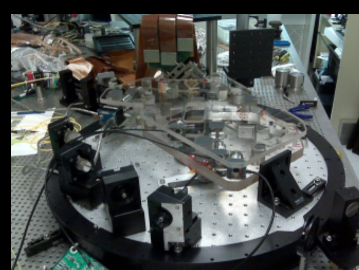
Formation Flying



Broadband Mirror Coatings

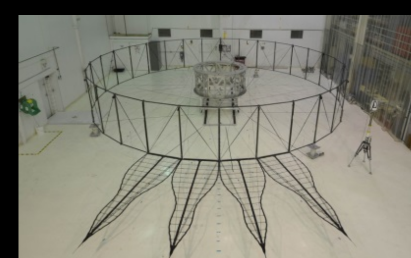
Telescope Mechanical Isolation Systems

Starlight Suppression Systems



Visible Nuller, GSFC

Pupil Mapping, Univ. Arizona



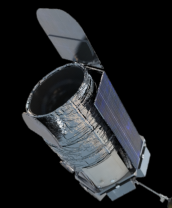
Starshade
NGAS, Princeton, JPL

The Program Address the Key Questions

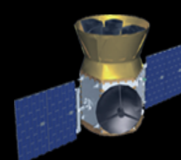
Through Science, Advanced Studies, and Technology Development

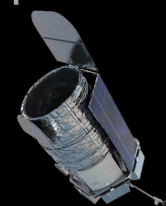
1. Discovering Planets: How abundant are exoplanets in our Galaxy?
   - Radial Velocity
   - Transit Photometry
   - Microlensing

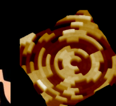
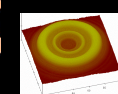

EPDS



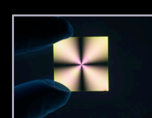
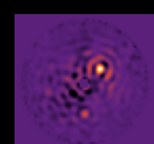
2. Characterizing Planets: What are the (large) exoplanets like?
   - Transit Spectroscopy
   - Direct Imaging

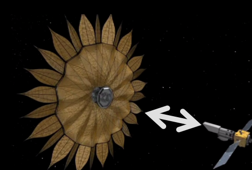
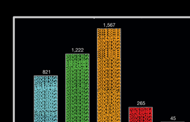


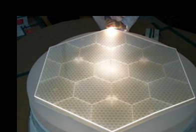


3. "Pale Blue Dots": Are the planets habitable? Are there signs of life?
   - Transit Spectroscopy
   - Direct Imaging
     - High Contrast
     - Small Inner Working Angle
     - Spectroscopy
     - η_{Earth}
     - Exozodiacal Dust
     - Yield

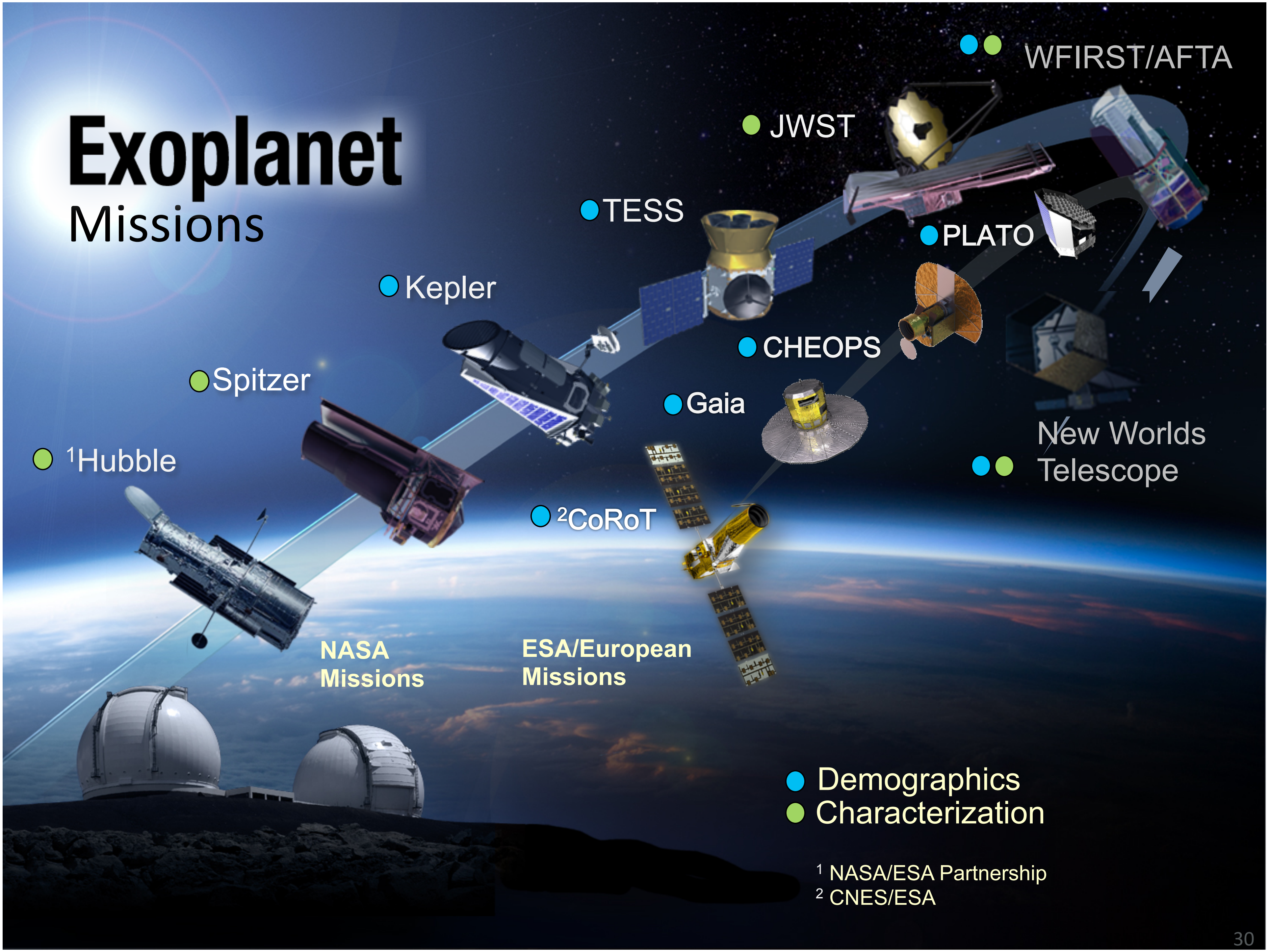







Ways to Become Involved

- ExoPAG: SAGs, and SIG
- EPDS initiative
- Program and decadal studies
- Competitive Funding:
  - Exoplanet Research Program (XRP) via ROSES
  - Astrophysics Data Analysis Program (ADAP, supports archival Kepler/K2 research)
  - K2 Guest Observer program
  - Astrophysics Theory Program (ATP)
  - Hubble Guest Observer program (supports exoplanet research)
  - SAT / TDEM (ROSES) for exoplanet technology development

Read more at: http://exep.jpl.nasa.gov


Exoplanet
Missions
WFIRST/AFTA
JWST
TESS
PLATO
Kepler
CHEOPS
Spitzer
Gaia
New Worlds
Telescope
1Hubble
2CoRoT
NASA
Missions
ESA/European
Missions
Demographics
Characterization
1 NASA/ESA Partnership
2 CNES/ESA

National Aeronautics and
Space Administration

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California Institute of Technology
Pasadena, California

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