Jet Propulsion Laboratory
California Institute of Technology

Missions and Technology in NASA's Exoplanet Exploration Program:

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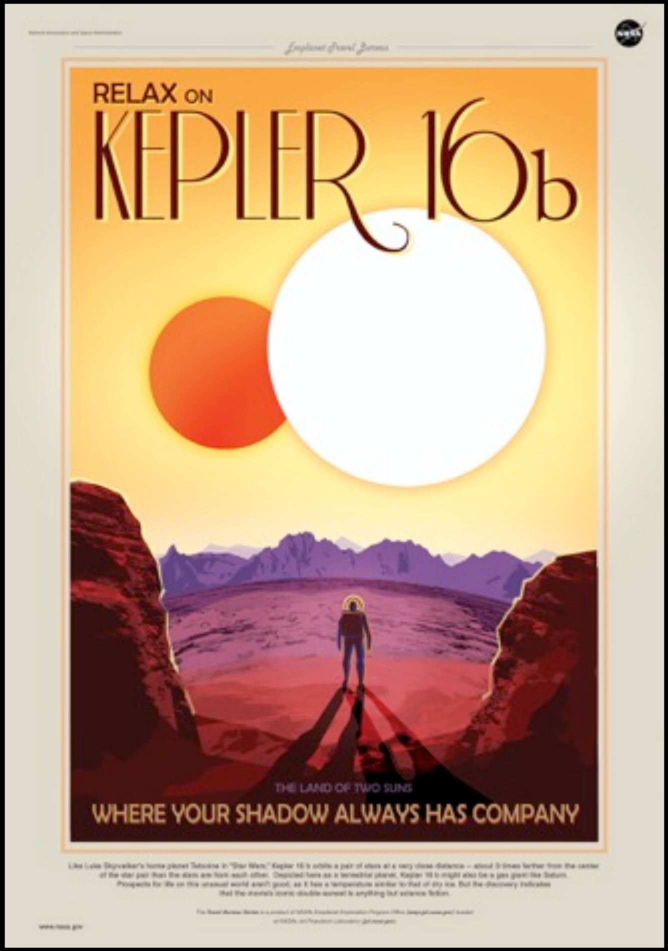
Deputy Program Scientist
NASA Exoplanet Exploration Program
July 16, 2015

Pathways 2015: Pathways Towards Habitable Planets
Bern, Switzerland

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



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

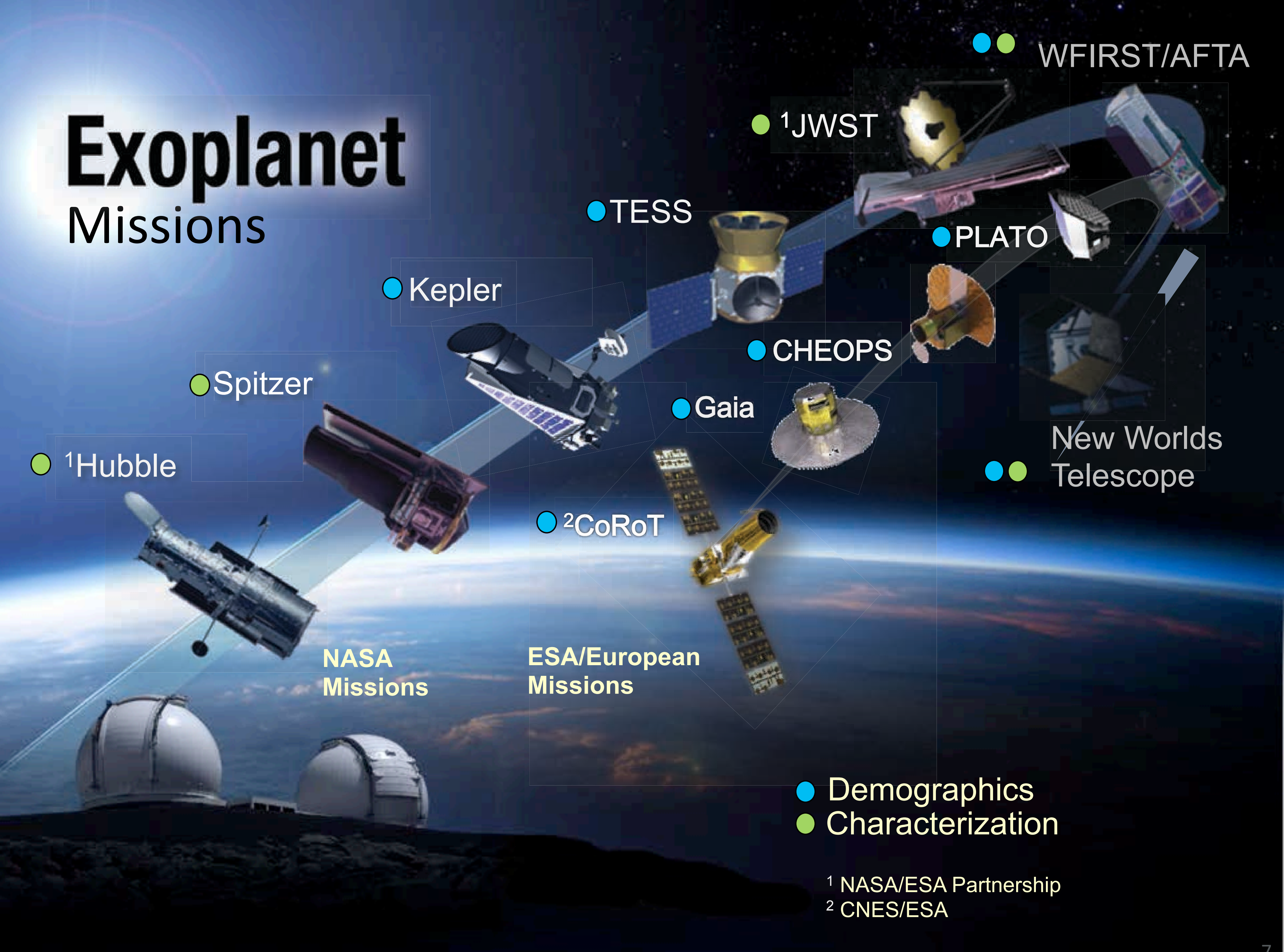
Exoplanet Exploration Program

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

NExSS

- Nexus for Exoplanet System Science (NExSS)
  - A NASA HQ research coordination network with an emphasis on studying planetary habitability
  - Unprecedented coordination between ALL 4 divisions of NASA's Science Mission Directorate (Astrophysics, Earth Sciences, Heliophysics, Planetary Sciences)
  - NASA identified 17 teams with synergistic research interests that were already funded by grants awarded through ROSES competitions
  - Initiative lead by: Mary Voytek (NASA HQ, Astrobiology), Shawn Domagal-Goldman (GSFC) and Co-Chairs: Natalie Batalha (ARC), Tony Del Genio (GISS), Dawn Gelino (NExScI)
- Exoplanet studies are inherently interdisciplinary, and by working together, we can work more efficiently to answer one of humanity's oldest questions: Are we alone?

The Exoplanet Exploration Program


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

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: A. Boss, Carnegie Institution of Washington

Key Exoplanet Science Questions

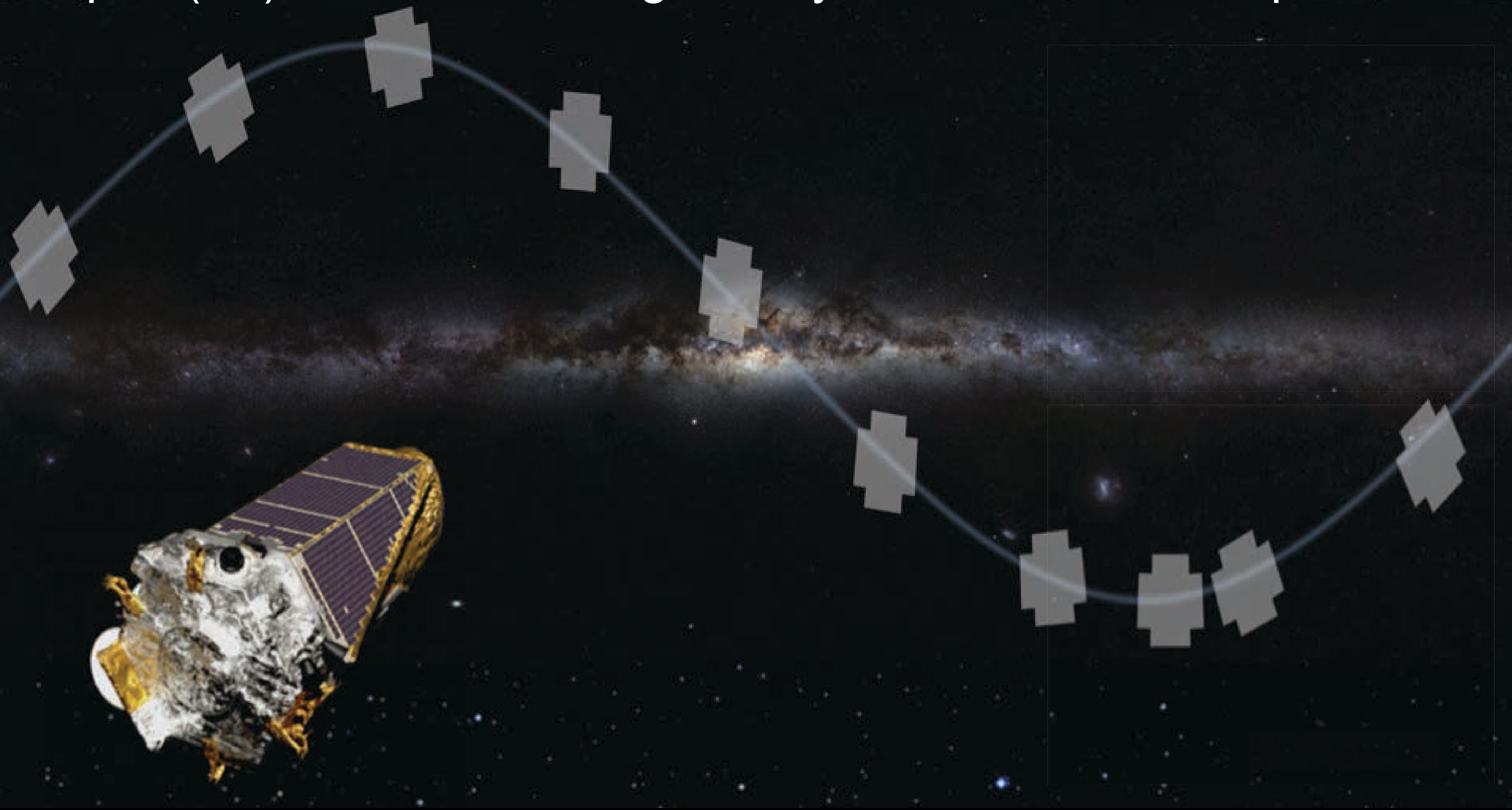
1. Discovering Planets: How abundant are exoplanets in our Galaxy?
   - Radial Velocity — <1 m/s
   - Transit Photometry — < 10 parts per million
   - Microlensing — Exoplanet populations and demographics
2. Characterizing Planets: What are the (large) exoplanets like?
   - Transit Spectroscopy — < 100 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 (K2) is now observing 80-day windows in the ecliptic



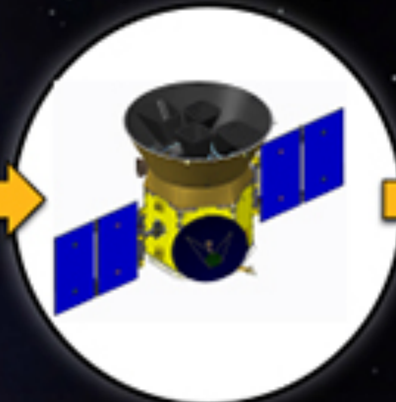
Transiting Exoplanet Survey Satellite

TESS

Launch Vehicle

- SpaceX Falcon 9 v1.1
- High Earth Orbit (HEO)
- 2:1 Resonance with Moon's Orbit

Observatory



- Orbital LEOStar-2
- Instrument-in-the-loop attitude control

Science Instrument

- Four Wide Field-of-View CCD Cameras
- 24°x 24°Field-of-View
- Well defined spacecraft interfaces

Project Overview

- Transiting exoplanet discovery mission
- 2 month Commissioning period
- 2 year all-sky survey (3 year science mission)
- Identifies best targets for follow-up characterization
- Deep Space Network (DSN) primary support
- Category II, Class C
- Planned Launch Readiness Date: August 2017
- PI Cost Cap: $228.3 M (RY$)

MIT KAVLI INSTITUTE

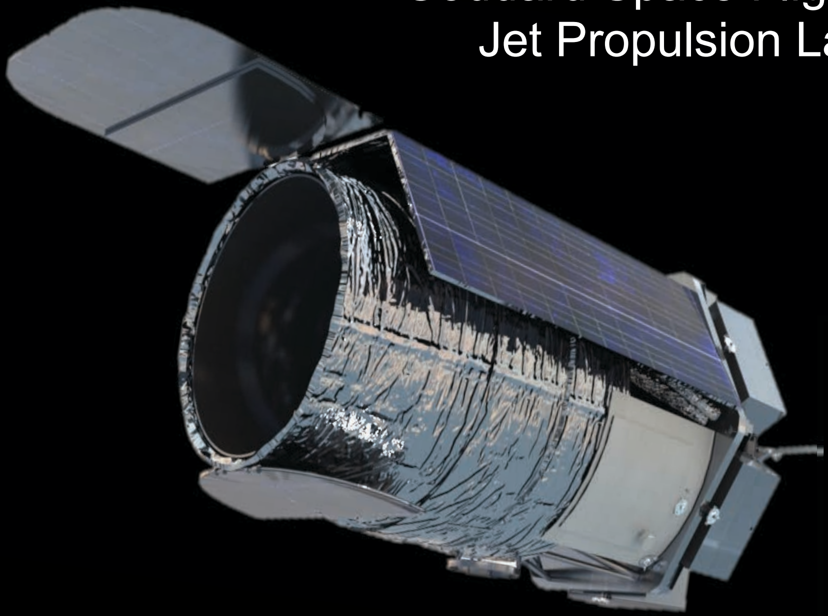
NASA

Orbital ATK

WFIRST / AFTA

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

Goddard Space Flight Center
Jet Propulsion Laboratory
STScI
NExScI



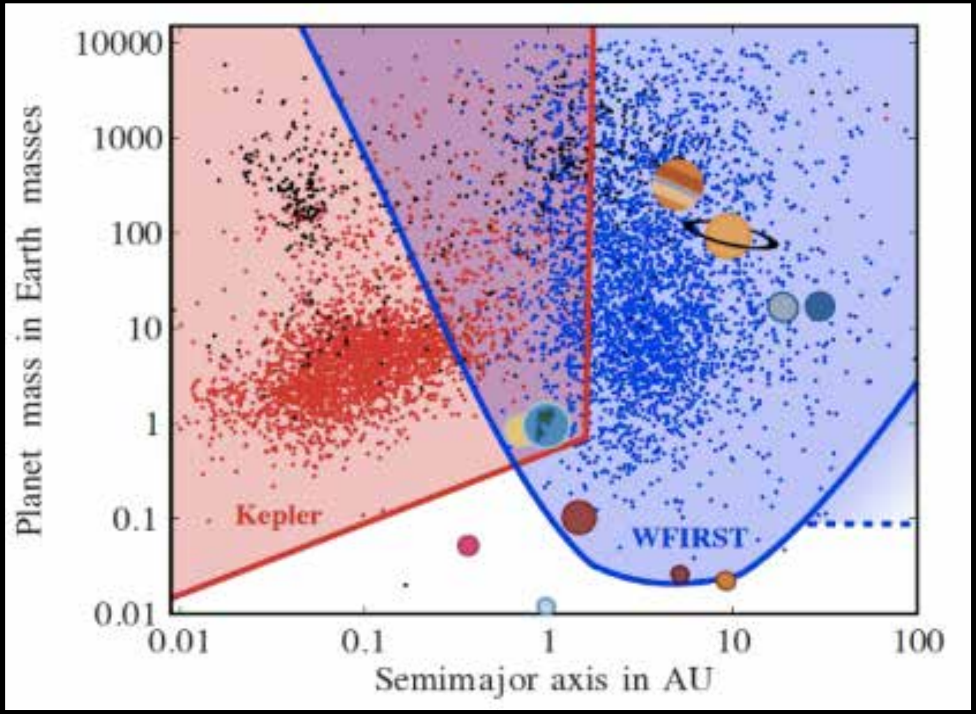
Wide-field Instrument

- 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

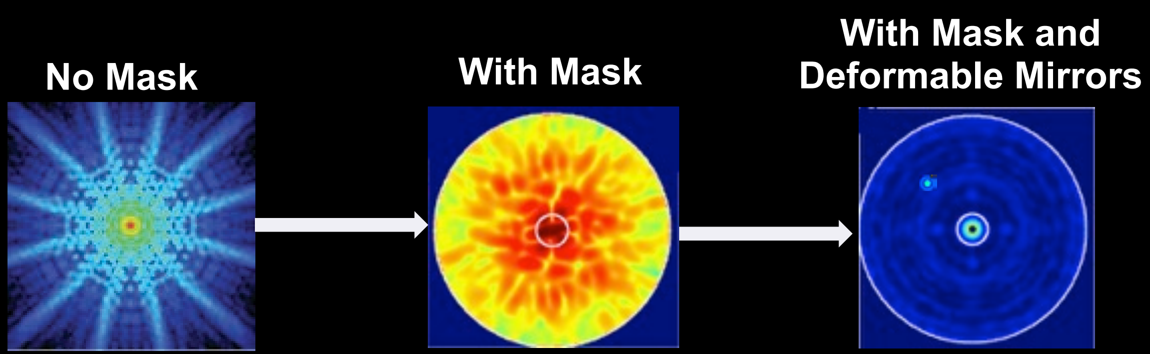
Direct Imaging of Exoplanet Nearest Neighbors

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



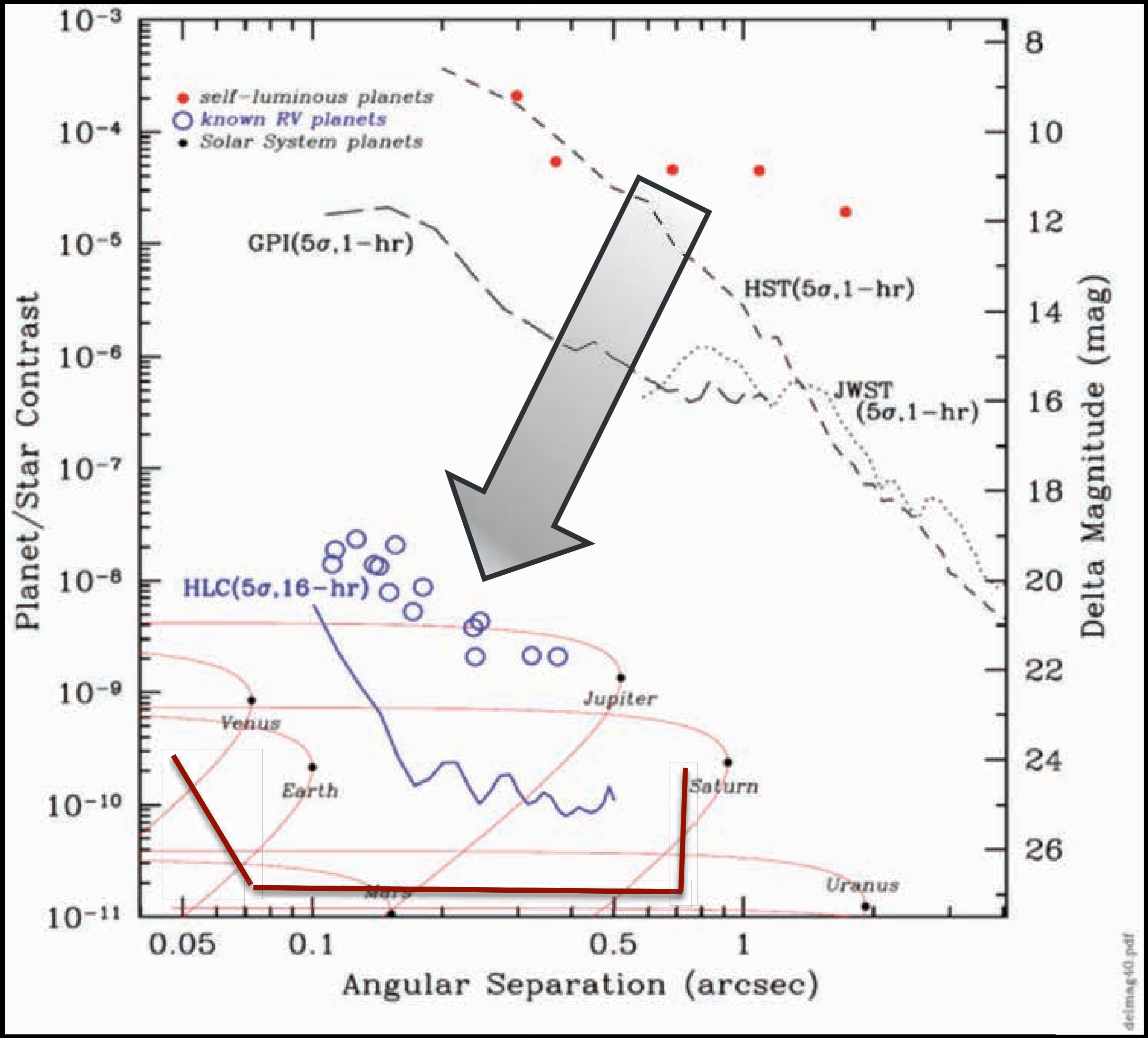
Coronagraph will develop the technologies for a future exo-Earth mission

WFIRST Coronagraph images cool gas and ice giants

GPI

WFIRST

New Worlds Telescope

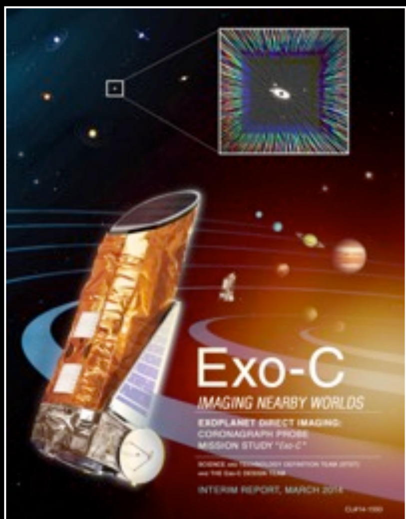


HST

JWST

W. Traub

Probe-Scale studies: High-Contrast Imaging



Exo-C:

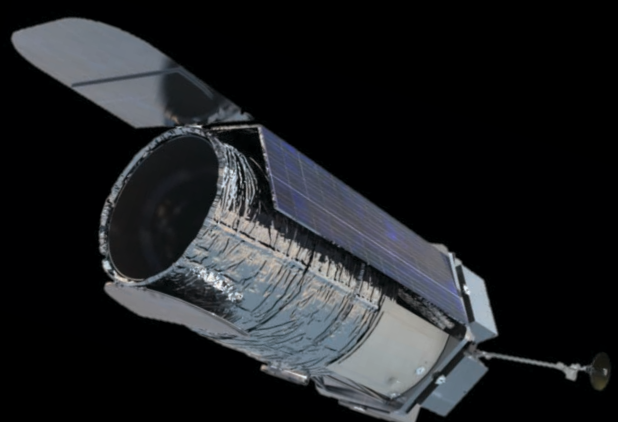
Internal Occulter
(Coronagraph)

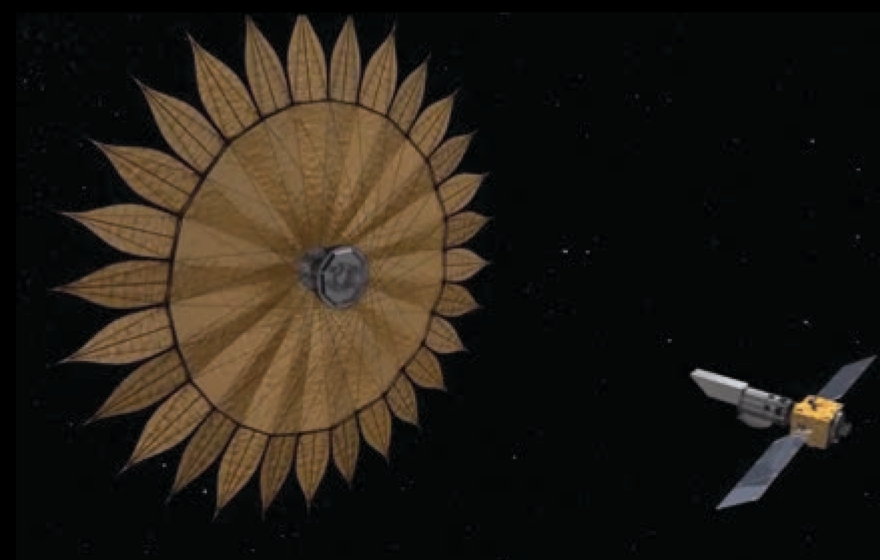
K. Stapelfeldt,
STDT Chair, GSFC

Exo-S:

External Occulter
(Starshade)

S. Seager,
STDT Chair, MIT





Enabling the Exo-Future:

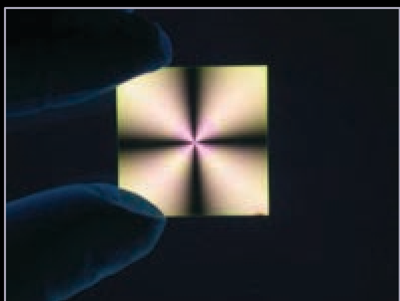
Technology Development

See: ExEP Technology Plan Appendix:

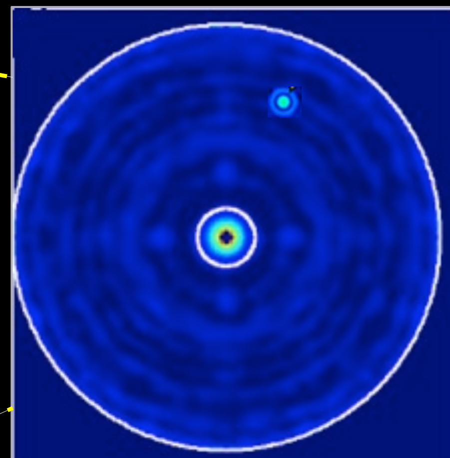
http://exep.jpl.nasa.gov/technology/

Technology Development for Coronagraphs

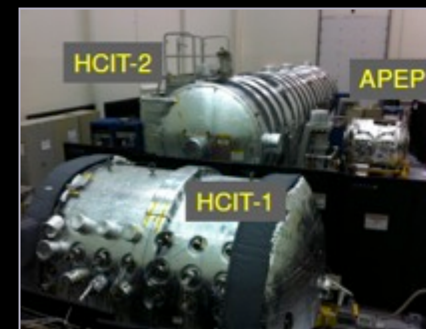
Occulting Masks/
Apodizers



Serabyn – Vector Vortex Mask

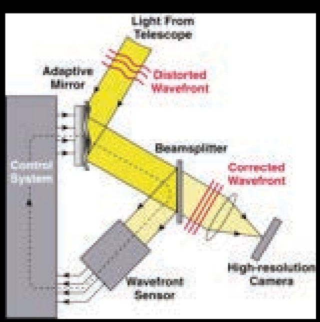


System Demonstration

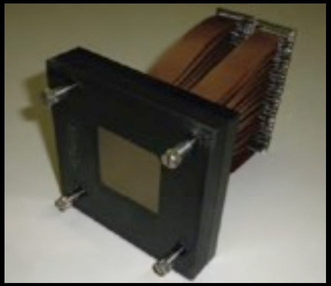


Jet Propulsion Laboratory

Low Order Wavefront
Sensing and Control

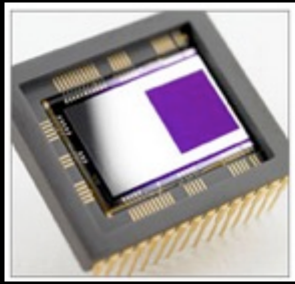


Deformable
Mirrors



Xinetics

Ultra-Low-Noise
Visible Detectors

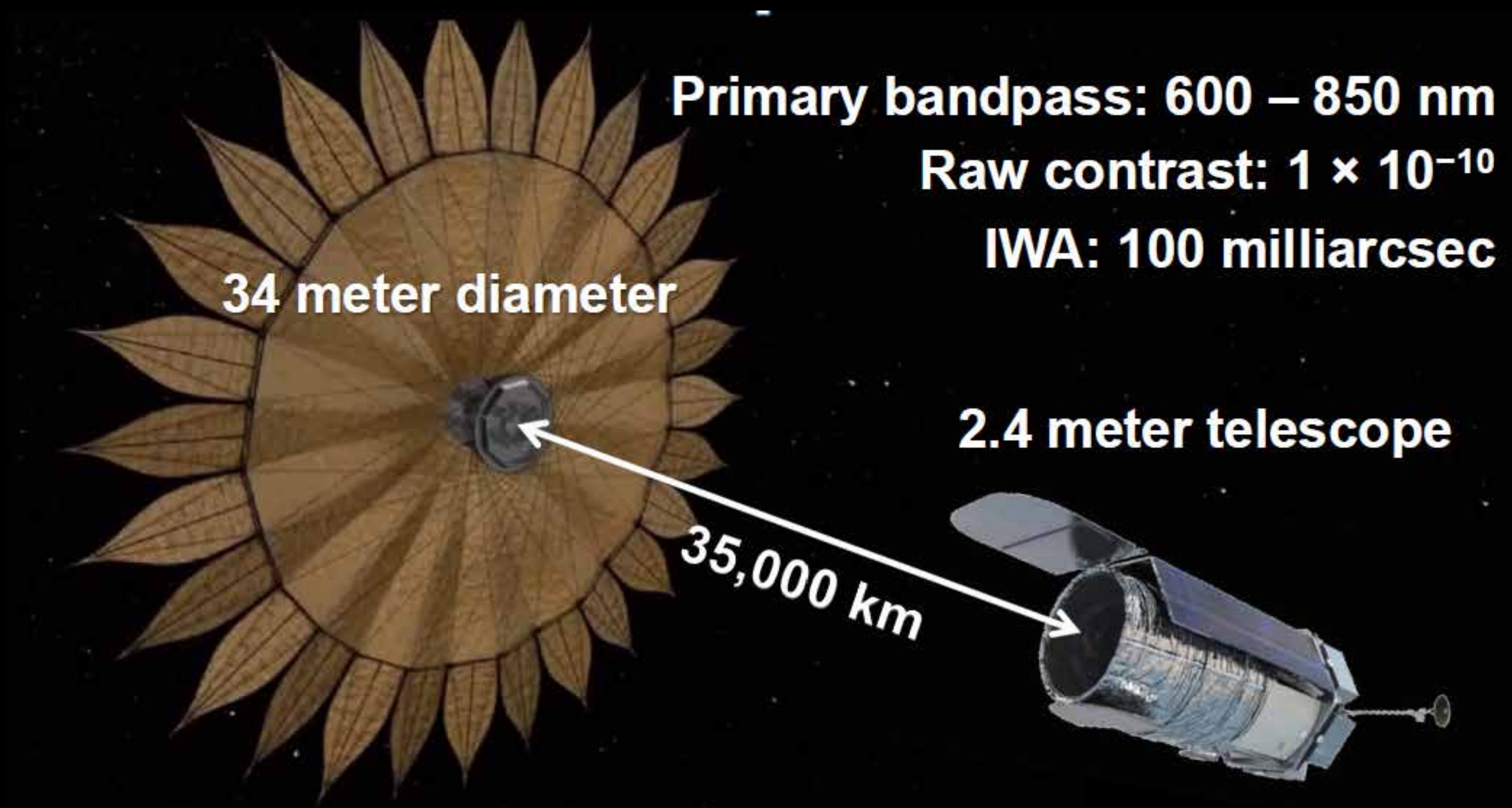


e2v Electron Multiplying CCD

Image Post Processing

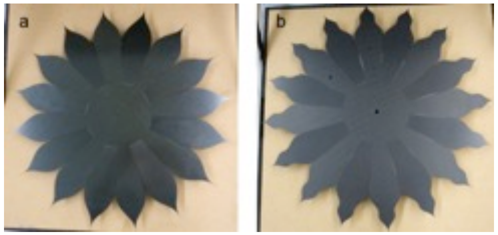
Soummer et al. 2011

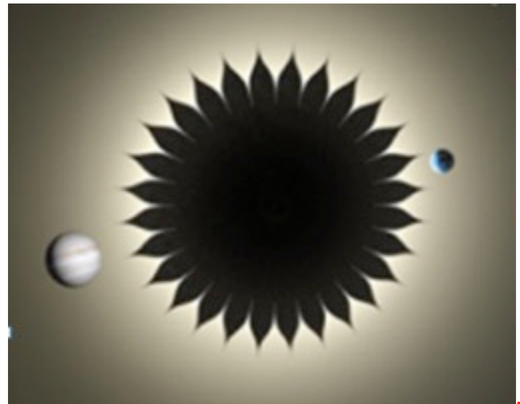
Starshade for a 2.4m telescope



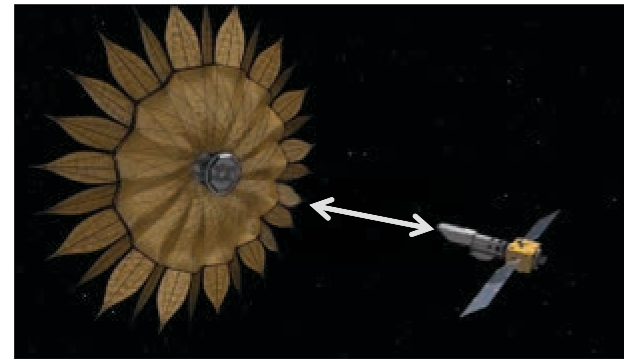
Technology Development for Starshades (External Occulters)

Control of Scattered Light

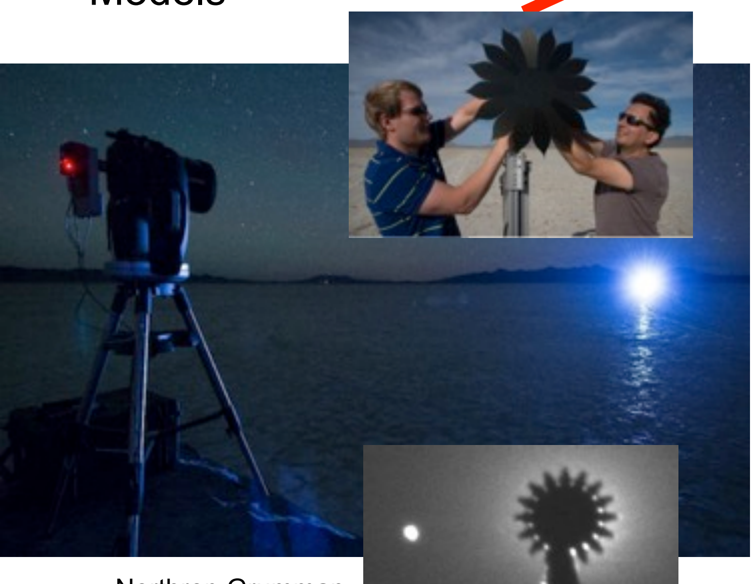




Formation Flying

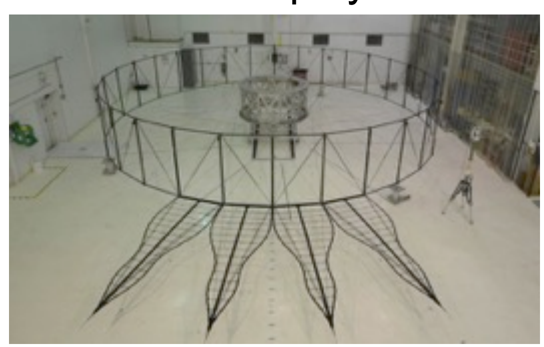


Validation of Optical Models



Northrop Grumman

Starshade Deployment



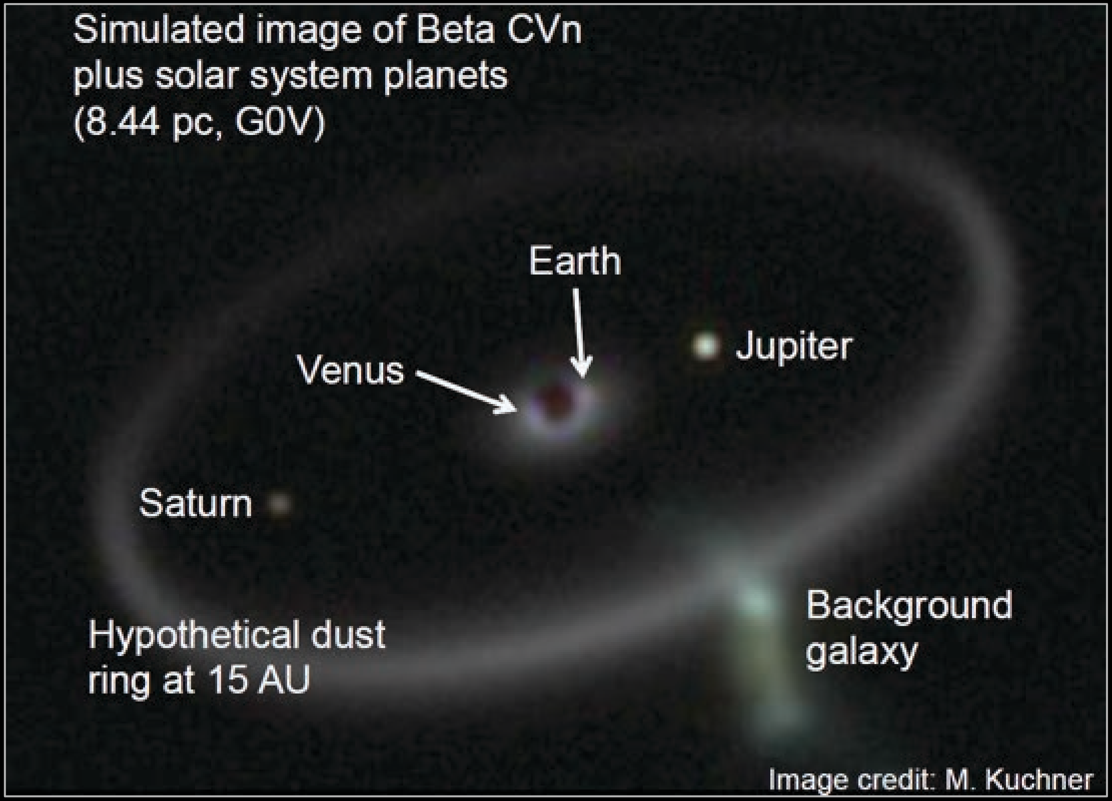
Northrop Grumman, Princeton, JPL

Petal Prototype

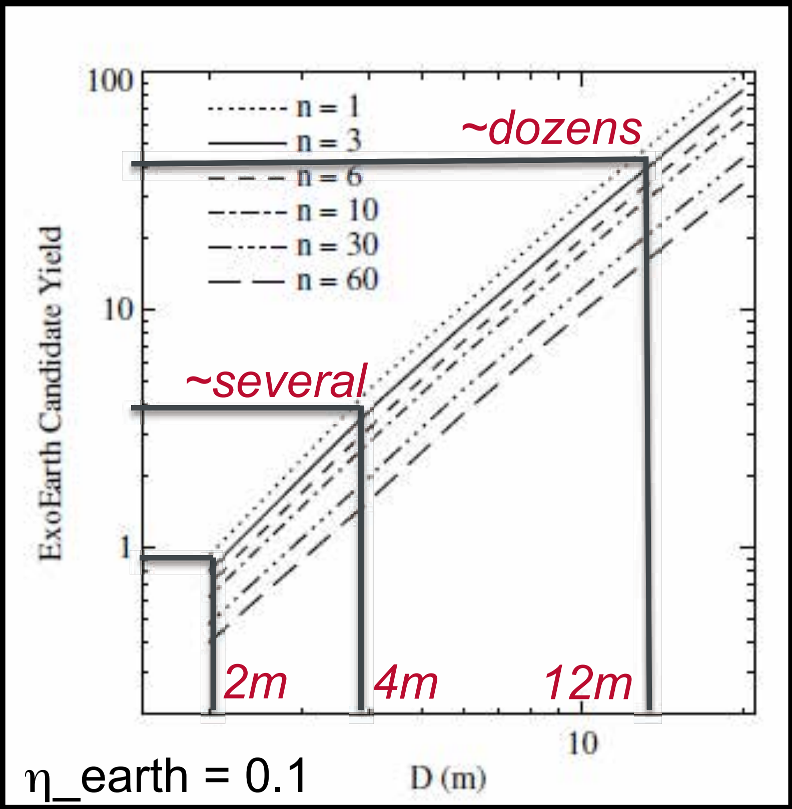
Princeton, JPL

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

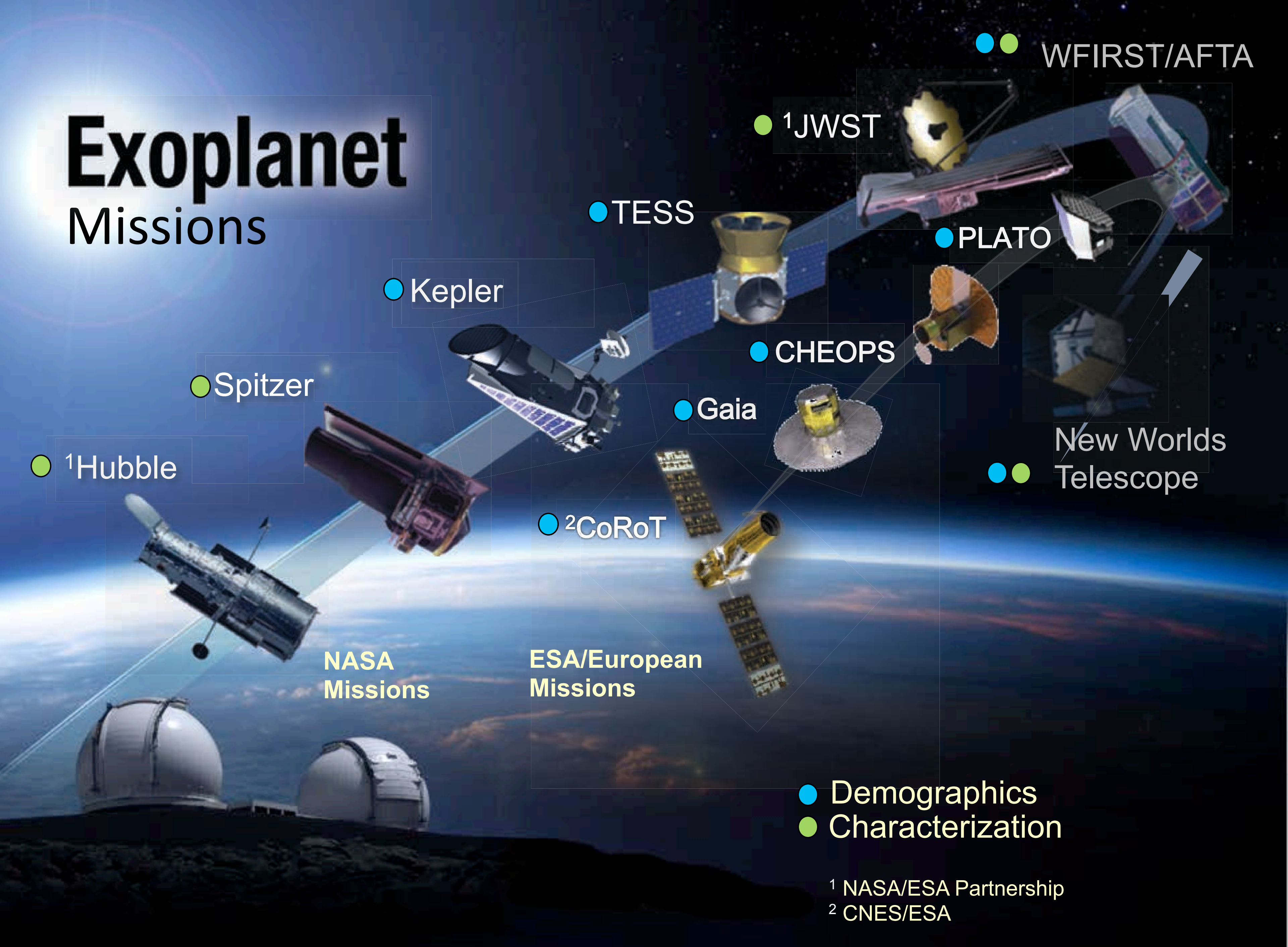


Exo-Earths require large telescopes



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)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Acknowledgements

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