Jet Propulsion Laboratory
California Institute of Technology

The Future: JWST, WFIRST, and Beyond

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July 27, 2018
Sagan Summer Workshop
Pasadena, CA

The case of 40 Eridani A

Constraining the presence of a habitable planet

- Very nearby K0 dwarf star at 5 pc distance; B and C components orbit each other 80″ away
- HZ lies at 0.13″ separation. An earth mass planet there:
  - Would induce 12 cm/sec of stellar reflex motion
  - Has a 0.4% probability of transiting
  - Would induce 0.5 μas of stellar astrometric wobble
  - Won't lens background stars (galactic lat. -38°)

- 40 Eri A is the host of Star Trek's fictional planet Vulcan
- There is no current means to detect a habitable planet in this system today

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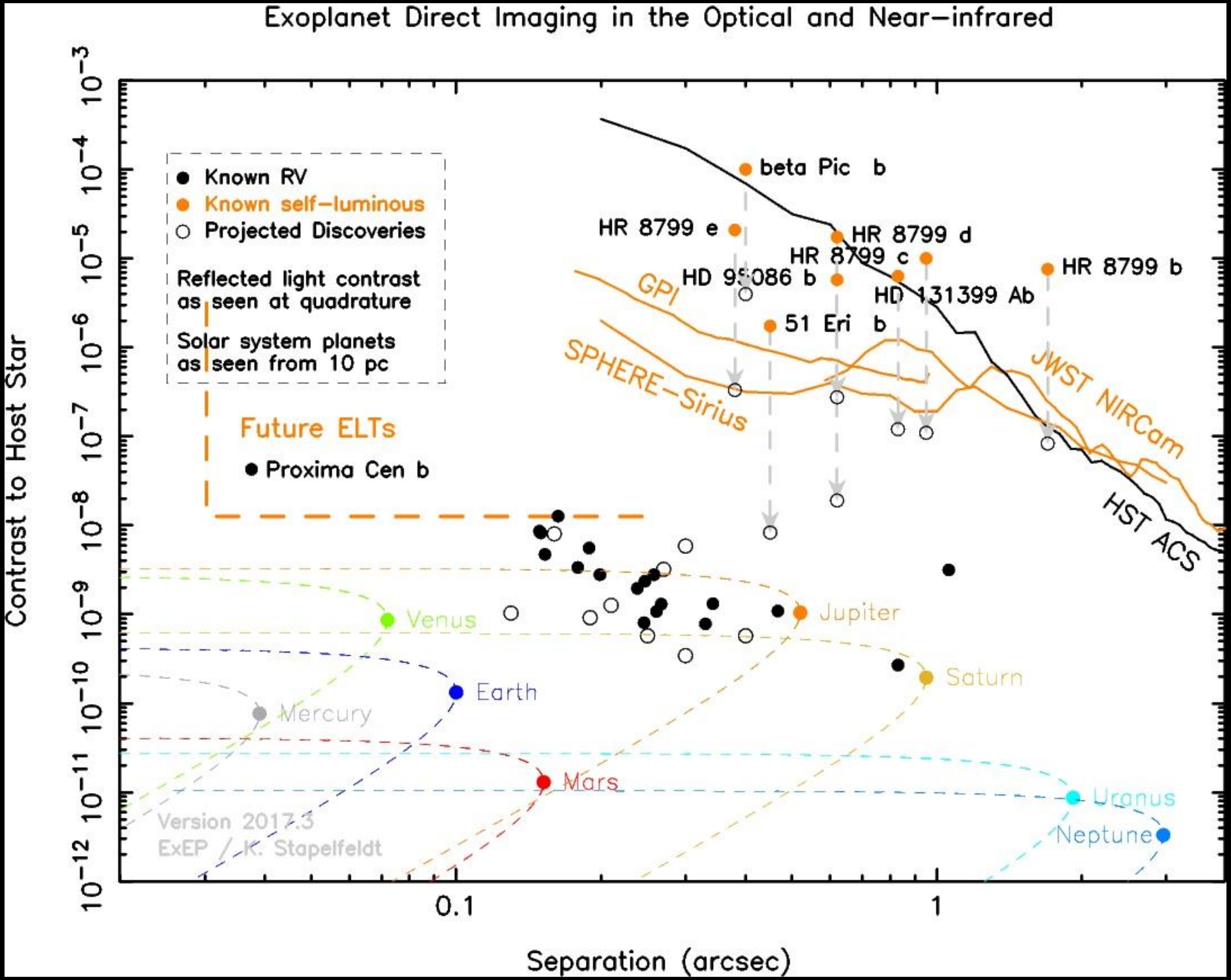
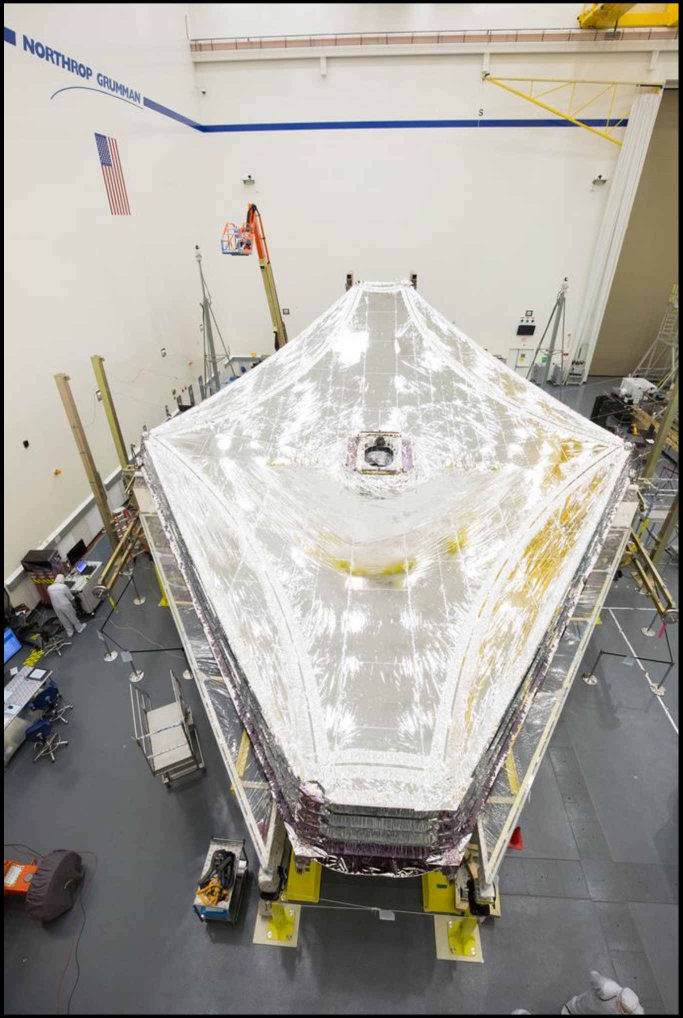
    Mass ratio ~5×10^{-6} to the star
- In direct imaging, an Earth analog here would:
  - Appear at R magnitude 27.6, and with contrast to the star of 3×10^{-10}
  - Be separated from the star by 3 resolution elements as seen by a 3 meter telescope observing in V band
  - Provide photons enabling its discovery *and* spectral measurements of its physical/chemical/biological? conditions

Contrast requirements for imaging exoplanets in reflected light



James Webb Space Telescope (JWST)

Is 30 miles from here at Northrop Grumman, Redondo Beach CA



JWST is …

- 6.5 m segmented telescope designed to operate at near-IR and mid-IR wavelengths (1-28 μm). Largest space telescope to date, first with segmented primary mirror.
- Joint NASA/ESA project with 4 science instruments
- Overall design decided 15 years ago, driven by cosmology. Operating temperature ~50 K.
- Launch on Ariane 5 now targeted for March 2021
  - Series of problems has led to 30 month schedule slip in the past year. Budget implications still being sorted out by NASA HQ
- While not specifically designed to exoplanet science requirements, it will nevertheless offer important new capabilities.

Transiting exoplanet studies with JWST

- Enables the first R= 1000 mid-IR spectra of exoplanets
- Spectroscopy will focus on bright stellar hosts with small transiting planets identified by K2 and TESS
- Hot Jupiters will be easily studies
- Should enable major progress in understanding the atmospheres of mini-Neptunes and super Earths, particularly in eclipse thermal emission measurements and thermal phase curves
- Transmission spectra of small exoplanets may be difficult due to small atmpospheric scale heights and the presence of clouds/hazes

JWST Transit spectra will be expensive …

(Morley et al. 2017)

Table 1. Number of transits or eclipses required to detect a Venus-like atmosphere[a]

Planet	Emission P = 0.1 bar	Emission P = 1.0 bar	Emission P = 10.0 bar	Transmission P = 0.01 bar	Transmission P = 0.1 bar	Transmission P = 1.0 bar
TRAPPIST-1b	6 (11)	9 (18)	17 (30)	23 (89)	11 (40)	6 (21)
TRAPPIST-1c	19 (37)	29 (58)	48 (92)	–	73 (50)	36 (25)
TRAPPIST-1d	–	–	–	59 (–)	25 (46)	13 (24)
TRAPPIST-1e	–	–	–	15 (–)	6 (66)	4 (71)
TRAPPIST-1f	–	–	–	73 (–)	27 (92)	17 (54)
TRAPPIST-1g	–	–	–	36 (–)	15 (–)	10 (76)
TRAPPIST-1h	–	–	–	16 (–)	6 (90)	4 (56)
GJ 1132b	2 (2)	2 (3)	3 (6)	27 (38)	13 (20)	11 (13)
LHS 1140b	–	–	–	–	– (96)	– (64)

[a] The detection criteria are (1) for transmission spectra, the simulated data must rule out a flat line at 5σ confidence on average, and (2) for emission spectra, the band-integrated secondary eclipse must be detected at 25σ. We base our calculations on models with a Venusian composition, zero albedo, and planet mass equal to the measured values from TTVs or RVs. For the case in parentheses, we use an albedo of 0.3 and planet mass predicted by the theoretical mass/radius relation. The – mark denotes cases where over 100 transits or eclipses are needed.

But potentially rewarding …

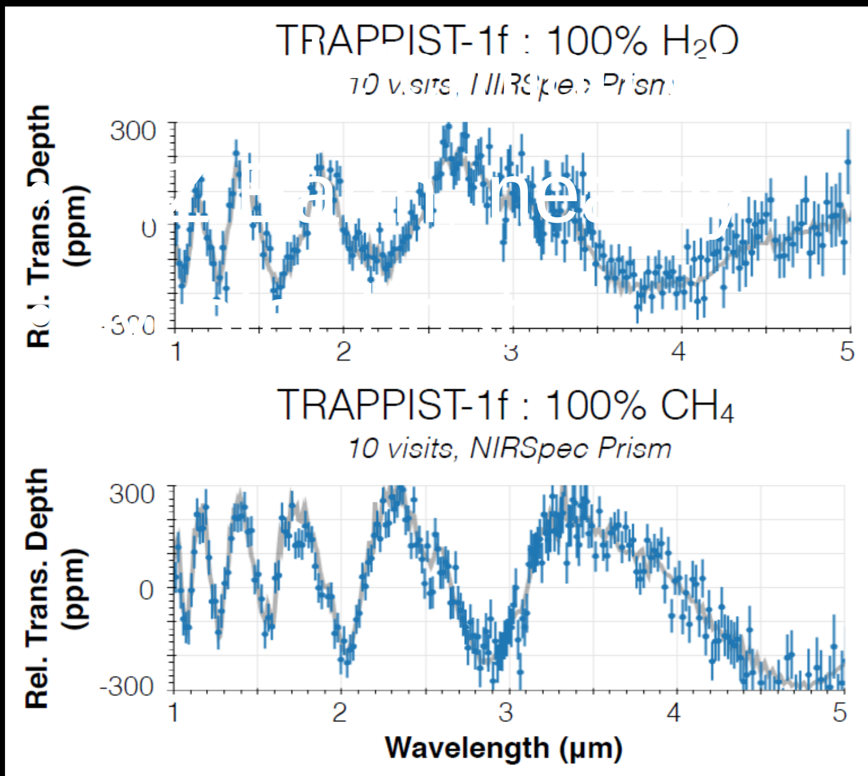
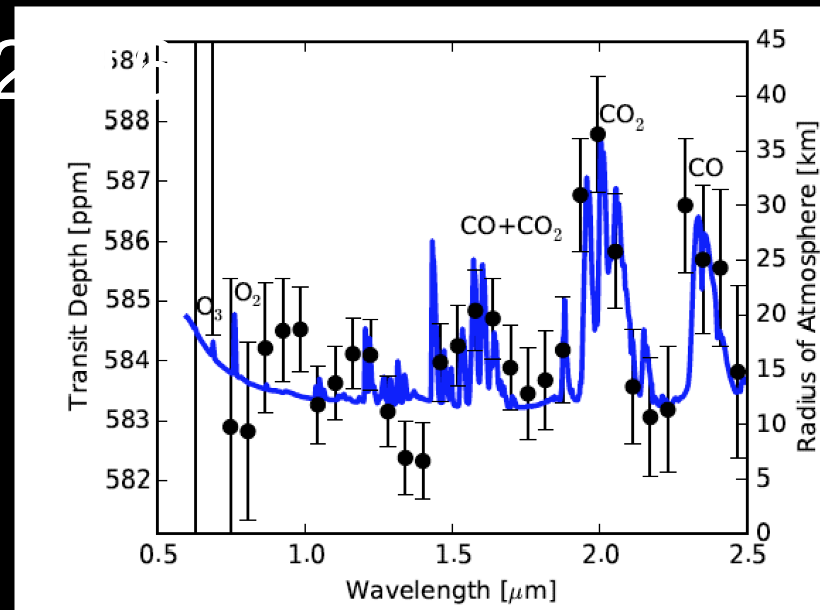


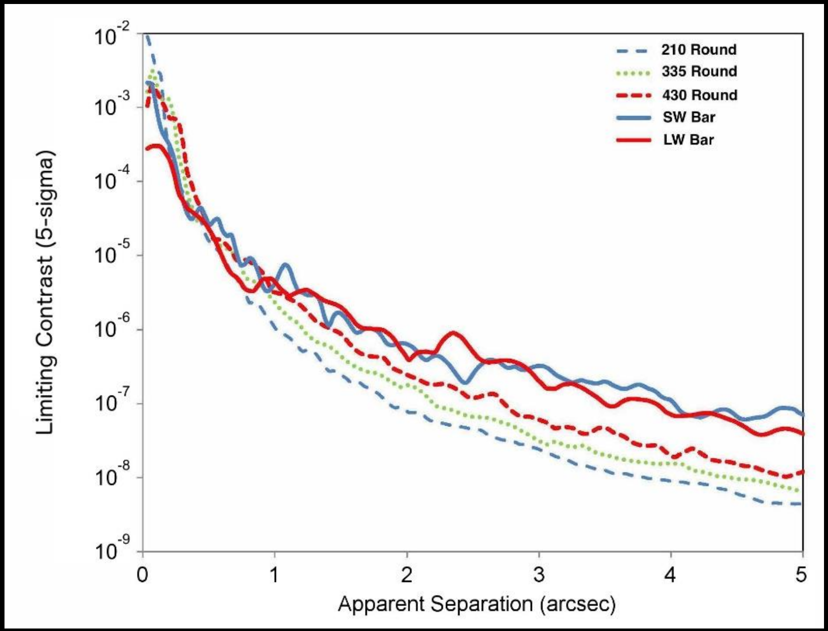
Figure by Natasha Batalha courtesy Kevin Stevenson



Simulated JWST spectrum of HZ Earth, nearby M star host 10 transits, photon limit only Schwieterman et al. 2016

Exoplanet Direct Imaging with JWST

- Three instruments provide specialized high contrast imaging modes
- Contrast will not be better than HST or ground AO
- Sensitivity will be orders of magnitude better in the mid-infrared, enabling exoplanet spectra from 2.5-10 microns
- Inner working angle is limited by complexity of telescope PSF and long wavelengths
- Best science is likely to be imaging of self-luminous planets cooler than prior facilities could detect

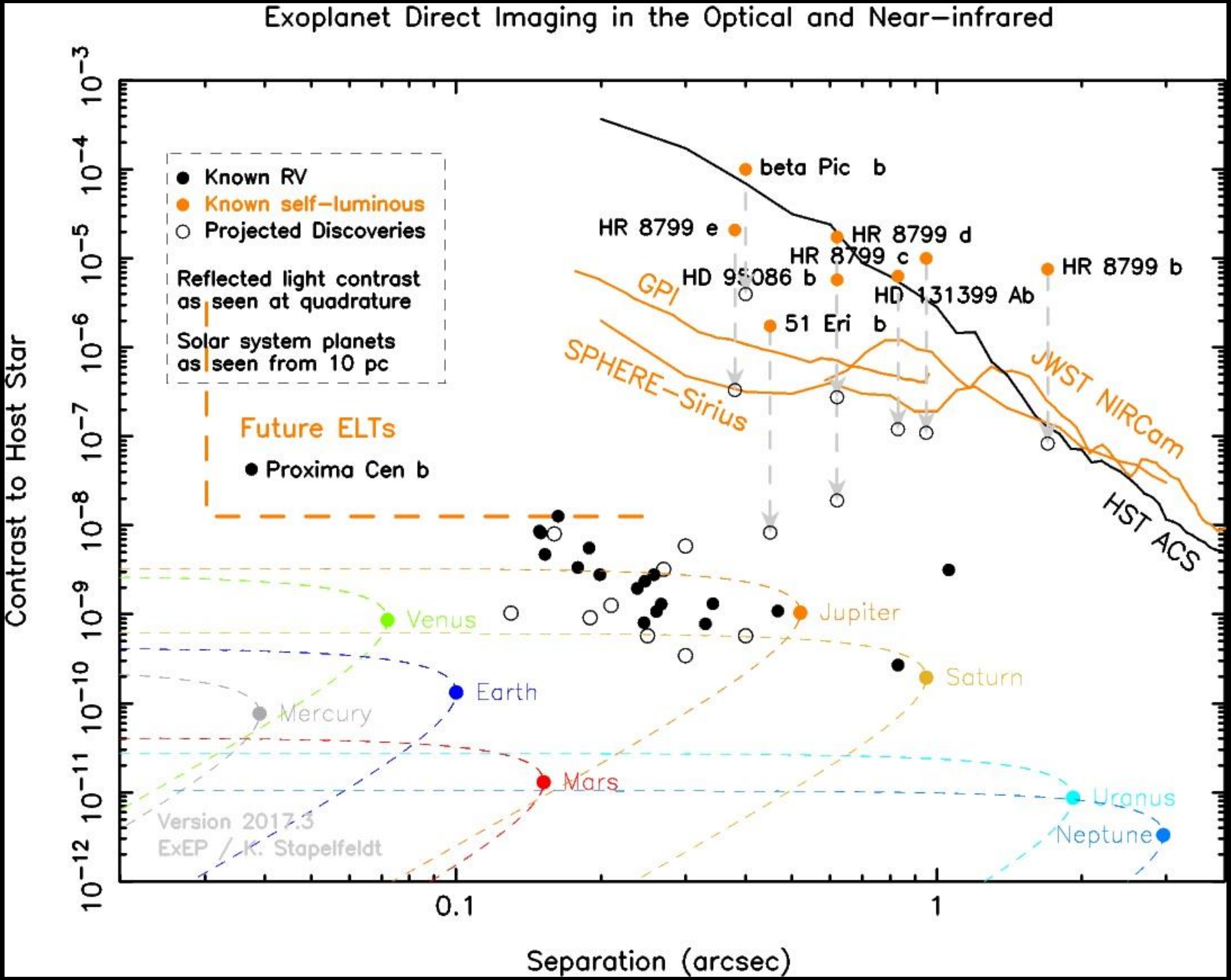


NIRCam contrast curve from Beichman et al. 2010

JWST Early Release Science has significant exoplanet component, PUBLIC DATA

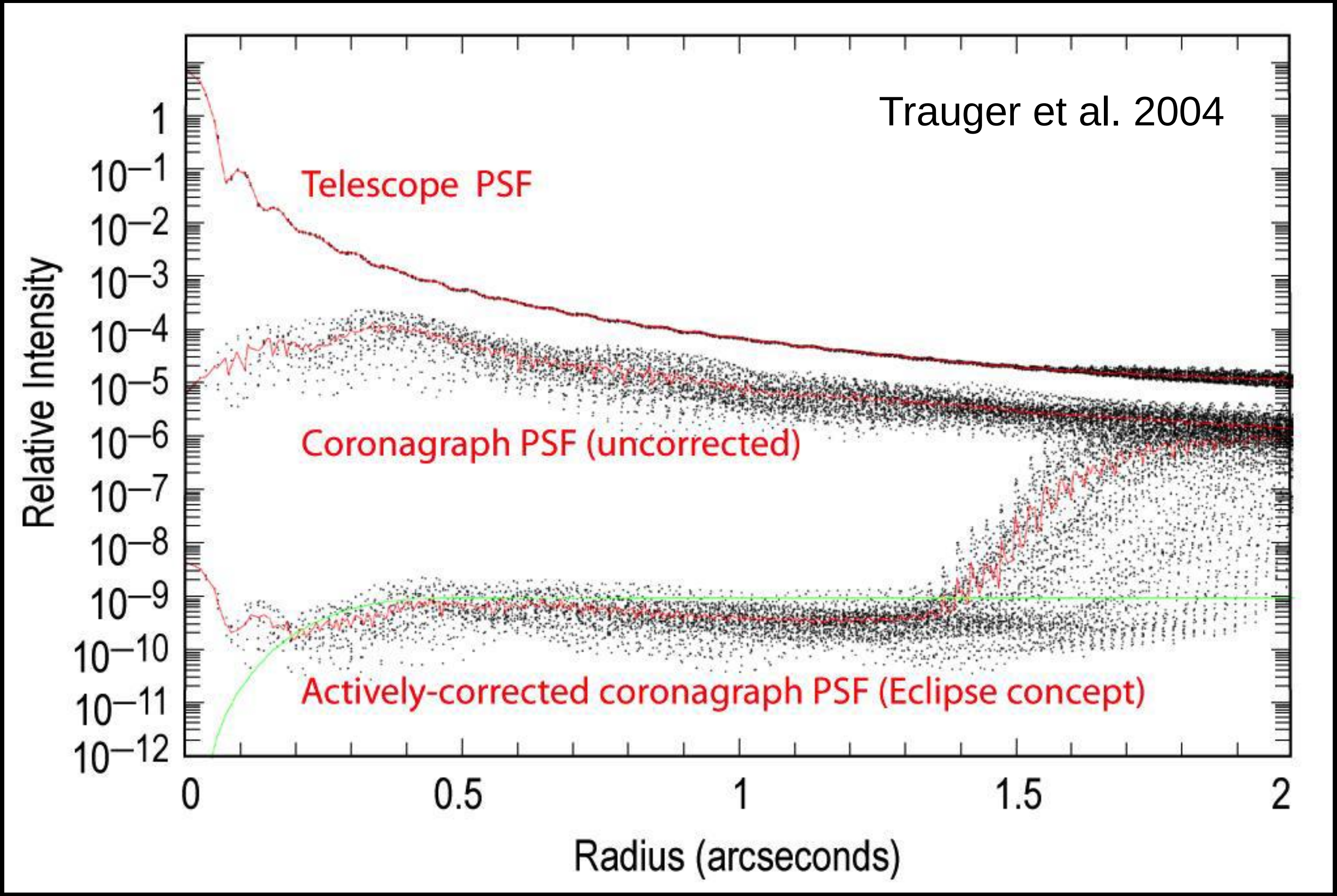
- The Transiting Exoplanet Community Early Release Science Program 78 hours: Batalha, Bean, & Stevenson
  - Will use all 4 instruments
  - Will observe in transmission, emission, and phase curves
- High Contrast Imaging of Exoplanets and Exoplanetary Systems with JWST 52 hours: Hinkley, Skemer, & Biller
  - Will use all 4 instruments to observe known exoplanet, debris disk, and upper limits to new exoplanet detections
  - Emphasizes coronagraphy but direct spectra and aperture mask imaging will be done
- Together these programs were awarded more than ¼ of all the JWST ERS time, can we do this throughout the mission ?

Contrast requirements for imaging exoplanets in reflected light



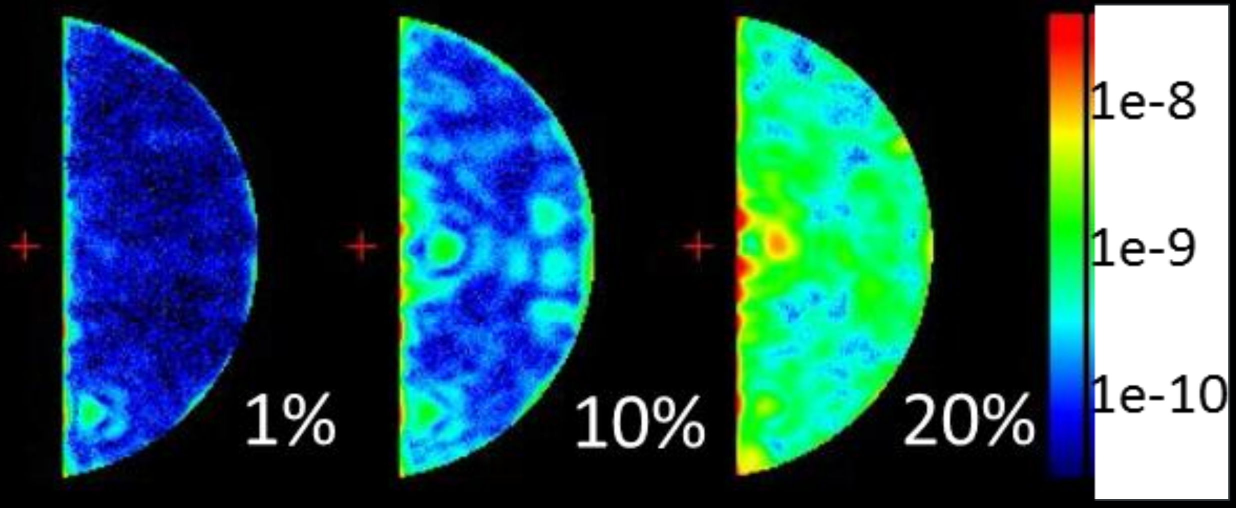
Wavefront control improves image contrast by many orders of magnitude

Wavefront errors come from imperfections in the optics, drift of telescope optical alignment & focus, pointing errors, and structural vibrations



Coronagraph technology today

- Development and laboratory contrast demonstrations have been ongoing for 10+ years, supported by NASA technology investments
- Has already demonstrated 10^{-9} visible contrast with 20% bandwidth at an inner working angle (IWA) of 3 λ/D in the laboratory (Trauger et al. 2012).
- We are within reach of the contrast and bandwidth needed to image a habitable planet around 40 Eri A, if the host telescope is sufficiently stable



Hybrid Lyot coronagraph, lab measurements of contrast versus bandwidth

Progress since this demo:
- Full dark hole created using two deformable mirrors
- Circular masks fabricated
- Mask rebuilt to provide better performance

NASA Exoplanet Exploration Program

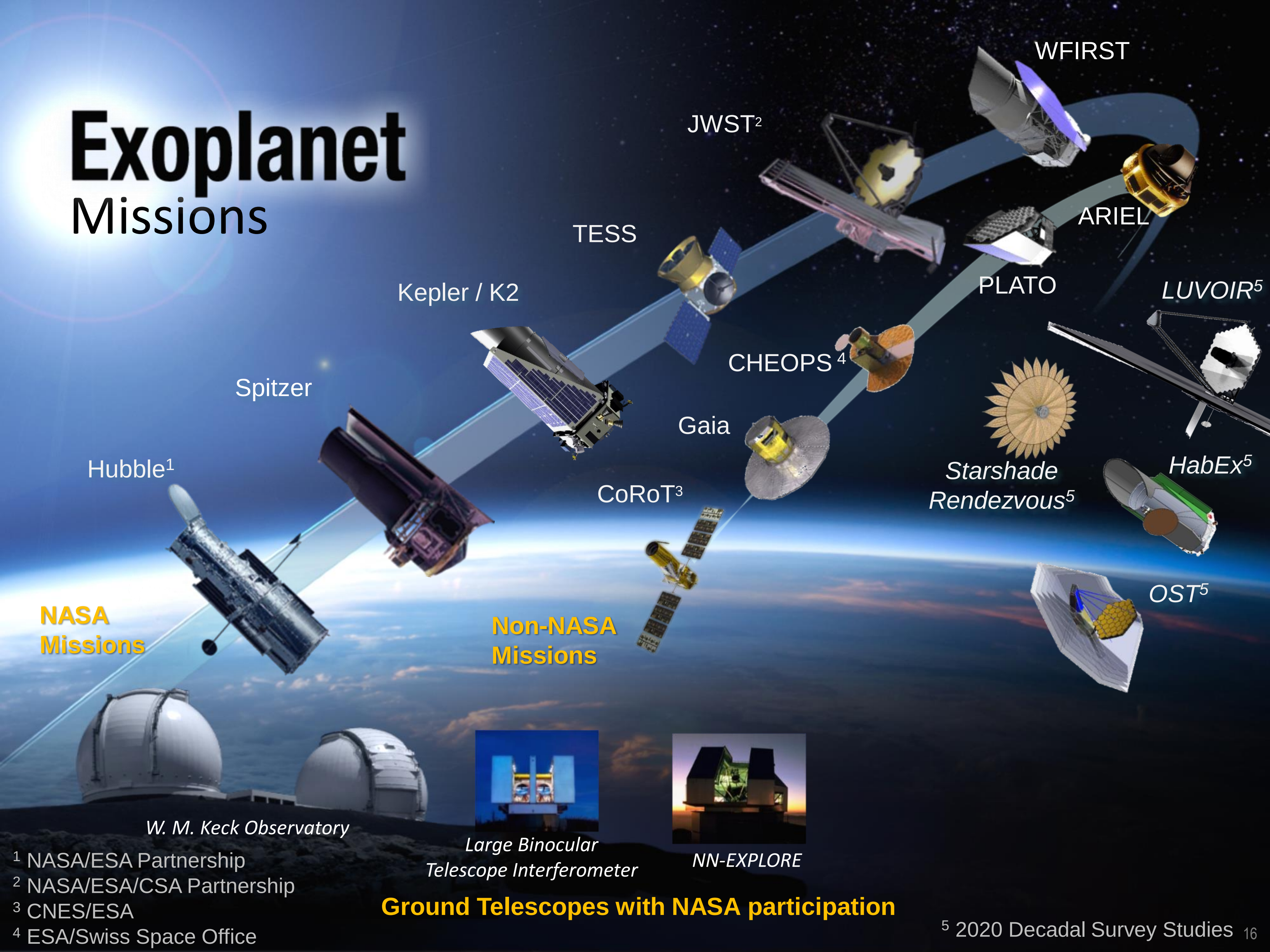
Part of the NASA Astrophysics Division, Science Mission Directorate

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


Exoplanet
Missions
WFIRST
JWST[2]
ARIEL
TESS
PLATO
Kepler / K2
LUVOIR[5]
CHEOPS [4]
Spitzer
Gaia
Starshade
Rendezvous[5]
HabEx[5]
Hubble[1]
CoRoT[3]
OST[5]
NASA
Missions
Non-NASA
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
[4] ESA/Swiss Space Office
[5] 2020 Decadal Survey Studies

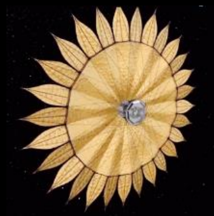
NASA Exoplanet Exploration Program

Space Missions and Mission Studies

K2

Probe-Scale Studies

Starshade



Coronagraph

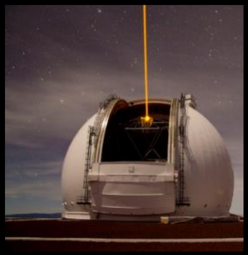
Communications

Supporting Research & Technology

Key Sustaining Research

NN-EXPLORE

Large Binocular Telescope Interferometer

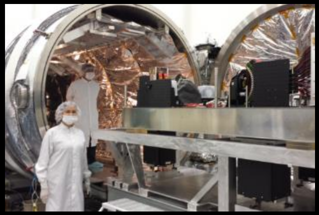


Keck Single Aperture Imaging & RV

Technology Development

Occulting Masks

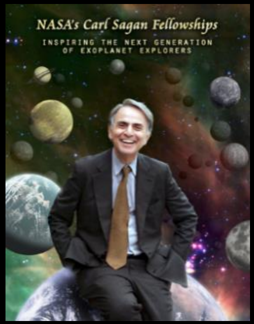
Deformable Mirrors

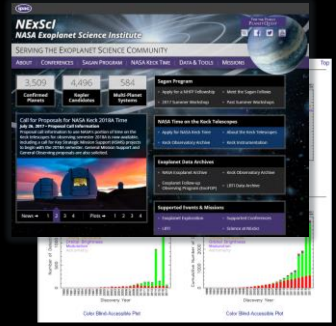


High-Contrast Imaging

Deployable Starshades

NASA Exoplanet Science Institute





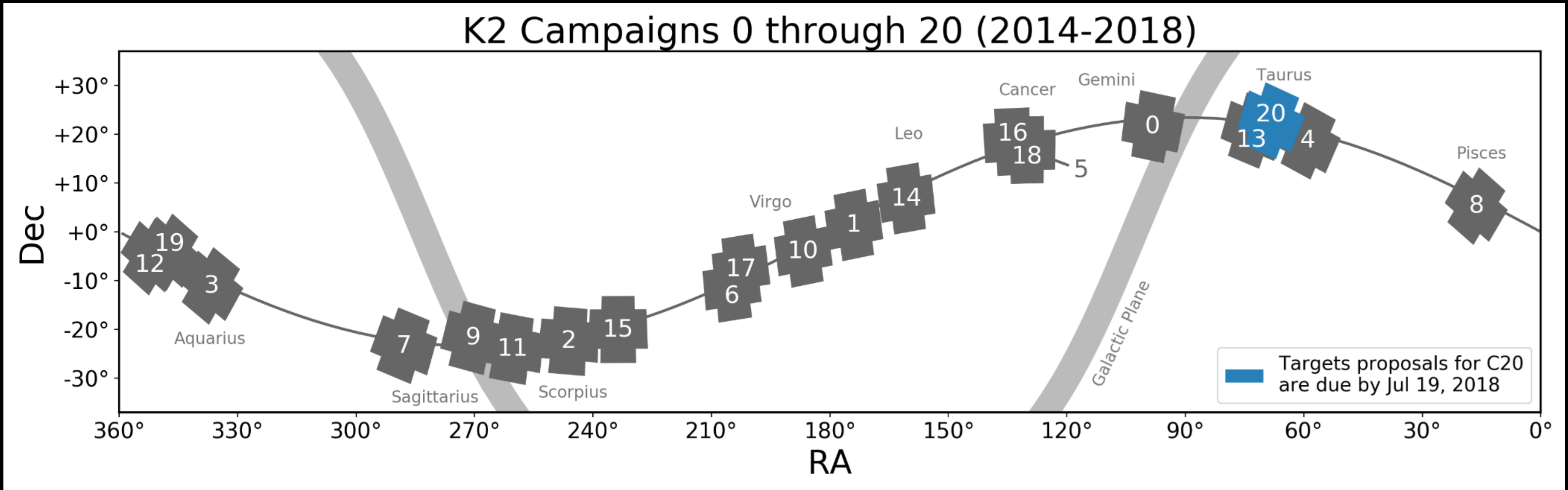
Archives, Tools, Sagan Fellowships, Professional Engagement

https://exoplanets.nasa.gov

K2 Mission

Transits – mission on standby

Kepler fields on the ecliptic: 323 confirmed planets plus 476 candidates



Campaign 17 completed, Campaign 18 suspended 7/6 after 51 days

Upcoming:

- Next week: downlink of Campaign 18 data, determination whether remaining fuel will support continued science operations or not
- Kepler/K2 Conference V March 4-8 2019 in Glendale, CA

https://exoplanets.nasa.gov/k2

NASA Exoplanet Science Institute

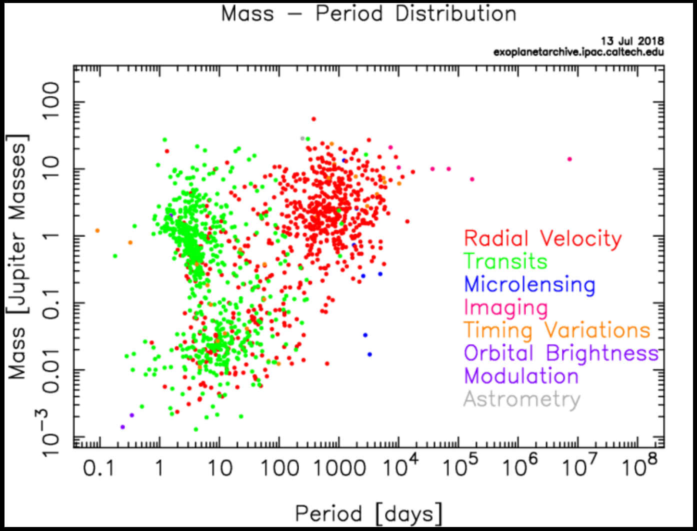
NExScI NASA Exoplanet Science Institute
California Institute of Technology

- exoplanetarchive.ipac.caltech.edu
  - Planet tables
  - Light curves
  - Analysis tools
  - Regularly updated
- Exoplanet Follow-up Observing Program
  data-sharing infrastructure for community followup of Kepler, K2, and TESS
- Sagan Summer Workshops
- Organizing Sagan component of NASA Hubble Fellowship Program

In the HZ

Confirmed

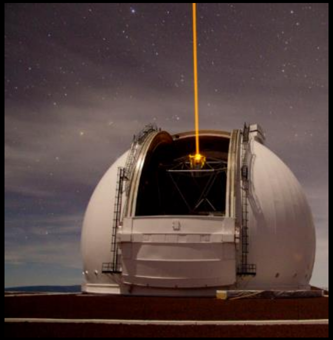
Candidates



Operating

Ground-Based Support for Space Missions

I. The twin 10m Keck telecopes at Mauna Kea, Hawaii



- NExScI administers NASA's 1/6 share
- Key Projects and smaller general observer Investigations
- Proposals for 2019A due on 9/13 (TBC)

Completed

Ground-Based Support for Space Missions

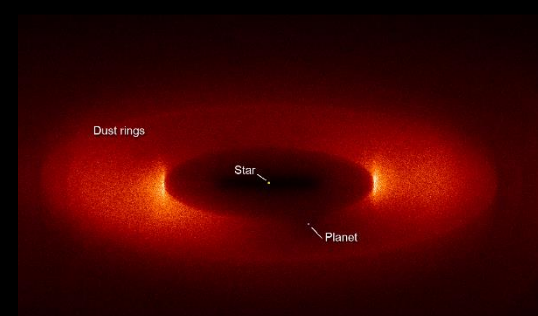
II. Large Binocular Telescope Interferometer, Mt. Graham Arizona,

Credit: ESO/Y. Beletsky

- Measuring HZ exozodiacal dust at 10 μm to inform designs of future missions
- Interim results (Ertel et a. 2018) find most stars not very dusty, median exozodi < 23 zodis for sun-like stars
- Project completed June 2018 with 39 stars observed
- Final science papers now in preparation

Phil Hinz, PI

The University of Arizona



Credit: NASA/GSFC

Groundbased support for Space Missions

Building

III. NASA/NSF Partnership for Exoplanet Research - Doppler Spectrometer

NN·EXPLORE
Partnership for Exoplanet Discovery and Characterization

- Motivation
  - 2010 Decadal Survey called for precise ground-based spectrometer for exoplanet discovery and characterization
  - Follow-up & precursor science for current missions (K2, TESS, JWST, WFIRST)
  - Inform design/operation of future missions
- Scope:
  - Extreme precision radial velocity spectrometer (<0.5 m/s) with 40% of time on WIYN telescope
    - Penn State NEID proposal selected in March 2016
    - Instrument to be commissioned spring 2019
    - R= 100,000; 380-930 nm wavelength coverage
  - Ongoing Guest Observer program using NOAO share of telescope time for exoplanet research

NEID

NN-Explore Exoplanet Investigations with Doppler Spectroscopy

PennState

PI: S. Mahadevan

3.5m WIYN Telescope
Kitt Peak National Observatory
Arizona

Technical readiness for direct imaging of habitable exoplanets:

The #1 medium-scale space mission priority of U.S. 2010 Decadal Survey

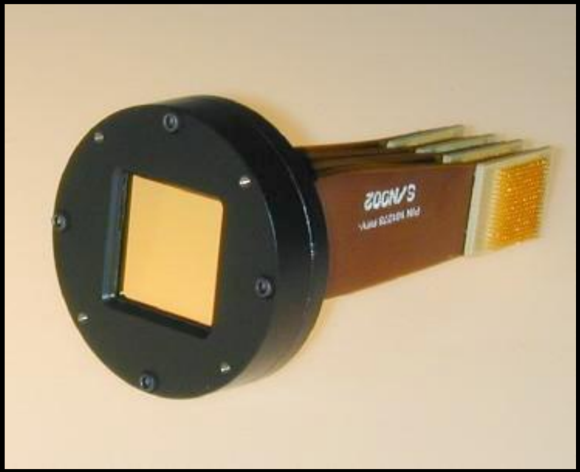
Coronagraph Technology Gap List

Table 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 $\leq 1\times10^{-10}$ contrast with IWA $\leq 3\lambda$/D and $\geq$ 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 $10^{-3}\,\lambda$ rms at sub-Hz frequencies.	Tip/tilt, focus, astigmatism, and coma sensed and corrected simultaneously to $10^{-4}\,\lambda$ (~10's of pm) rms to maintain raw contrasts of $\leq 1\times10^{-10}$ 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 $\leq 10^{-9}$ contrasts in a vacuum environment and 10% bandwidth.	≥ 64x64 DMs with flight-like electronics capable of wavefront correction to $\leq 10^{-10}$ 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.

Future imaging mission technology



Coronagraph Technology Gaps

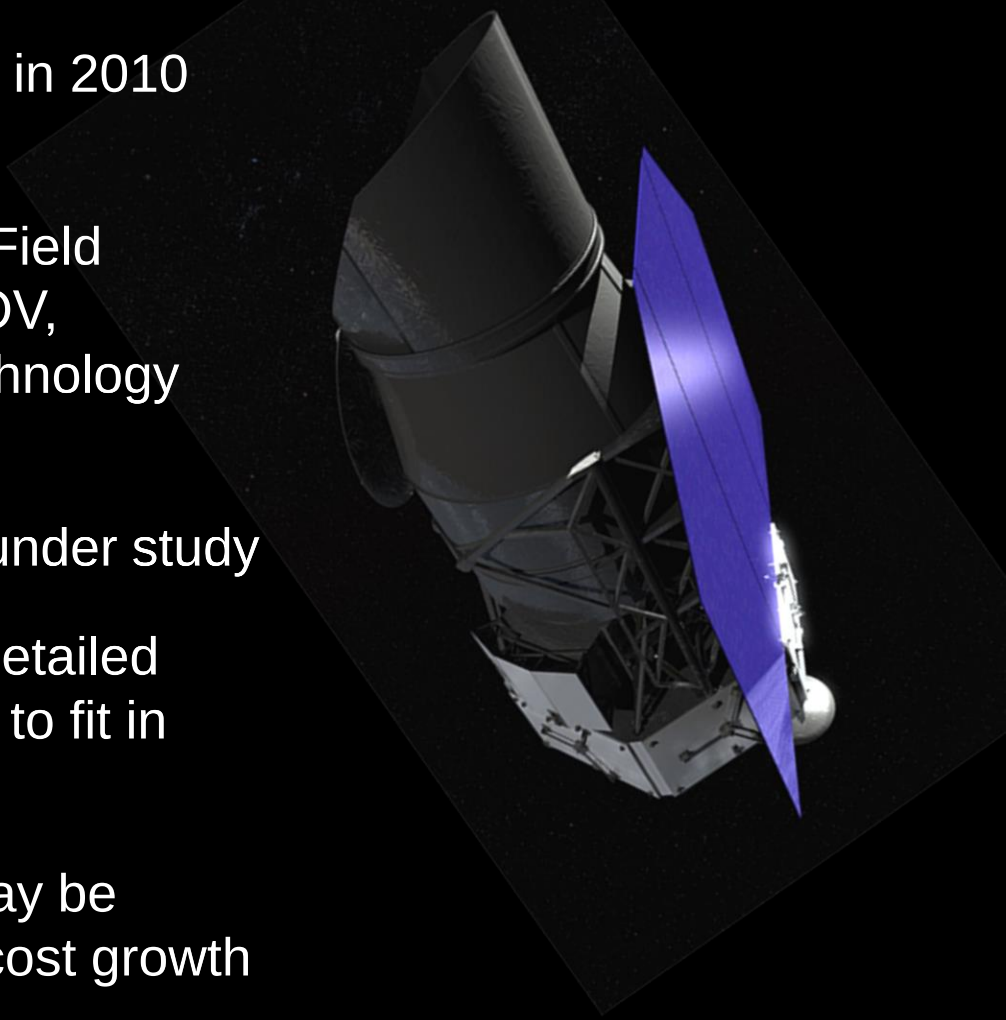
http://exoplanets.nasa.gov/exep/technology/

Mission in Formulation

Wide Field Infrared Survey Telescope (WFIRST)

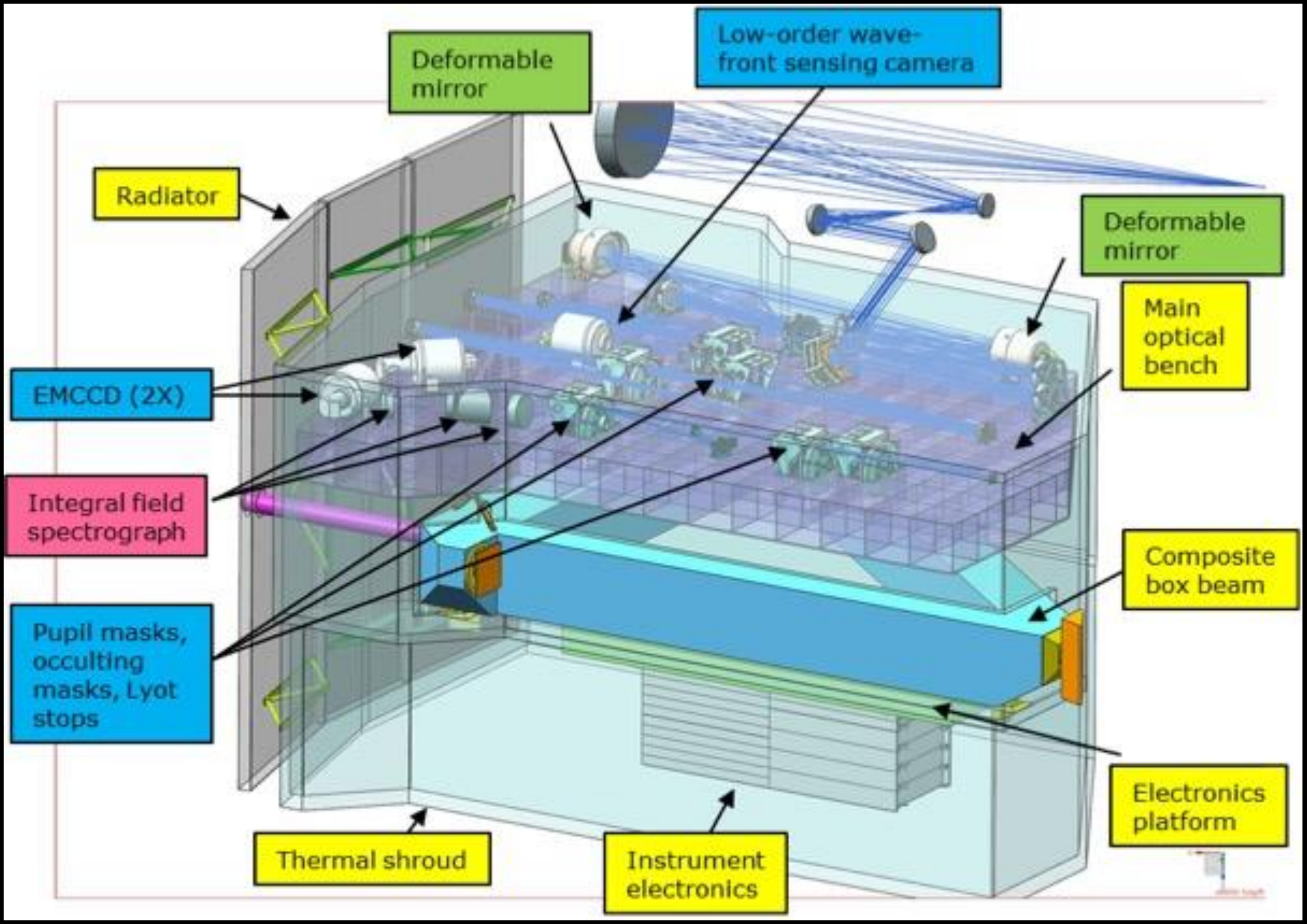
Dark Energy, Microlensing, Infrared Surveys, Coronagraphy

- Top priority new space mission in 2010 astrophysics Decadal Survey
- 2.4m surplus telescope, Wide Field Camera with 100x Hubble's FOV, coronagraph instrument as technology demonstration only
- Starshade rendezvous option under study
- Project is now in "Phase B" – detailed design, launch in 2025. Trying to fit in $3.2B cost cap.
- Project scope and schedule may be affected by JWST delays and cost growth



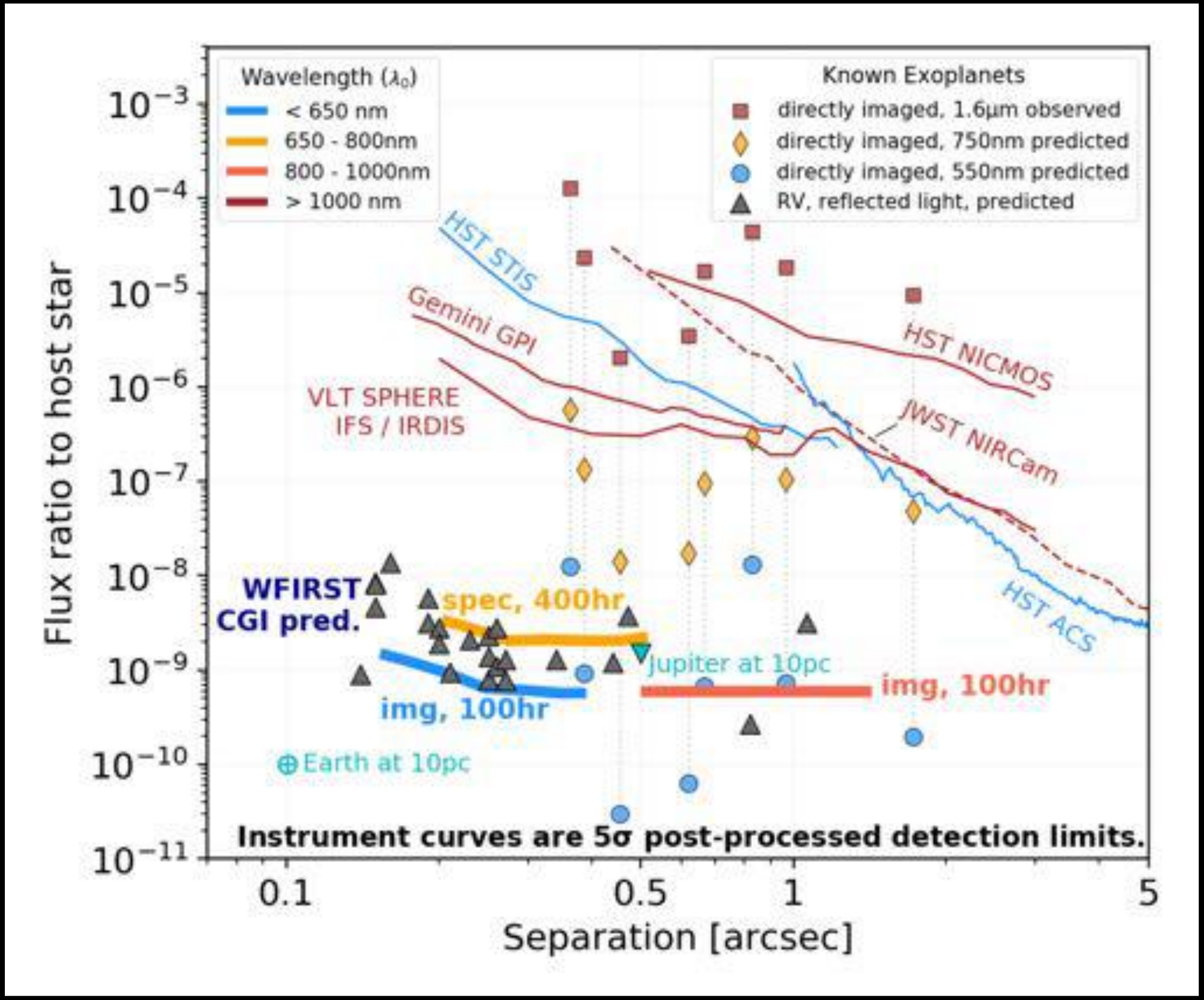
Credit: NASA/GSFC

WFIRST coronagraph instrument layout



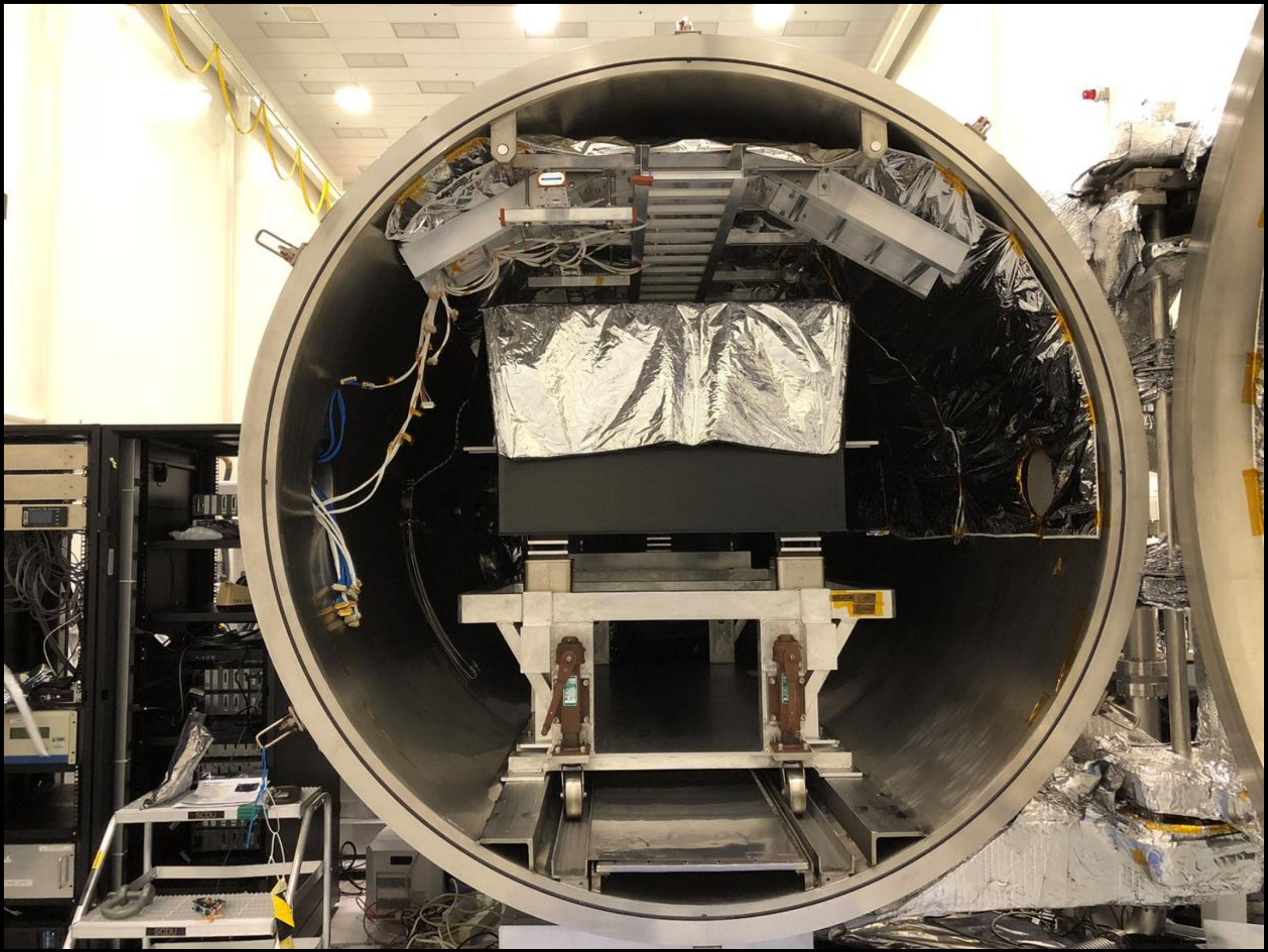
WFIRST coronagraph expected performance

A milestone on the way to exo-Earth contrasts



Decadal Survey Testbed (coronagraphy):

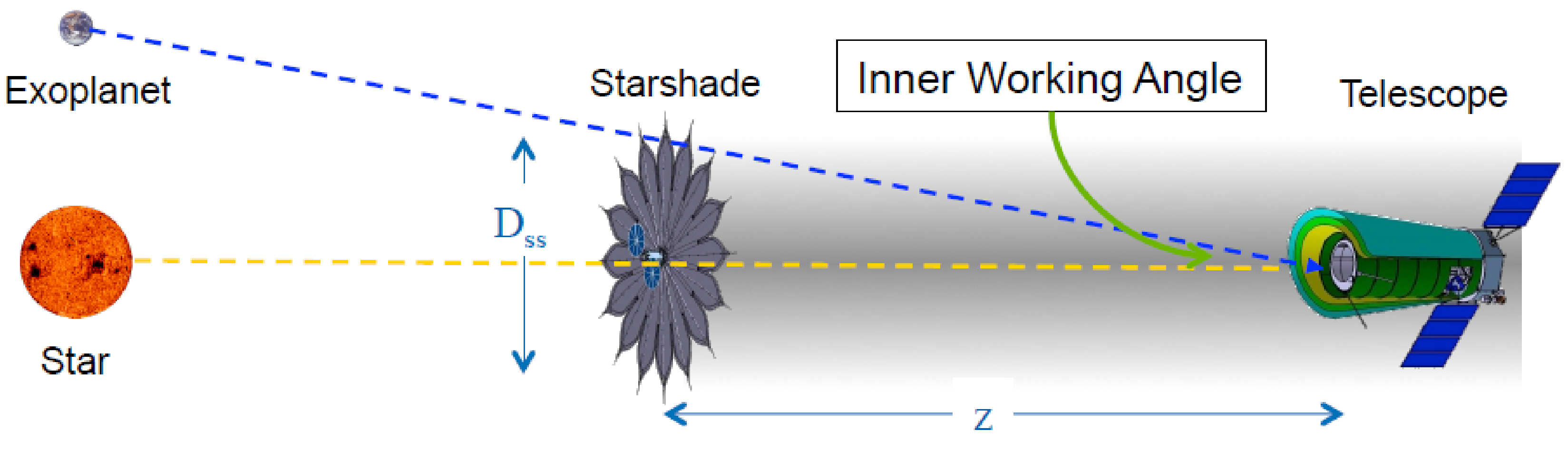
Goal: Lab demonstration of 10^{-10} broadband contrast within 1 year



Future mission concept

STARSHADE

for visible wavelengths; active area of NASA study/investment
Does not require high telescope stability. Needs fuel to reposition.
A deployed structure ≥ 30 m diameter, cannot fully test before flight



- Inner Working Angle is the closest separation of Planet and Star that we can expect to see with a given starshade
- For Hypergaussian starshade, this is approximately equivalent to:

$$\mathrm{IWA} = \frac{D_{SS}/2}{z}$$

Figure by Steve Warwick, NGST

Future mission technology

Starshade Technology Gap List

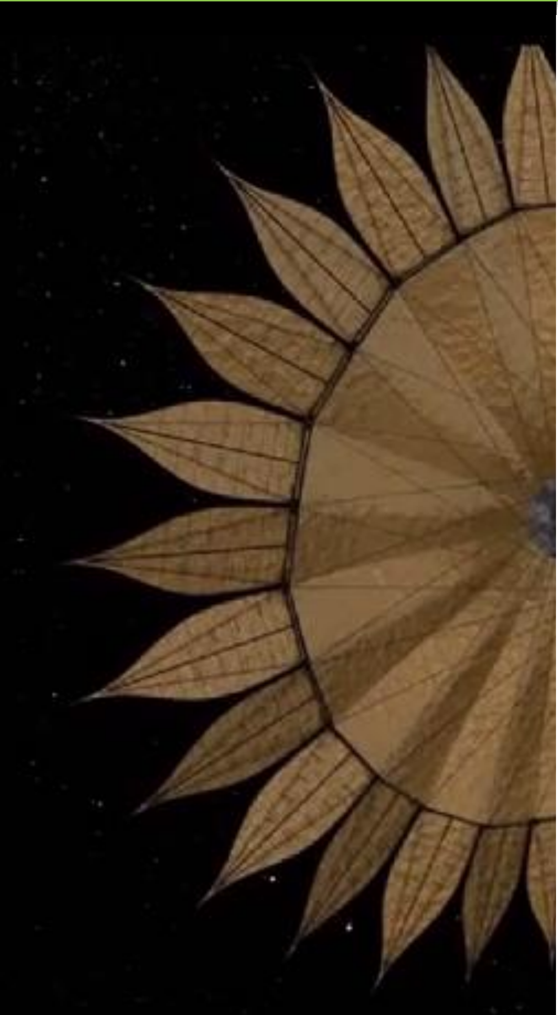


Table A.4 Starshade Technology Gap List

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 $\leq 3\times10^{-11}$ 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.

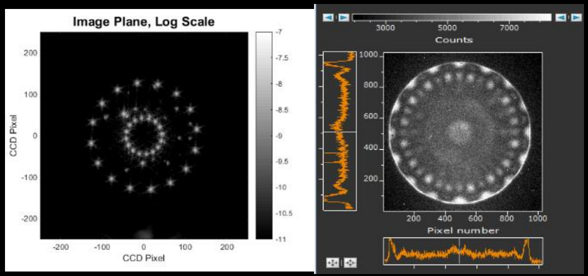
Starshade Technology Gaps

Starshade Technology Development "S5"

- Focused effort to ready starshade technology by 2020 – enable the option of starshade rendezvous with the WFIRST telescope for 10^{-10} contrast science
- Held 5 workshops on technology gaps and mechanical architecture trade
- Key Technology Achievements
  - Demonstrated starlight suppression modeling agreement within 10%
  - Princeton starlight suppression demonstration currently at 10^{-8} (mask limits)
  - Demonstrated half-scale deployment of inner disk optical shield
- Now finalizing plans for work through 2022

Starshade Workshops

Contrast at higher Fresnel number, exposure time: 100s



Suppression at flight Fresnel number, exposure time: 3000s

Inner optical shield deployment tests

Decadal Flagship Mission Studies

Future mission concepts

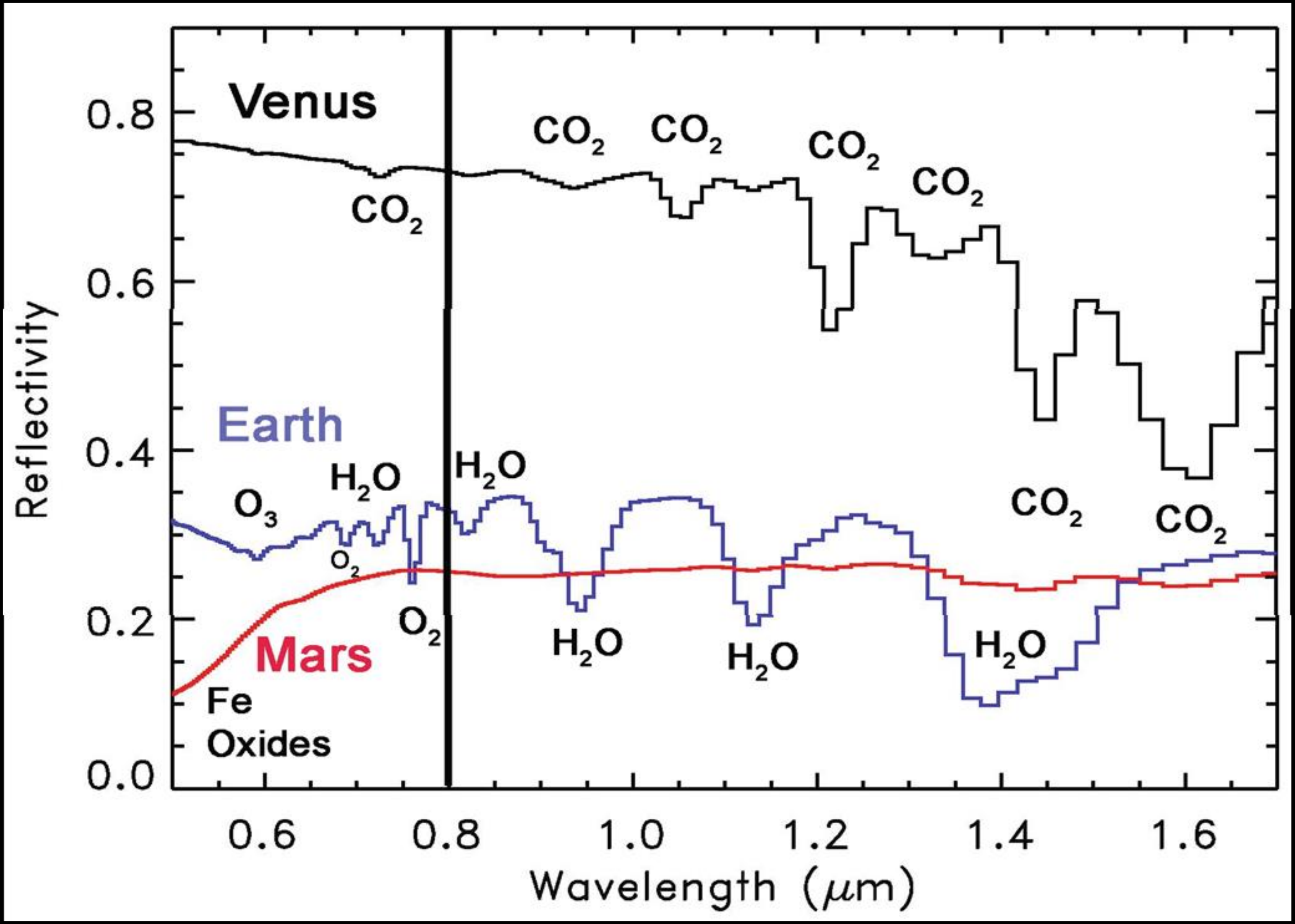
Possible New Worlds Exoplanet Telescopes

(for 2020 Decadal Survey; mid 2030s launch; work outside ExEP)

- Origins Space Telescope: Large mid/far-infrared mission
  - Primary exoplanet science case would be transit spectroscopy to build on JWST results
- Large Ultra-Violet Optical InfraRed Telescope (LUVOIR)
  - Coronagraphic imaging with deployed/segmented primary mirror
  - Large apertures & exoplanet survey sample
  - Equal weighting to exoplanets & general astrophysics
  - 4 instruments: Coronagraph, UV spectrometer, Optical/NIR general astrophysics camera, UV polarimeter (CNES)
- Habitable Exoplanet Mission (HabEx)
  - Coronagraph & starshade imaging with monolithic, off-axis telescope
  - Smaller apertures & exoplanet survey samples
  - 3 instruments: coronagraph, UV spectrometer & optica/NIR general astrophysics camera

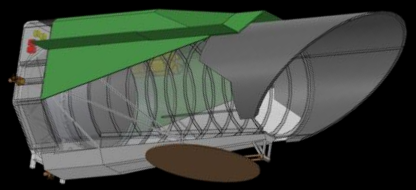
HabEx & LUVOIR's prime goal: spectra of rocky exoplanets

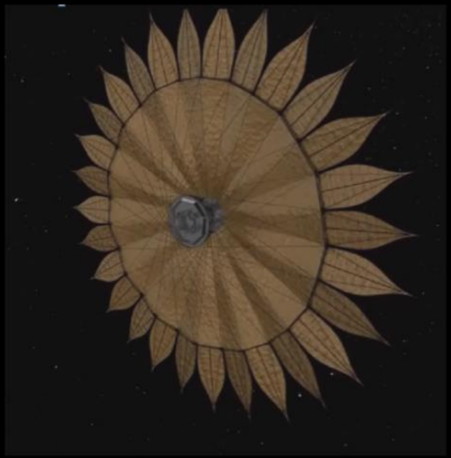
FROM TPF-C STDT report



Progress in HabEx and LUVOIR designs

(work outside of ExEP; both teams gave input on their tech priorities)

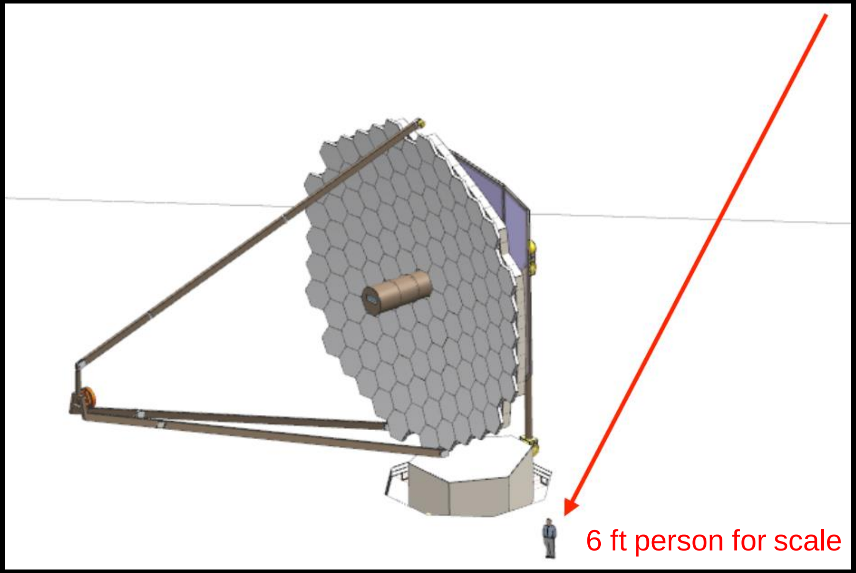




Above: HabEx 4m monolith telescope with lateral optical bench, solar pressure paddle & 72 m starshade.

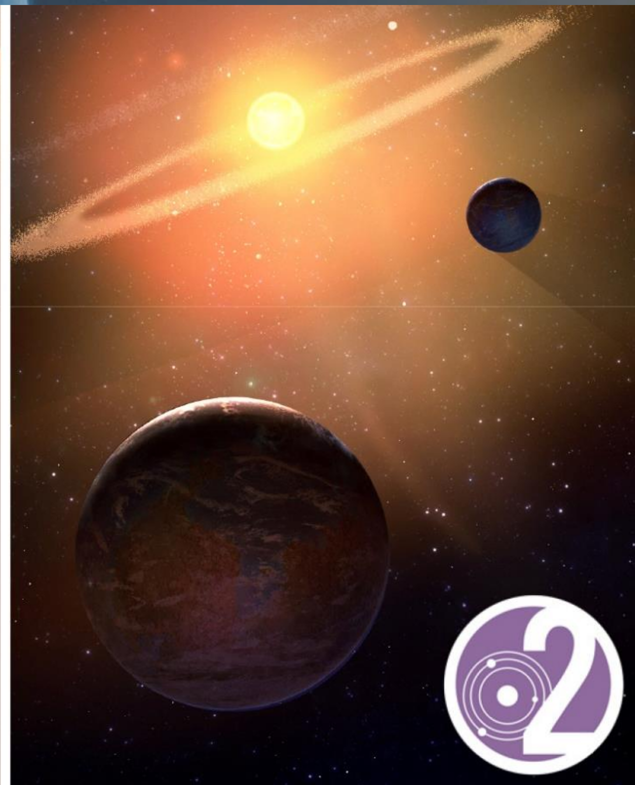
Right: LUVOIR 15m segmented telescope, 6 ring hex, deployed 70 m sunshade.

ExEP supports technology needs



HabEx Science Goals

Seek out nearby worlds and explore their habitability

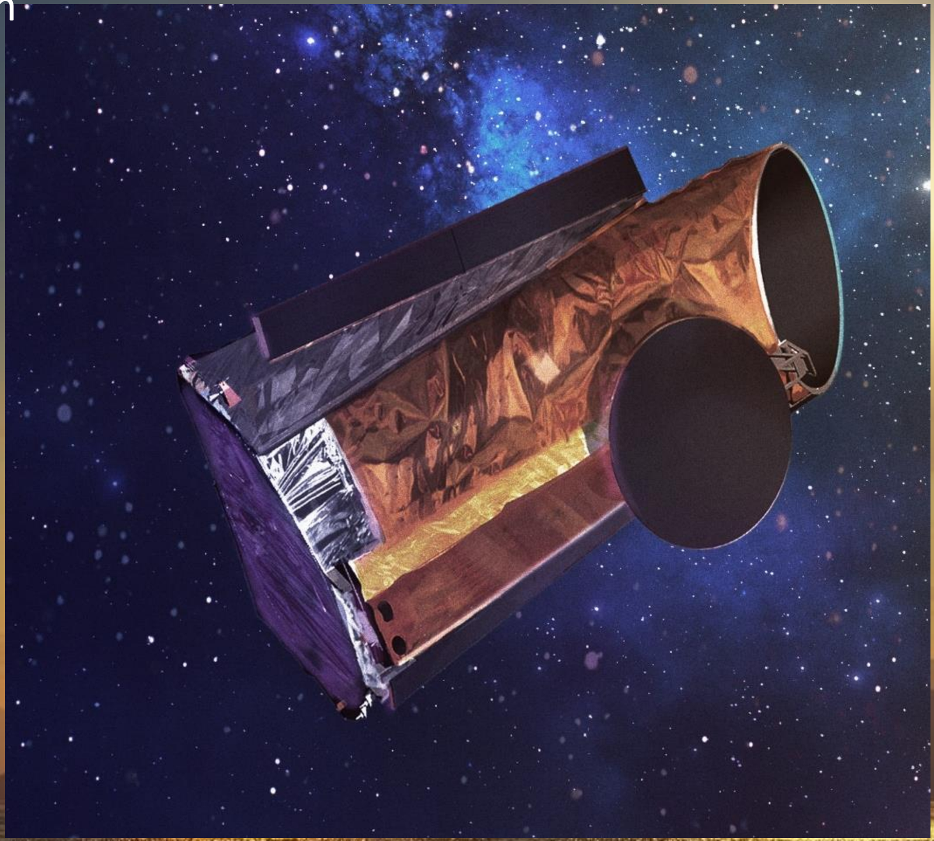


Map out nearby planetary systems and understand their diversity.

Open up new widows in the Universe from the UV to NIR.

HabEx Mission Architecture:

- 4 m off-axis f/2.5 primary mirror, monolith
  - preliminary design completed.
- Four Instruments:
  - Coronagraph Instrument
  - Starshade Instrument
  - UV Spectrograph (UVS)
  - HabEx Workhorse Camera (HWC)
- 72 m diameter starshade (tip-to-tip)
  - Co-launched with telescope
- Design heritage from Exo-C and Exo-S
- Launch vehicle & orbit:
  - SLS Block 1B to Earth-Sun L2
- Launch by mid-2030s, 5 year prime mission



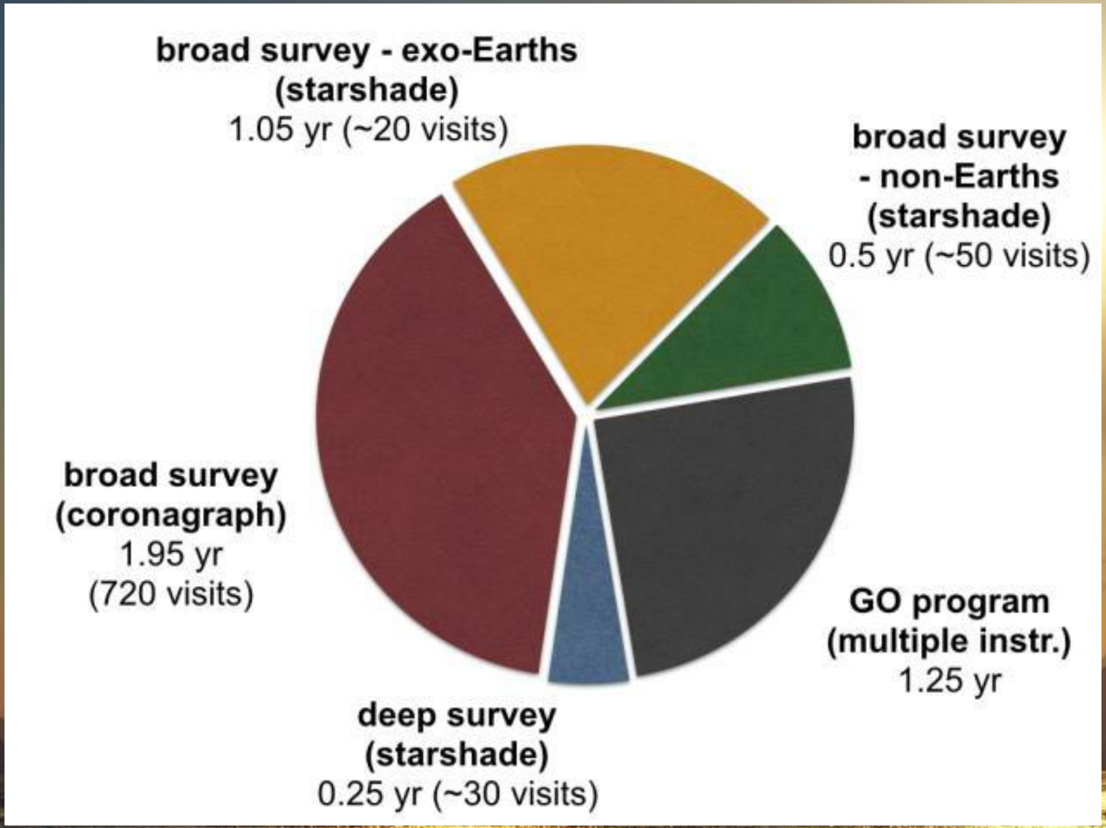
HabEx Mission Time Allocation

Deep Exoplanet Survey

- Nine nearby high-priority sunlike stars
- 3 months total with starshade
- Deep broadband image to the systematic floor
- Spectra
  - R=7 (grism) 0.3-0.45 µm
  - R=140 (IFS) 0.45-1.0 µm

Broad Exoplanet Survey

- ~110 stars with coronagraph
- Roughly 6 observations of each
- 50% completeness for exo-Earths
- Spectra with starshade covering 0.3-1.0 µm at once



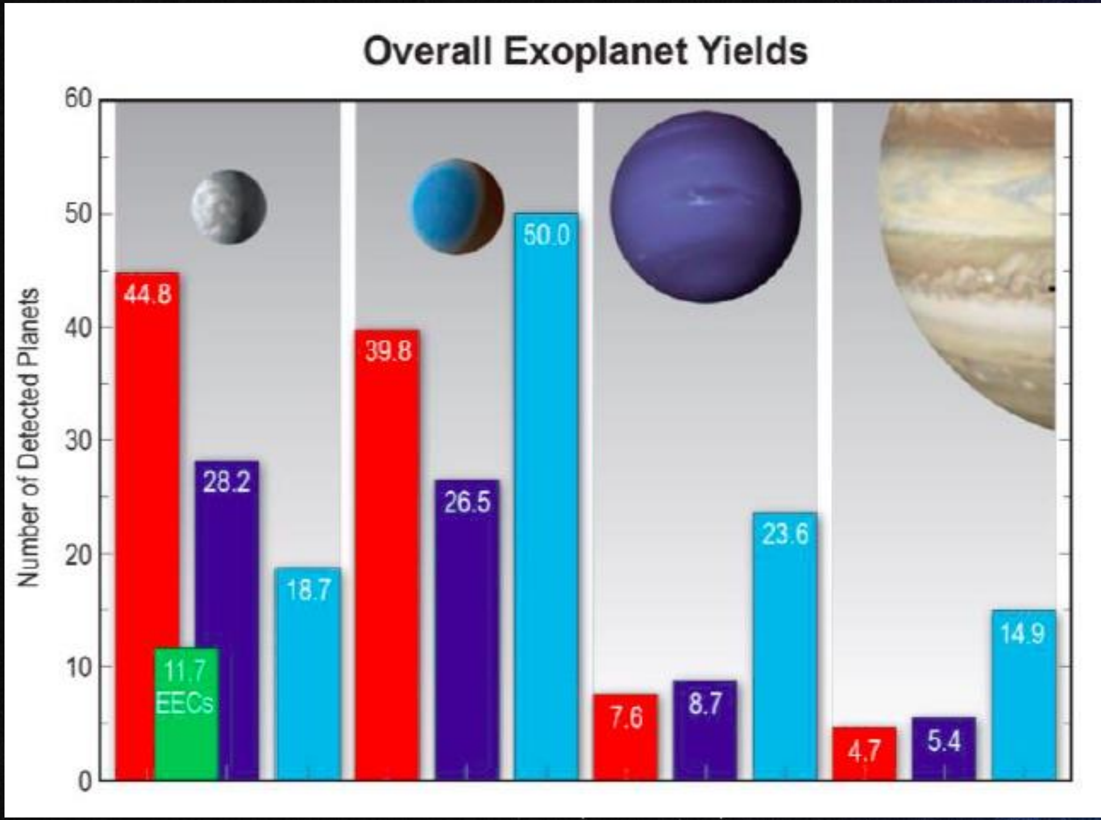
Yields of Characterized Planets

Yields*

Detect and characterize the orbits and atmospheres of:

- Rocky planets:
  - 92 rocky planets (0.5-1.75 R_E)
  - Includes 12 Earth Analogs (0.5-1.4 R_E)
- Sub Neptunes:
  - 116 sub-Neptunes (1.75-3.5 R_E)
- Gas Giants
  - 62 gas giants (3.5-14.3 R_E)

*Assumes SAG13 Occurrence Rates.



What is LUVOIR ?

Large UV / Optical / Infrared Surveyor (LUVOIR)

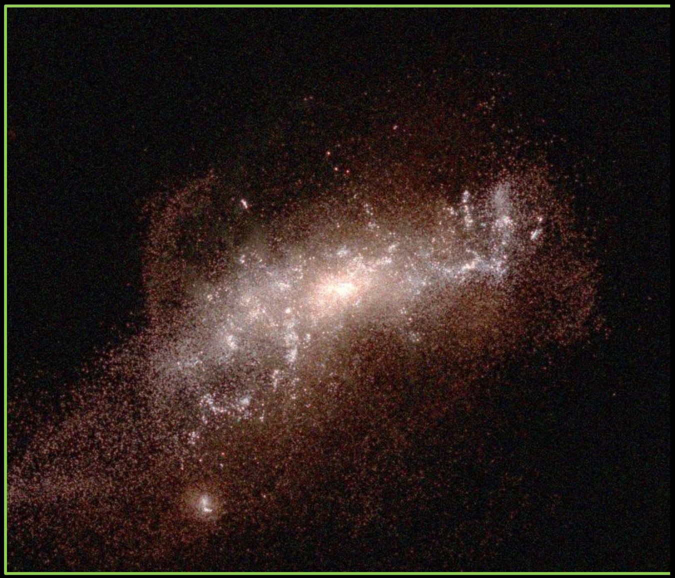
A space telescope concept in tradition of Hubble

- Broad science capabilities
- Far-UV to near-IR bandpass
- Two architectures: 9-m and 15-m telescopes
- Suite of imagers and spectrographs
- Serviceable and upgradable for decades of operation
- Guest Observer driven

"Space Observatory for the 21st Century"

Ability to answer the questions of the 2030s and beyond

Imagine Astronomy with LUVOIR …

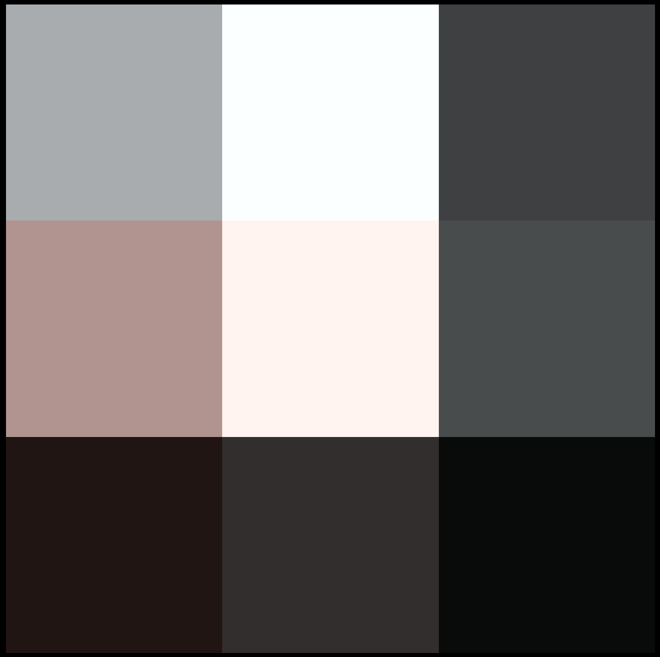


Low-mass galaxy at z = 2 with HST

Low-mass galaxy at z = 2 with 15-m LUVOIR

Credit: G. Snyder (STScI)

Imagine Astronomy with LUVOIR …

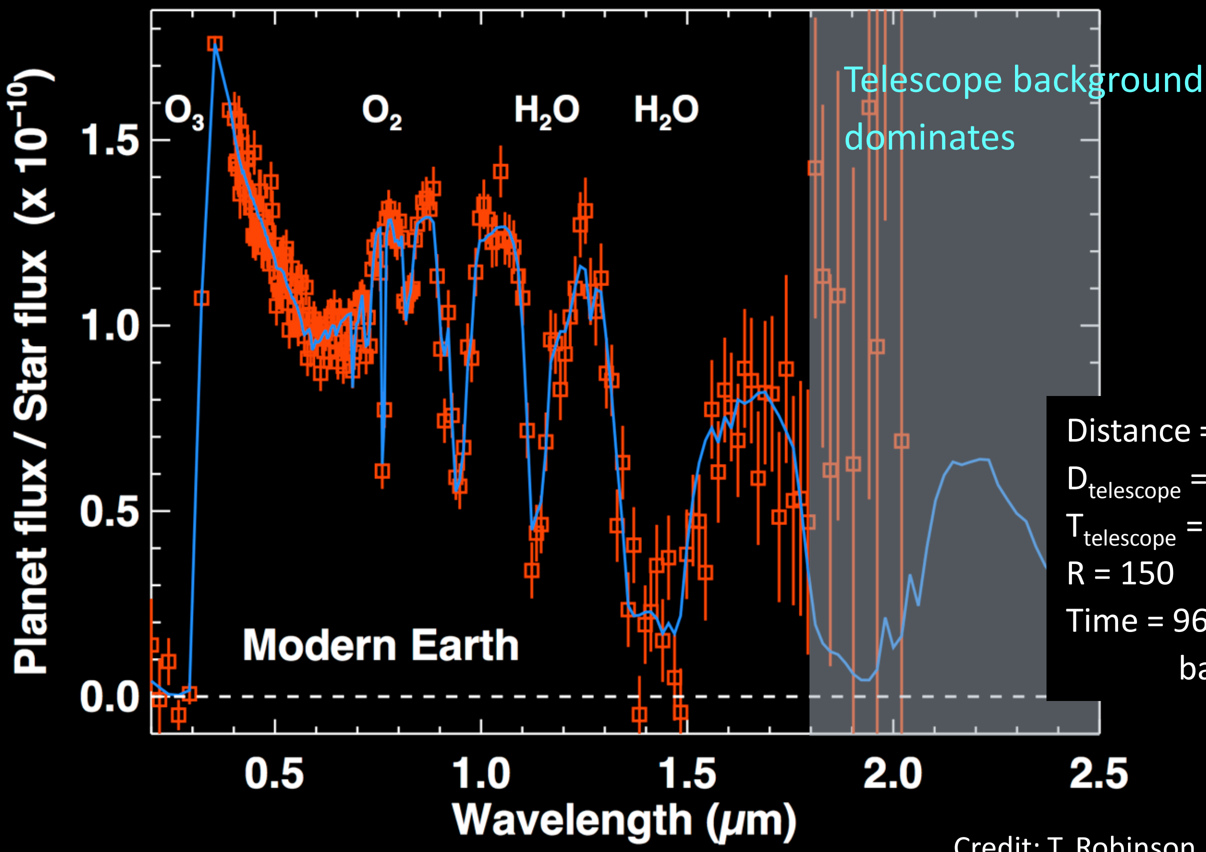


Pluto with HST

Pluto with 15-m LUVOIR

Credit: NASA / New Horizons / R. Parramon

Simulated LUVOIR Observation

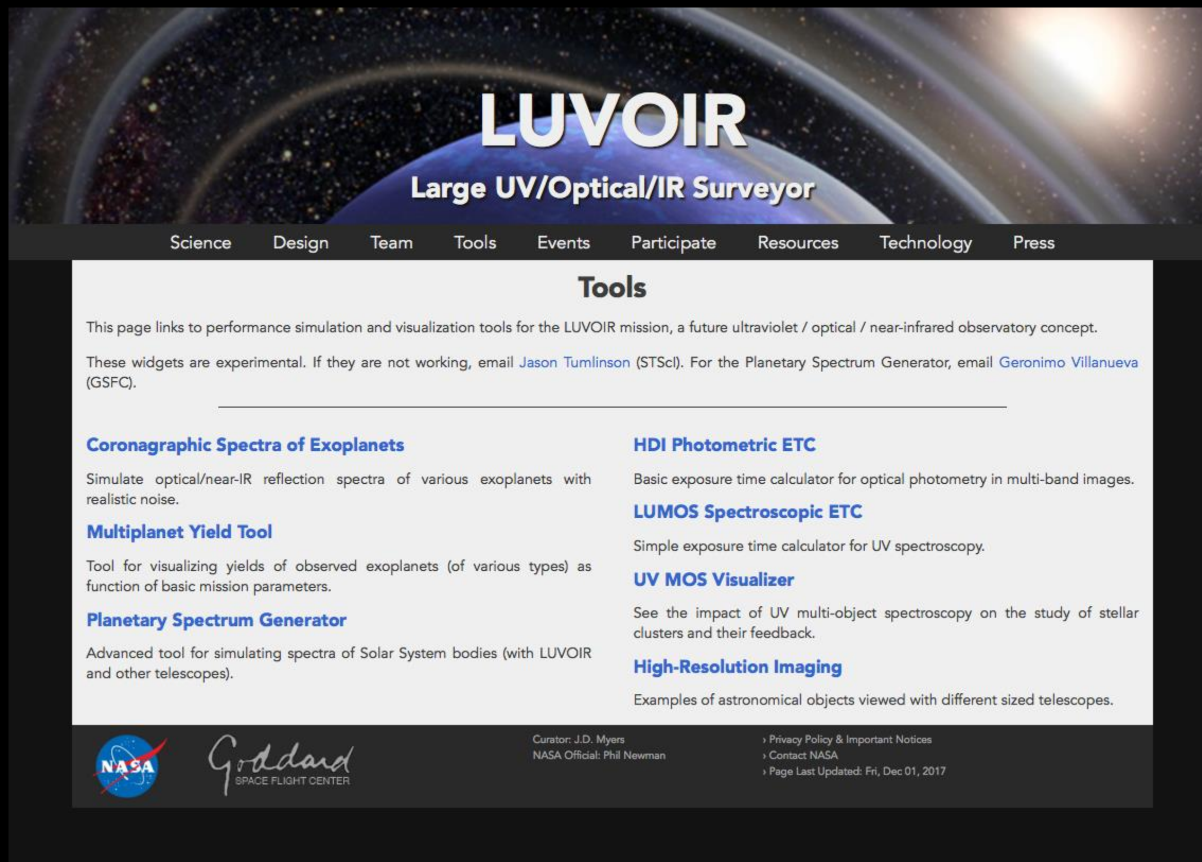


Distance = 10 pc
$D_{telescope}$ = 15-m
$T_{telescope}$ = 270 K
R = 150
Time = 96 hrs per band

Credit: T. Robinson / G. Arney

Design Your Own Observations Using Online Tools

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



LUVOIR
Large UV/Optical/IR Surveyor

Science | Design | Team | Tools | Events | Participate | Resources | Technology | Press

Tools

This page links to performance simulation and visualization tools for the LUVOIR mission, a future ultraviolet / optical / near-infrared observatory concept.

These widgets are experimental. If they are not working, email Jason Tumlinson (STScI). For the Planetary Spectrum Generator, email Geronimo Villanueva (GSFC).

Coronagraphic Spectra of Exoplanets

Simulate optical/near-IR reflection spectra of various exoplanets with realistic noise.

Multiplanet Yield Tool

Tool for visualizing yields of observed exoplanets (of various types) as function of basic mission parameters.

Planetary Spectrum Generator

Advanced tool for simulating spectra of Solar System bodies (with LUVOIR and other telescopes).

HDI Photometric ETC

Basic exposure time calculator for optical photometry in multi-band images.

LUMOS Spectroscopic ETC

Simple exposure time calculator for UV spectroscopy.

UV MOS Visualizer

See the impact of UV multi-object spectroscopy on the study of stellar clusters and their feedback.

High-Resolution Imaging

Examples of astronomical objects viewed with different sized telescopes.

NASA | Goddard SPACE FLIGHT CENTER

Curator: J.D. Myers
NASA Official: Phil Newman

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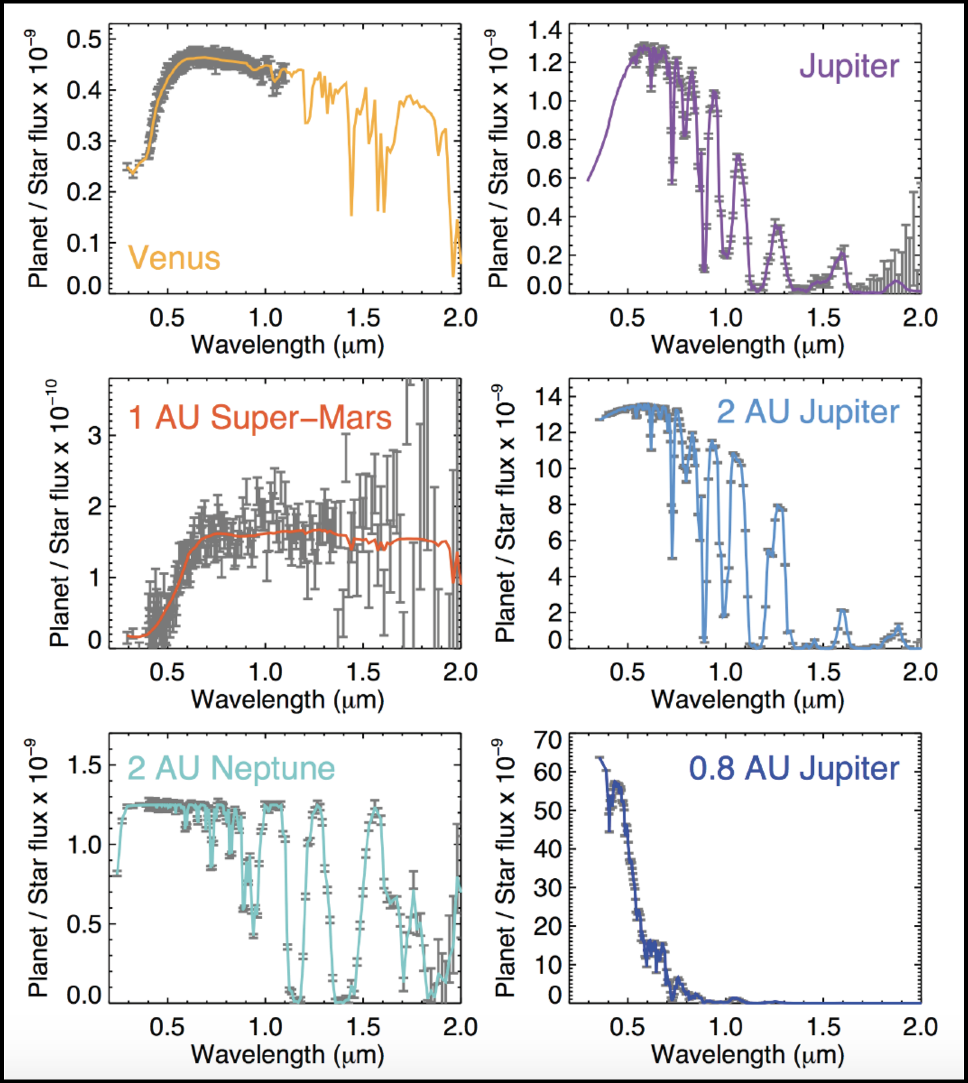
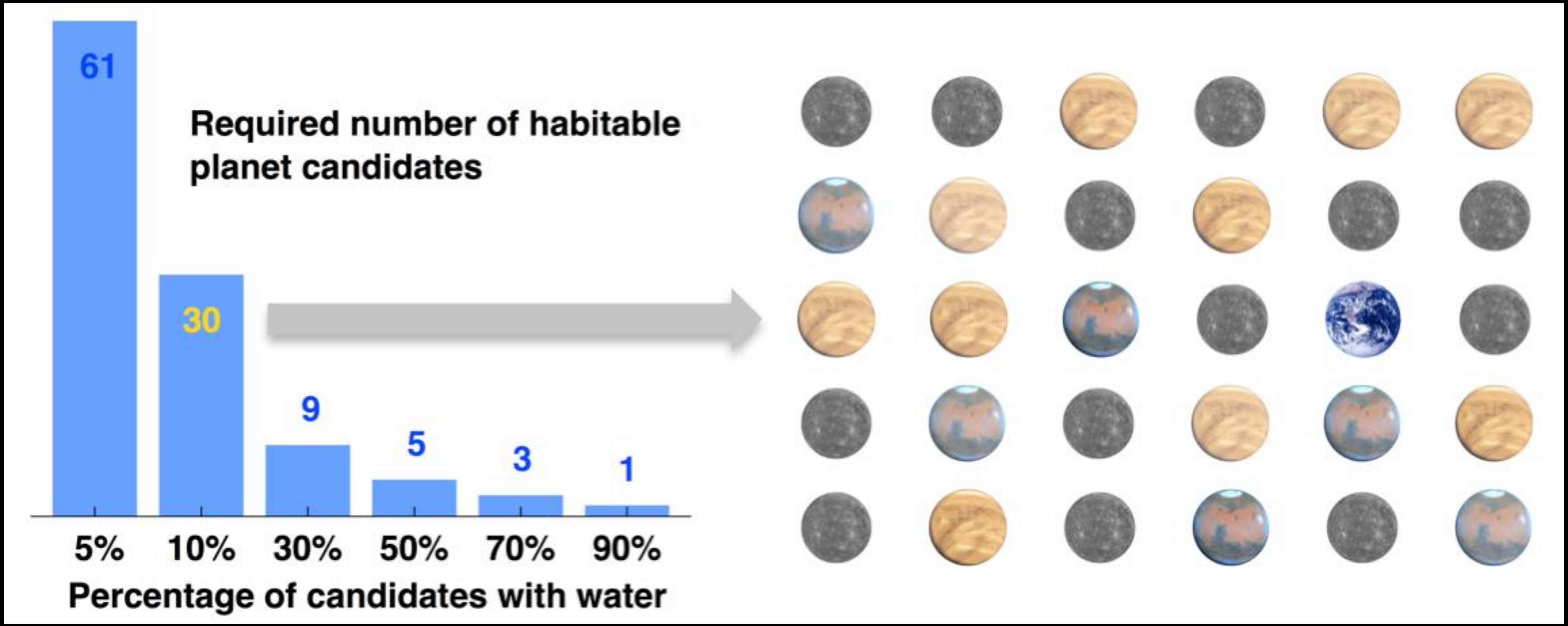
Sample LUVOIR Observations: An "Exoplanet Zoo"



How Many Candidate Habitable Planets Do We Need to Observe to Find One With Water? LUVOIR says 30.



Credit: C. Stark / A. Roberge

Two studies: Habitable Exoplanet Mission (HabEx) and Large UltraViolet Optical near-IR (LUVOIR) surveyor

- Both have goal of studying Earthlike planets in reflected light, visible & near-infrared. They differ in levels of ambition
  - HabEx to "search for" signs of habitability and biosignatures. ~50 HZs ?
  - LUVOIR to "constrain the frequency of" habitability and biosignatures = larger statistical survey of exoEarths, larger aperture. ~300 HZs ?
- HabEx to focus on exoplanets, "best effort" on general astrophysics. 4m aperture Study led by NASA JPL.
- LUVOIR gives equal priority to exoplanets and general astrophysics. Would be HST-like, expansive vision. Apertures 15, 8 m. Study led by NASA Goddard.
- They are likely to differ in cost and technical readiness
- Interim reports will be public soon; final reports mid-2019

Steps that will enable direct imaging and spectra of habitable exoplanets

- Understand the frequency of HZ rocky planets
- Measure the astronomical backgrounds
- Make precursor and follow-up observations to measure exoplanet masses and orbits, where possible
- Measure host star properties that affect habitability
- Develop our understanding of exoplanet atmospheres, biosignatures, and biosignature false positives
- Ready the starlight suppression technology
- Close in on the mission architecture

Important NASA Exoplanet websites and dates

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

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

WFIRST Project: http://wfirst.gsfc.nasa.gov

HabEx mission study: http://www.jpl.nasa.gov/habex

LUVOIR mission study: http://asd.gsfc.nasa.gov/luvoir

ExoPAG 18 meeting this Sunday 7/29

- At Cool Stars 20 conference, Cambridge MA

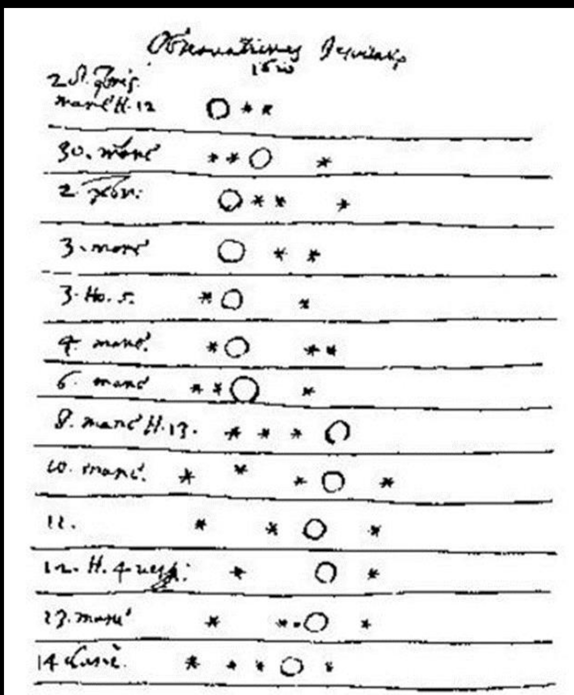
ExoPAG 19 meeting Jan 5-6 2019

- At AAS winter meeting, Seattle WA

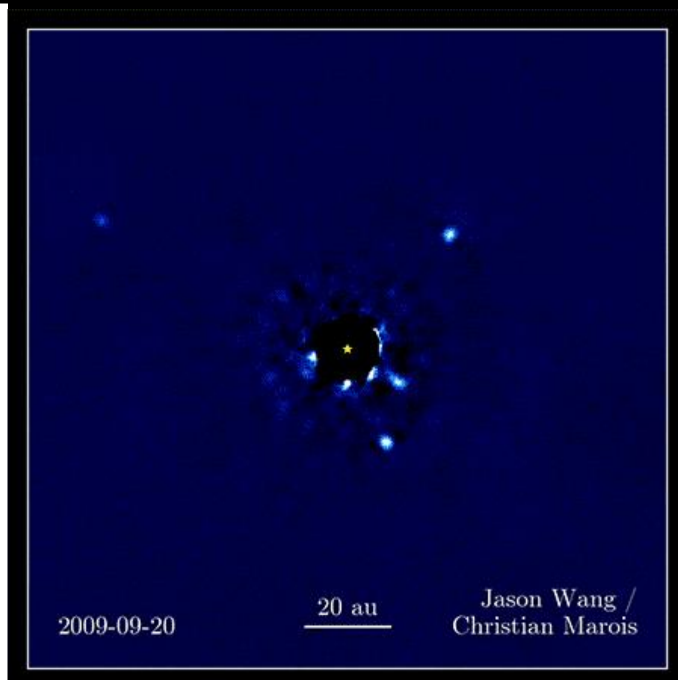
Sign up for ExoPAG mailing list:
https://exoplanets.nasa.gov/exep/exopag/announcementList/

A historical progression

1610	2008 / 2009-2016	2035 ?

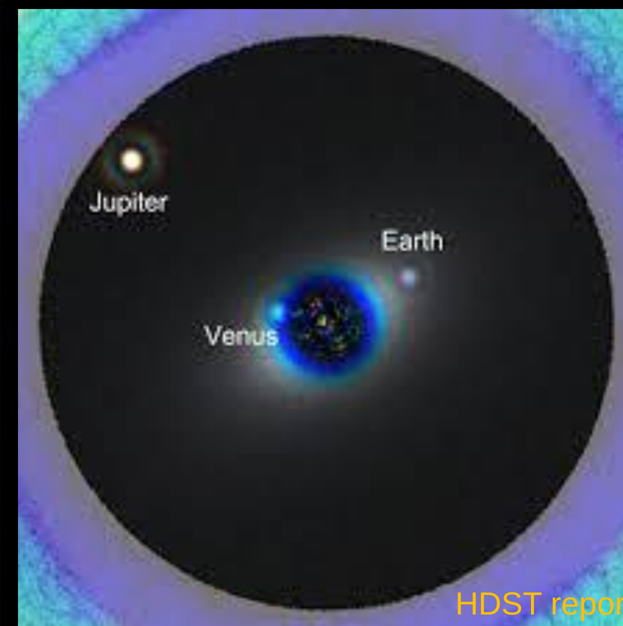


Galileo discovers Jovian satellite system

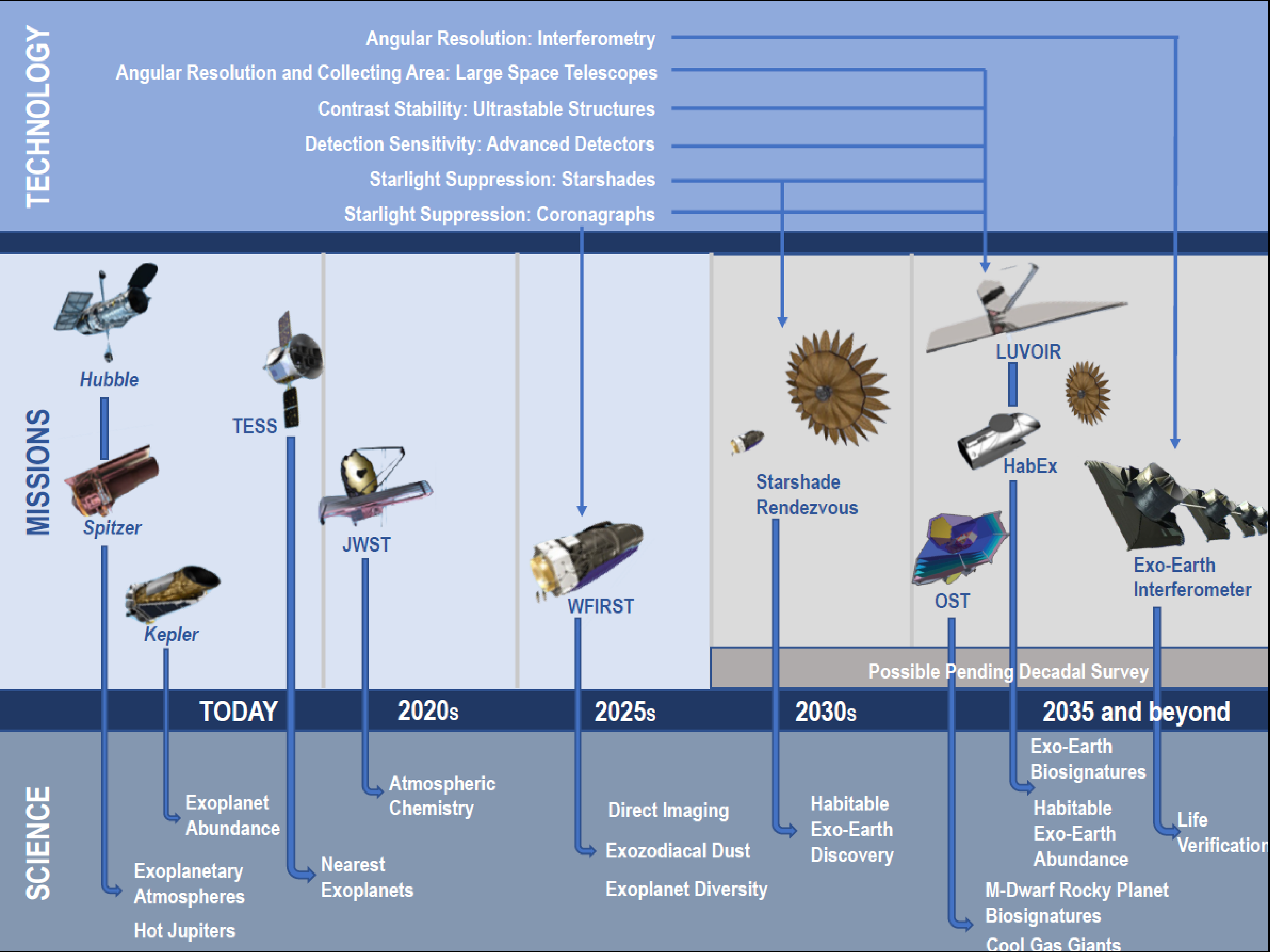


Marois et al. discover HR 8799 planetary system

Eight years of orbital motion



Future space telescopes confirm first habitable exoplanet


TECHNOLOGY
Angular Resolution: Interferometry
Angular Resolution and Collecting Area: Large Space Telescopes
Contrast Stability: Ultrastable Structures
Detection Sensitivity: Advanced Detectors
Starlight Suppression: Starshades
Starlight Suppression: Coronagraphs
MISSIONS
Hubble
Spitzer
Kepler
TESS
JWST
WFIRST
Starshade Rendezvous
LUVOIR
HabEx
OST
Exo-Earth Interferometer
Possible Pending Decadal Survey
TODAY
2020s
2025s
2030s
2035 and beyond
SCIENCE
Exoplanetary Atmospheres
Hot Jupiters
Exoplanet Abundance
Nearest Exoplanets
Atmospheric Chemistry
Direct Imaging
Exozodiacal Dust
Exoplanet Diversity
Habitable Exo-Earth Discovery
Exo-Earth Biosignatures
Habitable Exo-Earth Abundance
M-Dwarf Rocky Planet Biosignatures
Cool Gas Giants
Life Verification

Jet Propulsion Laboratory
California Institute of Technology

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