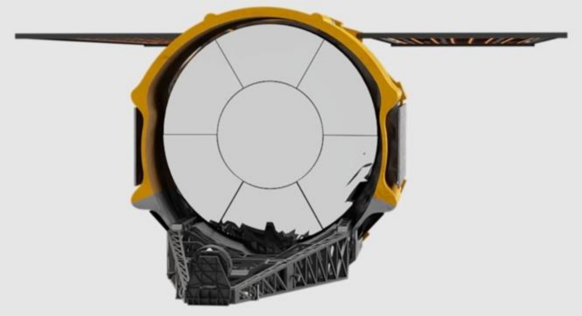
EXOPLANET EXPLORATION
Planets Beyond Our Solar System

https://science.nasa.gov/exoplanets


NASA/JPL-Caltech



How Roman Science Leads to HWO (the Habitable Worlds Observatory)

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Pre-Decisional Information – For Planning and Discussion Purposes Only

Talk overview

- NASA's ultimate goal in Exoplanet Science: To find temperate rocky exoplanets, assess their habitability, and search for biosignatures in their spectra
- HWO is the latest iteration of a mission toward this goal
- Preparing for HWO's Exo-Earth imaging: The precursor science that Roman WFI surveys will do
- Preparing for HWO's Exo-Earth imaging: The precursor science that Roman Coronagraph surveys could do

Preparing for HWO's exo-Earth imaging: technology – this is Alex Greenbaum's talk to follow)

A historical progression?

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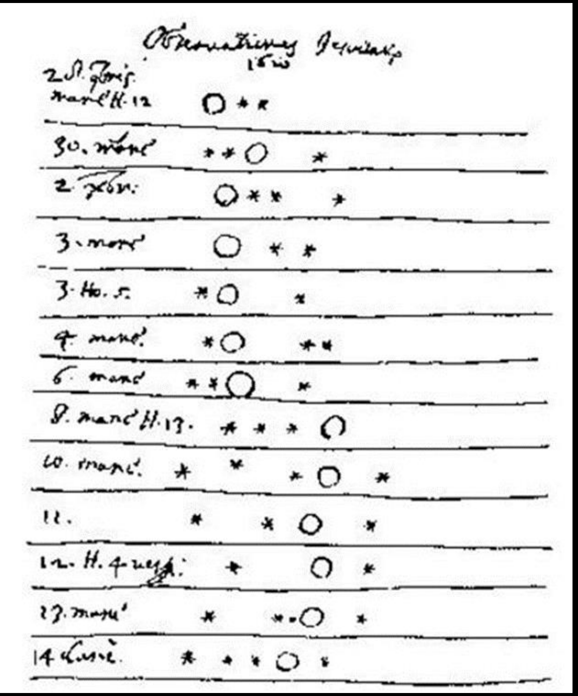
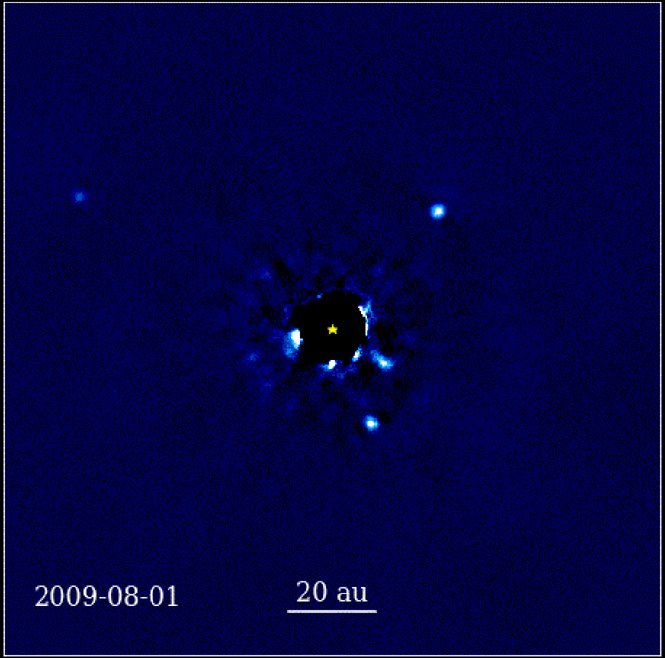


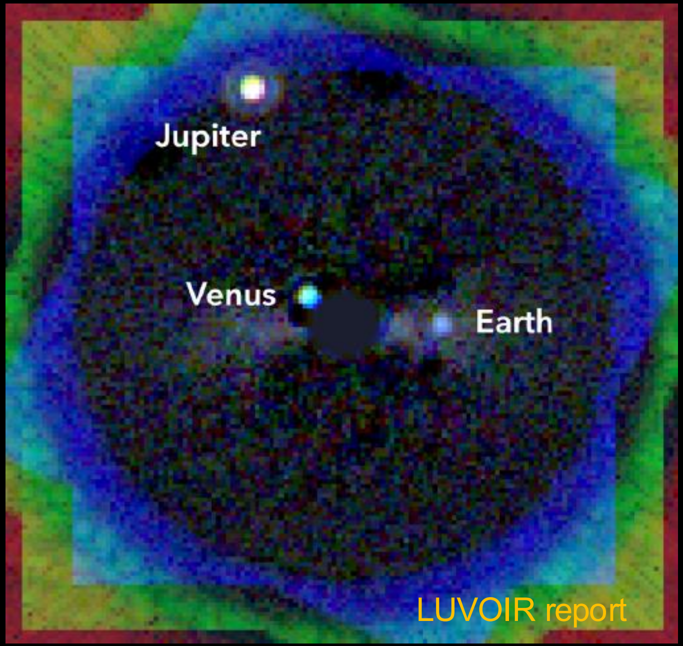
Galileo discovers
Jovian satellite system

2008, 2010



Marois et al. discover
HR 8799 planetary system

Early 2040s ?



Future space telescope
confirms the first habitable
exoplanet of a Sun-like star

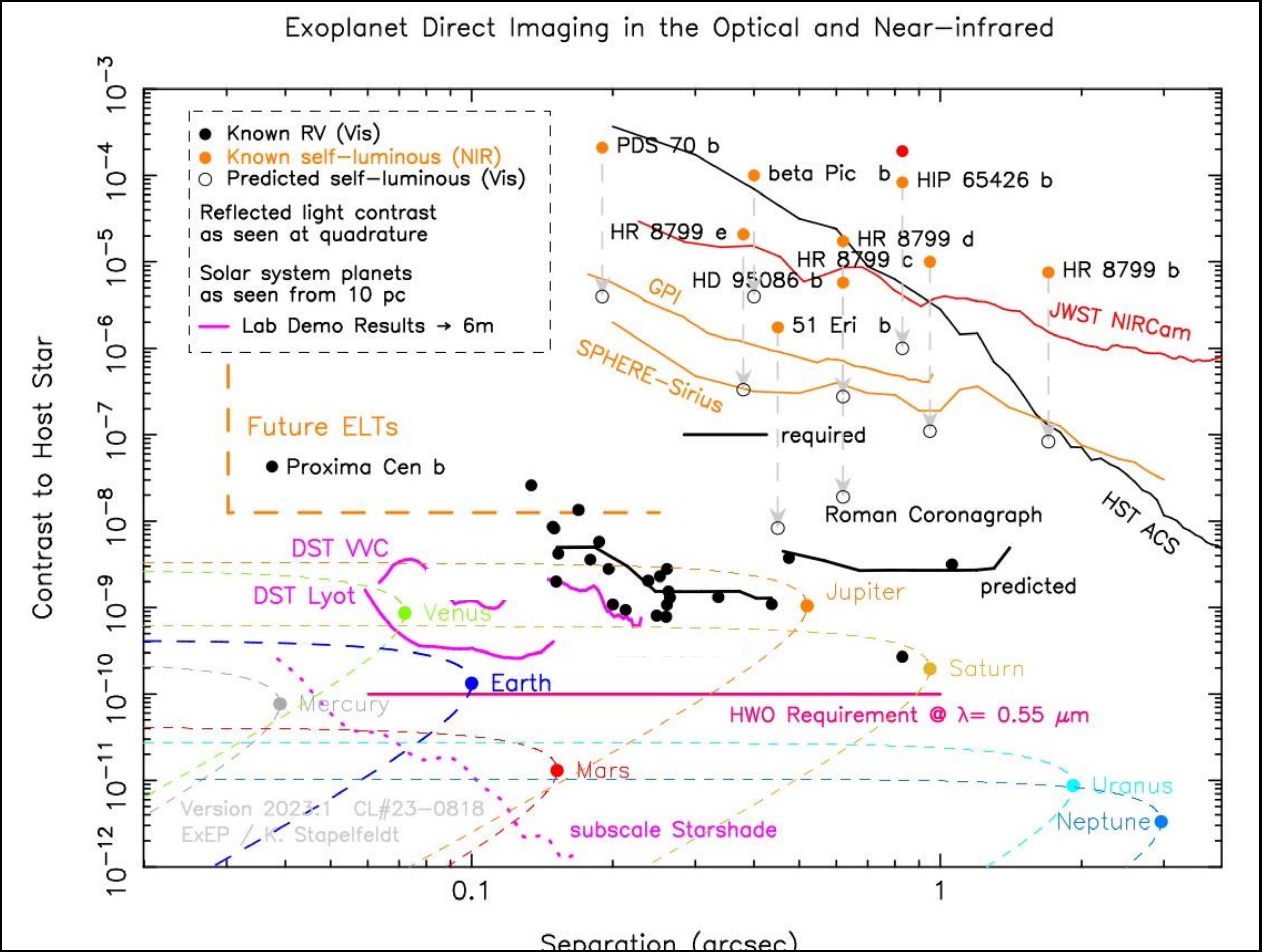
Why direct imaging: The case of 40 Eridani A

Constraining the presence of a habitable planet

- K0 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 ever transiting
  - Would induce 0.5 μas of stellar astrometric wobble
  - Won't lens background stars (galactic latitude -38°)

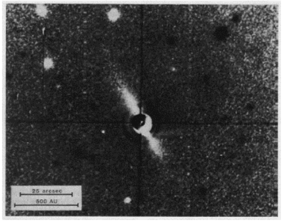
    Mass ratio ~5×10^{-6} to the star
- Current methods are not capable of detecting such a planet
- In direct imaging, an Earth analog here would:
  - Appear at R magnitude 27.6, and with contrast to the star of 3×10^{-10}
  - Be separated from the star by 3 resolution elements as seen by a 3 meter telescope observing in V band
  - Provide photons enabling its discovery *and* spectral measurements of its physical/chemical/biological? Conditions
- Can direct imaging get to the needed performance to detect such a planet ?

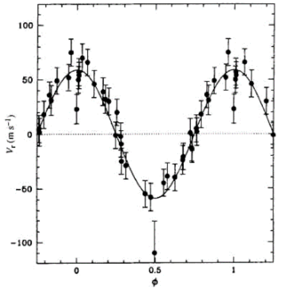
Contrast requirements for imaging exoplanets in reflected light

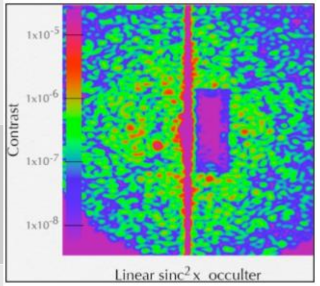


Timeline to HWO

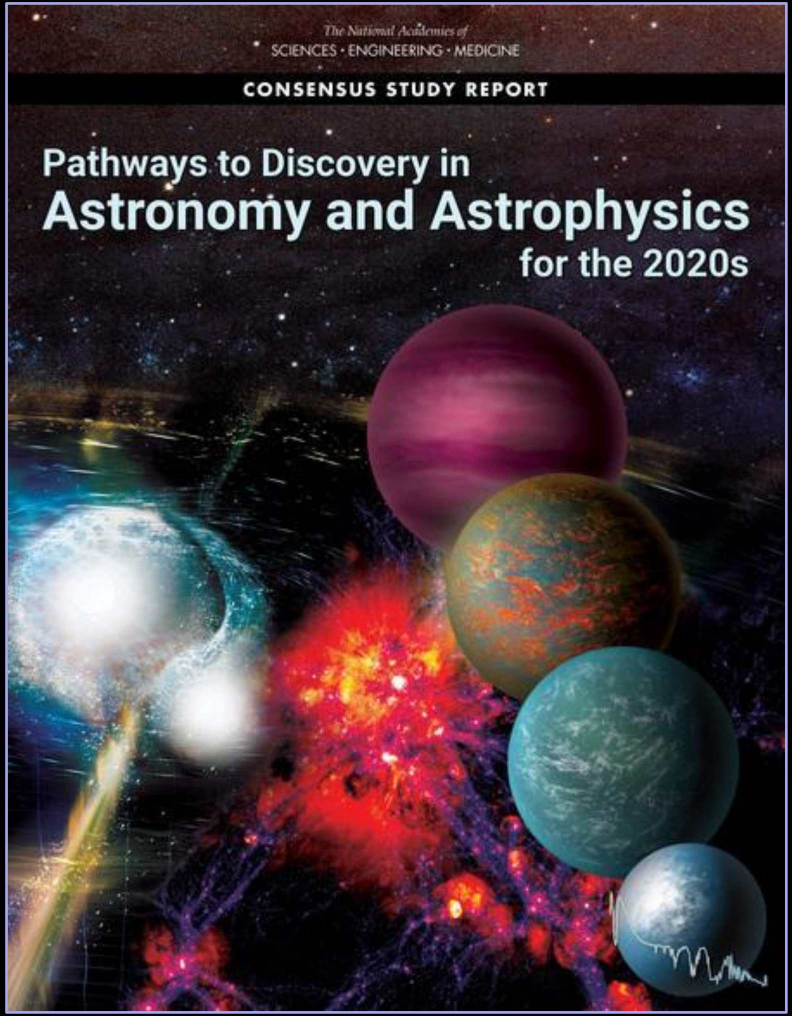
1984	beta Pictoris circumstellar disk: first high contrast image of an exoplanetary system (Smith & Terrile)
1990	Analysis of HST optics shows the contrast needed for exoplanets is not achievable (Brown & Burrows)
1995	51 Peg b: first detection of exoplanet of a sun-like star
1997	Thermal infrared interferometry mission concept (Angel & Woolf) for Terrestrial Planet Finder
2000	Decadal Survey endorses TPF tech development
2001-2007	TPF mission studies pivot to an optical coronagraph architecture, study reports finish & project shelved
2010	Decadal Survey endorses further technology development for "New Worlds Mission"
2016-2019	HabEX & LUVOIR mission studies refine the mission concept. JPL coronagraph lab tests achieve 4×10^{-10} contrast. Coronagraph added to Roman mission
2021	Decadal Survey formally endorses HWO as NASA's next large space telescope mission



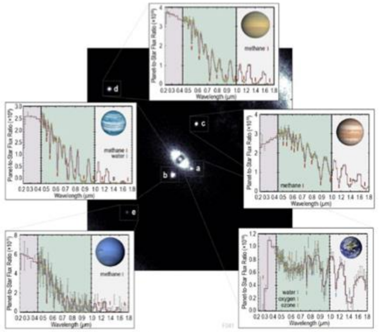




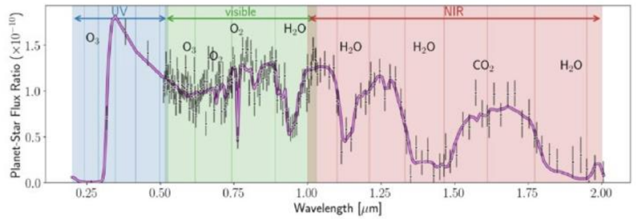
2021 Decadal Survey recommends a HWO mission



A Future IR/Optical/UV Telescope Optimized for Observing Habitable Exoplanets and General Astrophysics



Simulated space-telescope image of a complete planetary system including a life-bearing Earth-like planet



Simulated spectrum of an Earth-twin planet observed from the UV to near-IR by a space coronagraph

Recommendation: After a successful mission and technology maturation program, NASA should embark on a program to realize a mission to search for biosignatures from a robust number of about ~25 habitable zone planets and to be a transformative facility for general astrophysics. If mission and technology maturation are successful, as determined by an independent review, implementation should start in the latter part of the decade, with a target launch in the first half of the 2040's

The National Academies of
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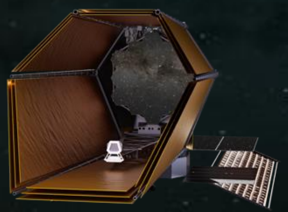
Screenshot

HWO PRELIMINARY SPECS & CANDIDATE INSTRUMENTS

Telescope

Diameter	≳6.0 m
Bandpass	~100–2500 nm
Diff. Limit @	~500 nm



Fourth Instrument

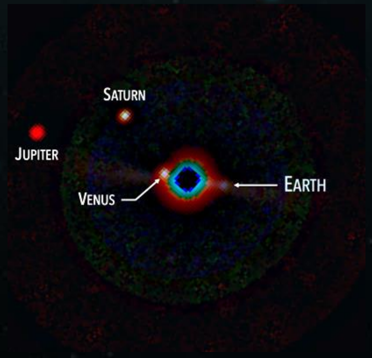
To be defined

Candidates include NUV Coronagraph, FUV IFS, UV Spectropolarimeter

Coronagraph

High-contrast imaging and imaging spectroscopy

Bandpass	~350–1700 nm
Contrast	≤ 10^{-10} $\lesssim 1 \times 10^{-10}$
Spectral resolution $R\ (\lambda/\Delta\lambda)$	Vis: ~140 NIR: ~70, 200



High-Res Imager

UV/Vis and NIR imaging

Bandpass	~200–2500 nm
Field-of-View	~ 3' x 2' $3' \times 2'$

60+ science filters & grism

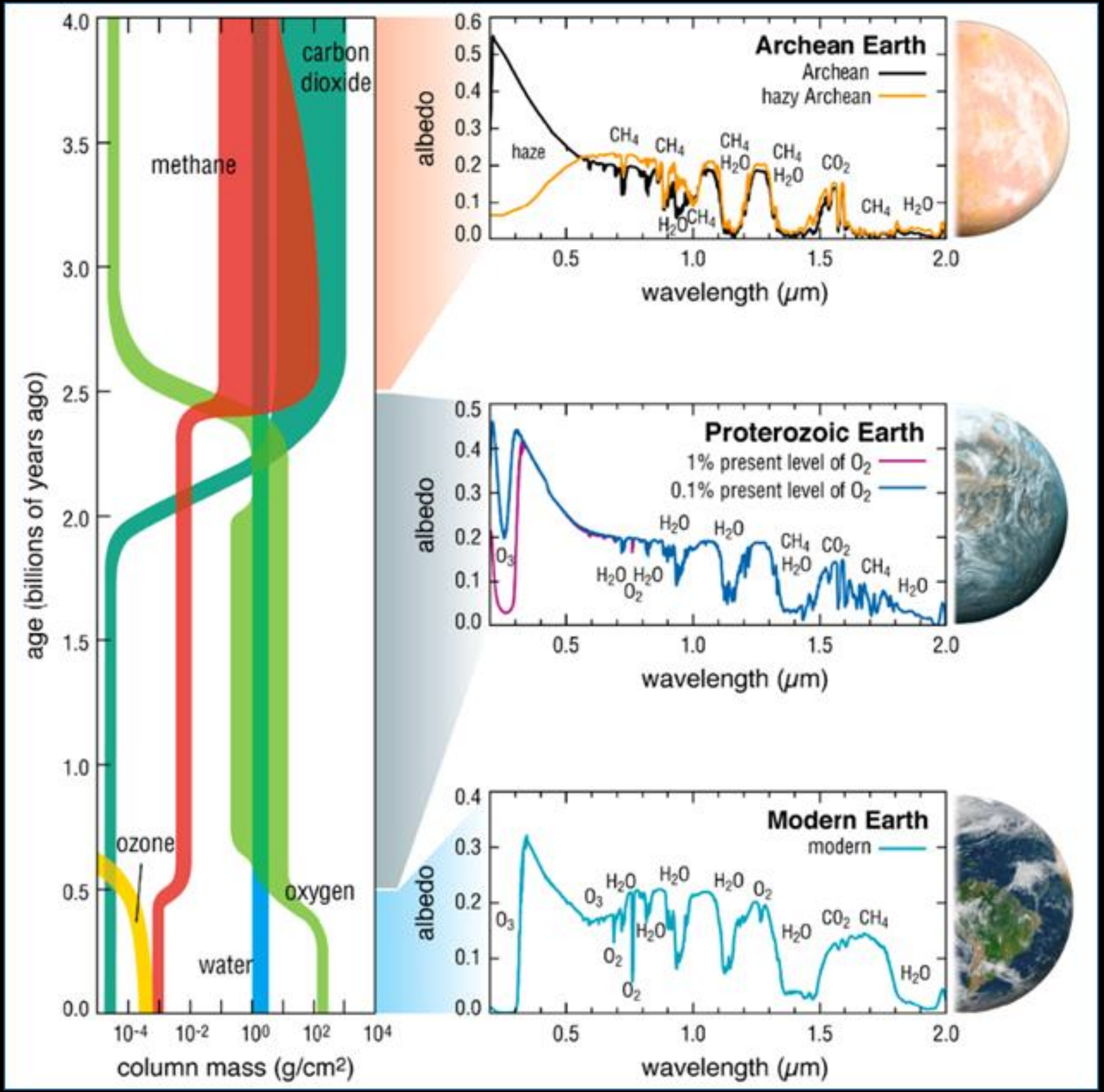
High-precision astrometry?

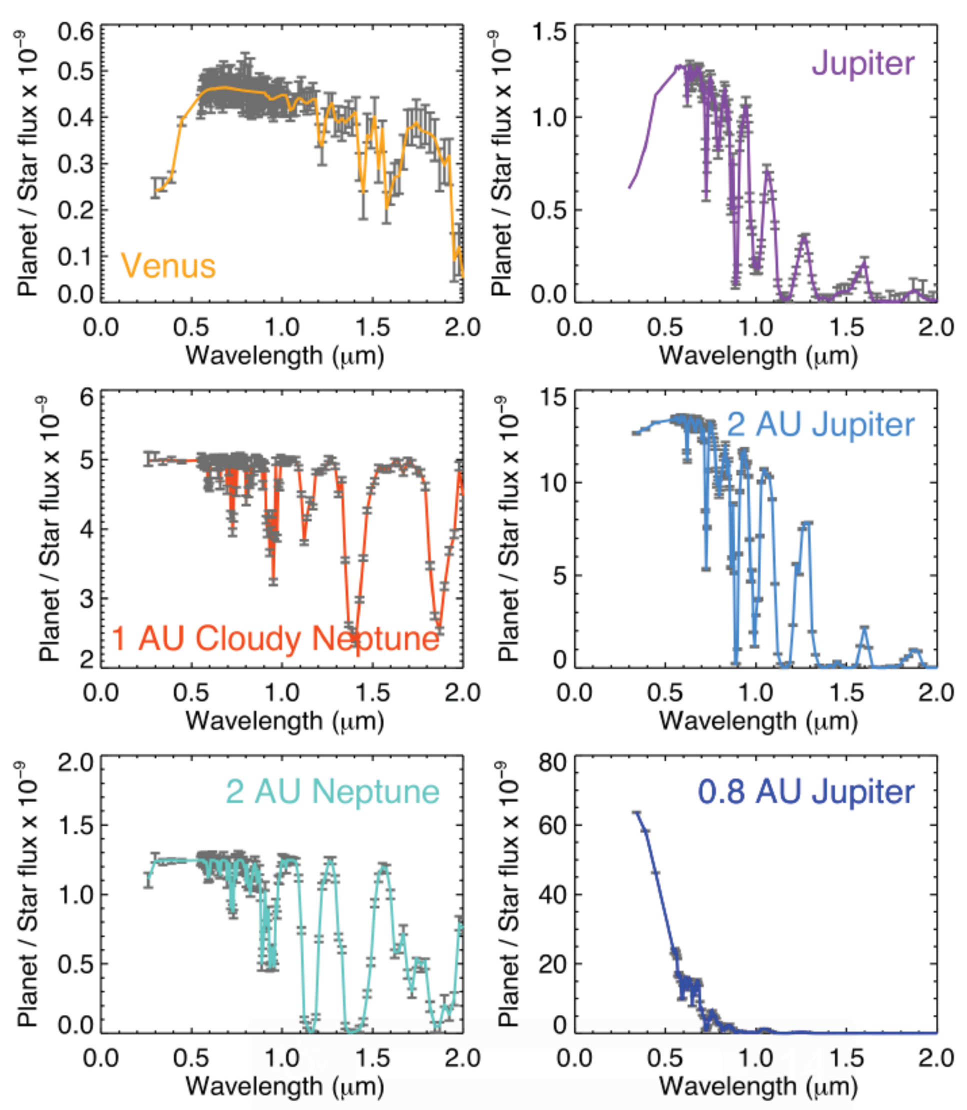
UV Multi-Object Spectrograph

UV/Vis multi-object spectroscopy and FUV imaging

Bandpass	~100–1000 nm
Field-of-View	~ 2' x 2'
Apertures	~840×420
Spec res $R\ (\lambda/\Delta\lambda)$	~500–50,000

HWO Science: Simulated reflected light spectra



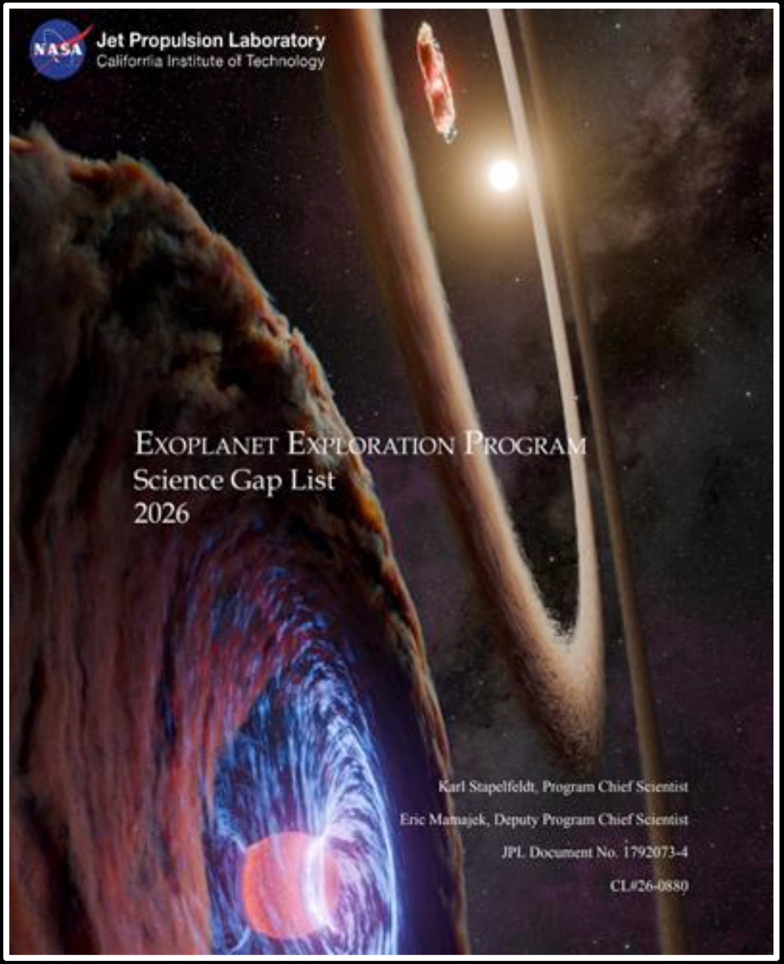


Credit: T. Robinson / G. Arney

What support does HWO science need ? See the 2026 Exoplanet Exploration Program Science Gap List

https://science.nasa.gov/astrophysics/programs/exep/science/

- Description of research areas where additional work would benefit current & future NASA exoplanet missions. *Tactical goals*, flowing from Decadal and NASA strategic goals
- Connects NASA exoplanet mission needs to work in theory, laboratory measurements, simulations, and observations
- Intended as a guide for proposers, proposal reviewers, and NASA HQ selection officials
- Updated throughout with 2025 inputs from the ExoPAG EC, community, and NASA HQ
- Now a 62 page document with 17 defined science gaps – half of which pertain to HWO



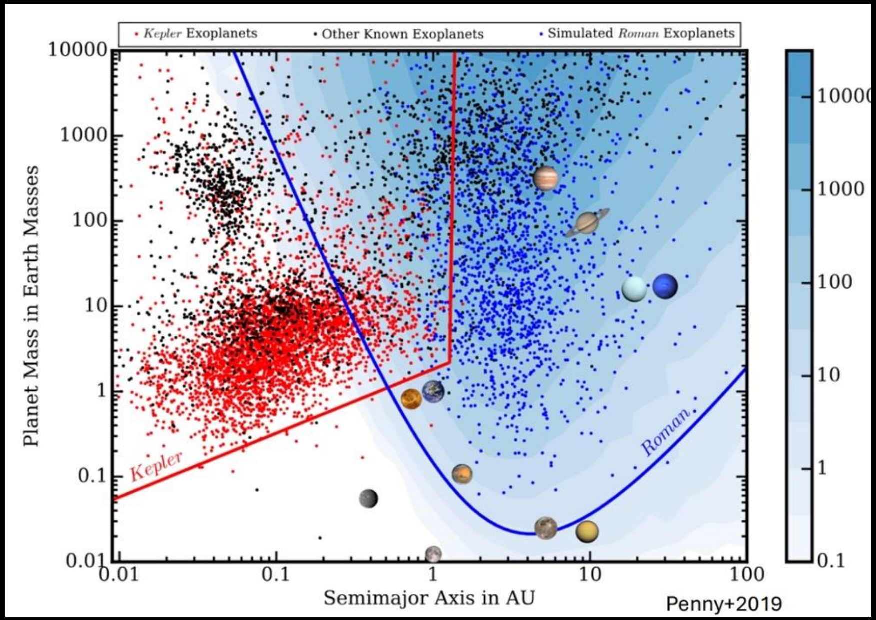
arXiv 2507.18665

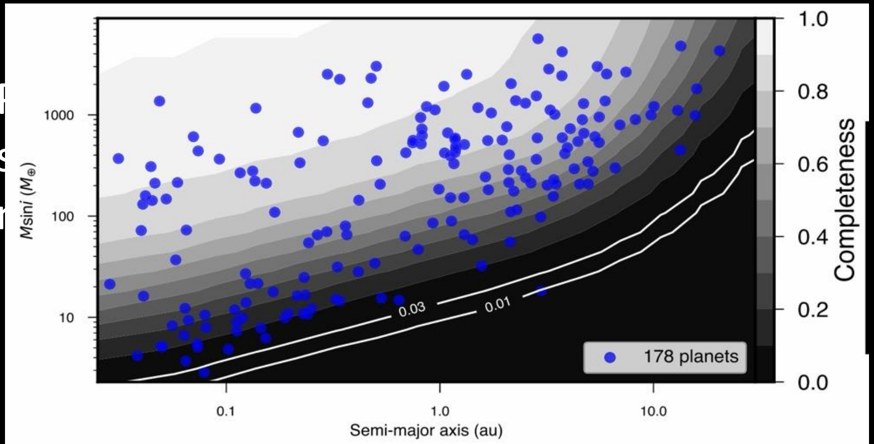
My picks for HWO science gaps that need work :

1. Uncertainty in eta_Earth (the frequency of HZ rocky planets) is +/- a factor of 3 about the adopted value of 0.24, directly affecting the yield of the mission. Should HWO accept this as a risk, mitigate it, or invest in more observations and more analysis of existing data ? ROMAN may help only a little here
2. Uncertainty in median exozodi level (the "dustiness of HZs") is also factor of three, 1-sigma, around the adopted value of 3x the solar system. This poses a risk to the quality of HWO spectra for HZ rocky planets, or the total mission lifetime. Should HWO accept this risk, mitigate it, or conduct more observations and analysis of existing data ? ROMAN has the potential for major impact here
3. What should be the strategy for determining masses of the planets that HWO detects ? To what precision does the mass need to be measured, in order to interpret an exoplanet reflected light spectrum ? ROMAN won't help much here
4. What are the properties of the likely HWO target stars, and how should they be used to prioritize among them ? ROMAN can help here

1. Exoplanet frequency from the Roman GBTDS

- As discussed in earlier talks, Roman µlensing will be highly complementary to other methods, filling in exoplanet demographics at/outside the ice line (top right figure)
- Sensitivity to habitable zone planets (0.3-1 AU) will depend on inward extrapolations – a mirror of the Kepler (and Roman transit) sensitivity
- Note different stellar types being probed by the different methods
- Sensitivity to ~Neptune-mass planets at a few AU will be much better than from radial velocity results (lower right), and thus defining for HWO's yield for these planets
- Roman results will likely come after HWO's design has gone final,



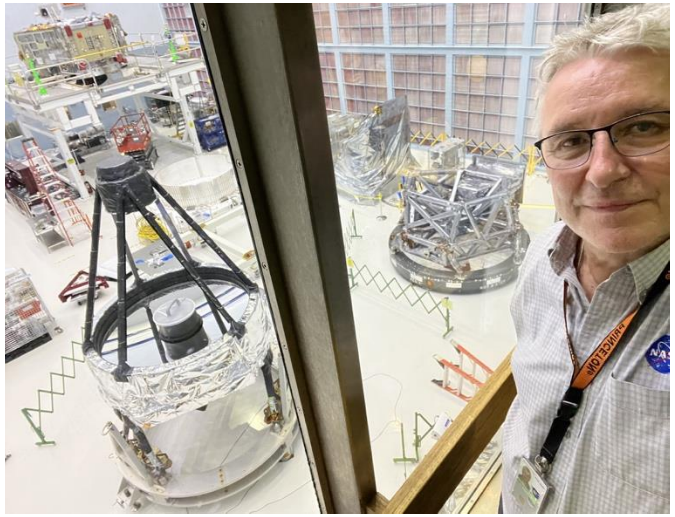


Fulton+ 2021

What HWO science can Roman Coronagraph do ?

(from easiest to hardest, my personal view)

1. Imaging the structure of **dusty debris disks** around nearby stars, especially ones too faint to previously detect – at least 100 possible targets
2. Optical photometry and spectroscopy of already-known **self-luminous exoplanets** & brown dwarf companions, to complement existing near-infrared measurements – a dozen? possible targets
3. Polarimetry of dusty debris disks, to constrain the dust particle properties – dozens of possible targets
4. Measuring "exozodi" **dust levels in the habitable zone** of sun-like stars – scores of likely HWO targets
5. Optical photometry and spectroscopy of never-before-imaged **Jupiter-like exoplanets as seen in reflected starlight** – perhaps ½ dozen targets. Really expensive.



2. & 4. Exozodiacal dust levels around HWO targets

- Interplanetary dust particles are released by asteroid collisions & cometary passages
- The dust population must be continuously replenished against particle loss processes
- Particle concentration in the ecliptic plane causes our solar system's zodiacal light
- Median particle size is 30 μm, but a wide size range is seen
- These particles lie interior to the main asteroid belt, near the Earth
- Even though its fractional luminosity is just 10^{-7} of the Sun, the zodiacal light is the most luminous component of our planetary system
- Other planetary systems have debris disks 100s to 1000s of times dustier than ours

Large Binocular Telescope Interferometer (LBTI)

Completed survey of extended 10 μm emission from dust orbiting nearby stars

- NASA funded a dedicated instrument to measure exozodiacal light in nearby planetary systems, it started operations in 2012 and funding ended in 2022.

- Operated at LBT on Mt. Graham in Arizona. Exozodi survey completed in May 2018 with 38 stars measured
- 4/23 sun-like stars have excess emission at levels ≥ 150 zodis.
- Result: "Most stars not very dusty": median level is 3 zodi but 95% confidence upper limit is 27 zodis (Ertel et al. 2020)
- Key implications: HWO can achieve its science goals against this nominal median background. But the uncertainties affect the S/N and integration times for HWO exoEarth spectroscopy, and thus potentially the mission lifetime requirements. It may be necessary for HWO to bypass and replace dusty targets.

15

A Roman Coronagraph Exozodi observing program

- Exozodi is a noise source that will compromise HWO's sensitivity for imaging & spectroscopy of HZ rocky planets. Even for levels a few times that of the solar system, It can be much brighter than the signal from the planet itself.
- For individual stars, the upper LBTI upper limits were ~120 zodis. Better upper limits are very desirable
- It is a programmatic priority to reduce the uncertainty in the median exozodi level, in order to predict the integration times needed for rocky planet spectroscopy with HWO
- The Roman Coronagraph can only access the HZ inner edge in ~6 HWO targets, but the middle of the HZ in more like ~70 targets.
- If the instrument performs well, a ~500 hour survey of these targets could be sensitive down to the ~12 zodi level for the median target (E. Douglas et al. 2022) - identifying dusty targets that HWO might want to skip
- A pilot program on 8 brighter targets is in the plan for Roman Coronagraph's first 6 months. Would detect as small nebulosity right at the inner working angle.

A Preliminary Target star list for *Habitable Worlds Observatory*
The 164 most accessible nearby habitable zones

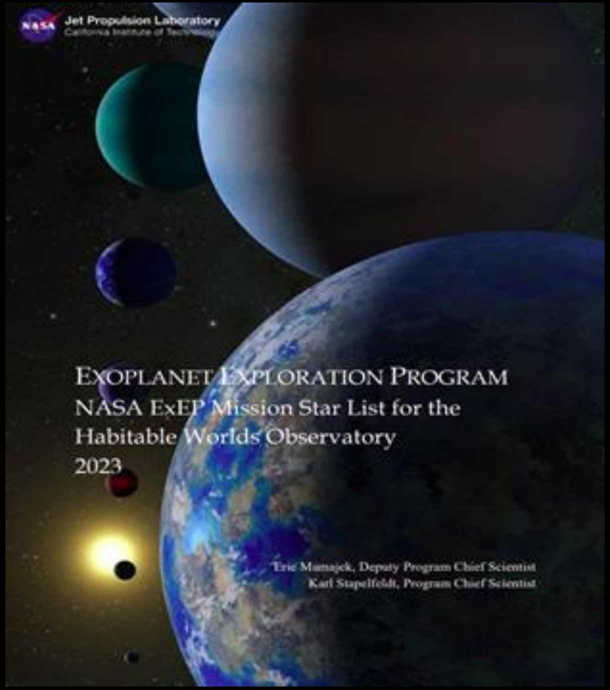
Mamajek & Stapelfeldt 2024 arXiv:2402.12414 & https://exoplanets.nasa.gov/exep/science-overview/
& online tables at the NASA Exoplanet Archive

Selection criteria:

1. HZ Earth analog bright enough for spectroscopy with 6m telescope in <2 months integration time
2. Detection contrast consistent with NASA technology goals, 10^{-10}
3. Inner Working Angle sufficient to search 100 nearby HZs, and thius achieve the Astro2020 goal of characterizing ~25 HZ rocky planets

Parameter	Tier A	Tier B	Tier C
IWA constraint	83 mas	72 mas	65 mas
Exoplanet brightness limit (Rc)	30.5 mag	31.0 mag	31.0 mag
Exoplanet-star Brightness ratio limit	4e-11	4e-11	2.5e-11
Disk criterion	No known dust disks of any kind	No disk, or KB disks OK if Ldisk/L* <= 10^{-4}	All disks OK, even if Ldisk/L* >= 10^{-4} or detected HZ warm dust disk
Treatment of binaries	Single or binary companion > 10" sep	Single or binary companion > 5" sep	Single or binary companion > 3" sep
Number of Stars	**47**	**51**	**66**

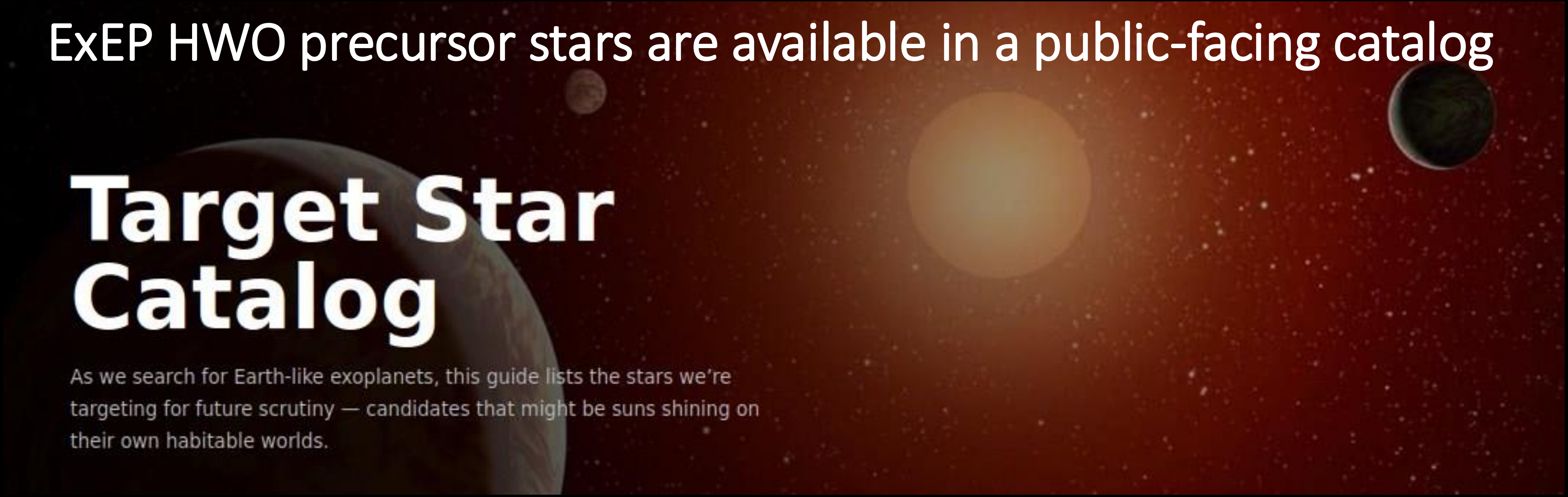
Sample	F	G	K	M
Tier A	14	15	17	1
Tier B	15	23	11	2
Tier C	37	17	12	0
Total (A+B+C)	66	55	40	3



The community is working extensively on this target sample

This is the most-cited paper on Habitable Worlds Observatory

ExEP HWO precursor stars are available in a public-facing catalog



- Goal : Grow public enthusiasm for "Where We Explore" with HWO. Highlight these naked eye star targets for amateur astronomers & the general public
- **https://science.nasa.gov/exoplanets/target-star-catalog/**
- 164 stars can be sorted by distance, brightness, constellation, presence of known planets, and stellar type.
- Links to "Eyes on Exoplanets" pages depicting the system
- "+" sign link takes you to description of the system including narrative text

Summary & Conclusions

- Exoplanet Demographic information from the GBTDS and other WFI surveys will constrain planet formation models, and thus impact the expected overall yields for HWO exoplanet detections
- If the Roman Coronagraph performs as expected, then it should be able to conduct surveys of HWO targets to screen for high exozodi dust and any close companions that might have escaped notice so far
- Roman coronagraph operations, data analysis methods, and science results will be pathfinders for all that HWO intends to do for high contrast imaging
- WFI dark energy surveys should be able identify interesting targets for HWO follow-up studies