NASA ExEP Mission Star List of Plausible Targets for Habitable Worlds Observatory - Community Webinar

Eric Mamajek & Karl Stapelfeldt
Program Chief Scientists
NASA Exoplanet Exploration Program Office
Jet Propulsion Laboratory, California Institute of Technology

Jessie Christiansen
Project Scientist, NASA Exoplanet Archive, NExScI/IPAC/Caltech

Anjali Tripathi
Science Ambassador, NASA ExEP, JPL/Caltech

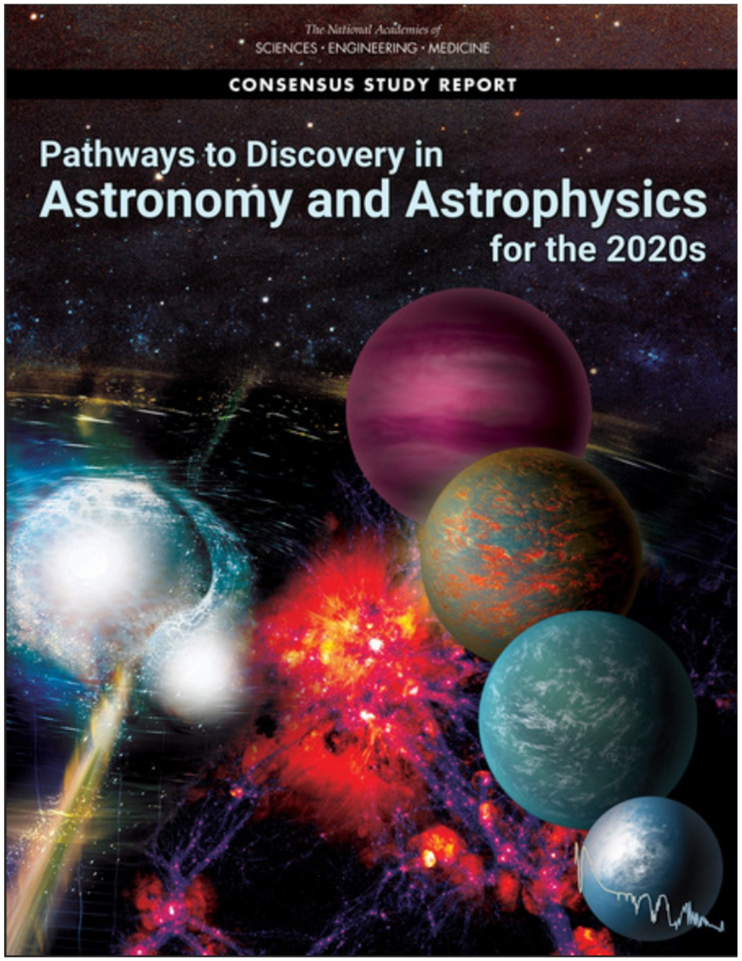
March 1, 2023

 Government sponsorship acknowledged CL#23-1166

NASA ExEP Mission Star List Webinar agenda

- Karl Stapelfeldt (ExEP): motivation for this target list (5 min)
- Eric Mamajek (ExEP) with details on construction of the list (20 min)
- Jessie Christiansen (NExScI) on the target table now available at NExScI (5-10 min)
- Anjali Tripathi (ExEP) discussing science engagement with list (5-10 min)
- Your questions & open discussion

ExEP Target List for Precursor & Preparatory Science



- Astro 2020 recommended a future IR/O/UV direct imaging mission and its approximate scope ("***Habitable Worlds Observatory***")
- Community can start work towards improving our knowledge of the stars that will likely be targets for fulfilling the Decadal goal to search for biosignatures from a robust # of ~25 potentially habitable planets

  (~100 cumulative habitable zones [HZs] surveyed)
- ***Challenge: Can we generate a provisional list to get to ~100 cumulative HZs in an architecture-agnostic way?***

Motivation for this target list

- Characterization of exoplanet host stars and their circumstellar environments is specifically called for (e.g. ROSES Precursor Science Gap #2; ExEP Science Gaps SCI-07 and SCI-10).
- Astro2020 has been specific enough about the ExoEarth direct imaging mission that it is now possible to identify the nearby stars where HZ rocky planets would be accessible for spectroscopy
- The 6m HWO is sufficiently different from the HabEx and LUVOIR-B mission concepts that its own specific target list would be needed
- Previous work (e.g. RV surveys, companion searches, stellar activity surveys) has covered only some of the targets due to the lack of a specific target list that the community can work from
- ExEP already developed an extensive database on nearby stars to support the 2019-2021 Extreme Precision Radial Velocity Working Group (EPRV WG), and this could be readily adapted and expanded upon for HWO targets
- Analysis takes independent approach from previous yield simulations that informed HabEx & LUVOIR target lists

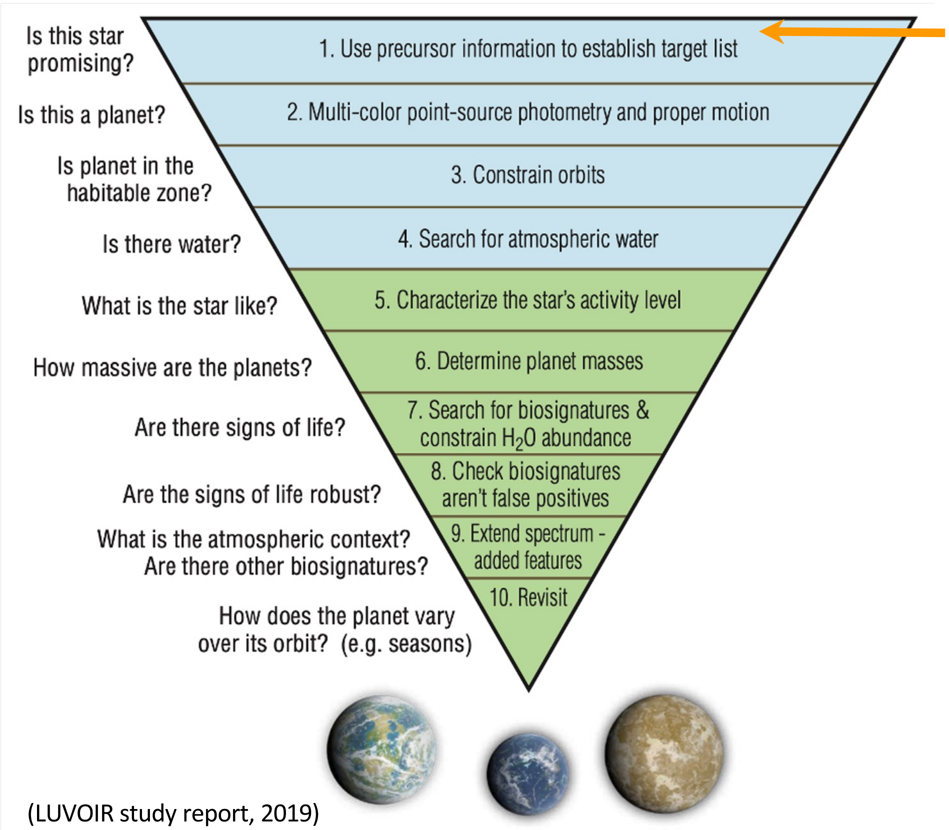
What the ExEP list and table IS and IS NOT

- The list **IS** intended to be a preliminary target list of stars that our criteria show have a high probability of surviving vetting and eventually being among the ~100 best HWO hab zone survey targets
- The list **IS** intended to motivate community science investigations:
  - "precursor science" to inform HWO design and
  - "preparatory science" to enhance HWO science return.
- The list **IS** timely given the new ROSES element D.16 Astrophysics Decadal Survey Precursor Science
- The list and table **ARE** a first version, and will be updated when needed
  - given the feedback so far, an update within a year seems warranted

What the ExEP list and table IS and IS NOT

- The list **IS NOT** the *final* targets for HWO hab zone survey, which likely won't fly until the early 2040s! Future teams will need to decide that.
- The list **IS NOT** exhaustive for all targets for which HWO will likely to be able to detect+spectrally characterize other planet types (e.g. larger planets).
- The list **IS NOT** the sole input catalog for yield codes like ExoSIMS, AYSO, etc. They work with larger star catalogs complete out to larger distances (although the new table may be helpful for updating stellar parameters for a subset of stars in these larger input catalogs)

ExEP Target List for Precursor & Preparatory Science



(LUVOIR study report, 2019)

Figure 3-11. *Science questions and observational strategy in the search for habitable planets and life. Blue steps at the top of the figure refer to identifying habitable exoplanet candidates; green steps at the bottom of the figure refer to characterizing habitable exoplanets and searching for biosignatures. Credit: T. B. Griswold (NASA GSFC)*

- **There will be surprisingly little flexibility in the choice of targets!**

  We have limited numbers of stars with the brightness and proximity required that could have exo-Earths with accessible
  - brightnesses,
  - planet-star brightness ratios, and
  - angular separations
- **We need carefully vetted stellar samples and parameters** (esp. luminosities), photometry, binarity (resolved & spectroscopic)
- We can check against previous efforts (target lists from LUVOIR & HabEx studies, EPRV Working Group report). Approximately ~10% stars missing from previous lists, and many study targets were unrecognized close binaries

Adopted target parameters for exo-Earths

- Consistent with the LUVOIR and HabEx studies, we adopted
  - Conservative habitable zone 0.95-1.67 AU, scaled by Luminosity$^{1/2}$
  - Geometric albedo of 0.2 independent of wavelength
  - Lambertian phase function
- Estimated brightnesses of hypothetical exo-Earths in Rc band (~550-800 nm):
  - More favorable to late-type stars than using V band
  - Includes wavelength of the O_2 A band, a key spectral diagnostic
  - For 6m aperture, 18% throughput, R=70, S/N=10, and max spectroscopy integration time of 60 days, **Rc= ~31 mag is the threshold for useful spectroscopy.**
  - These choices tend to be optimistic and thus are inclusive of more targets.
- Minimum planet-star brightness ratios and planet brightnesses
  - **Tier A**: >4e-11 (Δmag=26) , Rc < 30.5
  - **Tier B**: >4e-11 (Δmag=26) , Rc < 31
  - **Tier C**: >2.5e-11 (Δmag=26.5) , Rc < 31

Planet location and illumination

- The fiducial case of a 1 R_E planet observed at the Earth equivalent insolation distance (near inner edge of HZ) and quadrature illumination (phase = 90^o) is not sufficient to define all the stars where HZ rocky planets may be detectable
  - Larger rocky planets, or planets seen at gibbous phase, will be brighter and more detectable than the fiducial case
  - Planets in the middle or outer HZ will be better-separated from the star and potentially more detectable than the fiducial case
- We consider 12 test cases of planet location, size, and illumination phase, and only select targets for our list if the planet meets our criteria in at least 6 cases:
  - Planet radii of 1.0 R_E "Earths" & 1.4 R_E "Super-Earths",
  - Planets observed at two phase angles: 90° and 63° "gibbous",
  - Separations at:
    - Earth-equivalent installation distance (1au*),
    - middle of hab zone (1.3au*),
    - usable outer HZ limit (1.55au*)

* = scaled by $\mathrm{sqrt}(L_{star}/L_{sun})$

Relevant equations and test planet cases

C = Planet-star brightness ratio

F_p = planet flux

F_* = star flux

p=geometric albedo

ϕ = Phase function

α = Phase angle

Rp = planet radius

r = orbital separation

$$C = F_p/F_* = p\,\phi(\alpha)\,(R_p/r)^2$$

$$\phi(\alpha) = (\sin\alpha + (\pi - \alpha)\cos\alpha)\,/\,\pi$$

$$\Delta mag = -2.5 \log F_p/F_* = -2.5 \log C$$

$$mag_p = mag_* + \Delta mag$$

Planet apparent magnitude

Star apparent magnitude

Case #	Phase Angle	Orbital Radius[4]	Planet Radius	Delta(mag)
1	90°	1.00 au	1.0 Re	0.00 (reference)
2	90°	1.00 au	1.4 Re	-0.73
3	90°	1.31 au	1.0 Re	+0.59
4	90°	1.31 au	1.4 Re	-0.14
5	90°	1.55 au	1.0 Re	+0.95
6	90°	1.55 au	1.4 Re	+0.22
7	63.3°	1.00 au	1.0 Re	-0.64
8	63.3°	1.00 au	1.4 Re	-1.37
9	63.3°	1.31 au	1.0 Re	-0.05
10	63.3°	1.31 au	1.4 Re	-0.78
11	63.3°	1.55 au	1.0 Re	+0.31
12	63.3°	1.55 au	1.4 Re	-0.42

Treatment of binaries

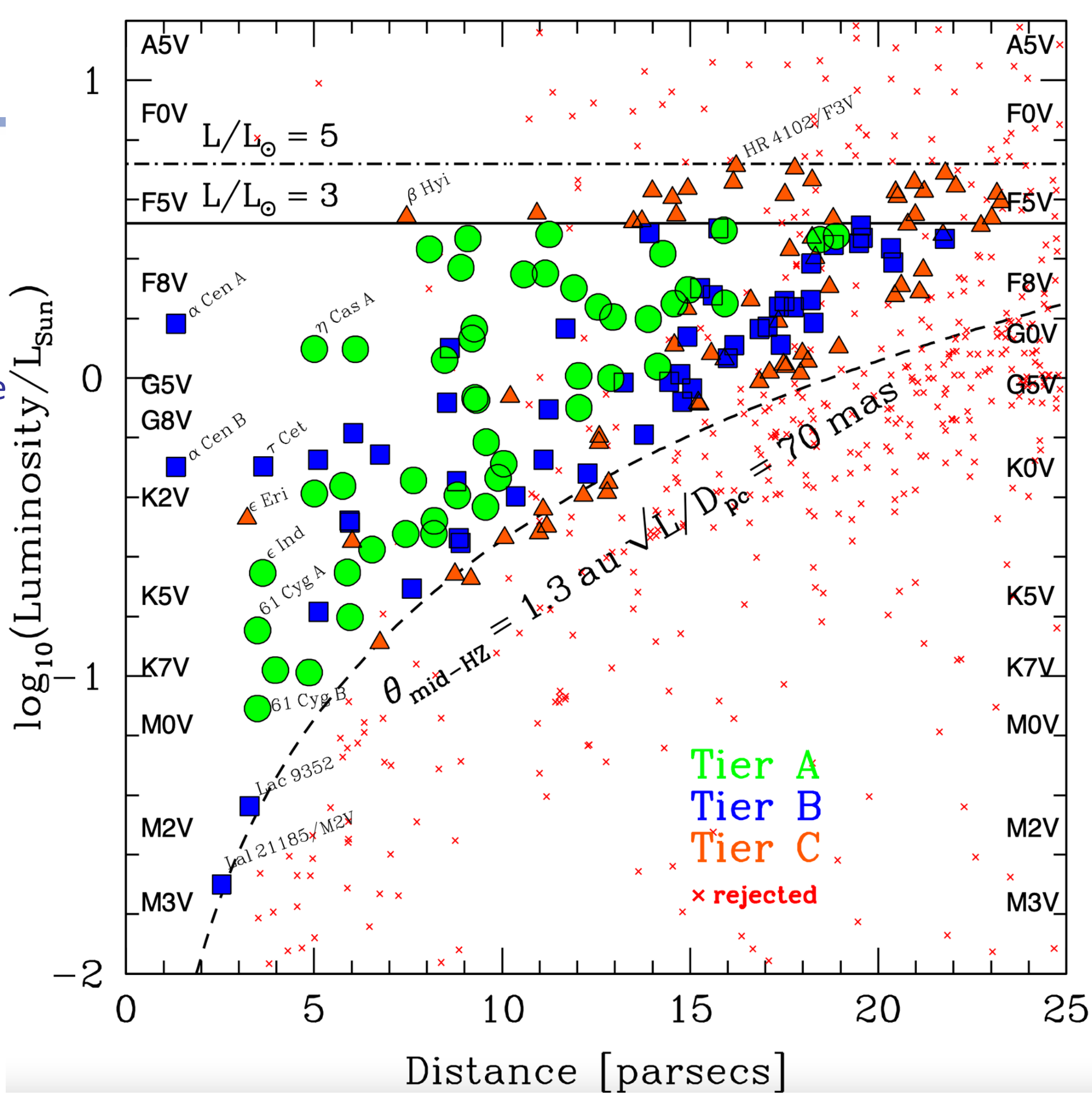
- **Light from companion stars can complicate or prevent high contrast measurements around the primary target**
- A large fraction of nearby bright stars are in multiple systems. *Using as many binaries as possible would ease requirements on the telescope and starlight suppression system.*
- **At wide enough separations**, the PSF wings from the companion will fall below the dark hole contrast floor and be negligible. For a 6m HWO, companion separations > 10” (500 λ/D at V band) should fall in this regime over the full range of wavelengths. <u>Tier A binary.</u>
- **At intermediate separations of 5-10”**, the above should be true at short wavelengths but not necessarily at all wavelengths of interest. <u>Tier B binary.</u>
- **At separations of 3-5”**, special starlight suppression methods will likely be needed to enable work with these targets. <u>Tier C binary.</u>
- **At separations < 3”** (including spectroscopic binaries) stars are judged as unlikely to be doable and do not appear on the target list
- A more rigorous treatment awaits specification of the HWO primary mirror surface quality, which determines the amount of companion spillover light

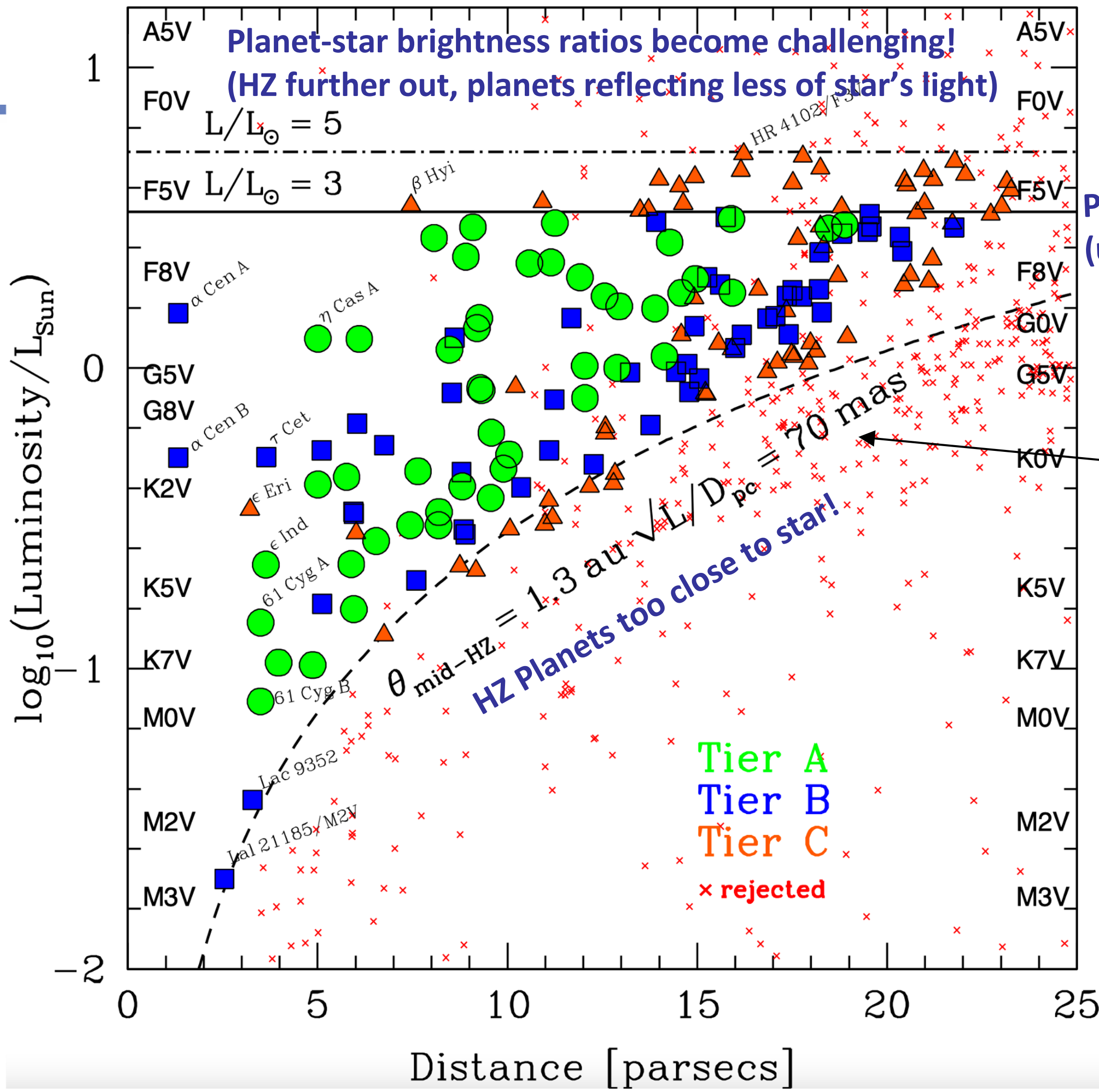
Inner Working Angle

- **We <u>do not</u> derive the needed IWA from assumptions about the telescope or starlight suppression system**
- Instead we used the master star list and tested progressively smaller IWA values until our criteria produced a list that met Astro2020's requirement to survey ~100 habitable zones. (72 mas; our Tiers A and B). A buffer of additional targets (Tier C) is provided by further reducing the IWA by 10% to 65 mas, and by being more permissive on target properties
- The inner working angles we derive are not tied to any specific wavelength; they must be satisfied at all wavelengths where spectroscopy is required
- It is up to HWO designers to decide what combination of aperture size, coronagraph architecture, and/or starshades should be used to provide the needed IWA performance

Input catalog of ~800 nearby stars from:

- LUVOIR & HabEx reports (which informed EPRV WG)
- SIMBAD and xHIP (Anderson & Francis 2012), selecting targets to increasing distance by spectral type until selection criteria were not match (<half of planet cases not detectable)
- In terms of distance limits of completeness, all stars were considered out to:
  - **BAF *s : d < 25pc**
  - **G *s : d < 20pc**
  - **K *s : d < 12pc**
  - **M *s : d < 5pc & V or G < 10 mag**
  - Additional more distant stars were considered (e.g. boundary cases, stellar companions), but input list was not complete past those limits





Why does the distribution of target stars look the way it does?

Dashed line defines Lum-dist combination that corresponds to middle of HZ equalling 70mas… NOT a hard selection limit, but shown to guide the eye

Other issues:

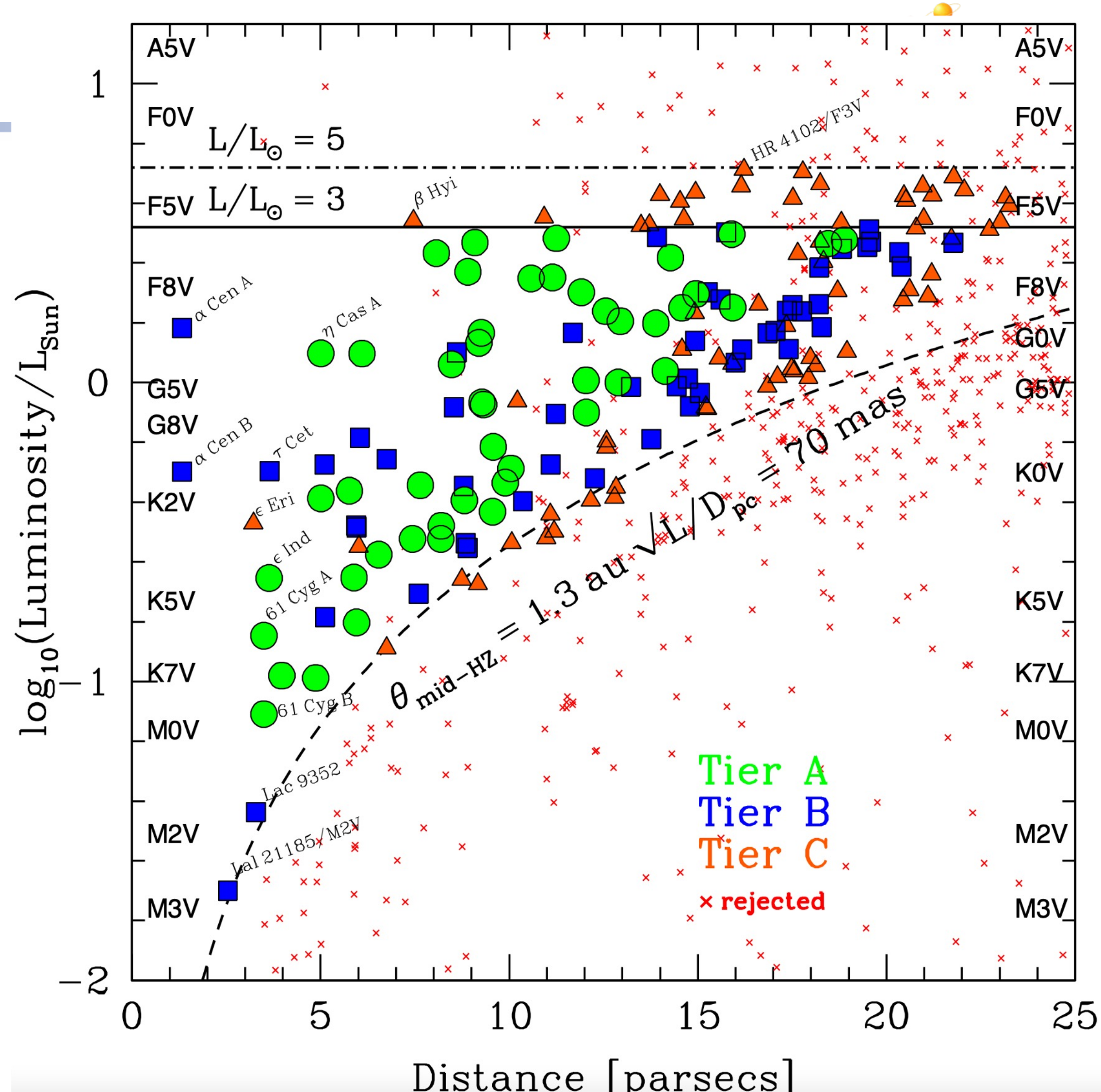
Stellar multiplicity
Large exoplanets in/near HZ
Disks / zodi background

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

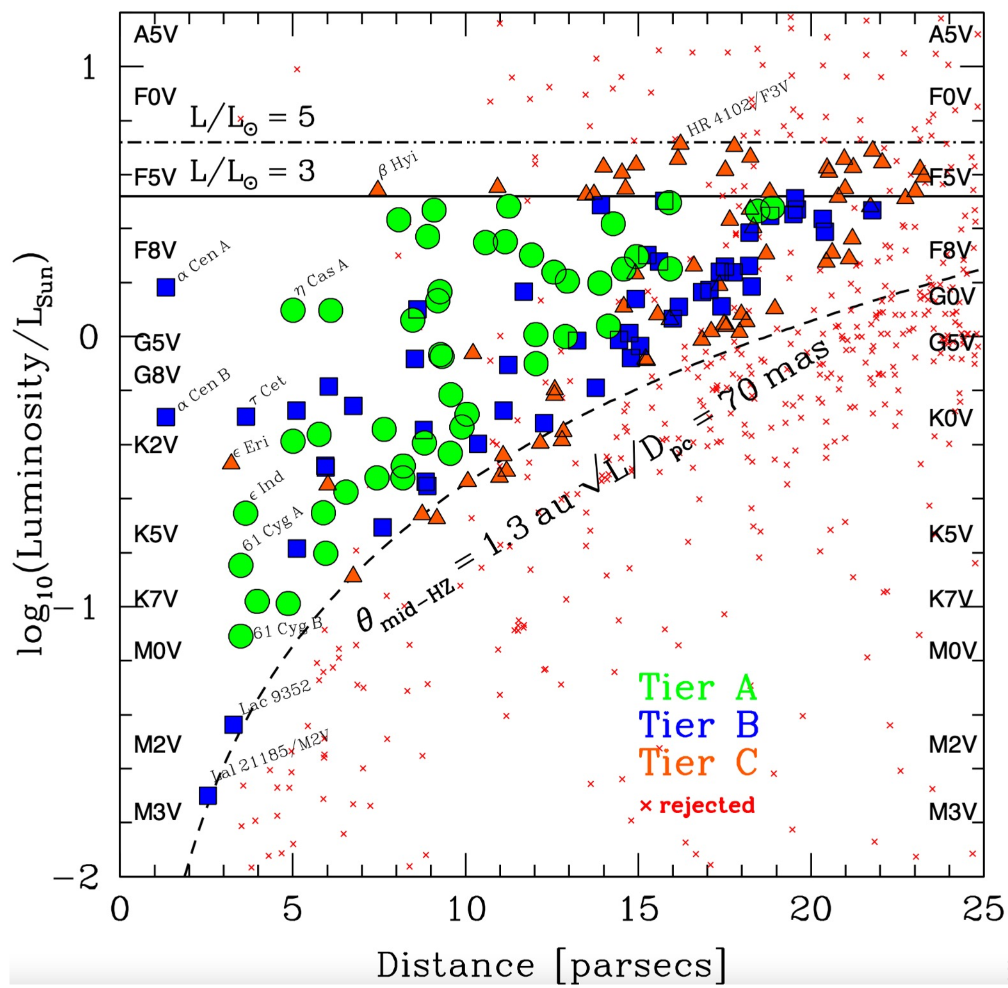
Approx. magnitude & distance limits:

F*s: V < 6.0, d < 23.3 pc
G*s: V < 6.4, d < 20.5 pc
K*s: V < 7.0, d < 12.8 pc
M*s: V < 7.5, d < 4.0 pc



ExEP Target List for Precursor & Preparatory Science

- Data in table:
  - **Star:** Designations, Parallax, distance, RA, Dec, Vmag, B-V color, Rc mag, spectral type, effective temperature (Teff), stellar luminosity, calculated stellar radius, calculated angular diameter, mass, metallicity, surface gravity (log*g*), Ca II H&K activity (logR’$_{HK}$), binary star separation and delta(mag), flags for disks and exoplanets
  - **Calculated for hypothetical Earth twin:** Earth equivalent insolation distance (EEID) in au and angular separation (in mas), planet-star brightness ratio, predicted Rc mag, predicted orbital period, predicted RV amplitude, predicted astrometric amplitude



ExEP Target List Appendices

Appendix A: Provisional NASA ExEP Target Star List for Precursor and Preparatory Science for Habitable Worlds Observatory (2023)

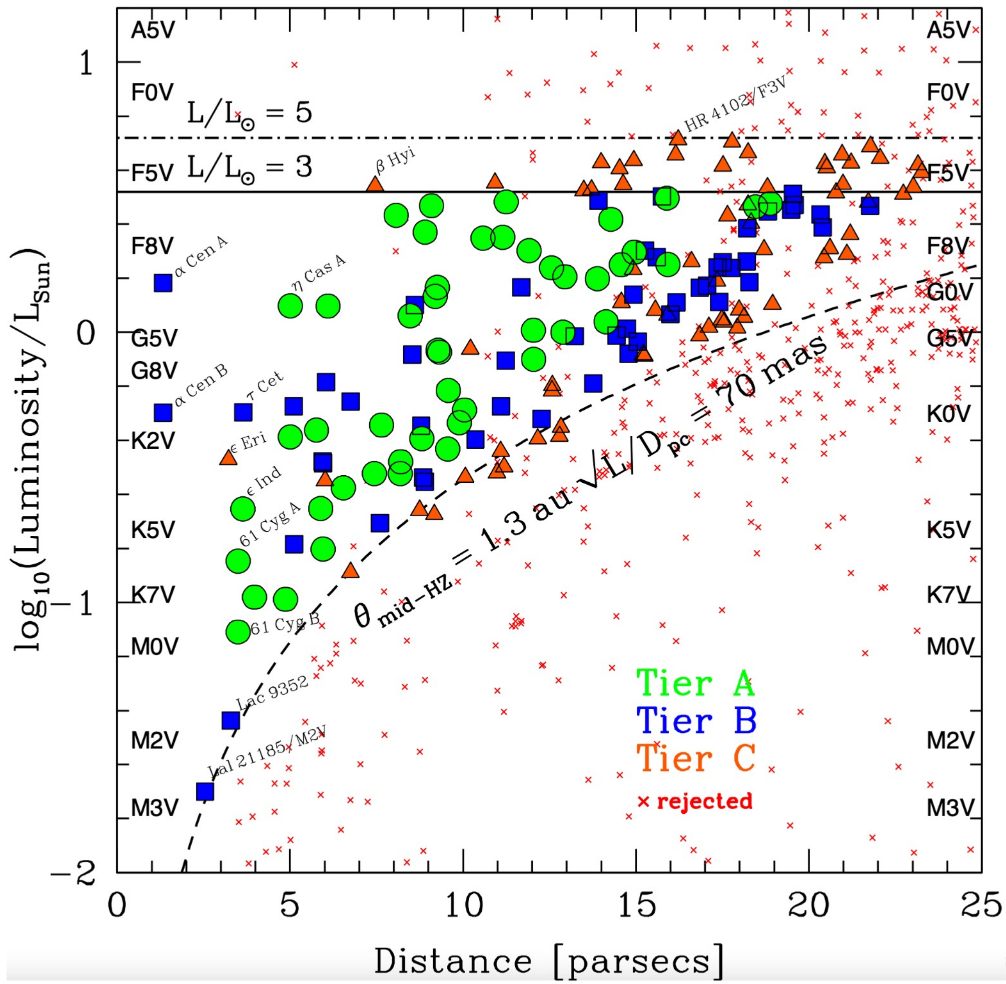
Appendix B: HabEx and LUVOIR-B Target Stars That Were Not Included in the ExEP List

Appendix C: ExEP Target Stars That Were Not Included in HabEx or LUVOIR-B Lists

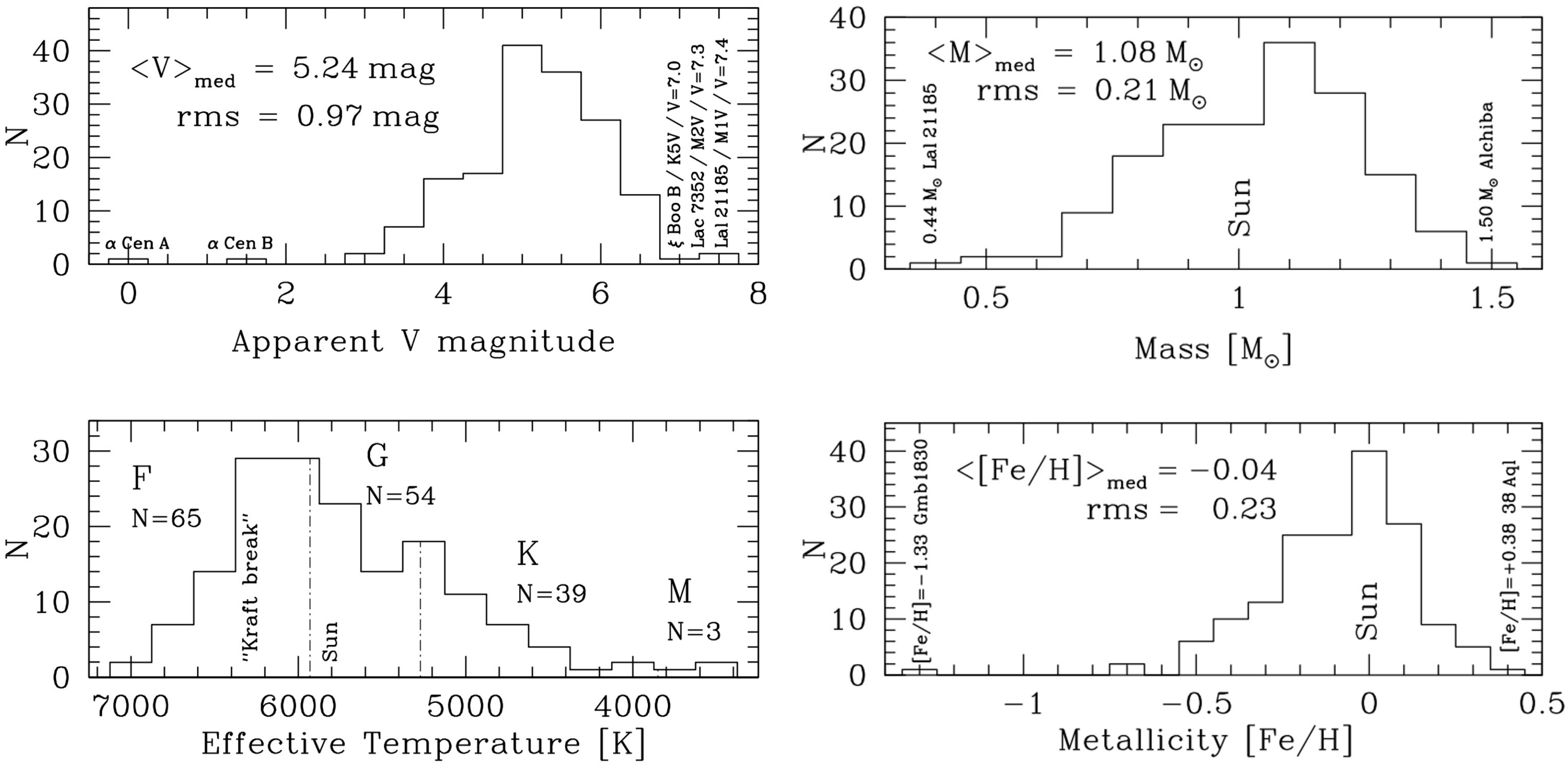
Appendix D: Problematic Targets like Binaries Requiring Further Analysis

Appendix E: Stars Previously Reported to be Binary but Likely Spurious

Appendix F: Table Column Descriptors and Notes



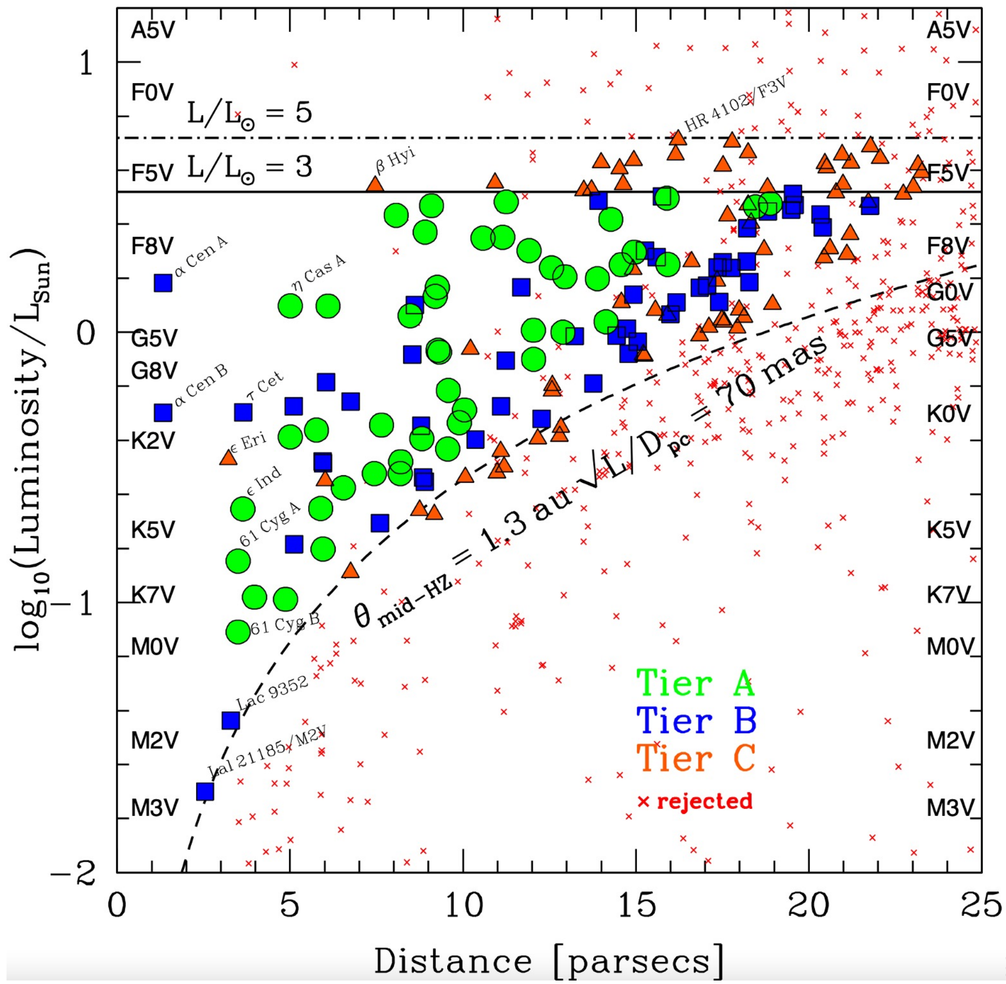
ExEP Target List for Precursor & Preparatory Science



Spectroscopic parameters Teff and [Fe/H] mostly from Soubiran+2022 PASTEL compendium. Masses from numerous literature sources.

ExEP Target List for Precursor & Preparatory Science

- Table of stars and related data and calculated quantities underwent peer review in Dec 2022 by subject matter experts (Rhonda Morgan, Josh Pepper, Aki Roberge, Dmitry Savransky, Chris Stark, Maggie Turnbull). Reviewers had good suggestions for additional data to add to future versions.
- **Data table and documentation are now posted on ExEP Science website: https://exoplanets.nasa.gov/exep/science-overview/**
- **Long term home for table & documentation will be on NExScI web page: https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=DI_STARS_EXEP (or just search for "HWO ExEP Precursor Science Stars")**
- Plan to update the table and documentation periodically as knowledge of stars improves or survey. List may evolve as parameters/strategy evolves.



Acknowledgement

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.