The Standard Definitions and Evaluation Team Final Report: A common comparison of exoplanet yield

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PROGRAMMATIC OVERVIEW AND BACKGROUND

Exoplanet Probe Studies

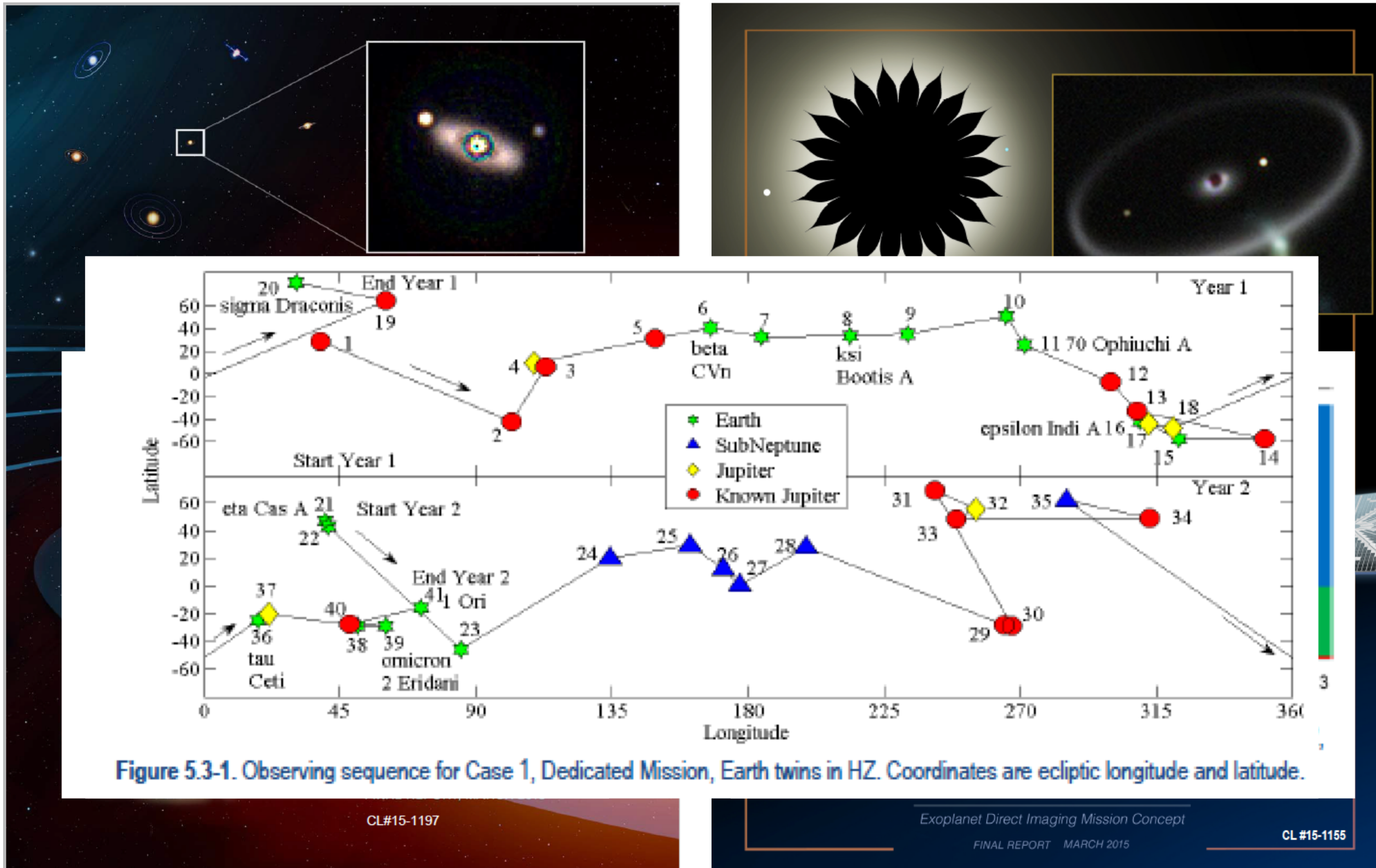
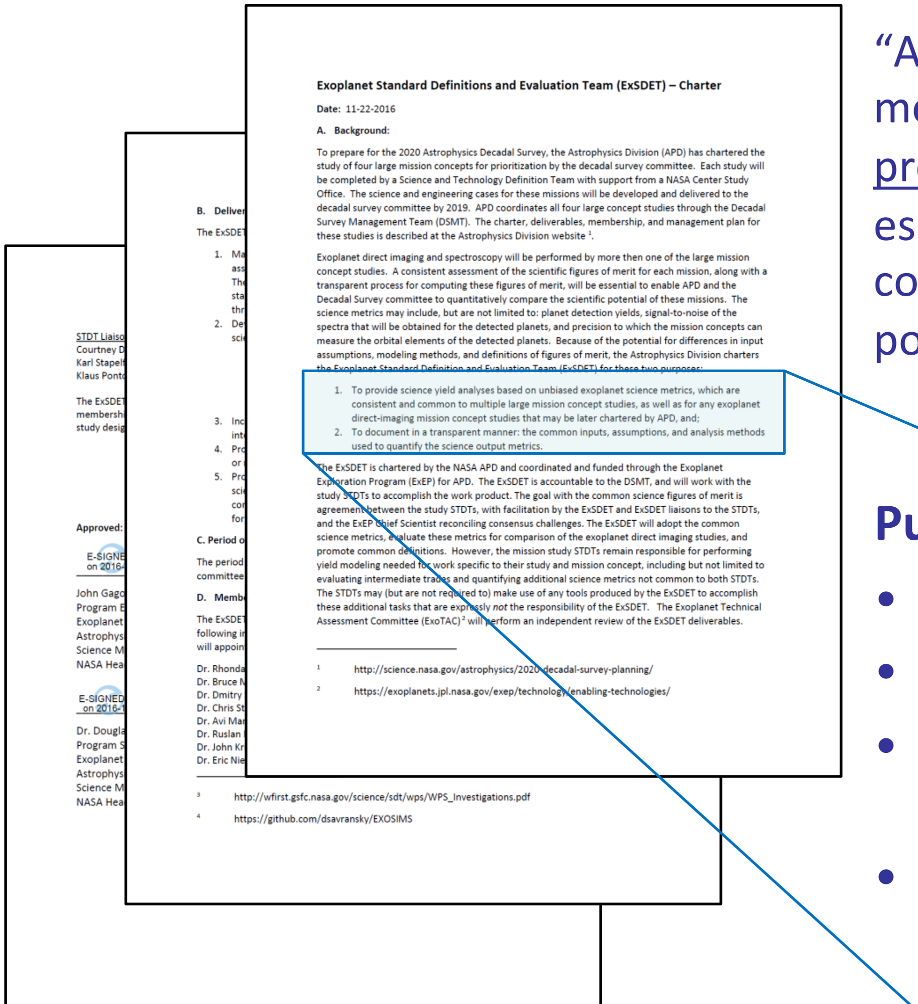


Figure 5.3-1. Observing sequence for Case 1, Dedicated Mission, Earth twins in HZ. Coordinates are ecliptic longitude and latitude.

Exoplanet Direct Imaging Concept Missions

Charter Established for ExSDET Activity

- NASA / APD Chartered the Exoplanet Standards Definition and Evaluation Team (ExSDET) in Nov 2016 to address the need for a consistent and common basis for Science Yield estimates.



Exoplanet Standard Definitions and Evaluation Team (ExSDET) – Charter

Date: 11-22-2016

A. Background:

To prepare for the 2020 Astrophysics Decadal Survey, the Astrophysics Division (APD) has chartered the study of four large mission concepts for prioritization by the decadal survey committee. Each study will be completed by a Science and Technology Definition Team with support from a NASA Center Study Office. The science and engineering cases for these missions will be developed and delivered to the decadal survey committee by 2019. APD coordinates all four large concept studies through the Decadal Survey Management Team (DSMT). The charter, deliverables, membership, and management plan for these studies is described at the Astrophysics Division website [1].

Exoplanet direct imaging and spectroscopy will be performed by more then one of the large mission concept studies. A consistent assessment of the scientific figures of merit for each mission, along with a transparent process for computing these figures of merit, will be essential to enable APD and the Decadal Survey committee to quantitatively compare the scientific potential of these missions. The science metrics may include, but are not limited to: planet detection yields, signal-to-noise of the spectra that will be obtained for the detected planets, and precision to which the mission concepts can measure the orbital elements of the detected planets. Because of the potential for differences in input assumptions, modeling methods, and definitions of figures of merit, the Astrophysics Division charters the Exoplanet Standard Definition and Evaluation Team (ExSDET) for these two purposes:

1. To provide science yield analyses based on unbiased exoplanet science metrics, which are consistent and common to multiple large mission concept studies, as well as for any exoplanet direct-imaging mission concept studies that may be later chartered by APD, and;
2. To document in a transparent manner: the common inputs, assumptions, and analysis methods used to quantify the science output metrics.

The ExSDET is chartered by the NASA APD and coordinated and funded through the Exoplanet Exploration Program (ExEP) for APD. The ExSDET is accountable to the DSMT, and will work with the study STDTs to accomplish the work product. The goal with the common science figures of merit is agreement between the study STDTs, with facilitation by the ExSDET and ExSDET liaisons to the STDTs, and the ExEP Chief Scientist reconciling consensus challenges. The ExSDET will adopt the common science metrics, evaluate these metrics for comparison of the exoplanet direct imaging studies, and promote common definitions. However, the mission study STDTs remain responsible for performing yield modeling needed for work specific to their study and mission concept, including but not limited to evaluating intermediate trades and quantifying additional science metrics not common to both STDTs. The STDTs may (but are not required to) make use of any tools produced by the ExSDET to accomplish these additional tasks that are expressly *not* the responsibility of the ExSDET. The Exoplanet Technical Assessment Committee (ExoTAC) [2] will perform an independent review of the ExSDET deliverables.

1 http://science.nasa.gov/astrophysics/2020-decadal-survey-planning/

2 https://exoplanets.jpl.nasa.gov/exep/technology/enabling-technologies/

3 http://wfirst.gsfc.nasa.gov/science/sdt/wps/WPS_Investigations.pdf

4 https://github.com/dsavransky/EXOSIMS

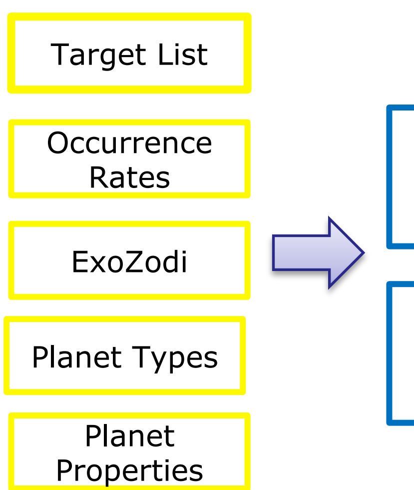
"A <u>consistent assessment</u> of the scientific figures of merit for each mission, along with a <u>transparent process</u> for computing these figures of merit, will be essential to enable APD and the Decadal Survey committee to <u>quantitatively compare</u> the scientific potential of these missions"

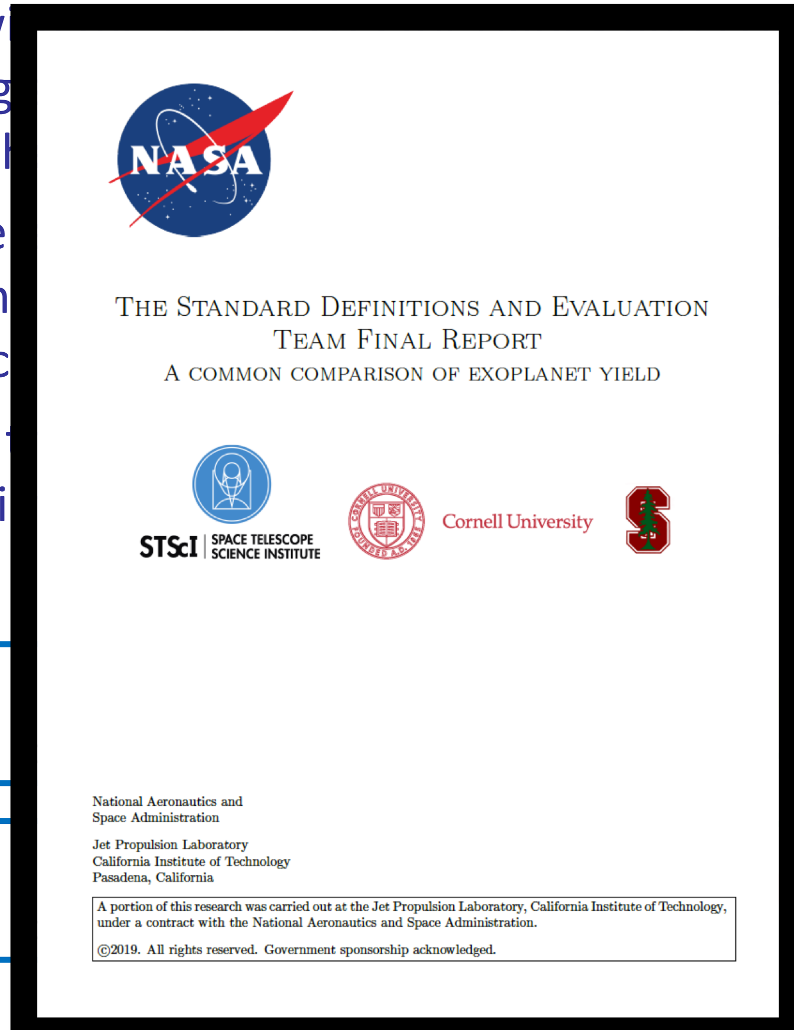
Purpose

- Provide science yield analyses
- Define unbiased exoplanet science metrics
- Be consistent and common to multiple large mission concept studies
- Document in a transparent manner

Summary of ExSDET Activity

- Over the past three years, Dr. Rhonda Morgan has led a geographically dispersed team in the development of a complex mission planning and science yield tool, EXOSIMS.
- She has worked closely wi … OIR to understand the observing … acterization of the baseline missions in th…
- There has been extensive … re and reconcile the common input param … YO and EXOSIMS to ensure accurate physic…
- The final report captures … rison of the mission variants and the i…




THE STANDARD DEFINITIONS AND EVALUATION TEAM FINAL REPORT

A COMMON COMPARISON OF EXOPLANET YIELD

STScI | SPACE TELESCOPE SCIENCE INSTITUTE

Cornell University

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

APPROACH

Standard Definitions and Evaluation Team

https://exoplanets.nasa.gov/exep/studies/sdet

ExoPlanet Exploration Program

Chartered to provide a consistent, transparent yield analysis using common input parameters

EXOPLANET PROGRAM About Studies News Meetings/Events Resources Technology NExScI ExoPAG | For the Public

Decadal STDTs SDET SSWG Probe Scale STDT

Standard Definition and Evaluation Team

Overview

Two of the four large mission concept studies for the Astrophysics Decadal Survey were designed to directly image and spectrally characterize earth-like exoplanets. In 2016, the Astrophysics Division chartered an Exoplanet Standard Definition and Evaluation Team (ExSDET) for the purpose of providing an unbiased science yield analysis of the multiple large mission concepts using a transparent and documented set of common inputs, assumptions and methodologies.

Over the course of the past three years, the ExSDET has responded to the direction provided in the charter and the required deliverables by performing the following tasks:

- Develop analysis tools that will allow quantification of the science metrics of the mission studies
- Incorporate physics-based instrument models to evaluate both internal and external occulter designs
- Establish the science metrics that define the yield criteria
- Cross validate the various analytical methodologies and tools
- Provide complete evaluations using common assumptions and inputs of the exoplanet yields for each mission concept.

The primary goal of the SDET Final Report is to present the best understanding of the exoplanet imaging and characterization capabilities of the current STDT observatory and instrument designs, along with their nominal operating plans, using common input assumptions and analysis methodologies. This report is explicitly *not* intended to present an exploration of the capabilities of the full design spaces available to the various mission concepts. Due to large uncertainties in the astrophysics inputs, particularly exo-earth occurrence rate, the yield values should be considered relative rather than absolute.

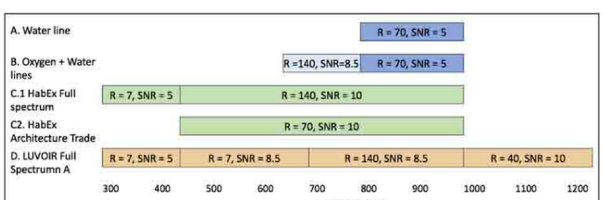


Figure 1. Characterization metric A facilitates a quick search for the water line at 940 nm with a

Documents

- SDET Charter
- SDET Final Report

Cases

- Case 1: HabEx 4H hybrid, metric C1
- Case 2: LUVOIR B, metric A
- Case 3: HabEx 4C, metric C2
- Case 4: HabEx 4S, metric C2

Links

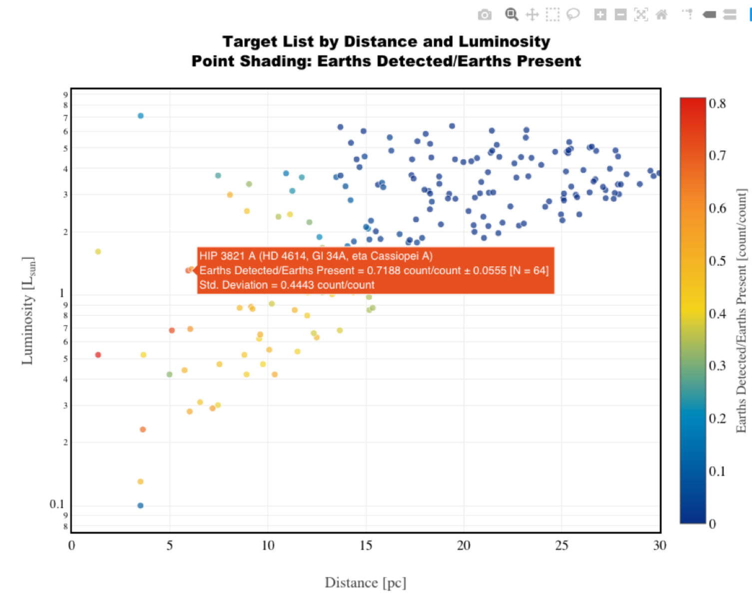
- EXOSIMS on Github
- AYO for LUVOIR
- Habitable Exoplanet Observatory (HabEx)
- Large UV-Optical-Infrared Surveyor LUVOIR

Papers

- EXOSIMS Overview in JATIS
- EXOSIMS Overview
- EXOSIMS Validation

- AYO 2014
- AYO 2015
- AYO 2016 Starshades

Interactive Detection Plot Widget



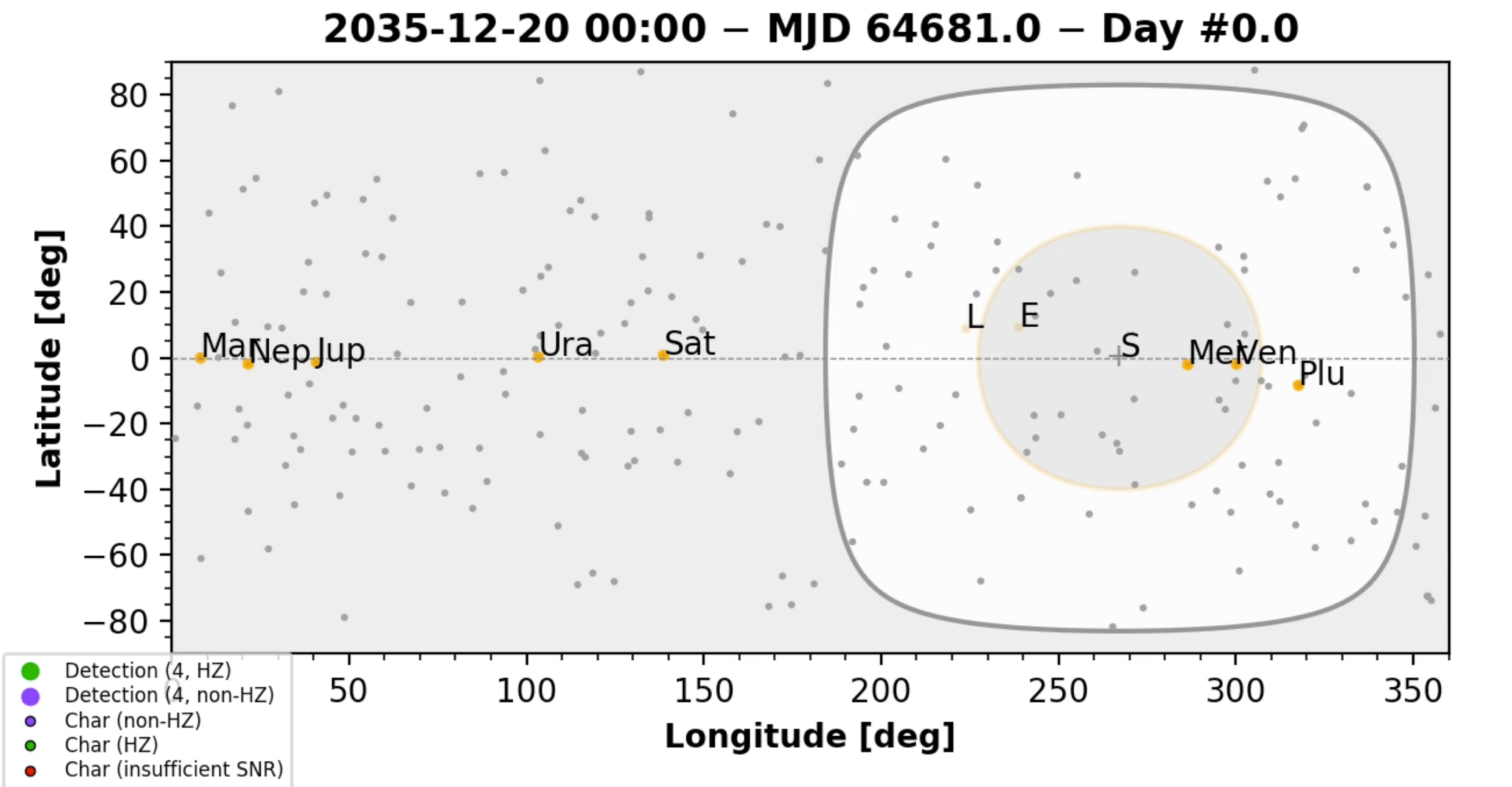
Detection QOI for Plot Shading: Earths Detected/Earths Present

Plot shading: Mean success fraction for exo-earth detections at that target, where success fraction is the number of exo-earths detected divided by the number of exo-earths present.

Outline

- ✓ Introduction
- Analysis
  - EXOSIMS overview
  - AYO overview
  - Observing scenarios
- Yield Definition
- Inputs
  - Occurrence Rates
  - Planet bins
  - Binary stars
  - Zodi
  - Exozodi
  - Orbit determination
  - Star catalog
- Yield Model Results
  - HabEx 4H
  - LUVOIR B
  - HabEx 4C
  - HabEx 4S
- Summary/Conclusions
  - EPRV precursor

EXOSIMS


2035-12-20 00:00 – MJD 64681.0 – Day #0.0
Latitude [deg]
Longitude [deg]
80
60
40
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0
−20
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−80
50
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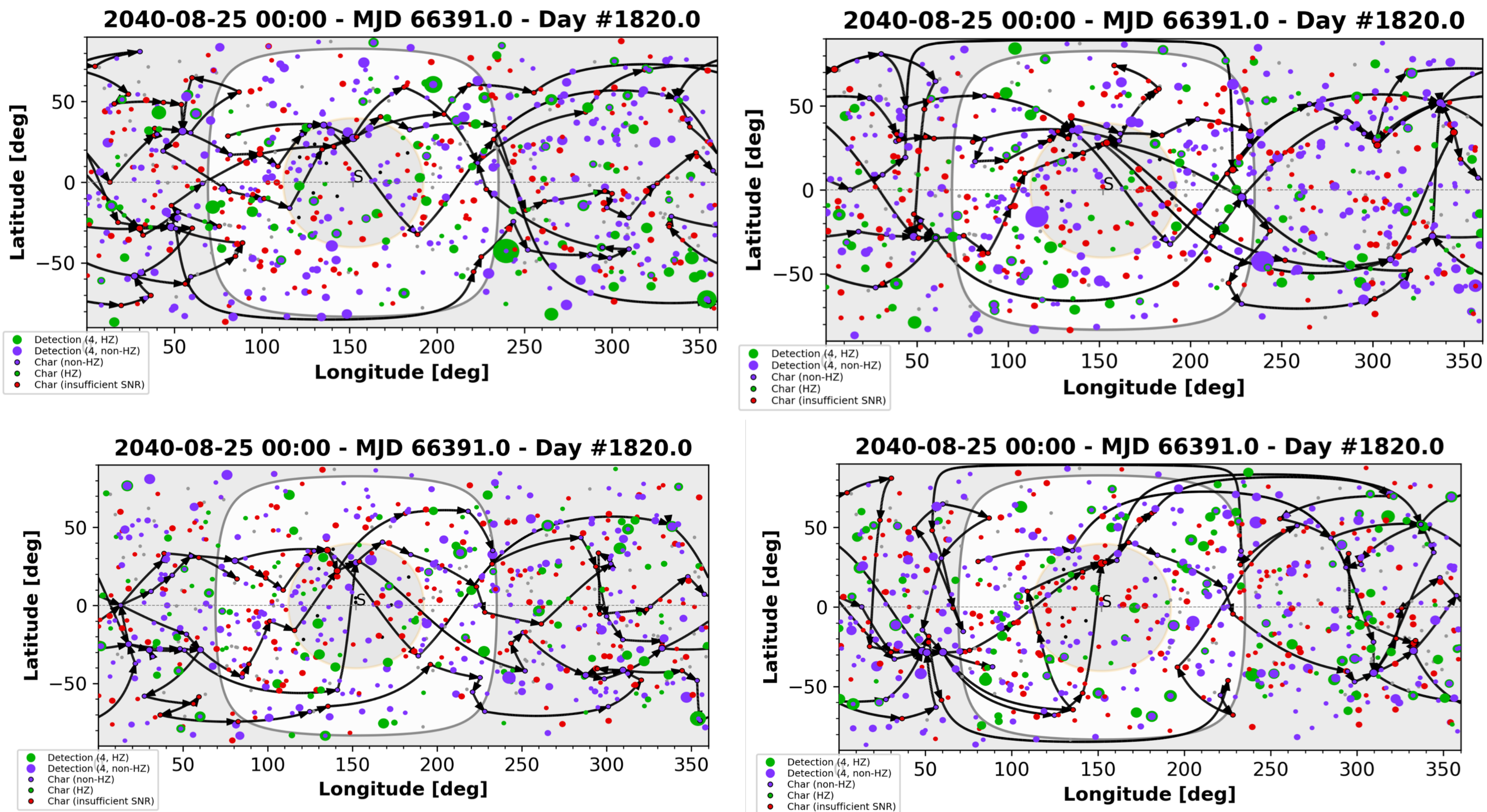
150
200
250
300
350
Mar
Nep
Jup
Ura
Sat
L
E
S
Mer
Ven
Plu
Detection (4, HZ)
Detection (4, non-HZ)
Char (non-HZ)
Char (HZ)
Char (insufficient SNR)

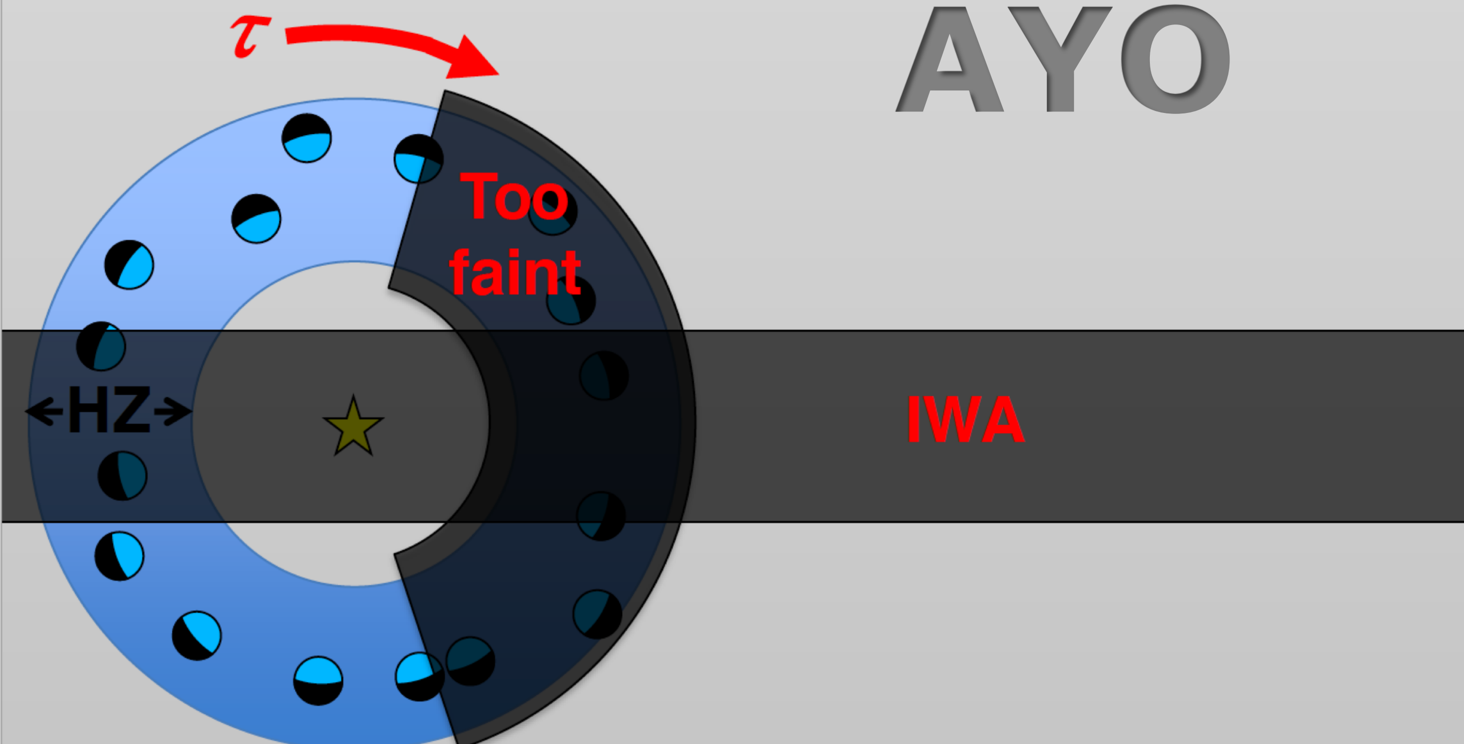
Monte Carlo Ensemble of 1000 DRMs

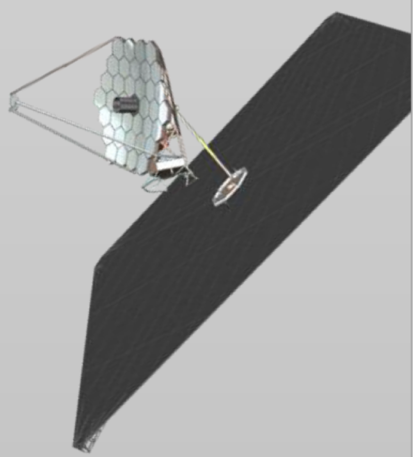


Run: HabEx_4m_TSDDtemp_top140DD_dmag26p0_20180410

Calculating Yield via Completeness

AYO

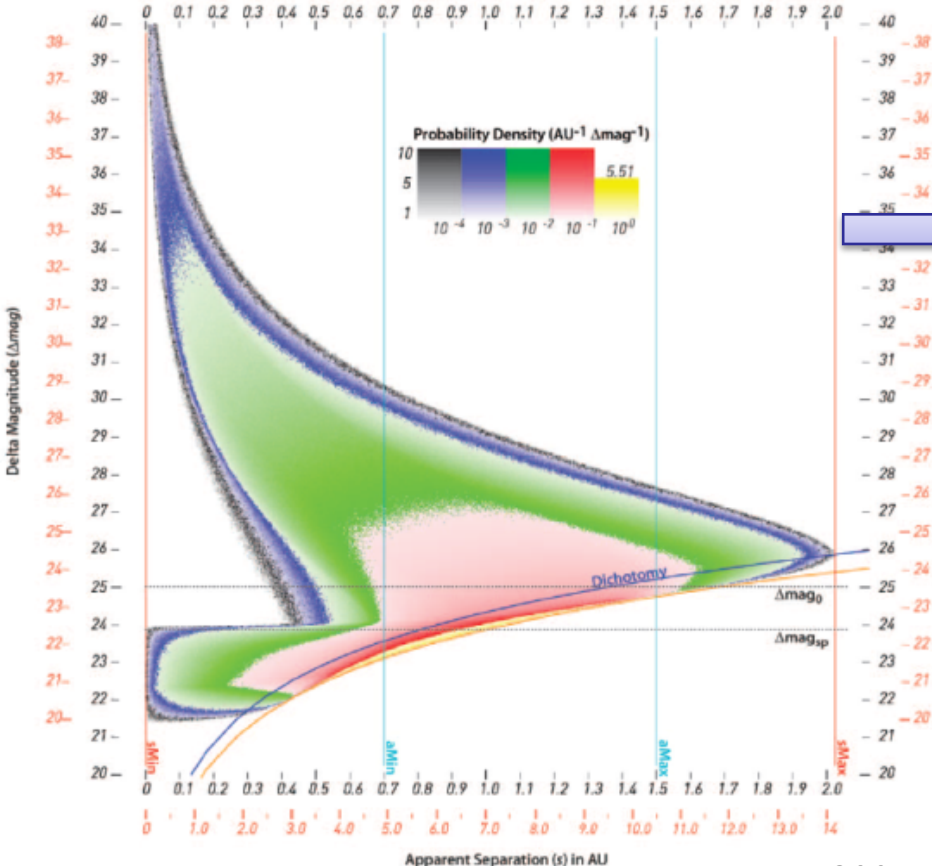




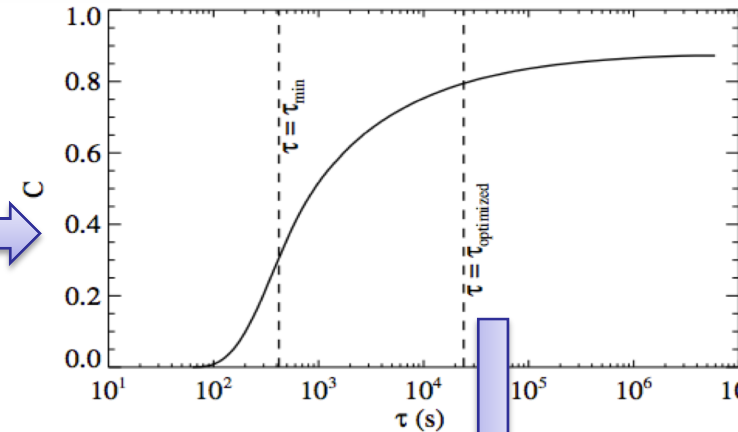
- Completeness, C = chance of observing a given planet "type" around a given star if that planet exists (Brown 2004)
- Yield = $\eta_{\text{planet}}\ \Sigma C$
- Calculated via Monte Carlo simulation with $\gtrsim 10^5$ synthetic planets per star

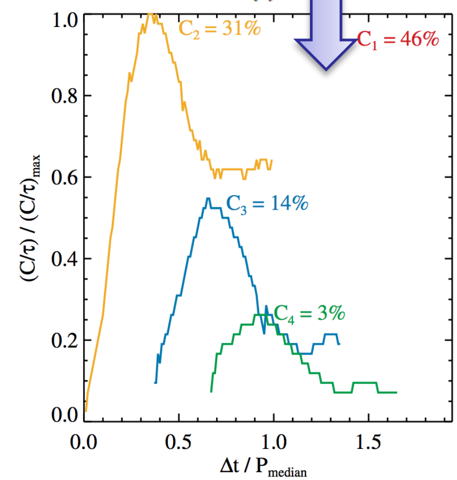
Credit: C. Stark

Completeness

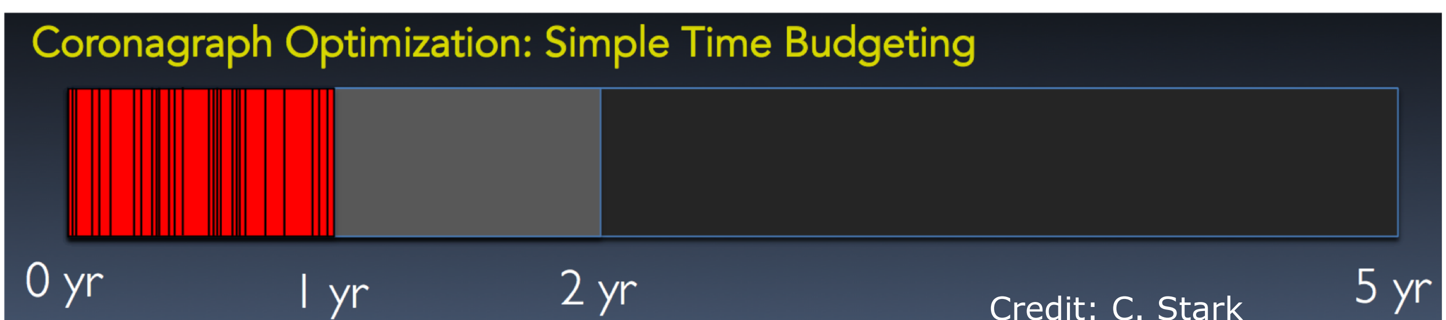


Brown 2005



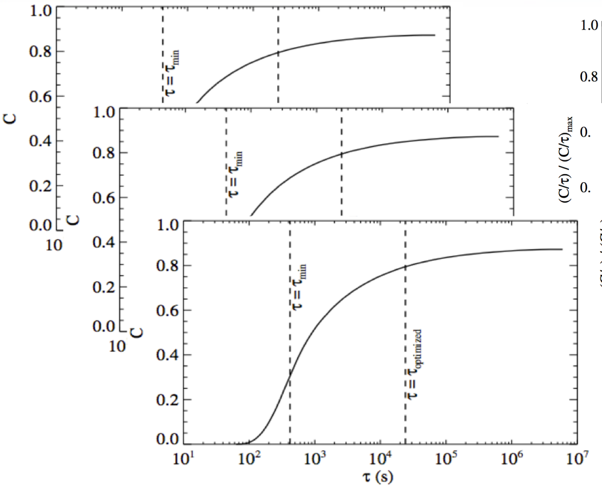


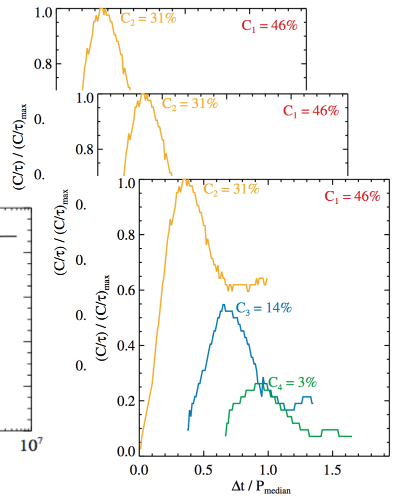
Stark 2015

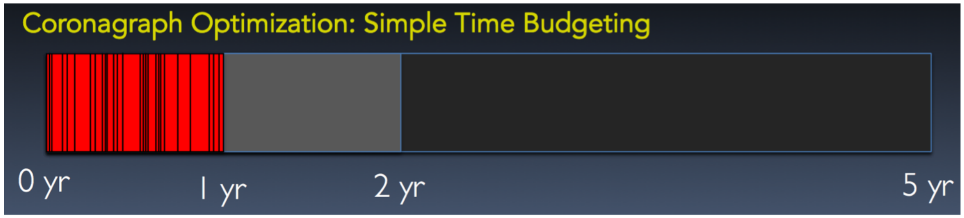


Two different yield simulation methodologies

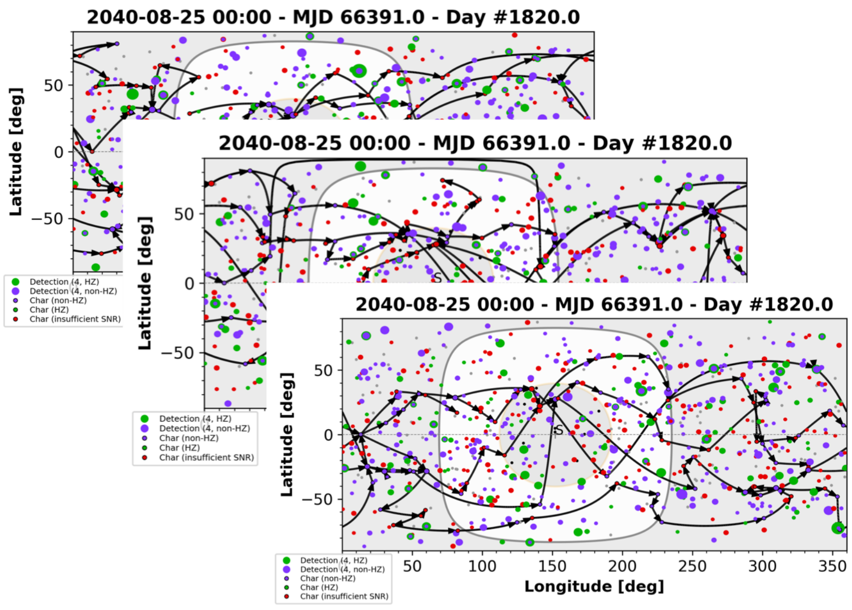
AYO

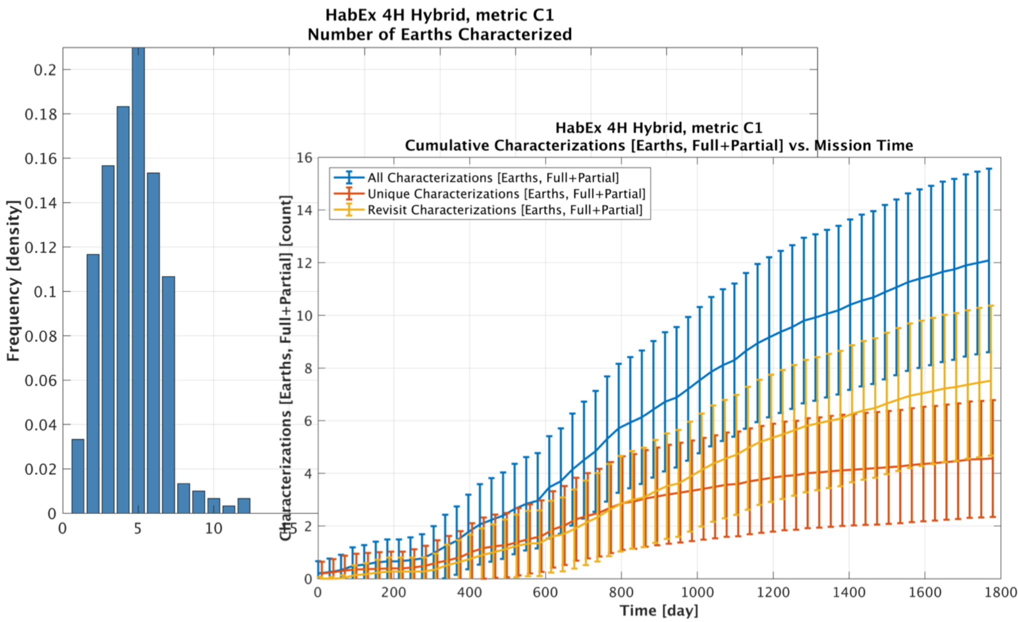






EXOSIMS

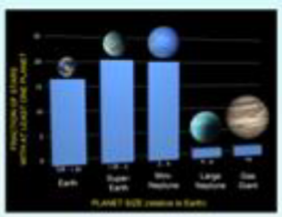




Calculating Yield with a DRM Code

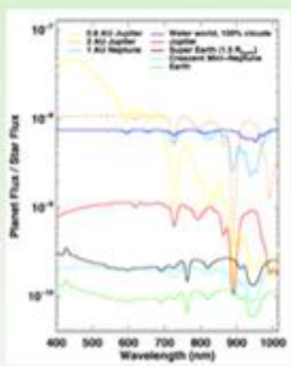
Astrophysical Constraints

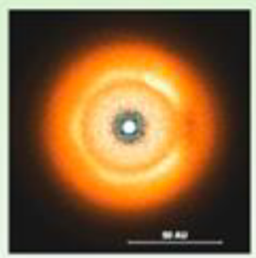
- η_{Earth}
- $\eta_{exozodi}$
- Planet sizes
- Albedos
- Phase functions



Observational Requirements

- Central wavelength
- Total bandpass
- Spectral resolution
- Signal-to-Noise
- Observing strategy





Technical Requirements

- Telescope diameter
- Contrast
- Contrast floor
- Inner working angle
- Outer working angle
- Total throughput
- Overheads

DRM

Credit: C. Stark

Physics Comparison of Count Rates

– LUVOIR B: 0.8 λ/D photometric aperture, 500 nm. 9 stars

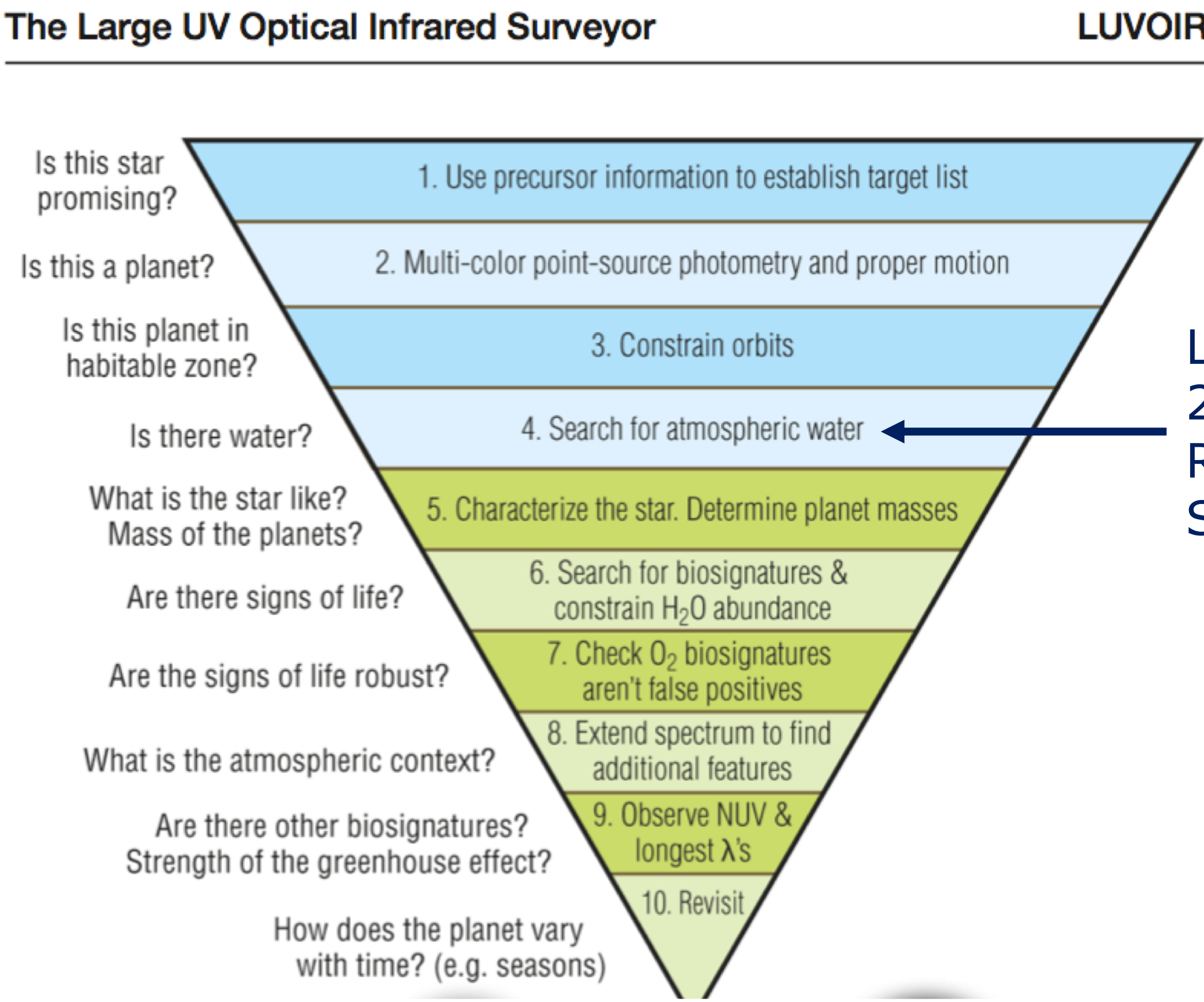
Average fractional difference in count rates:

Planet (s^-1)	Star leakage (s^-1)	zodi (s^-1)	exozodi (s^-1)	read noise (s^-1)	dark current (s^-1)	CIC noise (s^-1)	integration time (d)
0.09	-0.60	0.35	-0.59		1.00	-0.21	-0.56

- **Overall agreement is good**
- Sources of variation:
  - Star Leakage: EXOSIMS does not account for variable stellar diameter in the stellar leakage. A nominal 0.4 mas stellar diameter PSF was used.
  - Zodi: AYO assumes observation at minimum Zodi
  - Exozodi: EXOSIMS employs an empirical scaling model for exozodi based on observed local zodi variation and applies to planet inclination
  - CIC: AYO uses an optimized, variable frame time
  - Integration time: different integration time formulas are used

4 OBSERVING SCENARIOS

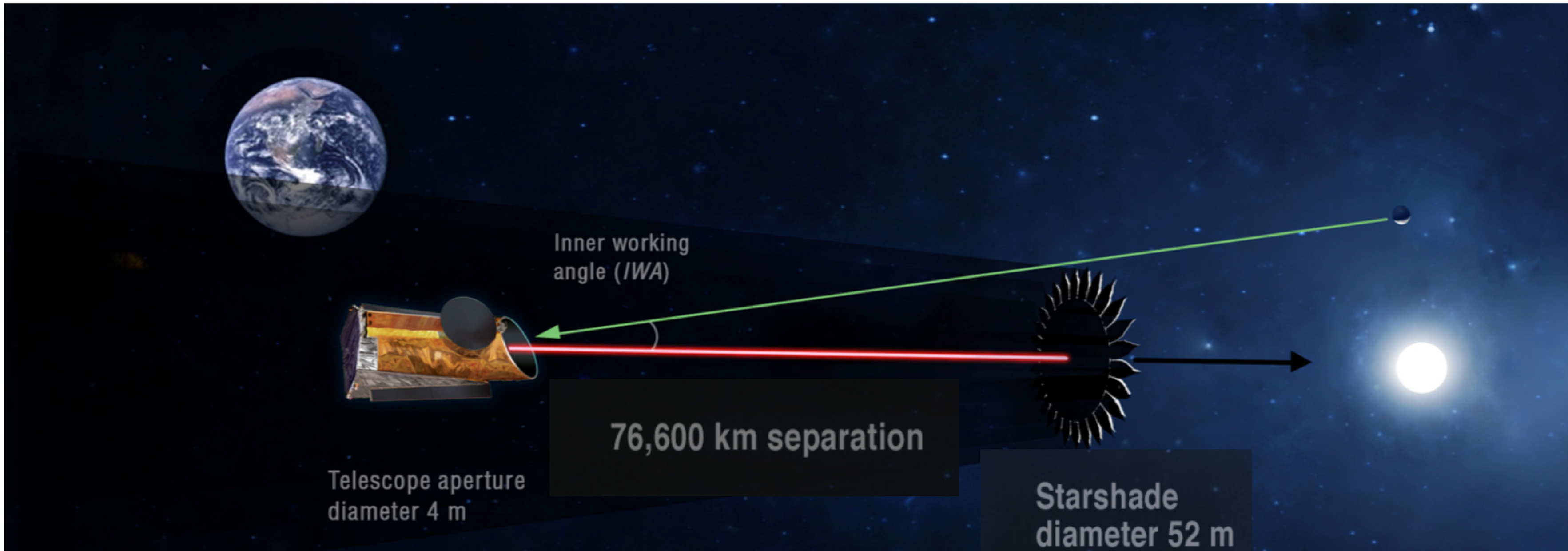
Scenario: LUVOIR B

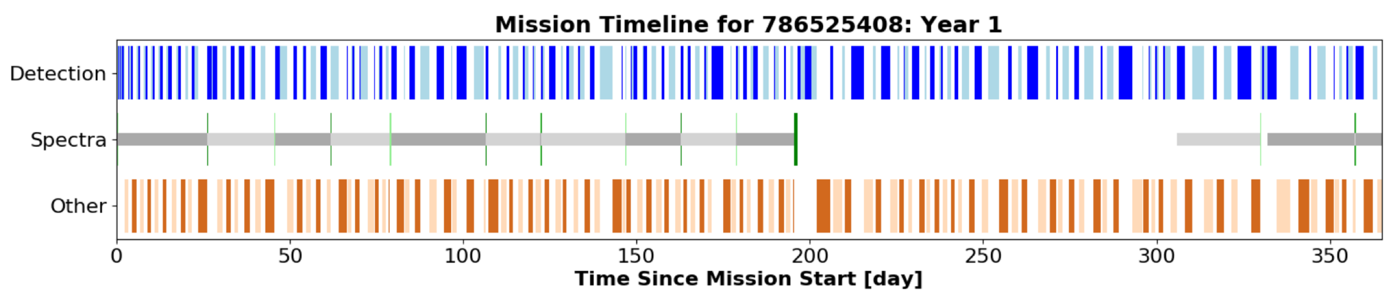


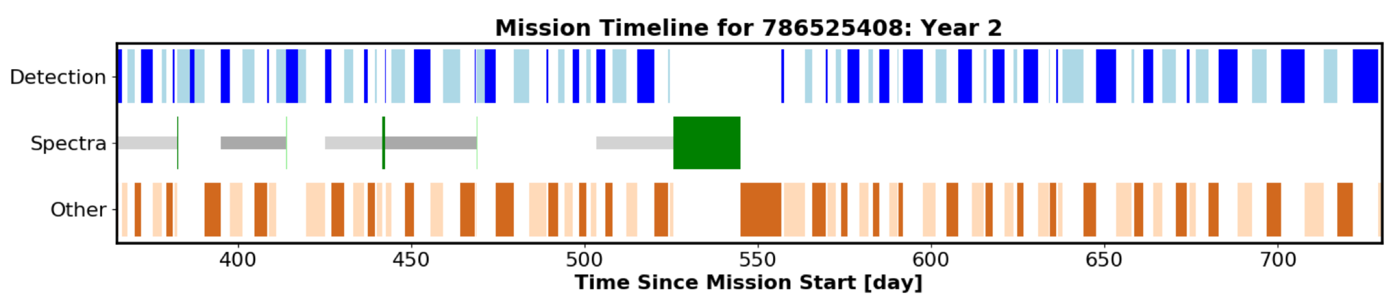
LUVOIR reported yield is 20% BW spectra
R=70
SNR =5

Credit: LUVOIR Final Report

Scenario: Habex 4H hybrid







Coro. Det,
SNR=7, 20% BW
Spectra, SNR=10:
450-1000 nm:
R=140
300-450 nm:
R=7

Four Observing Scenarios

Parameter	LUVOIR A & B	HabEx 4C	HabEx 4H hybrid	HabEx 4S
Starlight Suppression	Coronagraph	Coronagraph	Coronagraph + Starshade	Starshade
Blind Search and Orbit Determination	Coro.	Coro.	Coro.	Starshade
SNR	7	7	7	7
Bandwidth	20%	20%	20%	75%
Spectral Characterization	Coro.	Coro.	Starshade	Starshade
SNR	5	10	10	10
Bandwidth	20%	4 x 20%	100%	100%
Spectral Resolution	70	70	140*	70*

*R=7 in UV

Full spectra with HabEx coronagraph vs starshade

ExoPlanet Exploration Program

HabEx 4 m Starshade

450 – 1000 nm

R = 140, SNR = 10

Continuous spectra (metric C1)

int. time = 390 hrs

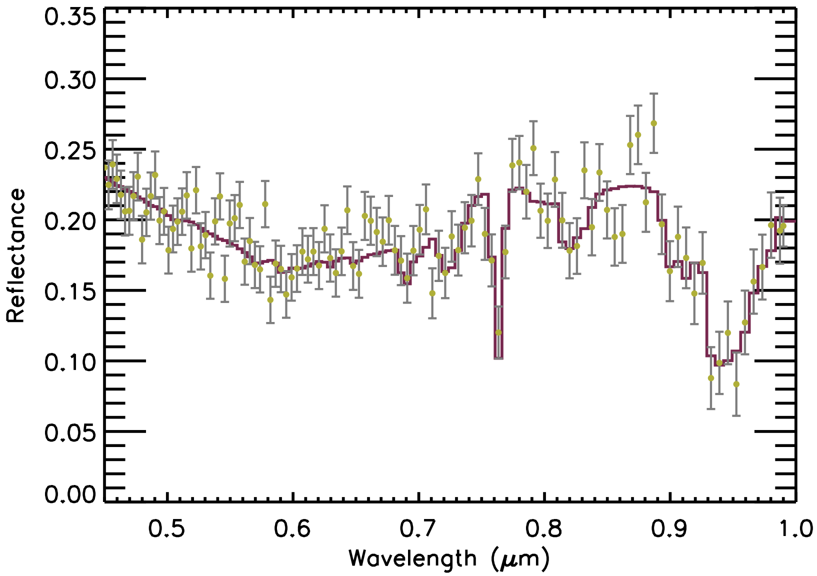
HabEx 4 m Coronagraph

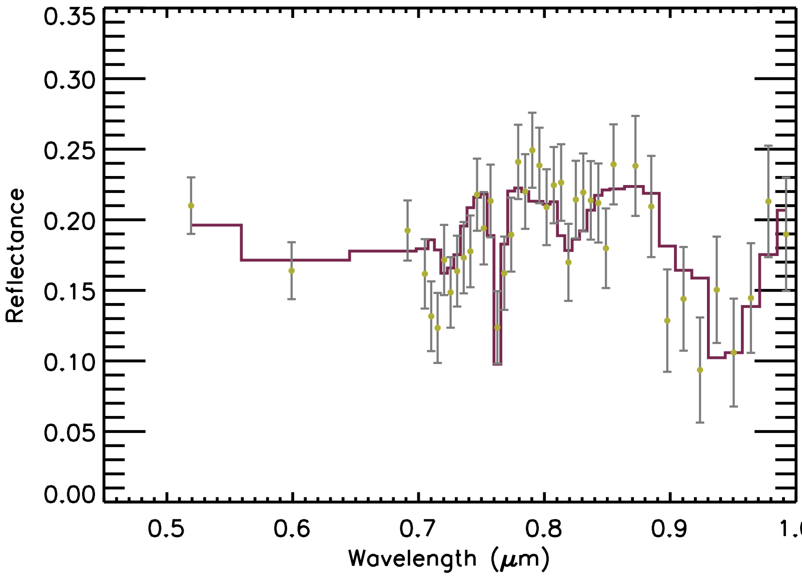
450 – 700 nm, R=7, SNR=8.5

700- 1000 nm, R = 140 , SNR=8.5

20% BW aggregated spectra D

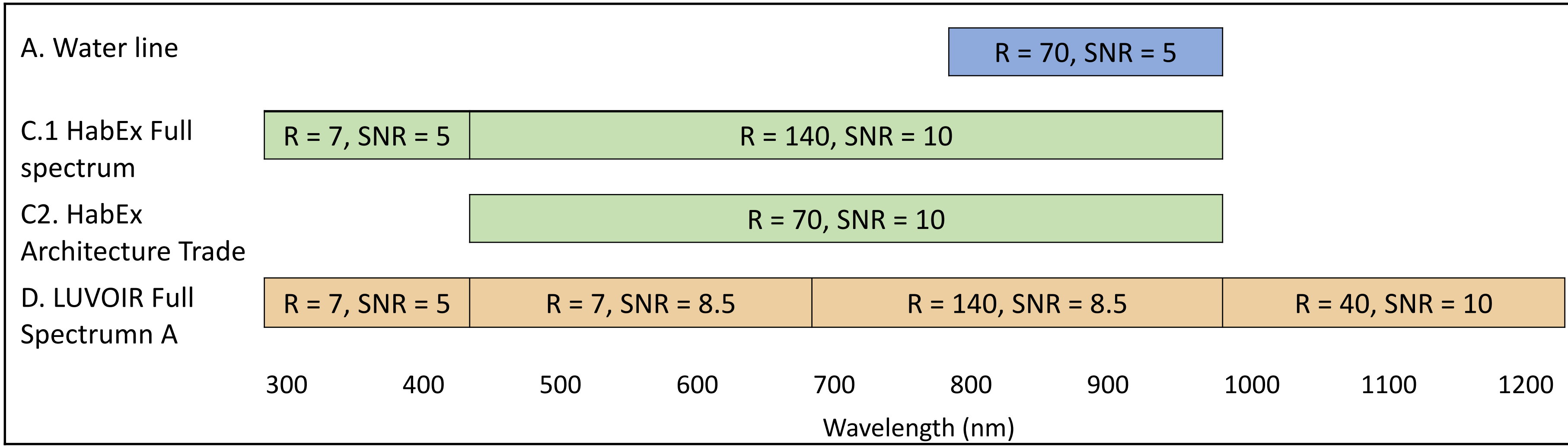
total int. time = 392 hrs



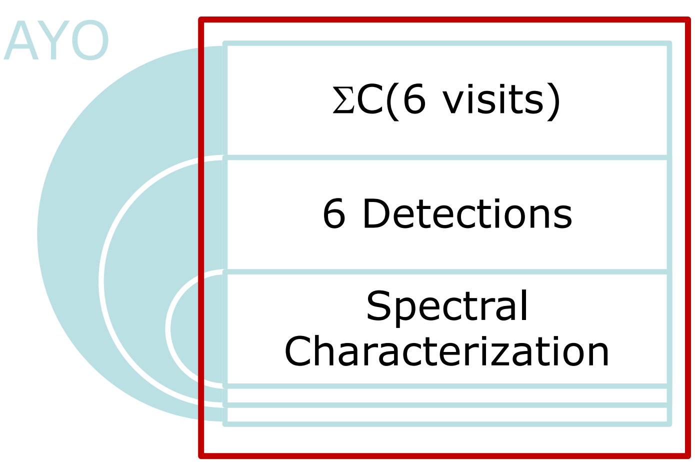


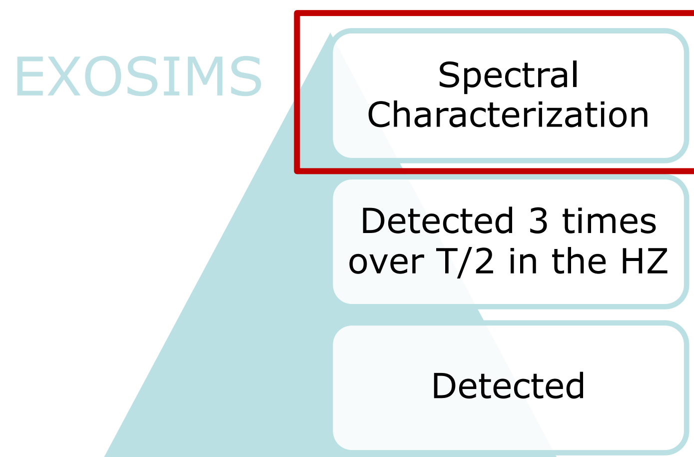
Credit: Ty Robinson

What is Yield?



- What is the science product? How is it calculated?





ASTROMETRIC INPUTS

SAG13 Occurrence Rates: Parametric fit for G-dwarfs

ExoPlanet Exploration Program

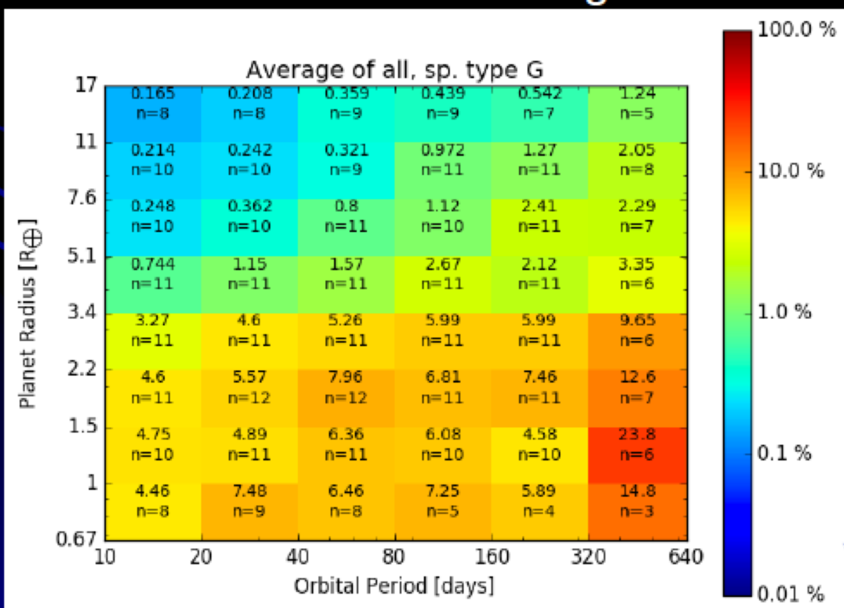
$$\frac{\partial^2 N(R,P)}{\partial \ln R \, \partial \ln P} = \Gamma_i R^{\alpha_i} P^{\beta_i} \quad \text{in region } R_{i-1} \le R < R_i$$

(R in Earth radius, P in years)

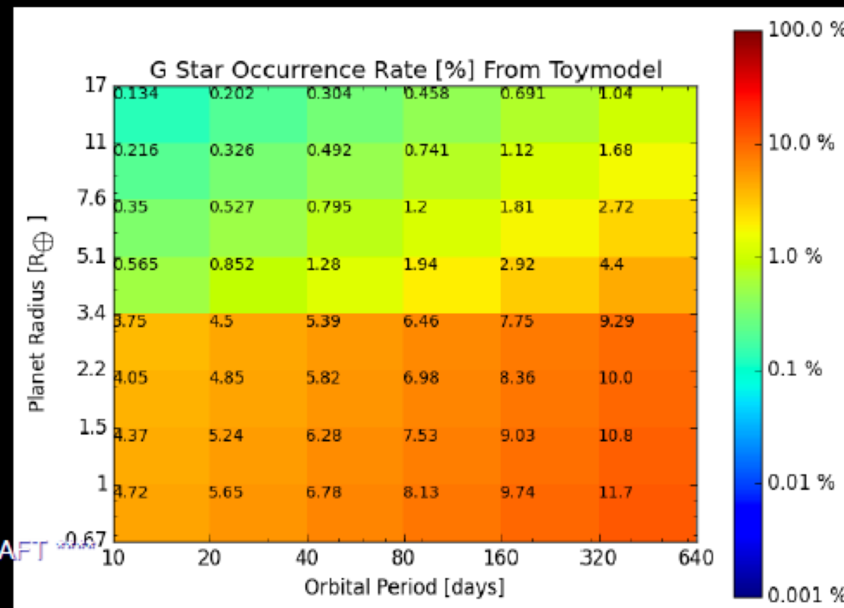
Γ_i	α_i	β_i	R_i
0.38	**-0.19**	**0.26**	**3.4**
0.73	-1.18	0.59	Inf

[to be updated with uncertainties]

Submission average



Parameteric fit (integrated across bins)

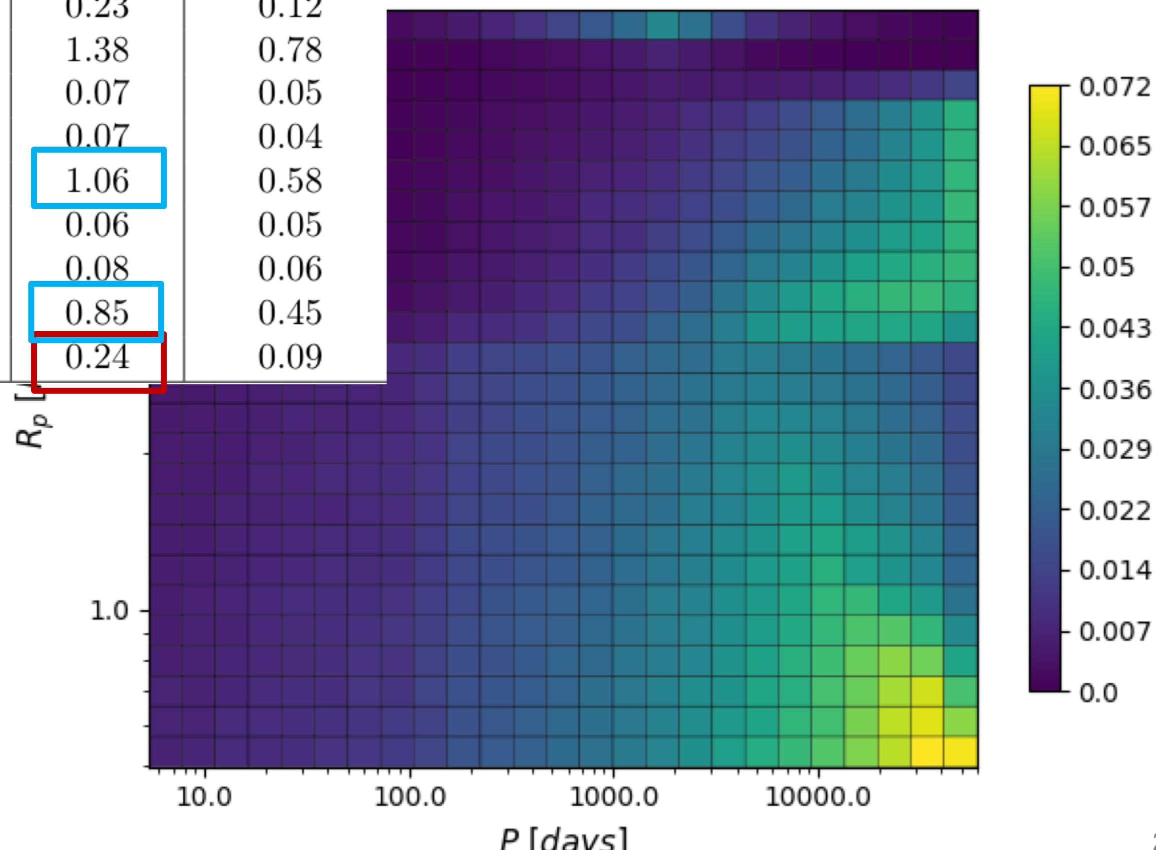


Dulz/Plavchan Occurrence Rates

ExoPlanet Exploration Program

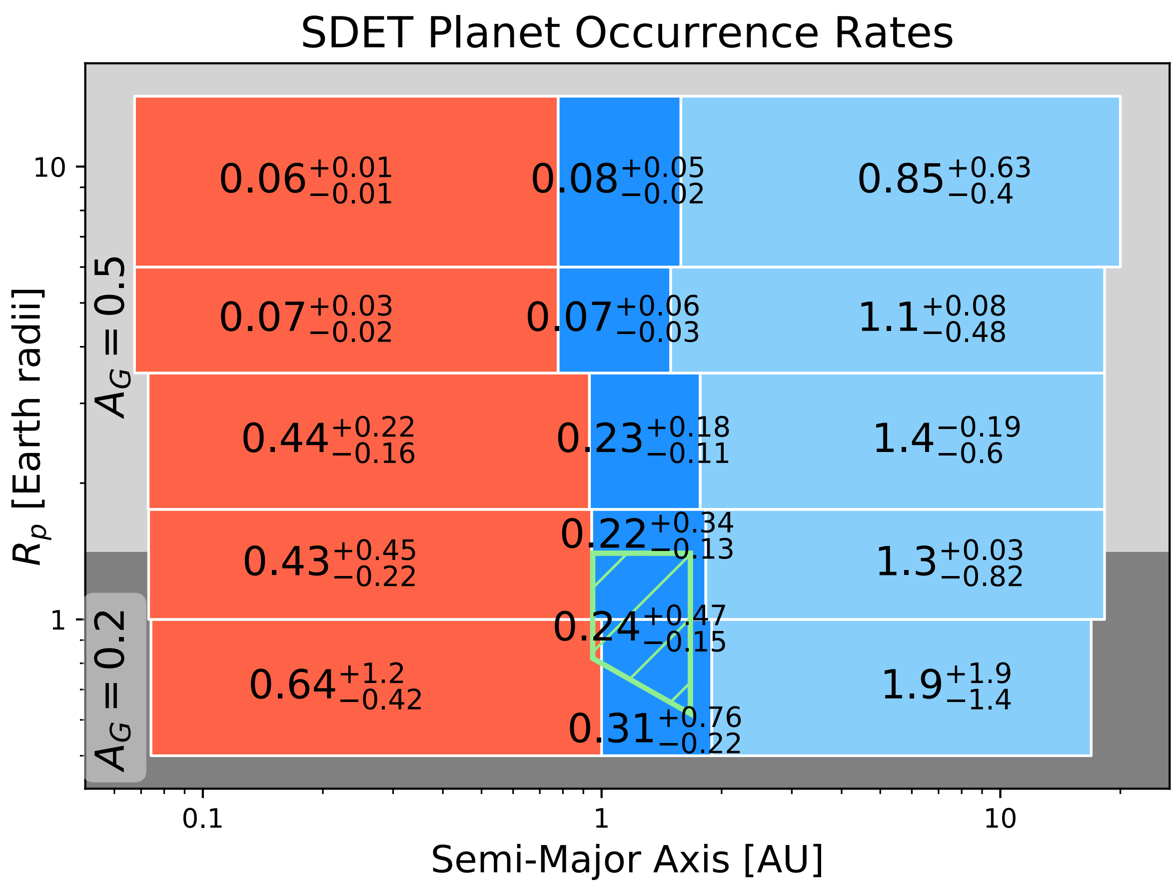
Planet Type	SAG13	Optimistic	Nominal	Pessimistic
Hot rocky	0.67	1.82	0.64	0.22
Warm rocky	0.30	1.07	0.31	0.09
Cold rocky	1.92	3.80	1.89	0.50
Hot super-Earths	0.47	0.88	0.43	0.21
Warm super-Earths	0.21	0.56	0.22	0.09
Cold super-Earths	1.42	1.36	1.33	0.51
Hot sub-Neptunes	0.48	0.66	0.44	0.28
Warm sub-Neptunes	0.22	0.41	0.23	0.12
Cold sub-Neptunes	1.63	1.19	1.38	0.78
Hot sub-Jovians	0.07	0.10	0.07	0.05
Warm sub-Jovians	0.07	0.13	0.07	0.04
Cold sub-Jovians	1.35	1.14	1.06	0.58
Hot Jovians	0.056	0.07	0.06	0.05
Warm Jovians	0.053	0.13	0.08	0.06
Cold Jovians	1.01	1.48	0.85	0.45
Earth	0.24*	0.71	0.24	0.09

- Fernandes et al. 2019 for large radius
- Hill stability criteria for large periods



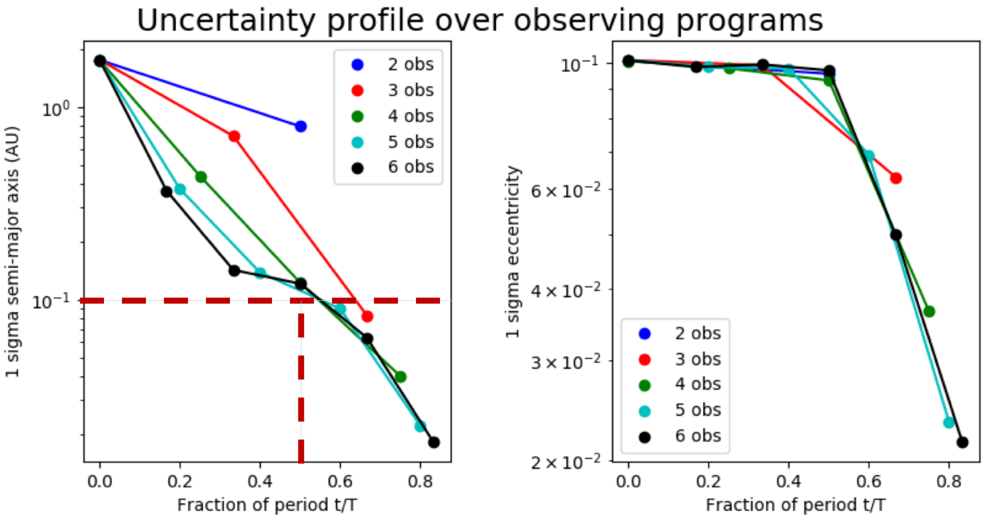
Planet bins

Dulz et al. occurrence rates with Kopporapu et al. bins

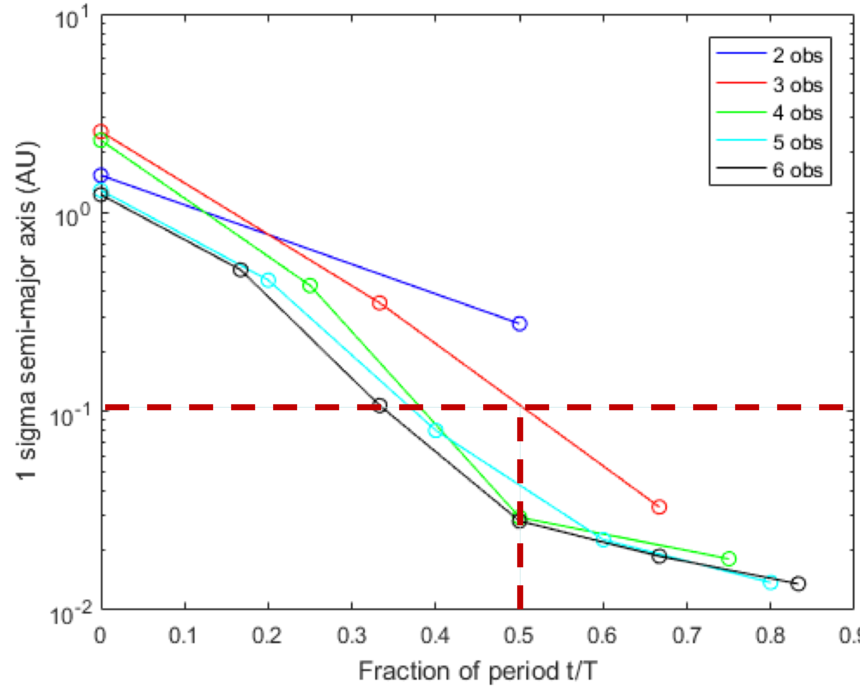


Orbit determination: Is it in the Habitable Zone?

ExoPlanet Exploration Program



Credit: A. Horning



Credit: E. Nielsen

- Assumed 5 mas astrometric uncertainty
- Heuristic:
  - 3 detections spanning half a period, generally
  - 4 detections required for higher inclination orbits

Stray Light from Binary Stars

Star Catalog

- EXOSIMS uses EXOCAT-1
  - https://exoplanetarchive.ipac.caltech.edu
- AYO uses union of the Hipparcos New Reduction catalog and the Gaia TGAS catalog
- Stark showed variation in catalog resulted in ~4% variation in yield, largely because Hipparcos is the backbone of both catalogs

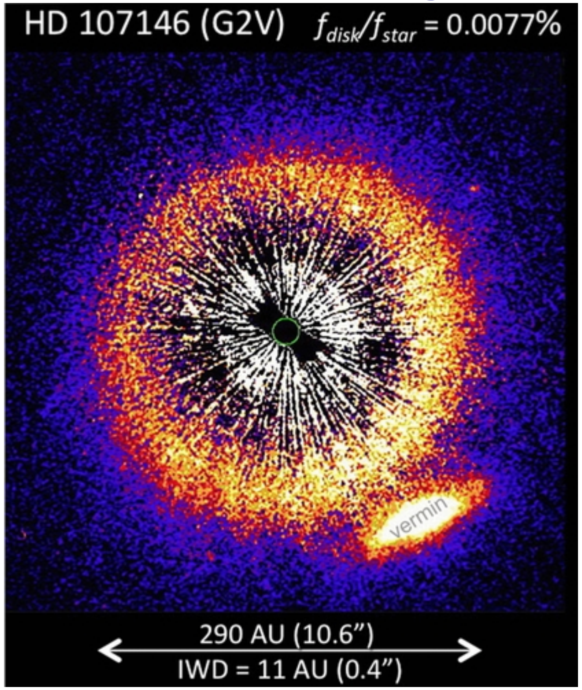
Stray Light from Binary Stars

- Scatter from binary companions can exceed the suppressed starlight
- We included stray light from the companion star using $\lambda/20$ nm RMS surface roughness and $f^{-2.5}$ model (based on WFIRST primary mirror)
  - Maggie Turnbull provided an addendum to EXOCAT-1 catalog with the WDS information for the brightest and closest binary companions

Zodiacal Light

Table from Leinert et al. 1998 based on color and pointing

Exozodiacal Light



Schneider et al. 2014

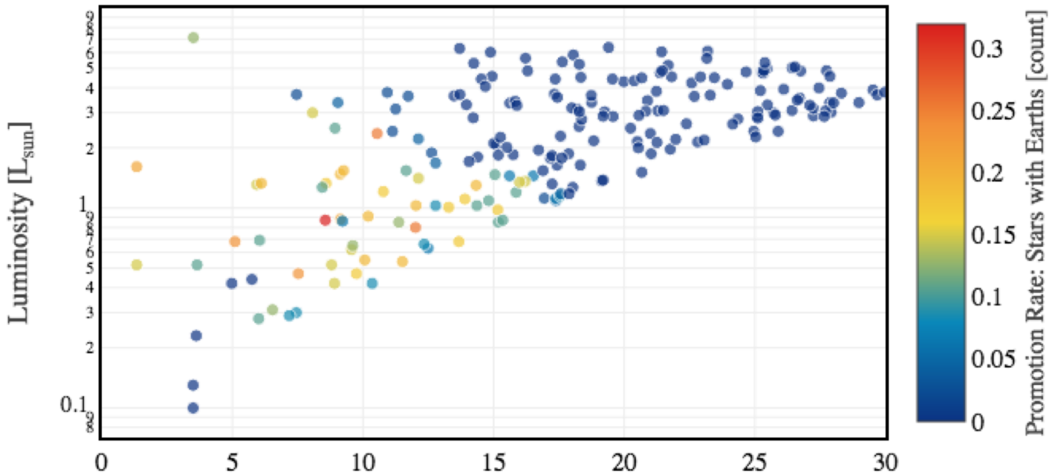
Smoothly varying $1/r^2$ optical depth of number of zodis from the LBTI HOSTS survey results

- EXOSIMS uses Lindler 2008 model for inclination, color

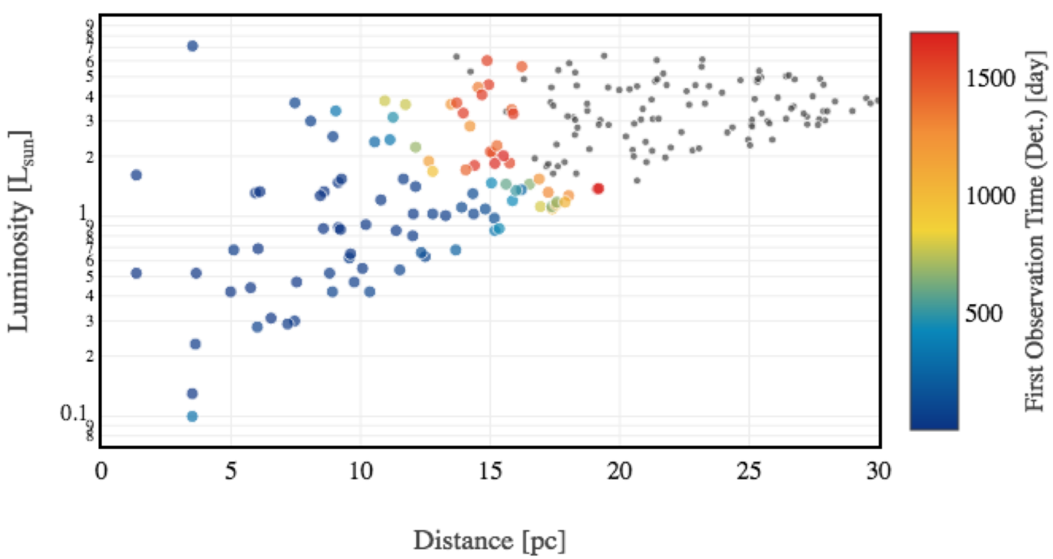
RESULTS

HabEx 4H: Coronagraph blind search

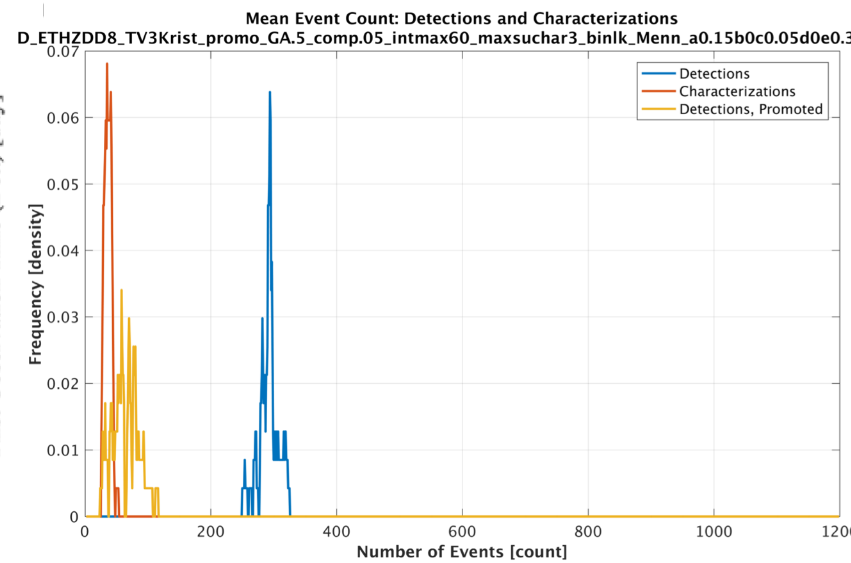
Promotion Rate



First Observation Time



- Stars are ranked C/t and observed in order
- Revisit after T/3 elapsed
- Promote for Characterization:
  - 3 detections spanning > T/2
  - In habitable zone
  - Radius is EEC



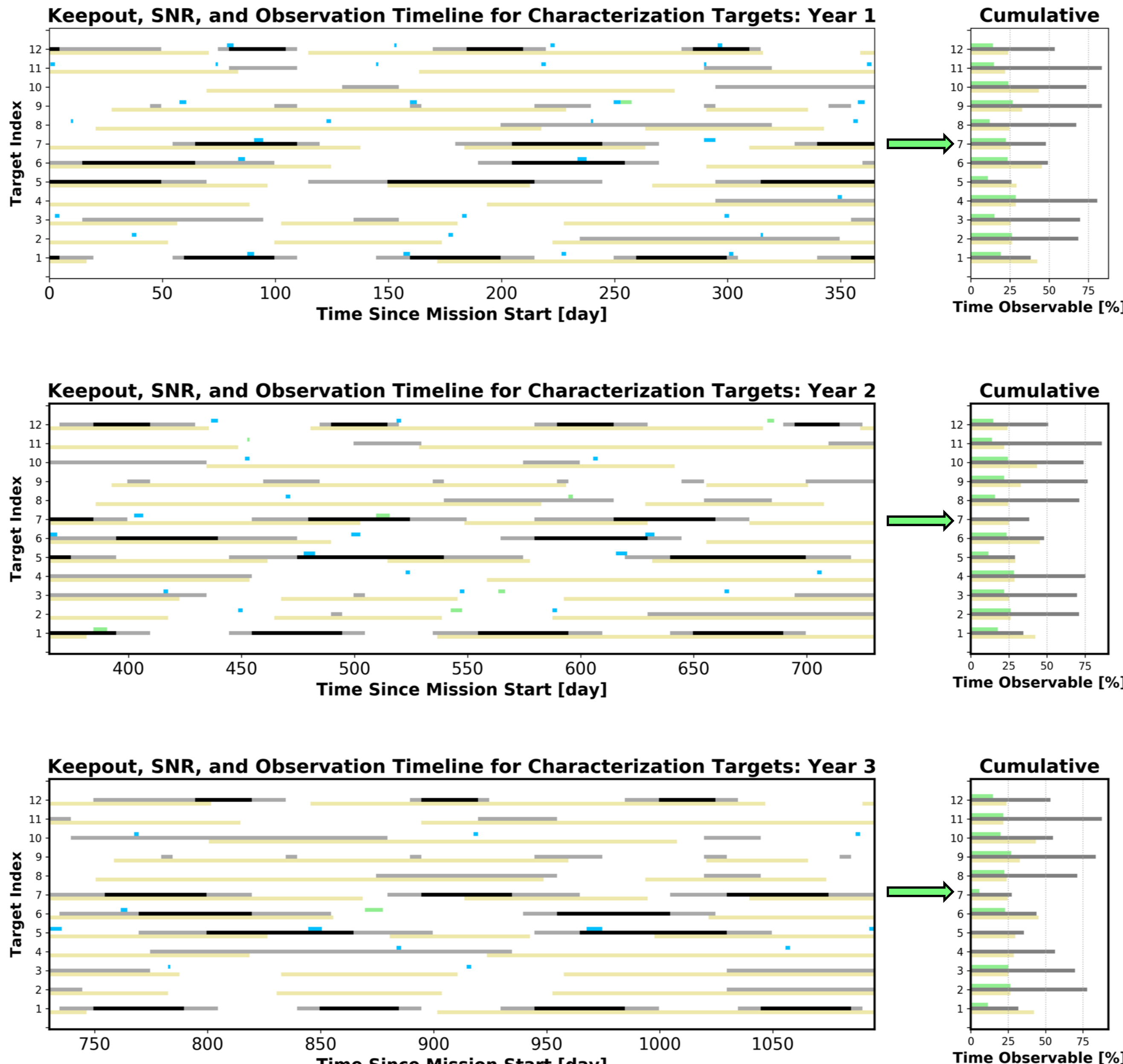
Starshade Uncoordinated Scheduling

Timeline: Observational Constraints
Keepout, SNR, and Observations for Characterization Targets
Characterizations: Green; Detections: Blue
Solar Keepout: Gold; Bad WA: Black; Low SNR: Grays

Key
- Keepout + SNR
- SNR
- Keepout

ExEP

Planet Exploration Program



Green is intersection of good SNR and keepout

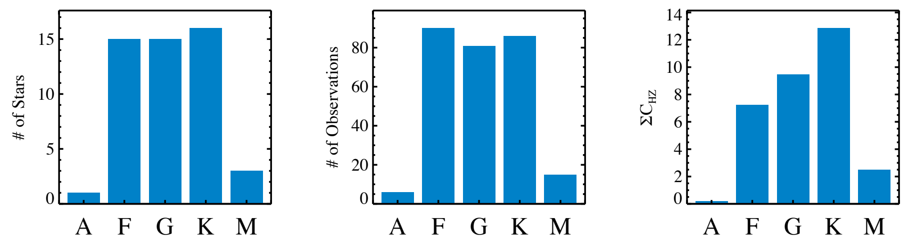
Target List

N_{stars} = 50 | $N_{observations}$ = 278
d_{max} = 15.1 pc | θ_{max} = 5.5 mas

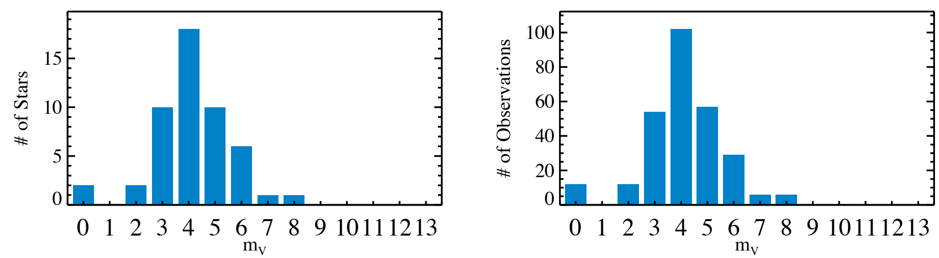
HabEx 4H Hybrid Yield

ExoPlanet Exploration Program

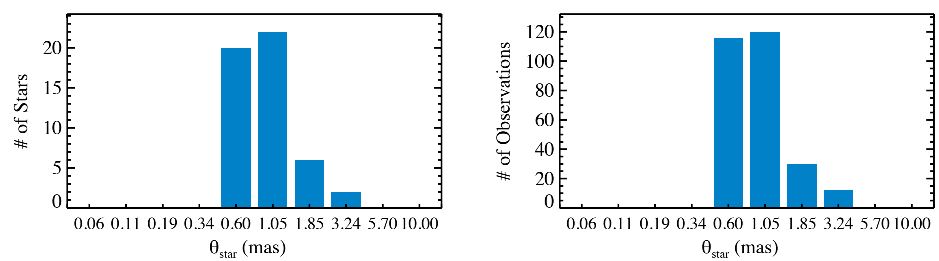
Spectral Type



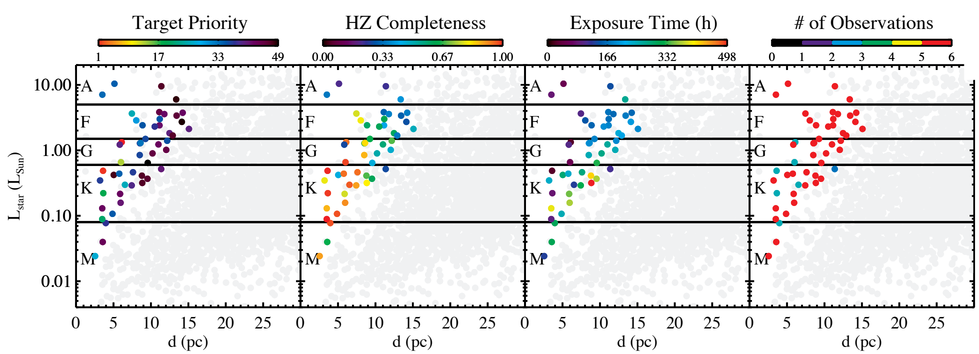
Apparent magnitude



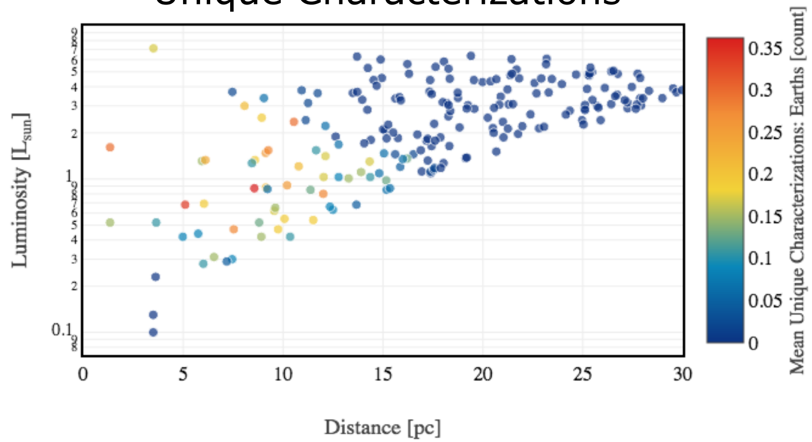
Stellar Diameter



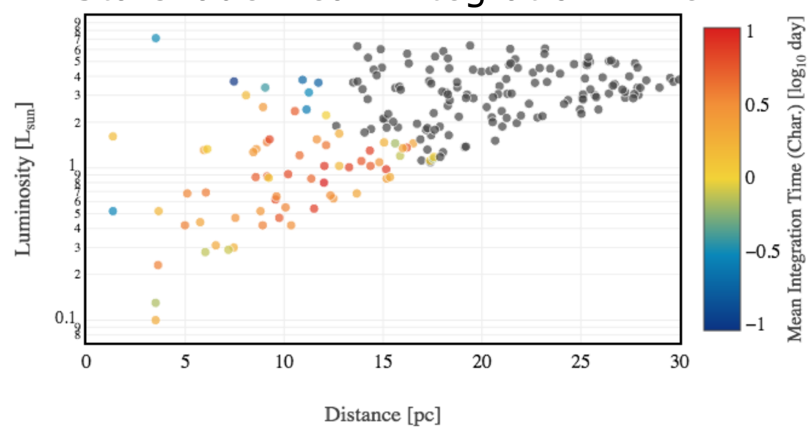
Luminosity–Distance Plots



Unique Characterizations



Starshade Mean Integration Time



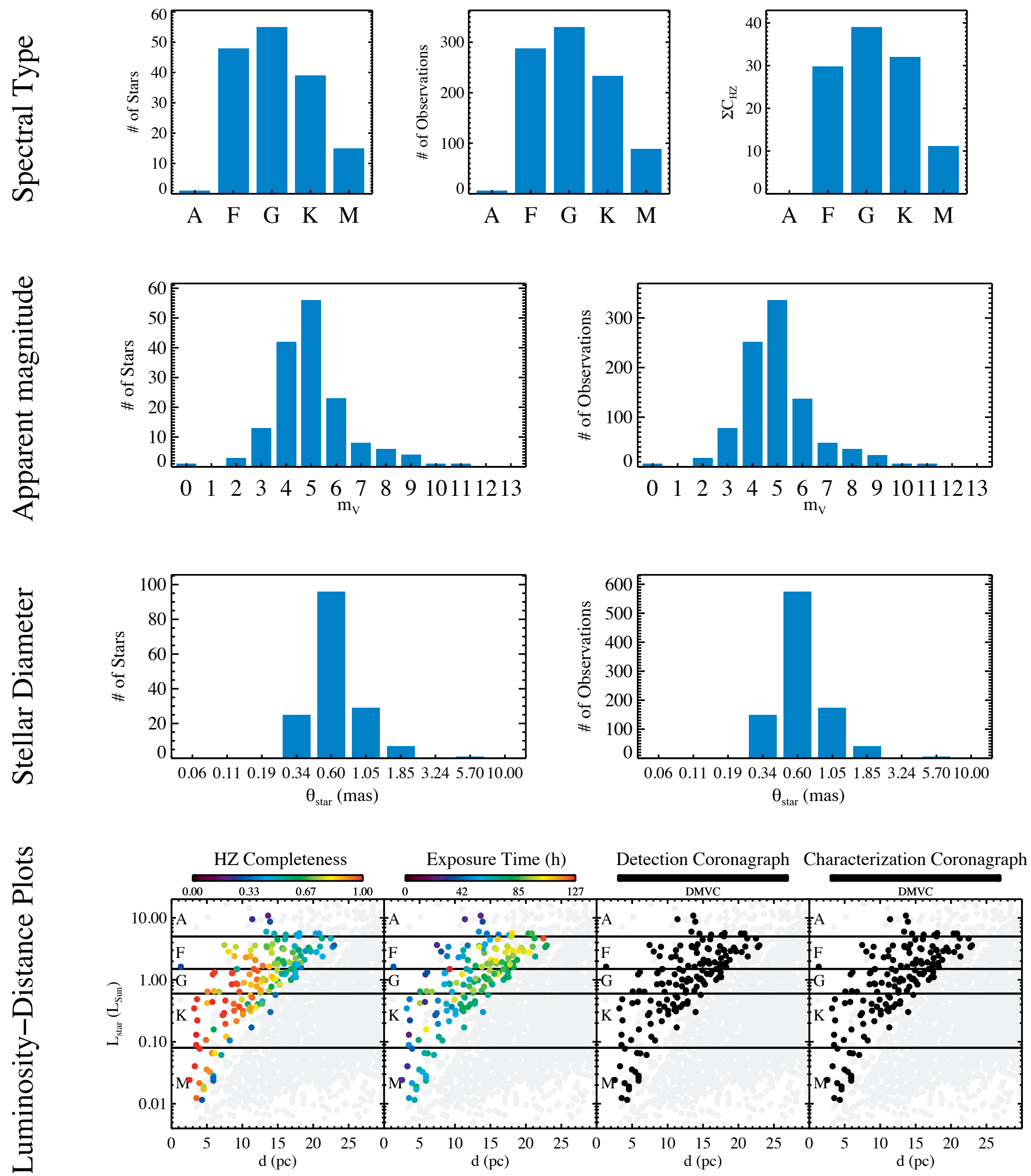
HabEx 4H Hybrid	
AYO	EXOSIMS
8	7

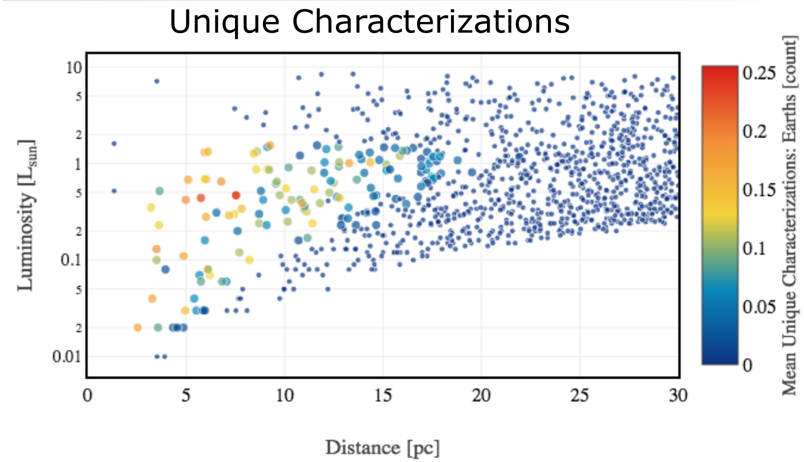
Target List

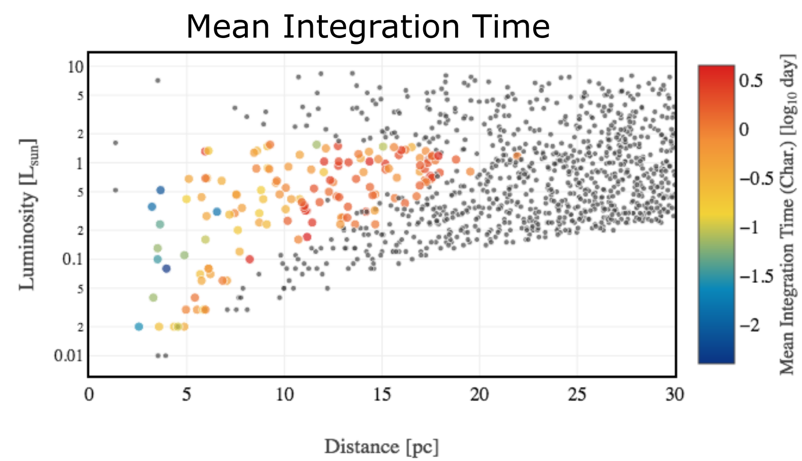
N_{stars} = 158, $N_{observations}$ = 946
Max Distance = 22.9 pc, Max Stellar Diameter = 9.3 mas

LUVOIR B yield

ExoPlanet Exploration Program





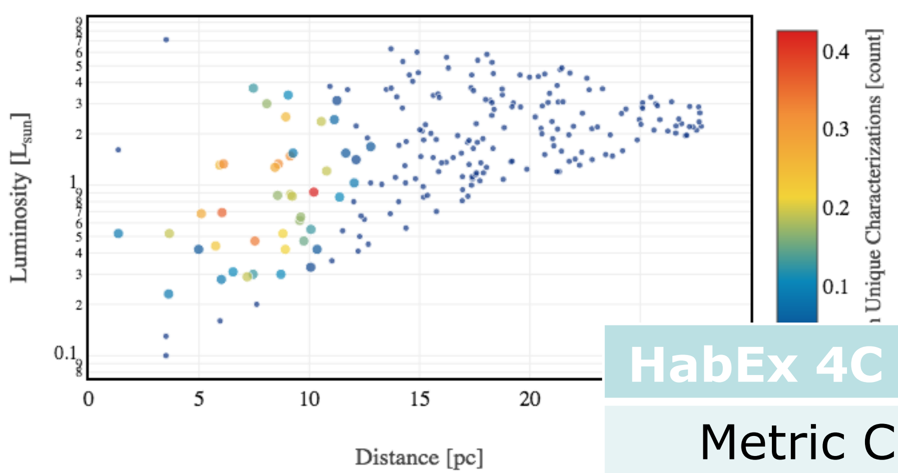


LUVOIR B, metric A	
AYO	EXOSIMS
28	18

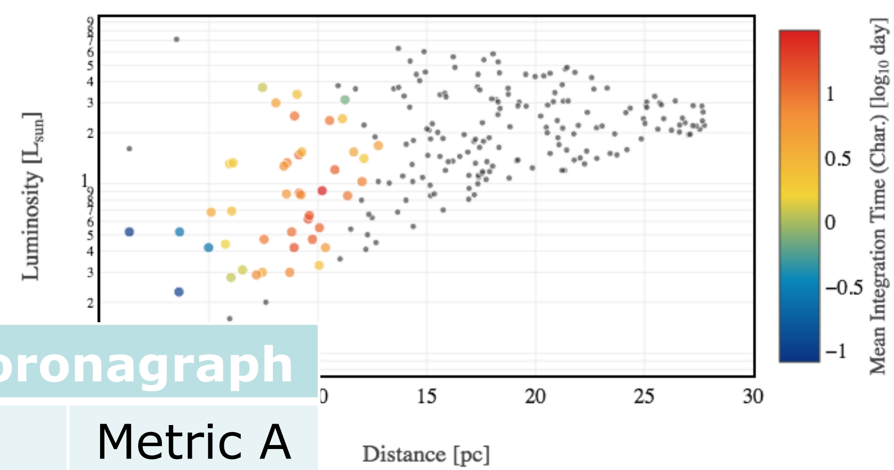
HabEx 4C: Coronagraph only
metric C2

ExoPlanet Exploration Program

Unique Characterizations

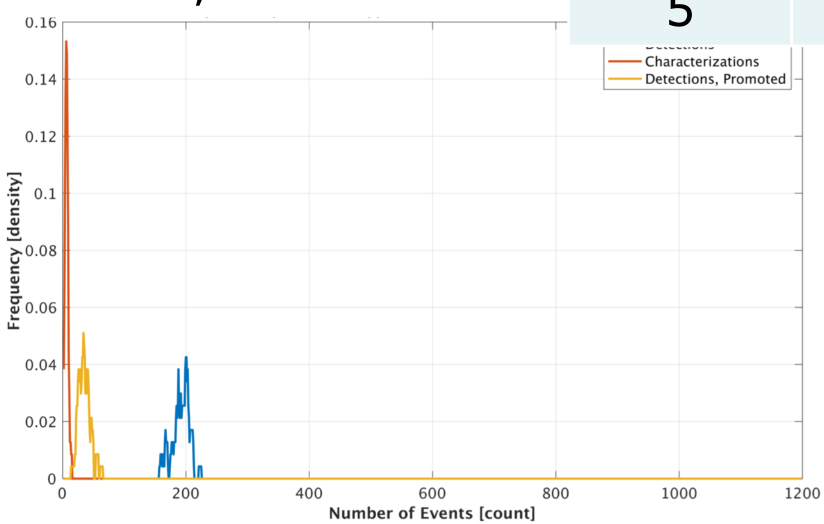


Mean Integration Time

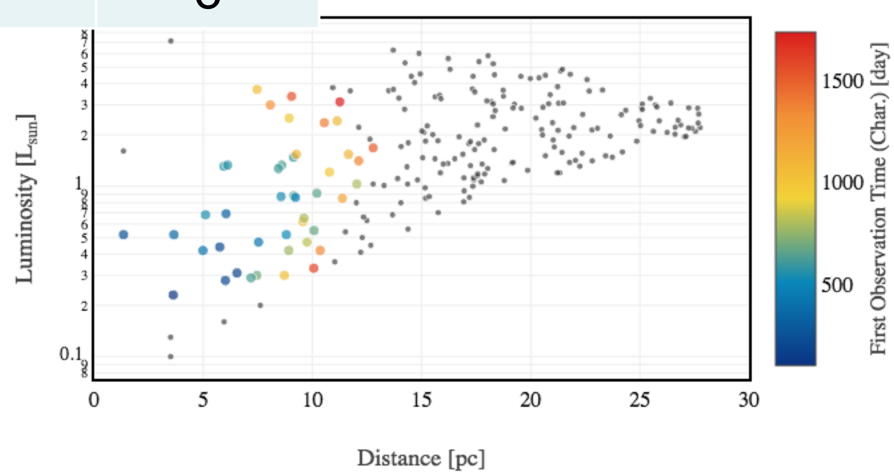


HabEx 4C Coronagraph		
Metric C2		Metric A
AYO	EXOSIMS	
5	3	6

Detection, Characterizati

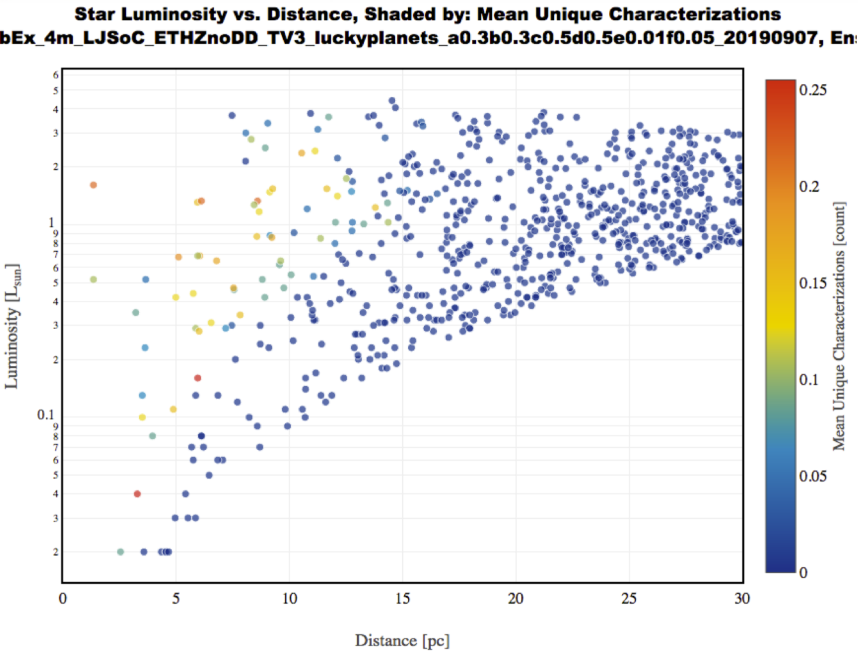


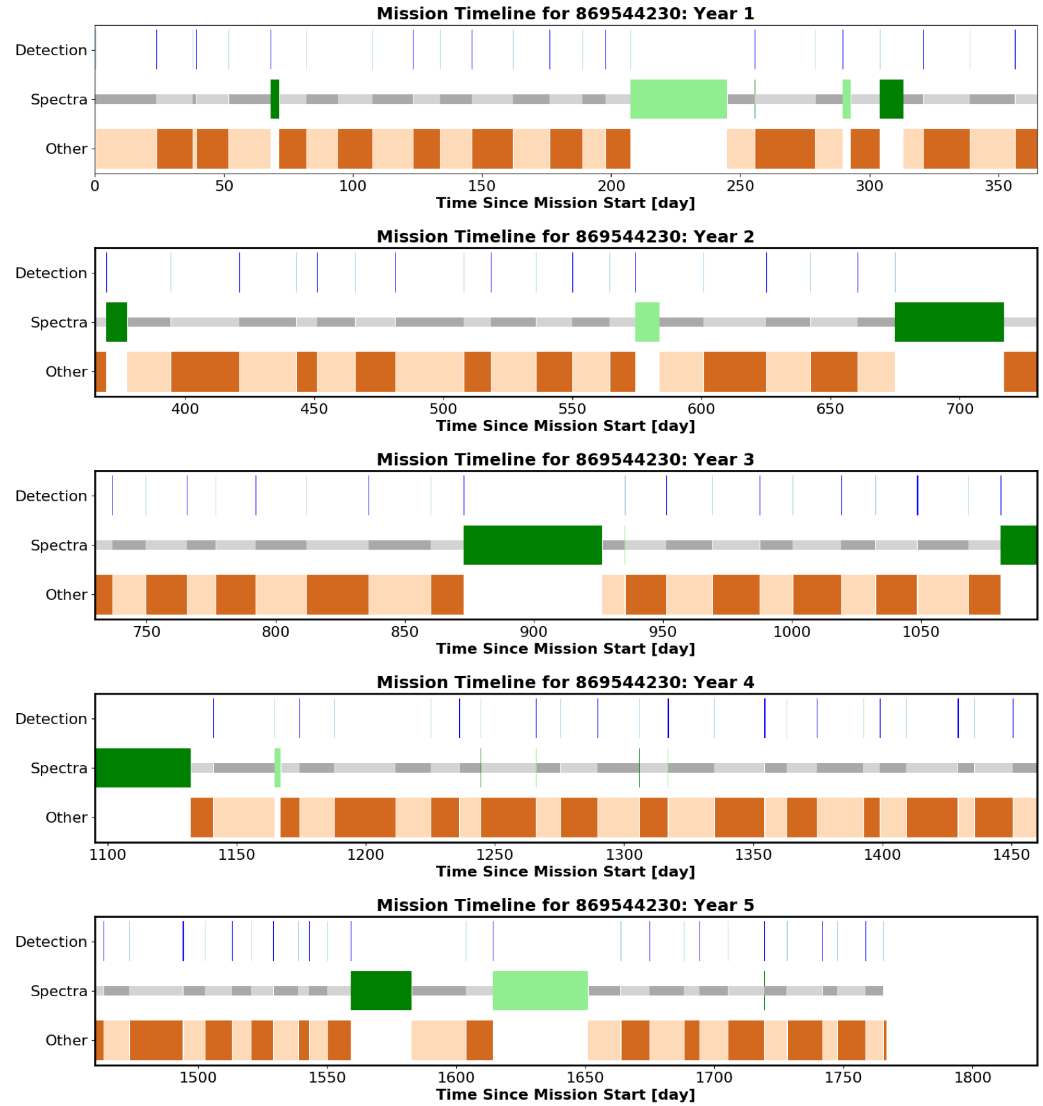
r Observation Time



HabEx 4S: Starshade only

ExoPlanet Exploration Program





HabEx 4S Starshade		
AYO	EXOSIMS	
	Char	orbit
5	3	2

Detection: 33 days = 1.8%
Spectra: 283 days = 15.5%
Slew: 1473 days = 80.6%
Other: 1456 days = 79.7%

Results Summary

ExoPlanet Exploration Program

	H_20 Line: metric A			Broad (metric C1)			Broad (metric C2)		
Scenario	**AYO**	**EXO SIMS**	**Omni**	**AYO**	**EXOS IMS**	**Omni**	**AYO**	**EXOSIMS**	**Omni**
HabEx 4H	-	9	29	**8**	**5**	**9**	**8**	**7**	**17**
LUVOIR A	**54***	-	50	-	-	-	-	-	-
LUVOIR B	**28***	**18**	28	-	4	6	-	7	10
HabEx 4C	-	**6**	12	-	2	3	**5**	**3**	5
HabEx 4S	-	3	18	-	3	9	**5**	**3**	13

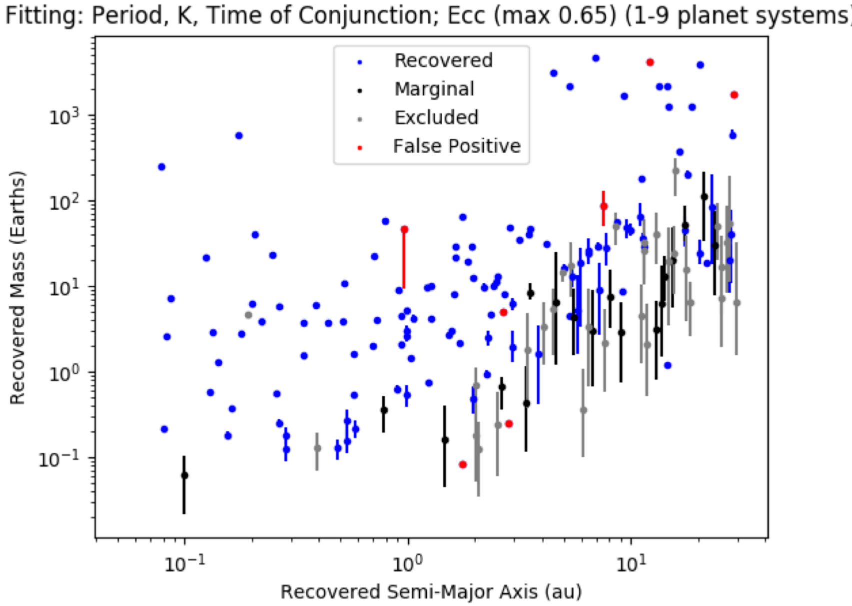
*AYO evaluated LUVOIR A & B for 40% of a 5 year mission. AYO yield is cumulative completeness.

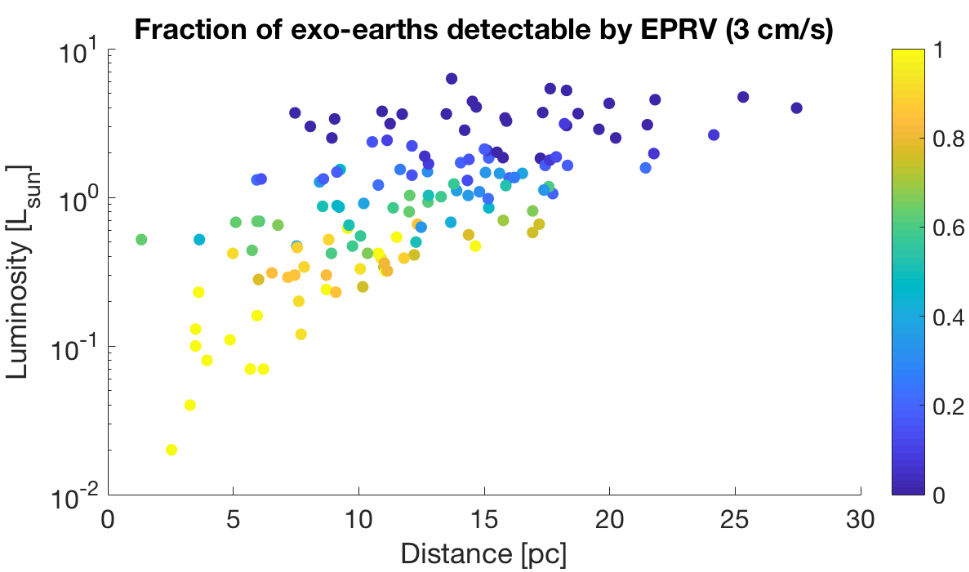
- Full spectra is costly.
  - Coronagraph search for water line is an efficient filter step
  - Starshade spectra has one cost for the full spectrum
- Blind search is costly
  - Front loading exoplanet mission portion may increase yield
- Starshade blind search is not as inefficient as one might expect, though orbit determination is a challenge
- HabEx is target starved and can return a fair number of EECs

Impact of EPRV Precursor

ExoPlanet Exploration Program

Sensitivity to simulated RV recovered planets





- Plavchan et al. modeled a ground-based Super-NEID
  - 3 cm/s RV machine
  - on a 10-m class telescope
  - surveying ~53 HabEx targets
  - 5 year, 25% time survey
- Heuristic sensitivity added to EXOSIMS
  - Monte Carlo universes of synthetic planets showed which were detectable by EPRV
- EPRV can find 30%-50% of present earths.
- ~50 earths *.24 *.5 = 6

Conclusions

- *A yield prediction for a flagship mission of this complexity needs more formality and more resources*
- Through a collaborative community based activity, we arrived at a widely accepted set of inputs for yield calculations and produced an Open Source code available for all studies
- The comparison of different yield methods shows very similar results for the same input assumptions.
  - Uncertainties in yield are dominated by uncertainty in knowledge of astrophysics inputs
- The knowledge gained through this activity has identified the areas to be addressed in the field of yield modeling to make these tools/processes as effective as possible for the future studies emerging from Astro 2020

BACKUP

Astrophysics Input Summary

Parameter	AYO	EXOSIMS	Description
$\eta_\oplus$	0.24	SAG13 power law	Fraction of sunlike stars with an exo-Earth candidate
R_p	$[0.6,\ 1.4] R_\oplus$		Exo-earth candidate planet radius[a]
a	$[0.95,\ 1.67]$AU		Semi-major axis for solar twin
e	0		Eccentricity (circular orbits)
$\cos i$	$[-1, 1]$		Cosine of inclination (uniform distribution)
ω	$[0, 2\pi]$		Argument of pericenter (uniform distribution)
M	$[0, 2\pi]$		Mean anomaly (uniform distribution)
Φ	Lambertian		Phase function
A_G	0.2		Geometric albedo of rocky planets
A_G	0.5		Geometric albedo of gas planets
z_c	23 mag asec^{-2}	Lindler model[b]	Average V band surface brightness of zodiacal light for coronagraph observations
z_s	22 mag asec^{-2}	Lindler model[b]	Average V band surface brightness of zodiacal light for starshade observations
x	22 mag asec^{-2}		V band surface brightness of 1 zodi of exozodiacal dust[c]
n	LBTI best fit distribution		Number of zodis for all stars

[a] Actual lower bound is $R_p > 0.8/\sqrt{a}$

[b] Lindler zodiacal light model as a function of ecliptic latitude and longitude at observation time

[c] Local zodi based on ecliptic pointing of telescope. On average, starshade observes into brighter zodiacal light.

[d] For solar twin. Varies with spectral type, as zodi definition fixes optical depth.

Instrument Parameters

ExoPlanet Exploration Program

Parameter	LUVOIR B	HabEx
Primary Diameter (m)	8.0	4.0
Obscuration Factor	0.14	0
Integration Time Limit	60 days	60 days
	Coronagraph Performance	
Raw contrast floor[a]	1×10^{-10}	1×10^{-10}
Raw contrast stability[b]	1×10^{-11}	2×10^{-11}
Post-processing Factor	0.25	0.29
Systematic noise floor	26.5 Δmag	26.5 Δmag
Core throughput[b]	0.46	0.5
Photometric Aperture	0.8 λ/D	0.7 λ/D
Inner Working Angle, $IWA_{0.5}$	3.9 λ/D	2.4 λ/D
Inner Working Angle, $IWA_{0.1}$	1.5 λ/D	1.5 λ/D
Outer Working Angle	60 λ/D	26 λ/D
Bandwidth ($\Delta\lambda$)	20%	20%
	Imaging Channel 1[†]	
Non-coronagraph Throughput	0.17	0.28
Bandwidth	20%	20%
	Imaging Channel 2[*]	
Non-coronagraph Throughput	0.39	0.42
Bandwidth	20%	20%
	Spectral Channel	
Non-coronagraph Throughput	0.39	0.42
Bandwidth	20%	20%
$\Delta\lambda/\lambda$	140	140
λ	500 nm	500 nm

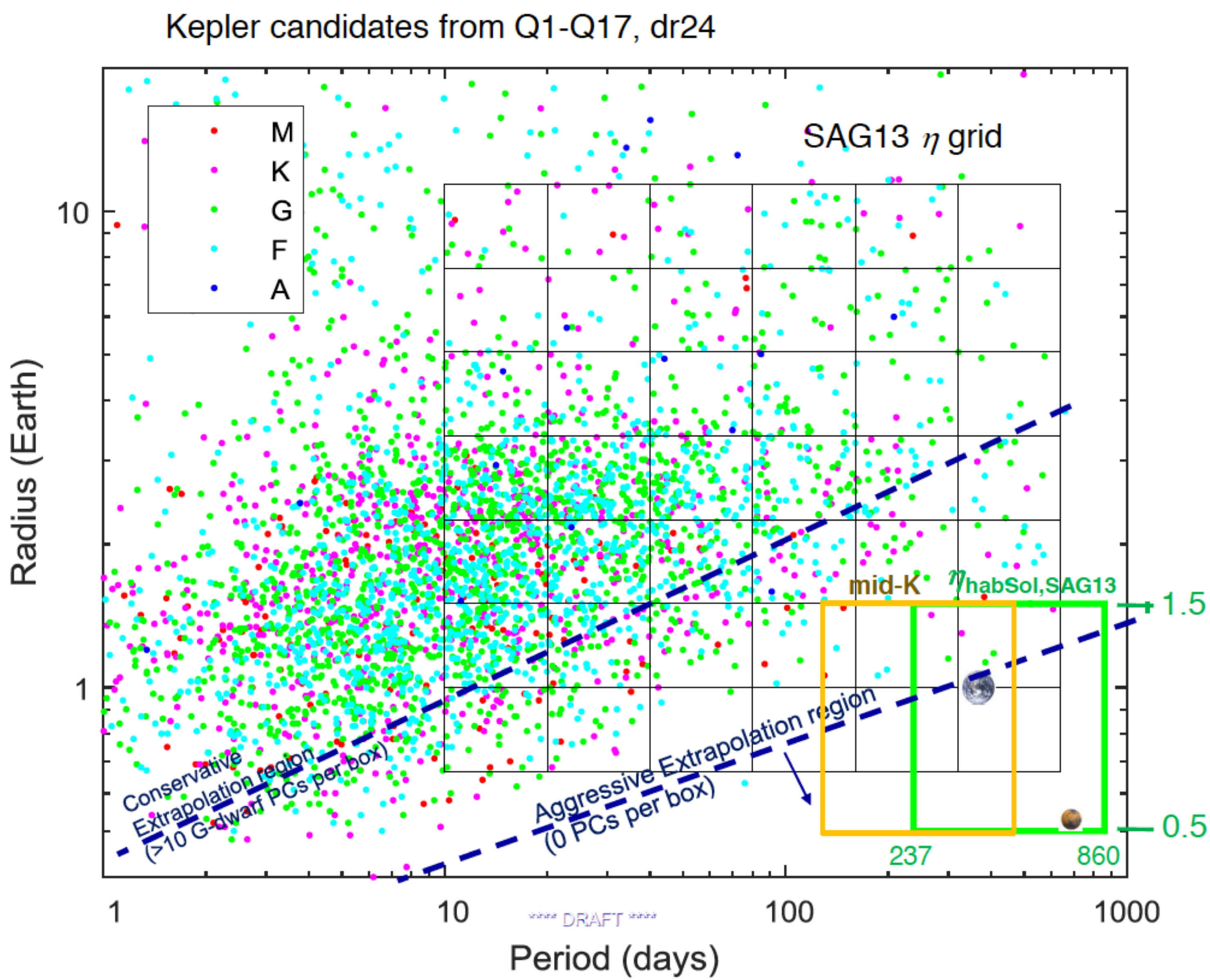
Instrument Parameters (cont.)

	Detectors	
Quantum Efficiency	0.9	0.9
Photon Counting Efficiency	0.75	0.75
Dark Current (e/s)	3×10^{-5}	3×10^{-5}
Read Noise (e/pix)	0	0
Clock-Induced Charge (e/s)	1.3×10^{-5}	1.3×10^{-5}
	Starshade	
Starshade Thrust (mN)	-	1040
Starshade Slew I_{sp} (s)	-	3000
Starshade Stationkeeping I_{sp} (s)	-	308
Starshade Wet Mass (kg)	-	11180
Starshade Dry Mass (kg)	-	4550
Starshade Separation (km)	-	76600

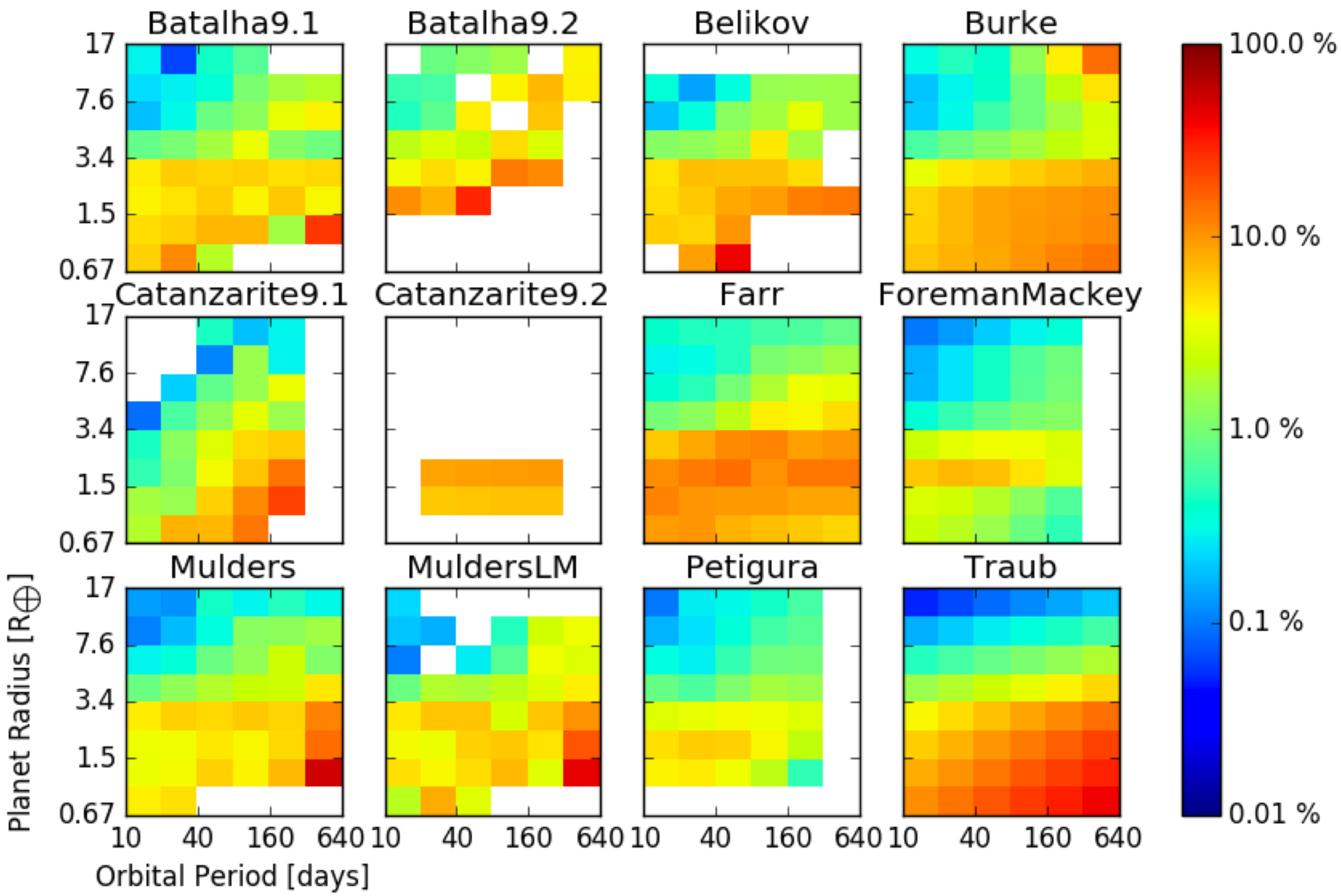
WFIRST EMCCD

SAG 13 Occurrence rates from Kepler

https://exoplanets.nasa.gov/exep/exopag/sag/#sag13

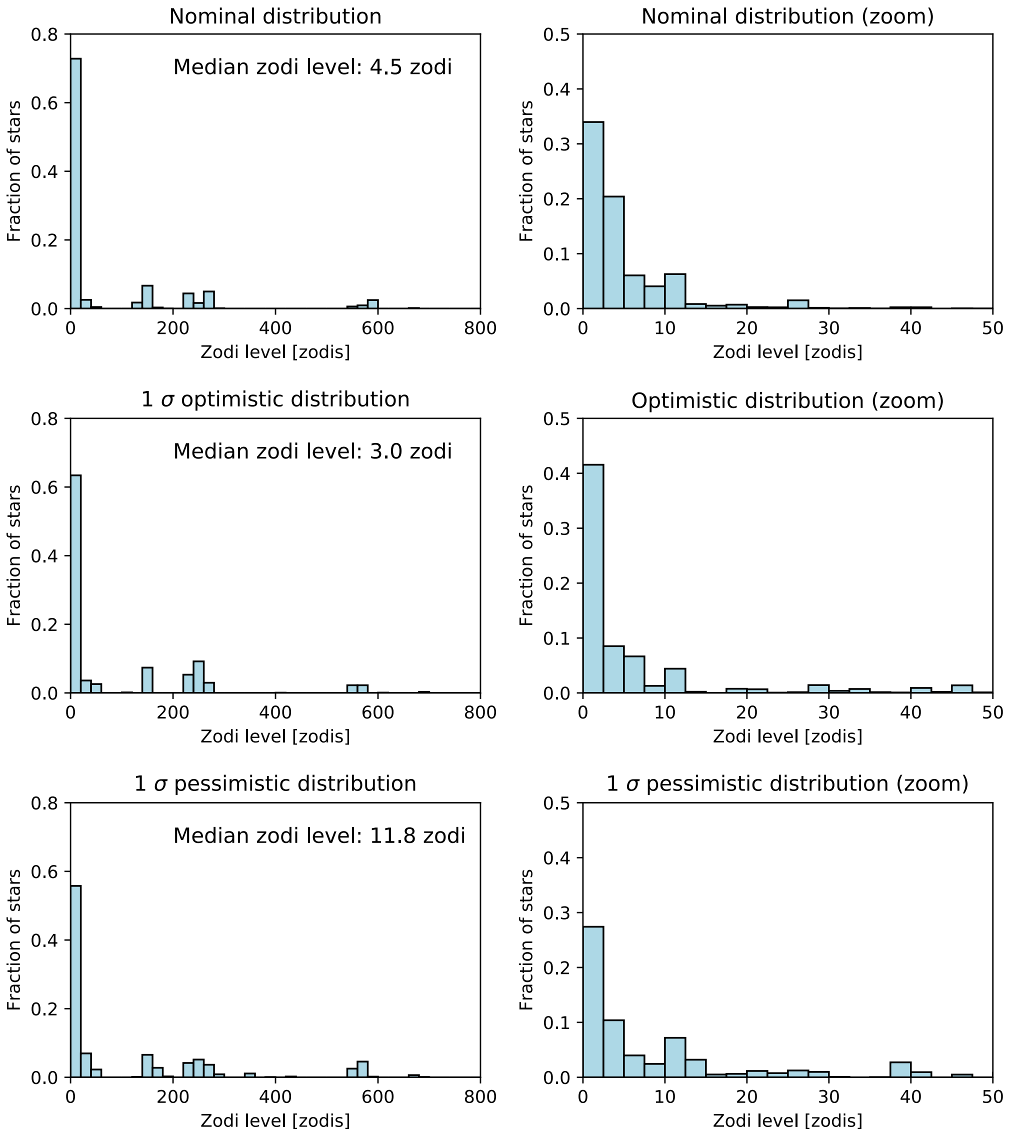


Crowd-sourced inputs



- Some overlap in data pipelines
- Some data re-binned from publications

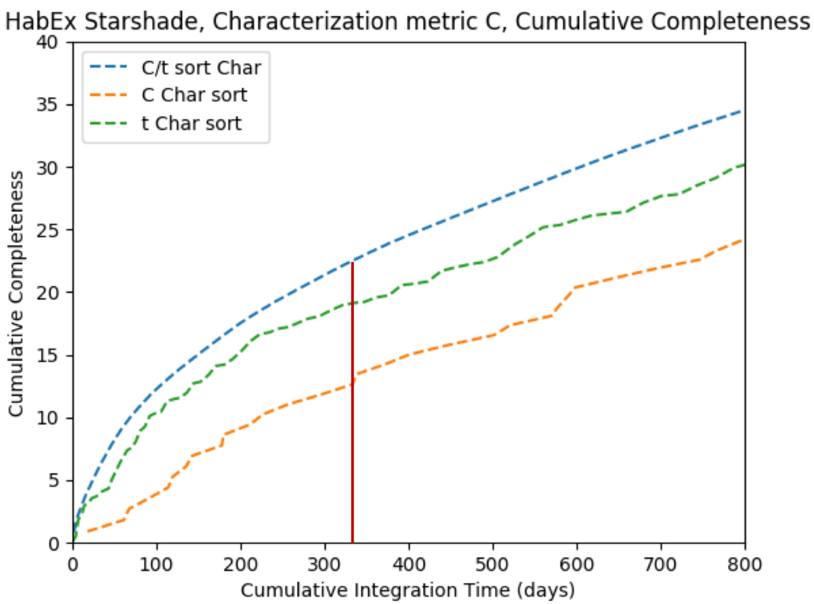
Exozodi

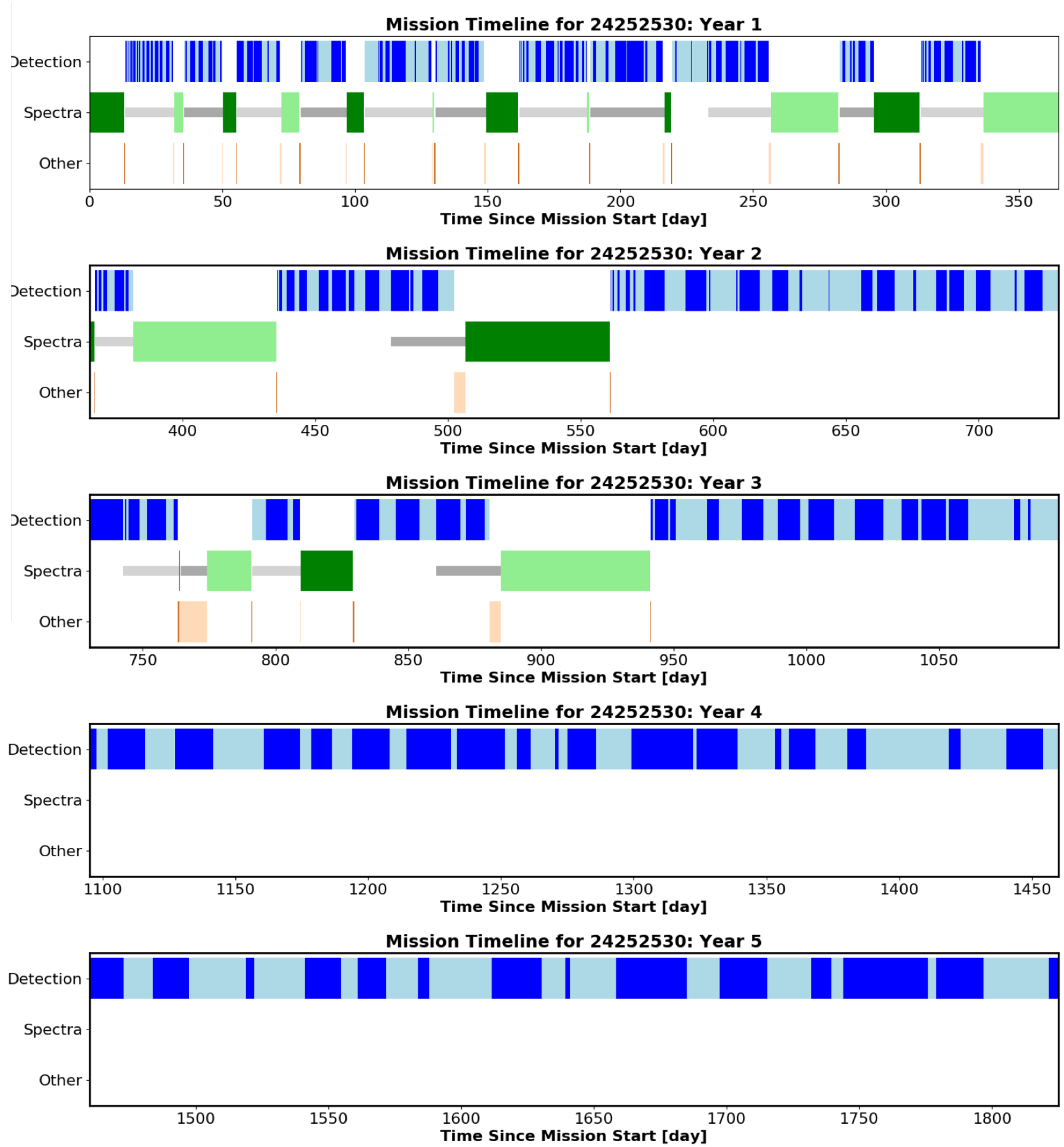


- LBTI HOSTS survey
  - 35 stars
  - Data fit to nominal distribution has median of 4.5 zodis
  - Yields evaluated with draws from nominal, optimistic, and pessimistic distributions

What is the best we can do? Simple upper bound

ExoPlanet Exploration Program





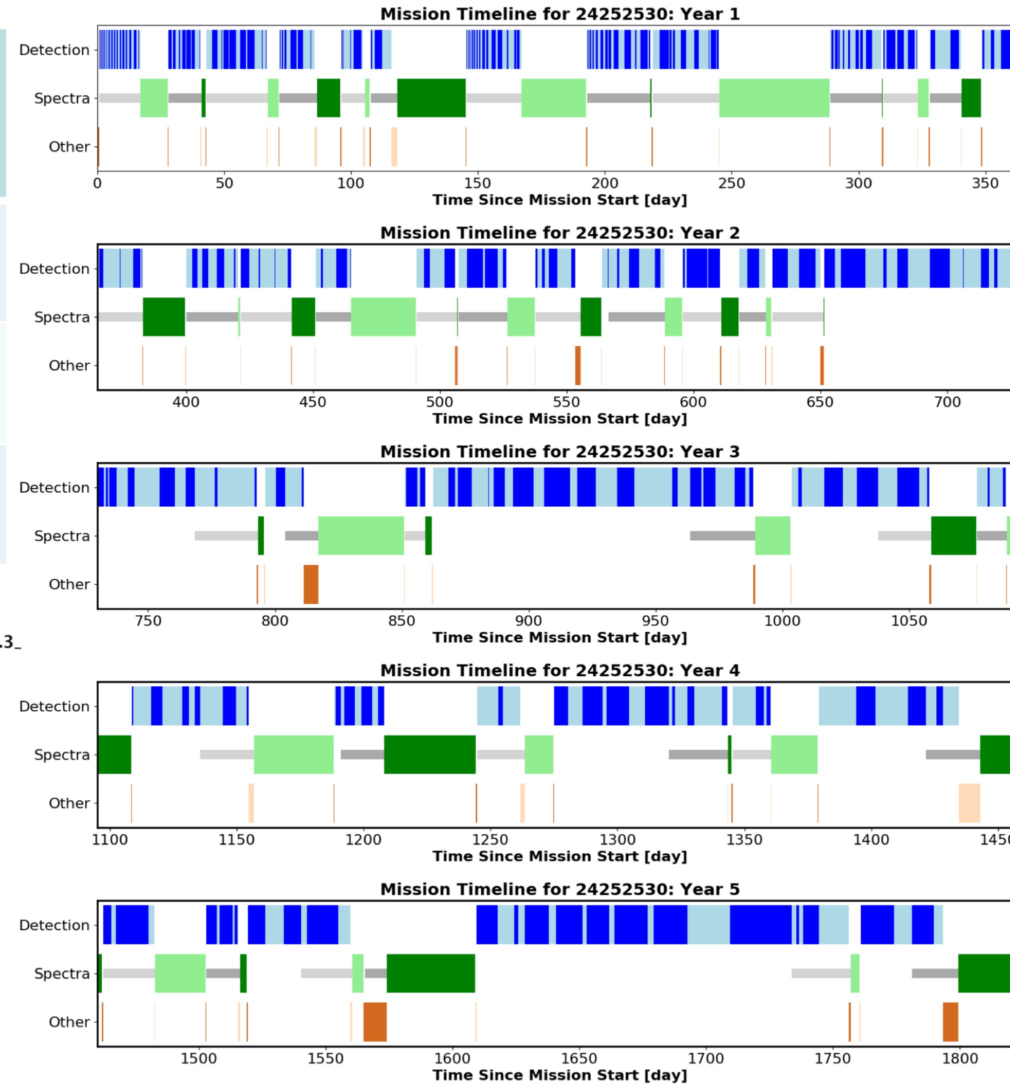
Detection: 1471 days = 80.5%
Spectra: 325 days = 17.8%
Slew: 342 days = 18.7%
Other: 32 days = 1.7%

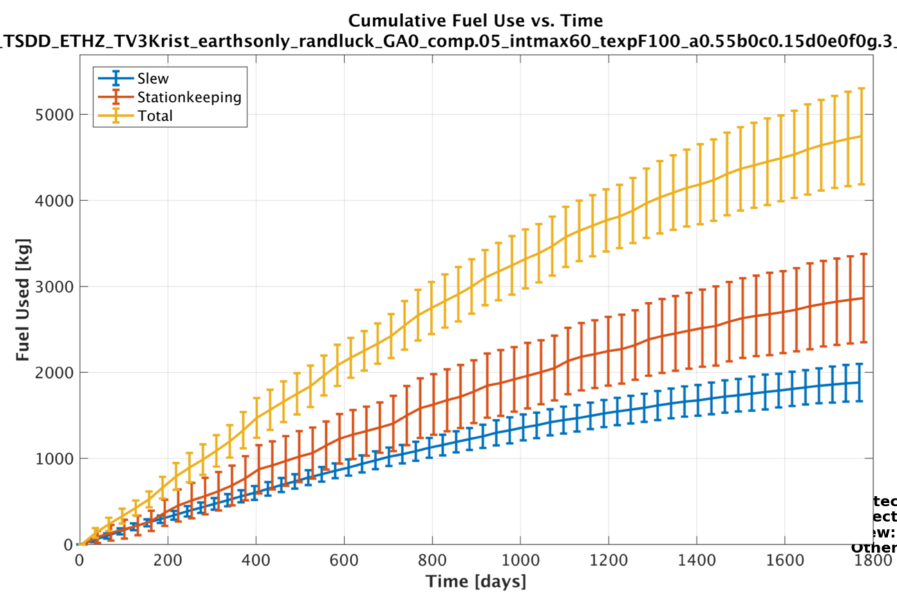
- 330 days (0.9 yrs) in HabEx report for EEC spectral characterization
  - 333 days: 21 earths
  - 110 days: 11 exo-earths x 3 visits
- 325 days for omniscient case to exhaust targets

Impact of Starshade slewing

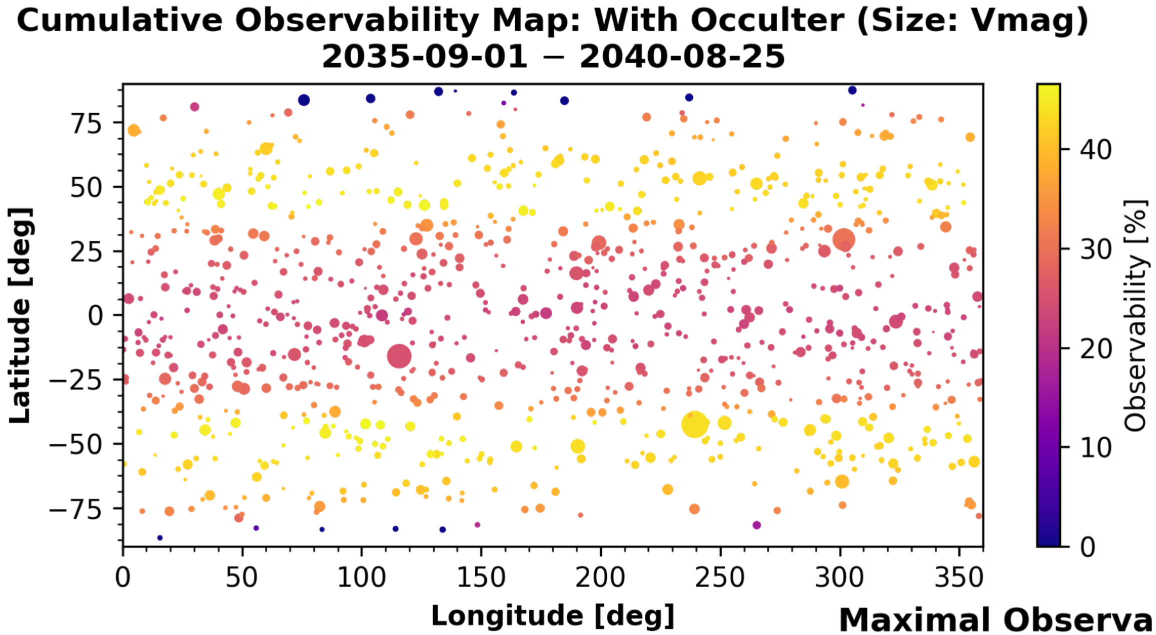
ExoPlanet Exploration Program

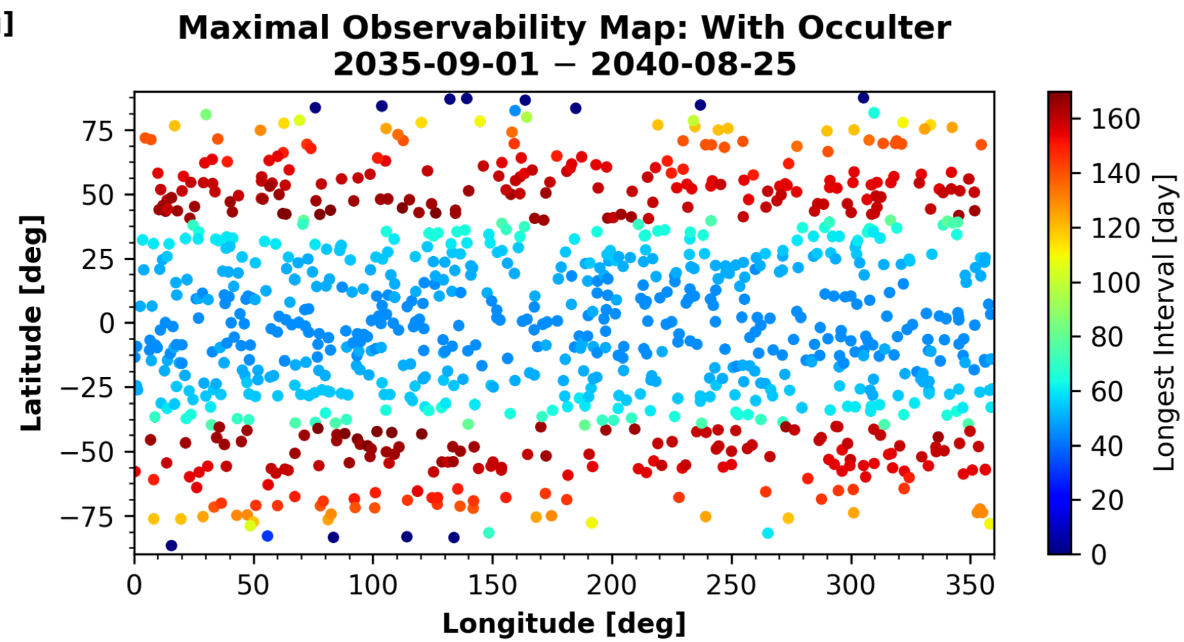
Case	EECs char'd	Total Int Time
Simplistic Upper bound	21	330 d
Omniscient at quadrature	19	325 d
Omniscient non-coordinated phase	15	520 d





Starshade Cumulative and Maximal Observability

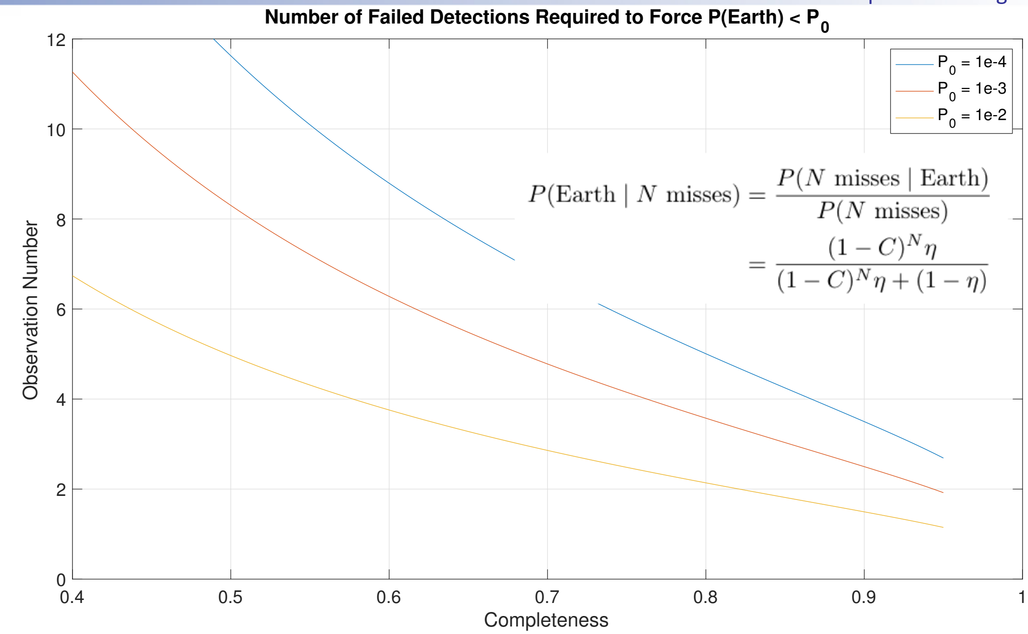


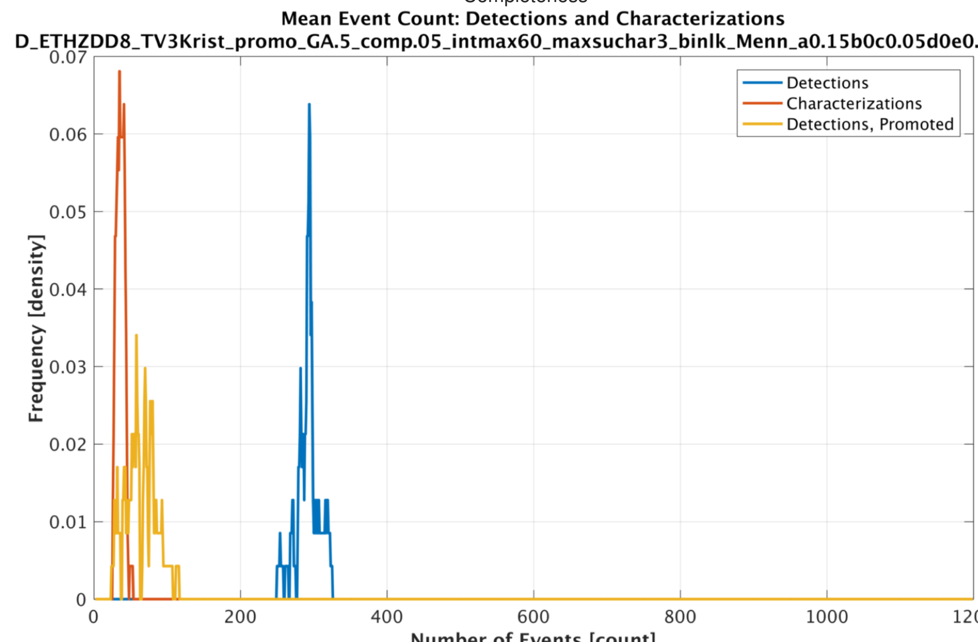


Crafting the coronagraph blind search

- Trade thoroughness for efficiency
  - Max null detections = 2
  - Max successful det = 4
  - Max det visits = 10

- Promotions after tuning is ~8

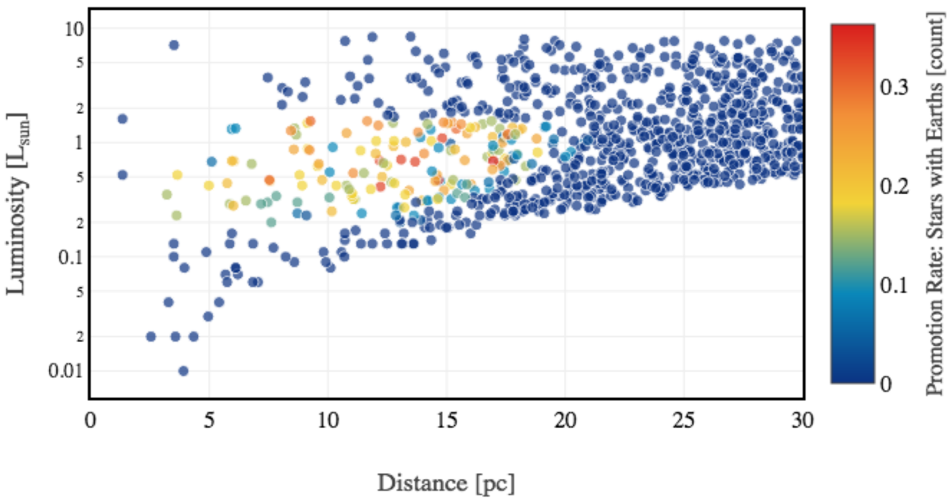




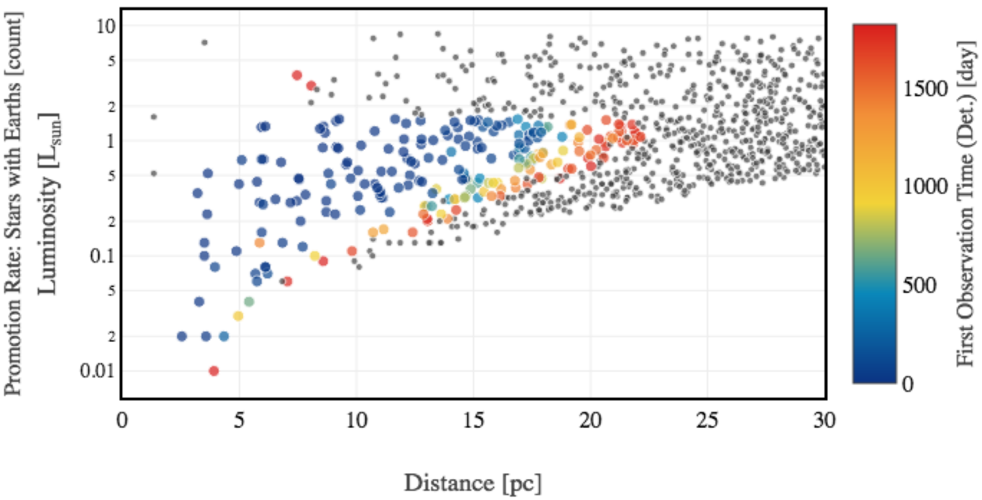
LUVOIR B Detections

ExoPlanet Exploration Program

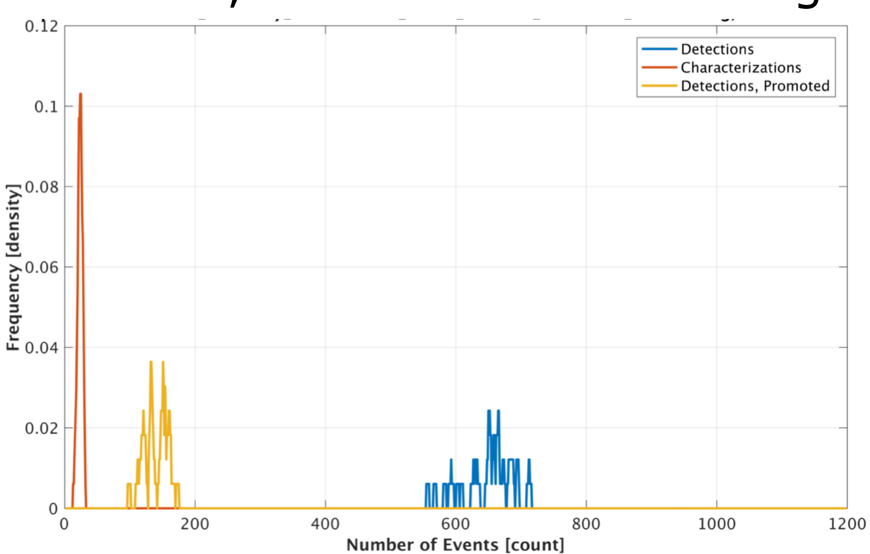
Promotion Rate



First Observation Time



Detection, Characterization Histogram



Cumulative Detections