Science Yield of Direct Imaging Missions

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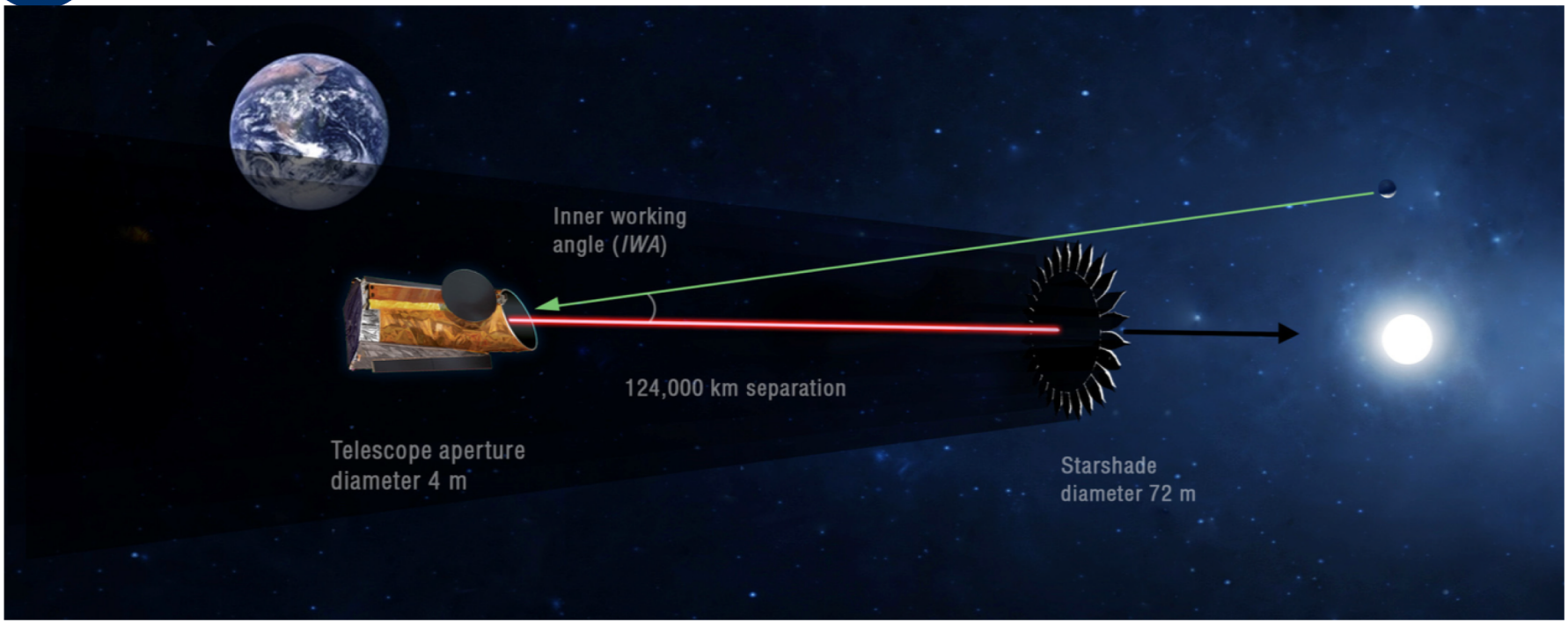
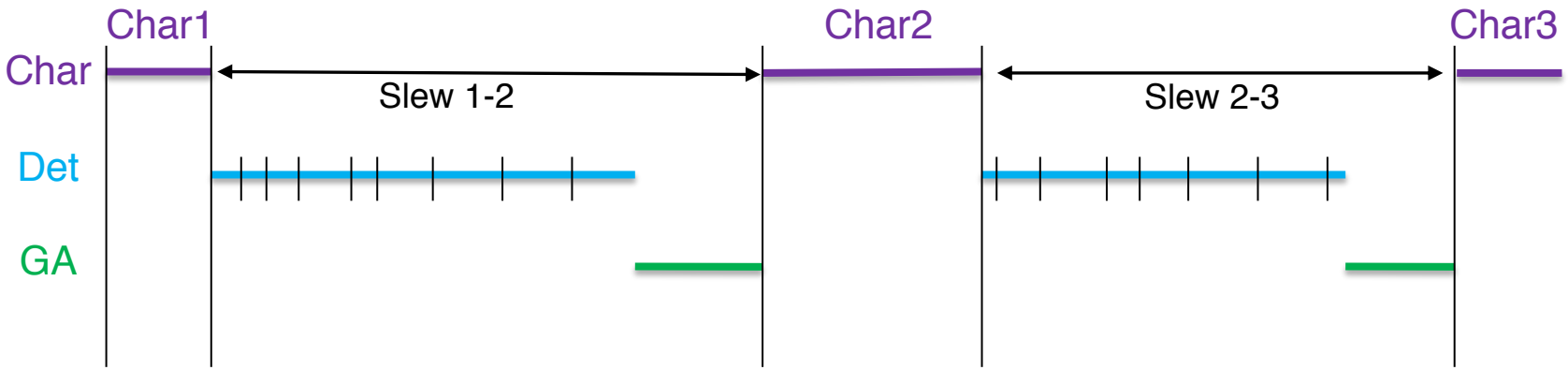
April 12, 2018

HabEx Concept Study

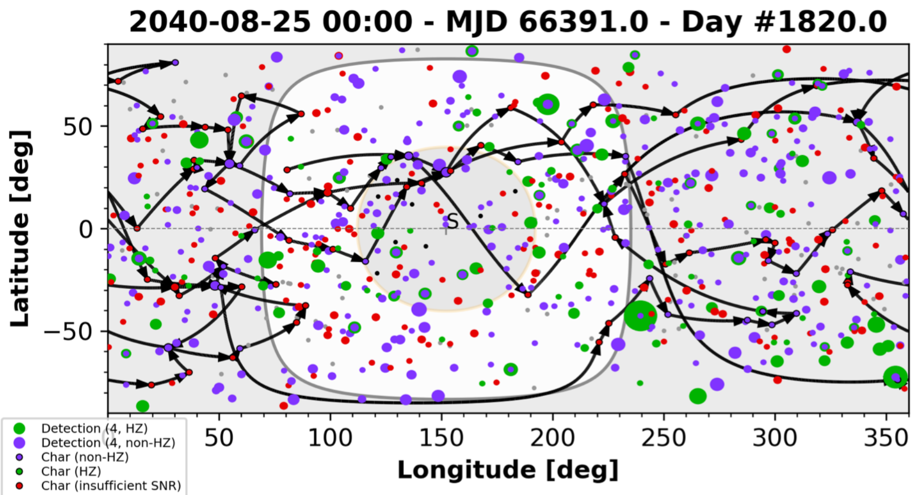


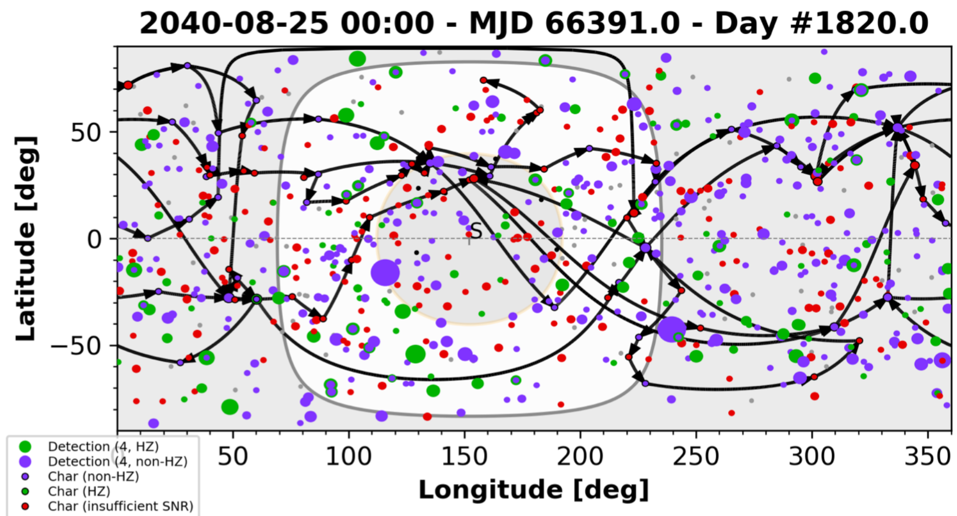


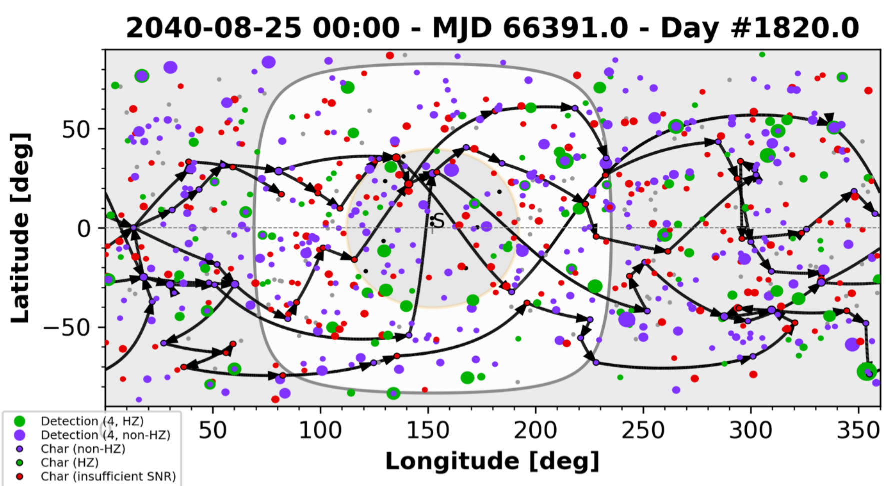
HabEx Concept

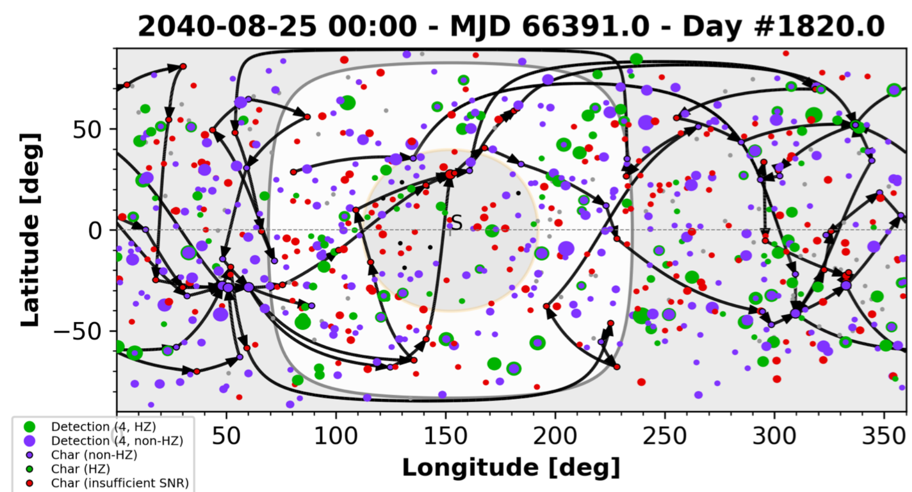
- Play DRM movie

Monte Carlo Ensemble of 1000 DRMs



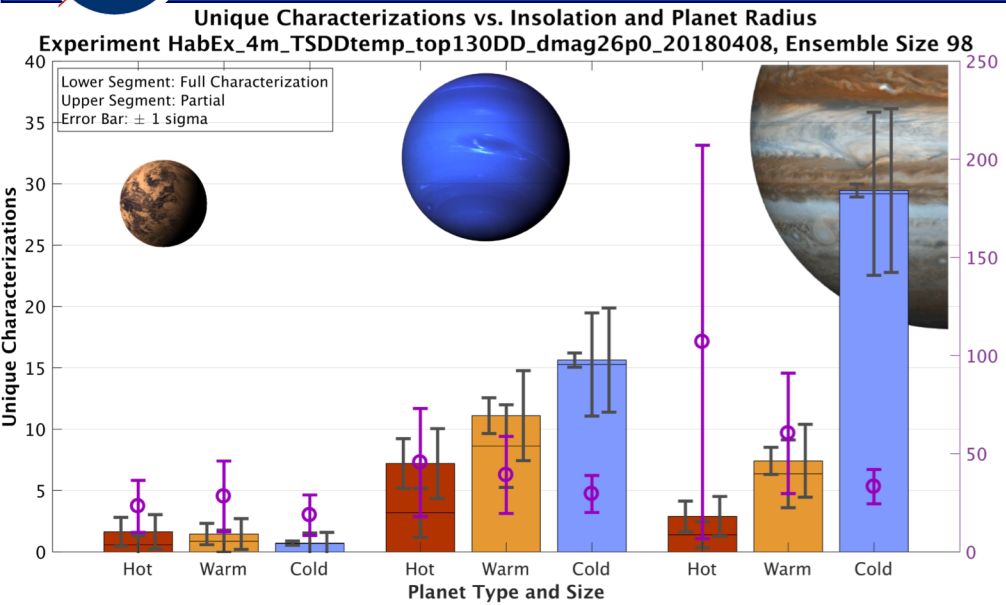


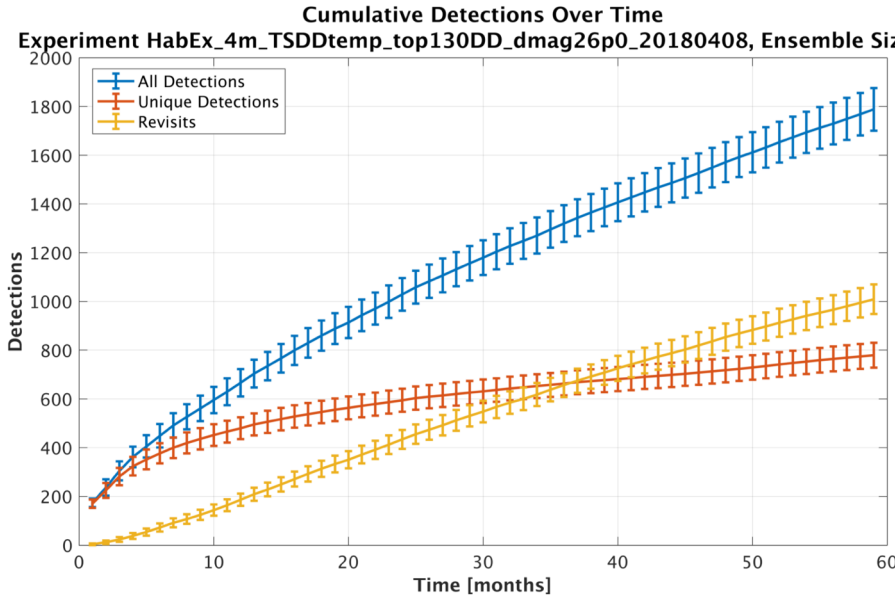


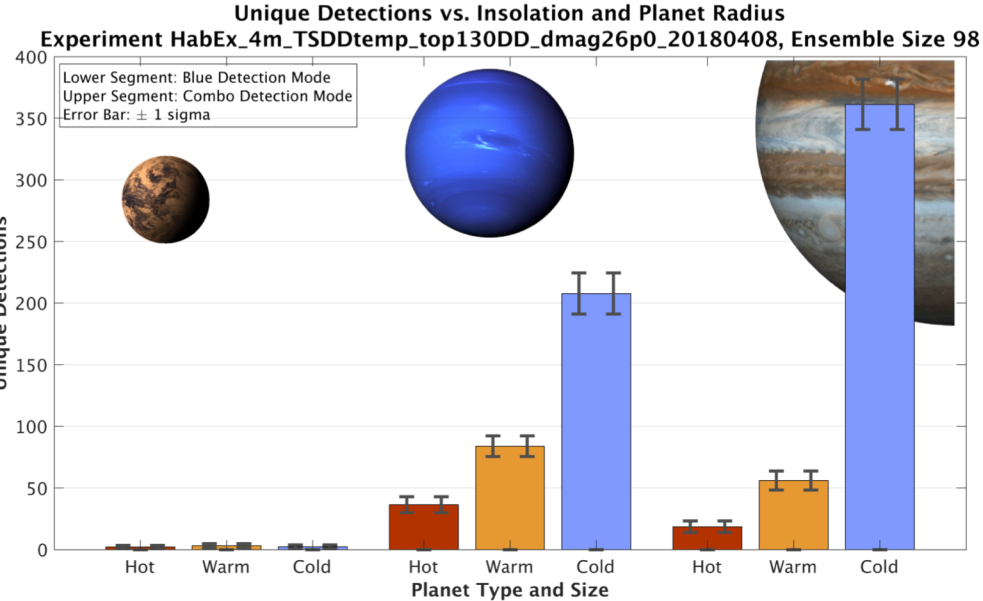


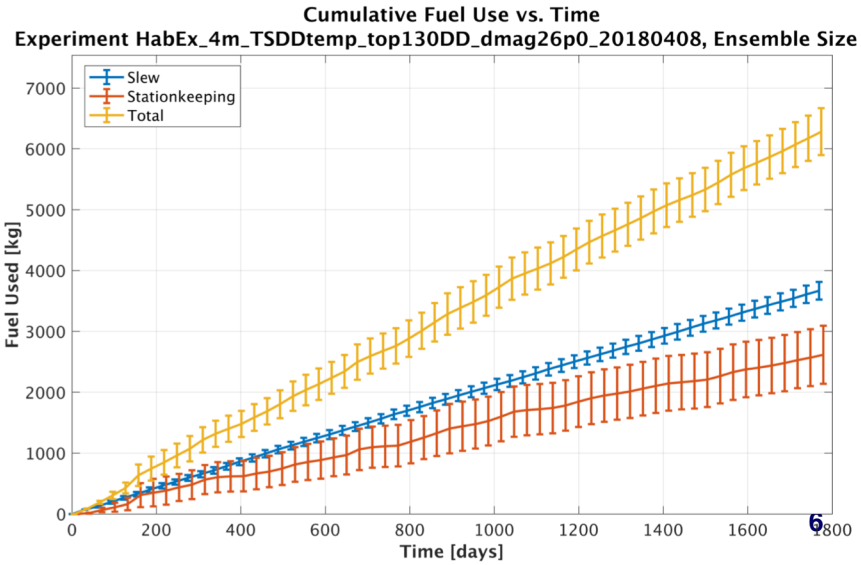
Run: HabEx_4m_TSDDtemp_top140DD_dmag26p0_20180410

HabEx

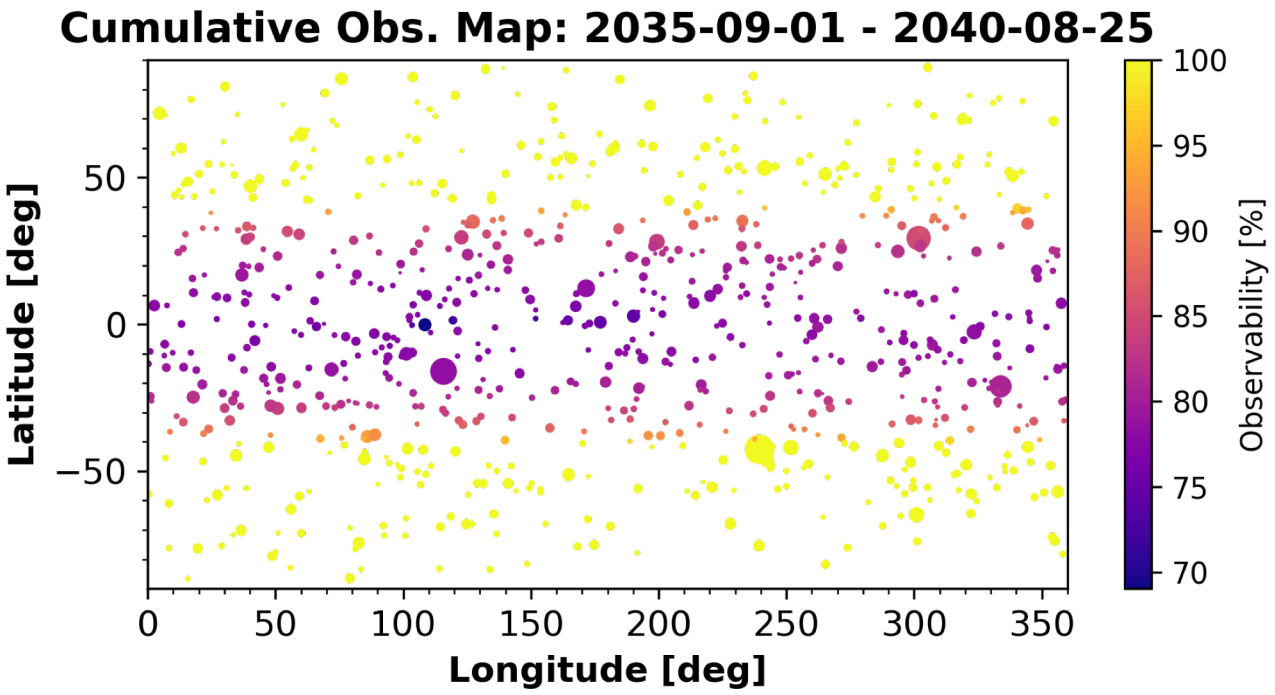

Unique Characterizations vs. Insolation and Planet Radius
Experiment HabEx_4m_TSDDtemp_top130DD_dmag26p0_20180408, Ensemble Size 98
Lower Segment: Full Characterization
Upper Segment: Partial
Error Bar: ± 1 sigma
Unique Characterizations
Characterization SNR
Hot
Warm
Cold
Planet Type and Size


Cumulative Detections Over Time
Experiment HabEx_4m_TSDDtemp_top130DD_dmag26p0_20180408, Ensemble Siz
All Detections
Unique Detections
Revisits
Detections
Time [months]


Unique Detections vs. Insolation and Planet Radius
Experiment HabEx_4m_TSDDtemp_top130DD_dmag26p0_20180408, Ensemble Size 98
Lower Segment: Blue Detection Mode
Upper Segment: Combo Detection Mode
Error Bar: ± 1 sigma
Hot
Warm
Cold
Planet Type and Size


Cumulative Fuel Use vs. Time
Experiment HabEx_4m_TSDDtemp_top130DD_dmag26p0_20180408, Ensemble Size 98
Slew
Stationkeeping
Total
Fuel Used [kg]
Time [days]

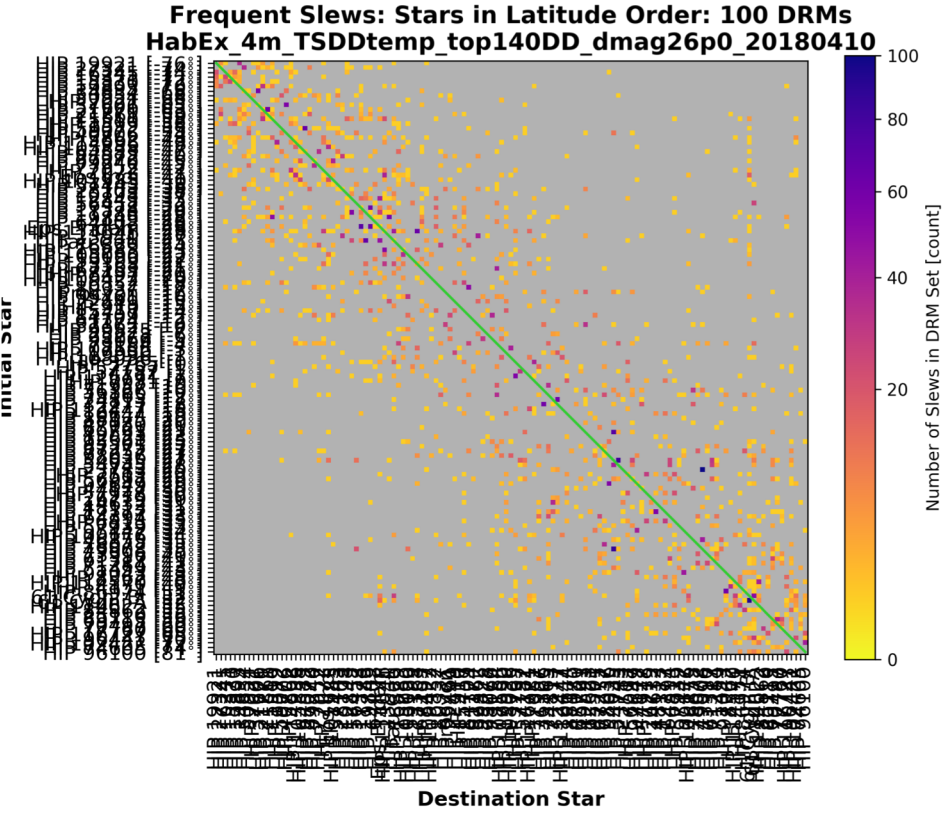
Starshade Sky Coverage Map

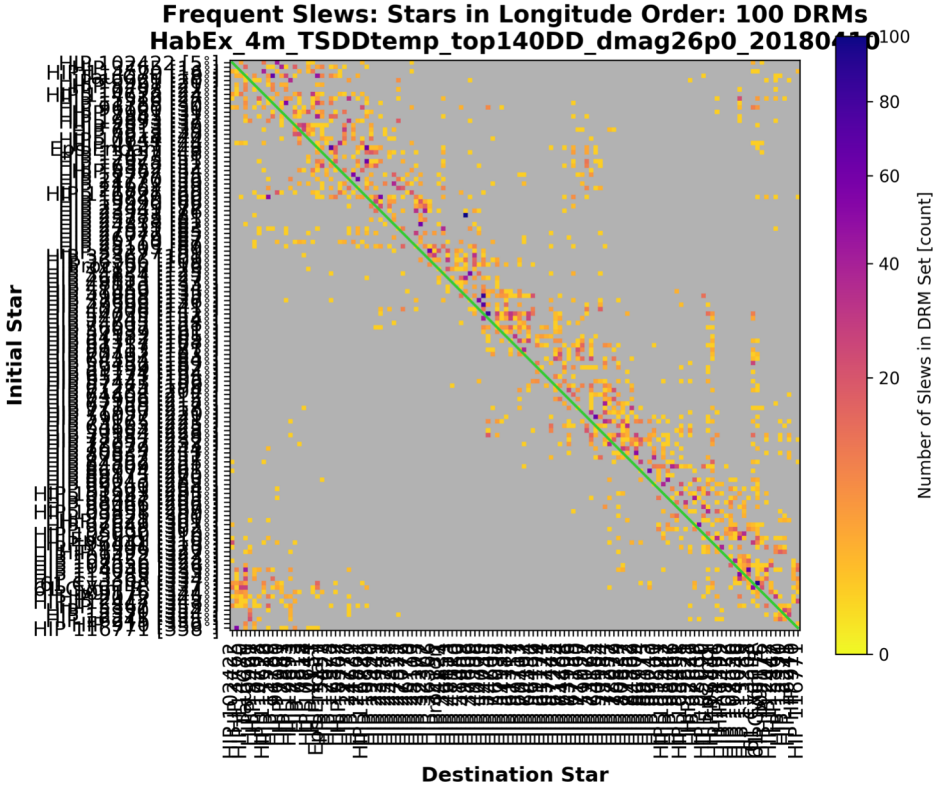


Cumulative fraction-of-time target is observable
Size of point is proportional to target Vmag.

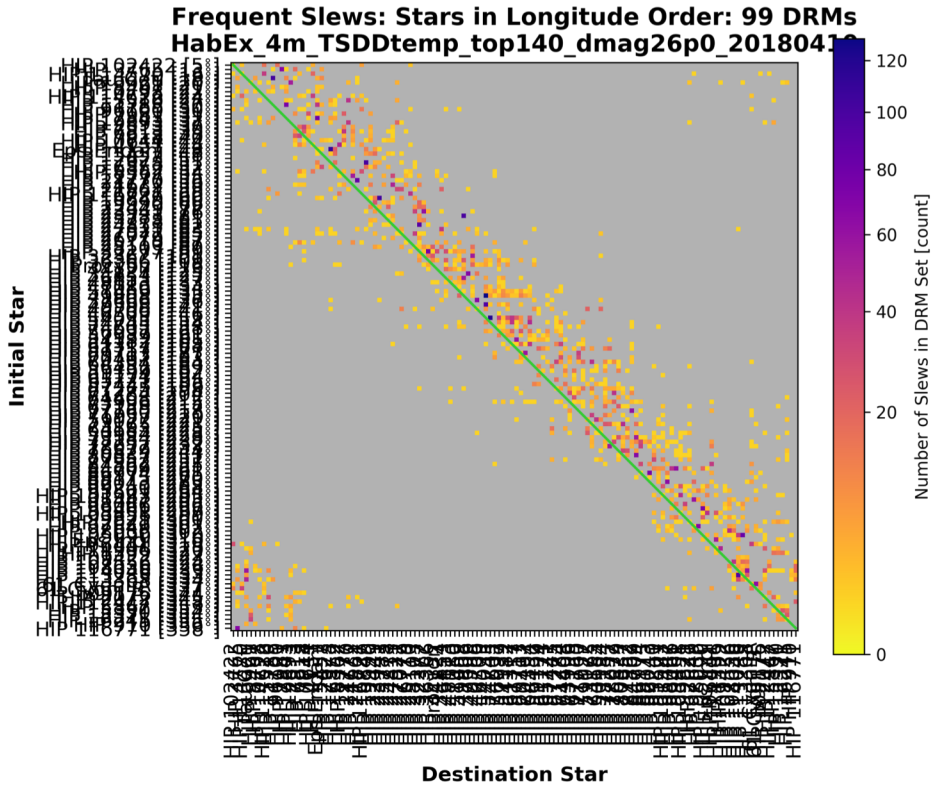
- Two year mission: 2036-2037 inclusive
- dMagLim = 26
- Sun keepout: > 45˚ and < 83.4˚ is OK
- Earth keepout: >1˚ is OK
- Moon keepout: >1˚ is OK
- Other bodies: > 1˚ is OK

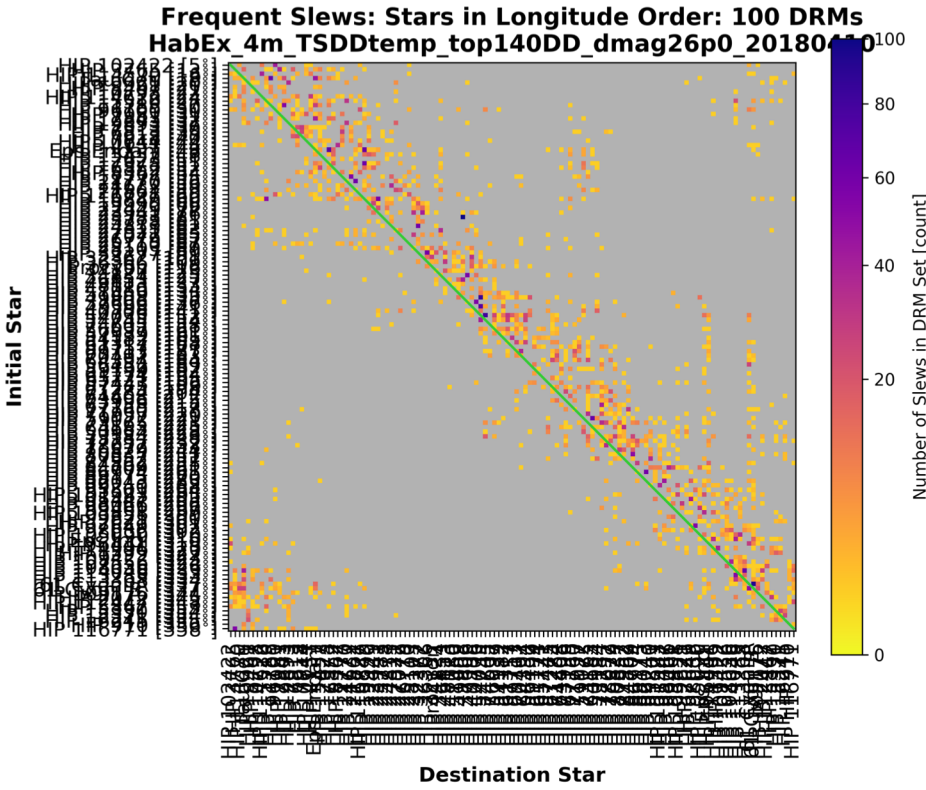
Starshade sailing in lat and lon



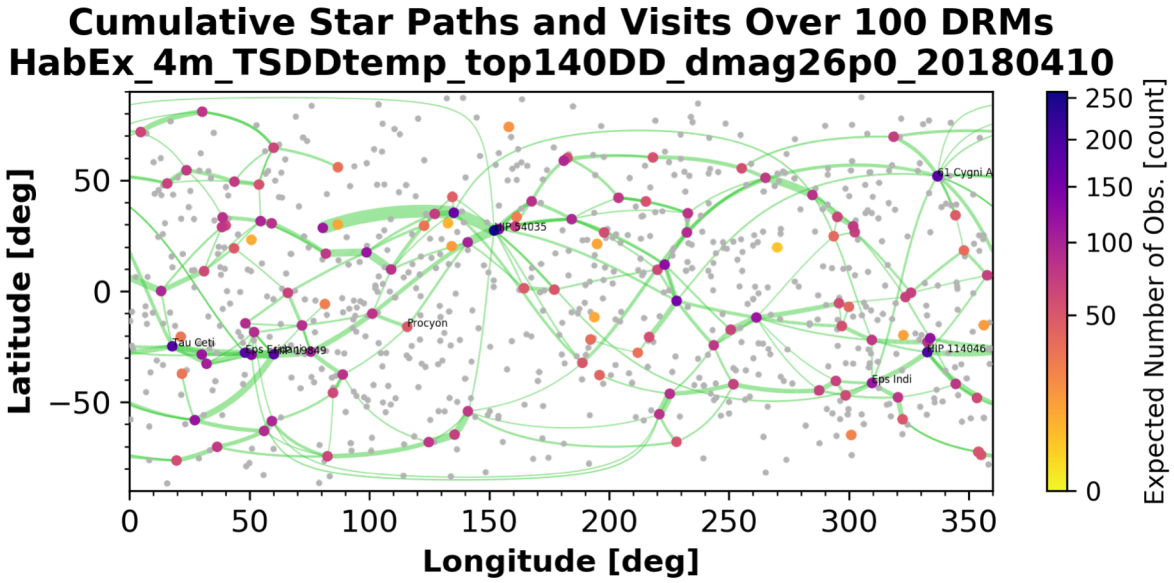


Slew efficiency for Deep Dive

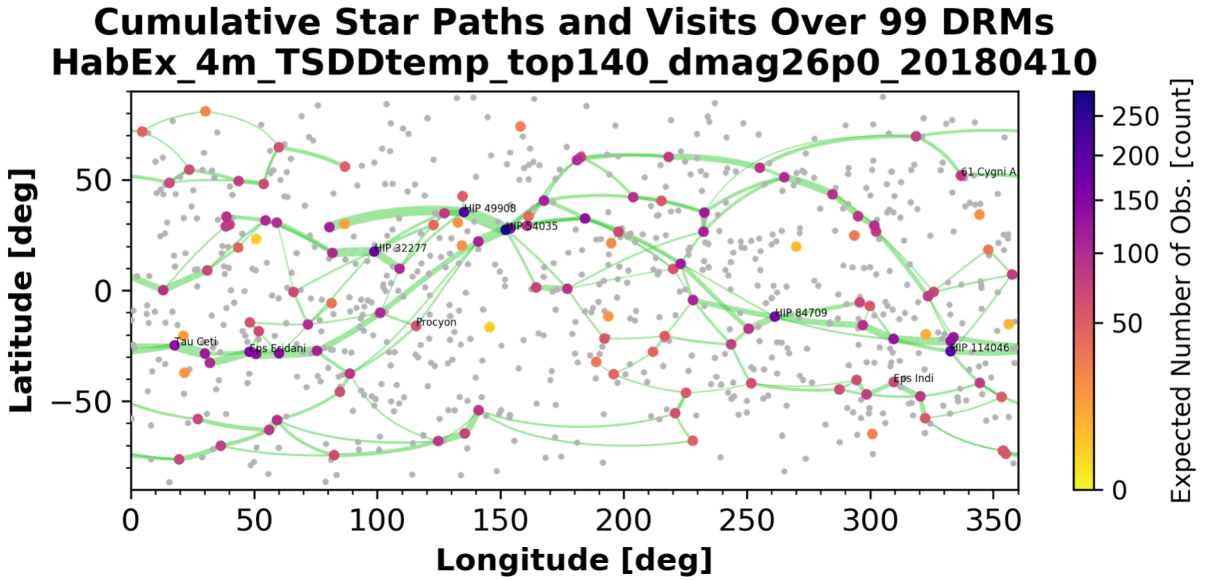




HabEx SS popular stars, paths



Prioritize deep dive 9 targets and revisits

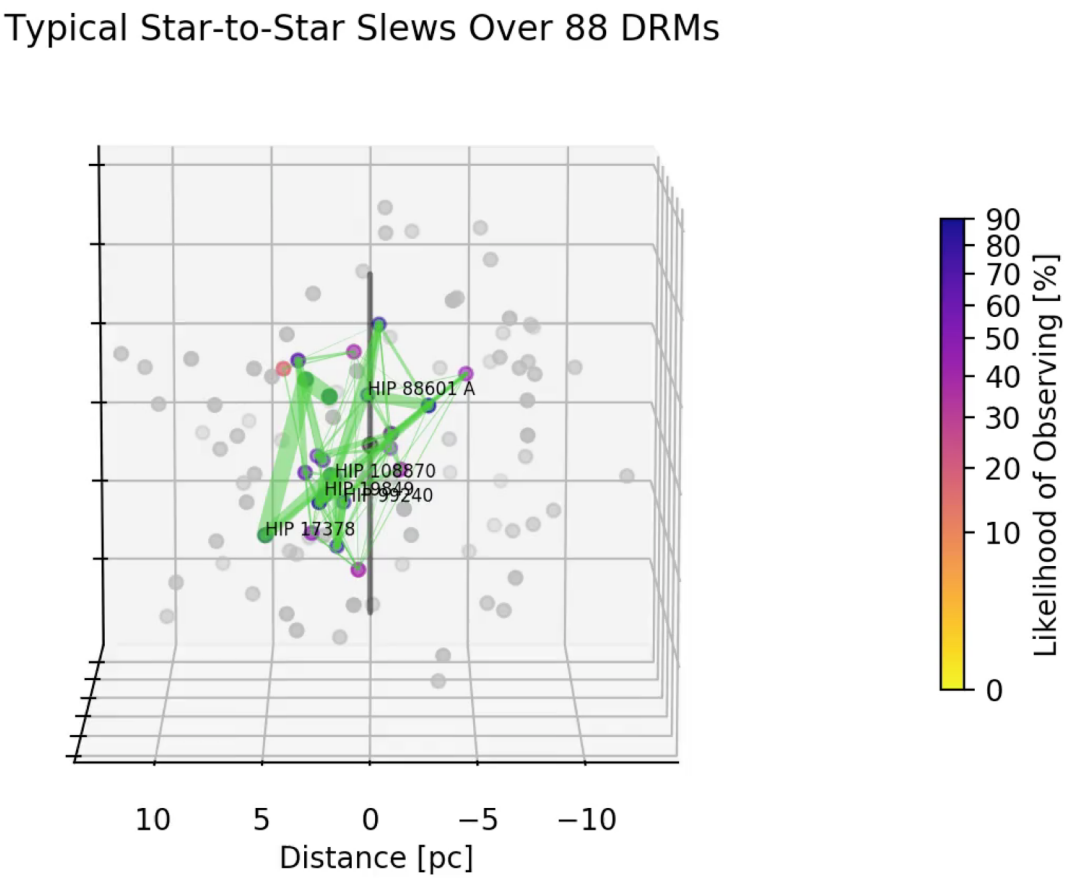


Equal Priority

Exo-S Ensemble paths and stars

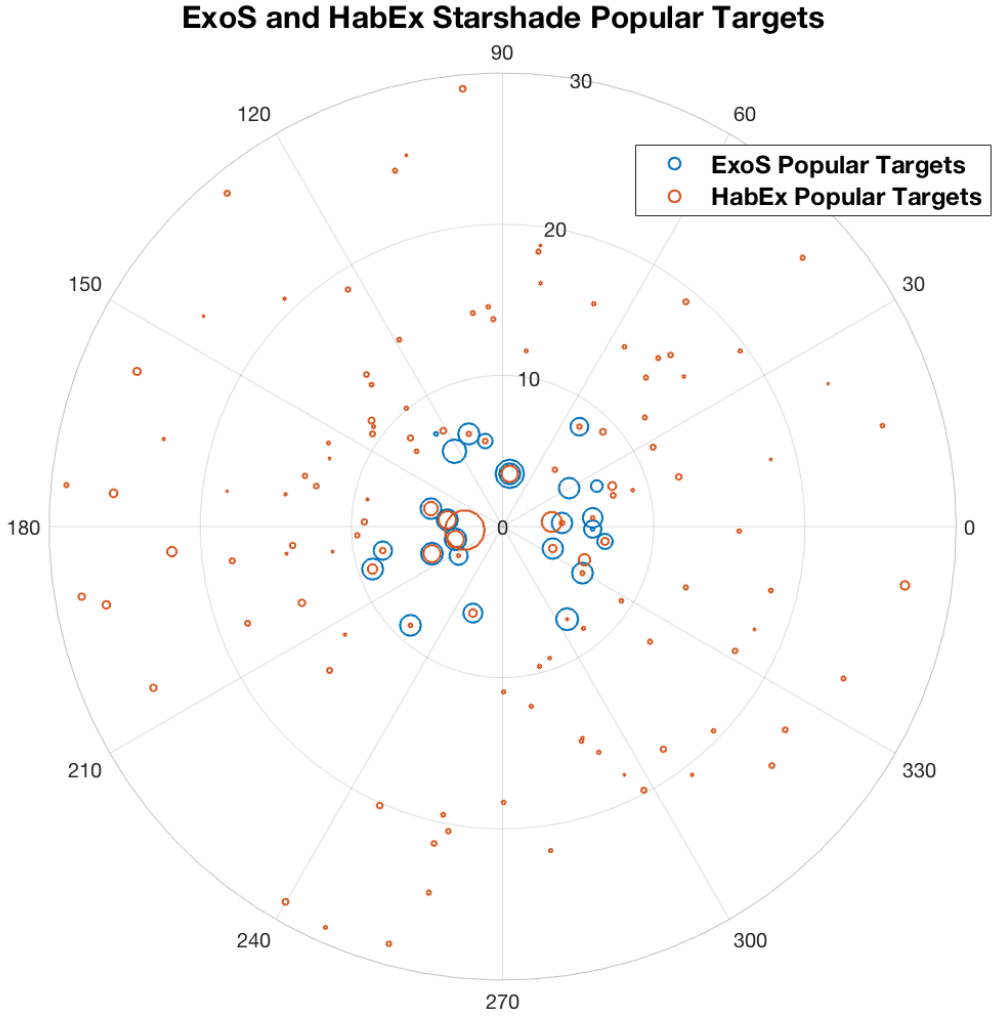
- Play Exo-S popular star 3D rotation movie

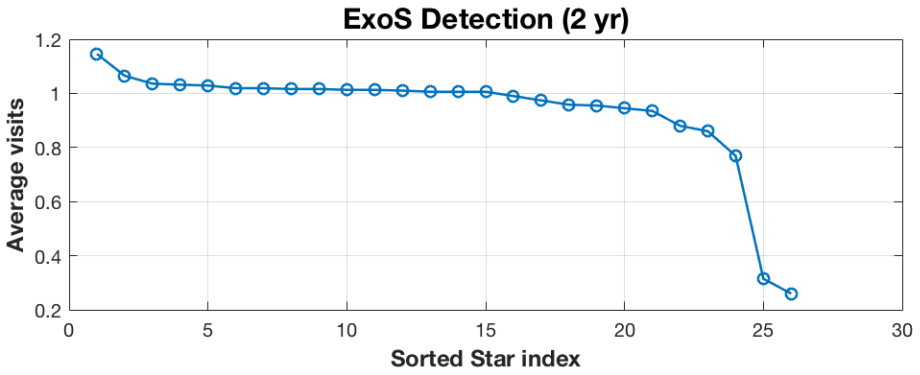
HabEx ensemble paths and stars

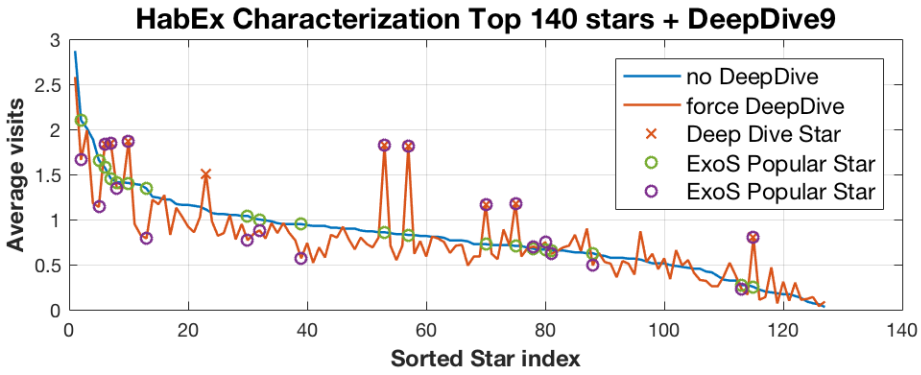


Exo-S and HabEx SS common stars

20 Targets are common to ExoS and HabEx frequently visited targets



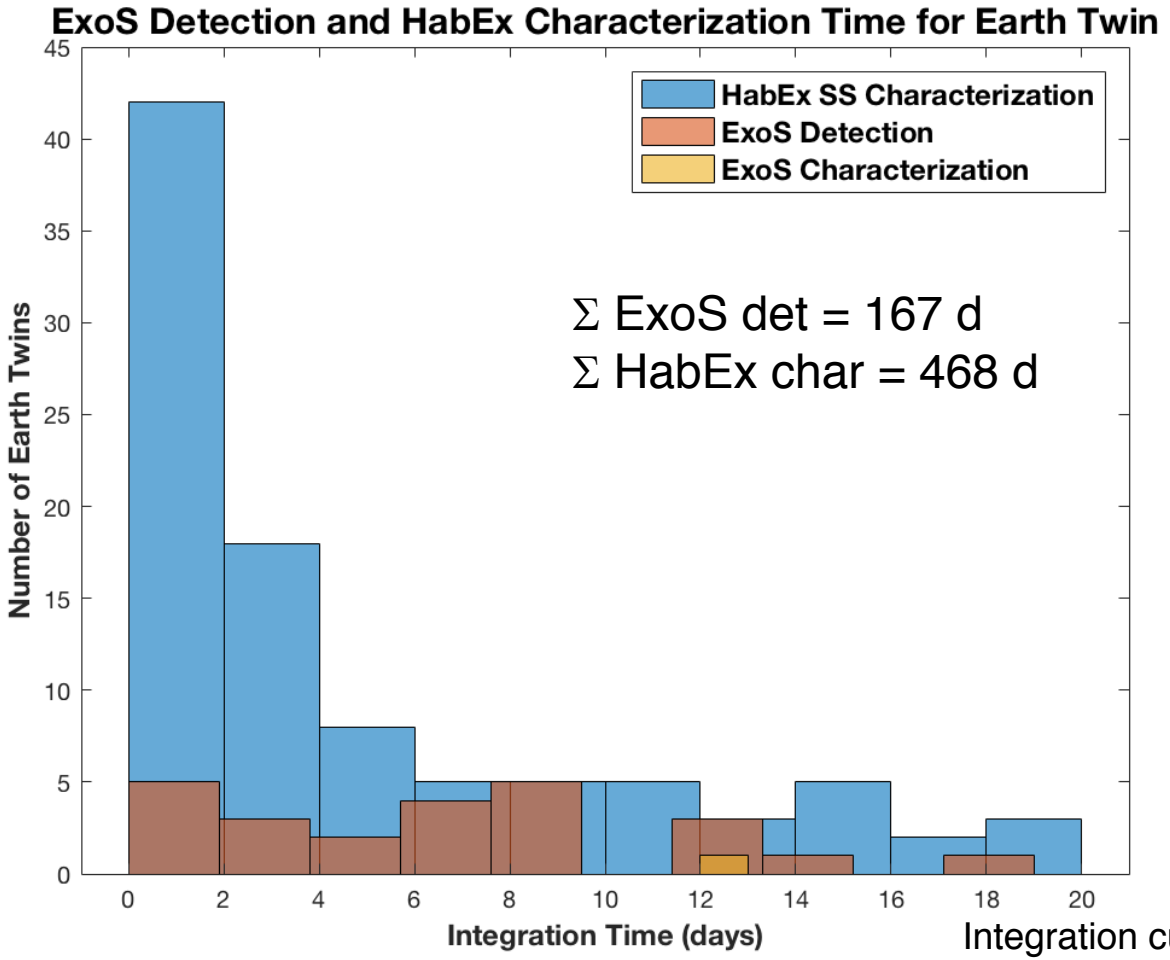




We can threshold for visits > 0.5
to create a top100 SS target list

Characterization time for Exo-S/HabEx

for Earth Twins around popular stars



Σ ExoS det = 167 d

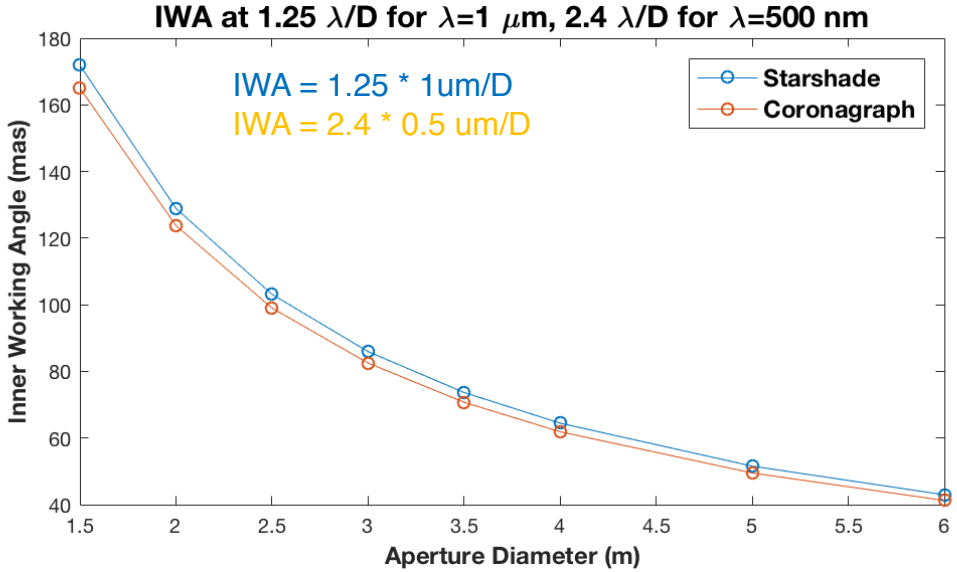
Σ HabEx char = 468 d

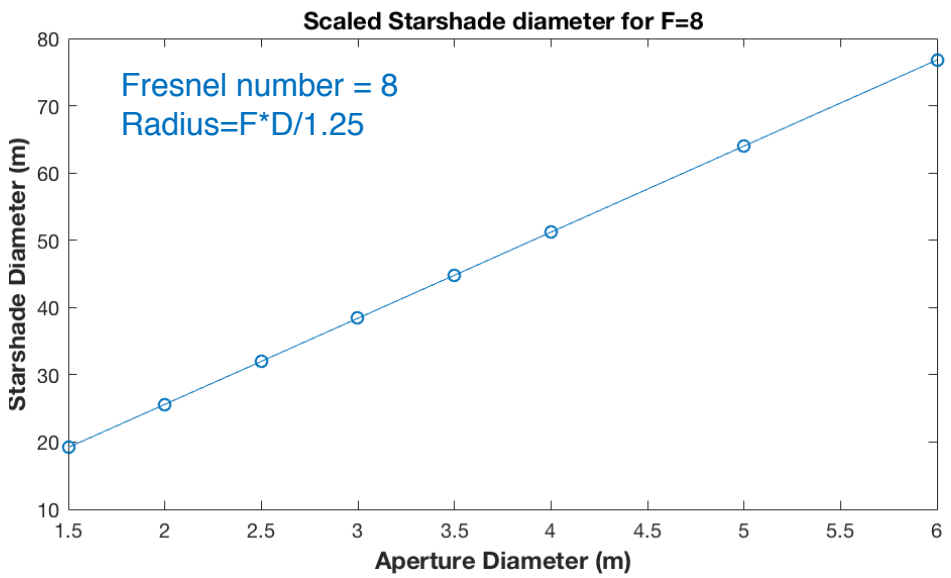
Integration cutoff = 20 d

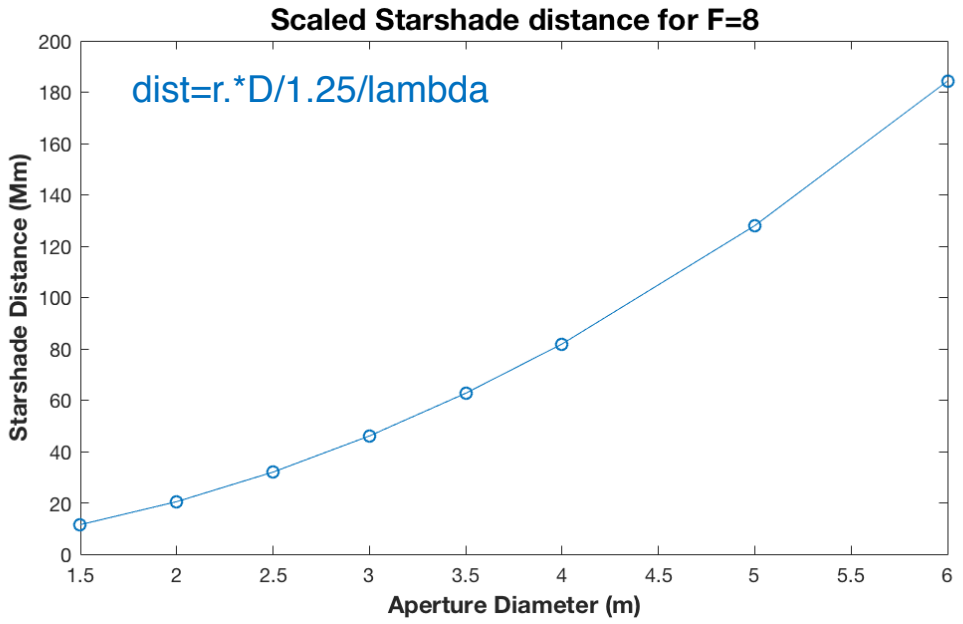
Given the top100 popular stars, what is the minimum telescope aperture to characterize earth twins?

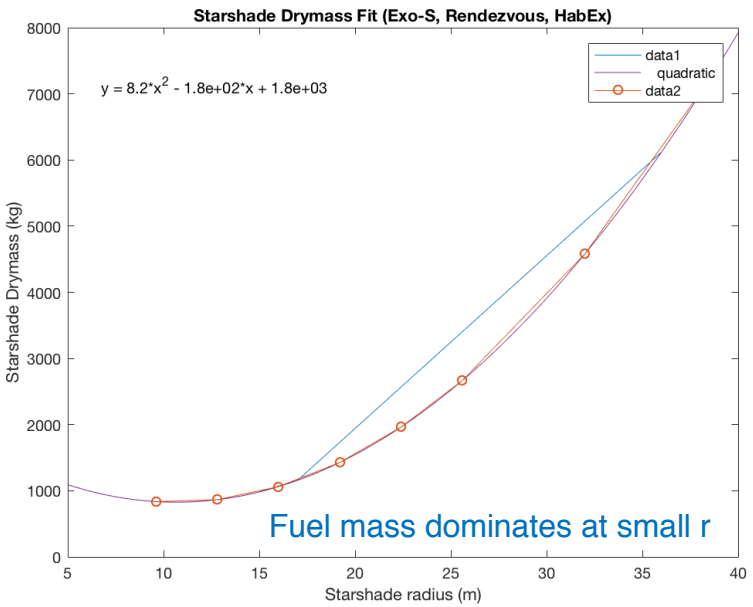
Scale Starshades to Telescope Diameter

preserve bandwidth

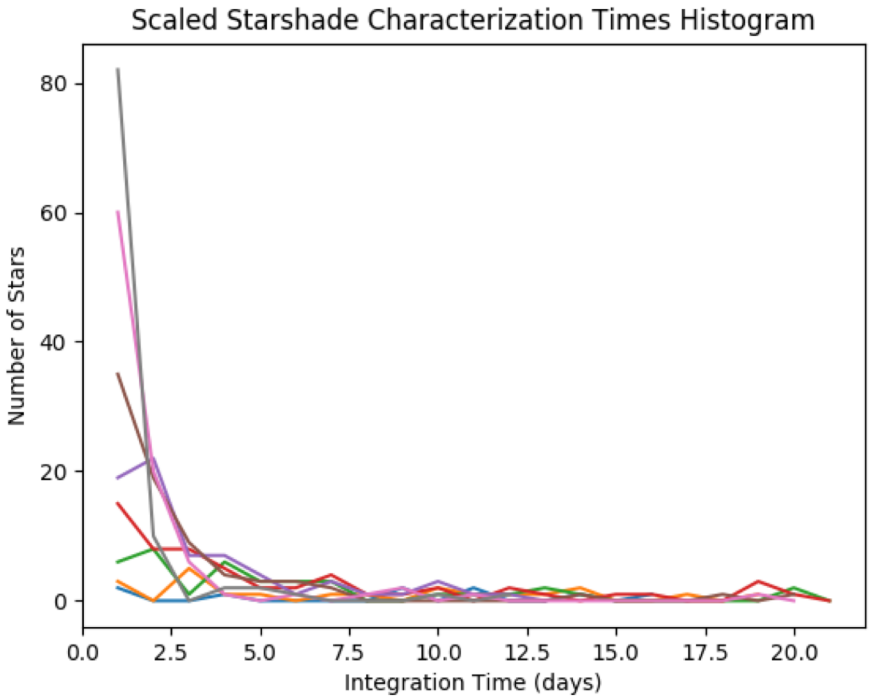


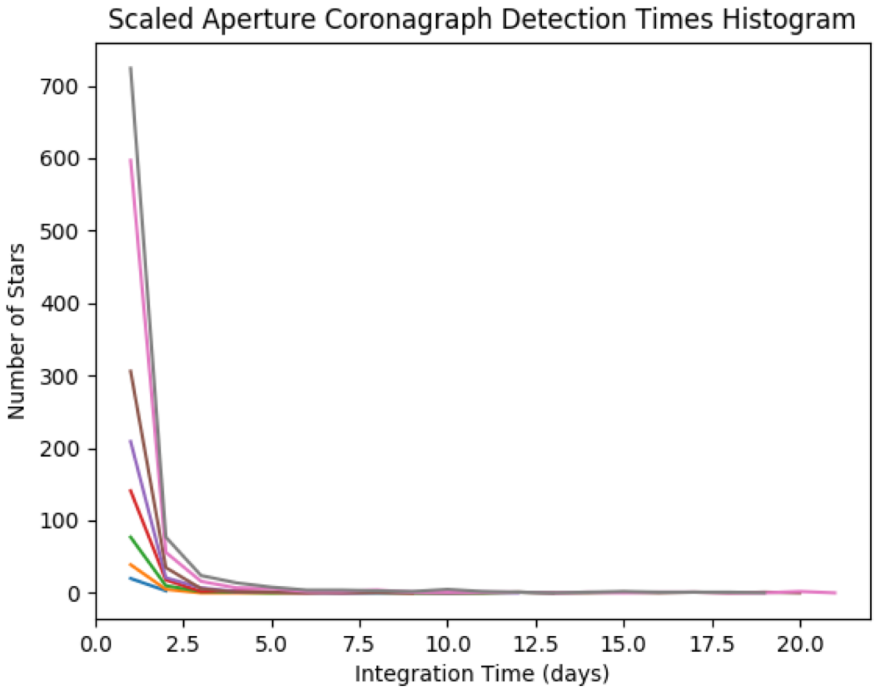


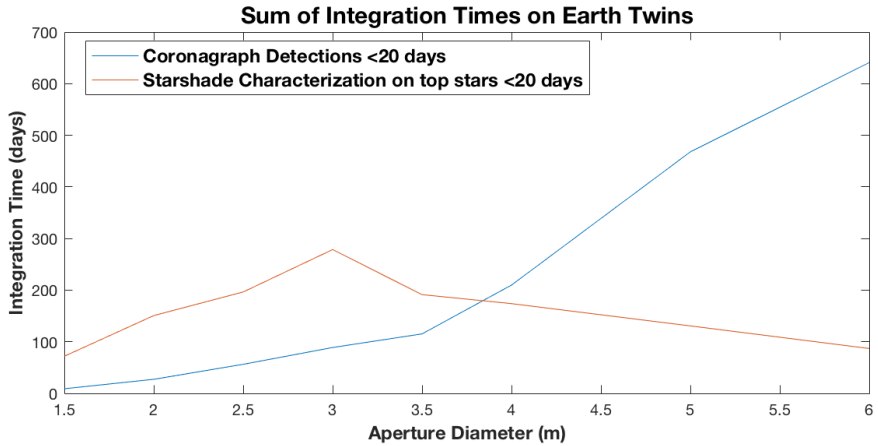




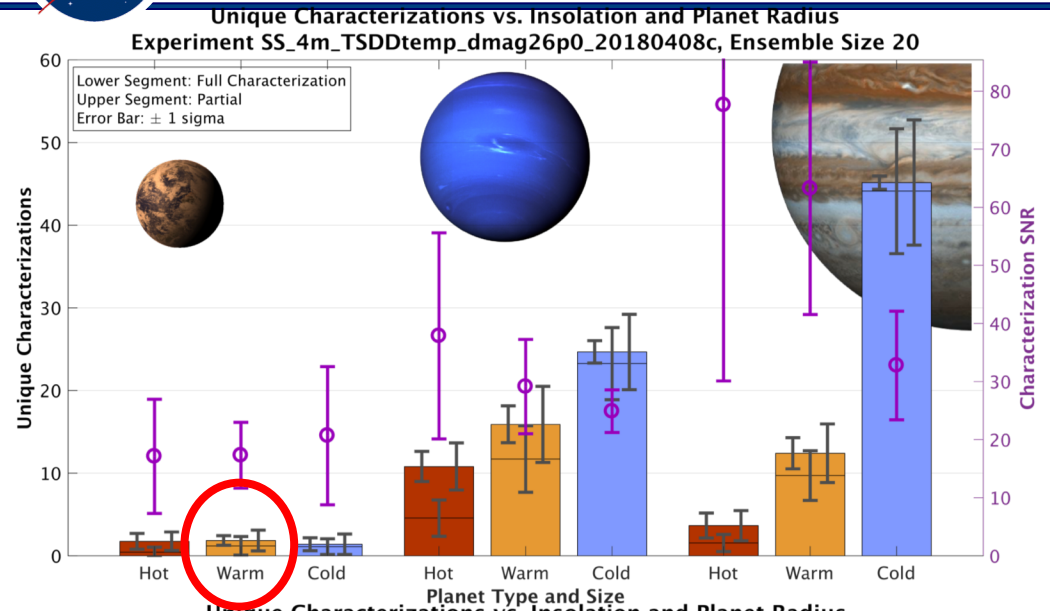
Integration times <20 days for the popular stars

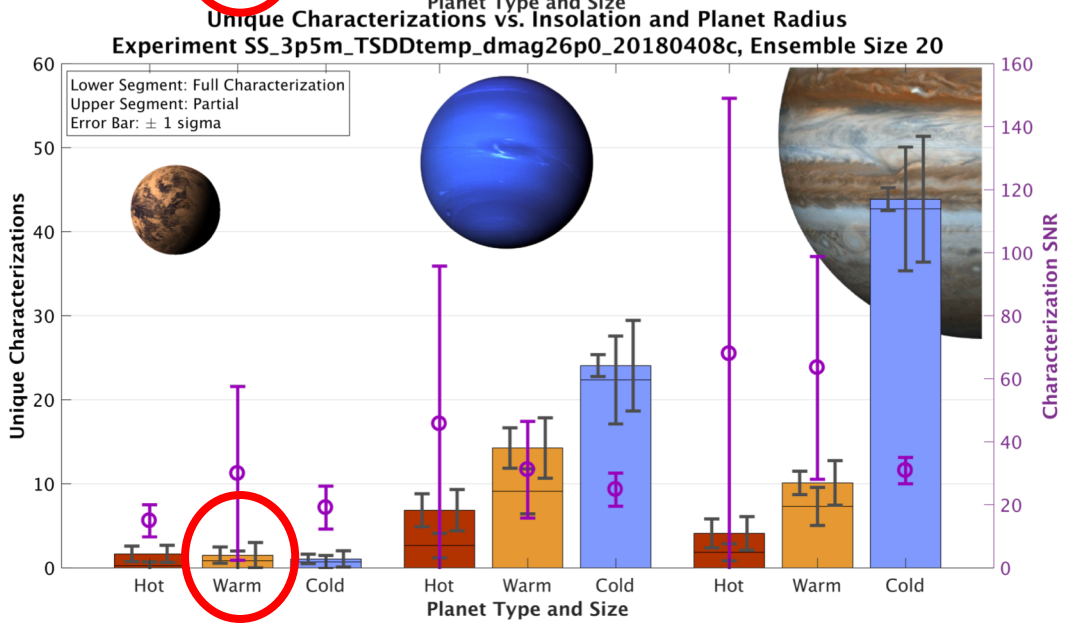






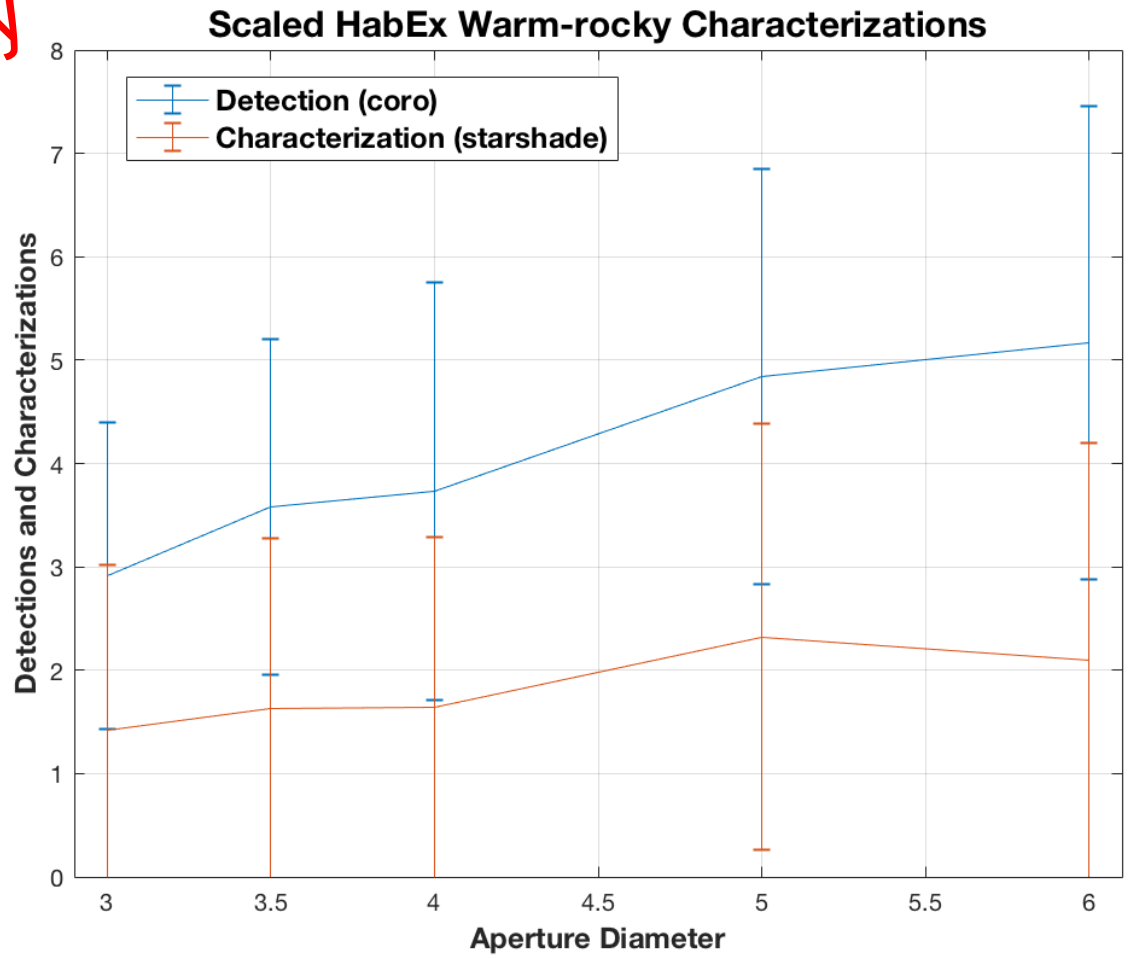
DRM results for starshades





Minimum Diameter

Preliminary



Exoplanet Standard Definitions and Evaluation Team Overview

- Purpose
  - Provide **transparent, common** exoplanet science yield estimates for Decadal large mission studies
  - Promote **standard and consistent** definition of inputs and outputs (planet and star properties, star lists, instrument properties, detection thresholds) for purposes of yield comparison
- The period of performance coincides with Decadal Study Teams
  - October 1 2016 to February 2019
  - https://exoplanets.nasa.gov/system/internal_resources/details/original/562_ExSDET_Charter.pdf
- Main deliverables
  - ***Interim Report*** apples-to-apples comparison *6/2018*
  - ***Final Report*** apples-to-apples comparison *5/2019*
  - ***Enabling*** deliverables *FY17*
    - Definition and Concurrence on
      - Inputs
      - Assumptions
      - Outputs
    - Cross Validation of EXOSIMS with Chris Stark's AYO
- Major Accomplishments
  - EXOSIMS v1.3 thru 1.34 released
  - First Draft Comparison in progress

ExEP Standard Definition and Evaluation Team Membership

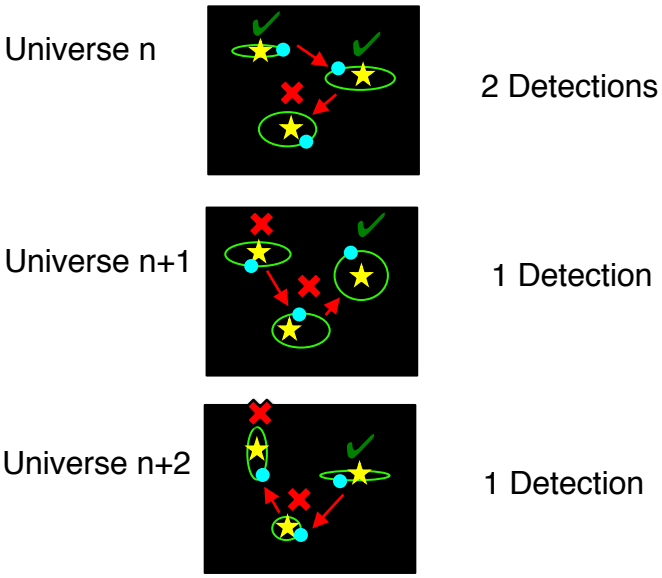
Team Member	Affiliation
Rhonda Morgan	ExEP
Bruce MacIntosh	Stanford
Chris Stark	StSci
Dmitry Savranksy	Cornell
Rus Belikov	Ames
Avi Mandell	GSFC
John Krist	JPL
Eric Nielson	SETI
Key StakeHolders	**Affiliation**
Gary Blackwood	ExEP
Karl Stapelfeldt	ExEP
Courtney Dressing	Caltech
Klaus Pontoppidan	StScI
Aki Roberge	GSFC
Shawn Domagal-Goldman	GSFC
Bertrand Mennesson	JPL

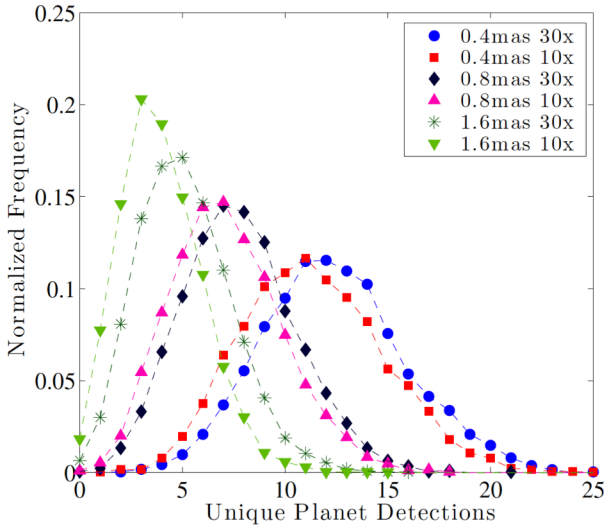
BACKUP

What is EXOSIMS?

https://github/dsavransky/EXOSIMS

- EXOSIMS
  - Open source. Python. Parametric. Probabilistic. Modular.
  - Creates ensembles of DRMs which can be analyzed statistically.



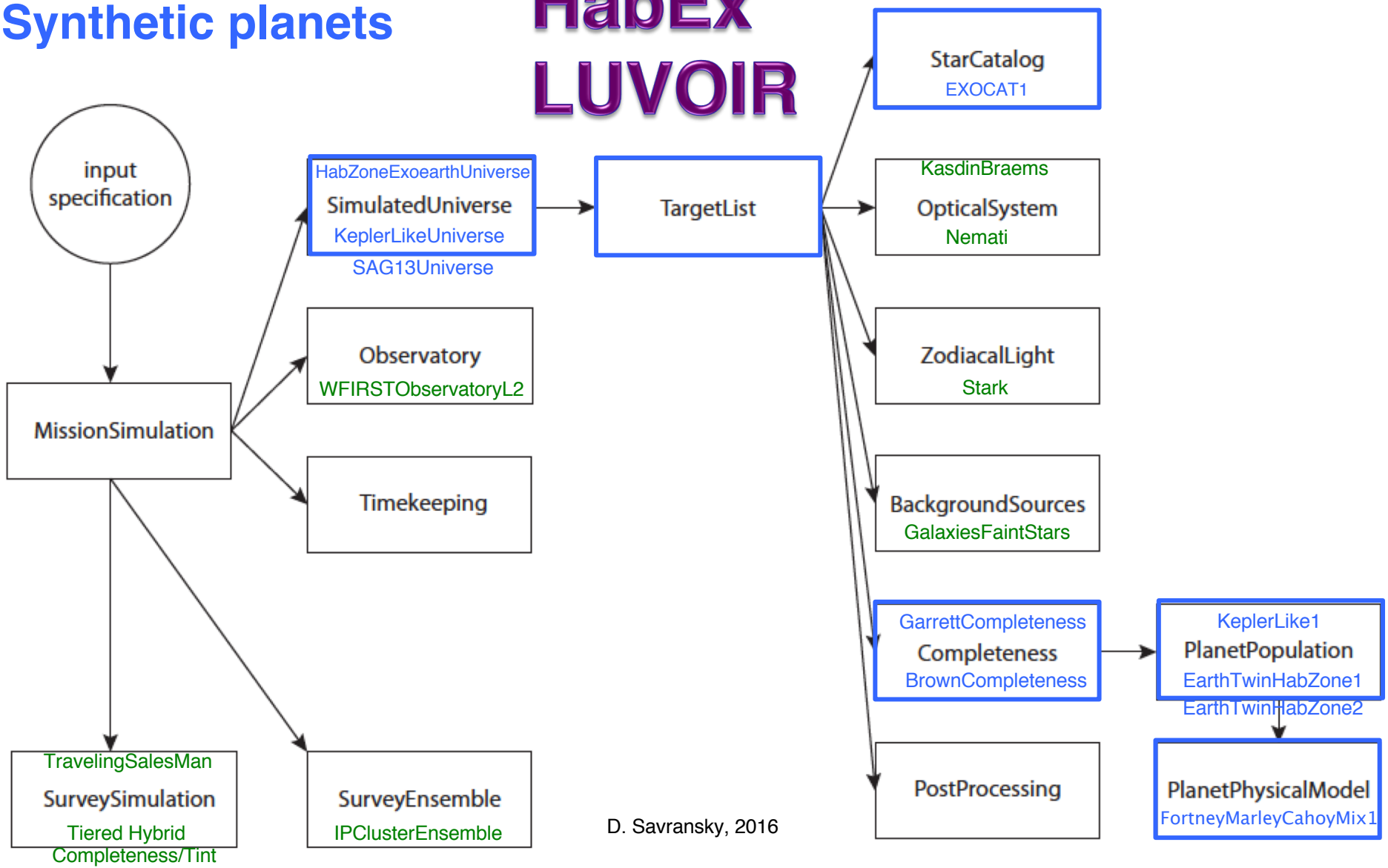


D. Savransky, et al., JATIS 2(1) 2016

EXOSIMS Architecture

Synthetic planets

HabEx
LUVOIR

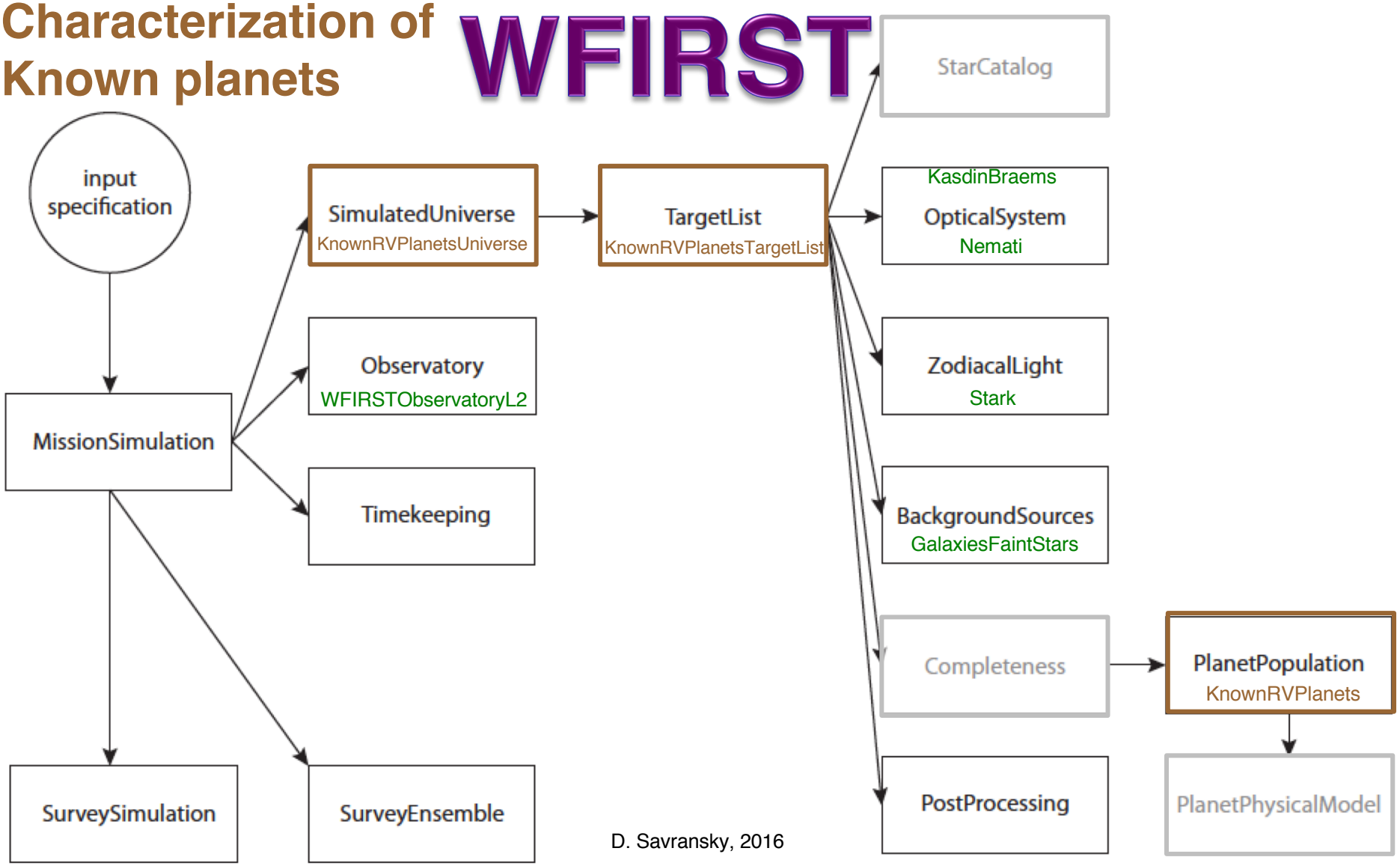


D. Savransky, 2016

EXOSIMS Architecture

Characterization of Known planets

WFIRST



D. Savransky, 2016

Inputs

ExEP Yield Input Parameters		
	Input	Notes
Astrophysics		
eta_earth	0.5	SAG-13 Integrated over box0.5< Rp 1.5 earth radius
planet radius	[0.5, 1.5] earth ra	log uniform random distribution
planet mass	1 earth mass	log uniform random distribution
geometric albedo	[0.2, 0.2]	Lambert phase function is used, uniform random distribution
semi-major axis	[0.75, 1.5] AU	log uniform random distribution
eccentricity	[0,0.35]	uniform random distribution
cos(inclination)	[-1, 1]	uniform random distribution
argument of perigree	[0, 360] degrees	uniform random distribution
ascension of the ascending node	[0, 360] degrees	uniform random distribution
exozodi mean and variance	23 mag/asec^2	constant, corrected for Mv
Telescope		
Diameter of pupil	4m, 6x4m, 6m	
obscuration factor	0	off-axis primary
throughput	0.6333	Telescope only, not coronagraph
Detection lambda	550 nm	
detection bandwidth	0.2	delta_lambda/lambda
SNR detection	5	
limiting deltamagnitude	26	
minimum completeness	0.1	

Inputs cont.

Occulters

Internal Coronagraph type	HLC	
IWA (only fixed by D)	2 lambda/D	
OWA	20 lambda/D	
Contrast	1.00E-10	
core throughput	2.00E-02	
core mean intensity	4.00E-14	
Throughput for Coronagraph	0.4	occ_trans for zodi transmission

Detectors

imaging or spectrometer	imaging	
dark current	5.00E-04	defaults are for WFIRST EM-CCD
readNoise	0.007 e-	
exposure time per frame	1000 sec	
QE	0.91	
pixelpitch	5.00E-06	
focal length		FHWM sampled by 3.3 pixels
CIC	3.00E-03	
ENF	1	
EM CCd gain	1	

Post Processing

post-processing contrast factor	1/10	input can be [0,1]. 1/10 and 1/30 are common

Mission

mission lifetime	3 years	
fraction to exoplanets	1	

HABEX WITH SAG-13 POWER LAW DISTRIBUTION

SAG13 Power Law parameters are Yield Simulation Inputs

Parametric fit (for G-dwarfs)

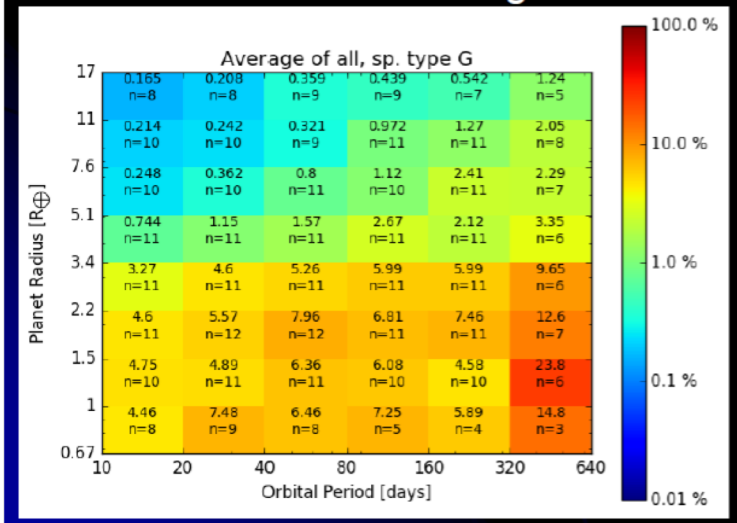
$$\frac{\partial^2 N(R,P)}{\partial \ln R\, \partial \ln P} = \Gamma_i R^{\alpha_i} P^{\beta_i} \quad \text{in region } R_{i-1} \le R < R_i$$

(R in Earth radius, P in years)

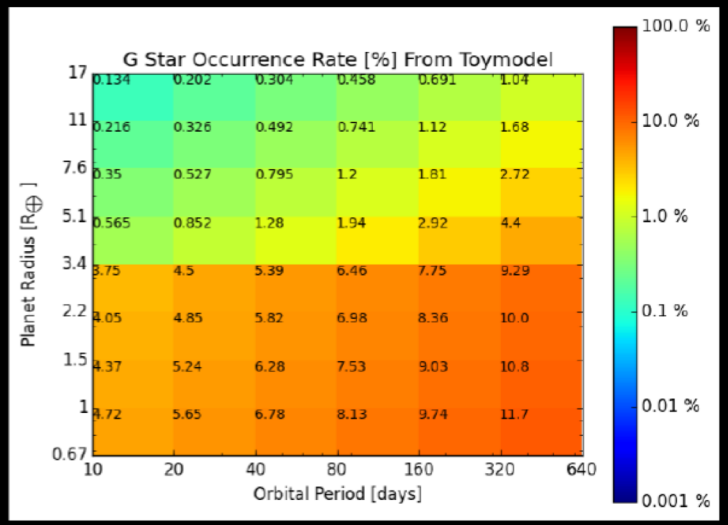
Two-piece broken power law →

i	Γ_i	α_i	β_i	R_i
1	**0.38**	**-0.19**	**0.26**	**3.4**
2	0.73	-1.18	0.59	Inf

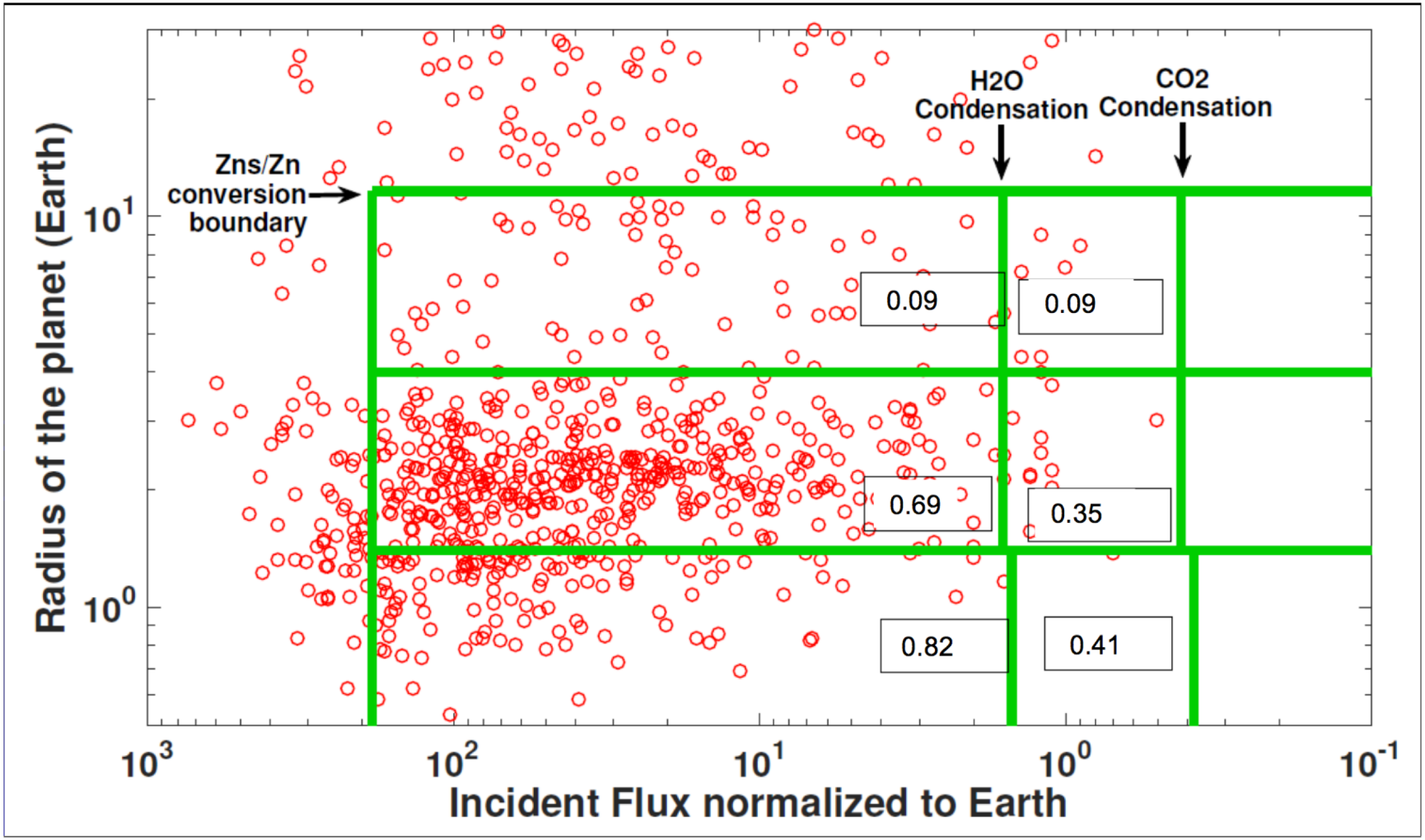
Submission average



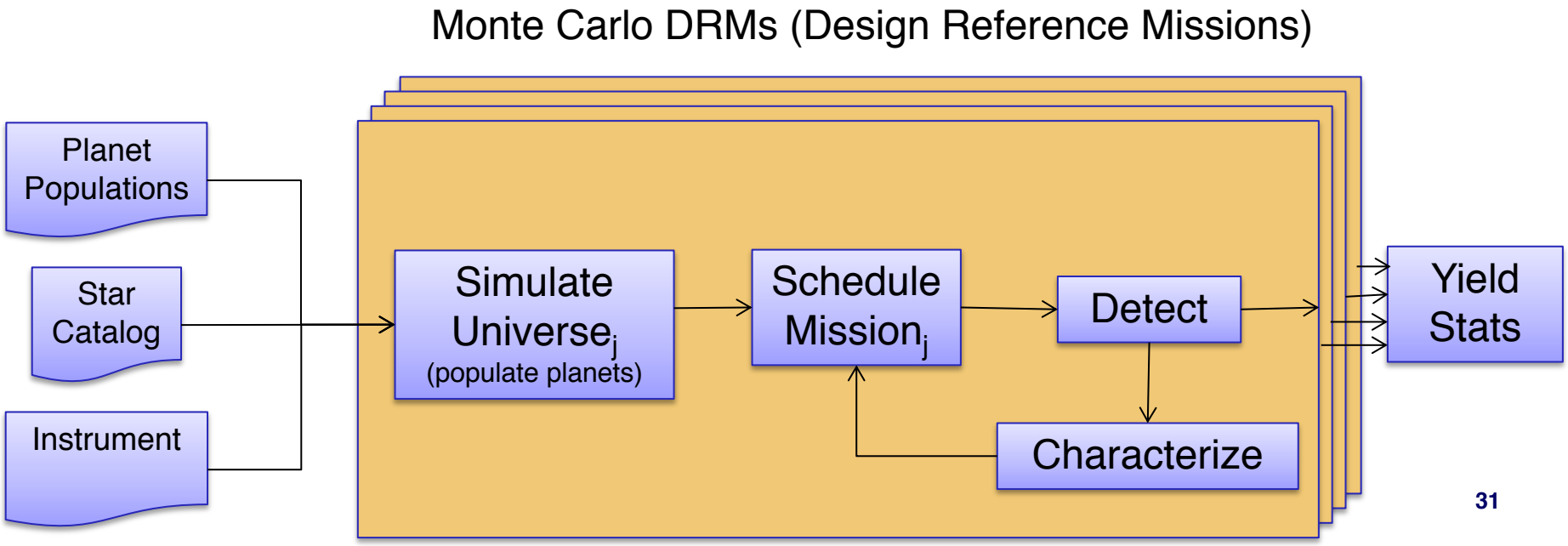
Parameteric fit (integrated across bins)



Planet Classifications



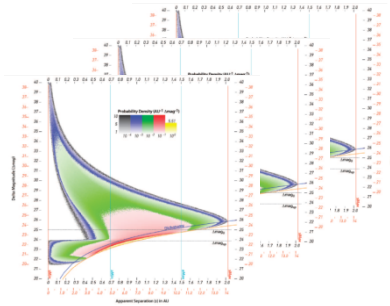
Simulated Mission Ensemble

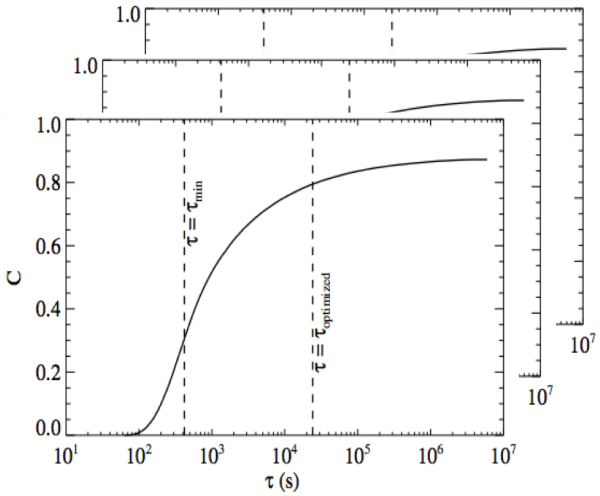


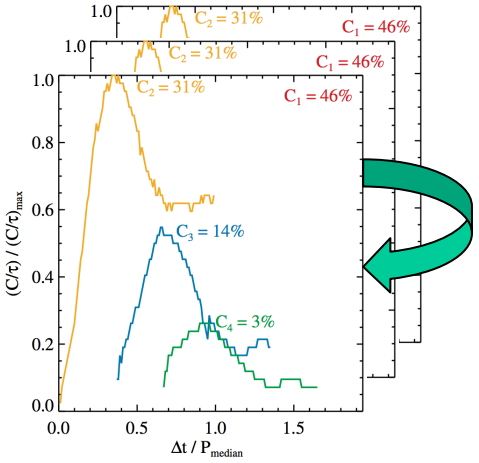
- Simulate a universe by sampling planet population distributions
- Schedule a mission using spacecraft and mission observing constraints
  - Dynamically respond to detections
- Repeat with a new universe 1,000 times

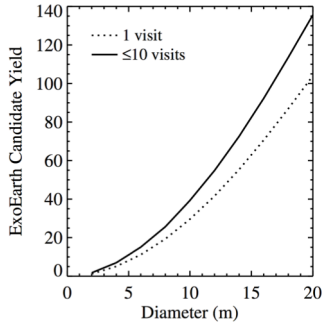
Chris Stark's AYO Approach

Completeness(T_{int})









Monte Carlo Planets around stars

Instrument

Optimize Int. Time Alloc.

Cumulative Completeness

Planet Classes

Star list

AYO: Altruistic Yield Optimization

Produces Static Time Budget