# ExEP Yield Modeling with EXOSIMS

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# Exoplanet Probe Studies

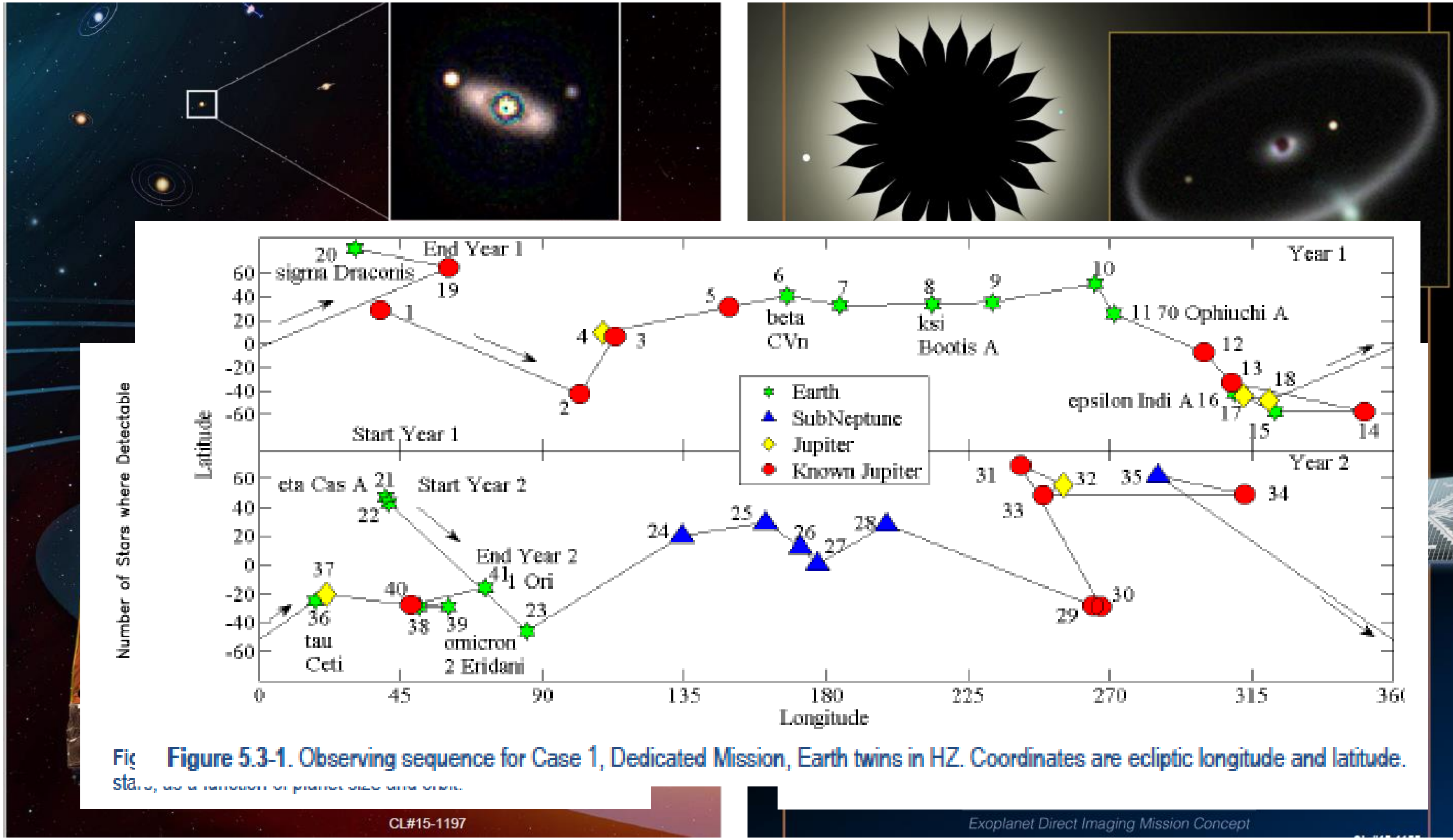



Figure 5.3-1. Observing sequence for Case 1, Dedicated Mission, Earth twins in HZ. Coordinates are ecliptic longitude and latitude.

# Yield Estimation for ExEP



- The Decadal concept studies include two studies featuring exoplanet science. In light of this, the Exoplanet Exploration Program Office commissioned the development of a yield model to be the **standard measure** of performance for work within the Exoplanet Program
  - The yield model will be **open source and distributable** for use by the community
- APD is chartering a Standards Definition and Evaluation Team to provide **transparent, common** exoplanet science yield estimates for Decadal missions and probes.
  - Standards team promotes **standard and consistent** definitions of inputs and outputs for purposes of yield comparison
  - Draft charter: https://exep.jpl.nasa.gov/reportsAndDocuments/

# ExEP Yield Tool



**Objective**:

1. A tool capable of the **consistent comparison** of the science performance of the full range of expected exoplanet mission concepts for the next Decadal Survey

   Coronagraph  starshade  segmented aperture  filled aperture

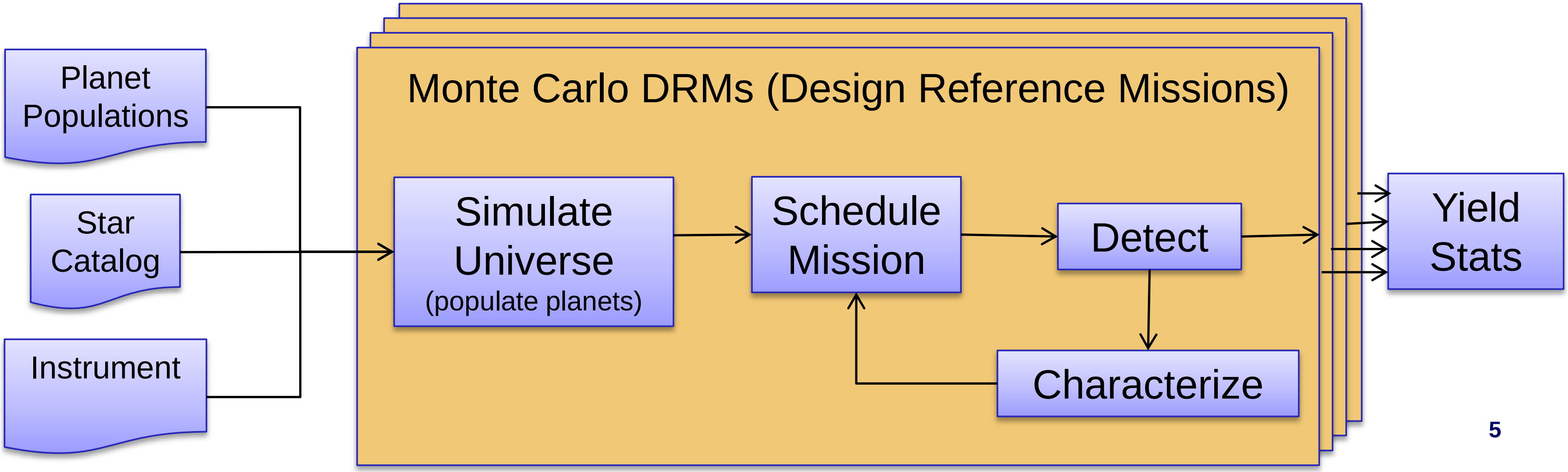
2. Validate the tool in a transparent manner to enable confidence in the tool

**Approach**: Utilize, expand, and validate the EXOSIMS framework:

- Modular
- Open Source
- Legacy

# Simulated Mission Ensemble





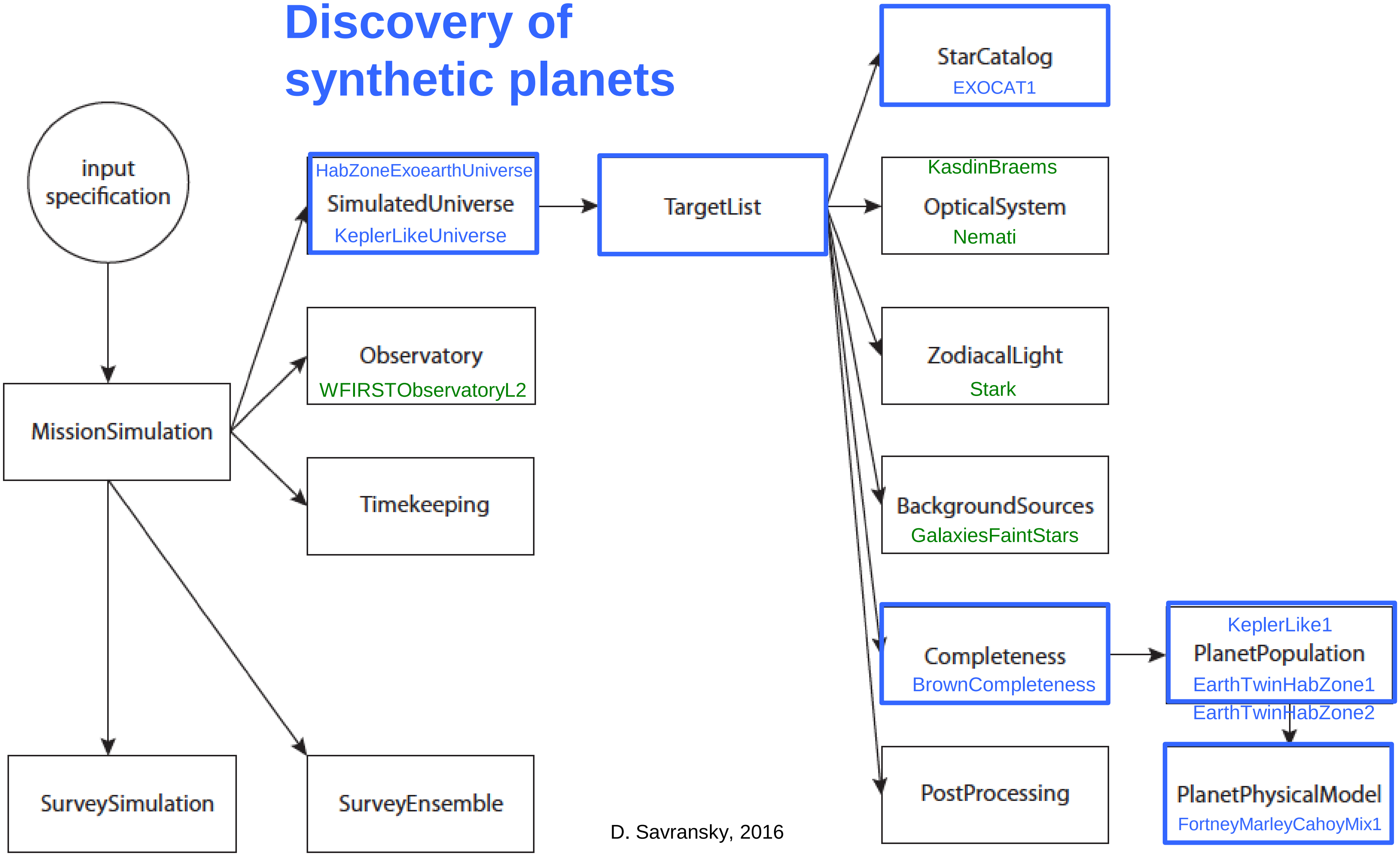



- Simulate a universe by sampling planet population distributions
- Schedule a mission using spacecraft and mission observing constraints
  - Dynamically respond to detections
- Repeat with a new universe 1,000 times

# EXOSIMS Architecture



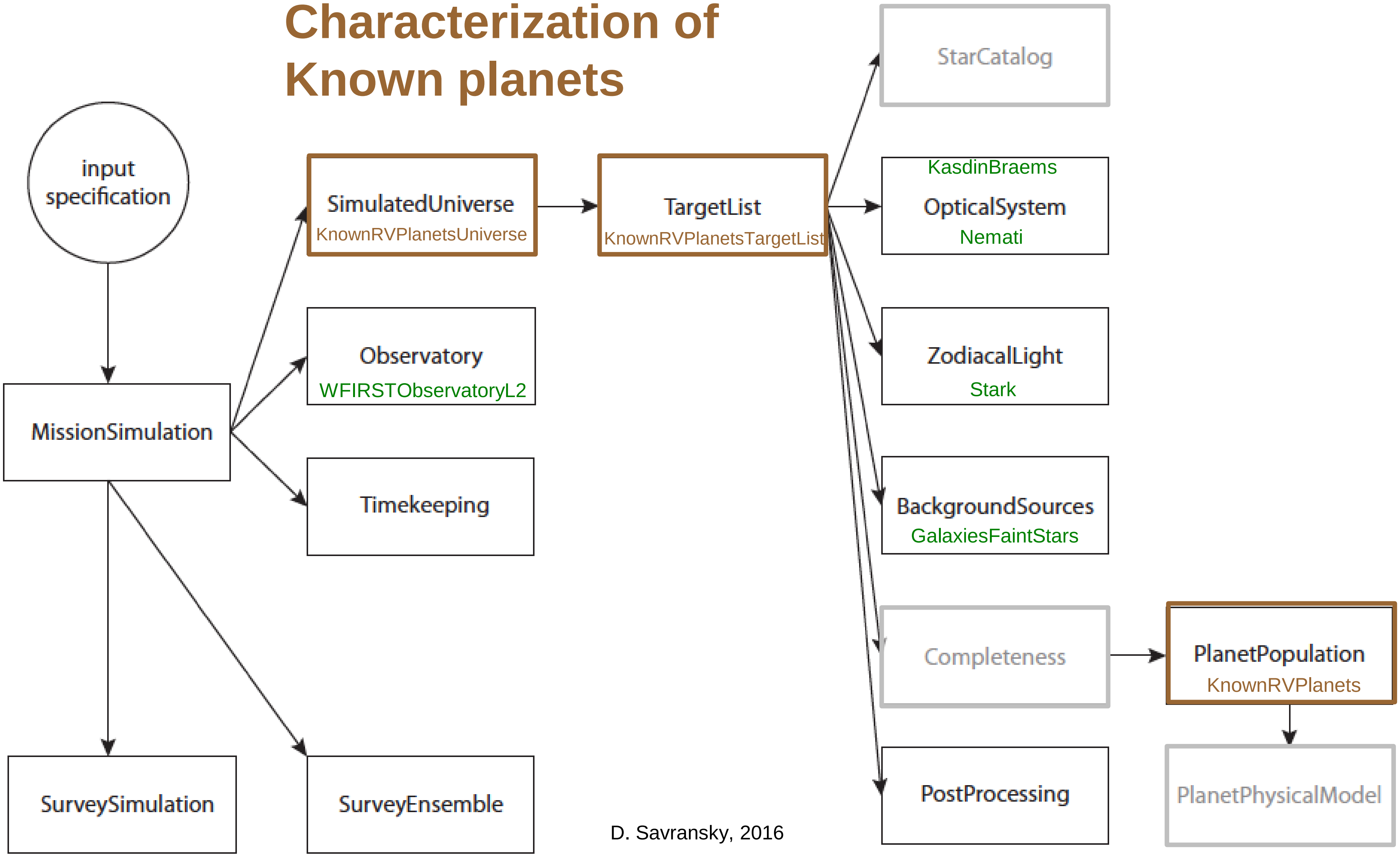
## Discovery of synthetic planets




D. Savransky, 2016

# EXOSIMS Architecture

## Characterization of Known planets




D. Savransky, 2016

# Code Validation is Important

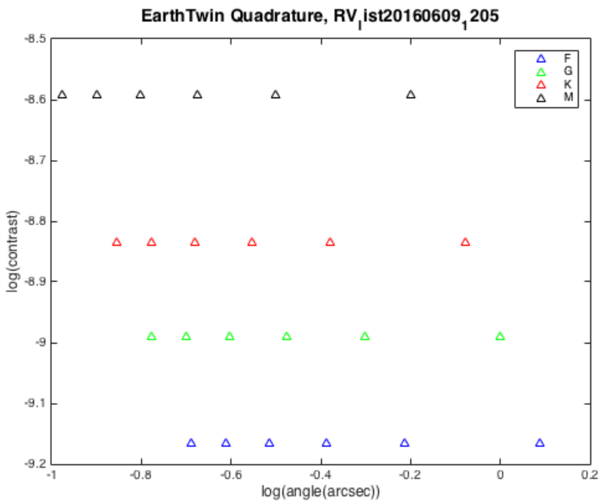
- **Validate the science calculation**
- **Validate software function**

***3150 lines of source code and 166 sub-functions***

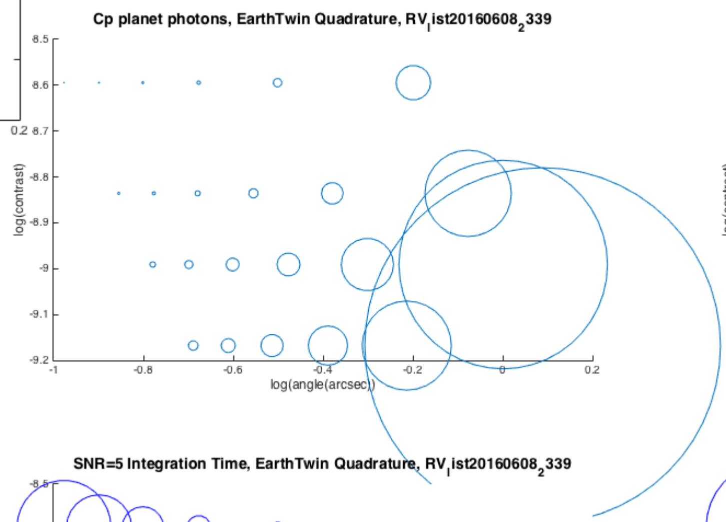
**1. Unit Tests**
   - Each sub-function of each module is tested
   - Write Python code to automatically verify expected values of test cases
     - Test code will be posted to github EXOSIMS repository
   - Unit tests are 75% complete.
   - Dozens of bugs identified and fixed

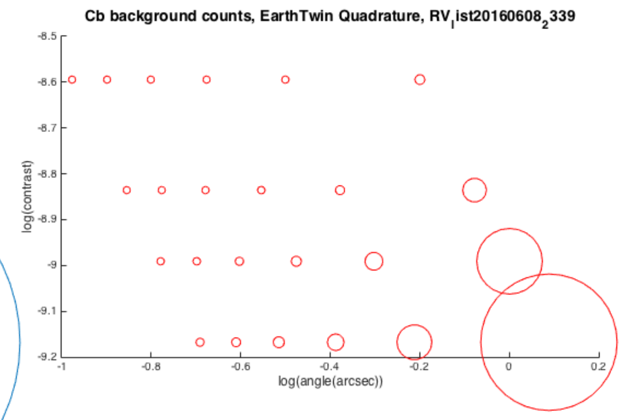
**2. End-to-End** Cross Validation
   1. Chris Stark's AYO code using standard inputs (ExoCat starlist, SAG13 occurrences) for Decadal Mission Concept Studies

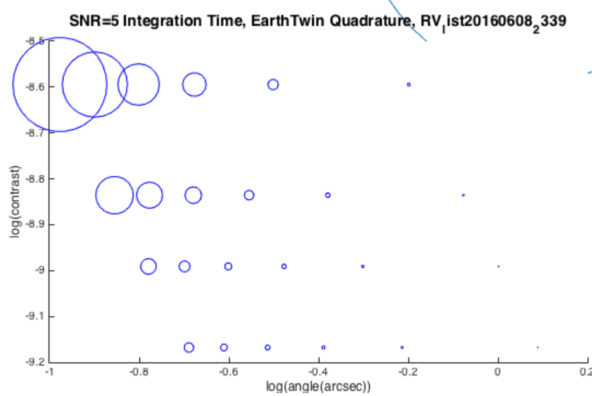
# Toy Universe for Point Checks

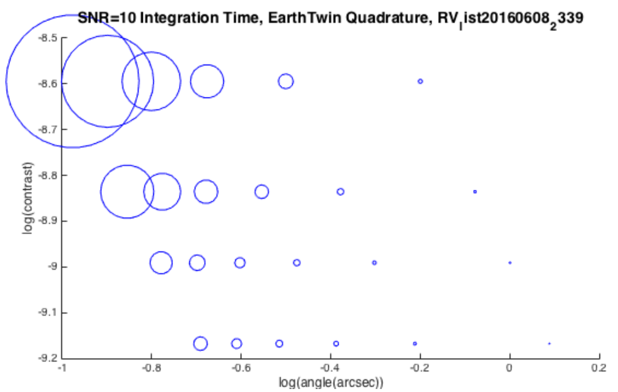



F,G,K,M stars at [5:5:30] pc



# Unit Testing is not Enough

# Yield Estimation for ExEP



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# Exoplanet Standard Definitions and Evaluation Team

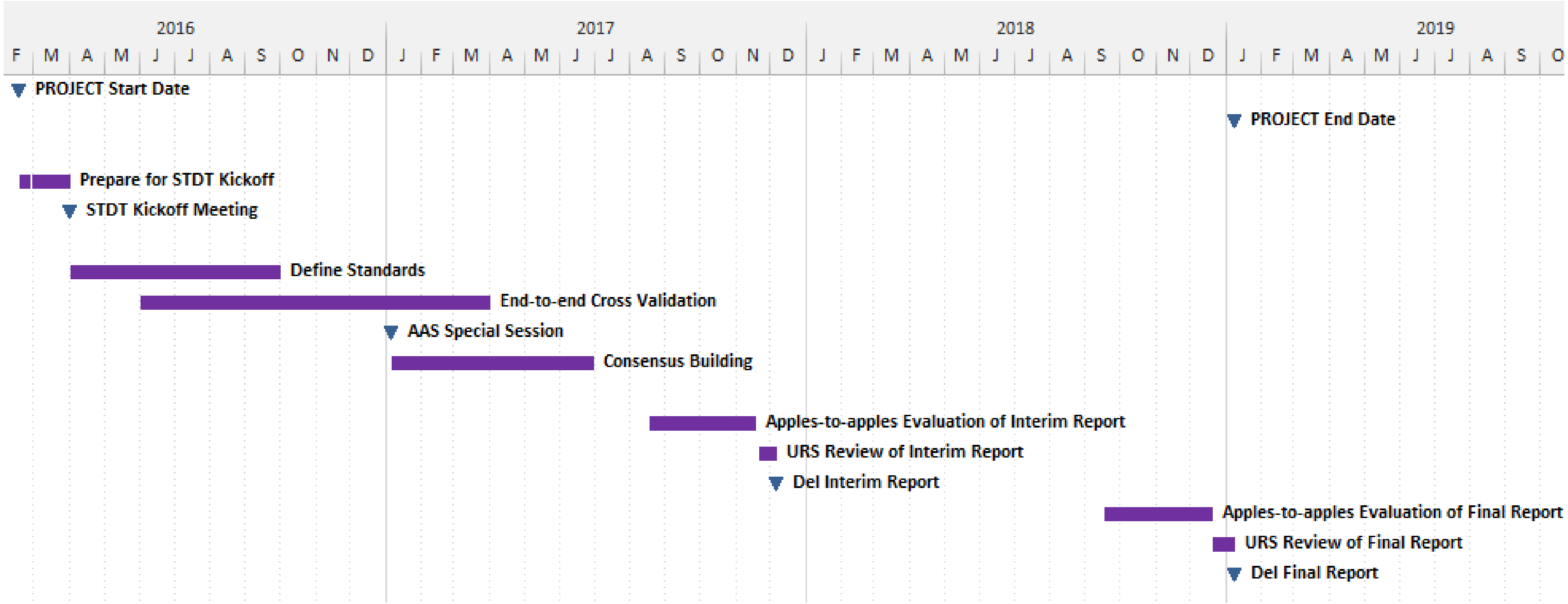


| Team Member | Affiliation |
| --- | --- |
| Dr. Rhonda Morgan | Lead, NASA ExEP, JPL |
| Dr. Bruce Macintosh | Stanford University |
| Dr. Dmitry Savransky | Cornell University |
| Dr. Chris Stark | Space Telescope Science Inst. |
| Dr. Avi Mandell | NASA Goddard Space Flight Center |
| Dr. Ruslan Belikov | NASA Ames Research Center |
| Dr. John Krist | NASA Jet Propulsion Laboratory |
| STDT Liaisons | Study, Affiliation |
| Dr. Courtney Dressing | LUVOIR, California Institute of Technology |
| Dr. Karl Stapelfeldt | HabEx, NASA ExEP, JPL |

- ExSDET will work with STDTs to adopt science metrics and common definitions and to iterate with the teams
- ExoTAC (Alan Boss, Chair) will perform independent review of the ExSDET deliverables, as they have for prior comparison studies

# Deliverables

- Main deliverables
  - Interim Report apples-to-apples comparison
  - Final Report apples-to-apples comparison
- Enabling deliverables
  - Definition and Concurrence on
    - Inputs
    - Assumptions
    - Output Metrics
  - Cross Validate EXOSIMS and AYO




Schedule synced to Decadal_Studies_Management_Plan_2015_12_28_final.pdf
Subject to approval by APD via PPBE

# Occurrence Inputs from SAG-13

SAG-13

## List of final deliverables (end of 2016)

- Proposed conventions for binning planet periods, sizes, and star temperatures (done)
- Living repository of occurrence rate datasets submitted by scientists (done)
- Code to visualize them and compute (first version done, evolving)
  - 3D matrix of SAG13 bin values representing a combination of all submissions [done, evolving]
  - 3D matricies showing variances and uncertainties in the values [done, evolving]
  - Some parameter related to eta_Earth, but much simpler, e.g. eta_[0.5-1.5]_[237-860d] (or define actual eta_Earth in terms of a region in R, P, T space and compute that?)
  - Gamma_Earth
- Analysis of variances and discrepancies between submissions, tracing the fundamental cause of each variance
- For regions where extrapolation is still necessary, recommended standard "pessimistic", "default", and "optimistic" assumptions for cases where an assumption has be made in mission studies.

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With additional guidance for extrapolation to longer period, large radii planets

# Possible Metrics

## Metrics should enable insight



### Fidelity of Classes/Bins

- Metrics should be reported at the fidelity of
  - Planet class
  - Spectral type
  - Most likely in correspondence with the inputs, e.g. the SAG13 bins

### Detection Statistics on a population:

- The widely used definition of Yield is
  - $Yield = \eta \sum_{i}^{N} C_i$
- We would like to provide additional information about the distribution of Probability of detection over the ensemble. Options include:
  - Providing Yield at the 95 percent confidence interval
  - $\sigma^2 = \sum_{i}^{N} \eta C_i (1 - \eta C_i)$ variance of the Poisson Binomial distribution
  - Or a Poisson Binomial distribution histogram
  - And include the sample size (stars observed)
- Probability of Not detecting any planets (True Negative):
  - $P_{NOT_N} = (1 - \eta_E C_i)(1 - \eta_E C_j) \ldots (1 - \eta_E C_N)$
- The Probability of Detecting at least *1* planet is

$$P_{ATLEAST1} = 1 - P_{NOT_N}$$

- Yield with $\sigma$ as a function of time (a plot), or in the first epoch, e.g. year.

# Possible Metrics (cont.)

## Characterization Metrics

  - Number of planets characterized (to desired BW & SNR)
  - Or the achieved SNR for key wavelengths for each planet
  - The time resolution of spectral observations (e.g., # spectrally characterized as a function of integration time at some given wavelength, SNR, and R)
  - Observing time spent on characterization
- The inclusion of revisits in the model can inform the probability of performing an orbital fit
  - Minimally, this metric is number of planets with orbital fits
  - Maximally, this metric address the goodness of fit as a function of number of revisits and epochs
  - Possibly how many detected planets' orbits can be constrained (e.g., # of planets detected > x times?)

## Mission/Technology Figures of Merits

- Fraction of Time spent integrating on detection and on characterization
- Fuel use (for star shades)

https://docs.google.com/document/d/1lS2-5u7zQwpIzVgSEiFJn7eRuuARLxSjqXYs0MVLHc0

# BACKUP

# Draft Input Parameter Request

ExoPlanet Exploration Program

ExEP Yield Input Parameters

| | Input | Default | Notes |
|---|---|---|---|
| **Astrophysics** | | | |
| type of planets | | EarthTwin | uniform random, keplerLike, KnownRV |
| EarthTwin | | | |
| eta_earth | | 0.16 | |
| planet radius | | 1 earth radius | |
| planet mass | | 1 earth mass | |
| geometric albedo | | 0.2 | Lambert phase function is used |
| semi-major axis | | [0.75, 1.5] AU | 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 |
| Zodical Light model | | Stark | local zodi, interpolates for longitude |
| exozodi mean and variance | | 22 mag/asec^2 | no spatial variance. Variance is log normal star to star. |

**Telescope**

| | Input | Default | Notes |
|---|---|---|---|
| Diameter of pupil | study parm | | |
| shape factor | | pi/4 | shapeFac * D^2 = Area |
| obscuration factor | | 0.2 | due to spiders, secondary |
| throughput | | 0.57 | Telescope only, not coronagraph |
| telescope keep out angle | | 45 degrees | sun avoidance |
| Detection lambda | | 550 nm | |
| detection bandwidth | | 0.2 | delta_lambda/lambda |
| Spectra central lambda | | 550 nm | |
| spectral BW | | R 70 | |
| SNR detection | | 5 | |
| SNR characterization | | 10 | |
| limiting deltamagnitude | | 26 | |
| minimum completeness | | 0.1 | |
| integration time cutoff | | 30 days | maximum allowed integration time |

**Occulters**

| | Input | Default | Notes |
|---|---|---|---|
| Internal Coronagraph type | | HLC | |
| IWA | | 2.5 lambda/D | |
| OWA | | 10 lambda/D | |
| Contrast | | | |
| Throughput for Coronagraph | | | |
| delta_mag limit | | 26 | |
| DetectionTimeMultiplier | | 1 | 2 for polarizations, another 2 for RDI |
| CharacterizationTime Multiplier | | 1 | 2 for polarizations |
| Optical Overhead time | | 1 day | |
| starshade diameter tip to tip | | | |
| number of starshade distances | | | |
| starshade distance | | | km |
| starshade blue edge | | | nm |
| starshade red edge | | | nm |

**Detectors**

| | Input | Default | Notes |
|---|---|---|---|
| imaging or spectrometer | | | |
| dark current | | 0.00009 e-/s | defaults are for WFIRST EM-CCD |
| readNoise | | 3 e- | |
| exposure time per frame | | 1000 seconds | |
| QE | | 0.88 | |
| R | | 70 | |
| CIC | | 0.0013 | |
| ENF | | 1.414 | sqrt(2) |
| EM CCd gain | | 500 | |

**Post Processing**

| | Input | Default | Notes |
|---|---|---|---|
| post-processing contrast factor | | 1/10 | input can be [0,1]. 1/10 and 1/30 are common |
| allowable false alarm probability | | 3.00E-05 | |
| allowable missed detction probability | | 1.00E-03 | |

**Mission**

| | Input | Default | Notes |
|---|---|---|---|
| mission lifetime | | 5 years | |
| fraction to exoplanets | | 0.5 | |
| start date | | January 1, 2036 | |

**Observatory**

| | Input | Default | Notes |
|---|---|---|---|
| settlingTime | | 1 day | after repointing, especially for occulter formation flying |
| occulter slew thrust | | 450 mN | |
| occulter slew Isp | | 4160 | specific impulse |
| occulter initial wet mass | | 6000 kg | |
| Telescope spacecraft mass | | 5800 kg | |
| occulter station keeping Isp | | 220 | specific impulse |
| default burn portion for slew | | 0.05 | |