Optimizing exoplanet direct imaging observations with precursor radial velocity data

Corey Spohn[1,2], Dmitry Savransky[1,2]

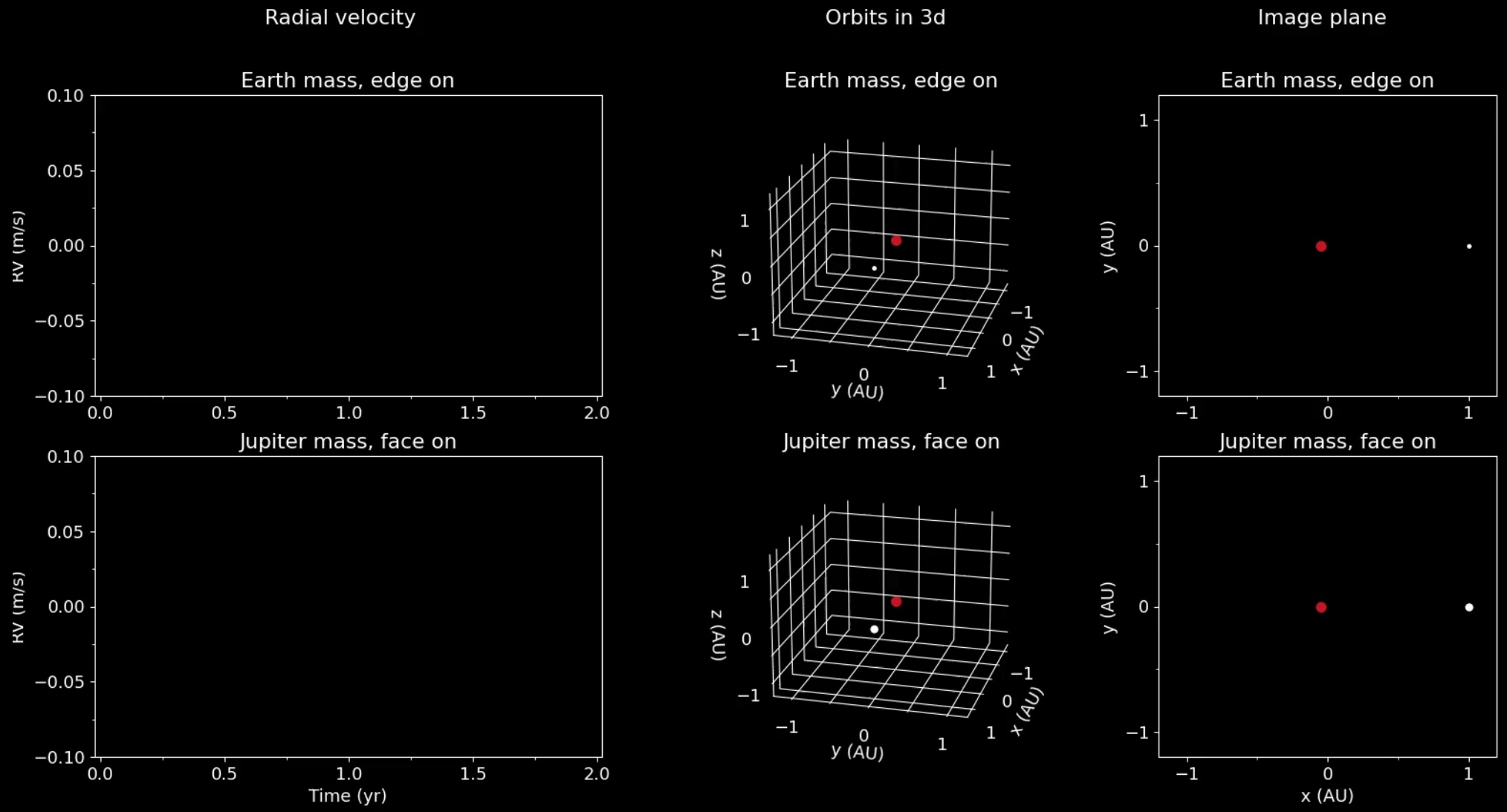
[1]Cornell University

[2]Carl Sagan Institute

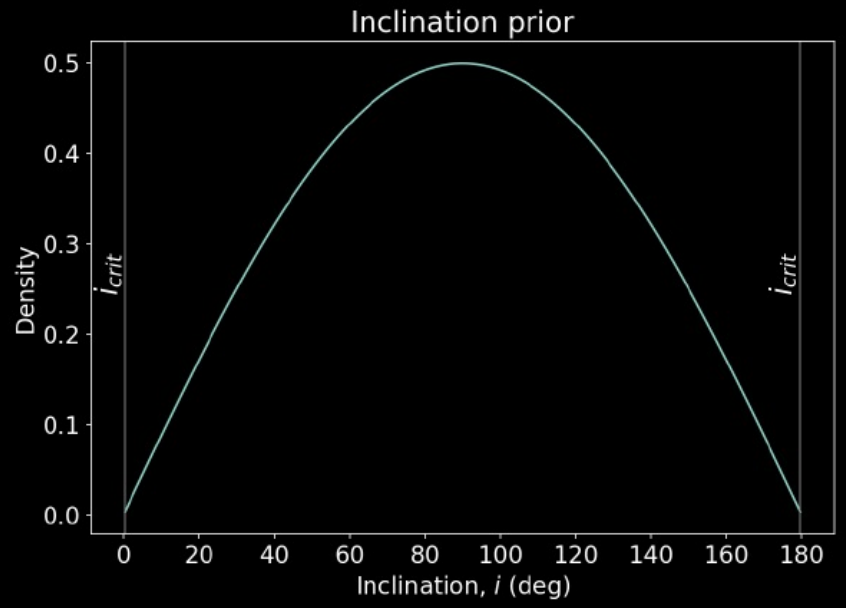
The goal

Maximize the number of direct imaging detections by using radial velocity (RV) data for observation scheduling

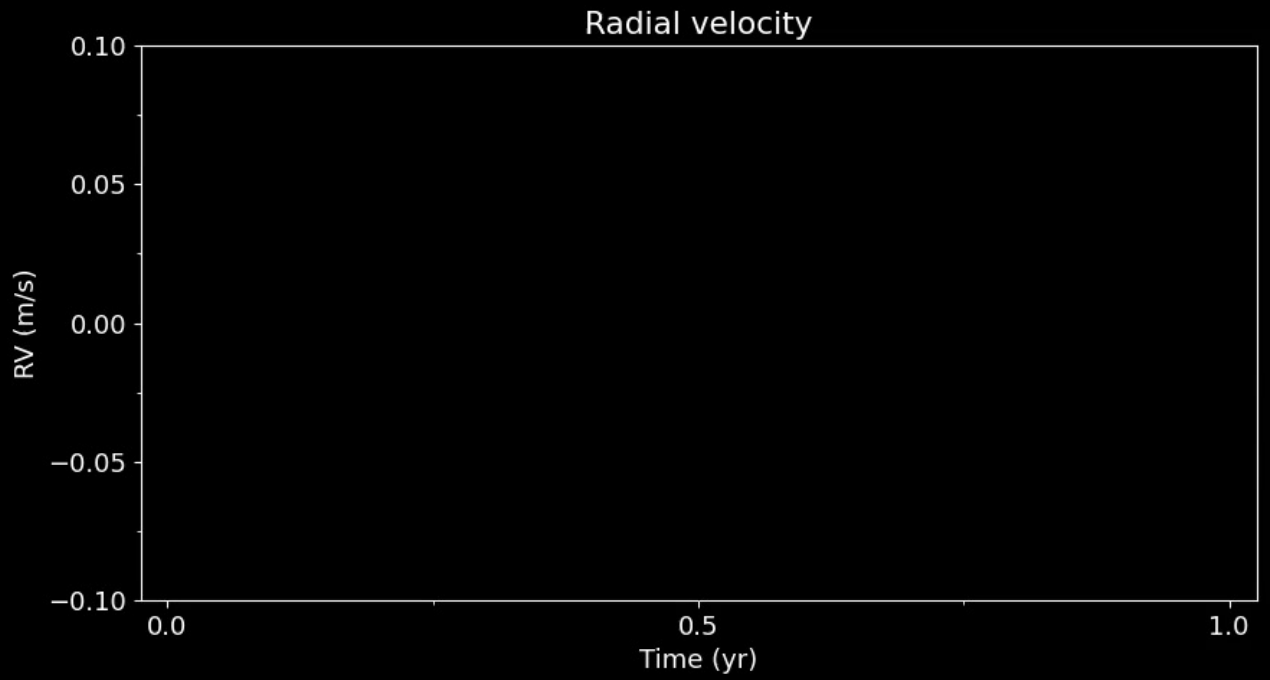
The main problem

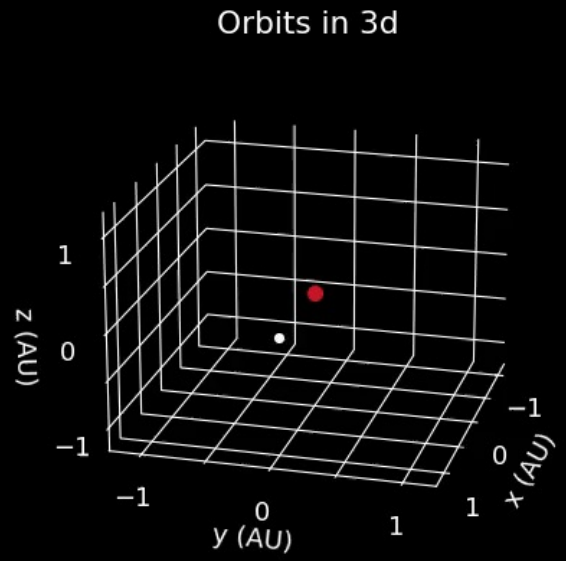


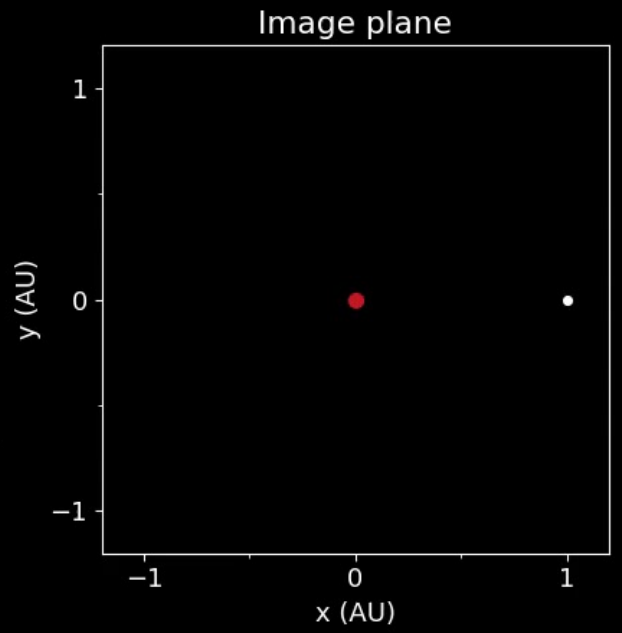
Sampling inclinations



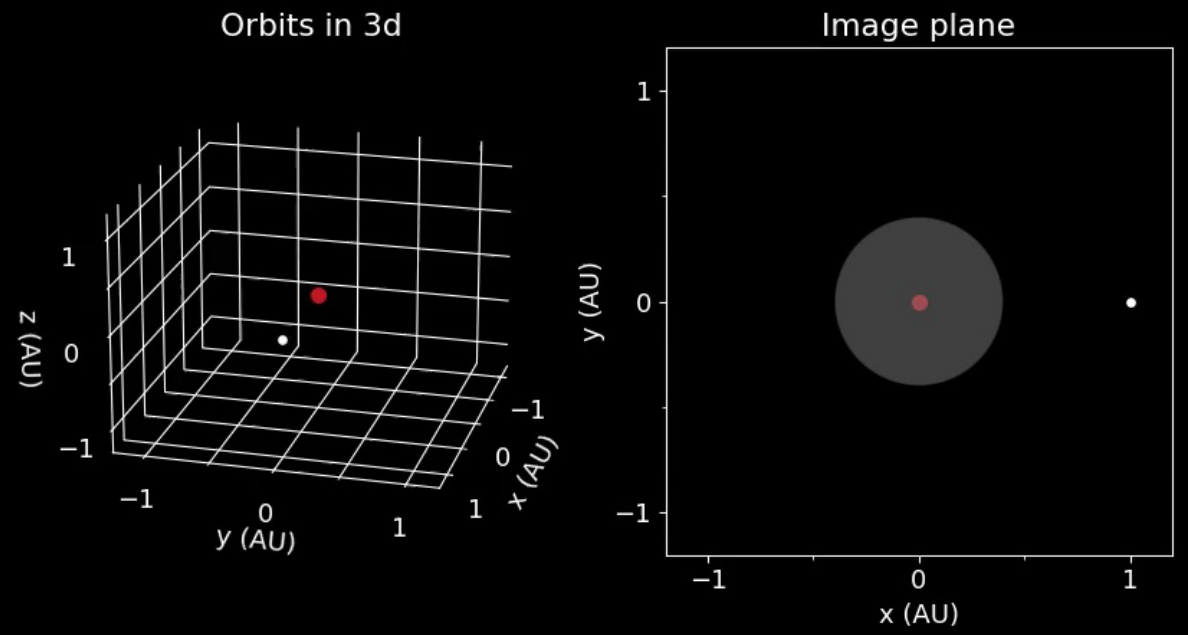
$$i_{\rm crit} = \sin^{-1}\left(\frac{M_p \sin i}{0.08 M_\odot}\right)$$

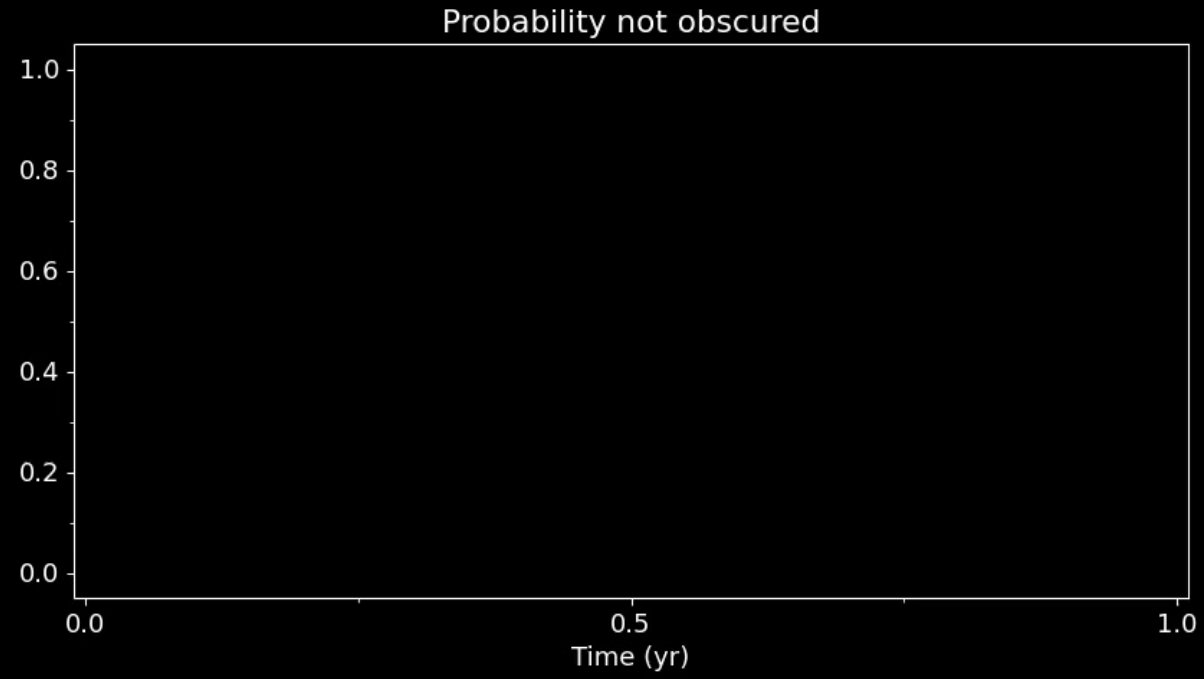




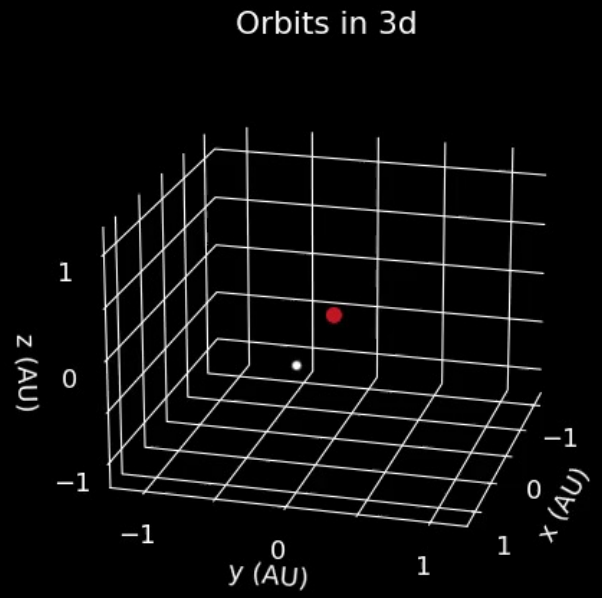


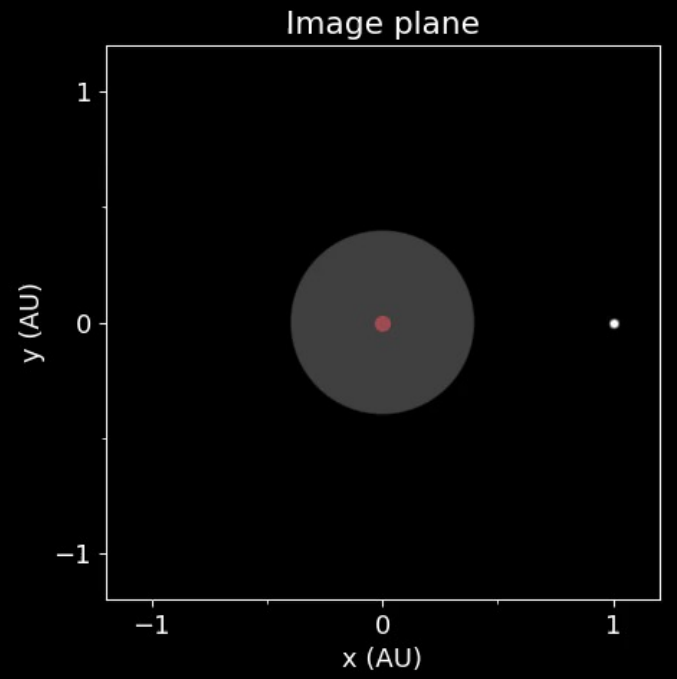
Obscuration constraint

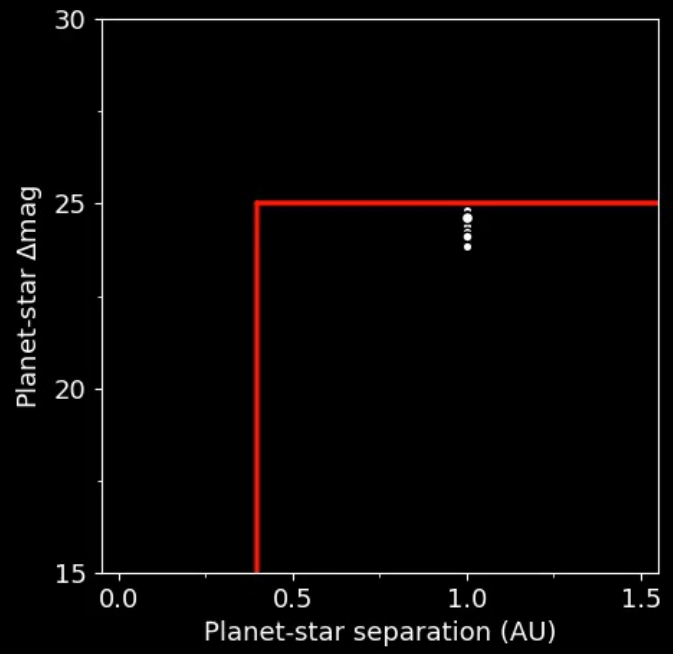


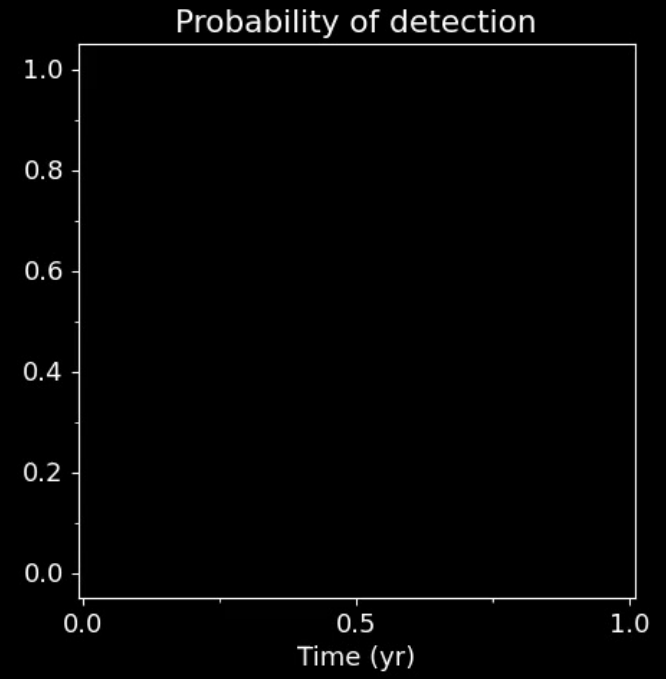


Photometric constraint

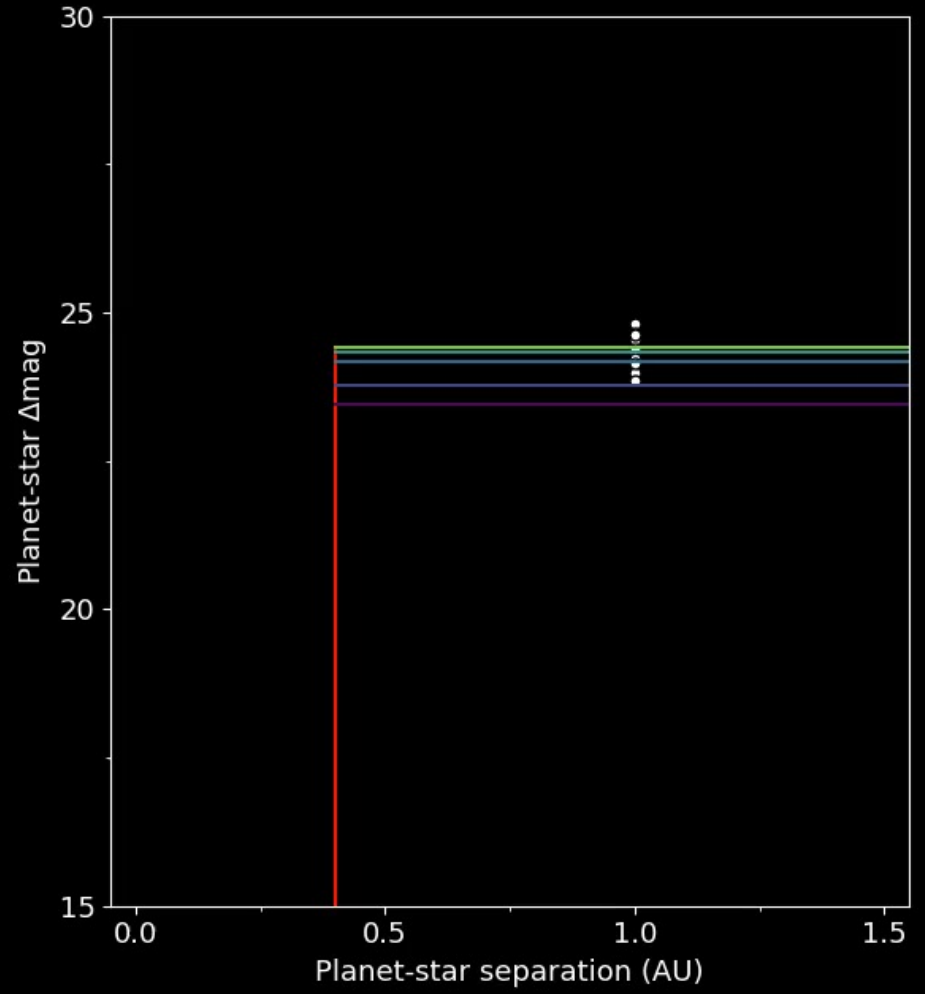


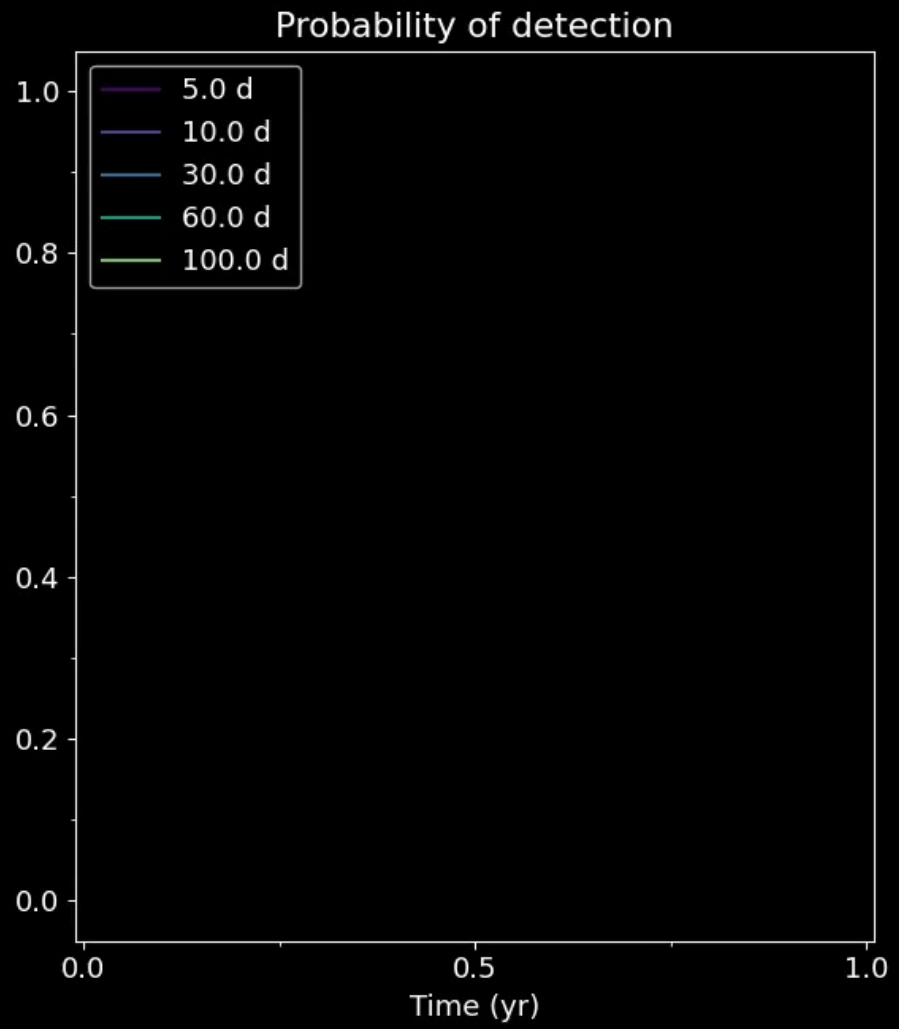




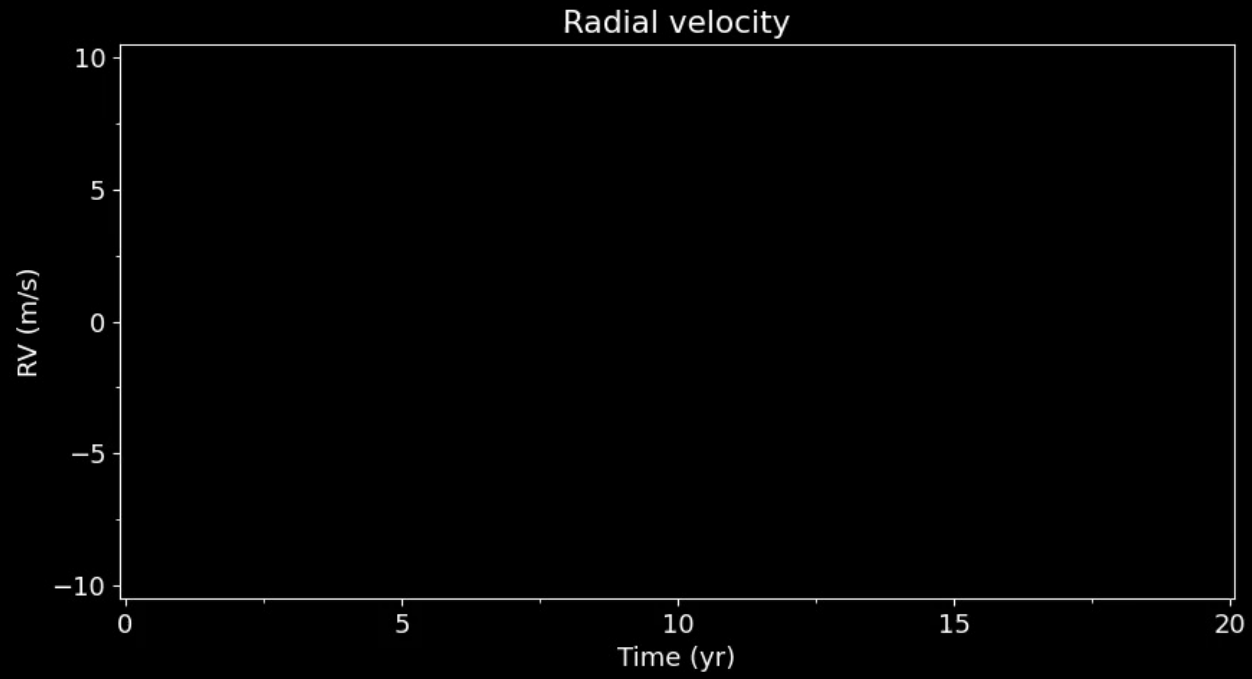


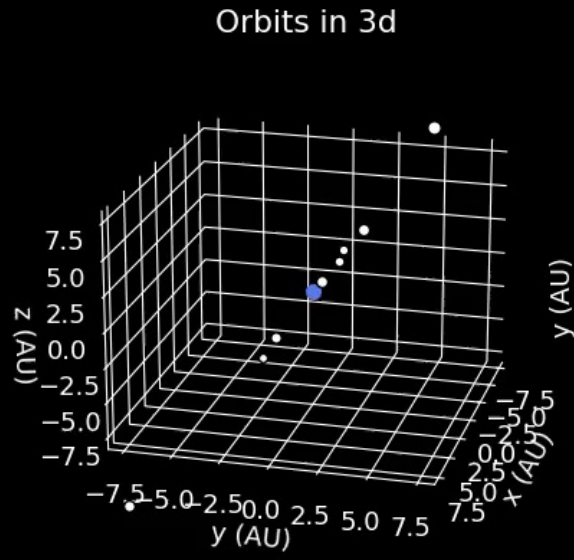
Integration time

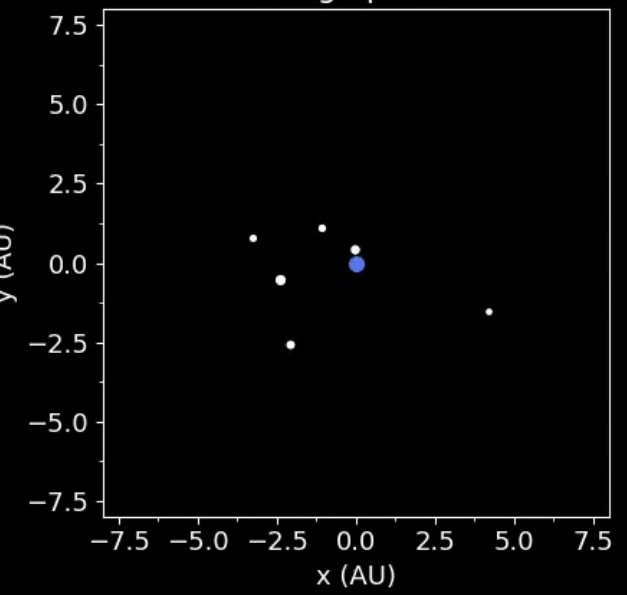




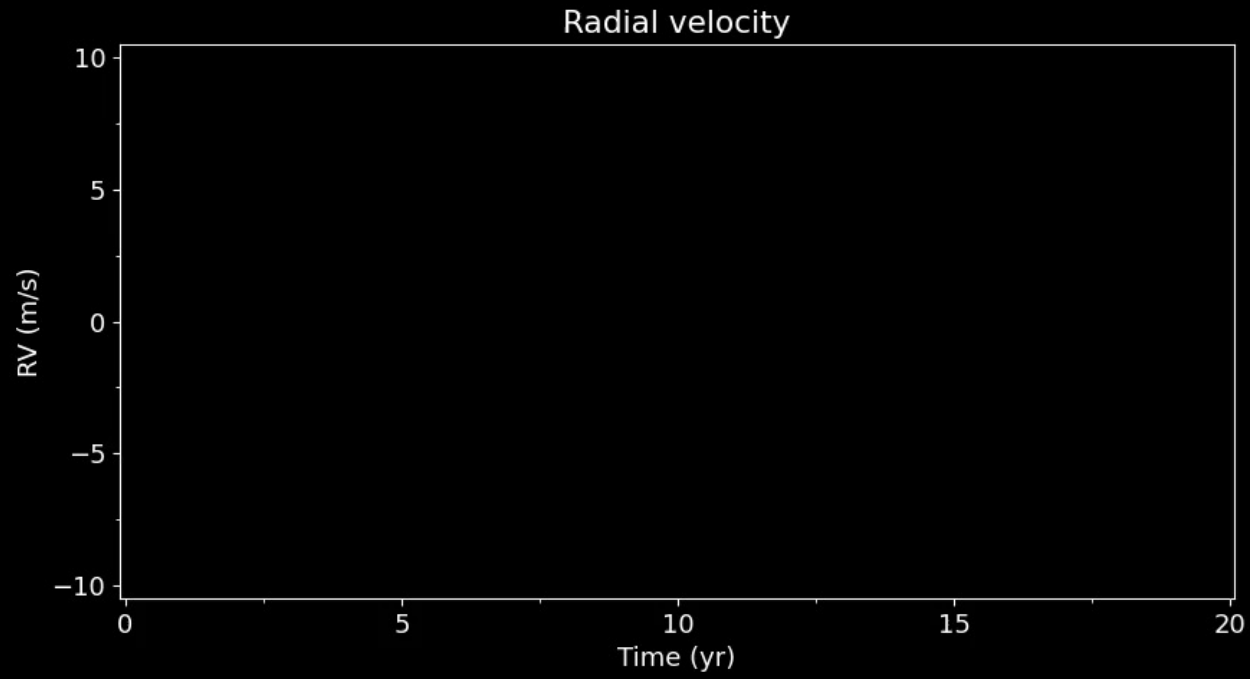
The real world

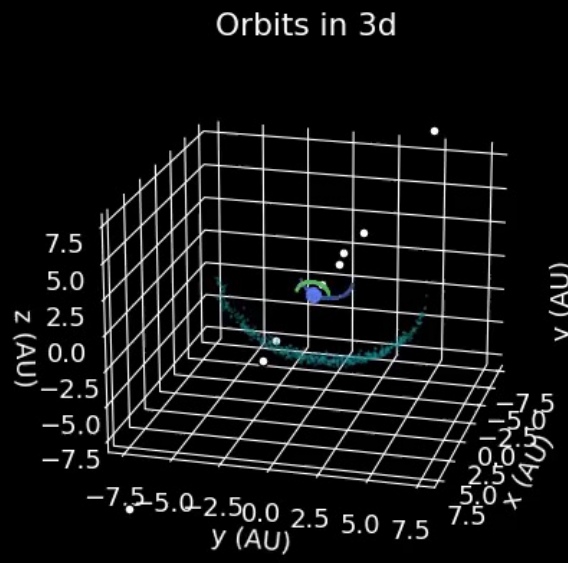


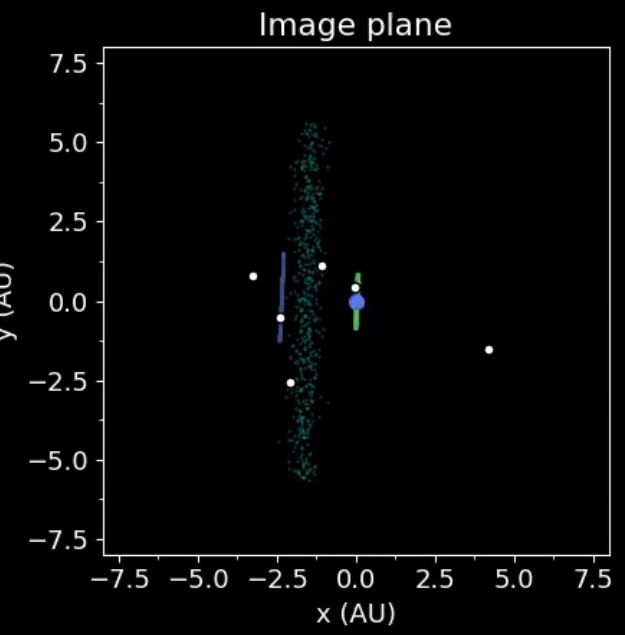




Multi-planet fitting and orbit construction

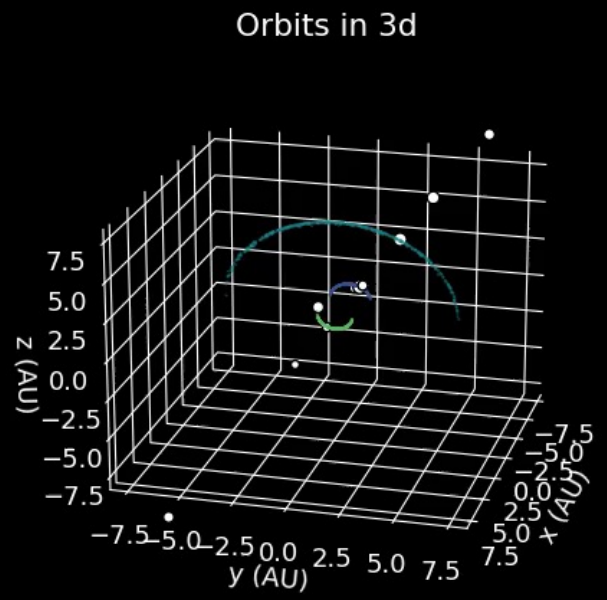


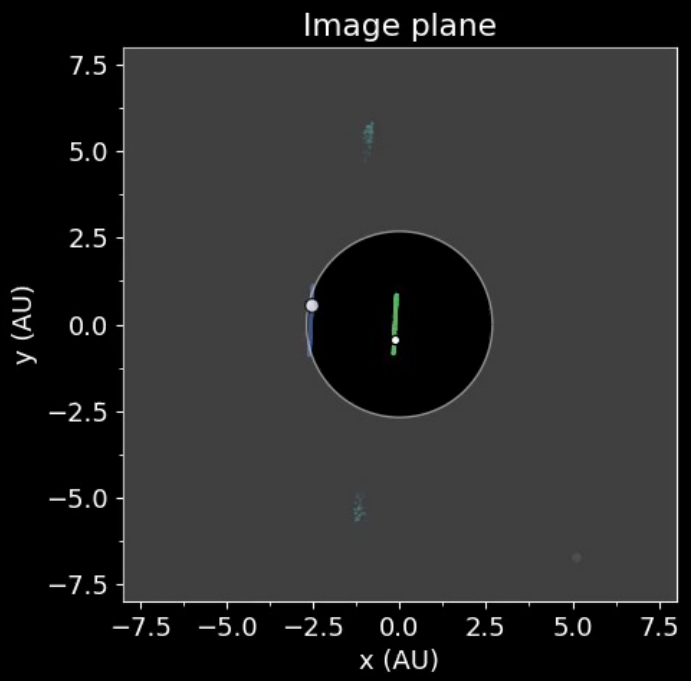


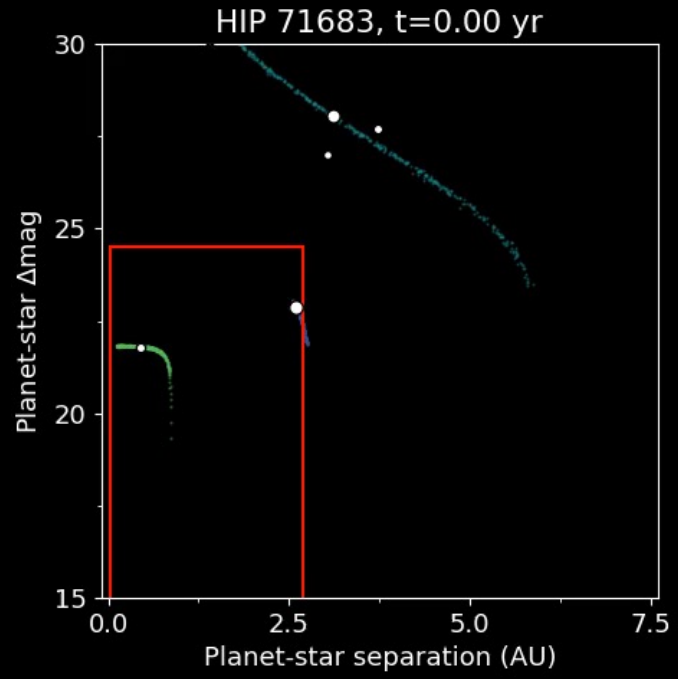


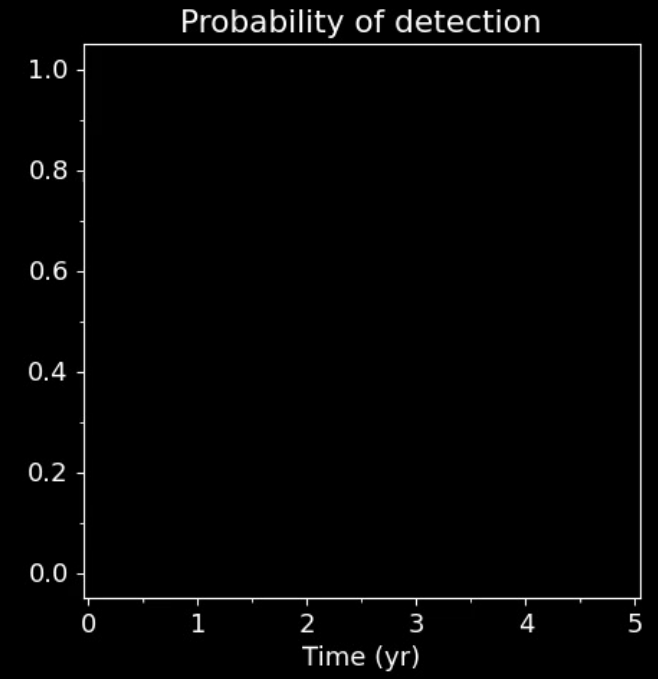
1. Rosenthal, L. J. *et al.* The California Legacy Survey. I. A Catalog of 178 Planets from Precision Radial Velocity Monitoring of 719 Nearby Stars over Three Decades. *ApJS* **255**, 8 (2021).

Multi-planet probability of detection









Optimization

$$\underbrace{\begin{bmatrix} P_{1,1,1} & P_{1,1,2} & \cdots P_{1,1,n} & P_{1,2,1} & P_{1,2,2} & \cdots & P_{1,n,m} \\ P_{2,1,1} & P_{2,1,2} & \cdots P_{2,1,n} & P_{2,2,1} & P_{2,2,2} & \cdots & P_{2,n,m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & & \vdots \\ P_{l-1,1,1} & P_{l-1,1,2} & \cdots P_{l-1,1,n} & P_{l-1,2,1} & P_{l-1,2,2} & \cdots & P_{l-1,n,m} \\ P_{l,1,1} & P_{l,1,2} & \cdots P_{l,1,n} & P_{l,2,1} & P_{l,2,2} & \cdots & P_{l,n,m} \end{bmatrix}}_{P_{i,j,k} = \text{ probability of detecting planet } i \text{ if star } j \text{ is observed at time } k} \underbrace{\begin{bmatrix} \text{obs}_{1,1} \\ \vdots \\ \text{obs}_{1,n} \\ \vdots \\ \text{obs}_{m,n} \end{bmatrix}}_{\text{Star/time observations}} > \underbrace{\begin{bmatrix} 3 \\ \vdots \\ 3 \\ \vdots \\ 3 \end{bmatrix}}_{\text{Constraints}}$$

$$\text{Objective: minimize} \sum_{j,k} \text{obs}_{j,k}$$

Mixed Integer Problem that can be solved using OR-Tools

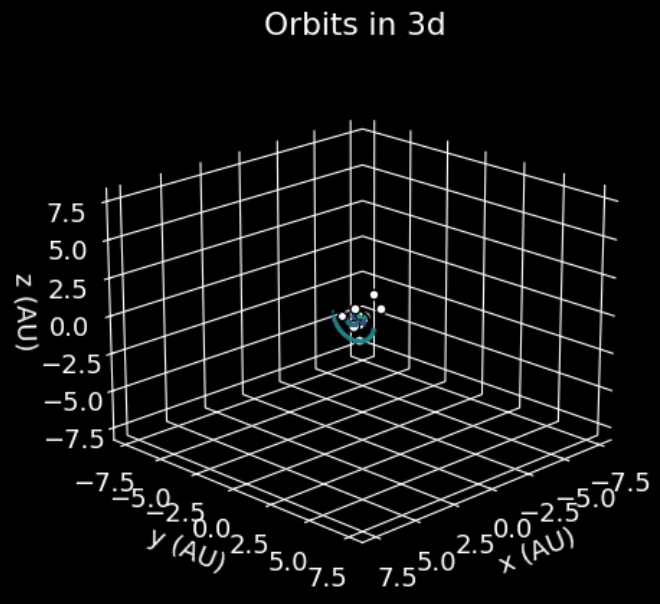
-Perron, L. & Furnon, V. OR-Tools. (2022).

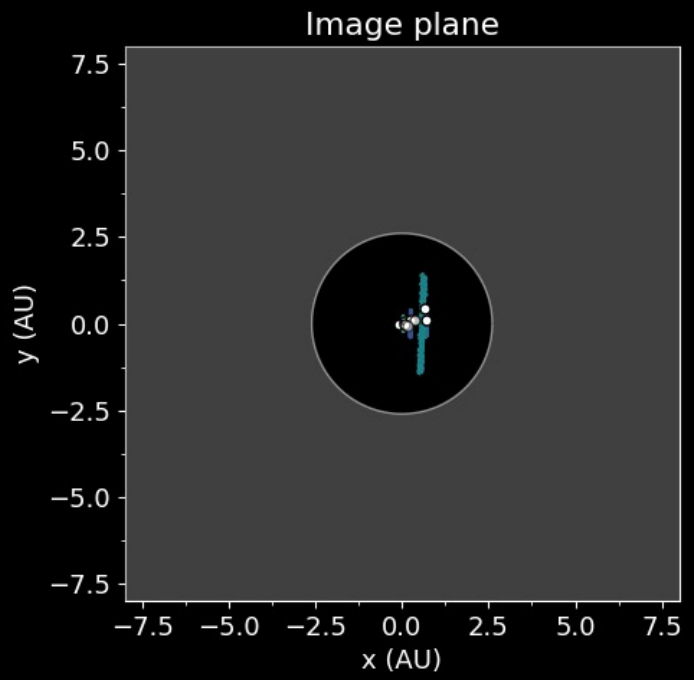
Case study

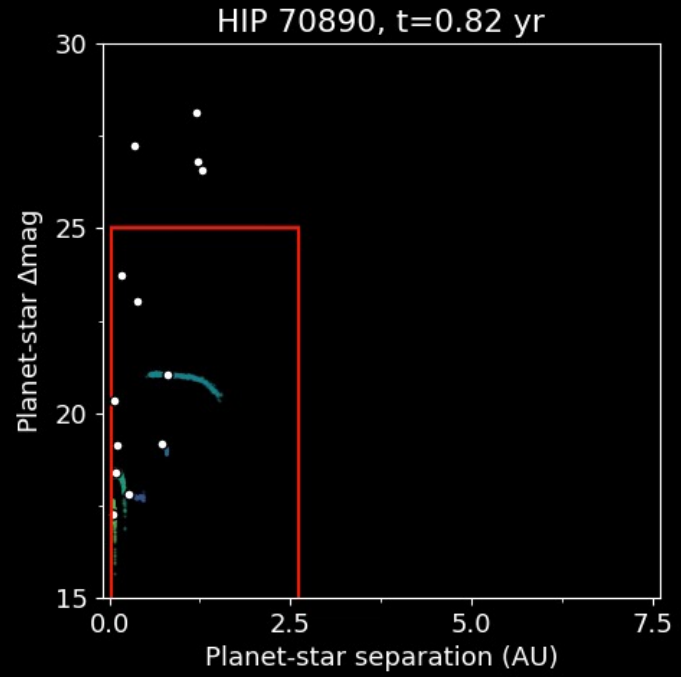
- RV data on the 10 closest stars from 2 instruments
  - 1 m/s precision instrument, 20-years
  - 3 cm/s precision instrument, 10-years
- 35 planets fitted
  - 90 planets generated
    - Occurrence rates from: Dulz, S. D. et al. Joint Radial Velocity and Direct Imaging Planet Yield Calculations. I. Self-consistent Planet Populations. The Astrophysical Journal 893, 122 (2020).
- 5 years for observations to be scheduled
- 1 day of integration time per observation
- IROUV-like telescope

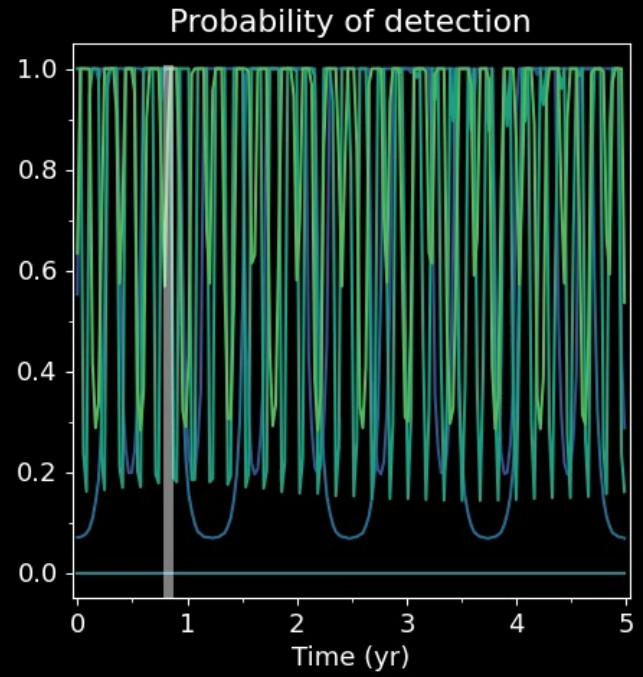
Results

- 24 of 27 detectable fitted planets were imaged
- 49 unique planets detected

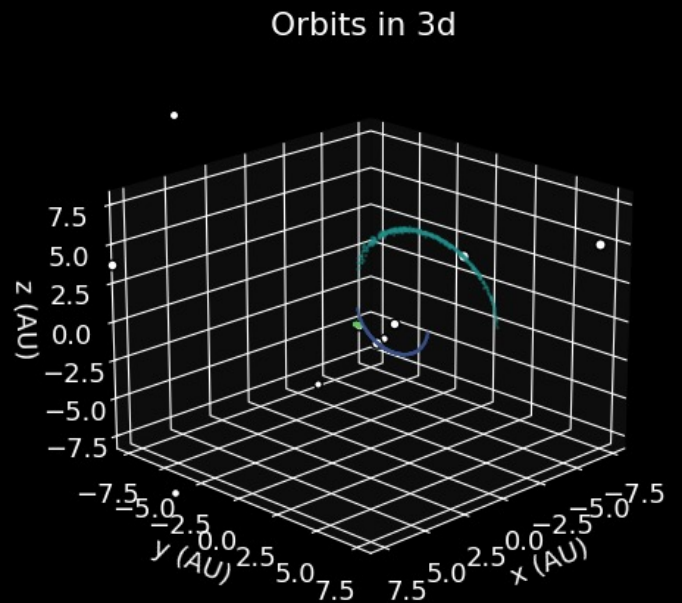


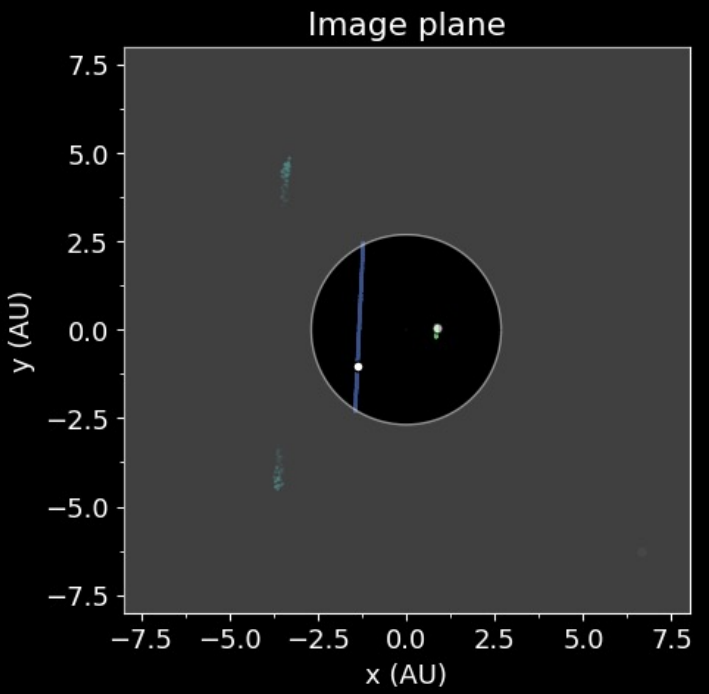


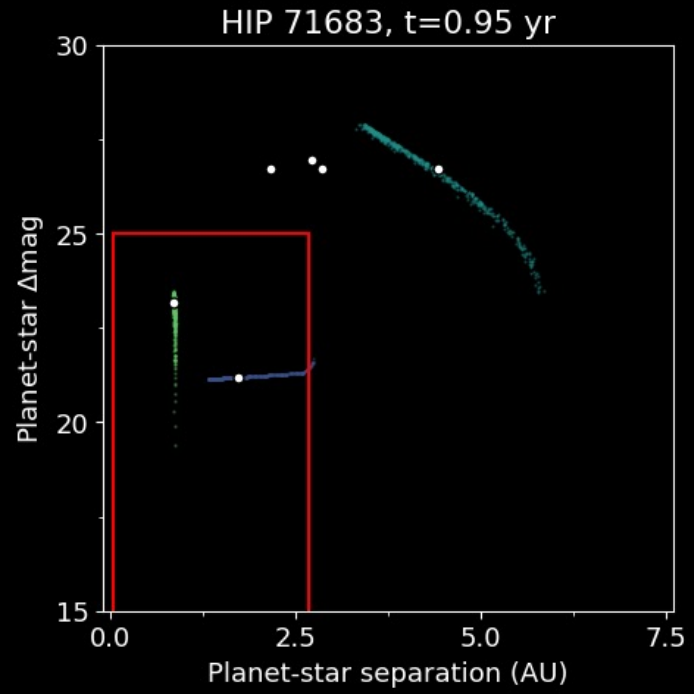


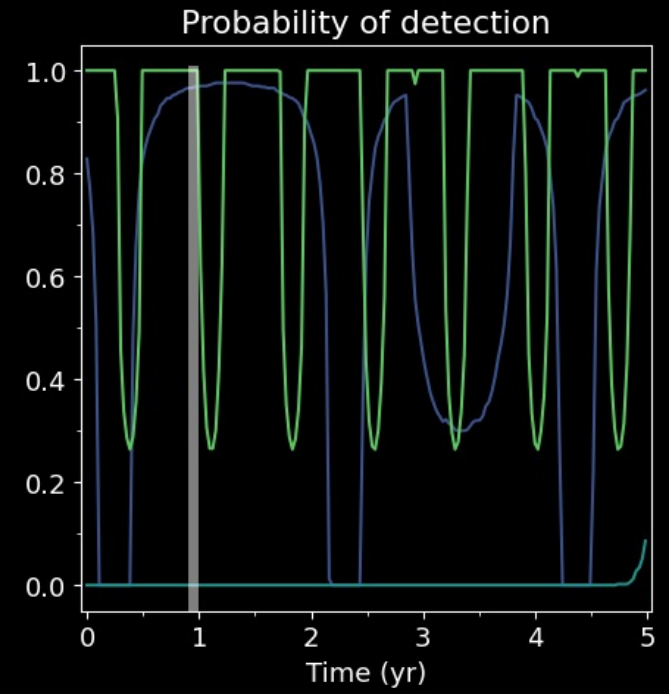


Successful detections

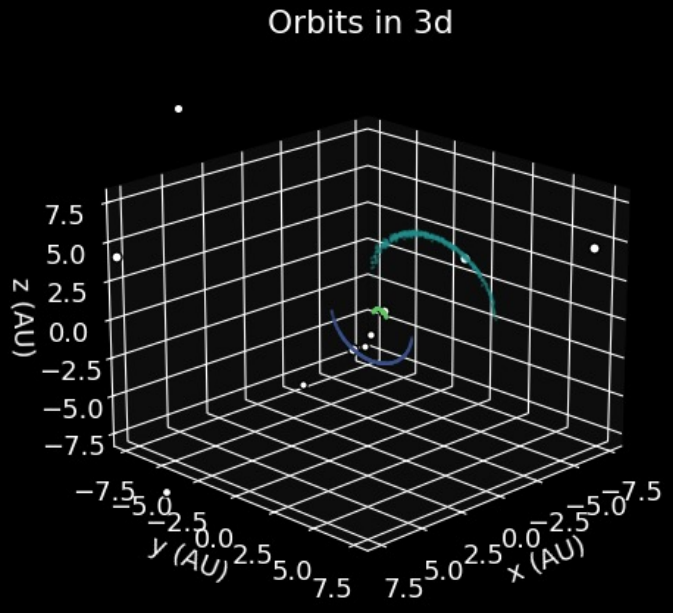


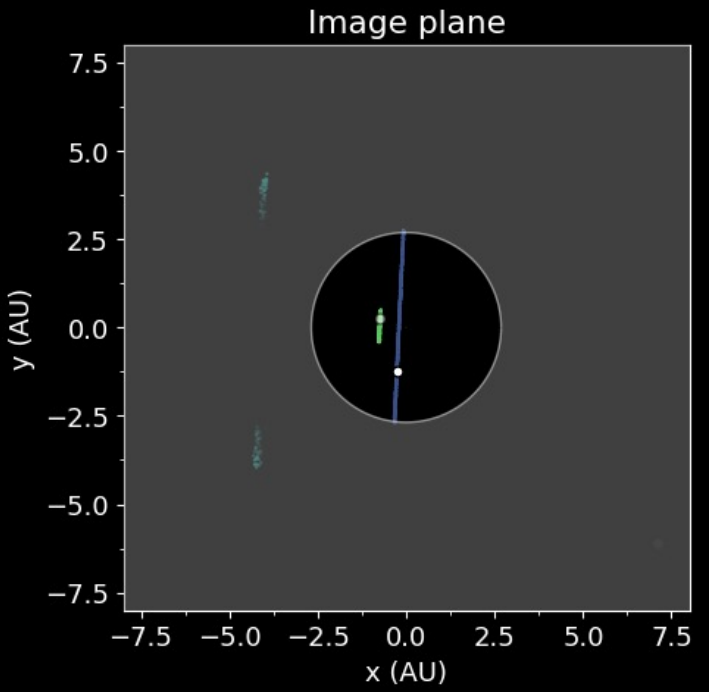


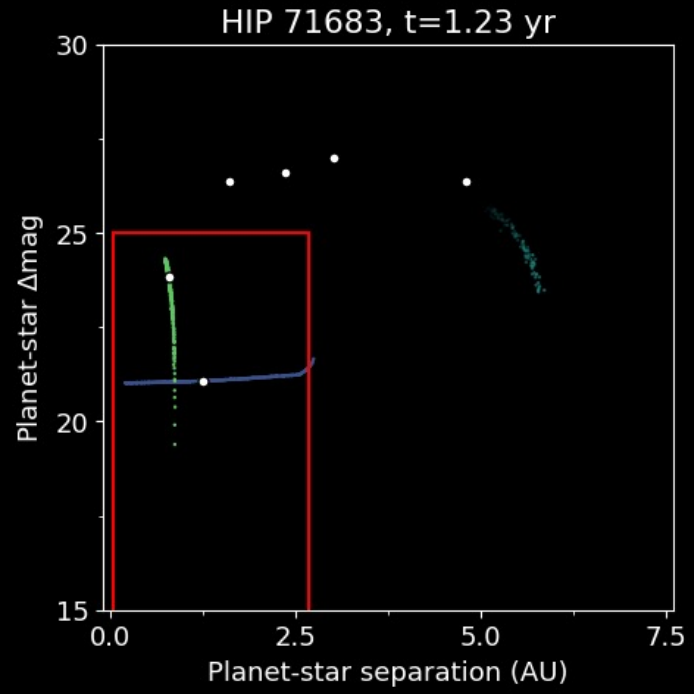


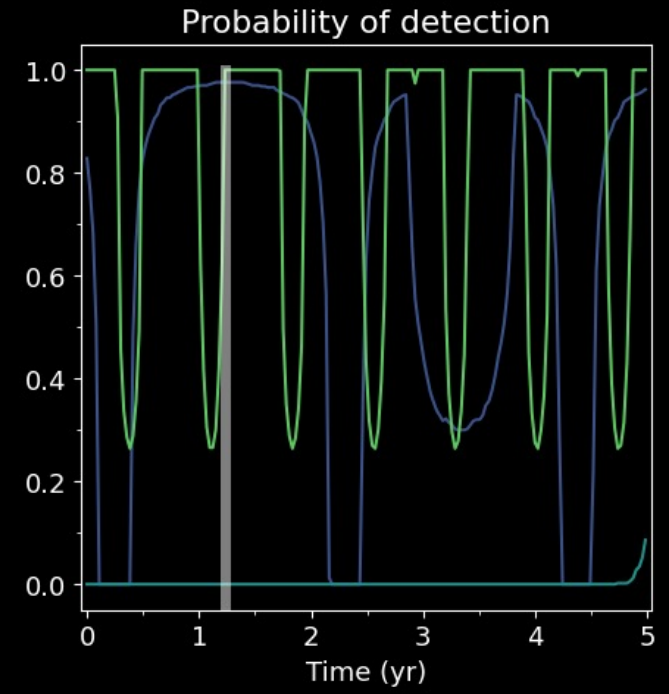


Successful detections

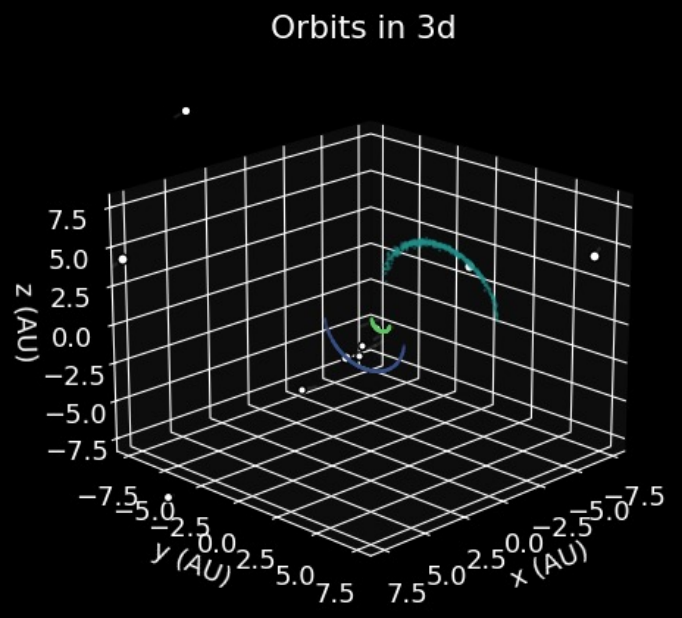


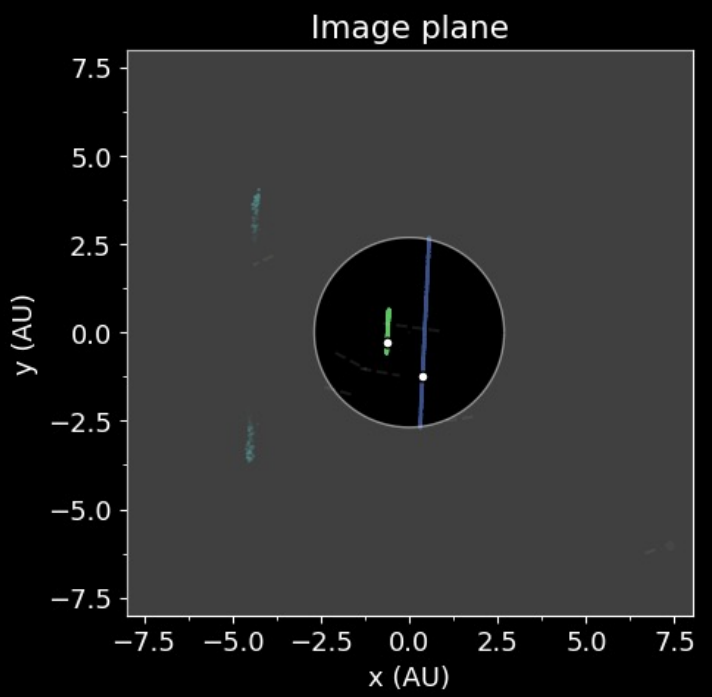


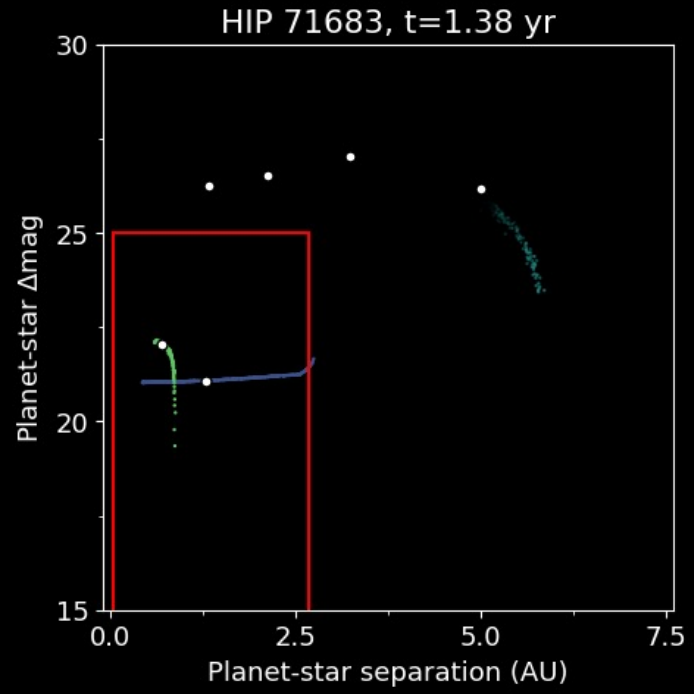


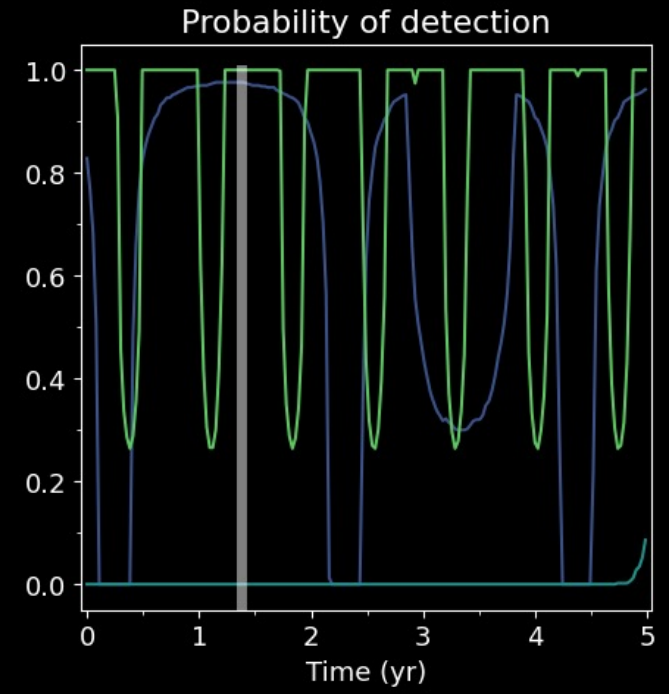


Successful detections

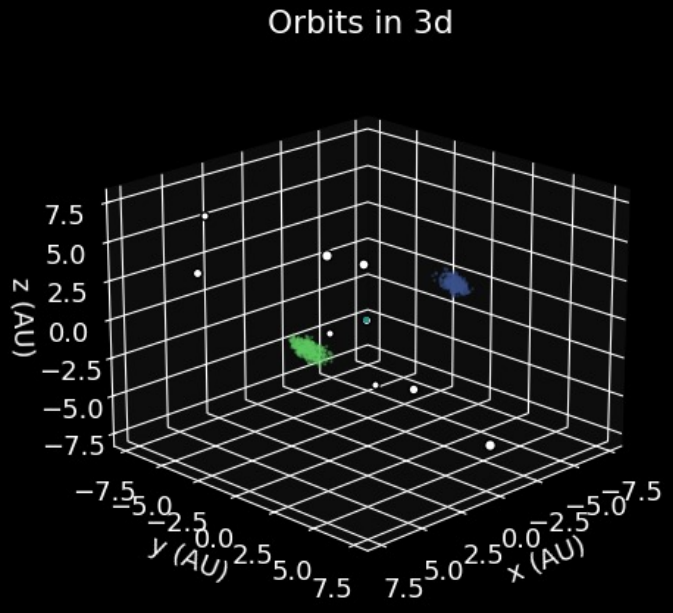


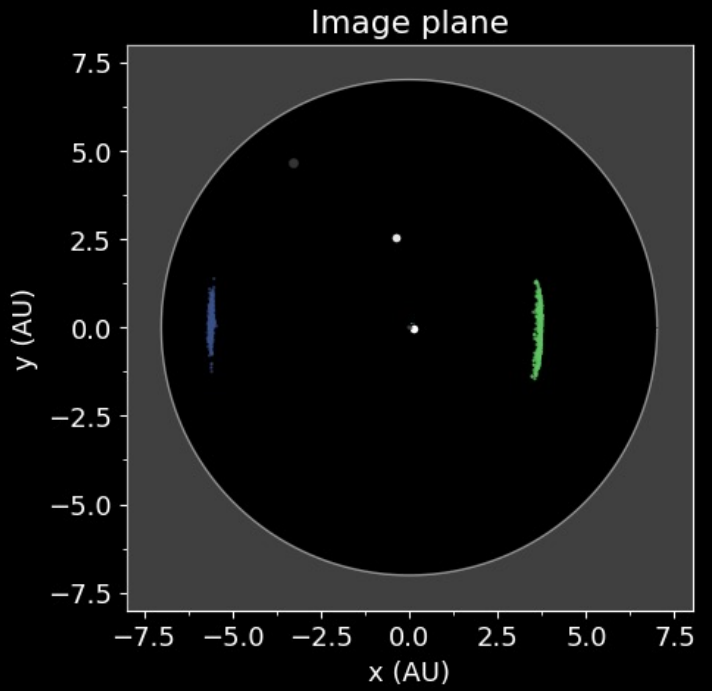


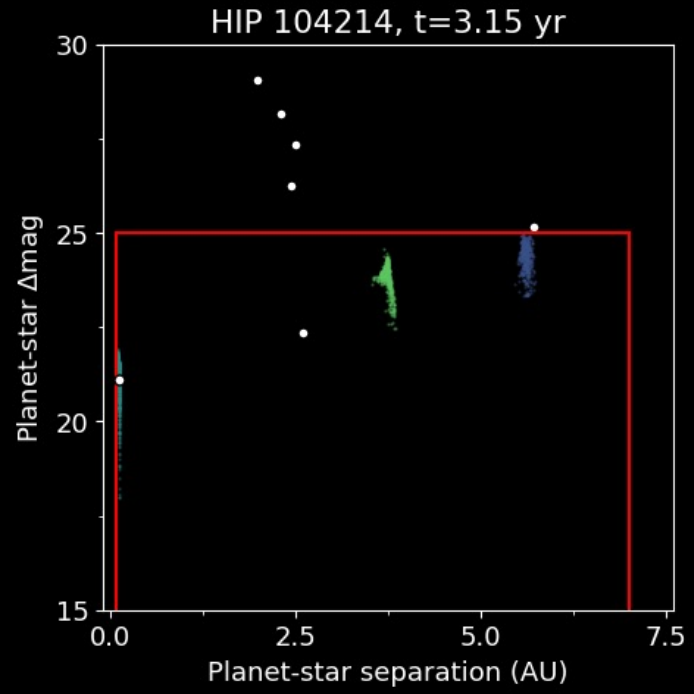


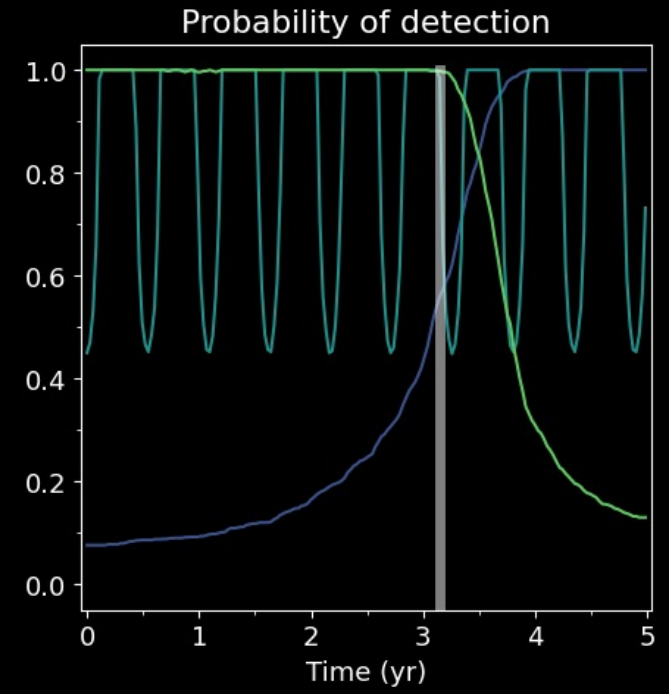


Failed detections

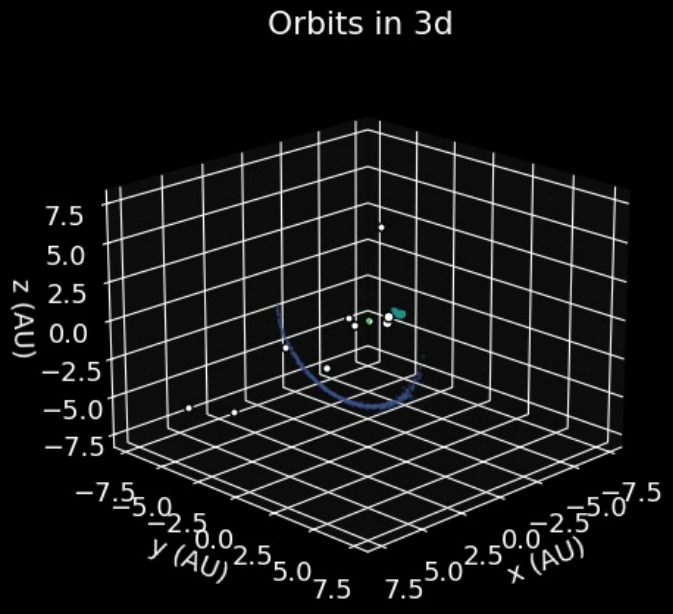


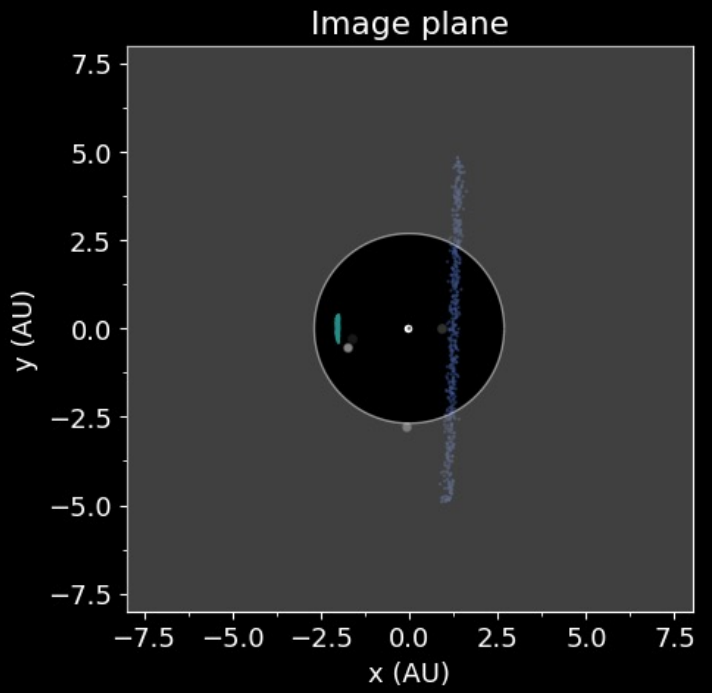


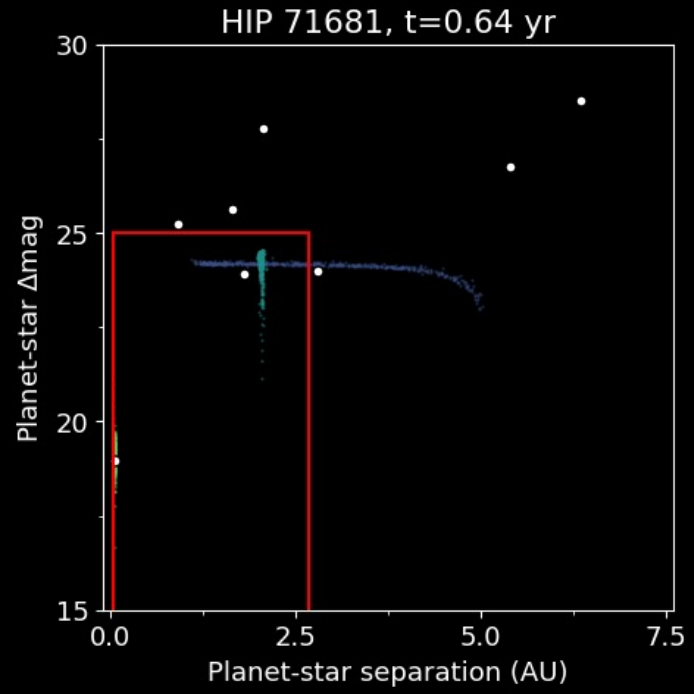


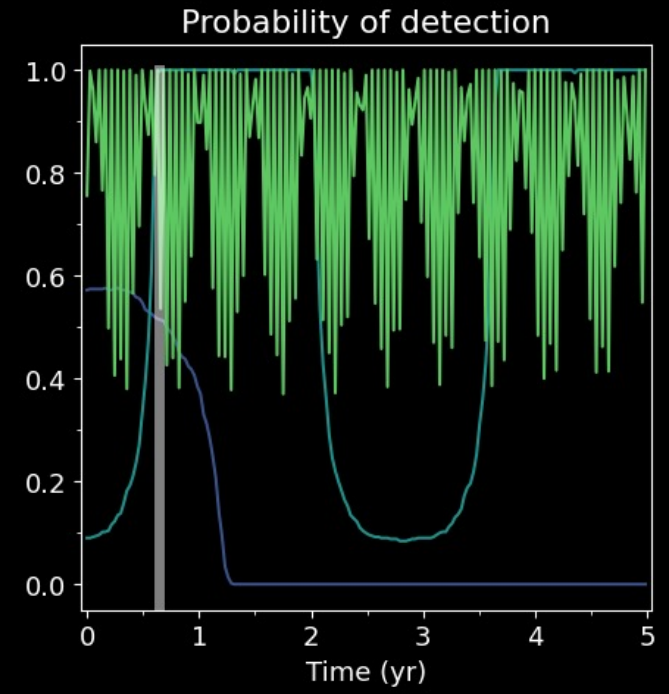


Failed detections

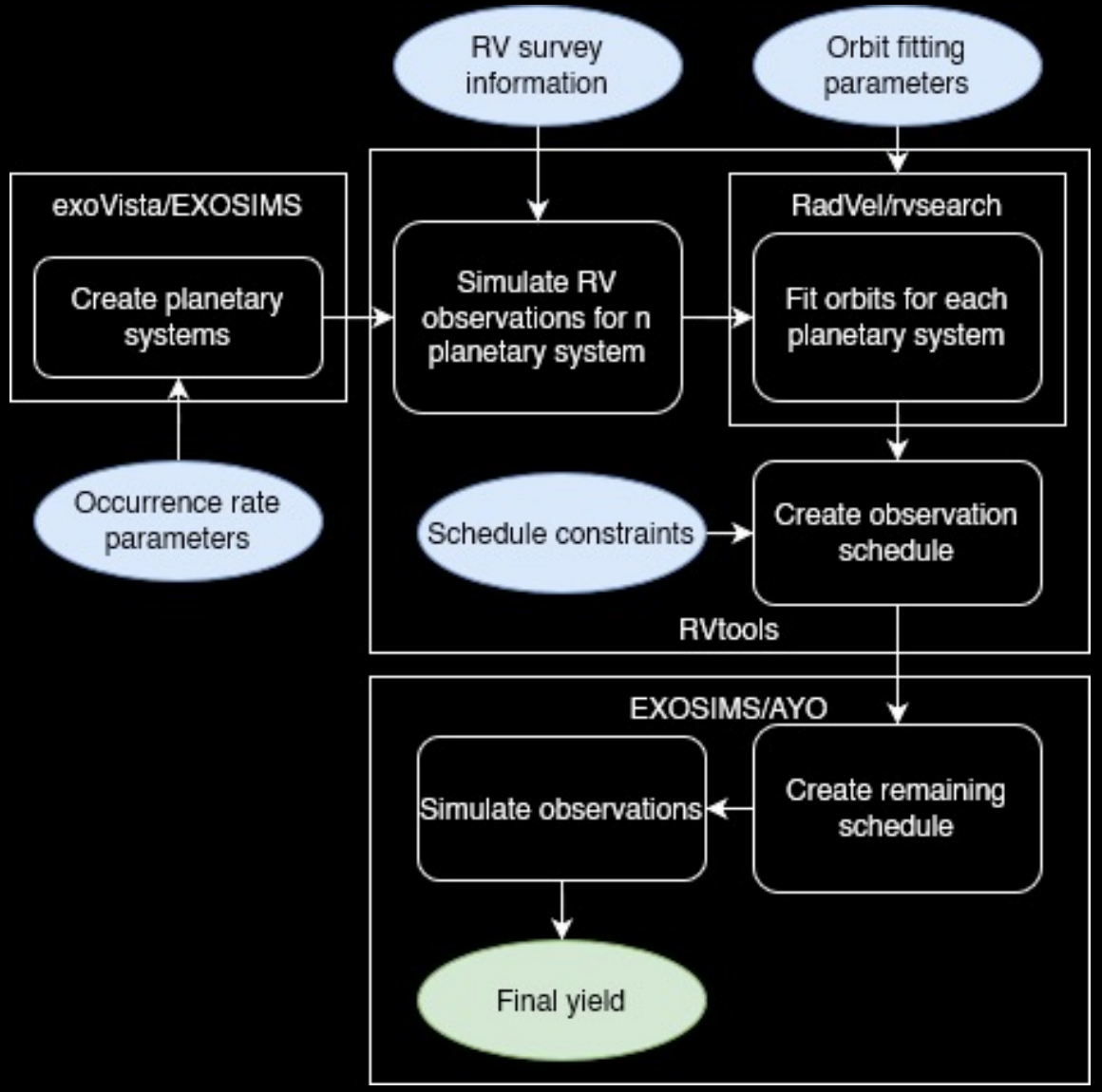








Full mission simulations



1. Stark, C. C. ExoVista: A Suite of Planetary System Models for Exoplanet Studies. *AJ* **163**, 105 (2022).
2. Savransky, D., Delacroix, C. & Garrett, D. EXOSIMS: Exoplanet Open-Source Imaging Mission Simulator. *Astrophysics Source Code Library* ascl:1706.010 (2017).
3. Fulton, B. J., Petigura, E. A., Blunt, S. & Sinukoff, E. Radvel: The radial velocity modeling toolkit. *Publications of the Astronomical Society of the Pacific* **130**, 044504 (2018).
4. Rosenthal, L. J. *et al.* The California Legacy Survey. I. A Catalog of 178 Planets from Precision Radial Velocity Monitoring of 719 Nearby Stars over Three Decades. *ApJS* **255**, 8 (2021).
5. Stark, C. C., Roberge, A., Mandell, A. & Robinson, T. D. Maximizing the ExoEarth candidate yield from a future direct imaging mission. *Astrophysical Journal* **795**, (2014).

Conclusions

- Full simulation of the radial velocity fitting process
- Estimation of planet detectability
- Scheduler with constraint programming

Future work

- Full mission simulations
- Integration time
- Updating fits based on images
- Effect of different occurrence rates, RV precision, RV observation schedules on planet yield