Exoplanet classification probabilities from initial detections in a direct imaging mission

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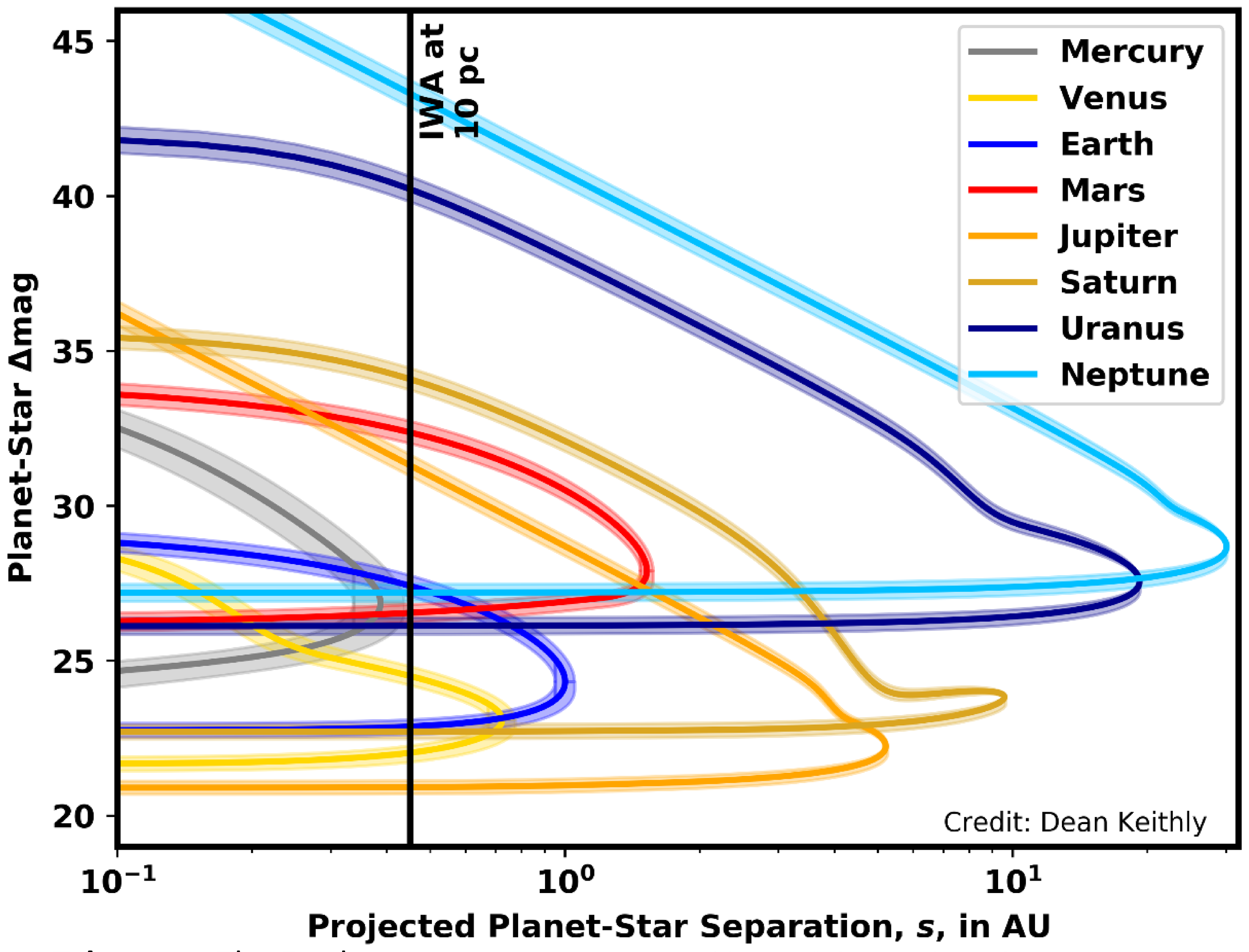
Objectives

A directly imaged exoplanet has photometric and astrometric properties Δmag and s, which can belong to many different classifications of planets.

1. If we directly imaged our solar system, could our planets be confused for one another? (can Earth and Uranus have the same the Δmag and s)
2. What do the Δmag vs s distributions of exoplanets classified by the Kopparapu et al. 2018 sub-populations look like?
3. Show our method of calculating exoplanet classification probability and demonstrate it works for an Earth Analog

Solar System Δmag vs s, i=0, 10 AU

Δmag vs s curves of Solar System with phase curves from Mallama et al. 2018
Planet properties from JPL HORIZONS, $\sigma_{\Delta mag} = 1\%$ and $\sigma_s = 5\ mas$ at 10 pc



Takeaway: The Earth Δmag vs s curve is crossed by 6 of the 7 other planets

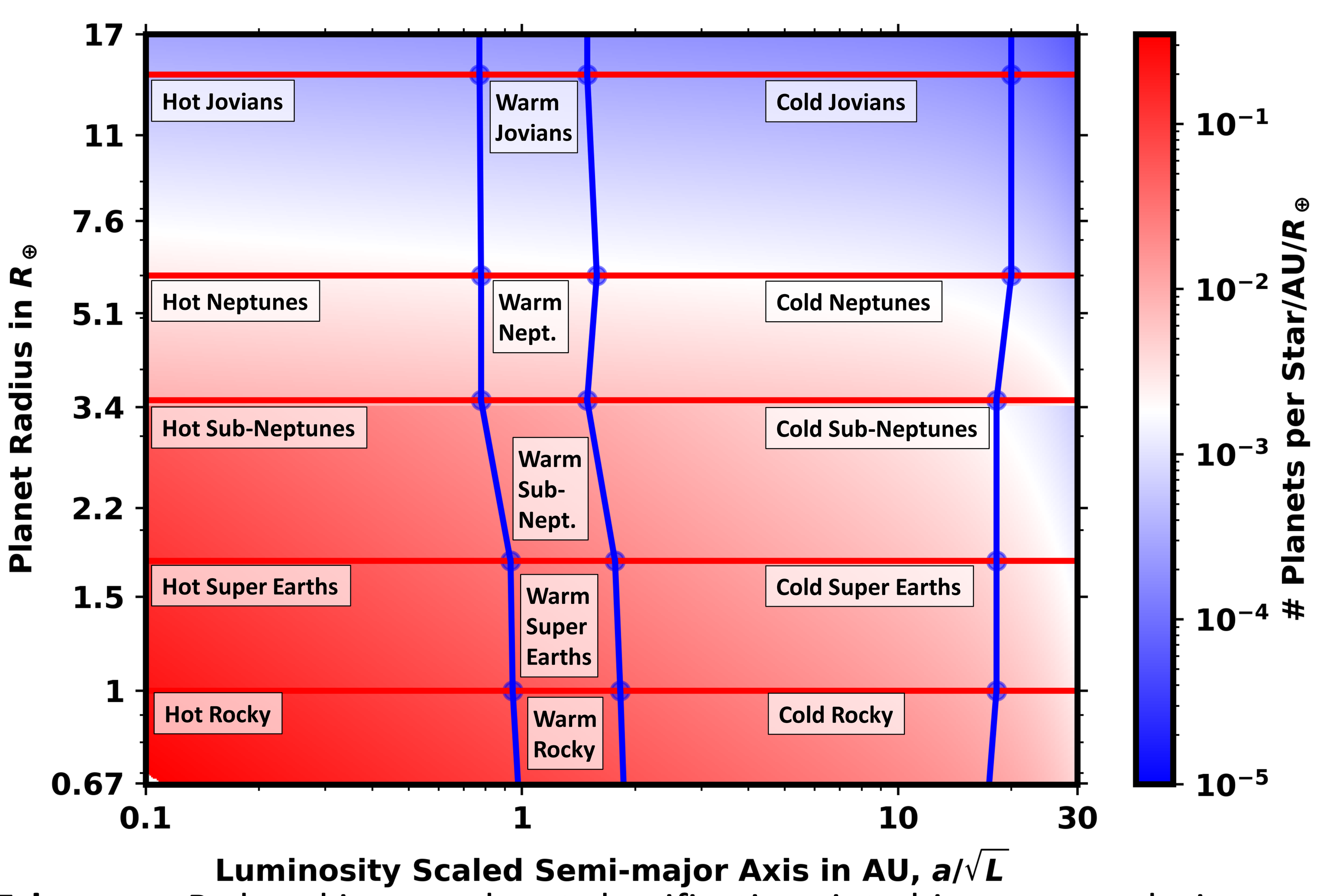
Takeaway: Many 'Earth-Like' planets detected by future direct imaging telescopes could be confused with other planet types

Takeaway: Exoplanets with a Δmag and s can belong to multiple planet sub-populations

SAG13, Classification, & Value

Underlying SAG13 distribution implemented in Keithly et al. (submitted) overlayed by Kopparapu et al. 2018 classification grid.

We can give different reward value for detected planets of different types. Many in the science community place sole value on Earth-Like detections.



Takeaway: By breaking exoplanet classifications into bins, we can design a mission to maximize detections of specific planet sub-types (e.g. Earth-Like)

Probabilities

We assume the underlying population of planets is consistent with the SAG13 planet population implemented in Keithly et al. (submitted)

Use 3σ bounds for integration

Assume meas. Error independence between Δmag and s

Joint Probability Distribution Function of Δmag vs s for sub-population ij

Classification Probability

$$P(ij, \Delta mag, s, \sigma_{\Delta mag}, \sigma_s) = \int_{\Delta mag(1-3\sigma_{\Delta mag})}^{\Delta mag(1+3\sigma_{\Delta mag})} \int_{s-3\sigma_s}^{s+3\sigma_s} f_{meas}(s, \Delta mag) f_{ij}(s, \Delta mag)\, ds\, d\Delta mag$$

$$f_{meas}(s,\Delta mag) = f_{\Delta mag}(\Delta mag) f_s(s)$$

$$f_s(s) = \frac{1}{\sigma_s\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{s-\mu_s}{\sigma_s}\right)^2}$$

Assume Gaussian error distribution in measured separation

$$f_{\Delta mag}(\Delta mag) = \frac{1}{\mu_{\Delta mag}\sigma_{\Delta mag}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\Delta mag - \mu_{\Delta mag}}{\mu_{\Delta mag}\sigma_{\Delta mag}}\right)^2}$$

Assume Gaussian error distribution in measured Δmag

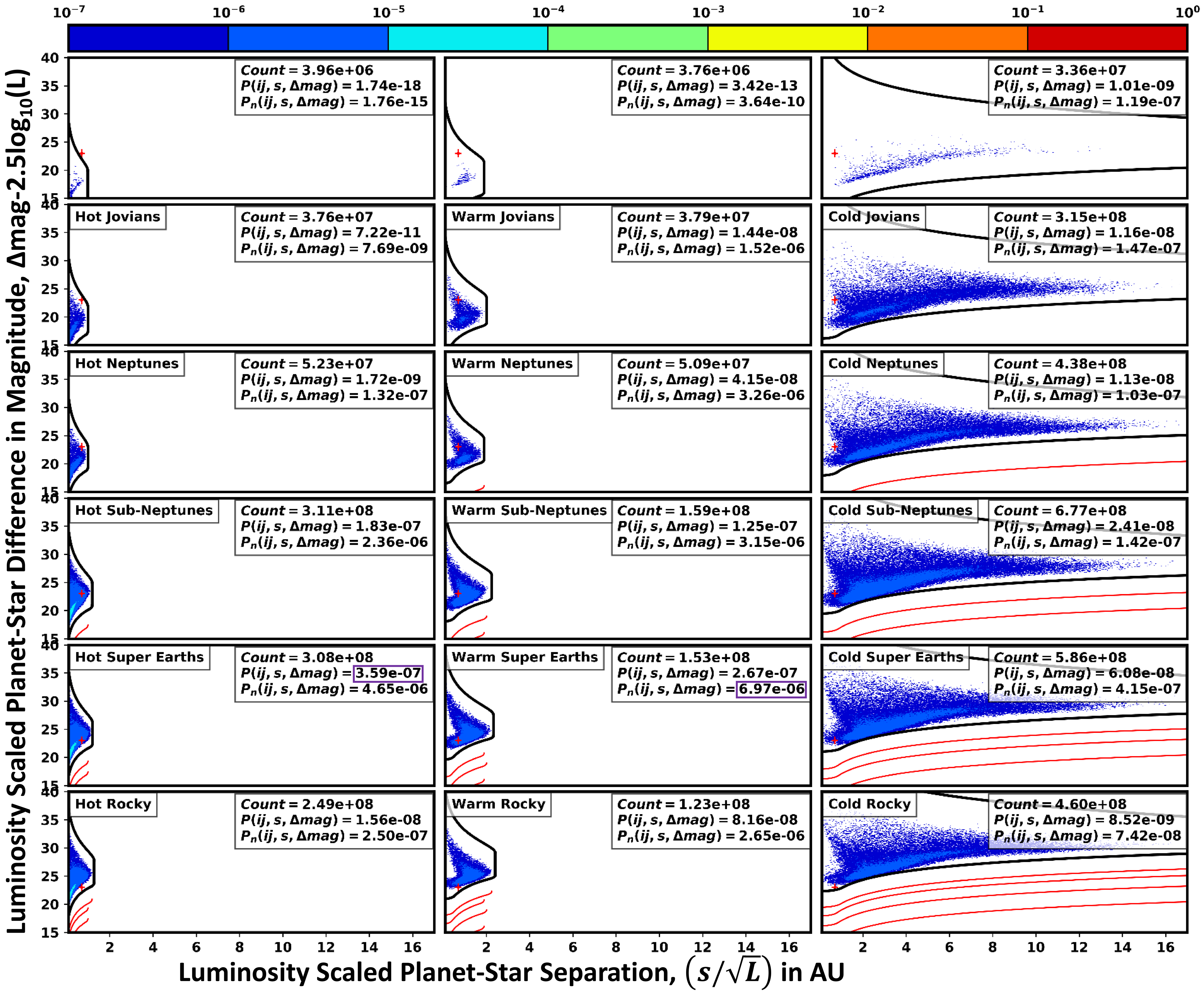
Normalized Classification Probability

$$P_n(ij, \Delta mag, s, \sigma_{\Delta mag}, \sigma_s) = \frac{P(ij, \Delta mag, s, \sigma_{\Delta mag}, \sigma_s)}{N_{ij}/N_{tot}}$$

N_{tot} =Total number of exoplanets simulated in Monte Carlo
N_{ij} =Total number of exoplanets in sub-type bin

Takeaway: Combining the planet sub-pop and instrument capabilities enables us to calculate a probability a detected planet belongs to any given sub-population

Exoplanet Joint Distributions by Sub-type



Red dot is an Earth Analog with $\Delta mag = 23$, $s = 0.7$ AU with $\sigma_{\Delta mag} = 1\%$ and $\sigma_s = 5\ mas$ (red error bars), for a reference star at 10 pc

Takeaway: Calculating $P(ij, \Delta mag = 23, s = 0.7\ AU, \sigma_{\Delta mag} = 1\%, \sigma_s = 5\ mas)$ shows Hot Super Earths to be the most likely sub-pop (purple) and Warm Super Earth's the 2nd most likely sub-pop

Takeaway: Calculating $P_n(ij, \Delta mag = 23, s = 0.7\ AU, \sigma_{\Delta mag} = 1\%, \sigma_s = 5\ mas)$ shows Warm Super Earths to be the most likely sub-pop (purple) and Hot Super Earth's the 2nd most likely sub-pop

Takeaway: We can calculate the probability a planet detected from a single image belongs to a specific sub-pop and use this for mission planning

Acknowledgements & References

[1] Garrett, Savransky, *Analytical Formulation of the Single-visit Completeness Joint Probability Density Function*, ApJ, 2016
[2] Kopparapu, et al., *Exoplanet Classification and Yield Estimates for Direct Imaging Missions*, ApJ, 2018
[3] Méndez, et al., *The Equillibrium Temperature of Planets in Elliptical Orbits*, ApJ, 2017
[4] Keithly, et al., *Optimal Scheduling of Exoplanet Direct Imaging Single-Visit Observations of a Blind Search Survey*, JATIS, (submitted)
[5] Mallama, Hilton, *Computing apparent planetary magnitudes for The Astronomical Almanac, Astronomy and Computing*, 2018

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