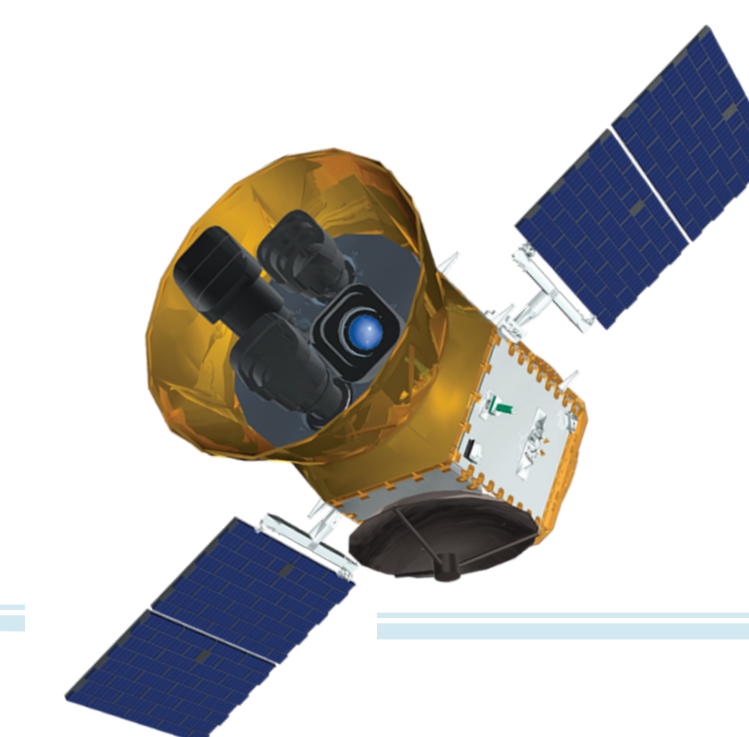# DETECTABILITY OF TRANSITING TERRESTRIAL PLANETS IN THE HABITABLE ZONE WITH TESS

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Abstract

In the Revised TESS Habitable Zone Catalog, Kaltenegger et al. (2021) identified the 2-min TESS target stars that were observed for sufficient duration over consecutive primary mission sectors to unambiguously capture a transit signature of planets orbiting in the Habitable Zone (HZ). The Catalog did not, however, identify the host stars for which transiting planets with HZ orbits and specified radii would be detectable based on the photometric precision of the retrieved light curves. We employ the Combined Differential Photometric Precision (CDPP) computed at 15 pulse durations in the Science Processing Operations Center (SPOC) transit searches of the primary mission light curves to estimate the signal-to-noise ratio (S/N) associated with transiting terrestrial planets ($1.0\ R_e <= R_p <= 2.0\ R_e$) in the HZ of the Catalog stars. We consider orbital periods under three HZ scenarios: Recent Venus, Earth Analog, and Early Mars. Given S/N, we further estimate the probability of detection of transiting terrestrial planets for each Catalog star and HZ scenario in the primary mission SPOC transit searches. We also present the expected yield by HZ scenario and planet radius under the assumption that all Catalog stars host such planets. Funding for the TESS mission has been provided by the NASA Science Mission Directorate.

Revised TESS Habitable Zone Catalog[1]

The Catalog identifies 4239 TESS 2-min target stars observed in a sufficient number of consecutive primary mission sectors to observe at least three transits of planets with Earth equivalent irradiation. Stellar parameters are obtained from TESS Input Catalog[2,3] (TIC) v8. Three HZ scenarios are considered for each Catalog star:

- **Recent Venus (RV) – inner HZ boundary**
- **Earth Analog (EA) – Earth-equivalent irradiation**
- **Early Mars (EM) – outer HZ boundary**

The following Catalog fields are employed for each member star and HZ scenario to estimate S/N and probability of detection for transiting terrestrial HZ planets:

- Dwell time – total exposure time of good quality primary mission observations
- Orbital period
- Semi-major axis
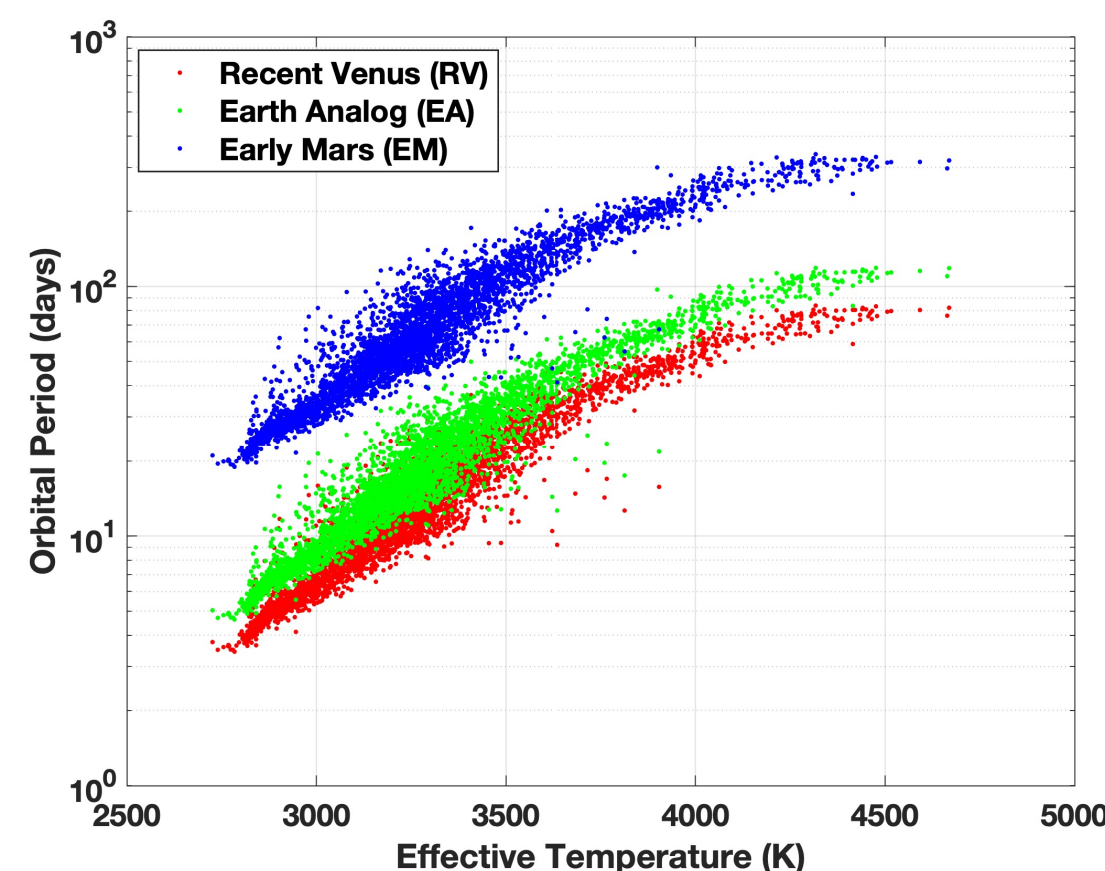
The orbital periods for all Catalog stars and HZ scenarios are shown in the figure above.

[1]Kaltenegger, L., Pepper, J., Christodoulou, P. M., et al. 2021, AJ, 161, 233
[2]Stassun, K. G., Oelkers, R. J., Pepper, J., et al. 2018, AJ,156, 102
[3]Stassun, K. G., Oelkers, R. J., Paegert, M., et al. 2019, AJ,158, 138

Combined Differential Photometric Precision

Source: TESS Data Release Notes, DR37
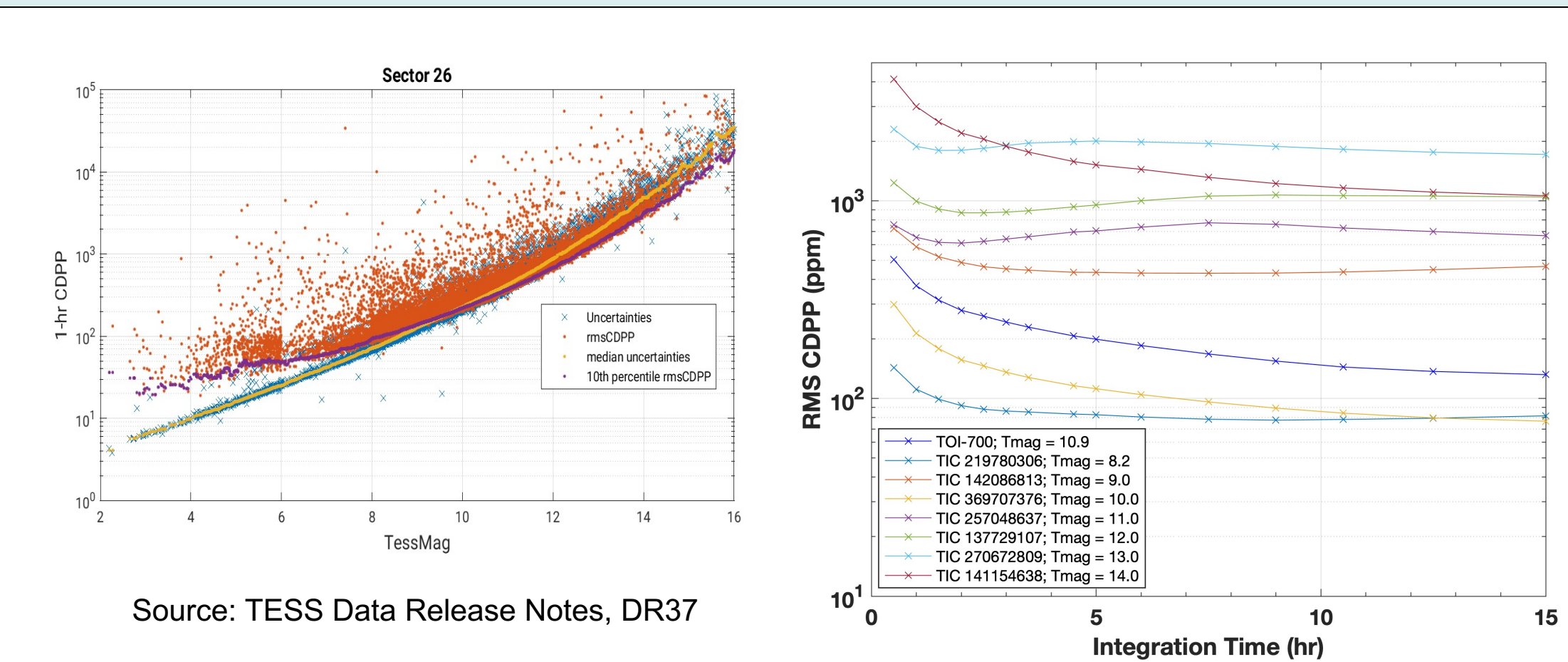
The noise component for single-transit S/N is the photometric precision of the given light curve on the timescale of the transit. Photometric precision is measured for each of 15 trial pulse durations in the SPOC transit search. The trial transit pulse durations range from 0.5–15.0 hr. For each pulse duration in the transit search, CDPP is computed for all 2-min cadences (after filling data gaps with an algorithm intended to preserve statistical properties). The RMS value of the CDPP time series is employed as the single photometric precision metric for each target star and trial transit pulse duration. For the purpose of estimating S/N, the RMS CDPP value at the trial transit pulse duration closest to the predicted mean transit duration is chosen for each Catalog star and HZ scenario.

RMS CDPP is shown at 1-hr on the left panel above versus magnitude for all 2-min target stars in Sector 26 (last sector of primary mission). RMS CDPP is shown on the right panel above versus integration time for representative Catalog stars (including TOI-700) across a range of magnitudes. TOI-700 (TIC 150428135) hosts three transiting exoplanets including TOI-700 d which is the first terrestrial HZ planet identified with TESS.[4]

[4]Gilbert, E. A., Barclay, T., Schlieder, J. E., et al. 2020, AJ,160, 116

Estimation of Transit S/N and Probability of Detection

Methodology

1. Estimate the number of observed transits (N_t) with integer part (N) and fractional part (ν) from the dwell time (T_d) and orbital period (P) for the given HZ scenario:

$$N_t = \frac{T_d}{P} = N + \nu$$

2. Compute the transit depth (δ) from the planet radius (R_p) and the stellar radius (R^*):

$$\delta = \left(\frac{R_p}{R^*}\right)^2$$

3. Compute the **mean transit duration (τ) over all impact parameters** from the stellar radius, orbital period, and semi-major axis (a) for the given HZ scenario:

$$\tau = \frac{P}{4}\arcsin\left(\frac{R^*}{a}\right)$$

4. Estimate the S/N for one transit (S_1) and N transits (S_N) from the transit depth (in ppm) and **RMS CDPP (C) at the integration time closest to the mean transit duration** for the given HZ scenario:

$$S_1 = \frac{\delta\,[\text{ppm}]}{C(\tau)} = 10^6\,\frac{(R_p/R^*)^2}{C(\tau)}$$
$$S_N = S_1\sqrt{N}$$

5. Estimate the detection S/N (S_{Det}) by computing a **weighted average probability of detection (P_{Det}) over the phases with N transits and N+1 transits** respectively for a given transit detection threshold (η); assume Gaussian noise statistics:

$$S_{Det} = P^{-1}(P_{Det})$$

where

$$P_{Det} = (1-\nu)\,P(S_N) + \nu\,P(S_{N+1})$$

and

$$P(S) = \frac{1}{\sqrt{2\pi}}\int_\eta^\infty e^{-\frac{1}{2}(x-S)^2}dx = \frac{1}{2}\,\text{erfc}\left(\frac{\eta-S}{\sqrt{2}}\right)$$

The SPOC transit search pipeline employs a wavelet-based matched filter for each trial transit pulse. The matched filters account for noise statistics that are both colored and time-varying. Probability of detection (P) is shown on the right versus the difference between transit S/N (S) and detection threshold (η) for a transit signal in Gaussian noise. The SPOC pipeline transit detection threshold (7.1σ) is utilized in this study.
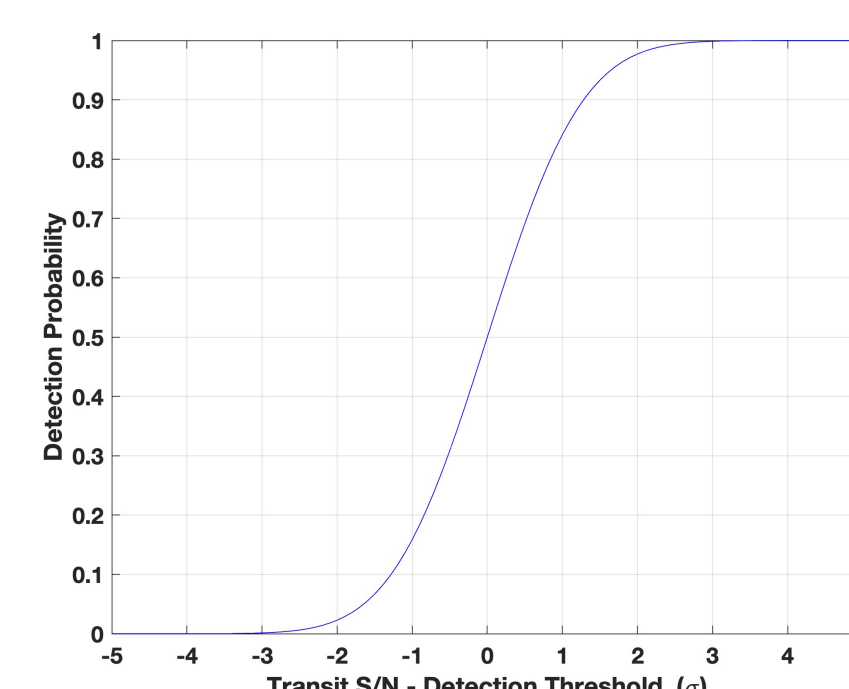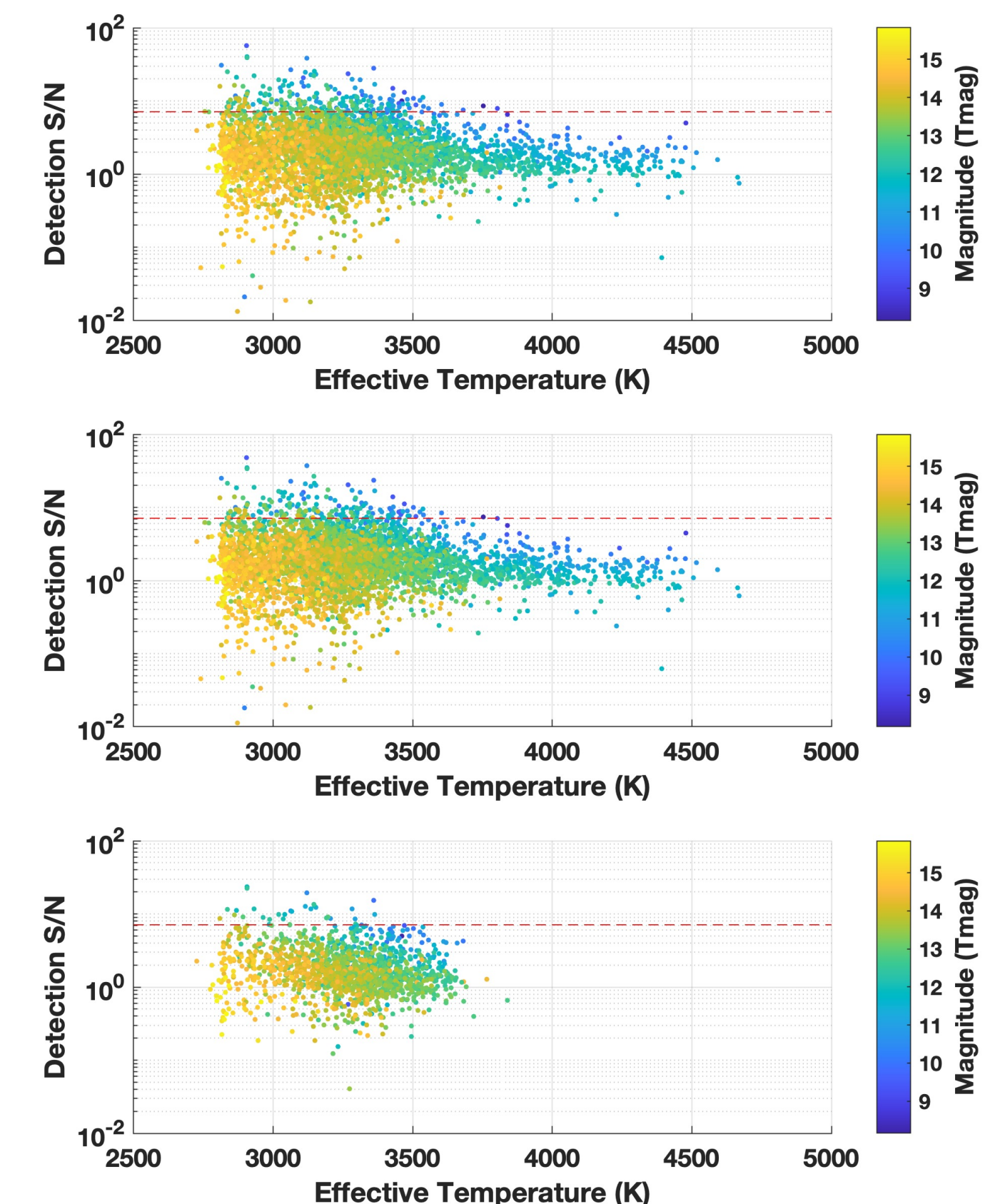

## S/N for Earth-size Planets with Earth Equivalent Irradiation
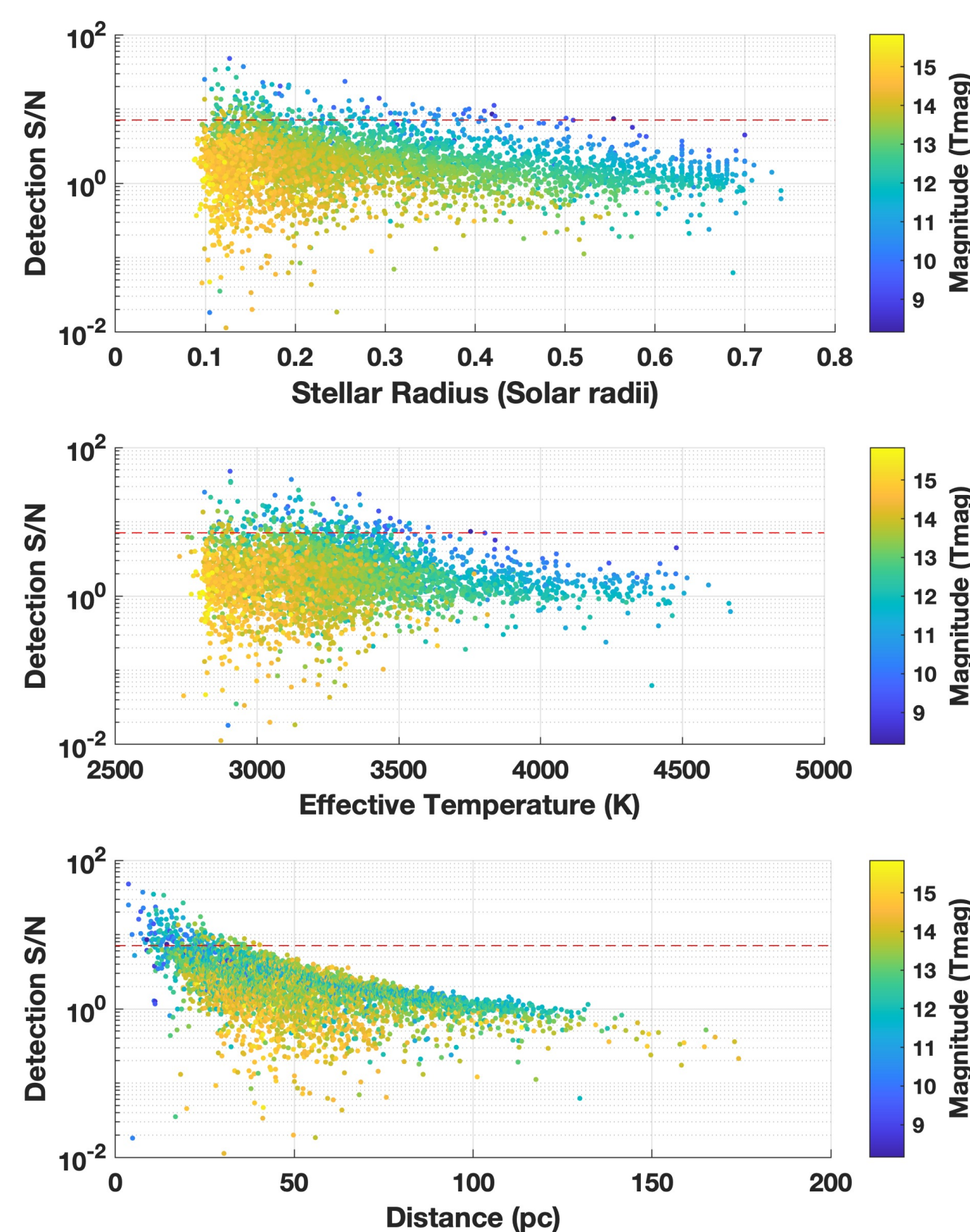
Primary mission detection S/N is shown above for transiting planets with $R_p = 1.0\ Re$ and Earth equivalent irradiation associated with all 4239 Catalog stars. SPOC detection threshold is shown in red. Upper panel: S/N versus stellar radius. Middle panel: S/N versus effective temperature. Lower panel: S/N versus distance. The number of Catalog stars for which S/N exceeds the detection threshold is 184 (4.3%); the sum of the detection probabilities is 193.7. Earth Analog planets with $R_p = 1.0\ Re$ are essentially undetectable beyond 40 pc.

## S/N for Earth-size Planets Across the Habitable Zone

Primary mission detection S/N is shown above versus effective temperature for transiting planets with $R_p = 1.0\ Re$ and all 4239 Catalog stars. SPOC detection threshold is shown in red. Upper panel: Recent Venus (inner HZ boundary). Middle panel: Earth Analog (Earth equivalent irradiation). Lower panel: Early Mars (outer HZ boundary). Fewer S/N estimates are shown at the outer HZ boundary because most EM planets are considered undetectable in the primary mission due to an insufficient number of transits ($N_t <= 2$) at the longer orbital periods. Transiting planets in EM orbits are only detectable on the cooler Catalog stars. The number of Catalog stars with transit S/N above threshold is 231 (RV), 184 (EA), and 32 (EM) respectively, while the sum of associated detection probabilities is 247.3 (RV), 193.7 (EA), and 38.9 (EM).

TOI-700
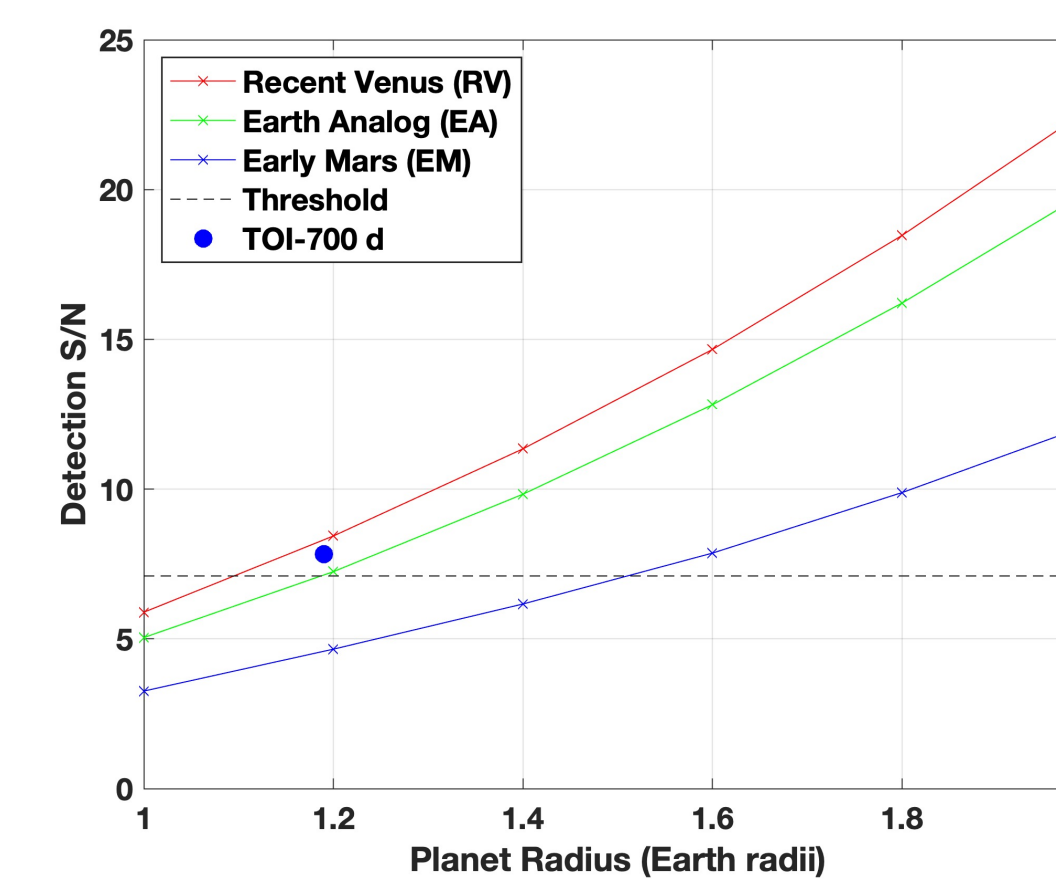
Estimated detection S/N for TOI-700 for $1.0 <= R_p <= 2.0$. S/N estimates are displayed in red for the RV scenario (inner HZ boundary), green for the EA scenario (Earth analog), and blue for the EM scenario (outer HZ boundary). SPOC detection threshold is shown with a dashed black line. The S/N for TOI-700 d based on published stellar and planet parameters (Gilbert et al. 2020) is marked with a blue circle. The S/N for TOI-700 d is greater than expected because (1) 8 transits were observed in the primary mission whereas 7.1 were predicted for the EA scenario, and (2) the transit duration (3.2 hr) exceeds the predicted mean value (2.5 hr) for the EA scenario.

Sensitivity to Terrestrial Planets
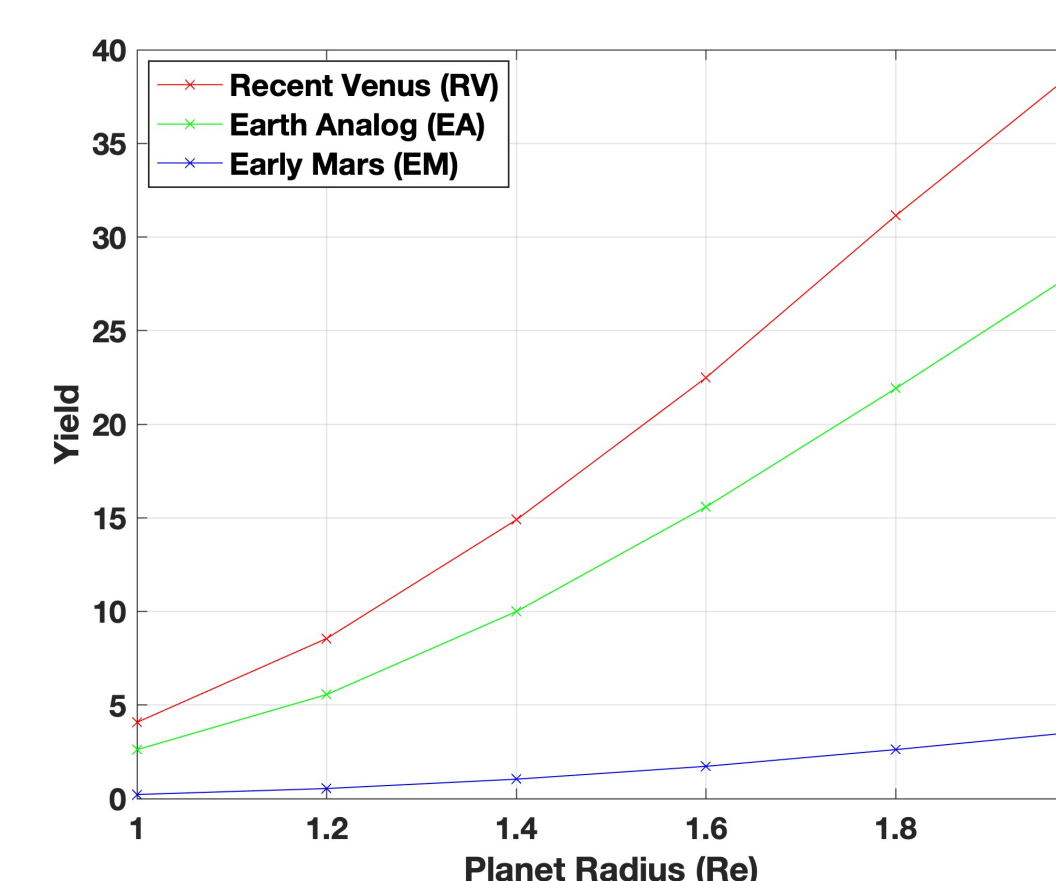
The sensitivity to transiting planets is shown above for all HZ scenarios and $1.0 <= R_p <= 2.0$. The expected yield of transiting planet detections in the primary mission is displayed in red for the RV scenario (inner HZ boundary), green for the EA scenario (Earth analog), and blue for the EM scenario (outer HZ boundary). The assumptions are that (1) all Catalog stars host planets with the given radius and HZ orbit, and (2) the orbital planes are randomly oriented. The yields account for both probability of detection and geometric probability of transit; terrestrial HZ planet occurrence rates are not considered. The expected number of detections under these assumptions grows faster with planet radius than the quadratic increase in S/N with radius.