Towards Precise Eta-Earth ($\eta_\oplus$) Estimates: Homogenous Reanalysis of Planetary Parameters and Statistical Validation for 187 Kepler Habitable and Near-Habitable Zone Confirmed and Candidate Planets

Md Abdullah Al Zaman*, Ian J. M. Crossfield

[1]Department of Physics and Astronomy, University of Kansas, USA

Email: abdullah.alzaman@ku.edu

Web: zaman-abdullah.github.io

ABSTRACT

Confirmed and candidate planets in the Habitable or near-Habitable Zones (HZ) orbiting Sun-like stars are crucial not only for the search for life beyond the Solar System, but also for understanding the architecture and formation of other solar systems and for conducting demographic studies. Current analyses of such planetary systems are limited both by the small sample size revealed by Kepler as well as by uncertainties in system parameters. Although a larger sample of HZ and near-HZ planets must await new observations from wide-field, space-based surveys, follow-up analyses and observations with existing facilities can improve the precision on stellar and planetary parameters, enable more accurate planetary classification, and a more reliable assessment of whether candidate systems are true planets or merely astrophysical false-positives. Here, we present a homogeneous transit light curve analysis of 187 HZ and near-HZ systems discovered by Kepler. Our analysis incorporates the latest Gaia DR3-derived stellar parameters, and we also present a statistical validation effort for all targets. The result is a uniform set of planetary radii, instellation fluxes, and orbital ephemerides suitable for prioritizing and scheduling follow-up observations to improve our understanding of planets in this regime. We show that longer-period (P>300) systems would particularly benefit from transit follow-up: just a single transit from facilities such as the 6m James Webb or the planned 3m Lazuli space telescopes could provide 4 times tighter precision on planet radii than four years of Kepler photometry, thereby dramatically shrinking relevant parameter uncertainties and allowing more confident planet/false-positive assessments.

Eta-Earth ($\eta_\oplus$)

The Habitable Zone (HZ) refers to the circumstellar region where a rocky planet with an Earth-like atmosphere is expected to have surface temperatures that allow liquid water to exist [1]. The search for planets within the HZ capable of harboring life has been a long-standing goal of the exoplanet community. Precisely characterizing planets in the HZ and near HZ is a fundamental step for constraining Eta-Earth ($\eta_\oplus$), defined as the occurrence rate of rocky planets orbiting Sun-like stars within their habitable zones. $\eta_\oplus$ is considered as one of the most important parameter in the field of exoplanets [2]. It helps us explore models of planetary formation, the diversity of planetary systems. It can explore interesting avenues like *"Is there life anywhere else in this universe?"* Precise estimates of $\eta_\oplus$ are essential for guiding future space missions, such as NASA's Habitable Worlds Observatory (HWO) and ESA's Large Interferometer For Exoplanets (LIFE). Following the Kepler mission, studies of $\eta_\oplus$ have reported values from less than 10 to 100% with considerably high uncertainties [3, 4]. The large uncertainties in $\eta_\oplus$ estimation stem from several factors. These include limited sample sizes and insufficient numbers of observed transits, as well as differences in the regimes of planetary properties such as radius, orbital period, and instellation flux. Additionally, variations in stellar properties and methodological differences in algorithms, treatments, and extrapolations contribute to the uncertainties.

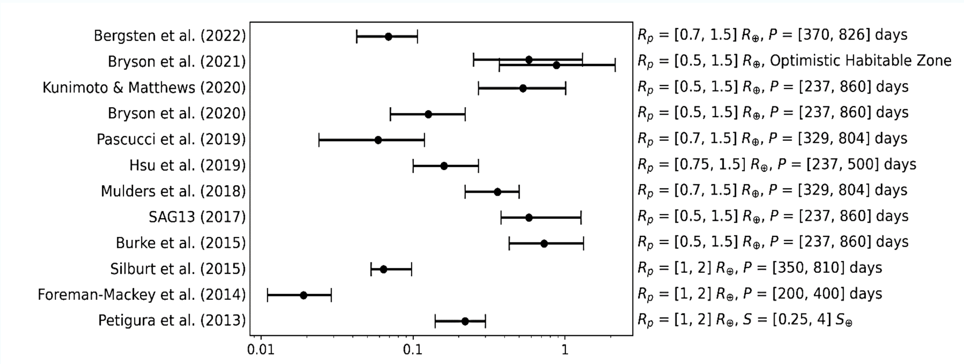
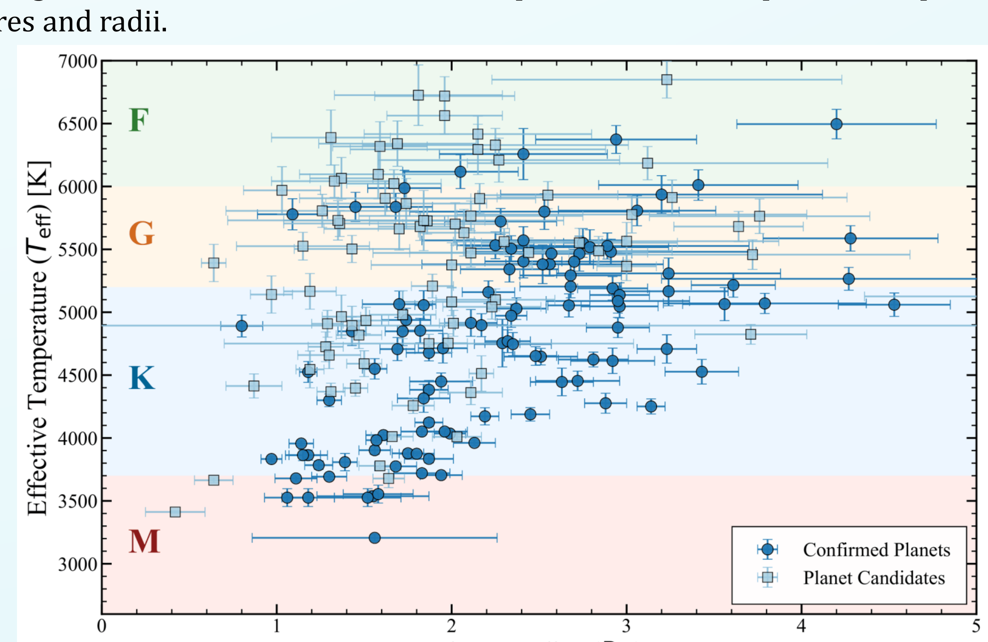


Figure 1: Comparison of habitable zone occurrence rates for Earth-sized planets. [4]

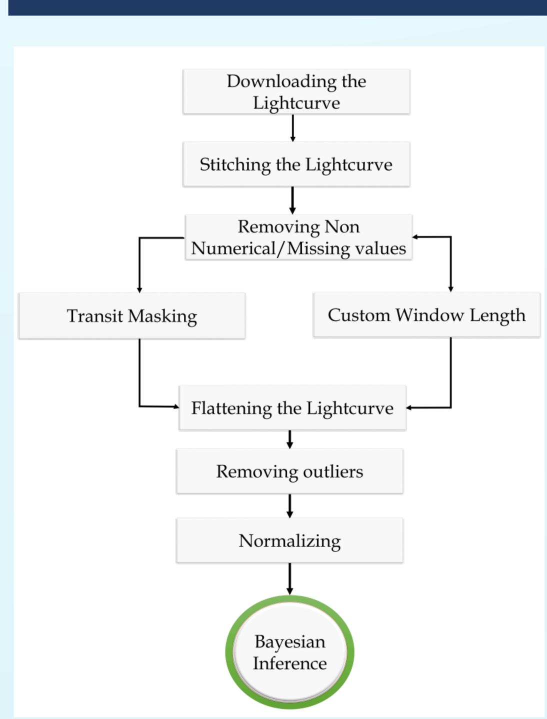
Kepler HZ and Near HZ Planet Sample

Refining planetary parameters is crucial for precise $\eta_\oplus$ estimates as it helps prevent misclassification of planets. Refinement also enables more accurate classification of planets within habitable zones (HZ), allowing us to distinguish potentially habitable worlds from false positives or less promising targets. Furthermore, it reduces systematic biases introduced by initial data calibration, stellar modeling uncertainties. Another key advantage is the ability to prioritize the most promising targets for follow-up by major missions like JWST and Lazuli Space Observatory. For our study, we selected 187 Kepler confirmed and candidate planets in the HZ orbiting main-sequence stars of spectral types F, G, K, and M, with stellar effective temperatures between 3200 K and 6800 K. The mean radius of the planets in our sample is around 2.15 $R_\oplus$, with orbital periods ranging from 8 days to 623 days, averaging around 192 days. Figure 2 illustrates the distribution of planets in our sample with respect to their effective temperatures and radii.

Figure 2. Distribution of planets in our sample in terms of stellar effective temperature and planetary radius. The shaded regions indicate different stellar spectral types (F, G, K and M), and the symbols distinguish confirmed planets from planet candidates.



Analytical Framework



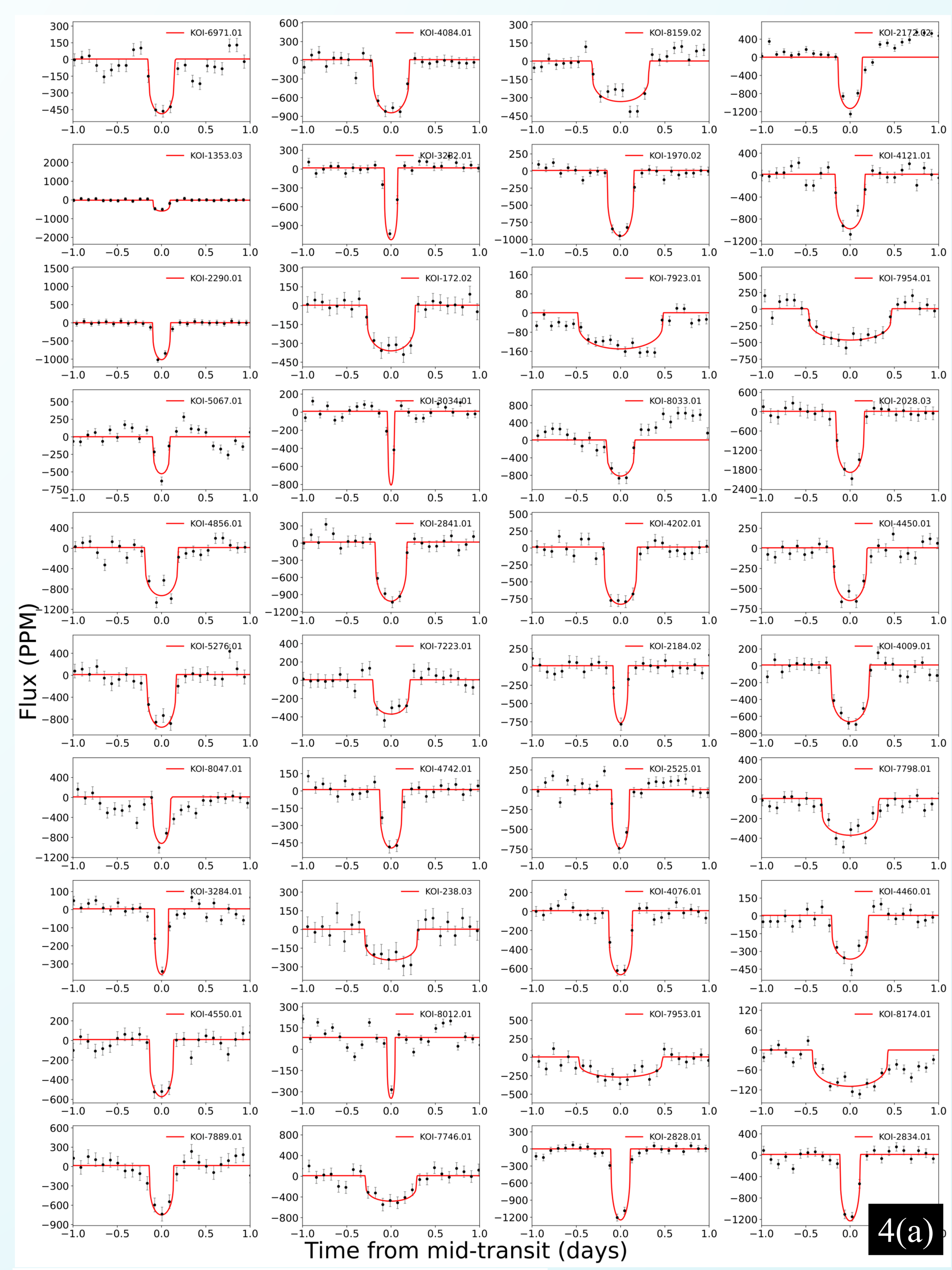
STERNA *is our pipeline for generating synthetic light curves for space telescopes. In this work, we use its comparison and benchmarking segment. STERNA was initially developed for the* ***Lazuli Space Observatory.***

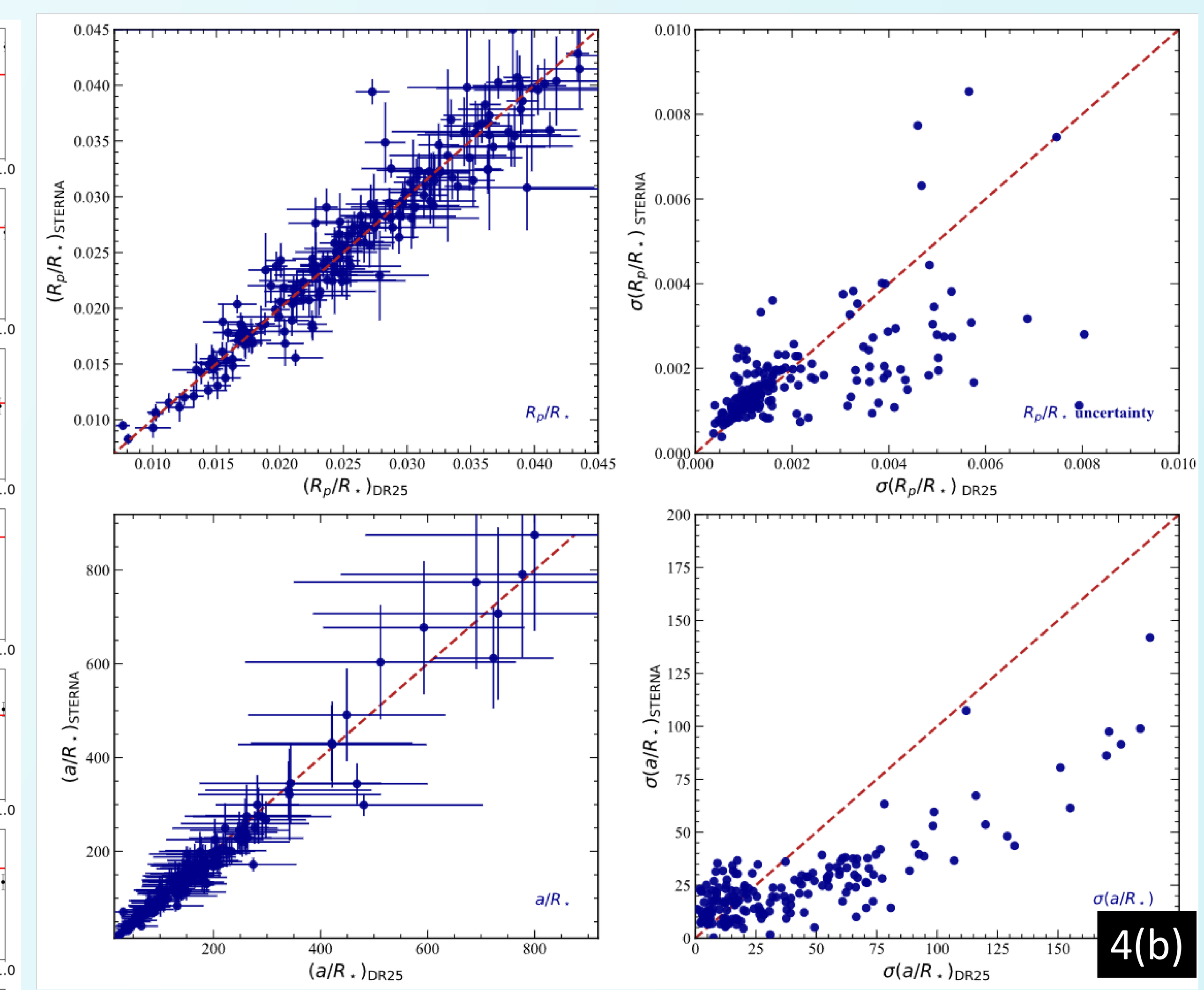
Table 1. Function, Prior Bounds, and Convergence Metrics for MCMC Transit Modeling

Parameter	Prior Type	Bound
R_p/R_*	Uniform Prior	$(R_p/R_*)_{guess} \pm 50\%$
Period (P)	Uniform Prior	$P_{\rm guess} \pm 1\%$
T_0	Uniform Prior	$T_{0,\rm guess} \pm 0.1 days$
a/R_*	Uniform Prior	$(a/R_*)_{\rm guess} \pm 40\%$
Inclination (i)	Geometric Prior in $\sin i$	87°–90°
u_1, u_2	Gaussian Priors	Standard form
Convergence Check Metrics:		
Gelman-Rubin ($\hat{R}$) statistic: $\hat{R} < 1.10$		
Acceptance fraction: $0.20 - 0.45$		
Convergence and trace plot monitoring		

Figure 3. Left panel: Illustration of the detrending procedure applied to the Kepler light curves and Right panel: Bayesian inference framework used for robust parameter estimation in this study

Results





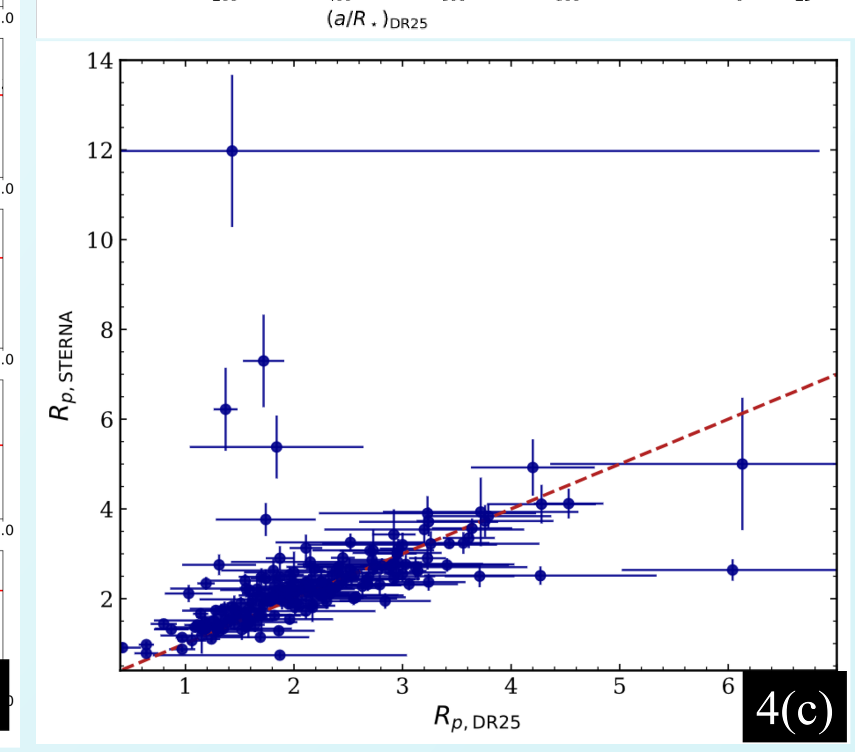


Figure 4: *(a) Transit fits for randomly selected (40) Confirmed/Candidate Planetes. (b) The two panels on the left compare the planet-to-star radius ratio (Rp/R*) and the scaled semi-major axis (a/R*), derived in this work, with the corresponding values from Kepler DR25. The two panels on the right show the improvement in parameter constraints by the STERNA fits relative to the DR25 catalog for both Rp/R*, and a/R* (c) shows for Radius (Rp) after using Gaia DR3 values.*

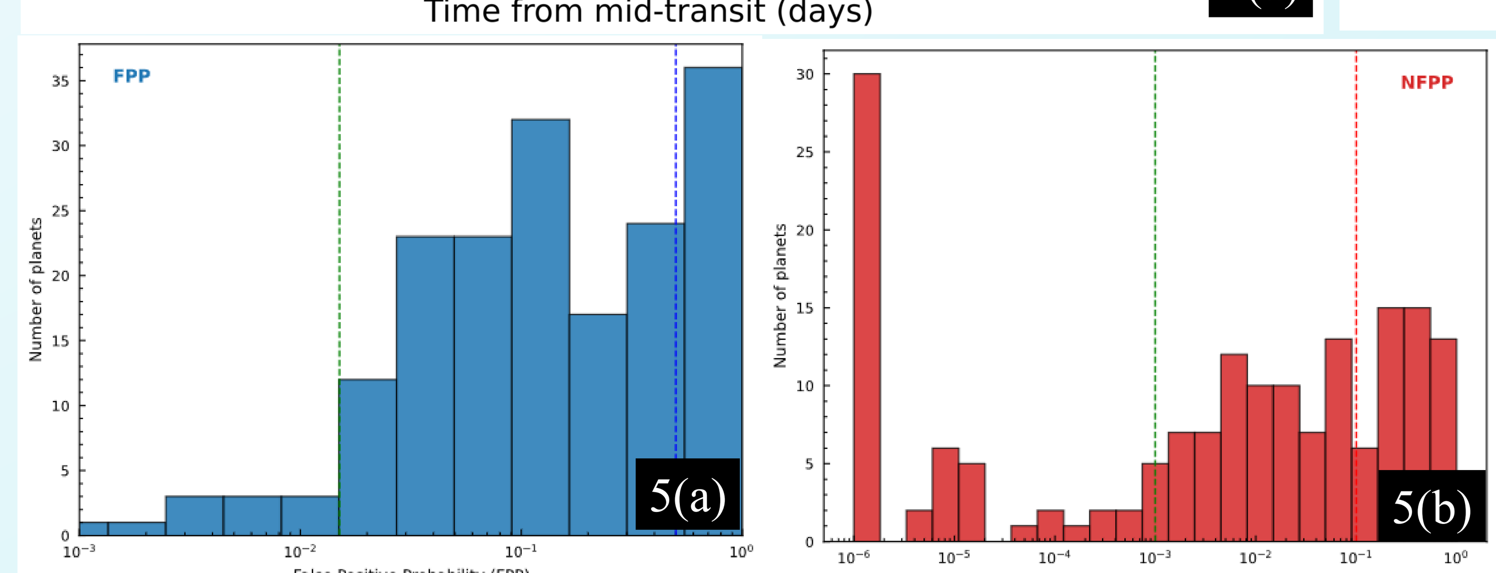


Figure 5: *False positive probability (FPP; left panel) and Nearby False Positive Probability (NFPP; right panel) distributions derived using TRICERATOPS [6]. The green dashed vertical line marks the validated-planet regime, defined by FPP<0.015 and NFPP)<10³. The blue dashed vertical line in the left panel denotes the likely-planet regime FPP)<0.5), while the red dashed vertical line in the right panel indicates the likely false-positive threshold NFPP)>0.1. Our statistical validation analysis finds that only eight targets rise to the level of statistically validated but most fall in an intermediate regime, with median FPP~0.1 and NFPP~0.01. Although higher Multiple Event Statistics (MES) values appear to have some influence on lowering FPP, no strong correlation is evident.*

JWST OR LAZULI WILL BE ABLE TO ENHANCE RELIABILITY WITH FOLLOW-UP OBSERVATIONS

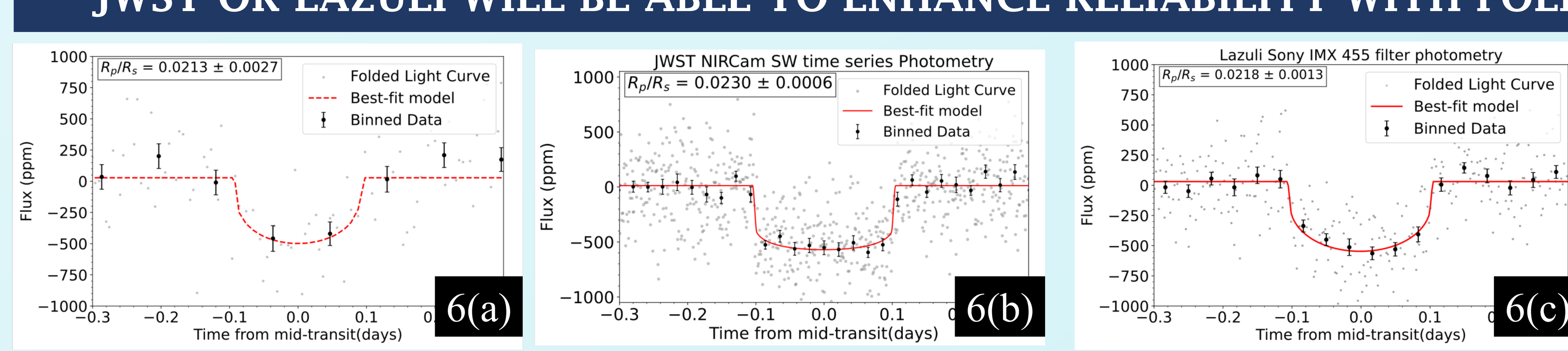


Figure 6: For planet candidate KOI-8047.01
(a) Shows Kepler analysis for four years of observation
(b) Shows simulated JWST NIRCAM SW time series photometry analysis
(c) Shows simulated Lazuli 3m Telescope WCC broadband photometry (SONY IMX 455)

References

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