Revealing the Population of Volatile-Rich Small Planets Around Cool Stars

Mike Greklek-McKeon

michael@caltech.edu

Co-Authors: H. Knutson, S. Vissapragada, R. Hu, M. Saidel, J. Gomez Barrientos, G. Levine, G. Vasisht, A. Fukui, J. Korth, F. Pozuelos Romero, H. Parviainen, K. Barkaoui, E. Pallé

BACKGROUND: Models predict that **water-rich planets may be common** around low-mass stars, but **definitive evidence for their existence remains elusive.** JWST has recently made the first detections of sub-Neptune atmospheres enriched in CH_4, CO_2 and H_2O, opening questions on atmospheric volatile enrichment mechanisms and whether these few planets represent the broader population of sub-Neptunes. To quantify the range of possible sub-Neptune atmosphere types, we must constrain the volatile atmospheric mass fractions of more small planets. This requires precise mass and radius measurements. Dynamical interactions in near-resonant multi-planet systems produce transit timing variations (TTVs), and measurements of these TTVs constrain the planetary bulk compositions. Over the past three years, **we have collected dozens of TTV observations** to characterize multi-planet M dwarf systems, **along with space-based XUV observations** to measure the planetary radiation environments. Our **survey results have found several new small volatile-rich worlds**, including some **top candidates for atmospheric characterization** with JWST and some of the coldest known volatile-rich rocky planets.

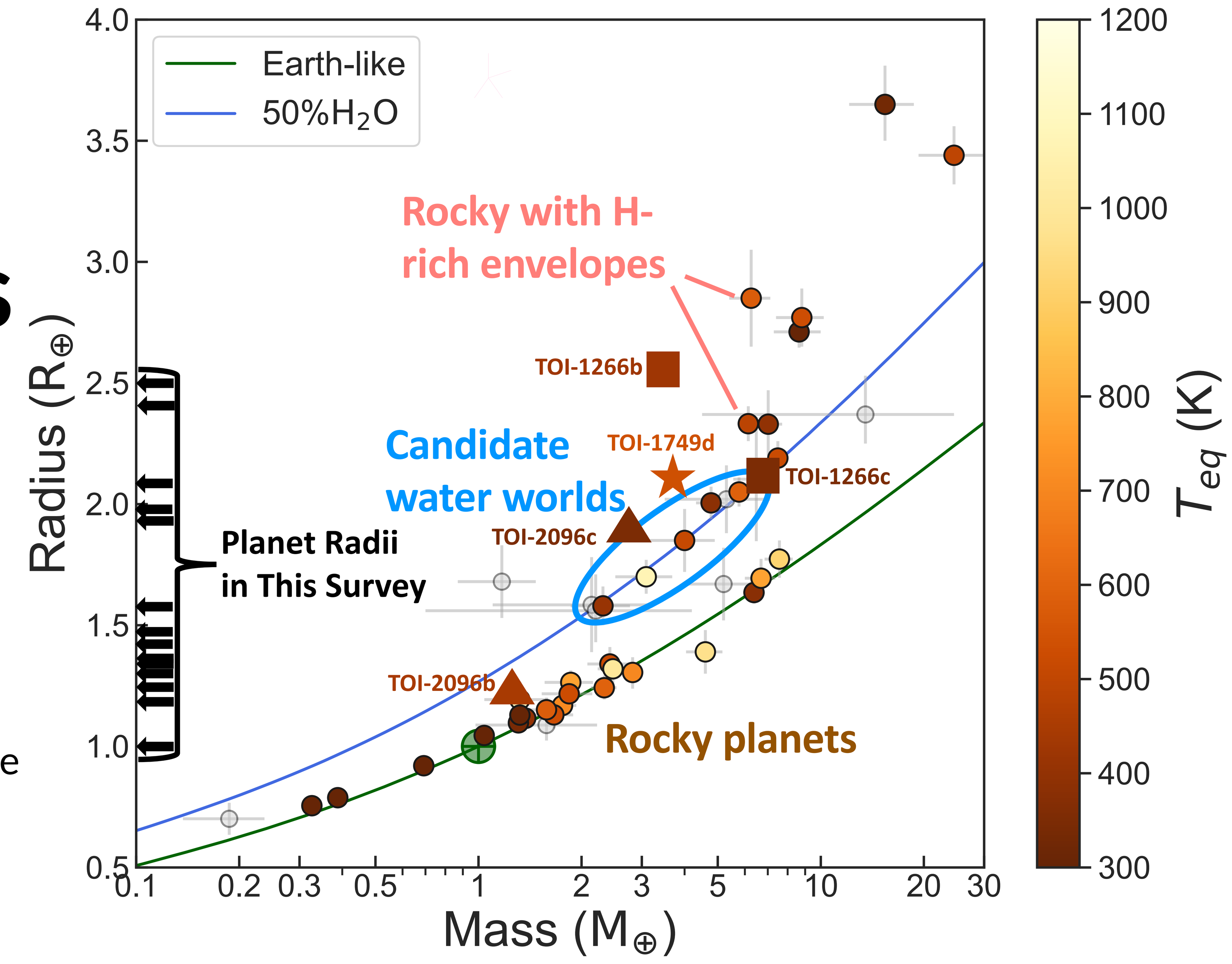
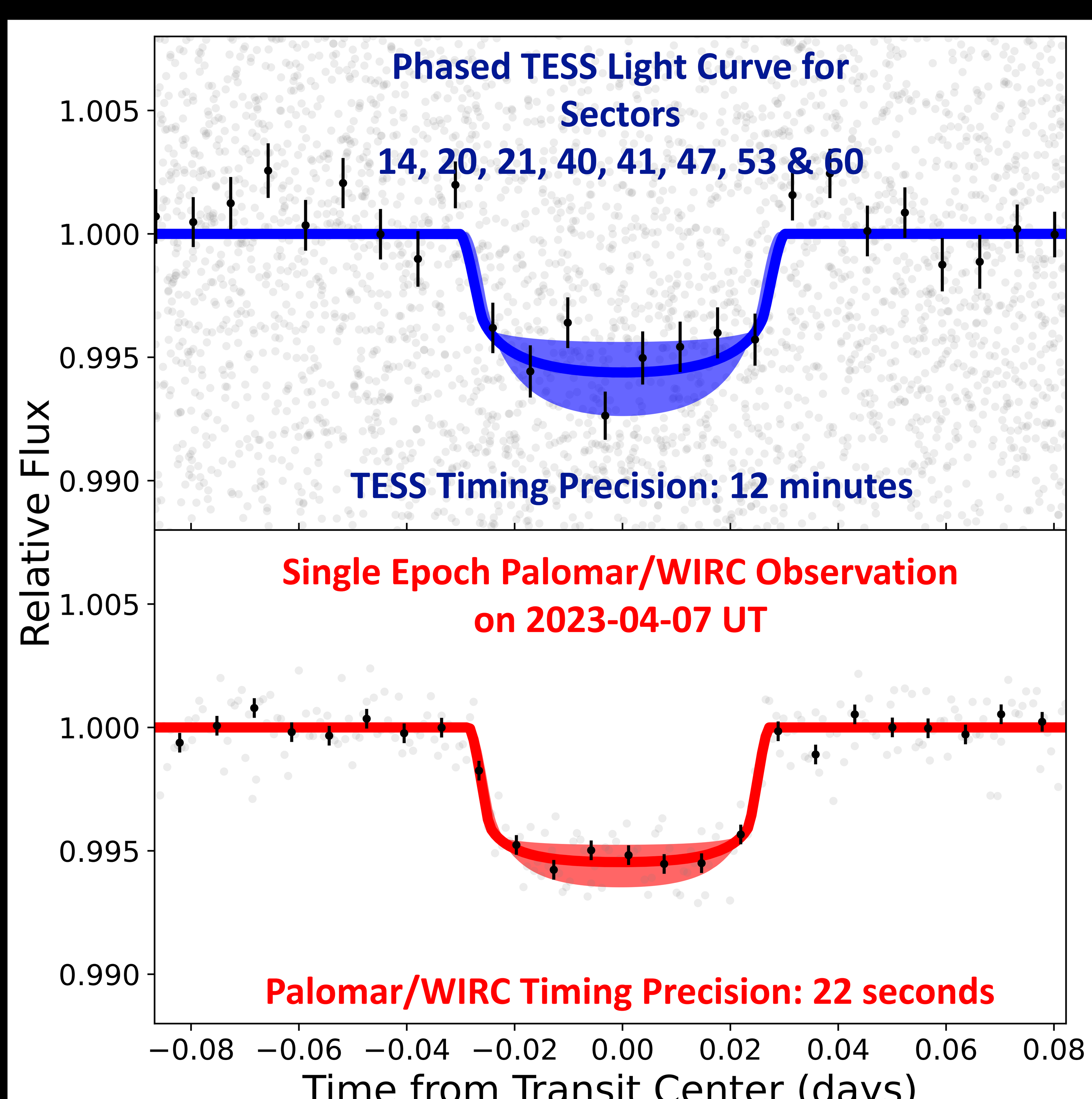


Figure 1: Mass-radius plot adapted from Luque & Pallé 2022, showing the population of small planets with well-characterized masses and radii. Radii of our 15 survey planets are marked, with symbols and labels for planets with preliminary mass detections.

Transit timing follow-up yields planetary bulk composition



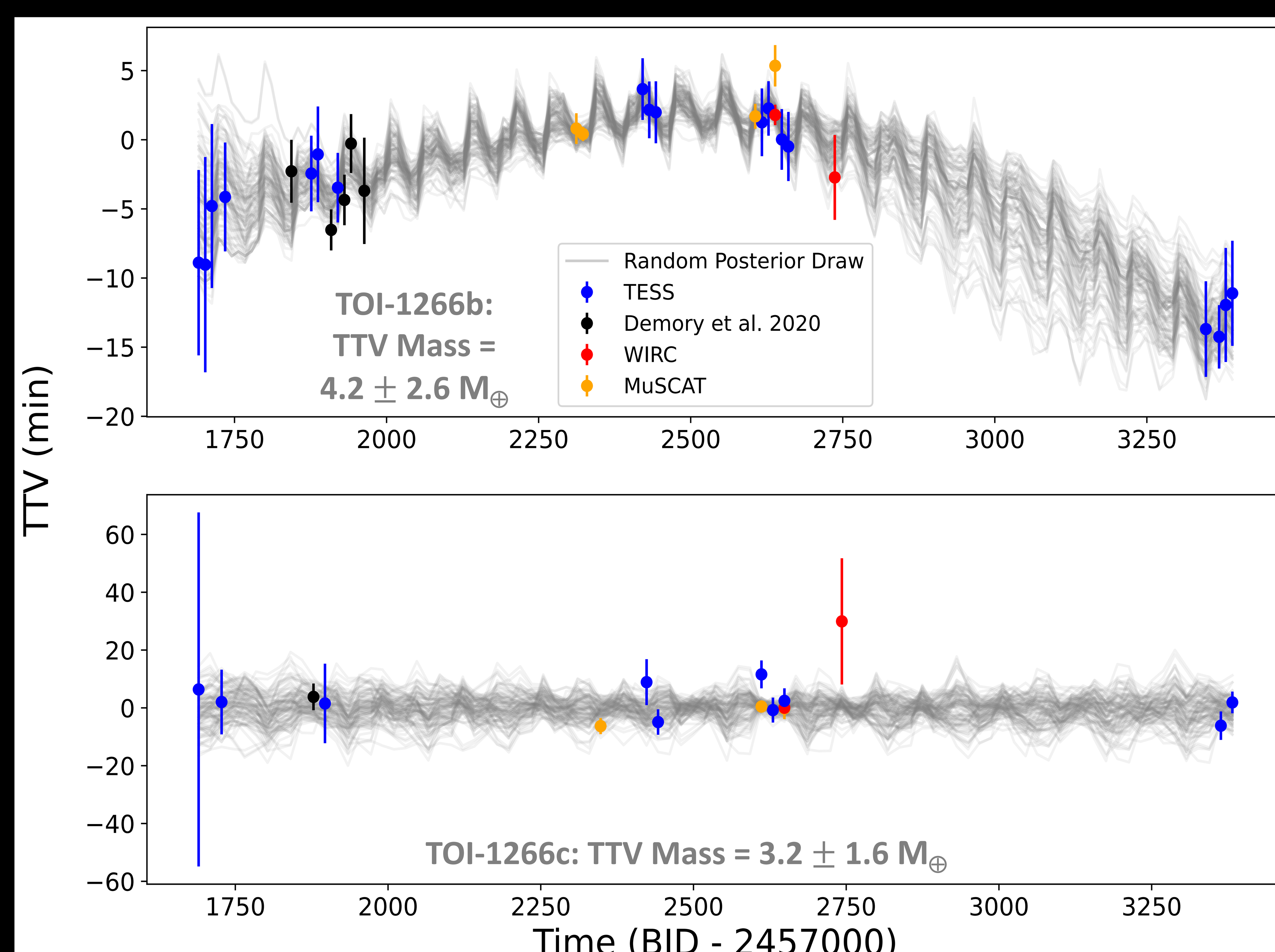
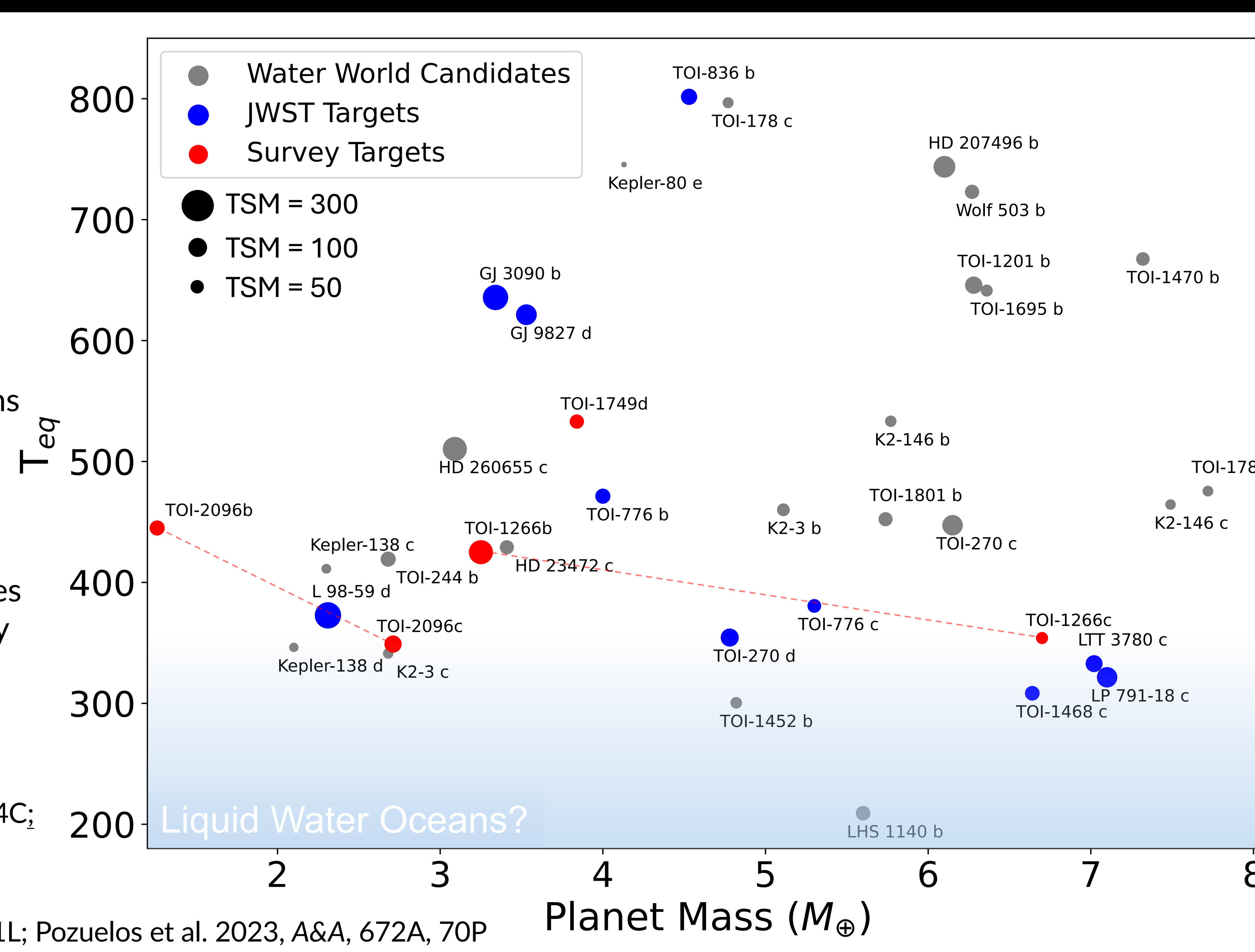


Figure 2: Transits of TOI-2096c (R = 1.9 $R_\oplus$, P = 6.4 days), which has an inner companion TOI-2096b (R = 1.25 $R_\oplus$, P = 3.1 days) near the 2:1 resonance around a 3300 K (mid-M) host star (Pozuelos et al. 2023). Top: Phased TESS photometry from all TESS sectors (grey points), binned to 10 minutes (black points), and the best-fit model with 1σ uncertainty in blue. Bottom: WIRC J band photometry for a transit of TOI- 2096c, with the best-fit model in red.

Figure 3: Observed TTVs for the TOI-1266 system, including initial discovery transit times from Demory et al. 2020 along with our Palomar/WIRC transits (red), and MuSCAT transits (yellow). We model the TTVs with TTVFast (Deck et al. 2014), and retrieved parameters include the planet-star mass ratios and $\sqrt{e}\cos(\omega)$ vectors. This solution constrains the eccentricities to < 0.1 for planets b and c. Cloutier et al. 2024 recently measured TOI-1266b and c's masses with RVs, and an upcoming TTV+RV joint-fit will significantly refine the planetary masses and bulk compositions.

METHODS AND RESULTS: We use the Wide-Field InfraRed Camera (WIRC) on the 200" Hale telescope at Palomar observatory in combination with a beam-shaping diffuser to measure several transits per planet in the TOI-663, 1266, 1749, 2096, and 2267 systems. **We use these high SNR transit measurements to achieve a timing precision that is unattainable with TESS.** We combine our WIRC timing measurements with TESS, other ground-based transits, and radial velocity observations to retrieve planetary masses, eccentricities, and bulk densities. We use the improved bulk composition constraints to identify volatile-rich planets amenable to atmospheric characterization, which is necessary to unambiguously determine volatile content.

Figure 4: Planet mass vs equilibrium temperature (T_{eq}; assuming efficient circulation and 0.3 albedo) for all M/K dwarf water world candidates (masses below 8 $M_\oplus$ and radii below 3 $R_\oplus$ with bulk densities above that of pure rock and below that of pure water). Blue points are planets with scheduled JWST observations and red points are targets from this survey with preliminary mass detections. Survey targets in the same system are connected by dotted lines. Blue shading indicates the region where liquid water may be possible (depending on atmospheric conditions).



REFERENCES:

Cloutier et al. 2024, *MNRAS*, 527, 5464C;
Deck et al. 2014, *ApJ*, 787, 132D;
Demory et al. 2020, *A&A*, 642A, 49D;
Luque & Palle 2022, *Science*, 277, 1211L; Pozuelos et al. 2023, *A&A*, 672A, 70P