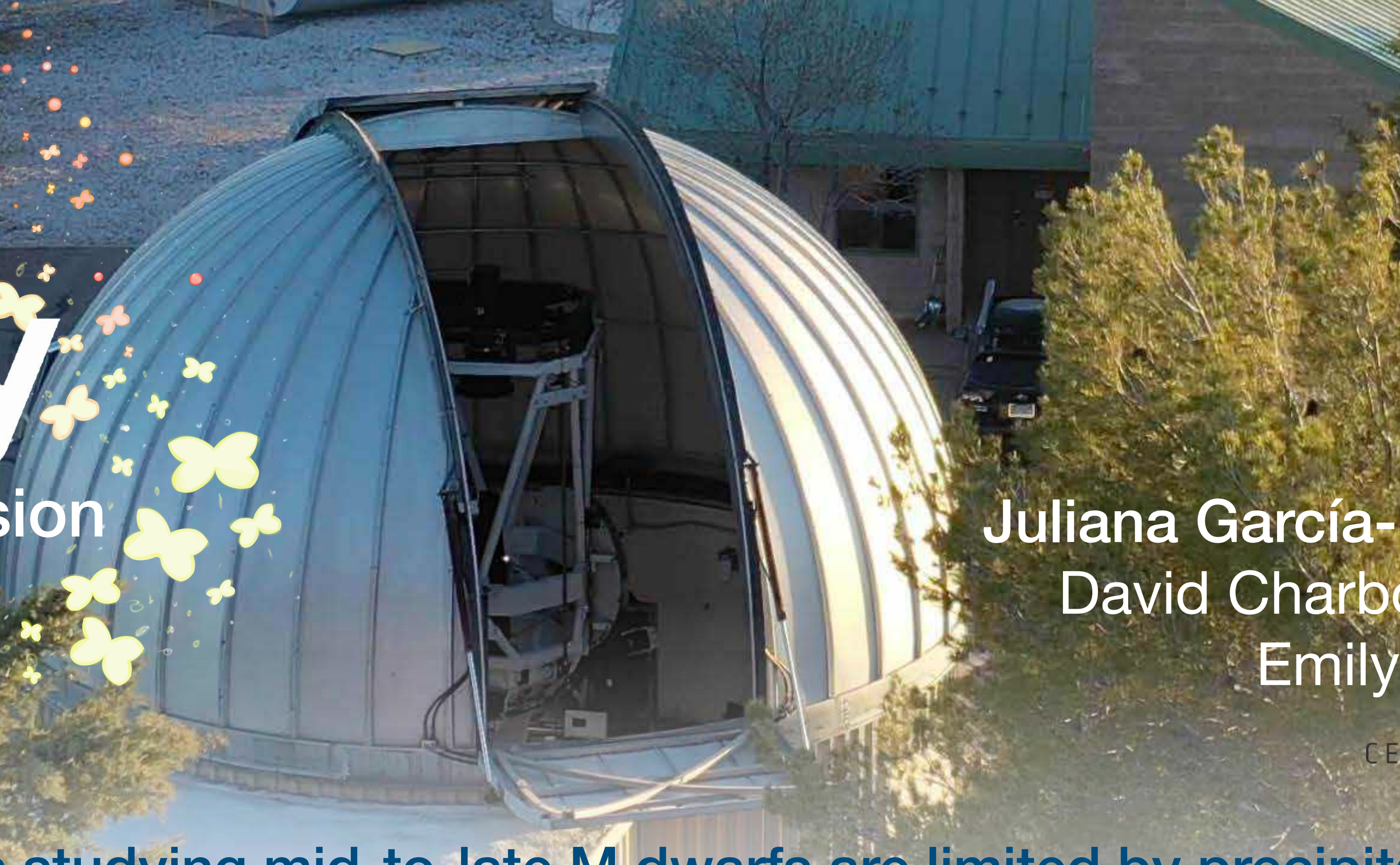
the Tierras Observatory

First-light results and intra-night precision



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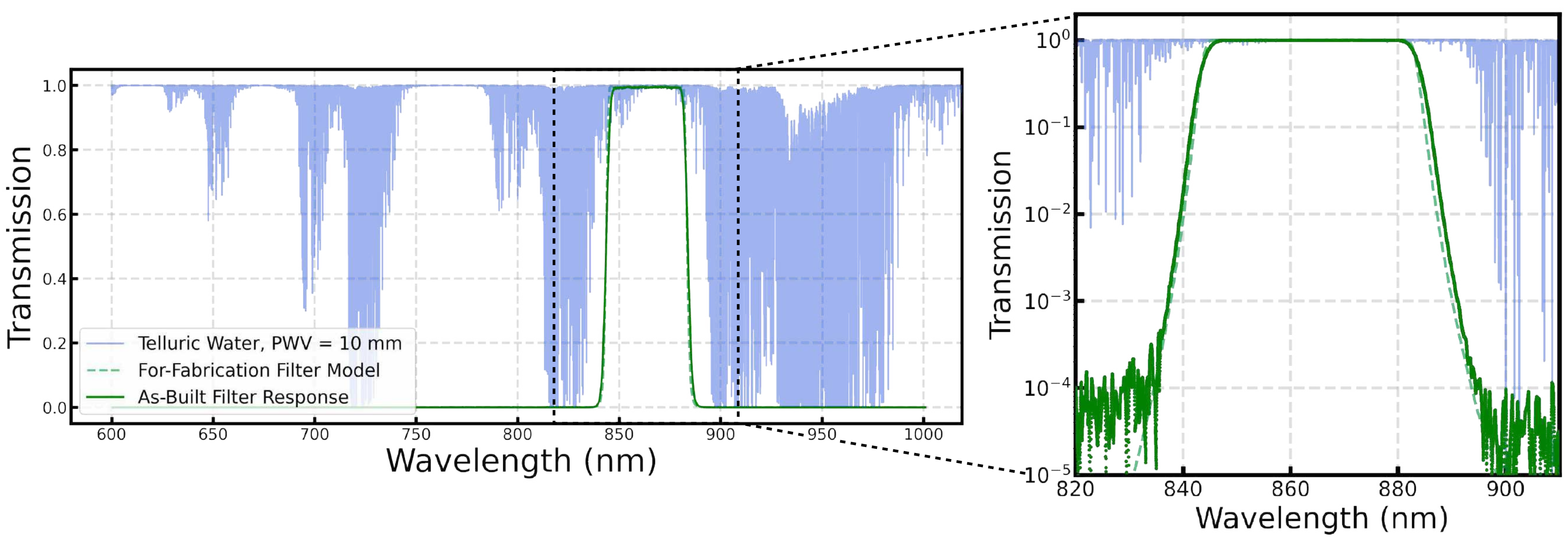
State-of-the-art ground-based robotic facilities studying mid-to-late M dwarfs are limited by precipitable water vapor (PWV) error. These experiments typically reach per-point intra-night photometric precisions >1000 ppm and night-to-night photometric precisions > 3000 ppm, since water features in the photometric bandpass result in a color-dependent offset when comparing the brightness of the red target to the blue field stars.

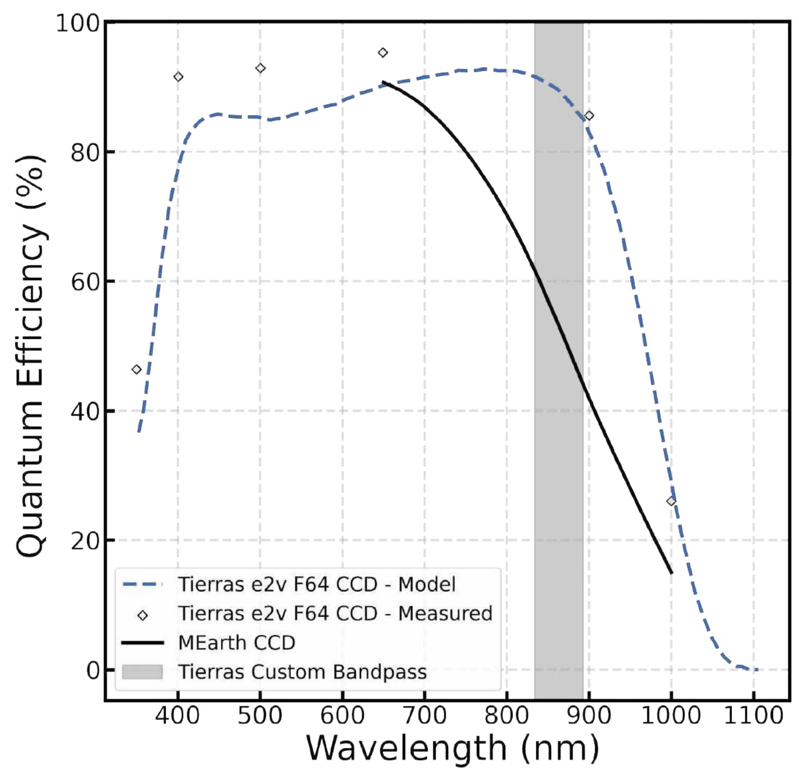
***Tierras* is designed to inoculate ground-based observations from PWV error.** We have refashioned the 1.3-m 2MASS N telescope located at the F.L. Whipple Observatory atop Mount Hopkins, Arizona, into an ultra-precise time-series photometer, designed to limit the contribution of PWV to the total photometric error to be below 230 ppm for M dwarf stars of spectral types M7 and earlier.

The design choices enabling our photometric precision goals include:

1. A **custom narrow bandpass filter** (40.2 nm FWHM) centered at 863.5 nm to avoid prominent telluric features and lower the PWV error contribution to be 138 ppm for M3-type stars and 230 ppm for M7-type stars.



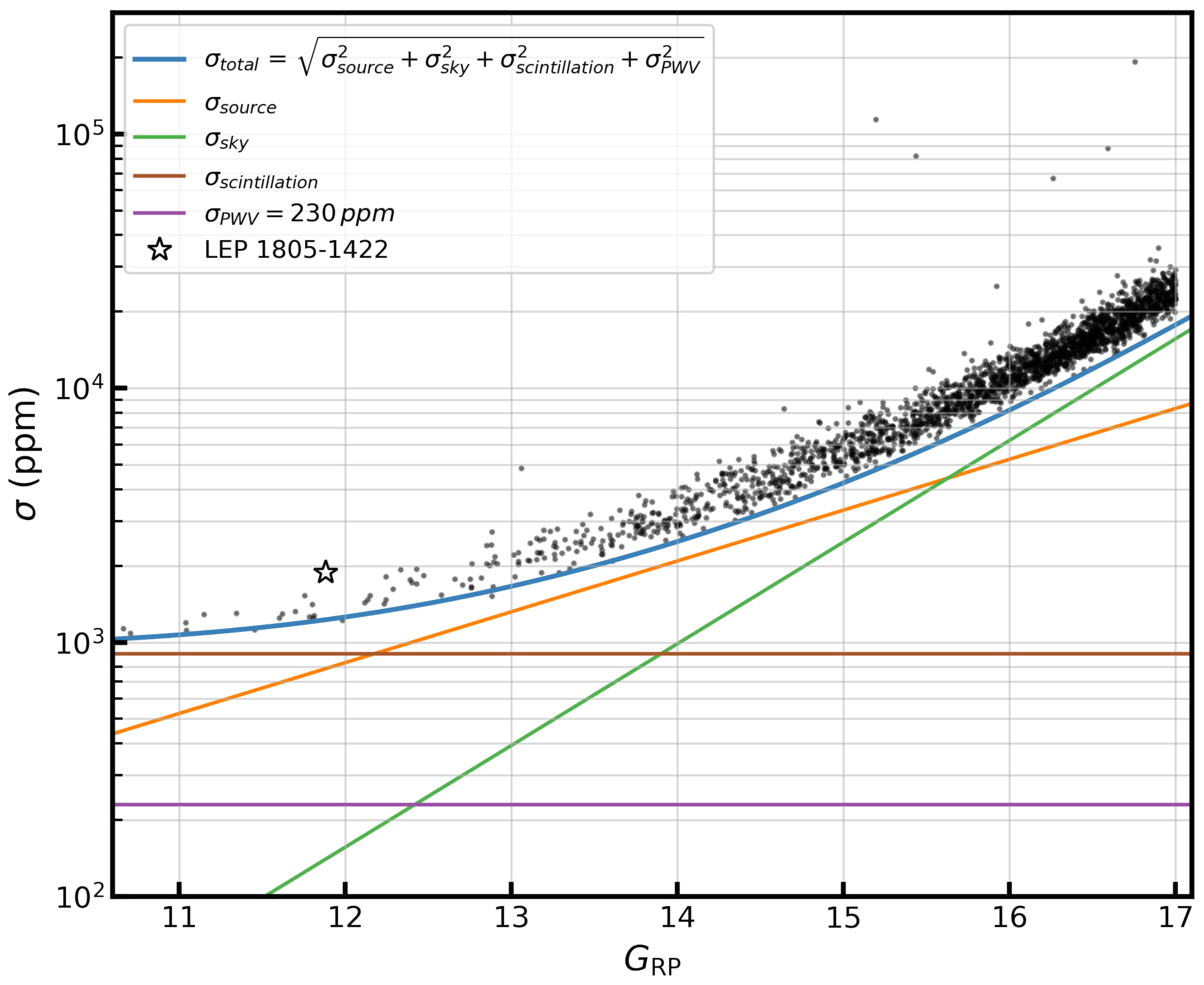
2. A $4K \times 4K$ **deep-depletion CCD** operating in fast frame transfer (shutter-less) mode with >85% quantum efficiency (QE) in our bandpass, low read-noise and low dark current. A custom dewar cools the CCD to -105°C.



For more information on the design of *Tierras* refer to **Garcia-Mejia et al. Proc. of the SPIE, 114457R, arXiv:2012.09744, (2020).**

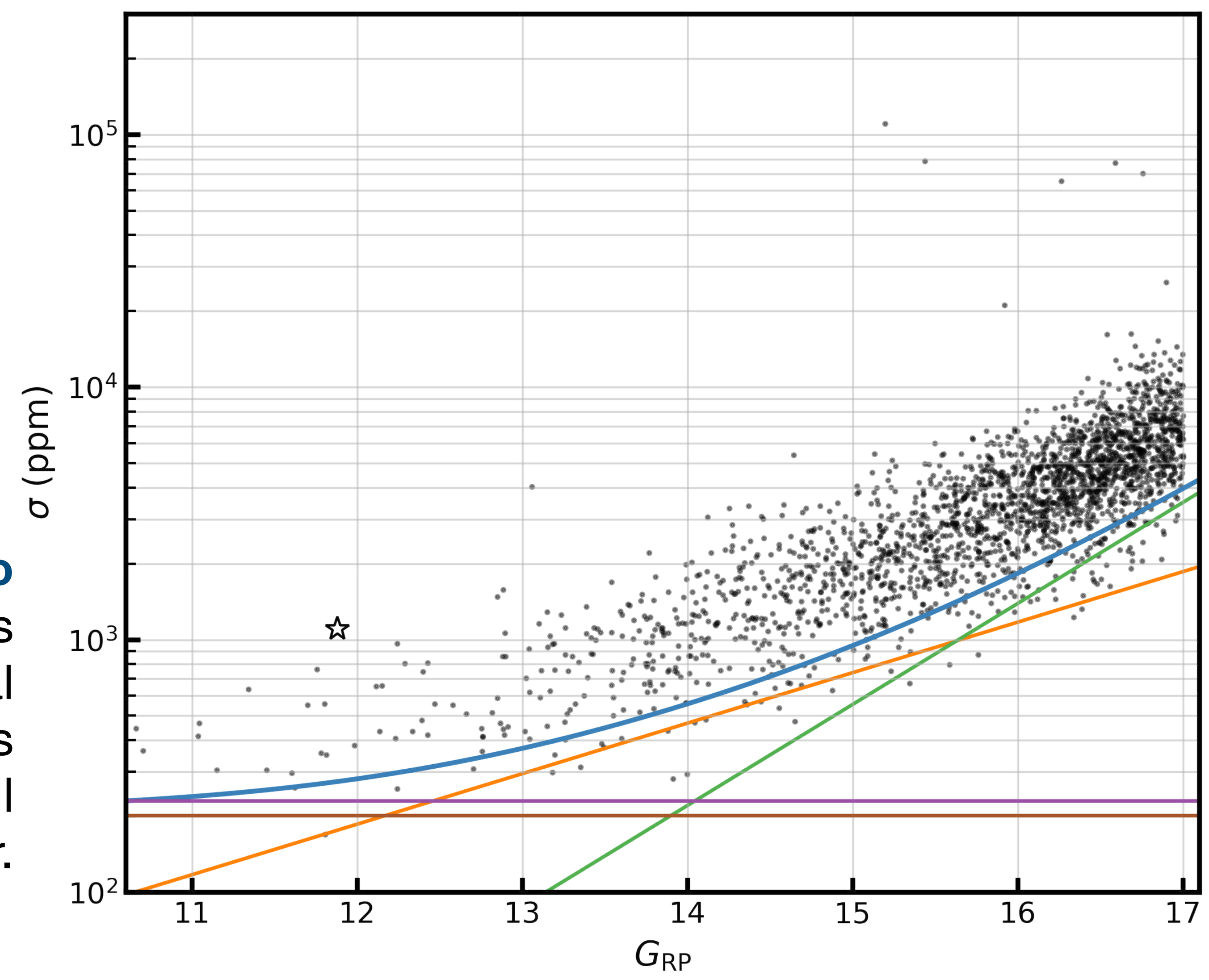
We have been on-sky since the Fall of 2022, and are achieving our desired intra-night photometric precision.

Below, we plot photometric error as a function of magnitude for 4250 sources with $G_{RP} \geq 17$ present in the *Tierras* field containing LEP 1805-1422, one of our target M dwarf stars ($R = 0.15\,R_\odot$, $G_{RP} = 11.88$). We gathered 170 60-sec exposures of this field on 2024 May 9 ($1.44 < X < 2.29$).

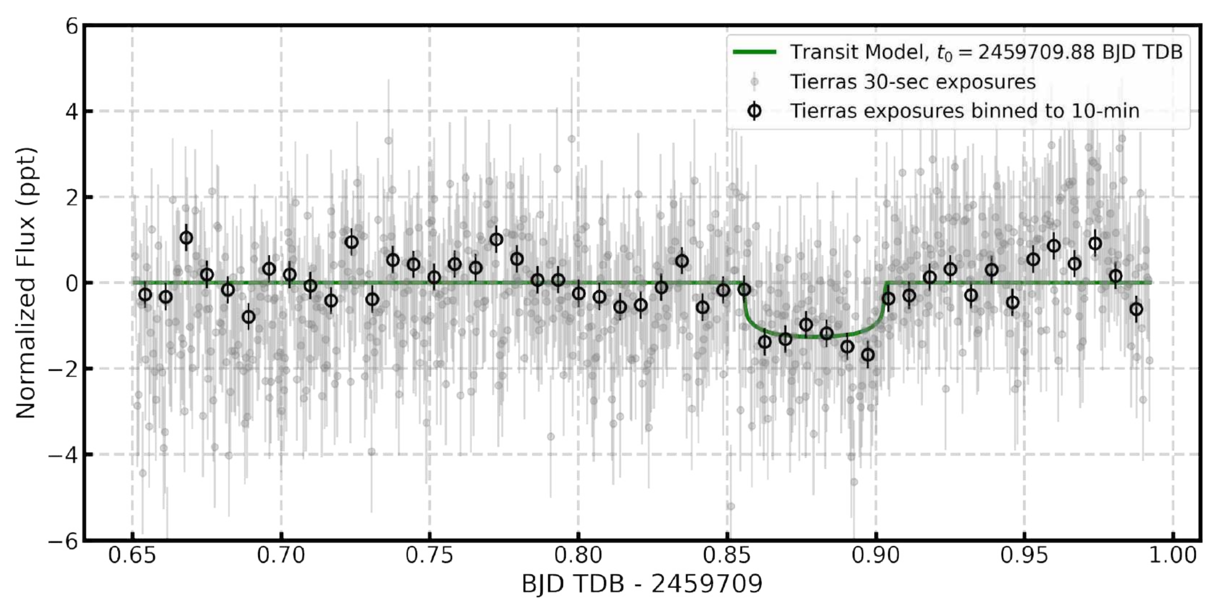


Left: we plot measured **photometric error for each source at native cadence** (black points). The photometric precision achieved by *Tierras* agrees with the total expected error, σ_{total}.

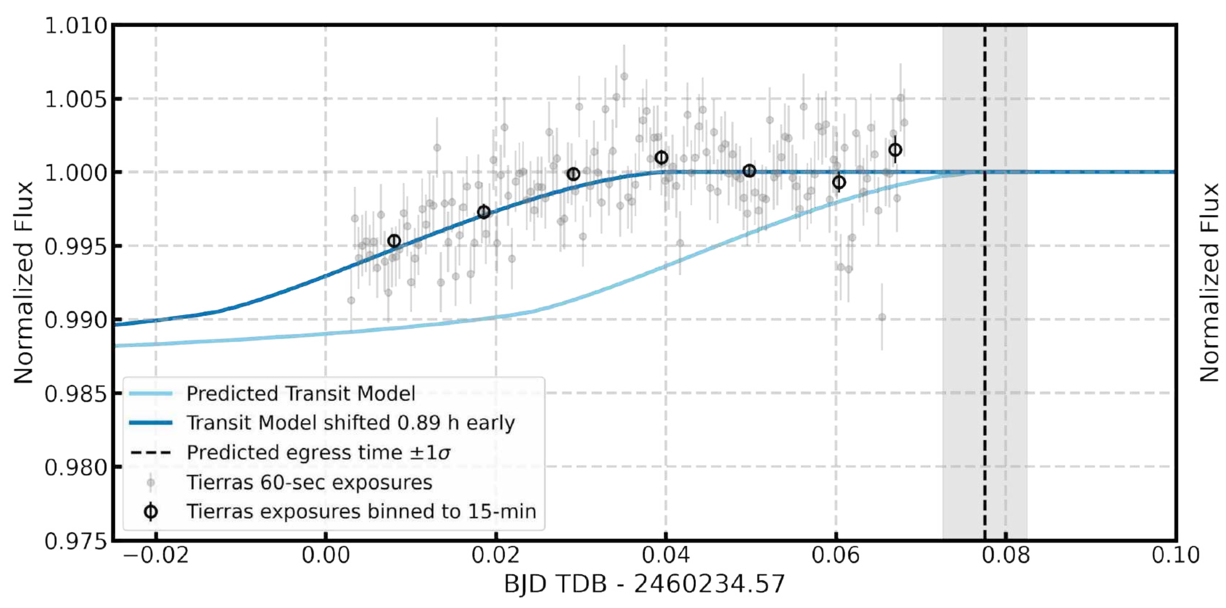
Right: **we bin the observations to 20 min;** their photometric precisions are well-matched to theoretical expectations. Ongoing improvements in tracking and flat-fielding will improve our data quality further.



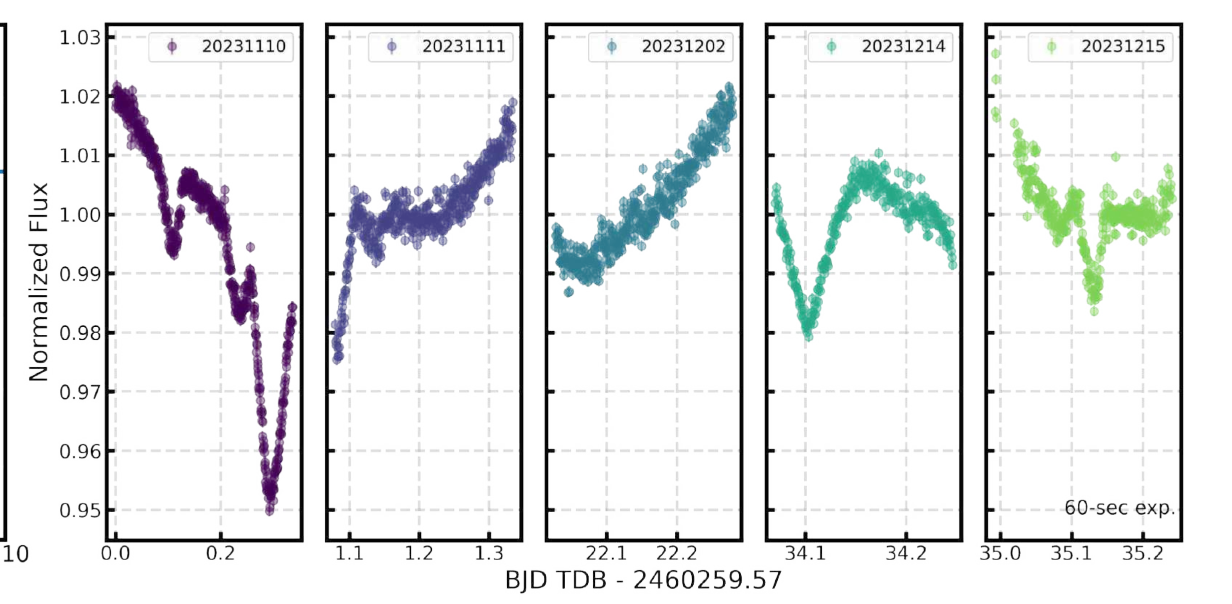
We can leverage this precision to recover **Earth-sized planets in a single transit.** Below is TOI-2013.01, a $1.15\,R_\oplus$ planet around a $0.33\,R_\odot$ star (Kemmer et al., 2022) as seen with *Tierras*.



We can engage in **TOI follow-up** of exciting targets, such as TOI-4600 c (Mireles et al., 2023), a 483-d $9.42\,R_\oplus$ planet around a $0.83\,R_\odot$ star.



And help disentangle the nature of poorly-understood phenomena, e.g., the **complex-periodic variable** LP 12-502, a 42 Myr old $0.83\,R_\odot$ star (Bouma et al., 2024).



The upcoming *Tierras* observing campaign will combine two observing strategies : the follow-up of TESS low-mass stars with one or more known terrestrial planets that have been observed for less than two sectors, and the survey of M dwarfs ($0.1 < M_*/M_\odot < 0.3$) within 20 pc of the Sun that will not be observed by TESS.