



# Validating TESS Planet Candidates with TRICERATOPS

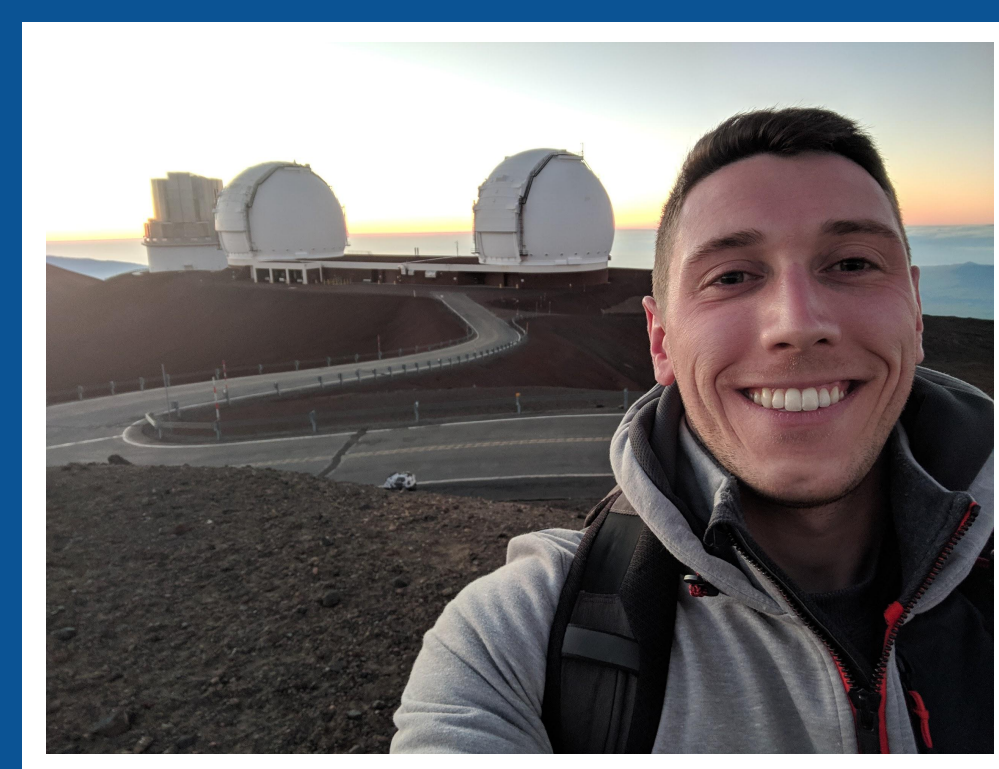
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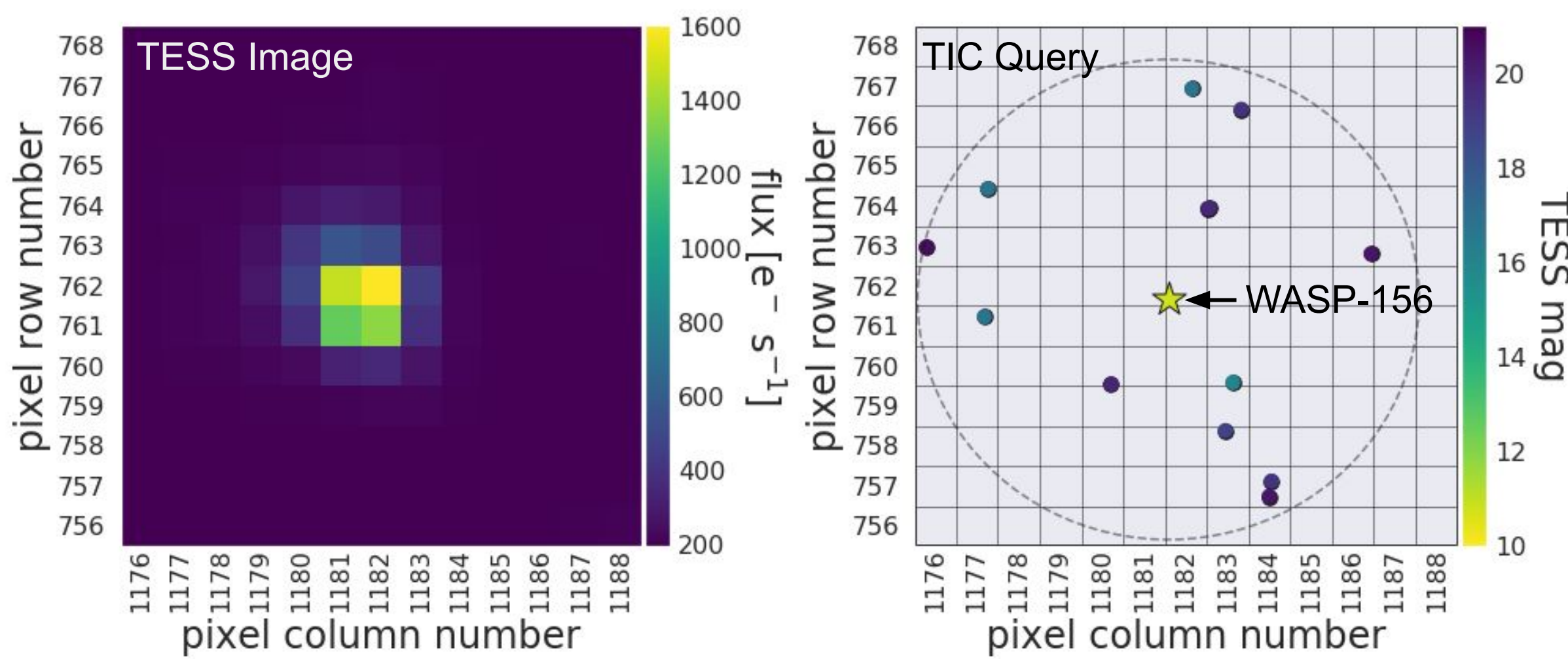
## Overview

TRICERATOPS (Tool for Rating Interesting Candidate Exoplanets and Reliability Analysis of Transits Originating from Proximate Stars) is a vetting and statistical validation tool for transiting planet candidates. TRICERATOPS analyzes planet candidates by considering numerous transit-producing scenarios and calculating the Bayesian probability of each. These probabilities can be used to identify likely astrophysical false positives and validate transiting planets. Although originally built for TESS Objects of Interest, TRICERATOPS is now also compatible with Kepler and K2 targets.

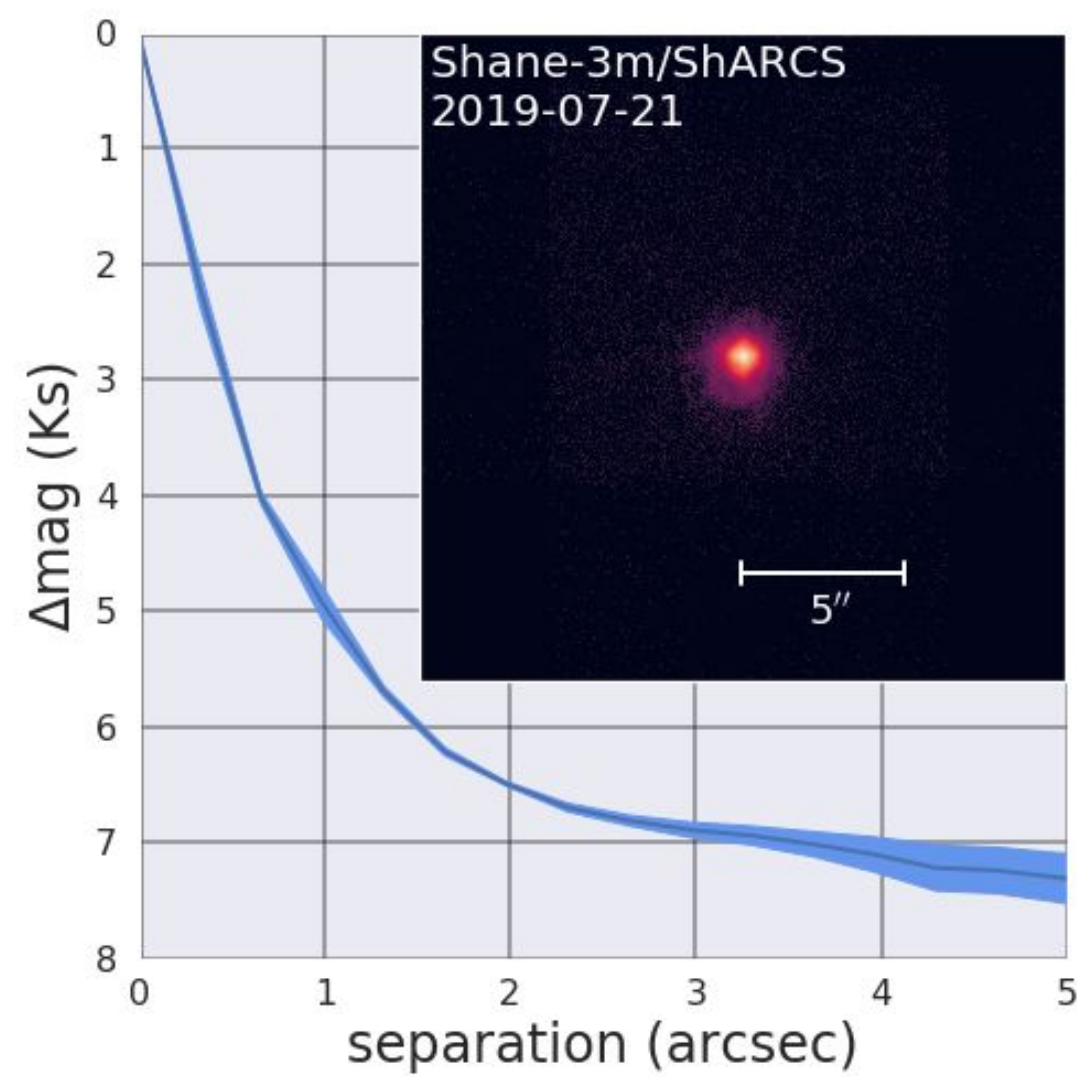
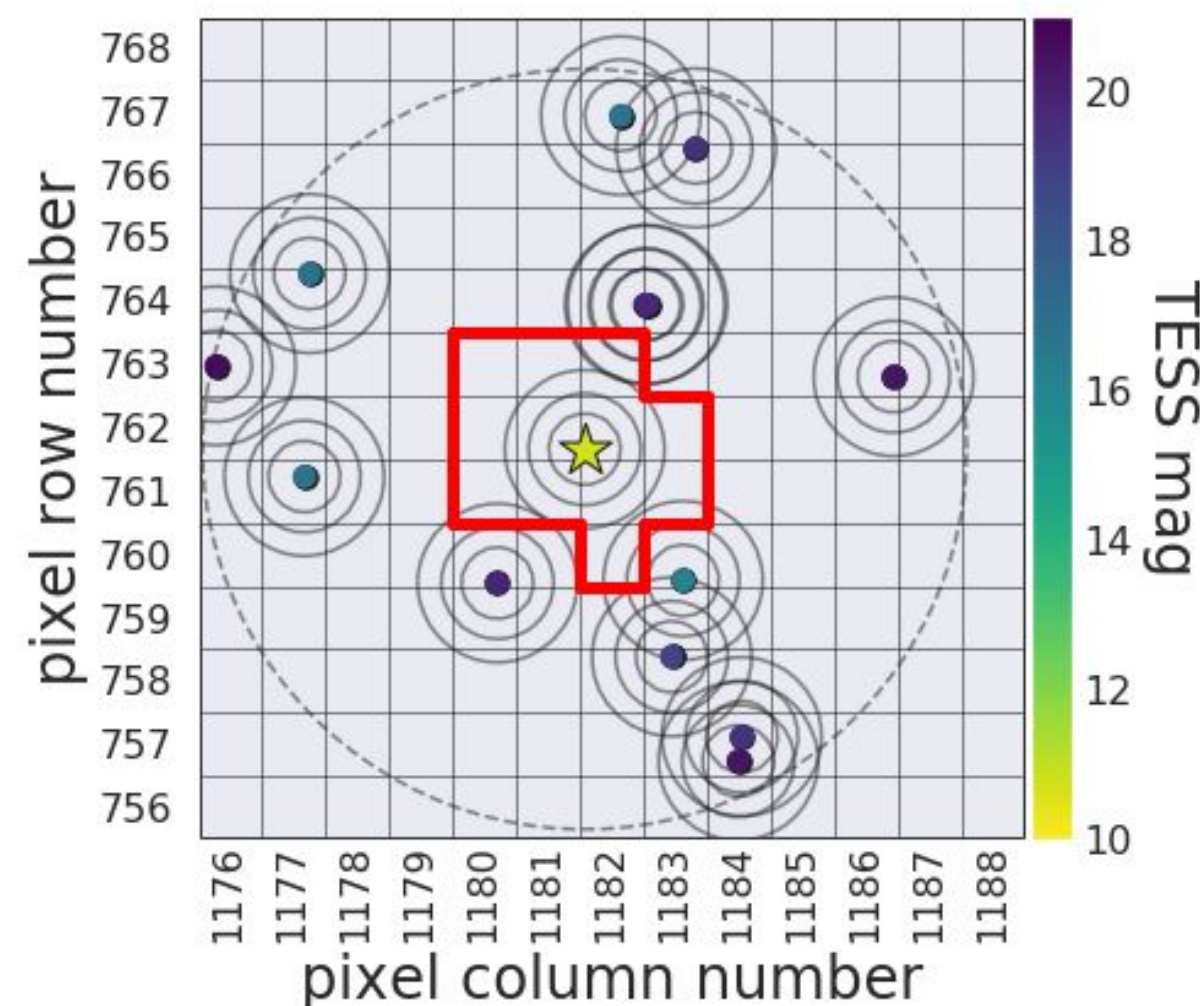
## Procedure

Below is an illustration of how TRICERATOPS analyzes planet candidates, using the confirmed planet WASP-156b (a.k.a. TIC 270380593.01 or TOI-465.01; Demangeon et al. 2018). See Giacalone et al. (2021) for more information on the analysis procedure.

Step 1: Identify the target and query the TESS Input Catalog (TIC; Stassun et al. 2018) for nearby stars, which can contaminate the photometric aperture and host eclipsing binaries mistakable for transiting planets.

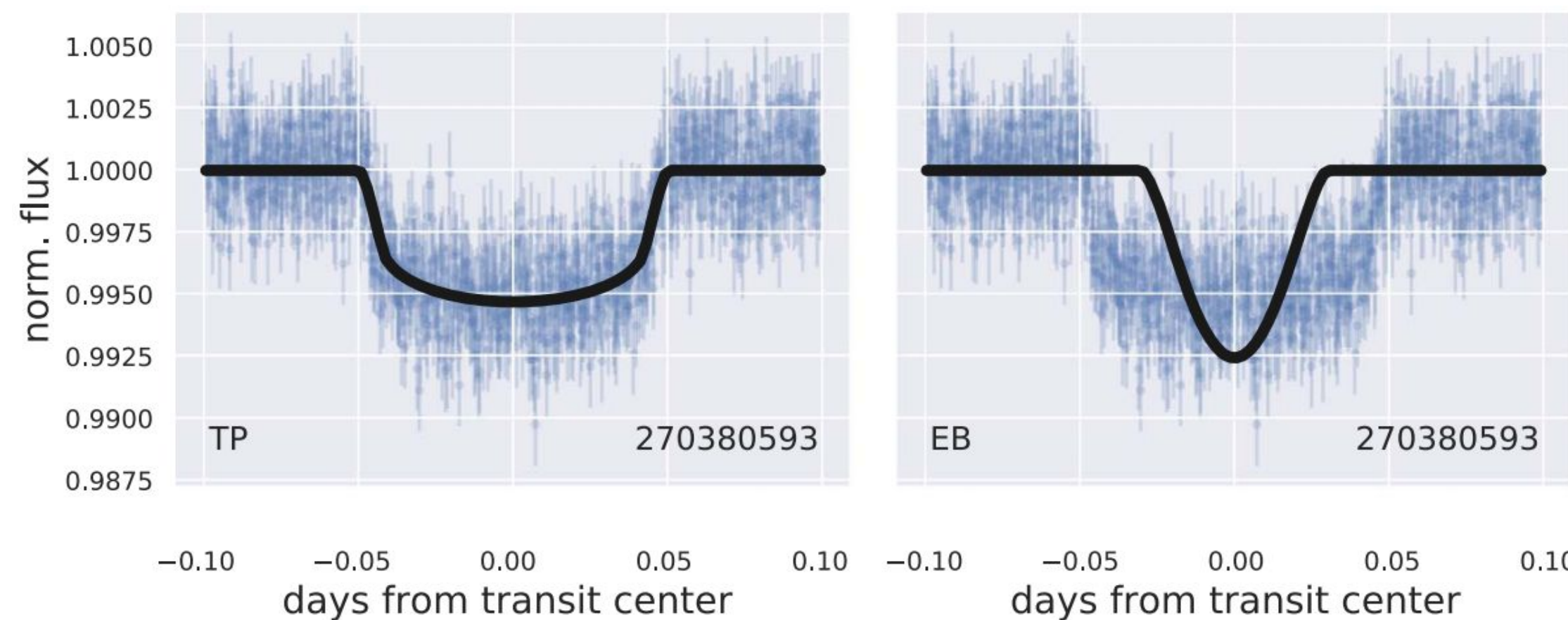


Step 2: Define an aperture (red polygon), model the TESS pixel response function for each star (black circles), and determine which nearby stars contaminate the aperture enough to cause a false positive. In this case, no nearby stars are bright or near enough to do so, so the transit must be coming from WASP-156 or a star blended with it.



Step 3: Fold in follow-up observations, such as adaptive optics imaging (example image and contrast curve shown to the left), to add additional constraints on the probabilities of false positive scenarios, such as those due to unknown stars blended with the target star.

Step 4: Simulate  $> 10^6$  systems for each transit-producing scenario, such as a transiting planet (TP) or eclipsing binary (EB), and compare their light curves (black curves) to the TESS light curve (blue points). Calculate the marginal likelihood of each scenario.

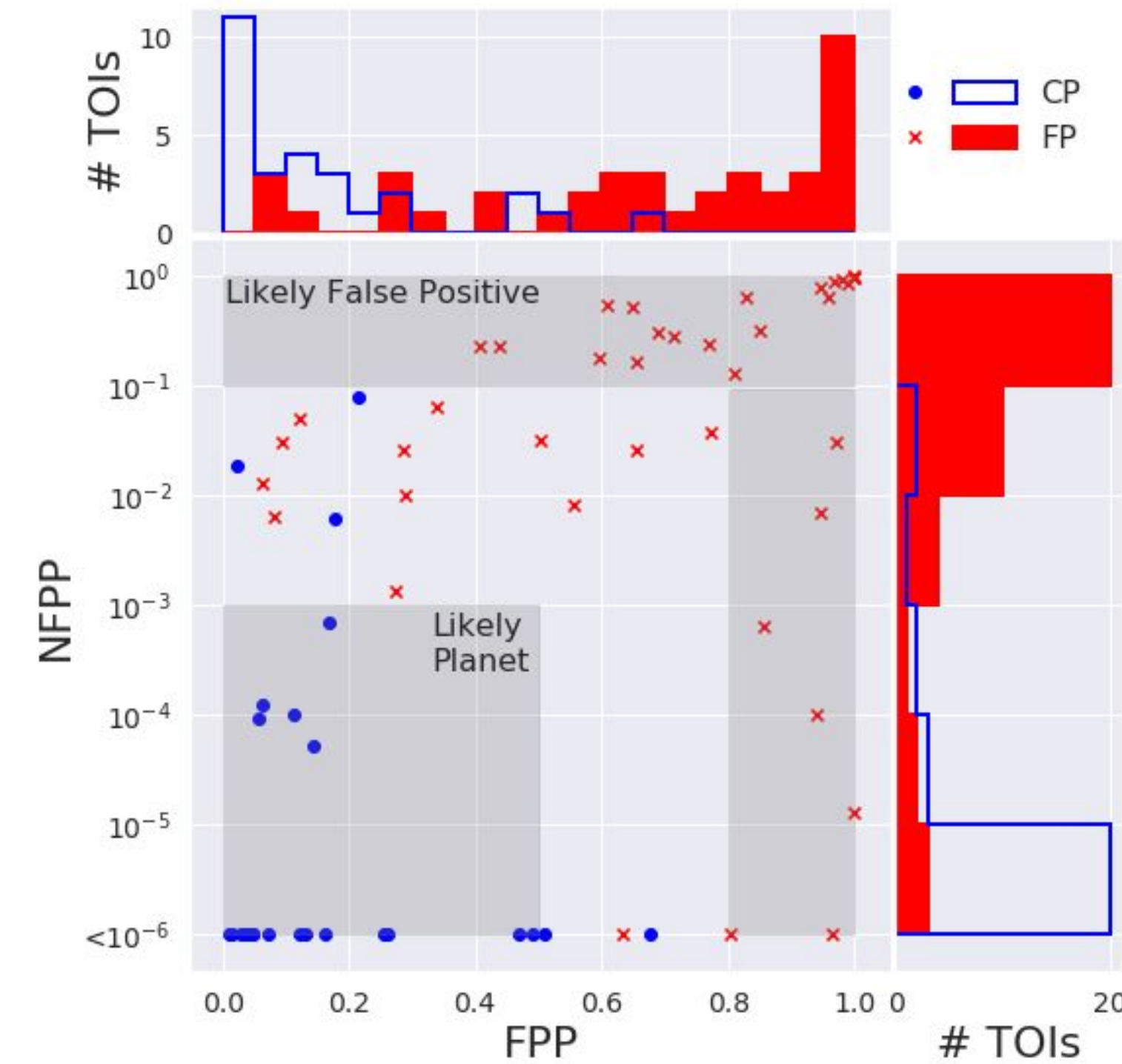


Step 5: Lastly, use these marginal likelihoods to calculate the **nearby false positive probability (NFPP)**; the probability that the transit comes from a known nearby star) and the **false positive probability (FPP)**; the overall probability that the planet candidate is a false positive). For WASP-156b, we find FPP = 0.1% and NFPP = 0, which is sufficient to consider the planet validated.

## Performance

We tested TRICERATOPS on 68 former TESS planet candidates, 28 of which are confirmed planets (CP) and 40 of which are astrophysical false positives (FP). We draw decision boundaries, indicated in gray, beyond which planet candidates are classified as **likely planets** (FPP < 50% and NFPP < 0.1%) or **likely false positives** (FPP > 80% or NFPP > 10%). We consider a planet **validated** when FPP < 1% and NFPP < 0.1% (Giacalone et al. 2021).

**TRICERATOPS can reliably distinguish between bona fide planets and astrophysical false positives.**

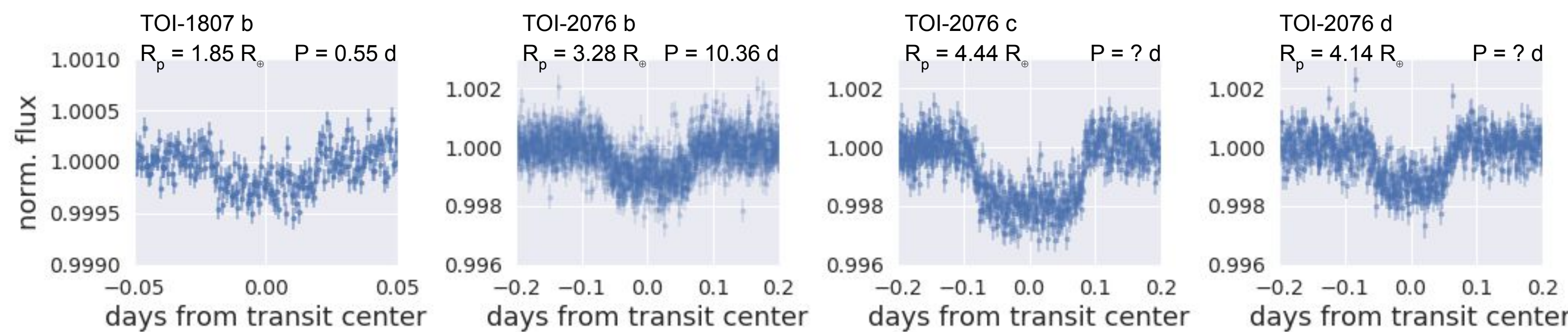


## Applications and Highlights

TRICERATOPS is best utilized to identify planet candidates most suited for future follow-up observations to characterize their systems. Some examples are shown below.

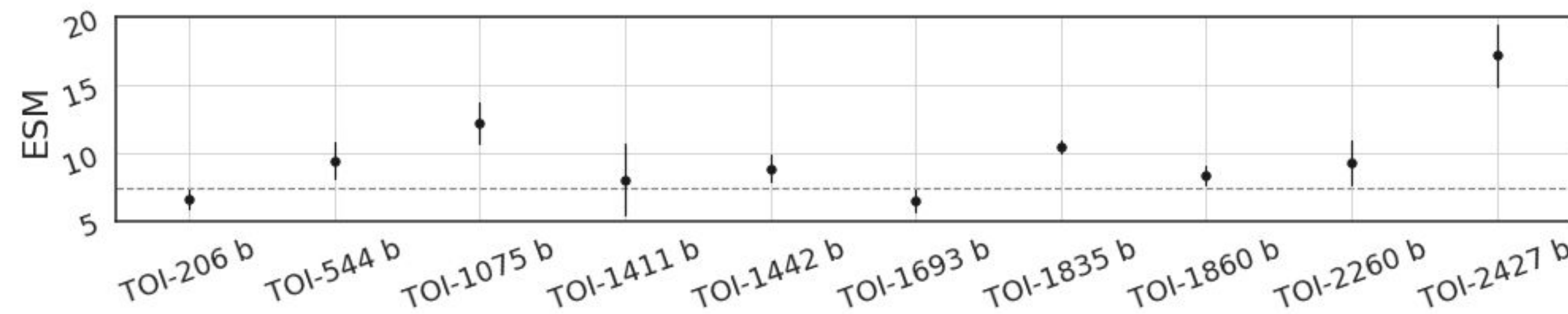
### TOI-1807 and TOI-2076

The transiting planets around these young (~200 Myr), co-moving stars were recently validated in Hedges et al. (2021) with the help of TRICERATOPS. Young stars make difficult targets for radial velocity observations because of their high activities, which can drive jitter from rotationally modulated spots of up to 100 m/s (Hillenbrand et al. 2015). By validating these planets, we can confidently pursue mass measurements with radial velocity observations.



### Hot, potentially terrestrial planets ideal for JWST emission spectroscopy

We recently used TRICERATOPS to validate potentially terrestrial ( $R_p < 2 R_\oplus$ ) TESS planets that would make the best targets for JWST emission spectroscopy observations based on their Emission Spectroscopy Metrics (ESM; Kempton et al. 2018). We have validated 10 such planets, which we plan to characterize further in the future (Giacalone et al., submitted).



## How to use TRICERATOPS

When making TRICERATOPS, we placed an emphasis on **ease-of-use** and **computational efficiency**. For a given planet candidate, it can be fully run in < 5 minutes on a standard 2-core laptop. TRICERATOPS operates in Python 3 and is **pip-installable**. The code is open-source and available on github: <https://github.com/stevengiacalone/triceratops/>

## References

- Demangeon et al. 2018, "The discovery of WASP-151b, WASP-153b, WASP-156b: Insights on giant planet migration and the upper boundary of the Neptunian desert," *Astronomy & Astrophysics*, 610, A63
- Giacalone et al. 2021, "Vetting of 384 TESS Objects of Interest with TRICERATOPS and Statistical Validation of 12 Planet Candidates," *The Astronomical Journal*, 161, 24
- Hedges et al. 2021, "TOI-2076 and TOI-1807: Two Young, Comoving Planetary Systems within 50 pc Identified by TESS that are Ideal Candidates for Further Follow Up," *The Astronomical Journal*, 162, 54
- Hillenbrand et al. 2015, "Empirical Limits on Radial Velocity - Planet Detection for Young Stars," *arXiv:1408.3475*
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## Acknowledgements

Support for this work is provided through the NASA TESS Mission Guest Investigator Program grant NNH17ZDA001N, which was awarded to C.D.D., and the NASA FINESST Program award 80NSSC20K1549, which was awarded to S. G. and C. D. D.

We thank Elliana Schwab Abrahams, Rachel Fernandes, and Timothy Morton for their feedback on the TRICERATOPS code.