High Tide: A Systematic Search for Ellipsoidal Variables

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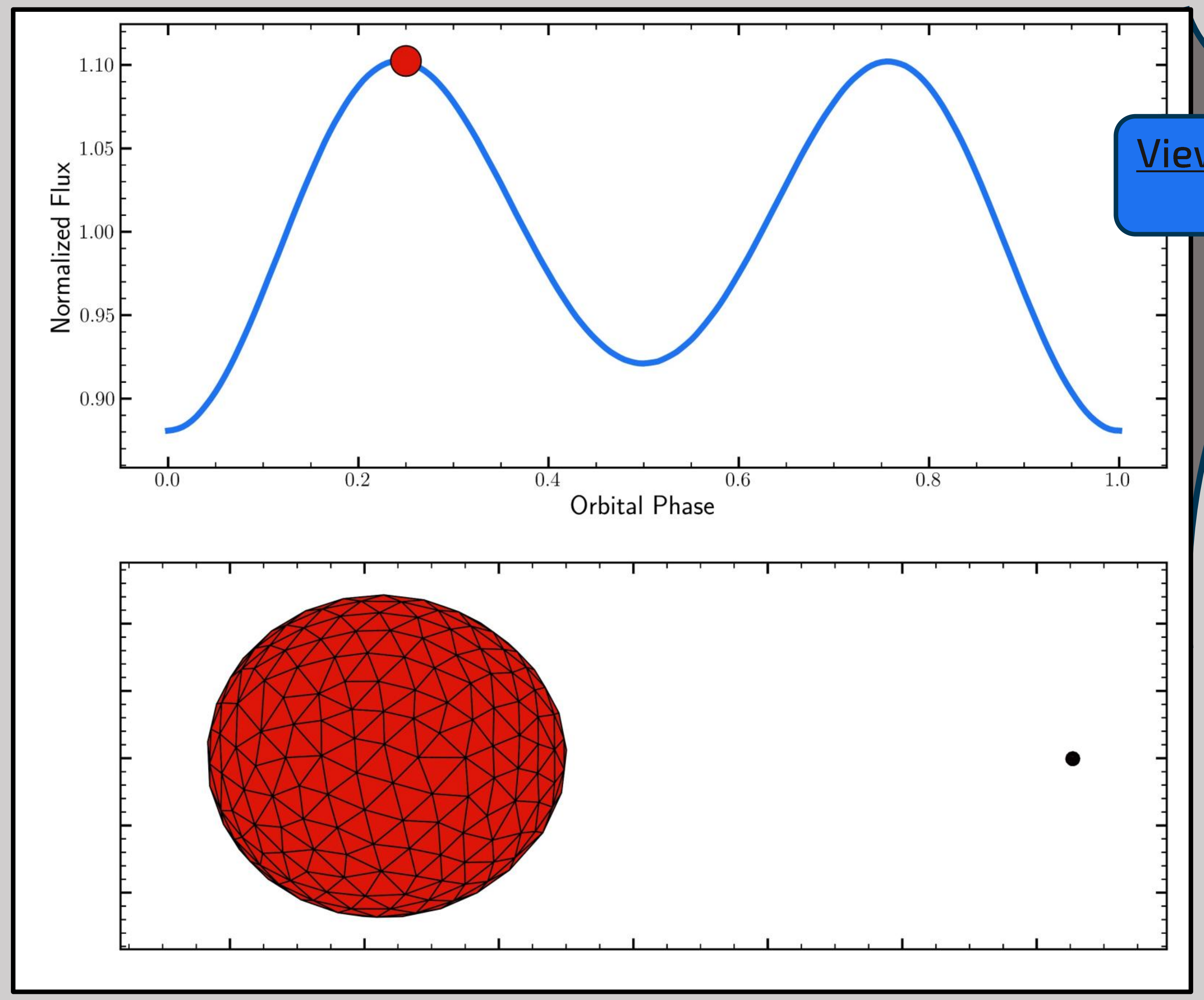
Searching for Non-Interacting Black Holes

We are interested in measuring compact object masses to study massive star evolution and core-collapse supernovae. Stellar mass black holes are typically observed in X-ray binary systems or as components of gravitational wave mergers.

The conditions leading to mass transfer or mergers are rare, so such systems represent a small fraction of the total black hole population. We set out to search for the large but mostly unstudied population of non-interacting black holes.

The search for non-interacting black holes typically begins with radial velocity surveys to identify stars with high binary mass function. Another approach is to search for ellipsoidal variables (ELLs) in time-domain photometric surveys. Ellipsoidal variations occur due to the tidal distortions of a star by its binary companion.



View the animated figure!

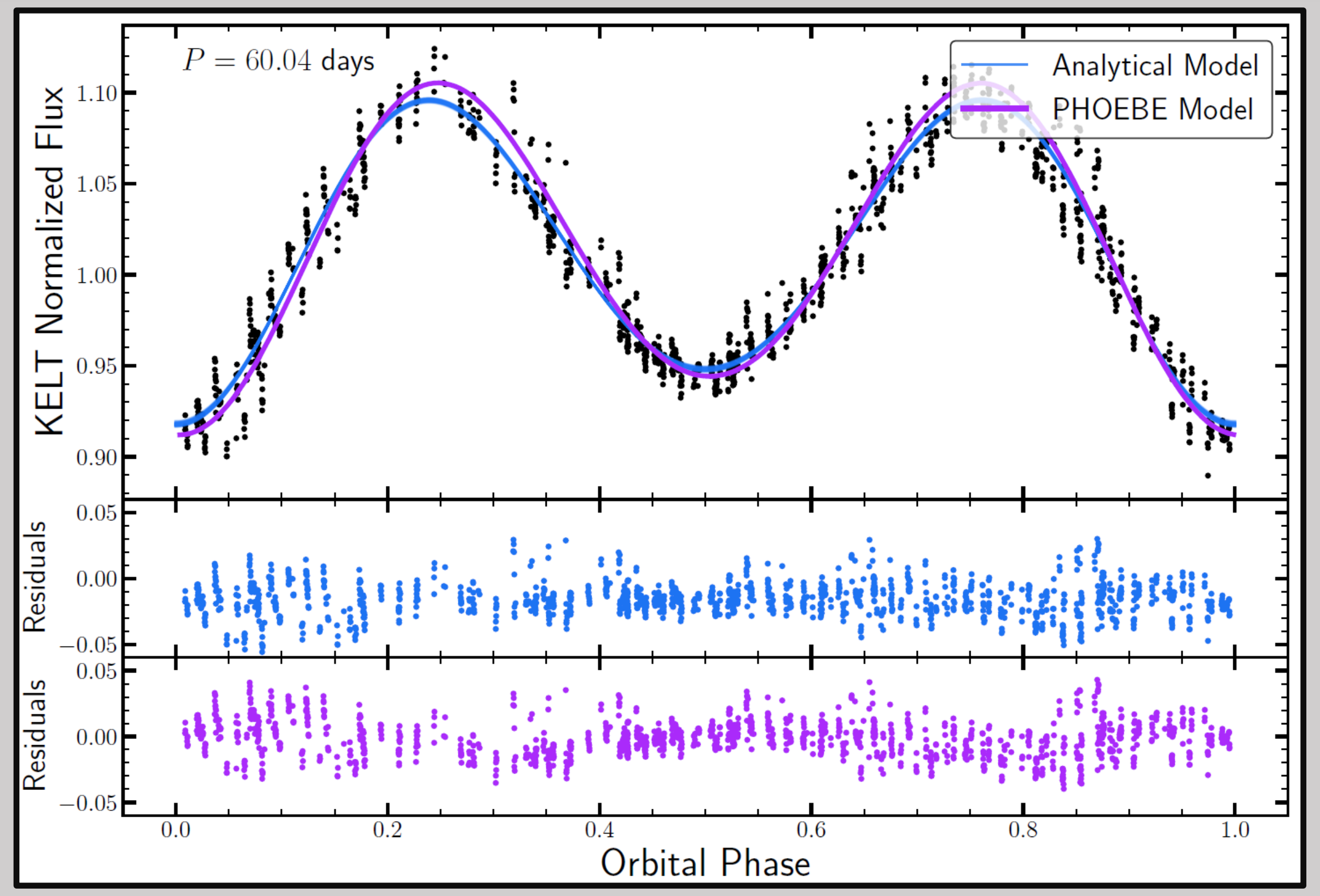
We search for ELLs using the All-Sky Automated Survey for Supernovae (ASAS-SN) and identify the systems that are the most promising hosts of compact object companions.

ASAS-SN is made up of 24 robotic 14-cm telescopes and observers over 100 million stars in the optical band.

Over 400,000 variables have already been classified as part of the ASAS-SN Variable Stars Database.

We select ~195,000 eclipsing binaries, rotational variables, and semi-regular variables for our ELL search catalog.

ELL Identification and Visual Inspection

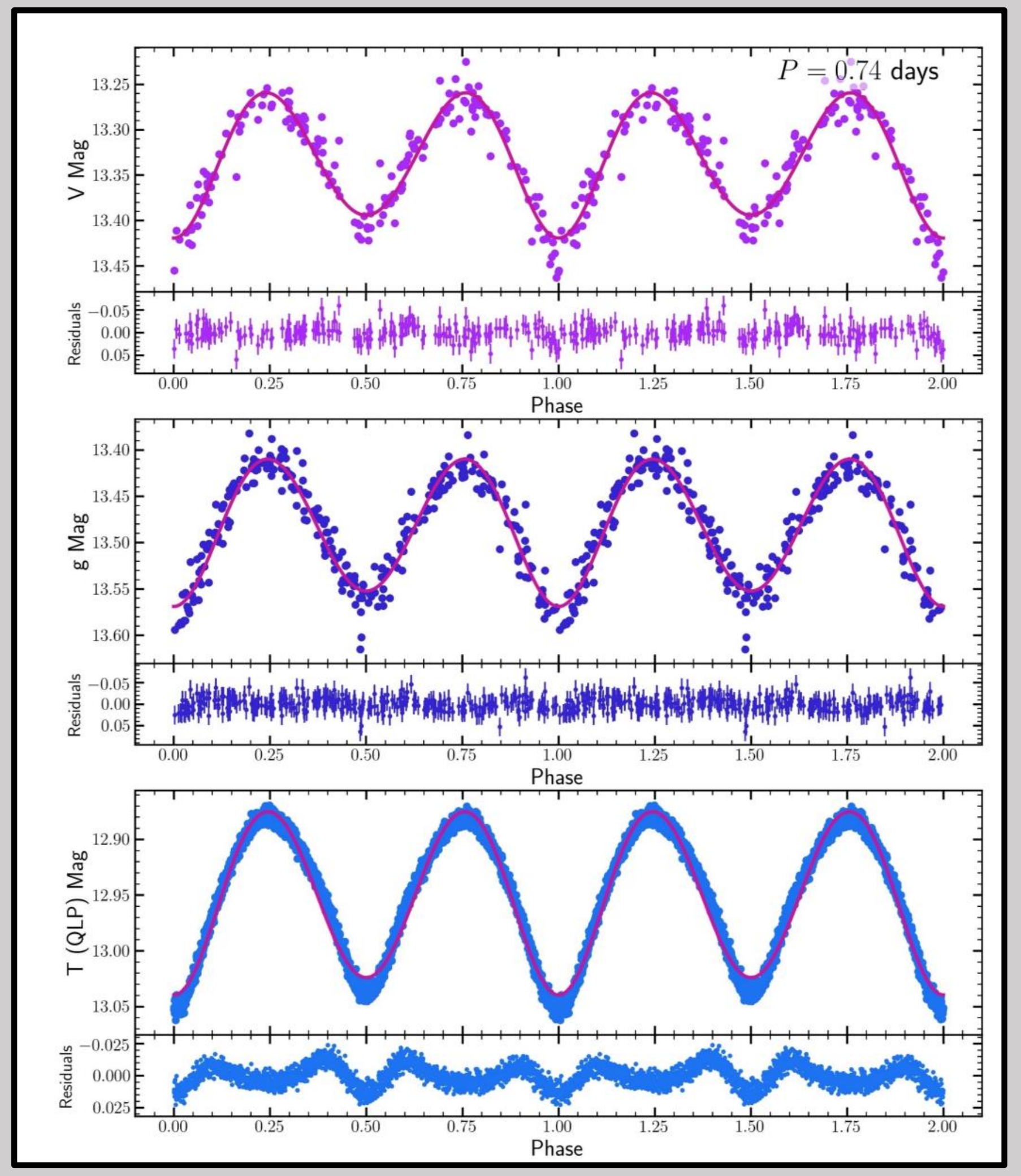


We use an analytic model of ellipsoidal variability to fit each ASAS-SN light curve in our sample.

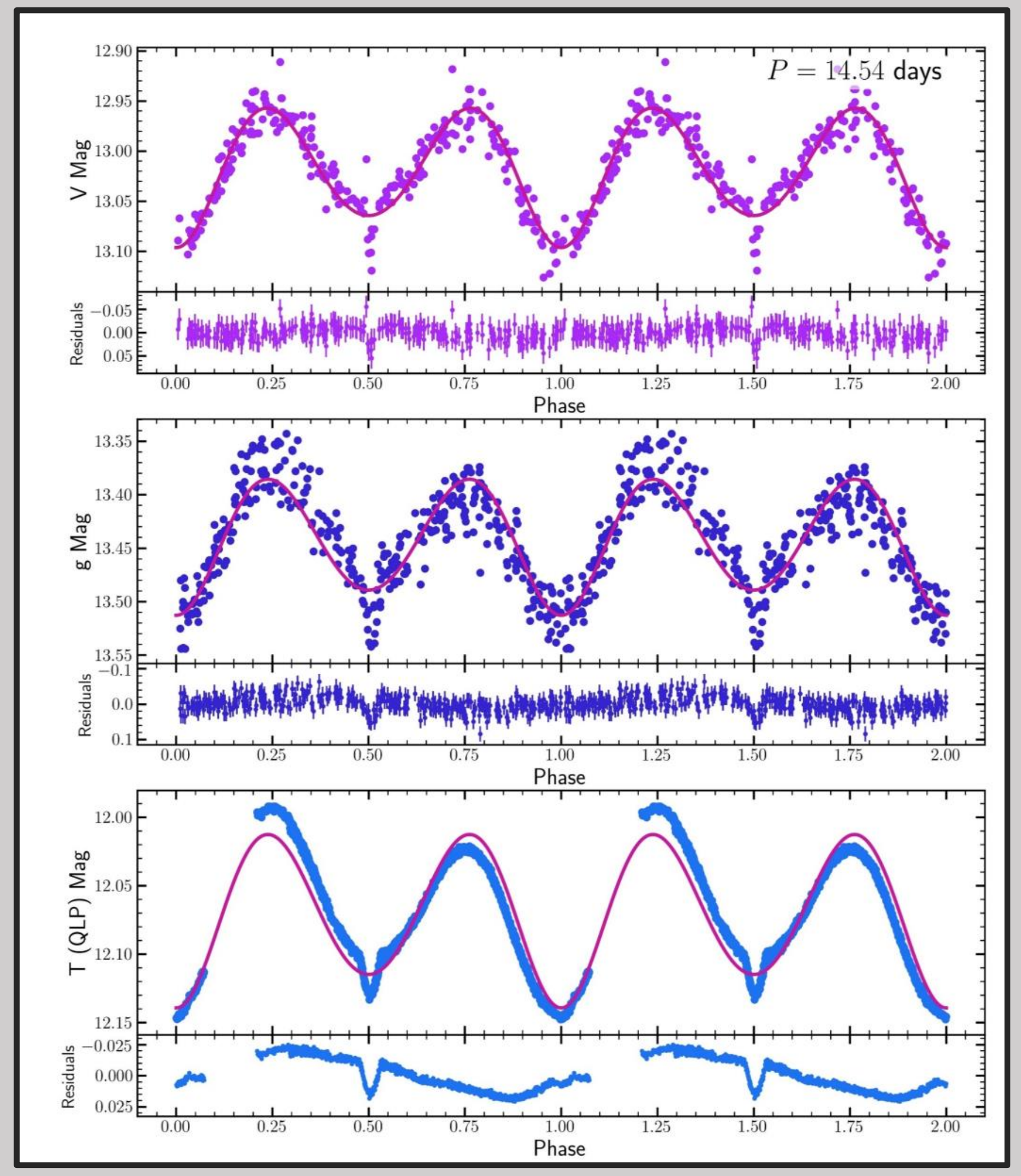
This figure shows a comparison of the analytic model to the PHOEBE model for the V723 Mon KELT light curve.

Since the light curves typically have uneven minima, we use a χ^2 ratio test to compare the analytic model fit to a cosine fit. We select ~10,000 stars for visual inspection.

The χ^2 ratio test is effective at selecting ELLs, but most of the visual inspection sample made up of rotational variables and eclipsing binaries. We use ASAS-SN *g*-band and TESS light curves for visual inspection.



ASAS-SN *V*-band (top), g-band (middle) and TESS (bottom) light curves for ASASSN-V J192943.61+641153.4. The solid lines show the least squares fit of the ELL analytic model. The smaller panels show the residuals. This V-band light curve was selected as an ELL by the χ^2 ratio test. The TESS light curve indicates that this is a contact binary, and the system is rejected as an ELL.

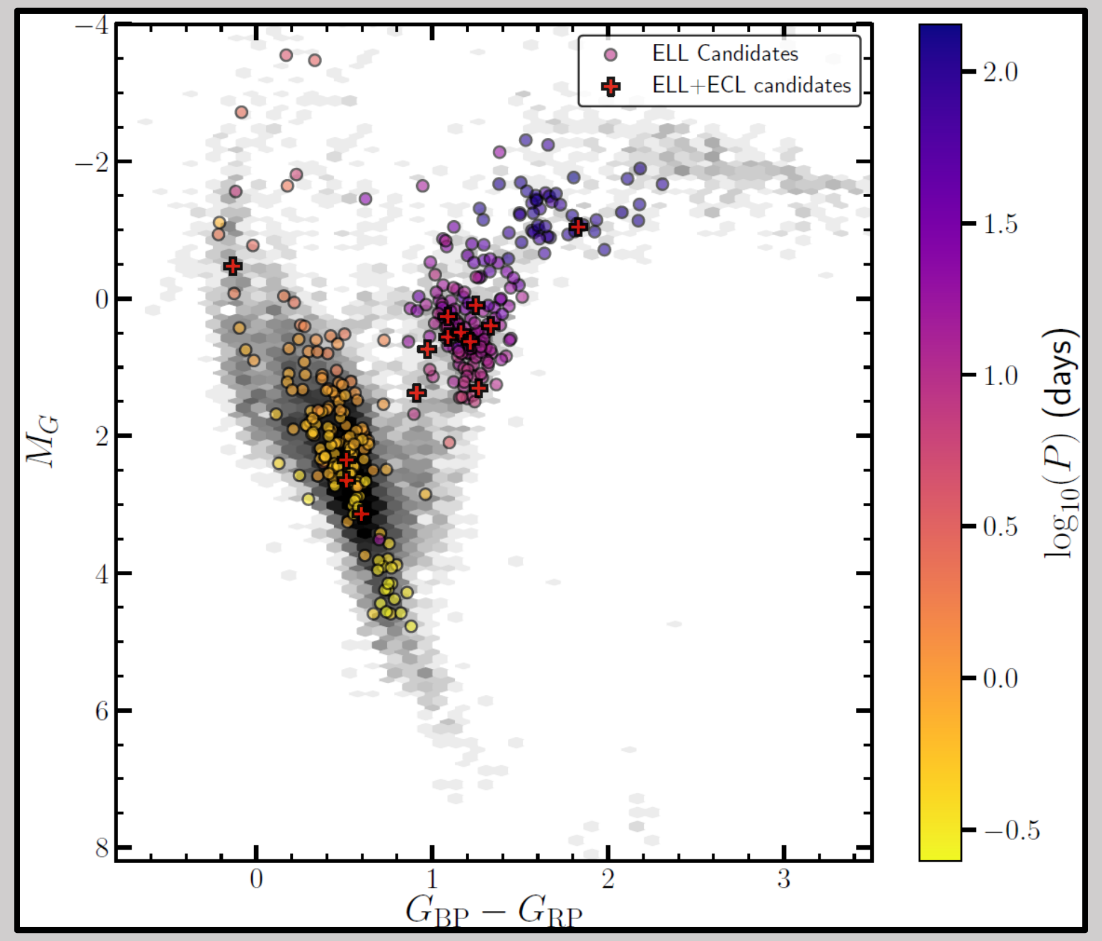


Some ELL variables, such as ASASSN-V J075030.20-053035.8, have narrow eclipsing features in addition to ellipsoidal variability. While these systems may be interesting for other purposes, they indicate that the unseen companion is not a compact object. TESS light curves are effective at identifying eclipses that can be missed in the ASAS-SN *V*- and *g*-band.

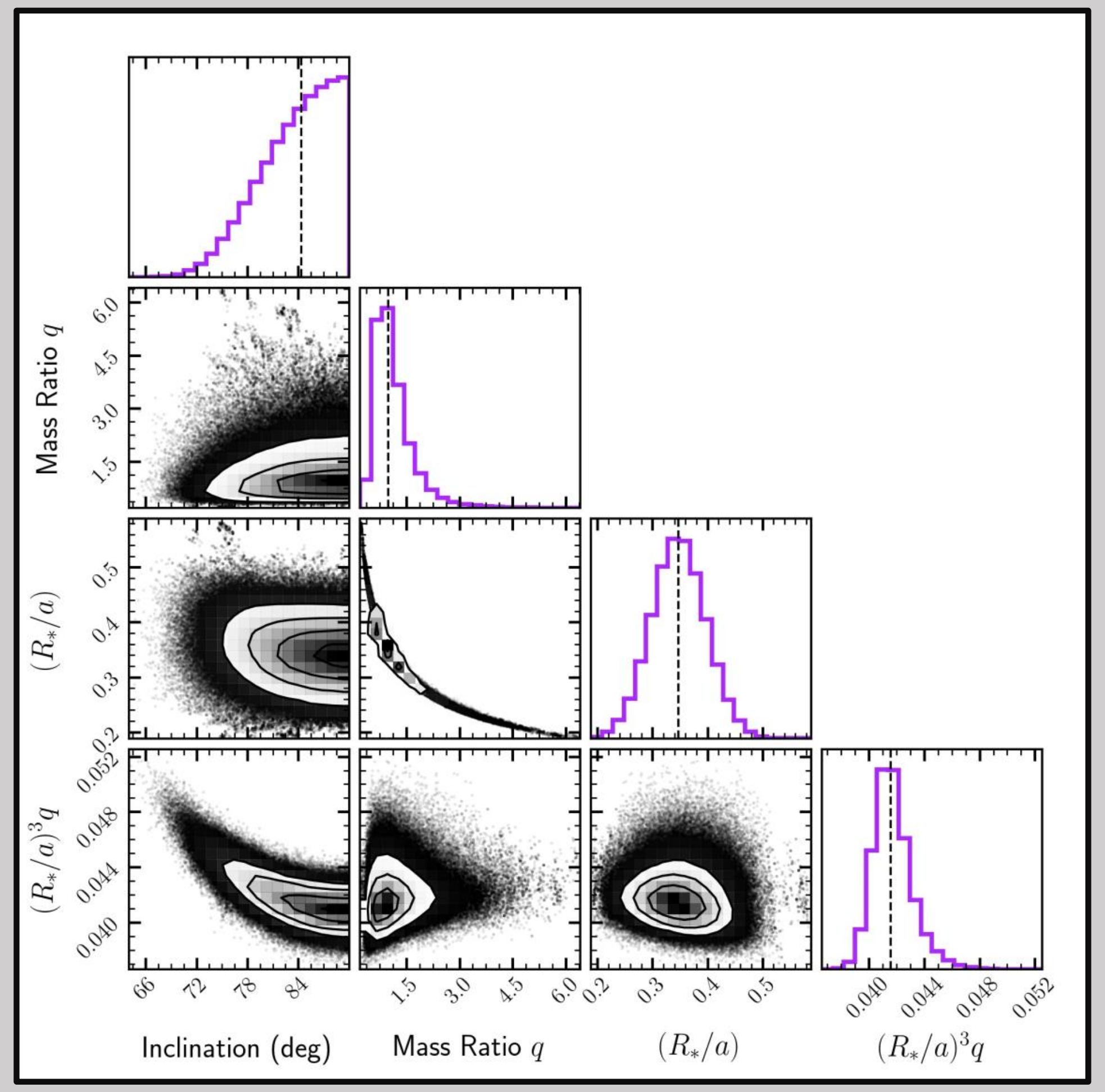
Calculating Minimum Companion Mass

We identified 369 ELL candidates using the χ^2 ratio test and visual inspection.

These ELL candidates have a range of periods from 0.25 days to 143 days. The color-magnitude diagram (right) shows the ELL candidates colored by the orbital period. We find that short-period ELLs are typically main sequence stars, while candidates in the red clump and the giant branch are typically in longer-period systems.



Without radial velocity data we cannot fully confirm the ELL nature of the candidates or the properties of the unseen companions. We can use the analytic model to estimate the minimum companion mass, and therefore prioritize radial velocity follow-up for the systems most likely to host a non-interacting compact object.



Since the mass ratio *q* is degenerate with the ratio of the radius of the primary to the binary separation (*R/a*), the quantity best described by the analytic model is $e_2 = q(R/a)^3$.

StarHorse uses *Gaia* parallaxes and spectral energy distributions to estimate stellar parameters. We can use their estimate of the luminous star mass M_* and radius R_* to write the minimum companion mass as

$$M_c > \frac{M_*^2 G P^2 e_2}{4\,\pi^2 R_*^3}$$

We calculate the minimum companion mass for our ELL variables with StarHorse mass and radius estimates.

14 systems have minimum companion masses greater than $1\ M_\odot$. Radial velocity observations are now needed to determine the nature of the unseen companion.