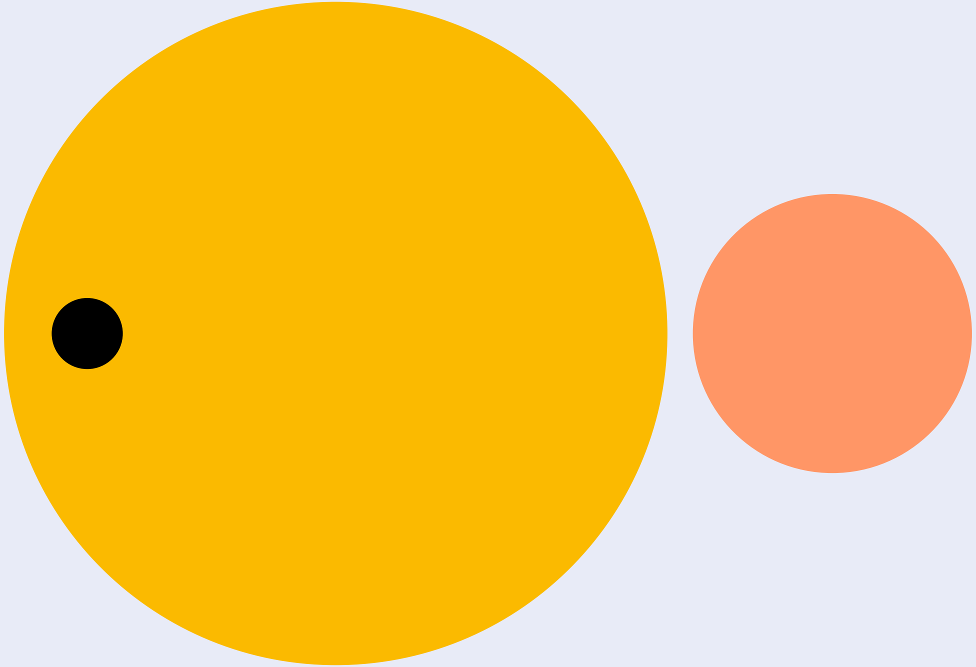
Finding Circumbinary Planets

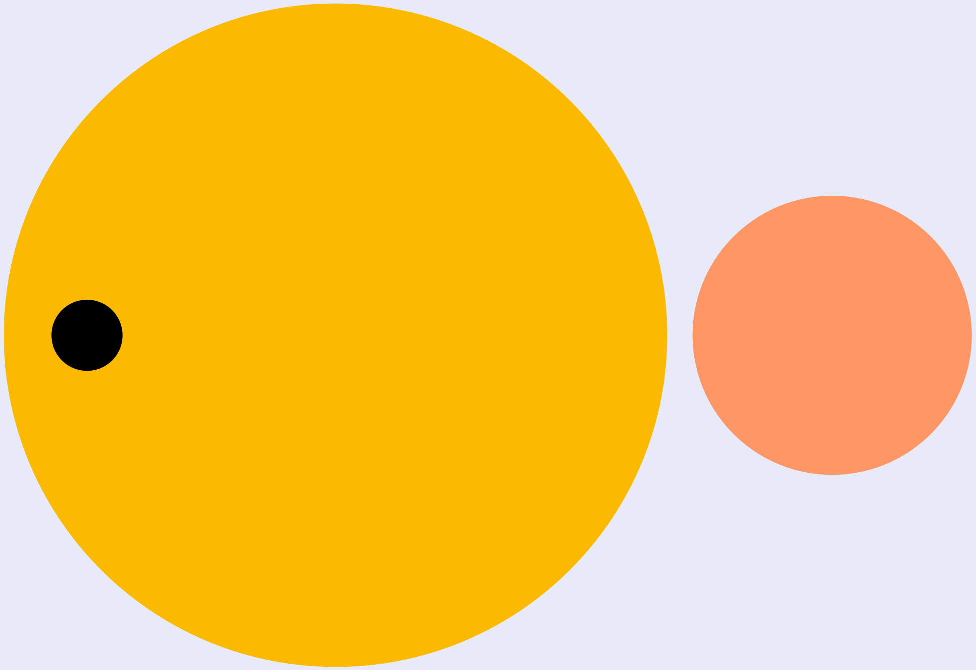
A Transit Detection Framework for TESS Eclipsing Binaries



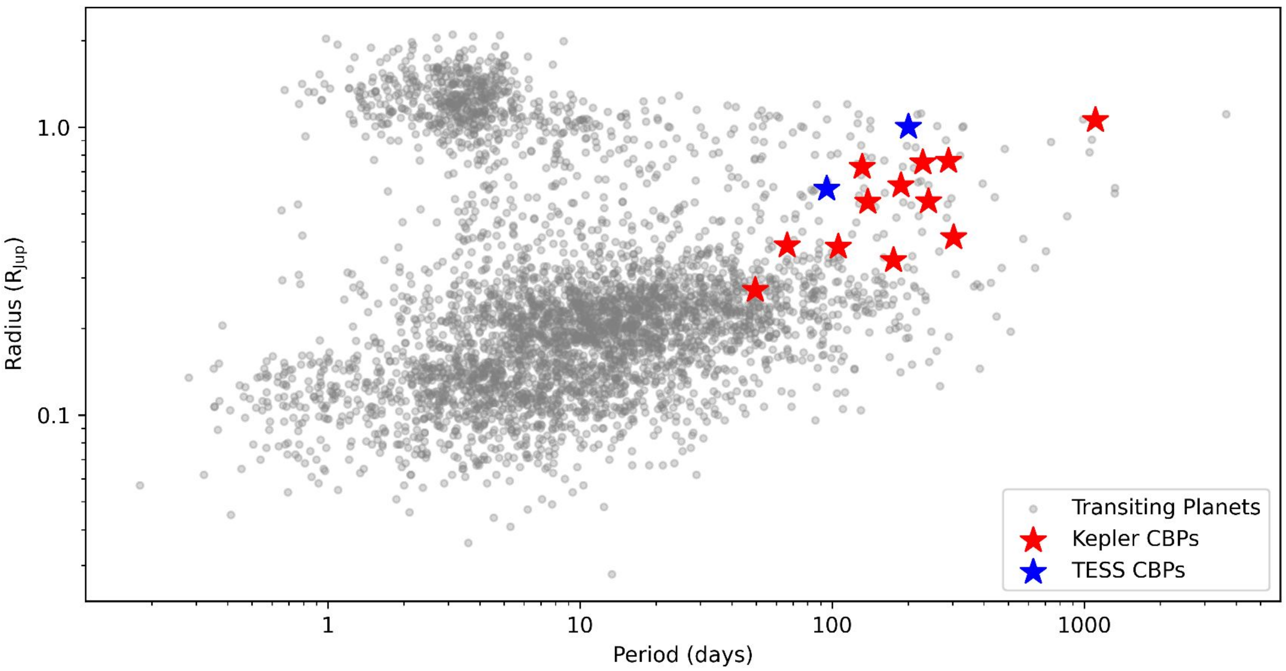
The Formation and Long-term Evolution of Circumbinary Planetary Systems Across the H-R Diagram | 15/01/2025

WARWICK
THE UNIVERSITY OF WARWICK

Context

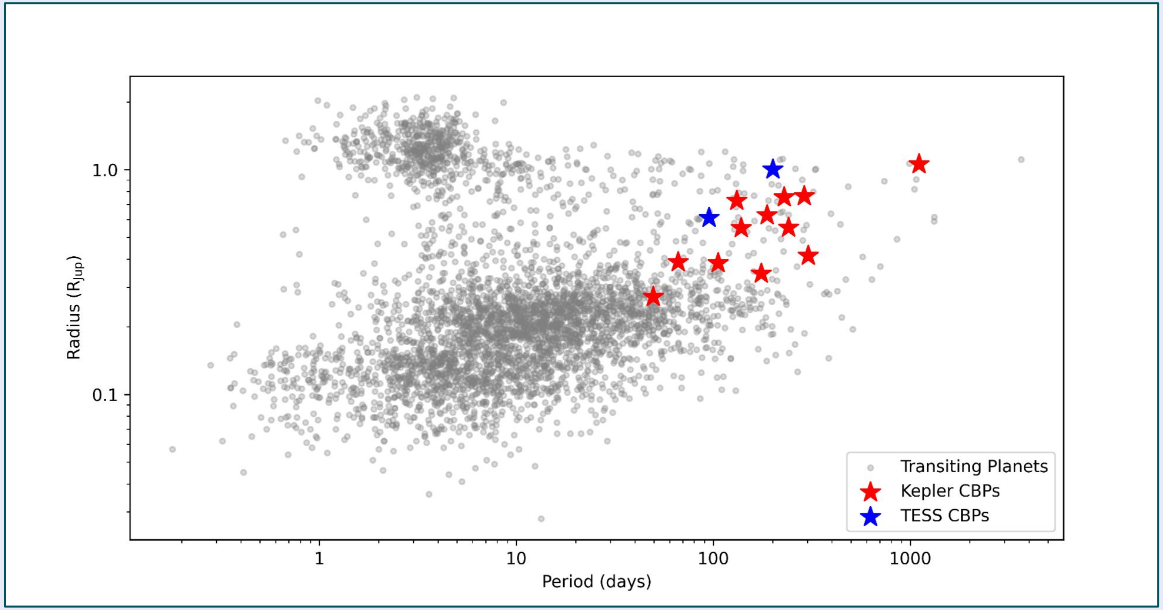


Transiting CBP Population



Strong Observational Biases

- Dynamical stability constraints => long periods
  - Need long, continuous time baseline photometry



Strong Observational Biases

- Dynamical stability constraints => long periods
  - Need long, continuous time baseline photometry
- If CBPs preferentially aligned with binary (e.g., Foucart and Lai 2013), biased towards eclipsing binaries
- Strong Transit Timing Variations (TTVs) and Transit Duration Variations (TDVs)
  - Cannot use traditional methods of finding planets (e.g. BLS)
- CBPs can stop (or start) transiting on long timescales (often decades)

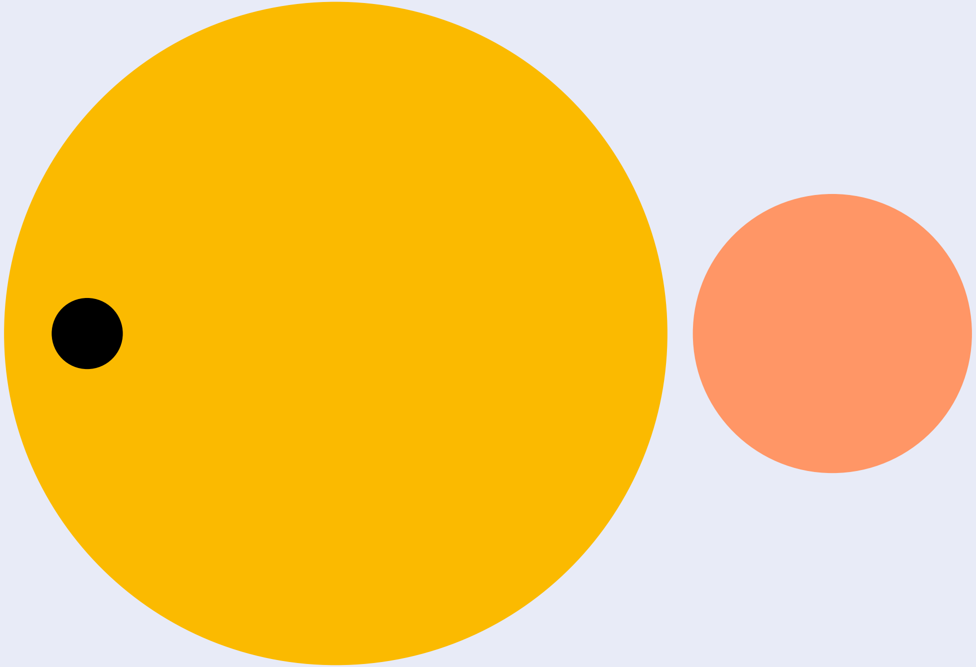
Importance of Increasing Sample Size

- CBP discoveries inform planet formation theories (e.g., Paardekooper et al. 2012, Penzlin et al. 2021, Coleman et al. 2023)
- Provide testbeds for studying three-body dynamics
  - Impact of stellar evolution (e.g., Kostov et al. 2016b)
  - Dynamical stability (e.g., Chavez et al. 2014, Quarles et al. 2018)
- Need more planets to make more robust statistical inferences about the overall population

Transiting CBP Detection

- Various detection algorithms have been developed
  - CB-BLS (Ofir 2008)
  - QATS-EB (Windemuth et al. 2019)
  - STANLEY (Martin and Fabrycky 2021)
- However, these search over a large parameter space and hence can be computationally intensive (for a blind search)
- Recently, there has been a lot of work looking for long-period planets by identifying single transit events (monotransits) with TESS (e.g., Gill et al. 2020abc, Grieves et al. 2022)

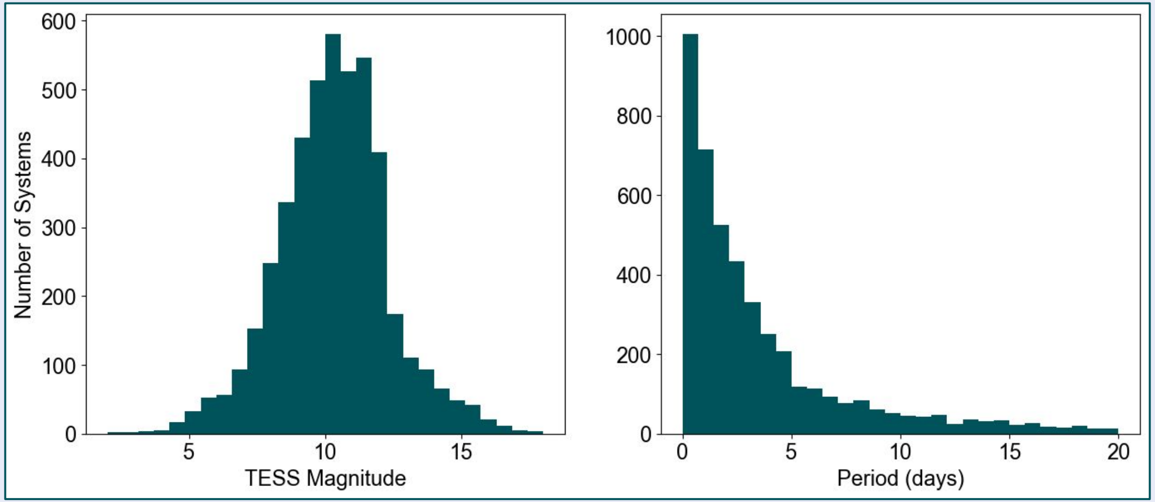
Transit Detection Framework



Eclipsing Binary Sample

TESS Eclipsing Binary Catalogue (Prša et al. 2022)

- 4584 EBs from Primary Mission SPOC 2-min cadence lightcurves



Eclipsing Binary Sample

Total sample

4584

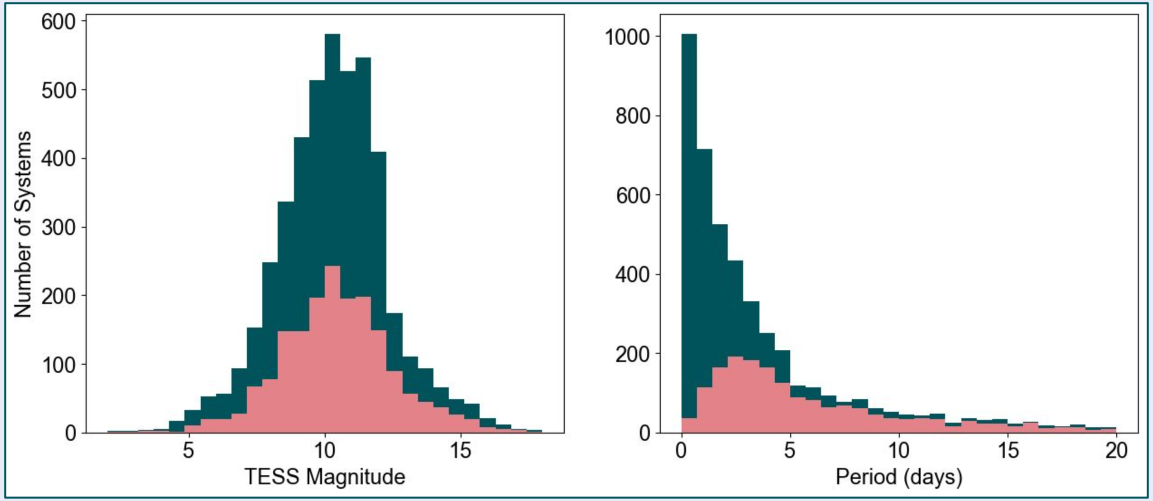
Ambiguous or insufficient time coverage

3996

Morphology < 0.5

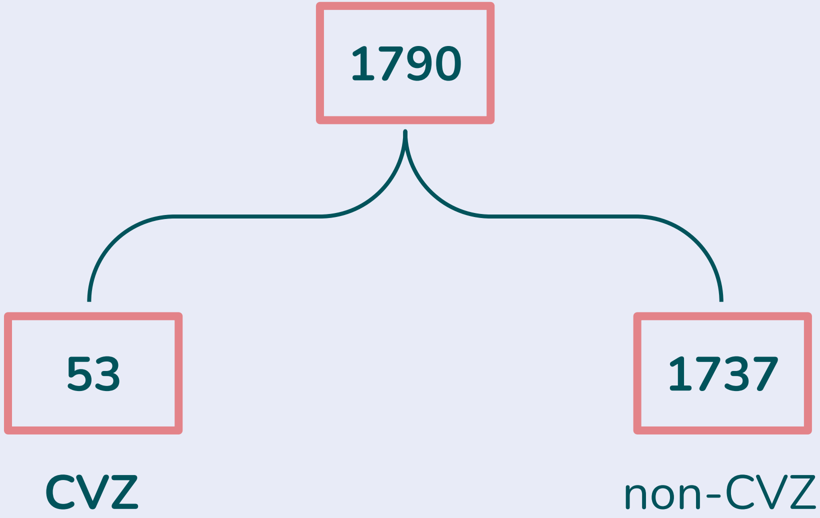
Final sample

1790



Eclipsing Binary Sample

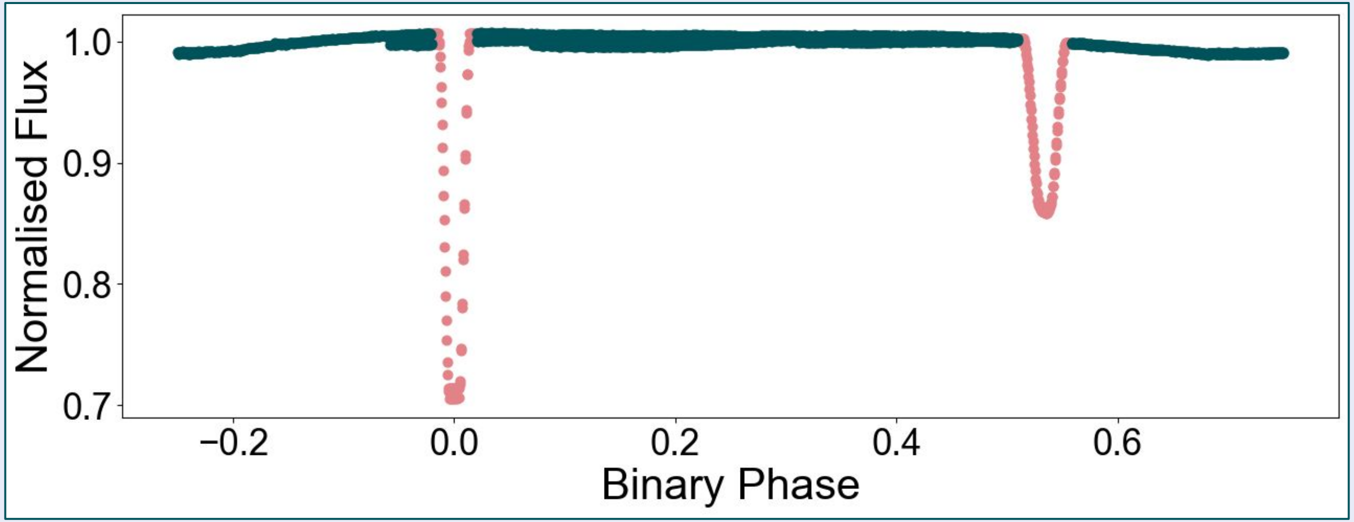
Split sample into CVZ and non-CVZ



Stellar Eclipses

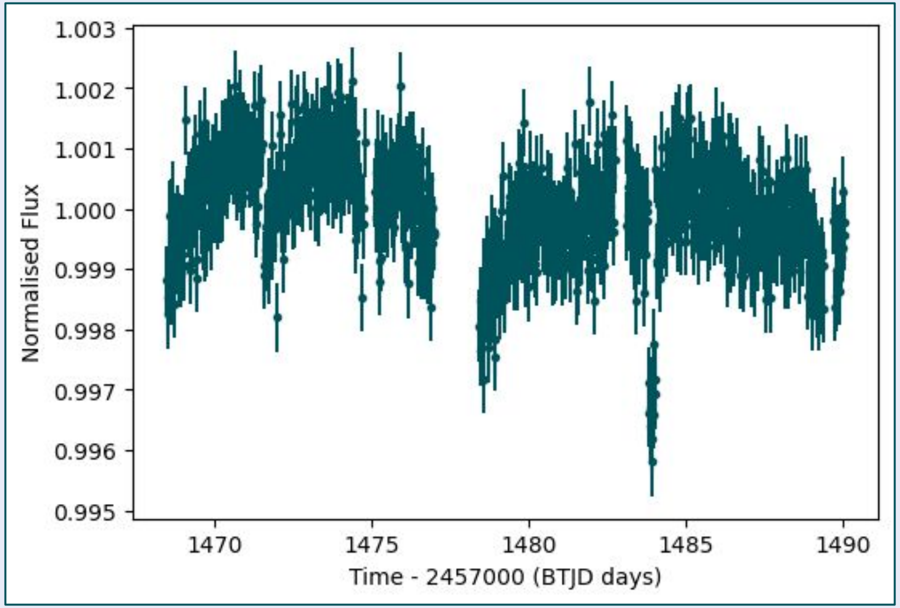
- Obtain a mask for in-eclipse data within the range

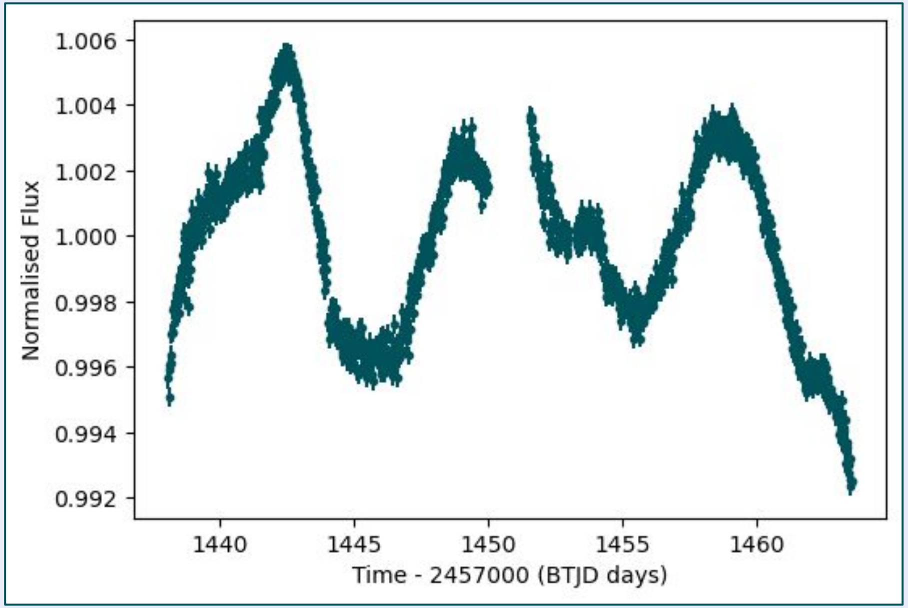
$$\phi_{p,s} - w_{p,s}/2 \leq \phi \leq \phi_{p,s} + w_{p,s}/2$$



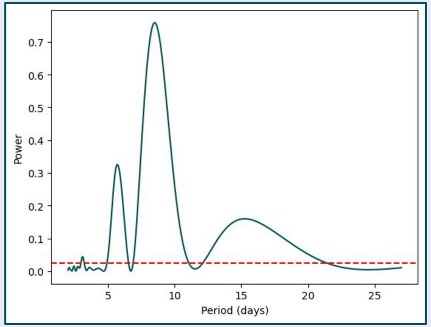
Detrending

Problem: Need a general detrending approach that accounts for differing noise properties (while still preserving transit signatures)





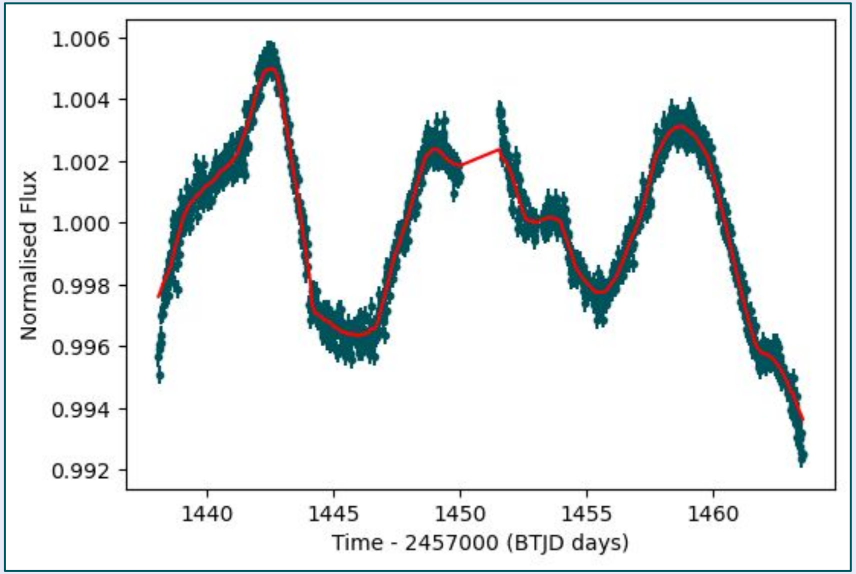
Step 1: Periodic Variability



Calculate Lomb-Scargle periodogram

If significant periodicity

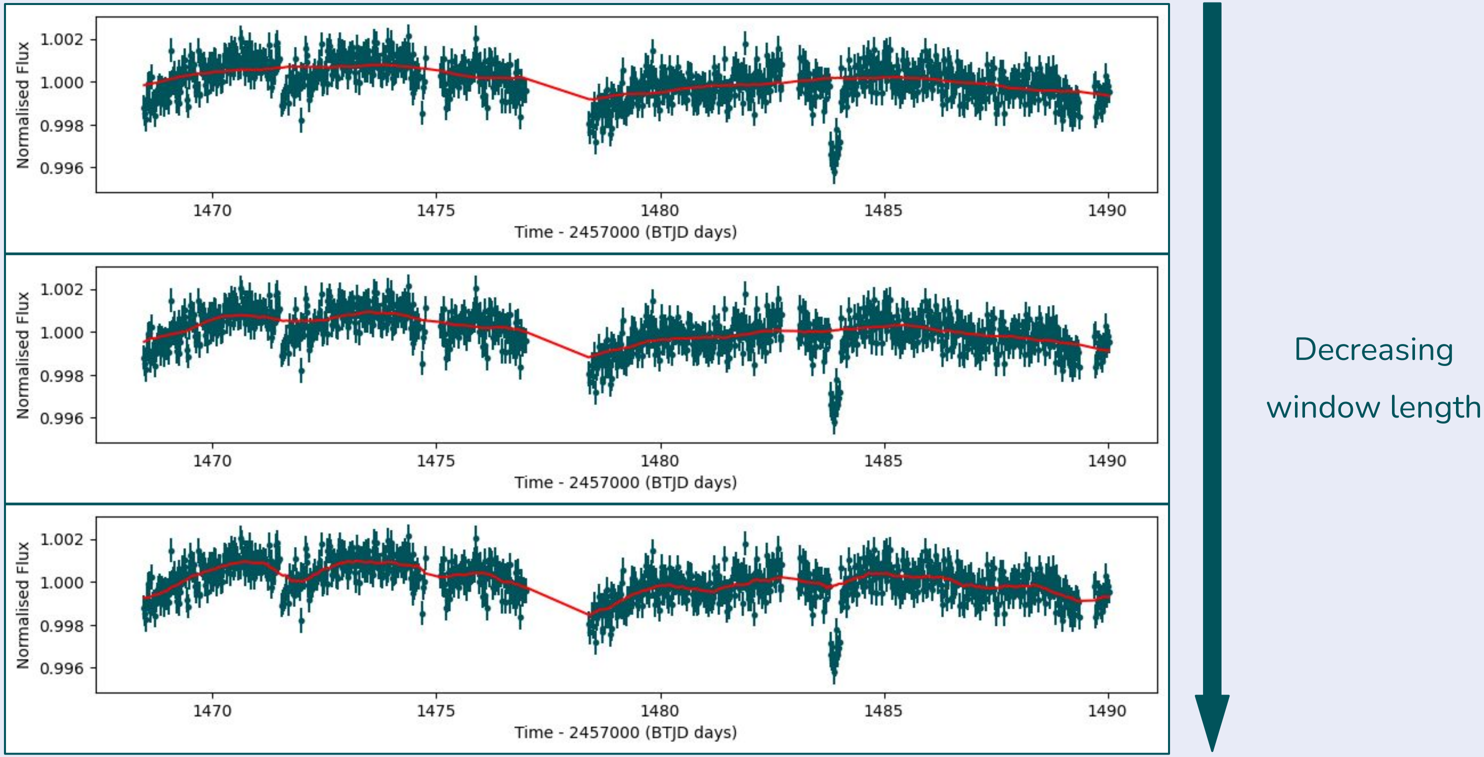
(FAP < 1%)



Fit lightcurve with sum of sines and cosines (Mazeh and Faigler 2010)

Step 2: Non-periodic Variability

Apply grid of biweight filters with variable window length ([1,3] days)

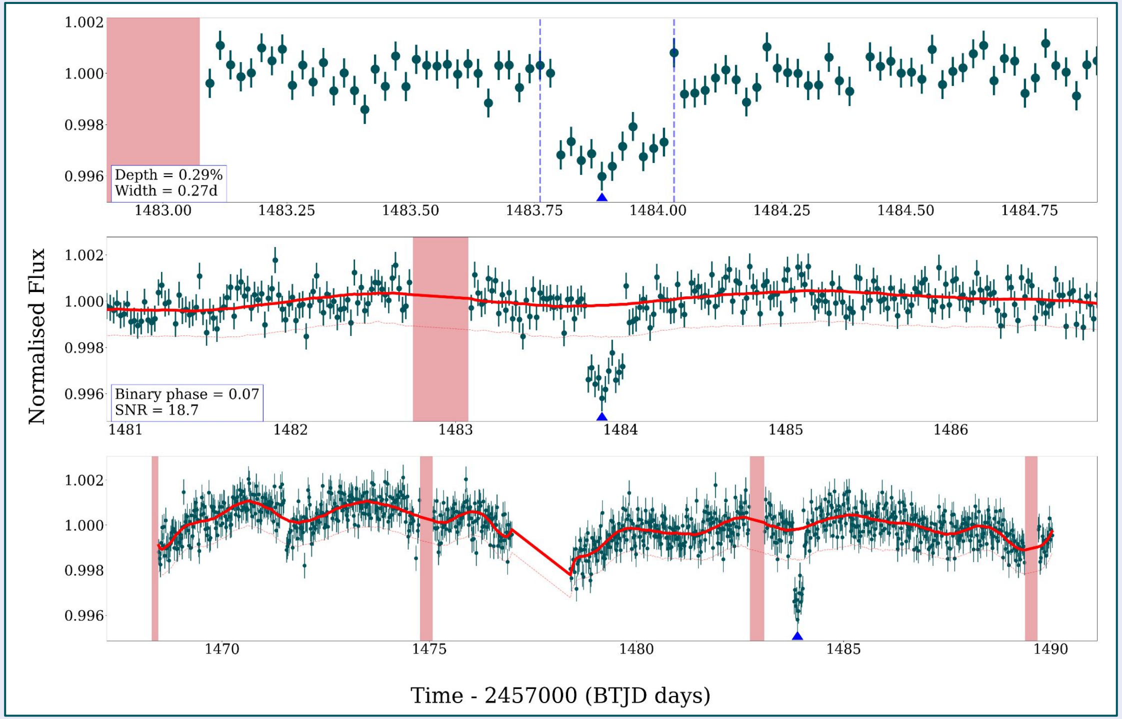


Transit Search

- Use TESS-SPOC FFI data (Caldwell et al. 2020)
  - SAP preferred over PDCSAP
- Search for monotransits by identifying Threshold Crossing Events (TCEs, same method as Hawthorn et al. 2024)
  - For each cadence, calculate the Median Absolute Deviation (MAD) of a 4 day window
  - TCE is flagged if three consecutive data points lie below a threshold based on the MAD (default 3 $\times$ MAD)

Transit Search

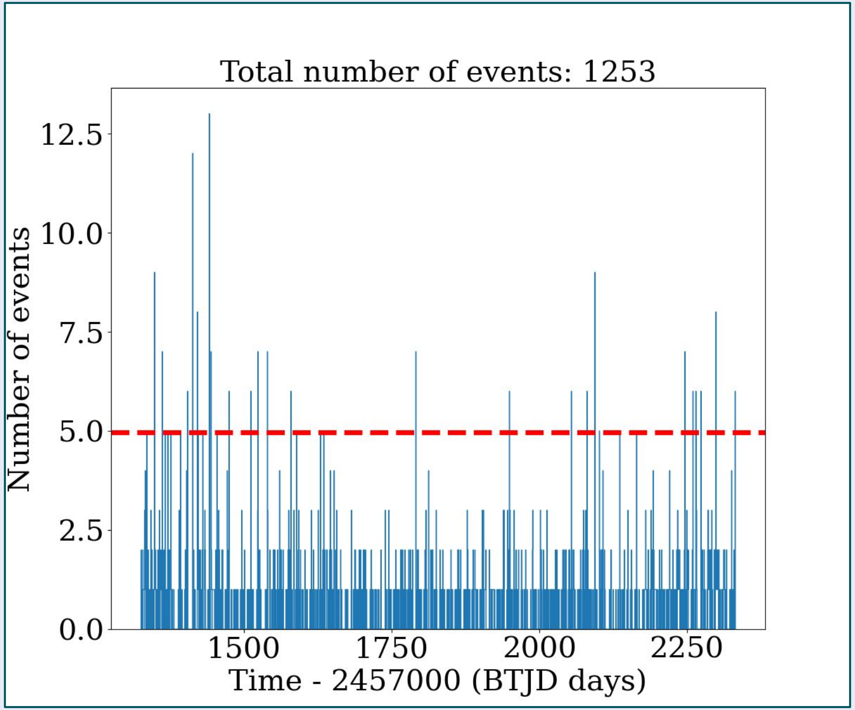
TOI-1338 b



Davies et al. (in prep.)

Vetting

Skye excess metric (see Thompson et al. 2018, Fernandes et al. 2022)



Vetting

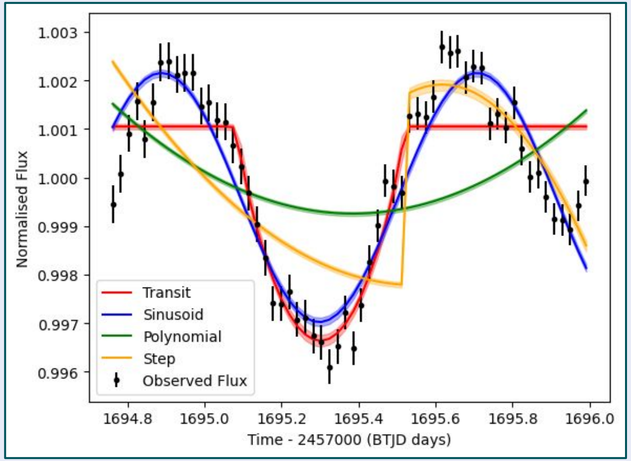
Other cuts:

- SNR > 5
- Duration < 1 day
- Detrending-dependence (see Dévora-Pajares et al. 2024)
    - If a given TCE is identified in < 90% of lightcurves after the variable biweight detrending, it is rejected

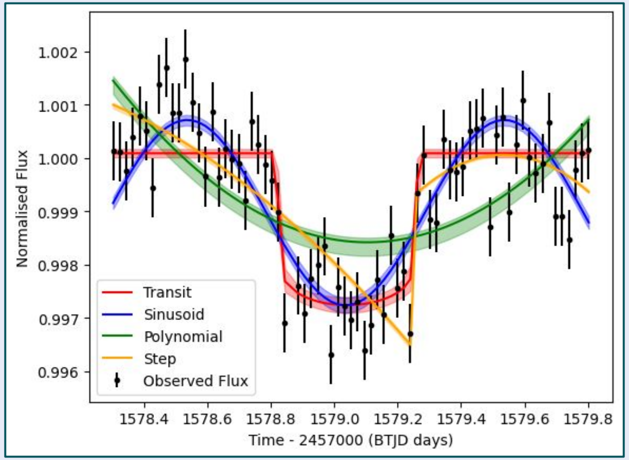
Vetting

Model comparison

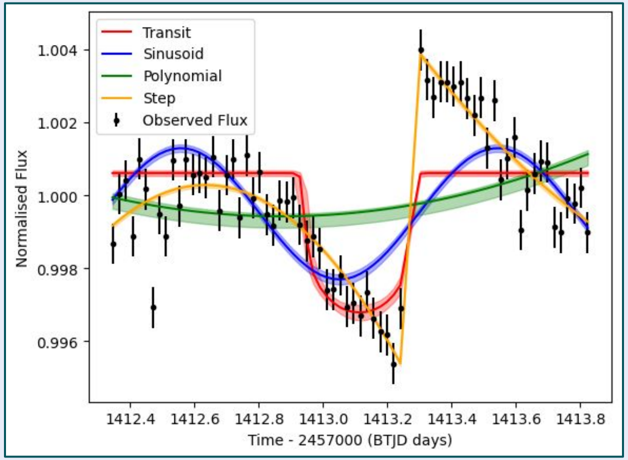
Davies et al. (in prep.)



Detrending artefact (sinusoid)

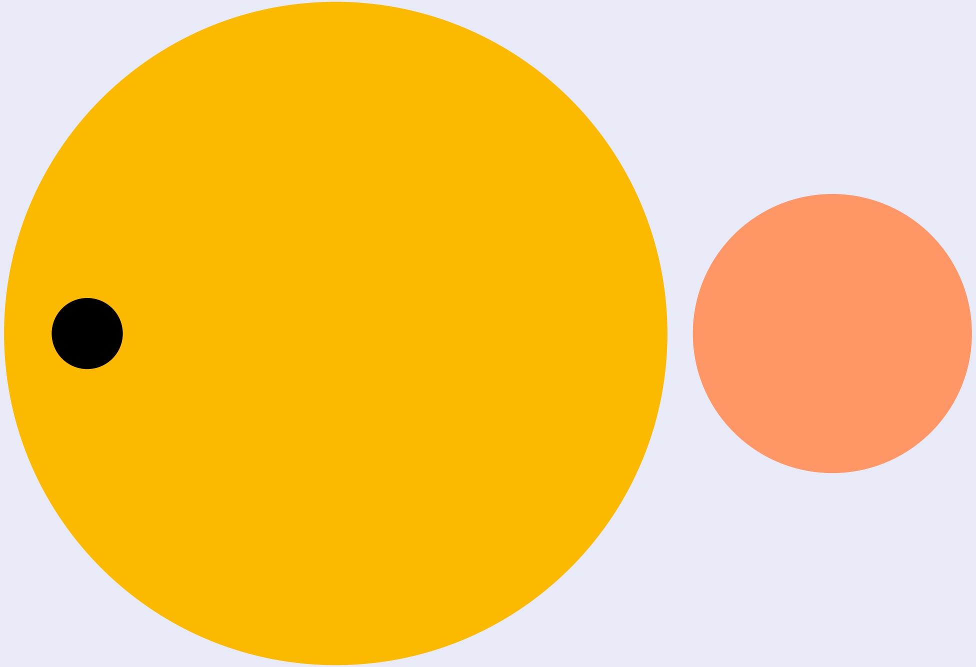


Transit

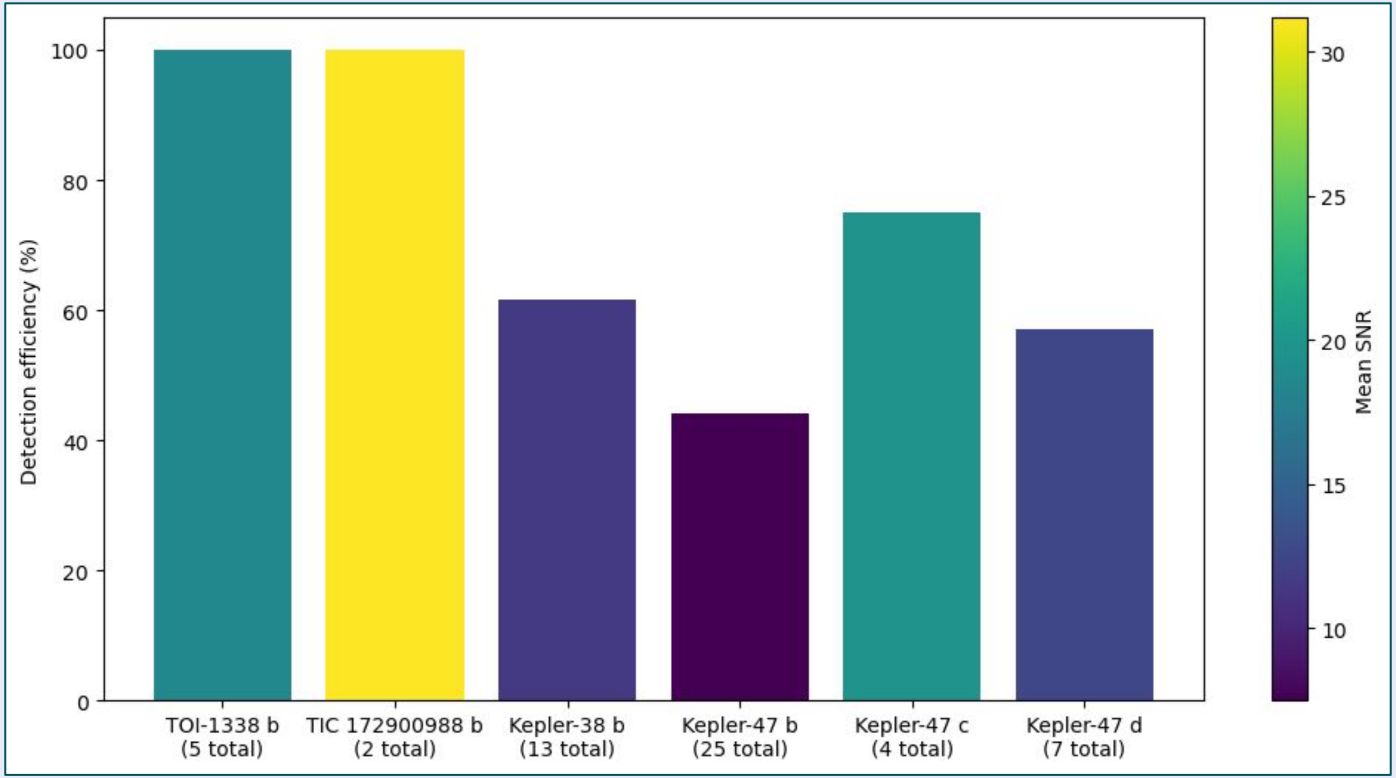


Detrending artefact (step)

Preliminary Results & Future Work



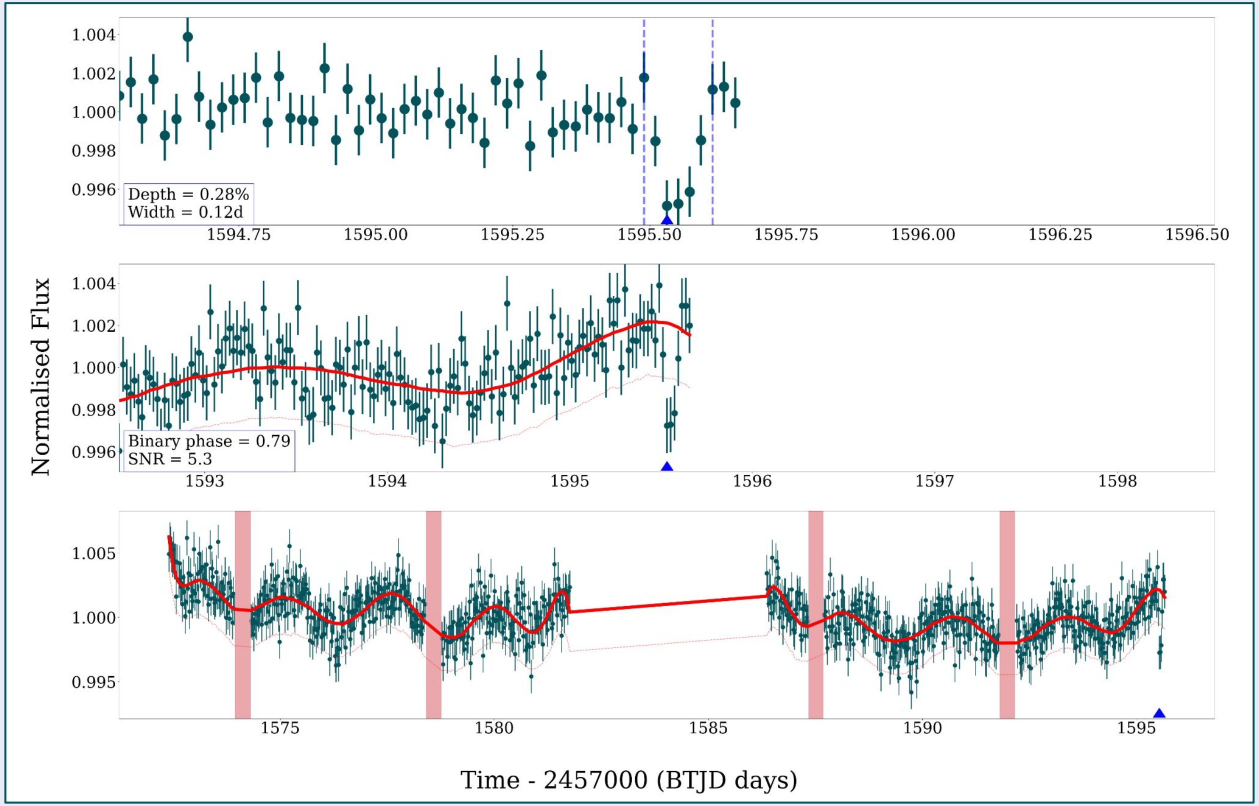
Testing on Known Transiting CBPs



Davies et al. (in prep.)

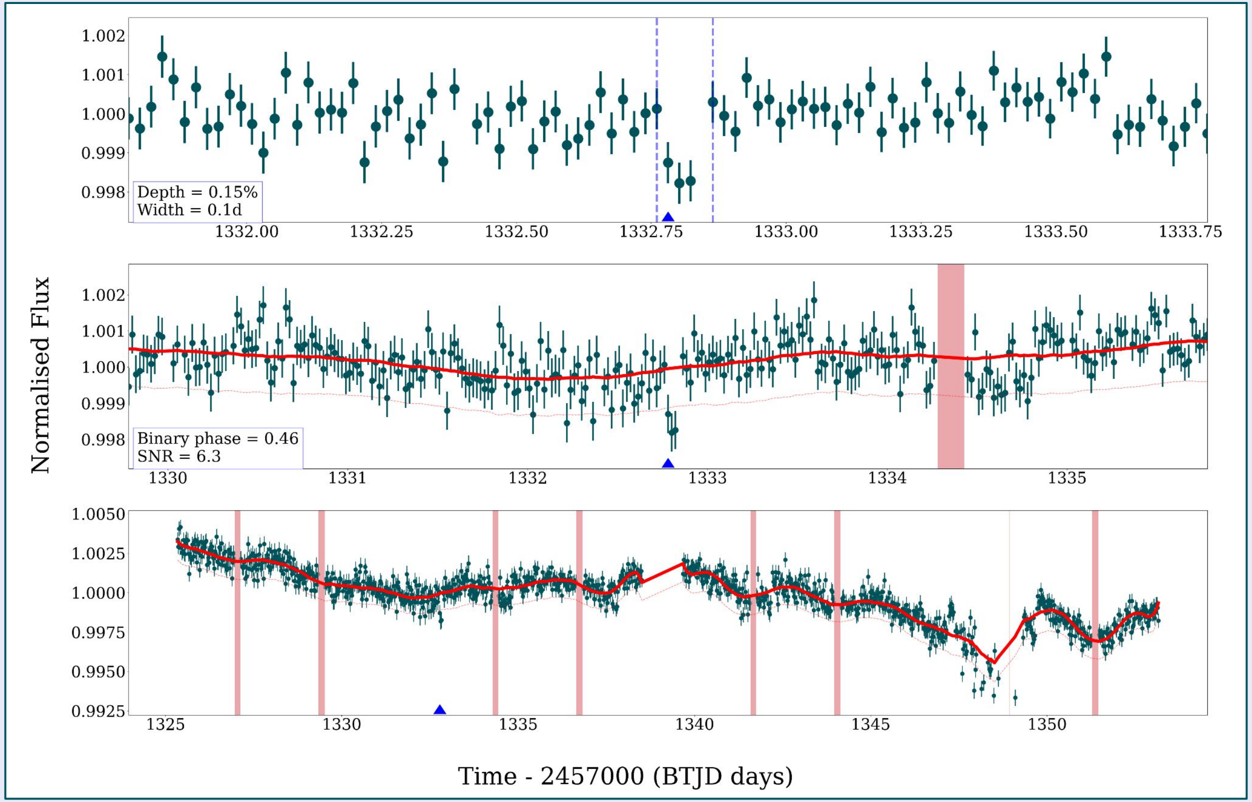
Output of CVZ Search

Candidate Events



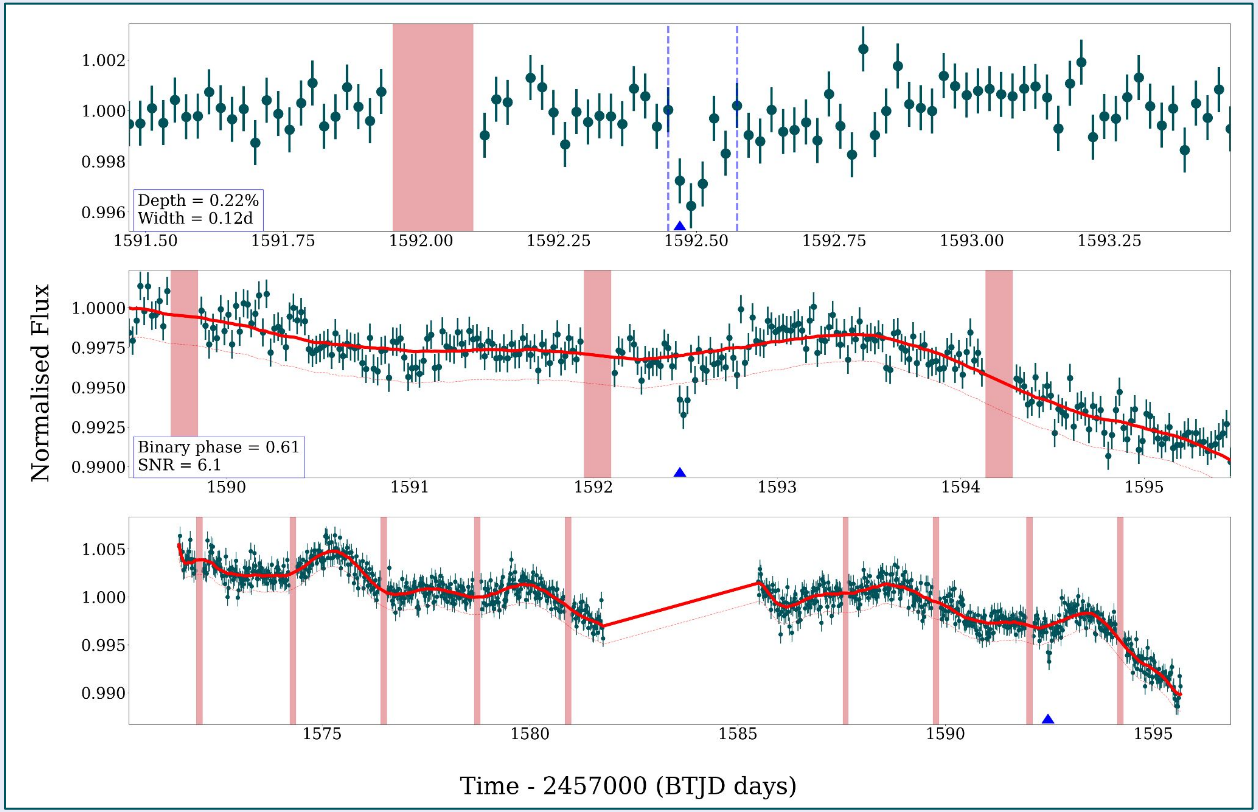
Davies et al. (in prep.)

Candidate Events



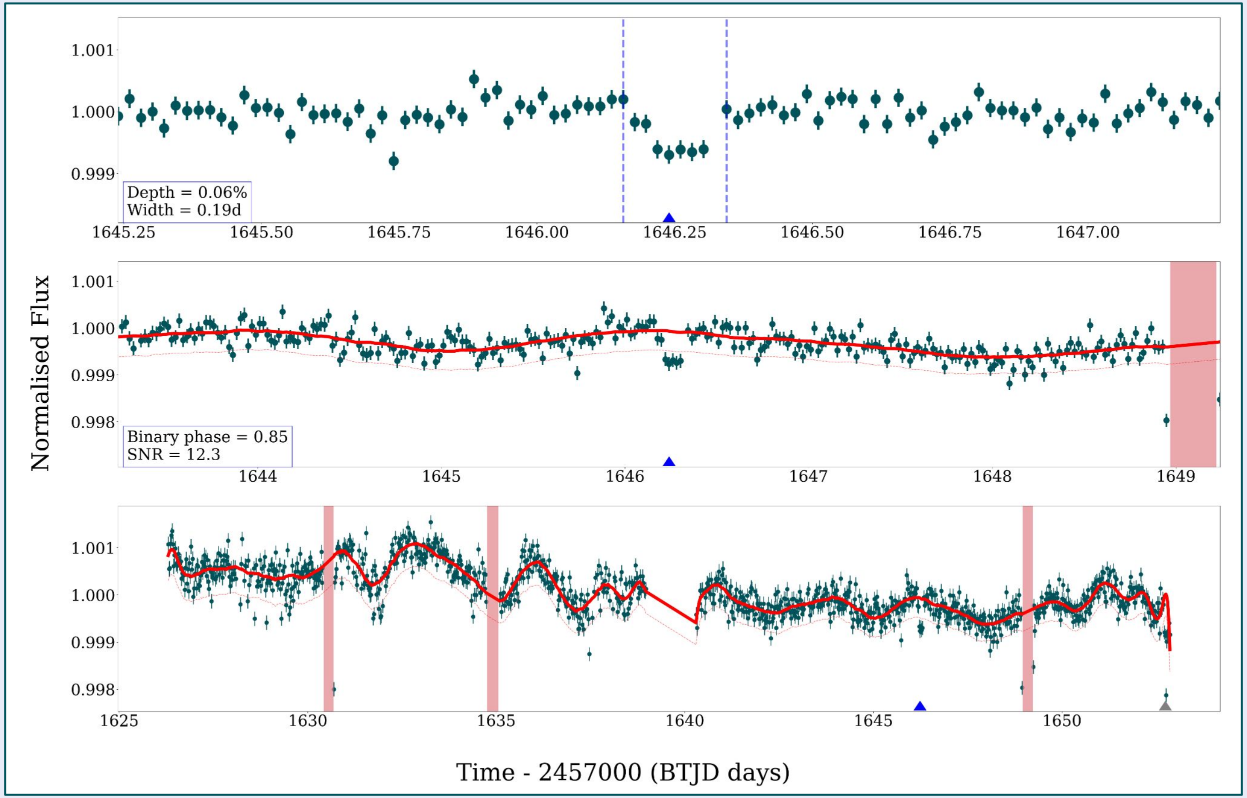
Davies et al. (in prep.)

Candidate Events



Davies et al. (in prep.)

Candidate Events



Davies et al. (in prep.)

Future Work

What *will* be done?

- Apply to the non-CVZ EBs
- Injection-retrieval tests
  - Quantify limits of detection algorithm

What *could* be done?

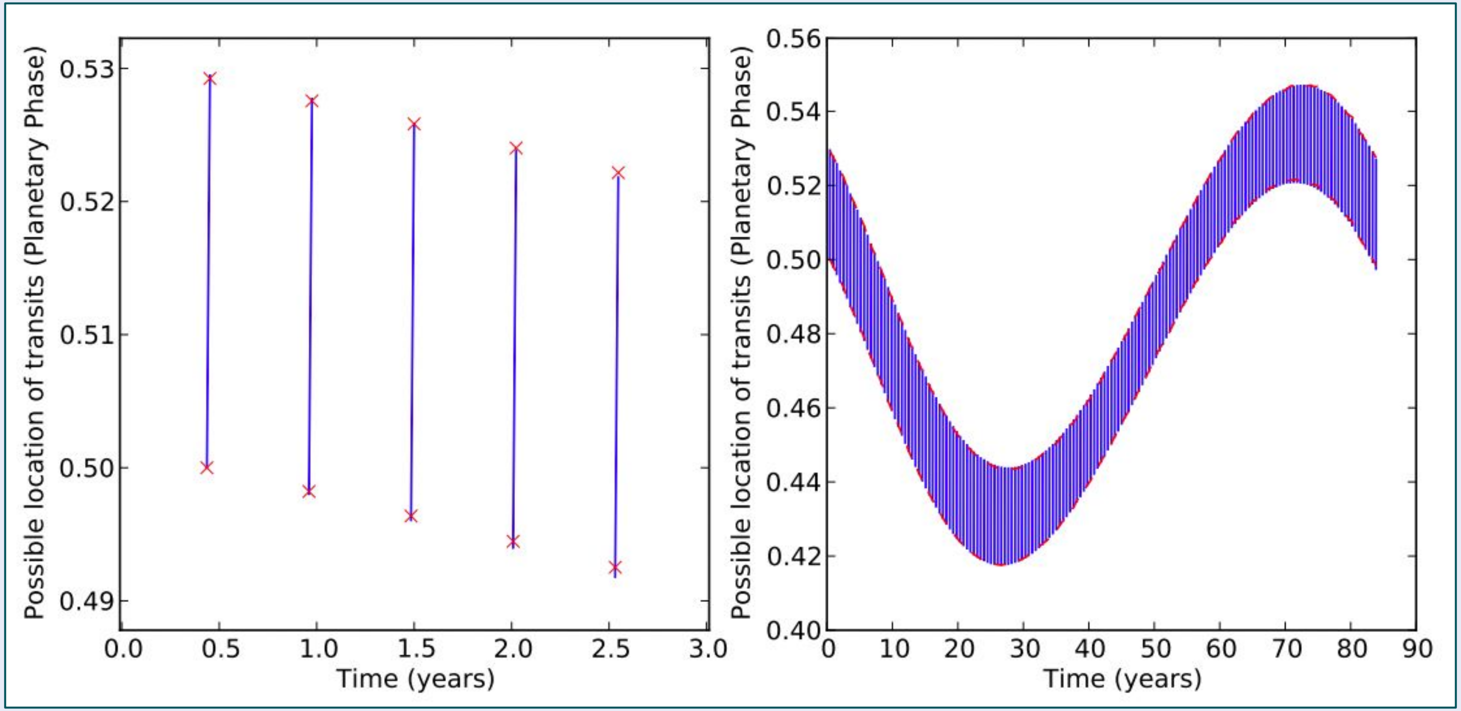
- Apply to larger sample of EBs
- Apply to non-eclipsing binaries to search for misaligned CBPs
- Estimate occurrence rate of CBPs using TESS data

Summary

- Automated detection of CBPs is difficult!
- Identifying individual transits has several advantages:
  - Useful for identifying sparse/non-periodic transits (misaligned CBPs, "one-two punch" effect)
  - Computational simplicity
- Developed a semi-automated transit detection framework for identifying individual transit events in TESS eclipsing binaries
- Method works for identifying known transiting CBPs, particularly those with high SNR
- Identified a handful of candidates which need validation
- Framework could be applied to many problems relating to CBPs

Backup slides

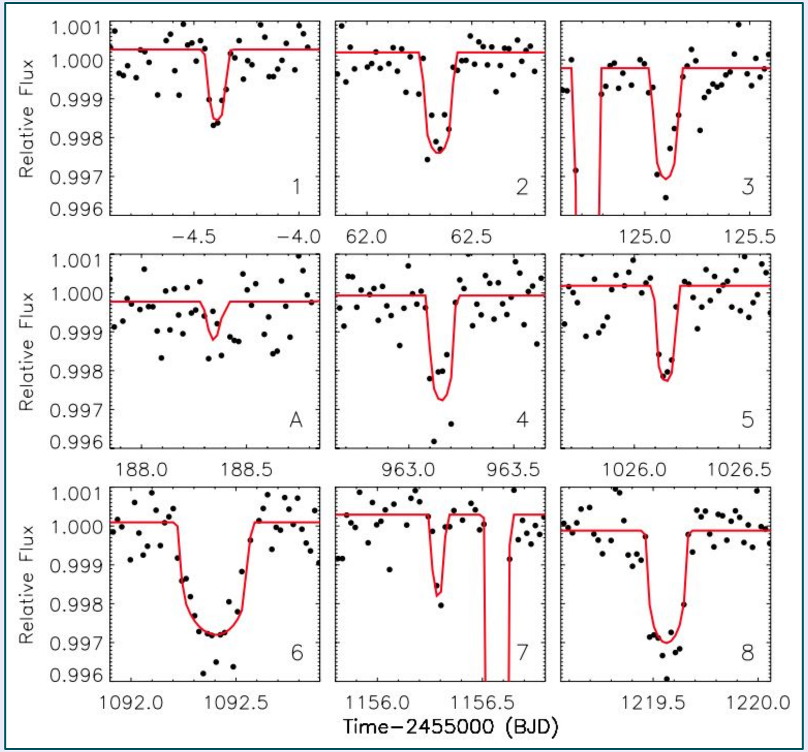
TTVs



Armstrong et al. (2013)

Ben Davies, University of Warwick (ben.d.r.davies@warwick.ac.uk)

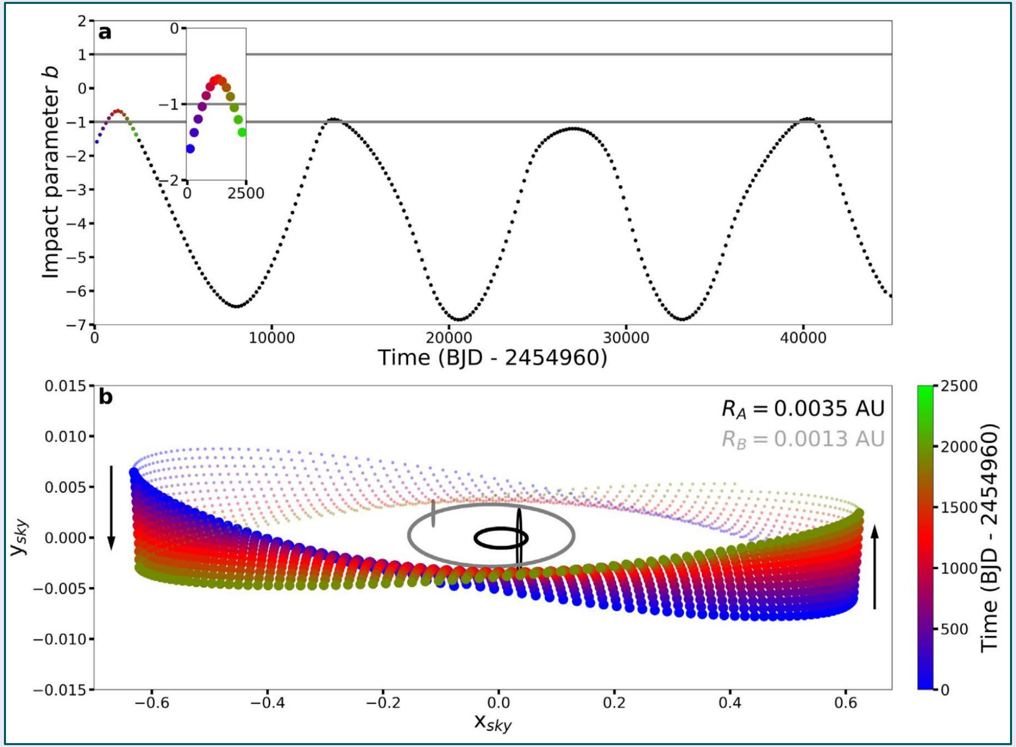
TDVs



Kepler-413 b, Kostov et al. (2014)

Ben Davies, University of Warwick (ben.d.r.davies@warwick.ac.uk)

Nodal Precession

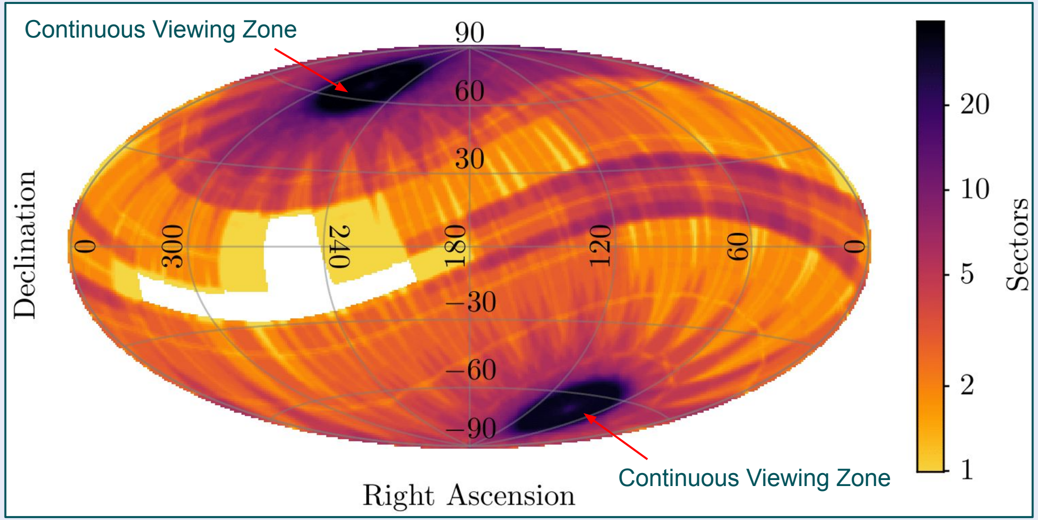


Kepler-1661 b, Socia et al. (2020)

Ben Davies, University of Warwick (ben.d.r.davies@warwick.ac.uk)

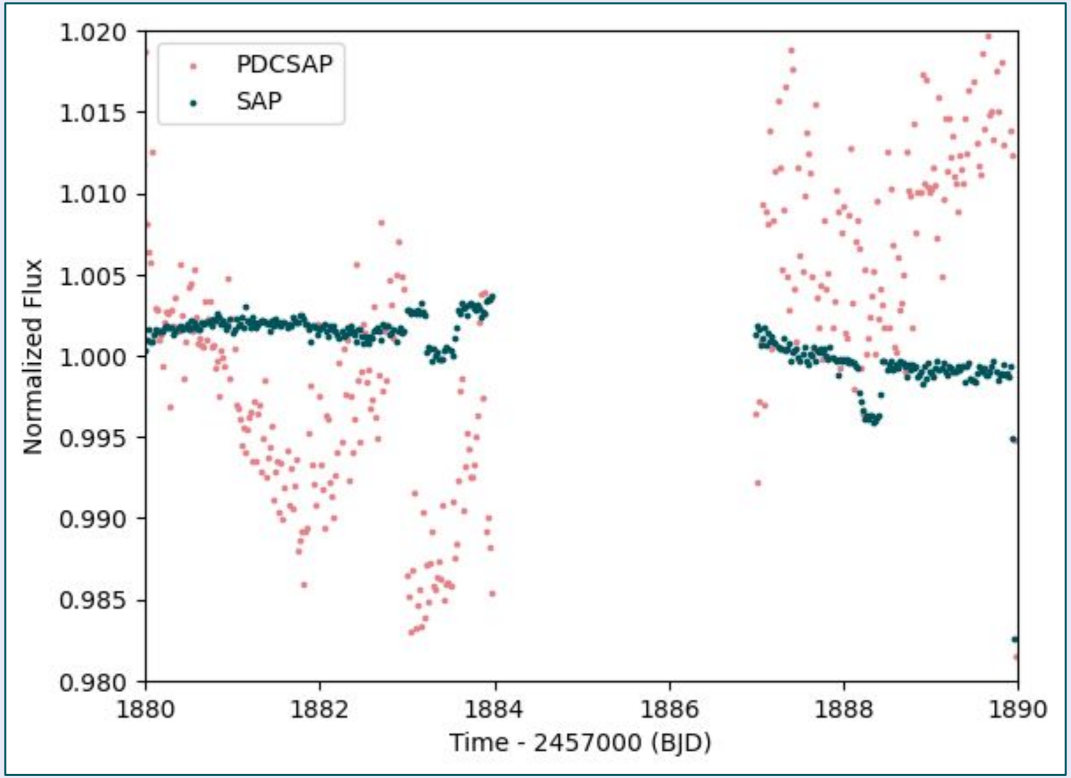
Transiting Exoplanet Survey Satellite (TESS)

- All-sky survey launched in 2018
- Survey broken up into sectors
  - 24º x 96º region of the sky observed for ~27 days



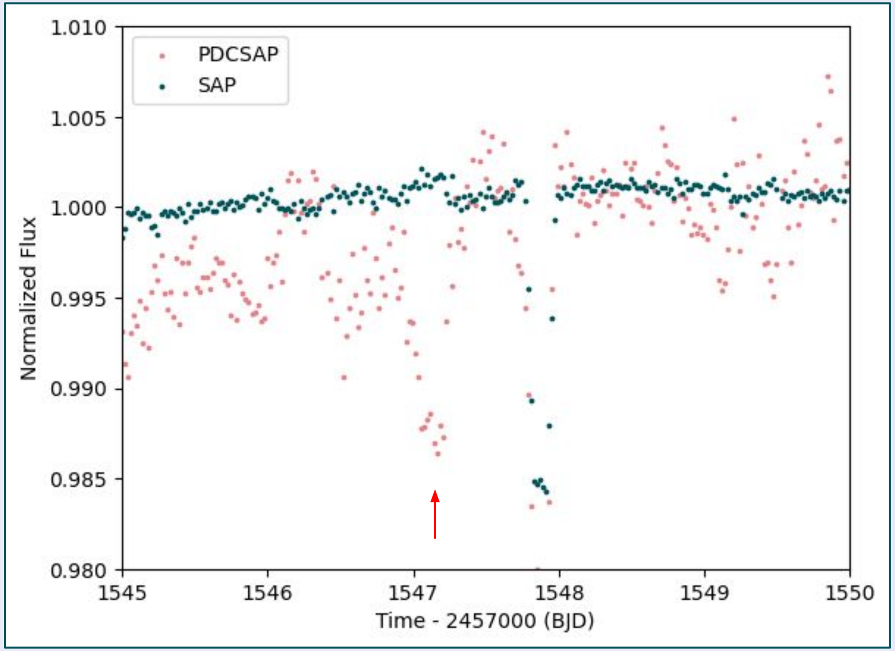
Credit: Y. Eschen

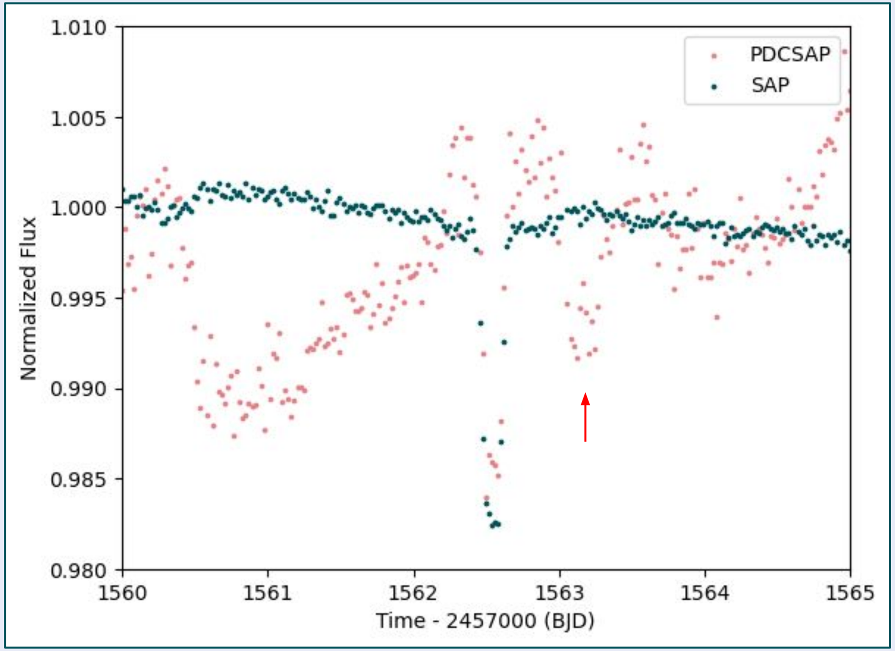
SAP vs. PDCSAP



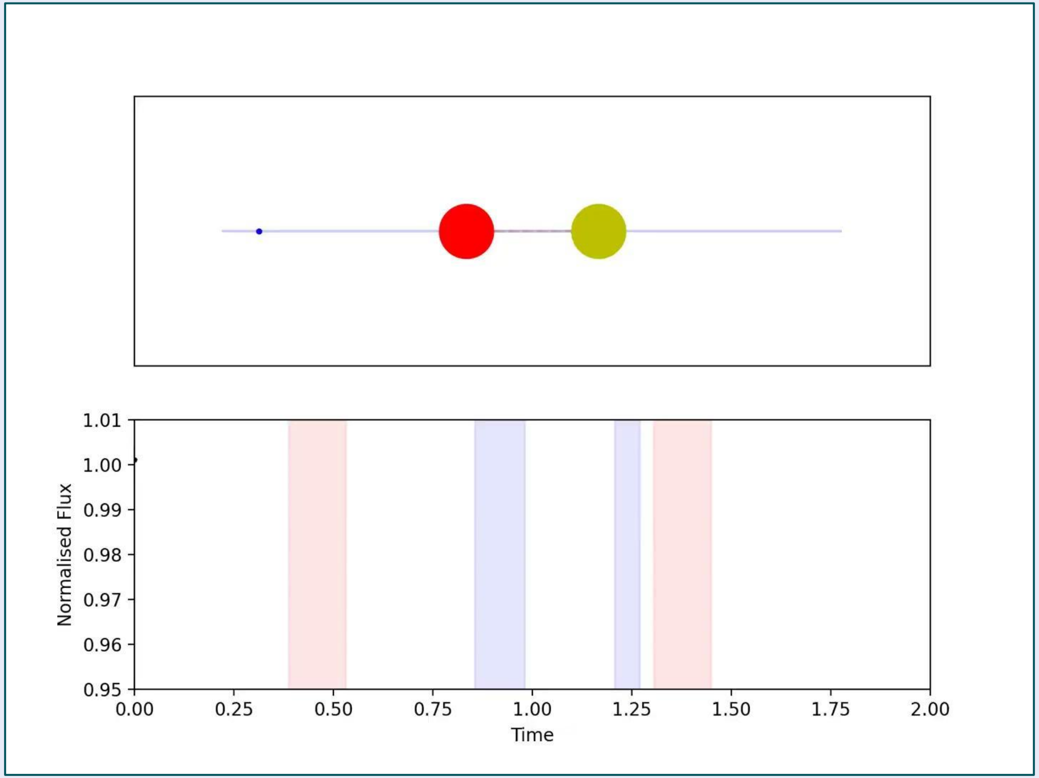
Ben Davies, University of Warwick (ben.d.r.davies@warwick.ac.uk)

SAP vs. PDCSAP





“One-two punch” effect



Ben Davies, University of Warwick (ben.d.r.davies@warwick.ac.uk)