The Path to Uncovering the Histories of TESS Circumbinary Planets

Presented by Dominic Oddo
For NASA ExoPAG 29th Meeting
On Saturday, January 6th, 2024

Dig this Definition

What do we mean when we say “planetary system architectures”?

- **Architecture: “The purposeful arrangement of materials into structures in a certain style”**

- **We can connect the dots between formation theories and observables to build a coherent “structure” of how CBPs come to be**
- **TESS observations represent an exciting new opportunity to examine CBPs and their architectures!**

Why Boogie Down with CBPs?

Developing a two-dimensional understanding of CBPs

Binary hosts

- Binary mass ratio
- Host metallicity
- Host binary period

Planets

- Physical sizes
- Planet orbital period
- Multiplicity

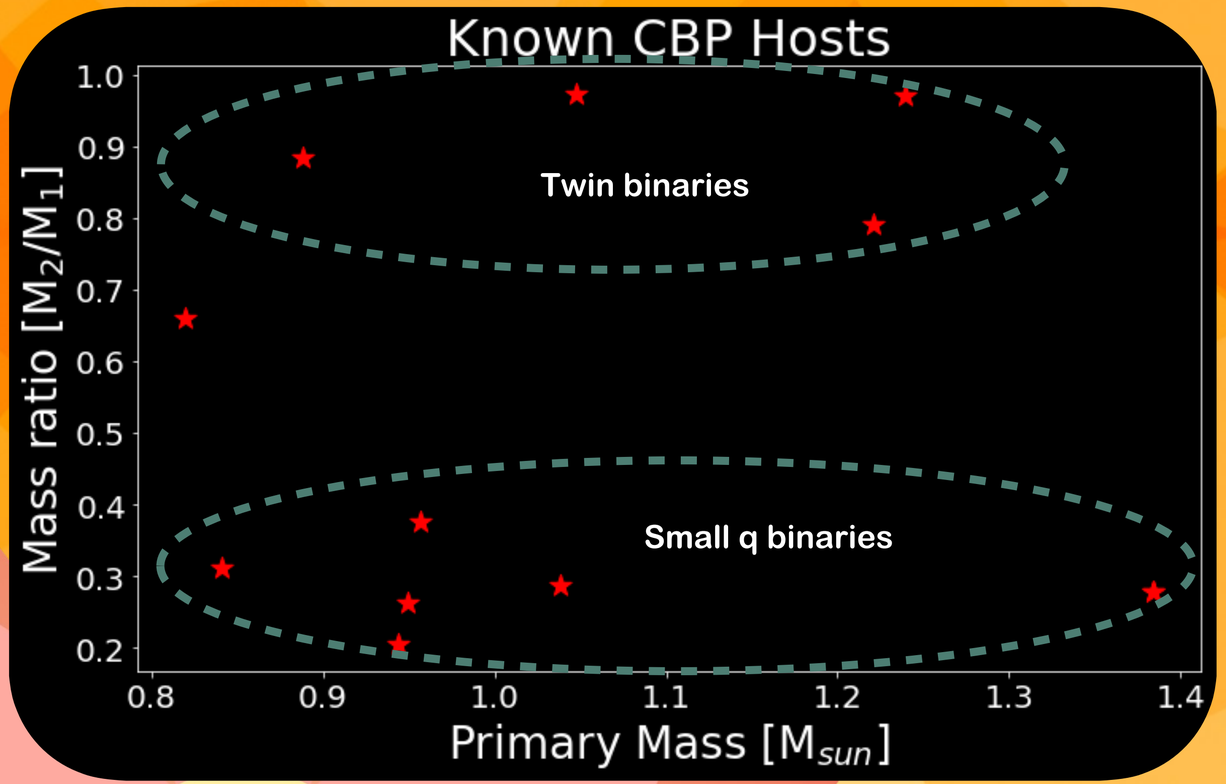
What sorts of binaries are most likely to yield CBPs and why?

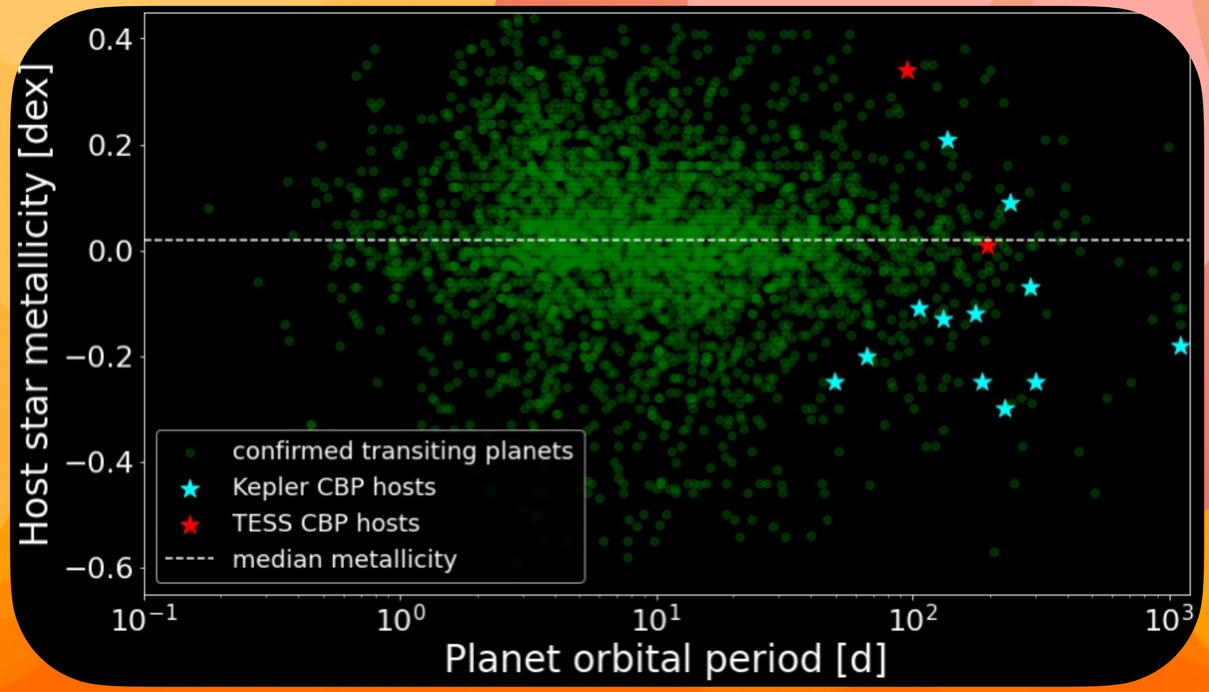
What do the known CBP systems tell us about their histories?

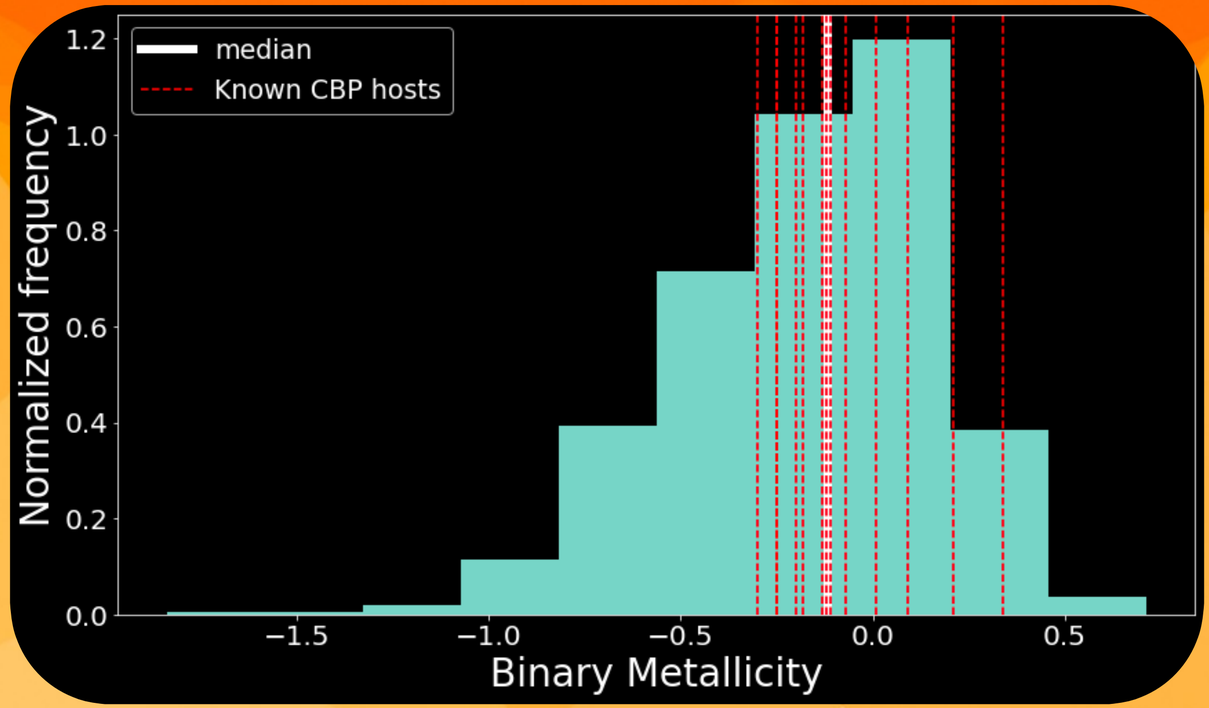
Do our expectations from theory match up with known trends?

Binaries

Mass ratios & metallicities



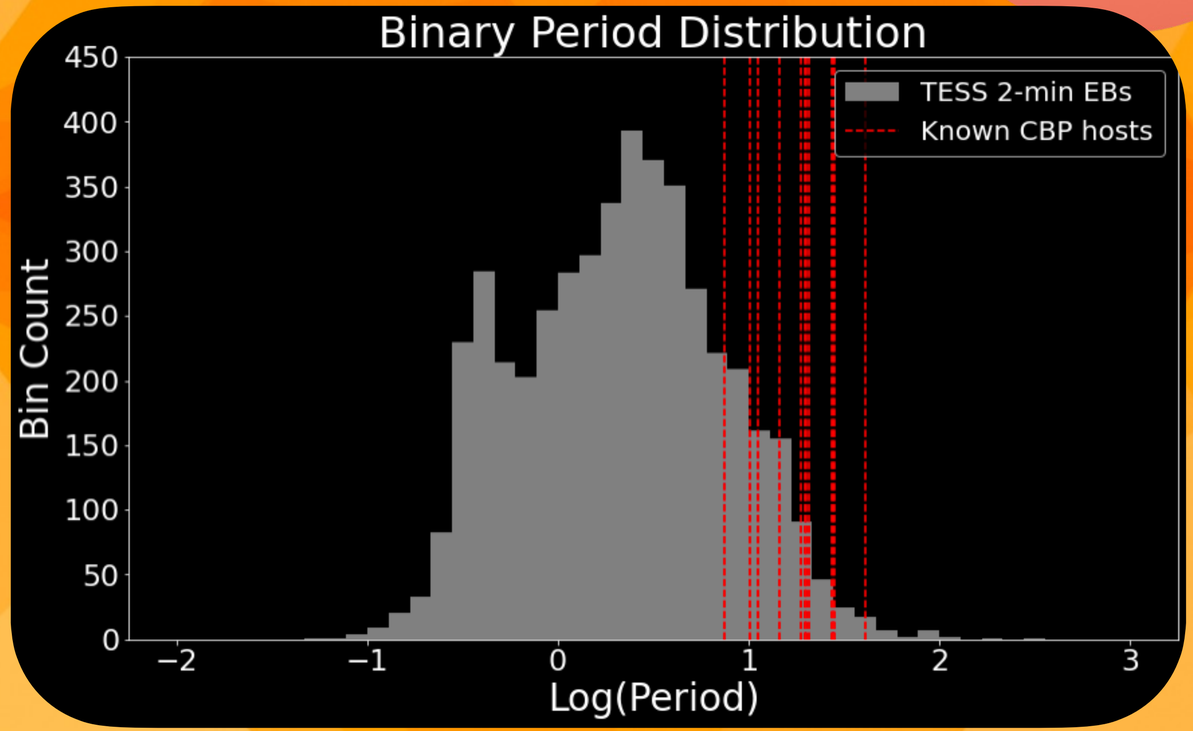




Binaries

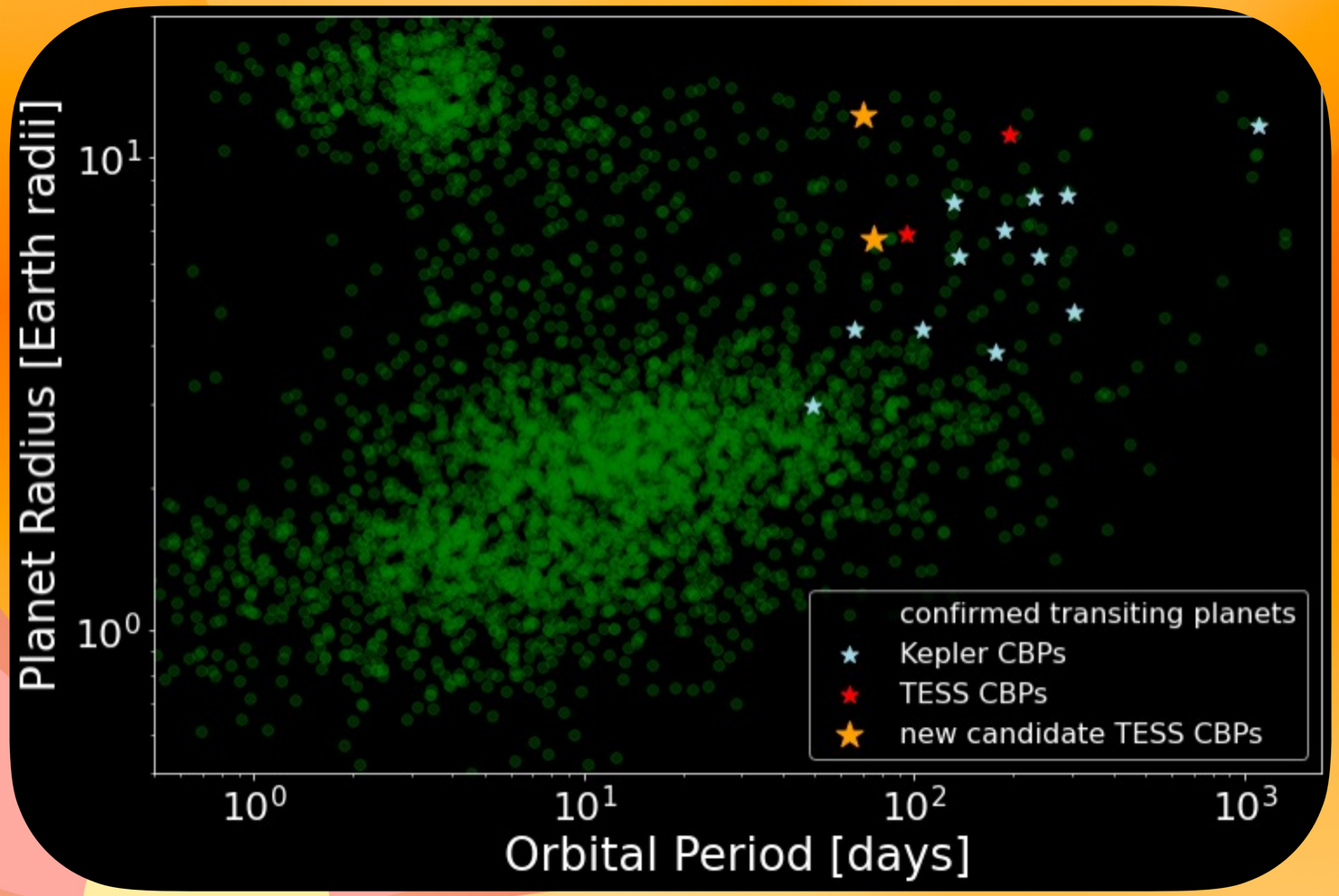
Binary periods

- CBP hosts approx. 7-40 d periods
  - But there are plenty shorter period EBs
- Tightest binaries form with help from a tertiary star (Kozai-Lidov oscillations)
  - Casts CBPs to inclined and eccentric orbits, making them difficult to find in transit



Planets

Sizes & periods



- CBPs tend to be larger and have longer orbital periods than most other transiting planets
  - Observational bias?
  - In situ formation not favored
  - Method of formation
    - Disk instabilities
    - Core accretion
    - Pebble accretion
- Dearth of Terrestrial CBPs
  - Bias or susceptible to ejection

Far Out! Planets

A pileup as evidence for migration through orbital resonances

- Many CBPs have been found near their stability limits for their respective binary: is this bias?
  - It's not bias, it's consistent with a log-uniform distribution of periods (Li, Holman, & Tao 2016)
  - Could be no pile-up at all, just change how you define stability (Quarles et al., 2018)
- If trend is confirmed, this is evidence of the importance of orbital migration in these systems
  - Theory says *in situ* formation is not favored (e.g. excitation of eccentricities leading to breaking collisions)

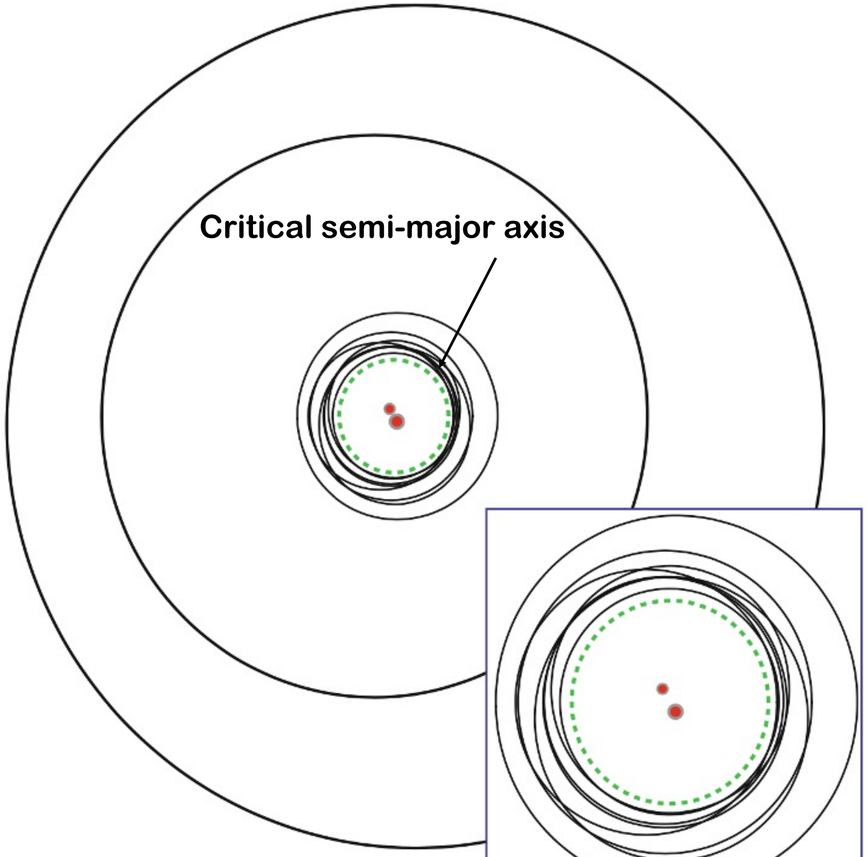


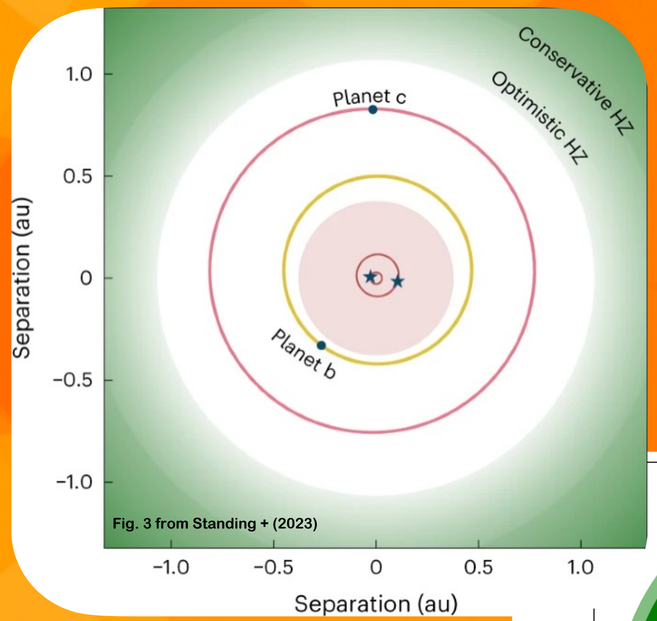
Figure 5 from Welsh & Orosz (2018)

Peace & Love

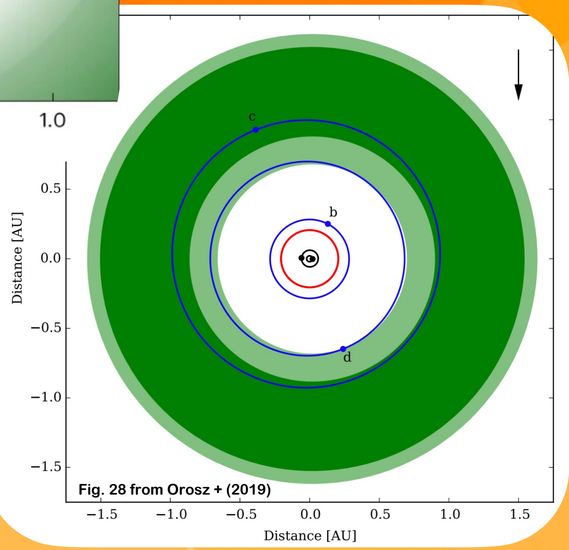
Multiplicity and small planet formation

- Two multi-planet systems discovered to date
  - Kepler-47: three planets
  - TOI-1338/BEBOP-1: two planets
- Detections of additional transiting planets around known CBP hosts are expected to be limited
- Planets form farther out and then migrate as resonant chain, but may be disrupted or ejected during migration through binary resonances
  - Especially for smaller rocky planets in the presence of a giant

TOI-1338/BEBOP-1



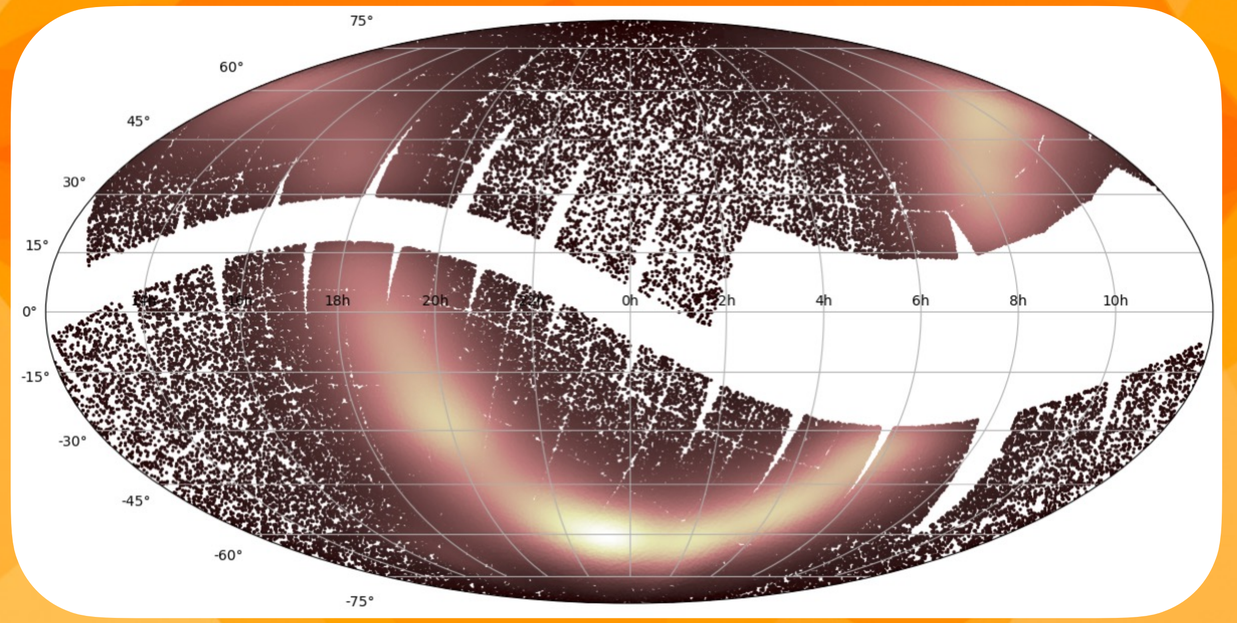
Kepler-47



The Lowdown on TESS

What TESS can (and can't) do for detecting CBPs

+ Huge data volume
  - ✶Hundreds of thousands of EBs & millions of light curves
– Short baselines for most EBs
  - ✶Multiple transits in one conjunction
  - ✶The Continuous Viewing Zone
  - ✶Non-transiting CBPs with ETVs
+ New science!

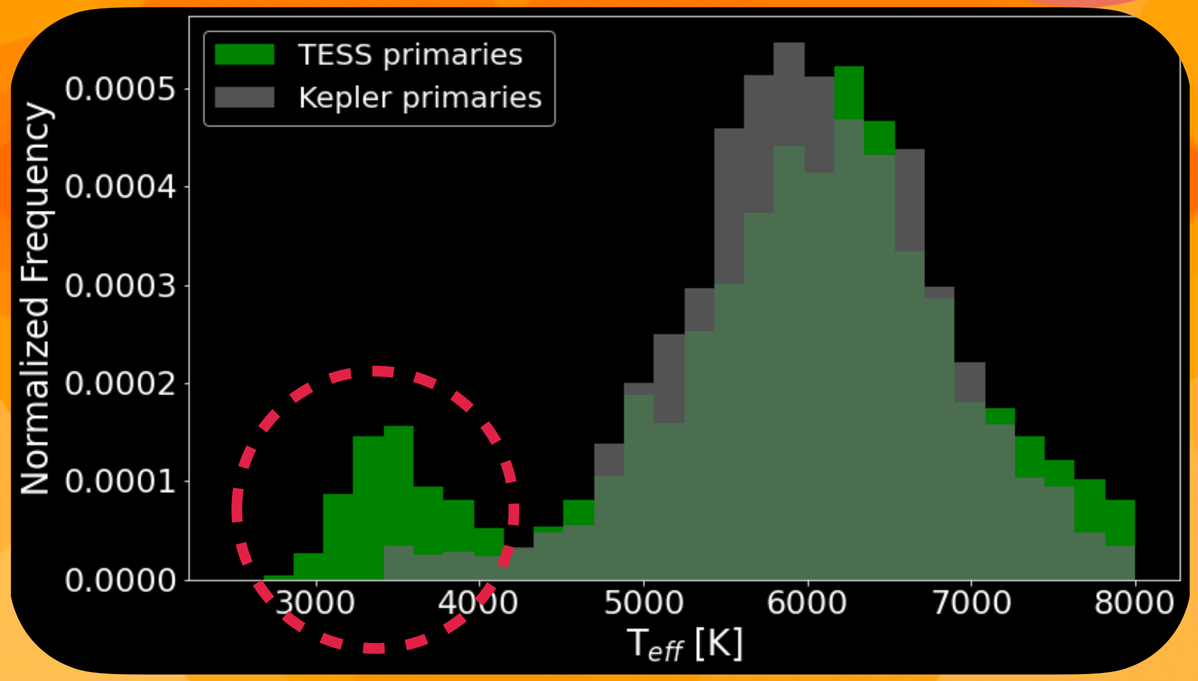


Acknowledgement to the GSFC team (B. Powell, E. Kruse, etc.) for the EB list

What's Happenin'

New Science: M+M Binaries

- Single-star M dwarfs are interesting for many reasons:
  - Hosts to diverse systems of planets
  - Challenging tests of planet formation (low- and high-mass alike)
  - More easily accessible HZ planets
- More M+M binaries are accessible than ever with TESS!
  - Represents a new chance to examine these questions from a different perspective

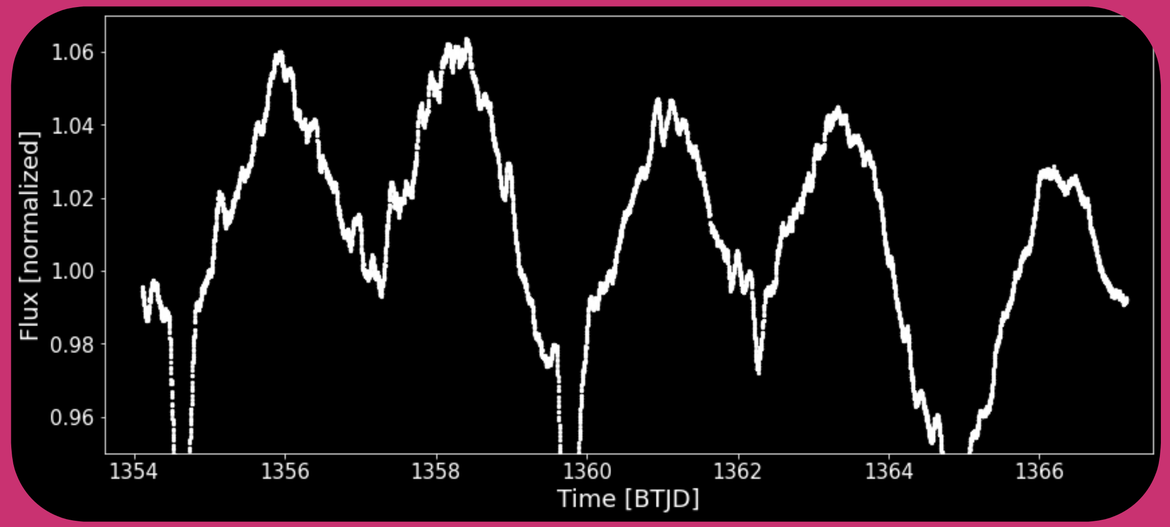


Finding CBPs is a Trip, Man

Challenges to finding transiting CBPs

Binaries

- **Noisy/unruly EBs**



- **Short baselines for most EBs**

Planets

- **Transit timing, depth, and duration variability**
  - **Requires individual event searches**
- **Transit dilution**

$$\frac{R_{CBP}}{R_p} = \sqrt{1 + q^{3.5}}$$

  - **Difficult to find smaller planets!**
- **Orbital precession decreases proportion of observable transits**

How Many Groovy TESS CBPs?

Veeeeeeeeeeeeery quick TESS CBP yield estimates

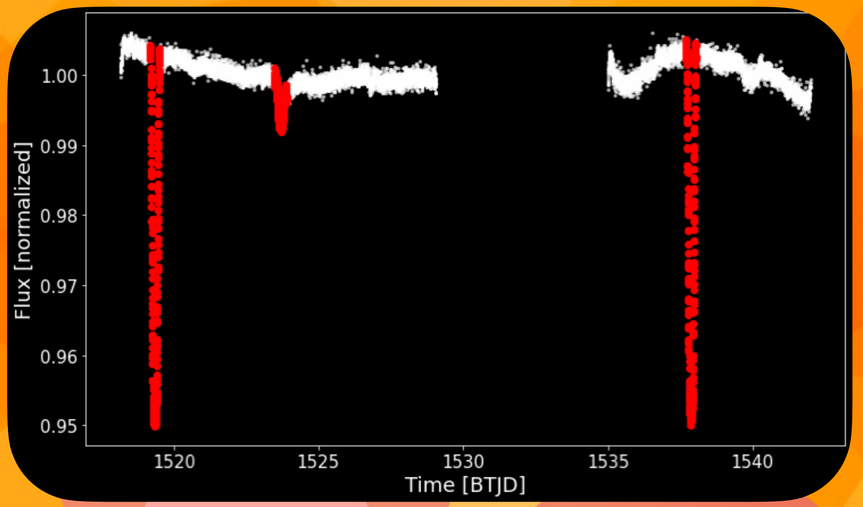
1. There are ~1700 “good” EBs in the Kepler field.
   Six with planets with sizes > 6 R_{earth} and P < 300 d
2. We’ve searched the TESS 2-min catalog (about 4500 EBs).
   In the CVZ, there are ~100 bright EBs in period range of interest
3. Based on Kepler discovery rate and this number of reliable EBs
   We should only expect between 0 and 2 detections in TESS 2-min EBs
4. **Current TESS yield is consistent with Kepler yield!**
   But a more careful accounting will be required to confirm this.

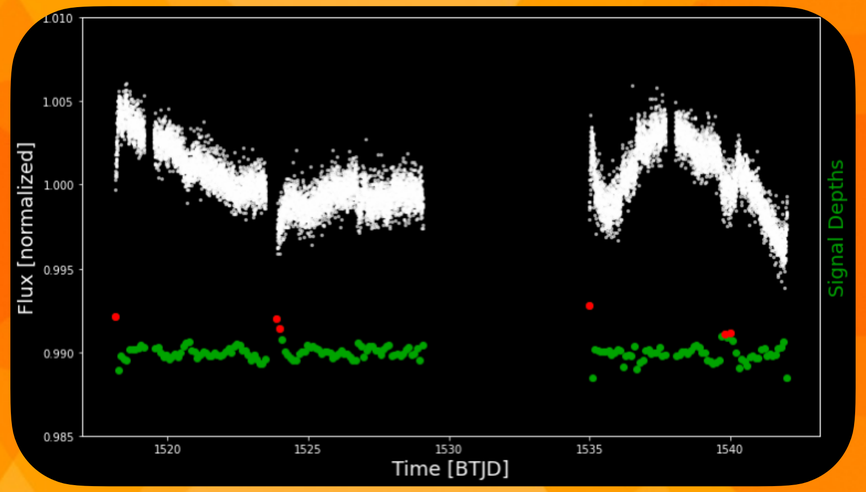
Hundreds?

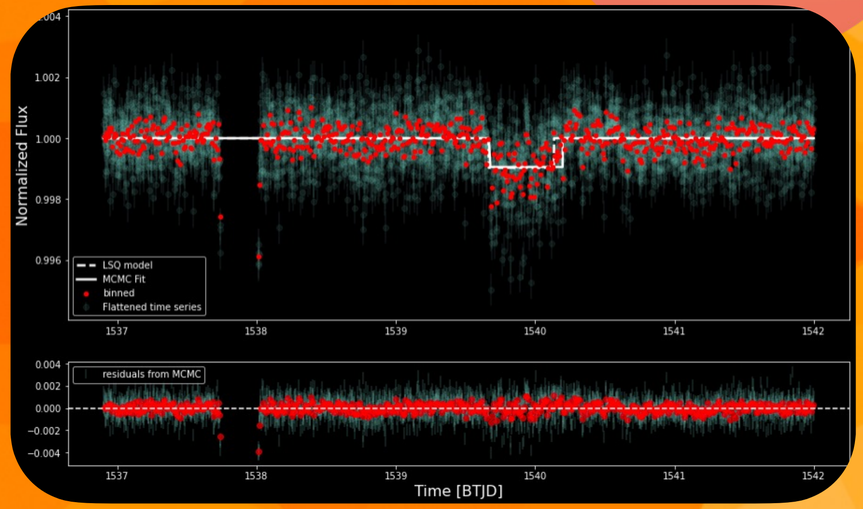
None?

The cosmic quest for TESS CBPs

Outlining our search for TESS CBPs







Generate light curves and identify binary eclipses

Move mask across light curve to find depth at given intervals

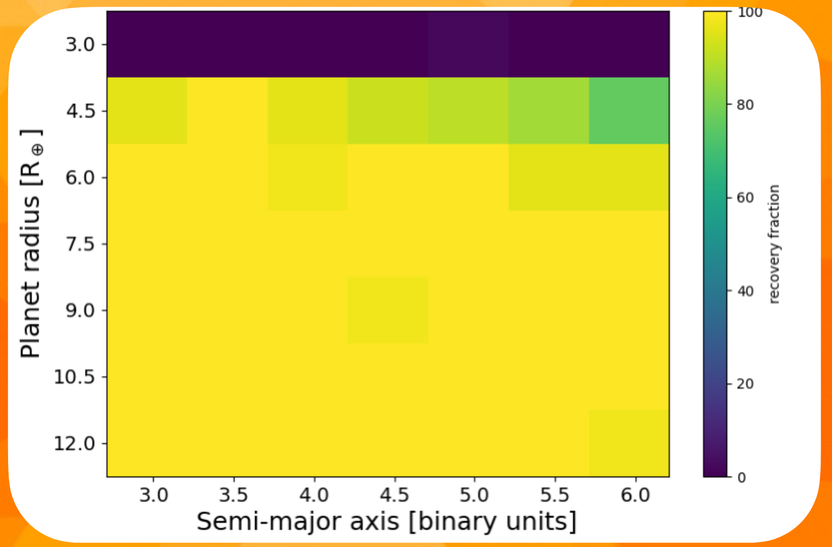
Identify, vet, and fit transit signals

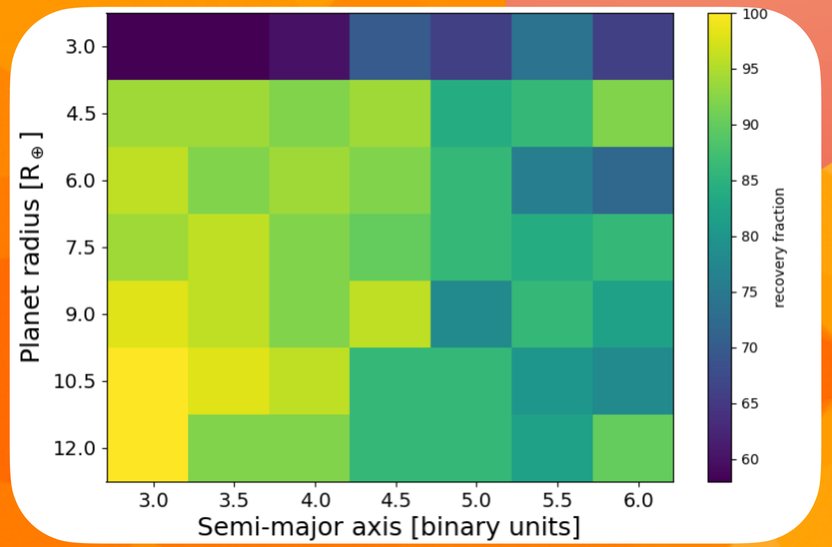
Attend my talk on Thursday for more about the search and results!

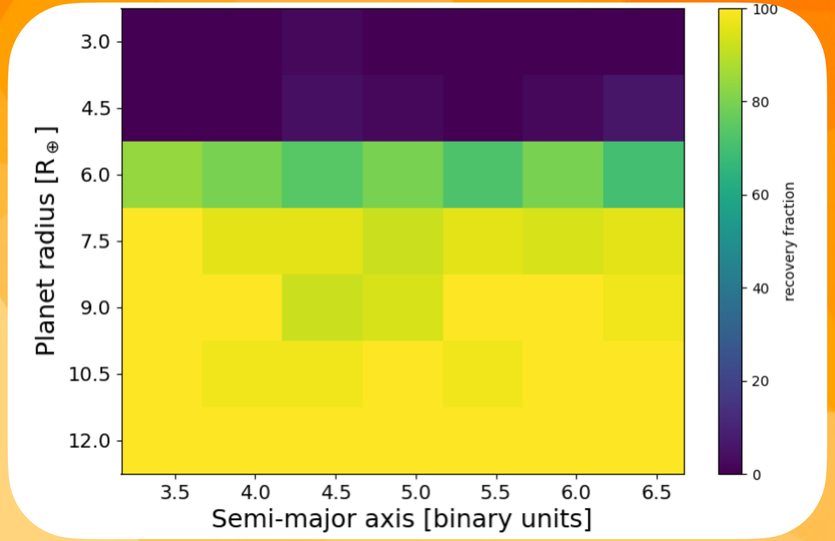
Injection Testing

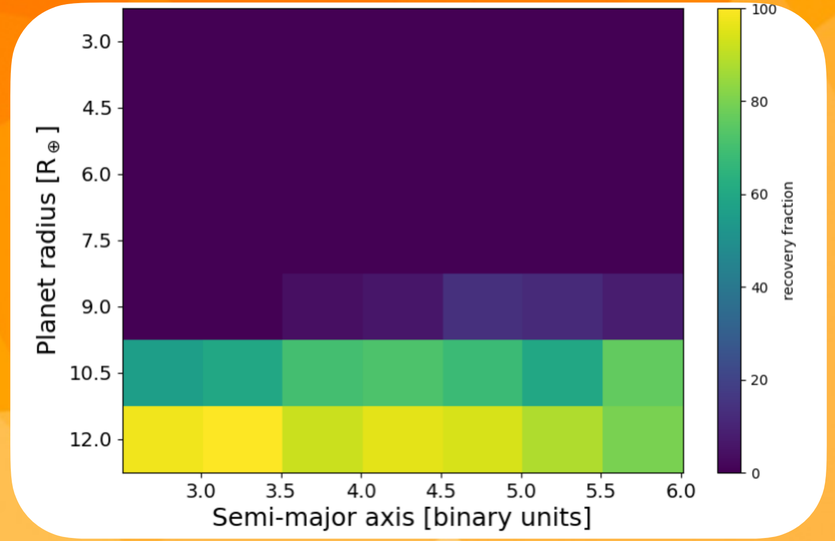
What are we sensitive to in our search? What can we really test?

- Sometimes we have sensitivity to Neptunes or Saturns
- Sometimes we have sensitivity to only giants
- Sometimes there is semi-major axis dependence
- Rarely do we have reliable sensitivity to terrestrial planets









Peace Out

Wrap up & summary

- CBP discoveries provide rich clues into planet formation around binaries and their architectures are influenced by both host binary and planet properties
  - Tight binary formation and evolution mechanisms
  - Planet formation and migration
- Finding transiting CBPs is challenging, but TESS provides a fair shot
  - TESS provides the opportunity for a CBP in an M+M binary for the first time!
- While a more careful calculation is needed, we are finding that TESS yields are consistent with expectations from Kepler yield

Thank you!

Personal website (inc. current CV)

Supported by

NASA

FINESST

JPL

Jet Propulsion Laboratory

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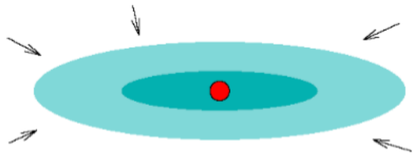
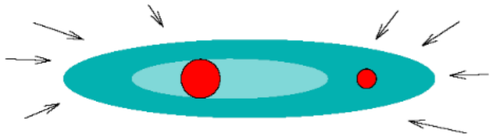
Tight Binary Formation

Leaving clues for observables

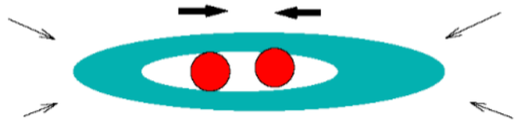
Disk instability



1. Primary component forms in over–density and grows



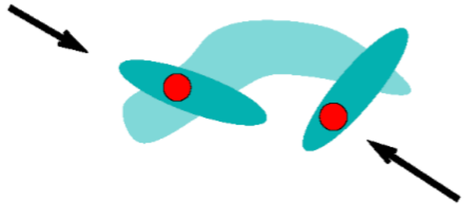
2. Accretion burst de–stabilizes the disk, secondary companion forms



3. Both stars grow and migrate inward

Core fragmentation

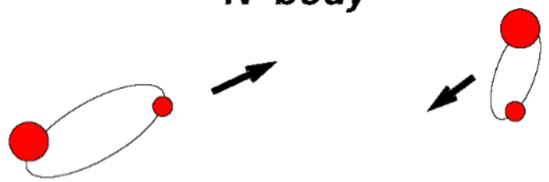
1. Two independent protostars



2. Approach and interaction

3. Both stars grow and migrate inward

N–body



1. Encounter of 3 or 4 stars

2. Chaotic motion

3. Ejection, eccentric binary/triple left

Tokovinin, A. Architecture of Hierarchical Stellar Systems and Their Formation. Universe 2021, 7, 352.