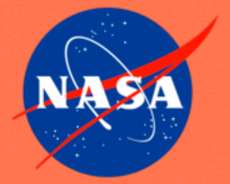
Supported by



FINESST grant

Don't FORCES It
Toward an occurrence rate for transiting TESS CBPs

Presented by Dominic Oddo
For CBP Workshop
On Wednesday, January 15th, 2025

Discovering CBPs

with Kepler and TESS

Kepler Mission (12 CPBs)

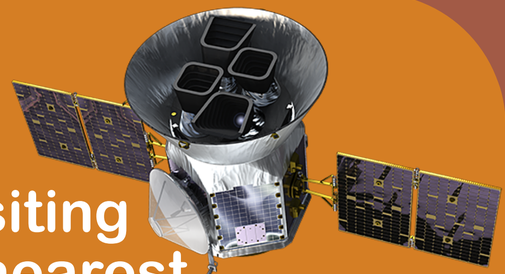
- Goal: search for earth-like planets orbiting sun-like stars
- Stared at a fixed part of the sky for about 4.5 years

:) longer baselines favor discovery of long-period transiting planets

:(small sample size made occurrence rates difficult to constrain

***Occurrence rate: ~10%

TESS Mission (2 CBPs)



- Goal: find small transiting planets orbiting the nearest, brightest stars
- Near full-sky coverage

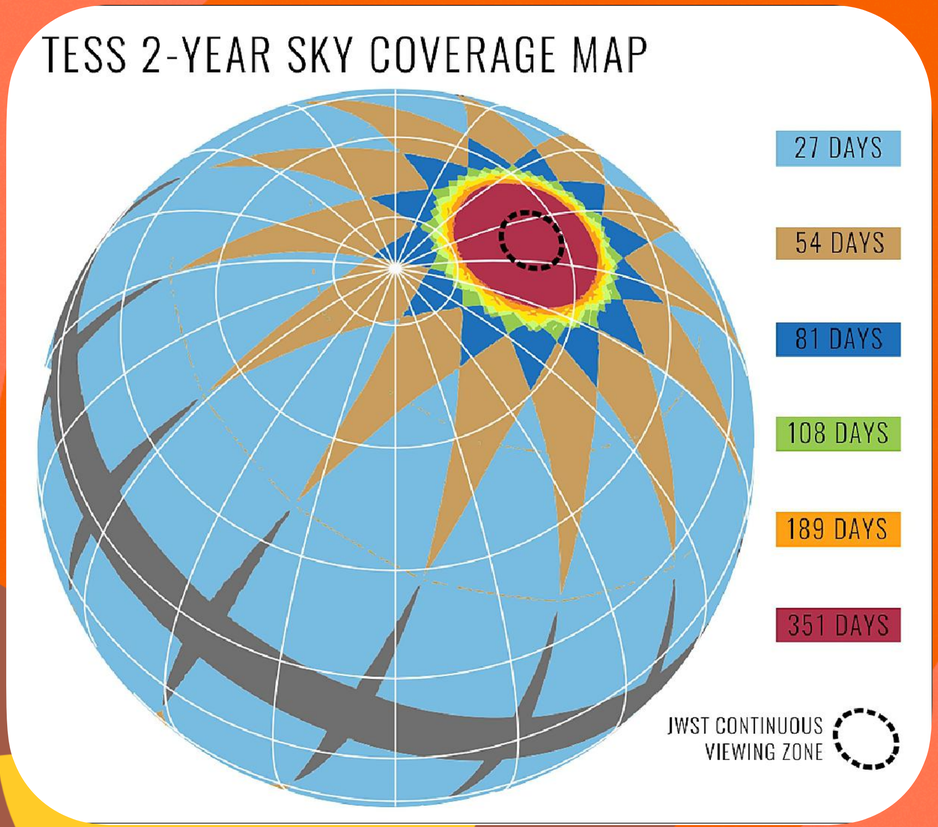
:) (approaching) a much more complete understanding of stellar sample

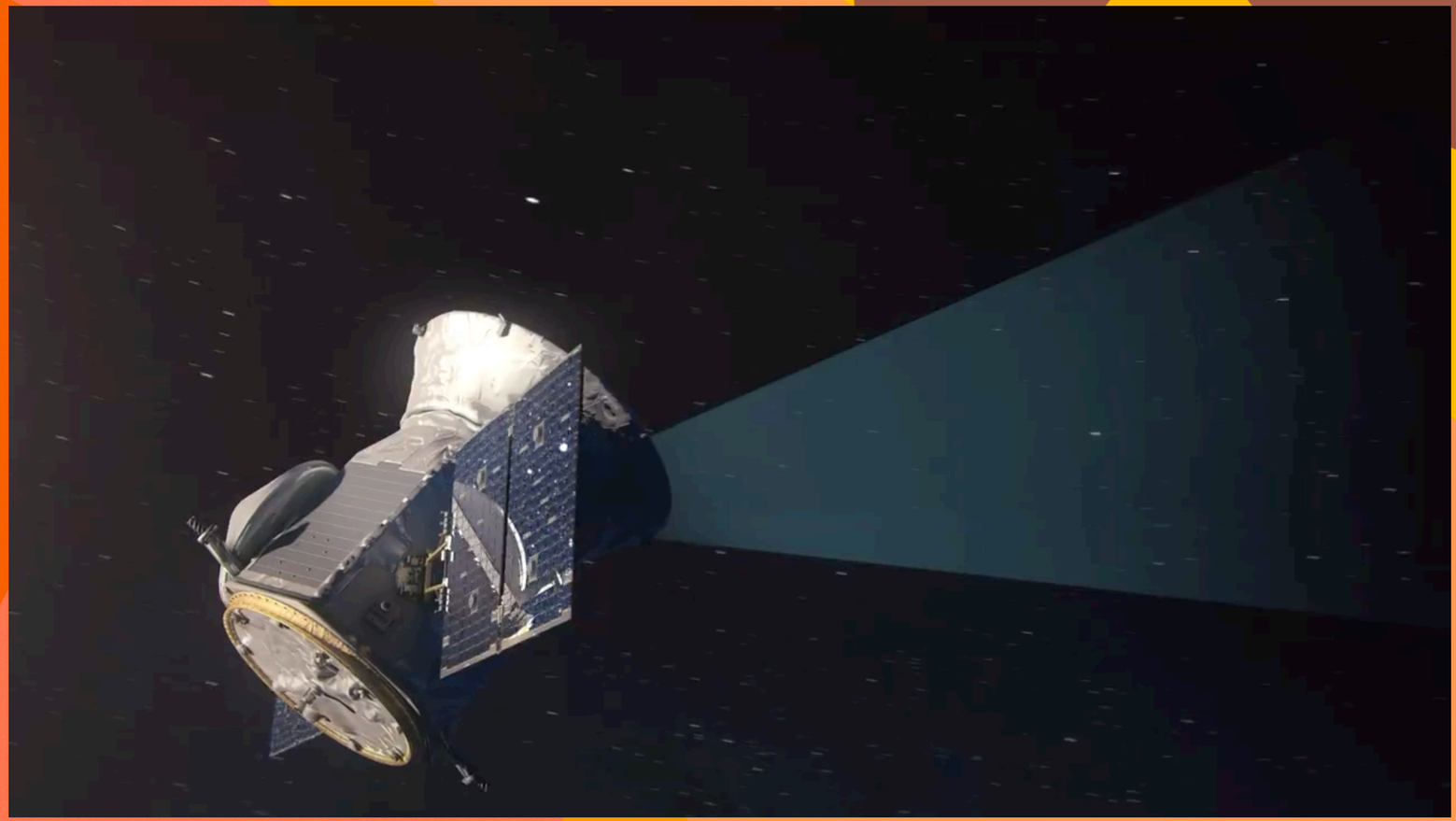
:) new science enabled!

:(short baselines make detection of long-period objects difficult

The Lowdown on TESS

The TESS observing strategy

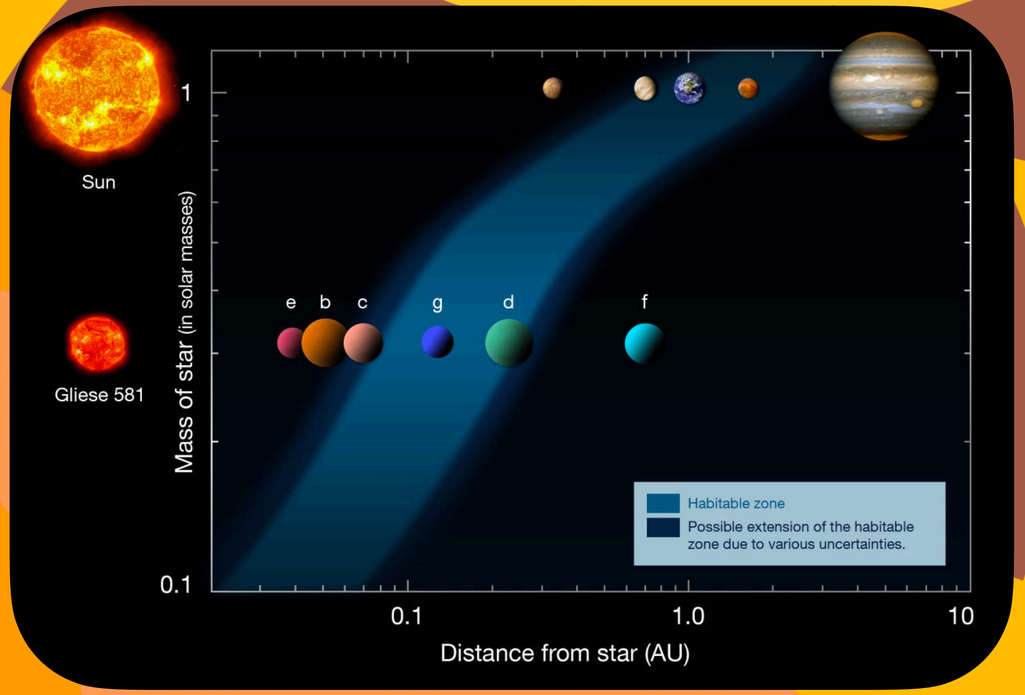


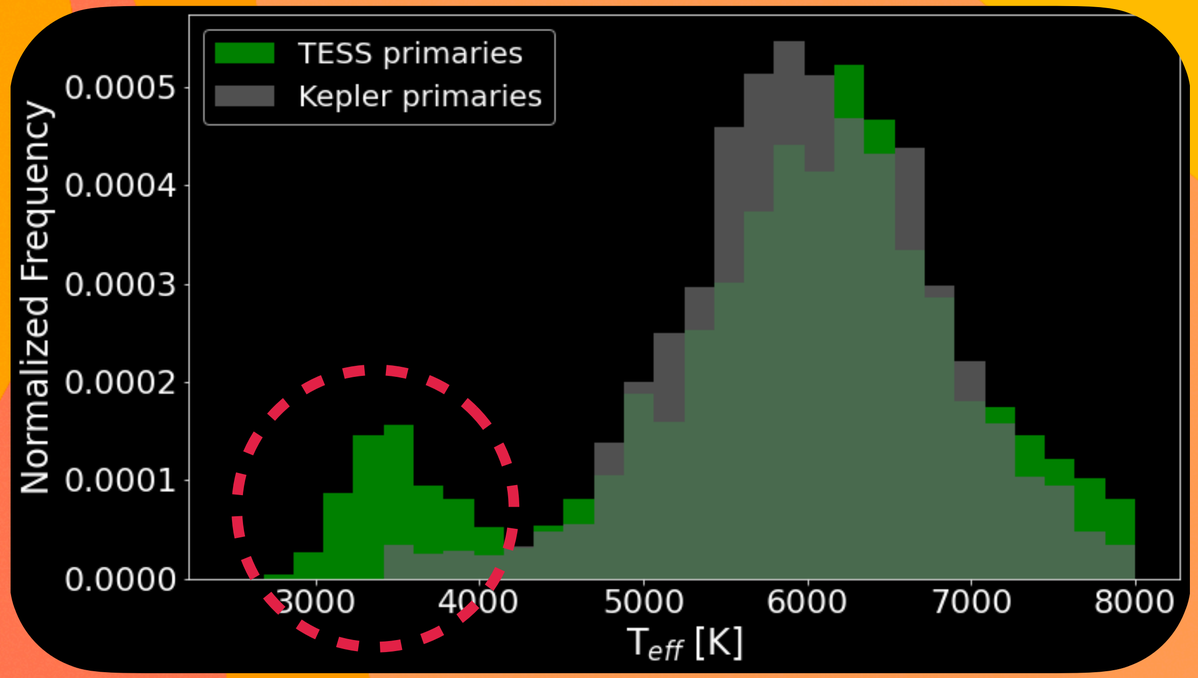


What's Happenin'

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 planets alike)
  - More easily accessible HZ planets
- Formation of low-mass binaries not well understood → do they form planets?
- More M+M binaries are accessible than ever with TESS!
  - Represents a new chance to examine these questions from a different perspective





To calculate an occurrence rate of transiting CBPs orbiting TESS M+Ms

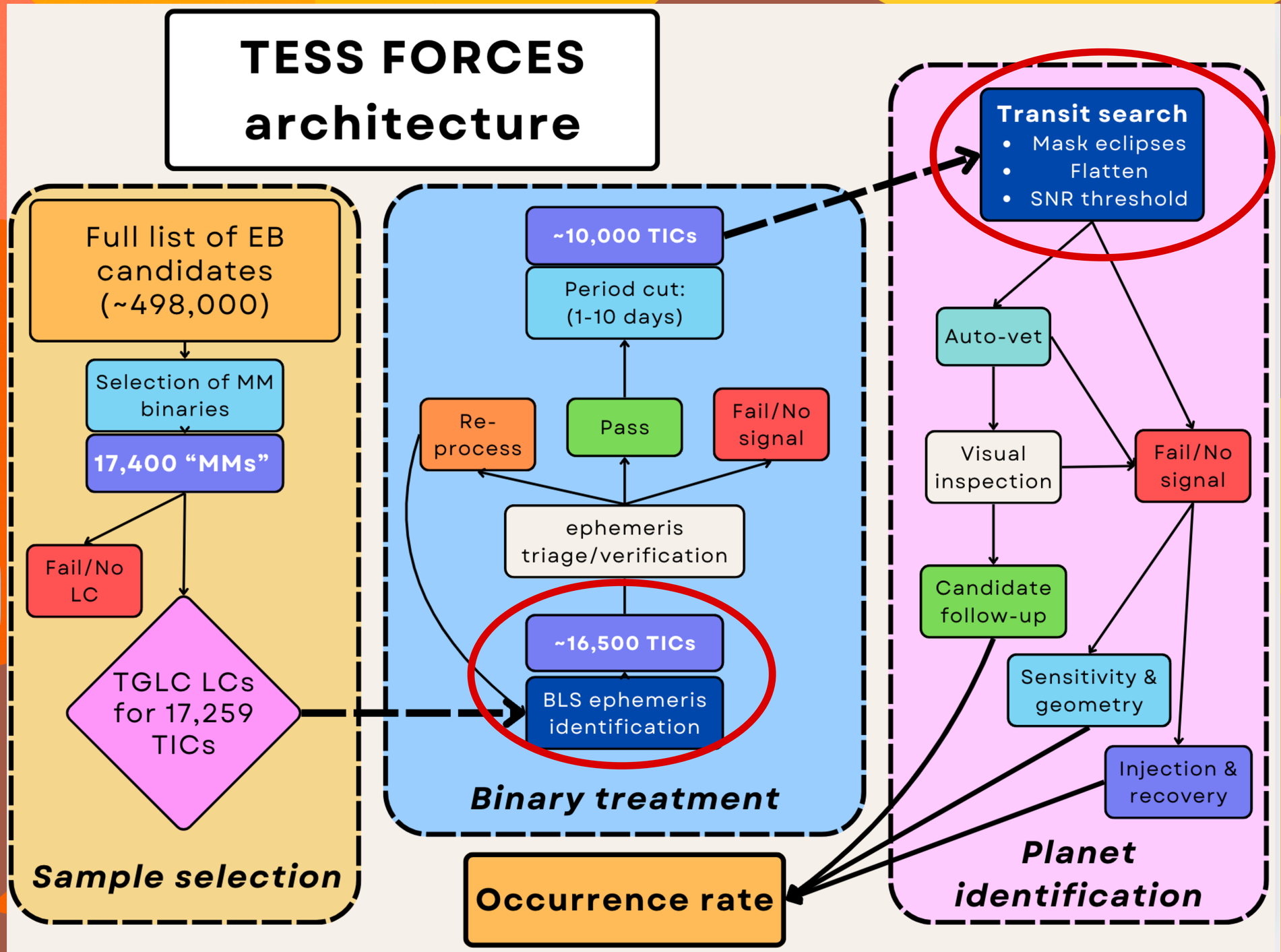
- Define a “complete” sample of stars
- Homogeneously remove variability, noise, etc.
- Search for and characterize candidate planets
- Justify candidates with vetting (preferably without human intervention)
- Characterize search sensitivity with injection/recovery
- Incorporate geometric and time-sampling constraints
- Calculate occurrence rate from detection statistics or forward modeling

Finding the Occurrence Rate of Circumbinary Exoplanetary Systems

LightCurveData

BinaryEphemeris

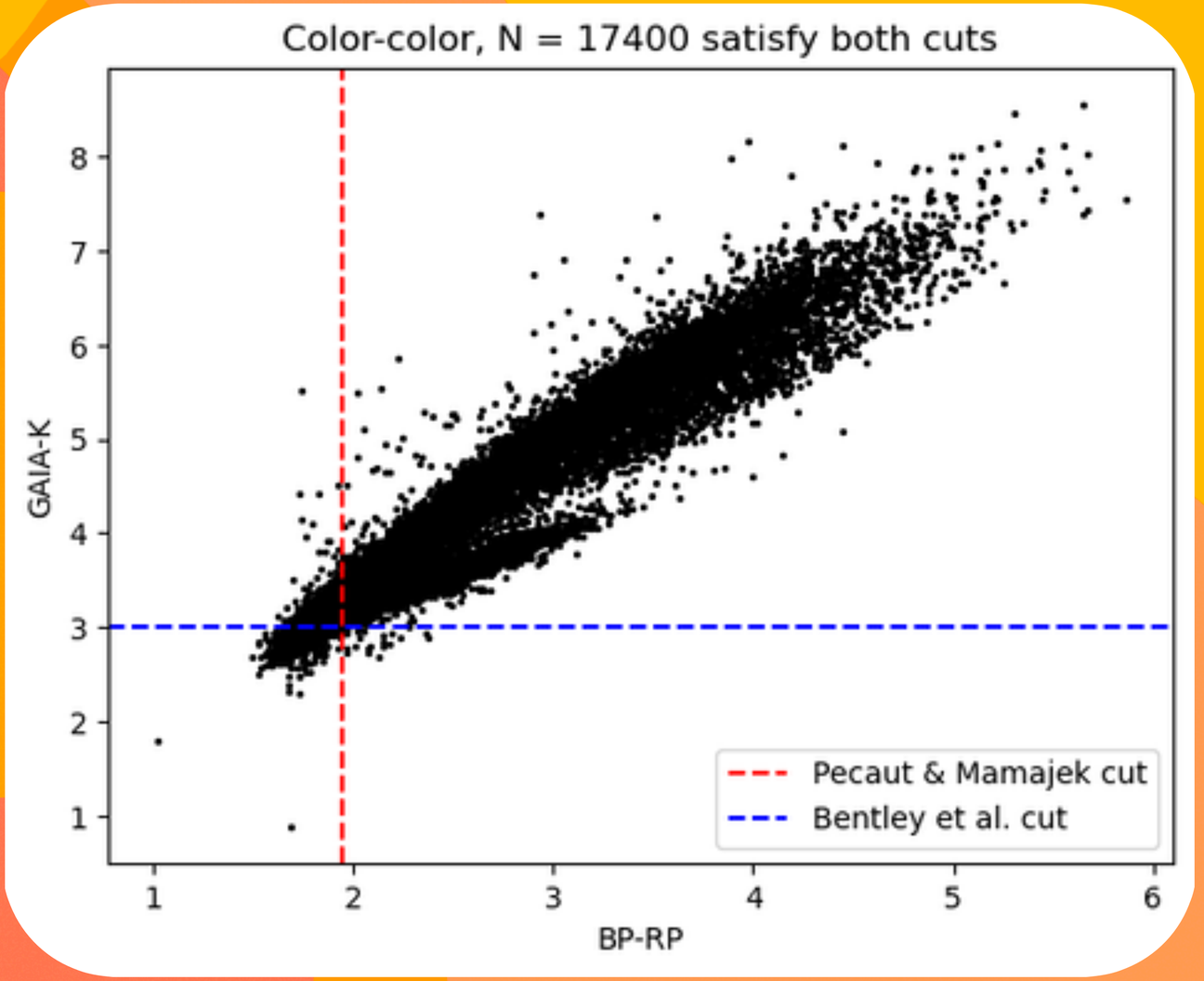
SNRSearch



EB Sample Selection

Color cuts and flaring (eventually)

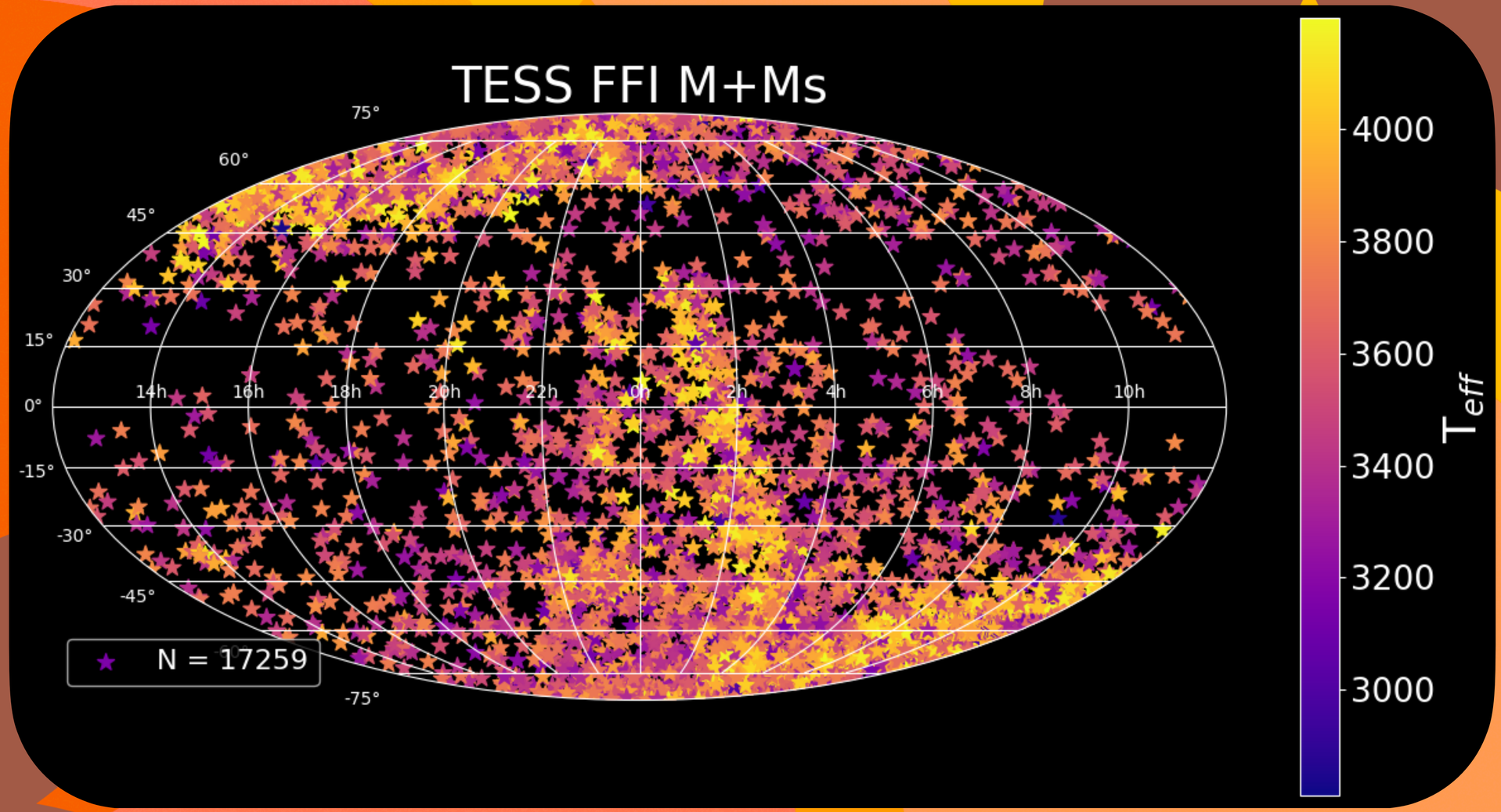
- Used two color cuts to identify low-mass binaries
- Could also utilize flaring as a trigger, but the absence of flaring doesn't disprove



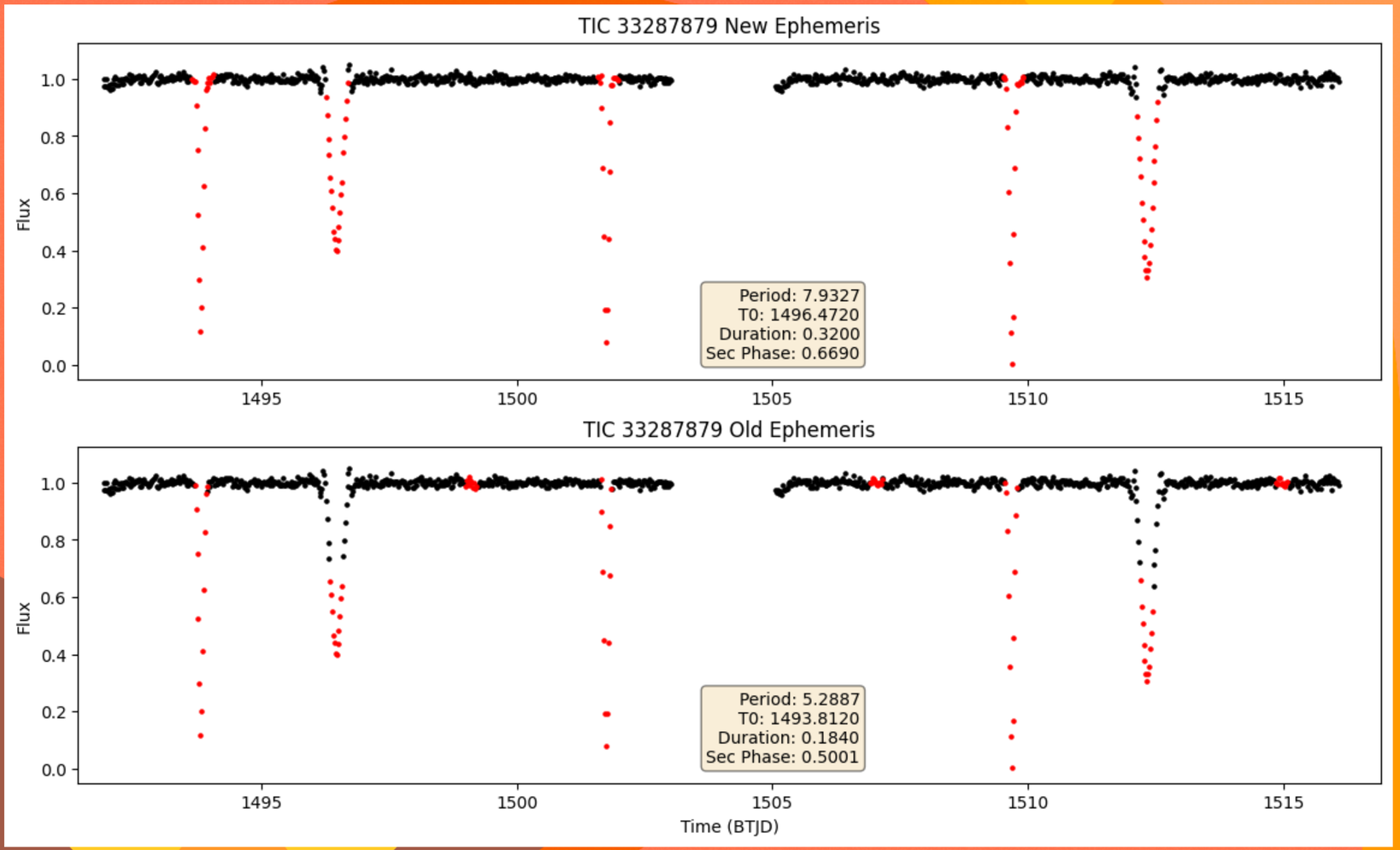
Characterizing TESS M+Ms

Compare to

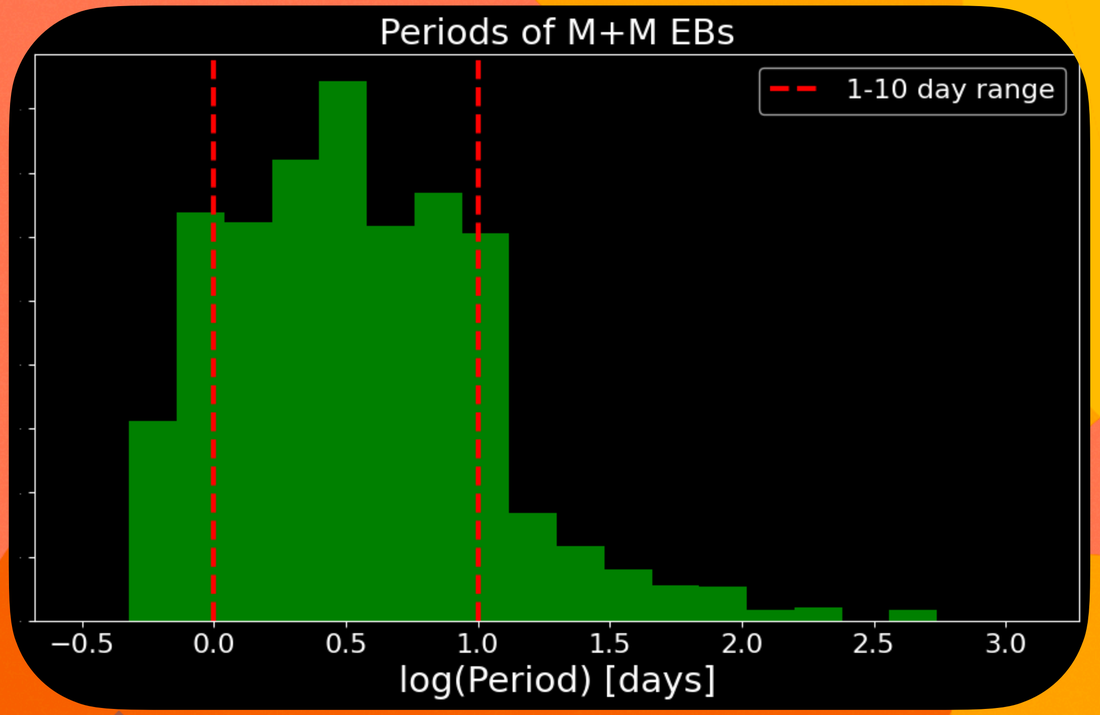
~4,500 EBs in TESS 2-min EB sample

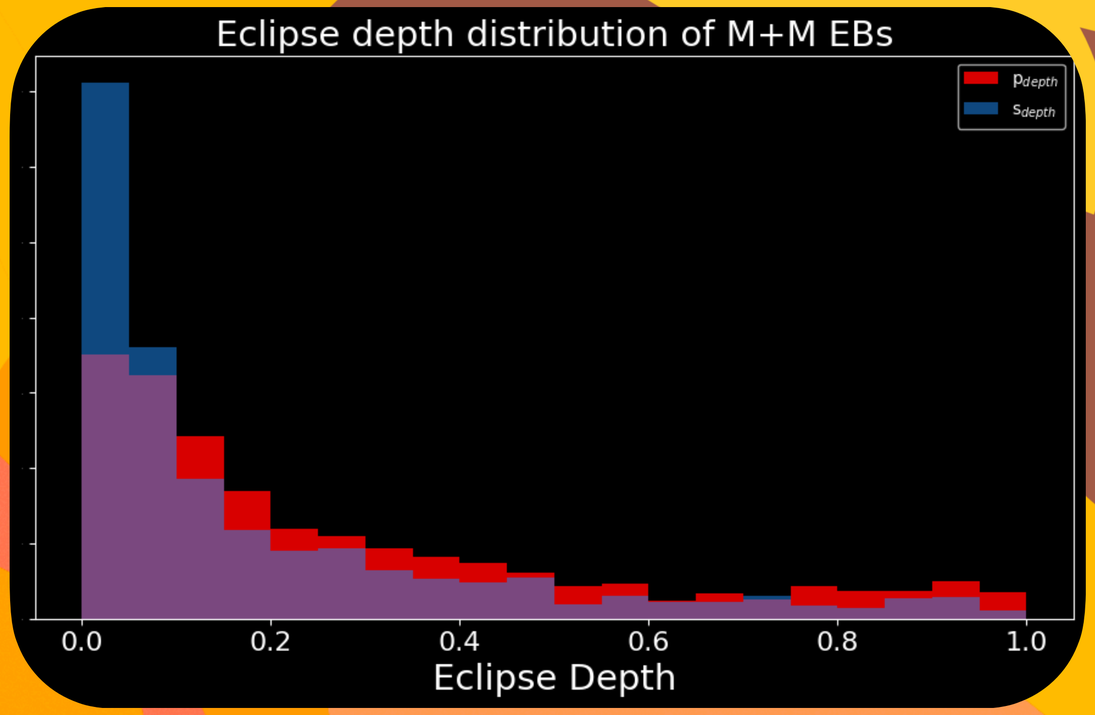


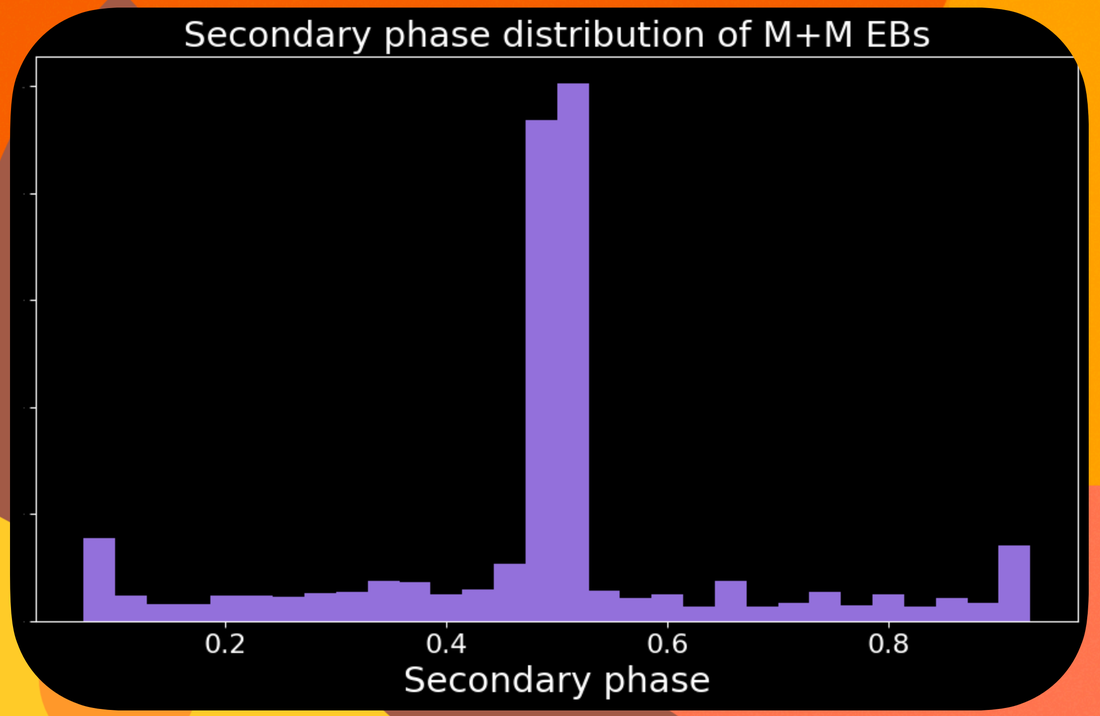
BinEphem Identification & Verification

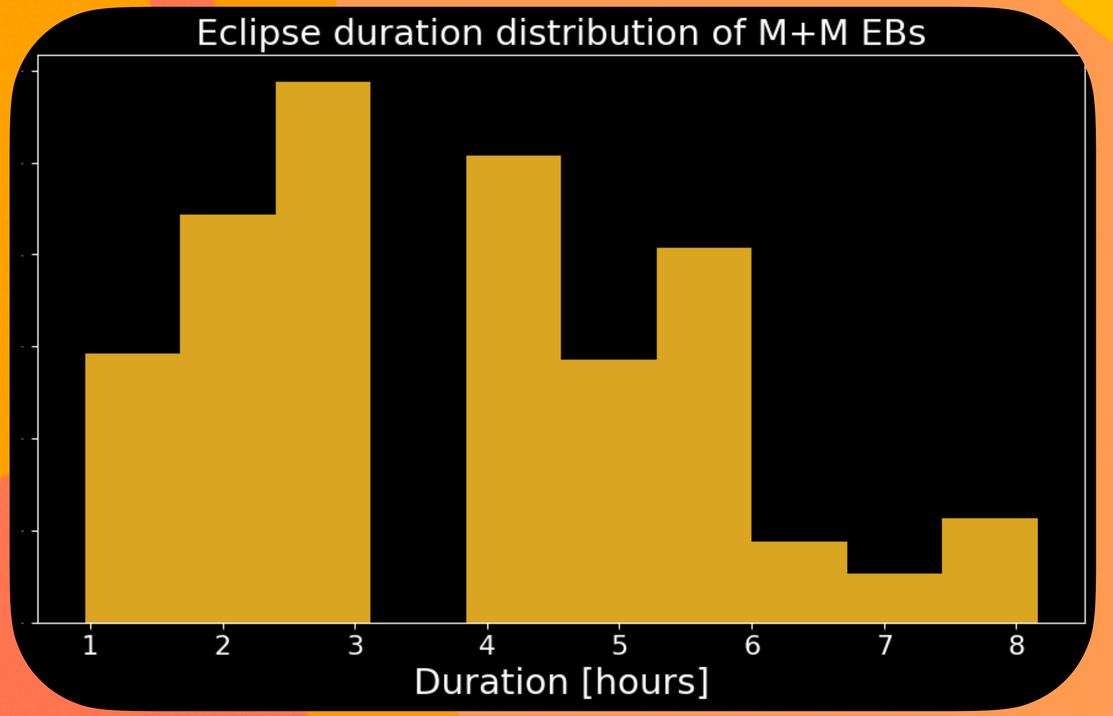


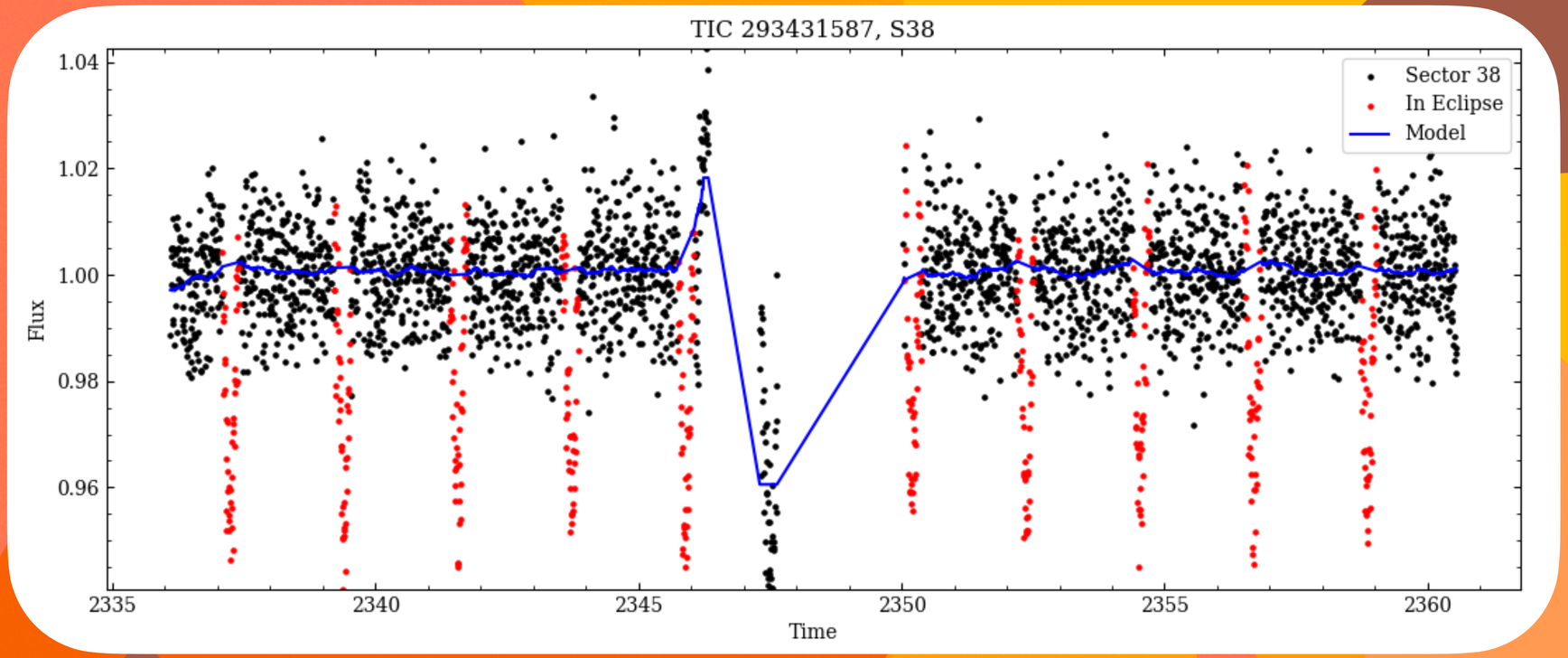
1. BLS period search (time-consuming, running on computing cluster)
2. Phase-folding and identification of secondary phase location
3. Primary and secondary eclipse counting and characterizing
    - Are there at least 2 primaries & 1 secondary (or vice versa)?
    - Check depth and duration consistency within a given sector (might change sector to sector due to different noise extraction)


Periods of M+M EBs
1-10 day range
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
log(Period) [days]

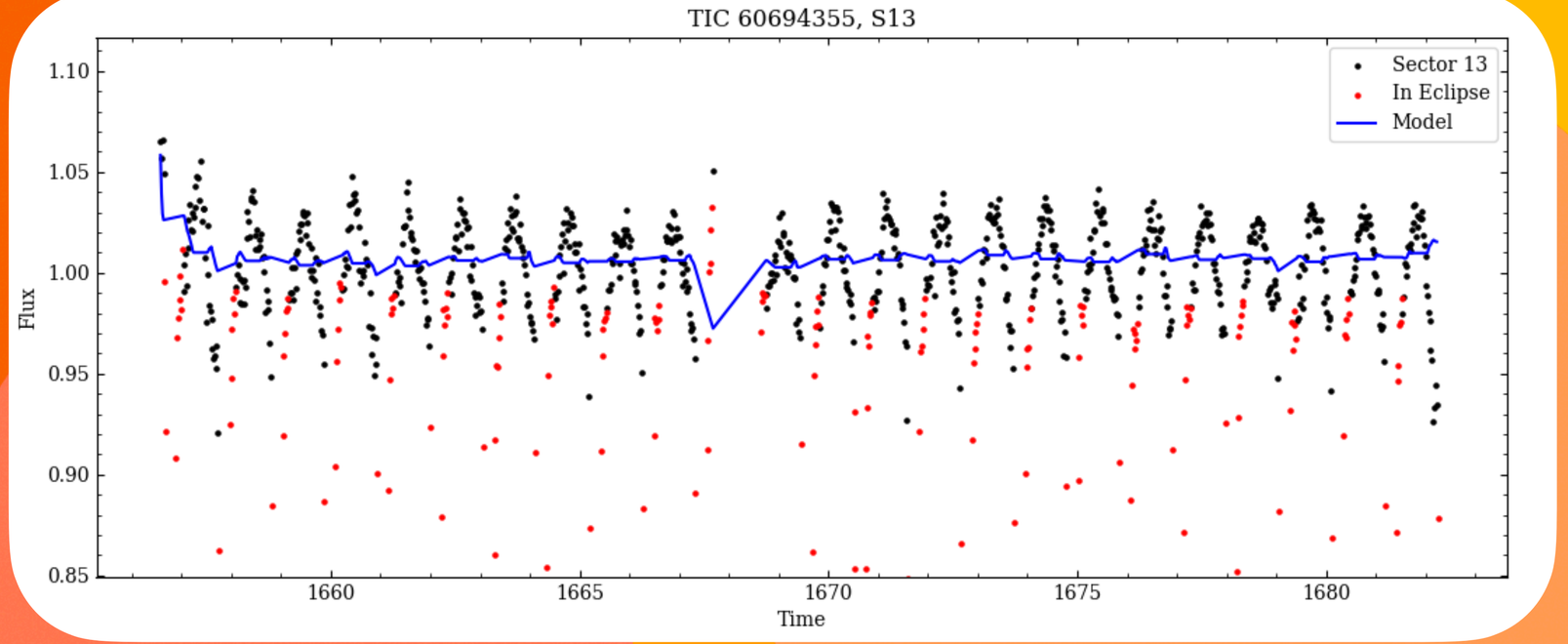

Eclipse depth distribution of M+M EBs
pdepth
sdepth
0.0
0.2
0.4
0.6
0.8
1.0
Eclipse Depth


Secondary phase distribution of M+M EBs
0.2
0.4
0.6
0.8
Secondary phase


Eclipse duration distribution of M+M EBs
1
2
3
4
5
6
7
8
Duration [hours]

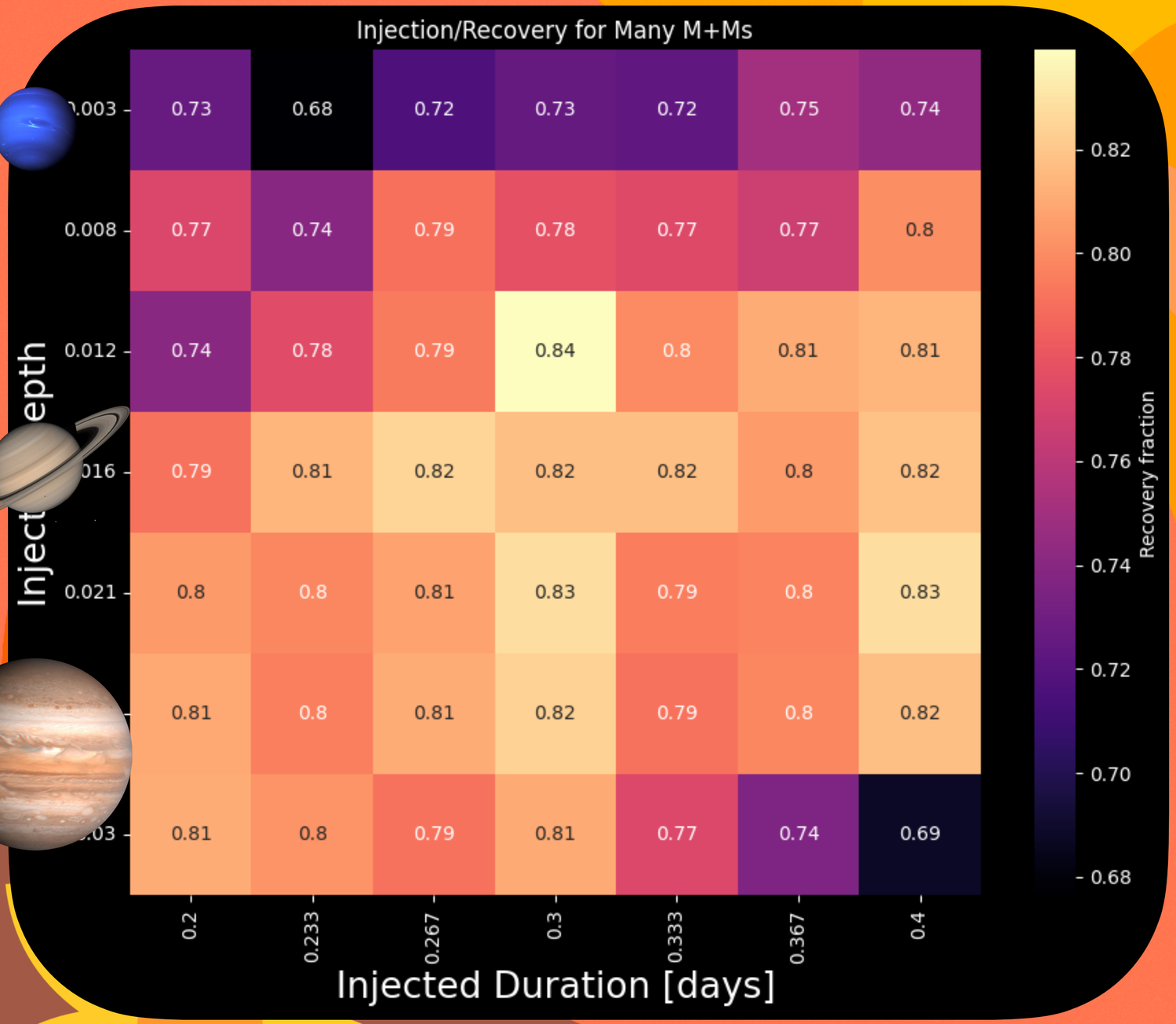


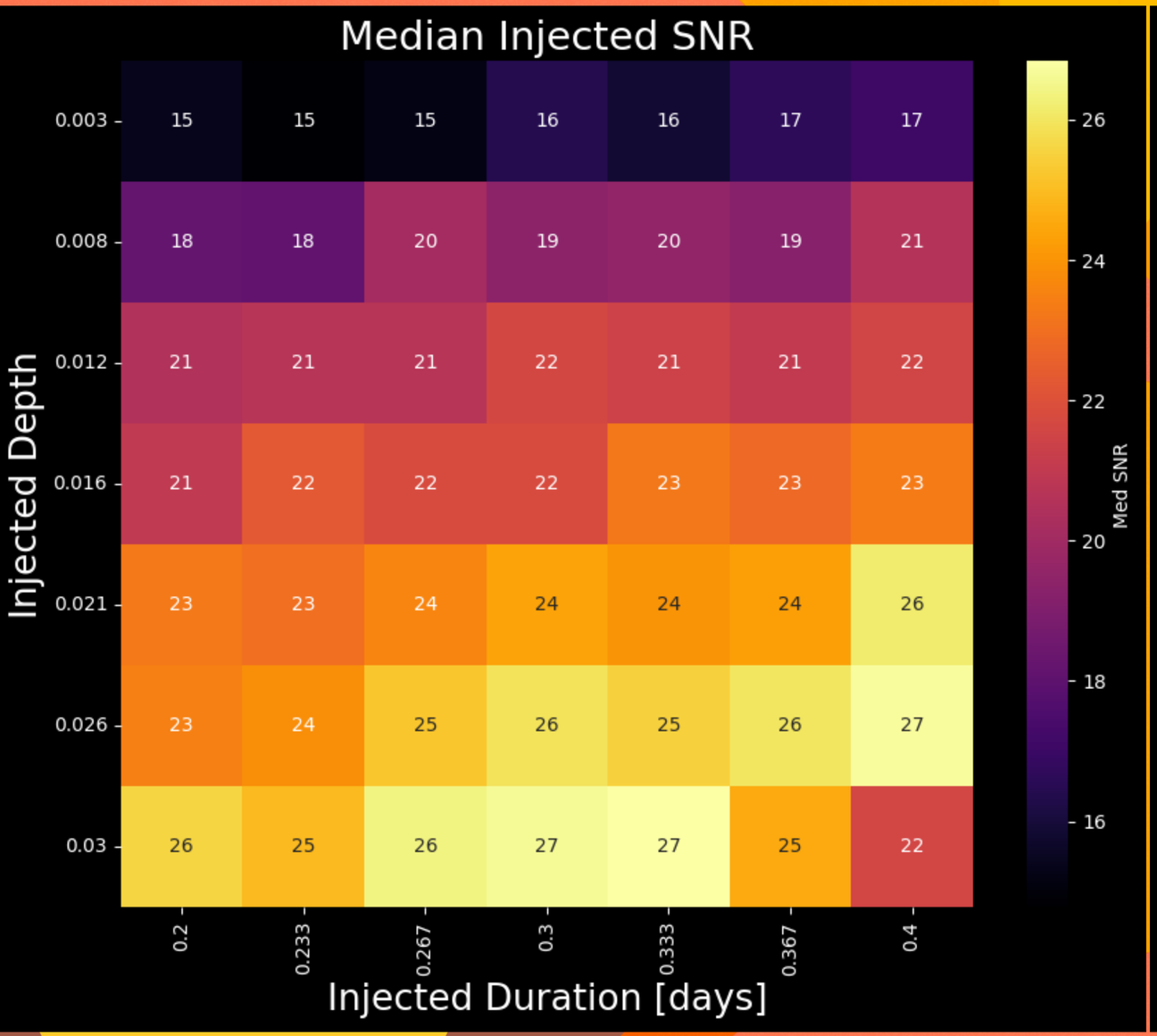
Some examples

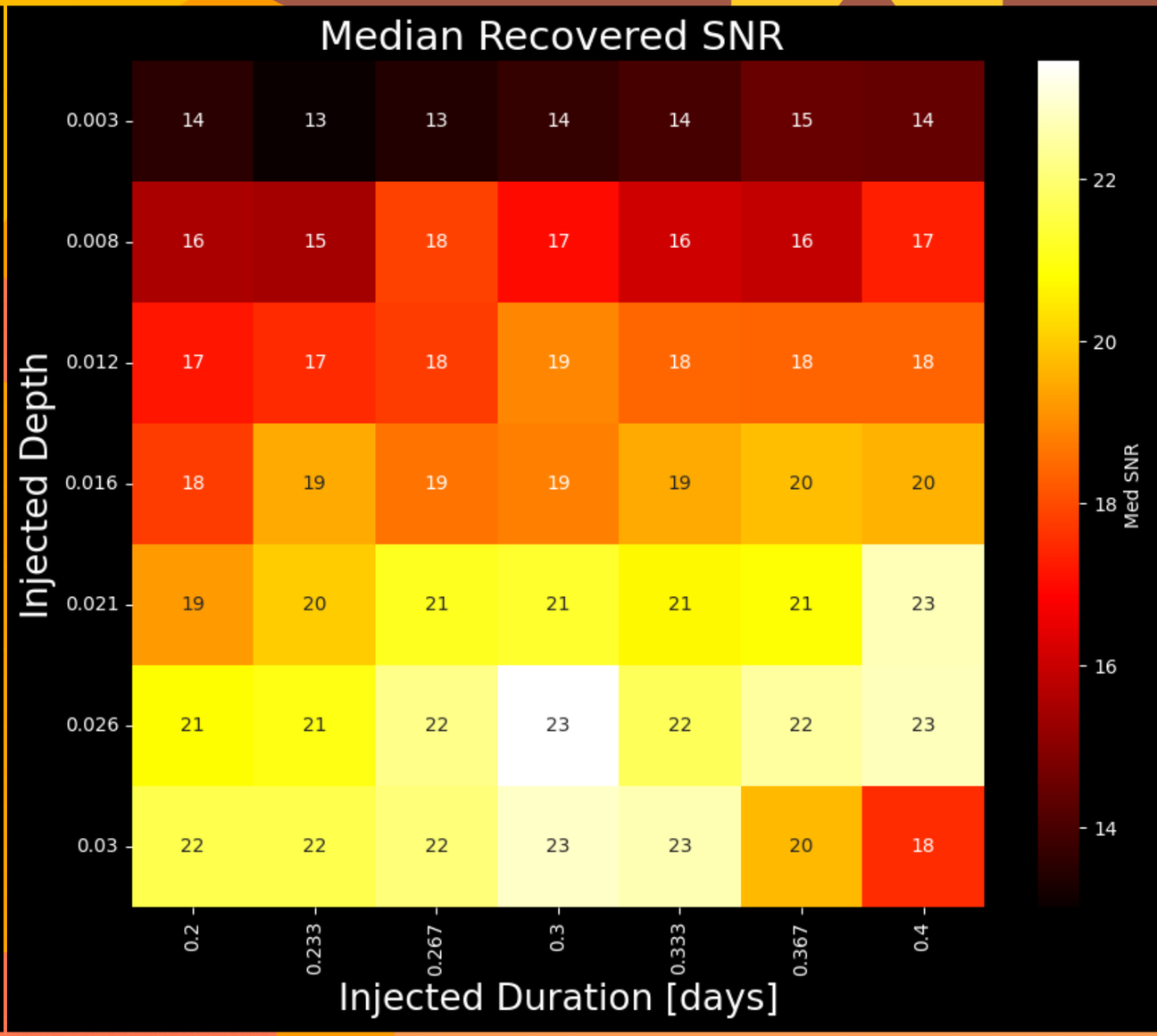


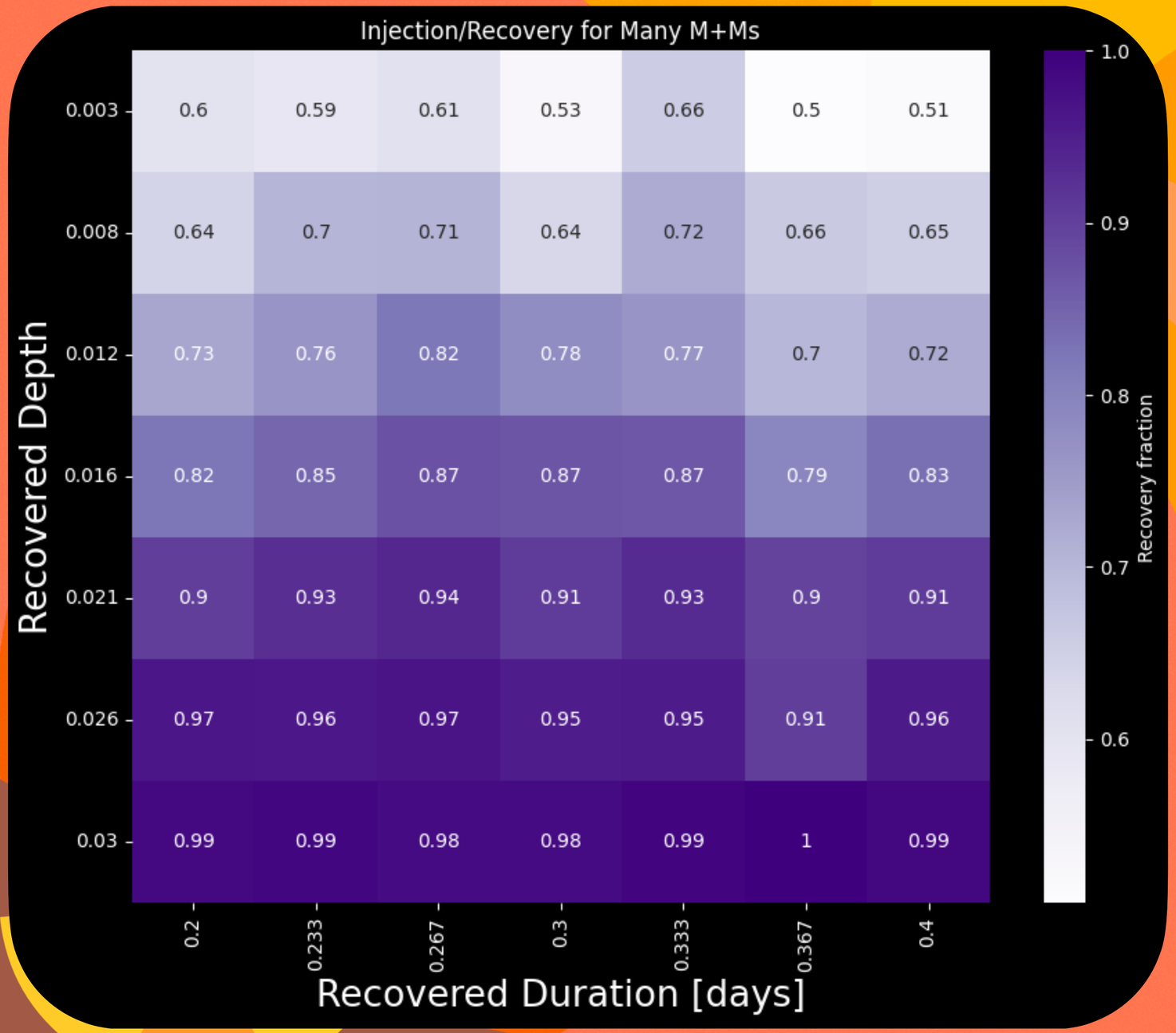
Injection & recovery testing

How sensitive are we to planets?

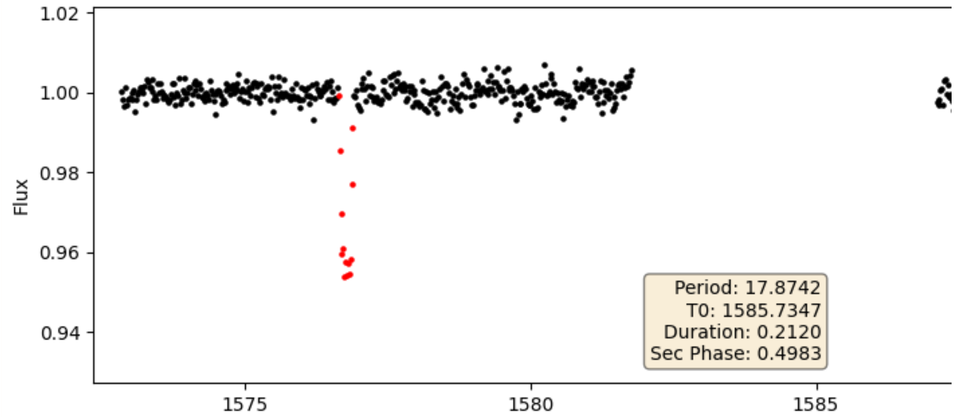


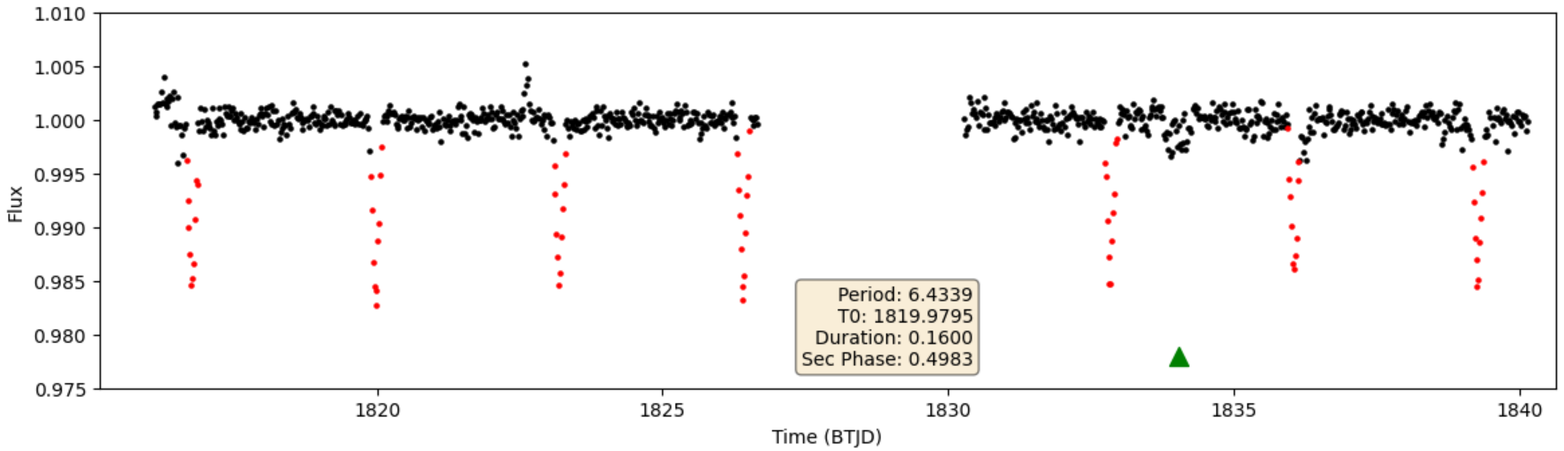

Median Injected SNR
Injected Depth
0.003
0.008
0.012
0.016
0.021
0.026
0.03
15 15 15 16 16 17 17
18 18 20 19 20 19 21
21 21 21 22 21 21 22
21 22 22 22 23 23 23
23 23 24 24 24 24 26
23 24 25 26 25 26 27
26 25 26 27 27 25 22
0.2
0.233
0.267
0.3
0.333
0.367
0.4
Injected Duration [days]
Med SNR
26
24
22
20
18
16

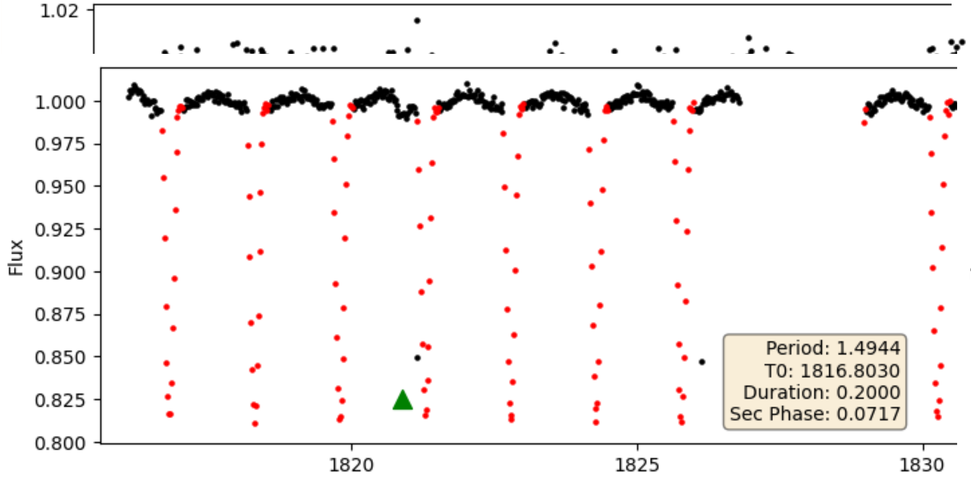

Median Recovered SNR
Injected Depth
0.003
0.008
0.012
0.016
0.021
0.026
0.03
14 13 13 14 14 15 14
16 15 18 17 16 16 17
17 17 18 19 18 18 18
18 19 19 19 19 20 20
19 20 21 21 21 21 23
21 21 22 23 22 22 23
22 22 22 23 23 20 18
0.2
0.233
0.267
0.3
0.333
0.367
0.4
Injected Duration [days]
Med SNR
22
20
18
16
14

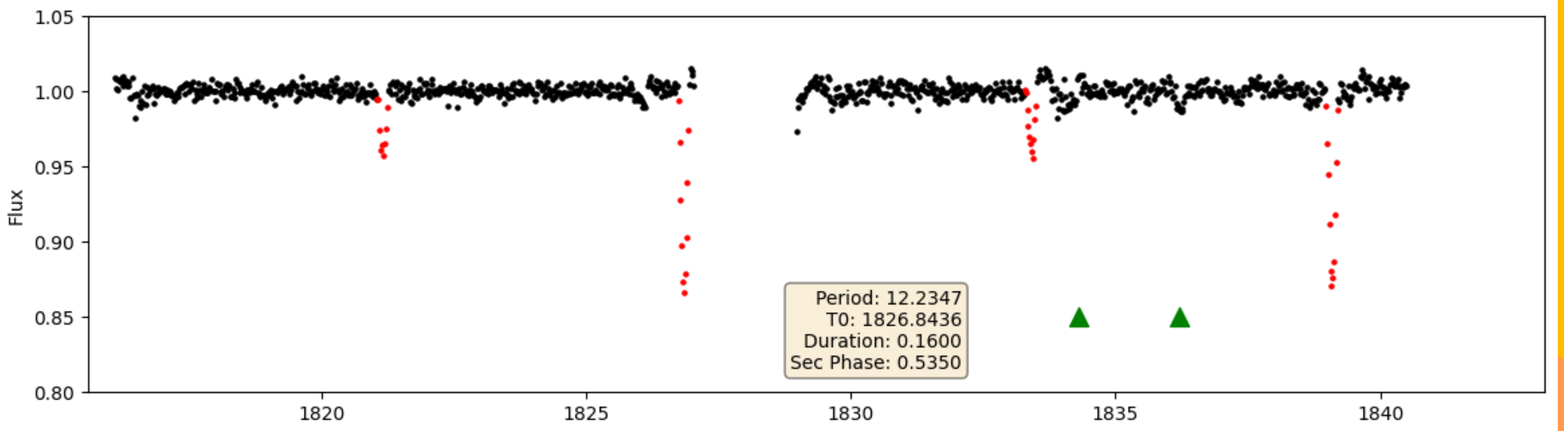


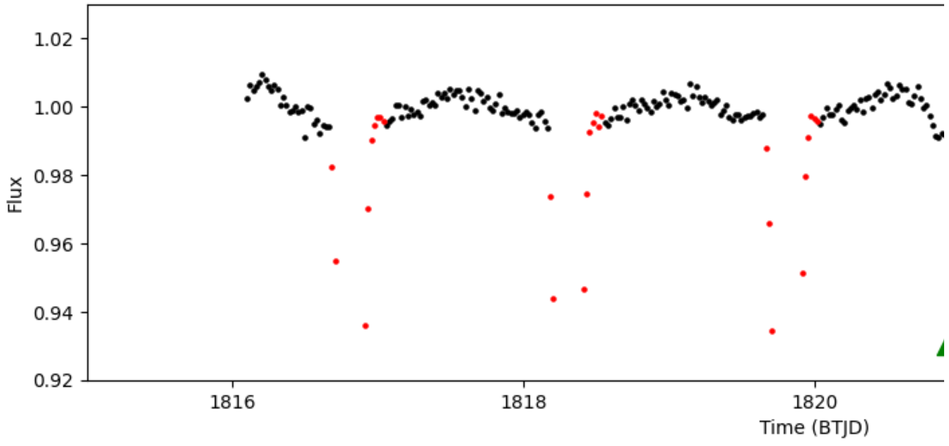
What do the differences between injected and recovered transit properties tell us about our pipeline?

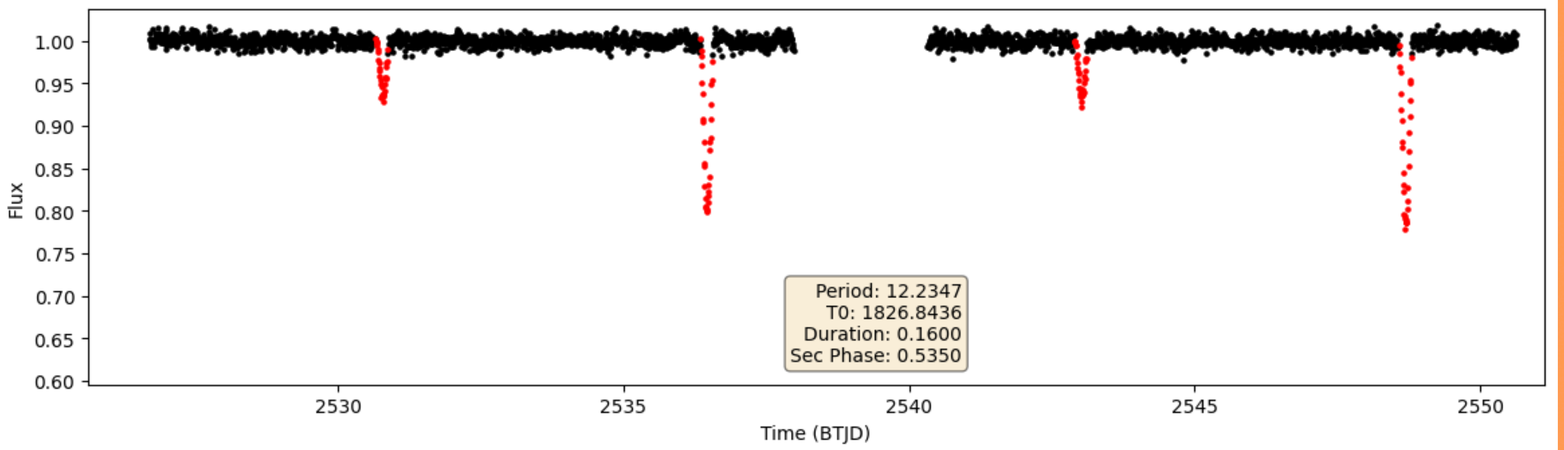

Flux
Period: 17.8742
T0: 1585.7347
Duration: 0.2120
Sec Phase: 0.4983


Flux
Period: 6.4339
T0: 1819.9795
Duration: 0.1600
Sec Phase: 0.4983
Time (BTJD)

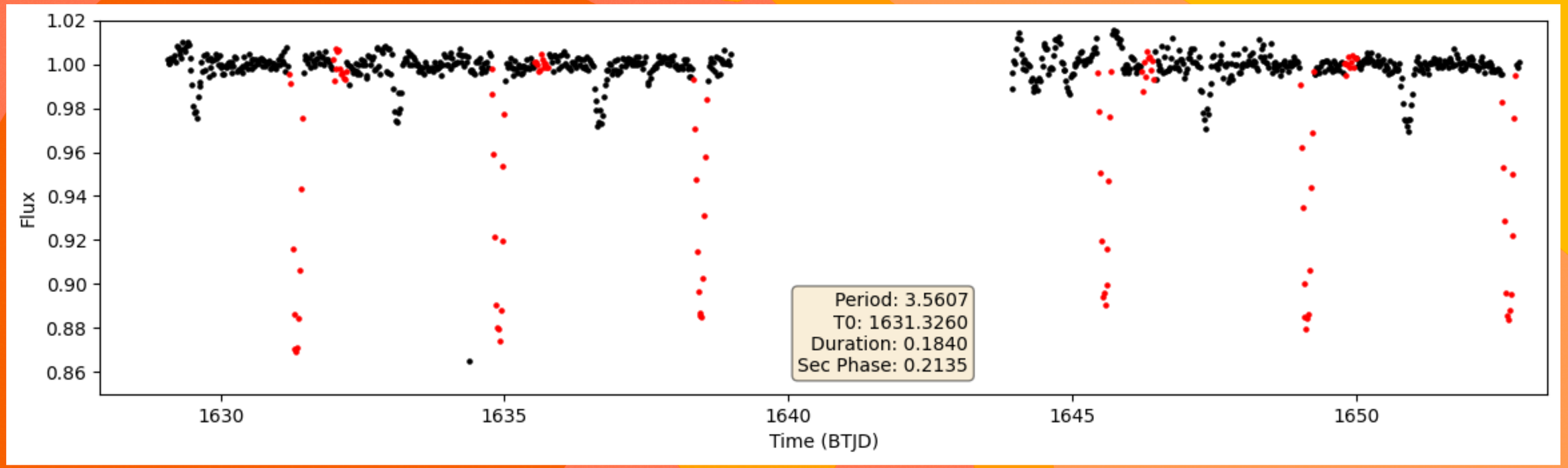

Flux
Period: 1.4944
T0: 1816.8030
Duration: 0.2000
Sec Phase: 0.0717


Flux
Period: 12.2347
T0: 1826.8436
Duration: 0.1600
Sec Phase: 0.5350


Flux
Time (BTJD)


Flux
Period: 12.2347
T0: 1826.8436
Duration: 0.1600
Sec Phase: 0.5350
Time (BTJD)

And some…blends?



Next natural step is to check other extractions and on-targeted-ness!

Peace Out

Wrap up & Summary

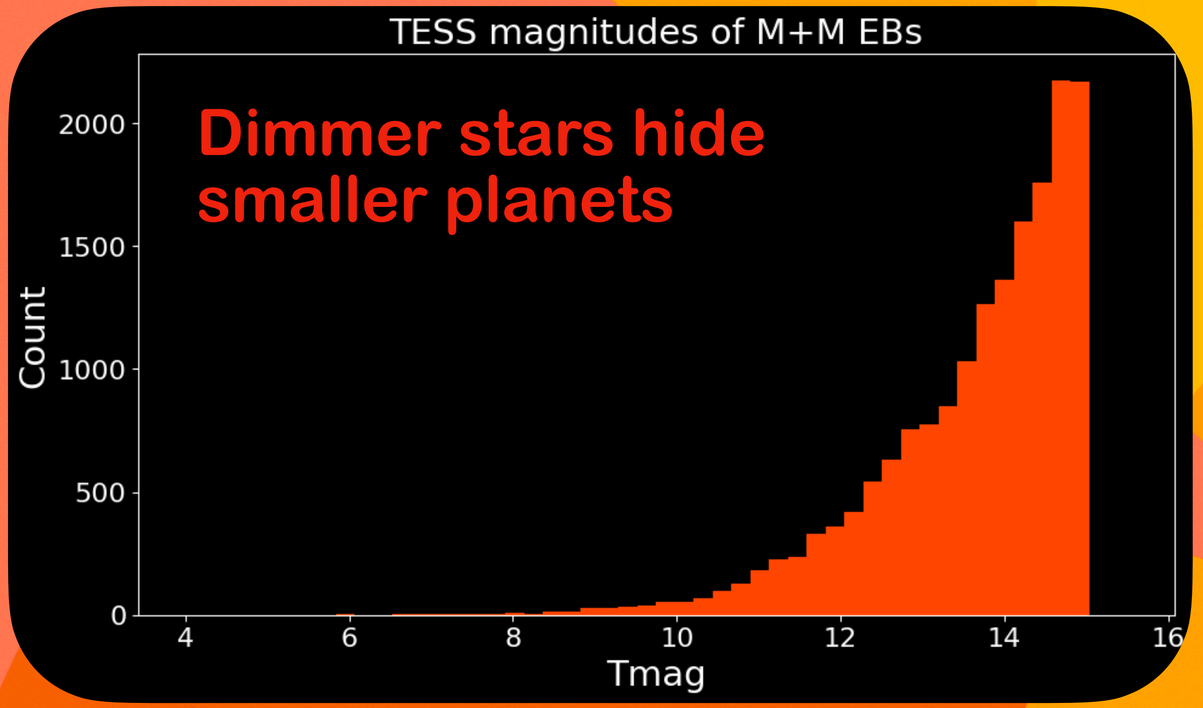
- CBPs provide rich grounds to examine planet formation in tight stellar binary systems
- TESS provides new opportunities by vastly expanding the EB sample - itself a rich science case - and opens the door to low-mass binary CBP science
- Finding transiting CBPs remains challenging, but TESS provides a fair shot
- I have been searching for transiting CBPs and will soon publish results from that search

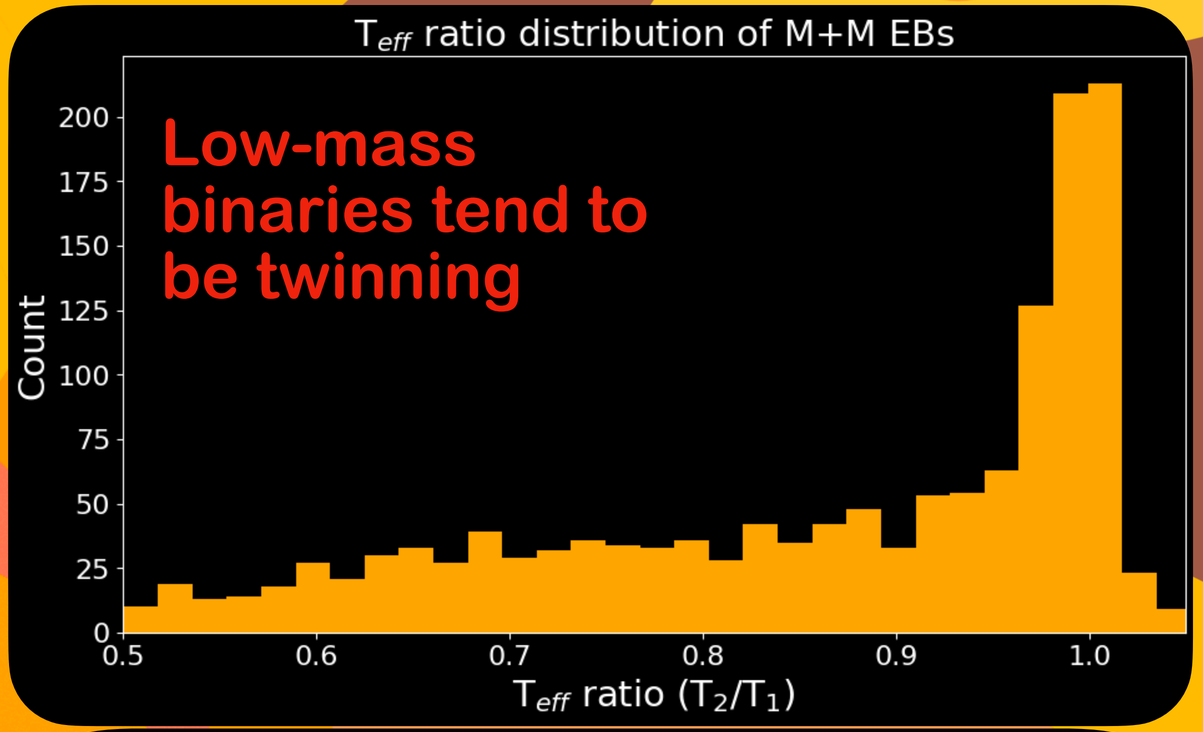
Supported by

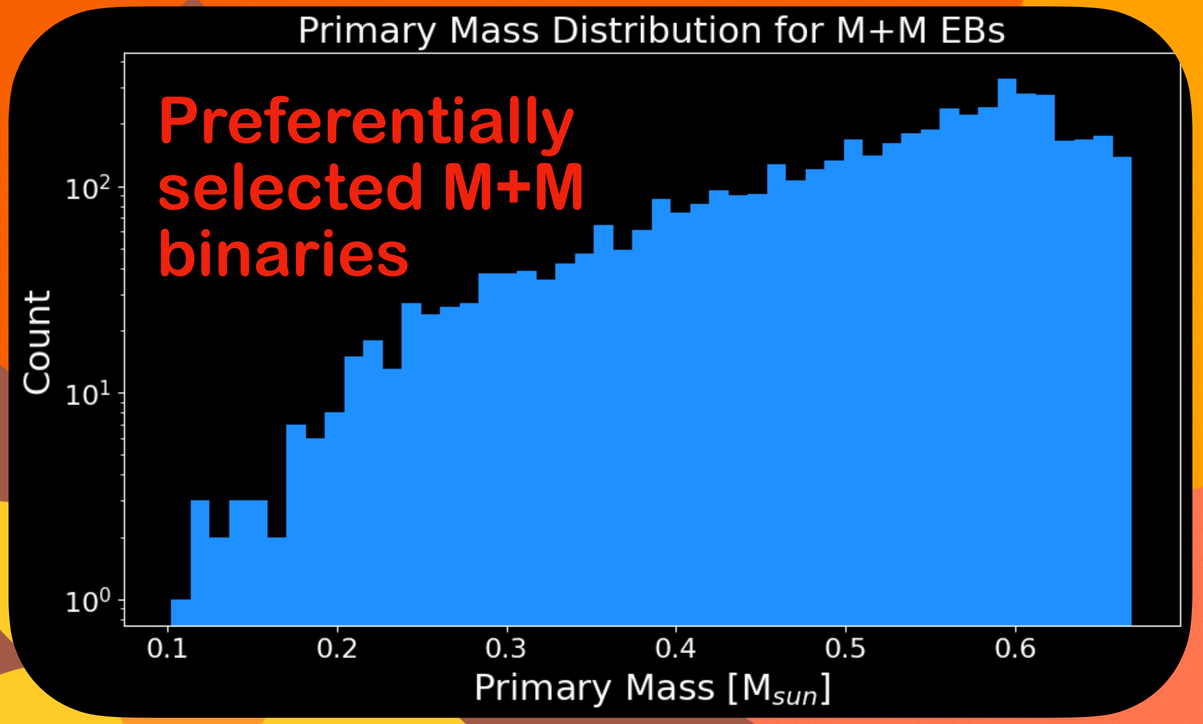
FINESST

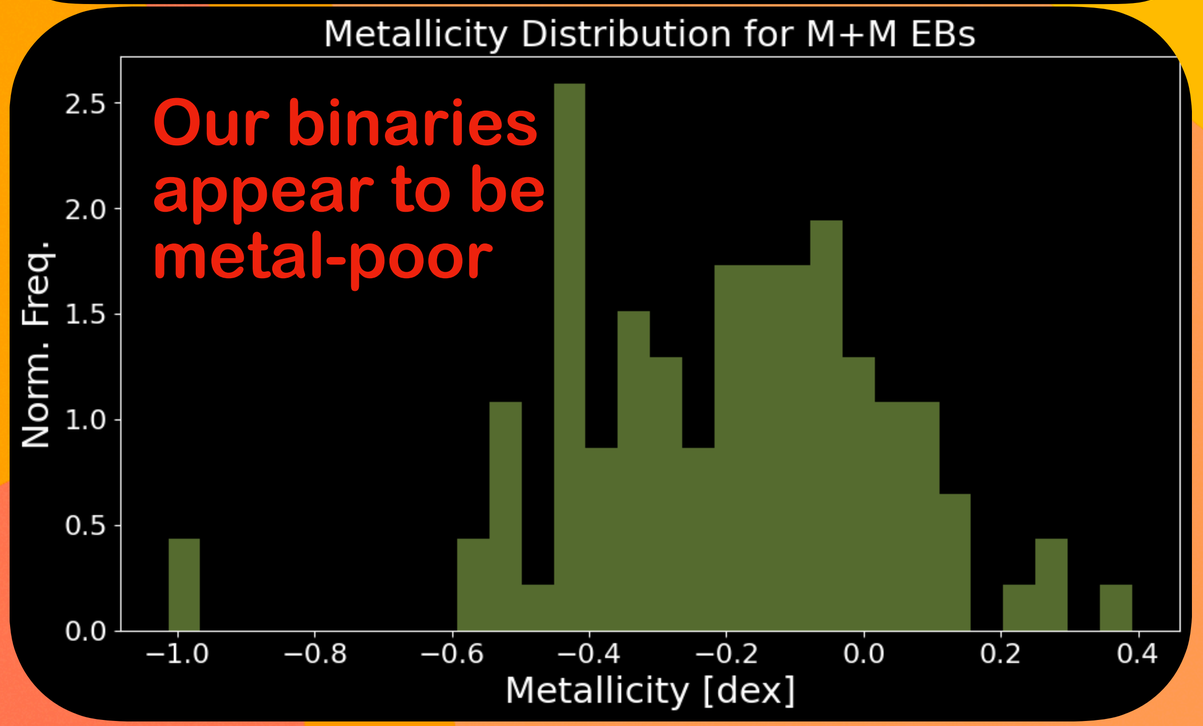
CENTER FOR ADVANCED RESEARCH COMPUTING

This project is supported by the UNM Office of the Vice President for Research


TESS magnitudes of M+M EBs
Dimmer stars hide smaller planets
Count
Tmag
0
500
1000
1500
2000
4
6
8
10
12
14
16

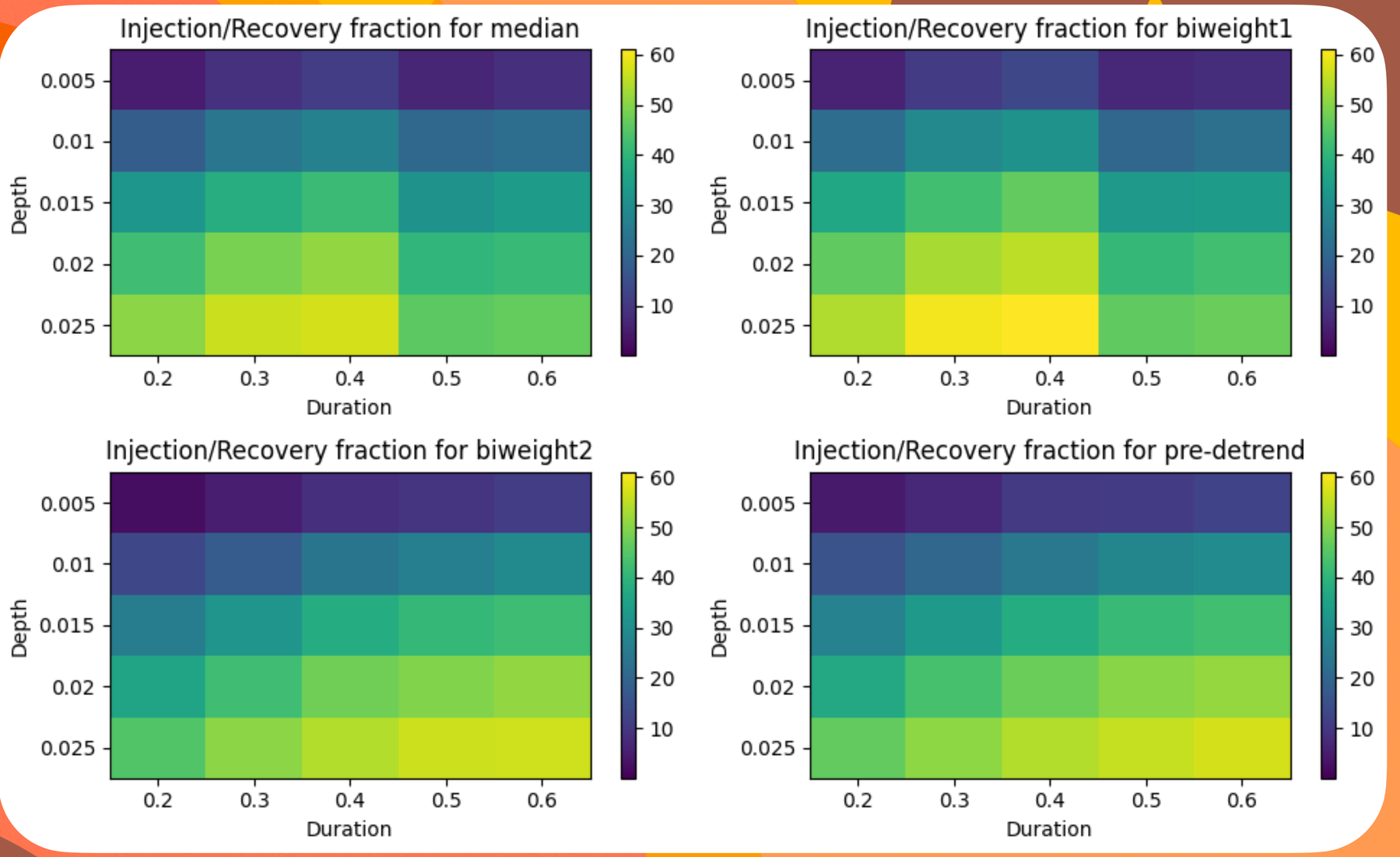

T_{eff} ratio distribution of M+M EBs
Low-mass binaries tend to be twinning
Count
T_{eff} ratio (T_2/T_1)
0
25
50
75
100
125
150
175
200
0.5
0.6
0.7
0.8
0.9
1.0


Primary Mass Distribution for M+M EBs
Preferentially selected M+M binaries
Count
Primary Mass [M_{sun}]
10^0
10^1
10^2
0.1
0.2
0.3
0.4
0.5
0.6


Metallicity Distribution for M+M EBs
Our binaries appear to be metal-poor
Norm. Freq.
Metallicity [dex]
0.0
0.5
1.0
1.5
2.0
2.5
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4

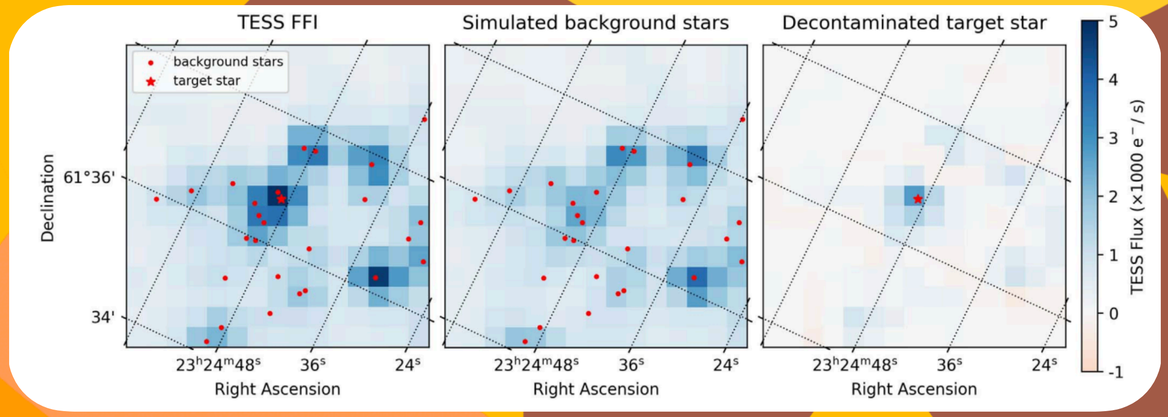
Detrending Binary Variability

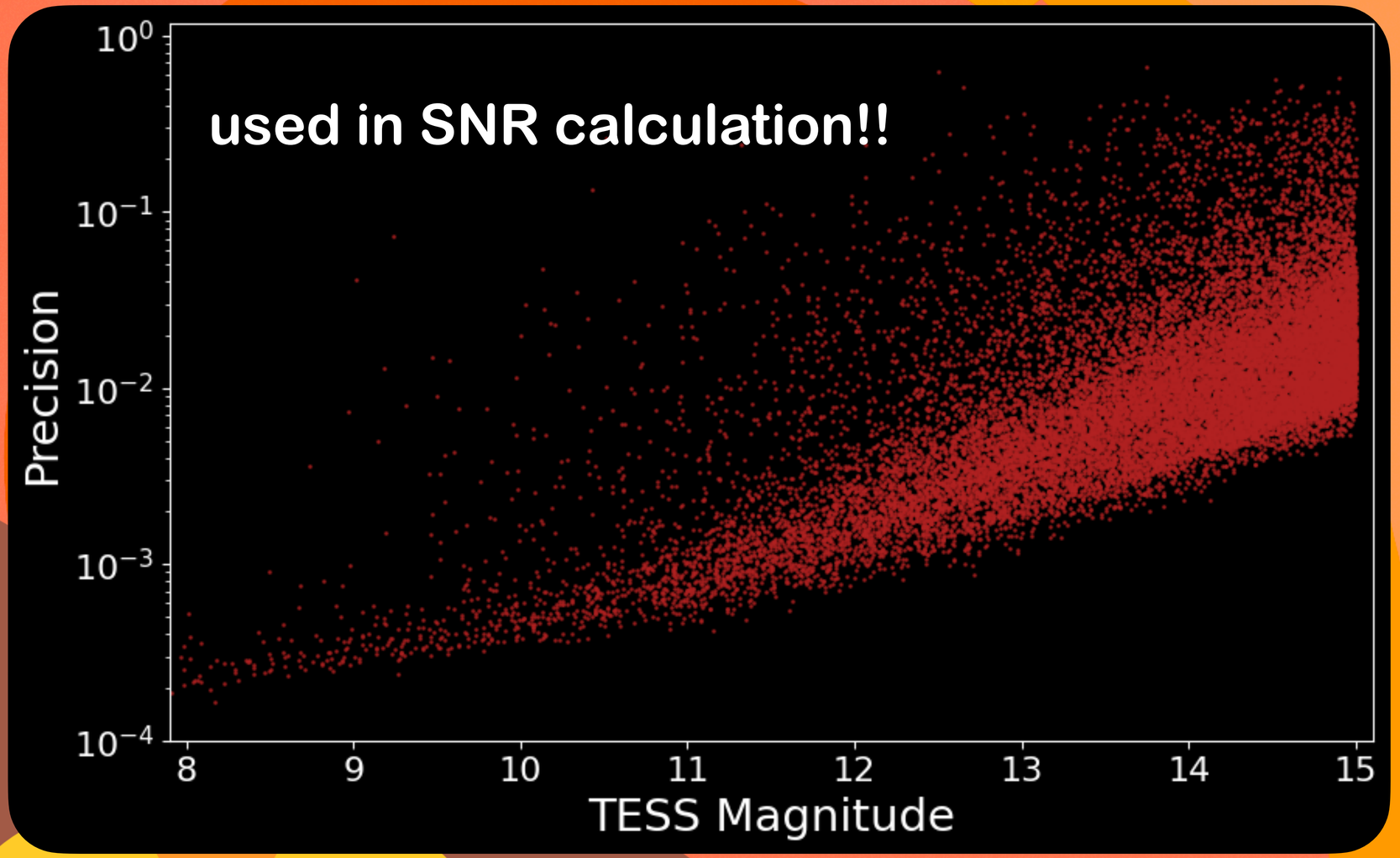
- Binary variability = cool binary physics
- Must balance between flattening variability and not erasing transits!
- Prescription should be scalable



TESS-Gaia Light Curve

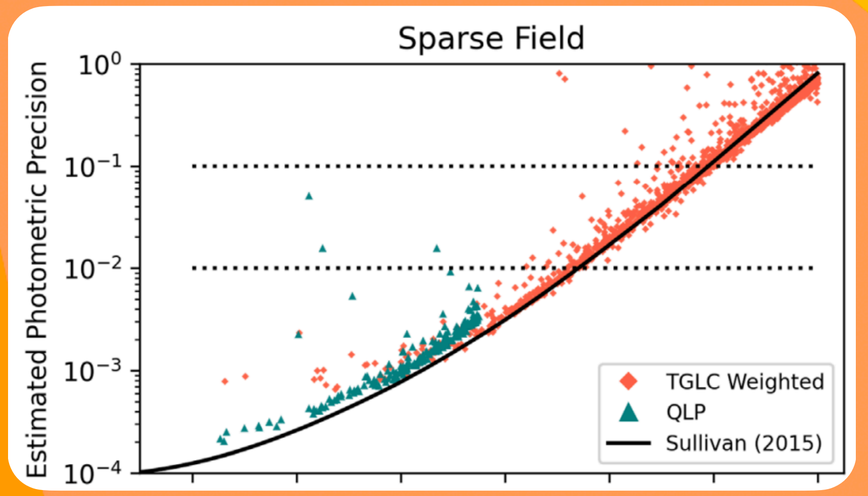
A new TESS LC extraction



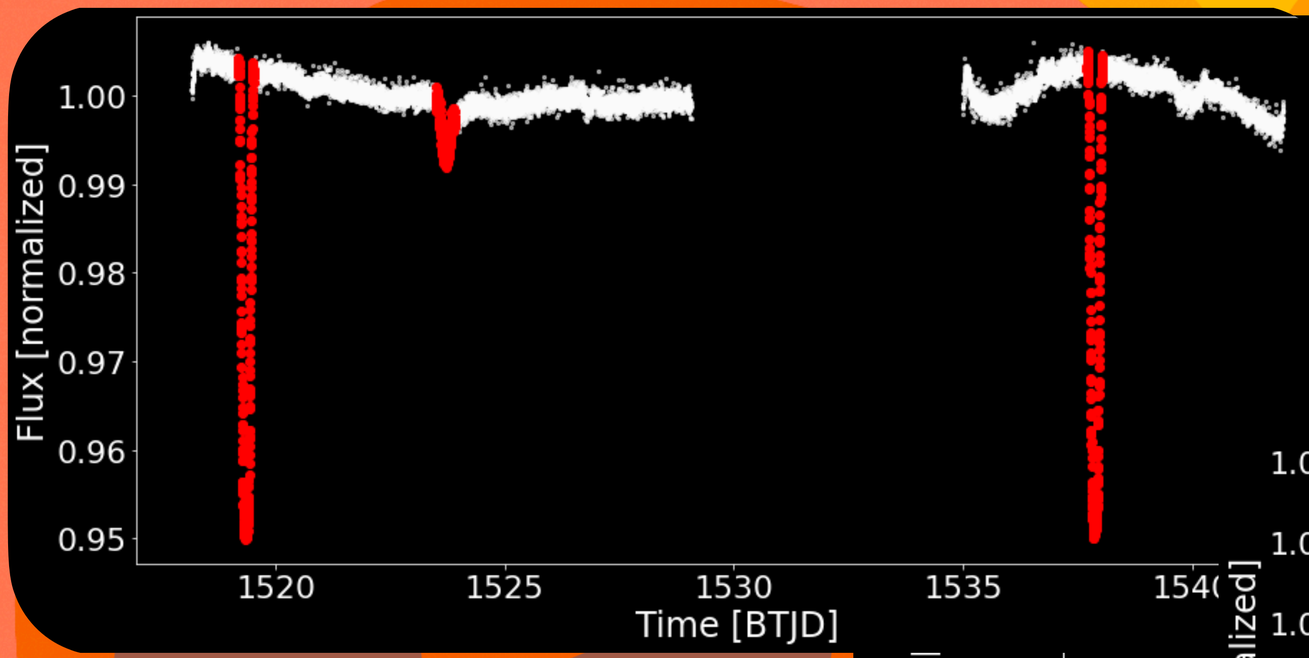


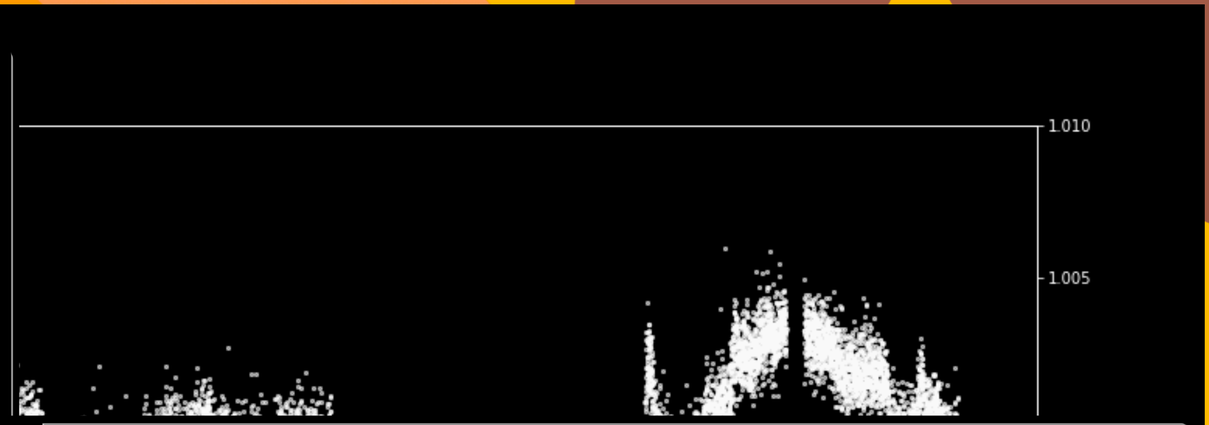
Compare to

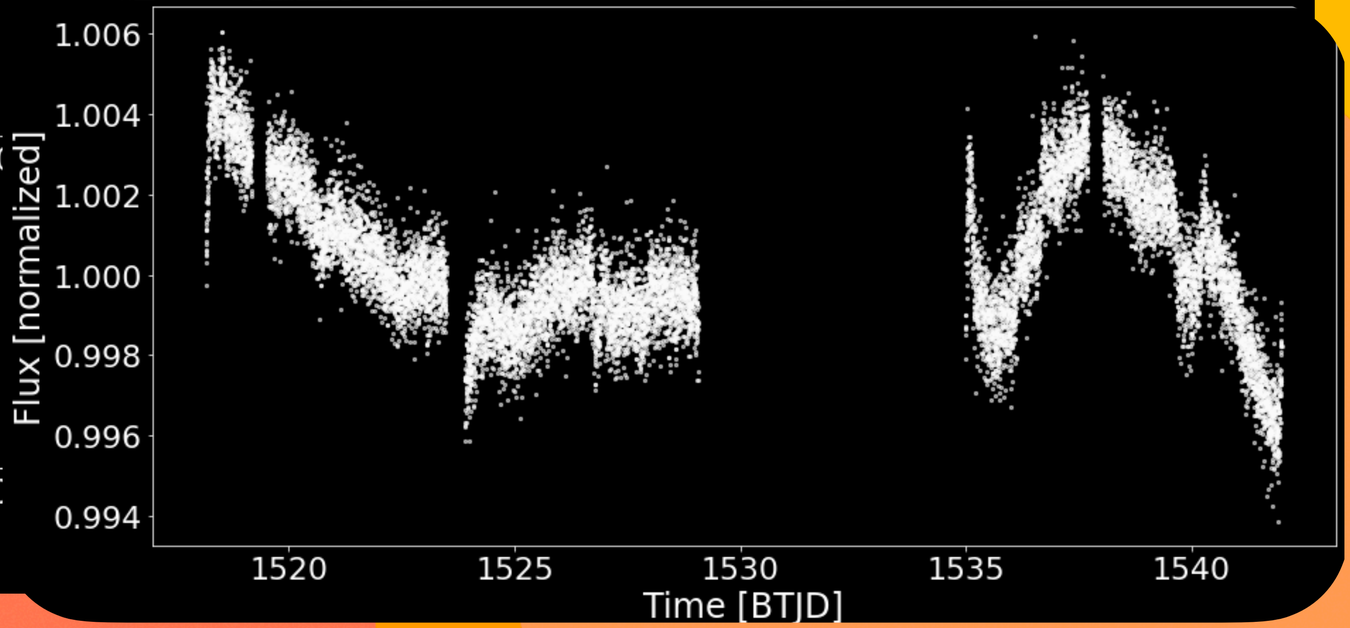
Figure 10 in Han & Brandt, 2023



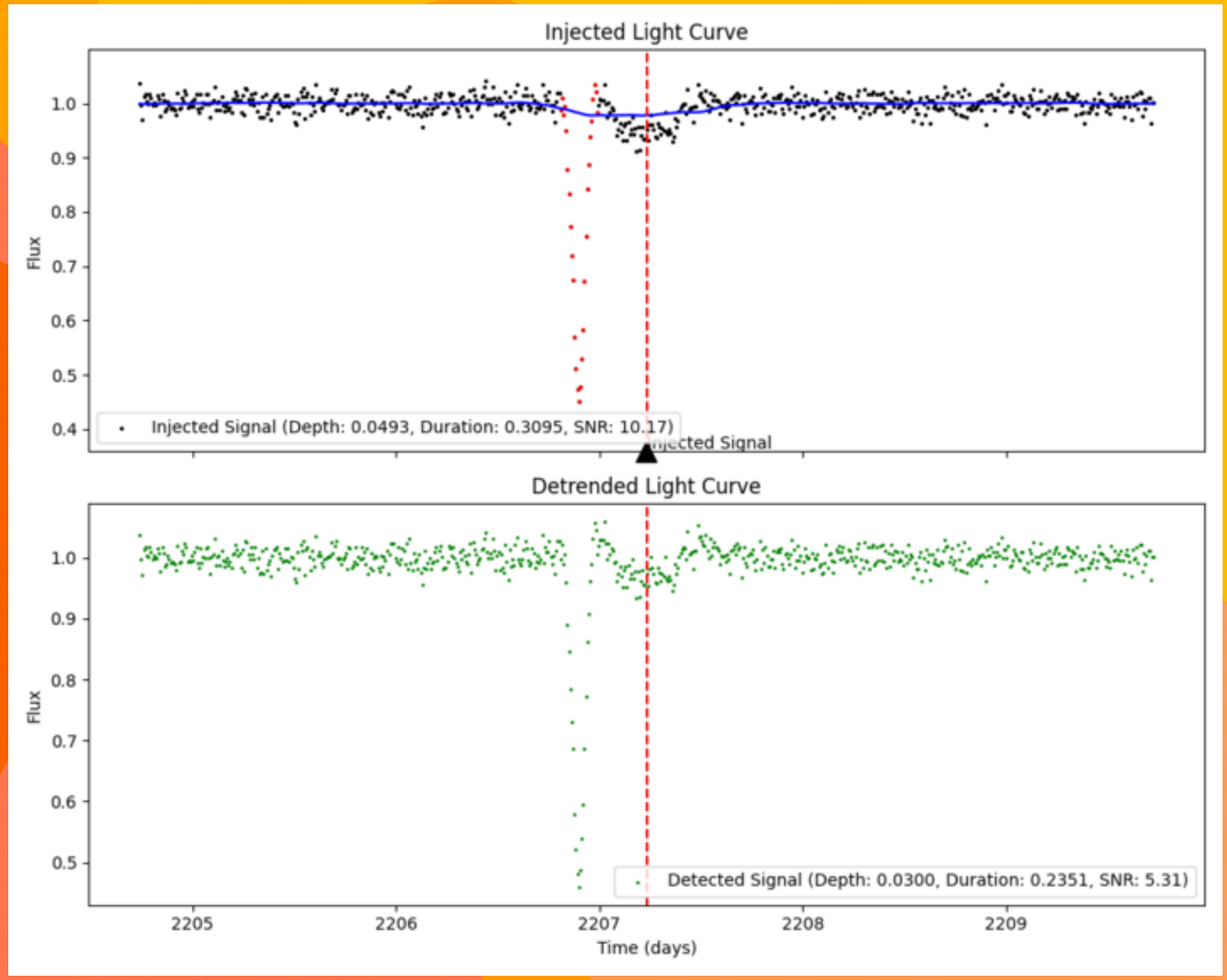
Finding Transits







How do transits get detrended out?

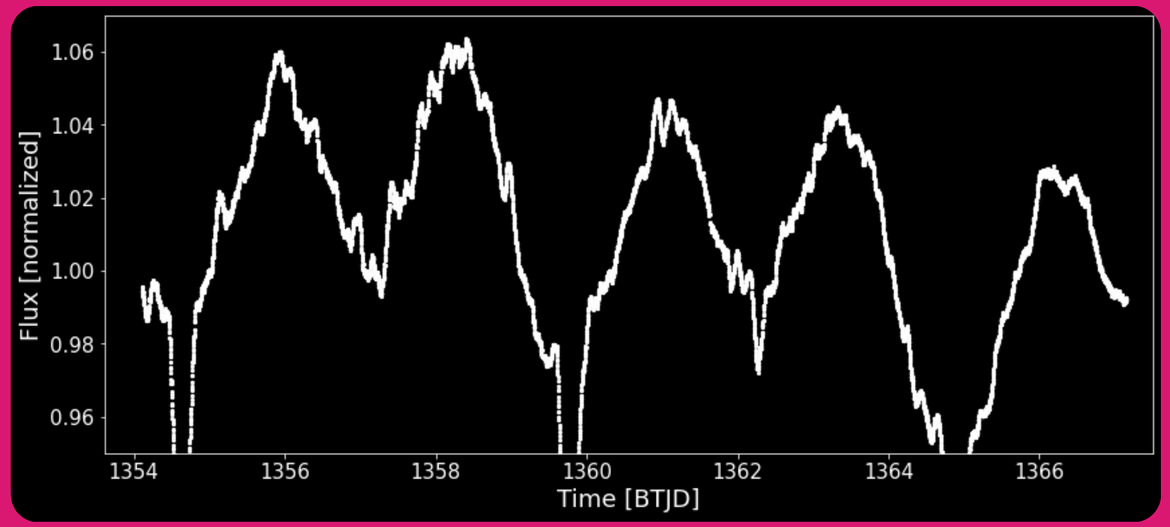


Finding CBPs is a Trip, Man

Challenges to finding transiting CBPs

Binaries

- Noisy/unruly EBs



- Short baselines for most EBs
  - Limits number of detectable transits

Planets

- Transit timing, depth, and duration variability
  - Requires individual event searches
- Dilution of transits
  - Difficult to find smaller planets!

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

Main FORCES Classes

LightCurveData

- Loads TGLC light curve
- Identifies and masks momentum dumps, scattered light, and other noisy points
- Masks eclipses based on binary ephemeris
- De-trends/flattens

BinaryEphemeris

- Calculates ephemeris
  - Ephemeris - eclipse times/depths/ durations, binary period
- Verifies ephemeris with eclipse counting, secondary location
- Legacy includes multiple eclipse identification codes/methods

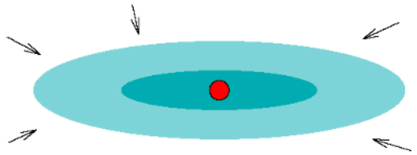
SNRSearch

- Fits for depth of trapezoidal transit shapes
- Calculates noise properties to set SNR threshold
- Checks transit shape
- Checks for periodicity

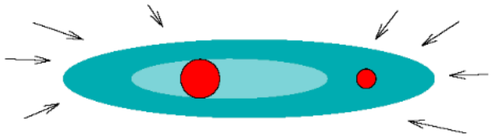
Tight Binary Formation

Leaving clues for observables

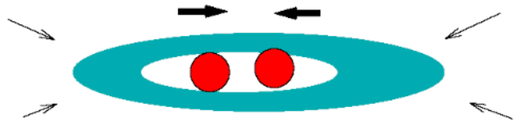
Disk instability



1. Primary component forms in over–density and grows



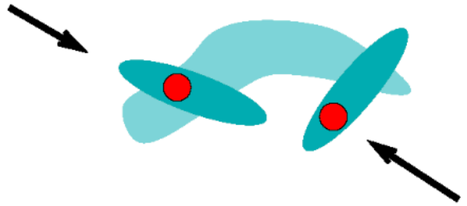
2. Accretion burst de–stabilizes the disk, secondary companion forms



3. Both stars grow and migrate inward

Core fragmentation

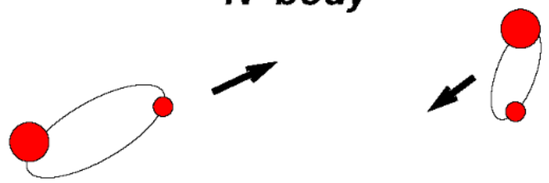
1. Two independent protostars



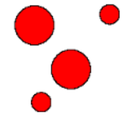
2. Approach and interaction

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.

What shrinks binary orbits?

Forming binaries on the shortest periods

- Tightest binaries form via Kozai-Lidov oscillations & tidal friction (KLOTF)
  - Due to influence from hierarchical triple system, which removes angular momentum from tight binary

- Effect on CBPs
  - Will cast CBPs to inclined and eccentric orbits, making them difficult to find

A triple origin for the lack of tight coplanar circumbinary planets around short-period binaries

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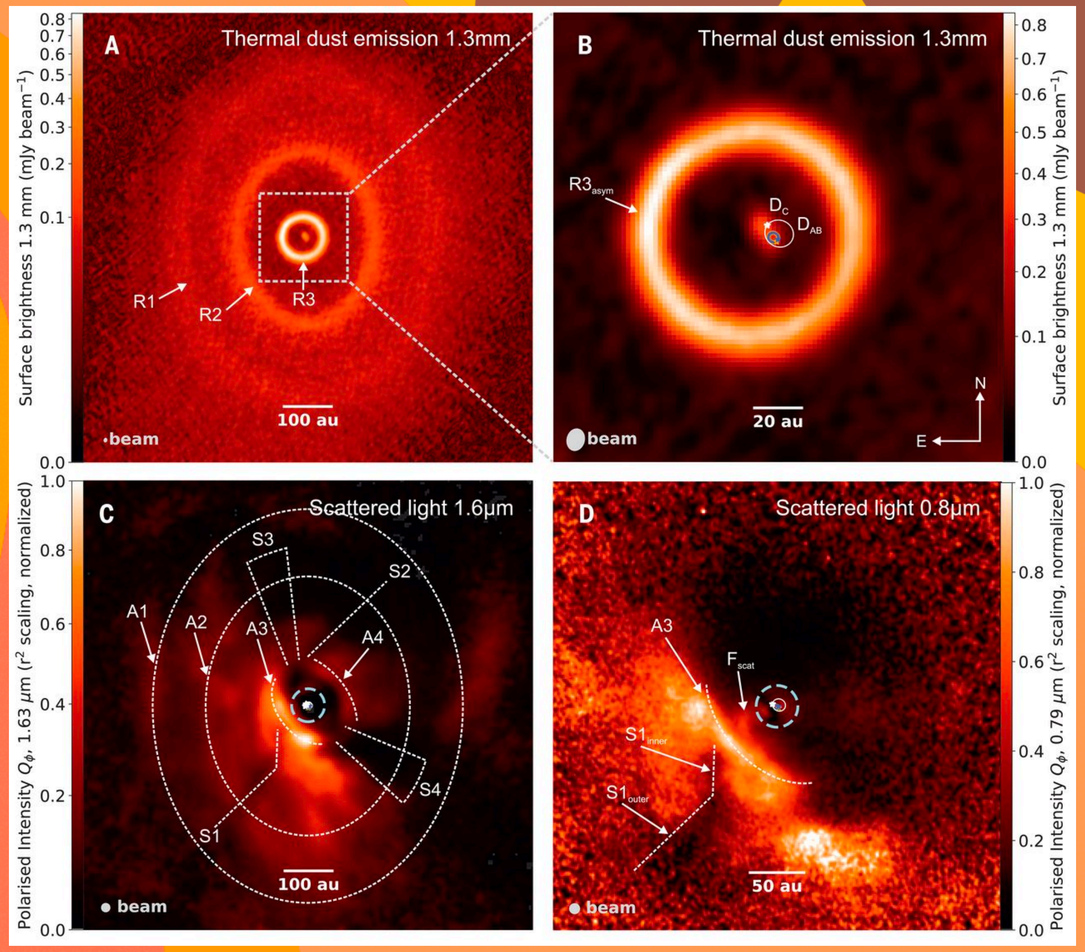
[2]*Technion - Israel Institute of Technology, Haifa 32000, Israel*



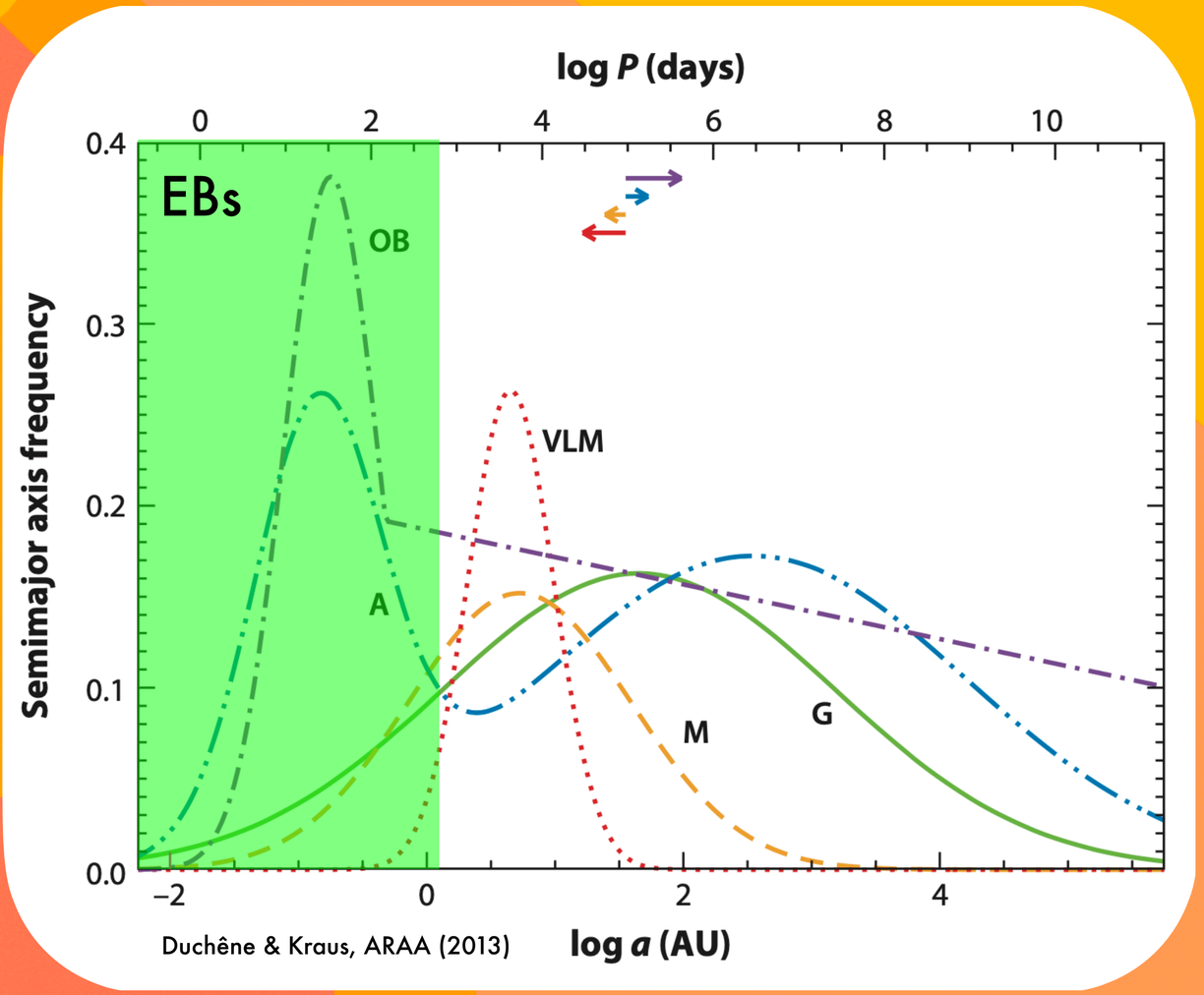
Kraus, S. et al., A triple-star system with a misaligned and warped circumstellar disk shaped by disk tearing. (2020).

Compare to binary populations

EBs sample a tail of the overall period distribution

Eclipse probability:

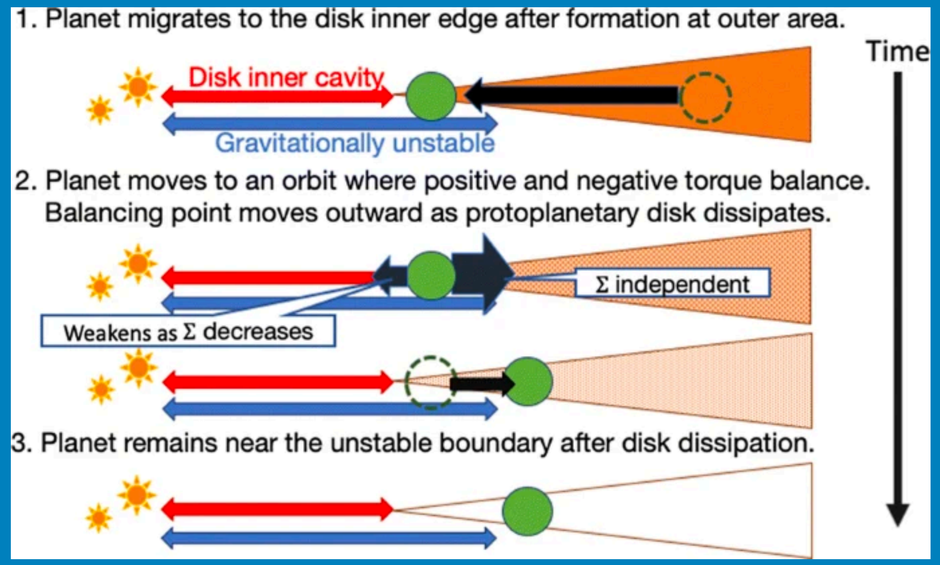
$$Prob \approx \frac{2R_*}{a}$$



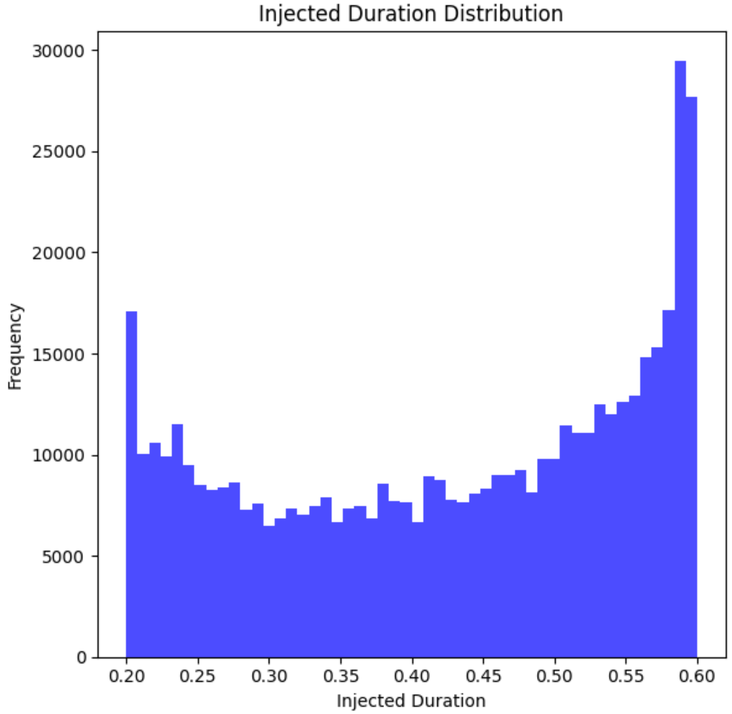
Forming CBPs

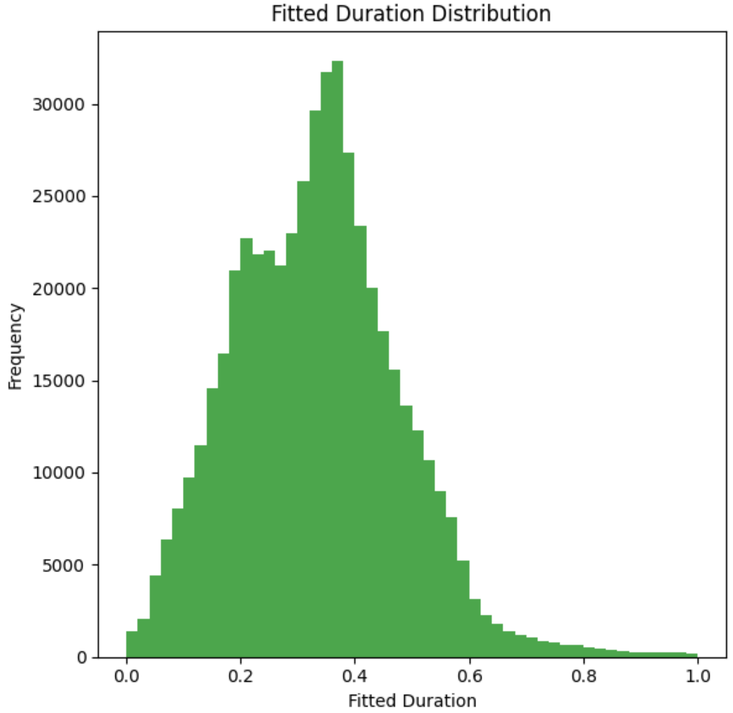
How DOES it work? —> migration!

- Things are more stable farther from the binary—> these regions look similar to single-star systems!
- This means that planets likely form farther out in the disk and then migrate inward
- Migration occurs as a result of torque imbalances, which serve to push the planet inwards



Yamanaka & Sasaki ((2019)


Injected Duration Distribution
Frequency
Injected Duration
0
5000
10000
15000
20000
25000
30000
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60


Fitted Duration Distribution
Frequency
Fitted Duration
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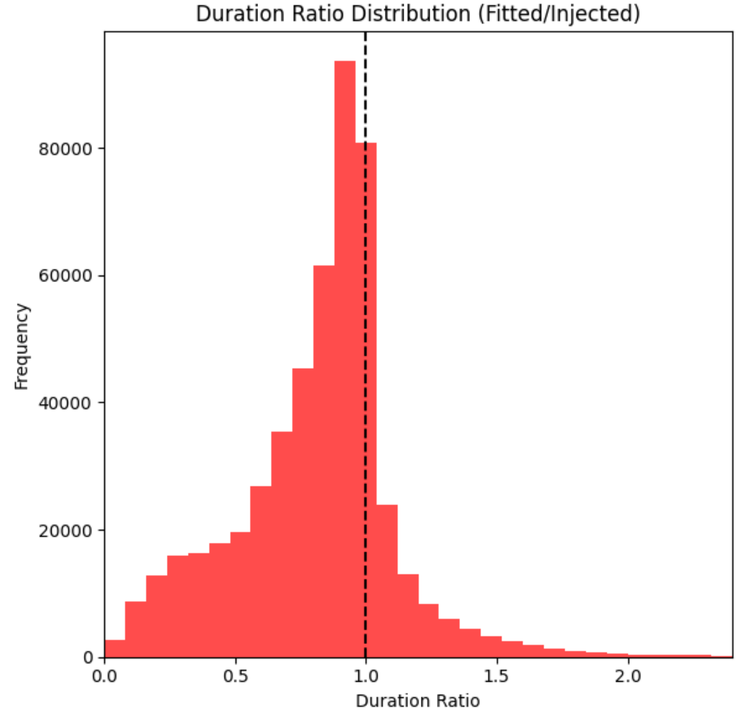
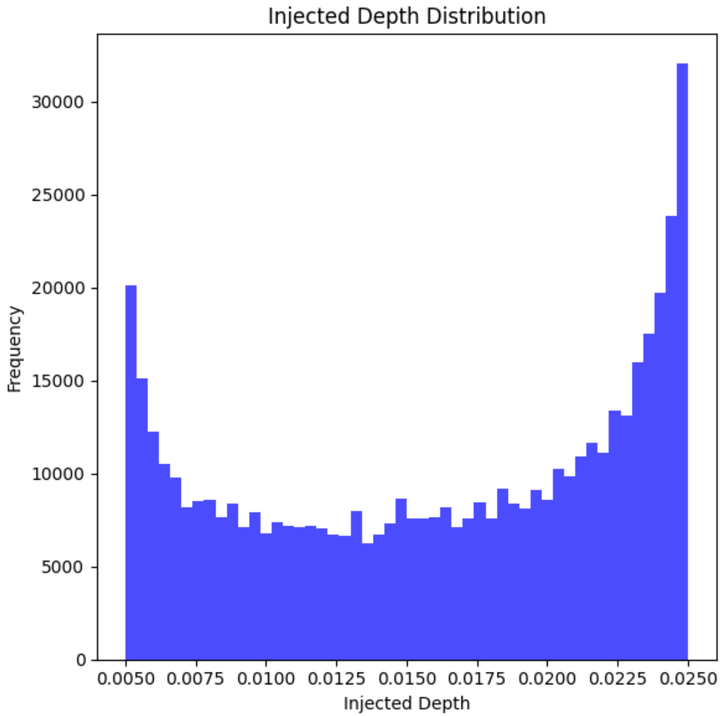
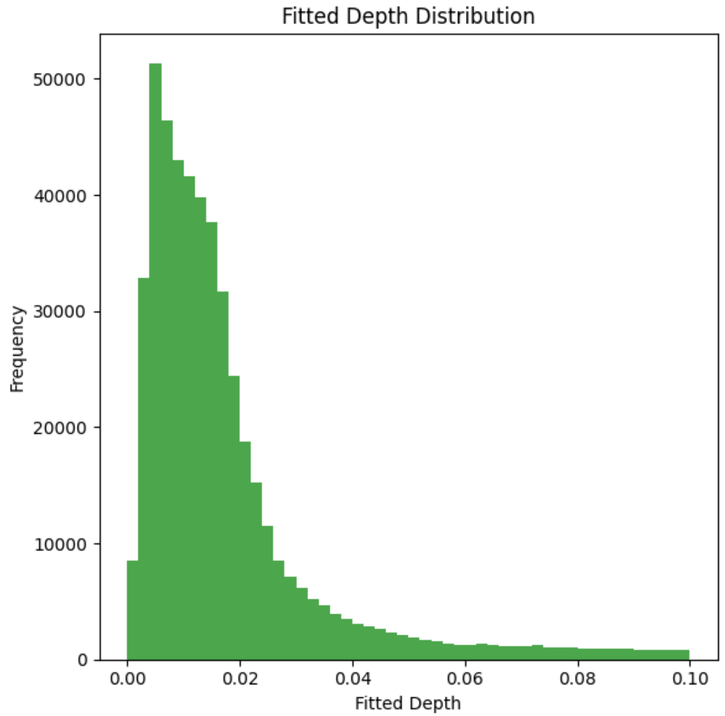
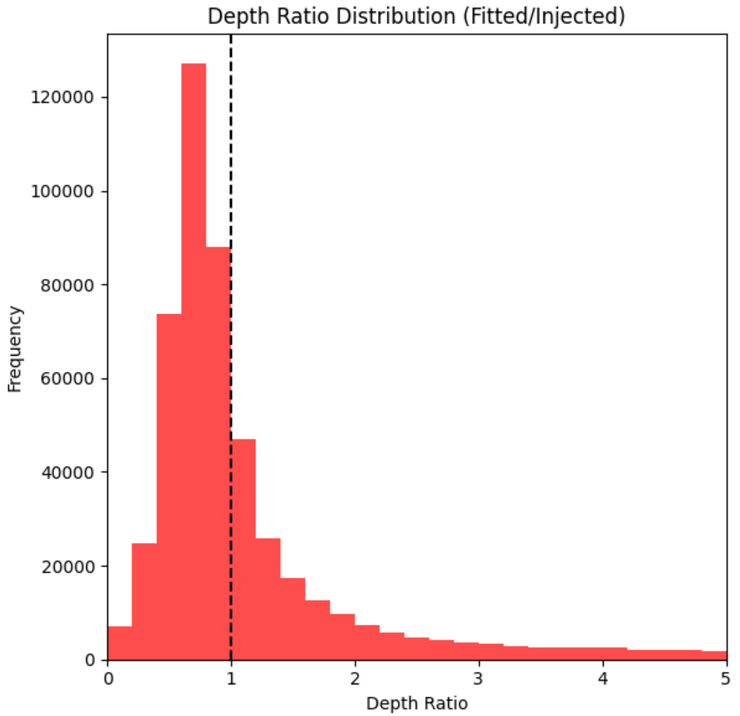
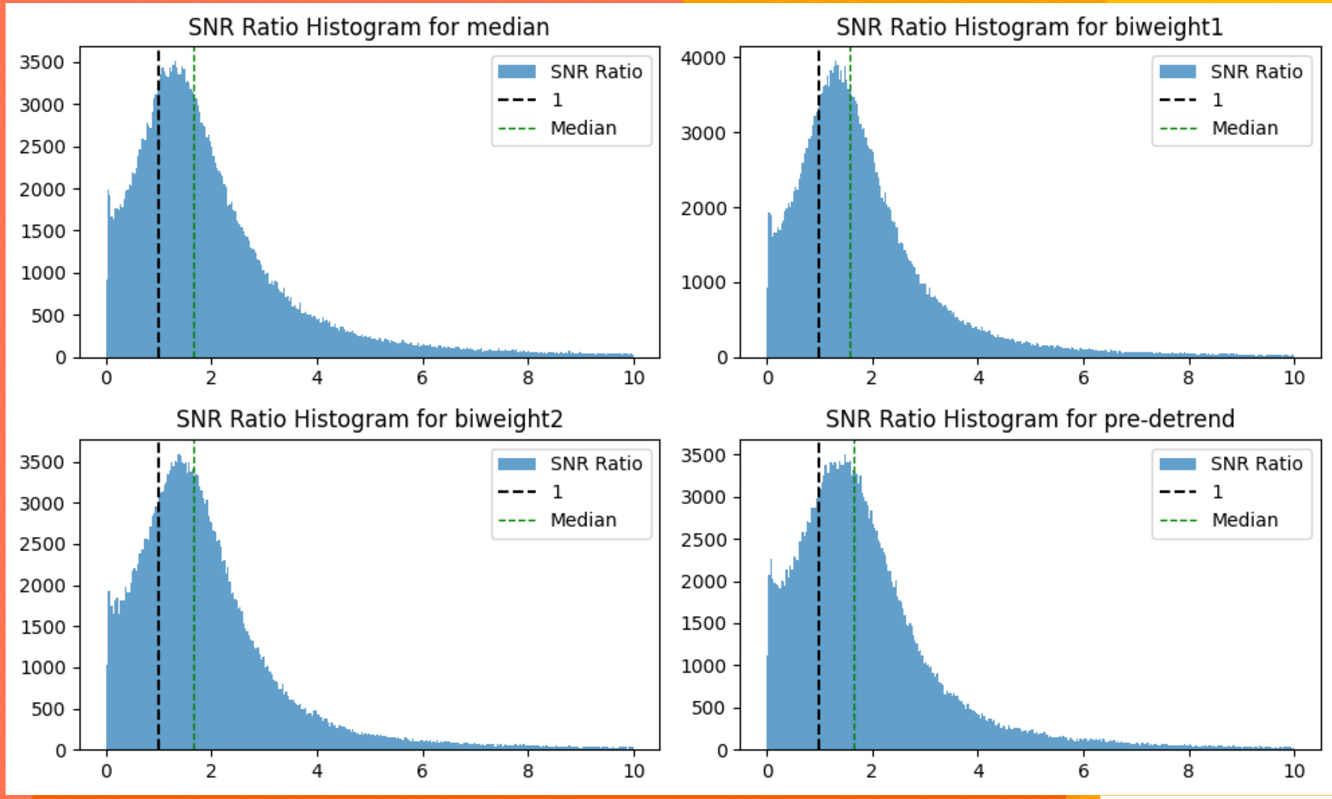
5000
10000
15000
20000
25000
30000
0.0
0.2
0.4
0.6
0.8
1.0

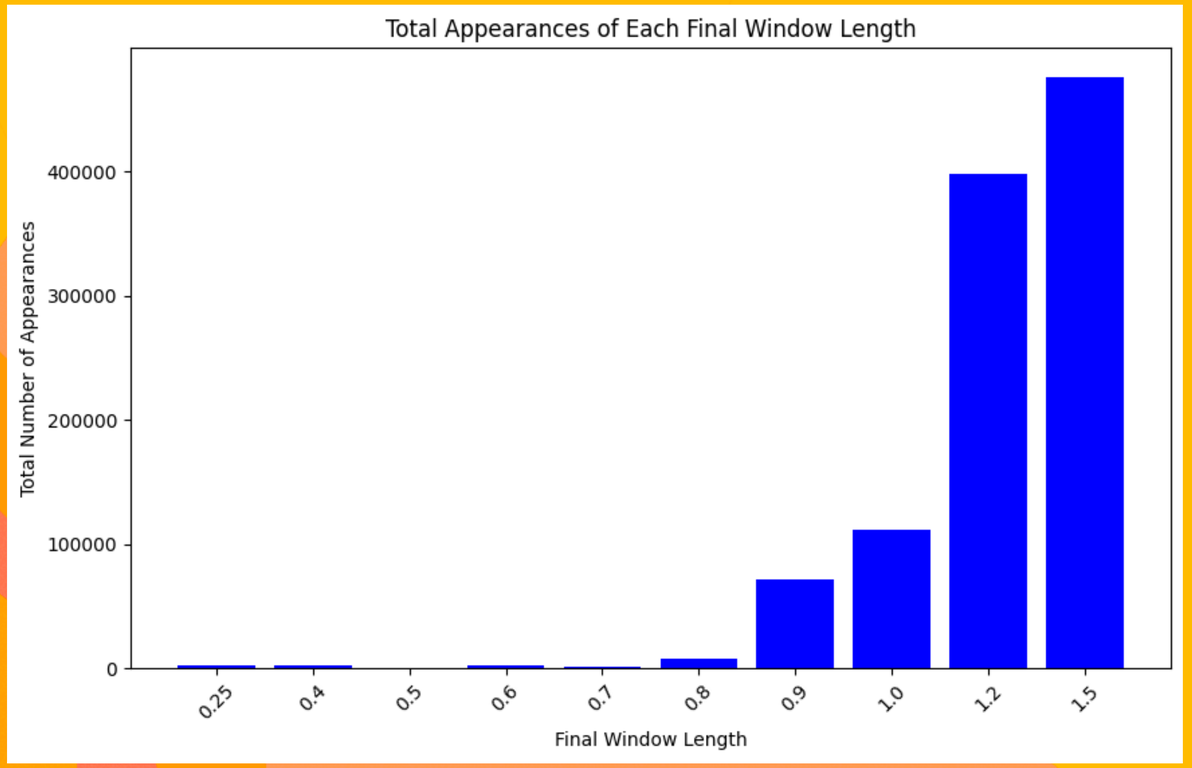

Duration Ratio Distribution (Fitted/Injected)
Frequency
Duration Ratio
0
20000
40000
60000
80000
0.0
0.5
1.0
1.5
2.0


Injected Depth Distribution
Frequency
Injected Depth
0
5000
10000
15000
20000
25000
30000
0.0050
0.0075
0.0100
0.0125
0.0150
0.0175
0.0200
0.0225
0.0250


Fitted Depth Distribution
Frequency
Fitted Depth
0
10000
20000
30000
40000
50000
0.00
0.02
0.04
0.06
0.08
0.10

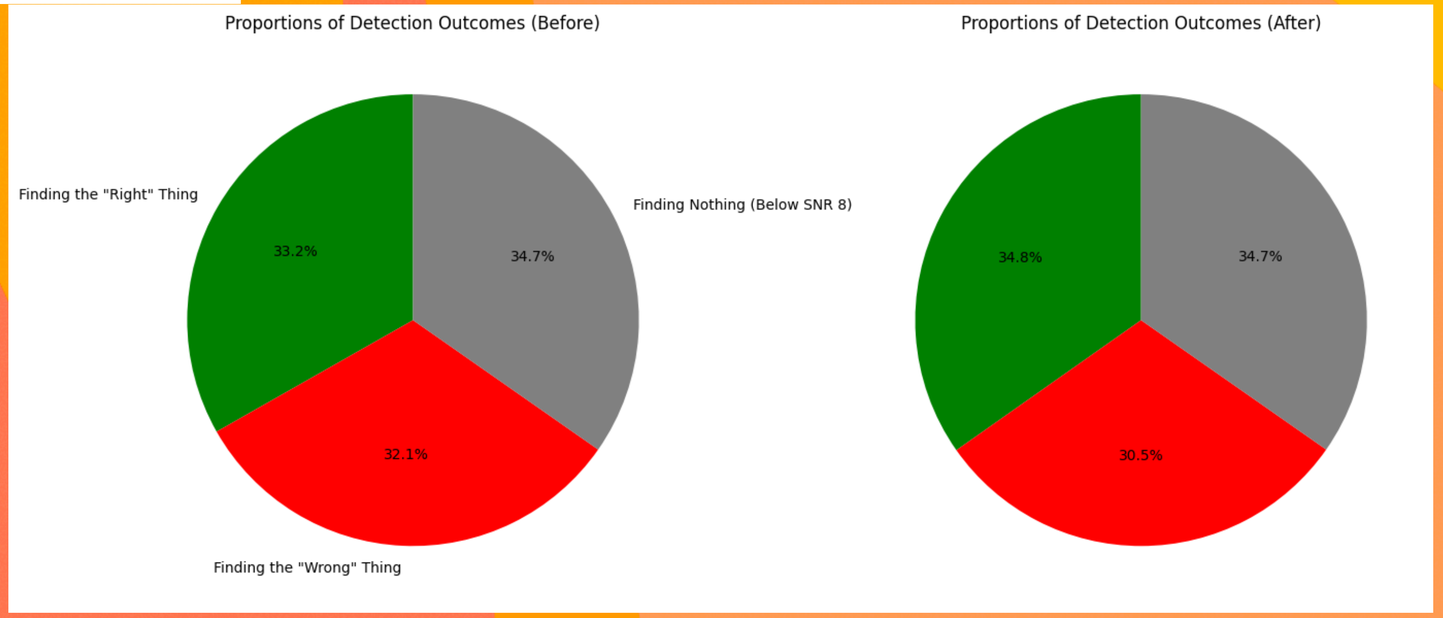

Depth Ratio Distribution (Fitted/Injected)
Frequency
Depth Ratio
0
20000
40000
60000
80000
100000
120000
0
1
2
3
4
5





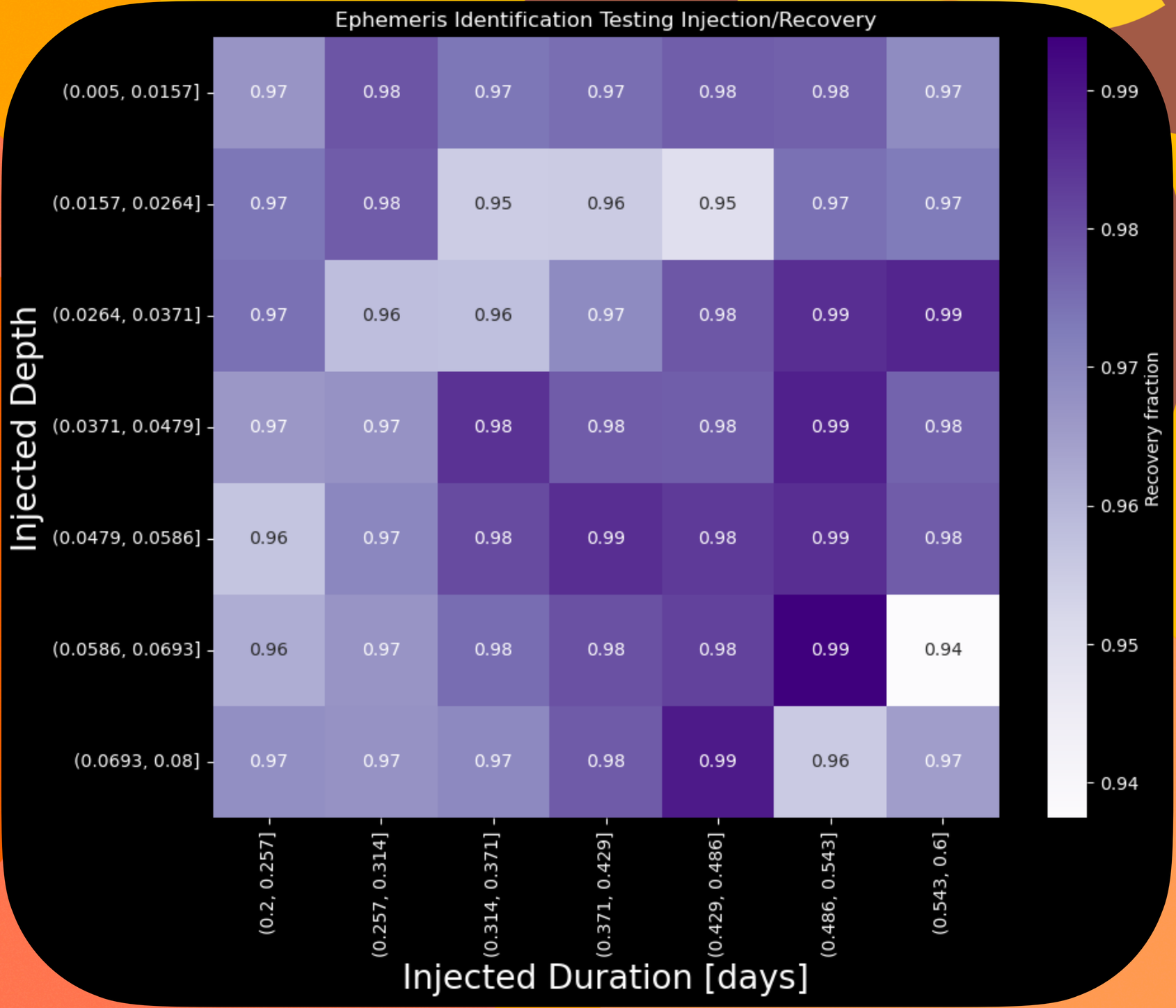
There are three cases here:

1. Finding the "right" thing here satisfies the logical conditions that the signal is above the threshold and is not detected as part of the binary ephemeris
2. Finding the "wrong" thing is when the signal is detected as part of the binary ephemeris
3. Finding "nothing" is when the signal is not detected at the threshold set



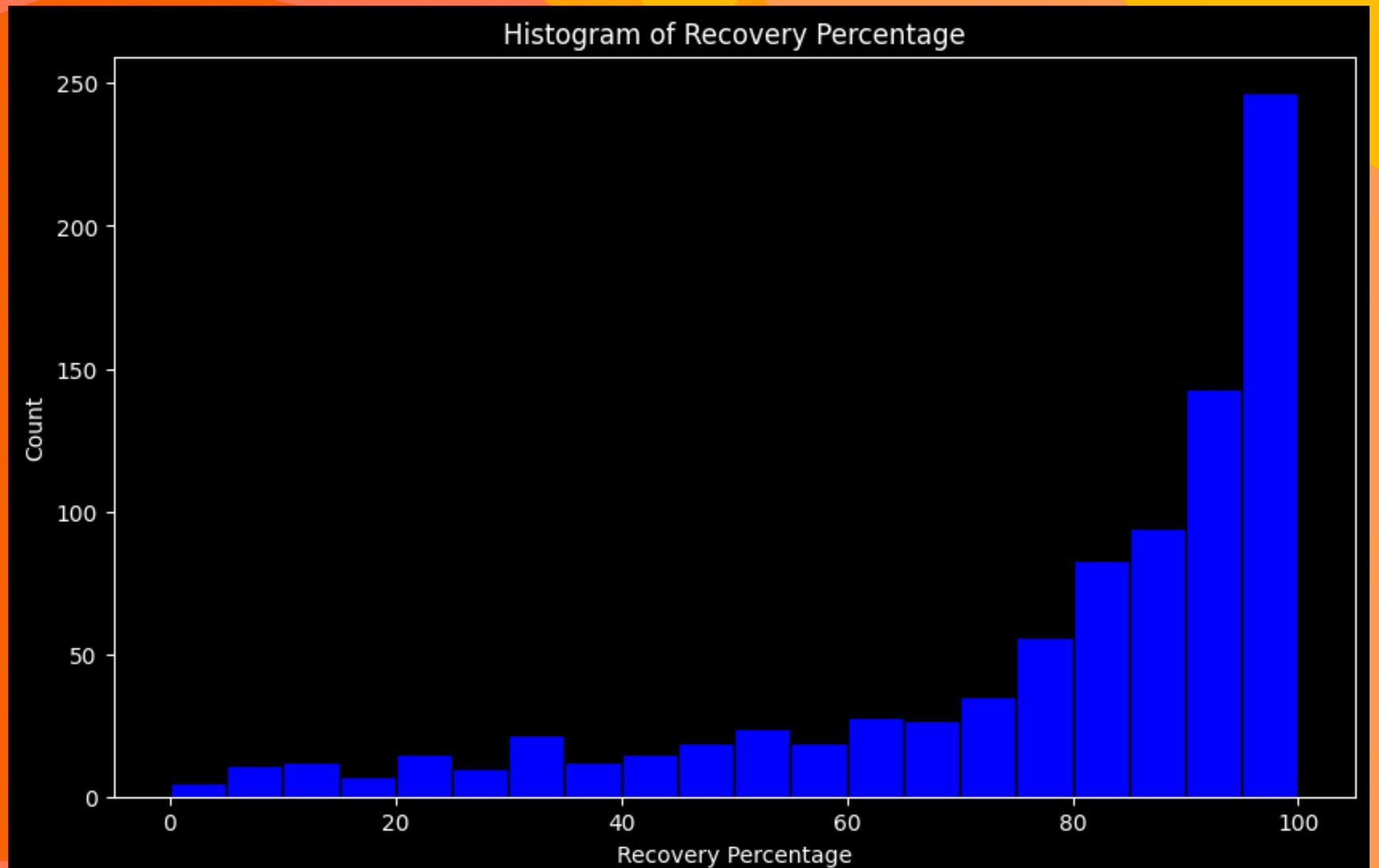
Ephemeris Identification Injection Testing

- Check to make sure we haven't identified the wrong signal
- These results demonstrate we strongly detect binary signals that are distinguishable from planet signals



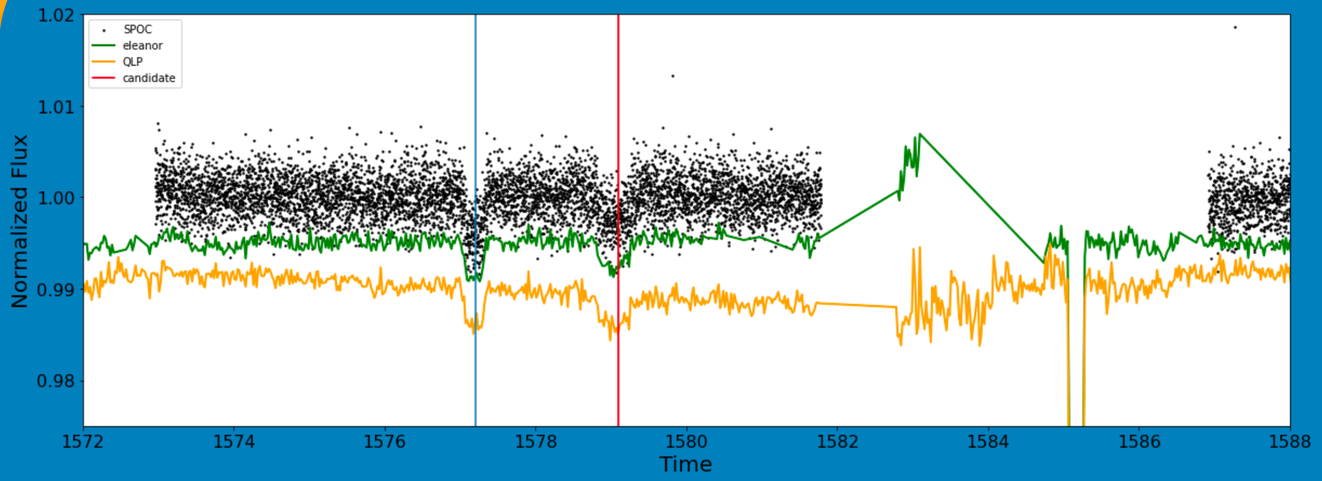
Injection and Recovery

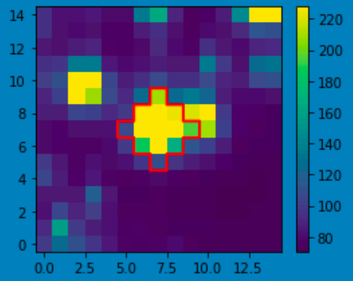
Supplementary Plot

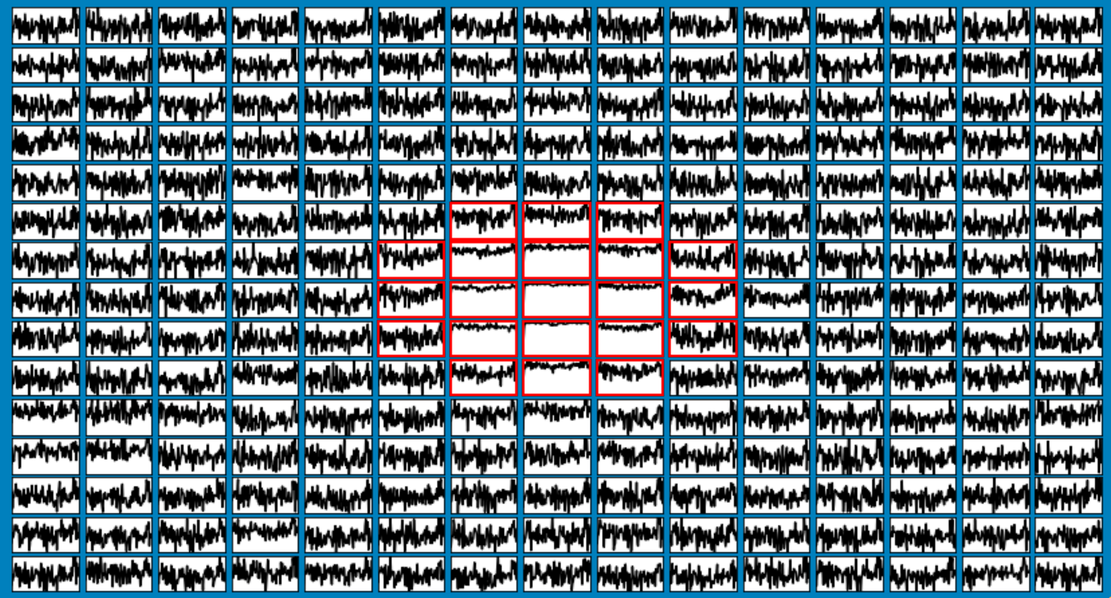


Vetting

Check other extractions and whether event is on target

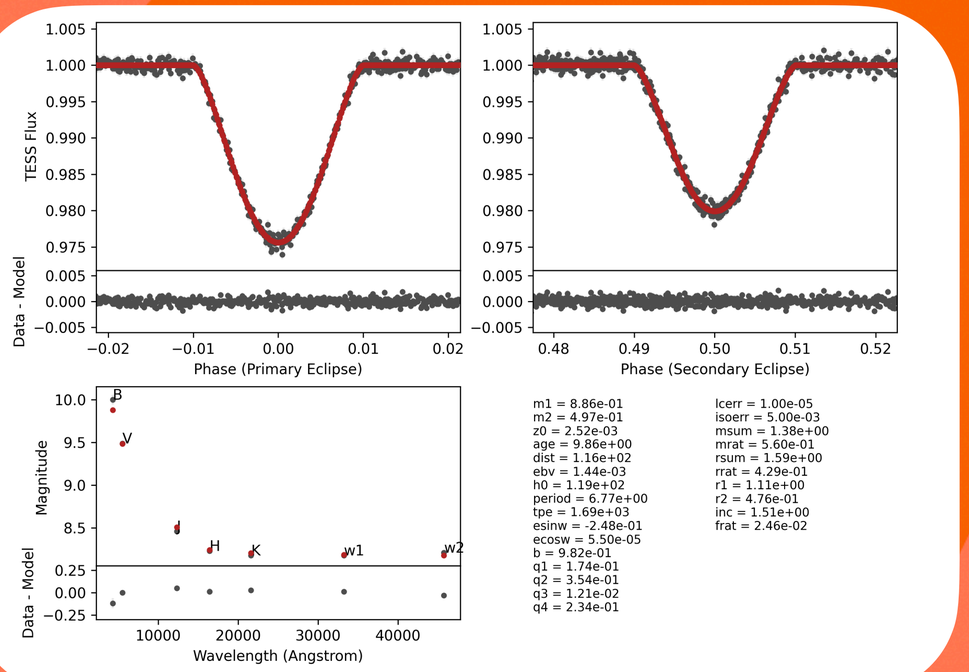






Know thy Binary

To know thy planet



m1 = 8.86e-01
m2 = 4.97e-01
z0 = 2.52e-03
age = 9.86e+00
dist = 1.16e+02
ebv = 1.44e-03
h0 = 1.19e+02
period = 6.77e+00
tpe = 1.69e+03
esinw = -2.48e-01
ecosw = 5.50e-05
b = 9.82e-01
q1 = 1.74e-01
q2 = 3.54e-01
q3 = 1.21e-02
q4 = 2.34e-01

lcerr = 1.00e-05
isoerr = 5.00e-03
msum = 1.38e+00
mrat = 5.60e-01
rsum = 1.59e+00
rrat = 4.29e-01
r1 = 1.11e+00
r2 = 4.76e-01
inc = 1.51e+00
frat = 2.46e-02

- Knowing the physical characteristics of the stars in the binary will in turn allow us to calculate physical parameters for the planets we find
- By using information about the binaries we get “for free” from light curves and fitting this in tandem with flux information in different bandpasses, we can extract physical parameters like mass and radius

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FFI-TEBLAT

The revival of the physical characterization of TESS EBs, now designed for FFI sample.

Not planning to use the MCMC functions and instead will fit only using leastsq (at least at first), and hoping to optimize for efficiency and speed. Will use some functions from TESS_FORCES, in particular the light curve data aspect.