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# PLATO's Single Transit challenge
## - lessons learned from K2 & TESS

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+ Martti Kristiansen, Magali Deleuil, Alex Santerne

GSP

# SINGLE TRANSITS

Why do we want to find them?
How do we find them?
How are we sure a signal is real?
How do we model them?
How many are there?
Why are they important for PLATO?

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# Underexplored parameter space

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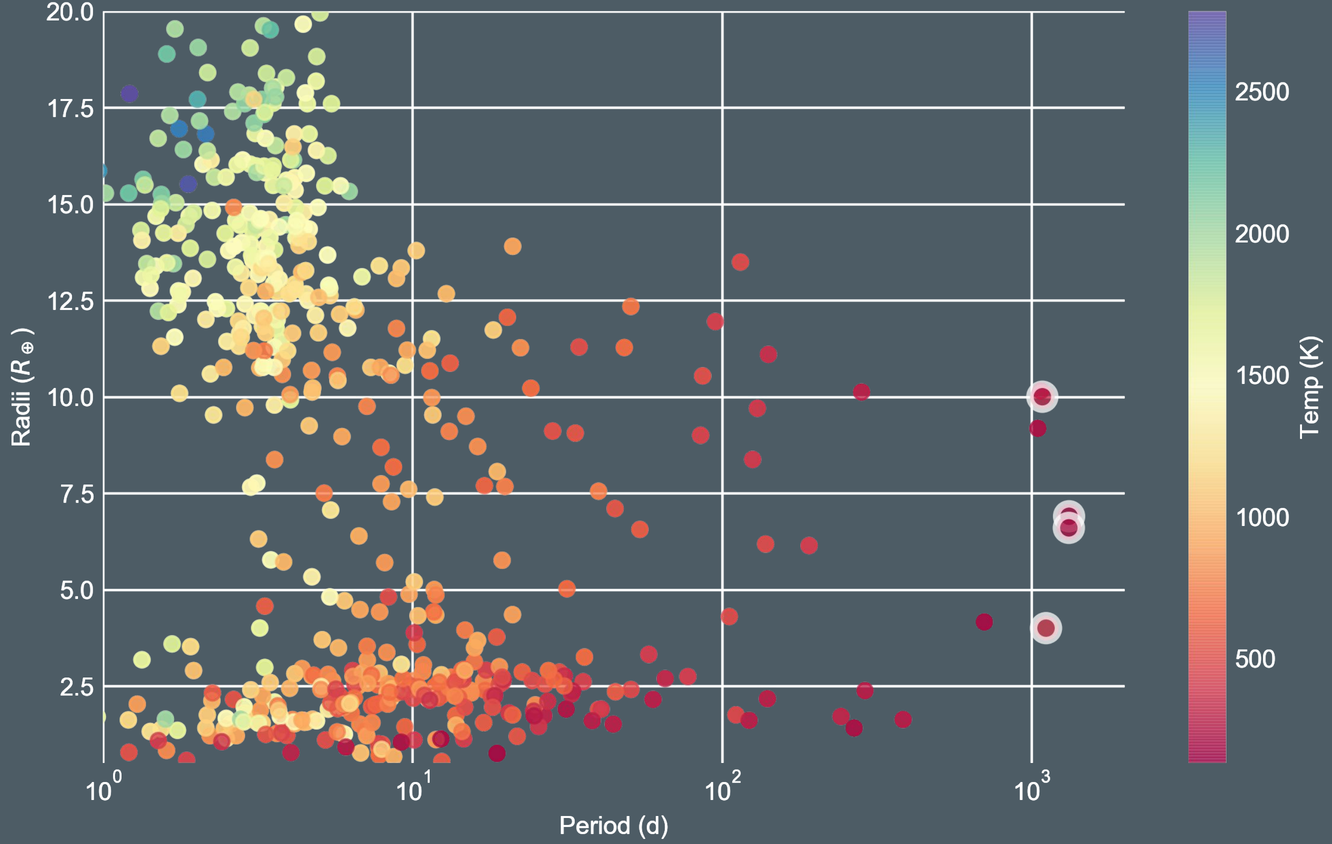
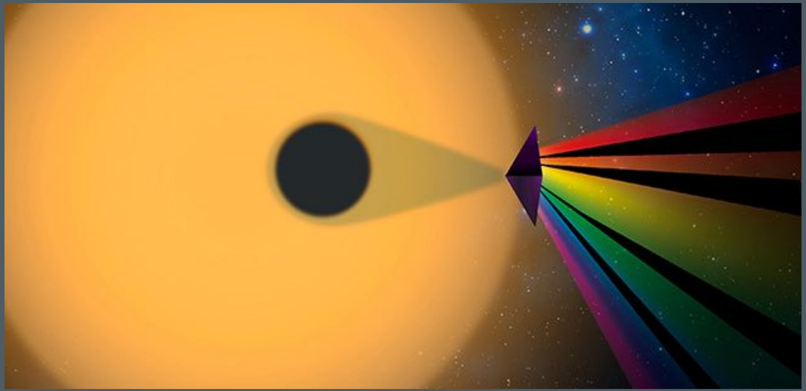


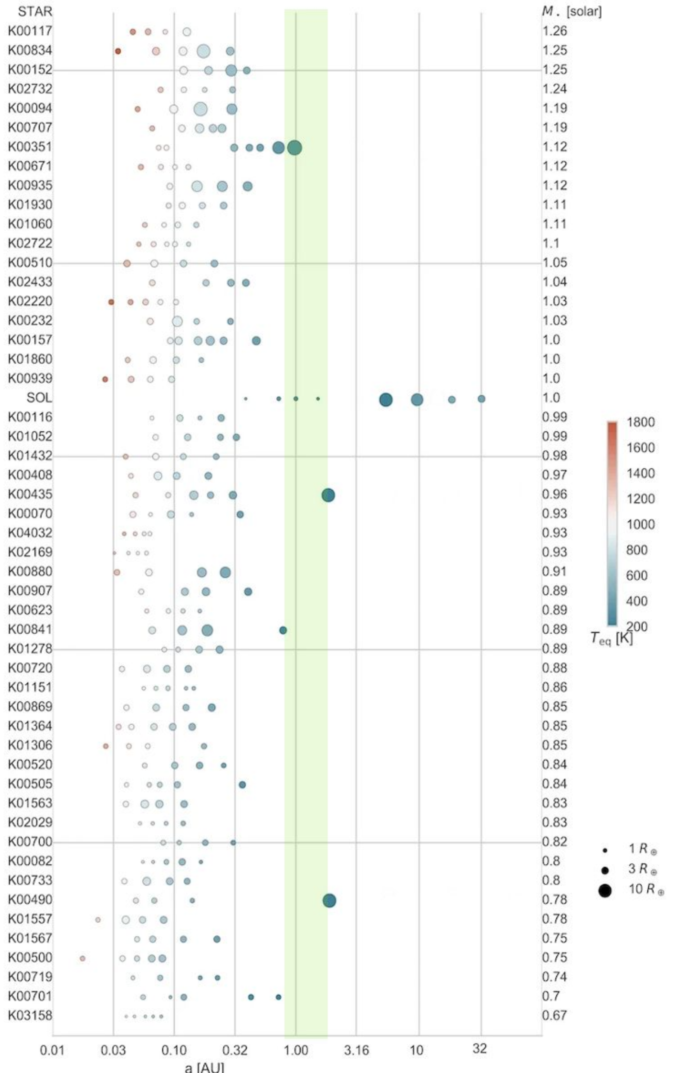
# Opens new frontiers of detection

- Spectra of cold giant planets
- Stable exo-moons
- Ring systems

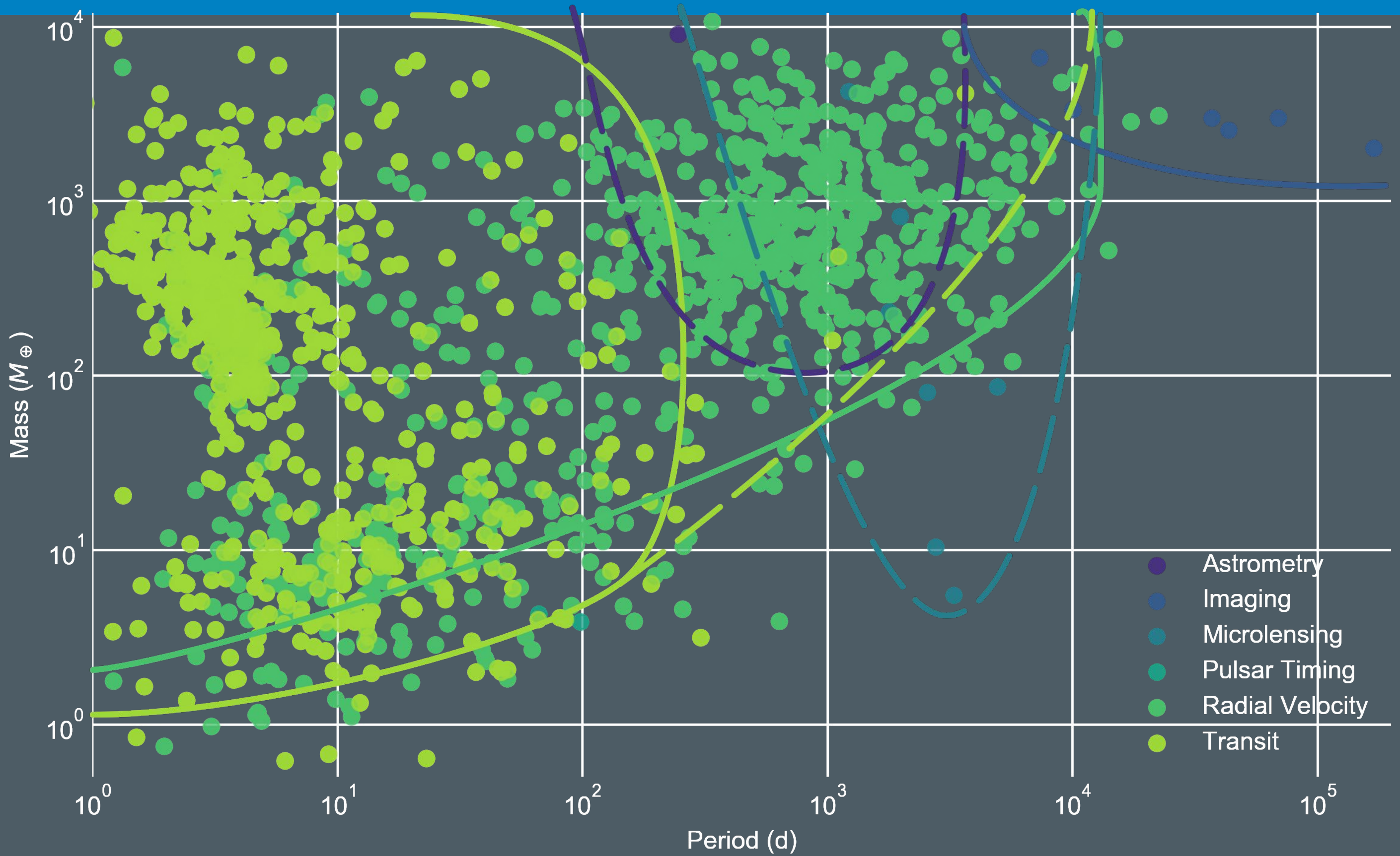


# Different from compact systems

- Different evolution & migration to compact multiplanet systems.
- Closer to solar system analogues?
- Warm jupiter population could explain hot jupiter migration
- Potentially find planets in the Habitable Zone



# Intersection with Gaia, RVs & Imaging



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# By-eye

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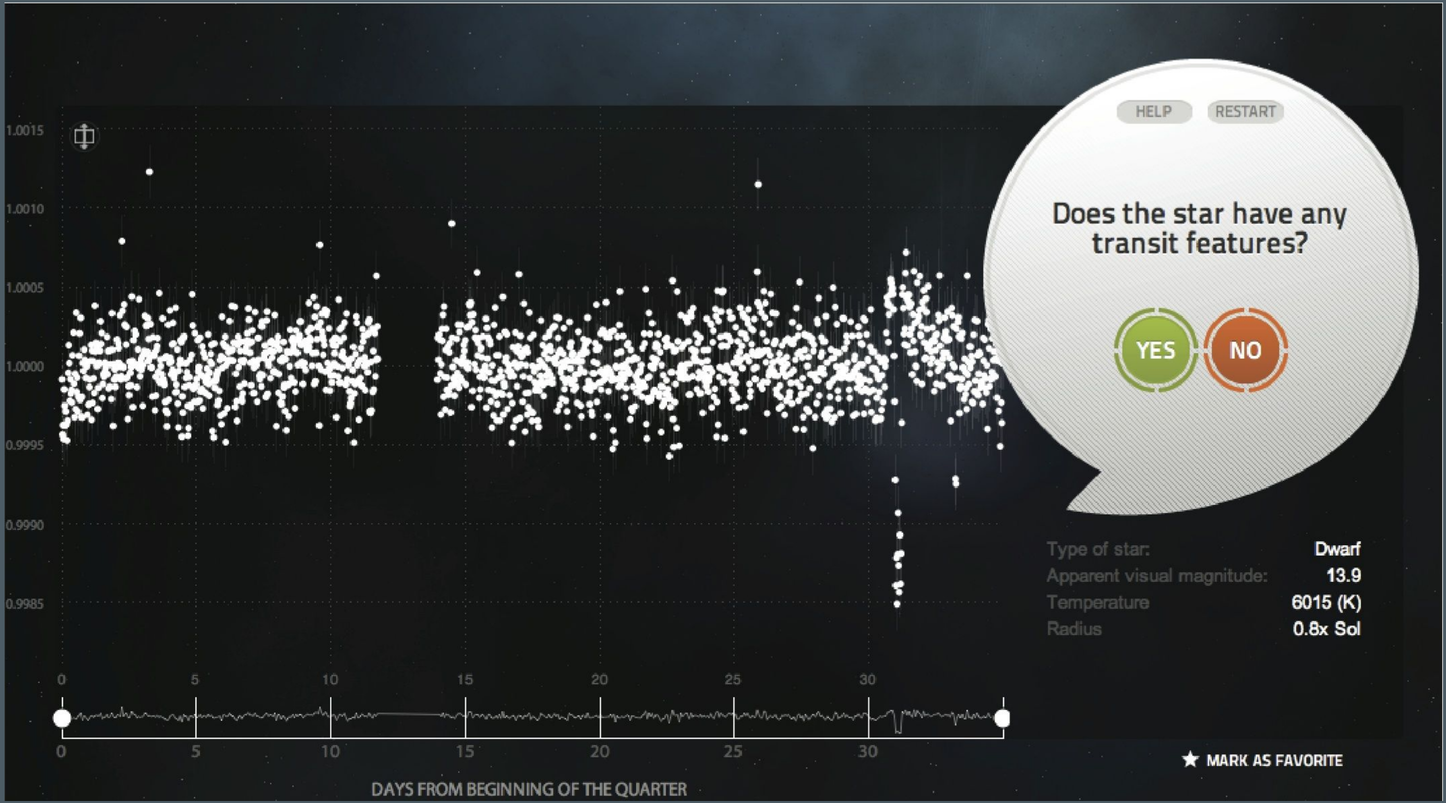
E.g. Amateur planet hunters shown detrended lightcurve. Used in

- Wang et al (2016, Kepler)
- Uehara et al (2017, Kepler)
- LaCourse & Jacobs (2017, K2)



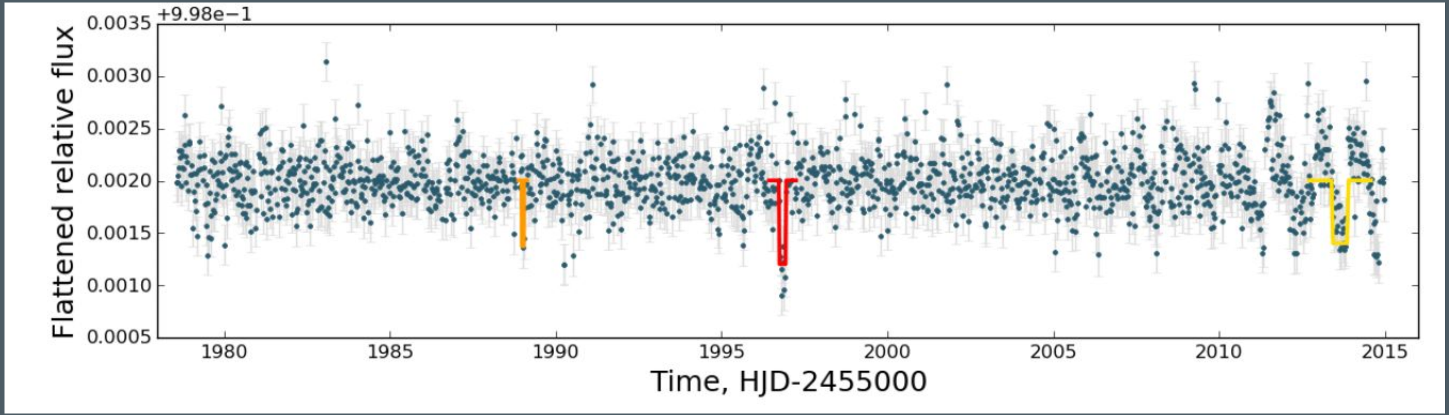
# Semi-automated detection

Searching candidates in all light-curves using:

- Consecutive low flux measurements
- Transit model matched filter response.

Candidates then vetted with by-eye inspection:

- Light curves, centroid curves, etc.



# Fully automated detection

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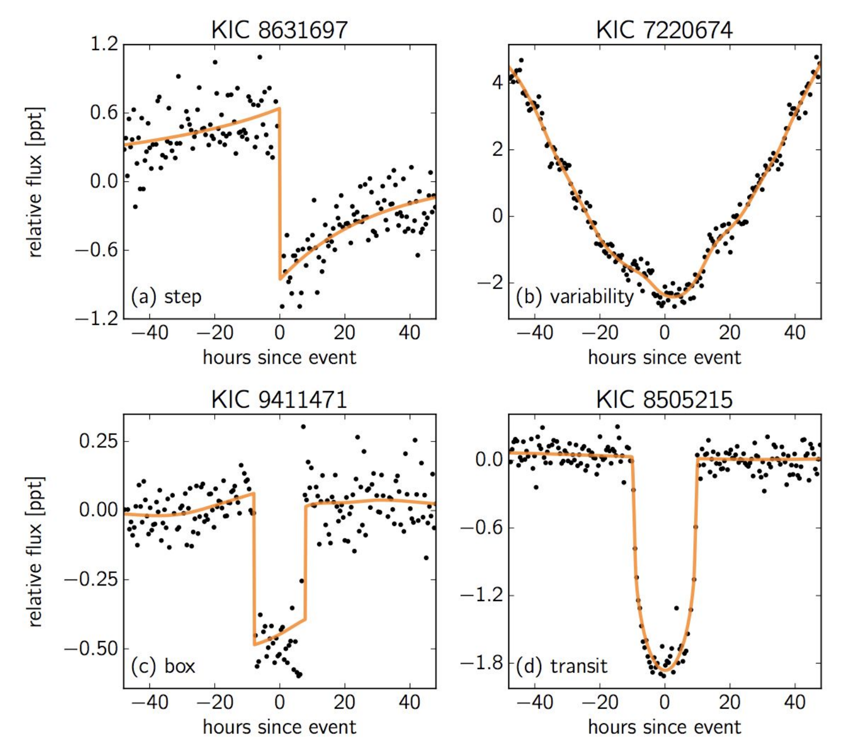
Scanned box across Kepler lightcurves

Compared fit of candidates to models for different types of FP: flux drop, variability, box and transit.

Used injection recovery (820,000 injections)

Used SNR limit of 25



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# False positives

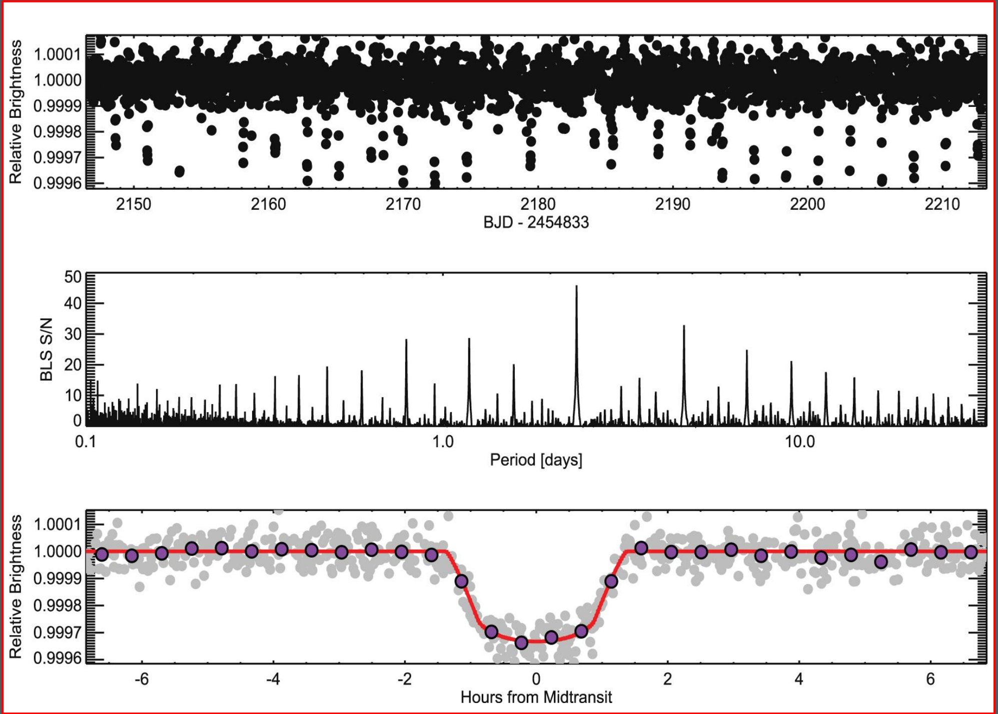


Typically candidates are vetted using

# Astrophysical false positives

“Tools” used for vetting periodic candidates may fail:

- Periodogram statistics

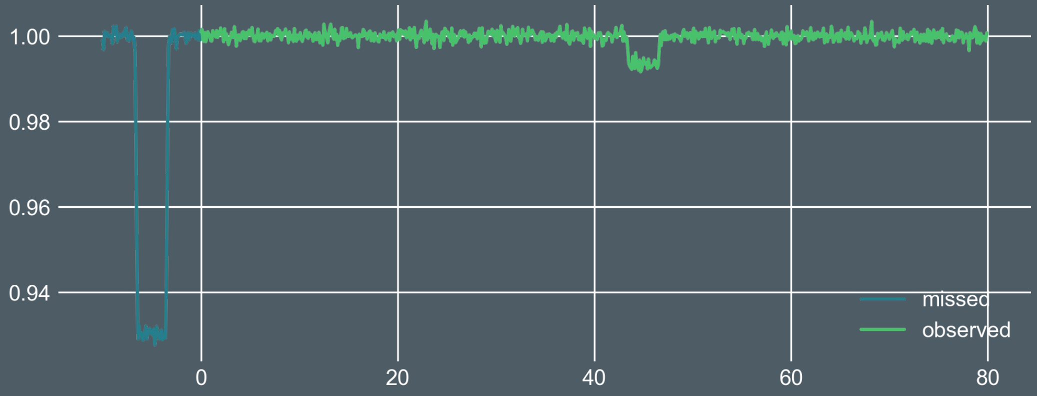


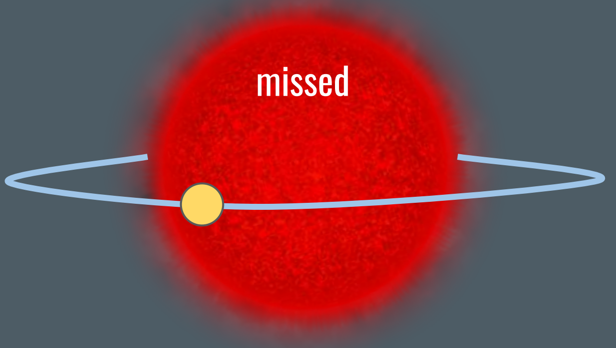
# Astrophysical false positives

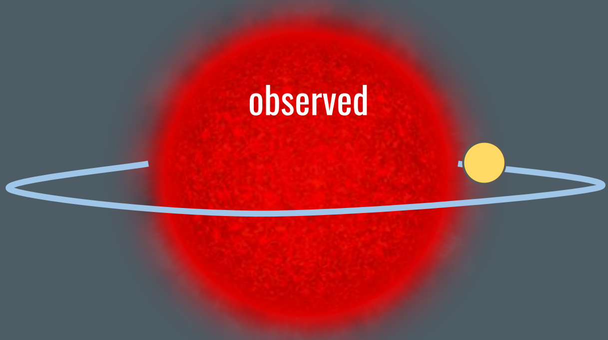


"Tools" used for vetting periodic candidates may fail:

- Periodogram statistics
- Searches for a secondary (or primary) eclipse



# Astrophysical false positives



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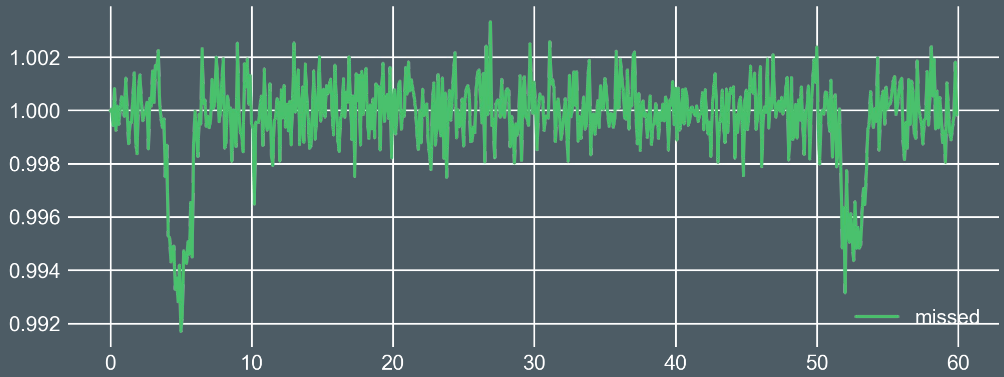
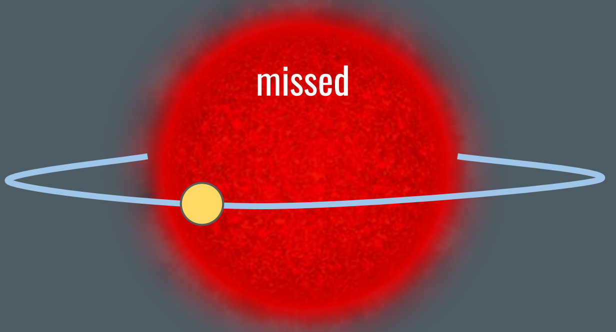
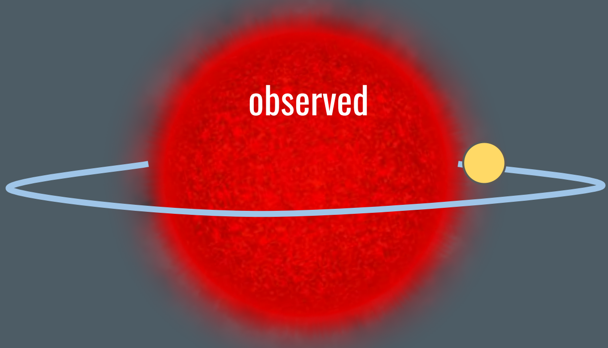
- Depth, duration & shape changes between transits



# Astrophysical false positives



"Tools" used for vetting periodic candidates may fail:

- Periodogram statistics
- Searches for a secondary (or primary) eclipse
- Depth, duration & shape changes between transits
- Duration/Period constraint

Giant / dwarf binary

# Other false positives

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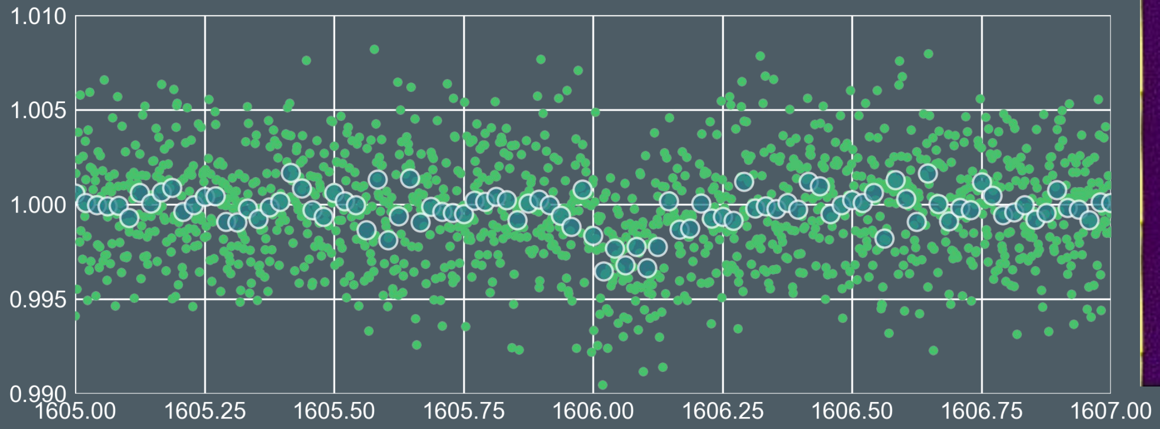
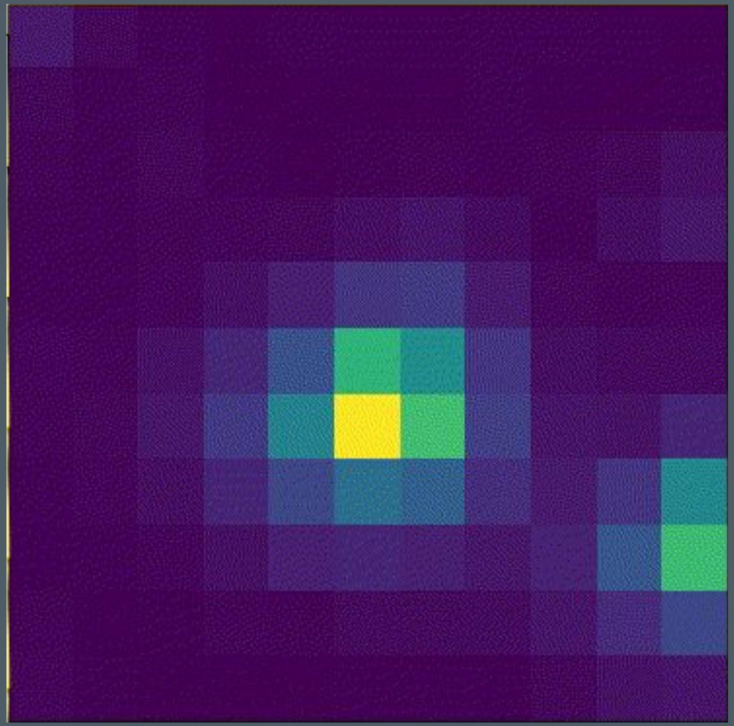
## Asteroids

- Affects both TESS & K2
- Lightcurve is ratio of flux in-aperture to background
- Out-of-aperture flux increase causes dip in lightcurve.

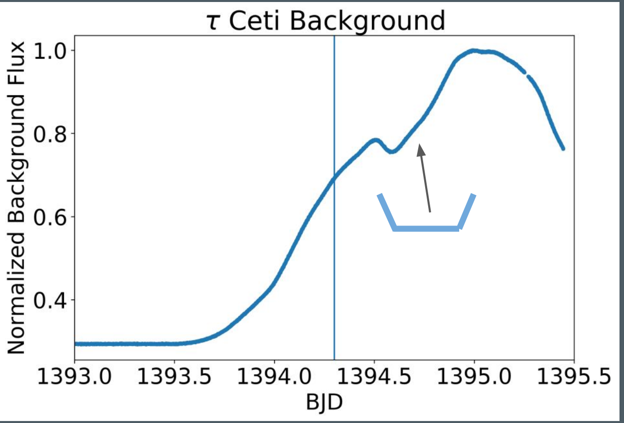


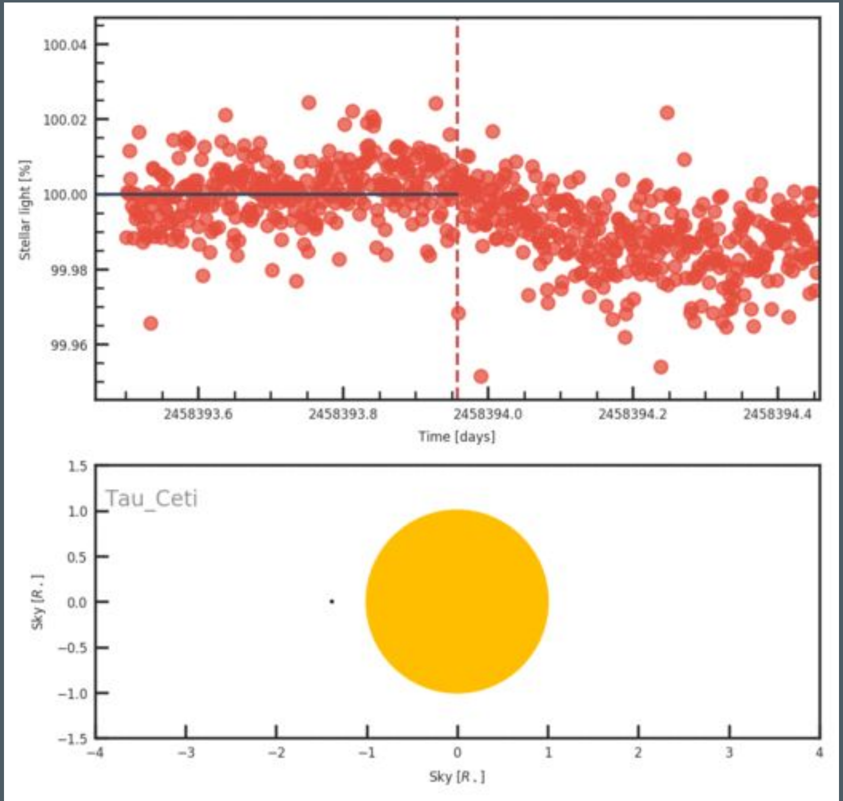



# Other false positives

## Reflections

- E.g. Tau Ceti as seen by TESS
- Poor detrending caused dip



# Other false positives

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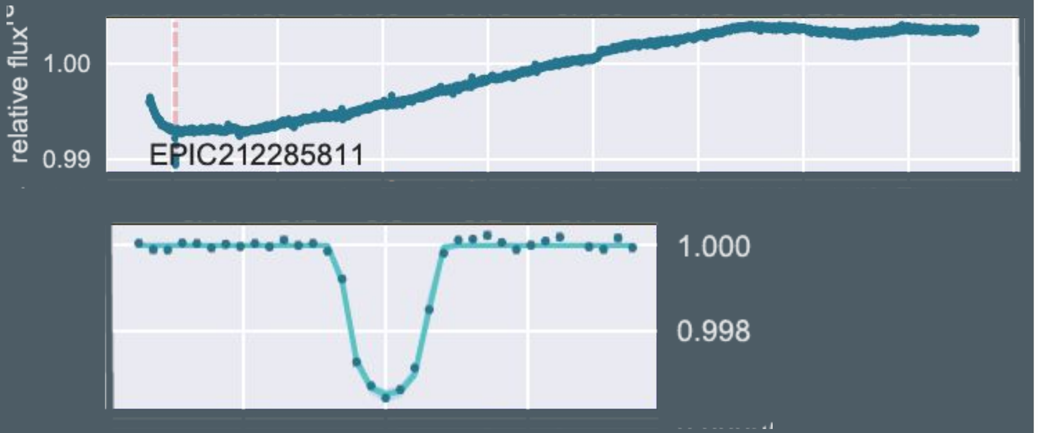
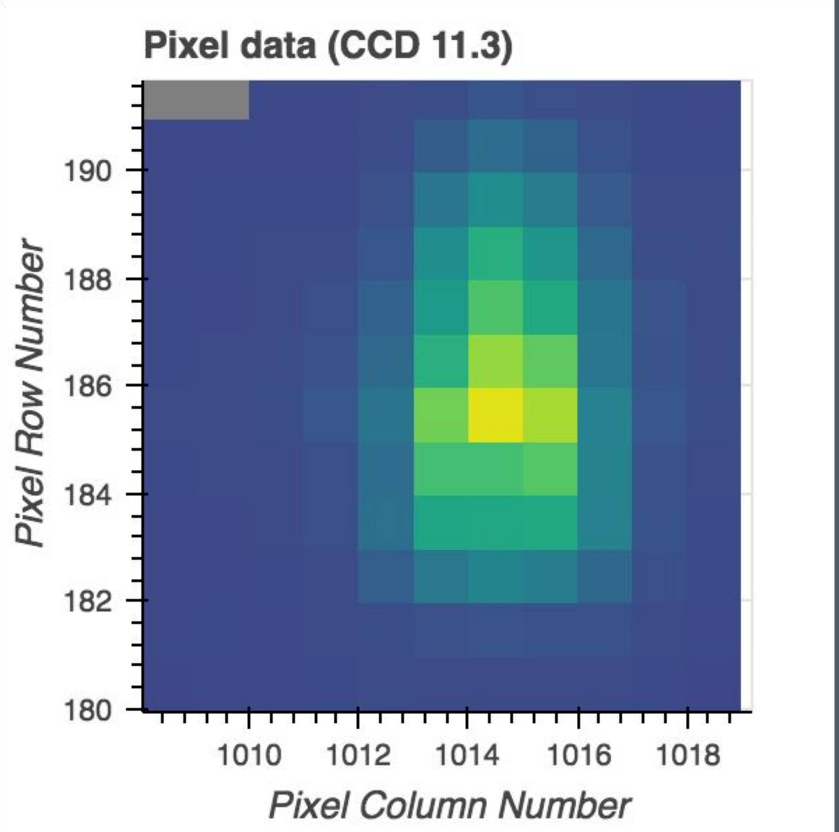
Instrumental

- Electrical cross-talk



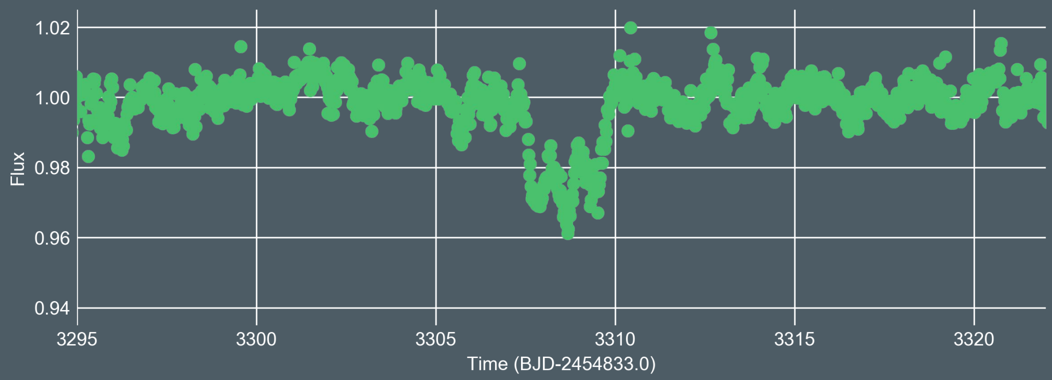

This was in my thesis ^ :/

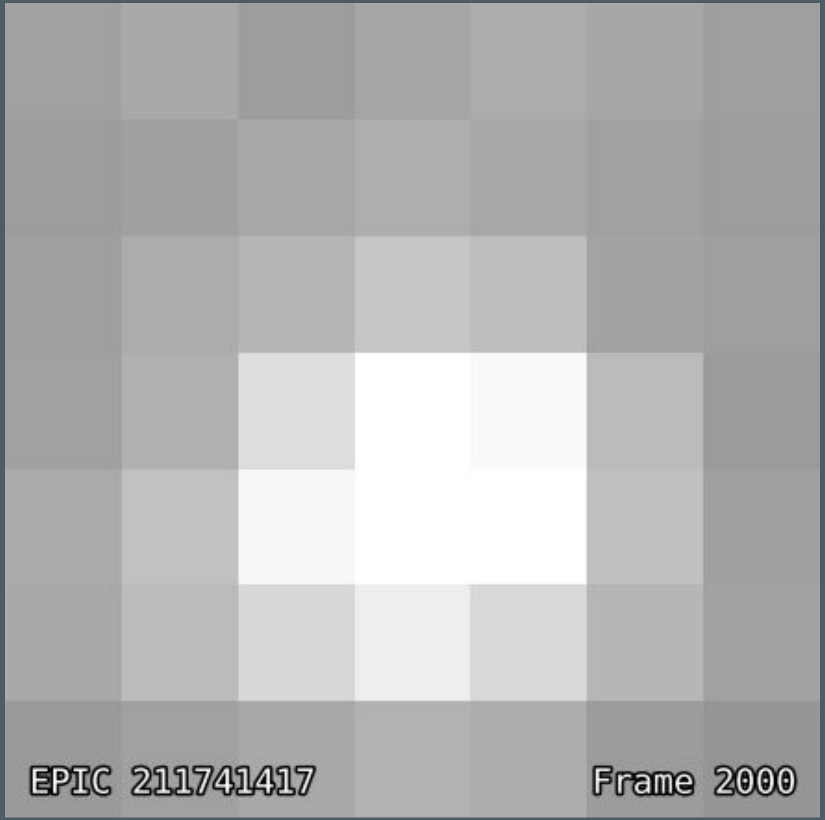


# Other false positives

Instrumental

- Rolling band
- Temperature-dependent electrical crosstalk -
- Flux variations on CCD have ~few hours timescale



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# Modelling single transits

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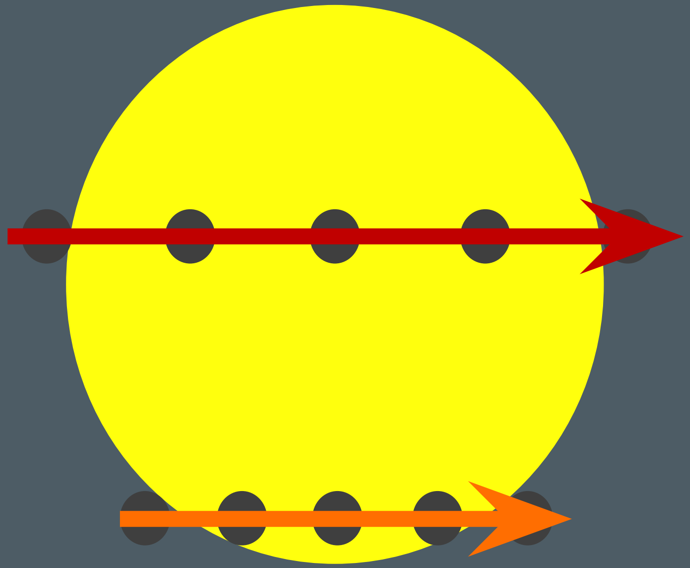

- Radius, as normal, from depth.
- Estimate impact parameter from ingress duration (and estimated Rp/Rs)
- Velocity from chord length and transit duration.
- Period from velocity

Density is key - Gaia helps!

# Period estimation ingredients

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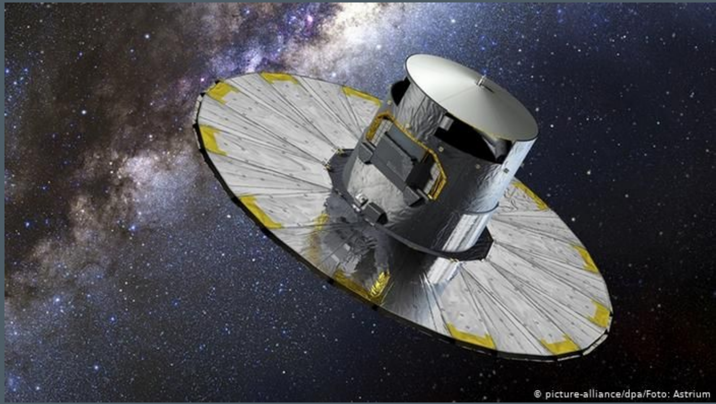
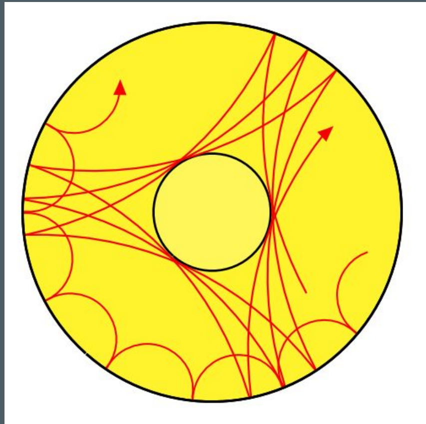
$$P_{circ} = \frac{8\pi^2 G}{3}\frac{\rho_\star}{\nu'^3} = \frac{2\pi g}{R_\star \nu'^3}$$




Well-constrained stellar density

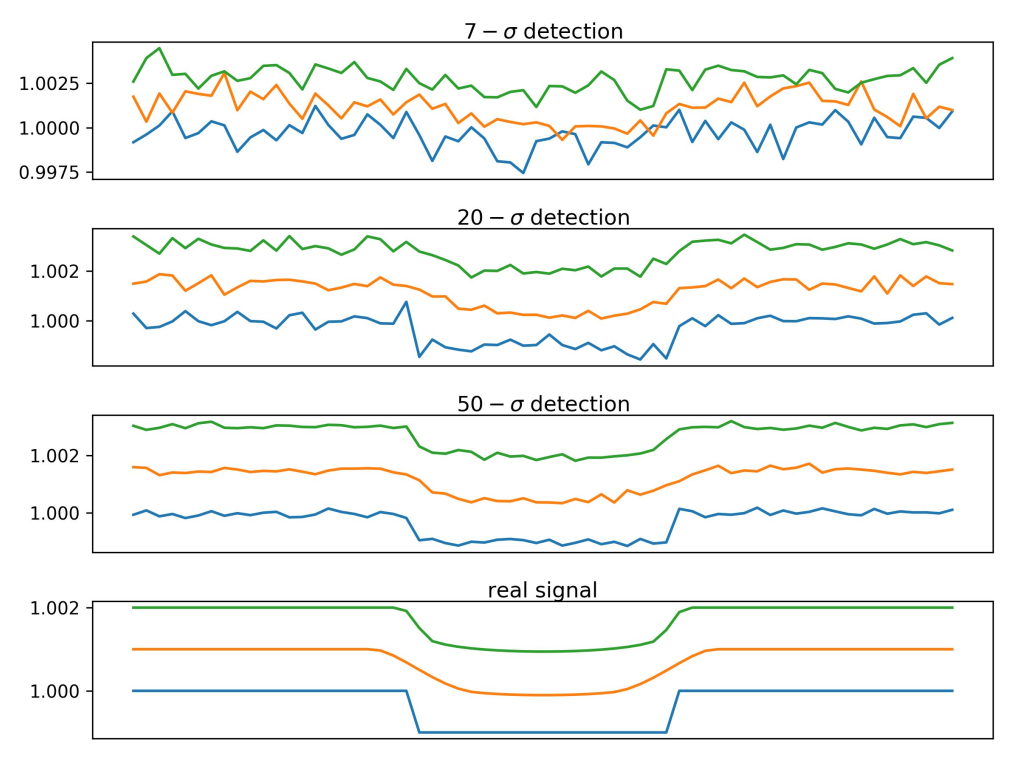
- Pre-Gaia (e.g. photometry): eρ=50%
- Spectra (e.g. logg to 0.1): eρ=30%
- With Gaia: eρ=15%
- Asteroseismology: eρ<10%



# Period estimation ingredients

Well-constrained ingress/egress duration

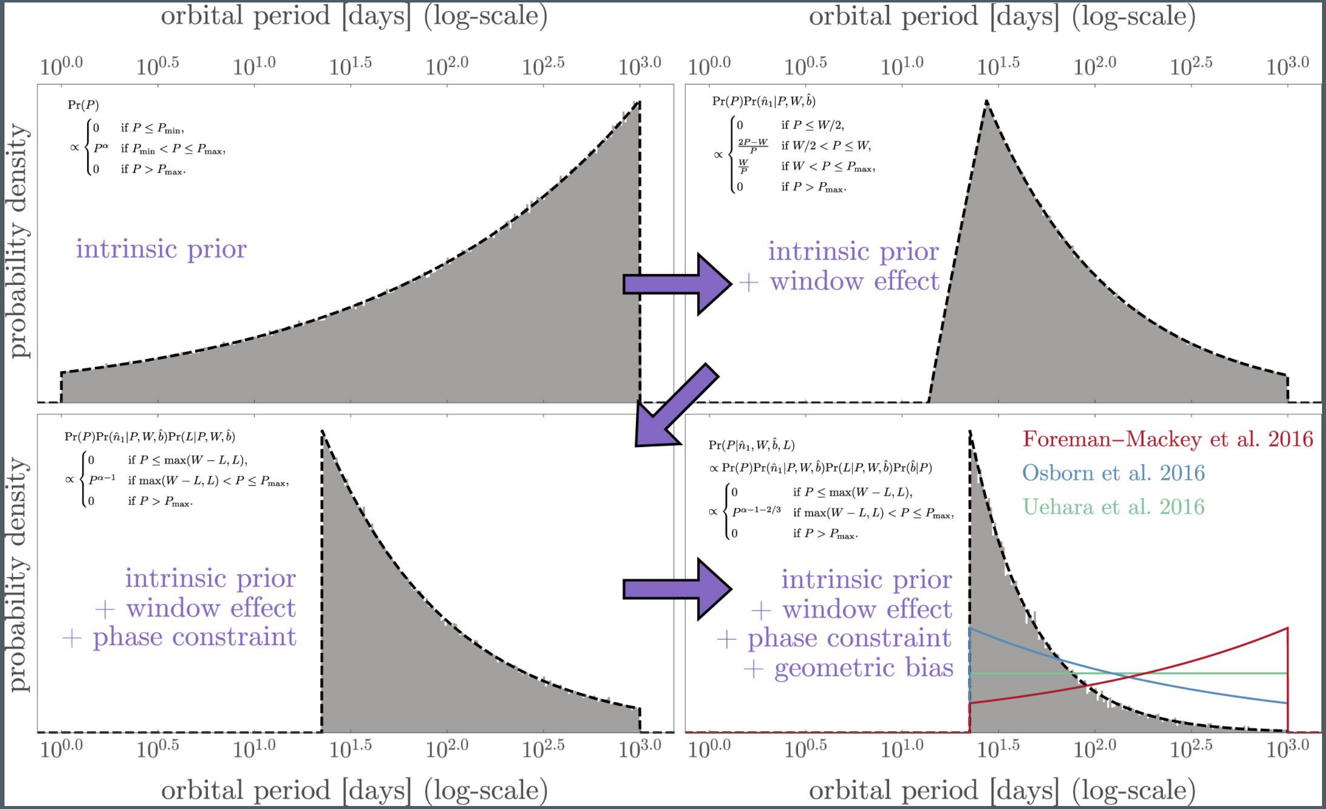
- Directly depends on transit SNR
- Cannot constrain period at SNR=7
- e(Period) α $r^{-2.5}$ - small planets unconstrained with lightcurve
- Large planets & longer transits better



# Period estimation ingredients

Correct prior on period (see Kipping et al 2019)

Scales with P^(-8/3)



# Problems with Modelling

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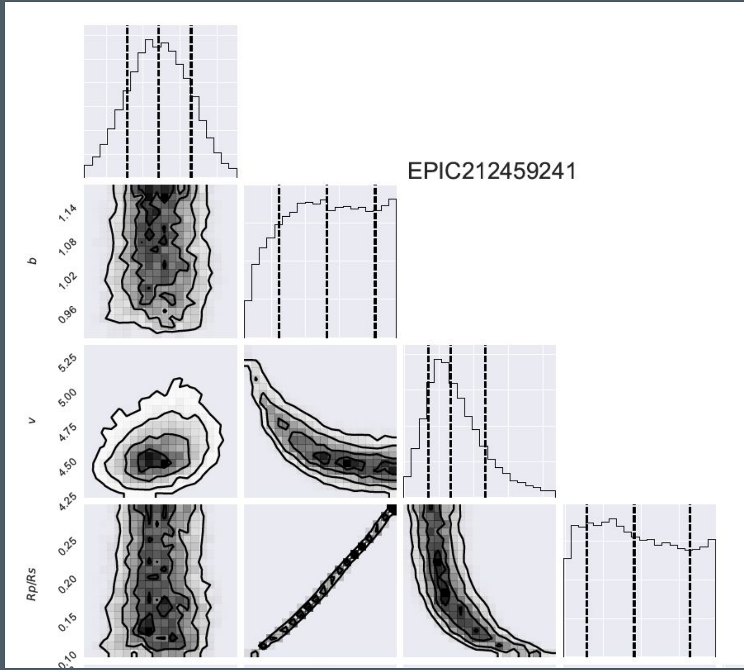
Problems:

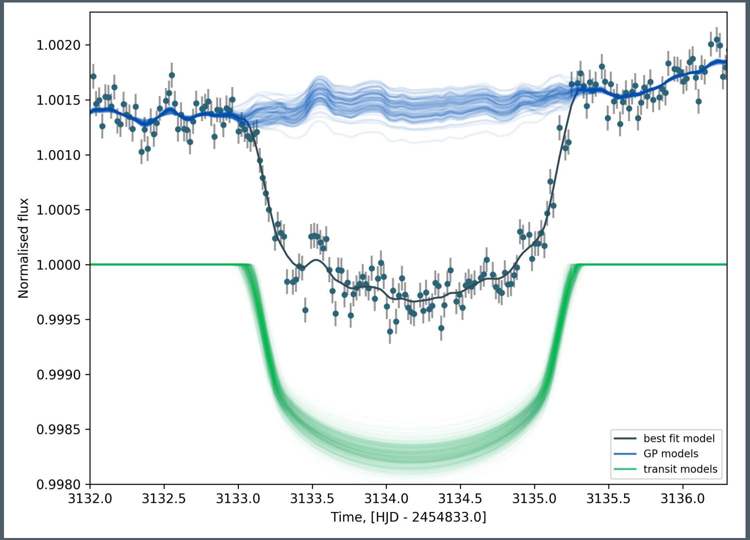
- Grazing eclipses totally unconstrained
- Eccentricity increases uncertainty on period by ~30%.

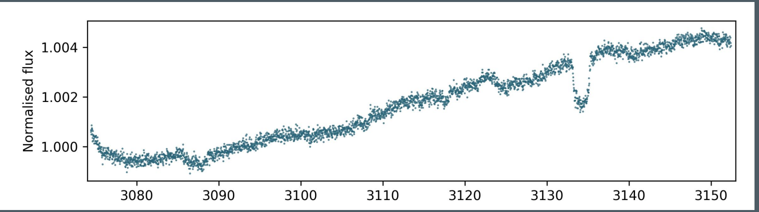


# Period Estimation

Existing Codes:

- "Namaste" (Osborn et al, 2016, 2018)
  - Fits for planetary velocity. Assumes circular orbit
- "Single" (Sandford, Espinoza et al., 2019)
  - Fits for period. Gaia parallaxes for radii/densities. Has eccentricity.
- "exoplanet" (Foreman-Mackey et al, in prep)
  - Easily modifiable to fit single transits.



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# Occurrence rates from Fernandes (2019)

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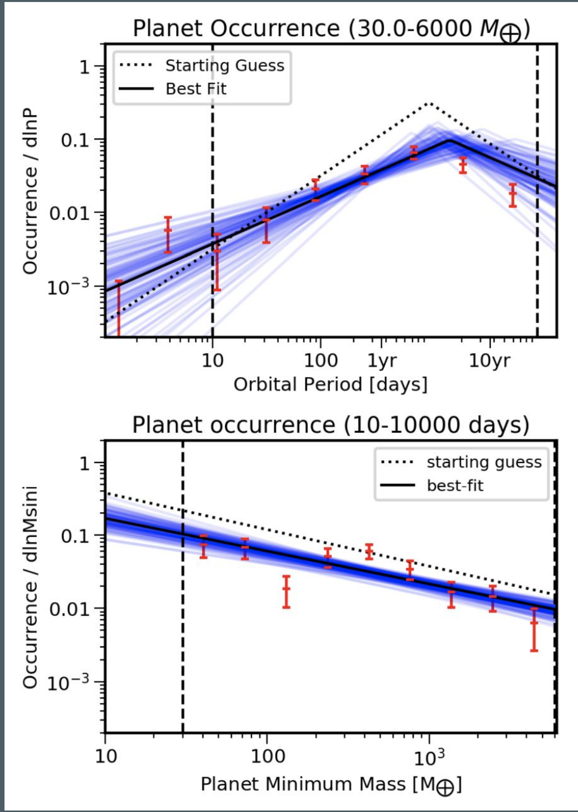
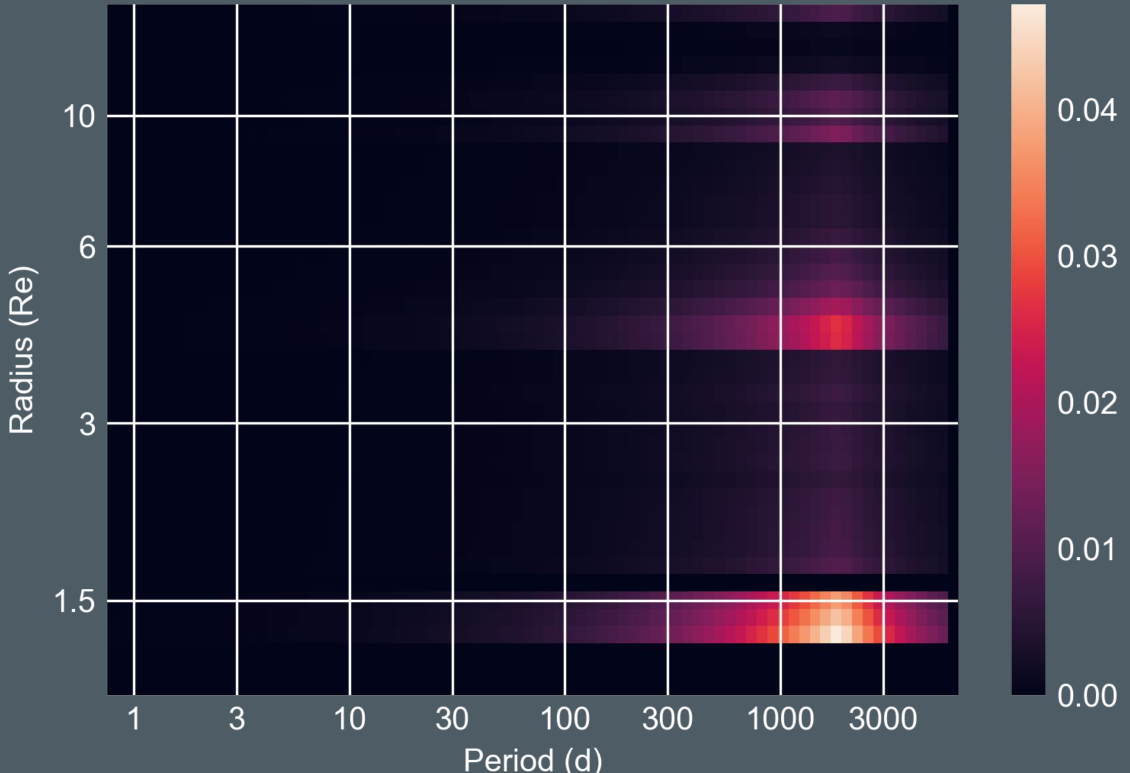
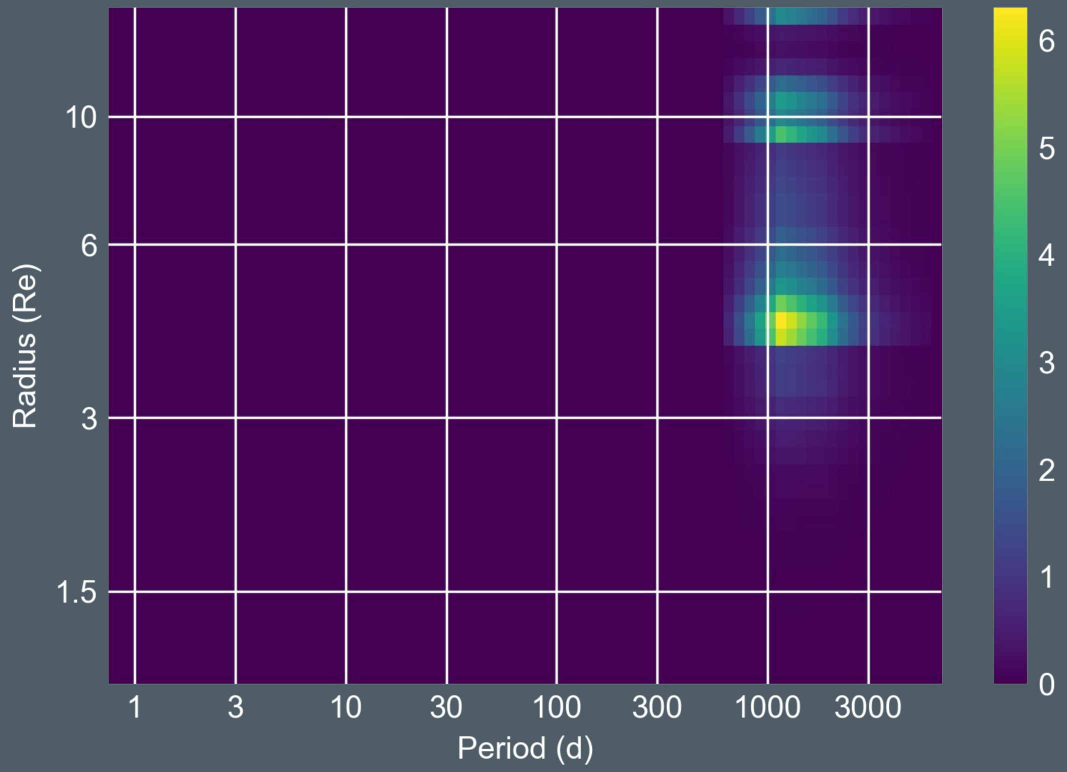


# Kepler Single Transits

Using Fernandes occurrence rate, Radii from Gaia and threshold of 10-sigma

230 planets expected



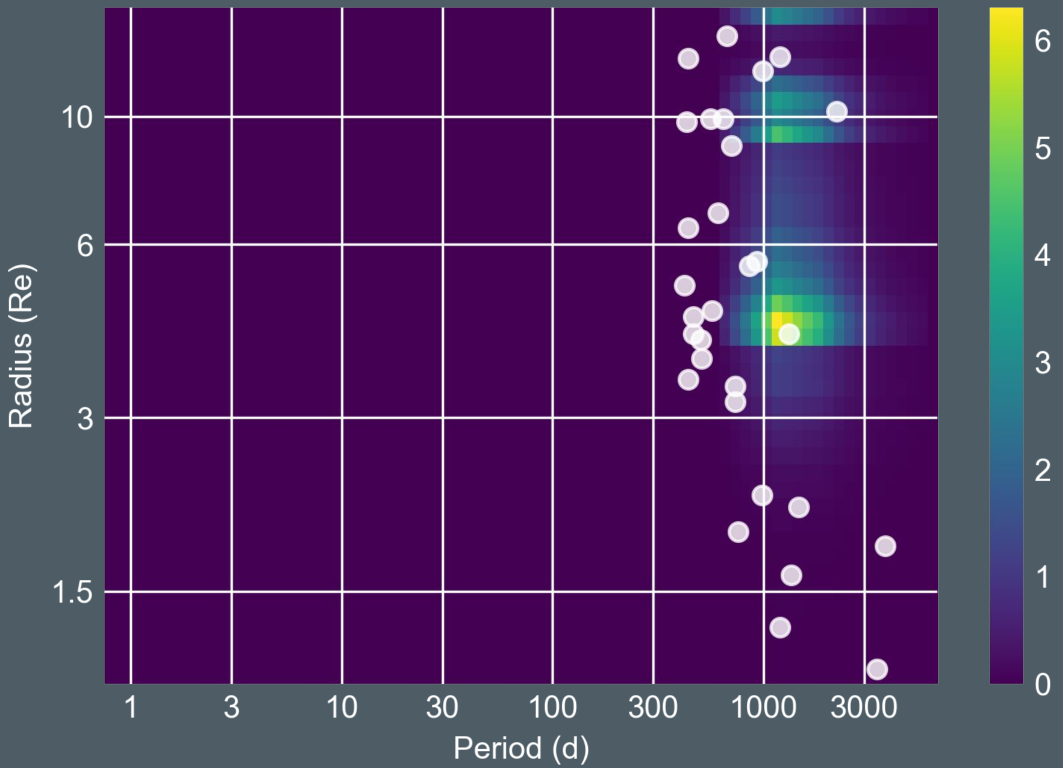
# Kepler Single Transits



Using Fernandes occurrence rate, Radii from Gaia and threshold of 10-sigma

230 planets expected

Yet only 30 detected…



# K2 Single Transits

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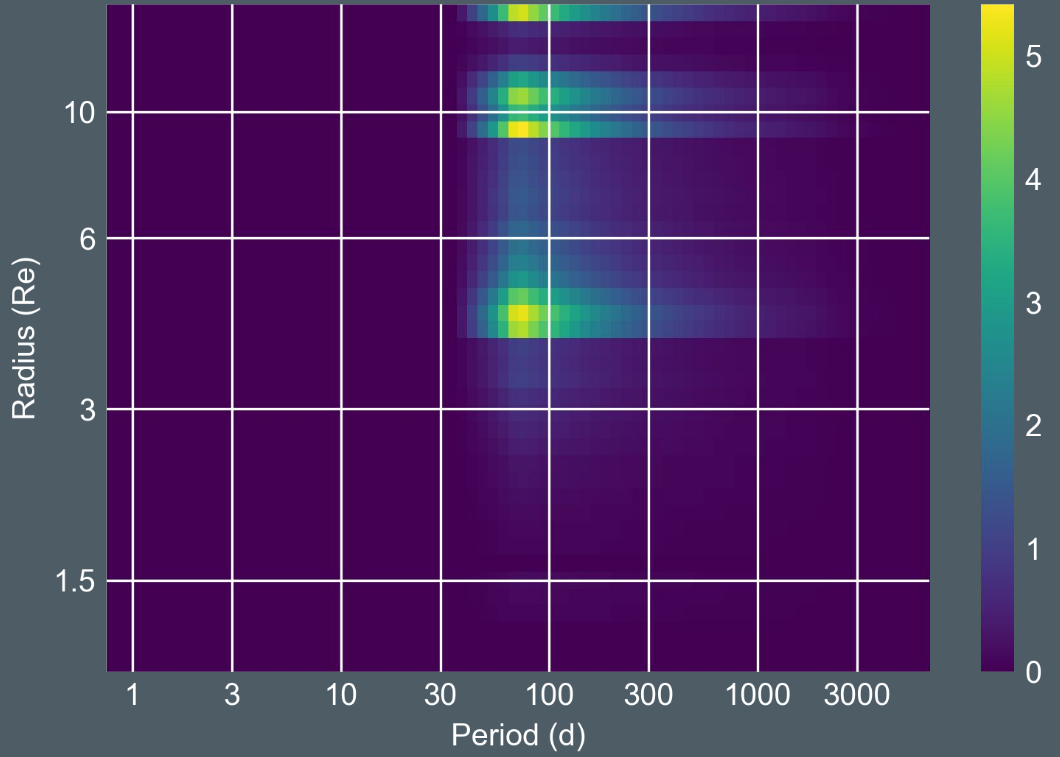
Higher number of transit expected in K2 with peak at 70d

- 390 expected in Campaigns 0-19



# K2 Single Transits

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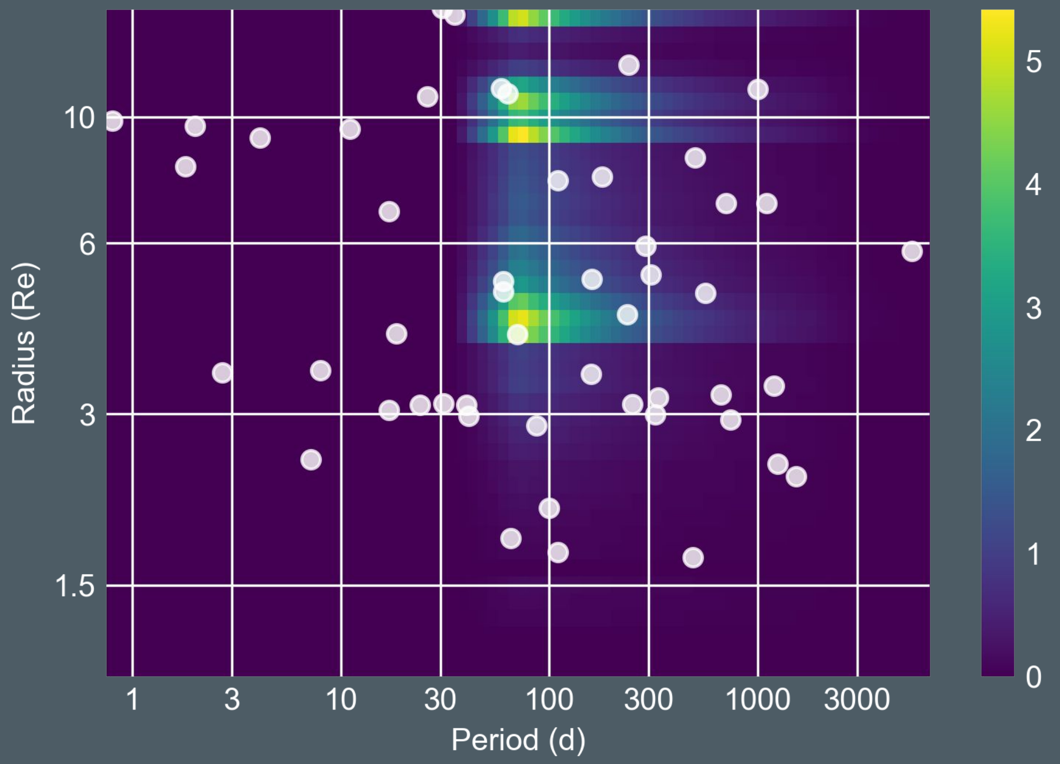
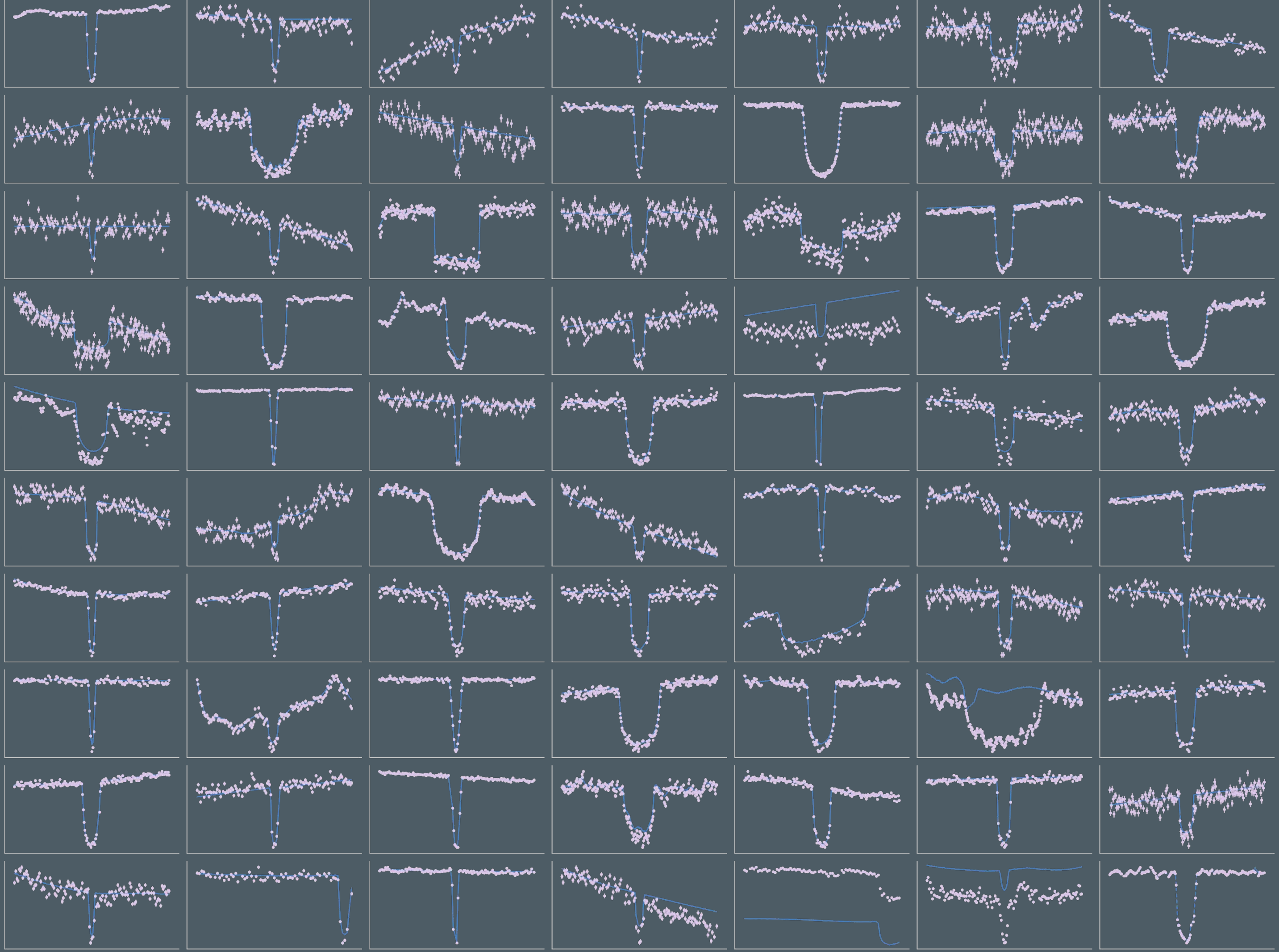
Our K2 Monotransit project:

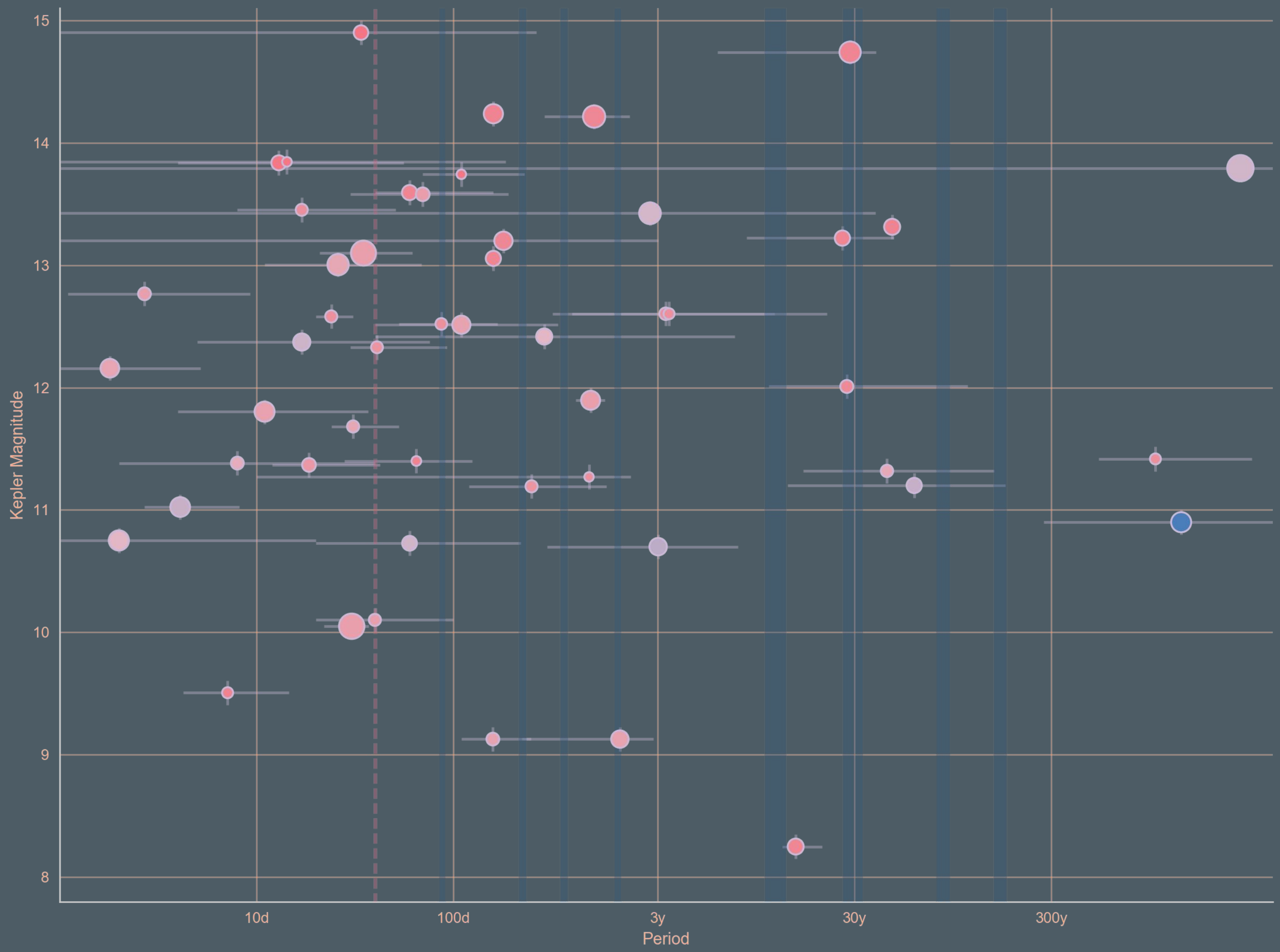
From >1000 candidates -> ~250 are astrophysical, and ~75 appear planetary.

Periods poorly constrained at the moment.

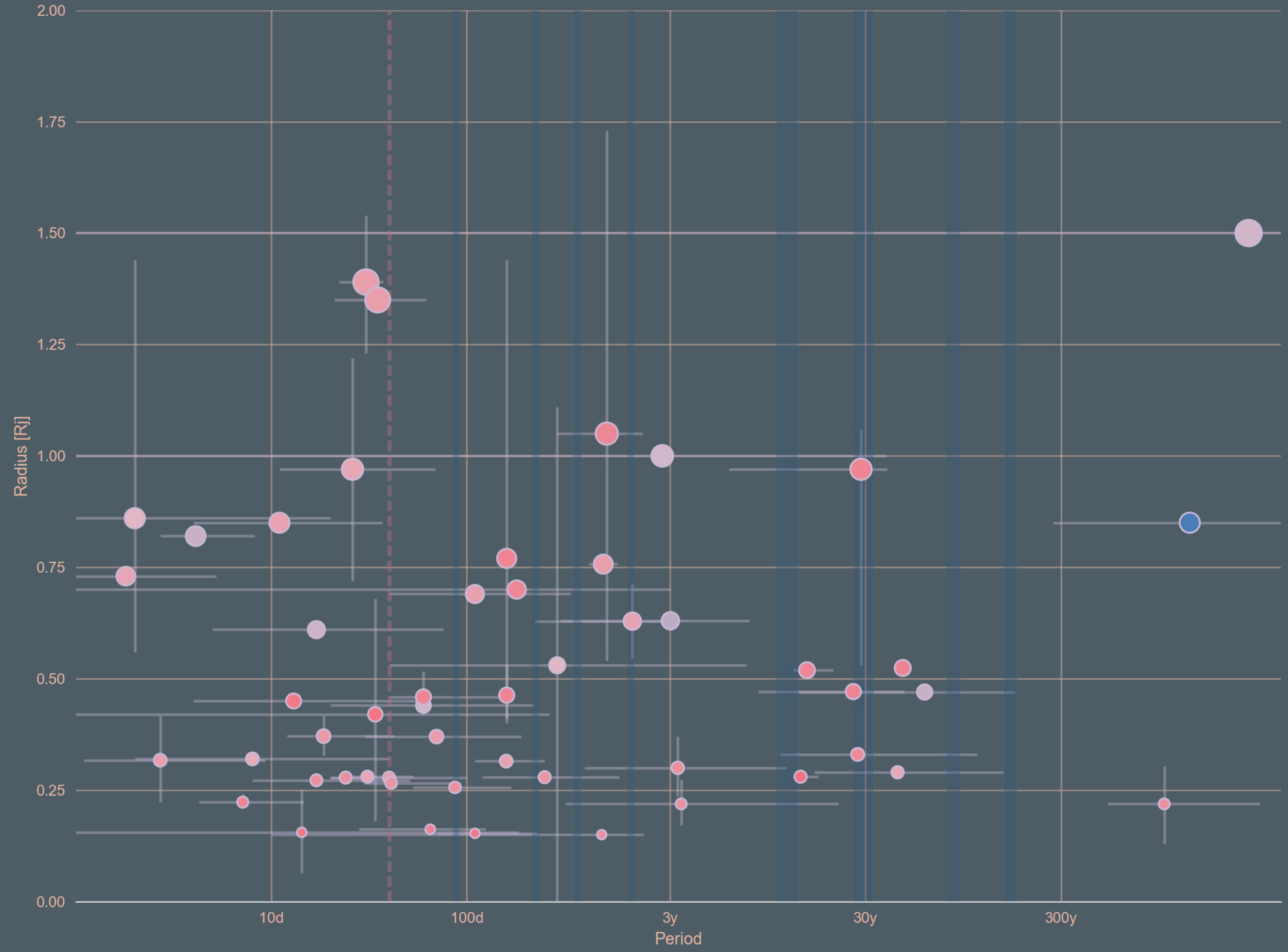
Includes validated P~10-year planet EPIC248847494b (Giles et al 2018)



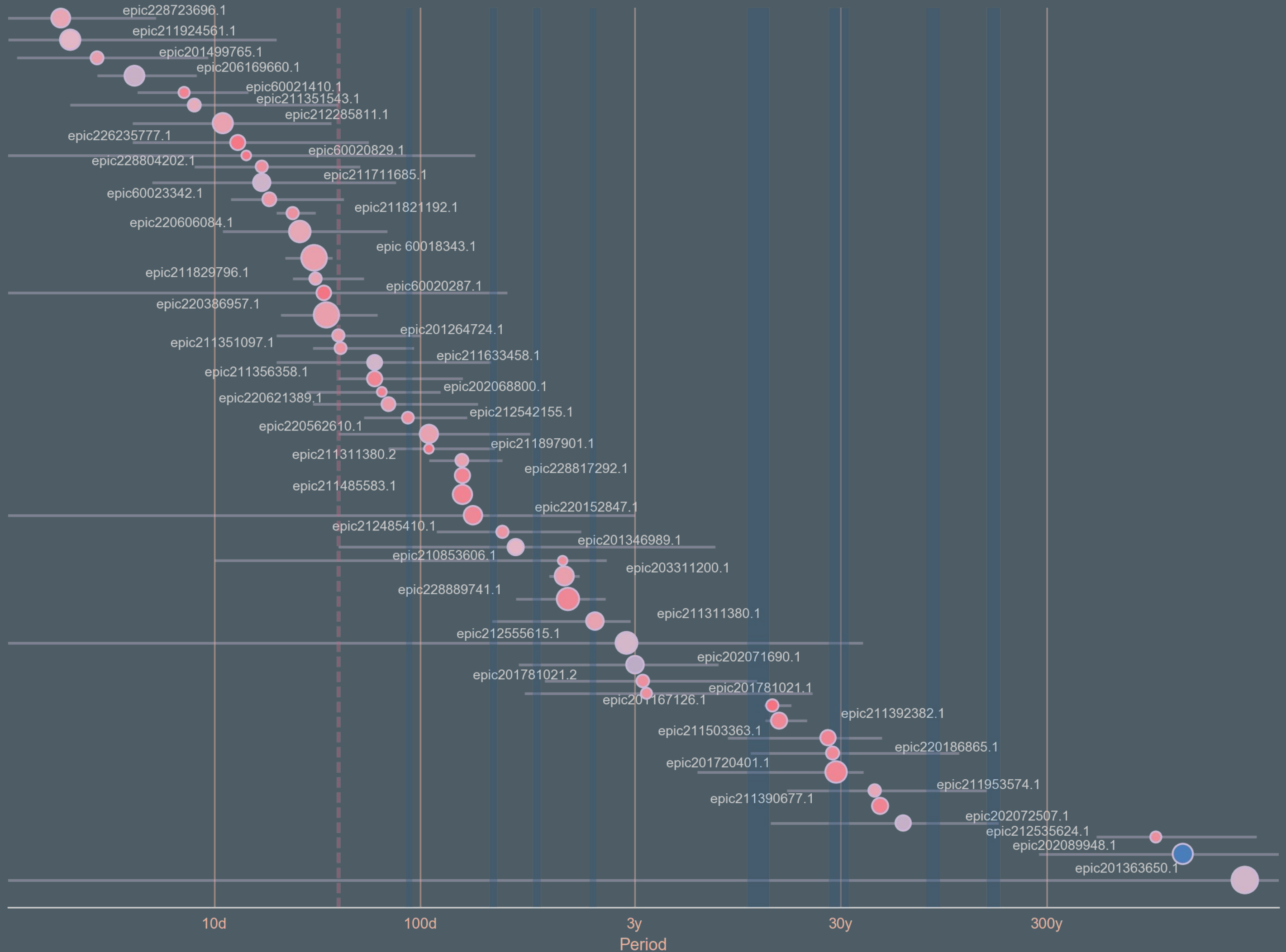




Kepler Magnitude
15
14
13
12
11
10
9
8
10d
100d
3y
30y
300y
Period



Radius [Rj]
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
10d
100d
3y
30y
300y
Period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epic211390677.1
epic202072507.1
epic212535624.1
epic202089948.1
epic201363650.1
10d
100d
3y
30y
300y
Period

# TESS Single Transits

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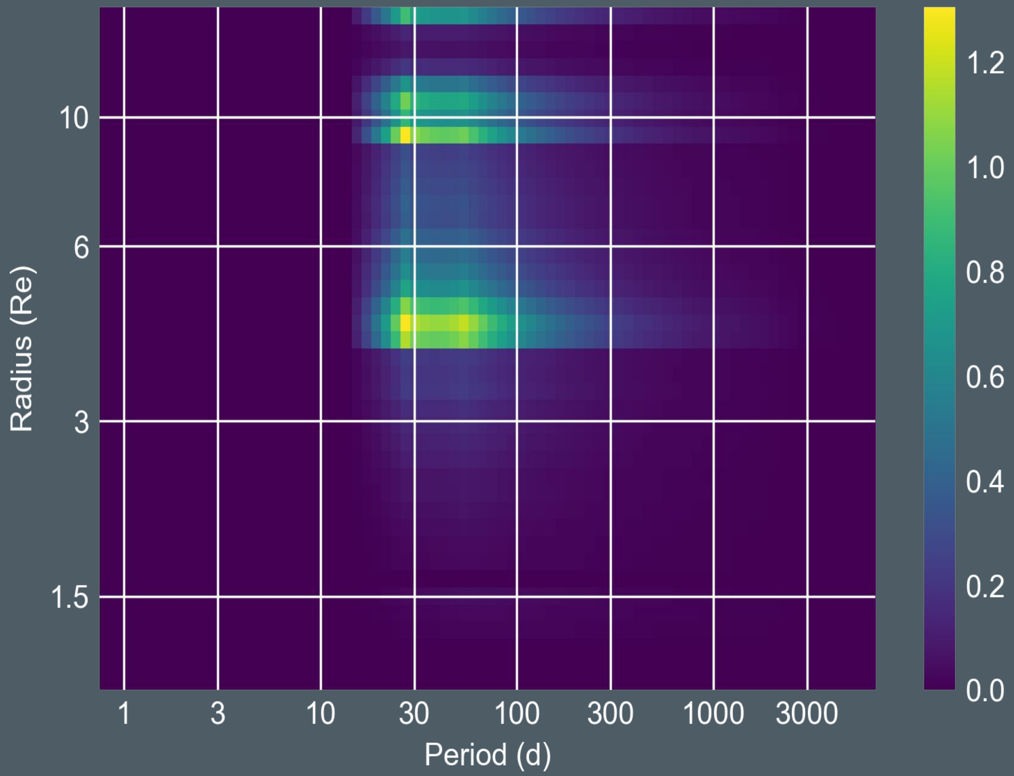
232 monotransit expected in S1-13

Our TESS Monotransit project:

From ~600 candidates for S1-12 -> 300 are astrophysical, and ~100 appear planetary.

Includes many bright candidates ripe for RVs (follow-up on-going).



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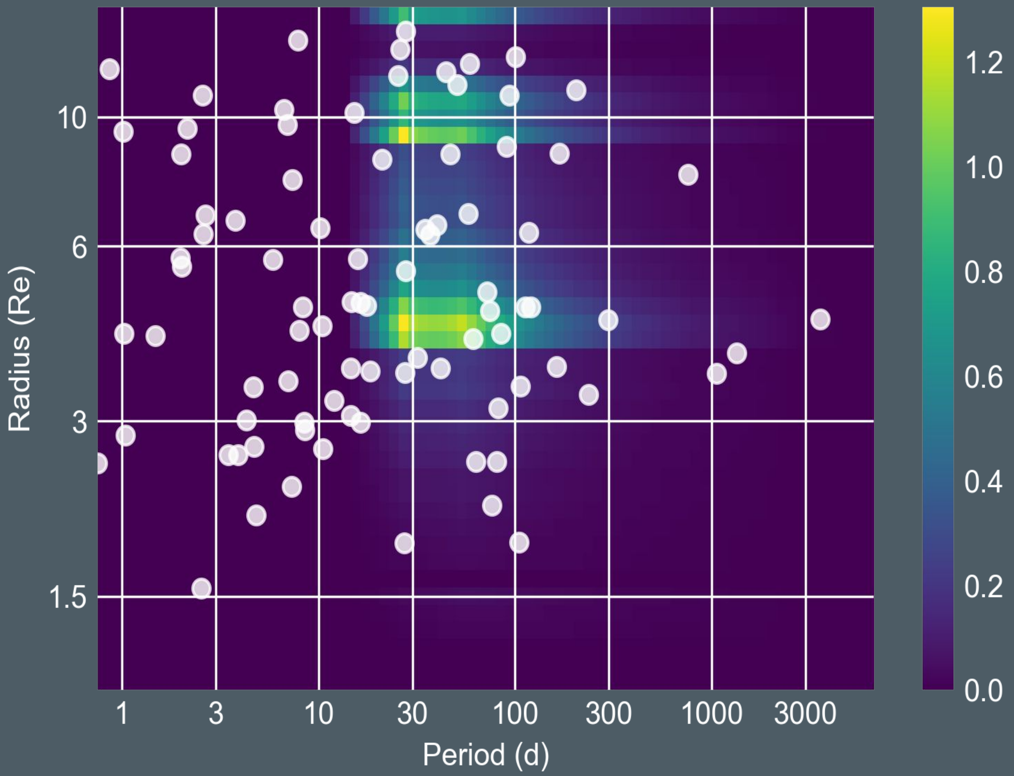
 - see Louise's talk

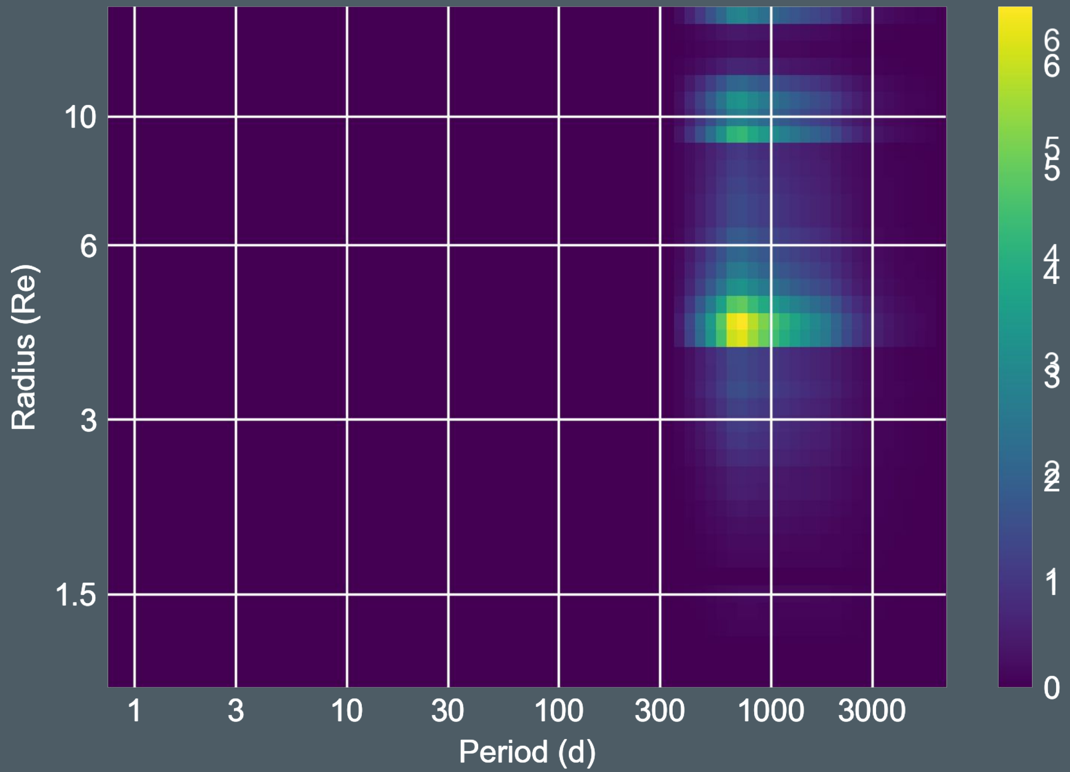


# Expectations for PLATO



Extrapolation from KIC: likely ~640 planets on P>2yrs detectable as singles (at 10-sigma) - 2.5x Kepler.

Many more multi-transiting planets also detectable before a second transit is observed.



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# Why PLATO needs singles

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- Long-period planets are interesting!
- 2-year stare fields = only 2 transits of exo-Earths
- Simultaneous RV + Plato photometry
- Initiating centroids, short-cadence photometry, imagettes, etc (e.g. P5 sample)

- Interestingness of long period planets:
    - Long-P planets are underexplored (occurrence rates, atmospheres, etc)
    - Unaffected by evolution/migration (closer to solar system analogues?)
    - Habitable Zone planets
    - Crossovers with populations of planets from Gaia, RV, WFIRST microlensing, and possibly even Direct Imaging

## PLATO Necessities:

- Needed as 2-year stare fields will produce only 2 transits of Earths
- Needed for simultaneous RV + Plato photometry

# False Positives in PLATO

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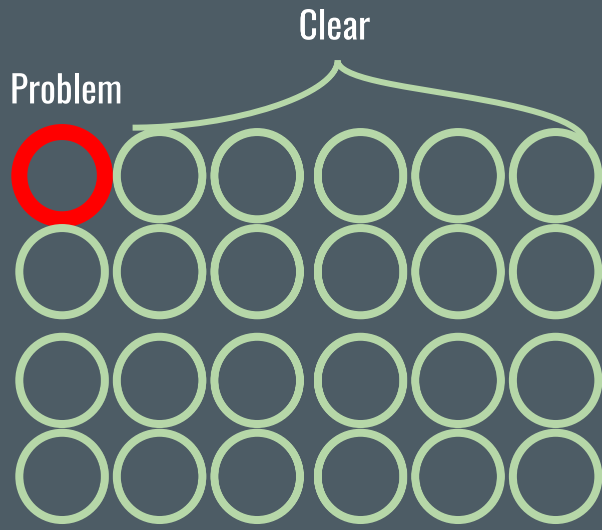
- Improved knowledge of EBs with Gaia DR3 astrometry & RVs.
- Asteroids: some but fewer than TESS/K2
- Reflected light:
  - At L2: effectively none
- Instrumental effects:
  - Per telescope or per telescope group: unlikely to be coherant
-



# Lessons



Don't expect single transits detected at 7-sigma.

But PLATO's design may limit the number of false positives

Need to either:

- Design a single-transit-specific pipeline to detect single transits
- Or make sure a general pipeline works for single transit cases

May need human vetting, or heavy injection-retrieval.

Thanks