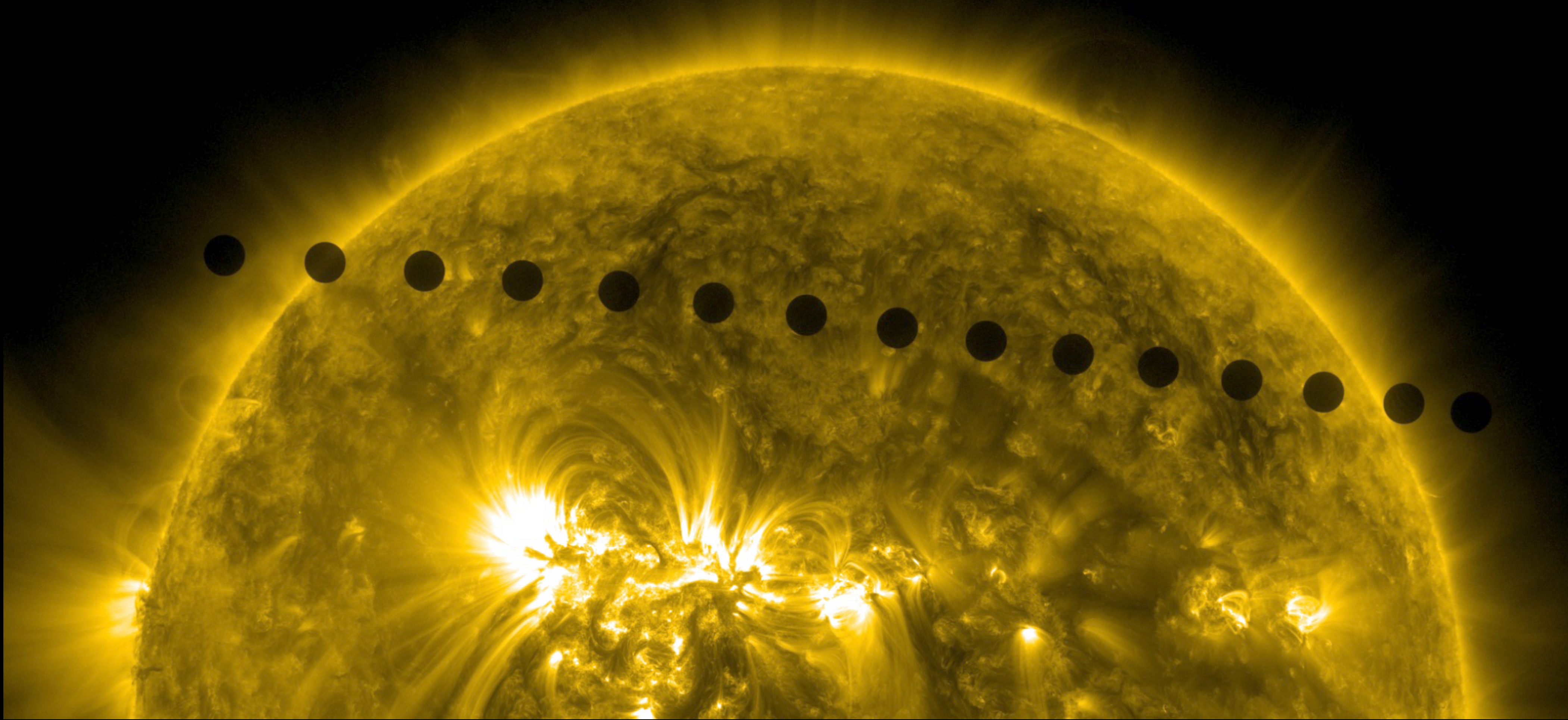
The Impact of Planet Reliability on $\eta_\oplus$



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Planet Reliability
What is it?

Detections that are classified as planet candidates, but they are not due to a bona-fide planet.

They contaminate your sample.

Type 2 statistical error.

- Astrophysical contamination due to eclipsing stellar binaries

- Instrumental contamination

Planet Reliability
What is it?

Large datasets (even purely white Gaussian noise) will experience extremely rare outliers.

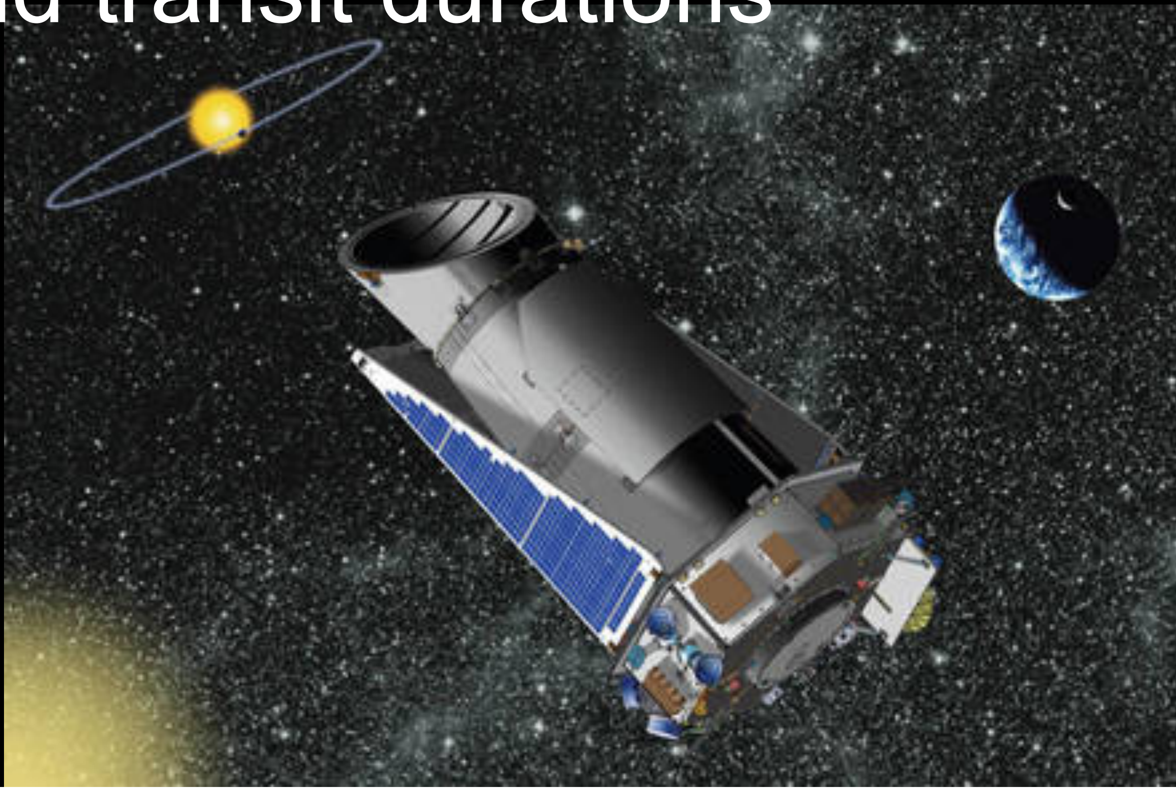
The larger the dataset, the larger the threshold needs to be to avoid contamination.

In practice, red noise, impulsive systematics, and astrophysical variability require larger thresholds.

Kepler Reliability

Kepler data set is large with 4 years of coverage.

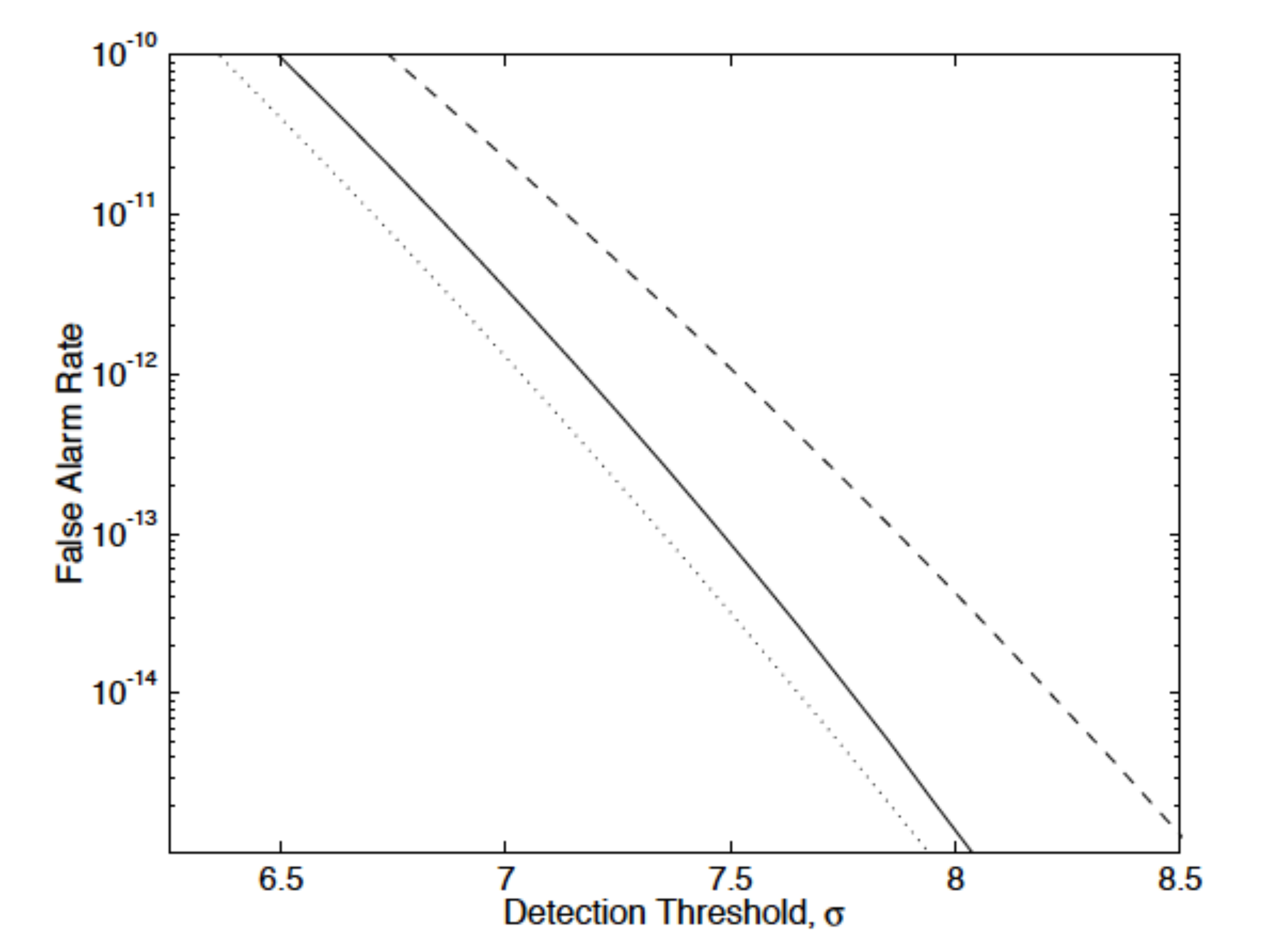
•~60,000 Observations
•~100,000 GK dwarf targets
•Periods, phases, and transit durations trials



~2x10^{12} Trials

Expected False Alarm Rate

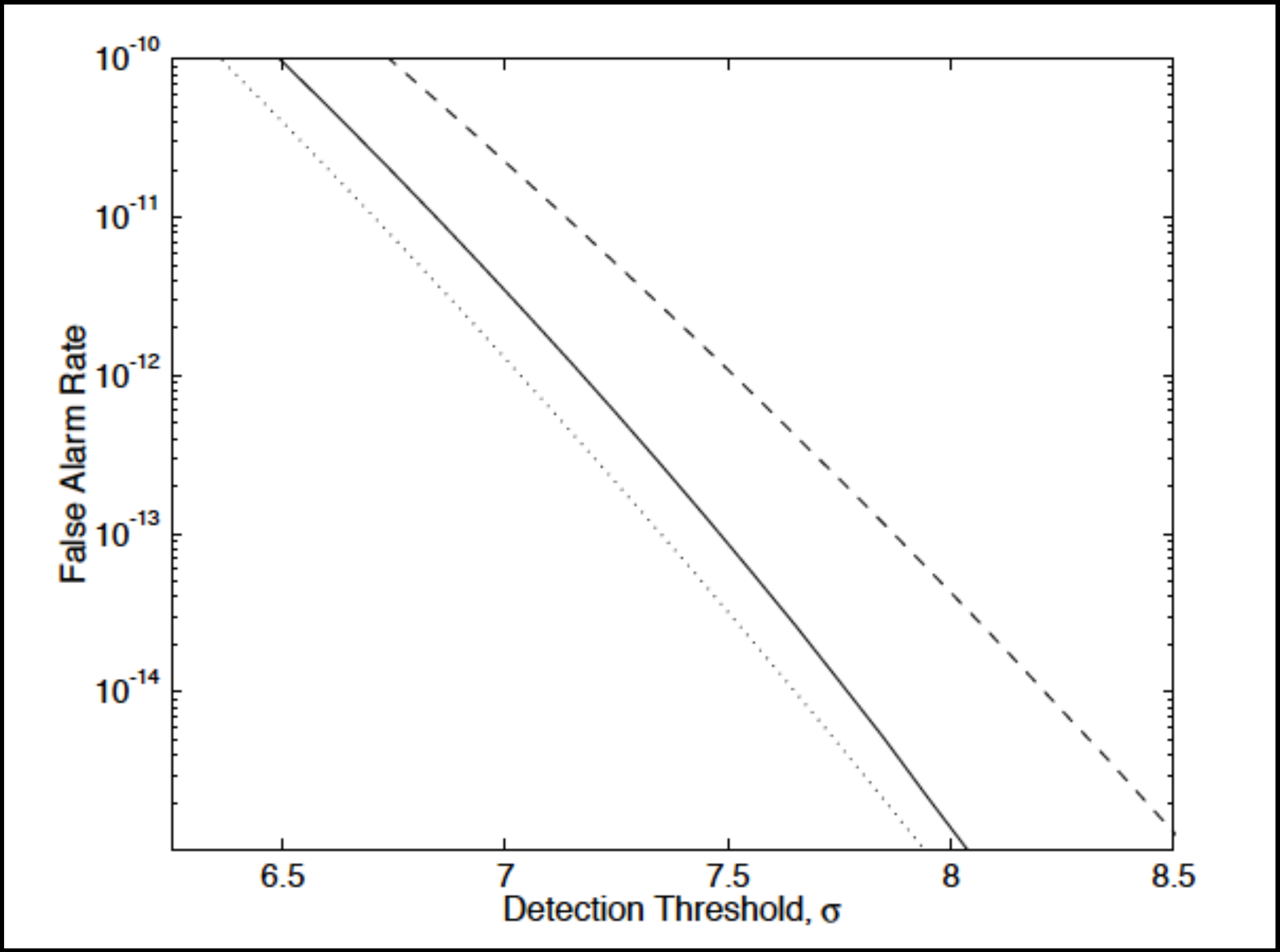
Jenkins (2002) examined Kepler expectation



Threshold of 7.1σ
allows for one false alarm

Expected False Alarm Rate

Jenkins (2002) examined Kepler expectation

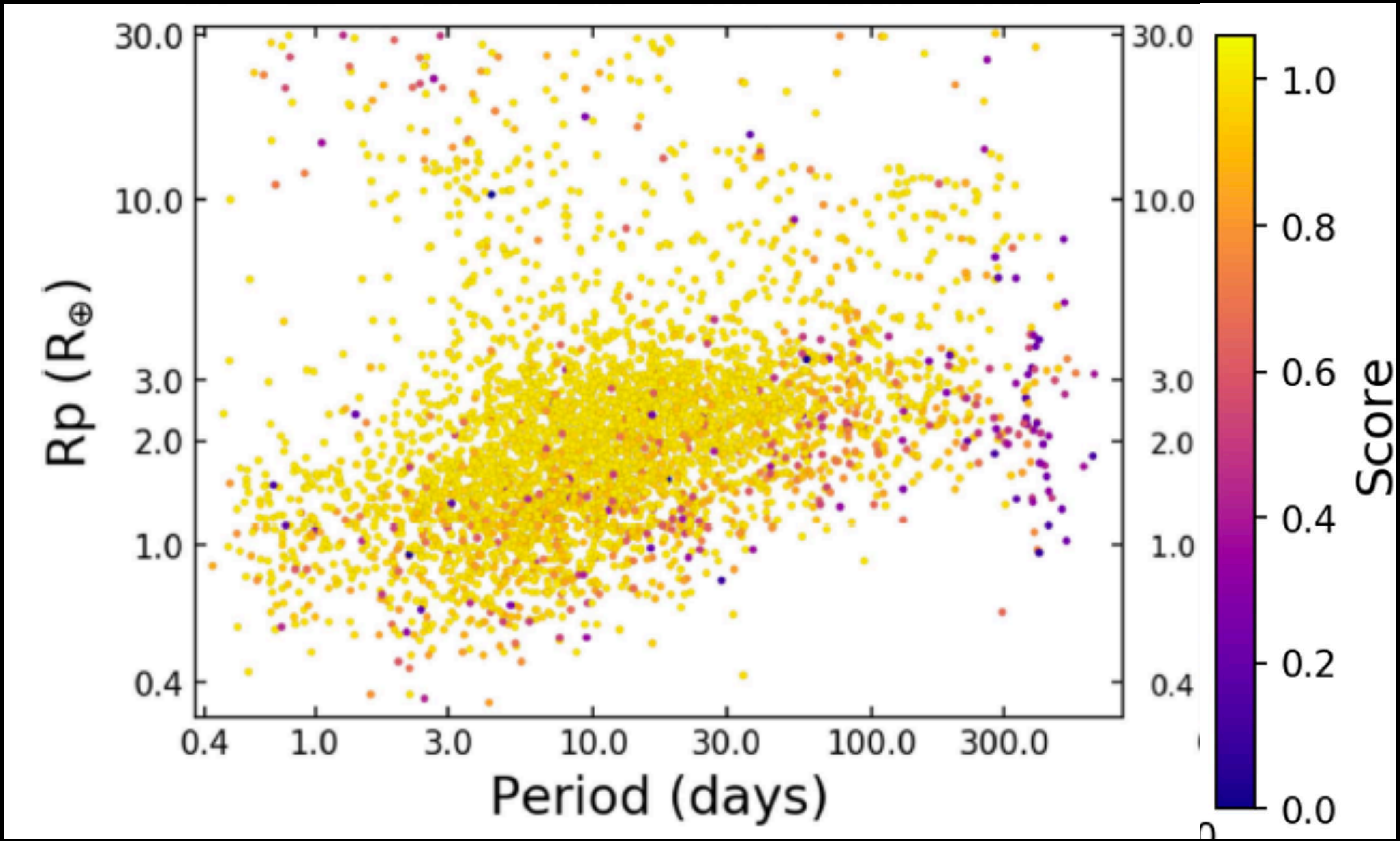


10 times higher FA rate every 0.4σ reduction in threshold.

Threshold of 7.1σ allows for one false alarm

Kepler Excess Detections False Alarms or Real?

Mullally et al. (2015) Q1-Q16 ; Burke et al. (2015) occ. rate.



Thompson et al. (2015) DR25

Kepler Excess Detections
False Alarms or Real?

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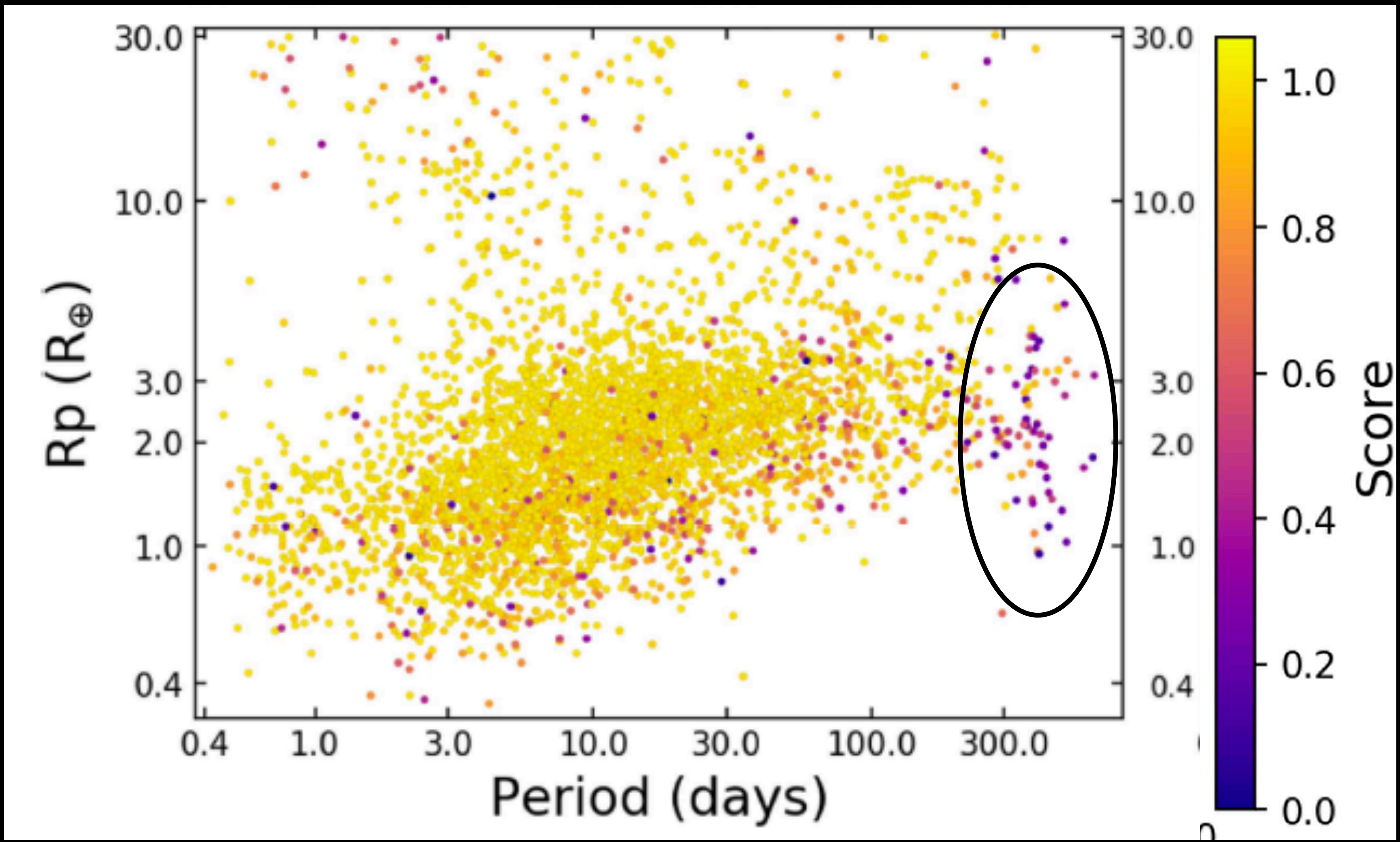


Thompson et al. (2015) DR25

FA Sample Examples

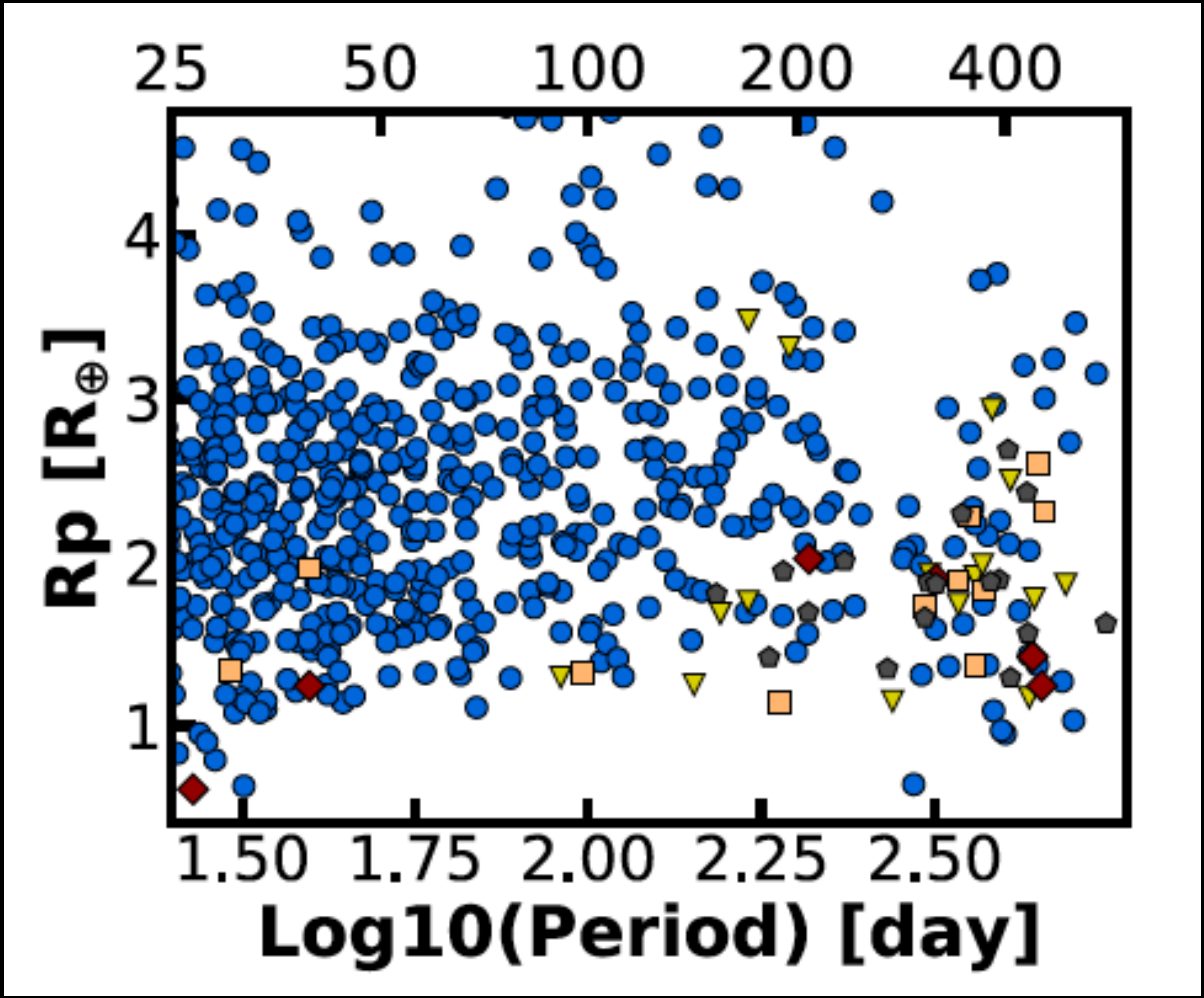
Four (1 inversion; 3 scrambling) datasets

Automated Kepler Robovetter applies ~50 vetting metrics to classify as planet candidate

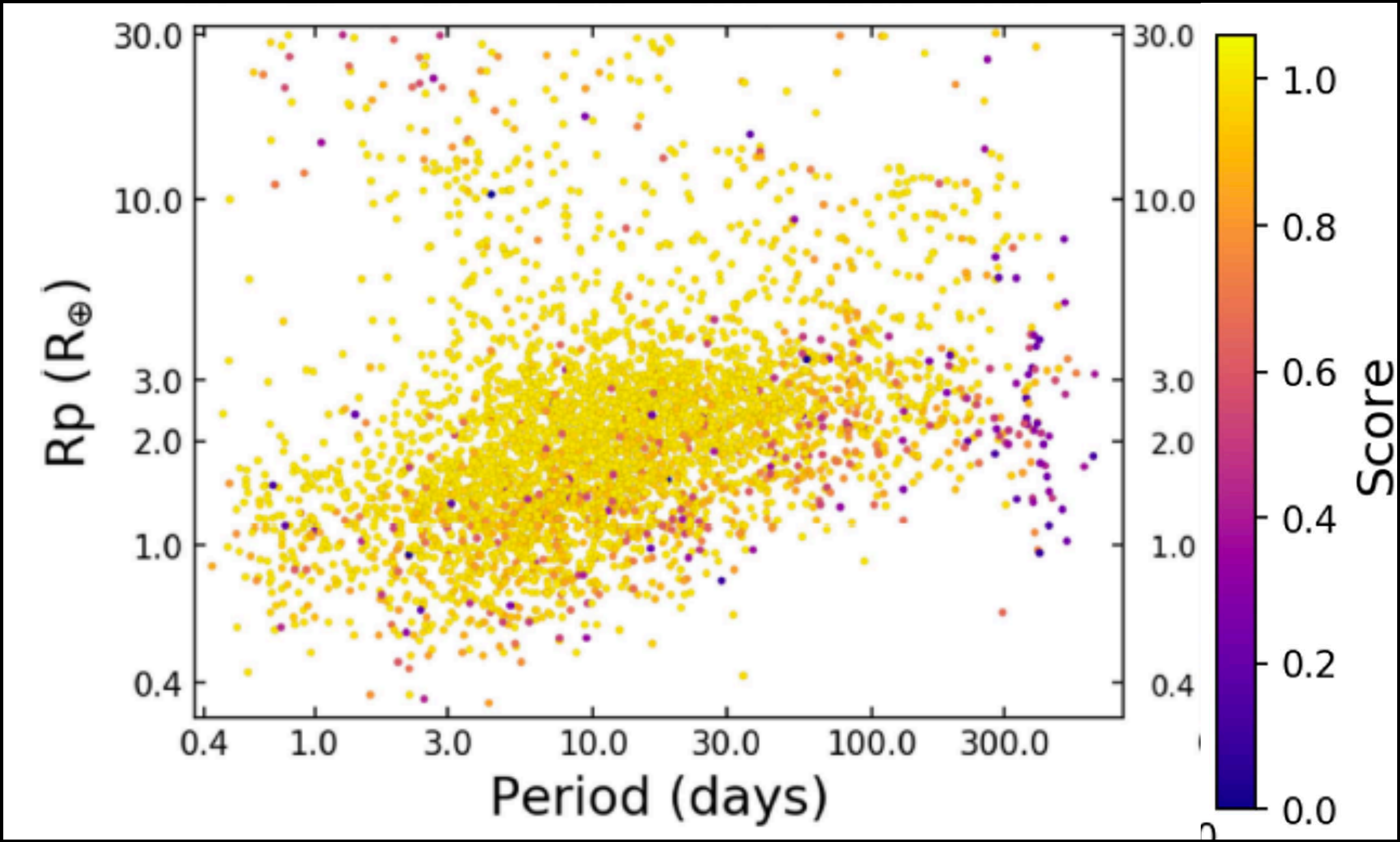
Results Publicly Available on the NASA exoplanet archive.

https://exoplanetarchive.ipac.caltech.edu/docs/KeplerSimulated.html

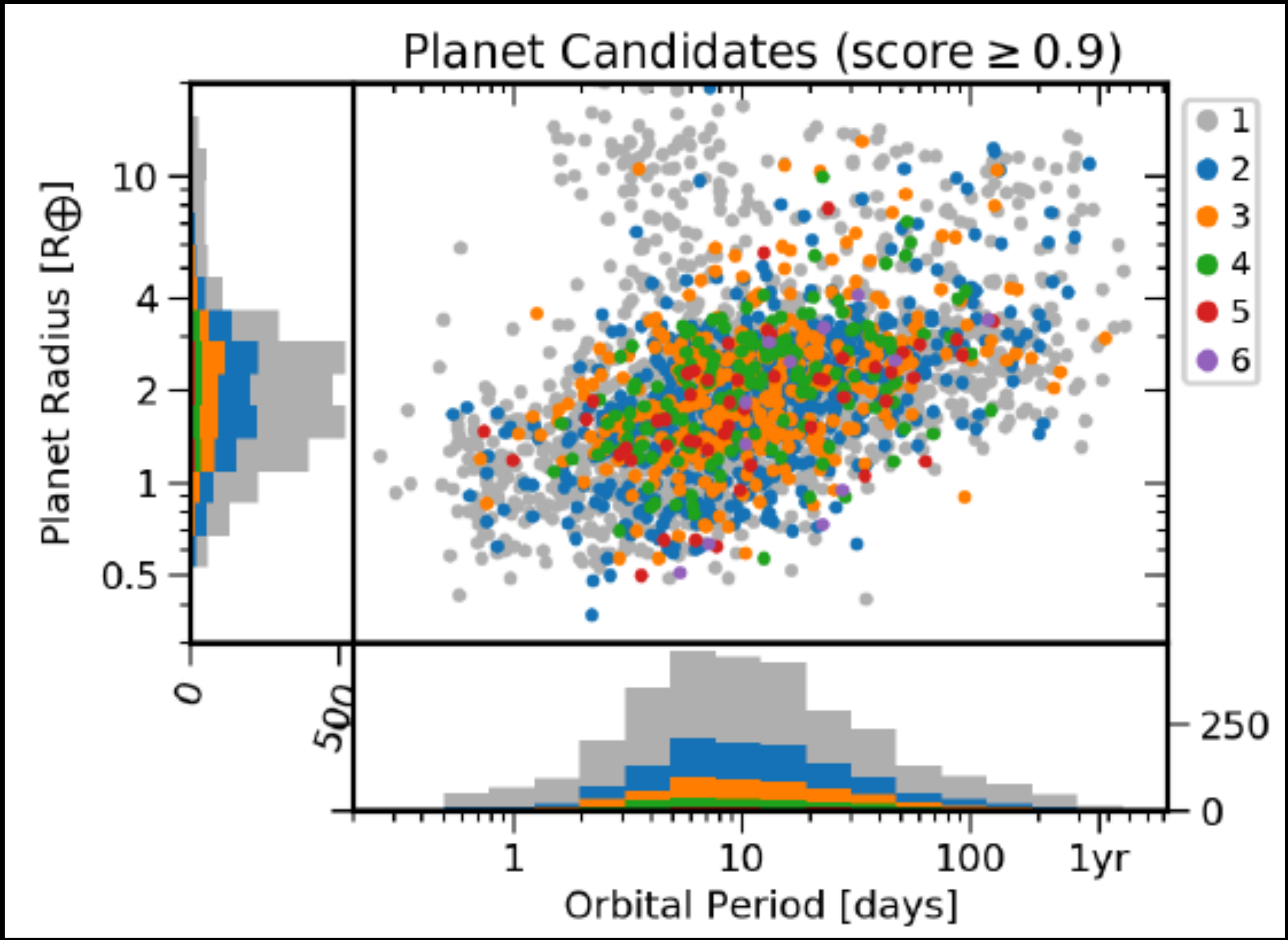
Kepler FA ‘Planet Candidate’ Sample



Is the long period Kepler planet candidate excess real?



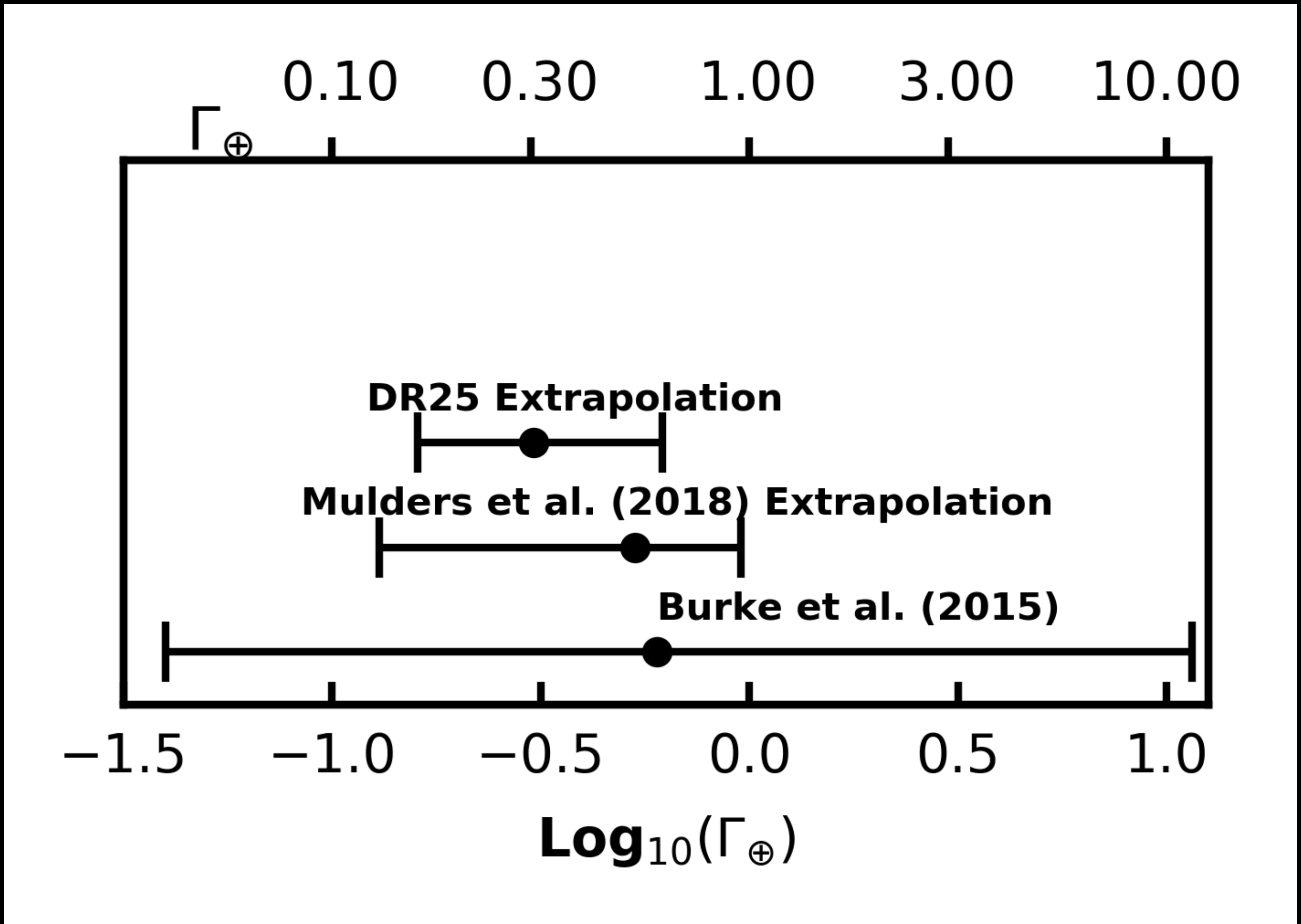
Only analyze high reliability candidates?



Robovetter score cut >0.9 removes the excess.

Mulders et al. (2018)

Is the long period Kepler planet candidate excess real?

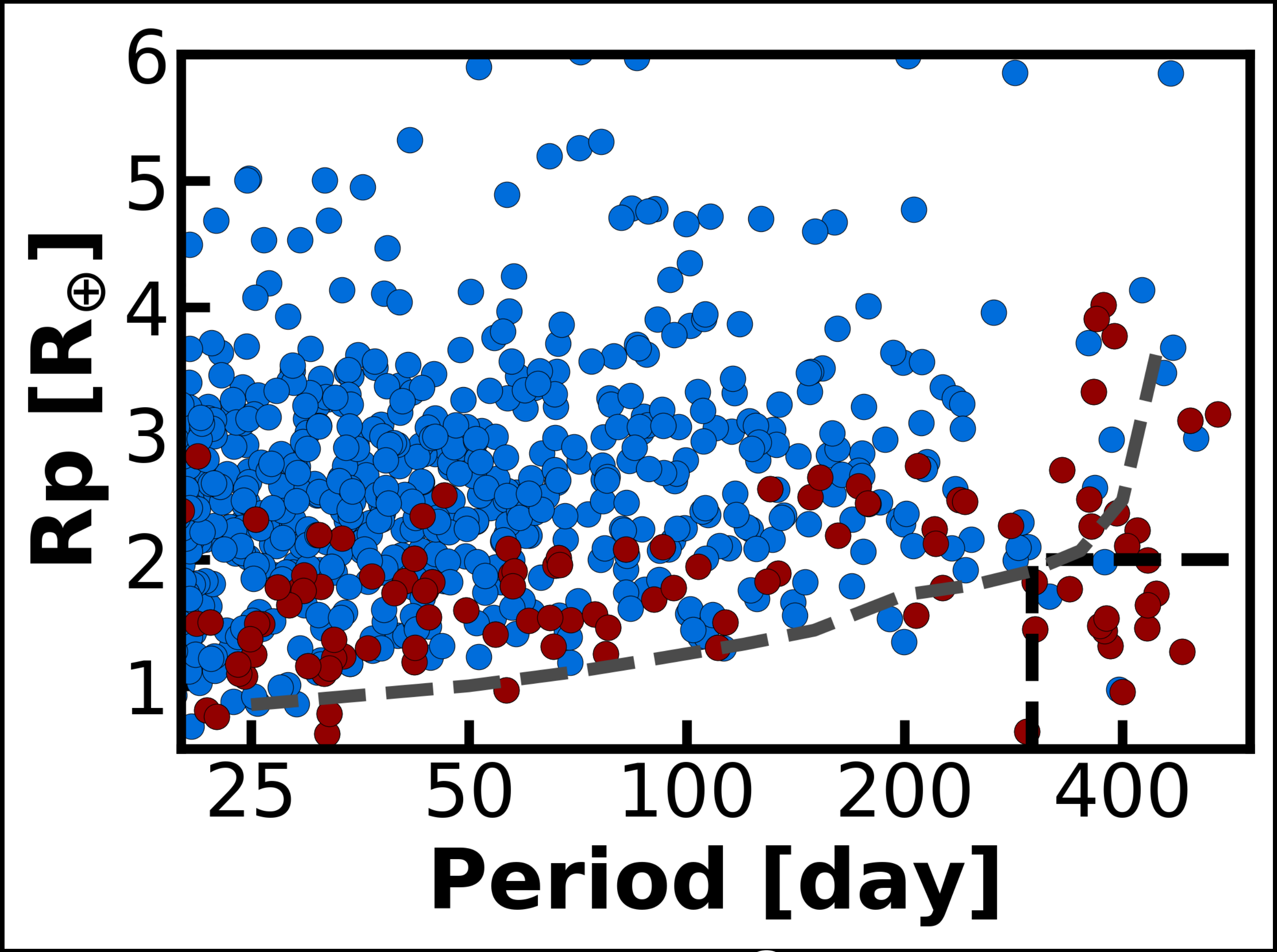


$$\Gamma_\oplus \sim \eta_\oplus$$

See SAG13 report discussion of this

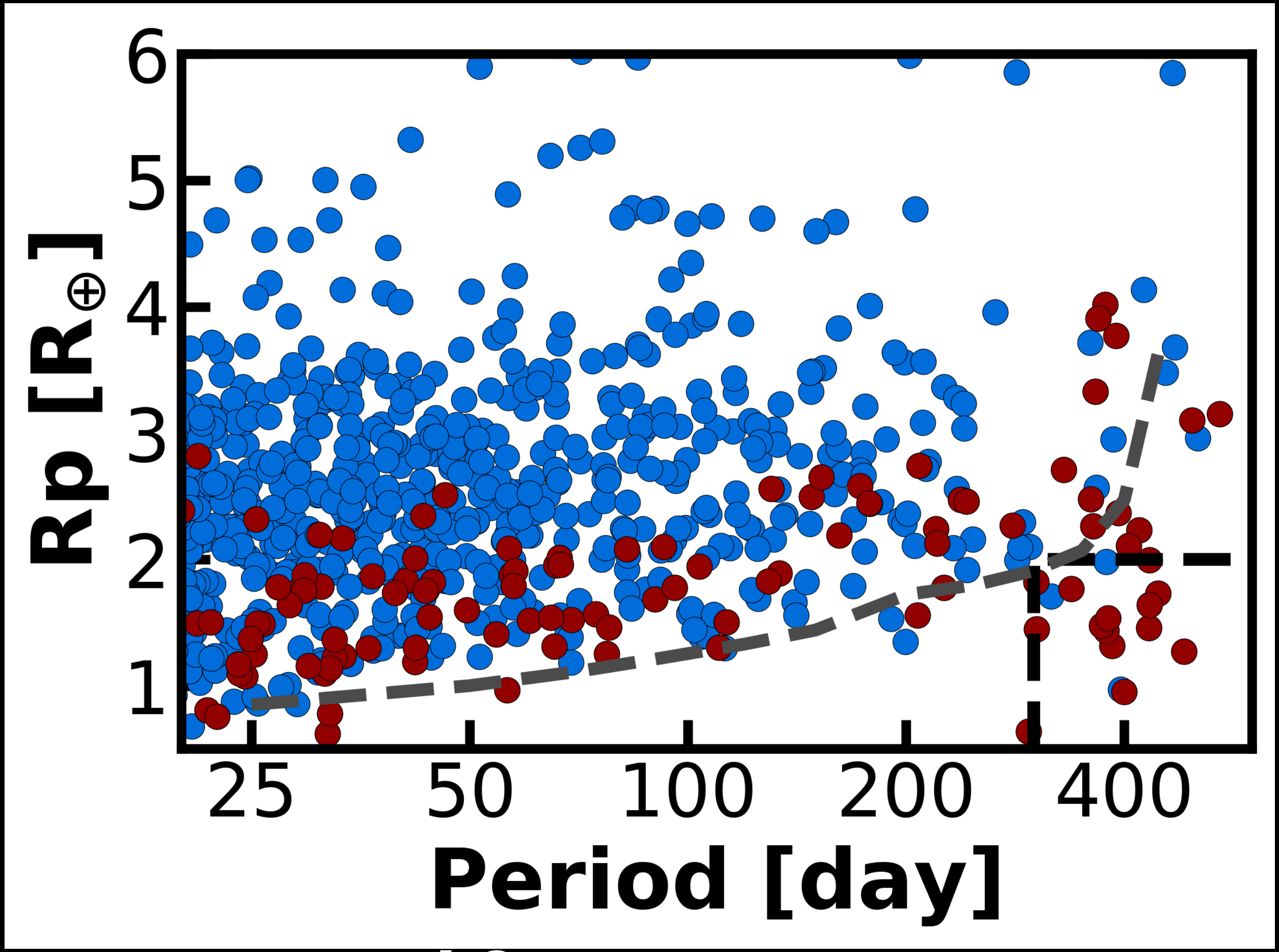
Points show ***2-σ ranges*** NOT 1-σ errorbars

Is the long period Kepler planet candidate excess real?



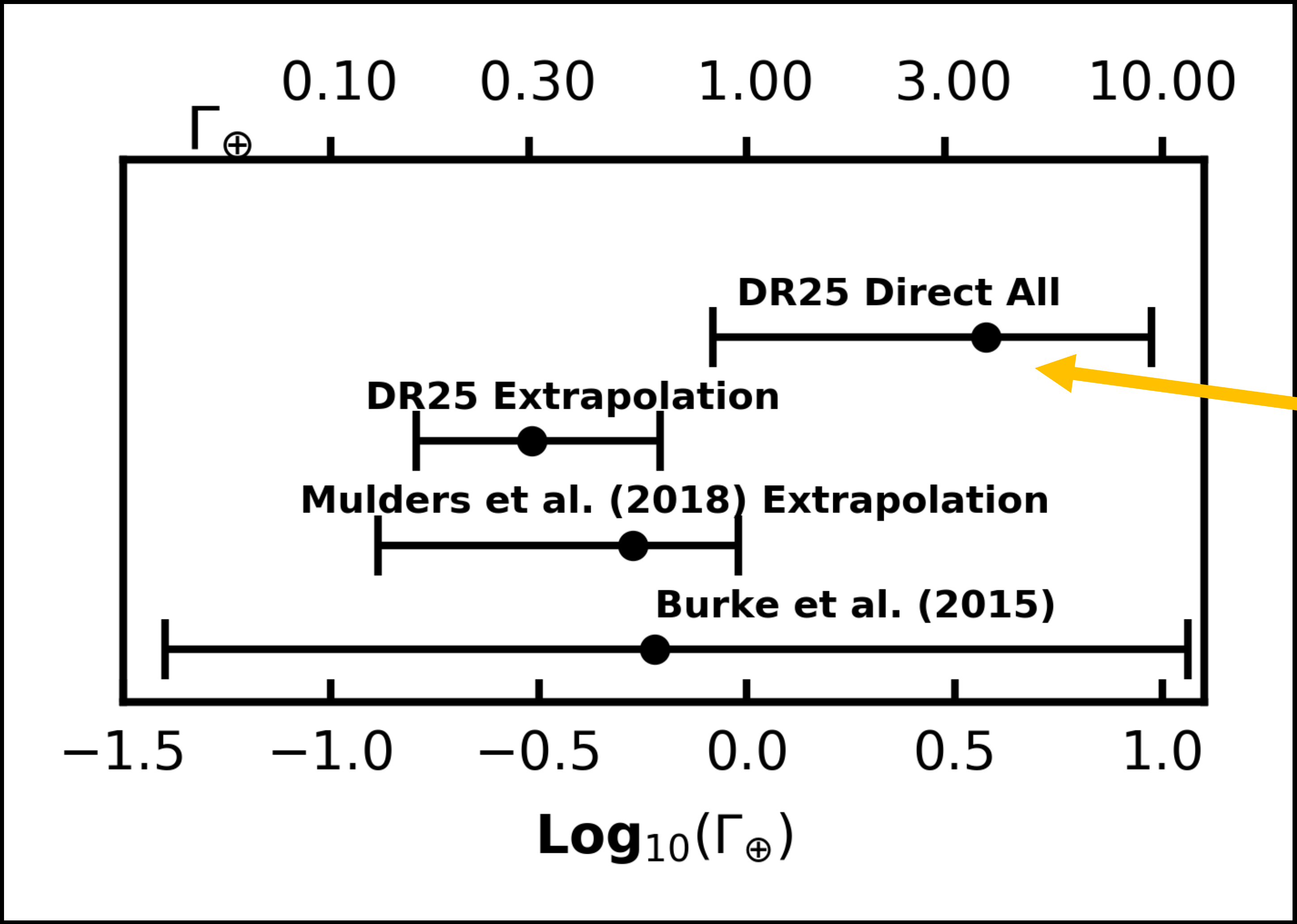
Extrapolated prediction is **3** planet candidates with P_{orb}>300 day and R_p<2 $R_\oplus$

Is the long period Kepler planet candidate excess real?



Kepler detected **16** planet candidates with P_{orb}>300 day and R_p<2 $R_\oplus$

Is the long period Kepler planet candidate excess real?



No contamination Corrections

Points show ***2-σ ranges*** NOT 1-σ errorbars

Is the long period Kepler planet candidate excess real?

Accounting for Contamination

Statistically **11** are expected to be real planets with

P_{orb}>300 day and R_p<2 $R_{\oplus}$

2-σ limit range 8-14 are real

Statistically Compelling Excess

Is the long period Kepler planet candidate excess real?

Accounting for Contamination

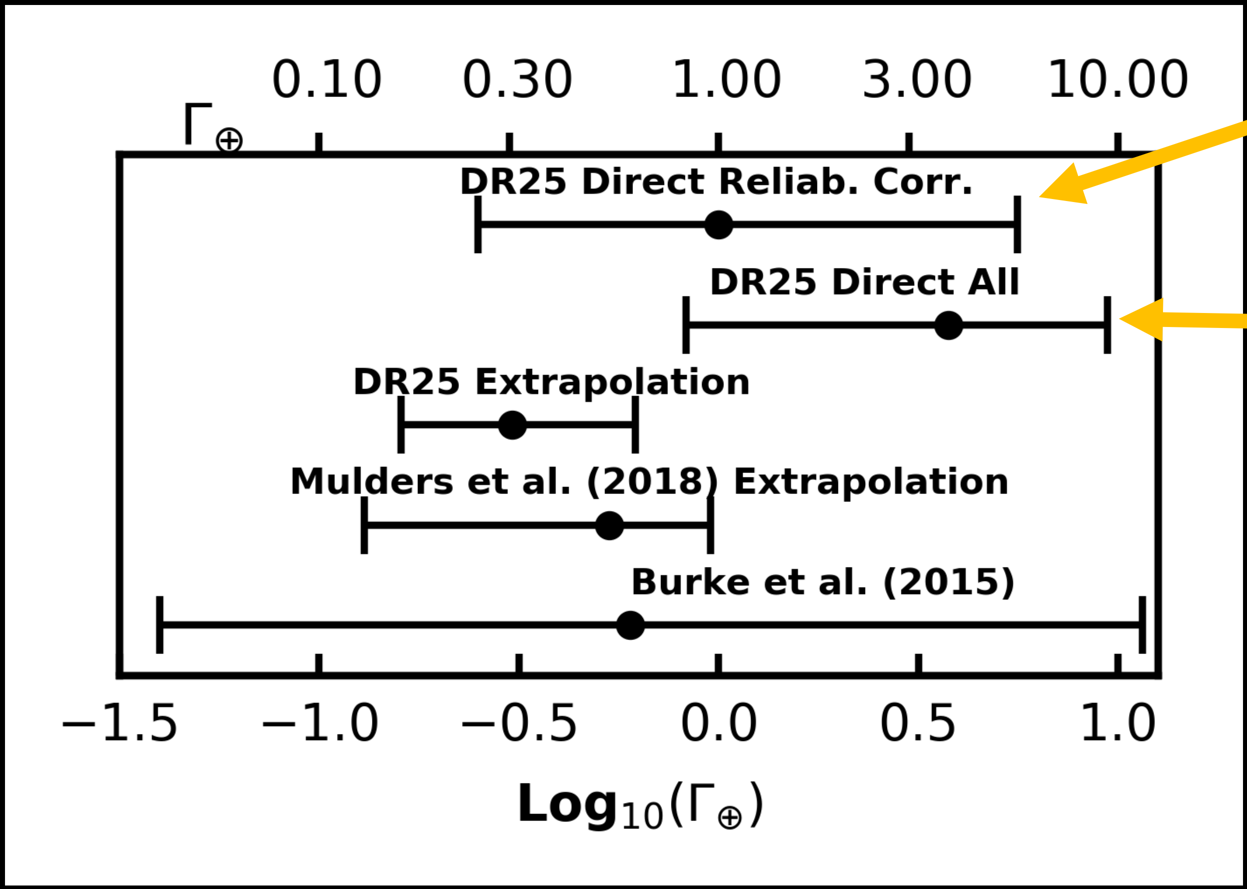
Statistically **11** are expected to be real planets with

P_{orb}>300 day and R_p<2 $R_{\oplus}$

2-σ limit range 8-14 are real

The contamination estimates are not high enough to explain the P>300 day Kepler planet candidate detections

Is the long period Kepler planet candidate excess real?

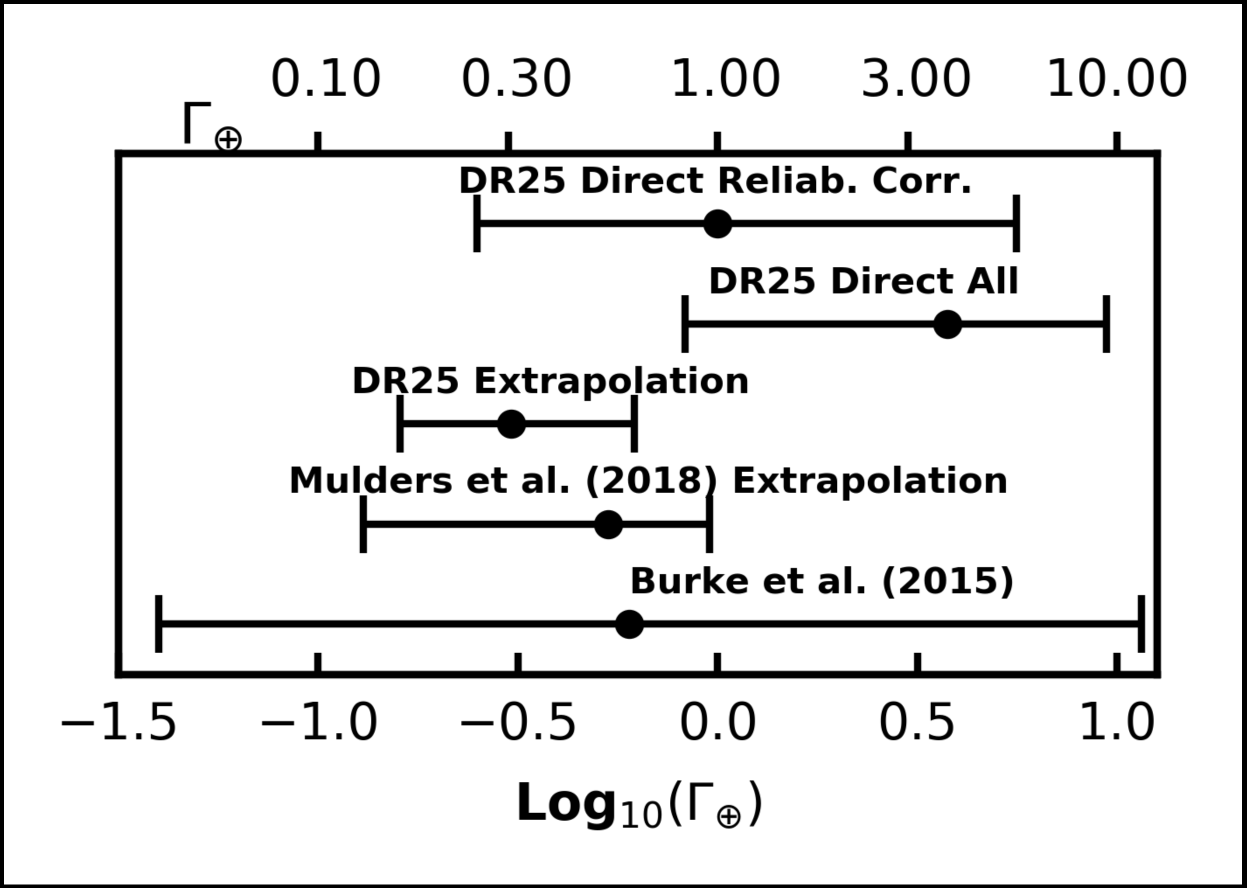


Contamination Corrected

No contamination Corrections

Points show ***2-σ ranges*** NOT 1-σ errorbars

Is the long period Kepler planet candidate excess real?

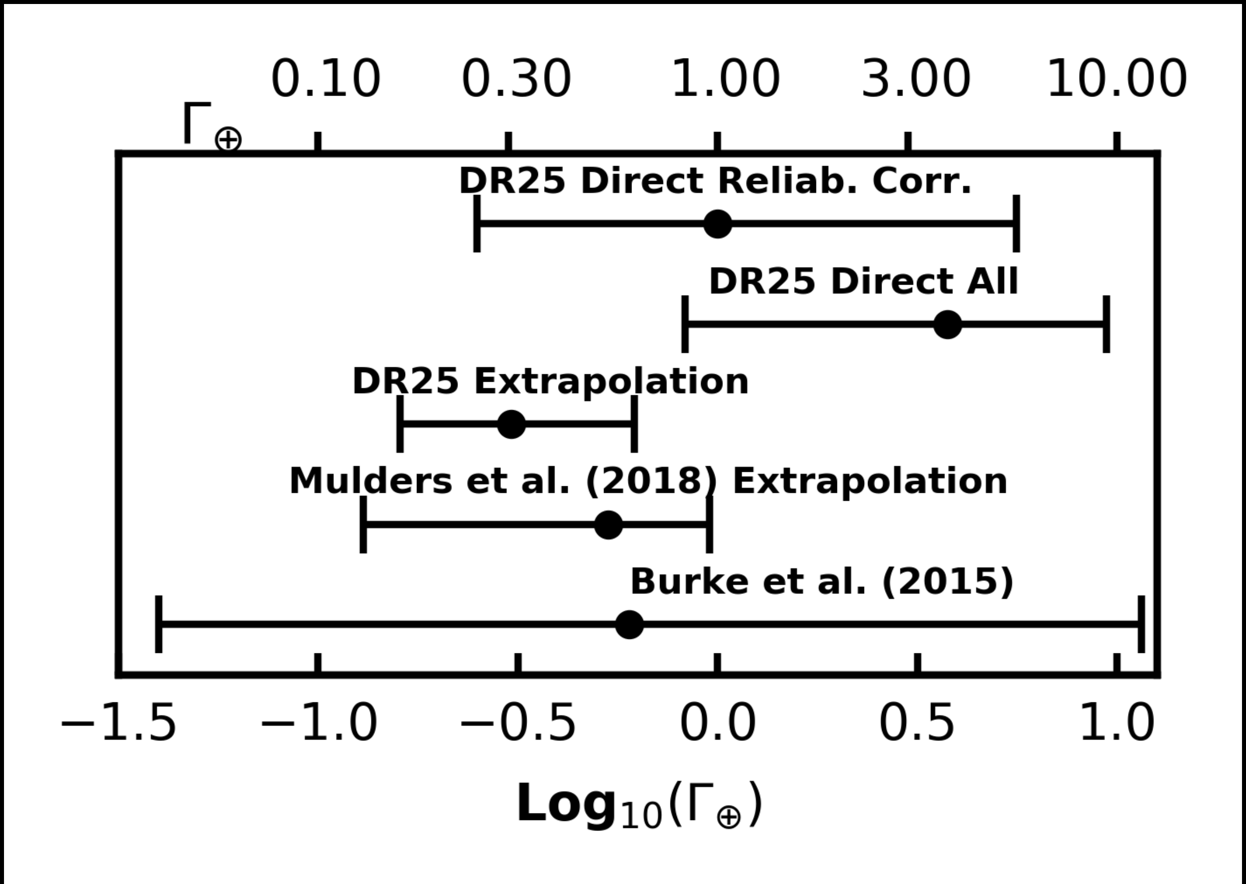


DR25 Kepler catalog

$\eta_\oplus$ continues to be high.

Points show ***2-σ ranges*** NOT 1-σ errorbars

Is the long period Kepler planet candidate excess real?



DR25 Kepler catalog

$\eta_\oplus$ continues to be high.

Range (1.4 dex) of allowed values remains high as well.

Points show ***2-σ ranges*** NOT 1-σ errorbars

Have results in the literature converged? Additional work needed

How to optimally use the false alarm contamination data?

Ignoring the poor reliability detections is not an option. Evidence suggests extrapolating from reliable region is underestimating $\eta_{\oplus}$

Stellar sample still needs work even with GAIA

- GAIA astrometric excess noise cuts preferentially remove small, long-period planet hosts?
- Planet hosts have spectra based parameters, non-hosts do not. Leads to systematic offset in detection contours

Have results in the literature converged? Additional work needed

Kepler DR25 Occurrence rate products AND KeplerPORTs code is the standard for generating detection contours for interpreting the Kepler DR25 planet candidate sample. Please use all of it not parts of it. KeplerPORTs is validated against 10^8 transit injection and recovery trials that are publicly available.

Improved high resolution imaging database and modeling of stellar blend scenarios.

Continued planet multiplicity modeling.

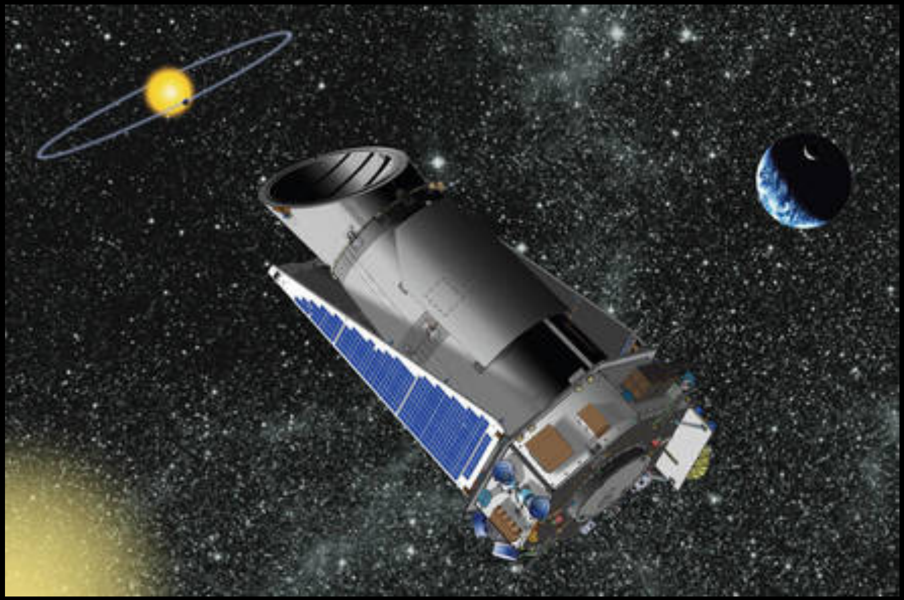
Planet Reliability Remains The Primary Obstacle For Refining $\eta_\oplus$

Without extrapolation, reducing uncertainty below 1.4 dex on $\eta_\oplus$ doesn't appear feasible.

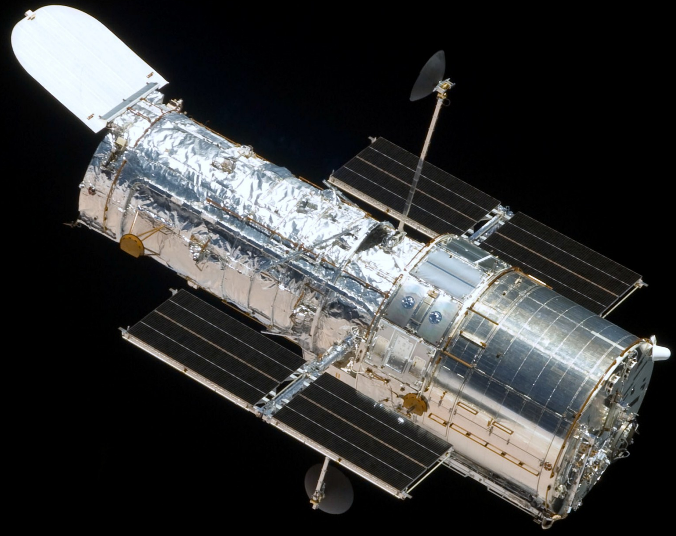
Does the false alarm contamination experiment accurately quantify low-level systematics?

It is statistical in nature. I can estimate that between 8 and 14 are real, but I can't tell you which of the 16 are real.

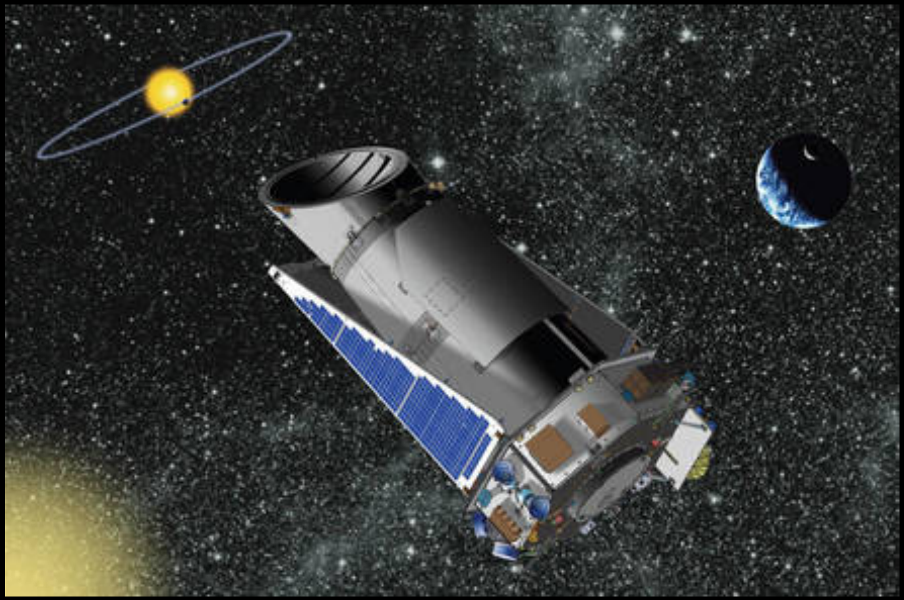
Planet Reliability Reduced and False Alarm Estimate Confirmed



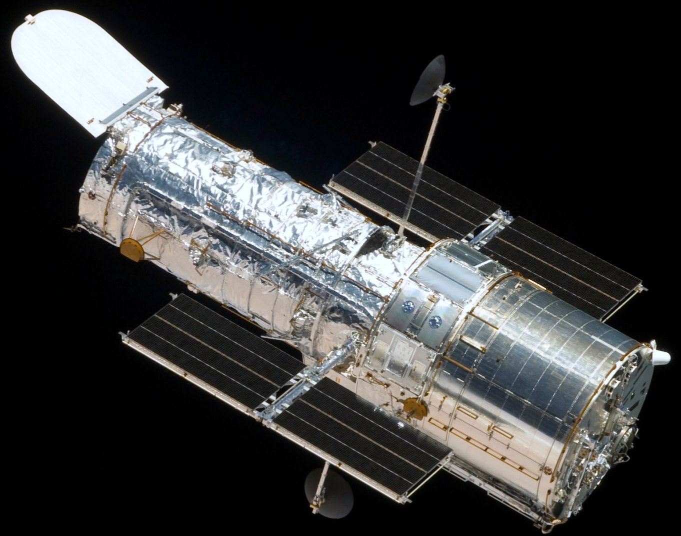
Can I phone a friend?



Planet Reliability Reduced and False Alarm Estimate Confirmed



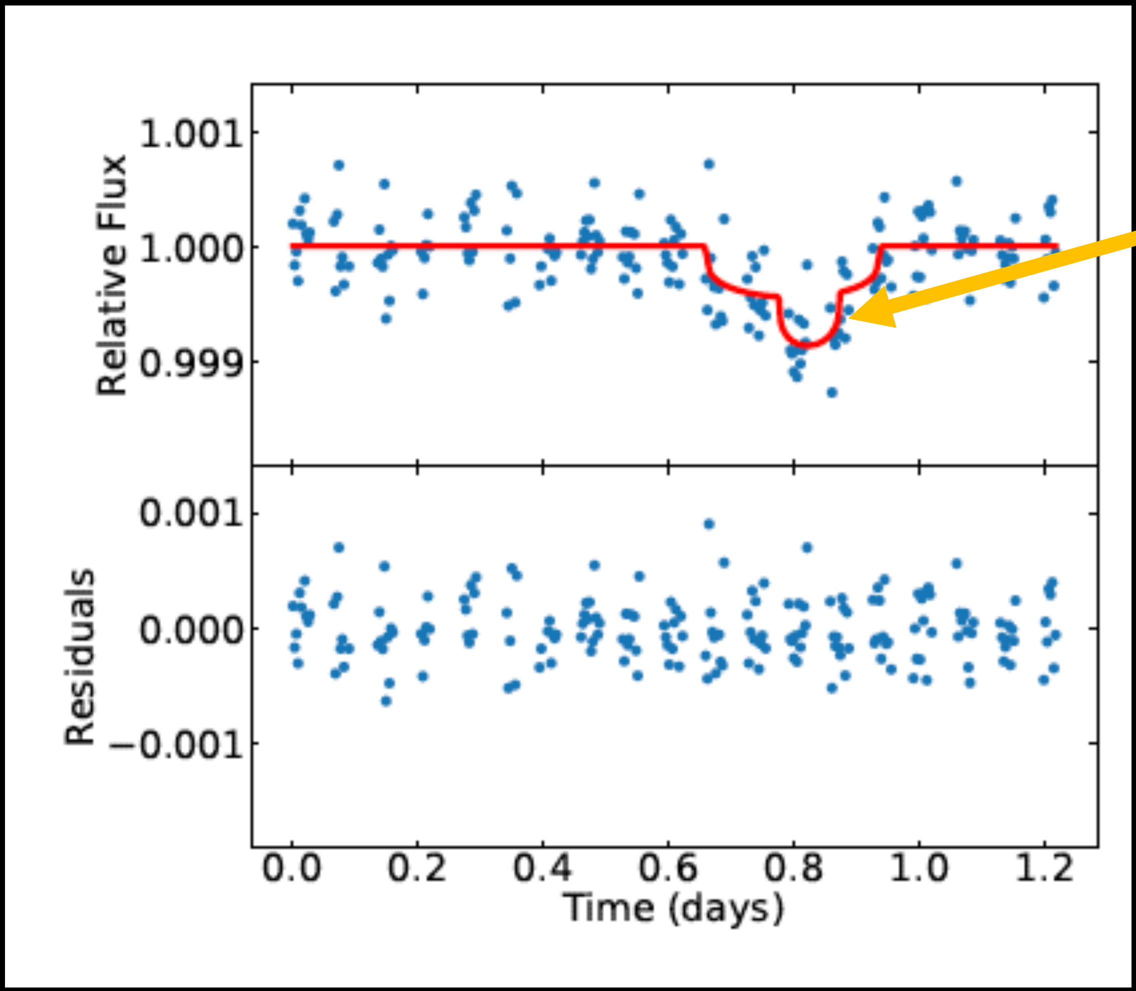
With HST



Single HST visit provides ~2x the SNR of a transit relative to single Kepler transit.

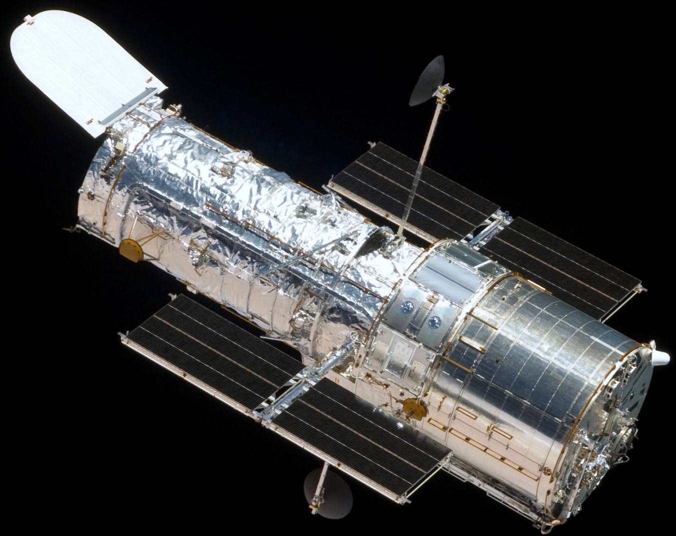
Single HST visit for KOI 7016.01 (Kepler-452b) SNR=8

Cycle 25 Program
Re-confirm Kepler-62f



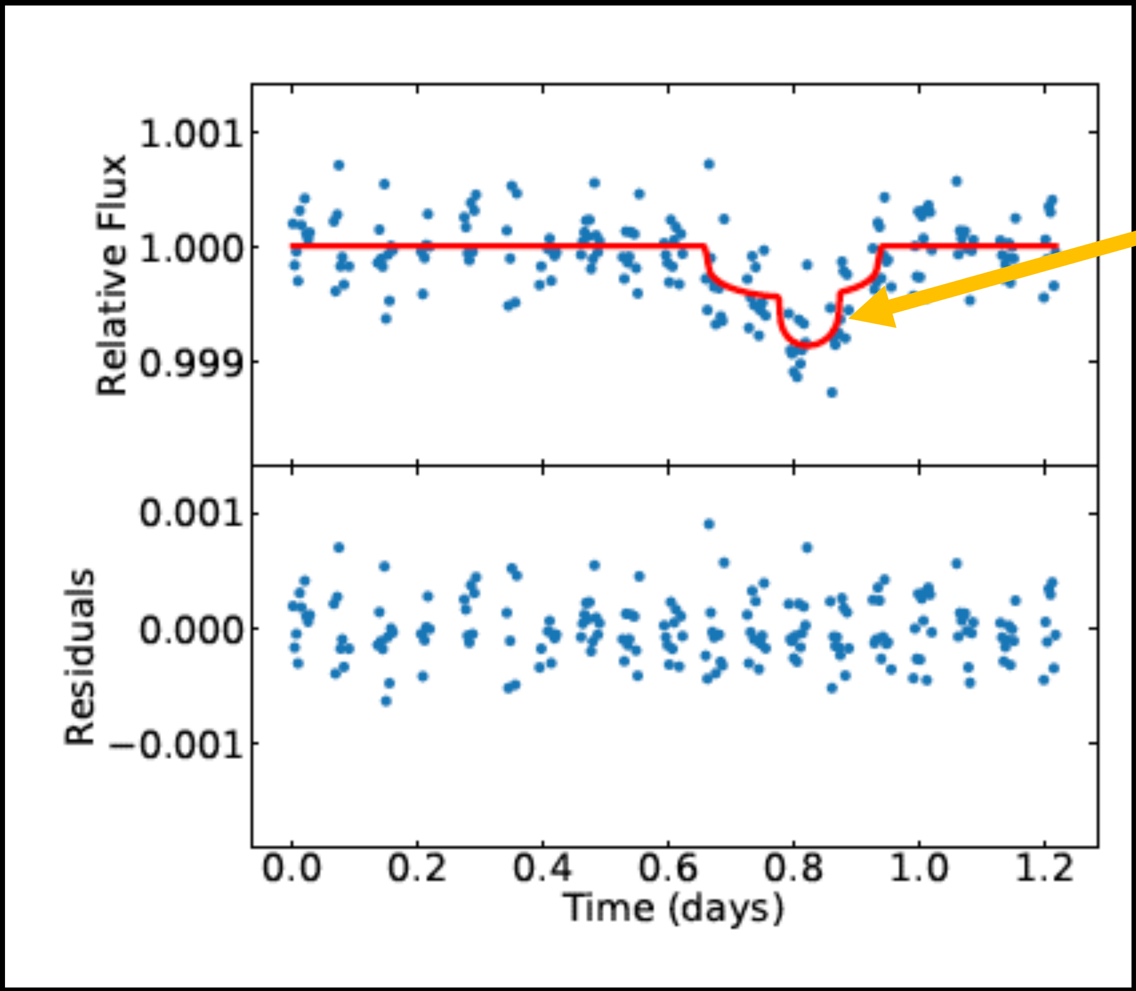
Simultaneous transit
with Kepler-62b

With HST



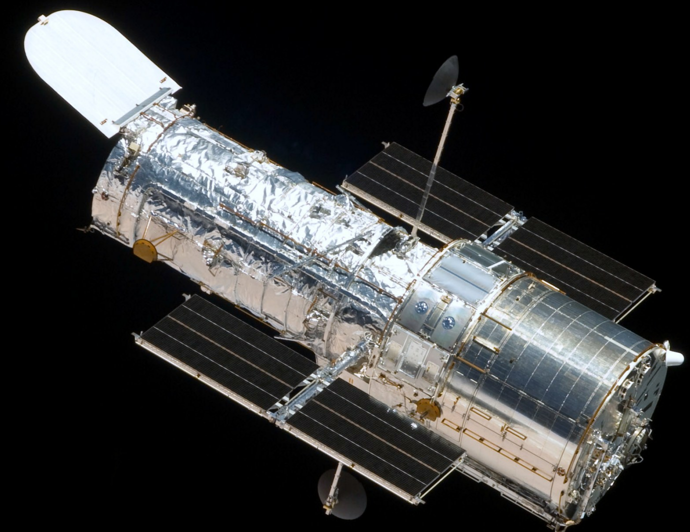
UVIS F350LP w/ spatial scanning
Continuous 19 Orbit Visit through SAA

Cycle 25 Program
Re-confirm Kepler-62f



Simultaneous transit with Kepler-62b

With HST



Achieved Poisson Expectation
75ppm/HST orbit (V=14)

Conclusion

Instrumental False Alarm Contamination Estimates For Kepler Are Available

Compelling excess of small, long-period Kepler planet candidates in the P_{orb}>300 day and R_p<2 $R_\oplus$ region.

The excess small, long-period Kepler candidates remain after accounting for the measured false alarm contamination.

Conclusion

My current recommendation is an estimate of $\Gamma_{\oplus} = 1.0$ with a systematic driven range of $0.25 < \Gamma_{\oplus} < 4.5$ from DR25 analysis.

Work remains to facilitate and reach consensus in the literature for occurrence rates in this regime.

However, the systematic range on $\Gamma_{\oplus}$(~1.4 dex) likely cannot be reduced further without HST follow-up to eliminate FA contamination from the error budget.

Conclusion

First tentative hints of a new feature in the terrestrial planet Habitable Zone region.

Potential to inform understanding the planet formation process.

Confirmation with HST for a significant sample of these candidates could provide the first bona-fide members of this feature, confirm the accuracy of the statistical false alarm contamination estimate, and provide observational support for refining $\Gamma_{\oplus}$ estimates.

Empirically Measure FA Rate
Data Permutation

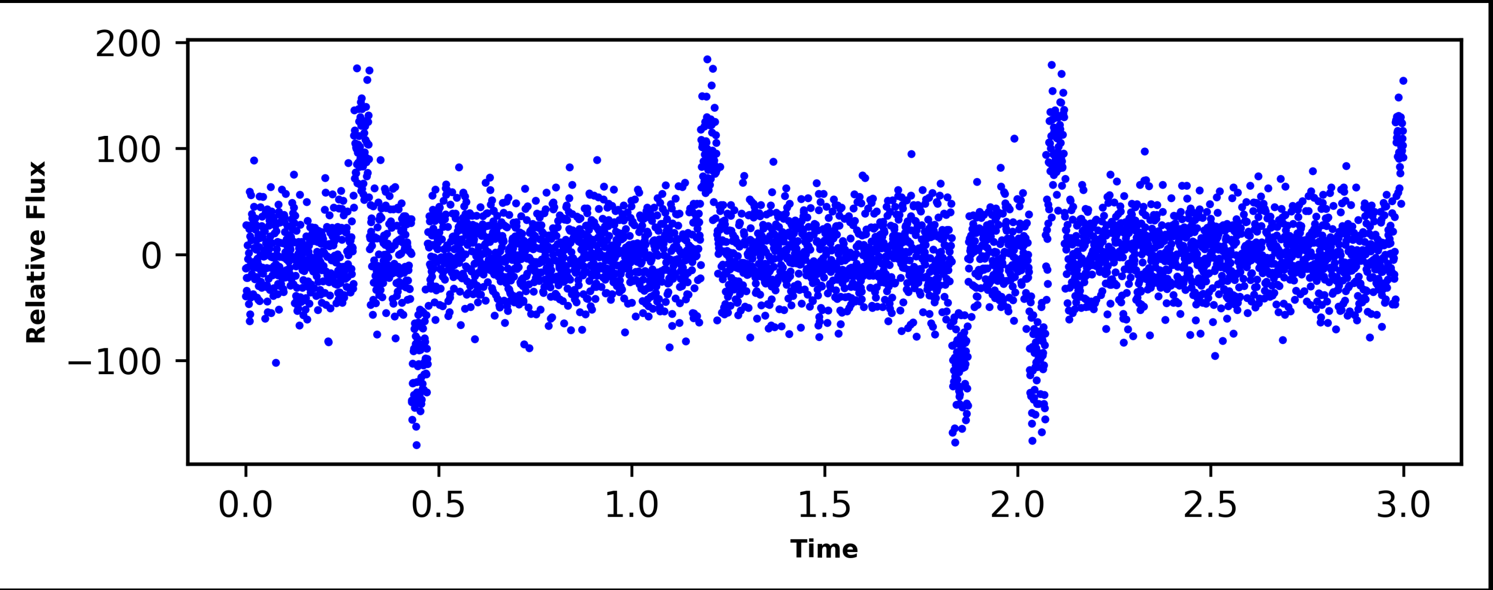
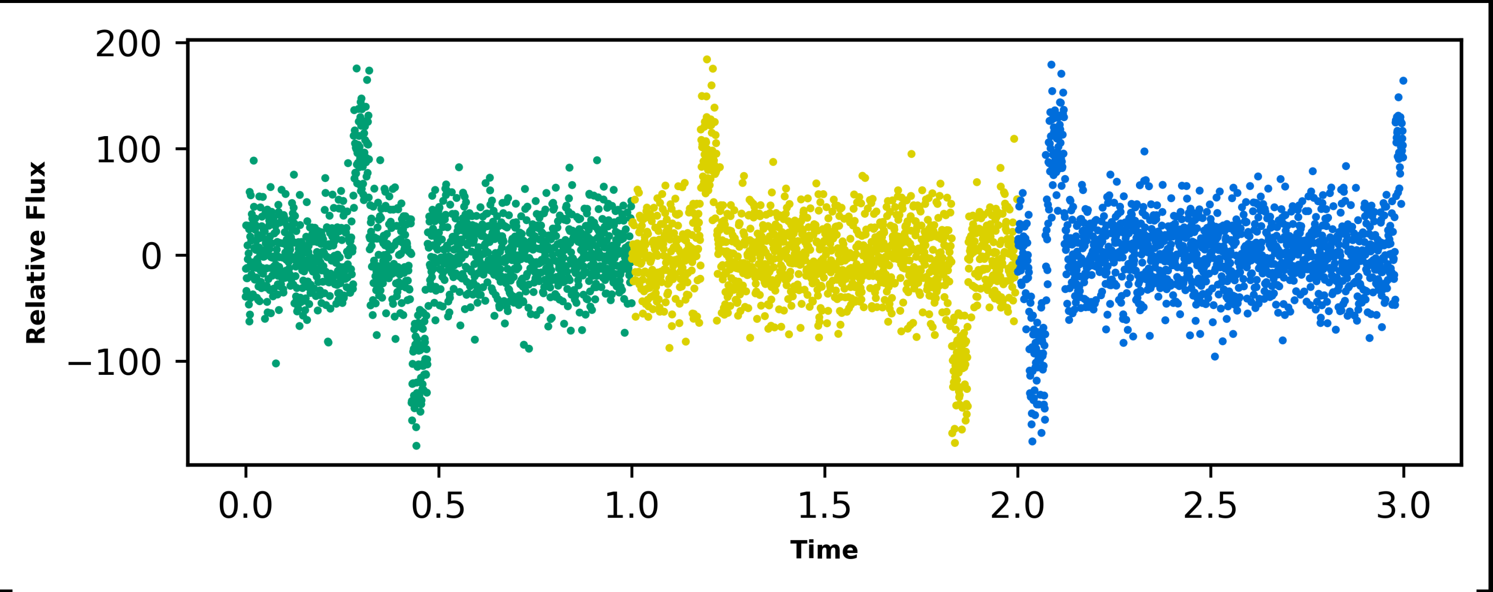


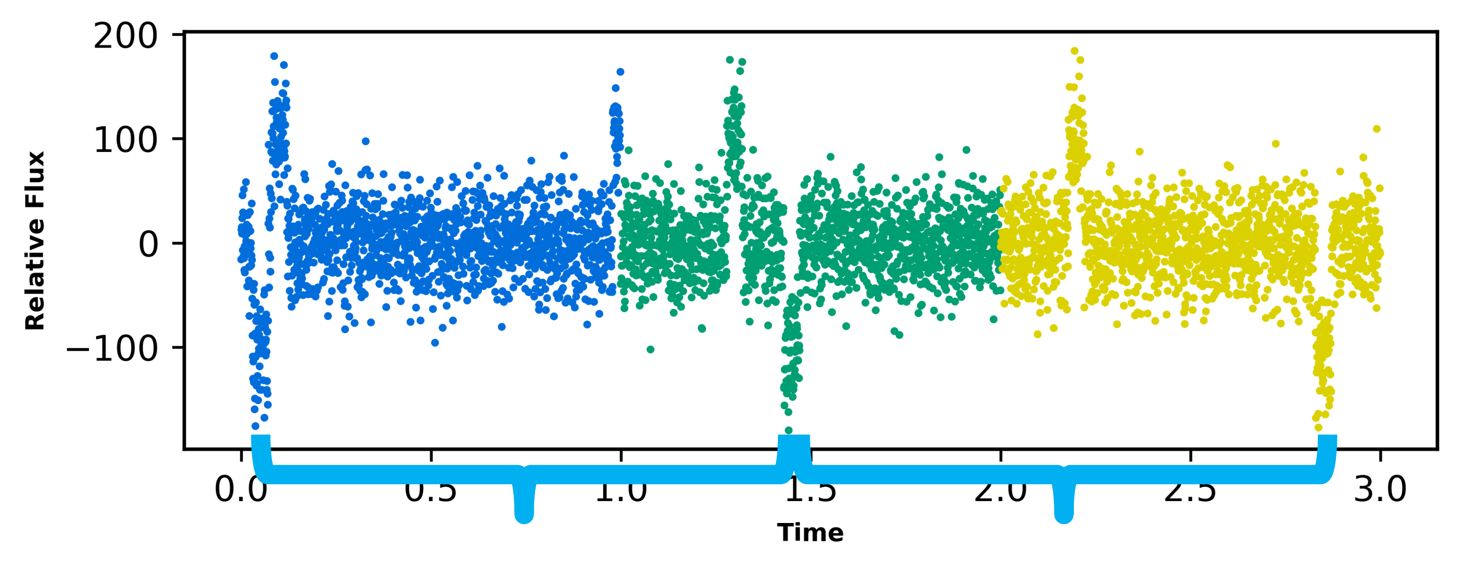
Illustration of data with systematics exaggerated!
No evenly spaced transit events

Empirically Measure FA Rate
Data Permutation

Original



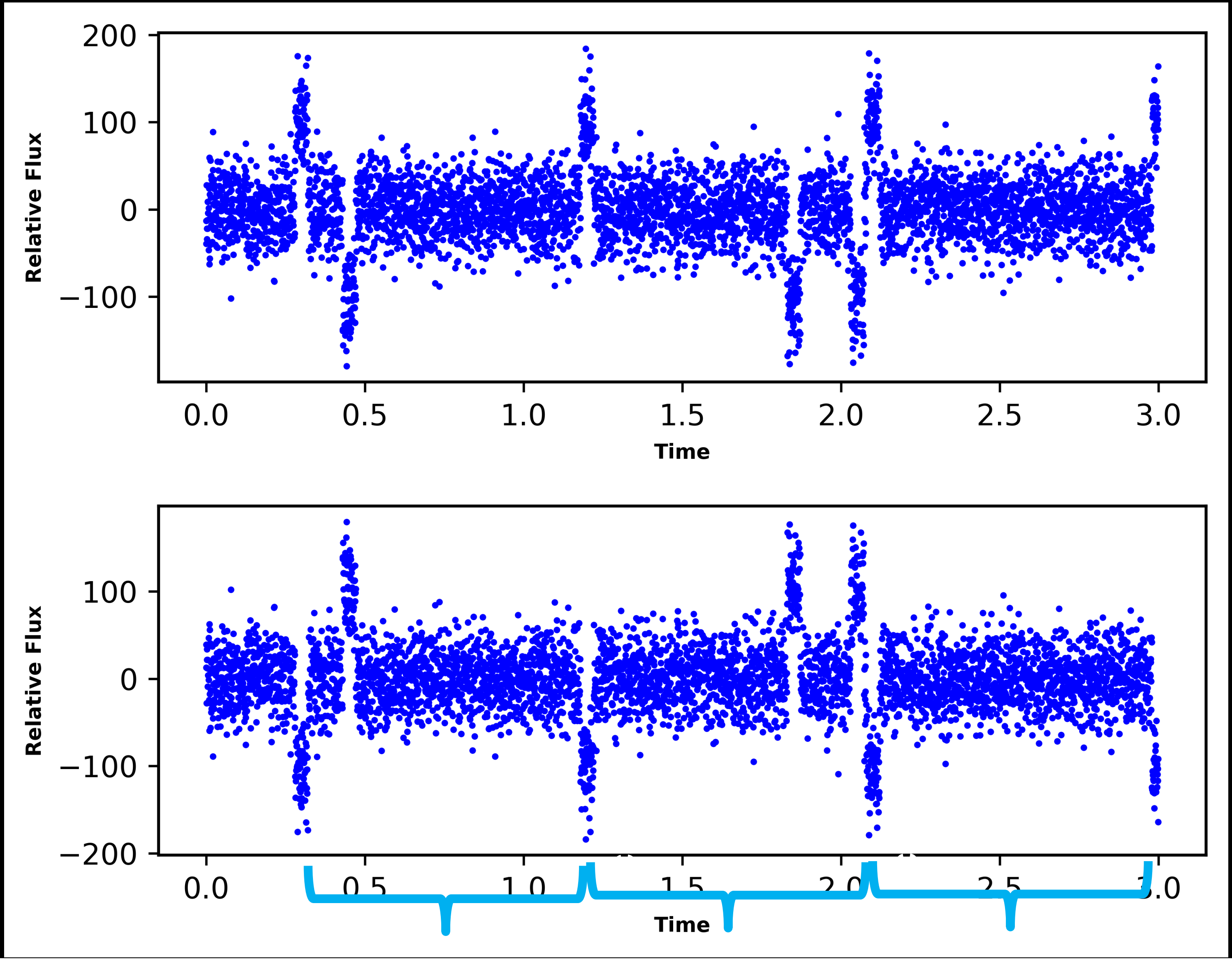
Scrambled Segments



Empirically Measure FA Rate
Data Permutation

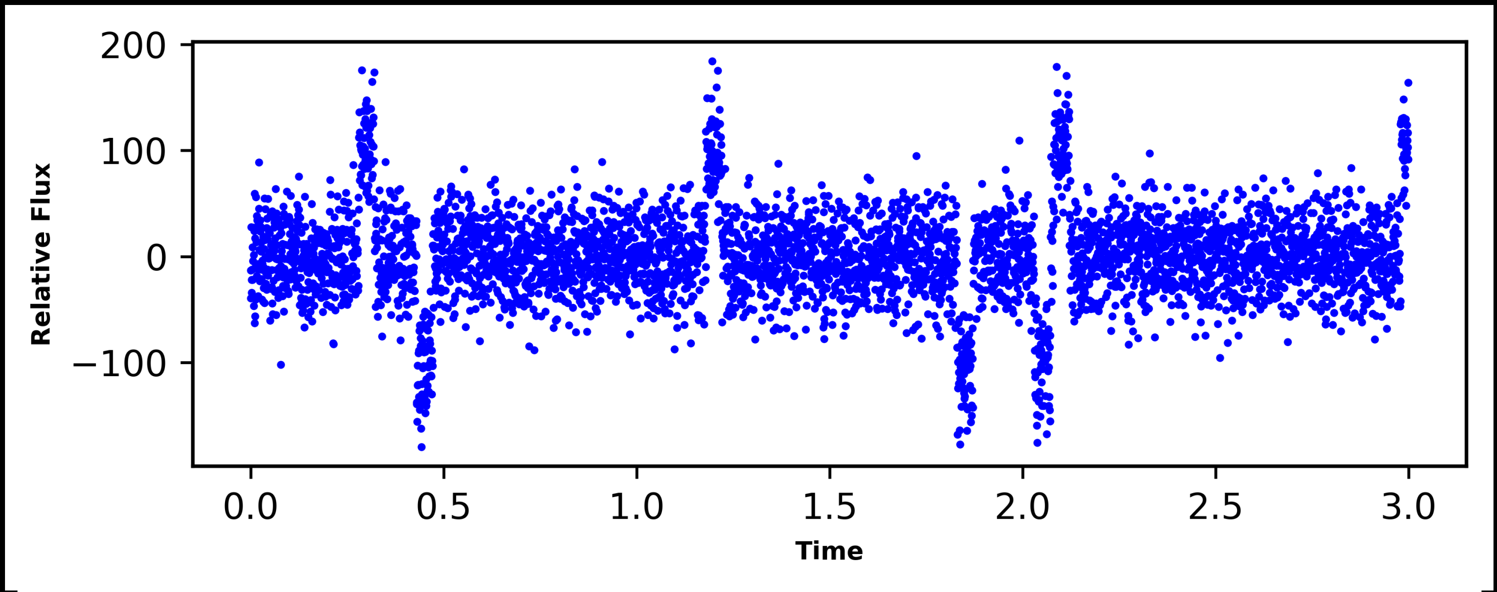
Original

Inversion

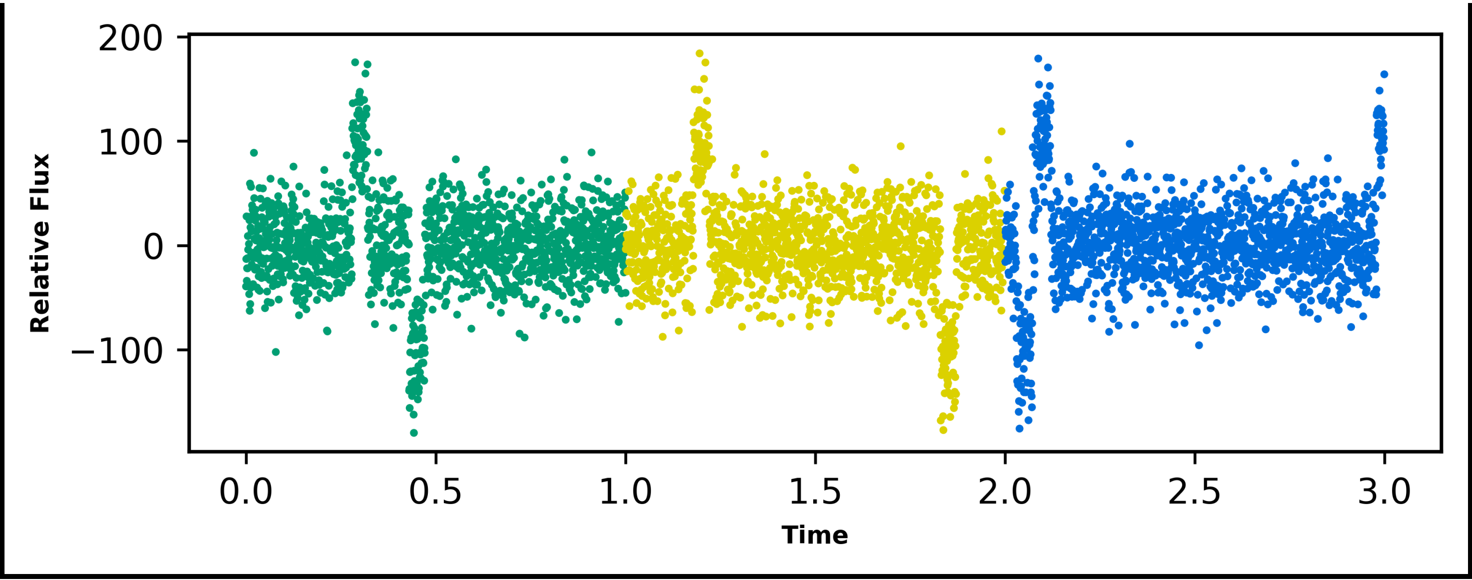


Empirically Measure FA Rate
Data Permutation

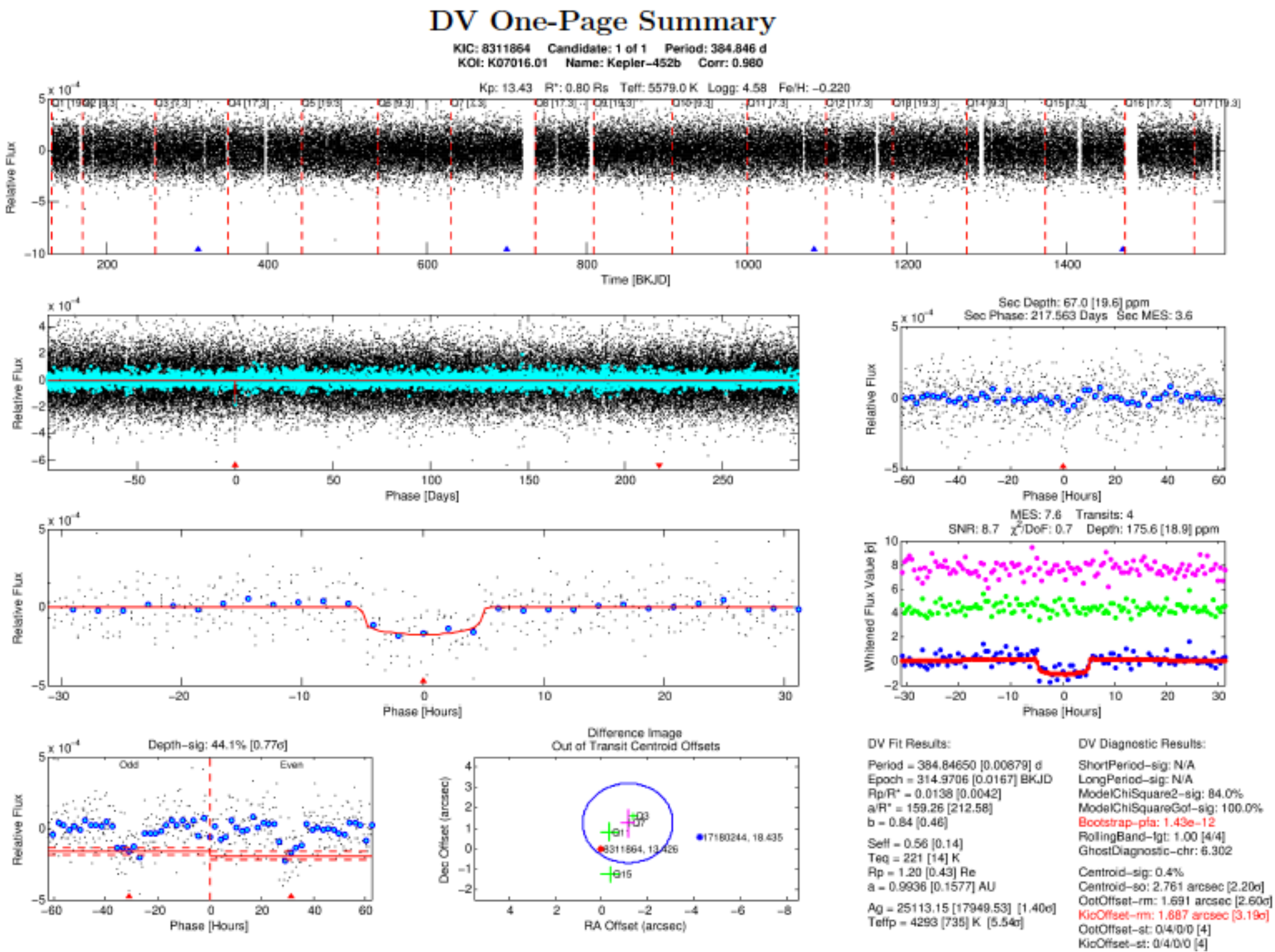
Original



Original Segments



FA Sample Examples



FA Sample Examples