Calculating the Occurrence Rate of Earth-Like Planets from the NASA Kepler Mission

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With thanks to collaborators:

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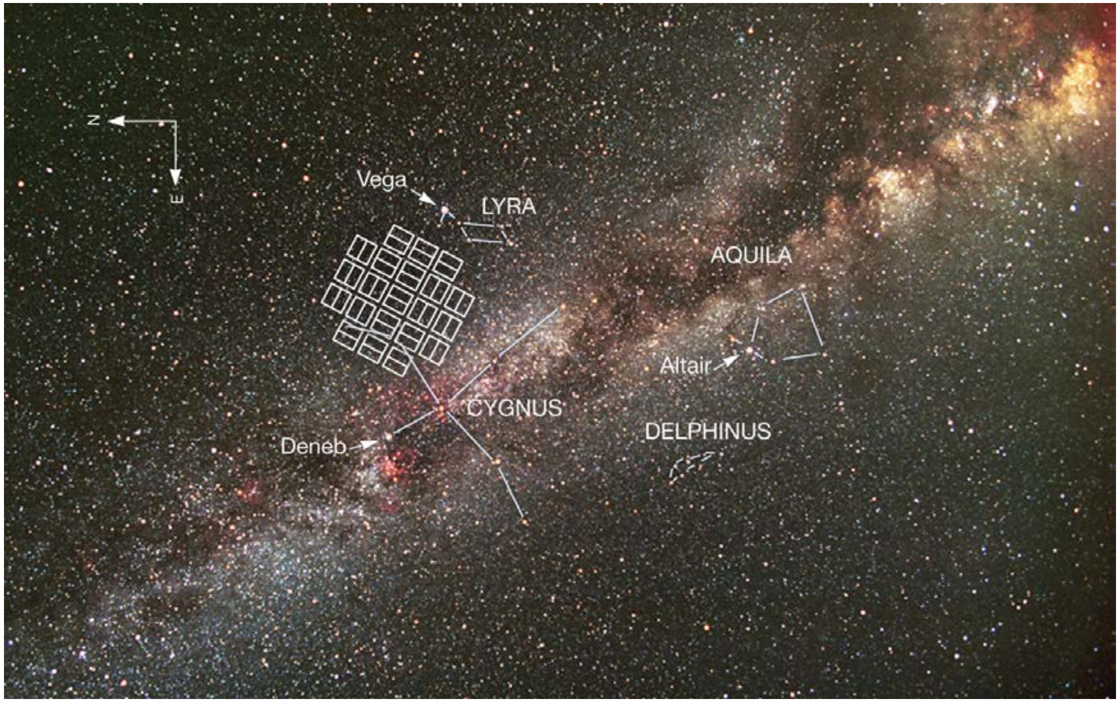
Mike Haas, Shawn Seader, and the Kepler team

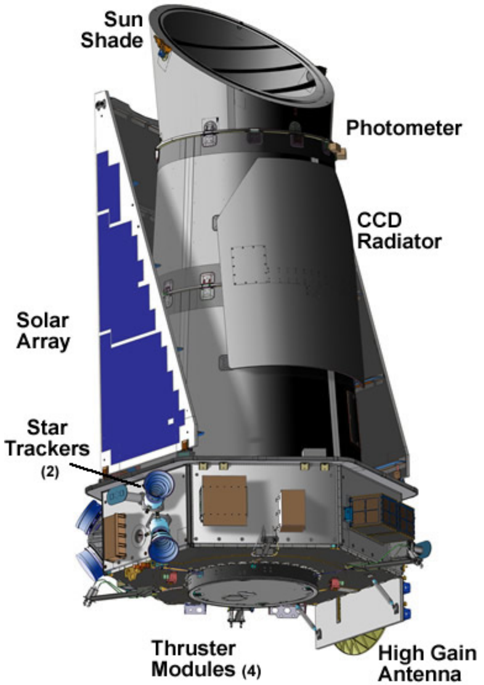
Overview

- Introducing the Kepler Mission
- What goes into determining η_{Earth}?
- An experiment to measure the pipeline completeness
- Implications

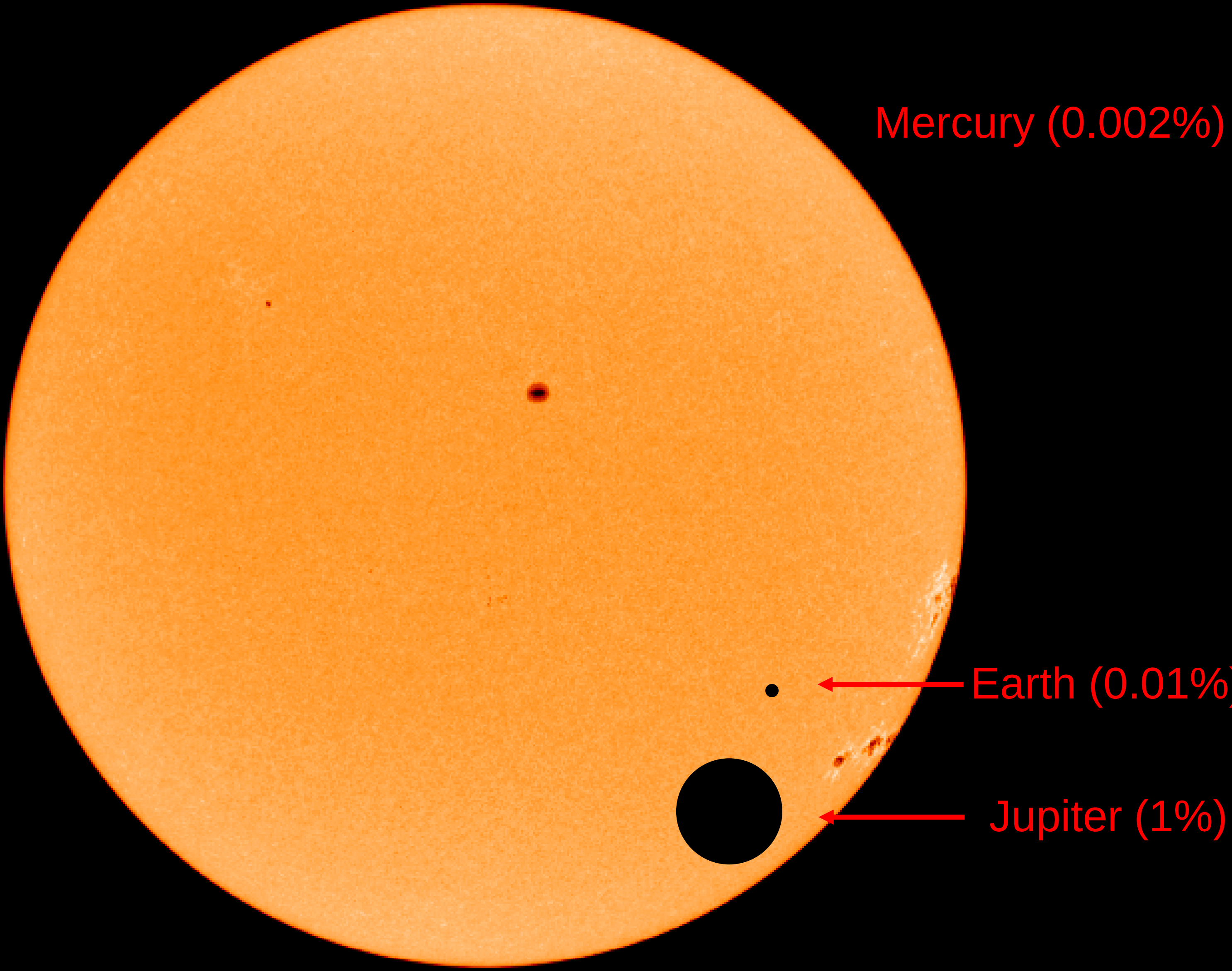
Designing Kepler

- Kepler was optimized for finding terrestrial planets (0.5 to 10 Earth masses) in the habitable zone (out to 1 AU) of stars like the Sun
- Continuously, simultaneously monitored nearly 200,000 stars, 1m Schmidt telescope, 30min integrations, field-of-view of >100 sq deg with 42 CCDs
- Photometric precision of 20 ppm in 6.5 hours on Vmag = 12 solar-like star
- Bandpass is 4300 - 8900 Å, plate scale is 3.98"/pixel

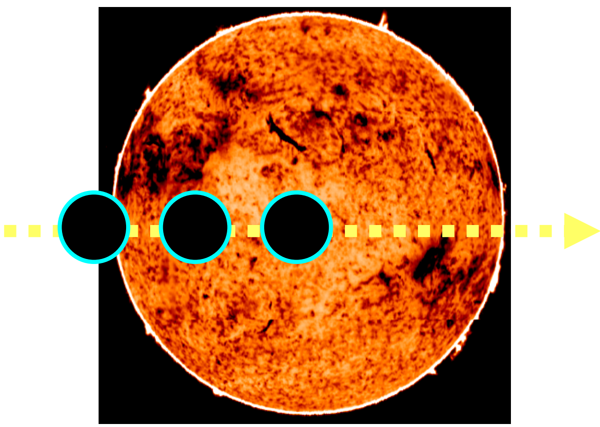


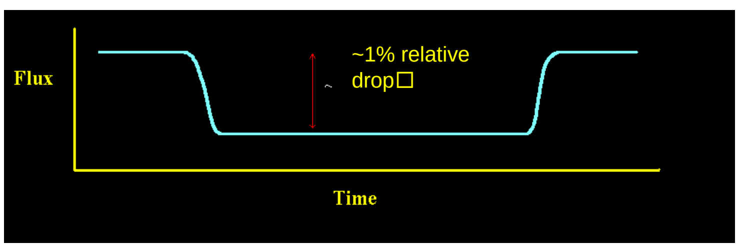


The Transit Method



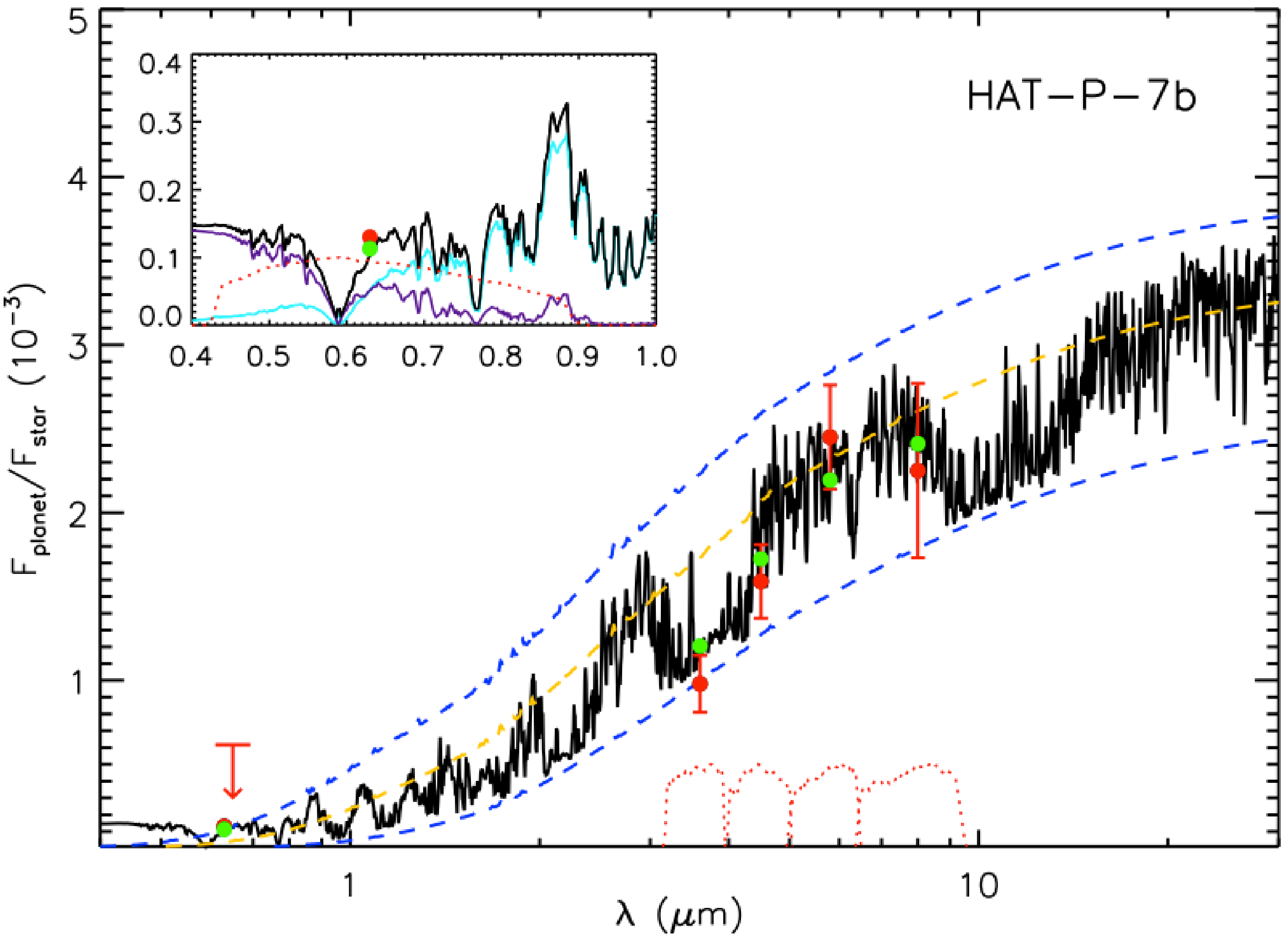
Transiting Planets





- Transiting planets are *extremely* informative
  - You can obtain bulk properties – radius, mass, density
  - You can measure atmospheric properties – emission, absorption
- But! Not every star with planets will show transits
  - Requires a geometric alignment that goes as Rp/a = 0.5% for Earth at 1AU
- Therefore, in a discovery survey, need to observe many stars
  - Go narrow/deep (Kepler)
  - Go wide/shallow (TESS, Plato)

First light curves from Kepler



Christiansen et al. 2010

The story so far…

- Kepler lost its second reaction wheel after four years of observations
- From the data in hand, we are compiling an increasing list of confirmed planets and planetary candidates
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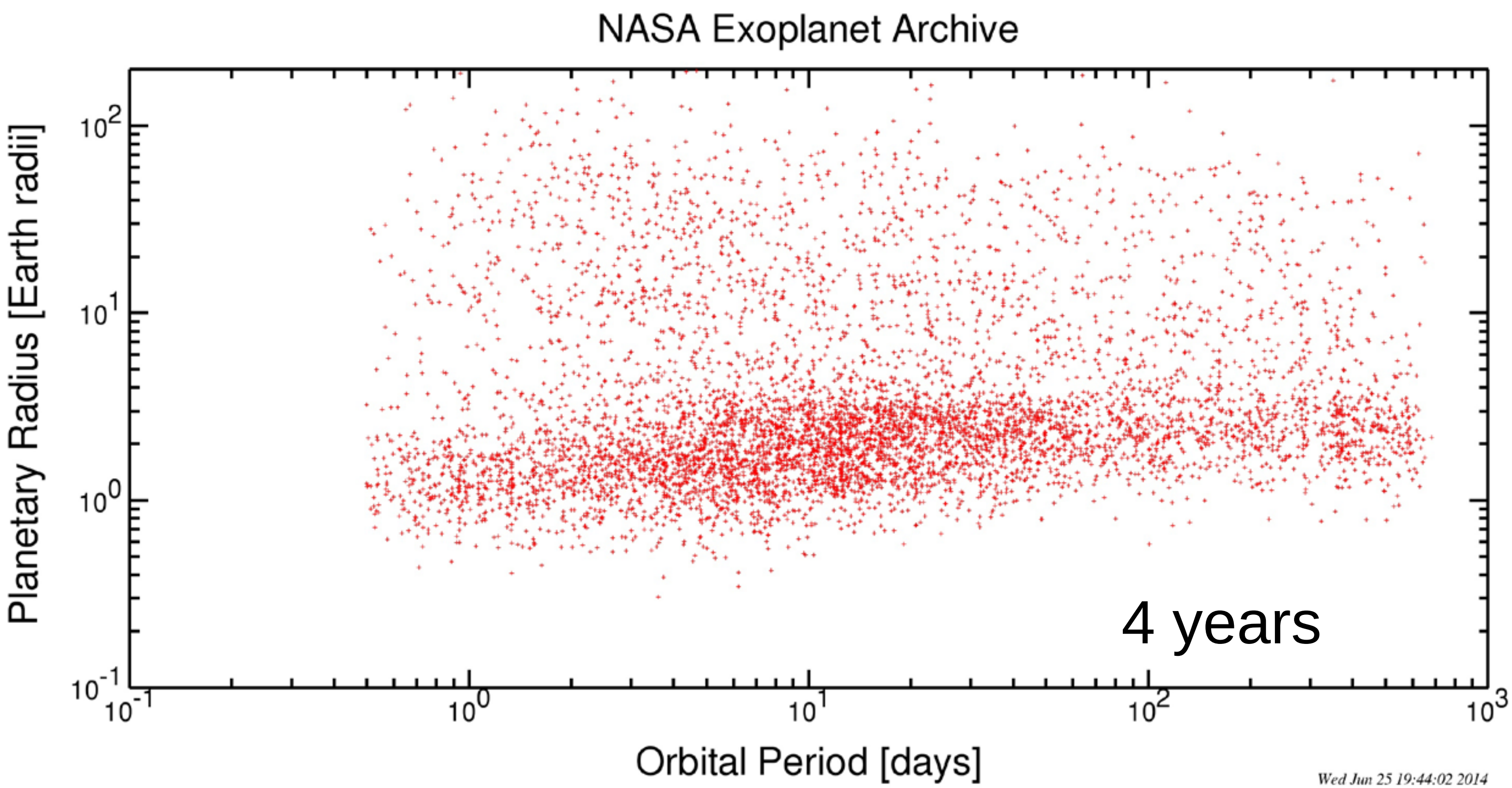


Determining η_{Earth}

We need to calculate both:

$N_{measured}$: the number of real Earth-like planets in the Kepler sample (i.e. understanding the reliability, or false positive rate)

$N_{detectable}$: the number of stars around which the Kepler pipeline would have detected such planets (i.e. understanding the completeness)

$$\eta_{EARTH} = \frac{N_{measured}}{N_{detectable}}$$, where

$$N_{detectable} = \sum_i P_{i,geo} P_{i,SNR}$$

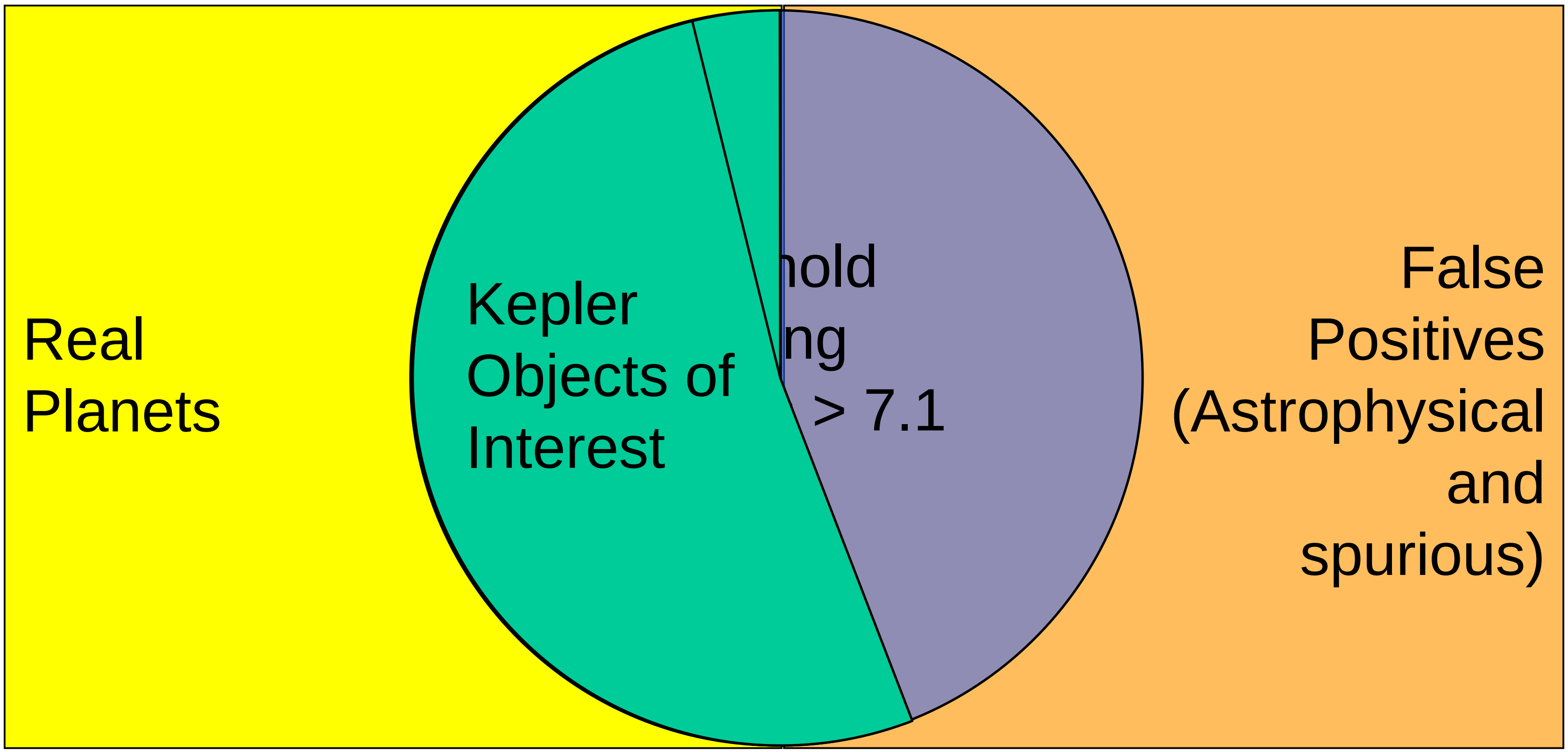
Geometric probability of ith planet to transit

Probability of ith planet to having strength SNR being detected

The aim of my investigation is to characterise $P_{i,SNR}$ for the Kepler pipeline, which we can then use to calculate the pipeline detection efficiency.

Put another way…

Completeness Study Working Group



False Positive Working Group

The Kepler Pipeline

Calibrates pixels

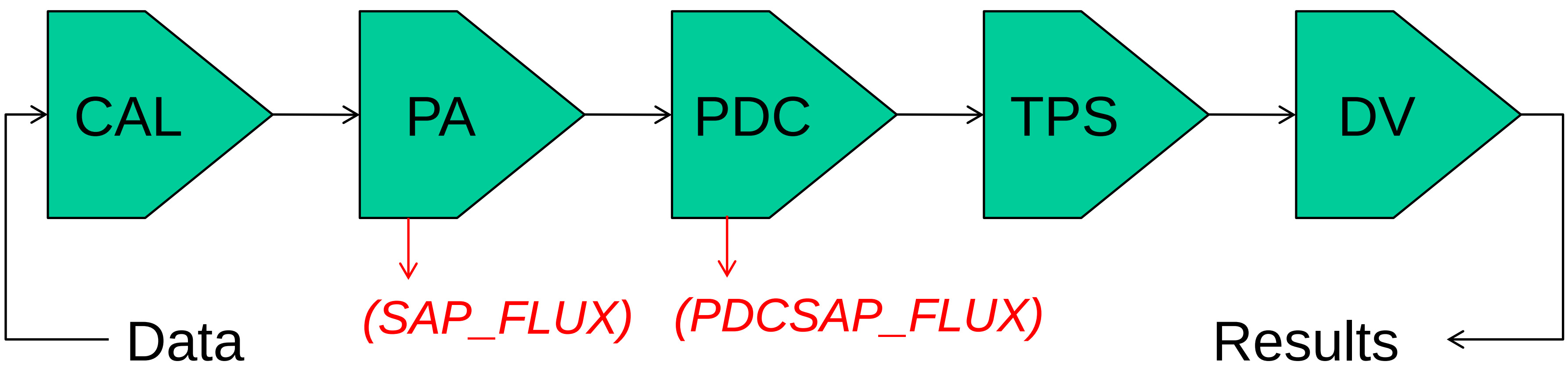
Performs aperture photometry

Corrects systematics

Whitens, finds periodic signals

Checks whether planet-like

What happens to a transit signal through the pipeline?



Injection of fake transits into Kepler pixels

- To characterize recoverability of signals, ideally we would perform a Monte Carlo analysis – for each star, inject a suite of fake transit signals into the pixels and find the limits of detectability
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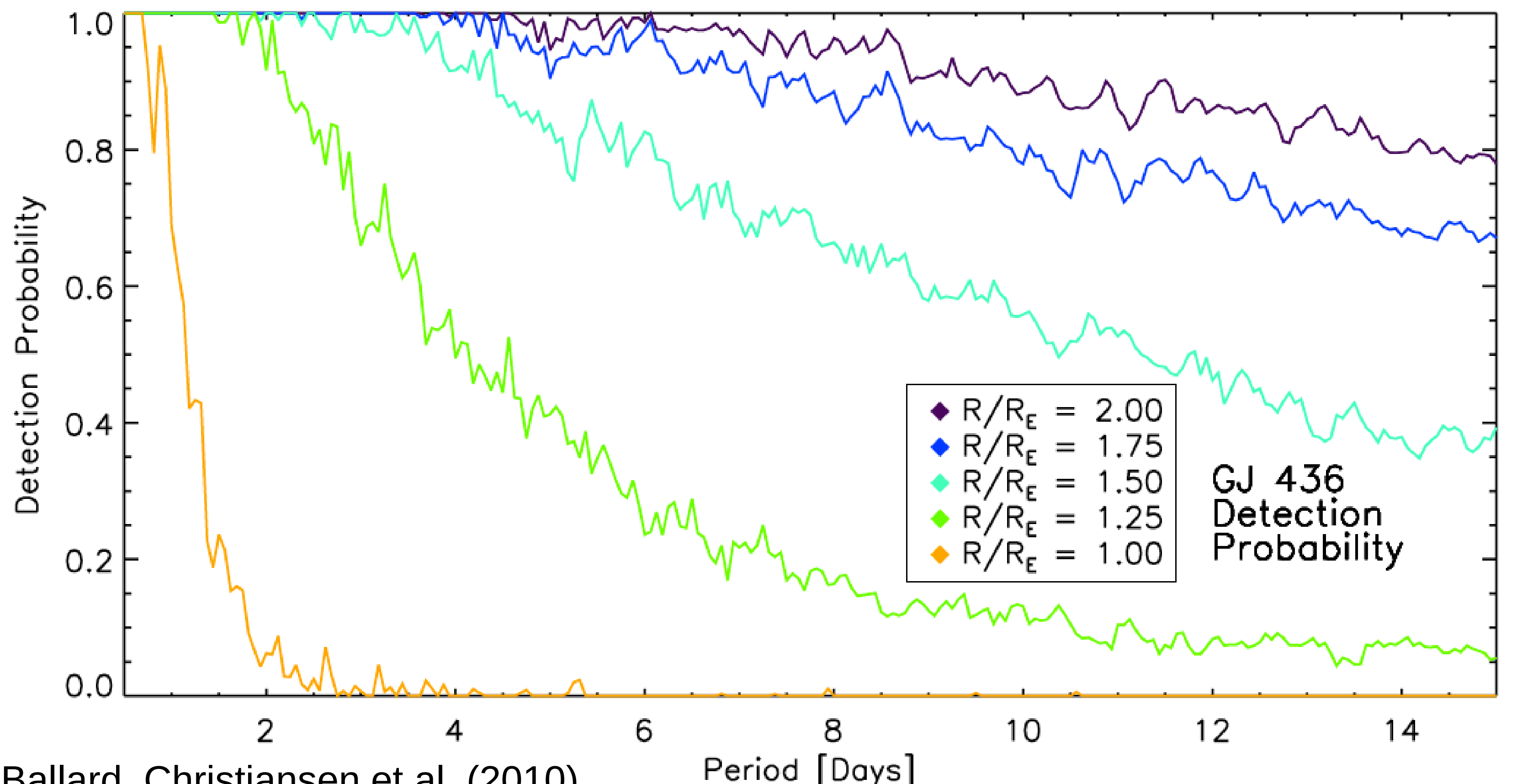
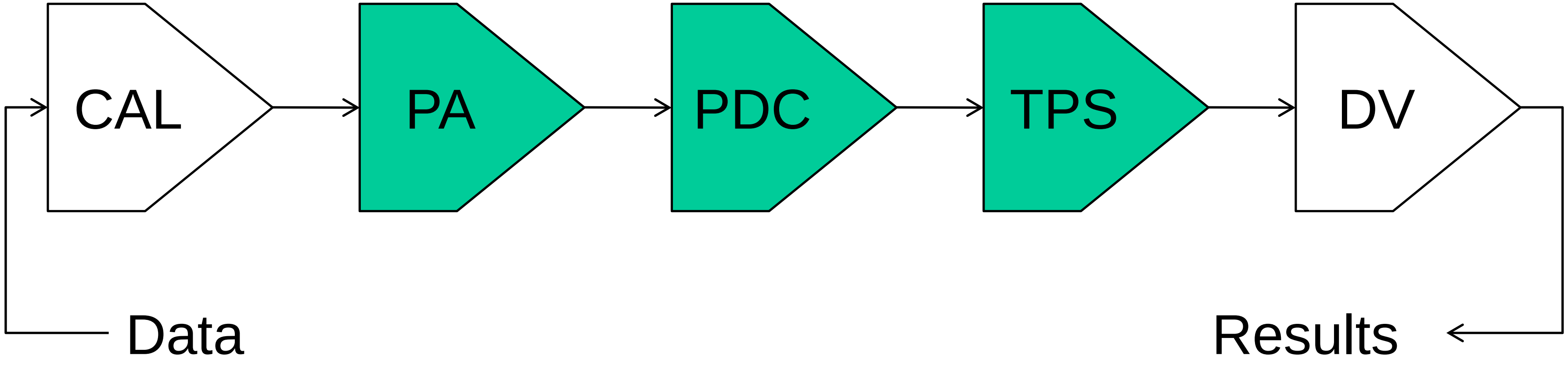


Ballard, Christiansen et al. (2010)

Experiment 1: Characterising preservation of single transits

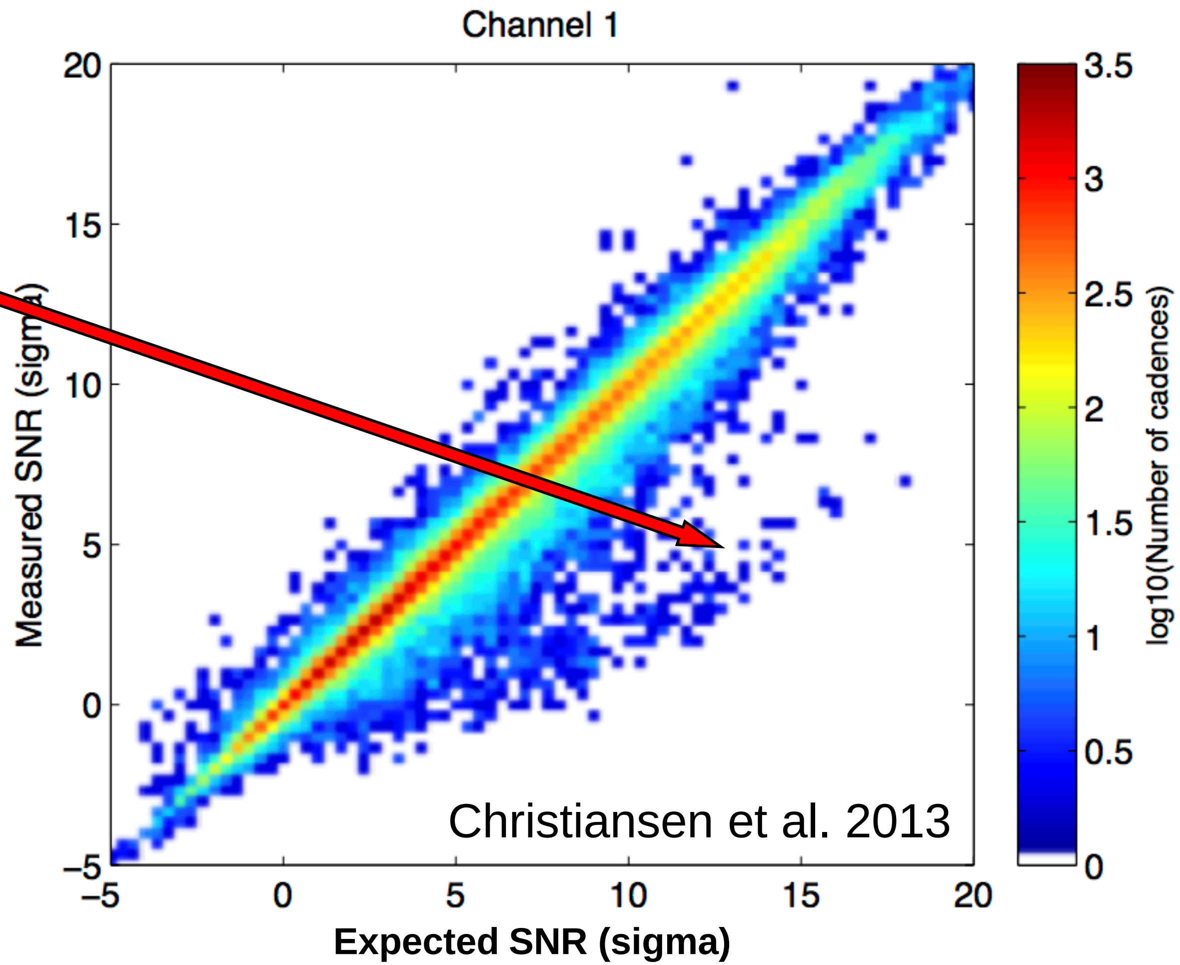
- Start with calibrated pixels
- Inject a transit signal into the pixels every star (from an initial distribution of planet parameters) for one ‘quarter’ (90 days) of data
- Process the data as normal from creating the photometry to detecting the events
- Compare the detection strength of the signal to the expected strength



Individual transits are well preserved

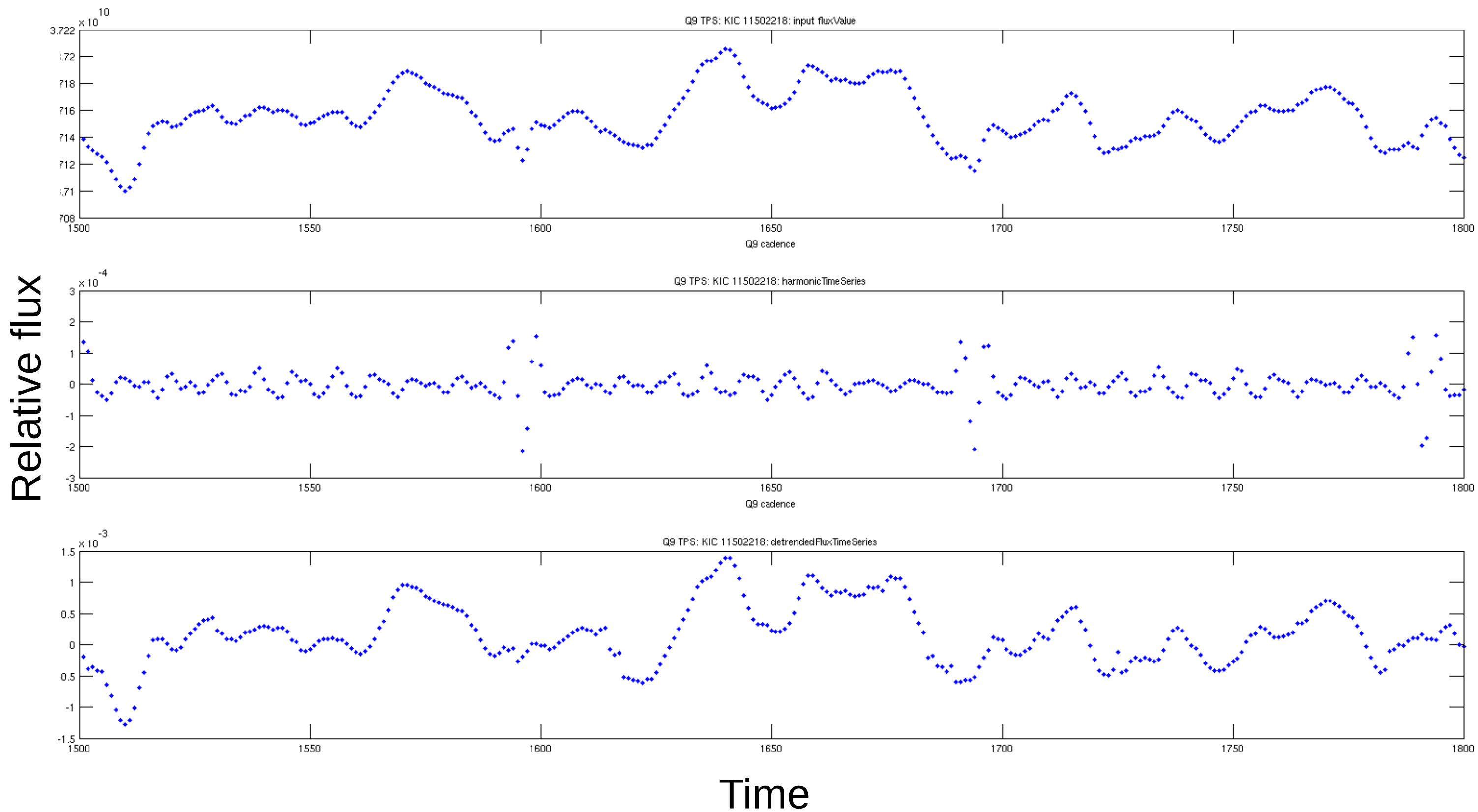
- Results from channel 1 (of 80 channels)
- Measured signal = 0.9973*expected signal – 0.0151

Harmonic fitter; transits near large data gaps



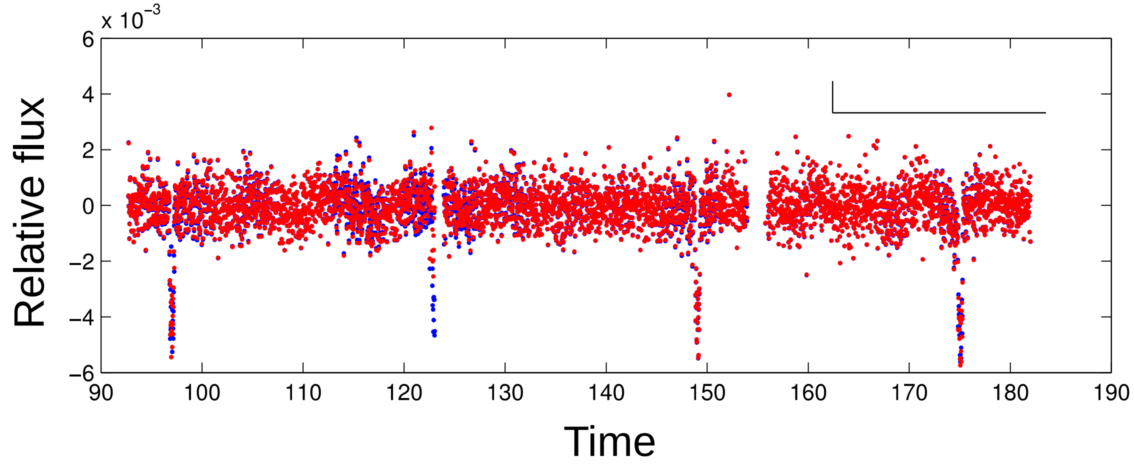
The harmonic filter removes short period signals

- Before whitening and folding, TPS fits out harmonics, to enable planet searches around active stars
- For transiting or eclipsing light curves with periods < 3 days, and especially < 1 day, the transits are modeled as a Fourier series and removed – important implications for completeness!



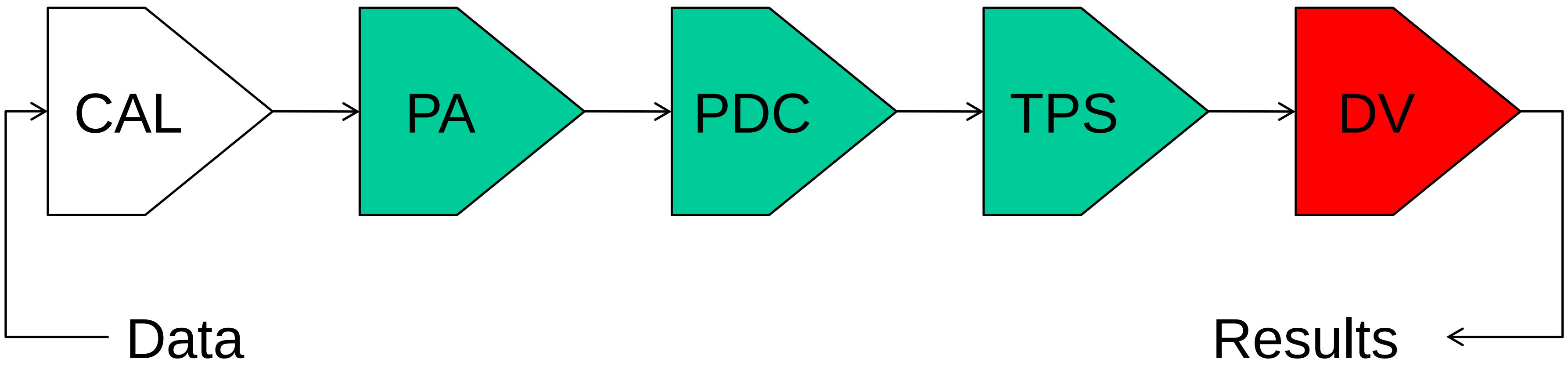
Transits near data gaps are distorted

- We perform additional systematic correction near data gaps, where the most significant systematics (largely due to thermal changes) occur, which typically distorts transits within 2 days of data gaps

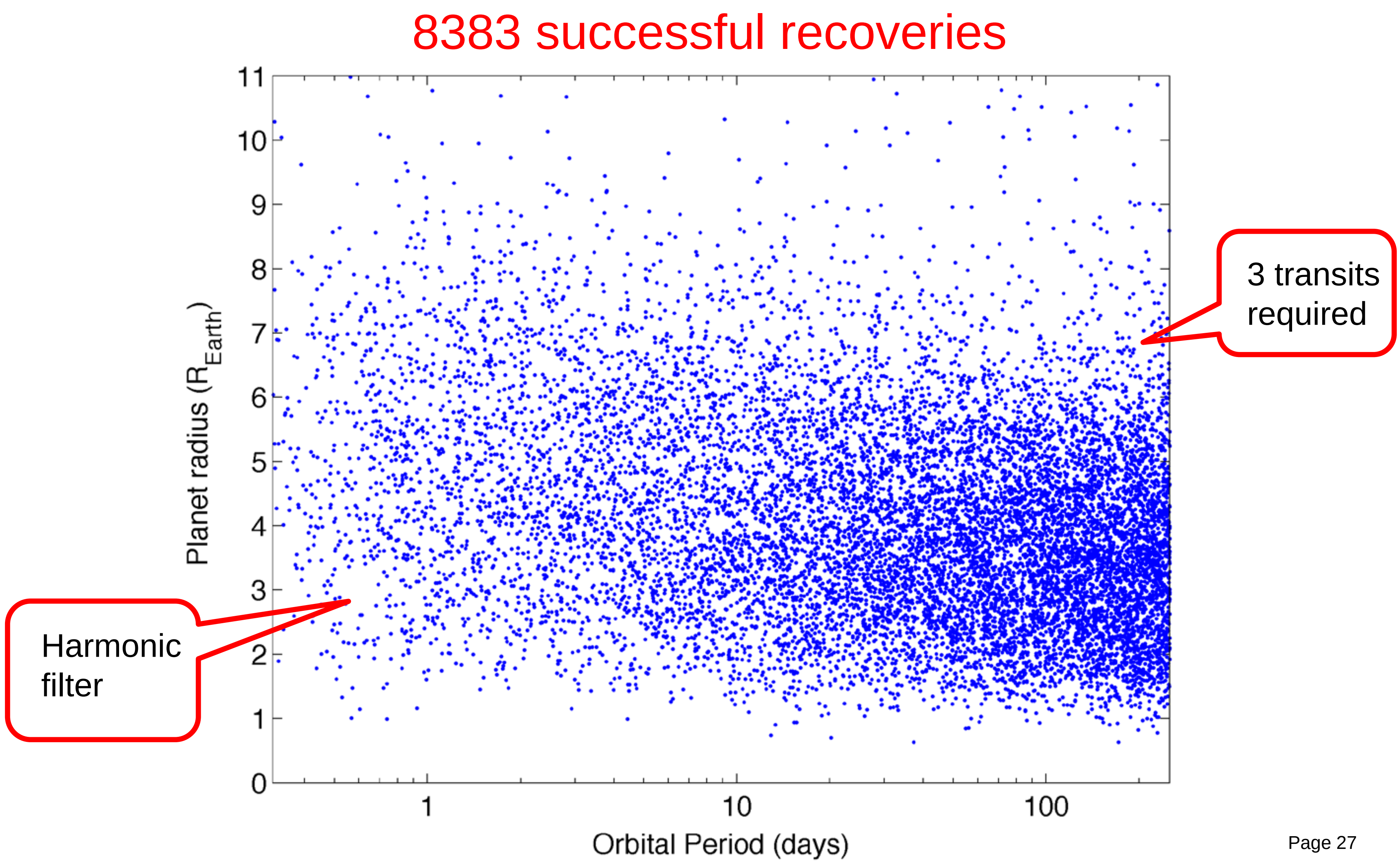


Experiment 2: Characterising recovery of transit signals

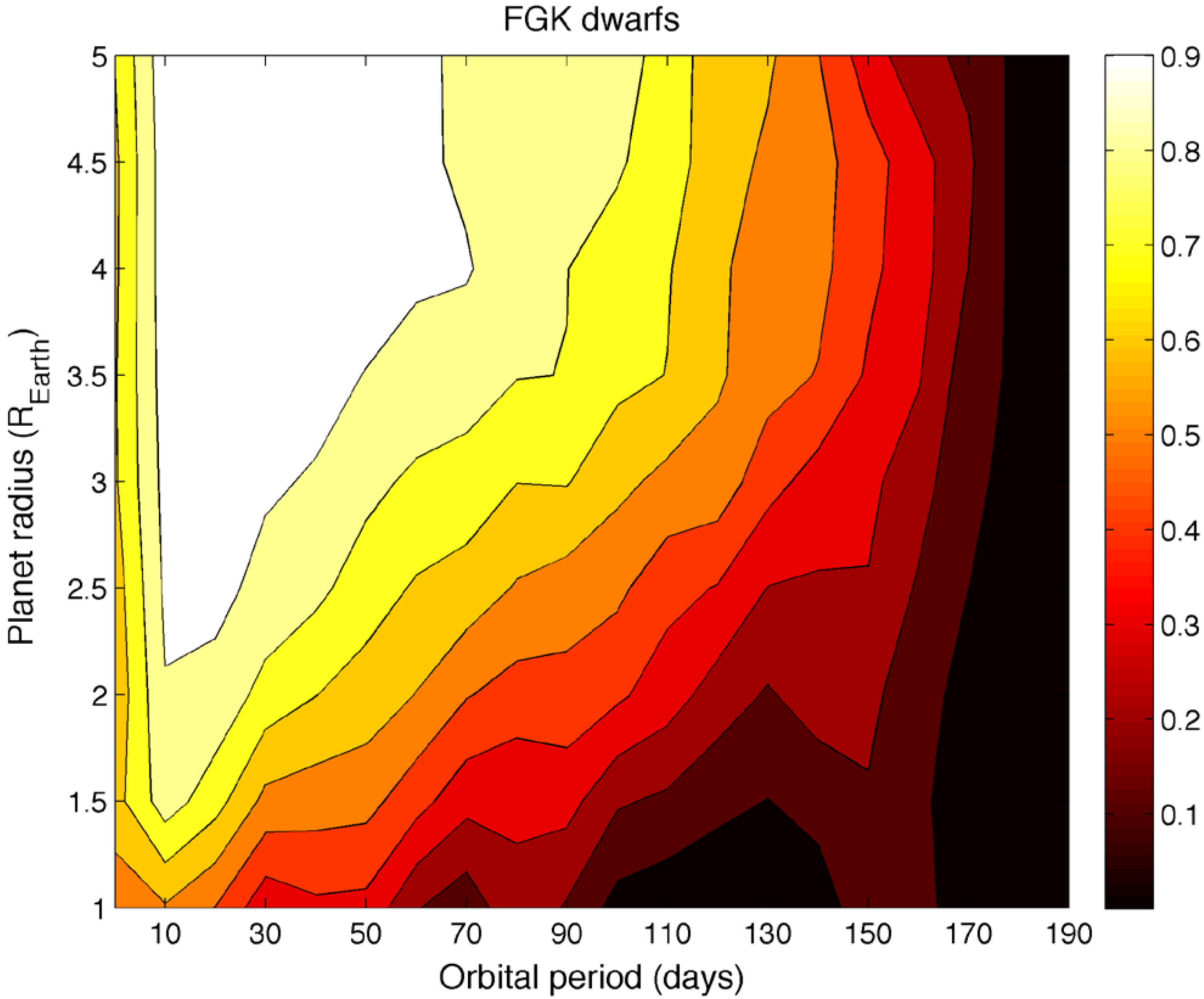
- Start with calibrated pixels
- Inject a transit signal into the pixels of 23926 FGK stars (from an initial distribution of planet parameters) for four ‘quarters’ (~360 days)
- Process the data as normal from creating the photometry to data validation, testing that our simulated planet passes all the tests
- Compare the distribution of detected planet signals to the expected distribution



Distribution of injected planet parameters



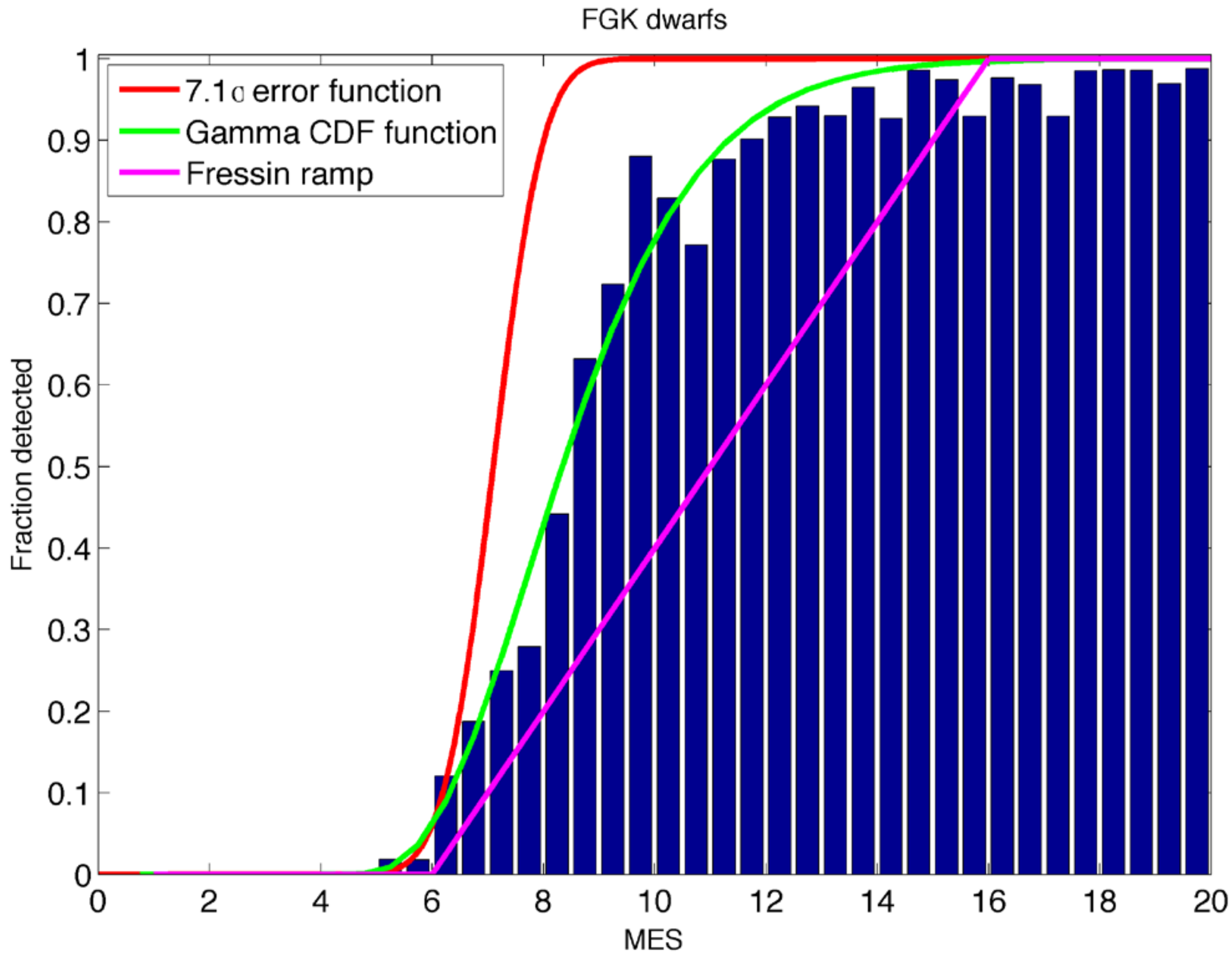
Detection contours



Sensitivity function

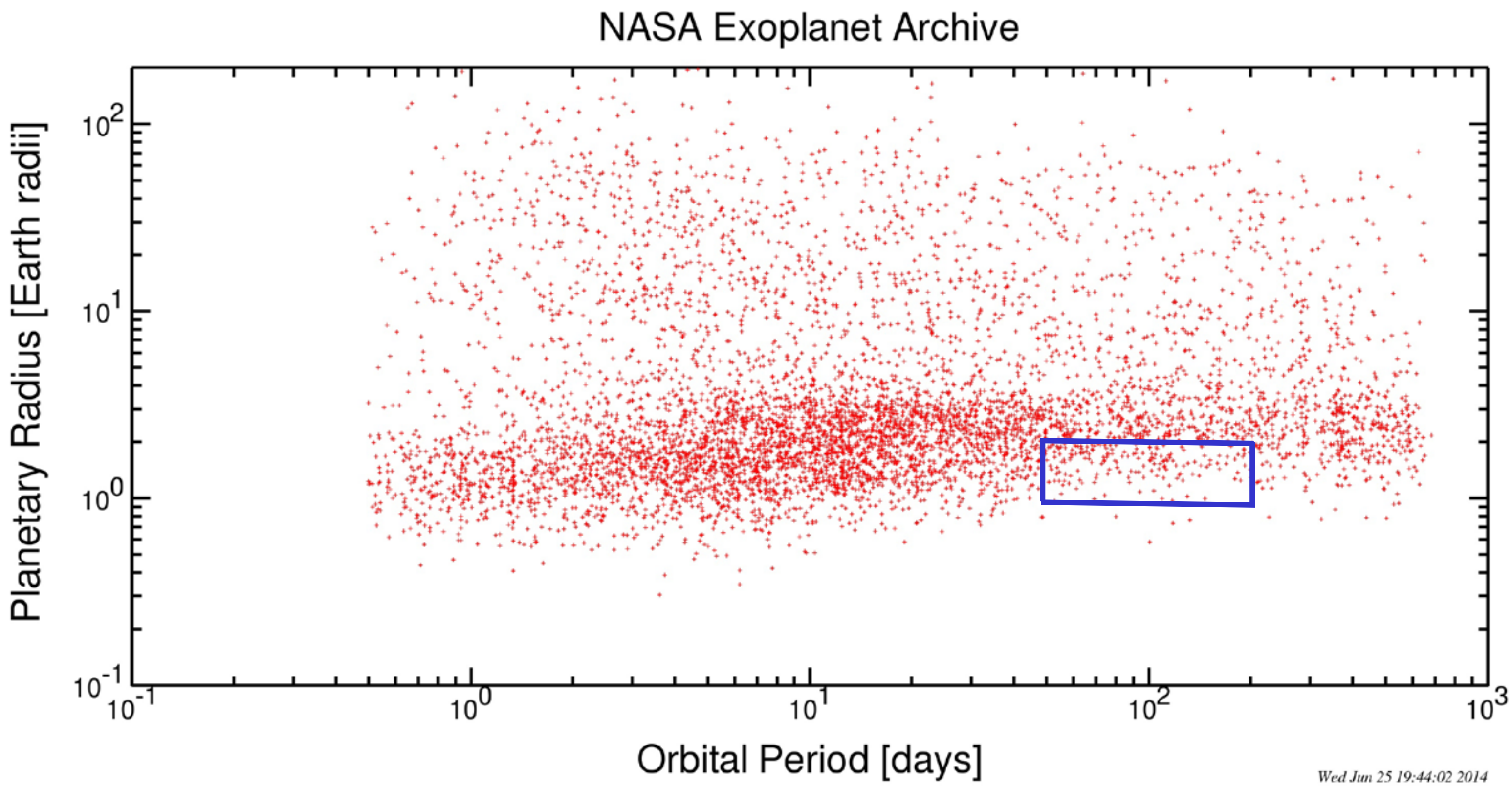
- Expected MES = multiple event statistic, 7.1sig threshold imposed by pipeline

(Additional vetoes (Seader et al. 2013) to weed out false alarms)



What does this mean for occurrence rate calculations?

- Using the method described by Youdin 2011, Burke et al. (in prep) – parametric occurrence rate (best fit = broken power law in radius and power law in period)
- 50-200 days, 1-2 Earth radius planets, using Q1-Q16 planet candidate catalogue (Mullally et al. in prep), get very preliminary result:



Q1-Q17 plans

More pipeline testing:

- We need to extent the test to periods longer than 180 days – we know there are systematics associated with the one-year period of the spacecraft orbit
- All available data (Q1-Q17), as many targets as the NAS can handle
- Periods ~0.5-500 days (window function drops off rapidly thereafter)
- Planets ~0.25-5 R_E (pending initial SNR tests)

Start people testing:

- Completeness doesn't end with the pipeline -> transit signal vetting procedures (both automated and manual) need to be quantified
- How many borderline signals get thrown away?
- Need to produce a 'people' sensitivity curve, analogous to the one presented here