The Impact of Stellar Variability on Kepler's Search for Transiting Planets

Jessie Christiansen

Kepler Participating Scientist

NASA Exoplanet Science Institute/Caltech

jessie.christiansen@caltech.edu

With thanks to collaborators:

Chris Burke, Bruce Clarke, Natalie Batalha,

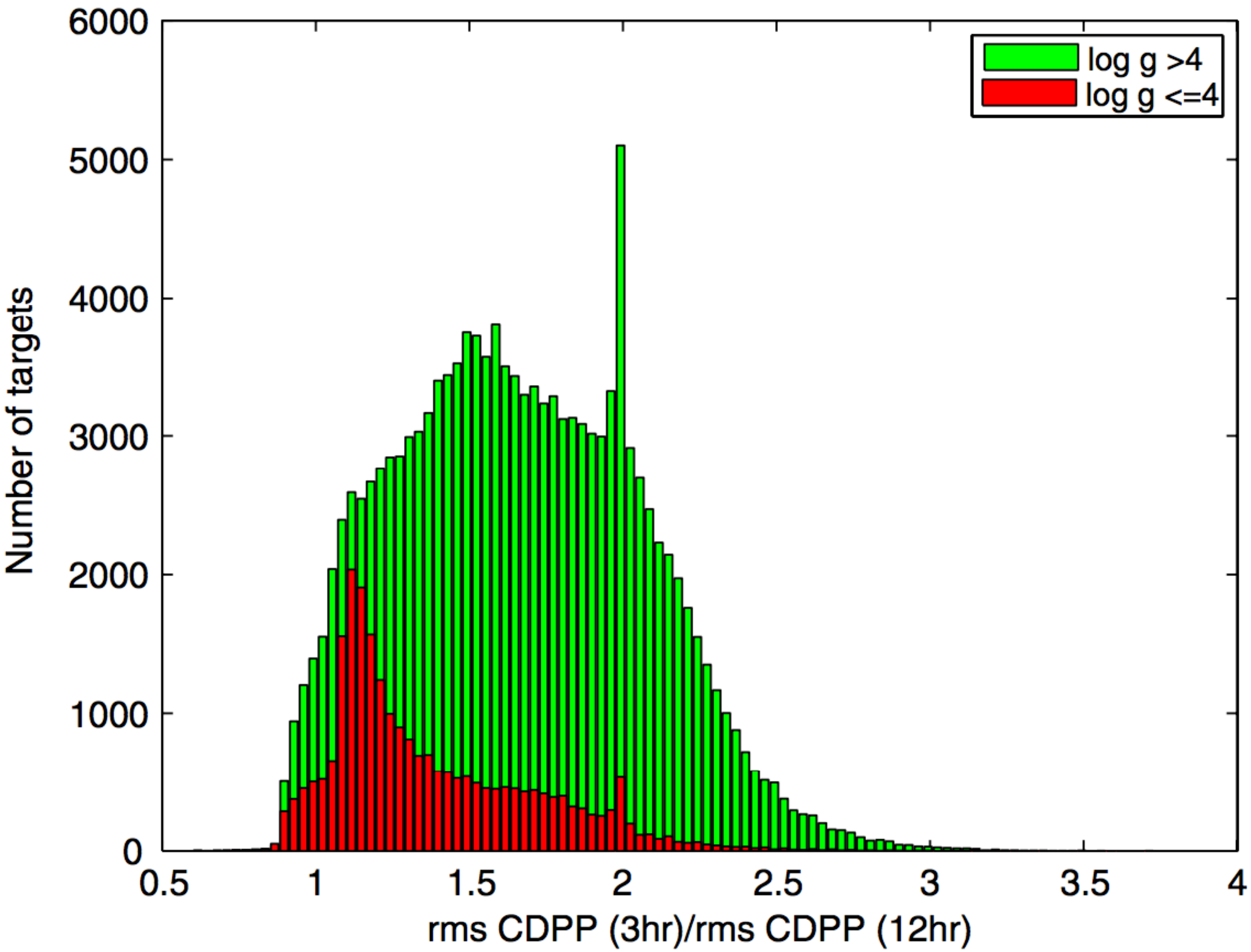
Mike Haas, Shawn Seader, and the Kepler team

Thinking about stellar noise, pre-Kepler

- Problem of correlated 'red' noise (non-stationary, non-Gaussian) impacting transit searches long identified (Borucki, Scargle & Hudson 1985).
- Based on extrapolation based on noise measured in the Sun, and assumptions about the Sun relative to other 'typical' stars - Jenkins et al. (2002), Batalha et al. (2002)
- Photometric precision of 20 ppm in 6.5 hours on Vmag = 12 solar-like star
- Considerable effort in the early 2000's to develop a two-step detection algorithm for transits that included stellar variability filters, e.g. Jenkins et al. (2002), Aigrain & Irwin (2004) and references therein
- Also, identification of interesting stellar types (non-FGK main sequence stars) with their own intrinsic variability
  - White dwarfs (Farmer & Agol, 2003)
  - Giant stars (Assef, Gaudi & Stanek, 2009)

Combined Differential Photometric Precision

- CDPP – calculated on timescales from 1.5-15 hours
- Measures the effective white noise (filtered data) seen by a transit of a given duration – how deep a transit would have to be to measure as SNR=1
- Instead of 20ppm, achieved more like 30ppm (attributed to increased stellar noise by Gilliland et al 2011, refuted by Basri et al. 2013) – See Jeff Smith's poster (P5.3) for some pipeline improvements



- Spot the red noise lurking in there…

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)

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

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

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

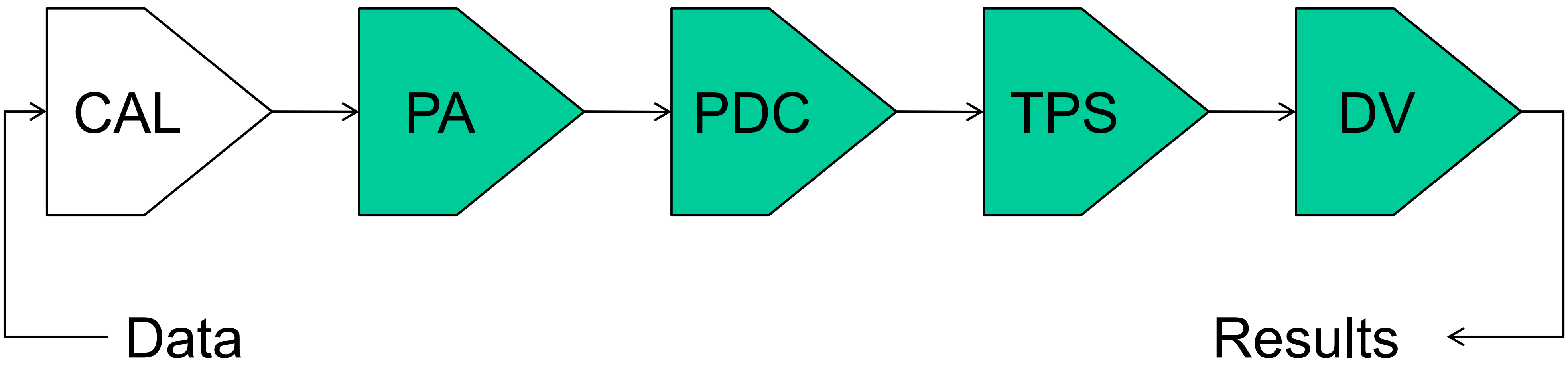
$P_{i,geo}$: Geometric probability of ith planet to transit

$P_{i,SNR}$: Probability of ith planet to having strength SNR being detected

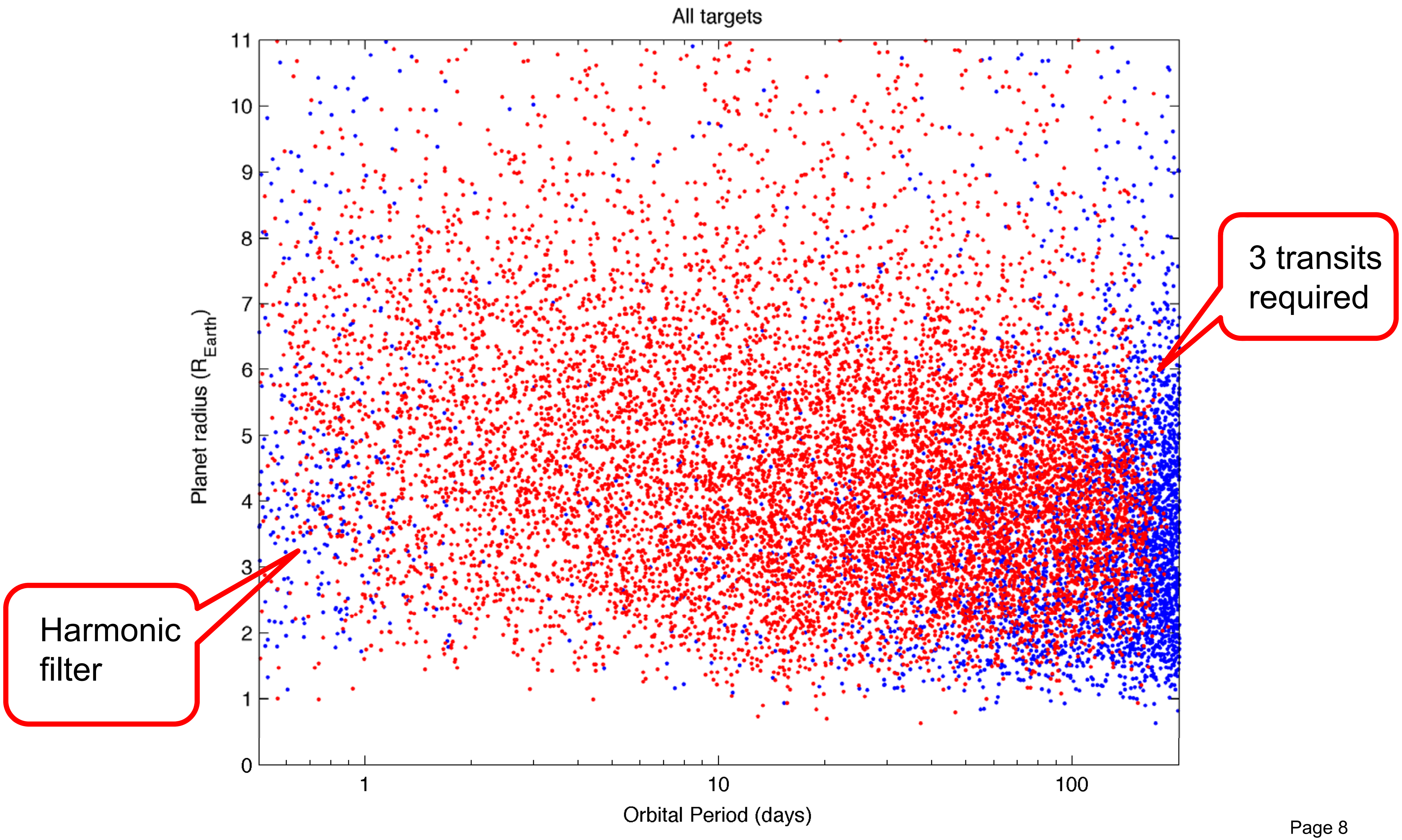
We have been running a long-term experiment with simulated transit signals to characterise $P_{i,SNR}$ for the Kepler pipeline

Quantifying recovery of transit signals

- Inject simulated transit signals into the pixels of targets across 16 CCDs, including 26,000 FGK main-sequence stars (4000-7000K, logg > 4.0) and 4000 non-FGK main-sequence stars for four ‘quarters’ (~360 days)
- Planet parameters from 0.5-200 days, $<11R_{Earth}$
- 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



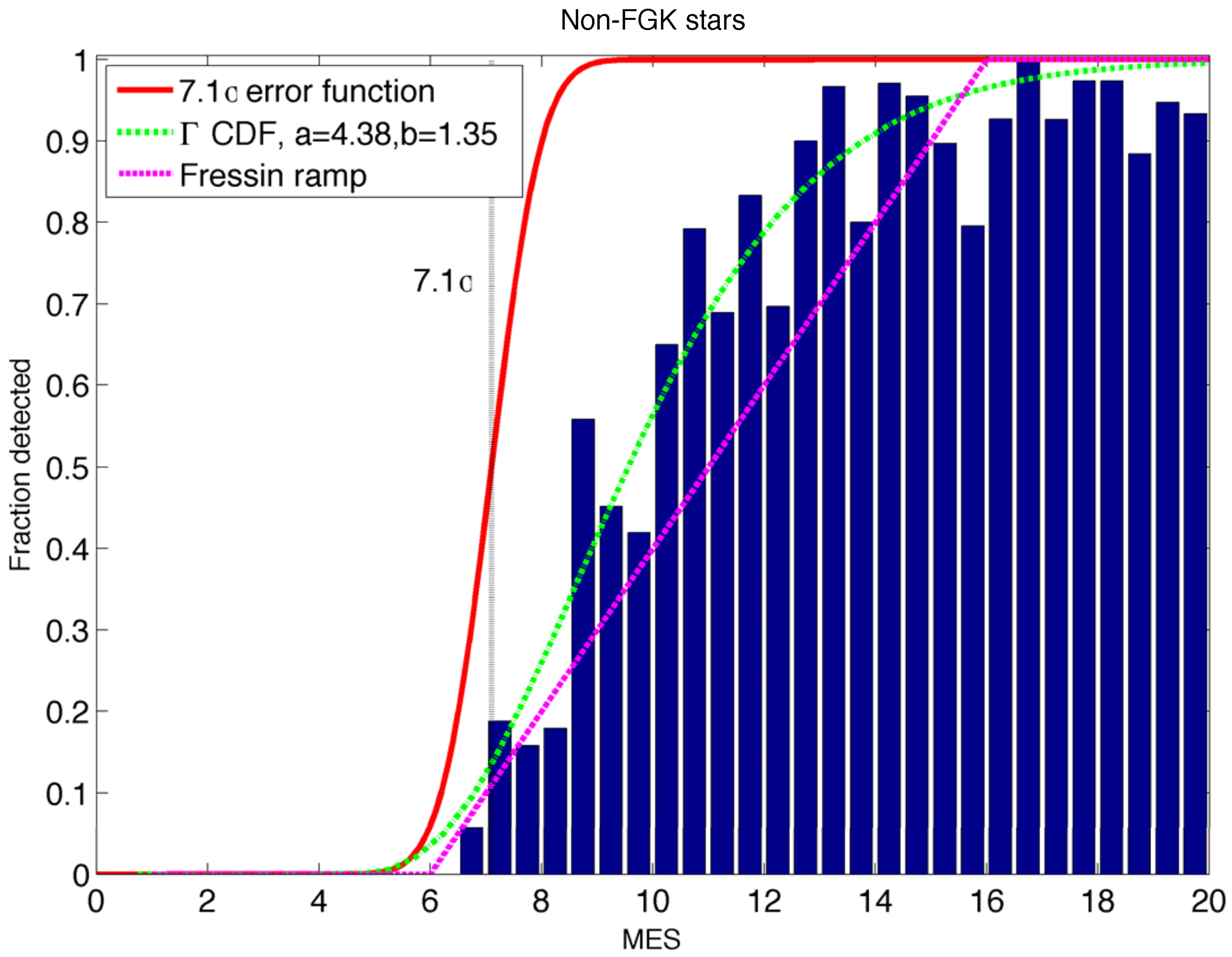
Distribution of injected planet parameters



Detection efficiency as a function of stellar parameters

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

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



What is happening to the transit signals?

- Signal masking in (correlated) noisy data

- Examine non-detections of injections with expected MES > 10
  - Non-FGK: 2.67 candidate per target when injection not recovered (vs. 1.16)
  - (FGK: 1.16 candidates per target when injection not recovered (vs. 1.12))
  - This effects the window function/duty cycle (number of searchable cadences)

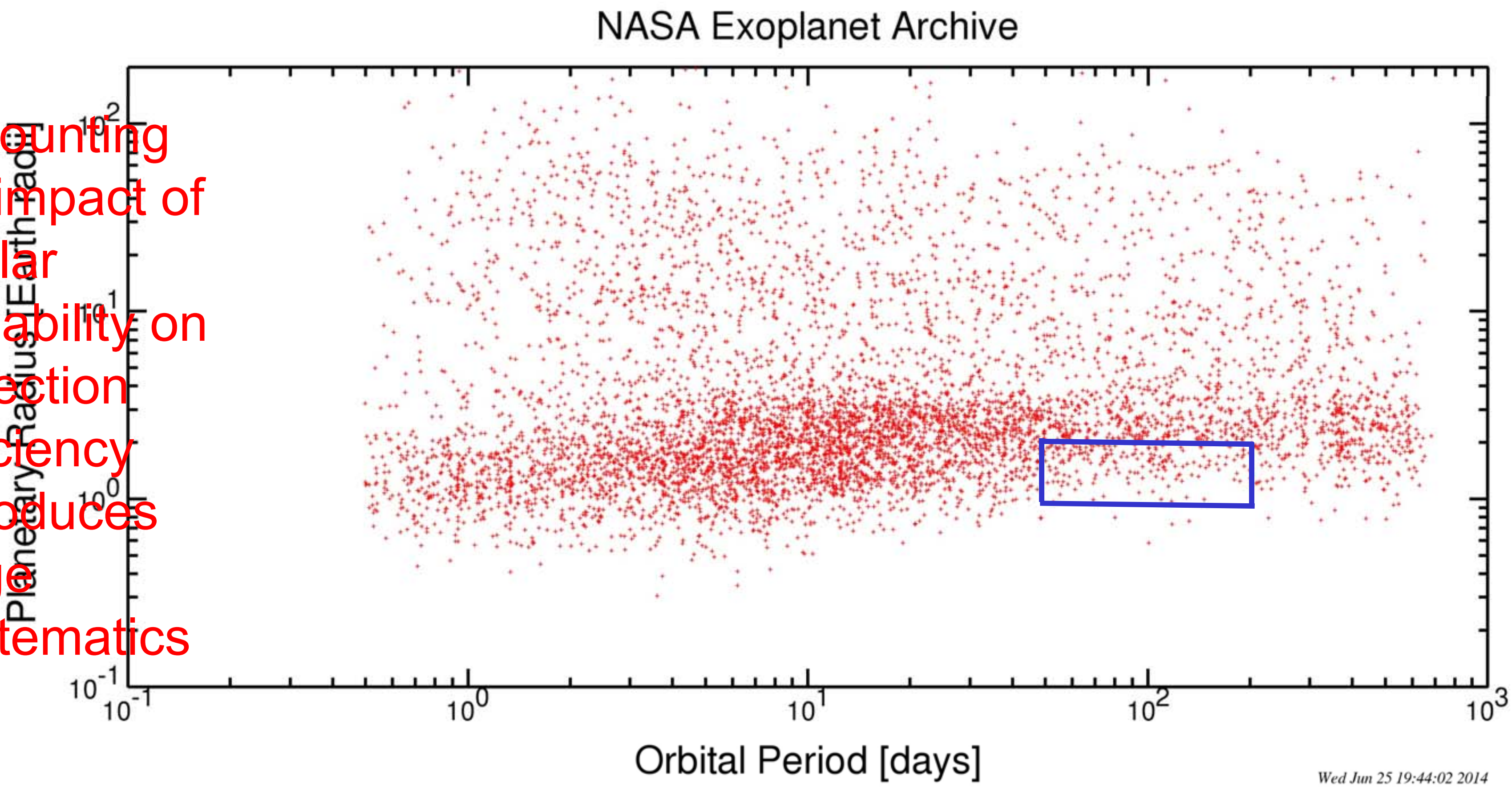
(N.B. impact for multi-planet systems…)

- Another possible loss may be in the vetoes (Seader et al. 2013)
  - In addition to the 7.1σ threshold, apply a set of χ^2 discriminators to remove false alarms - still need to look at for quiet vs. variable stars

What is the impact for occurrence rate calculations?

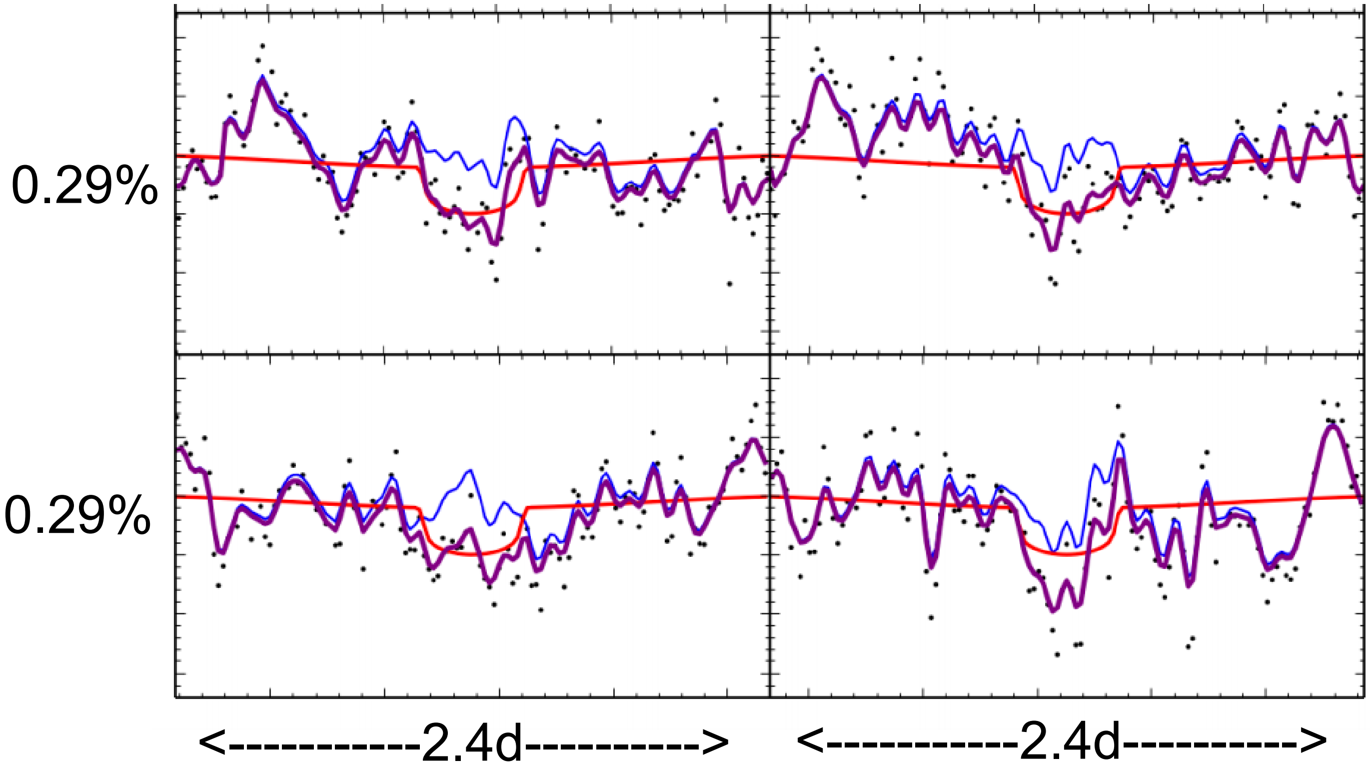
- Using the method described by Youdin 2011, Burke et al. (in prep) – parametric occurrence rate (best fit = broken power law in radius and power law in period)
- 50-200 days, 1-2 Earth radius planets, using Q1-Q16 planet candidate catalogue (Mullally et al. in prep), get very preliminary result:

Not accounting for impact of stellar variability on detection efficiency introduces large systematics



Dealing with stellar variability in transit characterisation – a cautionary tale

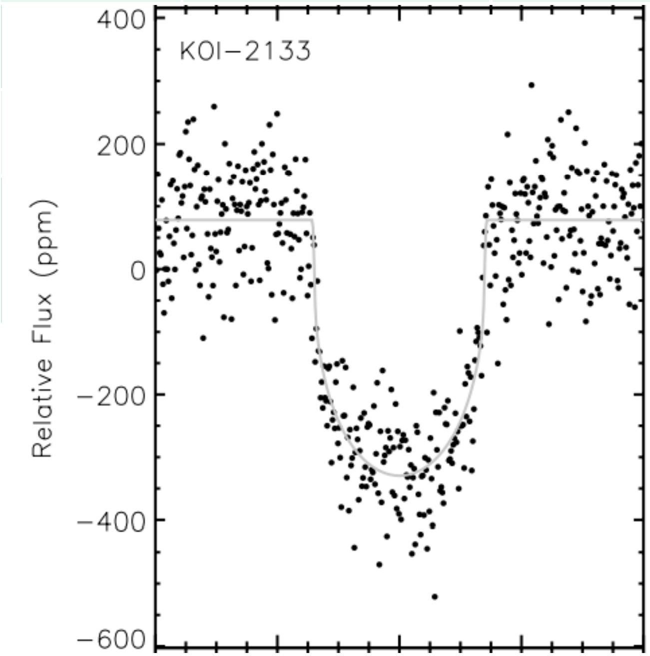
- Kepler-91/KOI-2133/KIC8219268, giant star with $M=1.3M_{Sun}$ and $R=6.3R_{Sun}$
- Transit candidate (6.2d) listed in Jenkins et al. 2010 and Tenenbaum et al. 2013
- Promoted to KOI status in Batalha et al. 2013 (Q1-Q6)
- Stayed a KOI candidate in Burke et al. 2013 (Q1-Q8)

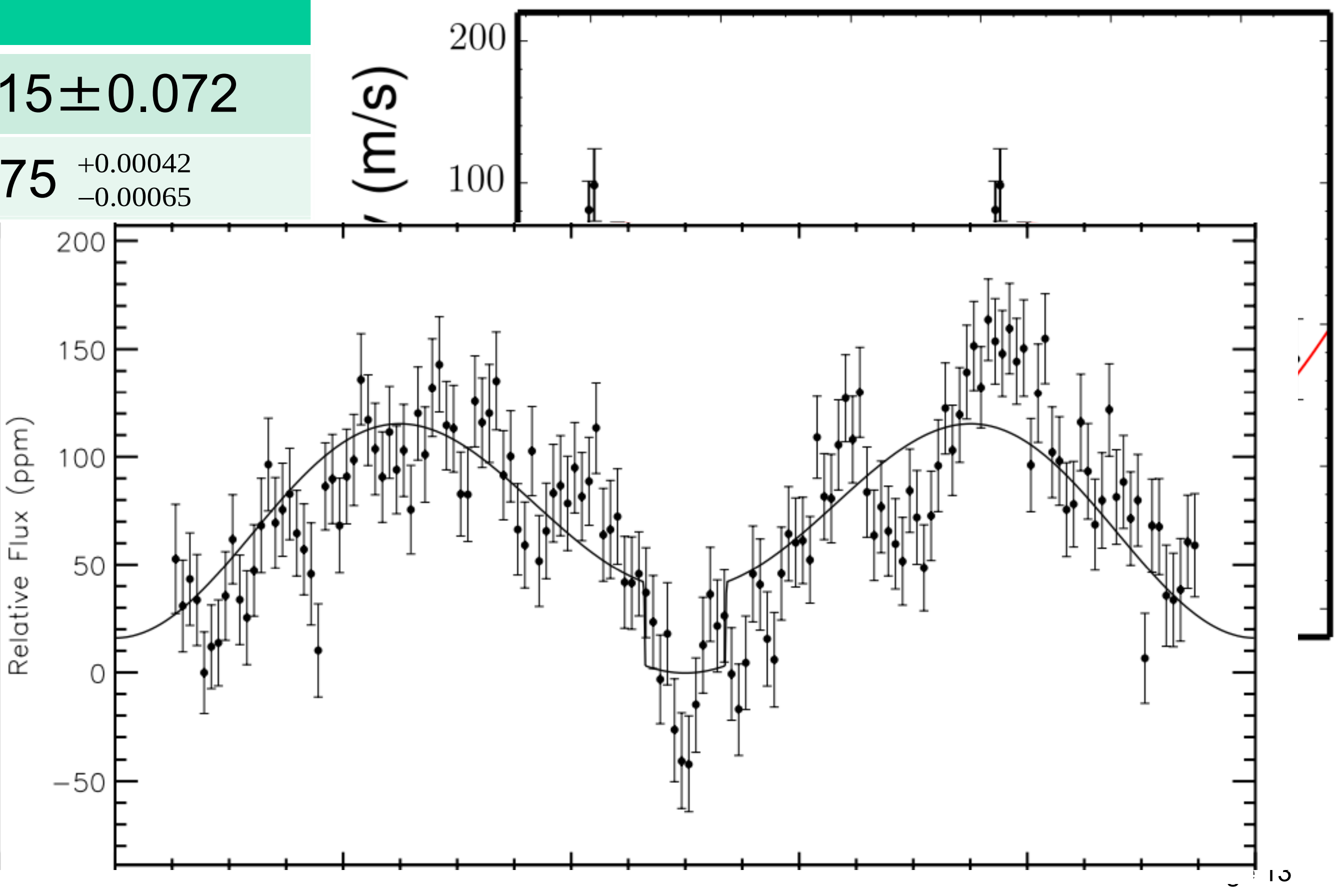


Dealing with stellar variability in transit characterisation – a cautionary tale

- Planet status refuted by Esteves et al. 2013 due to self-luminosity (Ag>>1)
- Planet status confirmed by Lillo-Box et al. 2014 due to light curve variations
- Planet status refuted by Sliski & Kipping 2014 due to asterodensity profiling
- Planet status confirmed by Barclay et al. 2014 with RV measurements and GPs

	a/R_s	R_p/R_s
T13	2.64±0.23	0.02115±0.072
E13	$4.51^{+0.12}_{-0.26}$	$0.01775^{+0.00042}_{-0.00065}$





Going forward…

- Account for stellar variability/noise in occurrence rate considerations!
  - Increased stellar noise increases the required SNR
  - AND makes detection more difficult at the same SNR
- Account for stellar variability/noise in transit characterisation!
  - Different treatments of the stellar noise

    = different transit depths/durations

    = different planet parameters

    = different planet interpretations!

- Keep playing with Kepler data!
  - New candidates and pipeline products coming soon