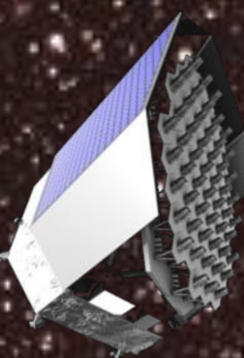
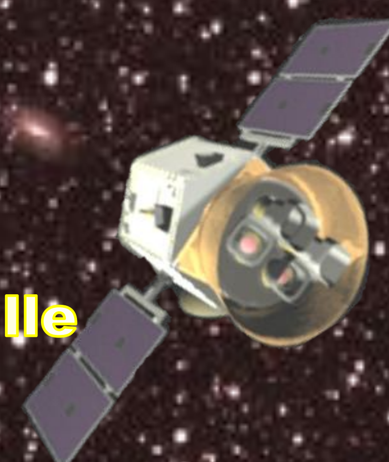
The Impact of Stellar Variability on the Detection of Transiting Earth-like Planets



Jon M. Jenkins

NASA Ames Research Center

Wednesday October 24 2018



Institute for Planetary Science
Laboratoire d'Astrophysique de Marseille
Marseille, France

Overview

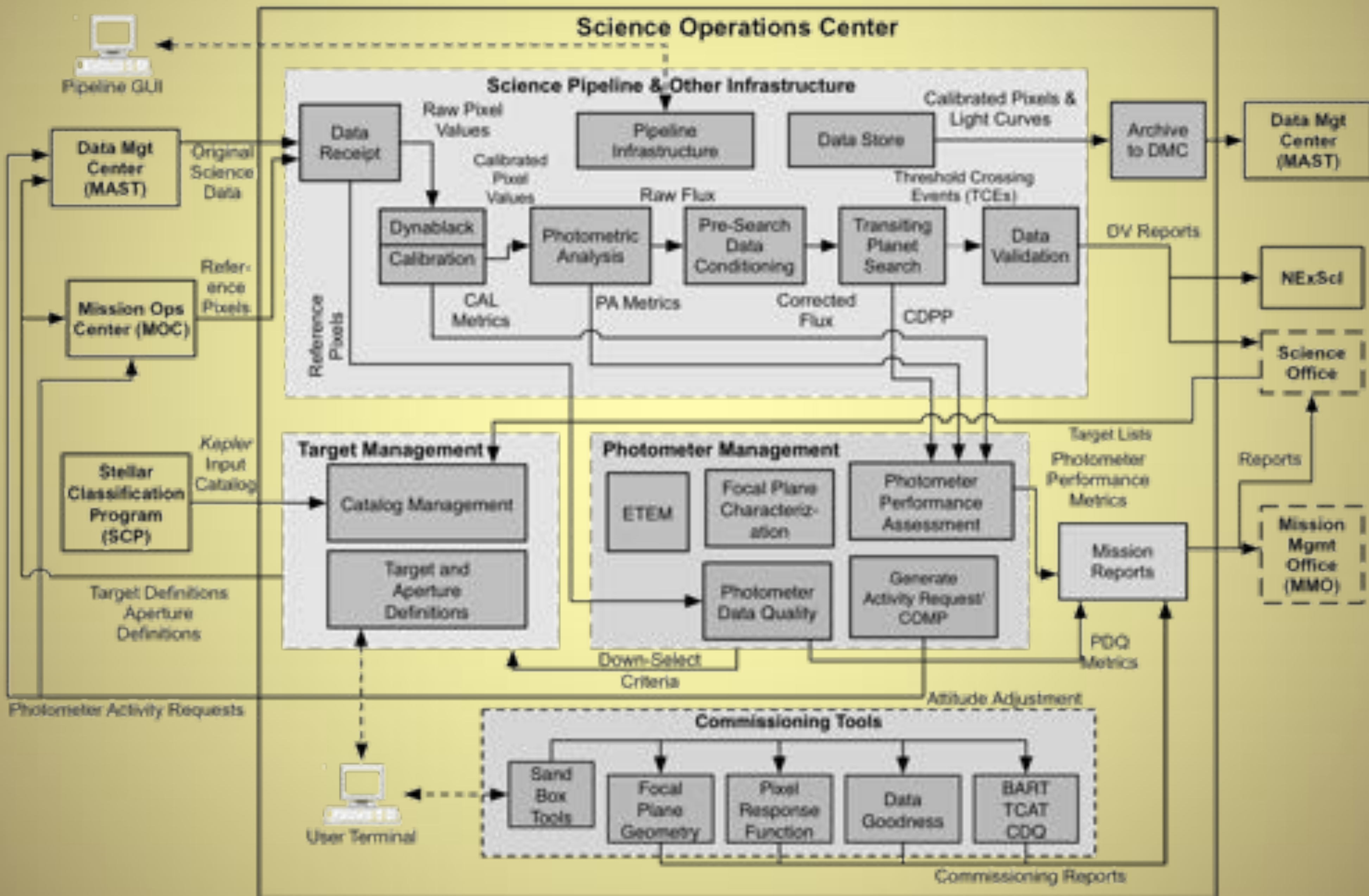
A Search for Earth-size Planets

- The Science Operations Center Pipeline
- Solar Variability
- Detection Theory
- A Wavelet-based Adaptive Matched Filter
- Observations of Stellar Noise on Transit Timescales
- Excess Stellar Variability
- Summary


KEPLER
SCIENCE DATA PROCESSING PIPELINE
DYN
CAL
PA
PDC
DV
TPS

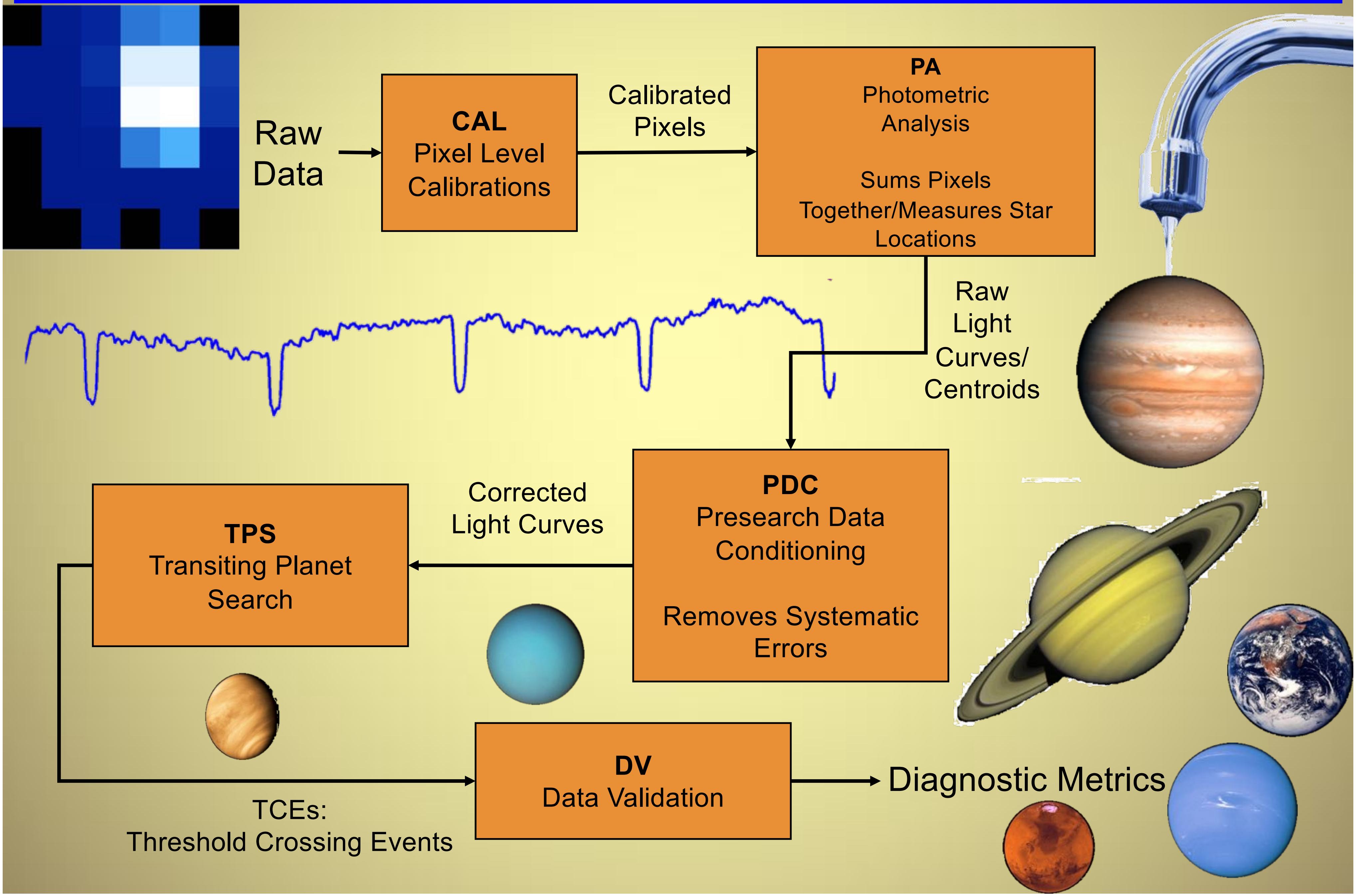
Science Operations Center Architecture

Kepler
A Search for Earth-size Planets



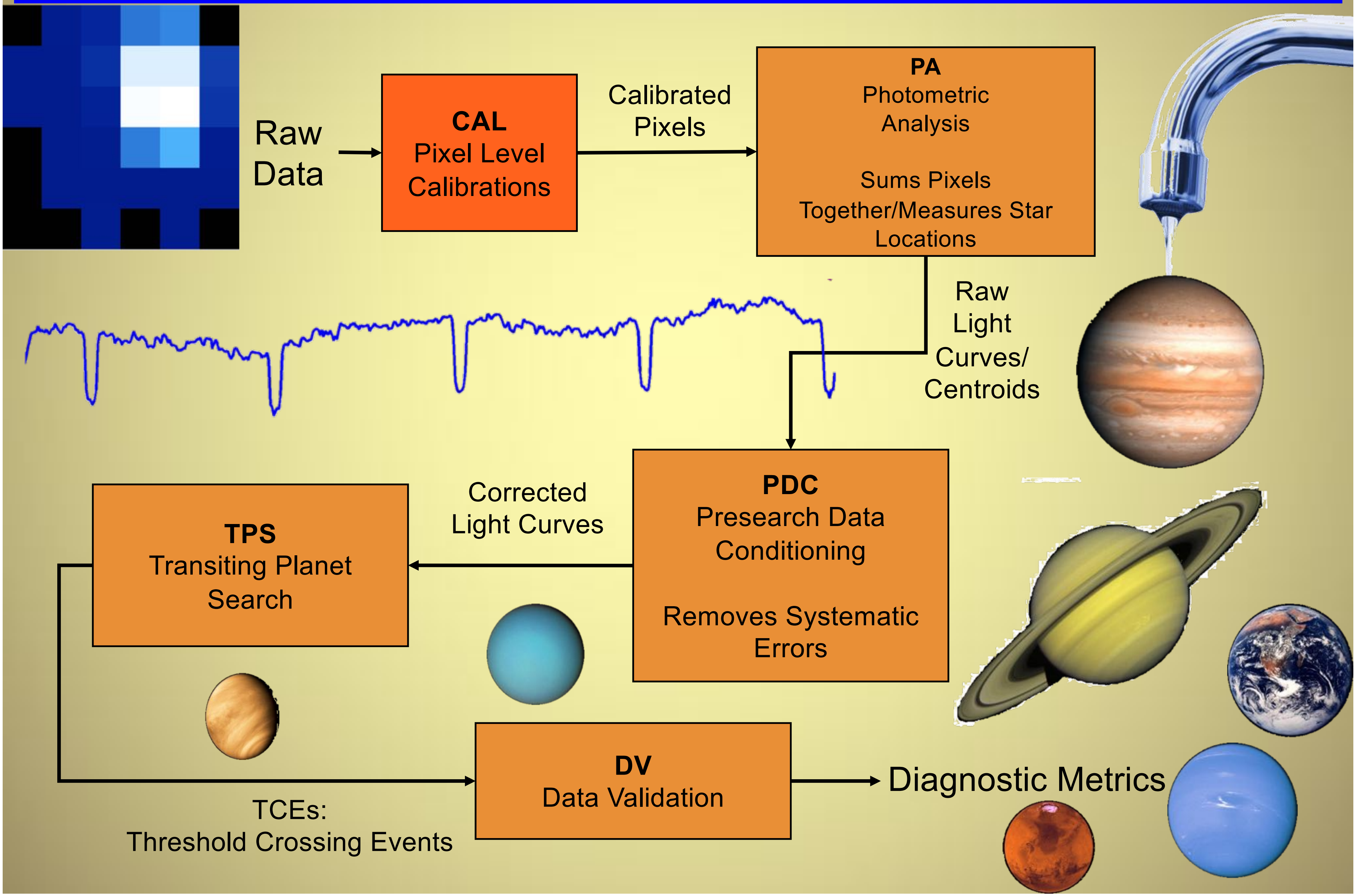
The Kepler Science Pipeline: From Pixels To Planets

Kepler
A Search for Earth-size Planets



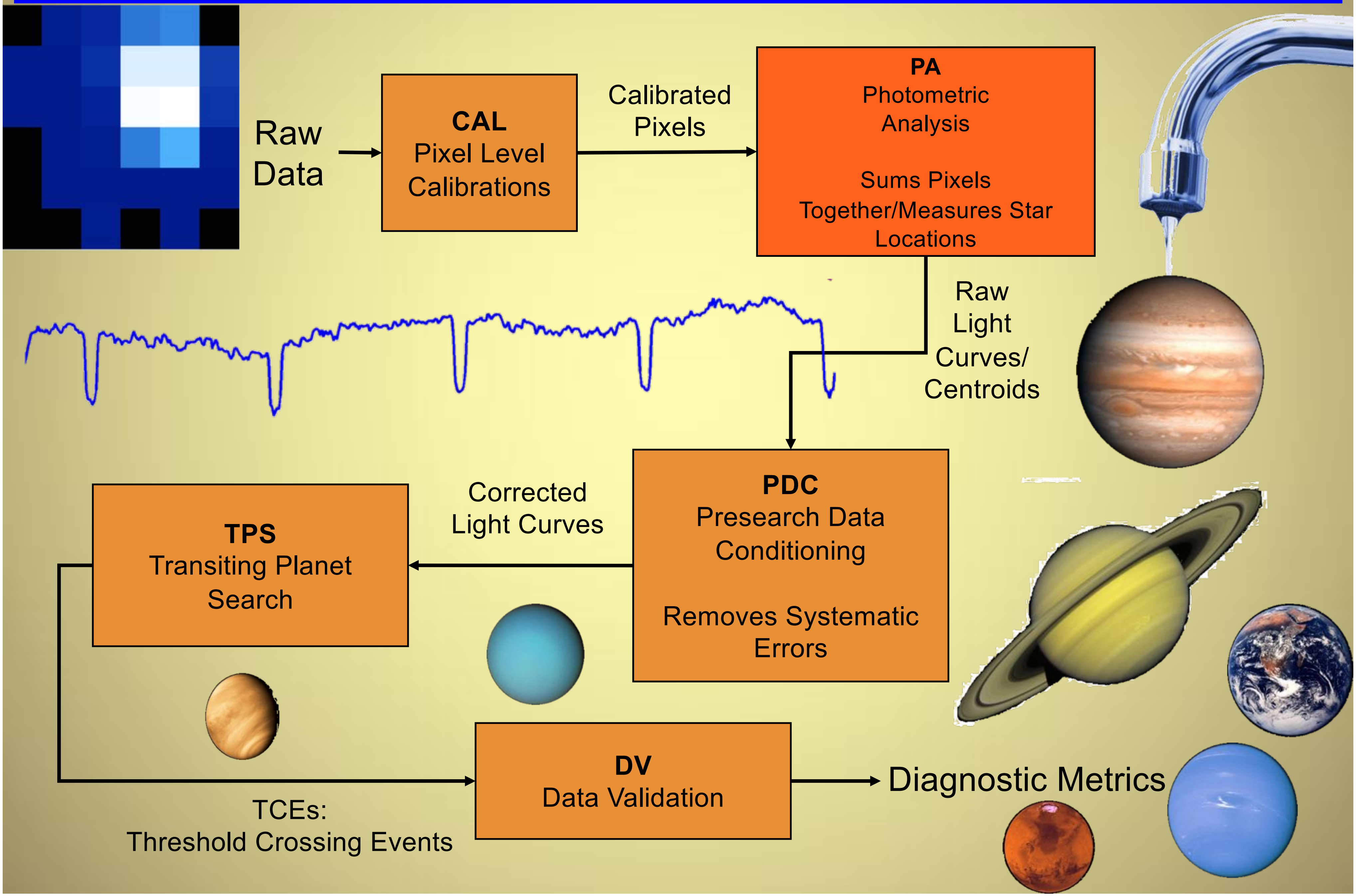
The Kepler Science Pipeline: From Pixels To Planets

A Search for Earth-size Planets



The Kepler Science Pipeline: From Pixels To Planets

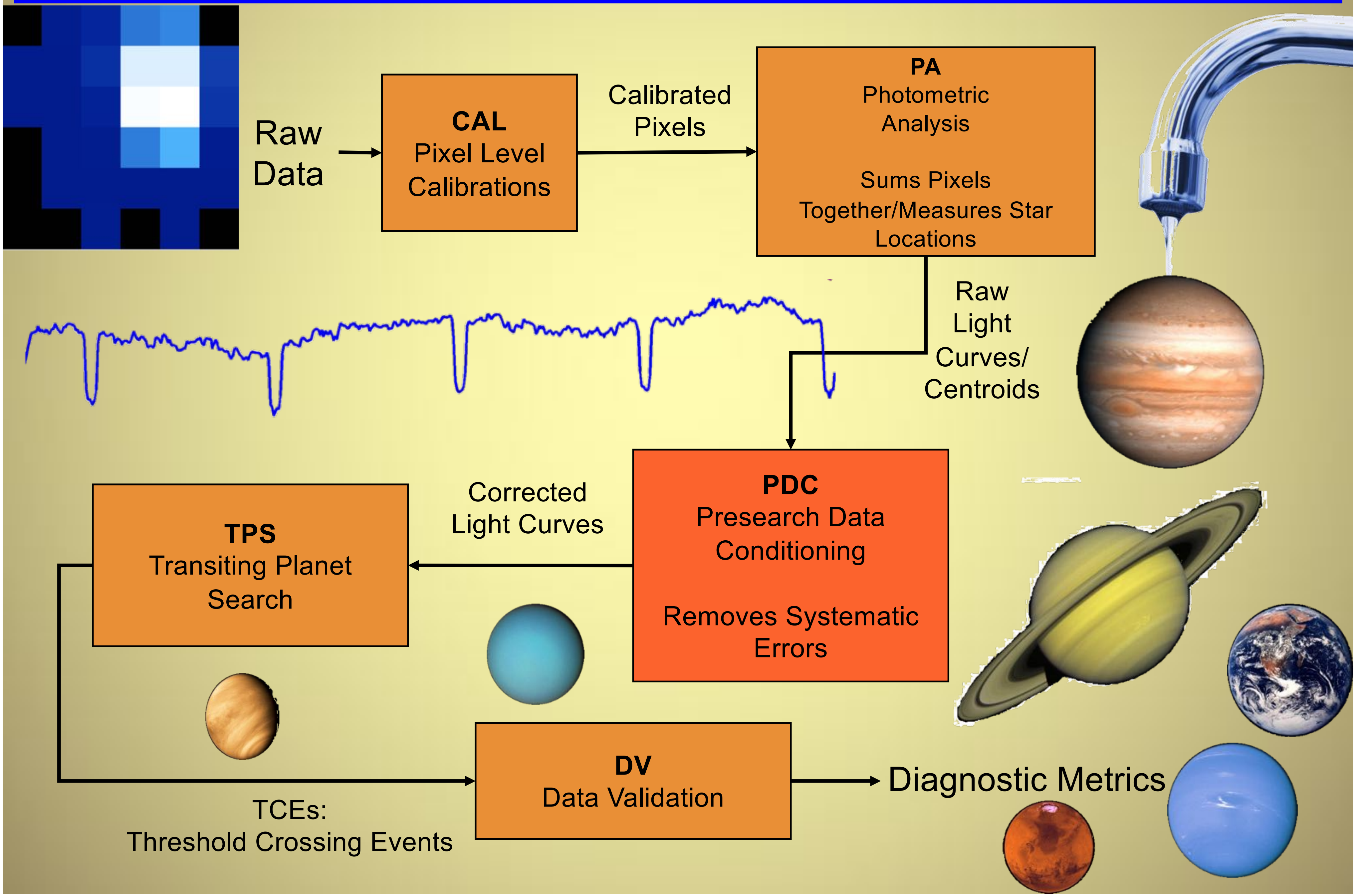
A Search for Earth-size Planets



The Kepler Science Pipeline: From Pixels To Planets

Kepler

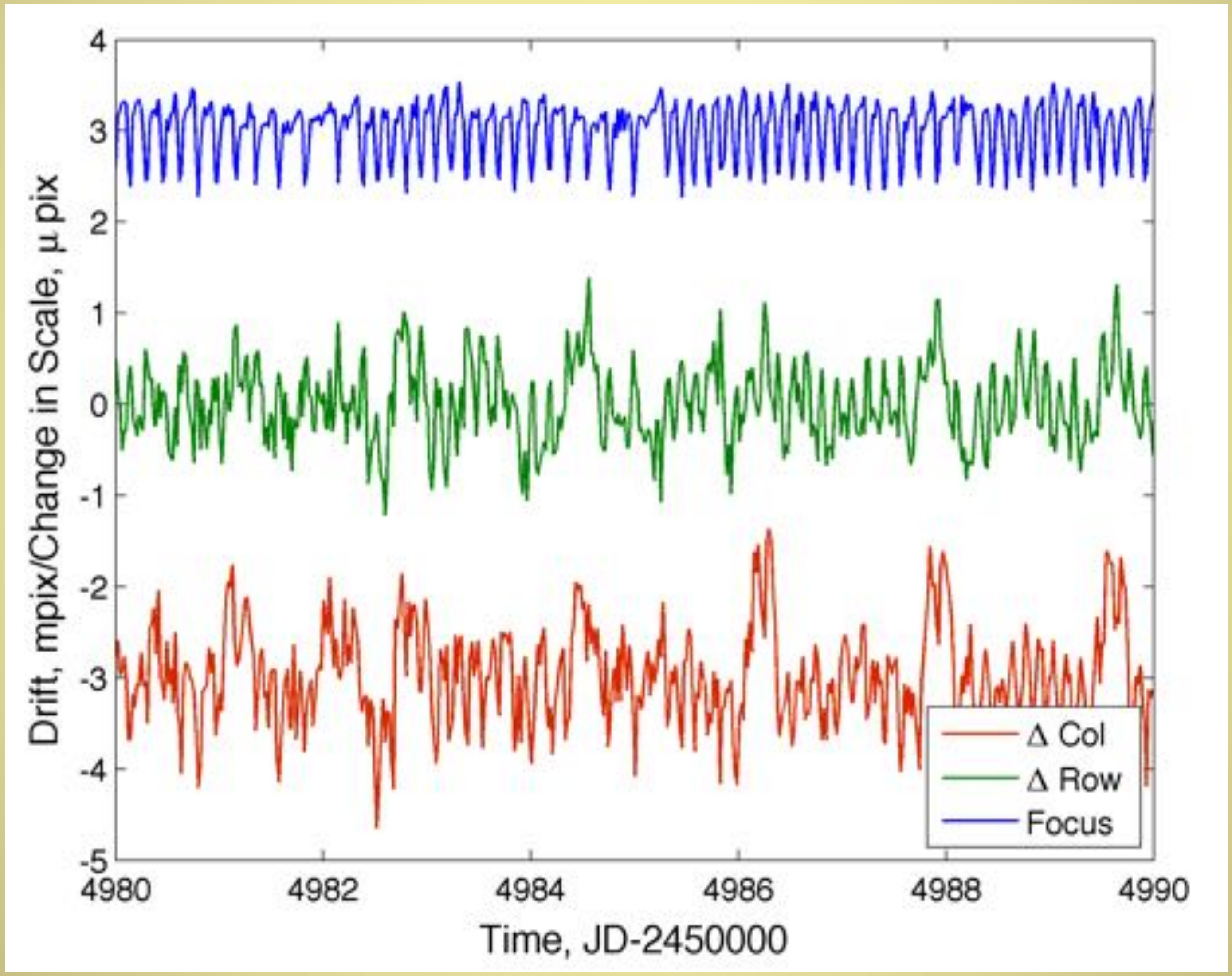
A Search for Earth-size Planets



Short Timescale Instrumental Errors

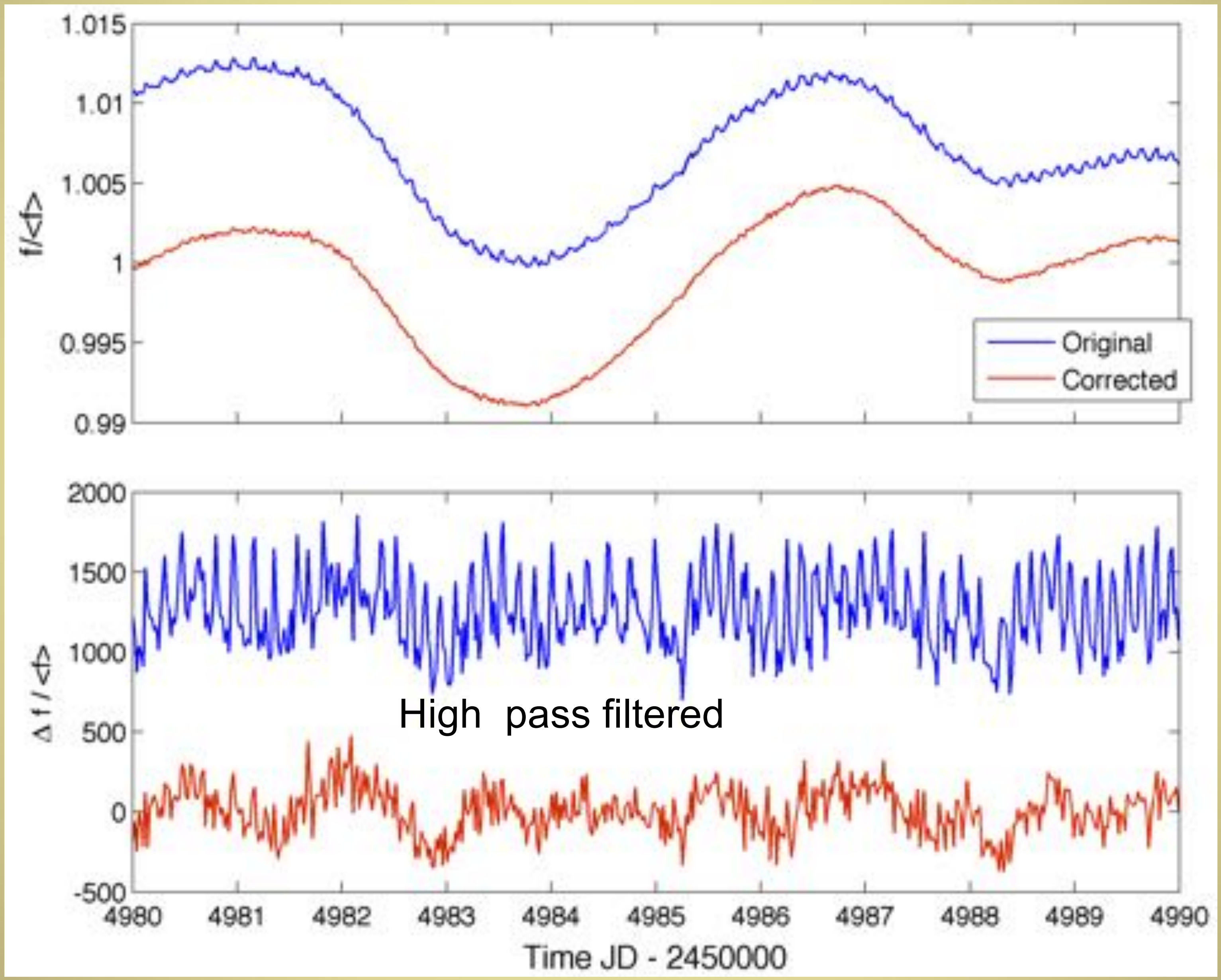
A Search for Earth-size Planets

Signature of a heater cycling on the reaction wheels 3/4

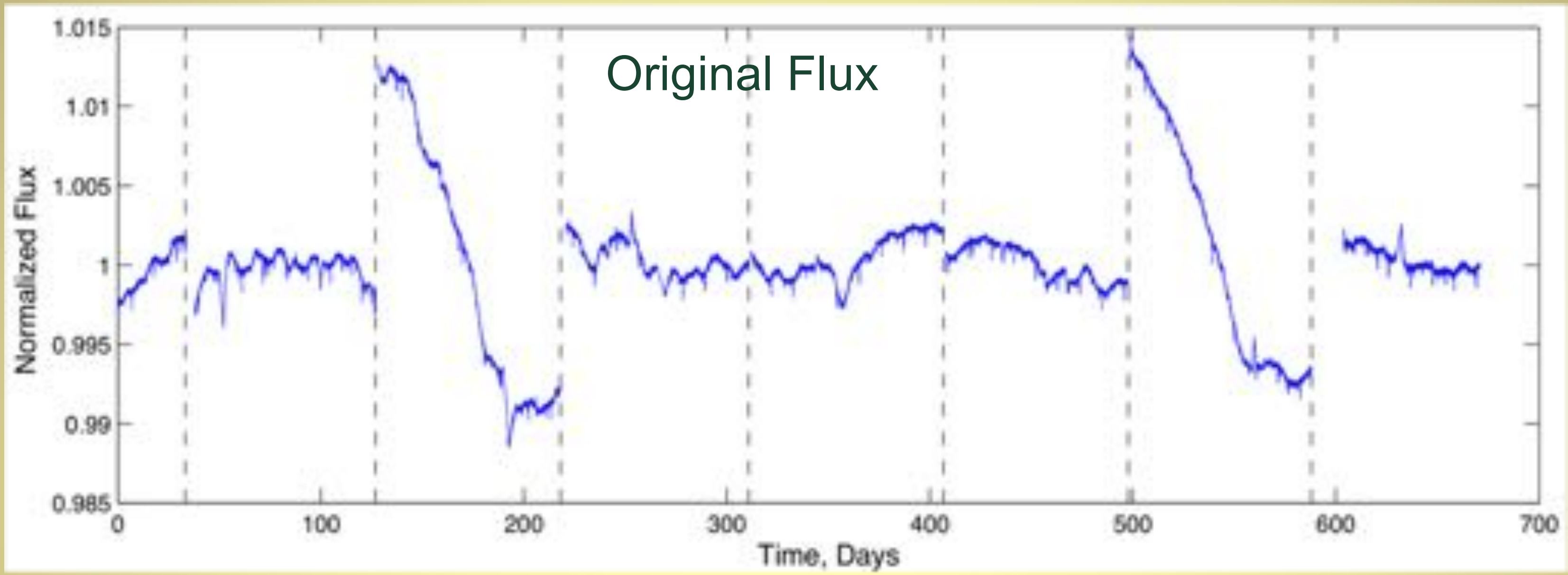


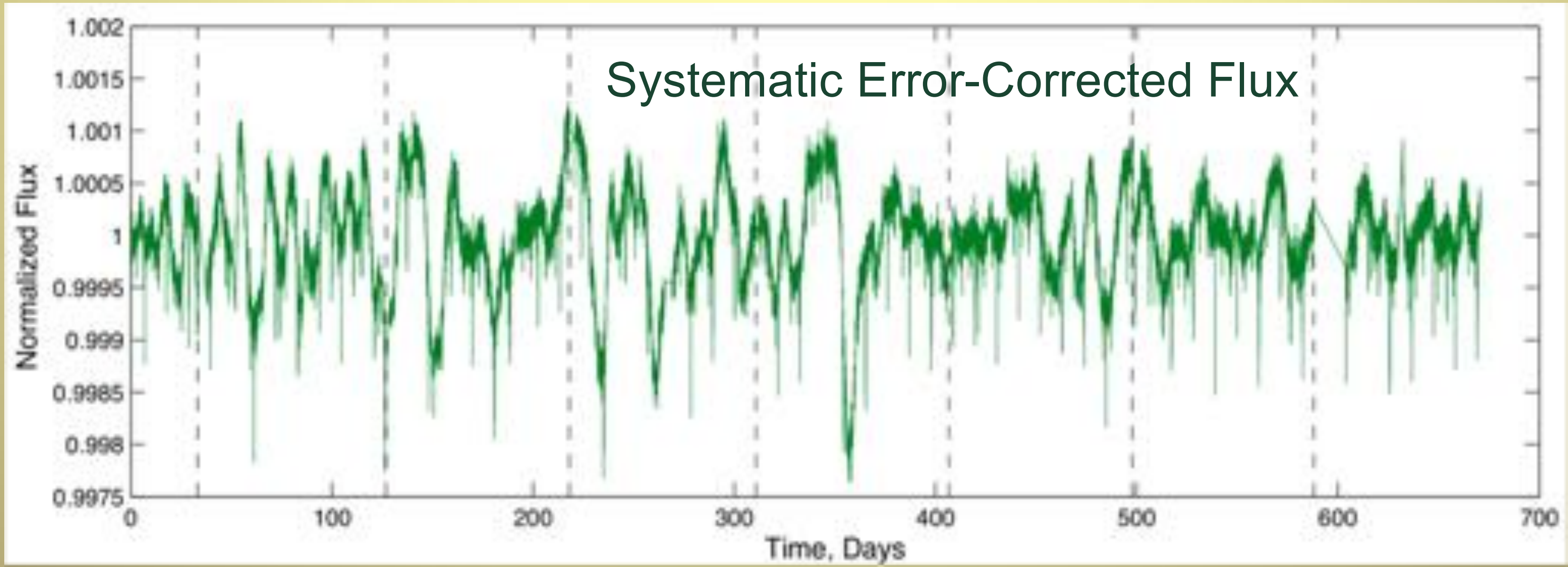
Kepler is sensitive to its thermal environment

Instrumental Effects in Photometry



Correcting Systematic Errors

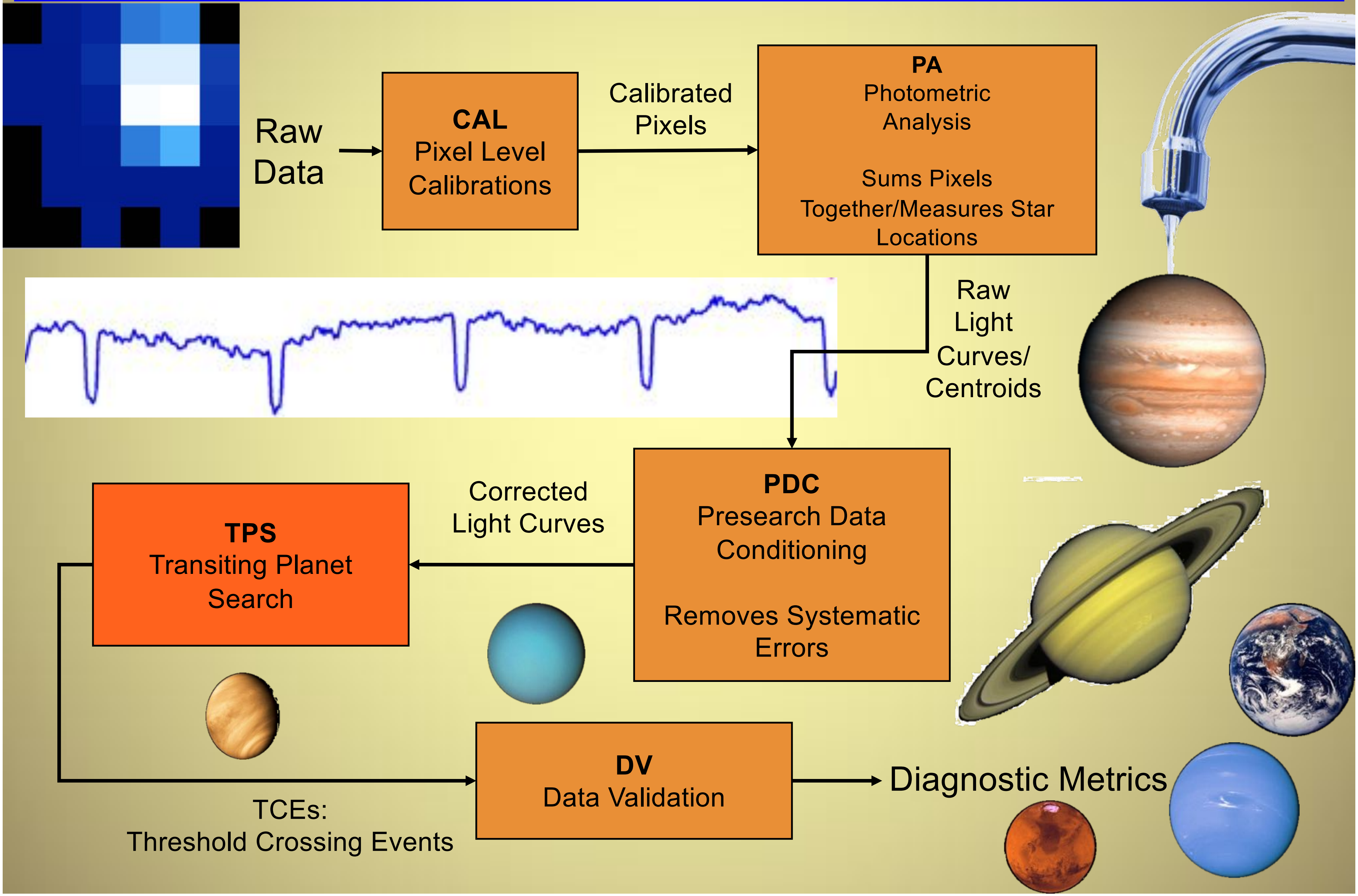


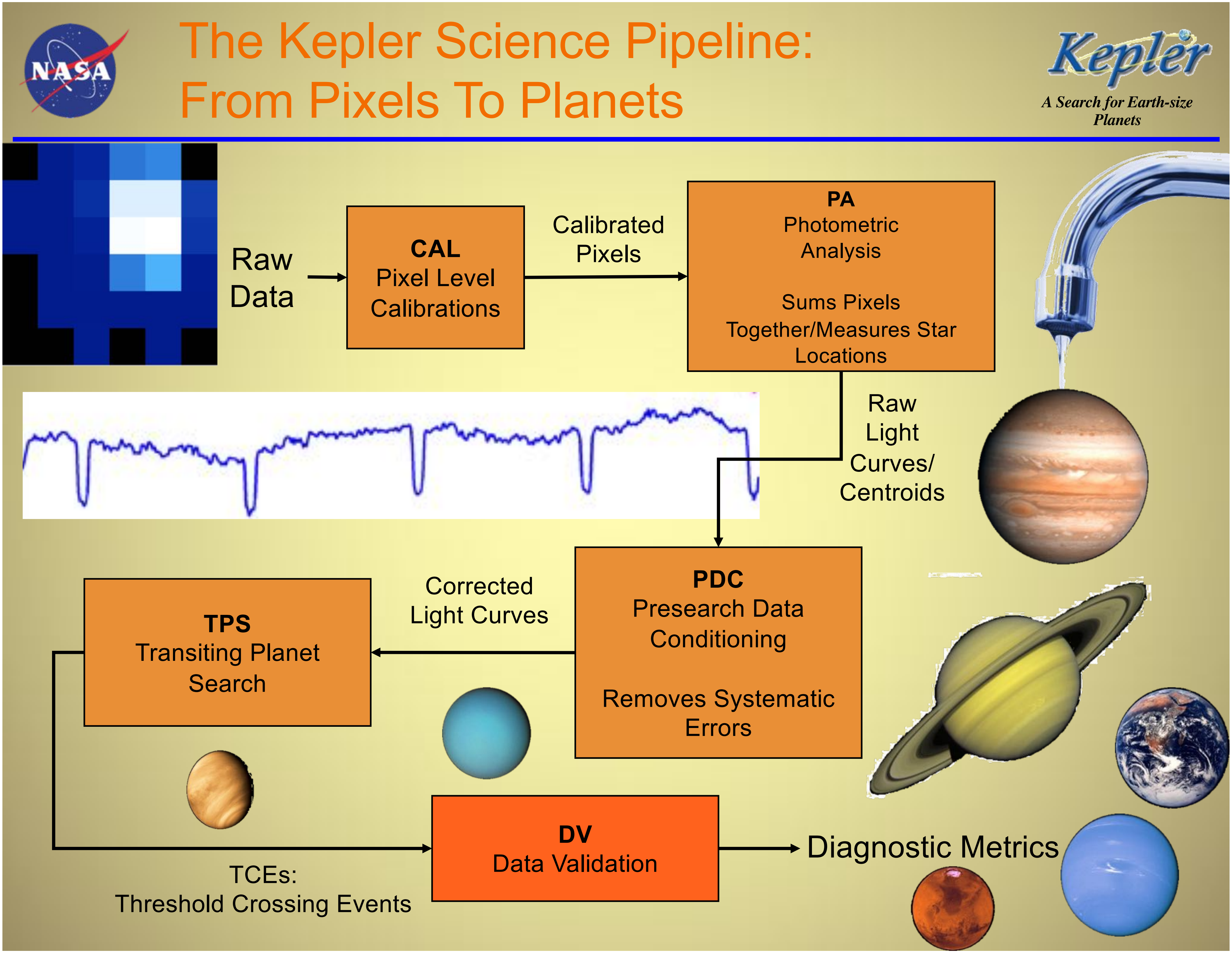


We apply a Maximum A Posteriori approach as per Stumpe et al. 2014

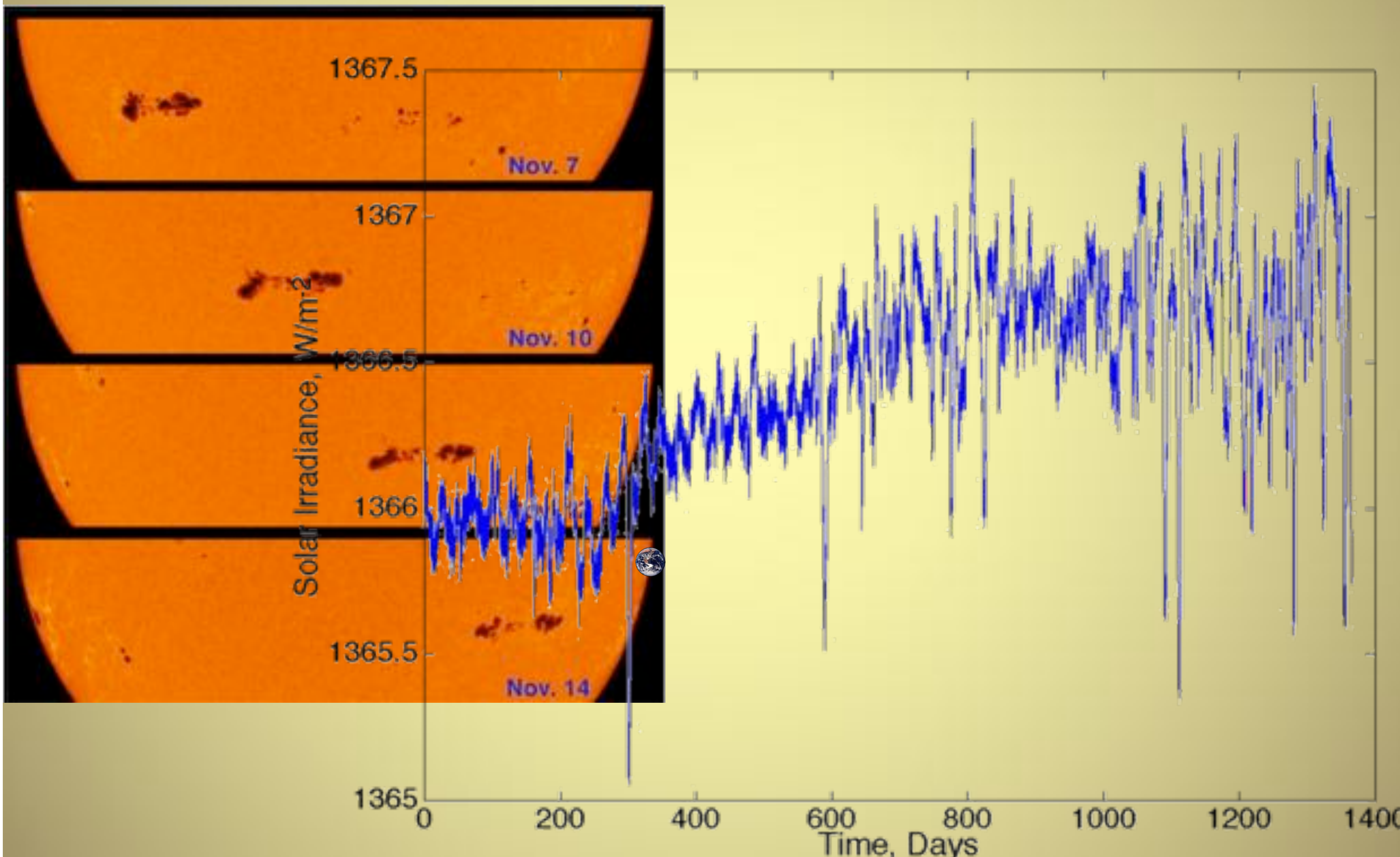
The Kepler Science Pipeline: From Pixels To Planets

Kepler
A Search for Earth-size Planets




The Kepler Science Pipeline:
From Pixels To Planets
Kepler
A Search for Earth-size Planets
Raw Data
CAL
Pixel Level Calibrations
Calibrated Pixels
PA
Photometric Analysis
Sums Pixels Together/Measures Star Locations
Raw Light Curves/ Centroids
PDC
Presearch Data Conditioning
Removes Systematic Errors
Corrected Light Curves
TPS
Transiting Planet Search
TCEs:
Threshold Crossing Events
DV
Data Validation
Diagnostic Metrics

Solar Variability



Detecting Deterministic Signals

A Search for Earth-size Planets

The problem:

- H0: $x(n) = w(n)$ or
- H1: $x(n) = s(n) + w(n)$

$s(n)$ is the signal of interest

$x(n)$ is the time series we observe

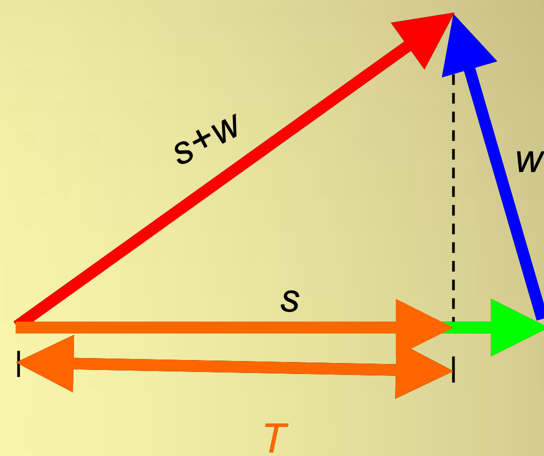
$w(n)$ is the observation noise (Gaussian)

The best method for detecting a known signal in additive Gaussian noise is a matched filter

A matched filter measures the correlation between the data and the signal, normalized by the rms variation of the observation noise

Detection Statistics

Define $$T = \frac{x^T s}{\sigma_w \sqrt{s^T s}}$$



Under H0: $$\langle T \rangle = 0, \quad \sigma_T^2 = 1$$

Under H1: $$\langle T \rangle = \frac{1}{\sigma_w}\sqrt{s^T s}, \quad \sigma_T^2 = 1$$

If $T < \gamma$, then choose H0, if $T > \gamma$, then choose H1

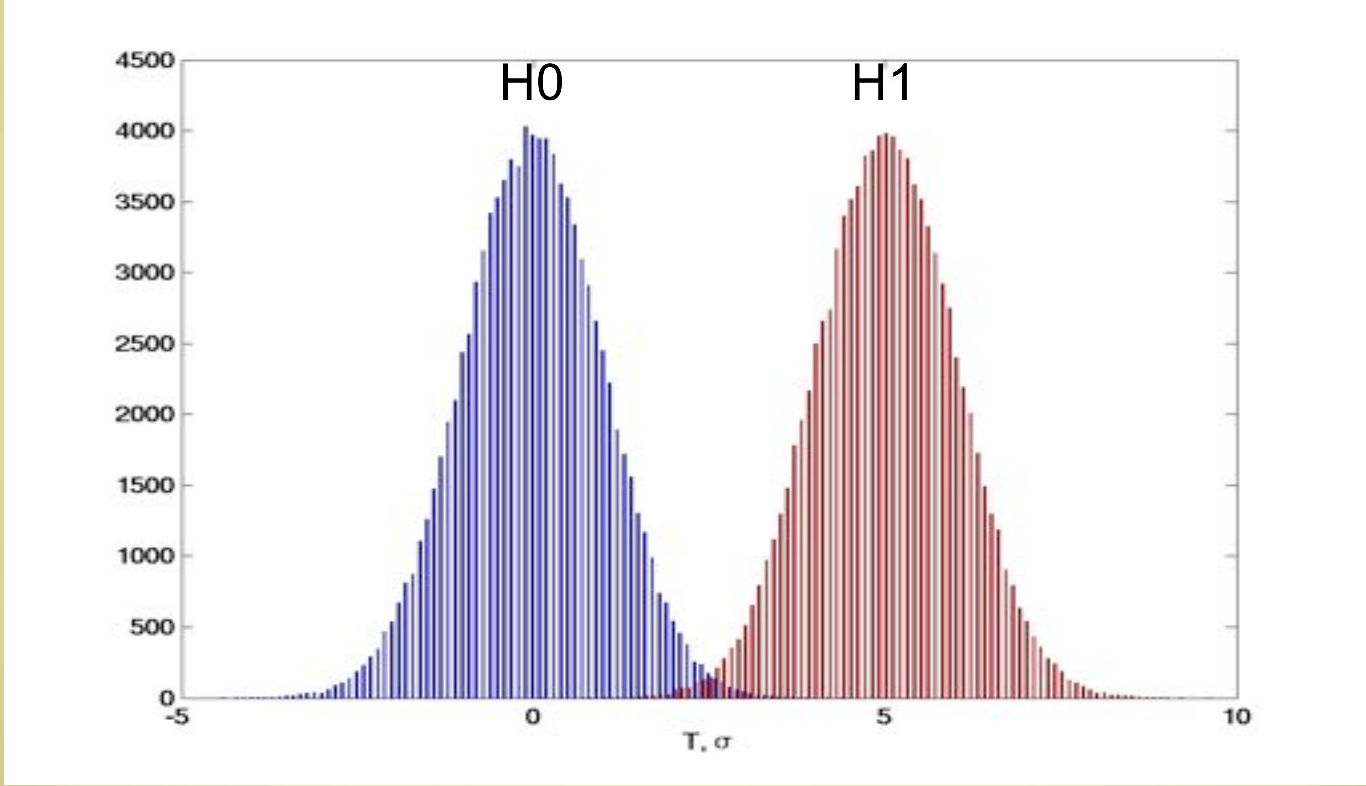
Receiver Operating Curves

A Search for Earth-size Planets

T is a Gaussian random variable

$$P_F = \frac{1}{\sqrt{2\pi}} \int_{\gamma}^{\infty} \exp\left(-\tfrac{1}{2} y^2\right) dy$$

$$P_D = \frac{1}{\sqrt{2\pi}} \int_{\gamma-\langle T \rangle}^{\infty} \exp\left(-\tfrac{1}{2} y^2\right) dy$$



How do we choose the threshold, γ?

If amplitude of *s* not known, we generally set γ to control P_F.
(Neyman-Pearson Criterion)

Detection Statistics For Colored Noise

w is (colored) Gaussian noise with autocorrelation matrix *R*
x is the data
s is the signal of interest

Decide *s* is present if

$$T = \frac{x^T R^{-1} s}{\sqrt{s^T R^{-1} s}} = \frac{(Hx)^T (Hs)}{\sqrt{(Hs)^T (Hs)}} = \frac{\tilde{x}^T \tilde{s}}{\sqrt{\tilde{s}^T \tilde{s}}} > \gamma$$

How do we determine R?

Looks like a simple matched filter!

If the noise is stationary, we can work in the frequency domain:

$$T = \int \frac{X(f)S^*(f)}{P(f)} df \Bigg/ \sqrt{\int \frac{S(f)S^*(f)}{P(f)} df}$$

PSDs for Solar-Like Variability

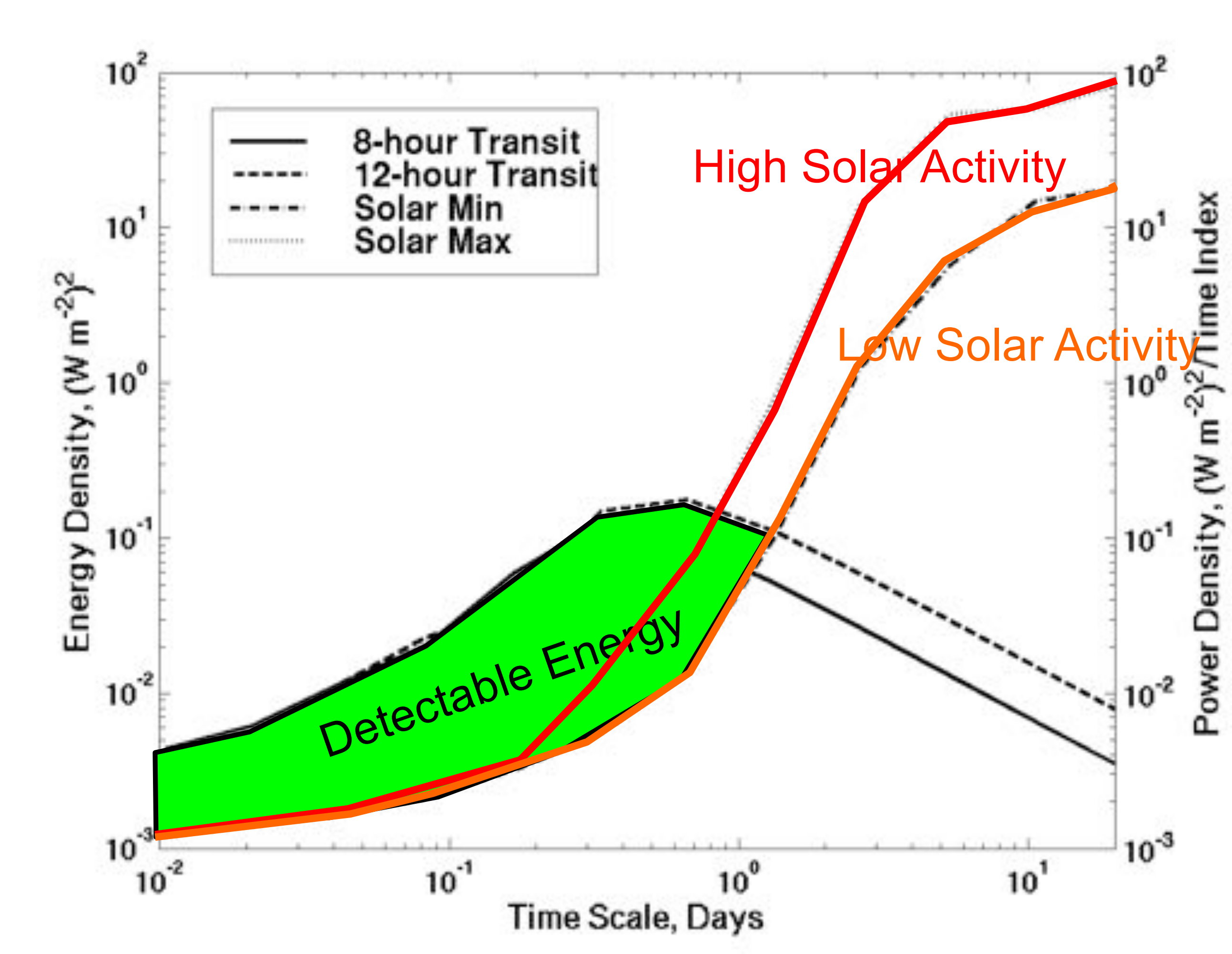
A Search for Earth-size Planets

Is stellar variability stationary?

No!

We must work in a joint time-frequency domain

Wavelets are a natural choice



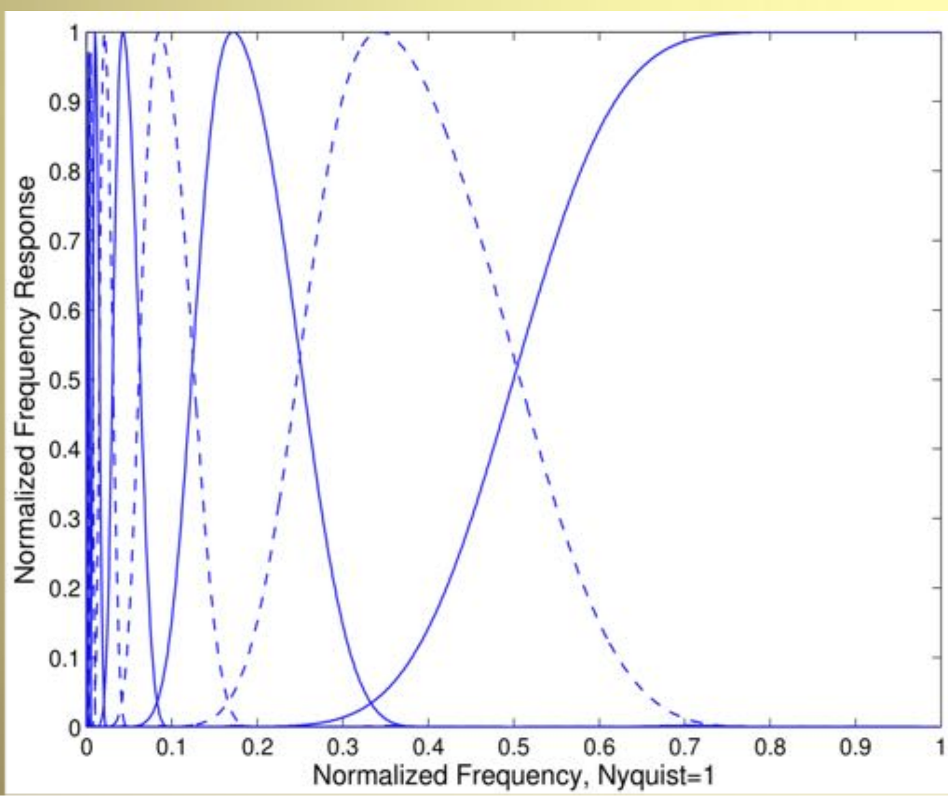
A Wavelet-Based Approach

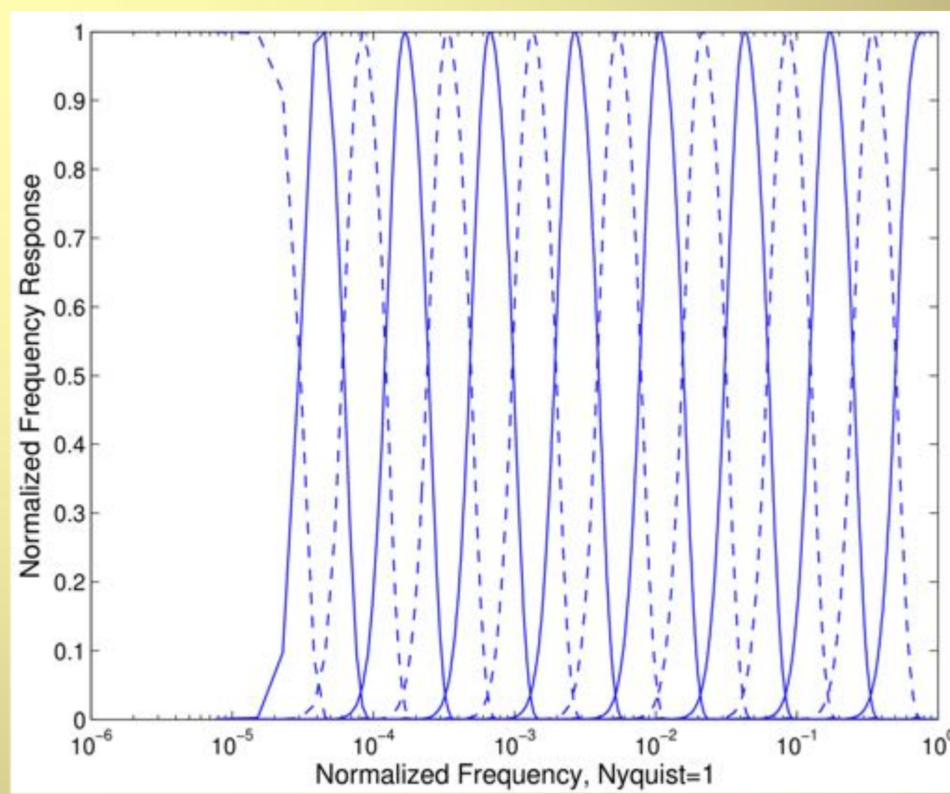
Kepler
A Search for Earth-size Planets

Filter-Bank Implementation of an Overcomplete Wavelet Transform

The time series *x(n)* is partitioned (filtered) into complementary channels

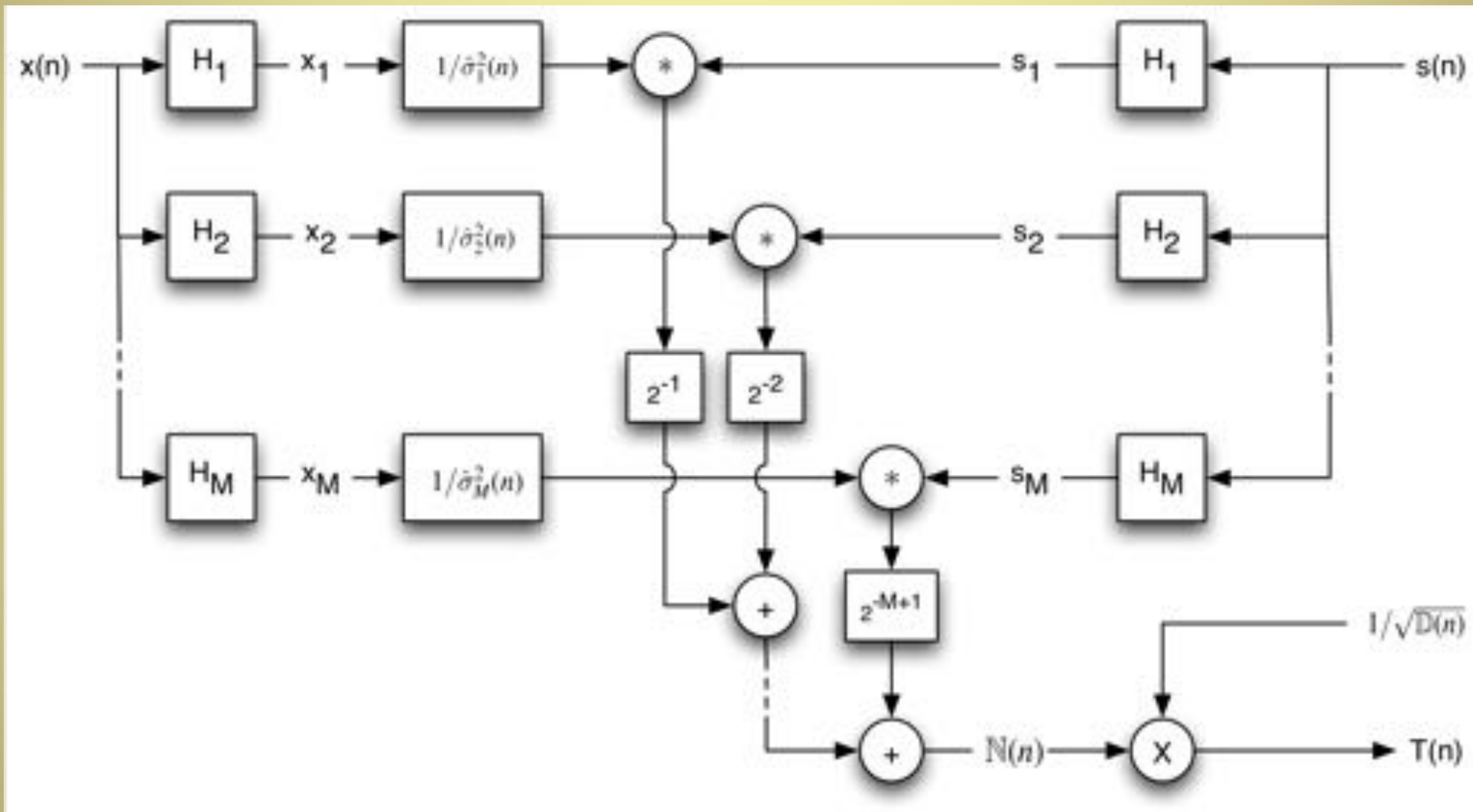
$$W_X(i,n) = \{h_1(n) * x(n), h_2(n) * x(n),\dots, h_M(n) * x(n)\} = \{x_1(n), x_2(n),\dots, x_m(n)\}$$





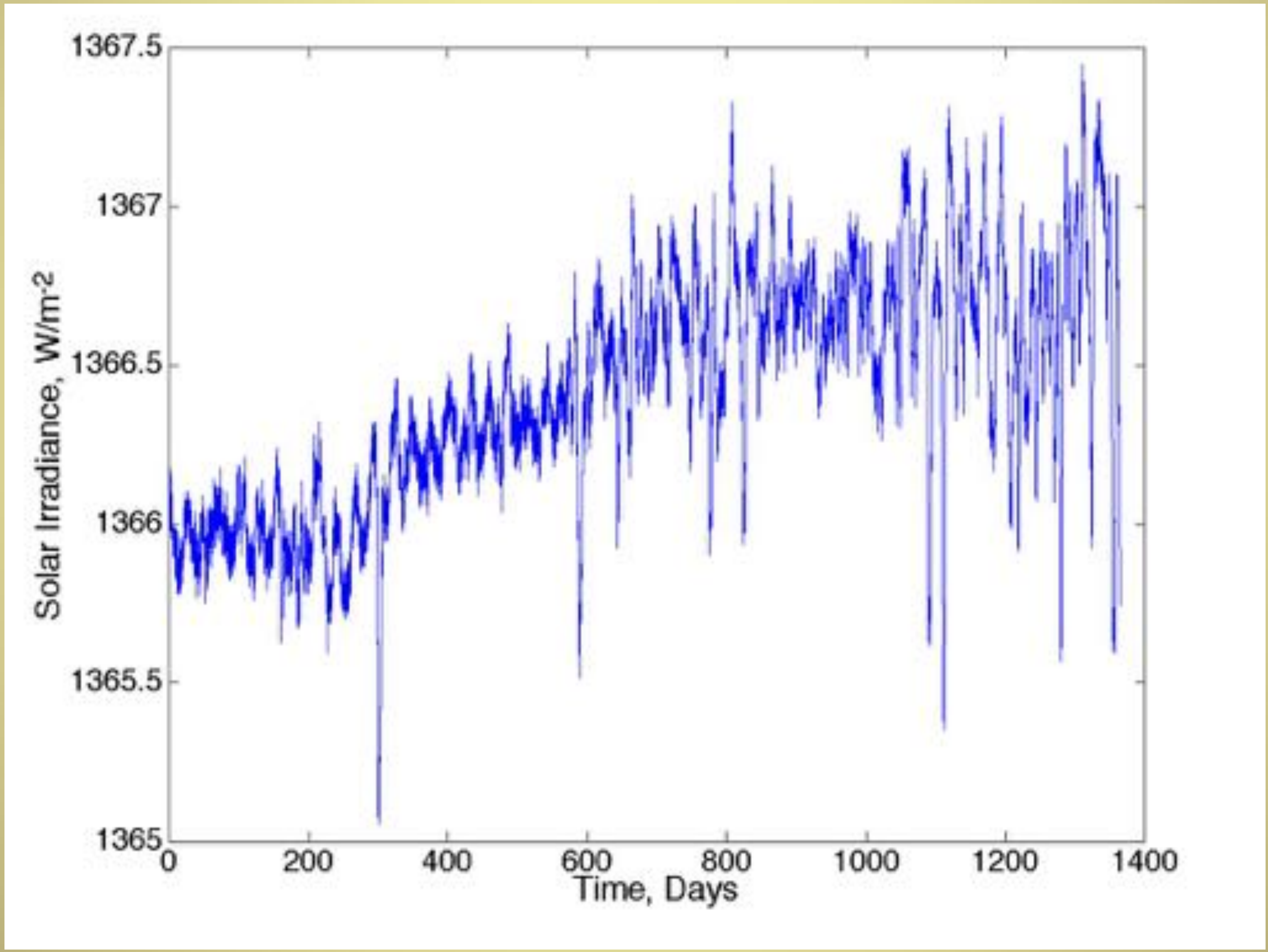
Signal Flow Diagram

A Search for Earth-size Planets



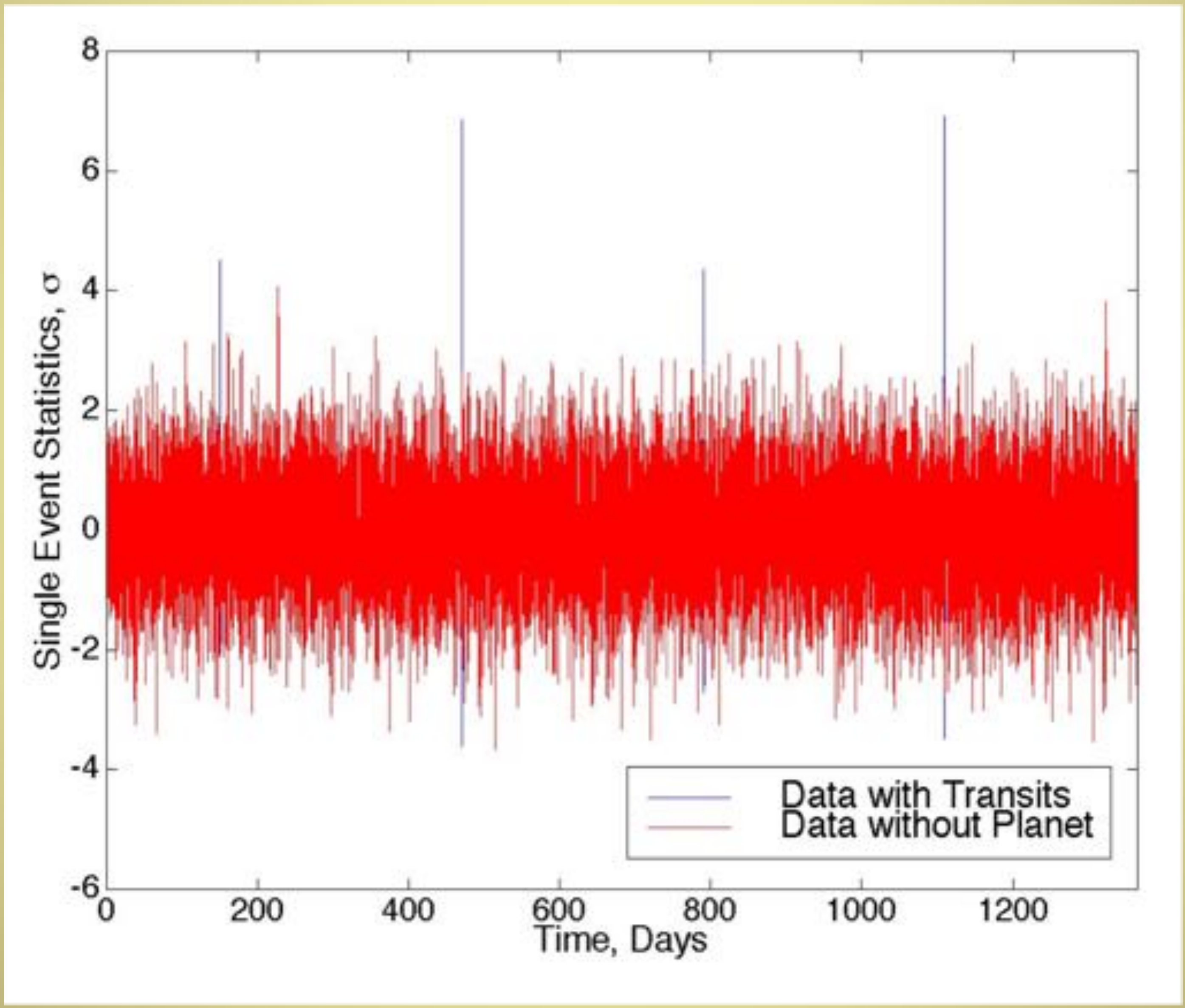
Kepler-like Noise + Transits

Kepler
A Search for Earth-size Planets



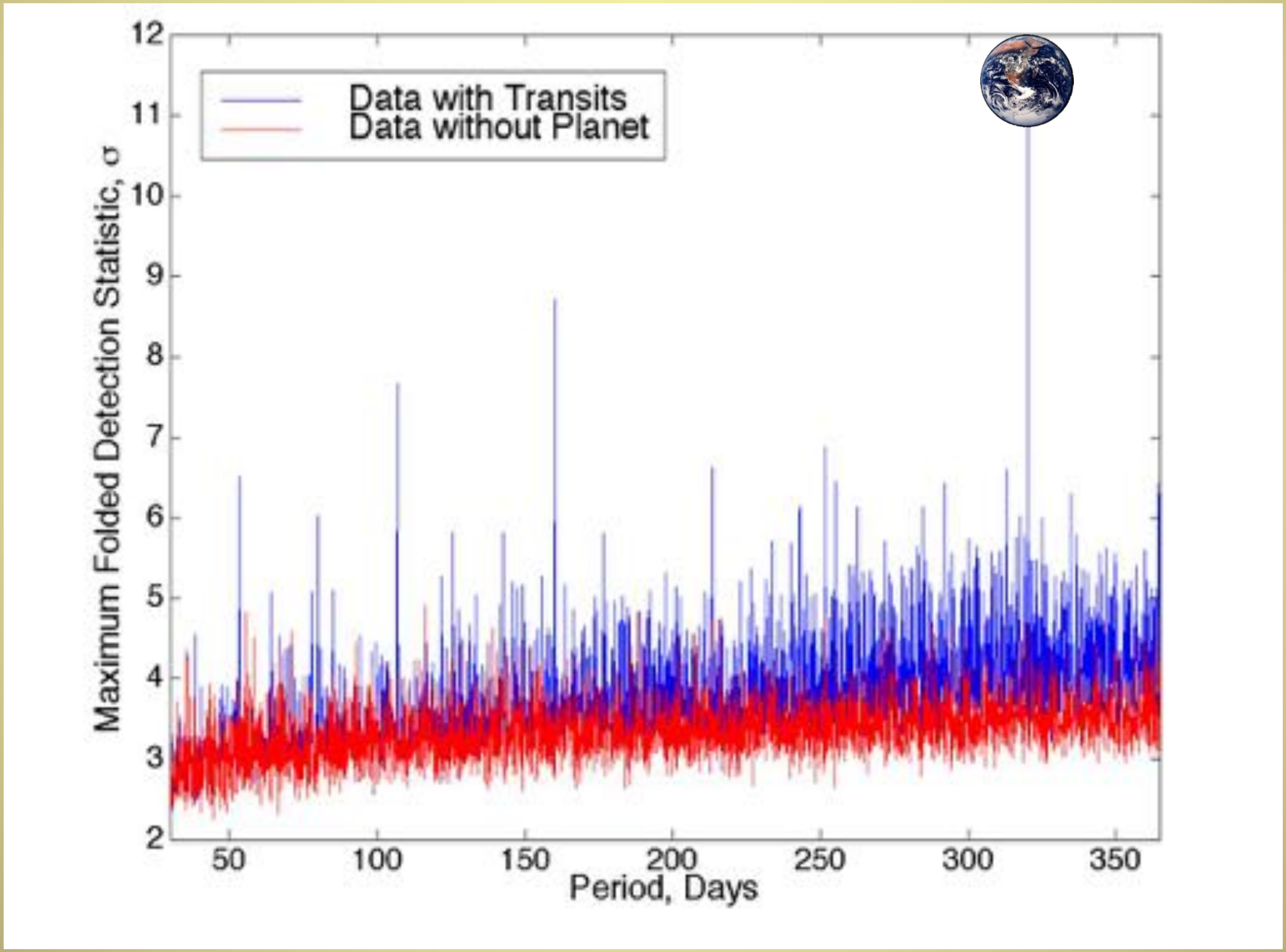
Single Transit Statistics

A Search for Earth-size Planets



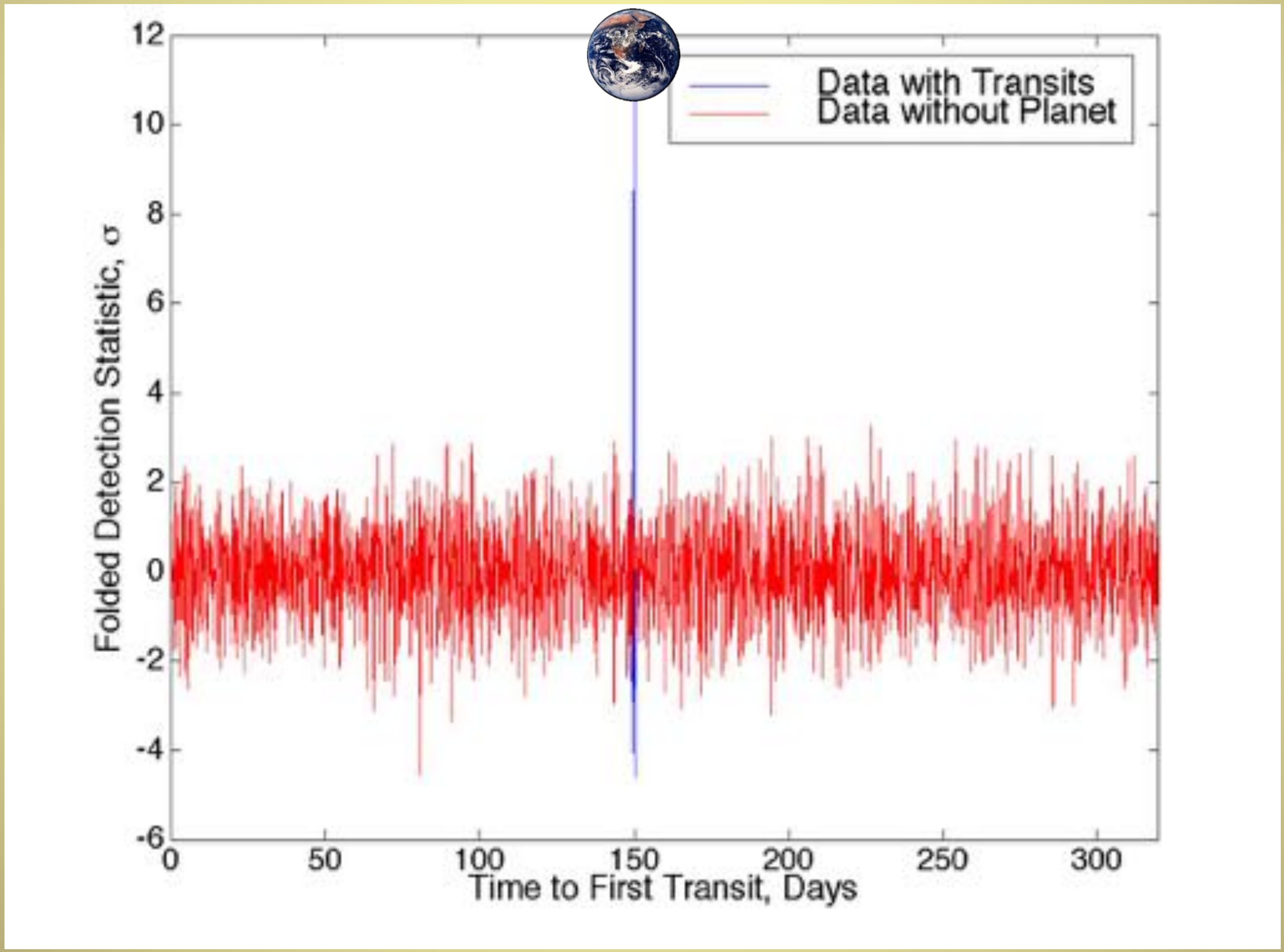
Folded Transit Statistics

A Search for Earth-size Planets



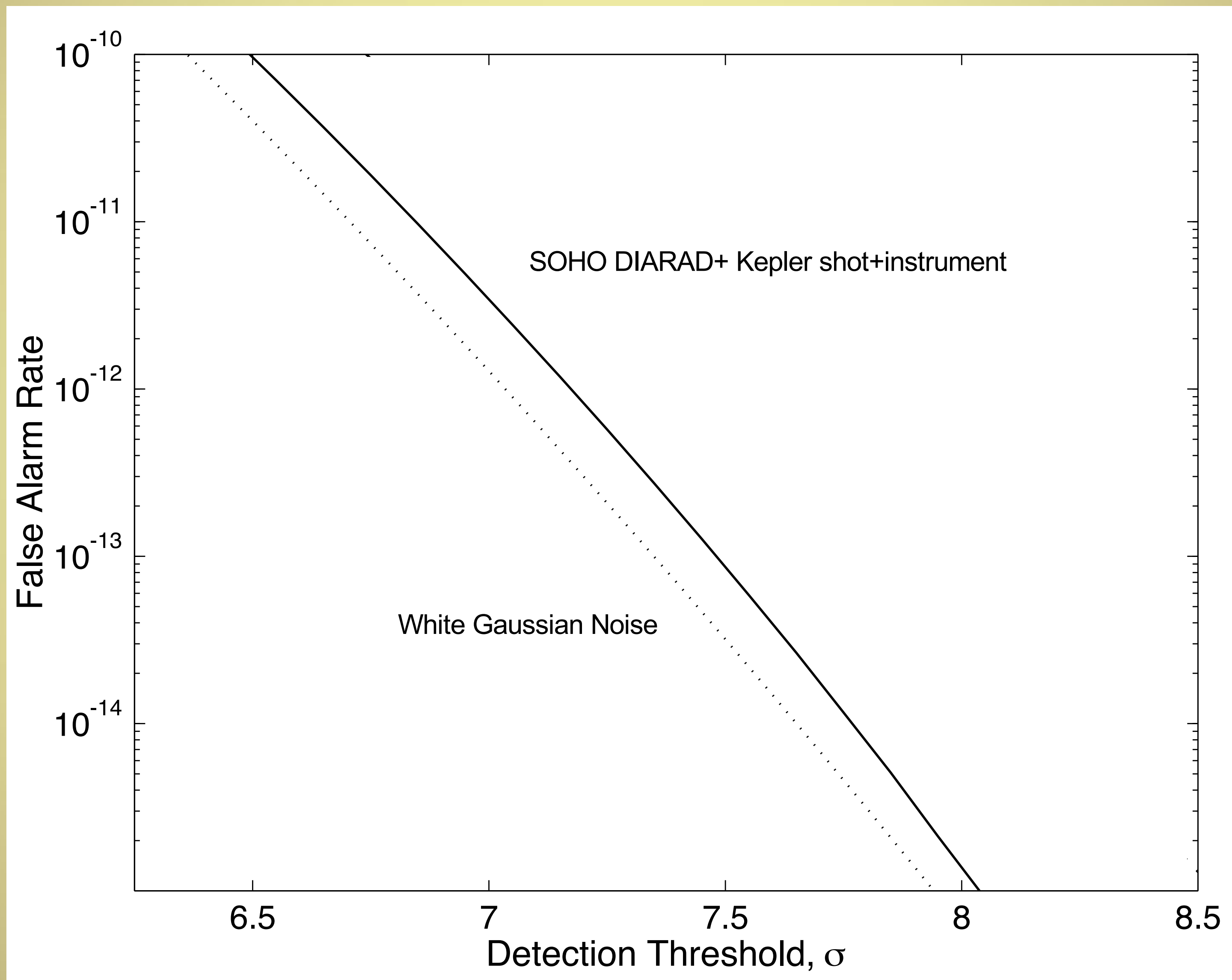
Folded Statistics at Best-Matched Period

A Search for Earth-size Planets



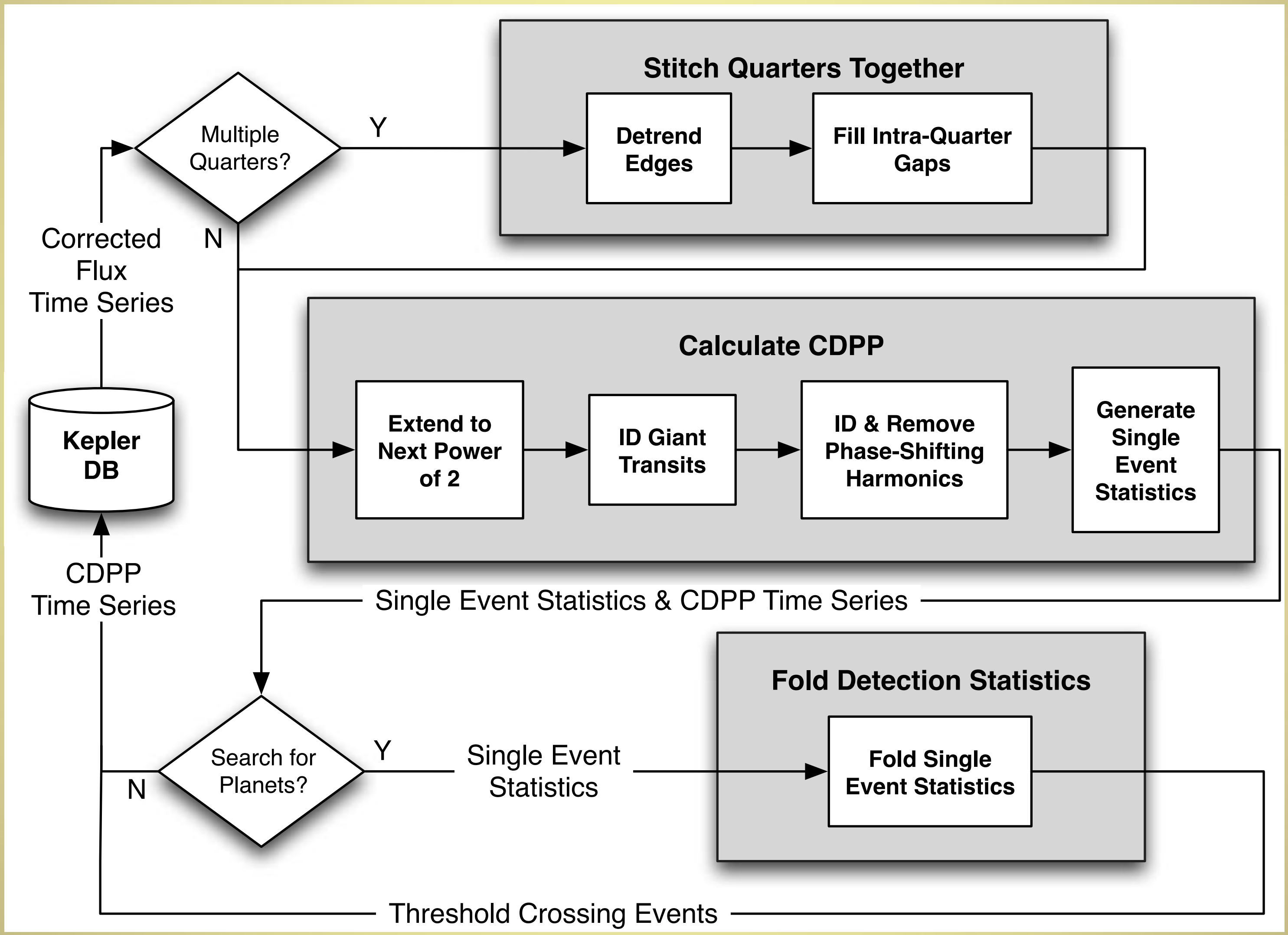
Setting the Threshold

A Search for Earth-size Planets



Transiting Planet Search Architecture

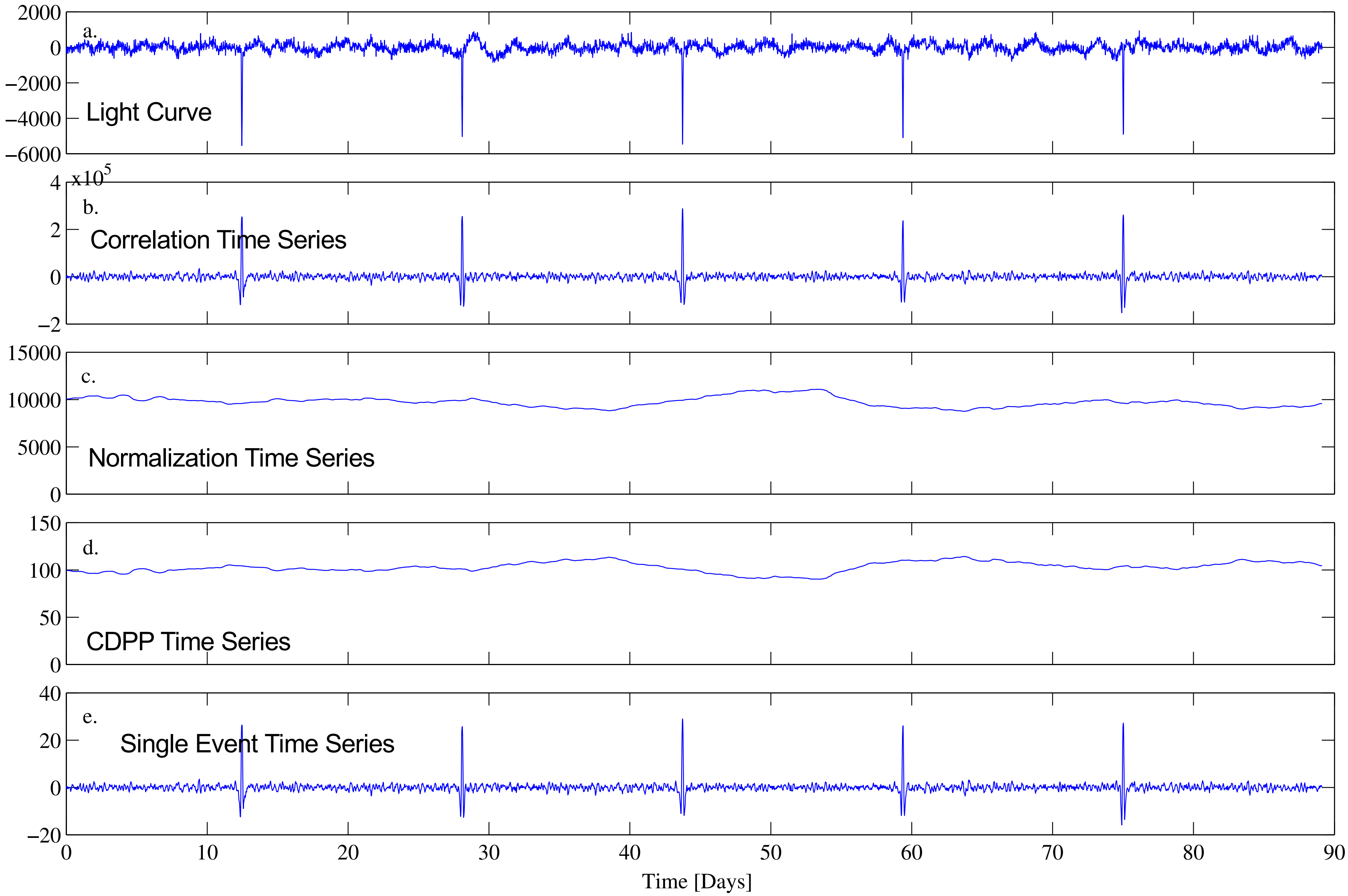
A Search for Earth-size Planets



Details here: https://archive.stsci.edu/kepler/manuals/KSCI-19081-002-KDPH.pdf

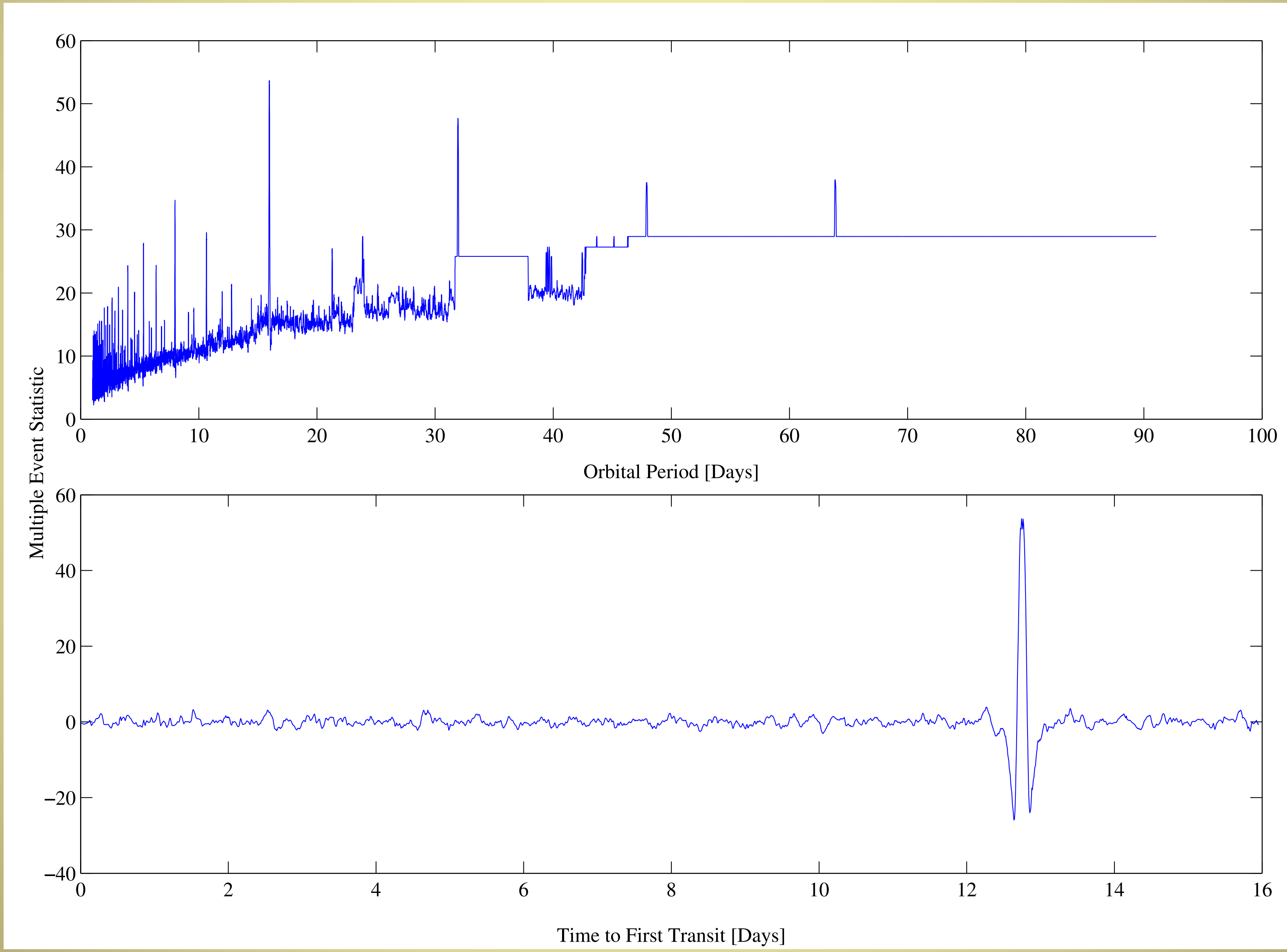
A Kepler Example: Calculating CDPP

A Search for Earth-size Planets

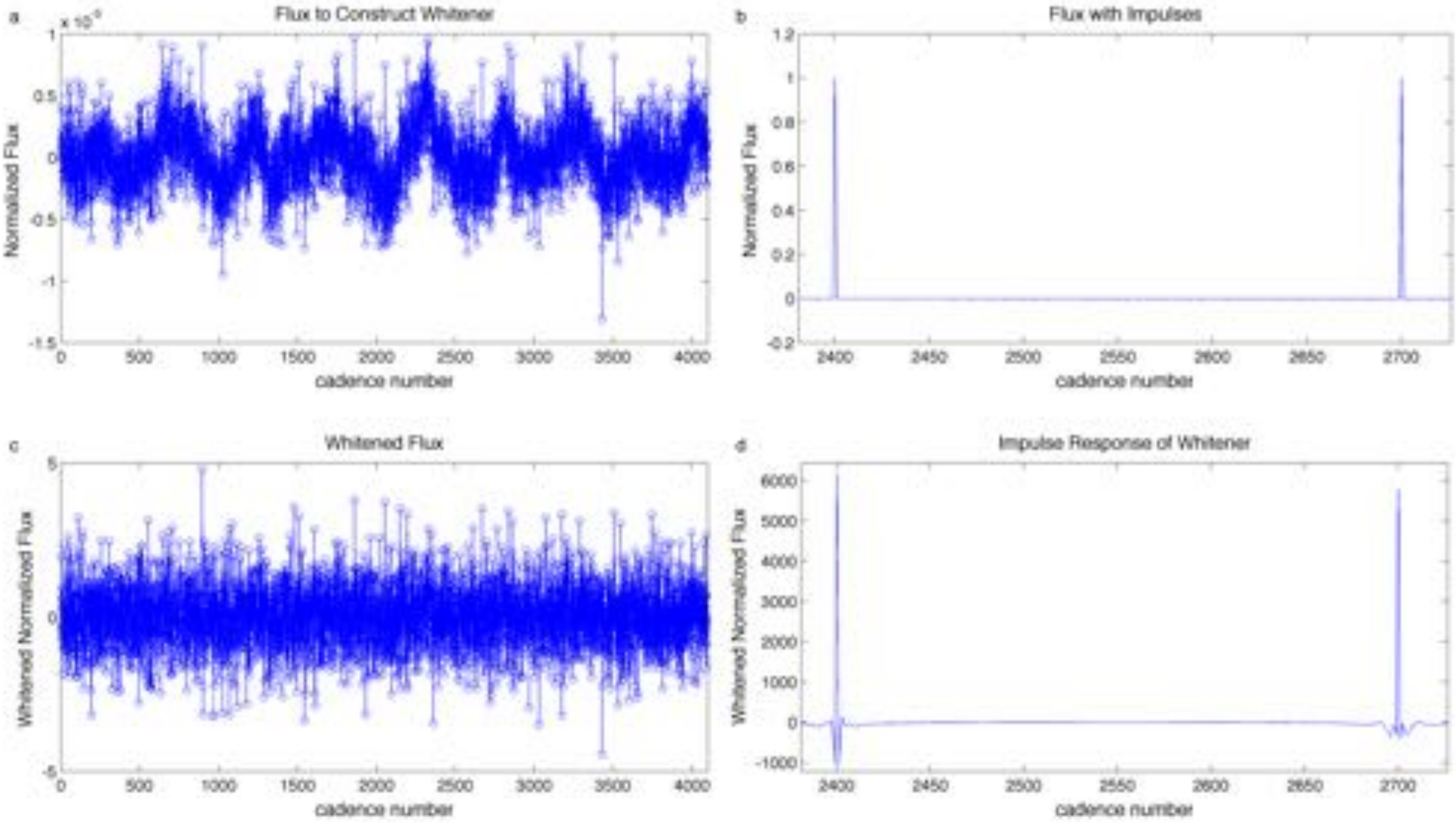


A Kepler Example: Calculating CDPP

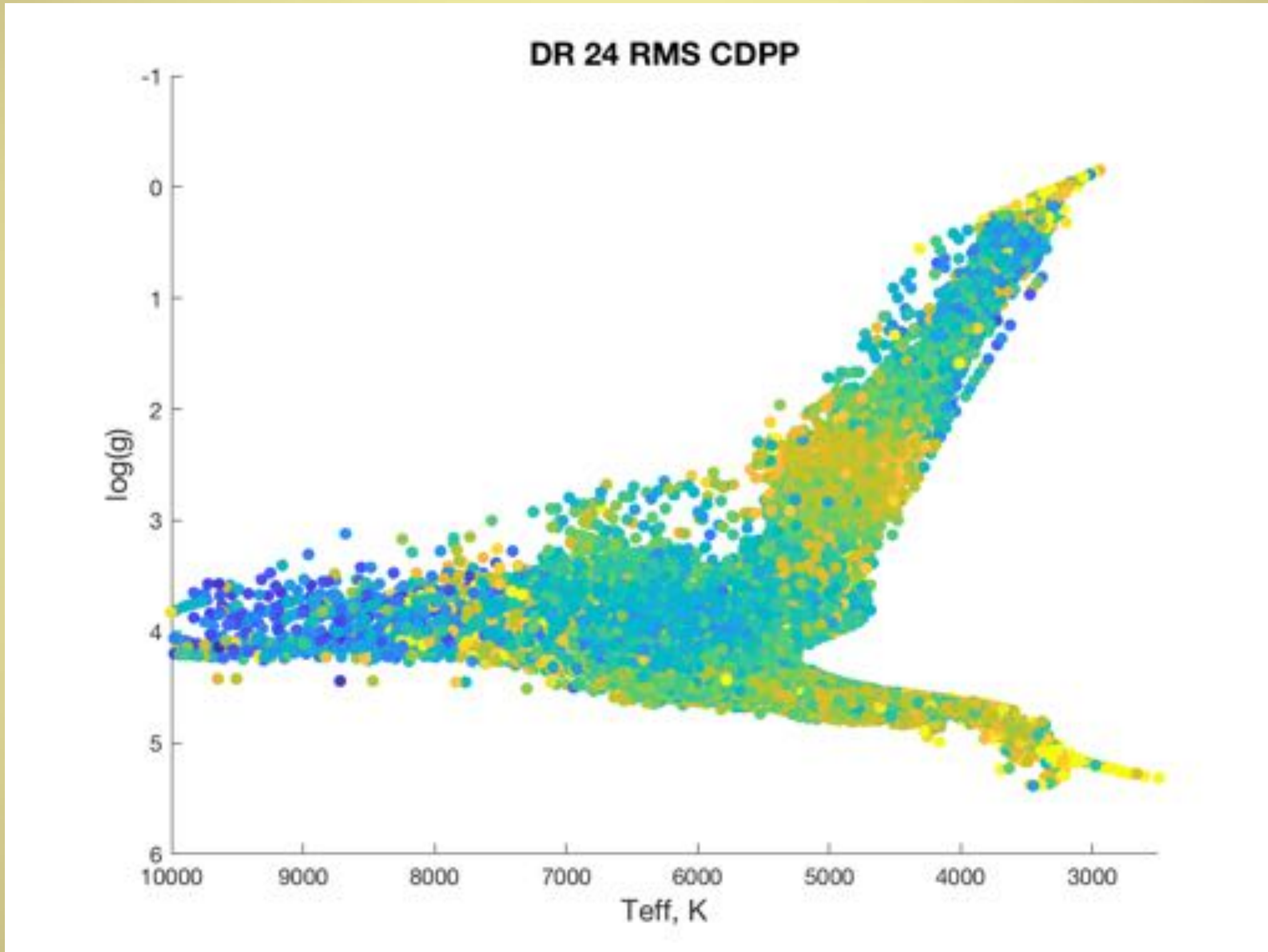
Kepler
A Search for Earth-size Planets



A Kepler Example: Adaptive Whitening



Photometric Precision



G dwarfs appear to be quiet, and M dwarfs appear to be much noisier

Excess Stellar Variability

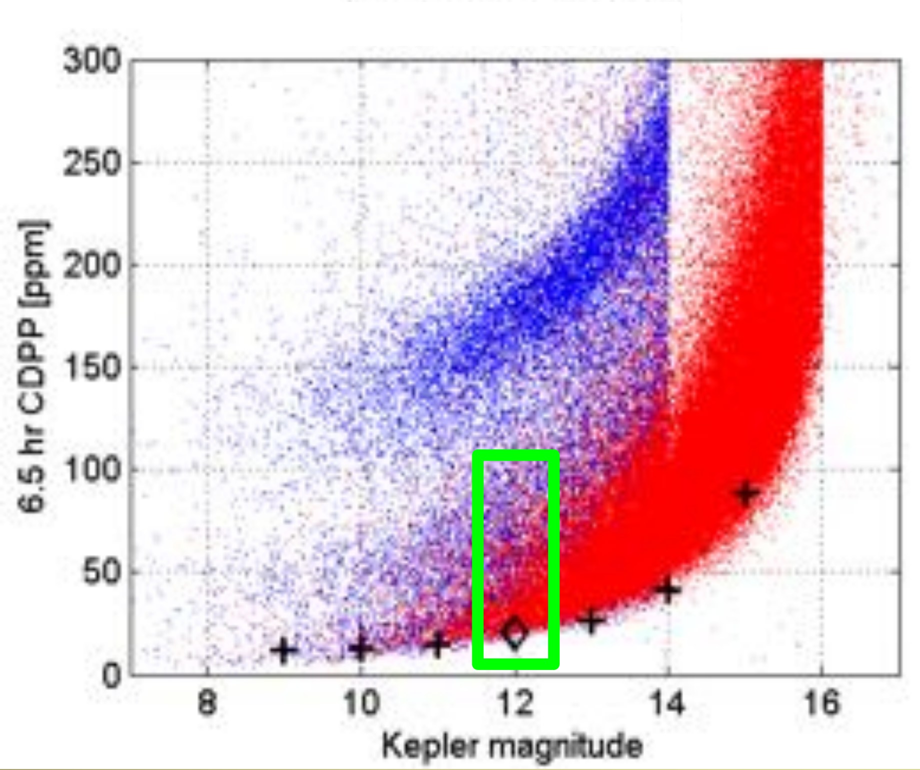
Kepler
A Search for Earth-size Planets

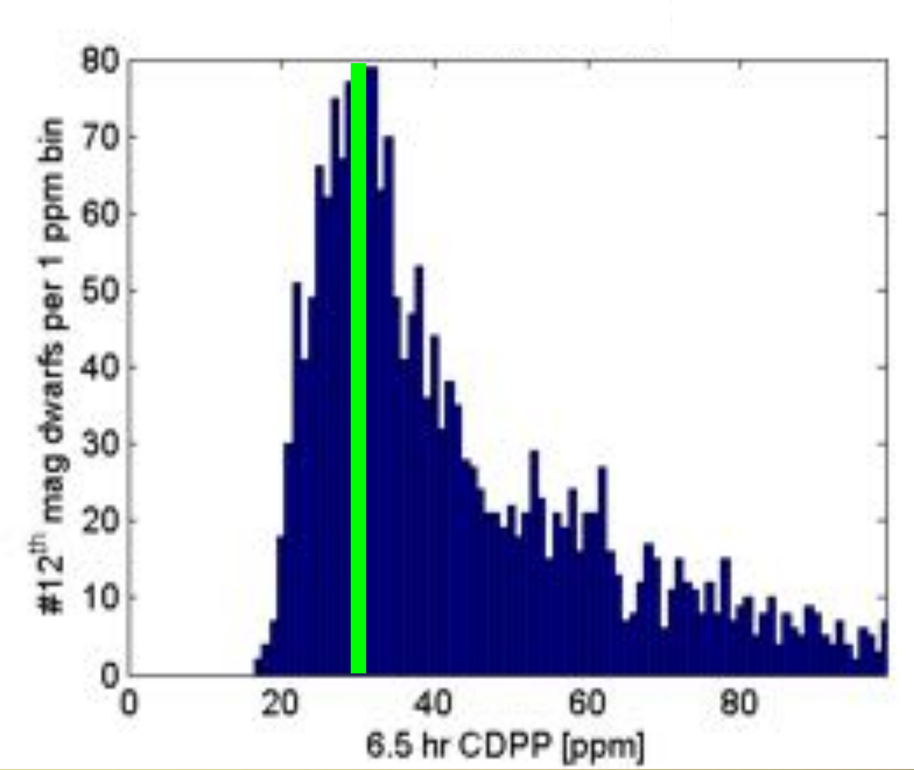
Original Noise Budget (Kp=12):
- 14 ppm Shot Noise
- 10 ppm Instrument Noise
- 10 ppm Stellar Variability

=> 20 ppm Total Noise

Reality (11.5 ≤ Kp ≤ 12.5)
- 17 ppm Shot Noise
- 13 ppm Instrument Noise
- 20 ppm Stellar Variability

=> ~29 ppm Total Noise





Kepler

A Search for Earth-size Planets

Summary

- Stellar variability presents a fundamental limit on the detectability of transiting Earth-like planets
- Adaptive matched filters can provide near-optimal detection of Earth-size transits and characterize the observation noise
- Larger than expected stellar variability can be compensated for by increasing the duration of the campaign
- Controlling instrumental noise and systematics is also very important as shot noise, instrument noise and stellar variability should be comparable in a well designed mission