# Time Series Analysis in the Search for Other Worlds through Transit Photometry


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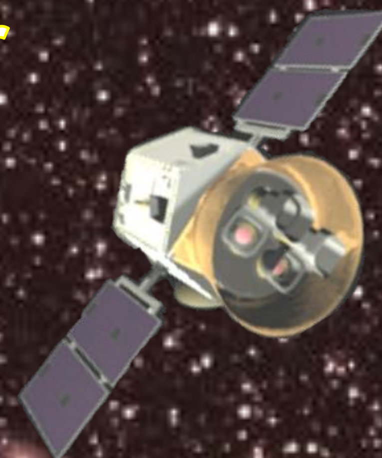


**Monday January 21 2019**

**Astronomical time Series 2019**

**Max Planck Institute for Astronomy**
**Heidelberg, Germany**

# Overview

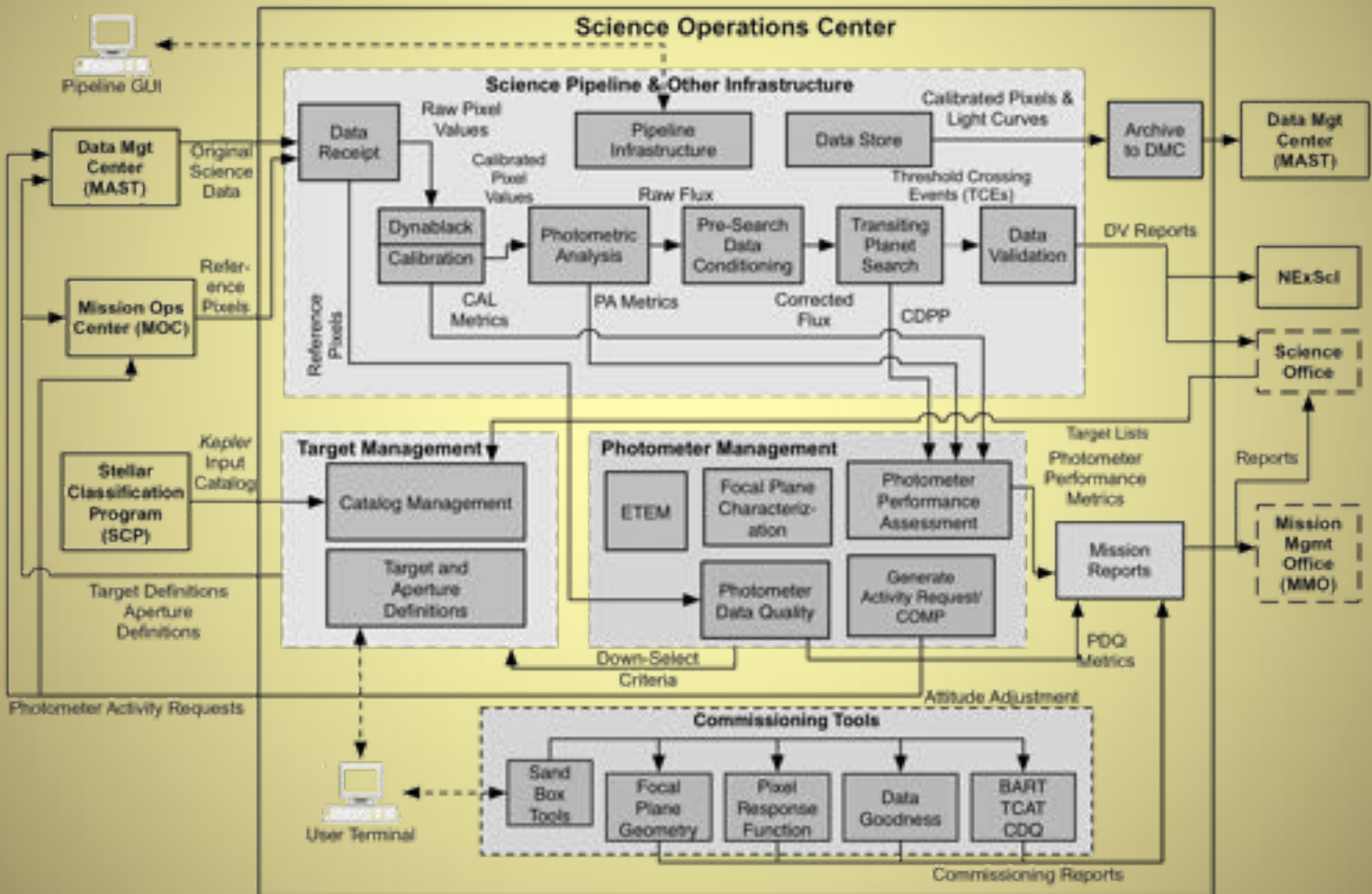


- The Science Operations Center Pipeline
- Solar Variability
- Detection Theory
- A Wavelet-based Adaptive Matched Filter
- Observations of Stellar Noise on Transit Timescales
- Excess Stellar Variability
- Summary


KEPLER
SCIENCE DATA PROCESSING PIPELINE
DYN
CAL
PA
PDC
TPS
DV

# Science Operations Center Architecture

Kepler
A Search for Earth-size Planets



# The Kepler Science Pipeline: From Pixels To Planets

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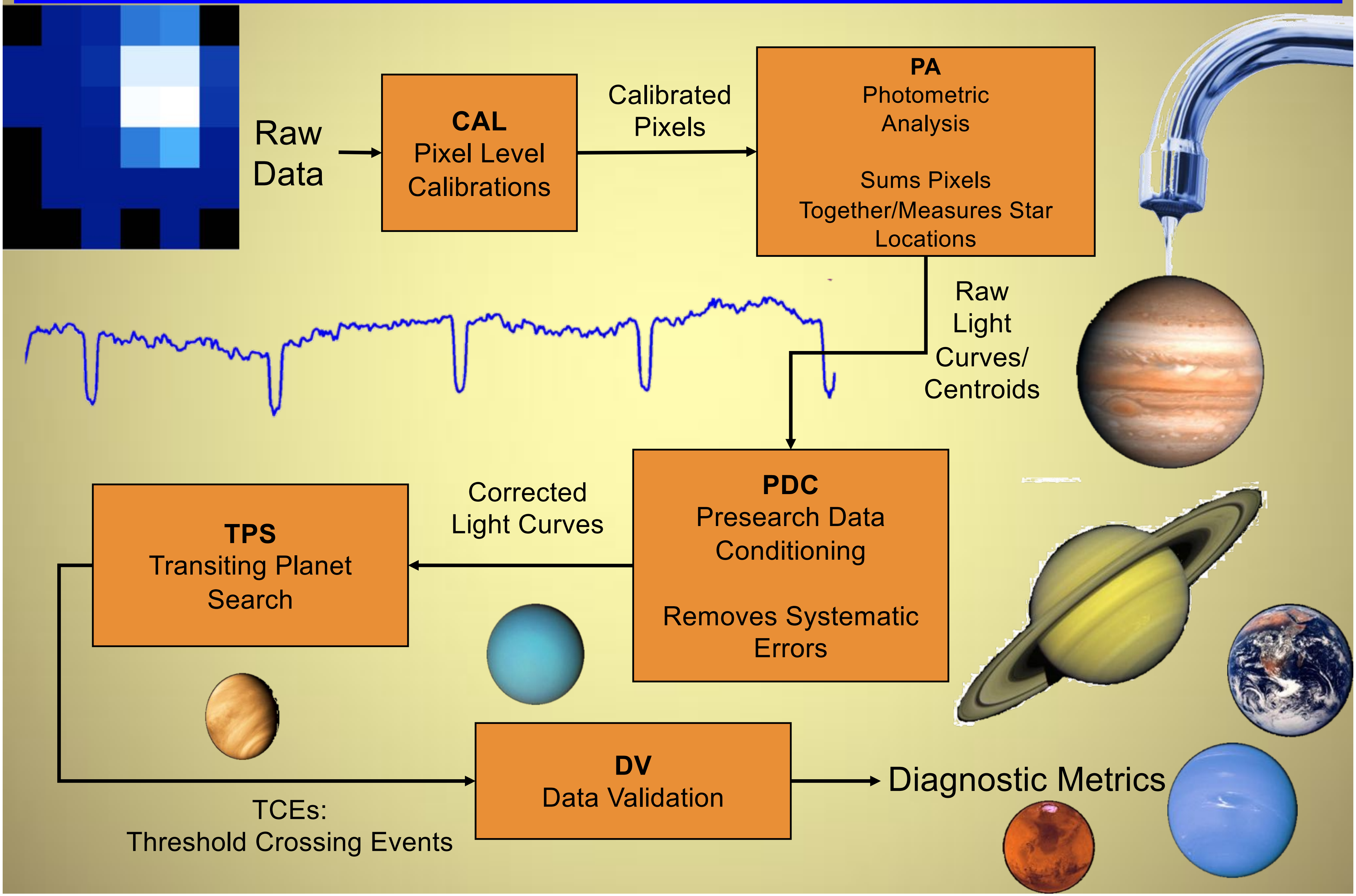
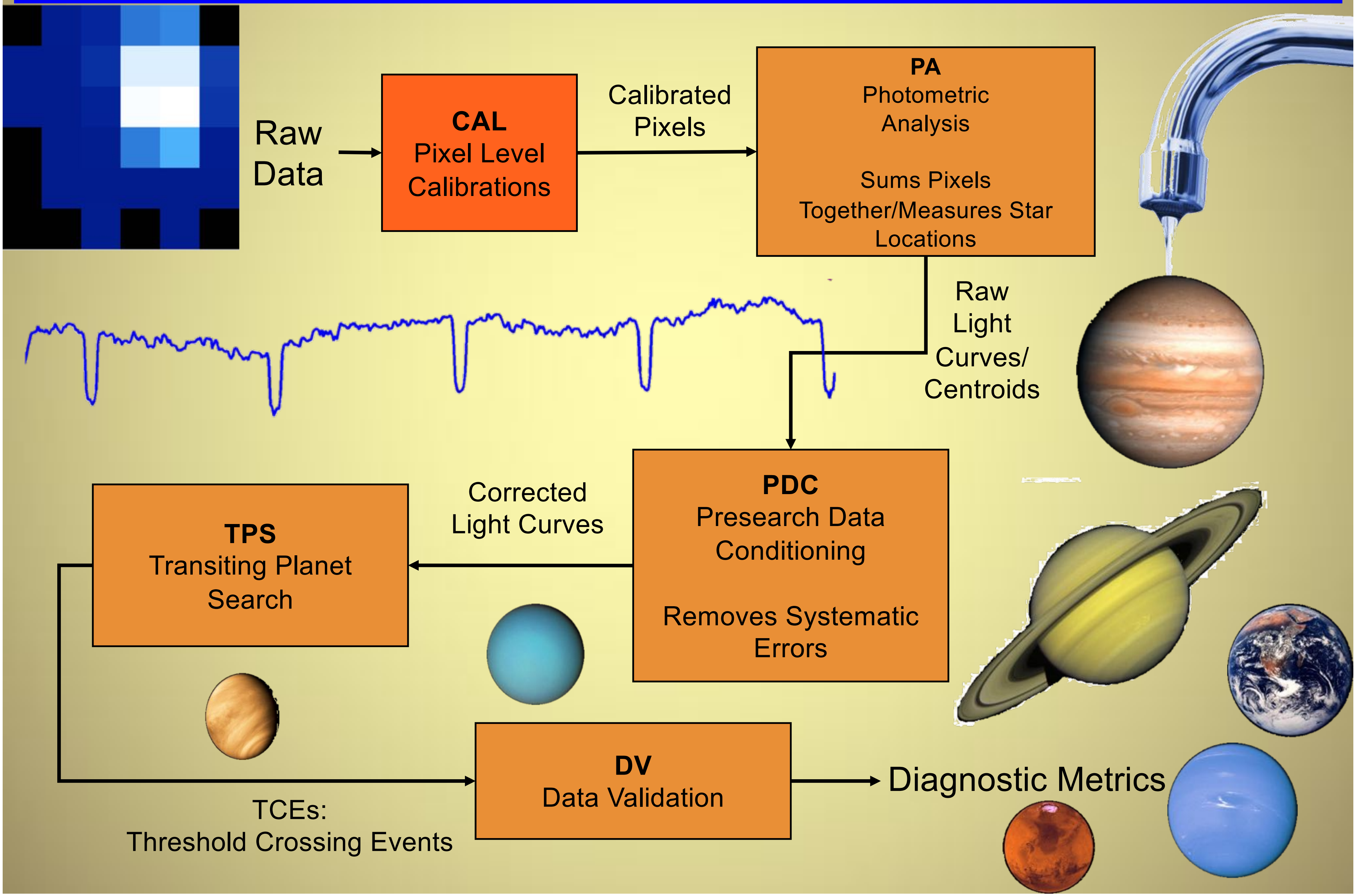


# The Kepler Science Pipeline: From Pixels To Planets

*A Search for Earth-size Planets*



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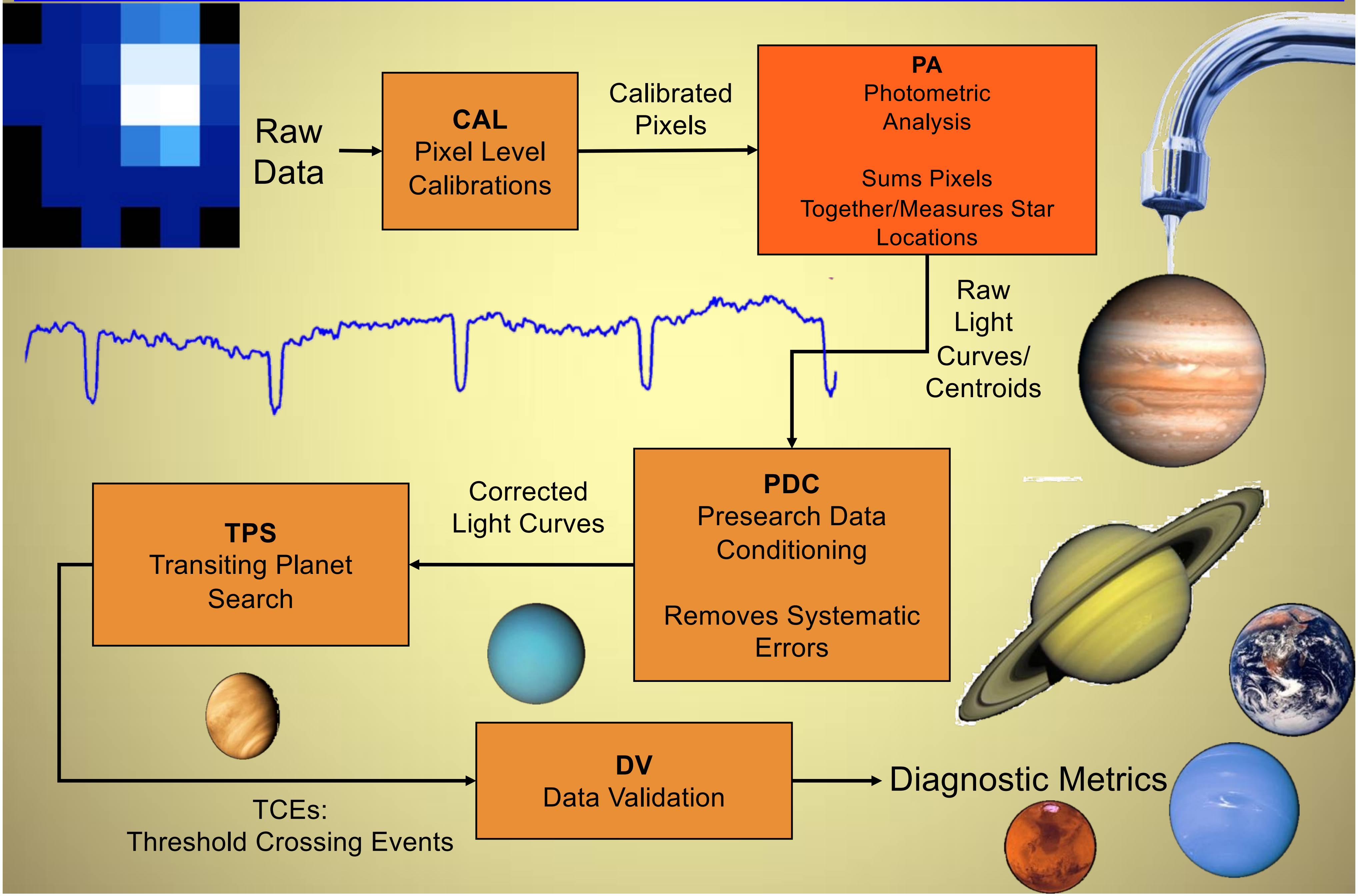

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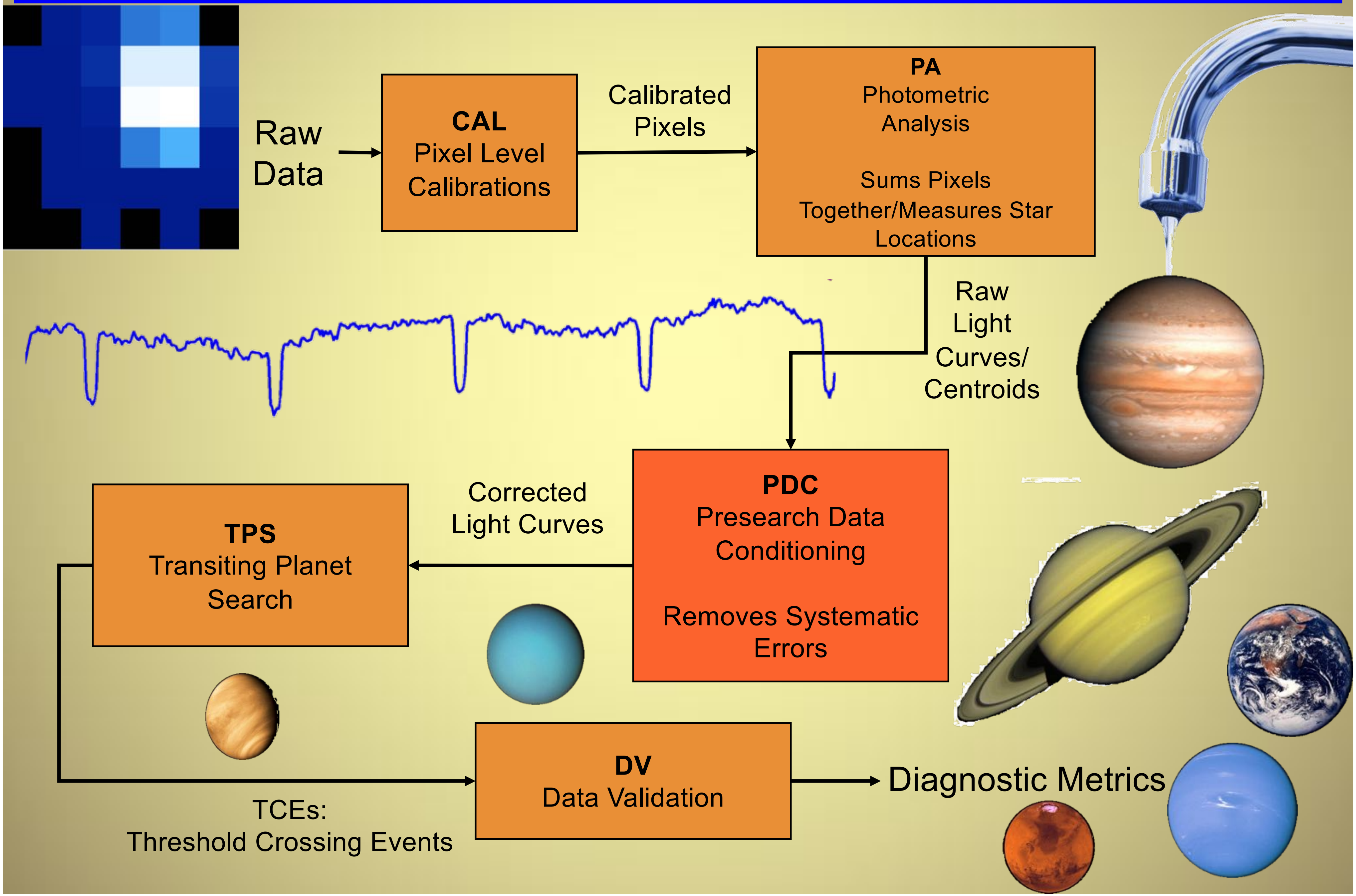

# Short Timescale Instrumental Errors

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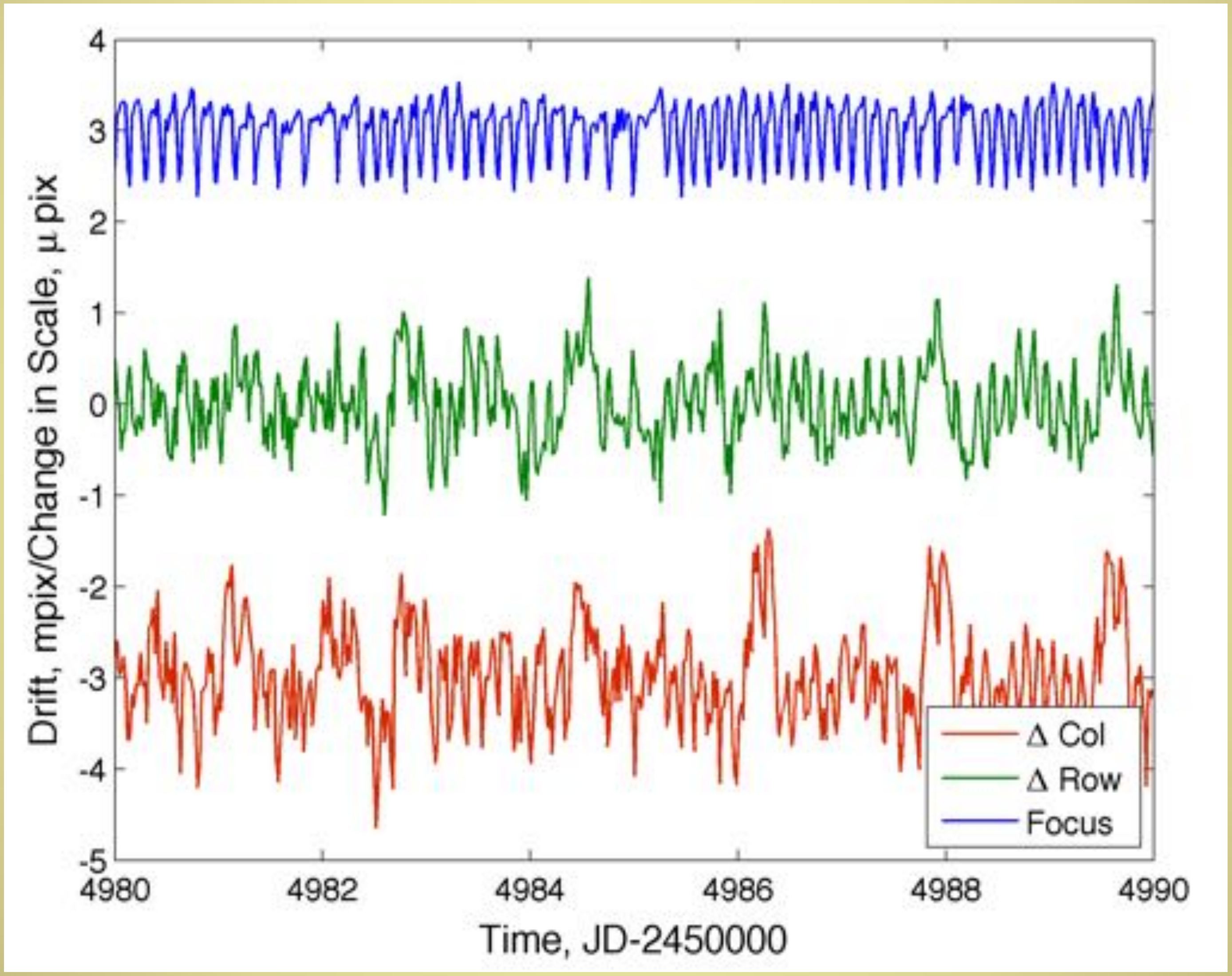
Signature of a heater cycling on the reaction wheels 3/4




*Kepler* is sensitive to its thermal environment

# Instrumental Effects in Photometry

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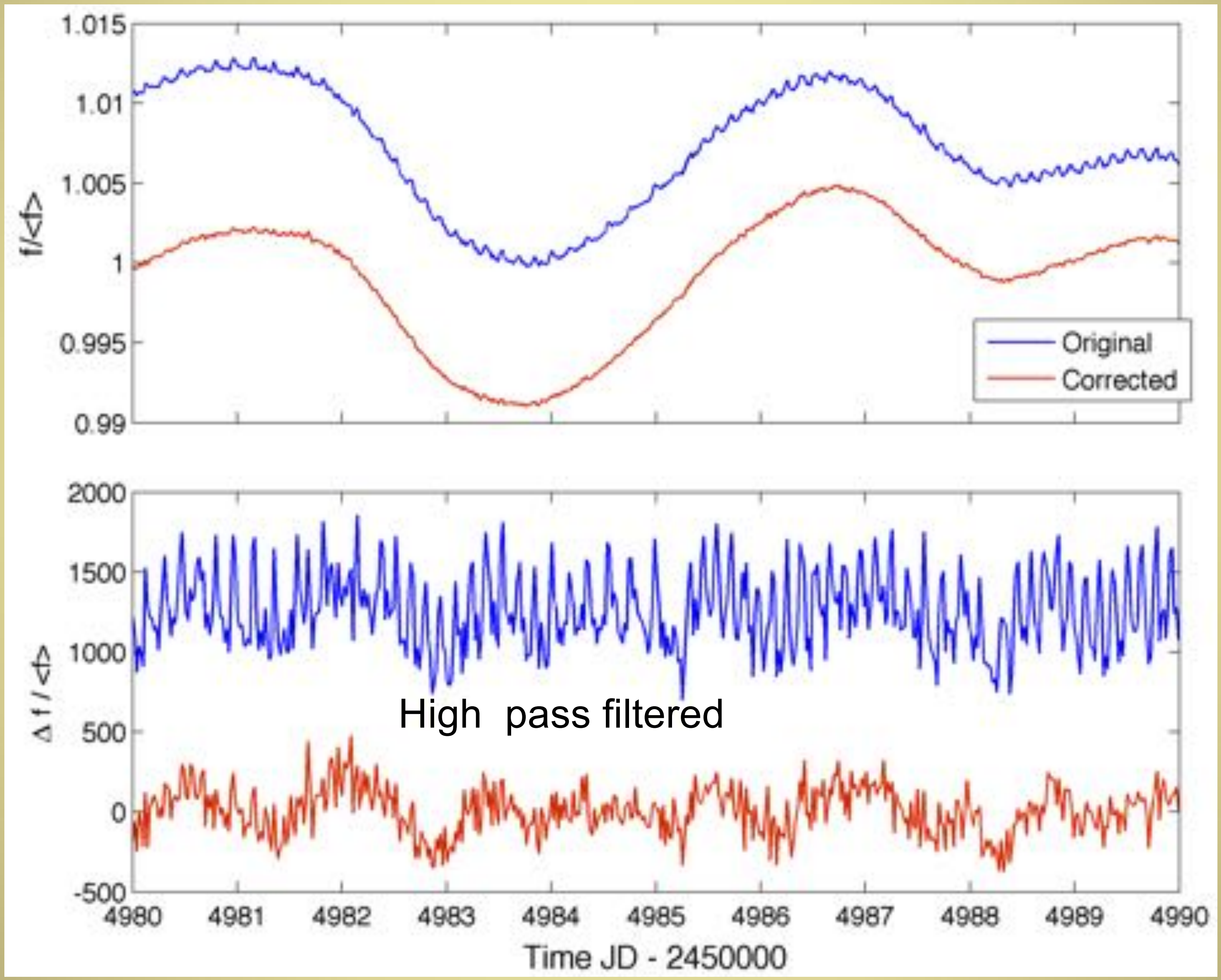
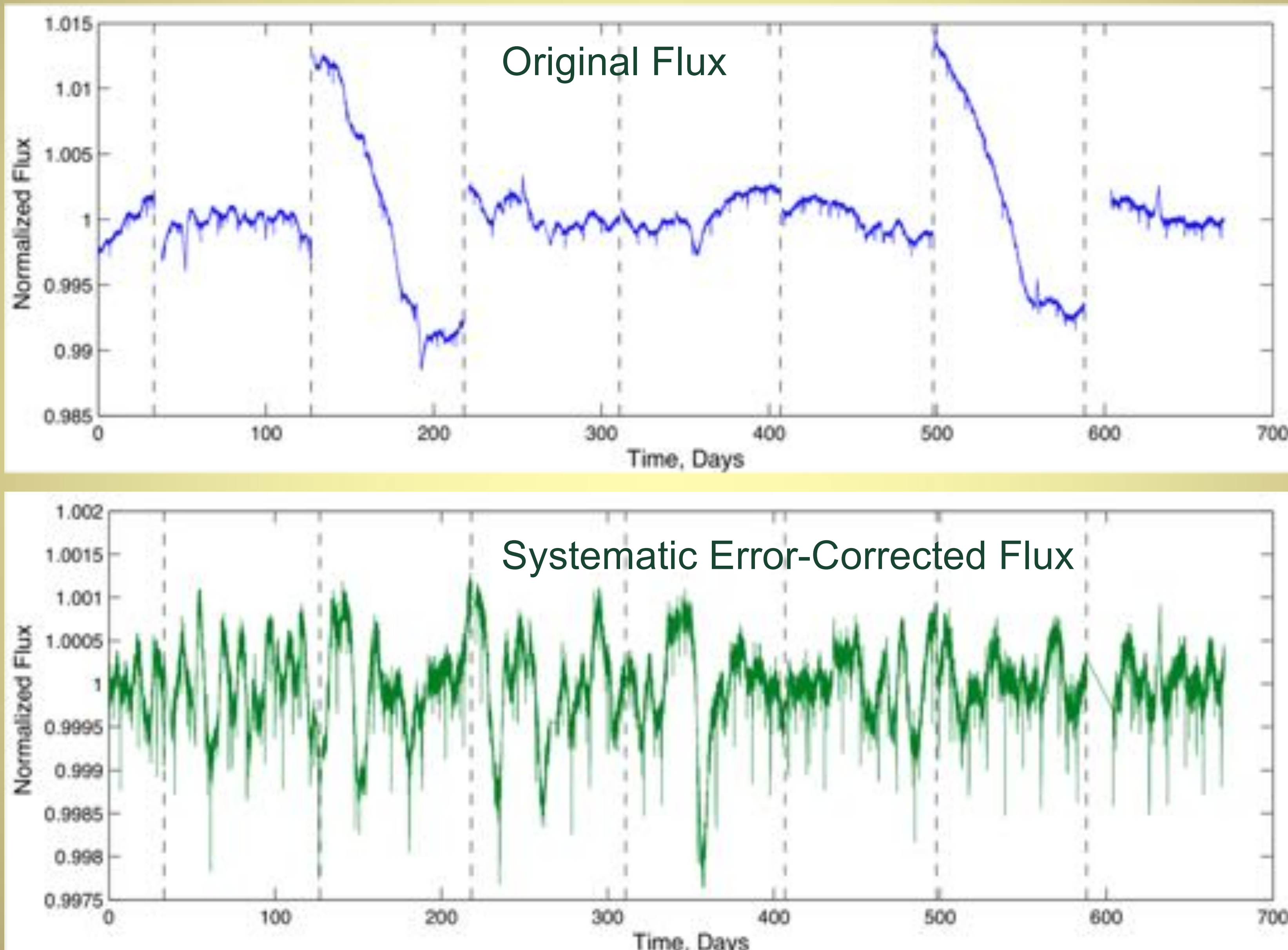


# Correcting Systematic Errors






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

# The Kepler Science Pipeline: From Pixels To Planets

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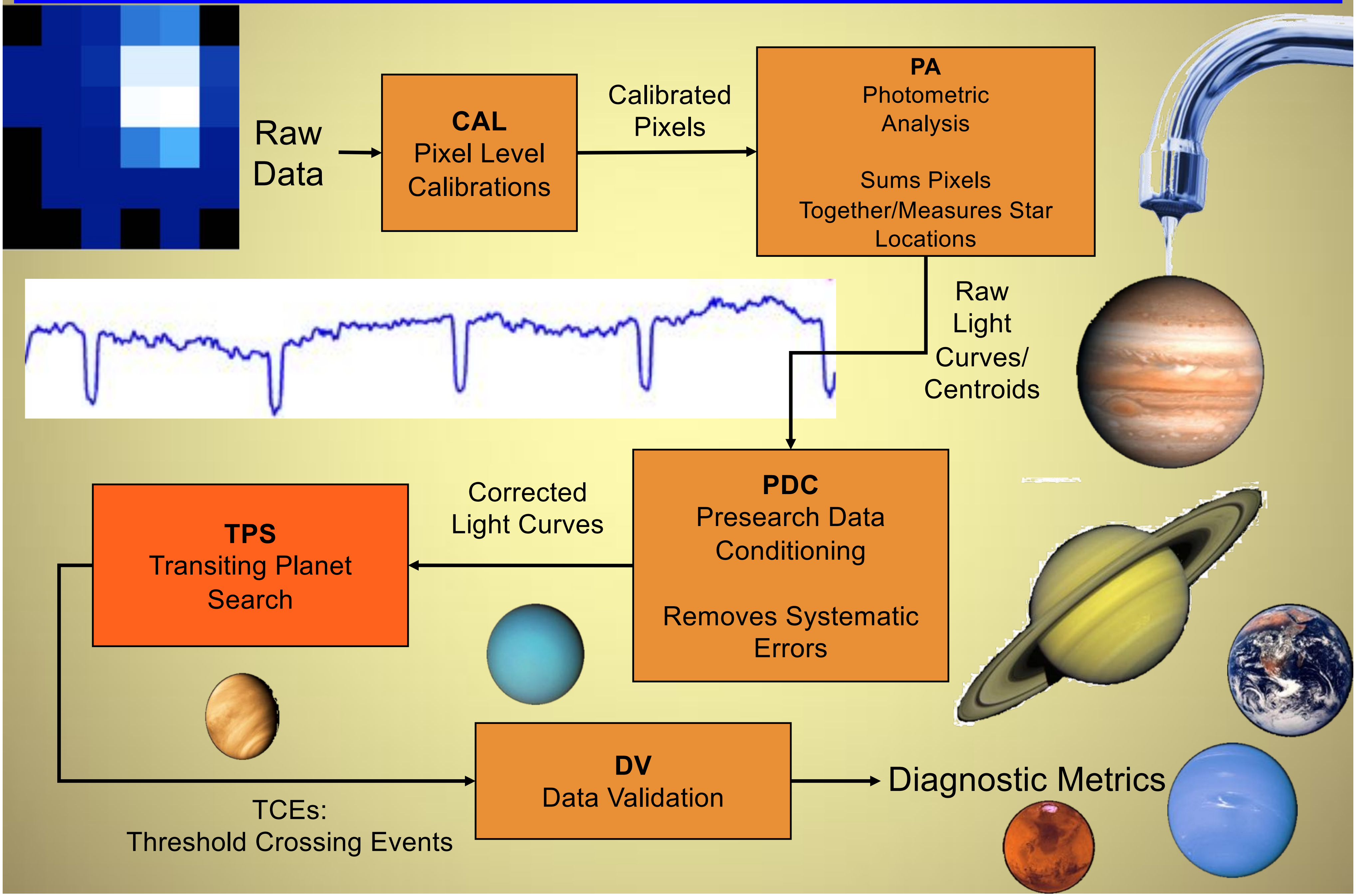

# The Kepler Science Pipeline: From Pixels To Planets

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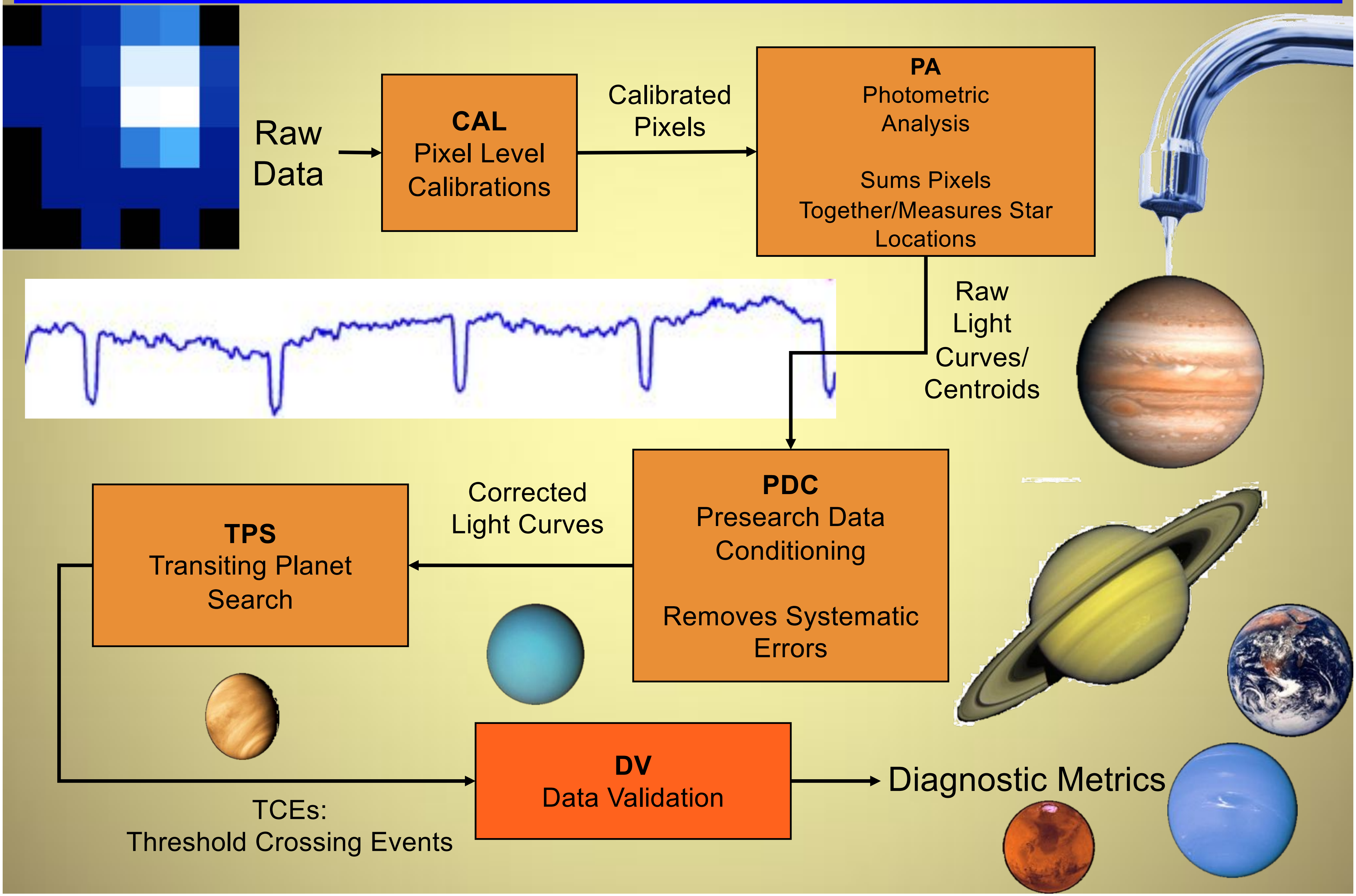

# Solar Variability

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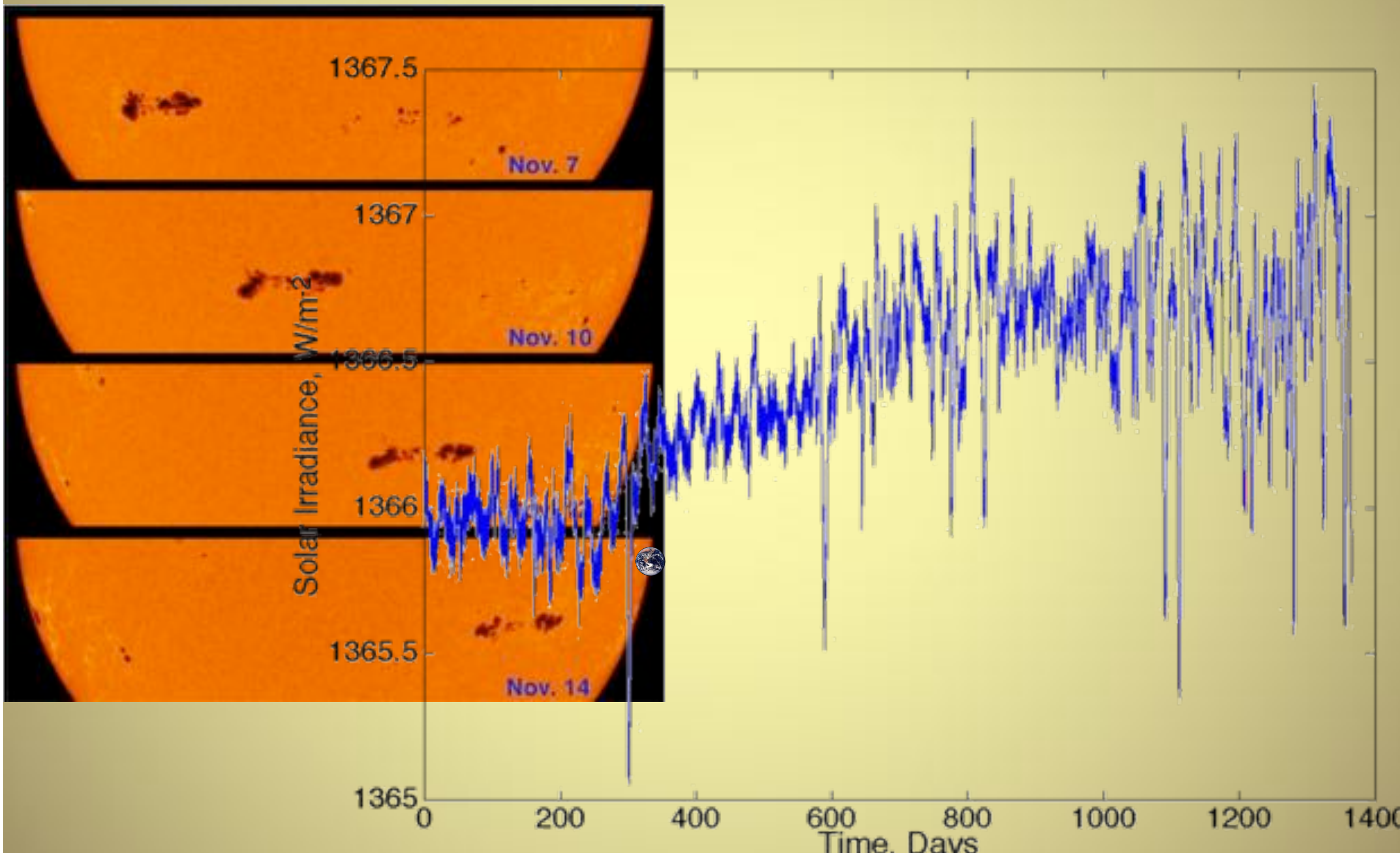

# Detecting Deterministic Signals

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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

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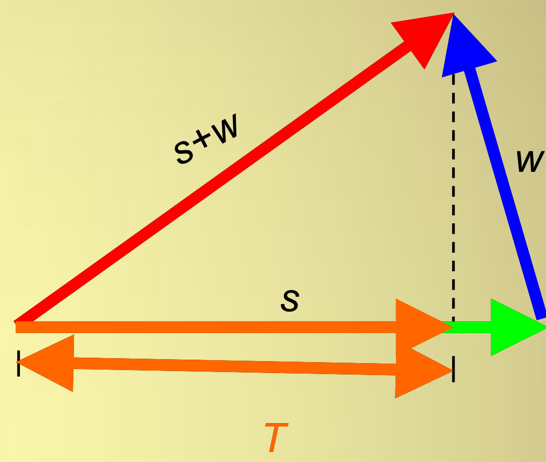
Define $$T = \frac{x^T s}{\sigma_w \sqrt{s^T s}}$$




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

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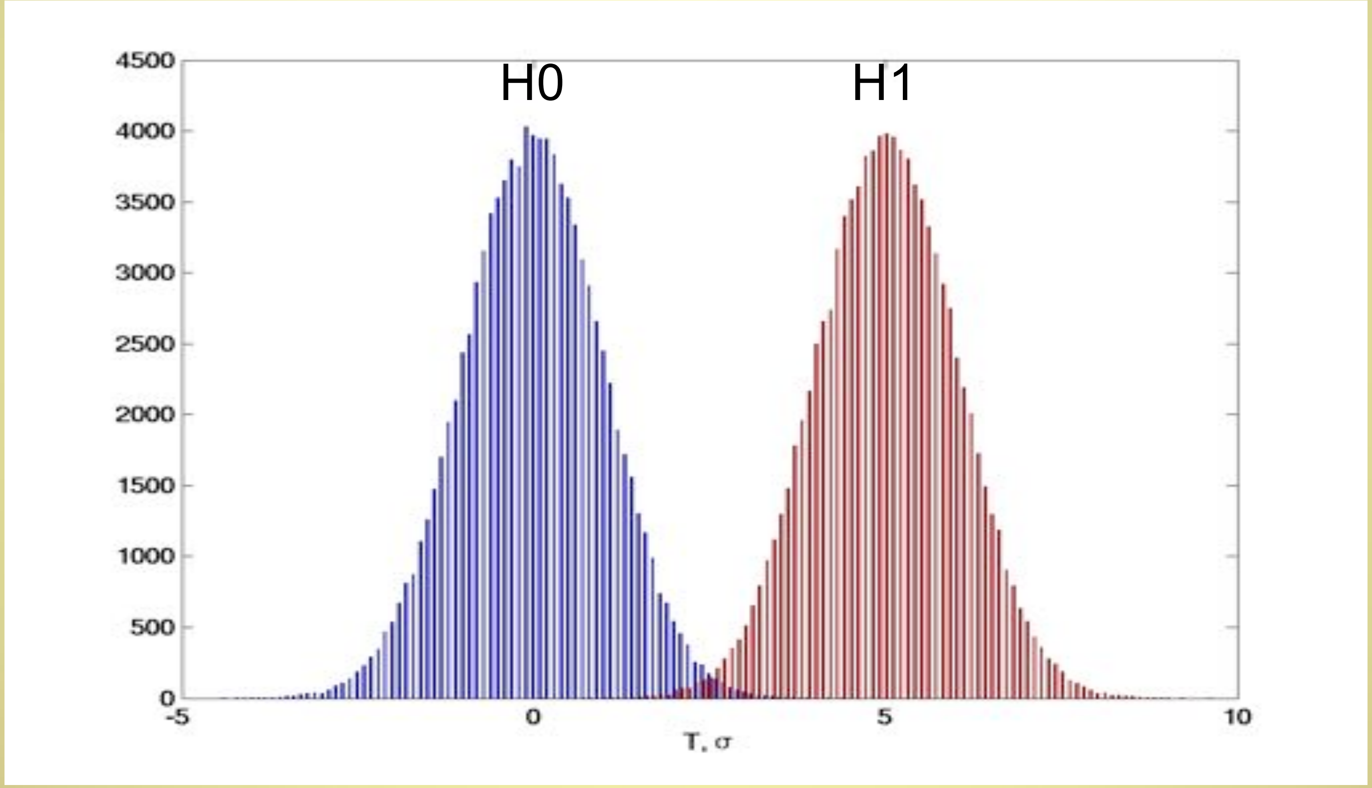
*T* is a Gaussian random variable

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




How do we choose the threshold, $\gamma$?

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

# Detection Statistics For Colored Noise

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*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

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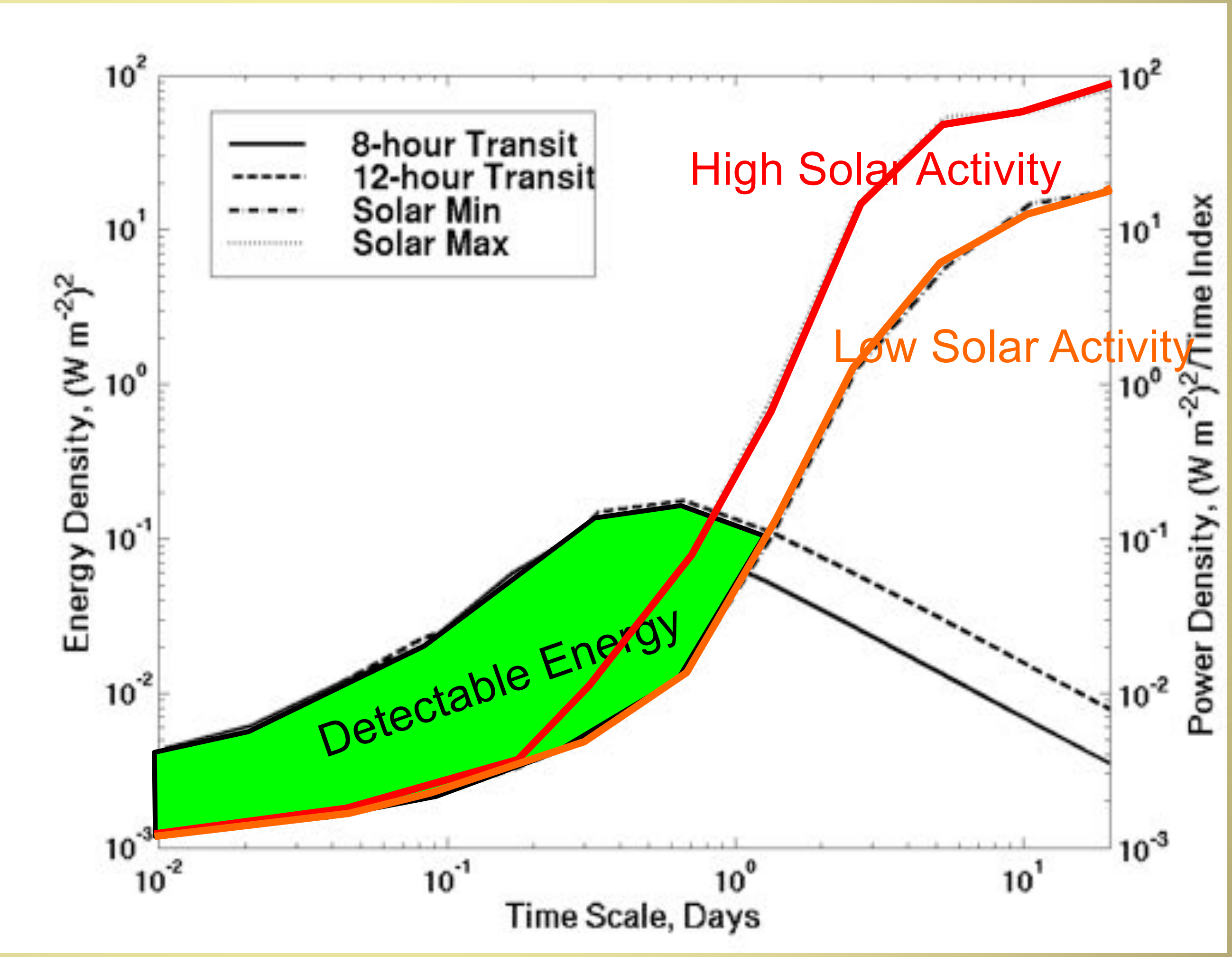
Is stellar variability stationary?

No!

We must work in a joint time-frequency domain

Wavelets are a natural choice



# A Wavelet-Based Approach

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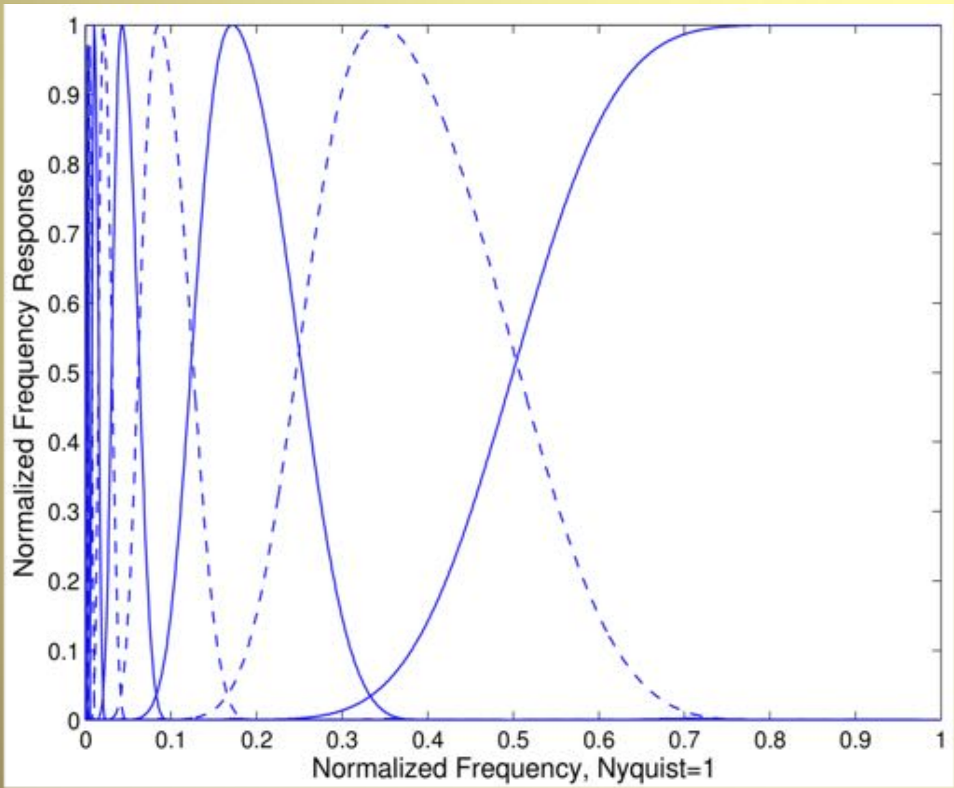
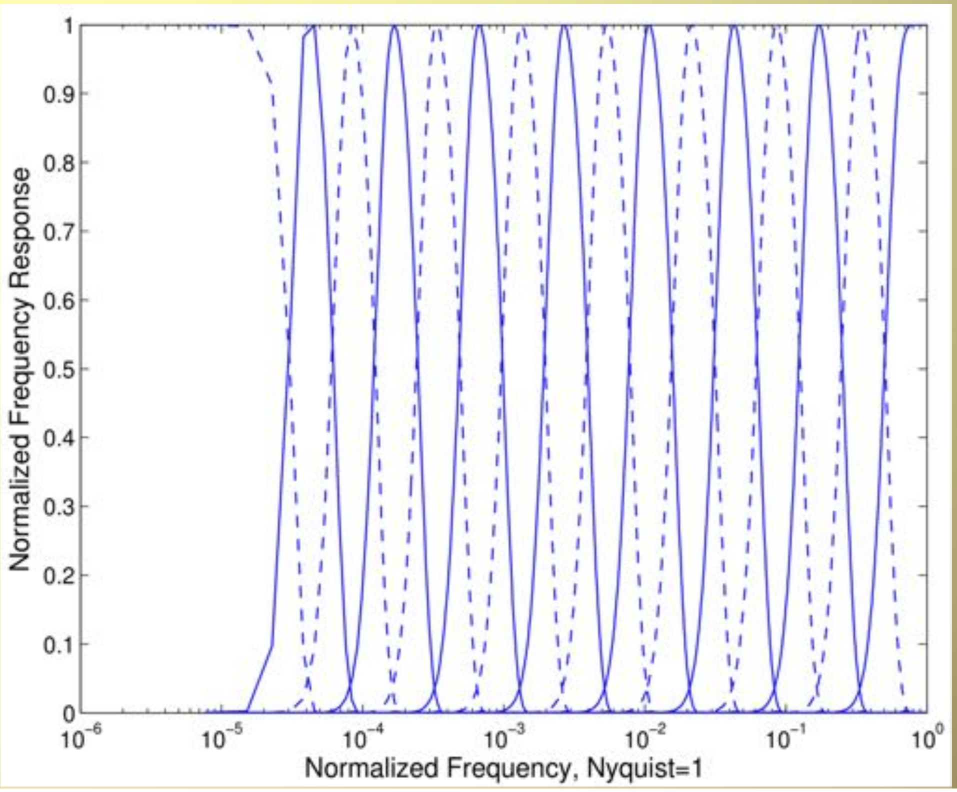
Filter-Bank Implementation of an Overcomplete Wavelet Transform

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

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

# Signal Flow Diagram

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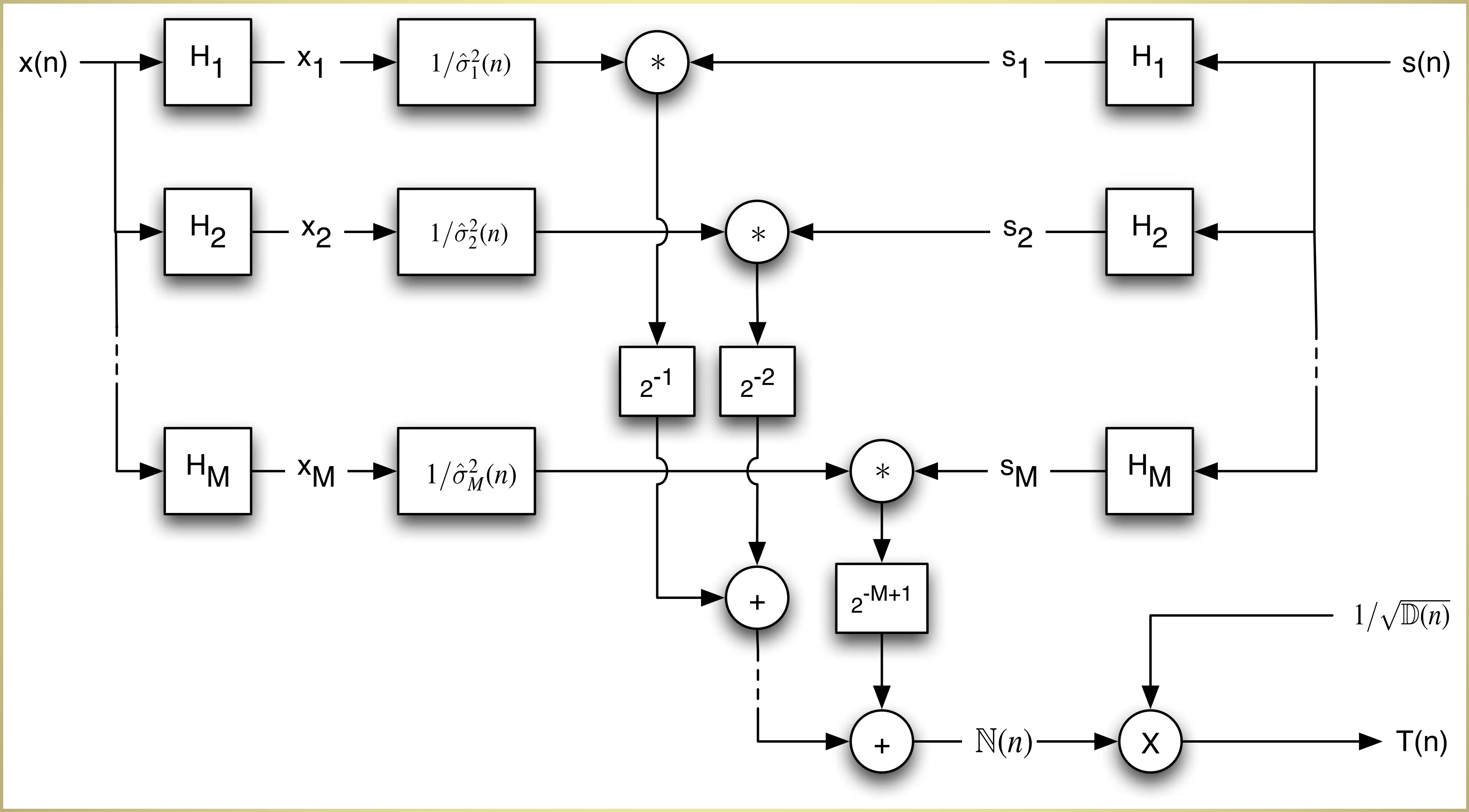

# Kepler-like Noise + Transits

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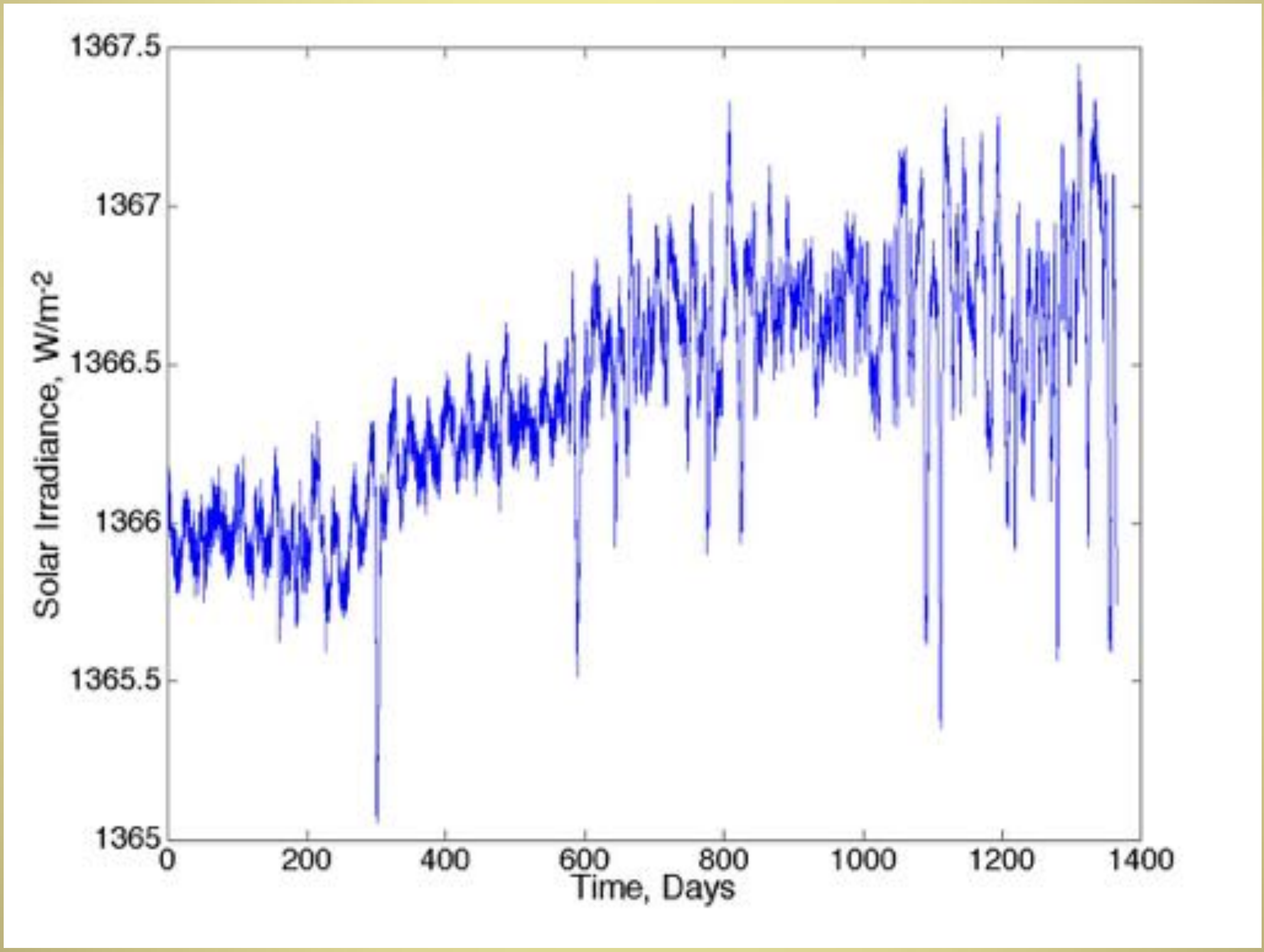

# Single Transit Statistics

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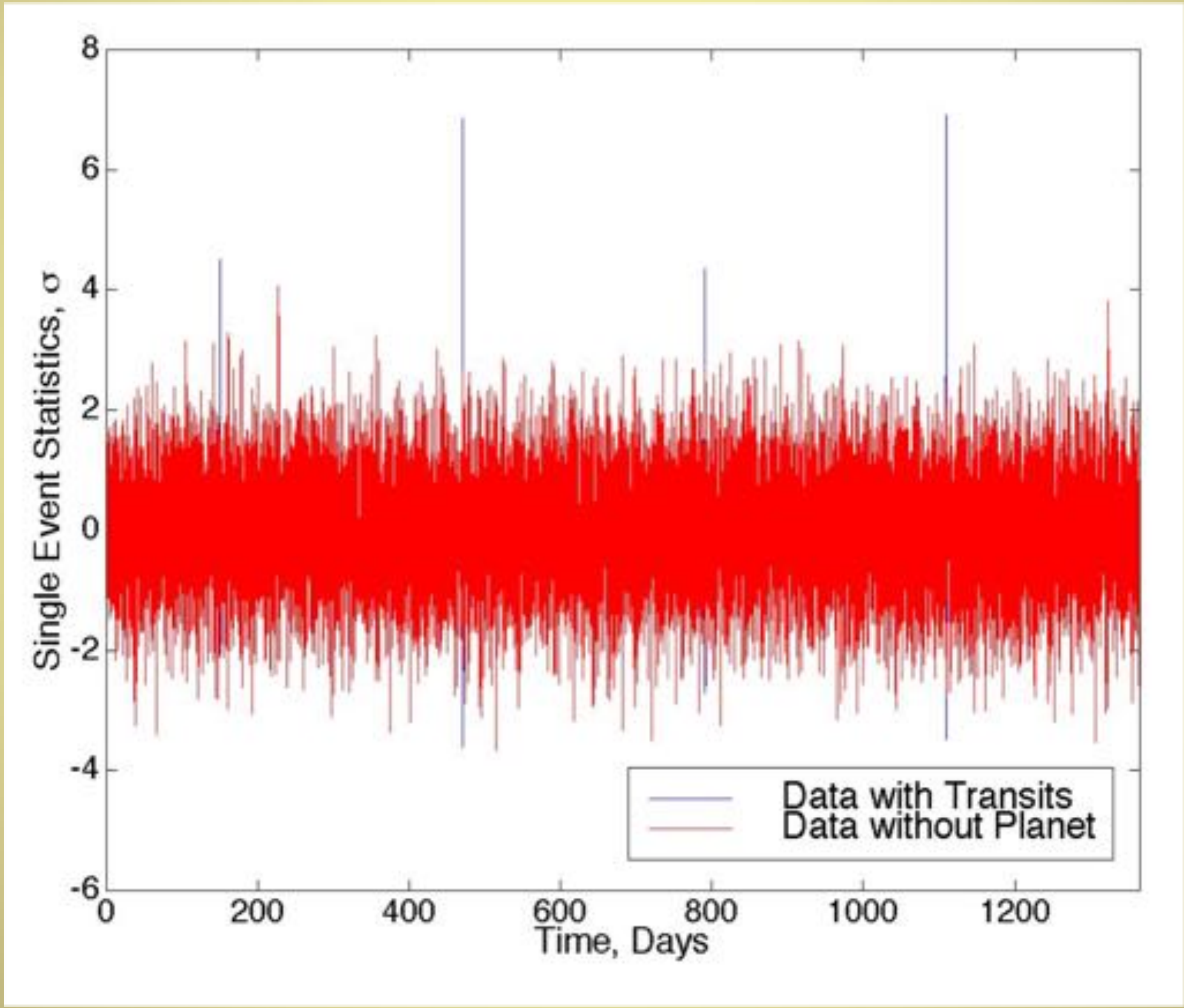

# Folded Transit Statistics

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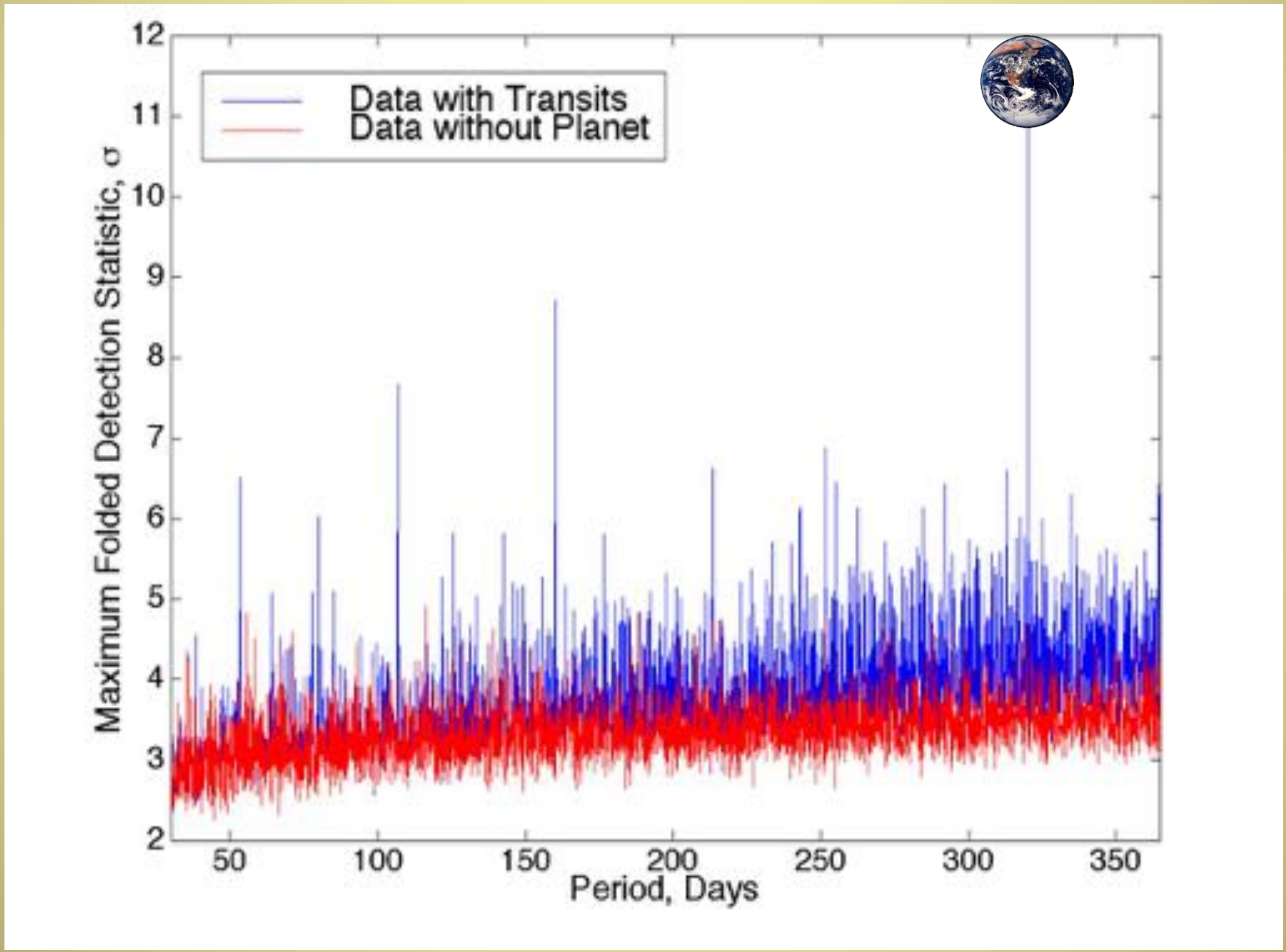

# Folded Statistics at Best-Matched Period

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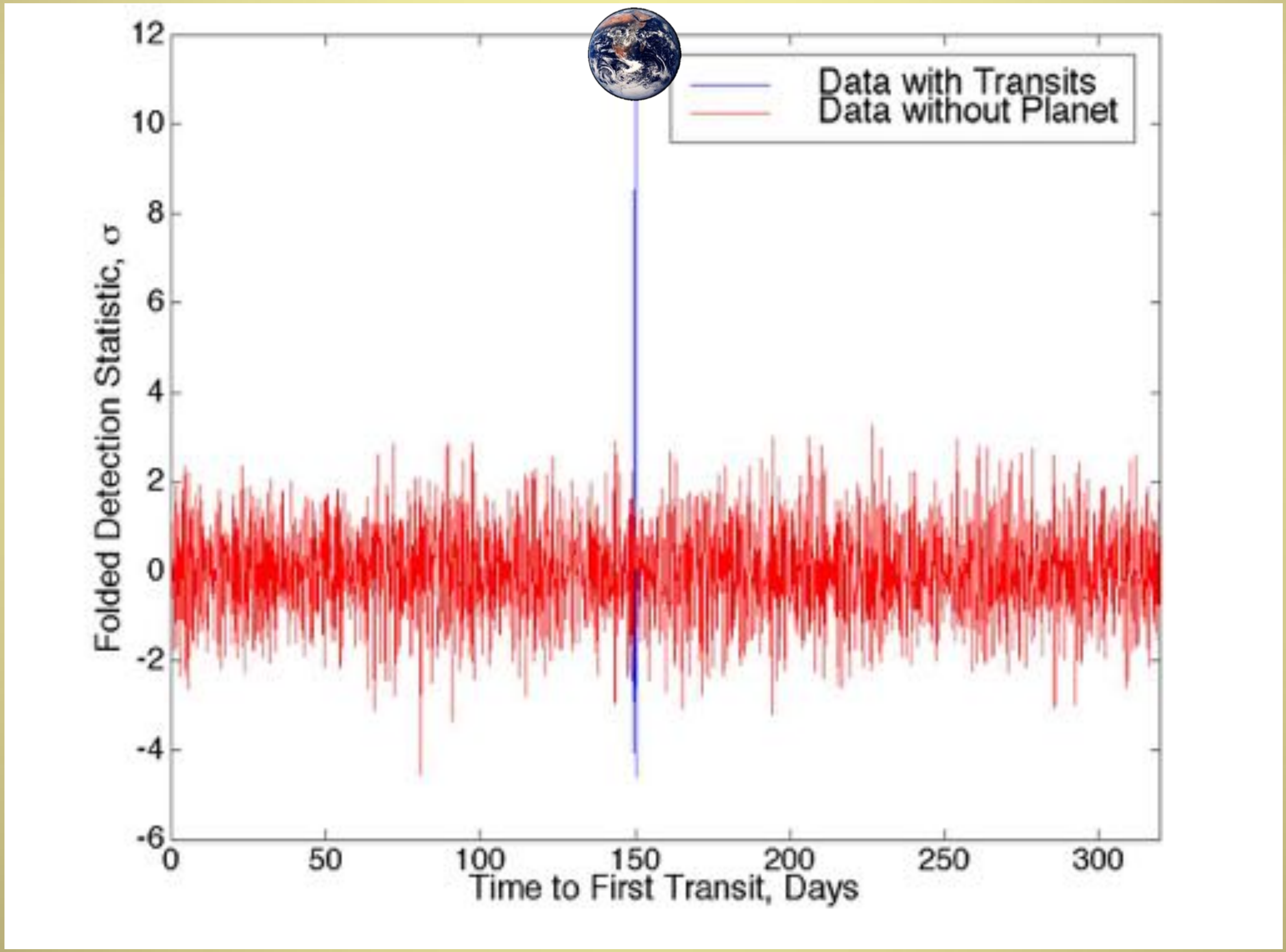

# Setting the Threshold

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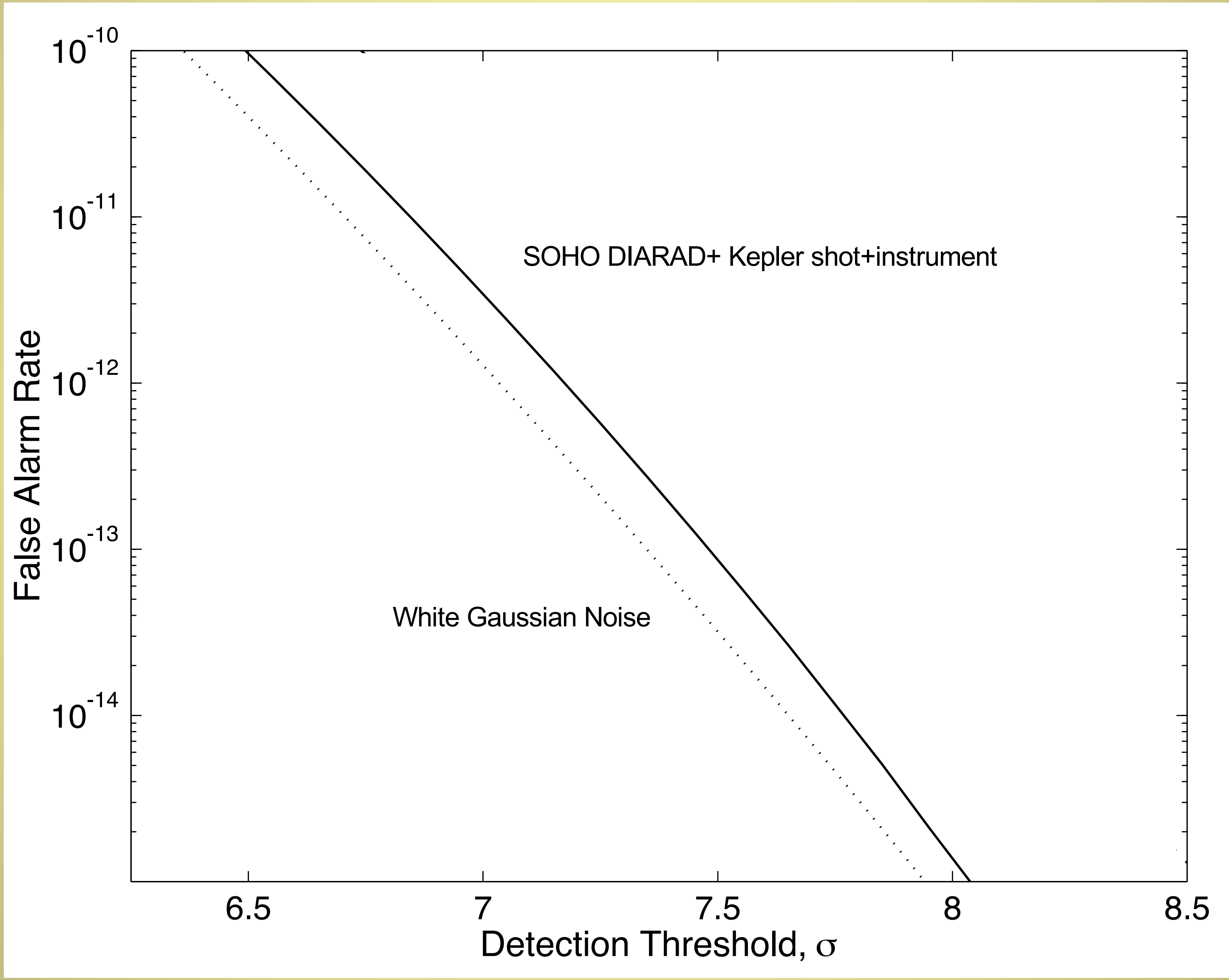

# Transiting Planet Search Architecture

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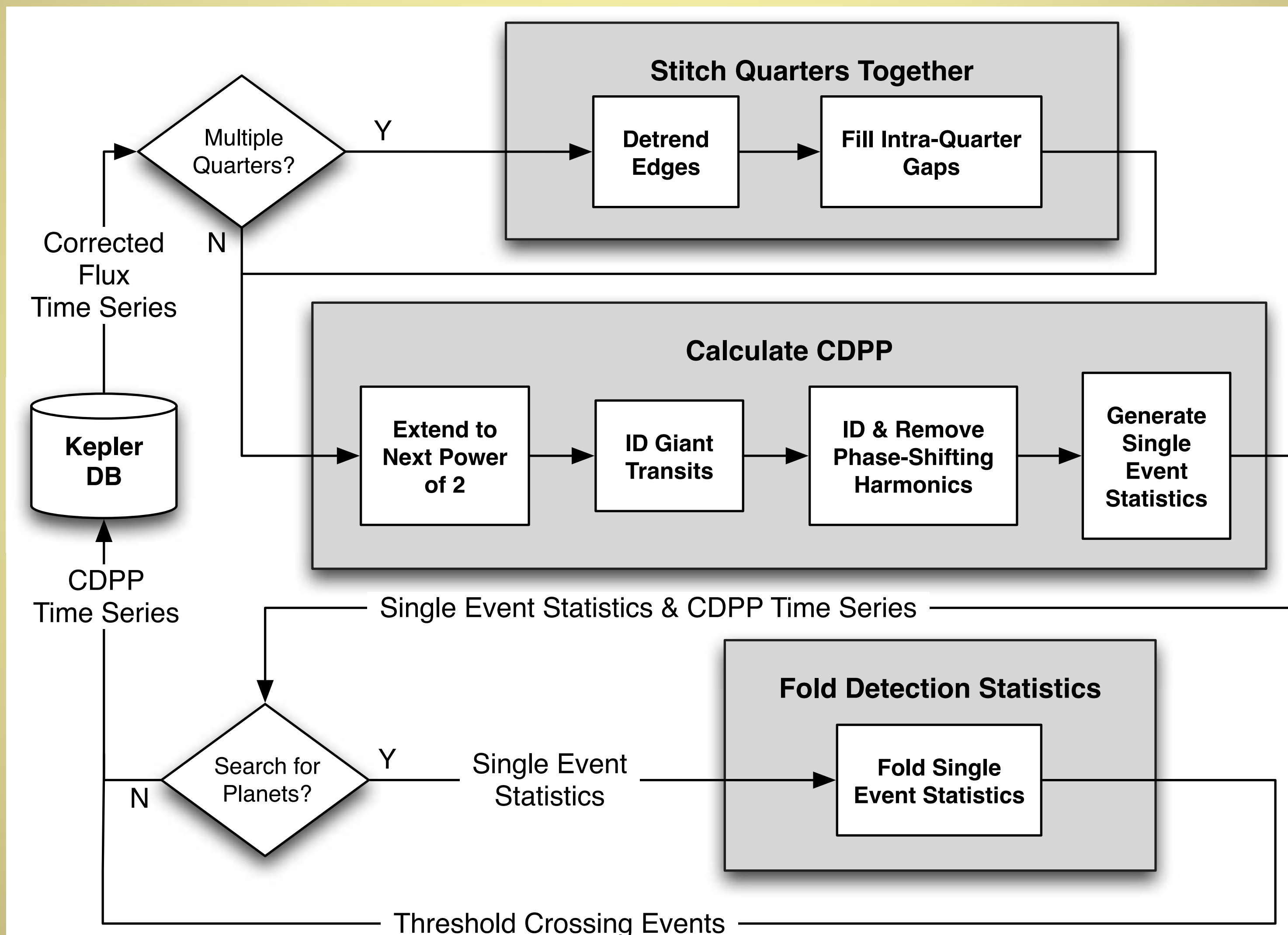


Details here: https://archive.stsci.edu/kepler/manuals/KSCI-19081-002-KDPH.pdf

# A Kepler Example: Calculating CDPP

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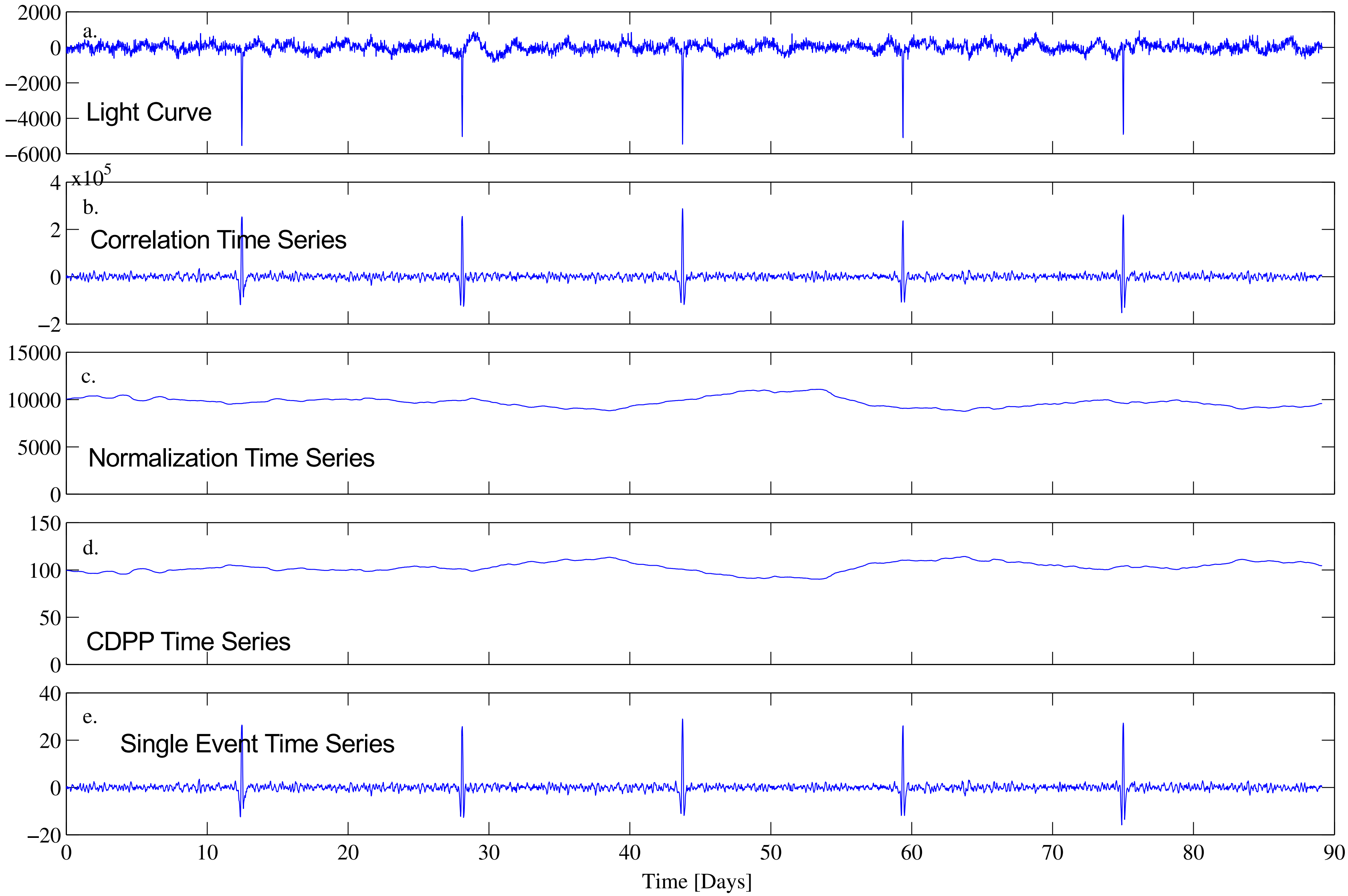

# A Kepler Example: Calculating CDPP

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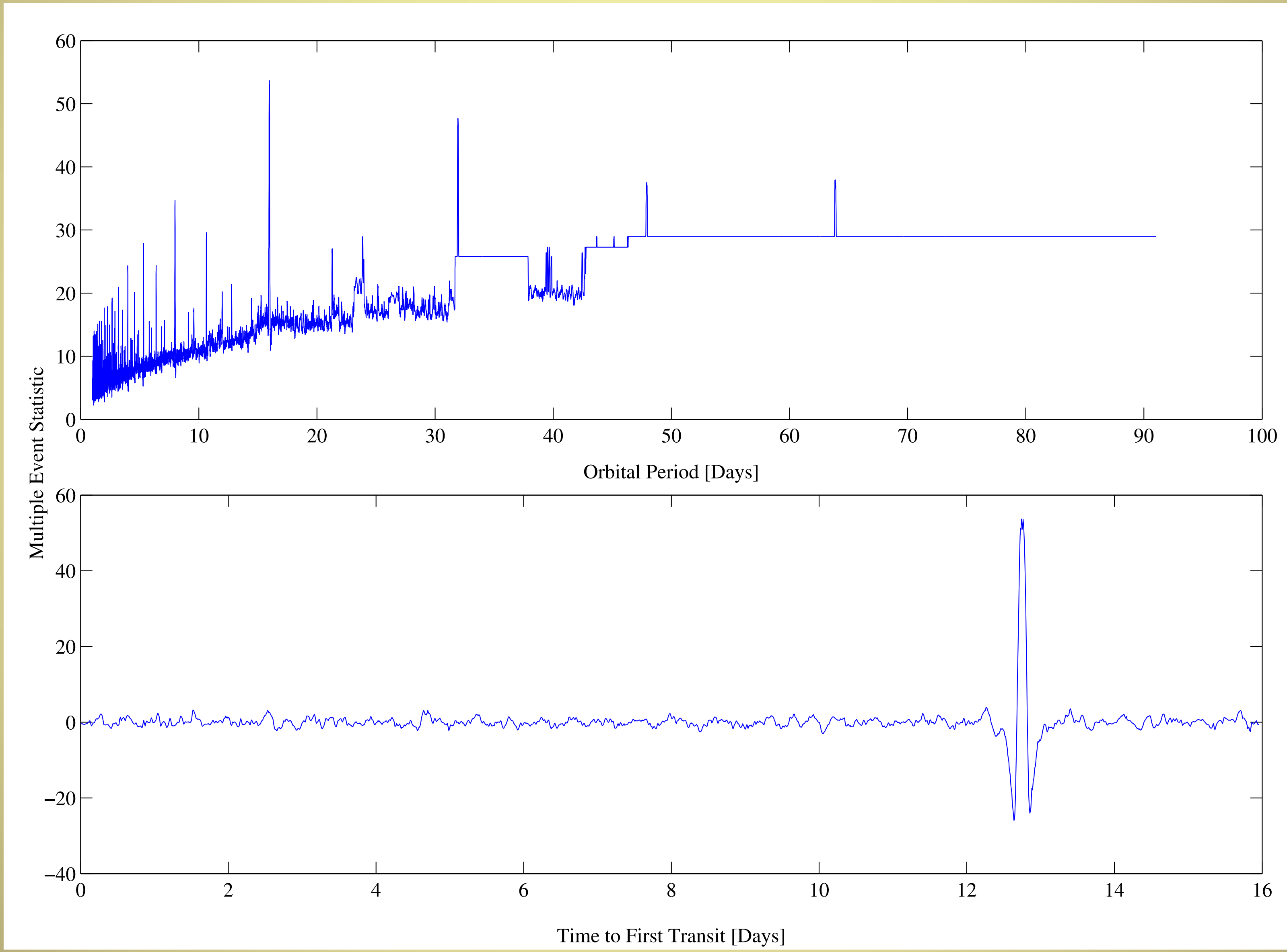

# A Kepler Example: Adaptive Whitening

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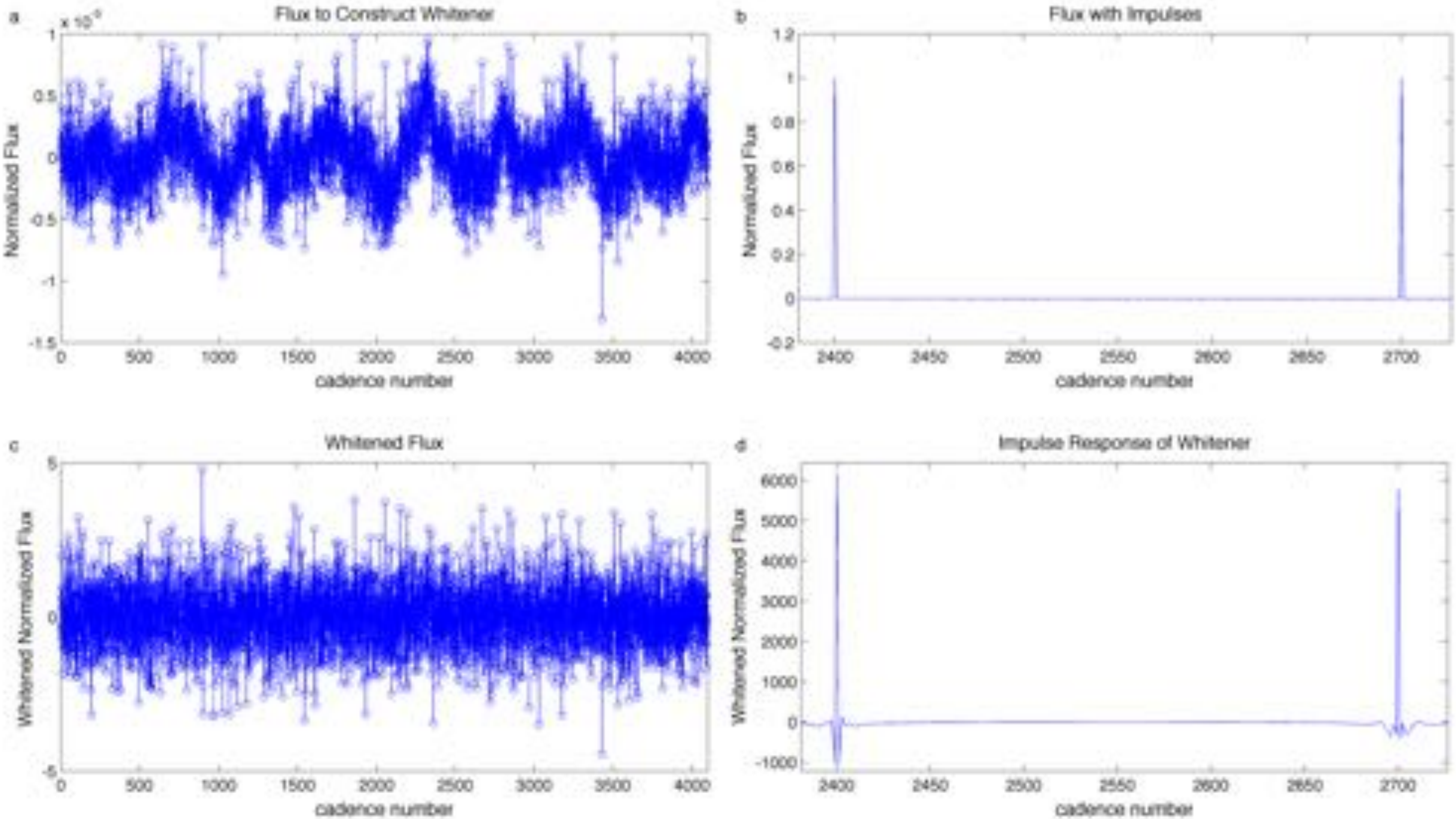
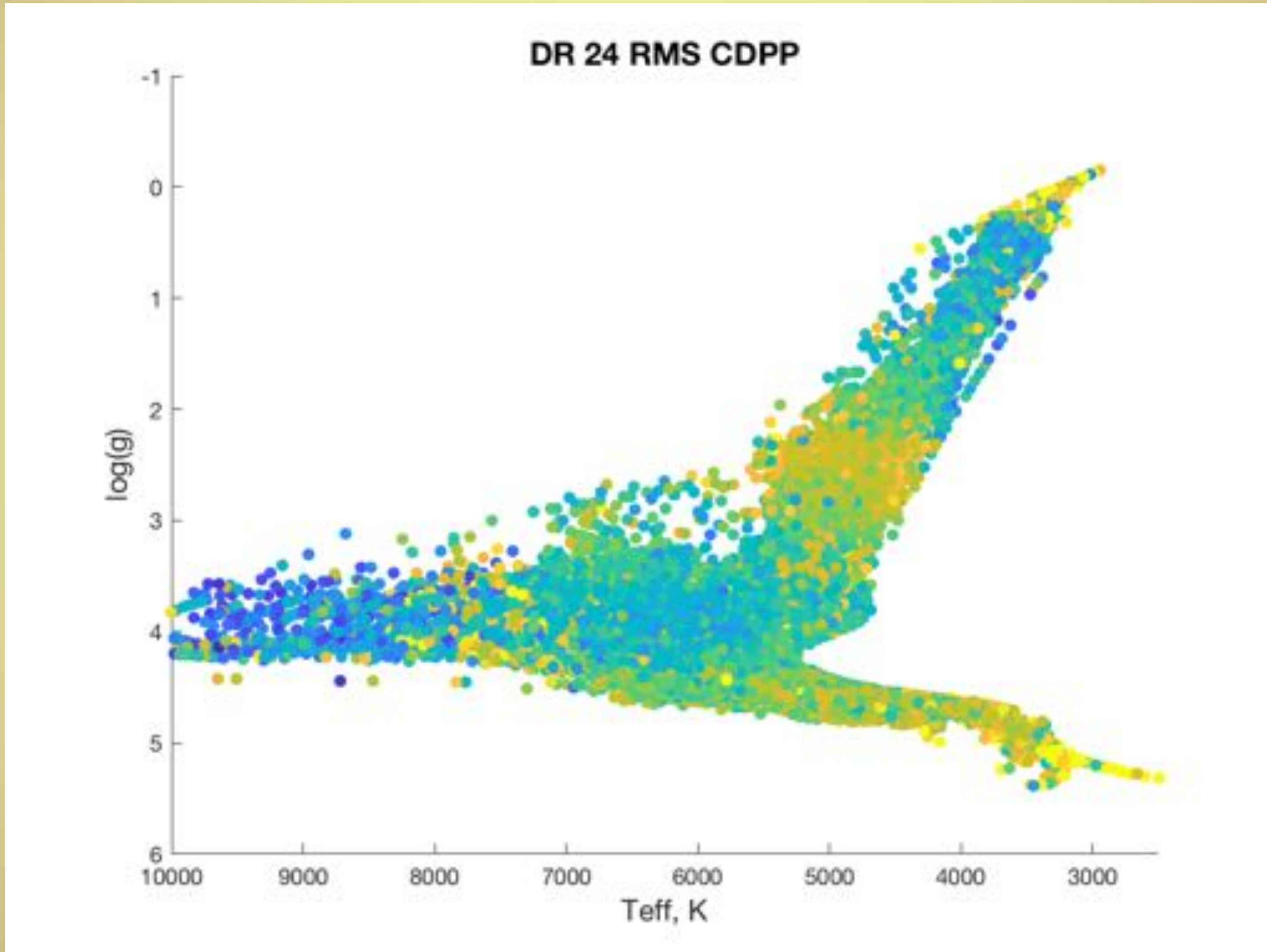


# Photometric Precision




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

# Excess Stellar Variability

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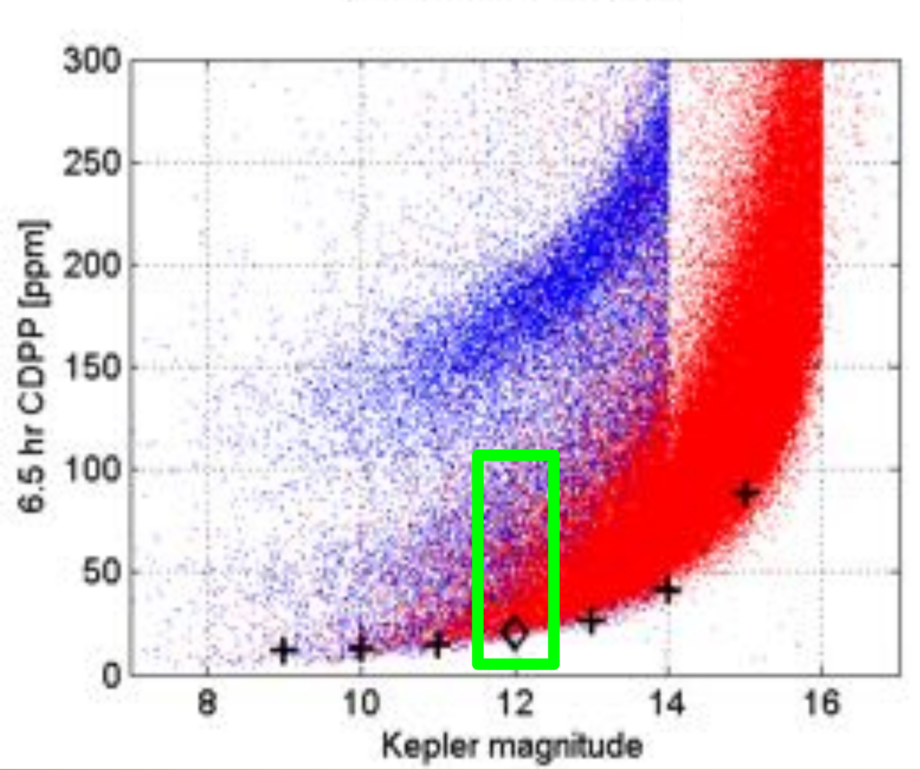
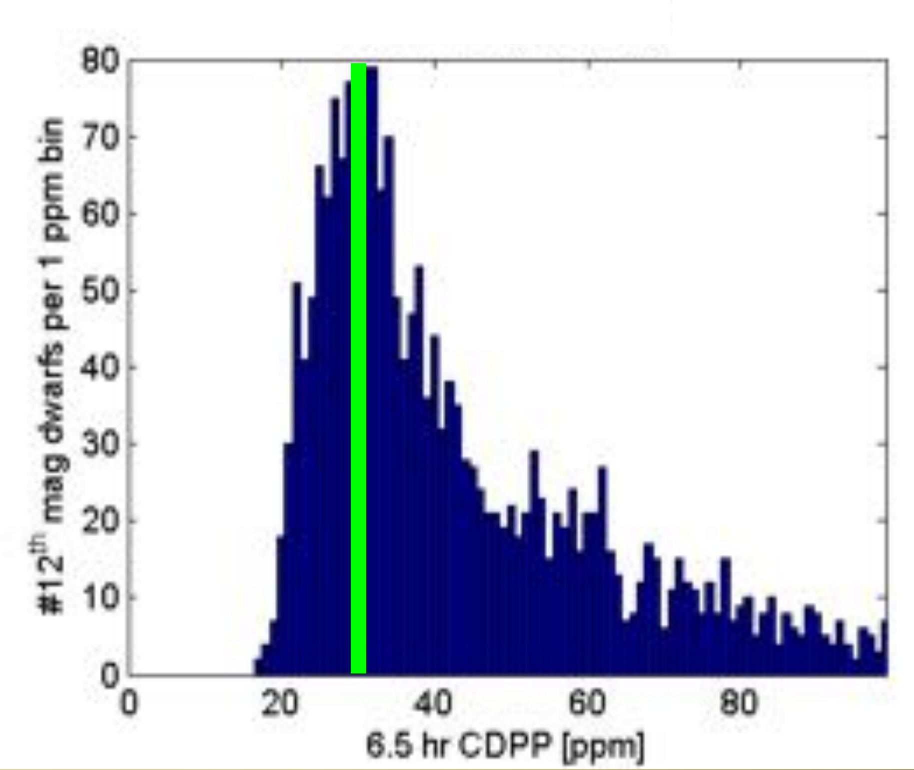
Original Noise Budget (Kp=12):
- 14 ppm Shot Noise
- 10 ppm Instrument Noise
- 10 ppm Stellar Variability

=> 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



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# 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