Recent Results from the *Kepler Mission:* Hard Planets are Good to Find

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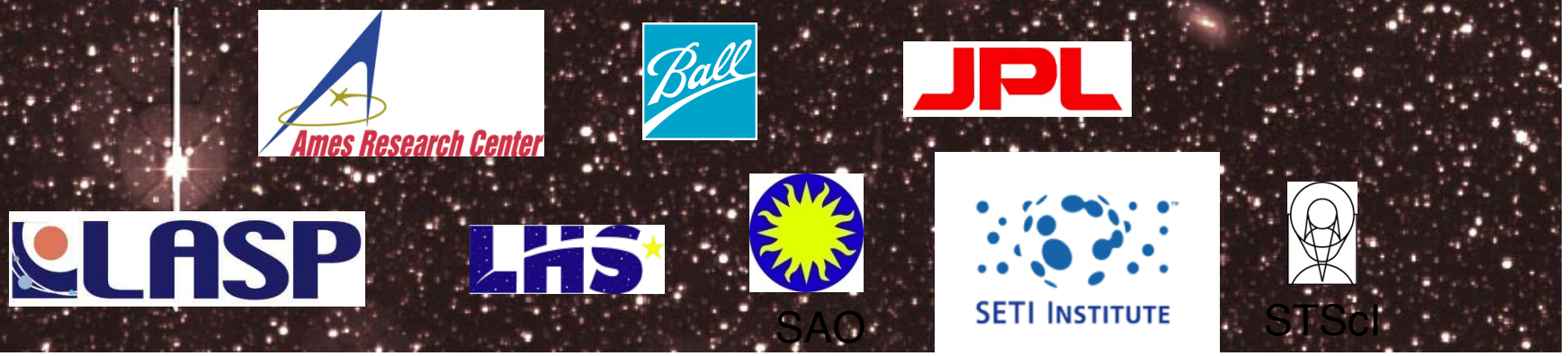
SETI Institute/NASA Ames Research Center

Friday February 17, 2012

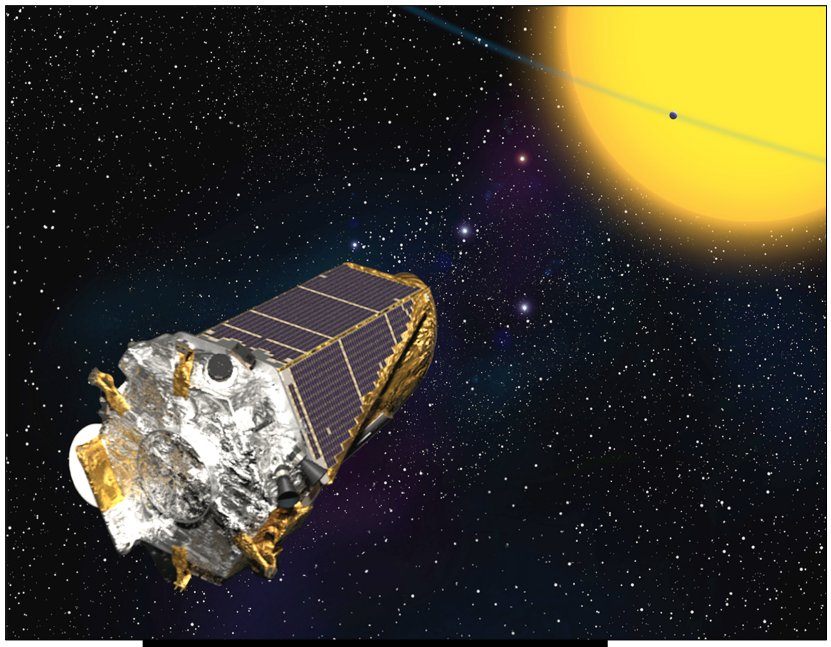
16th International Conference on Gravitational Microlensing

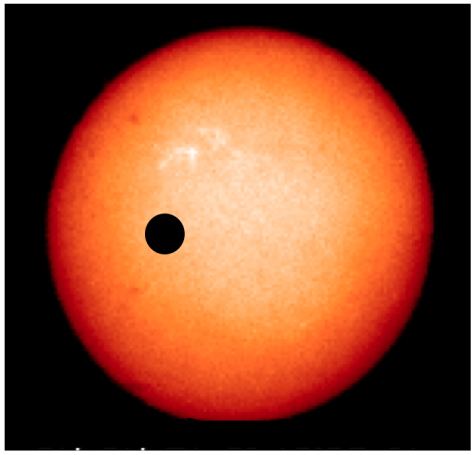


Overview

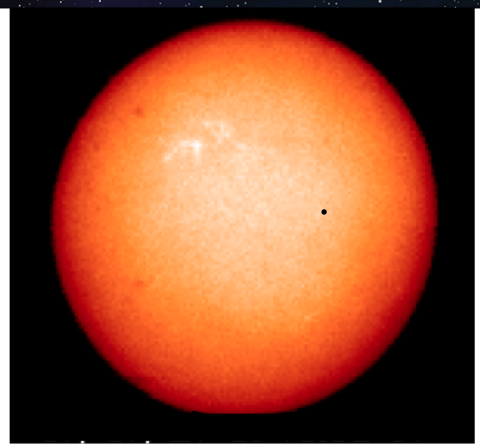
Kepler
A Search for Earth-size Planets

- **Key Challenges**
- **The Kepler Mission**
- **Key Science Results**
- **Correcting Systematic Errors**
- **Stellar Variability**
- **Summary**

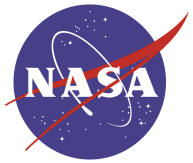




Jupiter:
1% area of the Sun (1/100)



Earth or Venus
0.01% area of the Sun (1/10,000)



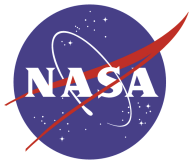
Critical Questions:

Kepler
A Search for Earth-size Planets

- Are terrestrial planets common or rare?
- What are their sizes & orbital distances?
- How often are they in the habitable zone?
- What is their dependence on stellar properties?

Bottom Line: Are We Alone?

Key Challenges



Key Technical Challenges

Kepler
A Search for Earth-size Planets

1. Terrestrial planets are really small ~100 ppm deep signatures

⇒ 20 ppm photometric precision

2. Transits occur on timescales of one hour to ~ ½ day

⇒ Sample at ½ hour cadence

3. Transiting planets are rare (geometric probability of alignment is ~0.5% for Earth analogs)

⇒ Observe ~100,000 stars

4. We don't know when a transit will occur

⇒ Stare at one FOV for 3.5-10 years and don't blink

Kepler's Cannonball

Kepler
A Search for Earth-size Planets

Kepler's Required Photometric Precision:

20 ppm

On a 4" cannonball this is ~1 μm

The average human hair is 80 μm

In order to find Earth-like planets transiting Sun-Like stars we absolutely must polish Kepler's cannonball!

The Long and Winding Road to *Kepler*

Kepler
A Search for Earth-size Planets

- **1984 Borucki and Summers – first serious publication**
- **1992 Proposal to NASA - DENIED**
- **1994 Proposal to NASA Discovery Program - DENIED**
- **1996 Proposal to NASA Discovery Program – DENIED**

⇒ Vulcan Transit Survey

- **1998 Proposal to NASA Discovery Program - DENIED**

⇒ Kepler Technology Demonstration

- **2000 Proposal to NASA Discovery Program – AWARDED**

LAUNCH

The *Kepler Mission*

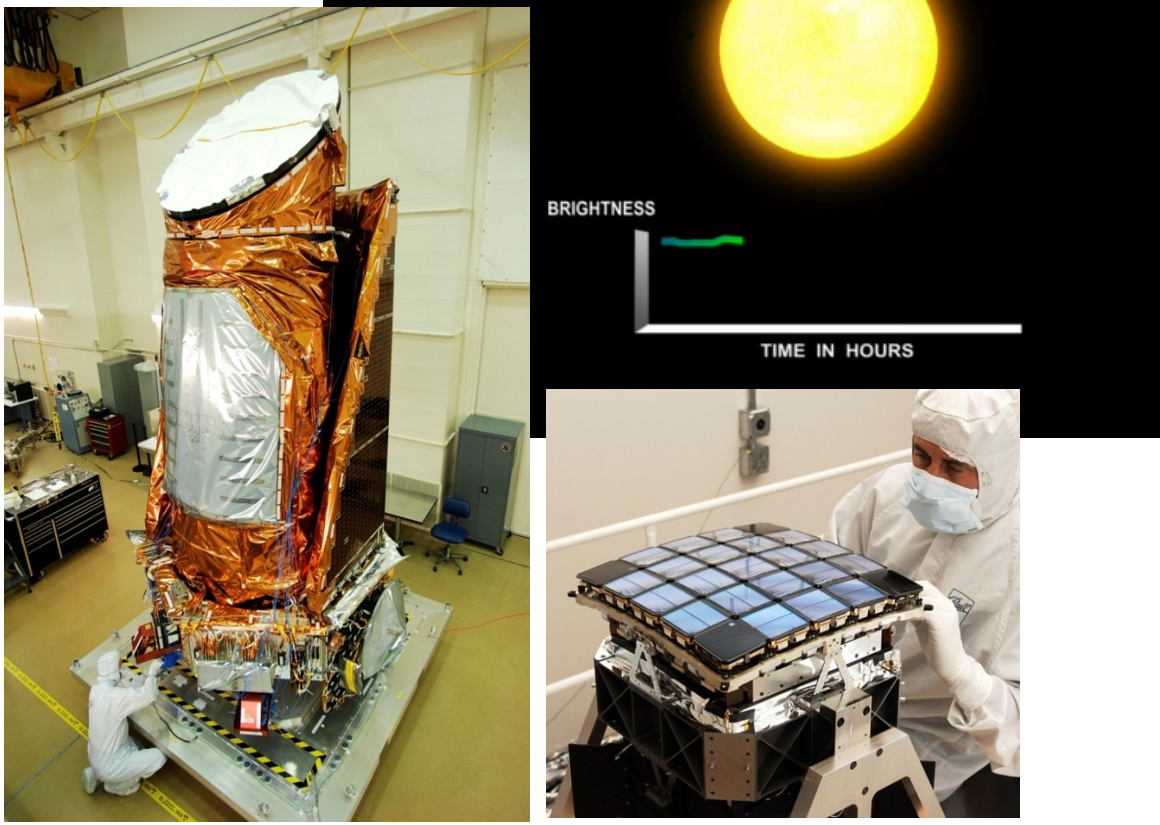
The Solution: The Kepler Mission

Kepler
A Search for Earth-size Planets

KEPLER: A Wide Field-of-View Photometer that monitors ≥100,000 Stars for 3.5 yrs with precision to find Earth-size planets in the Habitable Zone

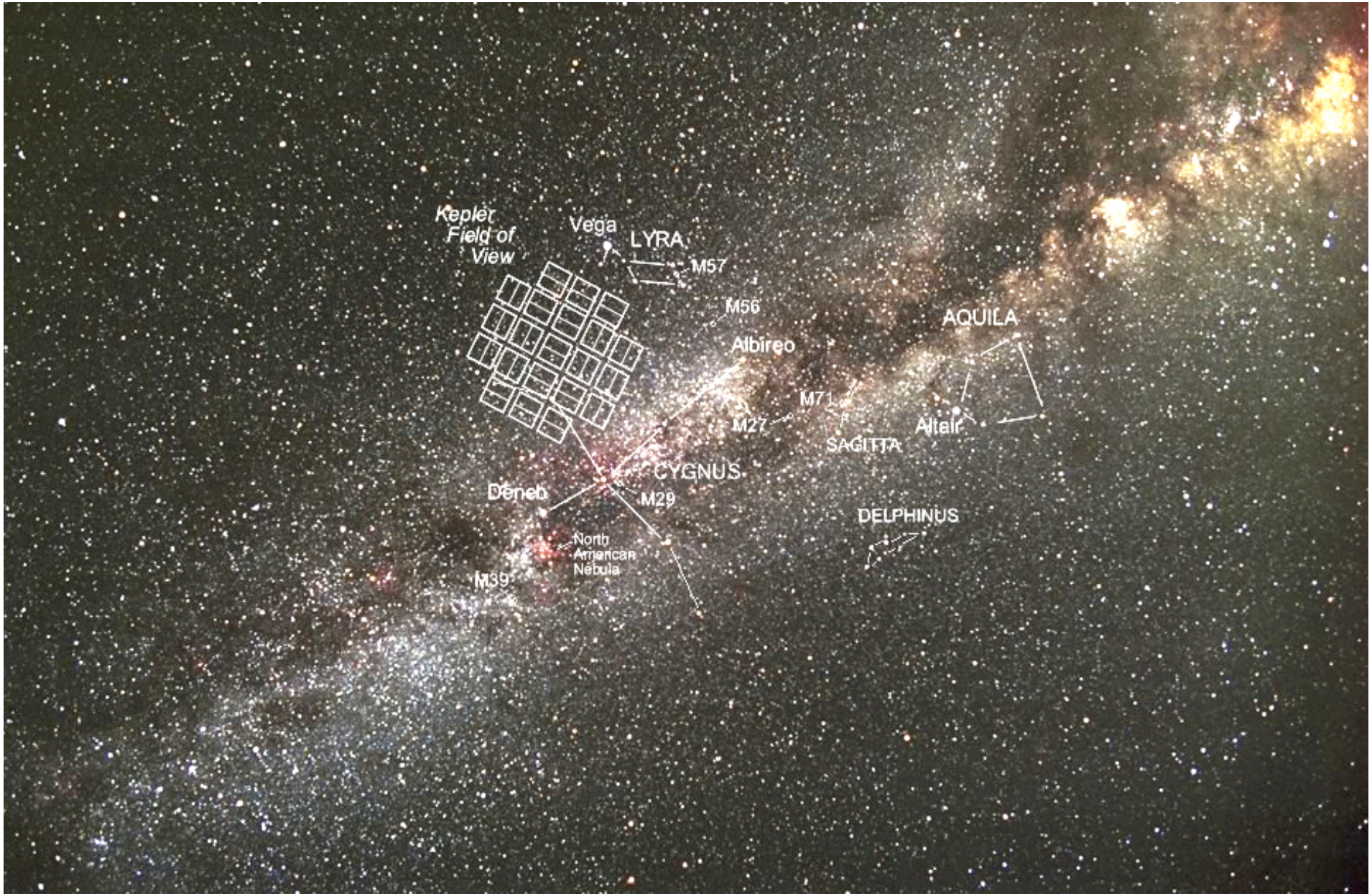
Transit Detection using:

- 0.95 meter aperture
- Wide FOV: 100 sq deg
- 42 CCDs
- >= 3.5 years
- Fixed pointing
- Heliocentric orbit
- 170k targets: 30 min
- 512 targets: 1 min



Field of View in Cygnus

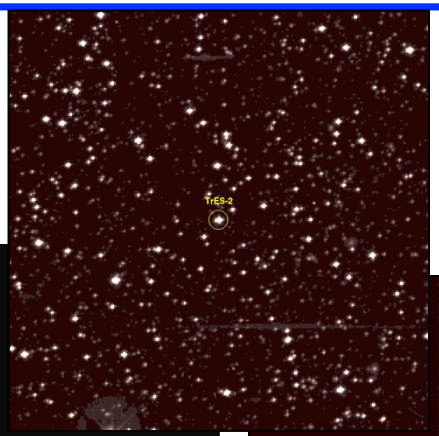
Kepler
A Search for Earth-size Planets

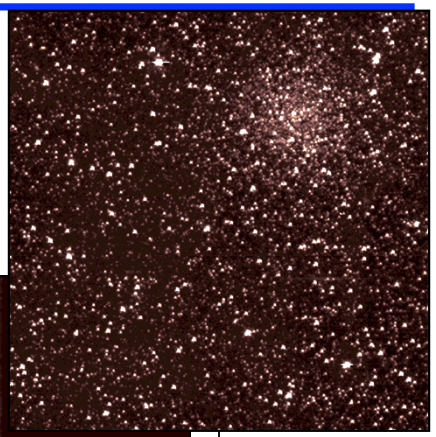


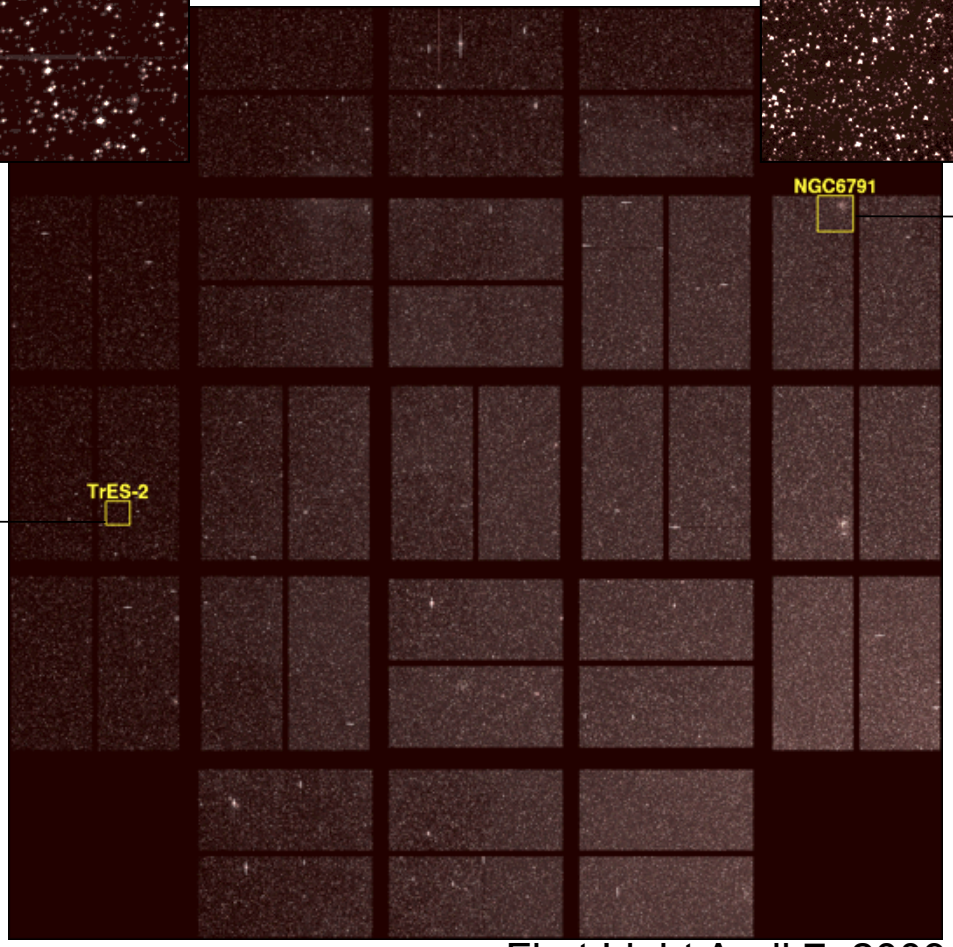
First Light Full Field Image

Kepler
A Search for Earth-size Planets

Launched
March 7, 2009



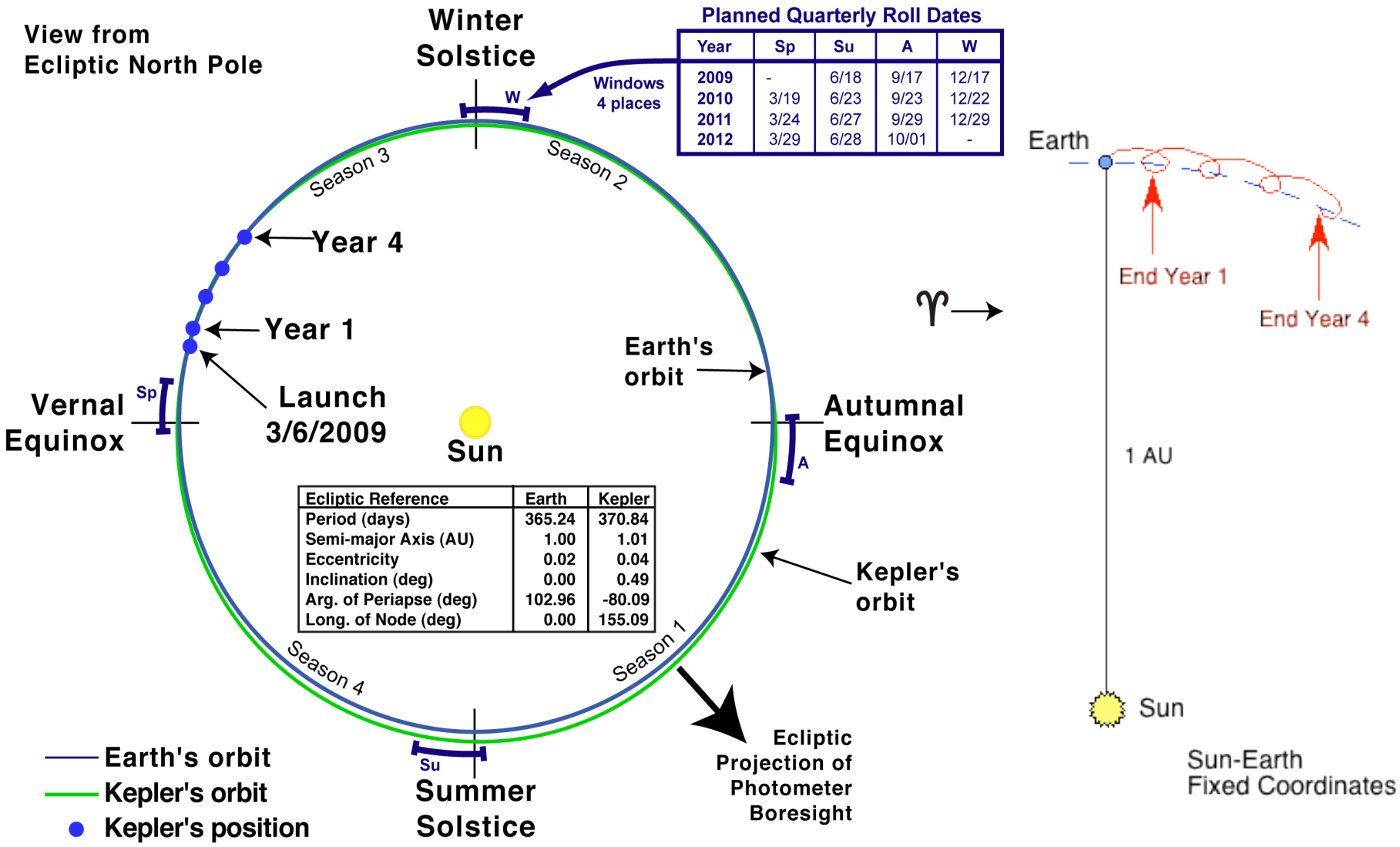




First Light April 7, 2009

Earth-Trailing Heliocentric Orbit

Kepler
A Search for Earth-size Planets

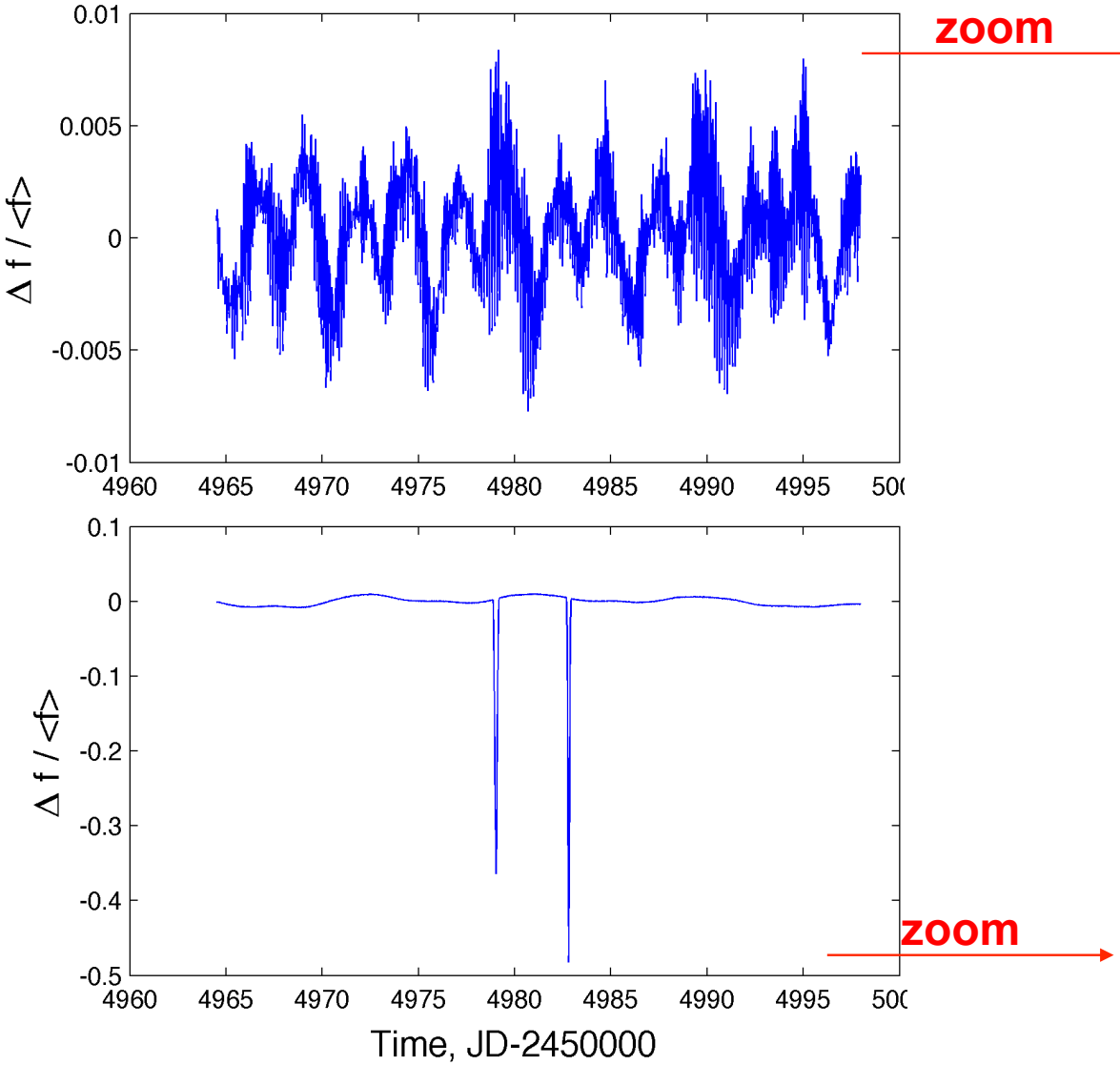


Year	Sp	Su	A	W
2009	-	6/18	9/17	12/17
2010	3/19	6/23	9/23	12/22
2011	3/24	6/27	9/29	12/29
2012	3/29	6/28	10/01	-

Ecliptic Reference	Earth	Kepler
Period (days)	365.24	370.84
Semi-major Axis (AU)	1.00	1.01
Eccentricity	0.02	0.04
Inclination (deg)	0.00	0.49
Arg. of Periapse (deg)	102.96	-80.09
Long. of Node (deg)	0.00	155.09

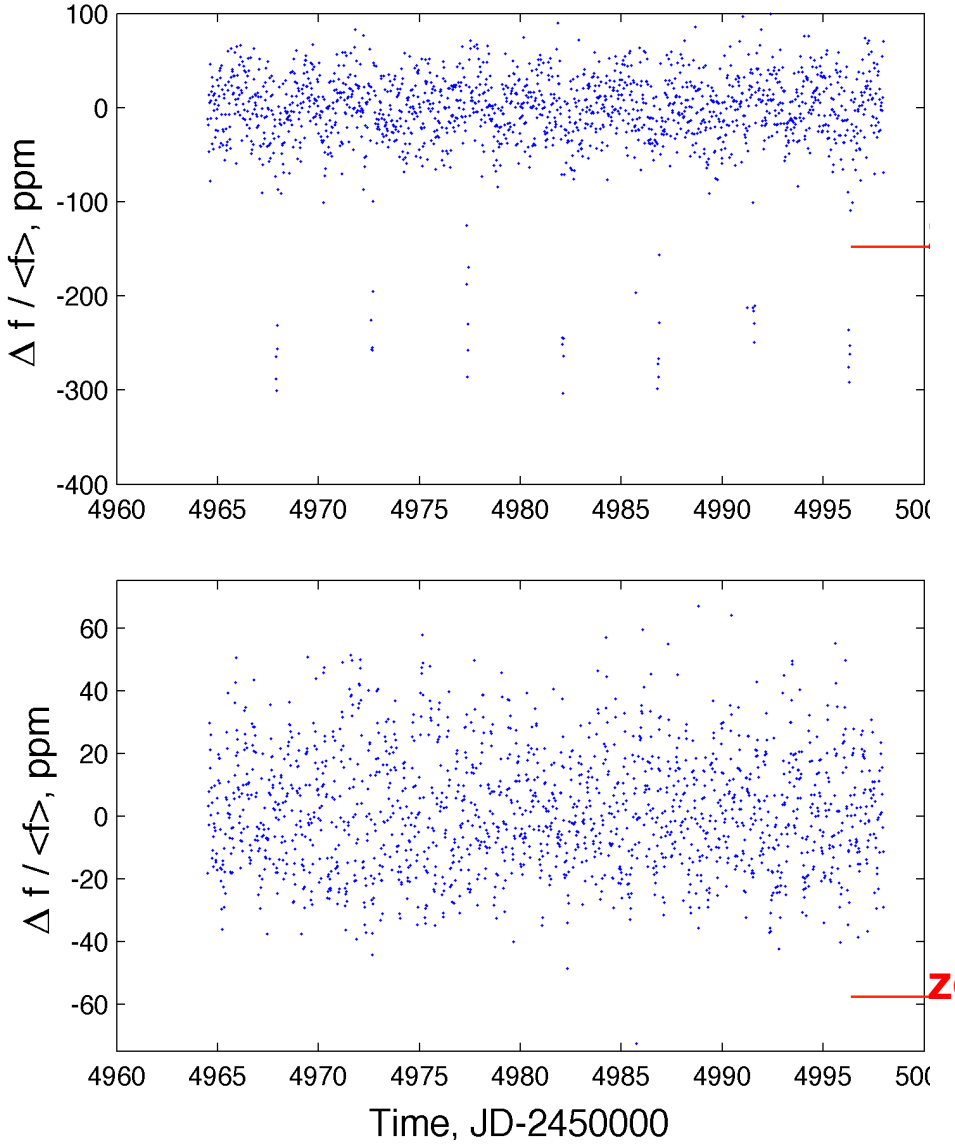
Orbit provides an extremely benign environment

Flux Time Series (1)



Flux Time Series (2)

Kepler
A Search for Earth-size Planets



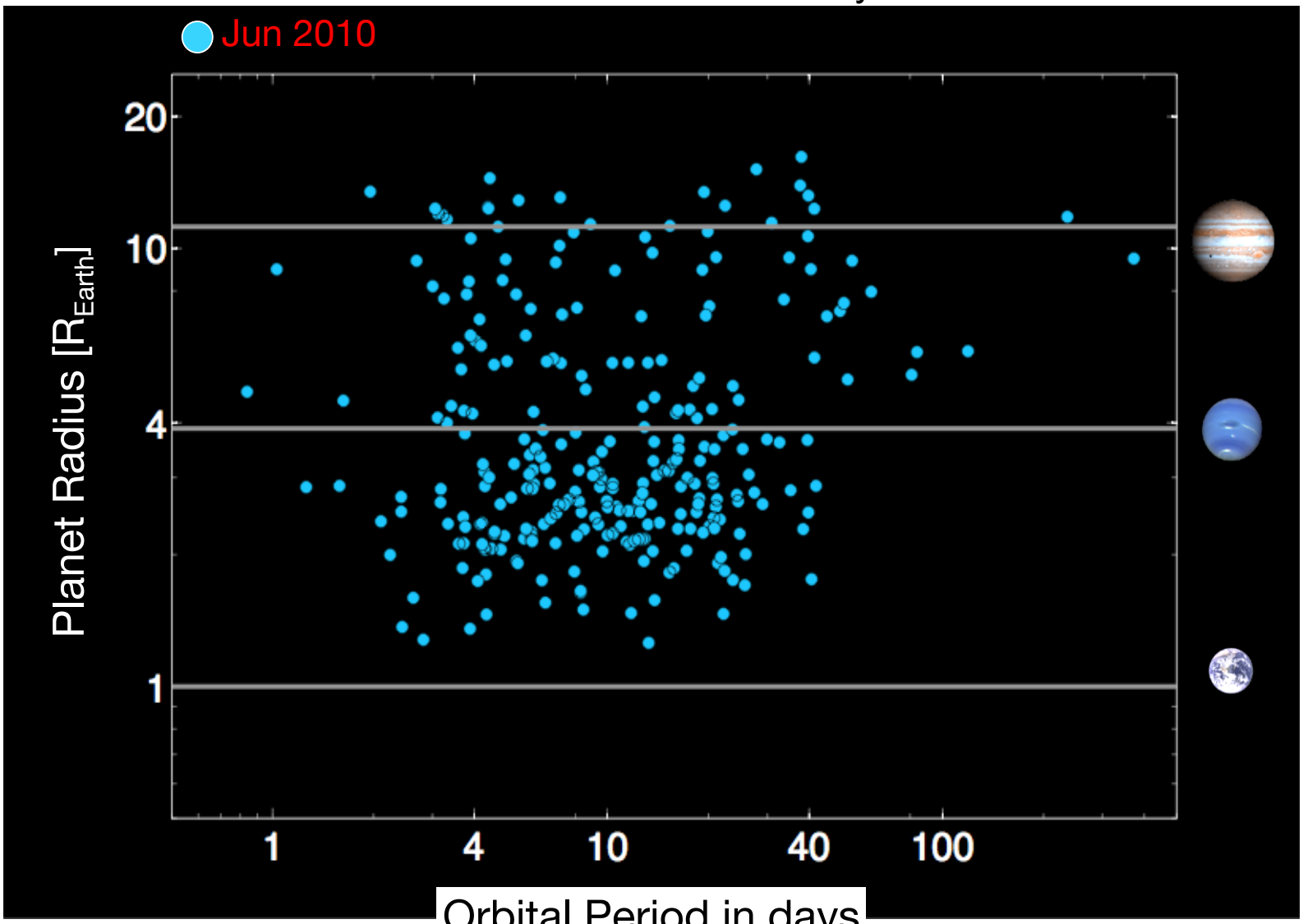
zoom

Key Science Results

Planet Candidates as of June 2010

Kepler
A Search for Earth-size Planets

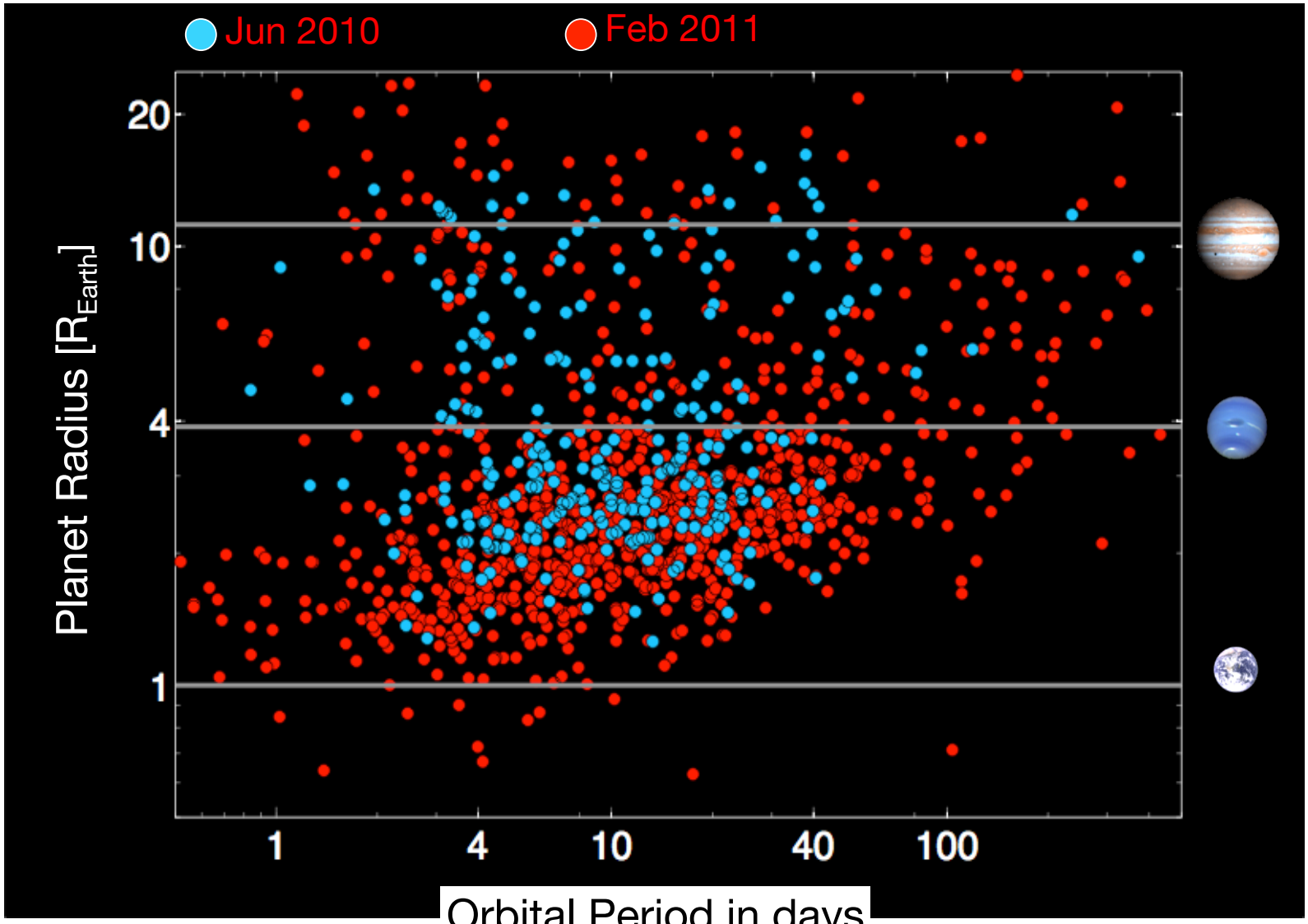
Based on 43 days of data



Planet Candidates as of Feb 2011

Kepler
A Search for Earth-size Planets

Based on 13 months of data

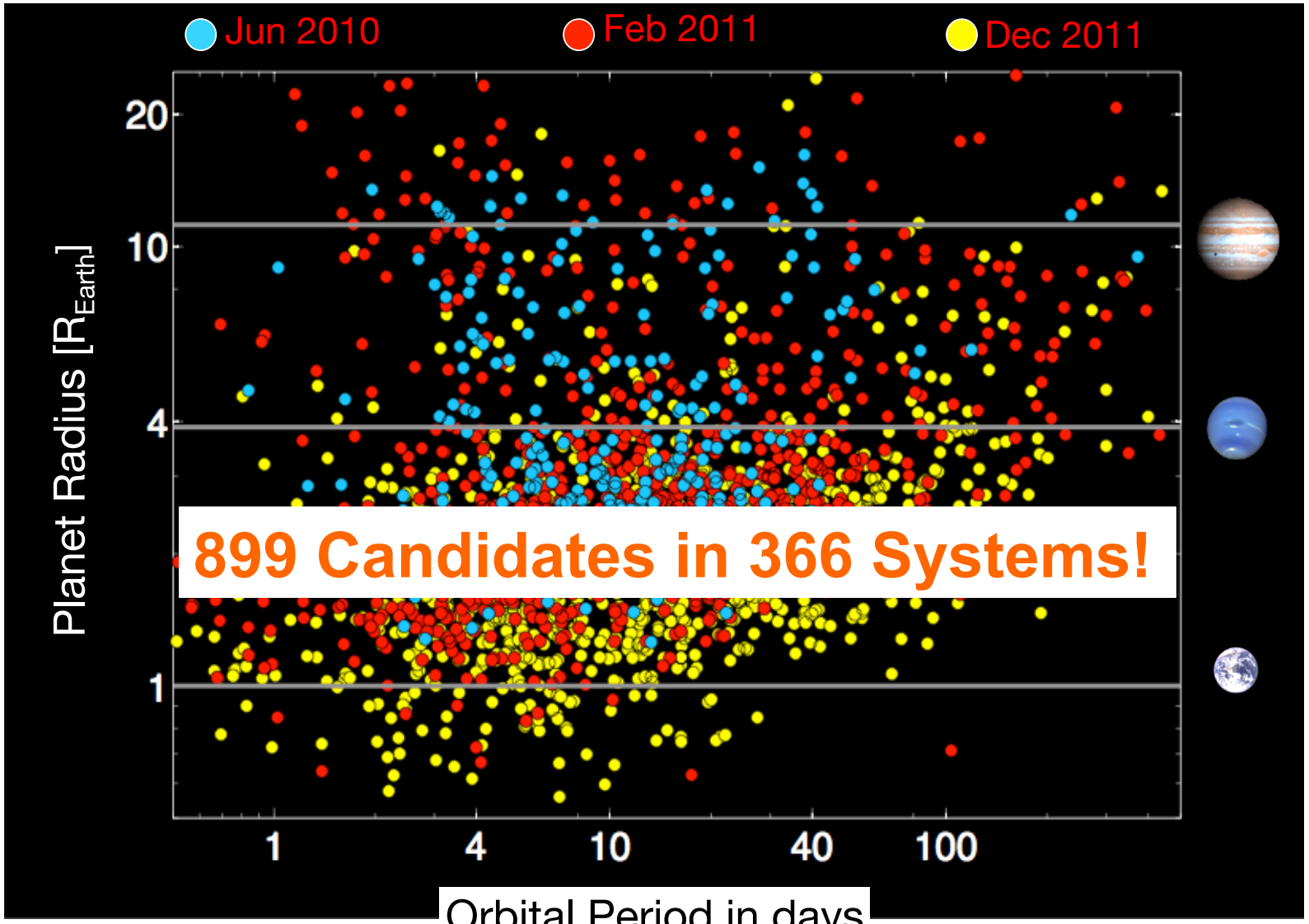


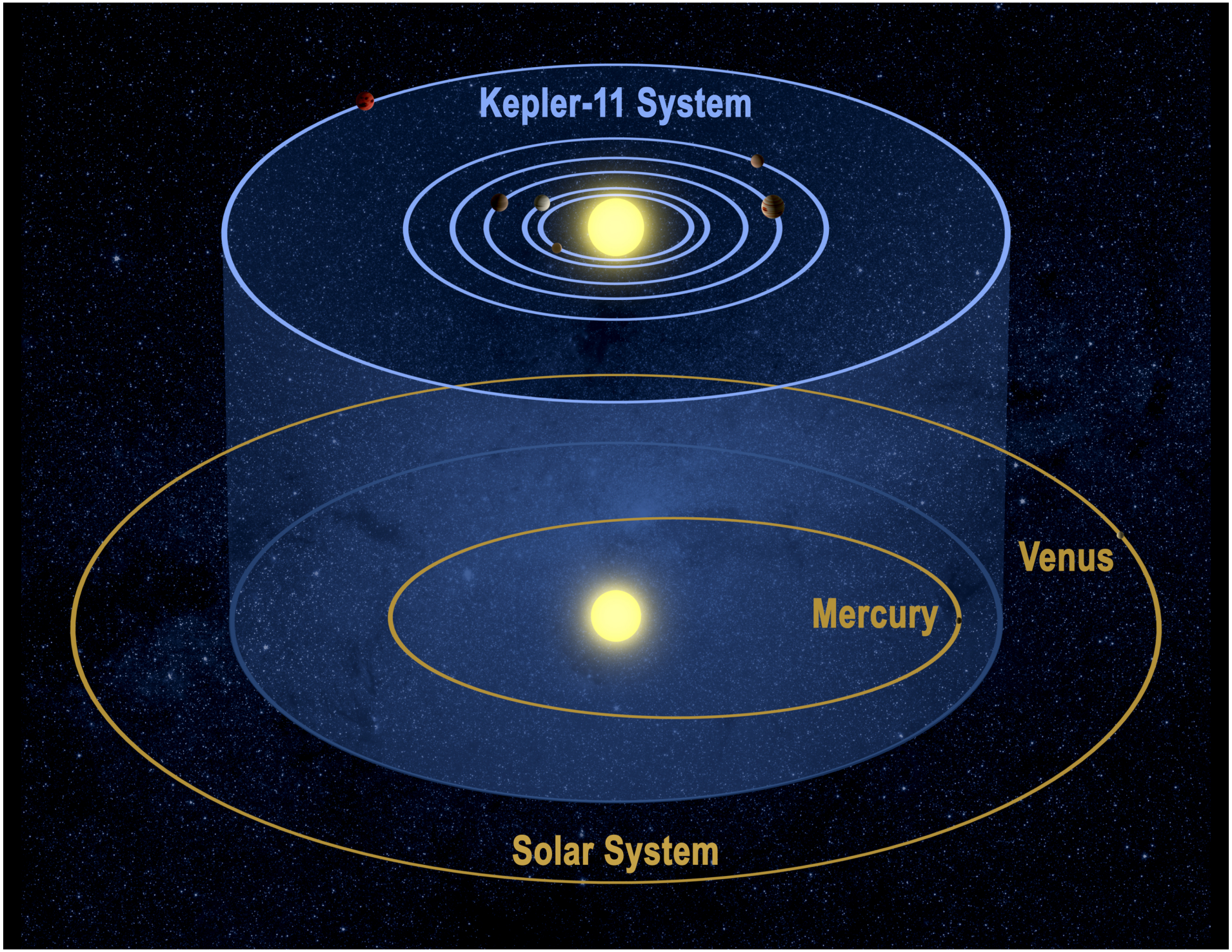
2300 Planet Candidates

as of Dec 2011

Kepler
A Search for Earth-size Planets

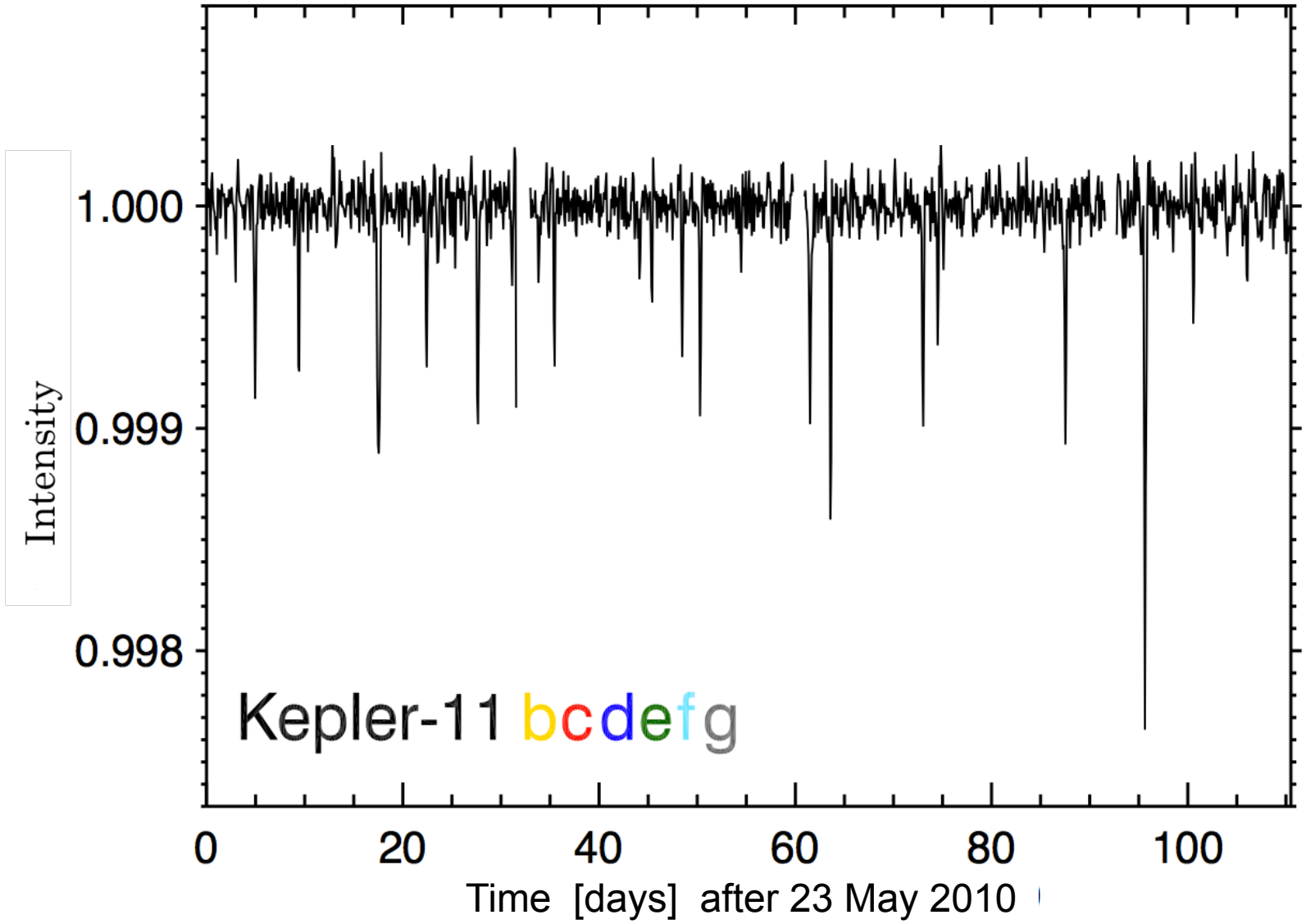
Based on 16 months of data




Kepler-11 System
Venus
Mercury
Solar System

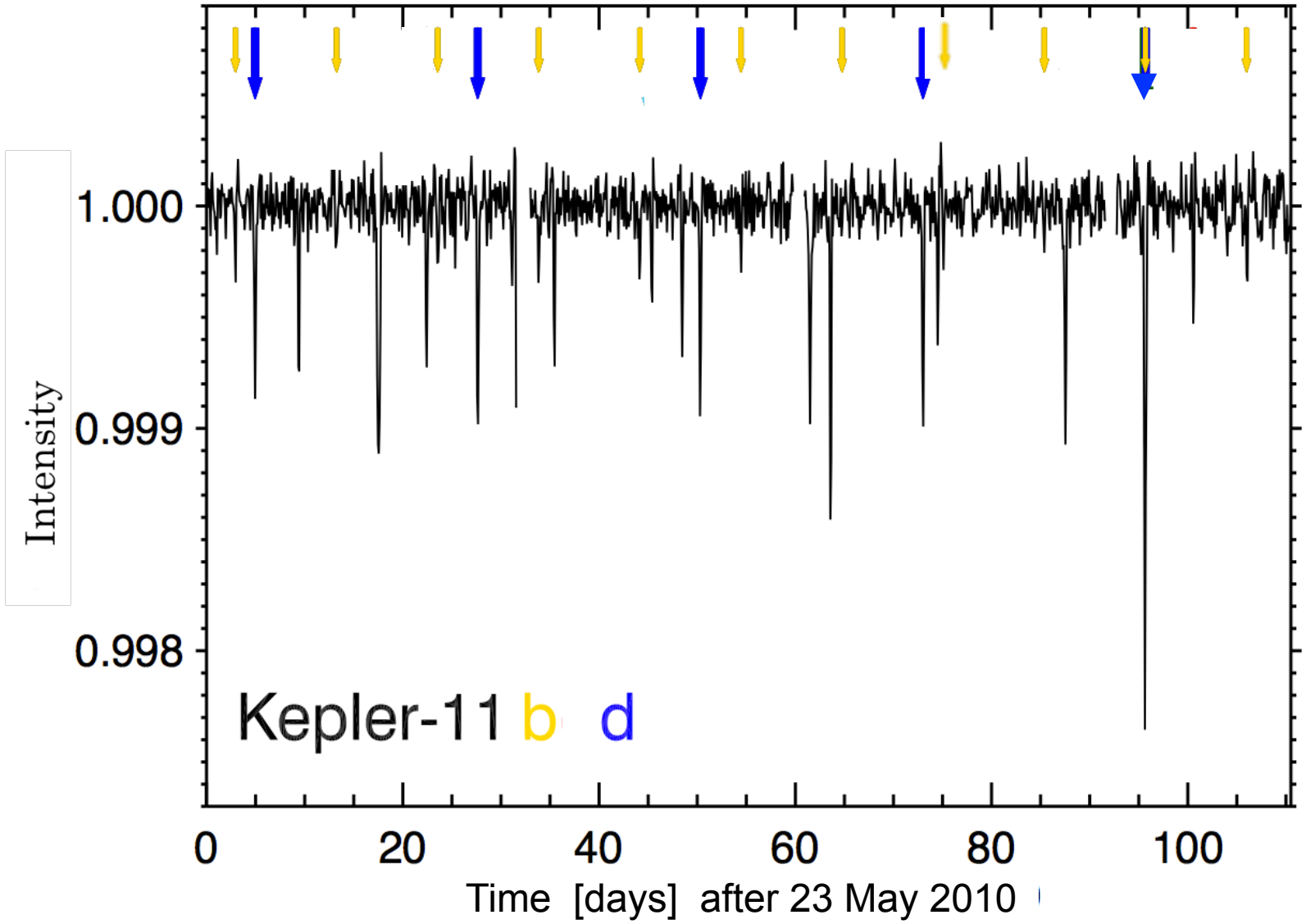
Kepler-11: Six Transiting Planets

Kepler
Search for Earth-size Planets



Kepler-11: Six Transiting Planets

Kepler
Search for Earth-size Planets



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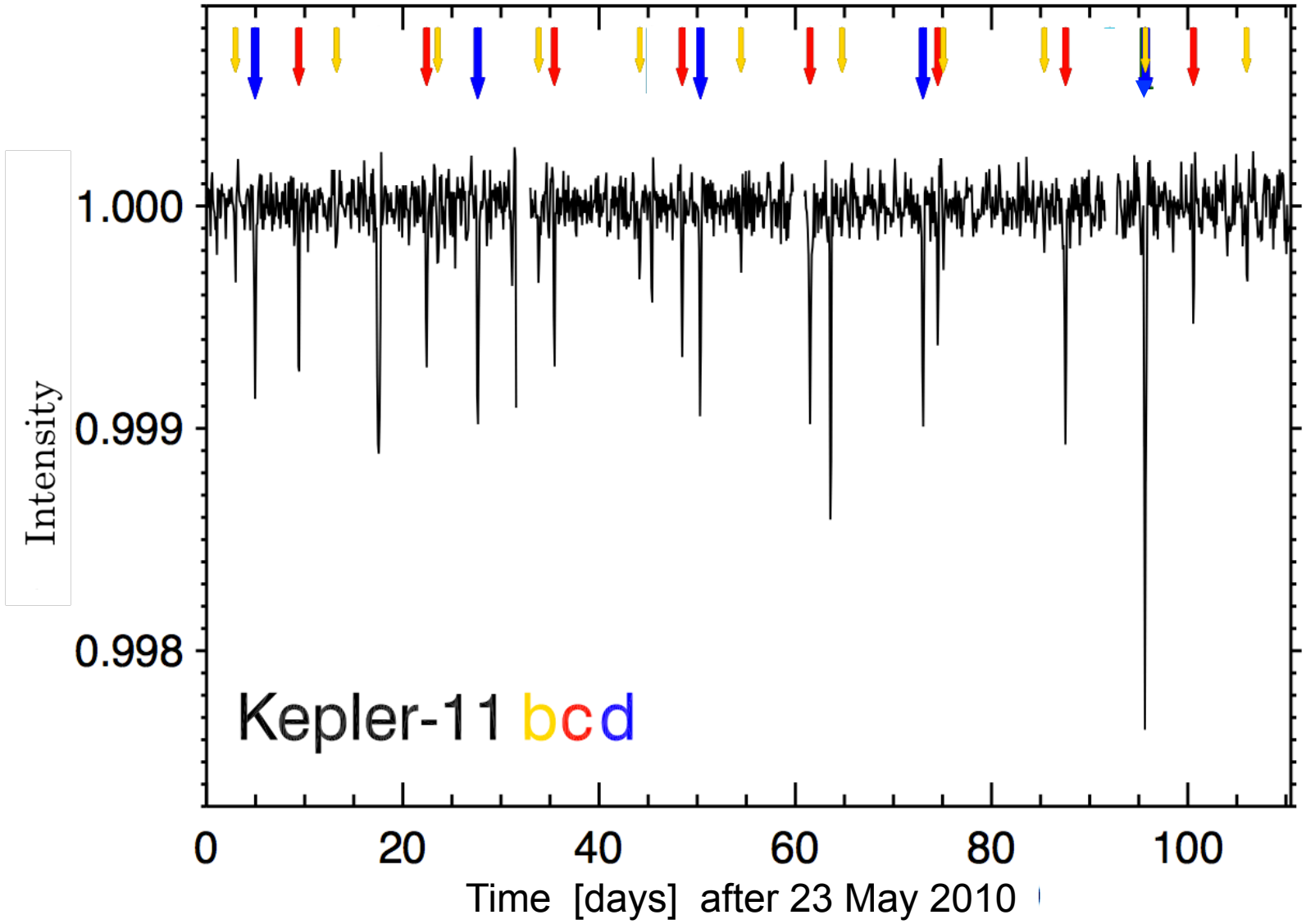

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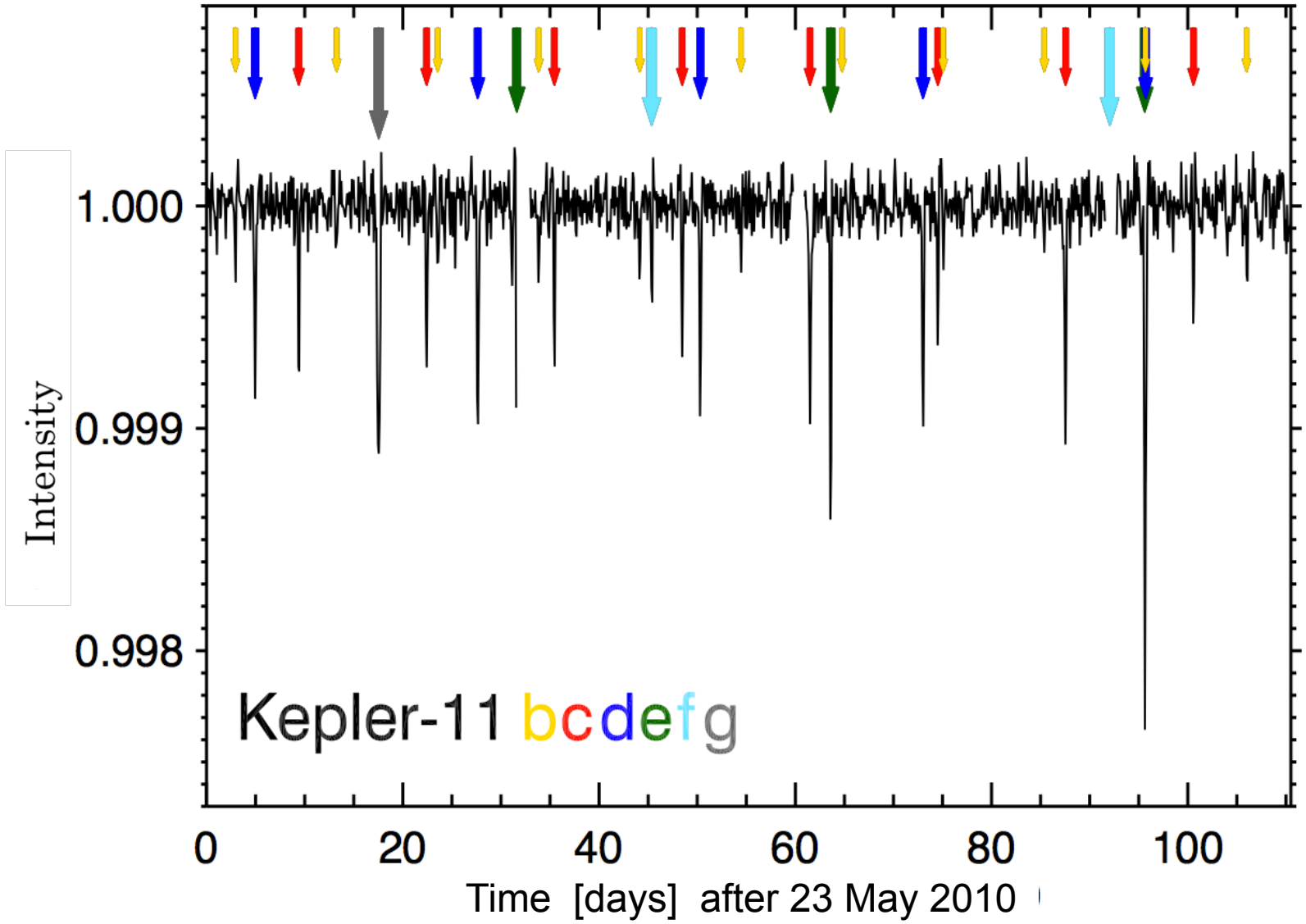
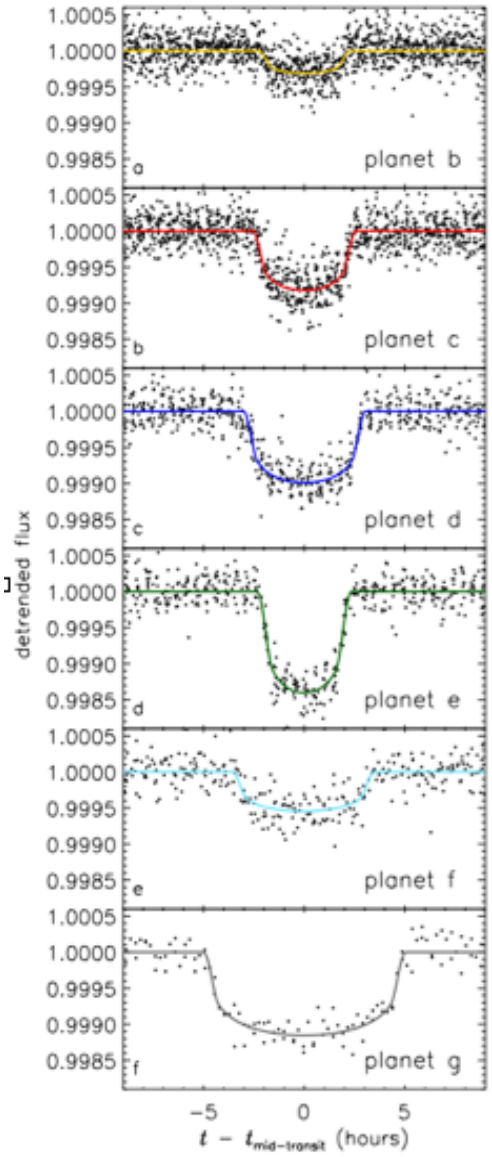
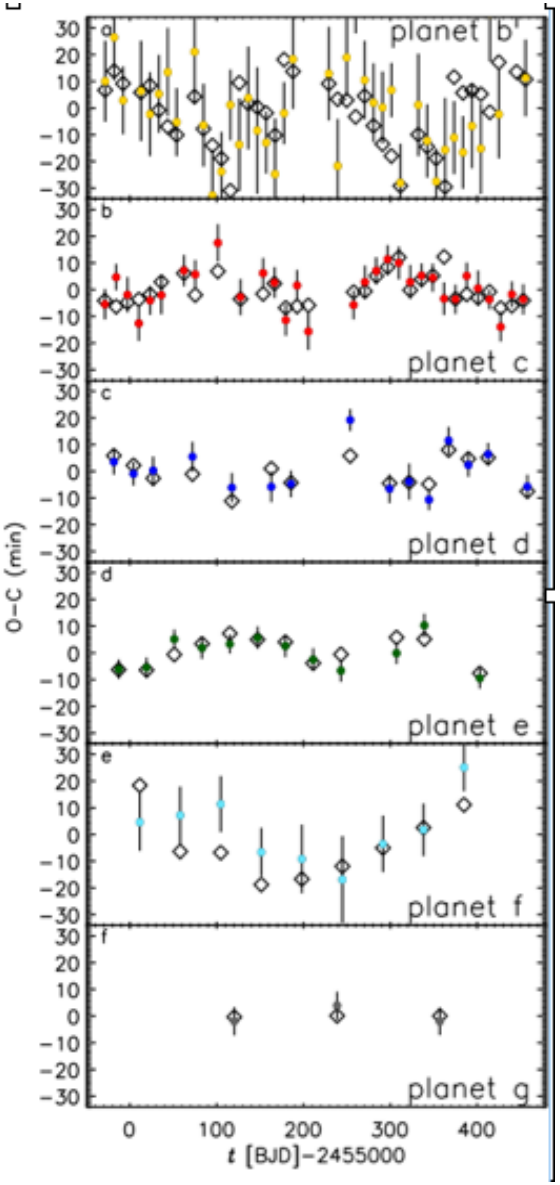


Transit-Timing Variations:

Transits



Time: Lead or Lag

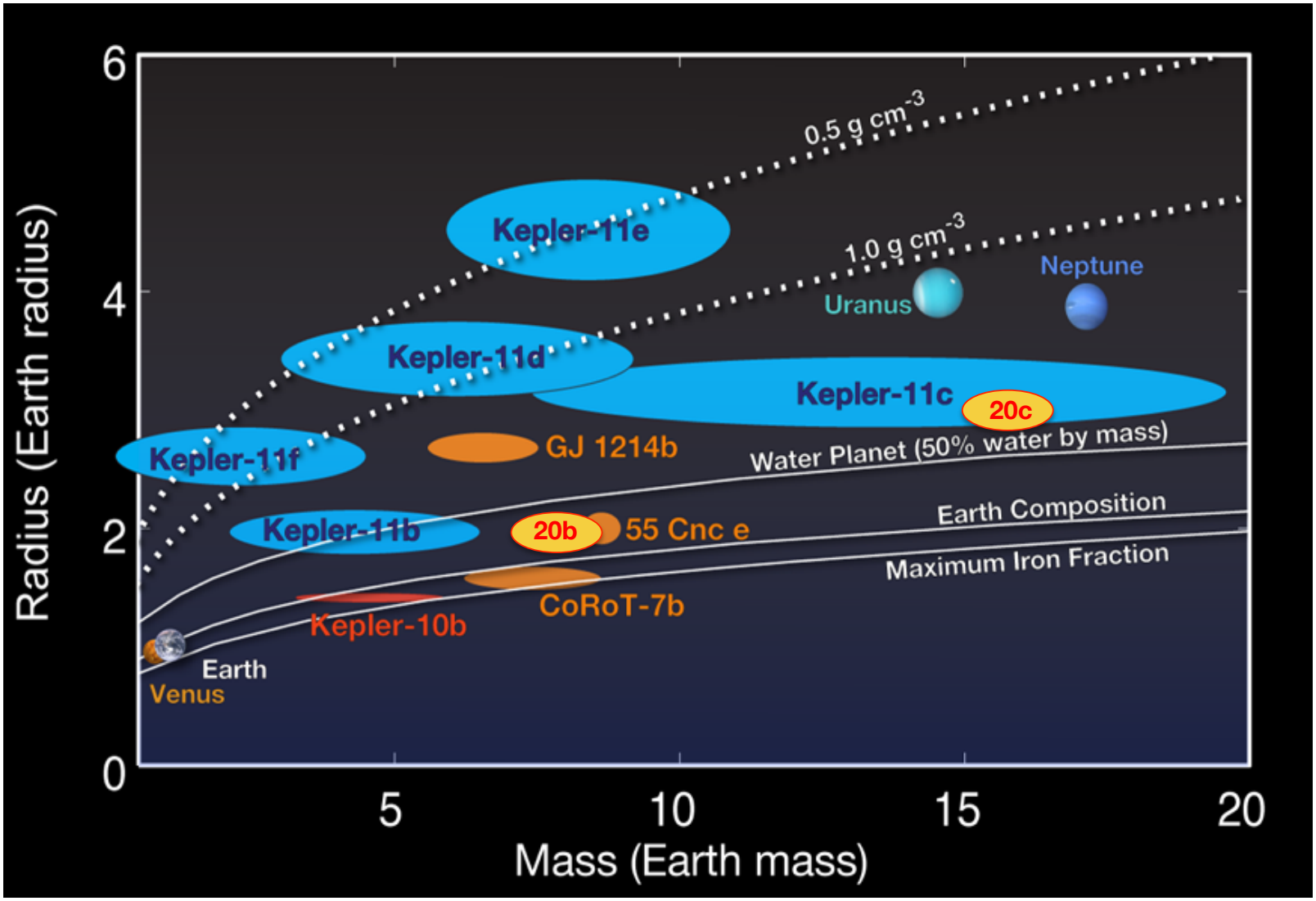


Transit-Time Variations due to planet-planet Interactions:

Planet Masses

Mass-Radius Relationship

Kepler
A Search for Earth-size Planets



Mass-Radius Relationship

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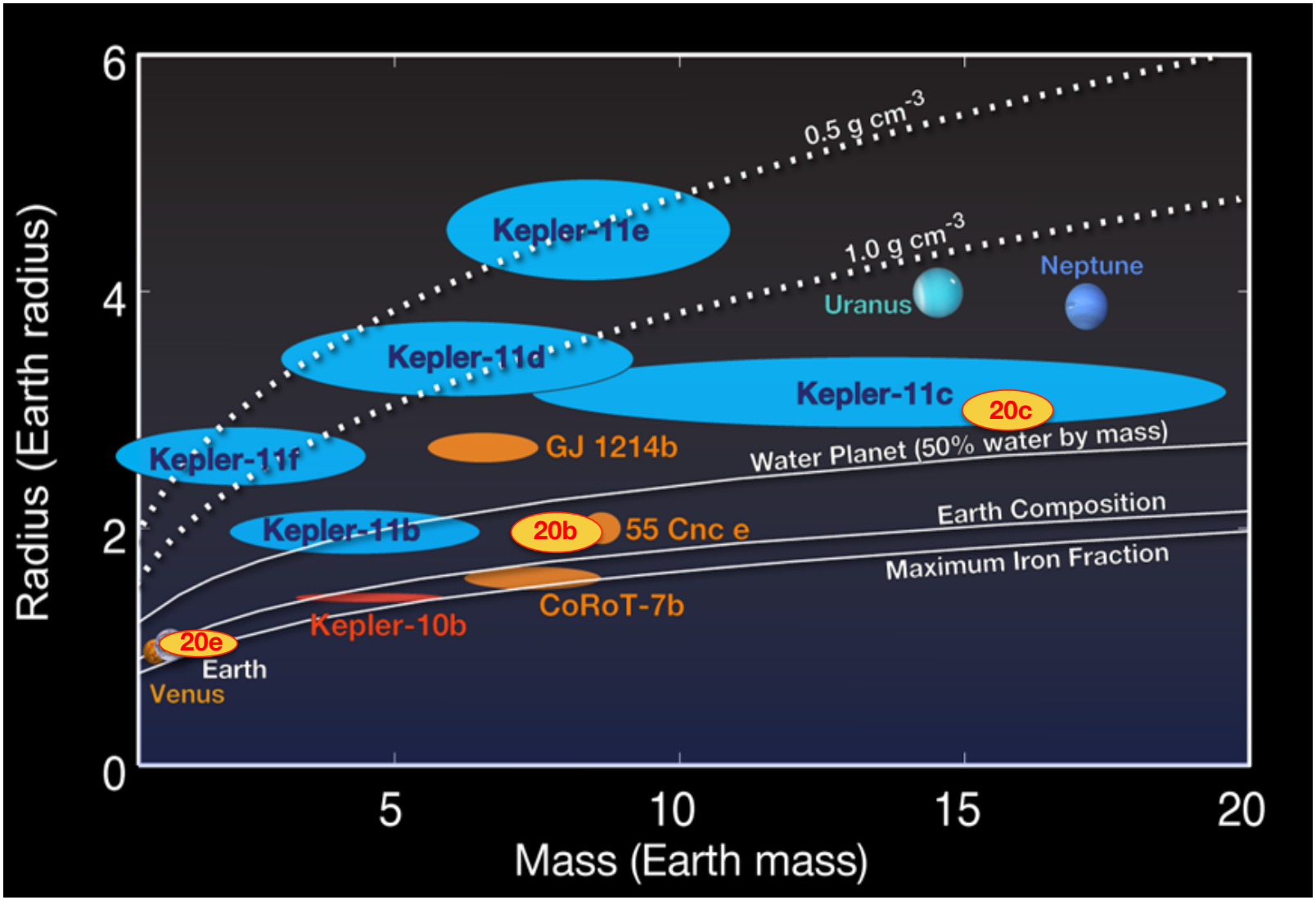

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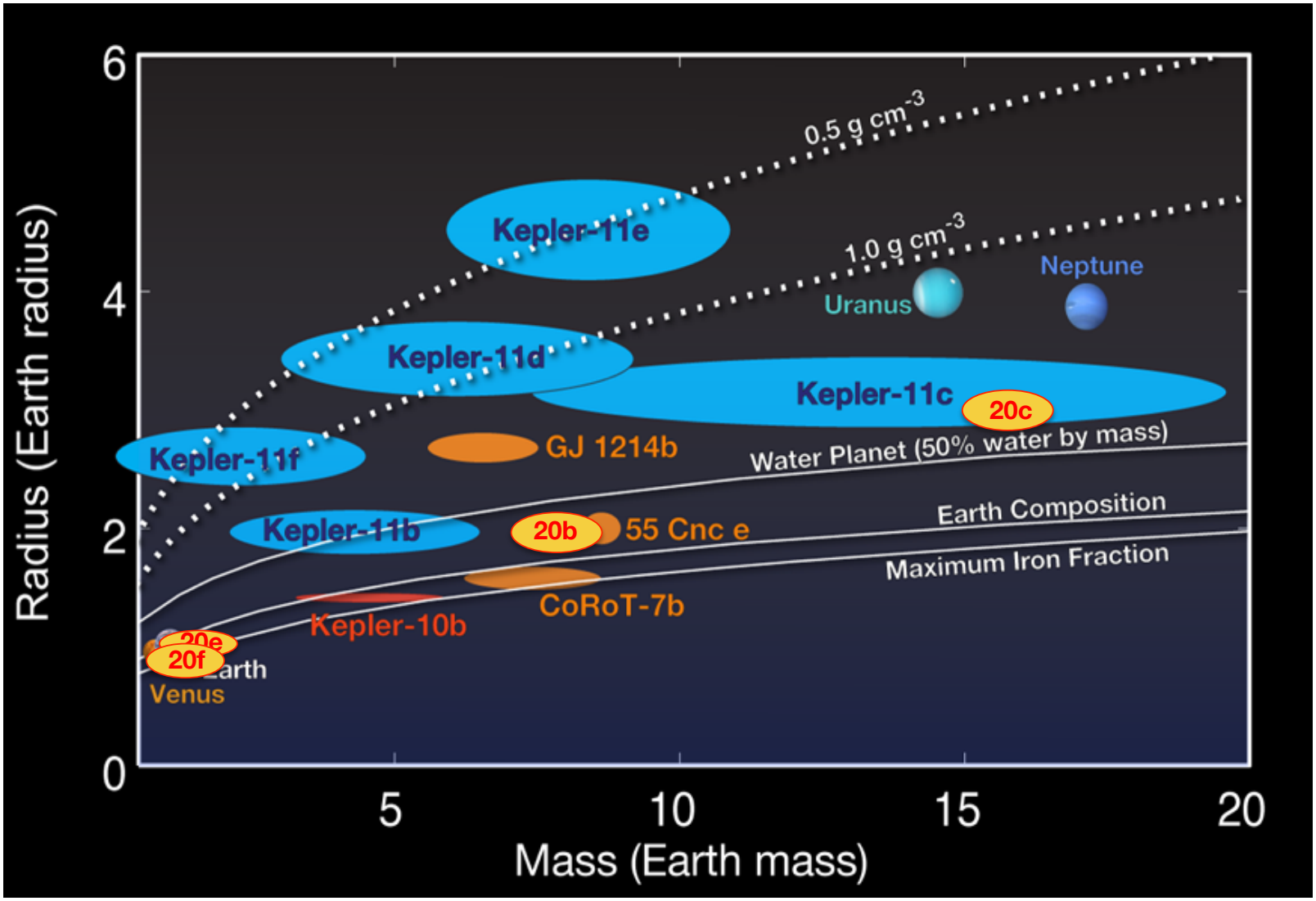
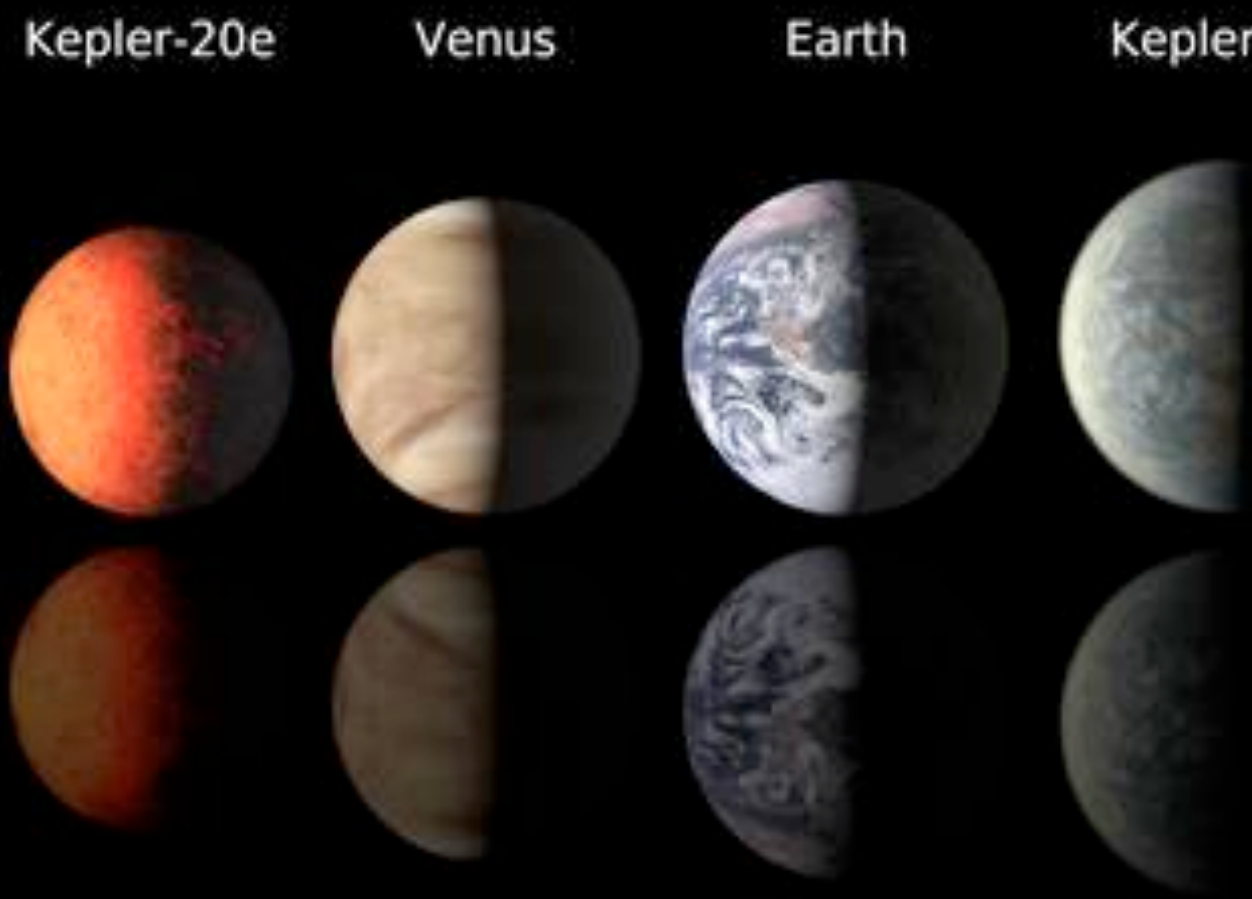
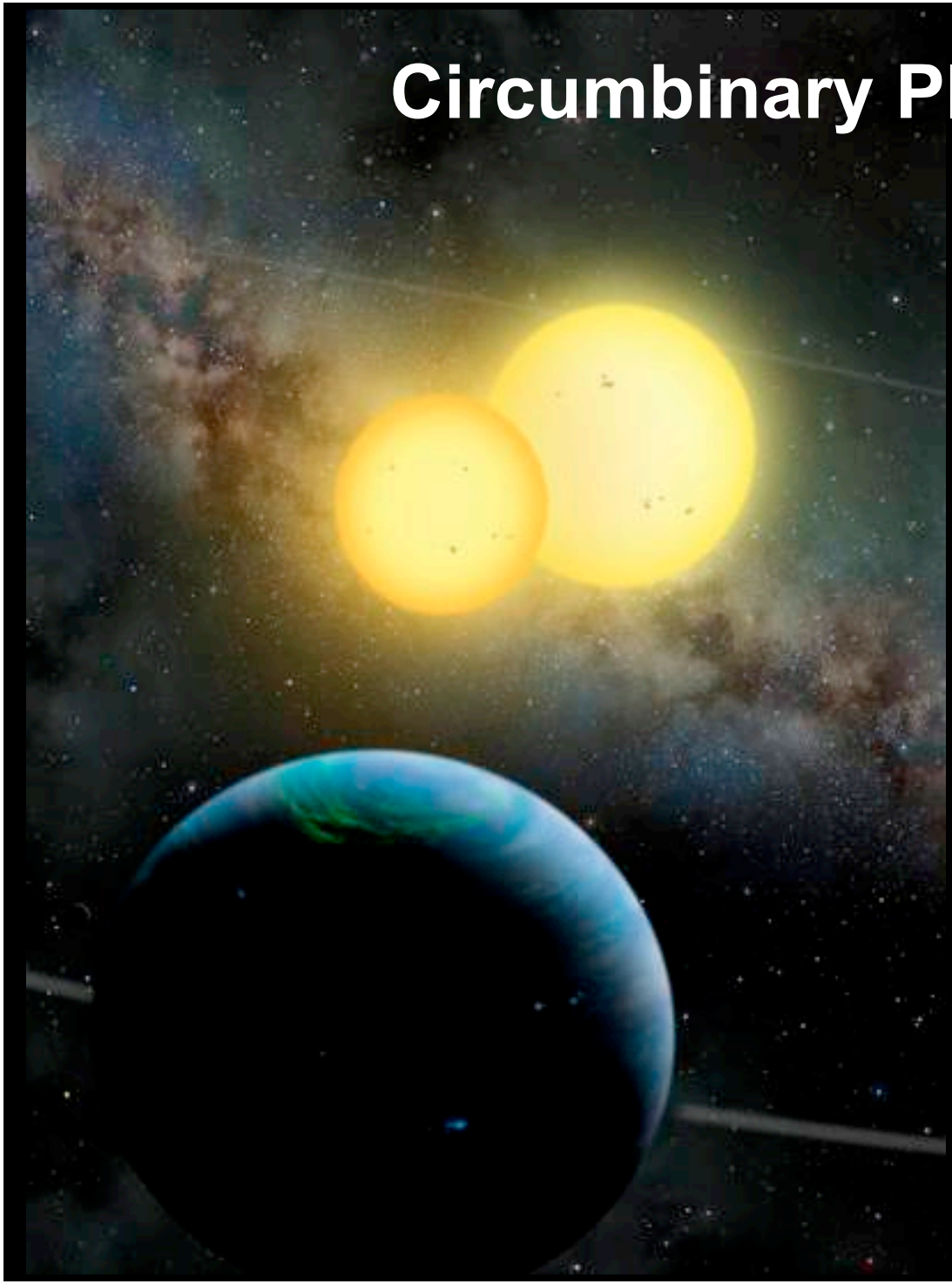


Kepler discovers two Earth-size planets, which are presumably rocky, Kepler-20e and Kepler-20f. These planets are members of multiple solar systems that contain additional larger gas giant planets in longer period orbits.



Circumbinary Planets



Artist view of Kepler 35.
With the discovery of the Kepler 34 and 35,
The Kepler mission has opened the new field of circumbinary planetary astronomy.

The planets orbiting in these Binary systems will experience Large incident flux changes, making their weather present seasonal changes many times during each planets year.

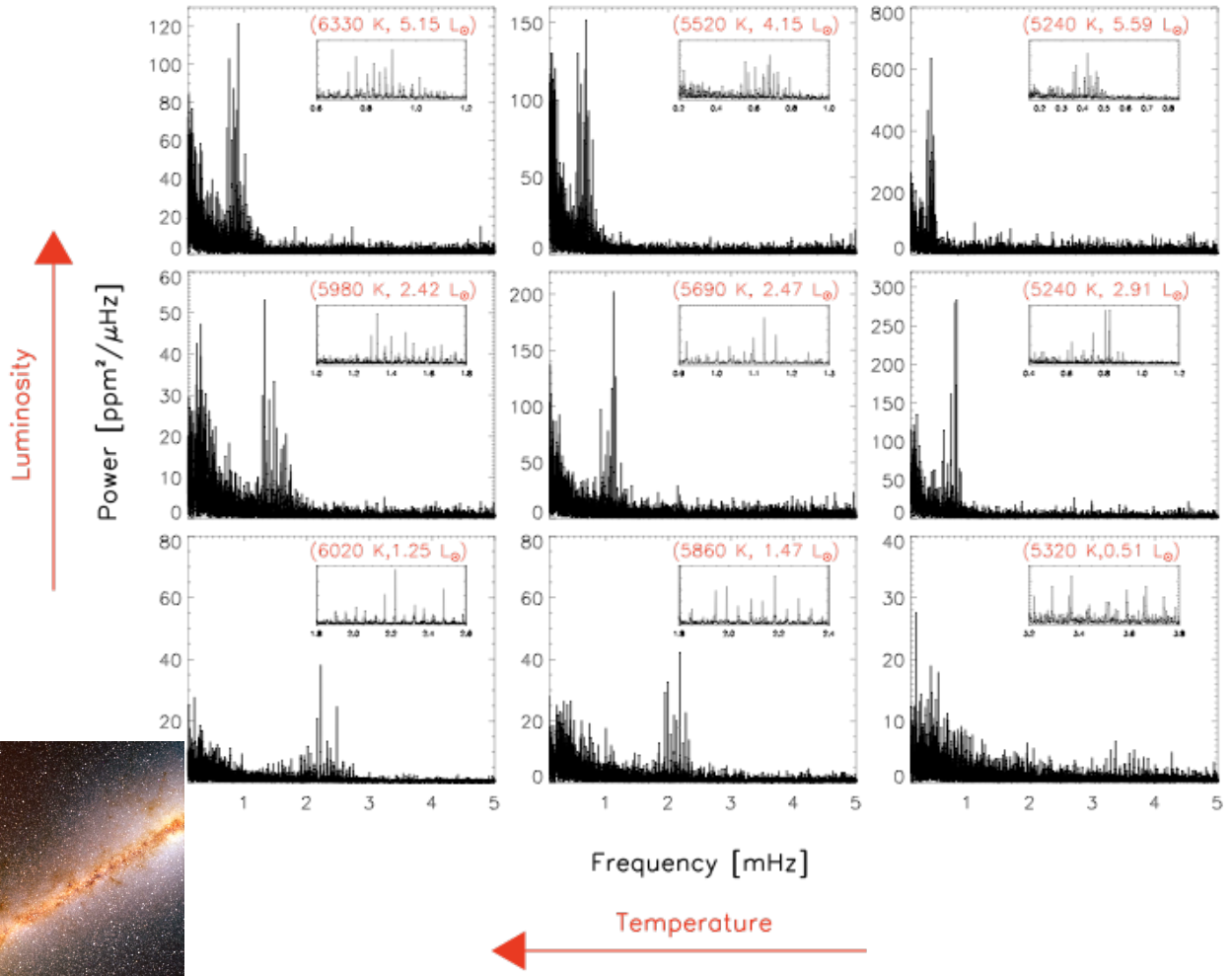
Why Do Stars Sing?

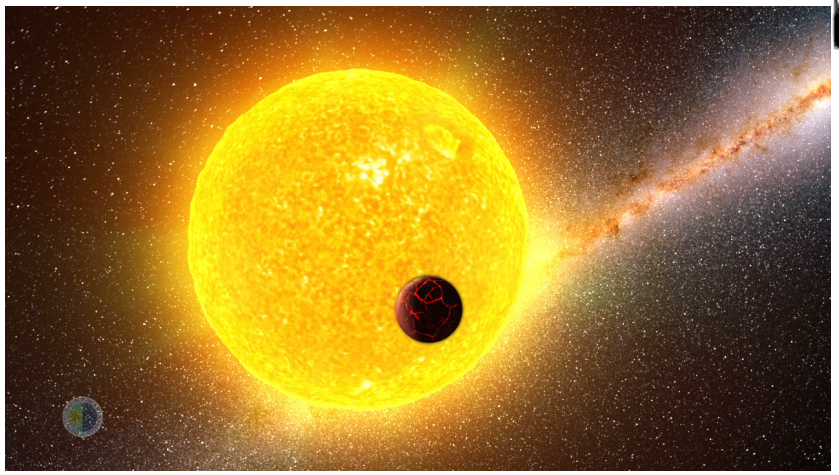
Kepler
A Search for Earth-size Planets

Stars are large resonant cavities that ring like bells

We've measured acoustic modes for >500 solar-like stars

Asteroseismology gives unprecedented precision in size, mass of stars

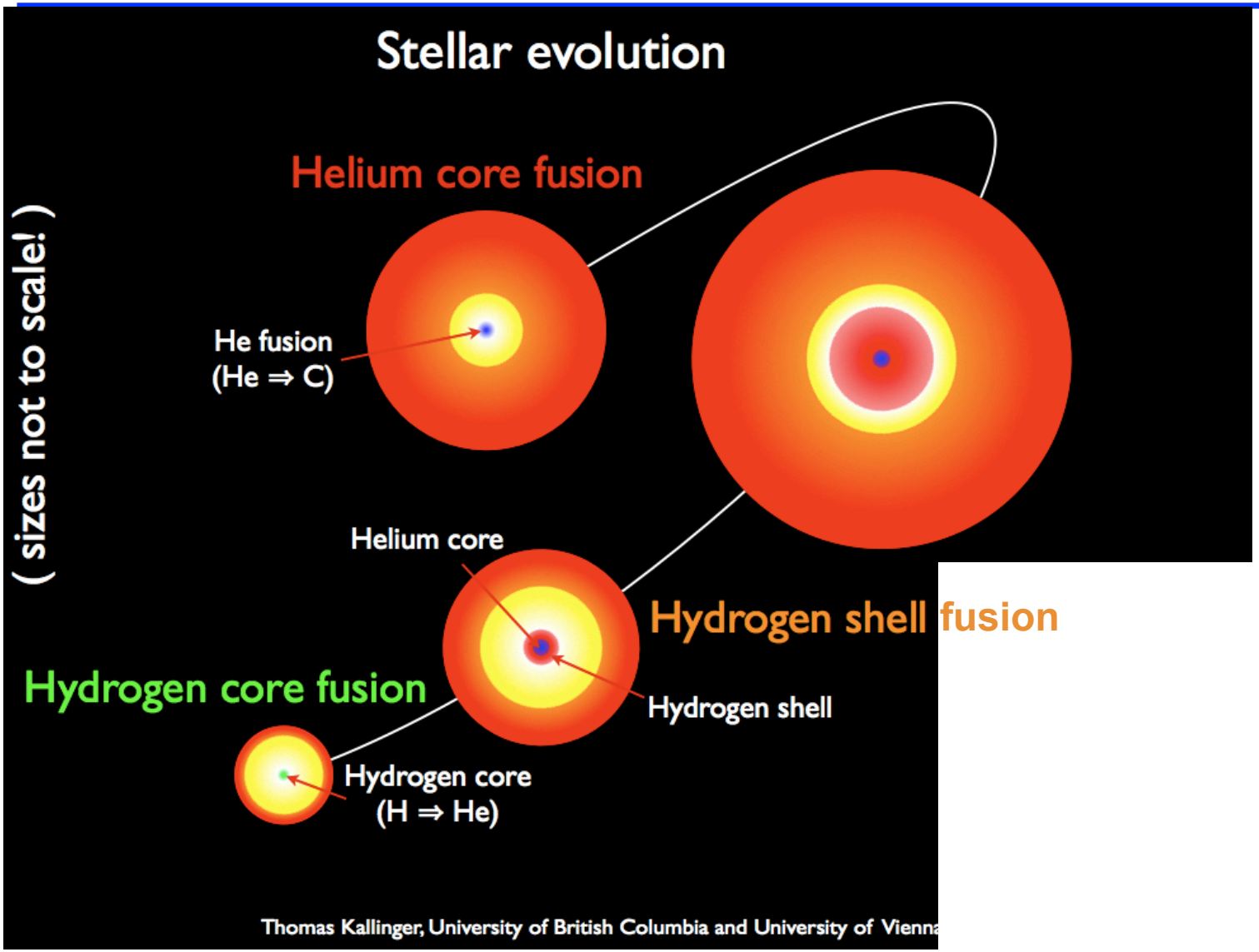




Chaplin et al 2011, Science.

Star Songs Tell the Deep Inside Story of the Stars

Kepler
A Search for Earth-size Planets

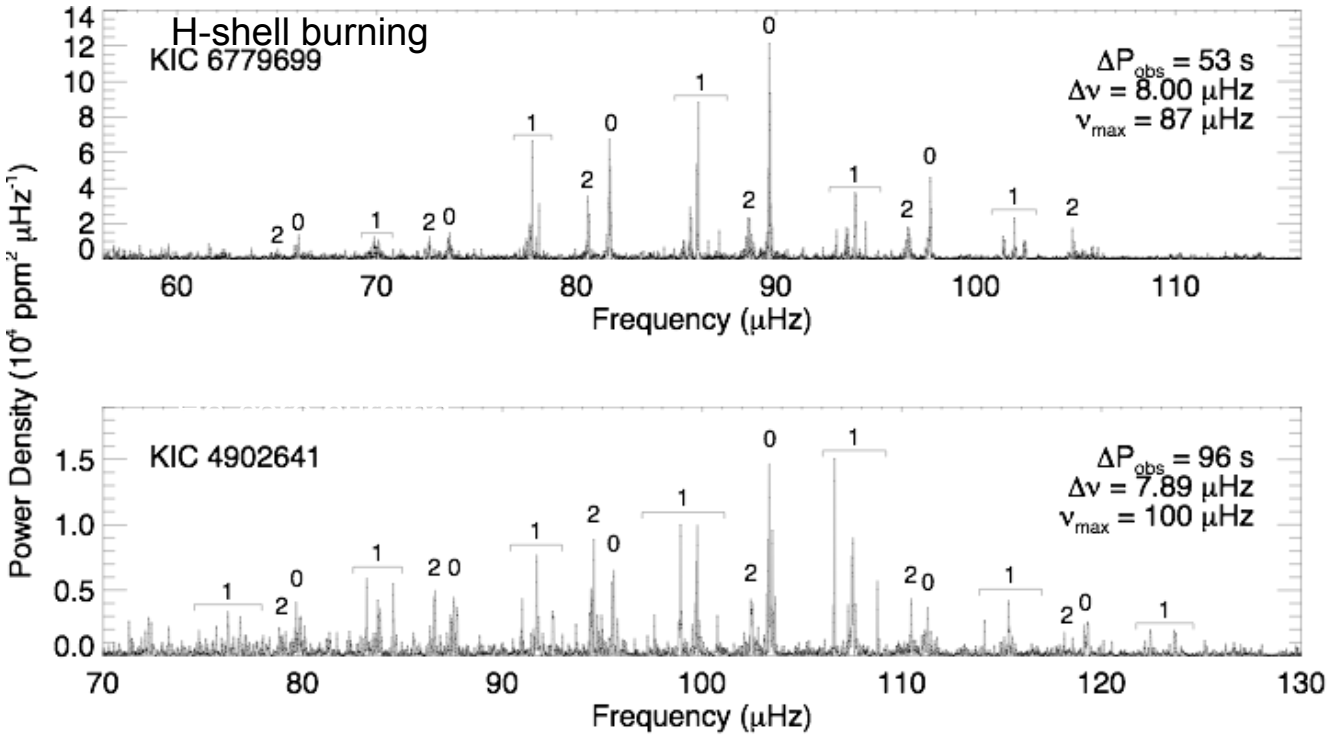


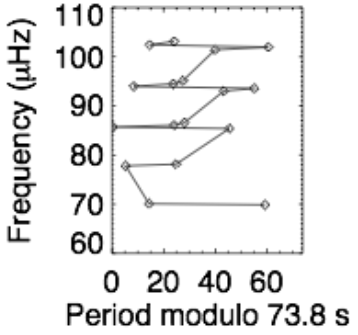
Contrasting H-Shell Burning, and He-Core Burning Red Giants.

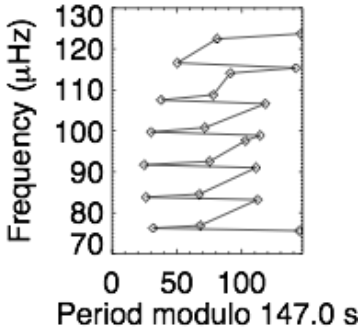
Kepler
A Search for Earth-size Planets

Power spectra.

Échelle diagrams.





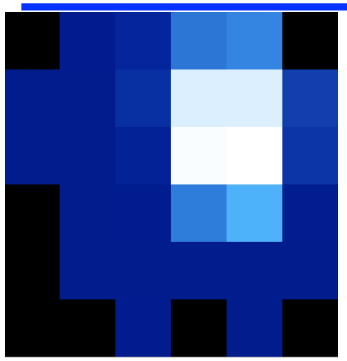


Bedding et al. 2011, Nature.

Correcting Systematic Errors

The *Kepler* Science Pipeline: From Pixels To Planets

Kepler
A Search for Earth-size Planets



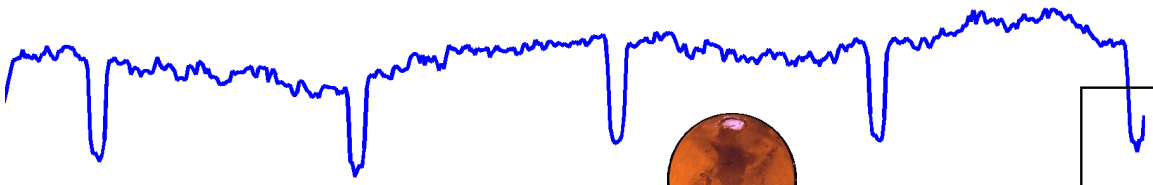
Raw Data

CAL
Pixel Level Calibrations

Calibrated Pixels

PA
Photometric Analysis

Sums Pixels Together/ Measures Star Locations



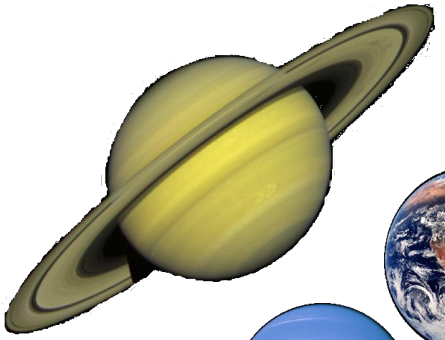
Raw Light Curves/ Centroids

Corrected Light Curves

PDC
Presearch Data Conditioning

Removes Systematic Errors

TPS
Transiting Planet Search



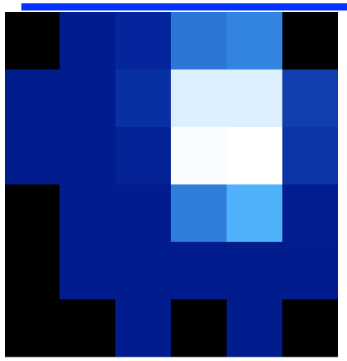
TCEs:
Threshold Crossing Events

DV
Data Validation

Diagnostic Metrics

Step 1: Calibrating Pixels

Kepler
A Search for Earth-size Planets



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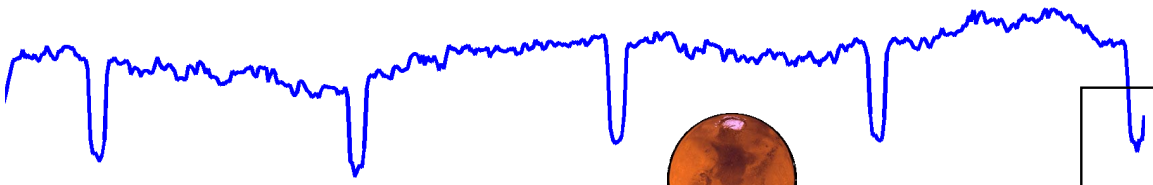

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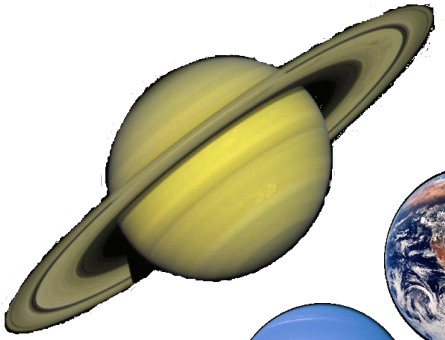

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Step 2: Photometric Analysis

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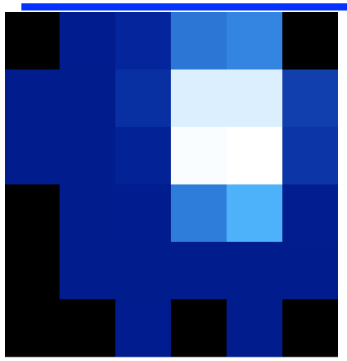

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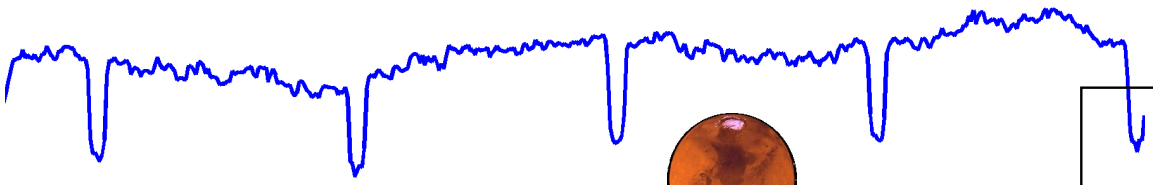

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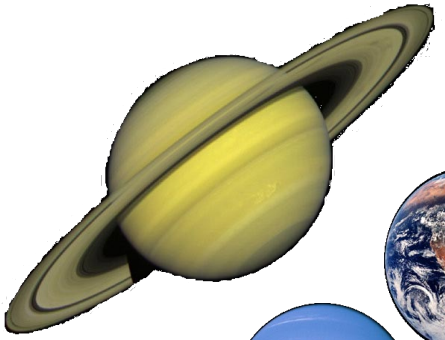

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Threshold Crossing Events

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Step 3: Removing Systematic Errors

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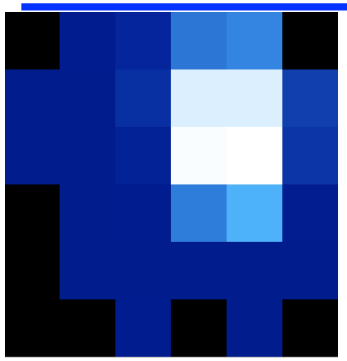

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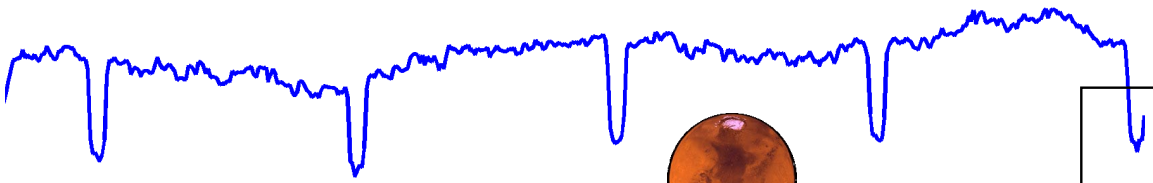

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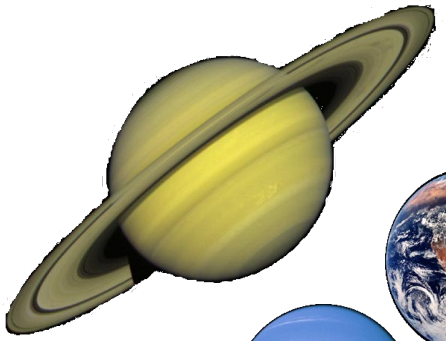
Transiting Planet Search



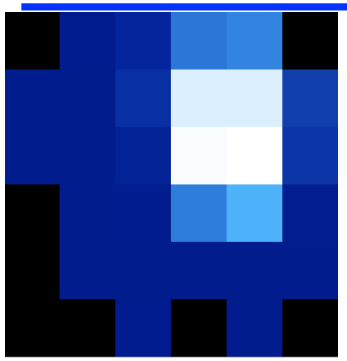
TCEs:
Threshold Crossing Events

DV
Data Validation

Diagnostic Metrics

Step 4: Searching for Planets

Kepler
A Search for Earth-size Planets



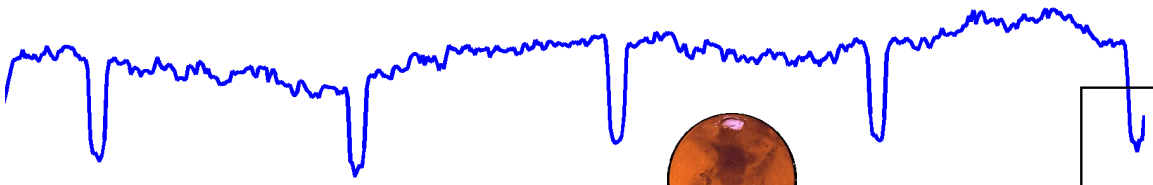
Raw Data

CAL
Pixel Level Calibrations

Calibrated Pixels

PA
Photometric Analysis

Sums Pixels Together/ Measures Star Locations



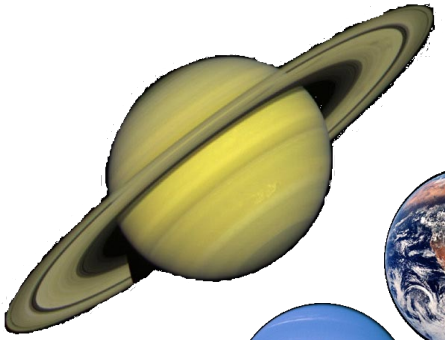
Raw Light Curves/ Centroids

Corrected Light Curves

PDC
Presearch Data Conditioning

Removes Systematic Errors

TPS
Transiting Planet Search



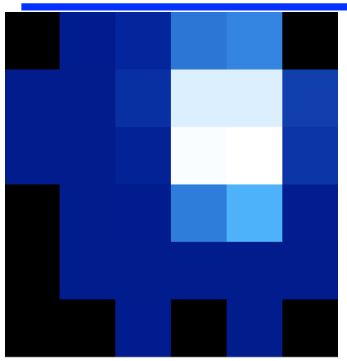
TCEs:
Threshold Crossing Events

DV
Data Validation

Diagnostic Metrics

Step 5: Validating Potential Planets

Kepler
A Search for Earth-size Planets



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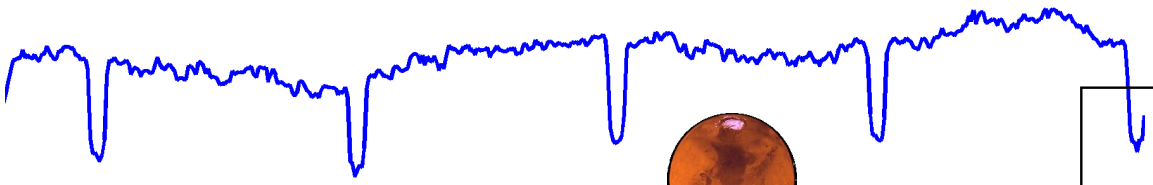

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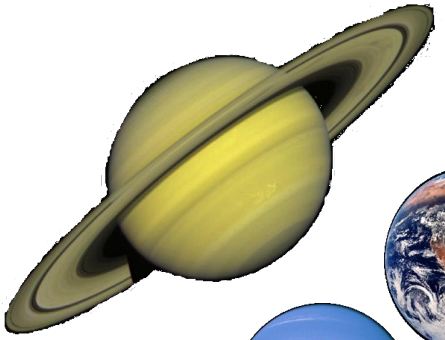

TCEs:
Threshold Crossing Events

DV
Data Validation

Diagnostic Metrics

Short Timescale Instrumental Errors

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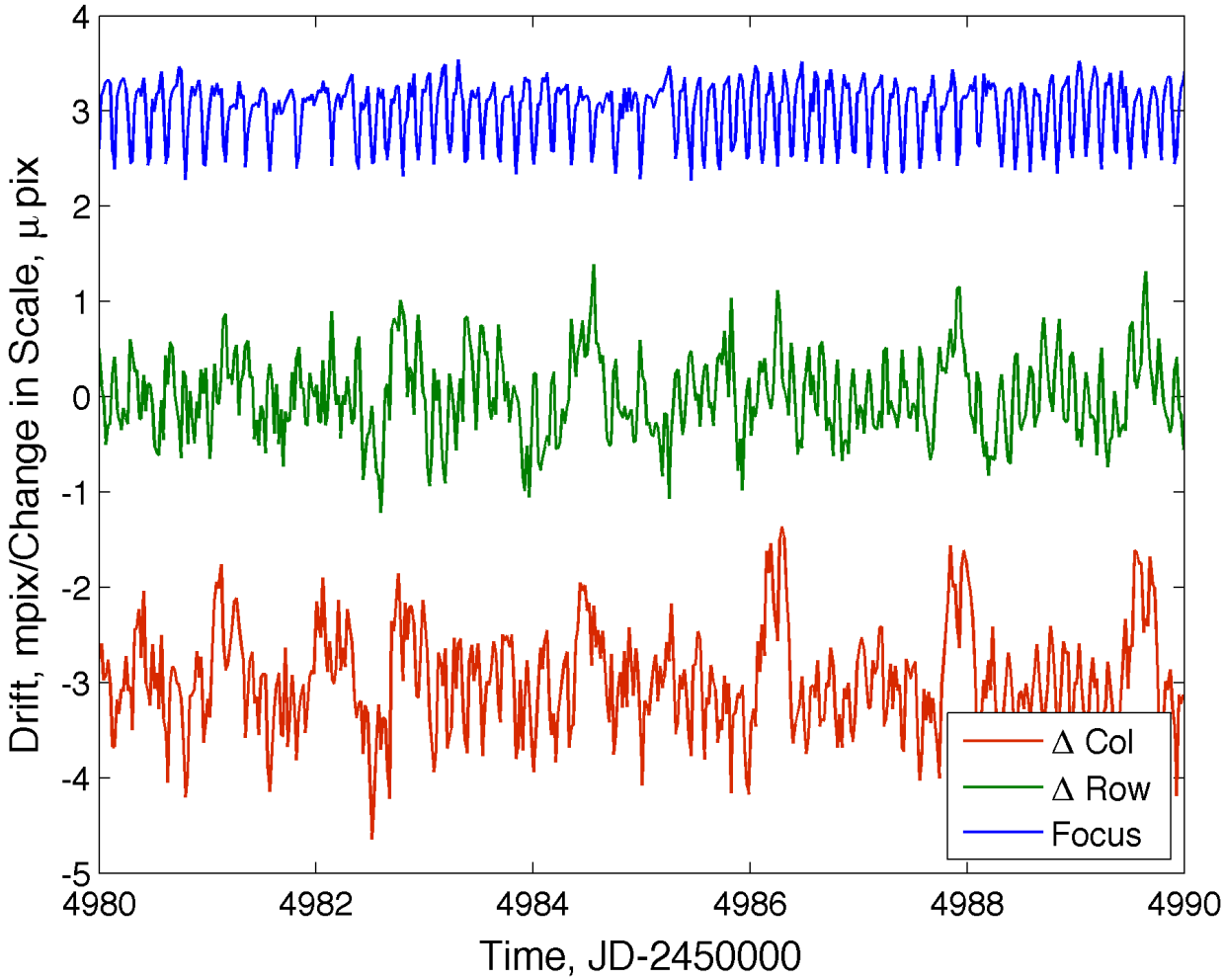
Signature of a heater cycling on the reaction wheels 3/4



***Kepler* is sensitive to its thermal environment**

Correcting Instrumental Effects

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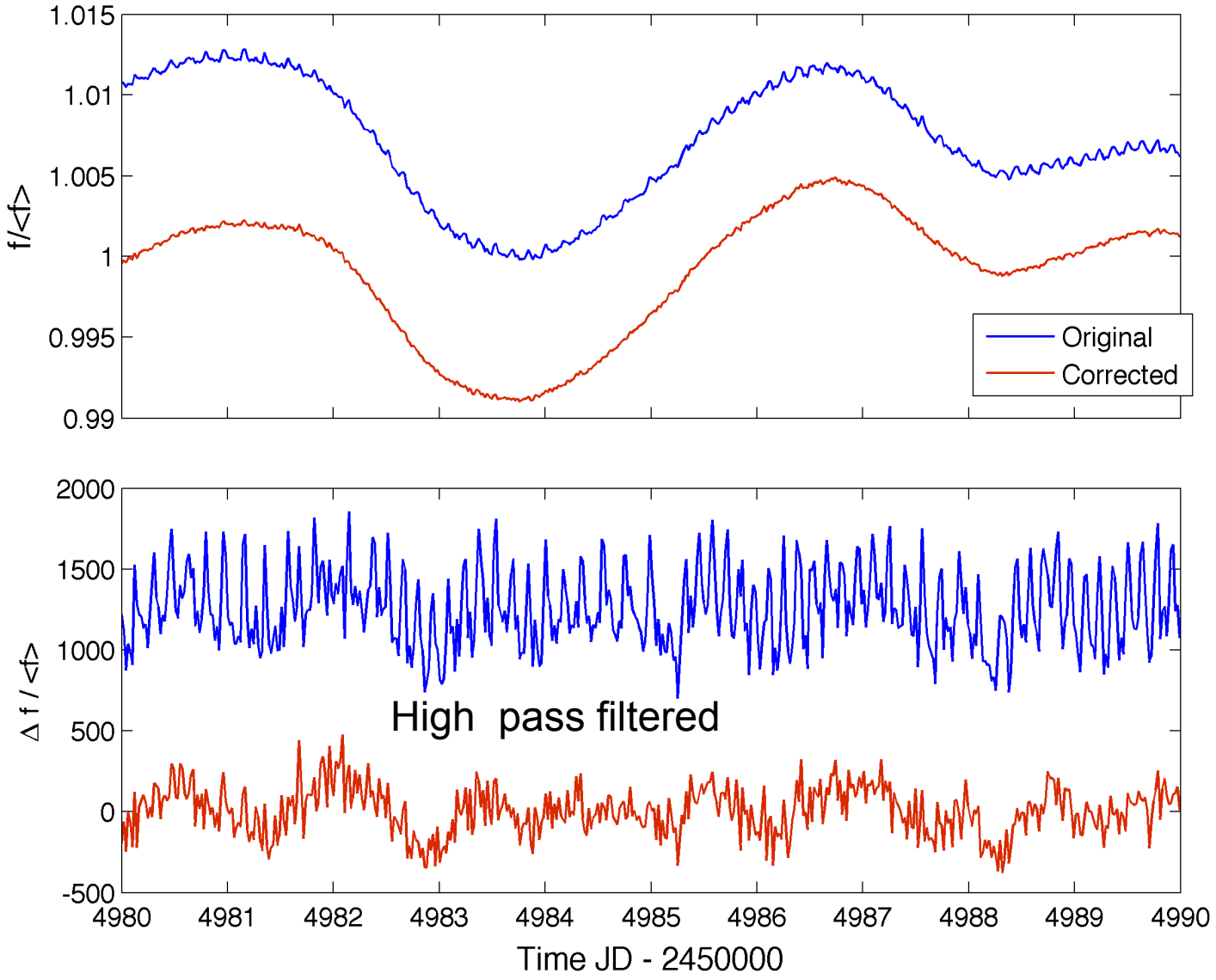
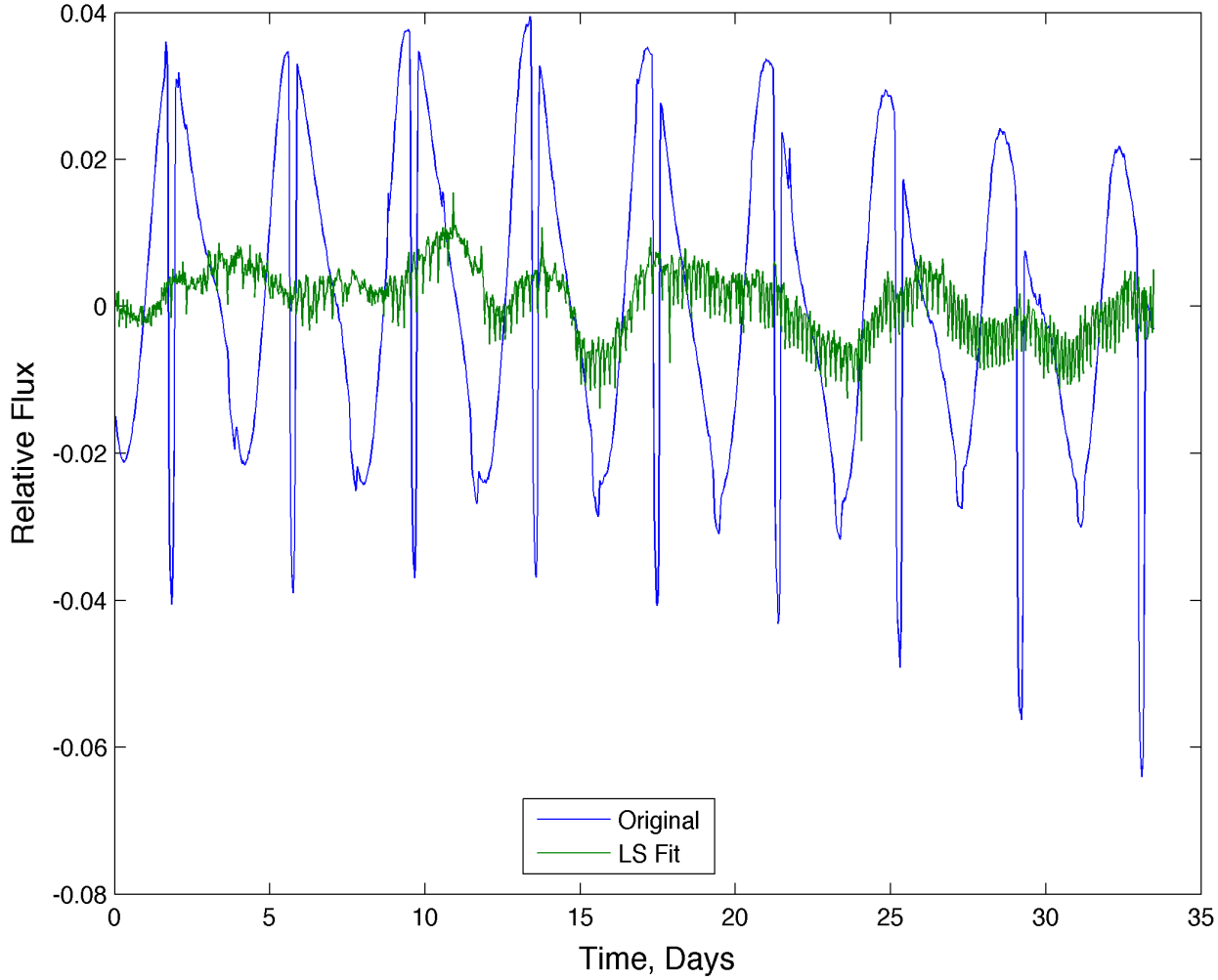
A Search for Earth-size Planets



PDC Often Over-Fits Variable Stars



A star fitted with systematics (green) extracted by SVD from 1400 “quiet” stars from Q1 on channel 2.1.

PDC Is Fundamentally Flawed

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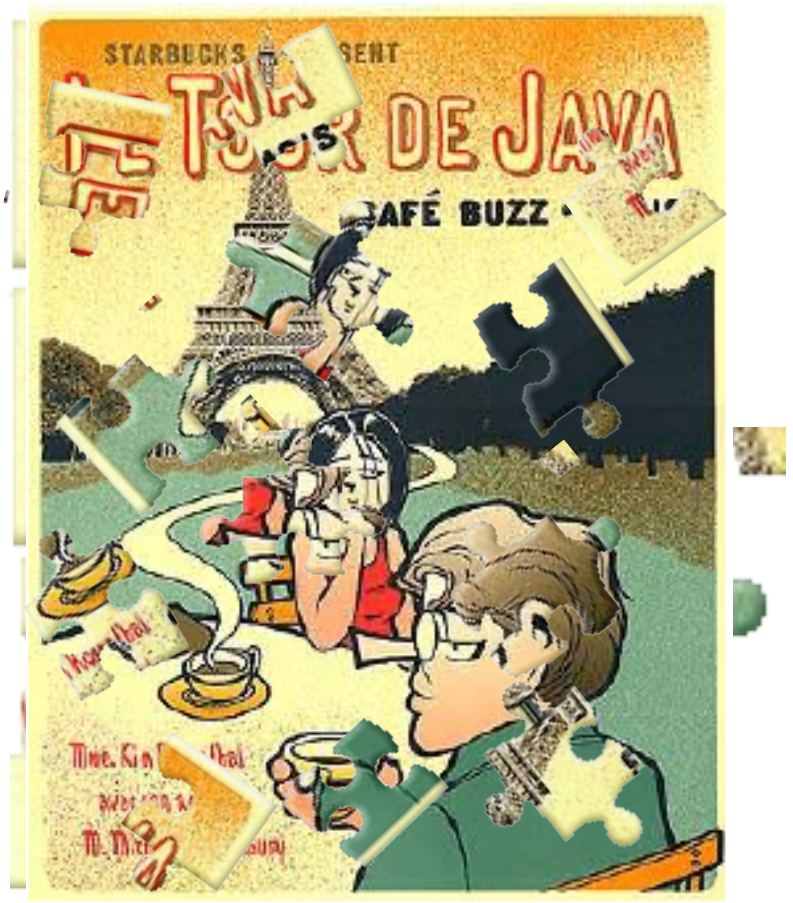
PDC co-trends against instrumental signatures using least squares (LS) approach

LS attempts to explain ***all*** of a given time series, not just the part the model can explain well

There is no way a simple LS fit can "put on the brakes"

PDC often trades bulk RMS for increased noise at short time scales



A Bayesian Solution

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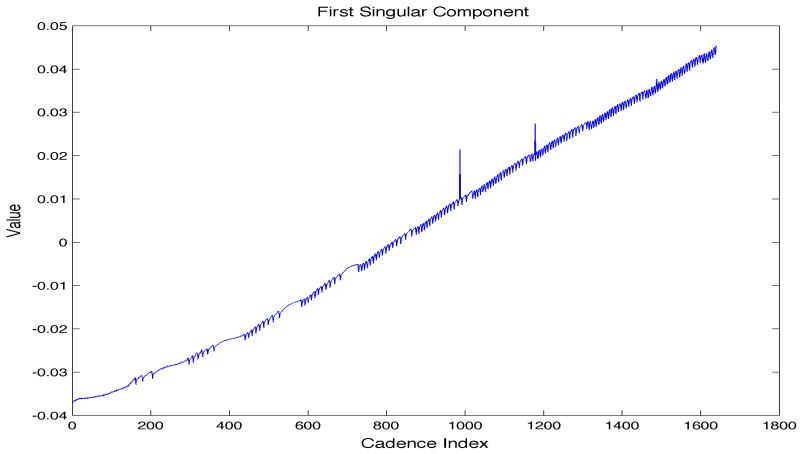
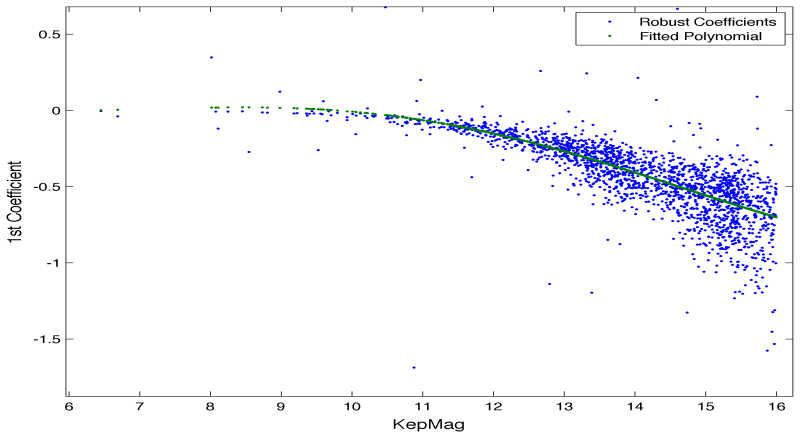
A Search for Earth-size Planets

- Examine behavior of ensemble of stars responding to systematics
- Formulate prior probability distributions for model coefficients
- Maximize Posterior Distribution:

$$\hat{\theta} = \arg\max_{\theta} \left\{ \log\left[p(x|c)\right] + \log\left[p(c)\right] \right\}$$

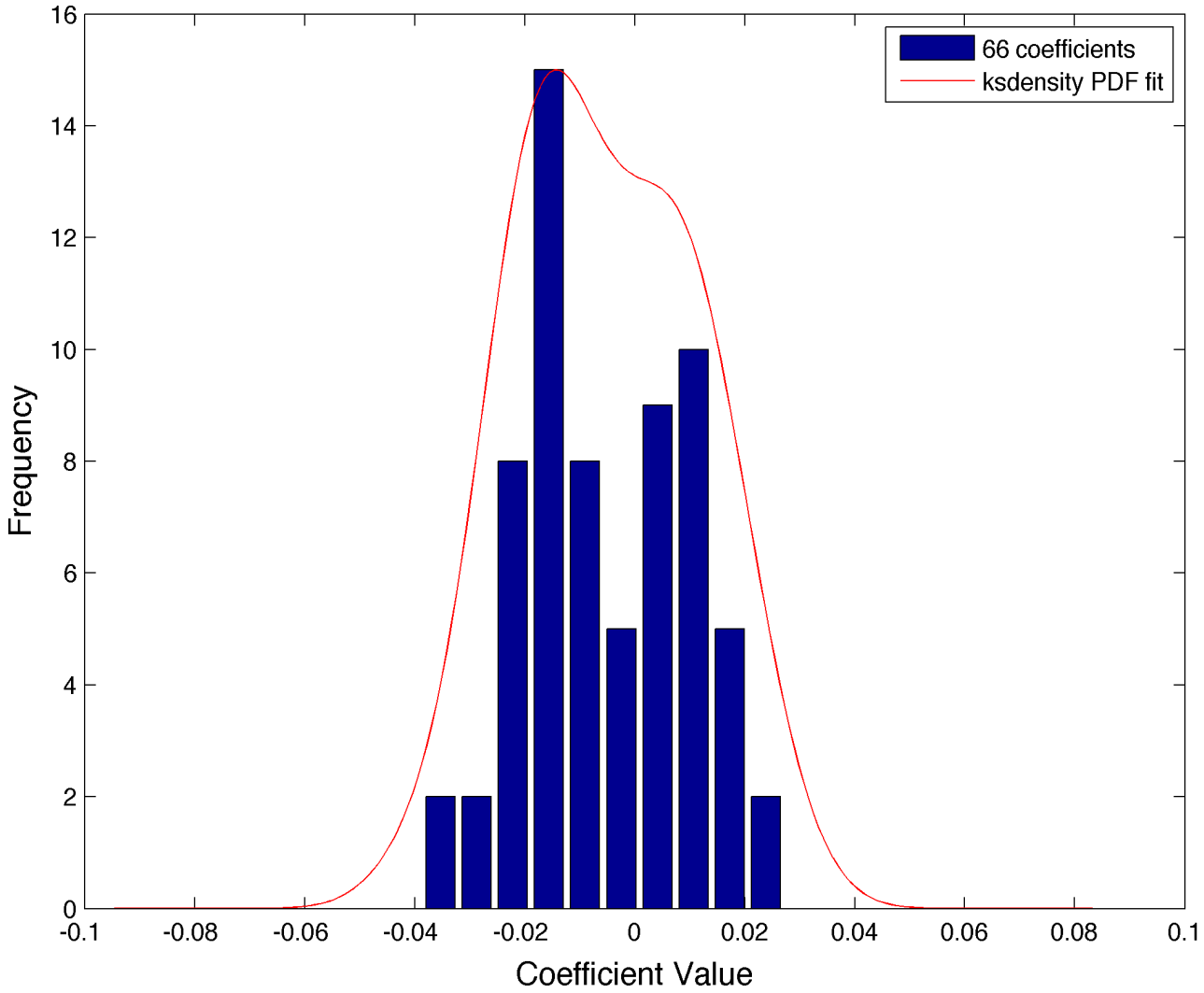
Maximum Likelihood Prior PDF





"A Bayesian is one who, vaguely expecting a horse, and catching a glimpse of a donkey, strongly believes he has seen a mule."

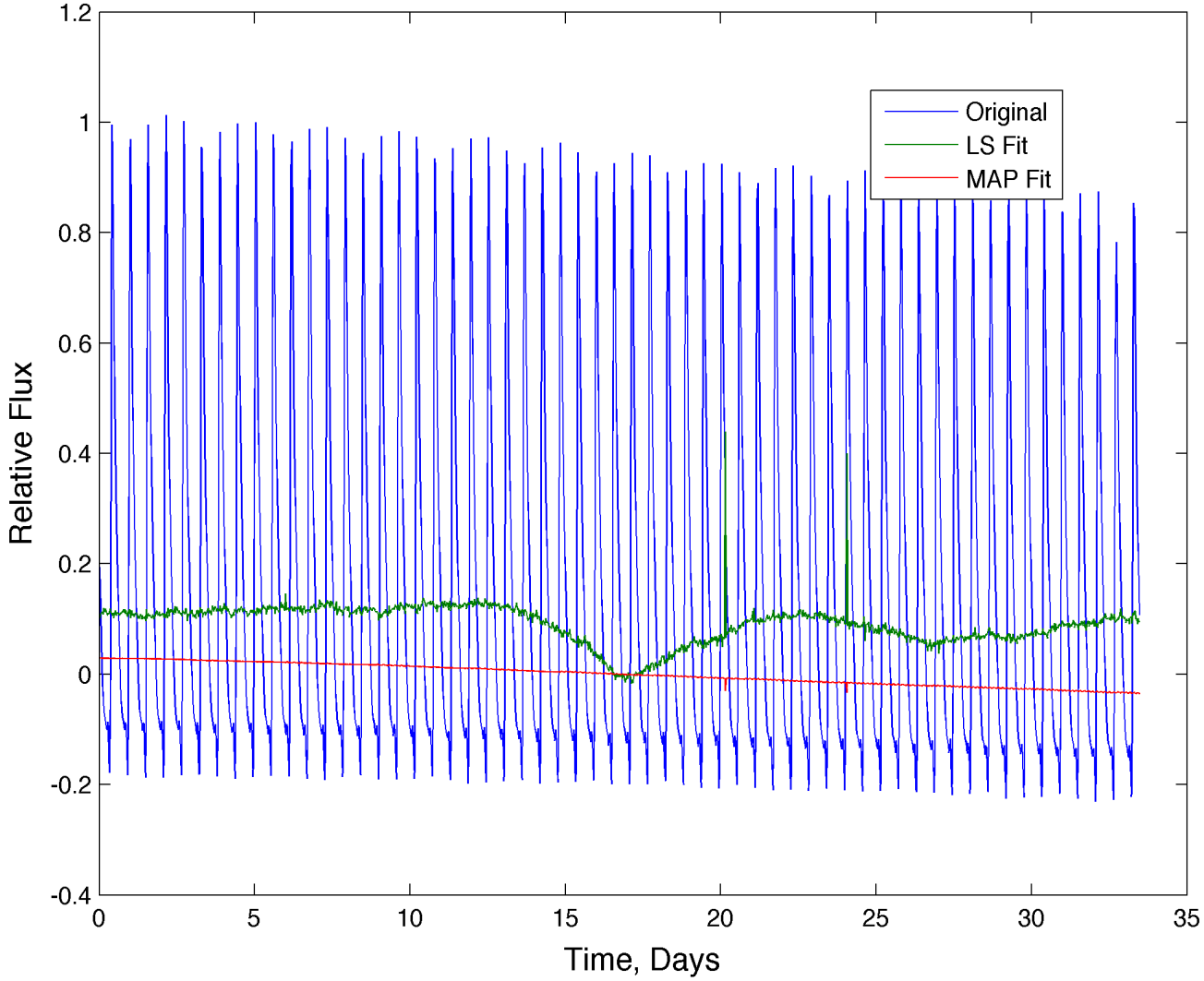
Actual PDFs Are Non-Gaussian



Example 1

Kepler
A Search for Earth-size Planets

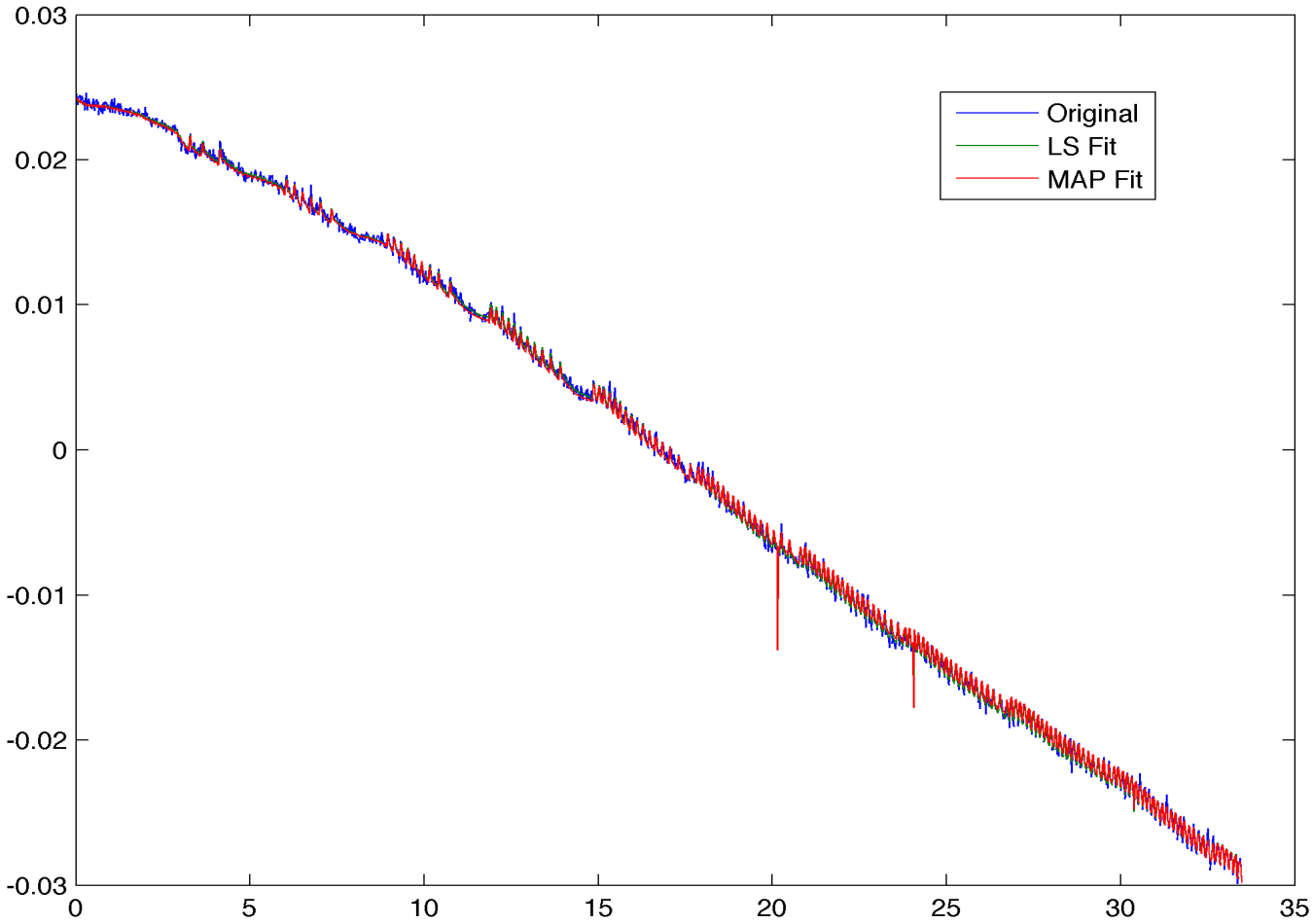
An RR Lyrae star that is treated poorly by robust LS, but is well-served by MAP



Example 2

A "quiet" star dominated by systematics.

The LS and the MAP fits are comparable.



PDC-MAP Example

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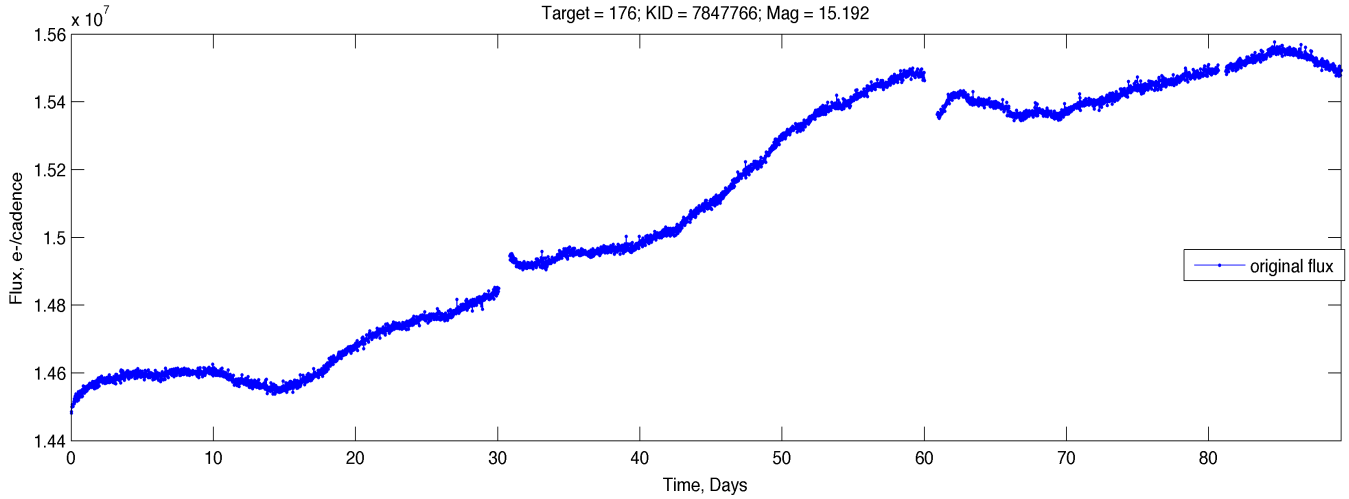
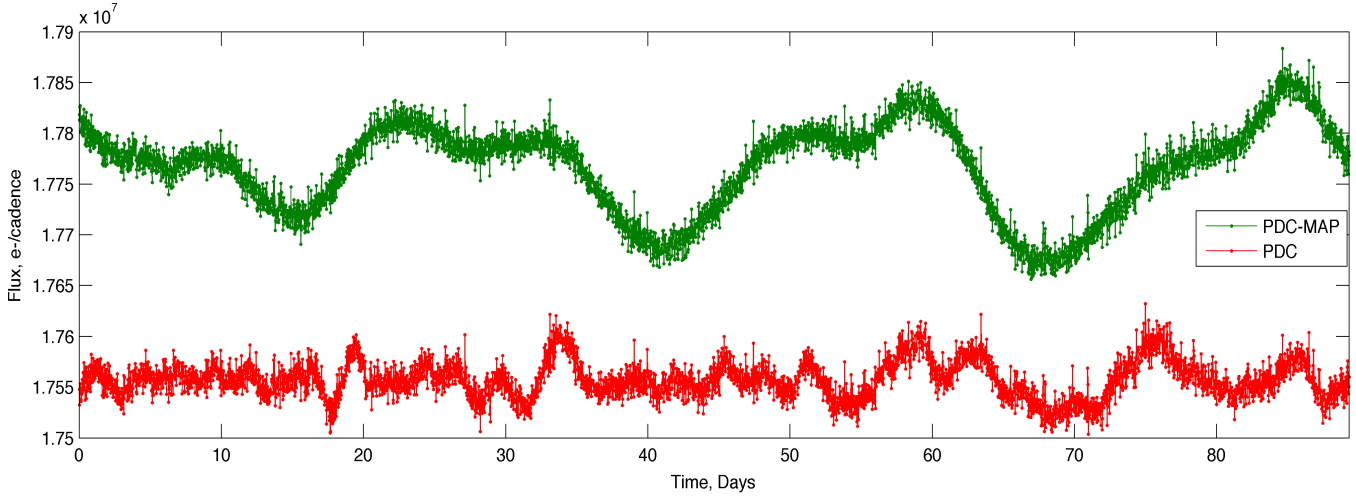
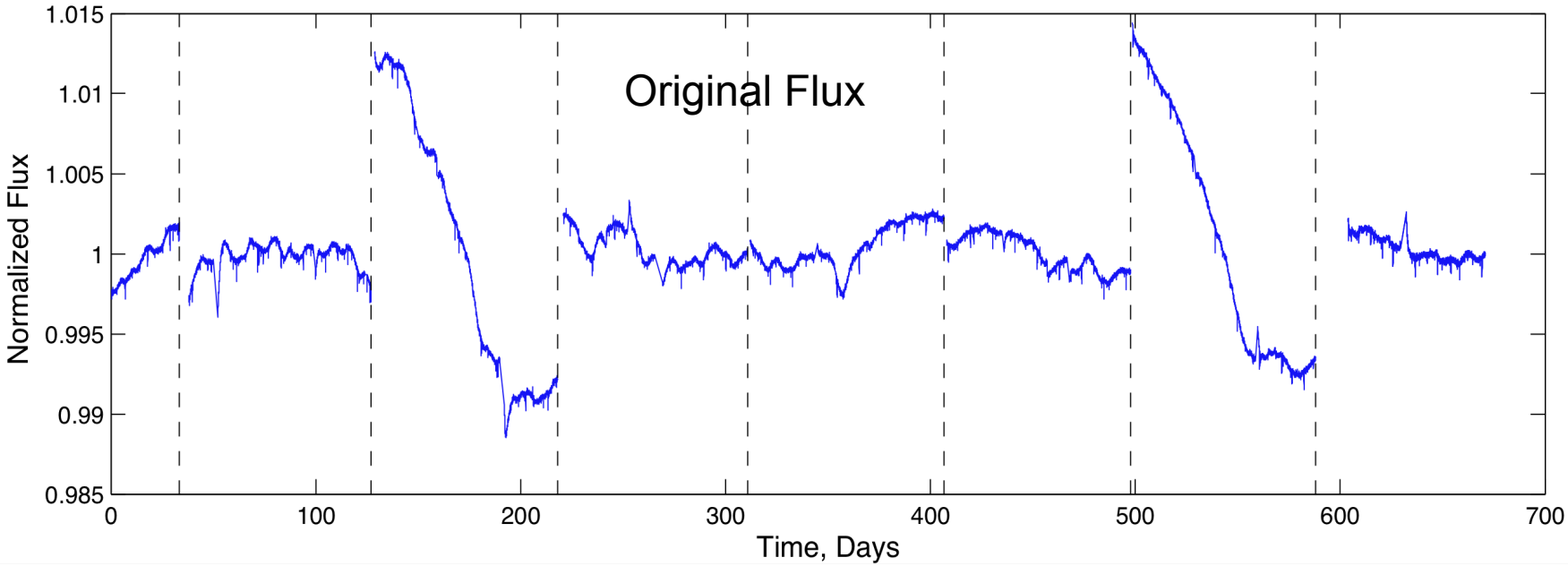




SIGNIFICANT PROGRESS IN DEALING WITH SYSTEMATIC EFFECTS

Kepler
A Search for Earth-size Planets

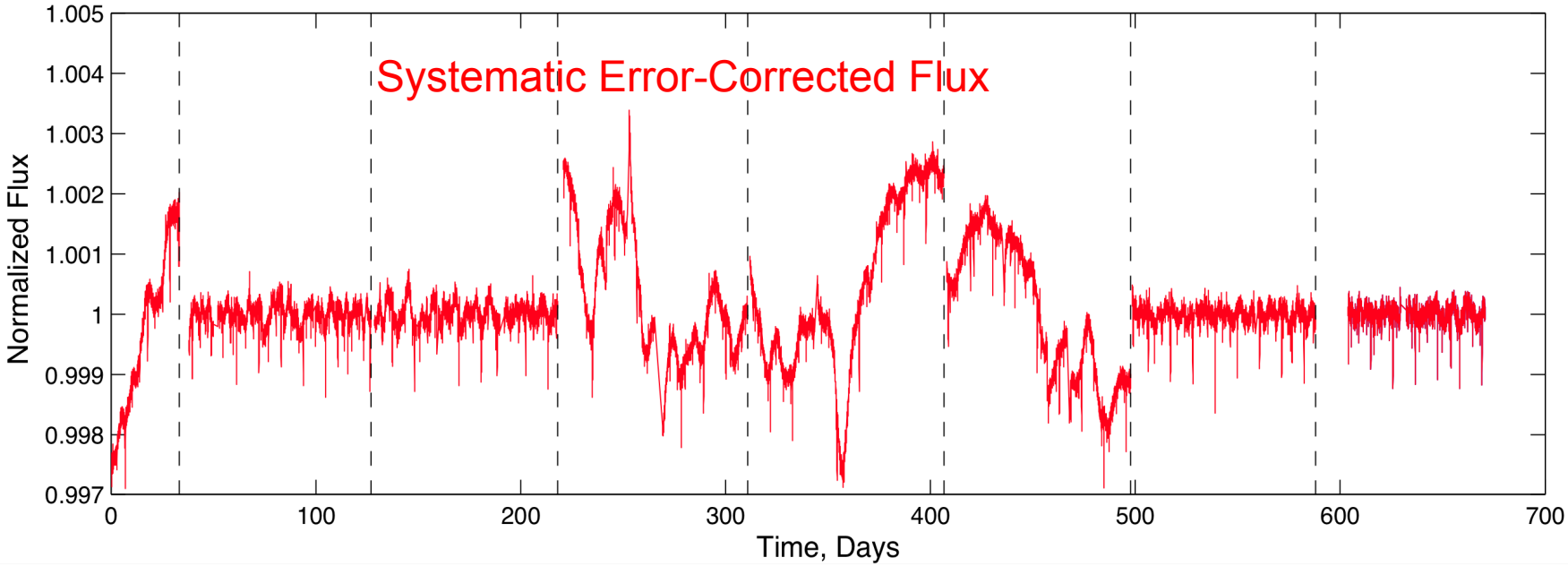


The *Kepler* photometer is extremely sensitive and responds to the changing thermal environment

The systematic effects observed in the raw light curve are much greater than the transit signatures of the 5 planetary candidates therein (Kepler-20)

SIGNIFICANT PROGRESS IN DEALING WITH SYSTEMATIC EFFECTS

Kepler
A Search for Earth-size Planets

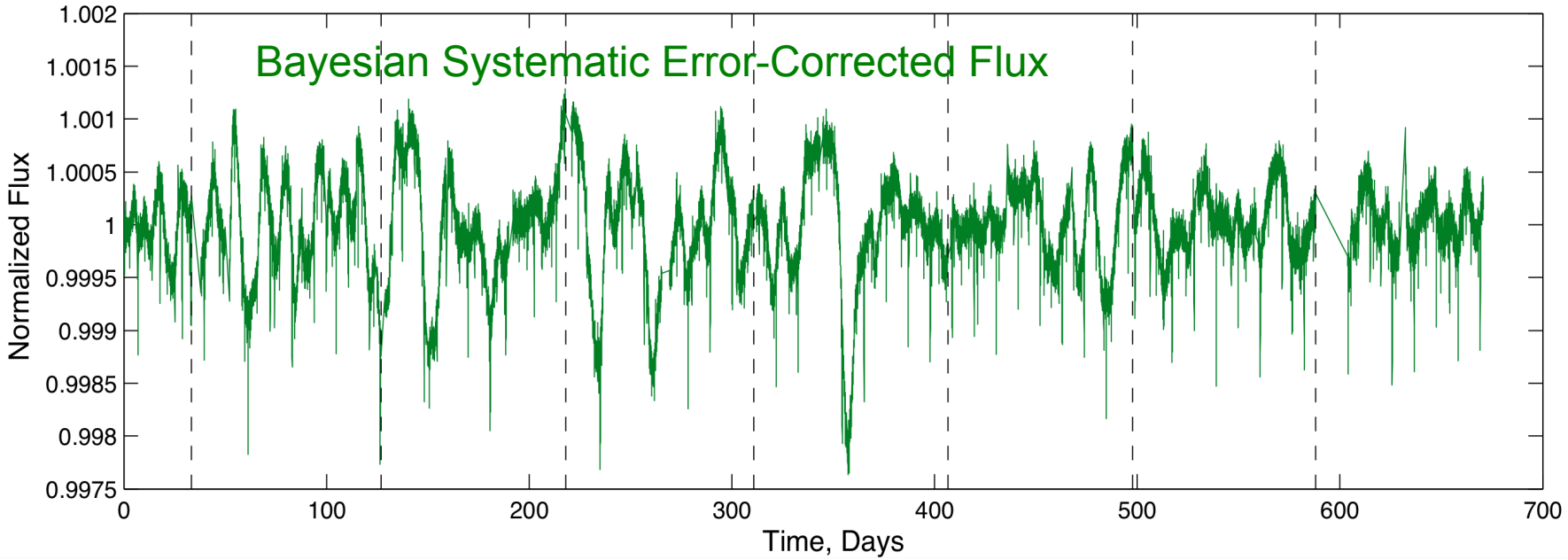


Original systematic error correction performance was inconsistent:

- Often removed/distorted astrophysical signatures
- Often introduced noise, making transit detection more difficult

SIGNIFICANT PROGRESS IN DEALING WITH SYSTEMATIC EFFECTS

Kepler
A Search for Earth-size Planets



New Bayesian systematic error correction performance

- Preserves astrophysical signatures in almost all cases
- Time series are better conditioned for transit search
- Noise on transit timescales is reduced by ~15%

Stellar Variability

Excess Stellar Variability

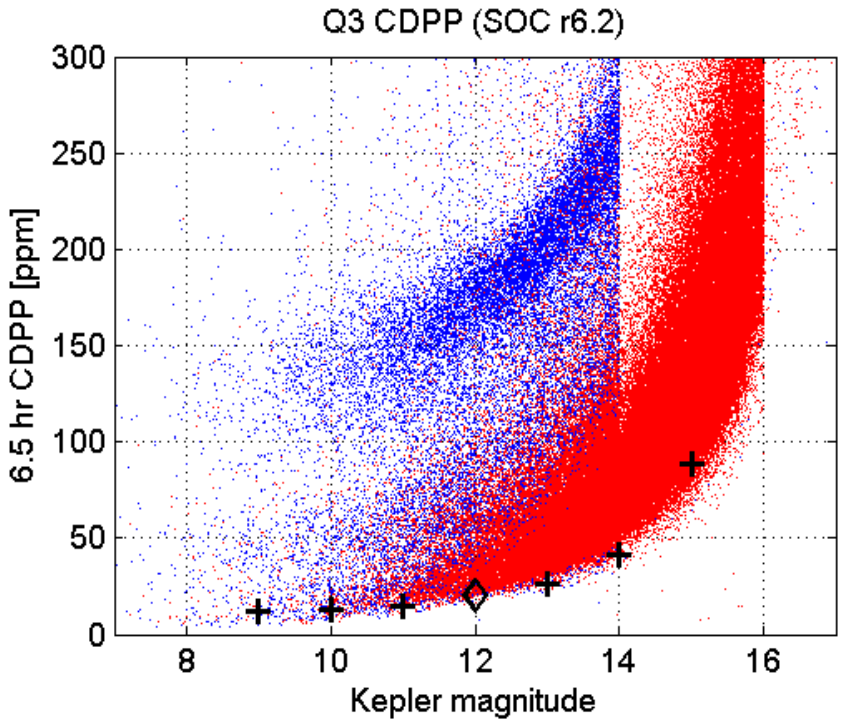
Kepler
A Search for Earth-size Planets

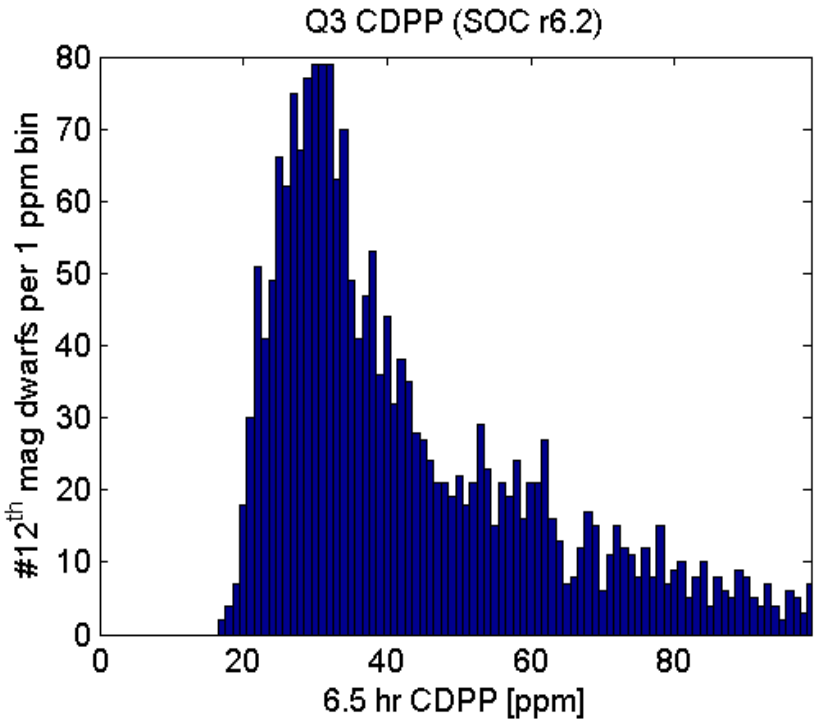
Original Noise Budget (Kp=12):
- 14 ppm Shot Noise
- 10 ppm Instrument Noise
- 10 ppm Stellar Variability

=> 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





Intrinsic Stellar Noise of 12th Magnitude Dwarfs

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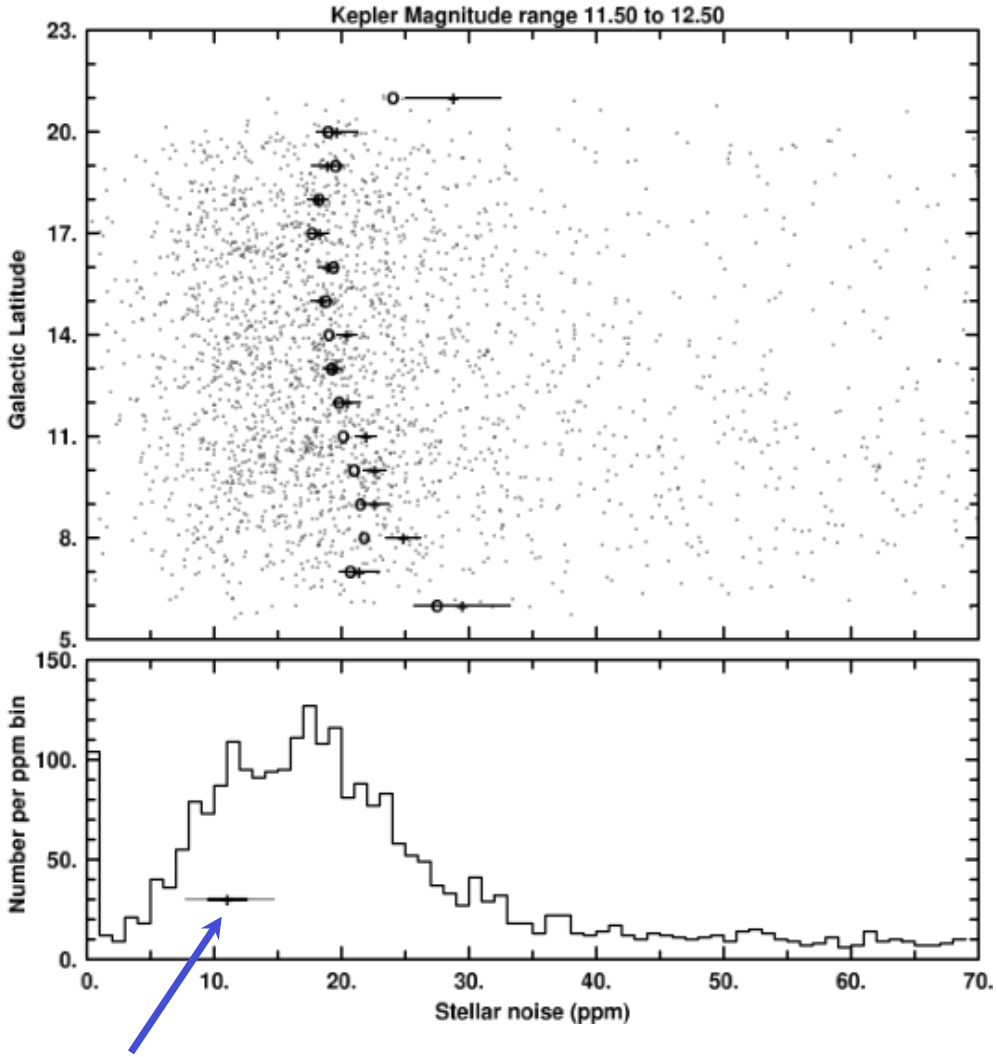


Range of solar variability

After applying a process to separate stellar, fundamental and instrument terms:

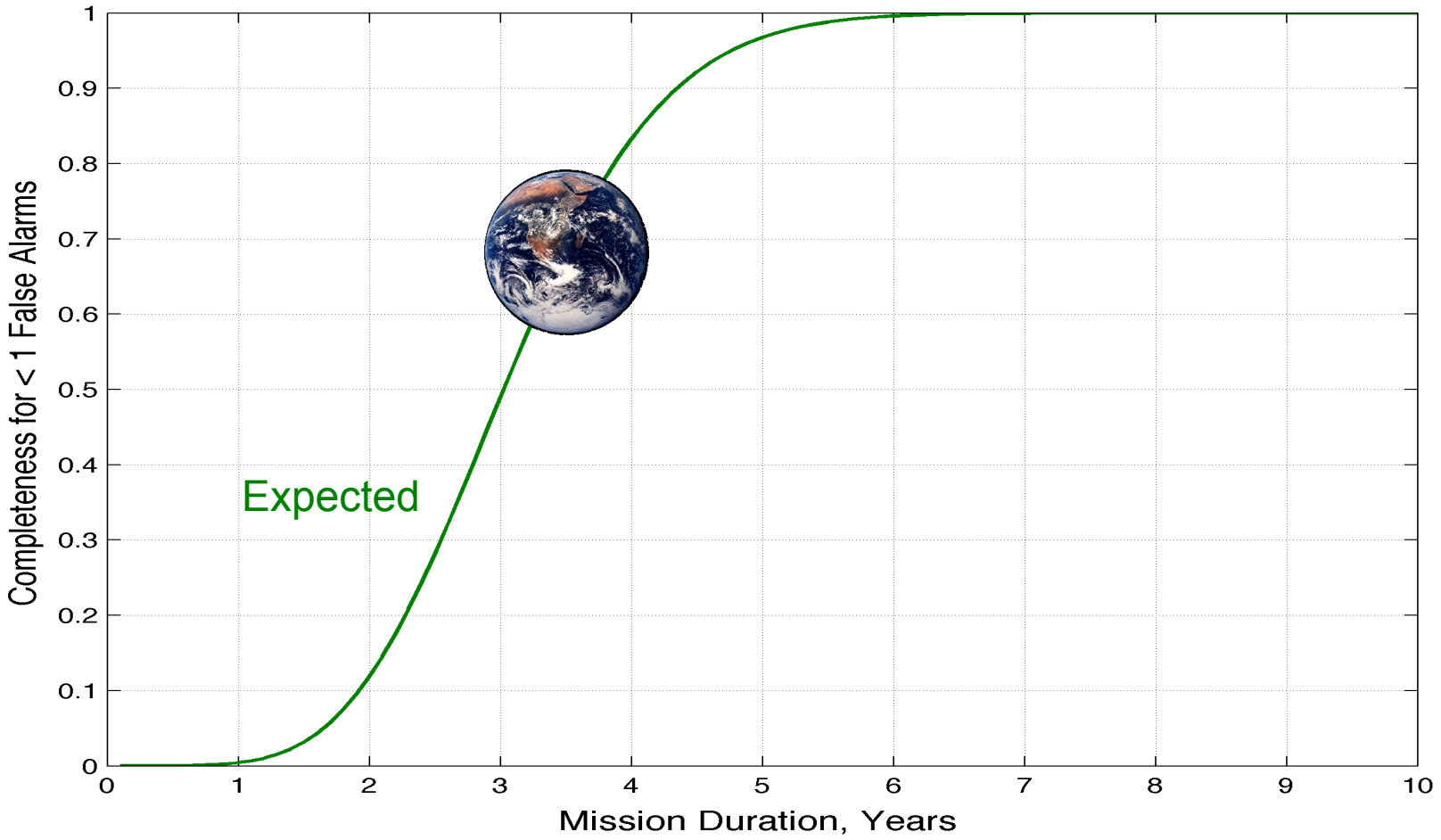
Majority of solar-type stars within Kepler FOV are significantly noisier than the Sun with global measure about X2 solar.

This has been reconciled with a galactic synthesis model for stellar parameter distribution coupled with projections for granulation and activity related noise terms.

Gilliland et al. 2011

Completeness Vs. Time

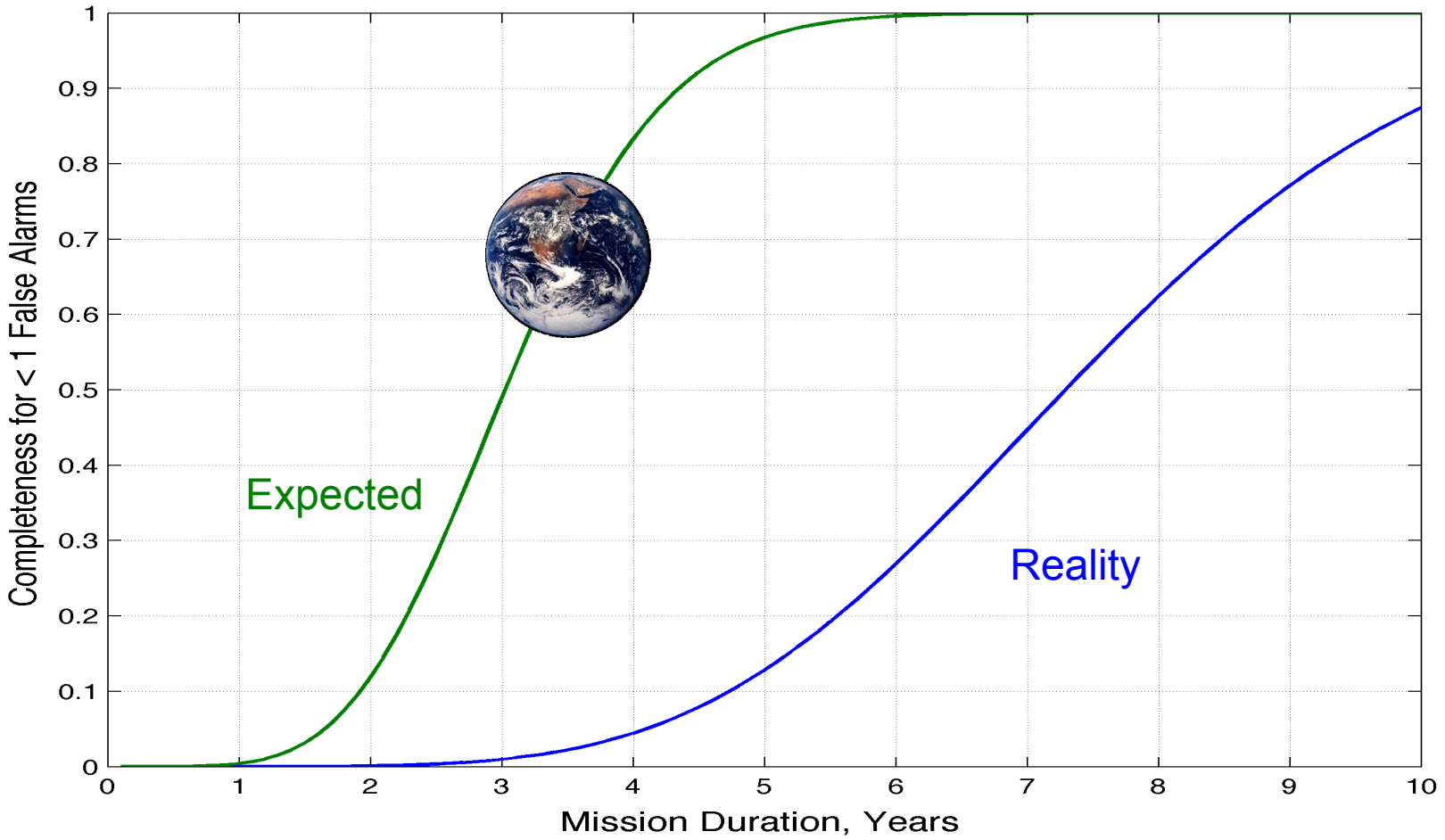
Kepler
A Search for Earth-size Planets



Original expectations yielded ~60% completeness for Earth analogs at 3.5 years

Completeness Vs. Time

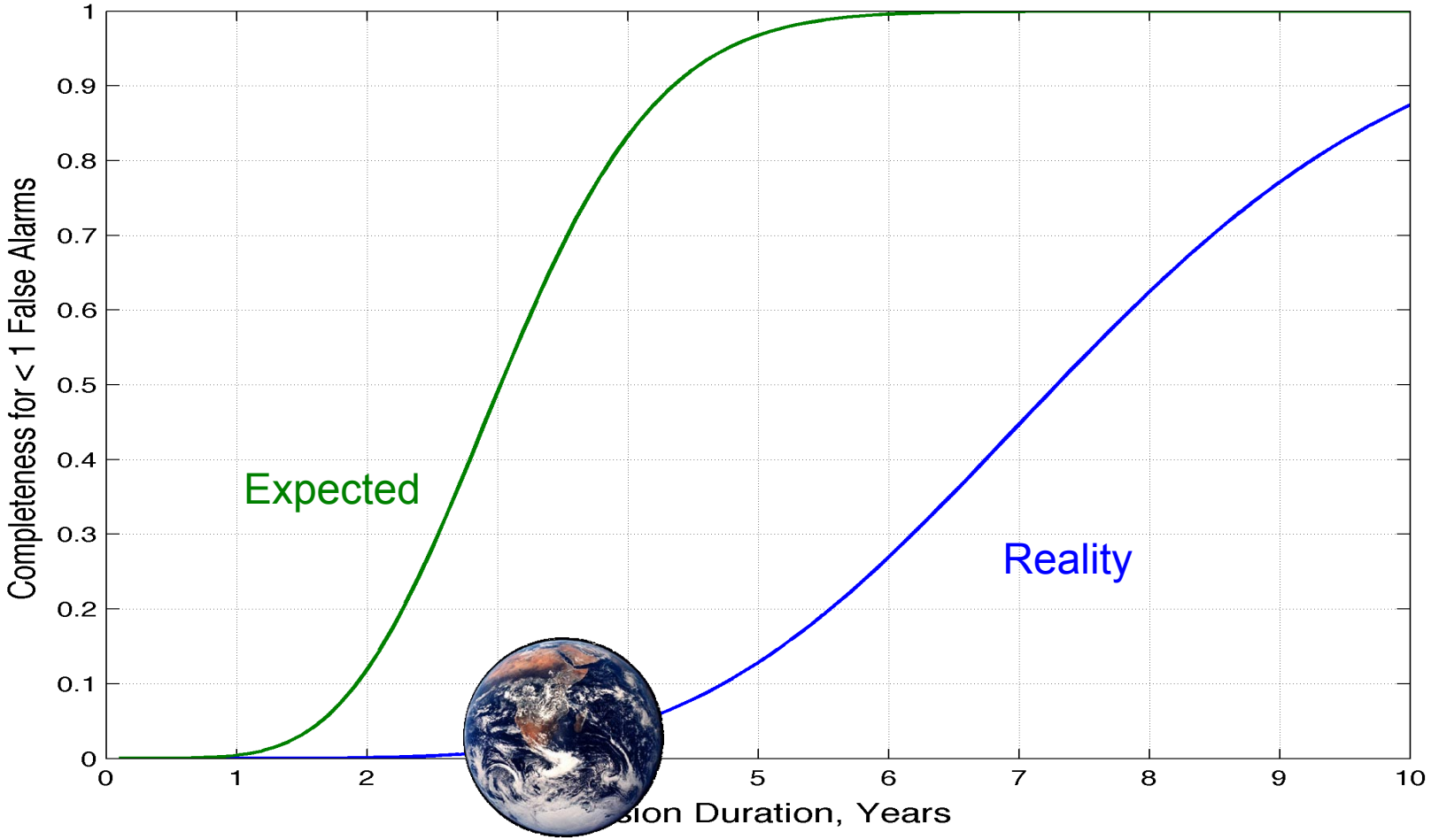
Kepler
A Search for Earth-size Planets



Current expectations yield ~2% completeness for Earth analogs at 3.5 years

Completeness Vs. Time

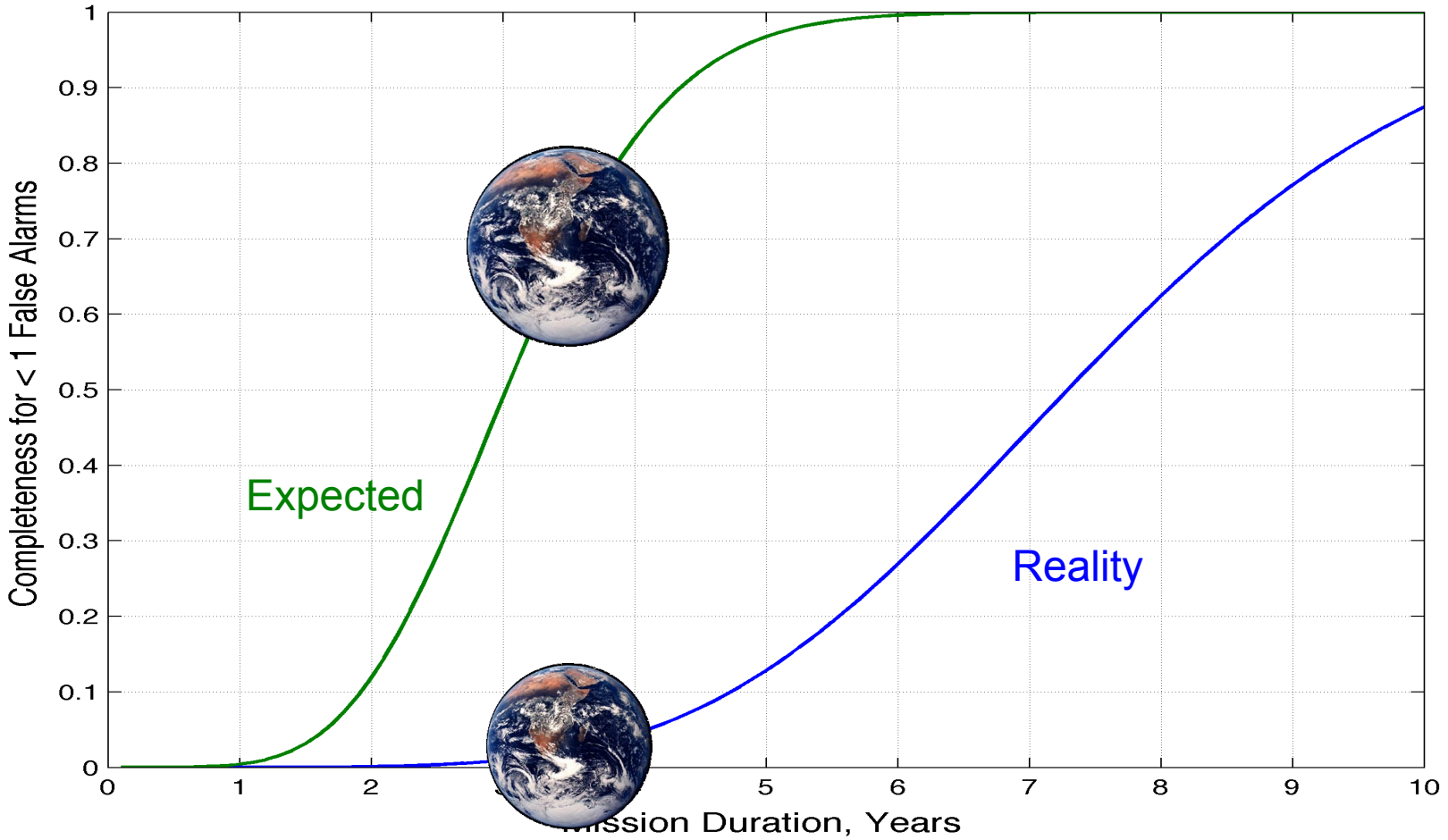
Kepler
A Search for Earth-size Planets



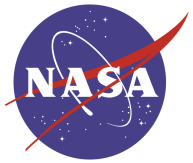
~60% completeness for 1.2-R_e planets in same orbits at 3.5 years

Completeness Vs. Time

Kepler
A Search for Earth-size Planets



Kepler will recover ~60% completeness for Earth analogs after 8 years



Summary

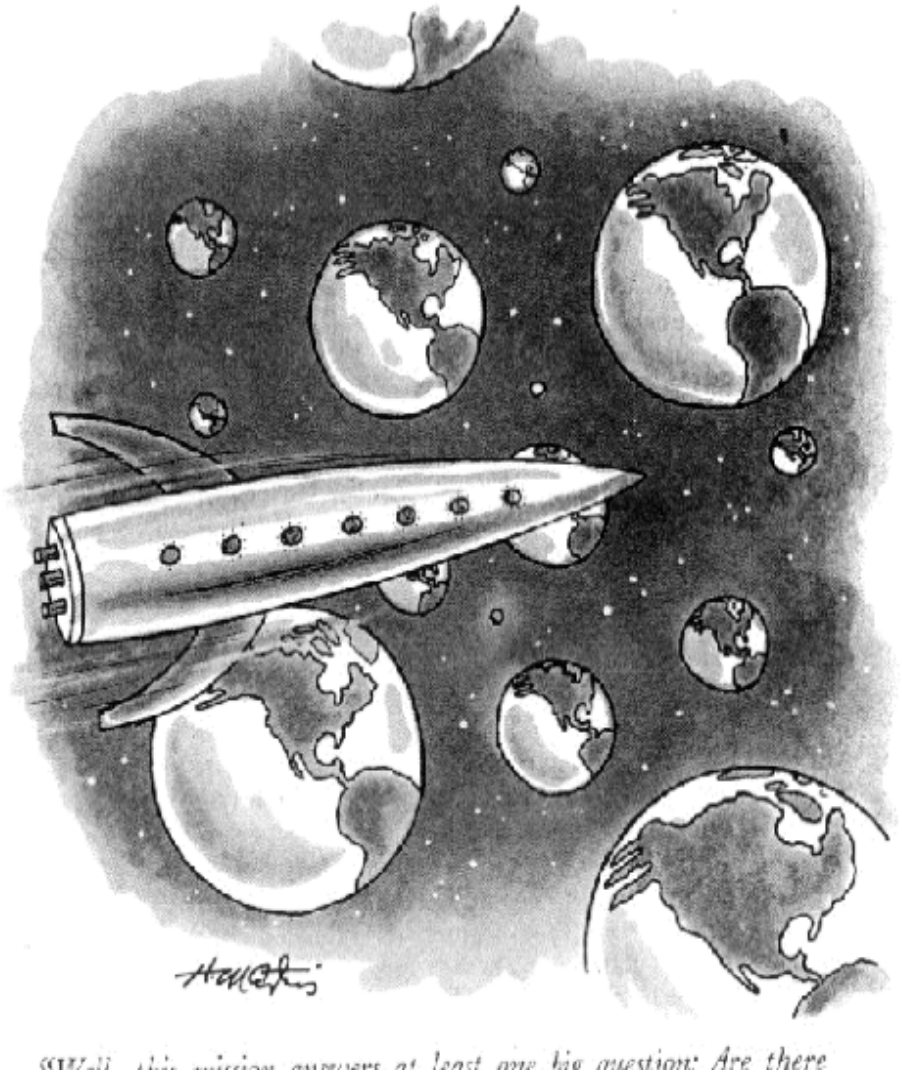
Kepler
A Search for Earth-size Planets

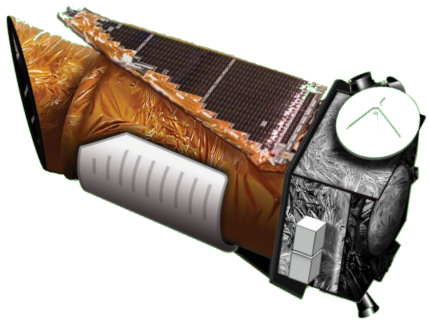
- *Kepler* has initiated an explosion of exoplanet research, effectively tripling the number of known exoplanets
- There are an astonishing number of multiple planet systems and these are remarkably coplanar – like the solar system
- *Kepler* asteroseismology has led to major breakthroughs: (1) for dwarfs many precision applications and ensemble comparisons enabled, (2) the finding of, and outline of how to interpret g-, or mixed-modes in red giants
- *Kepler* has provided a first glimpse of stellar variability for solar-type stars at levels relevant to the Sun: many stars are quieter than the Sun, but majority are noisier
- An extended mission of 8 years will compensate for higher than expected stellar variability on transit time scales

- **We're just getting started: hold on to your hats!**

The Future!?!

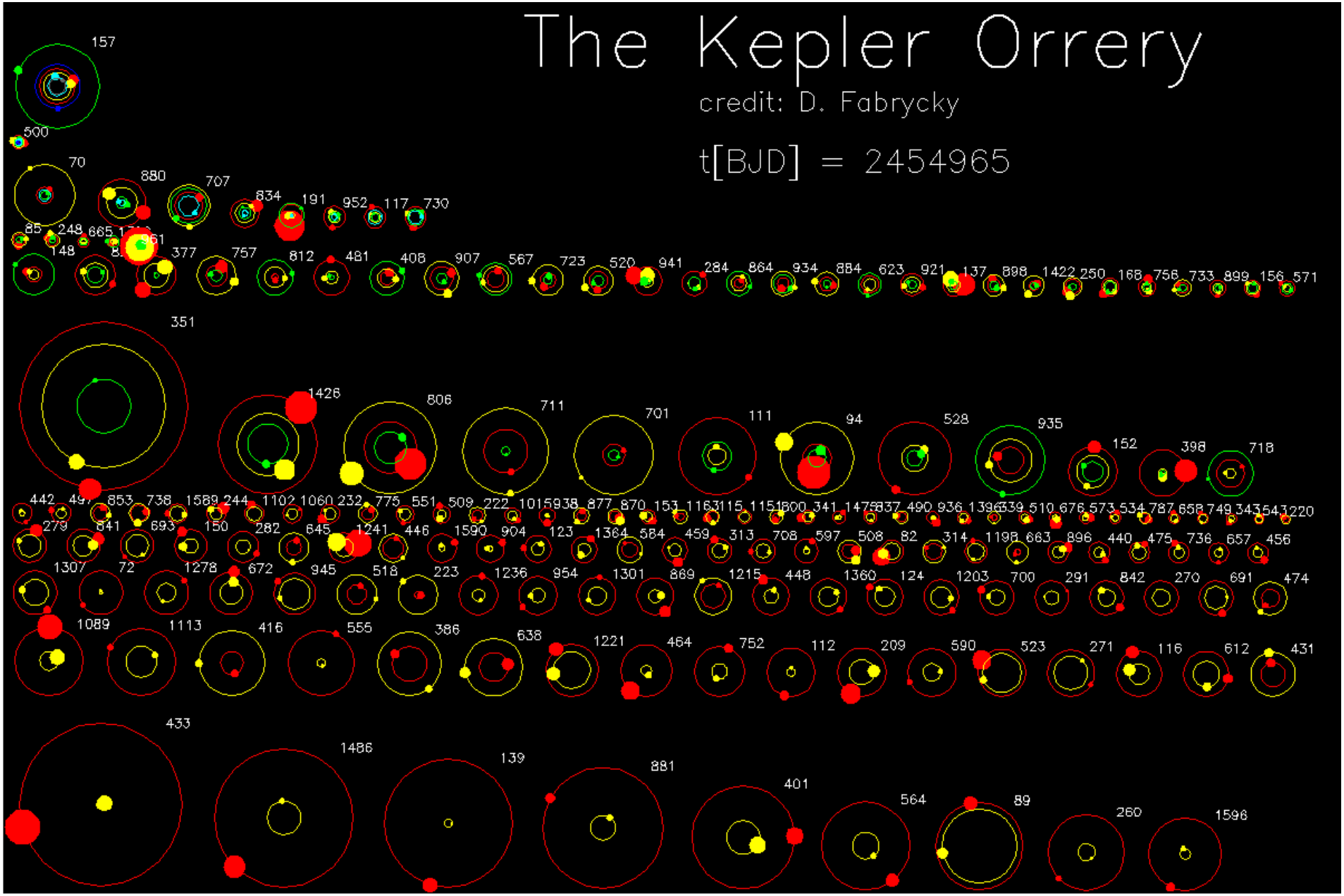
Kepler
A Search for Earth-size Planets





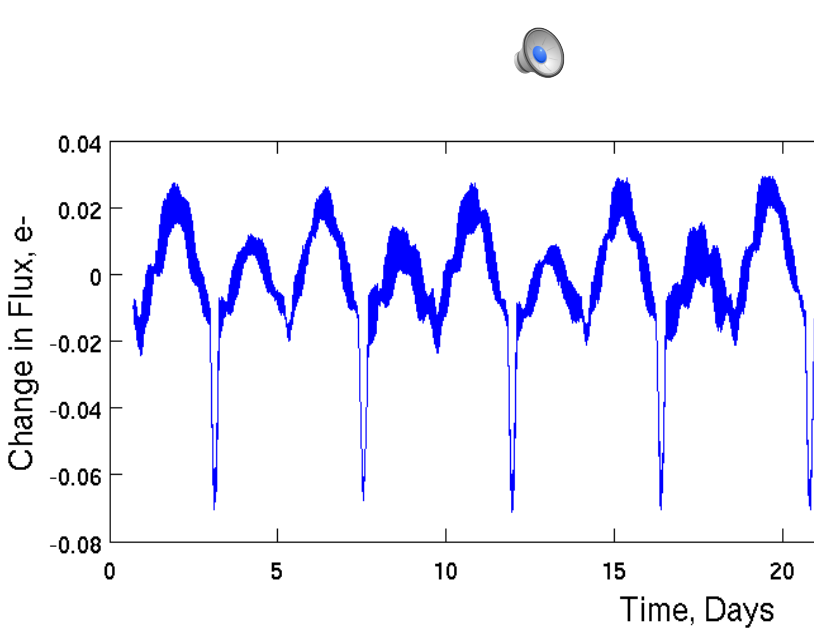
"Well, this mission answers at least <u>one</u> big question: Are there other planets like ours in the universe?"

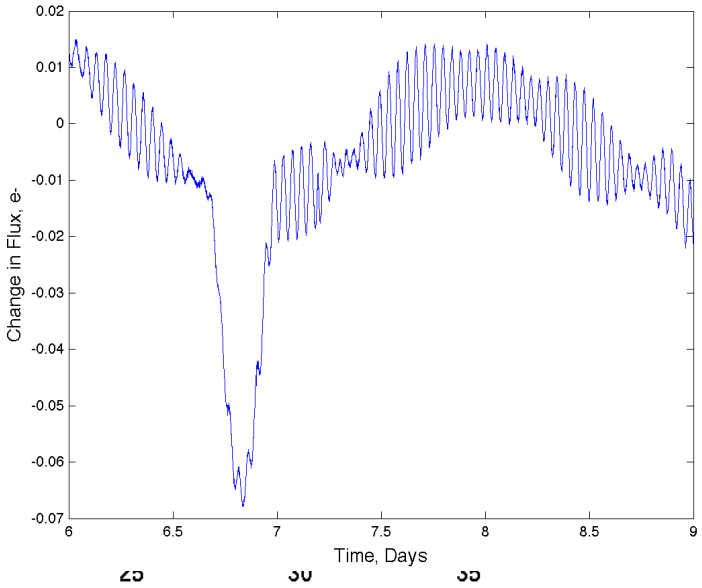
Drawing by H. Martin; © 1991
The New Yorker Magazine, Inc.

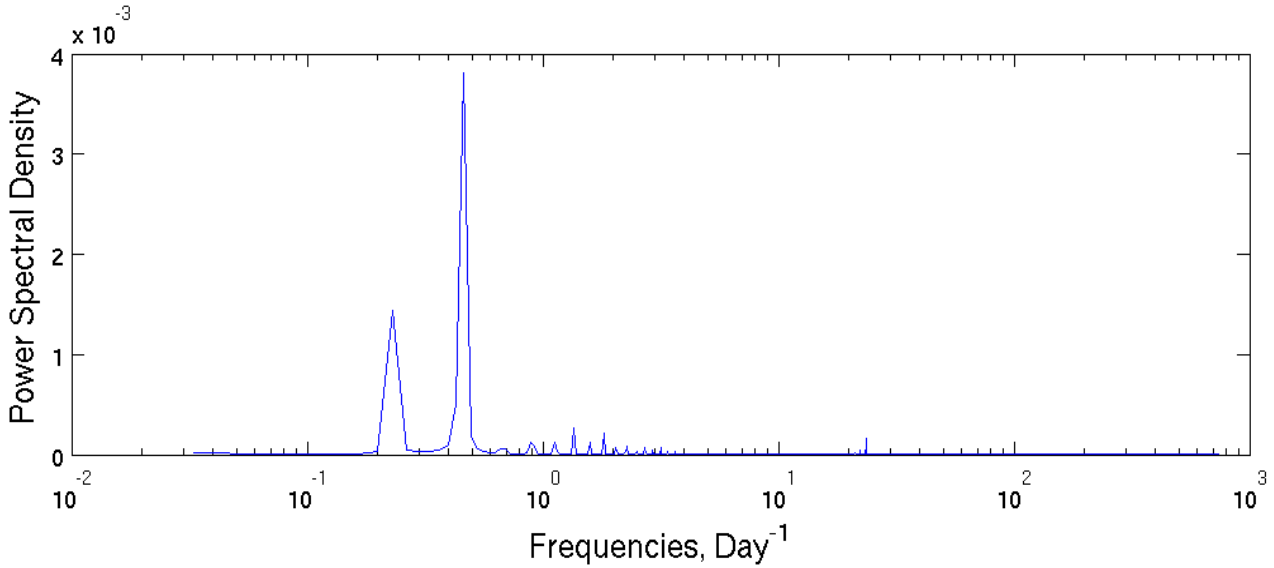

The Kepler Orrery
credit: D. Fabrycky
t[BJD] = 2454965

Music From the Stars

Kepler
A Search for Earth-size Planets







Music From the Stars

Kepler
A Search for Earth-size Planets