

Kepler Mission Update and Looking Forward to TESS

**Jon M. Jenkins
NASA Ames Research Center**

**Wednesday March 25, 2015
ATLAST Colloquium**

NASA Goddard Space Flight Center

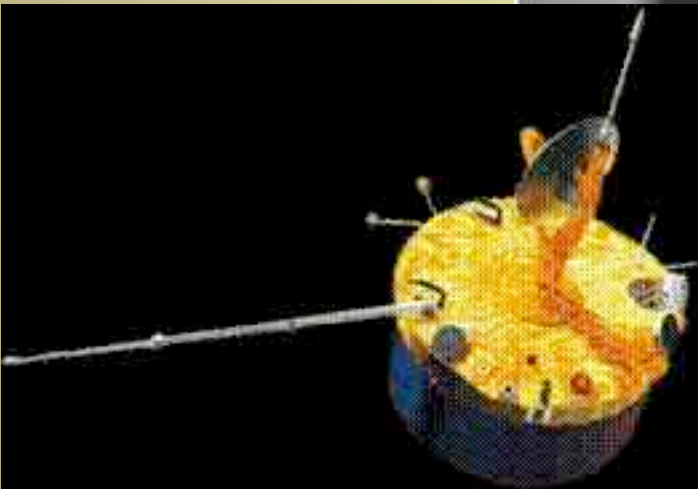




What Was Life Like Before Exoplanets (1994)?

Kepler
A Search for Earth-size Planets

Dreaming of Alien Worlds...



Pioneer Venus Orbiter

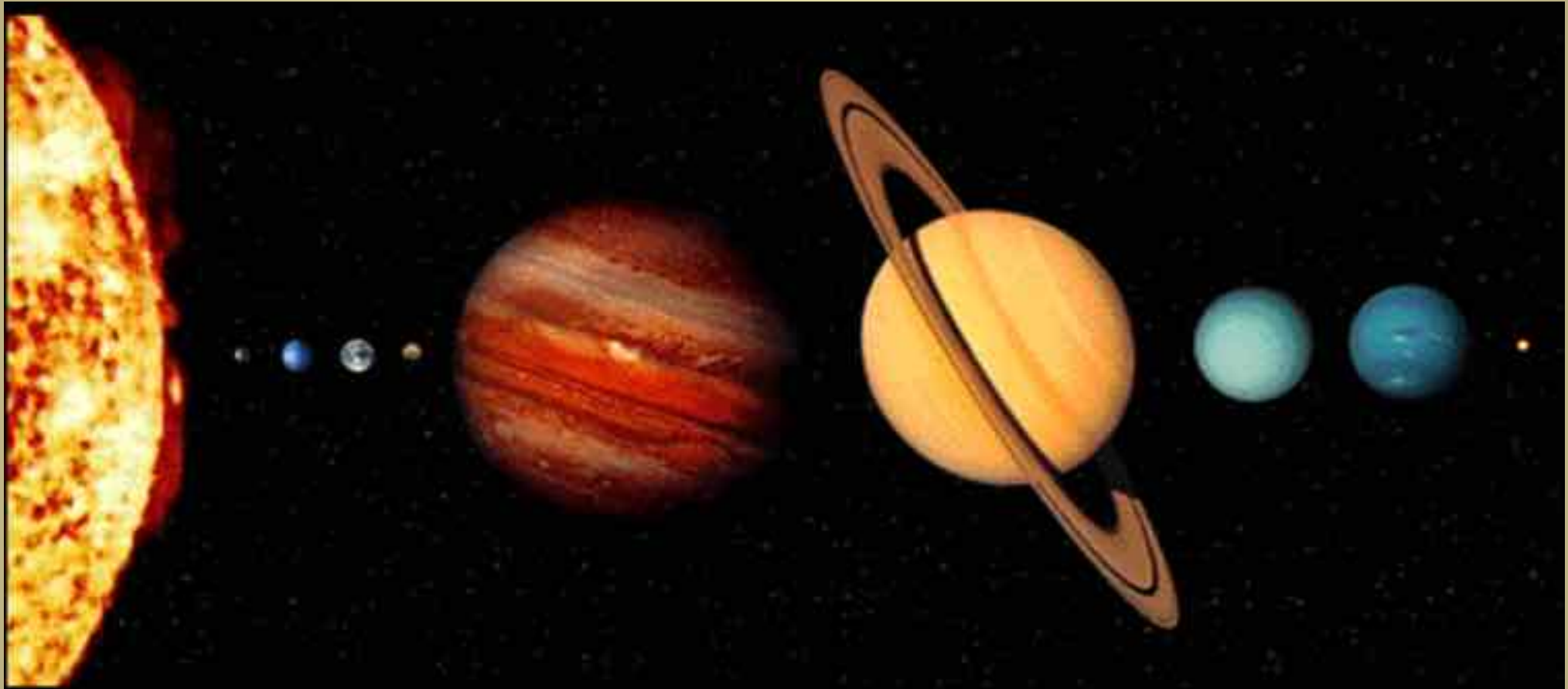




All the Known Planets in 1994

Kepler

*A Search for Earth-size
Planets*

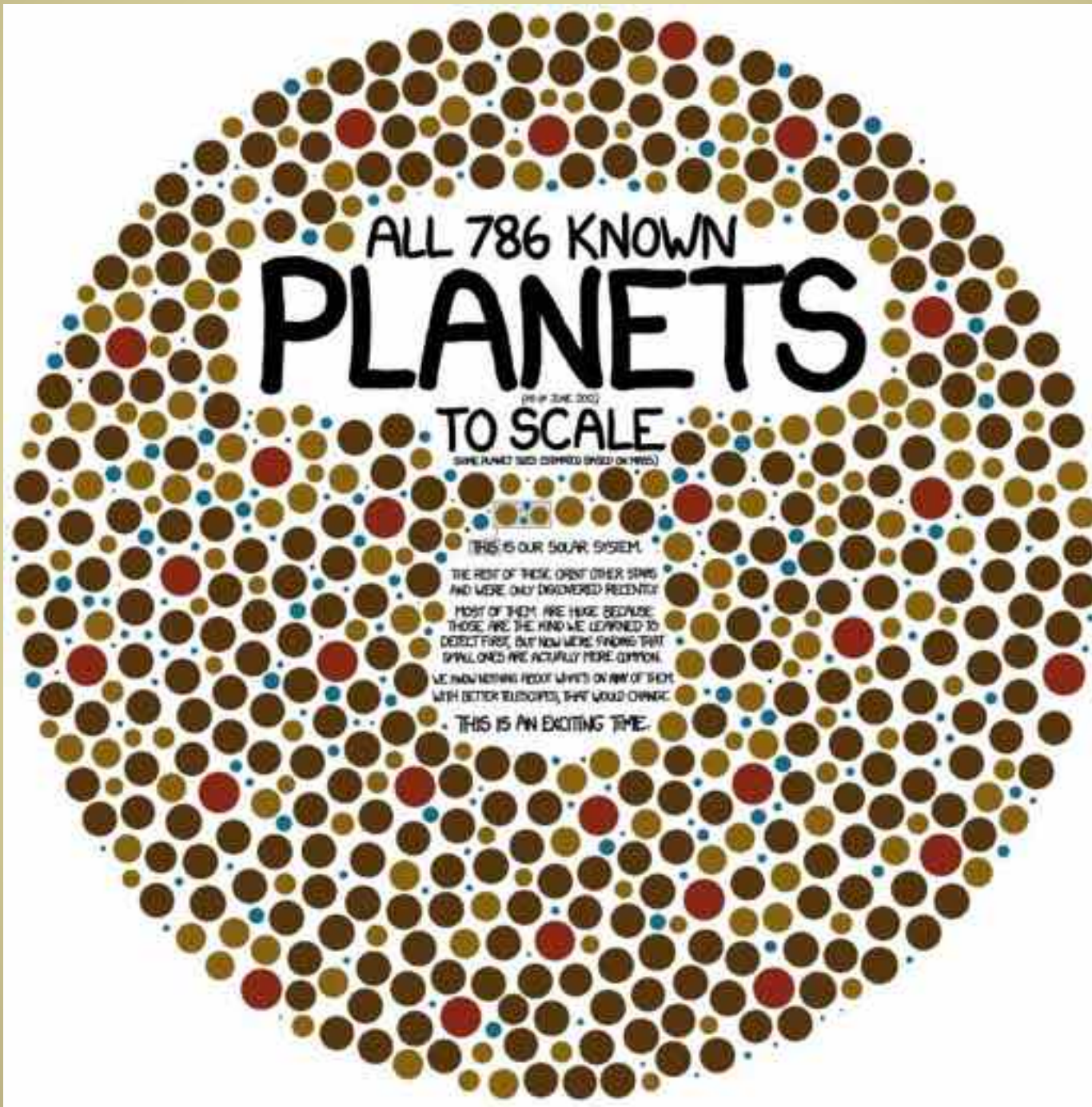




A More Recent Picture of Planets

Kepler

*A Search for Earth-size
Planets*



ALL 786 KNOWN PLANETS

(75 OF JUNE 2012)

TO SCALE

(SOME PLANET SIZES ESTIMATED BASED ON 1995)



THIS IS OUR SOLAR SYSTEM.

THE REST OF THESE ORBIT OTHER STARS
AND WERE ONLY DISCOVERED RECENTLY.

MOST OF THEM ARE HUGE BECAUSE
THOSE ARE THE KIND WE LEARNED TO
DETECT FIRST, BUT NOW WE'RE FINDING THAT
SMALL ONES ARE ACTUALLY MORE COMMON.

WE KNOW NOTHING ABOUT WHAT'S ON ANY OF THEM.



How Does Kepler Work?

Kepler

*A Search for Earth-size
Planets*





Binary Stars Don't Have Planets?*

Kepler
A Search for Earth-size
Planets

Kepler-16b, aka "Tatooine"



Laurance Doyle



* M stars don't have planets, either?

Kepler-47 System



Kepler-47 c



Kepler-47 b

Habitable Zones

Solar System

Mercury

Venus

Earth

Mars



Planets and orbits to scale



NASA's 1995 ExNPS Report

Kepler
A Search for Earth-size
Planets

Executive Summary
Introduction
The Formation of Stars and Planets
The Instrumental Challenge
The Space Infrared Interferometer
Technology Challenges for a Space
Infrared Interferometer
Supporting Ground-Based Programs
Supporting Space Missions
Additional Astrophysics with a Space
Infrared Interferometer
The Road Map and Recommendations
References
Appendices
Acronyms

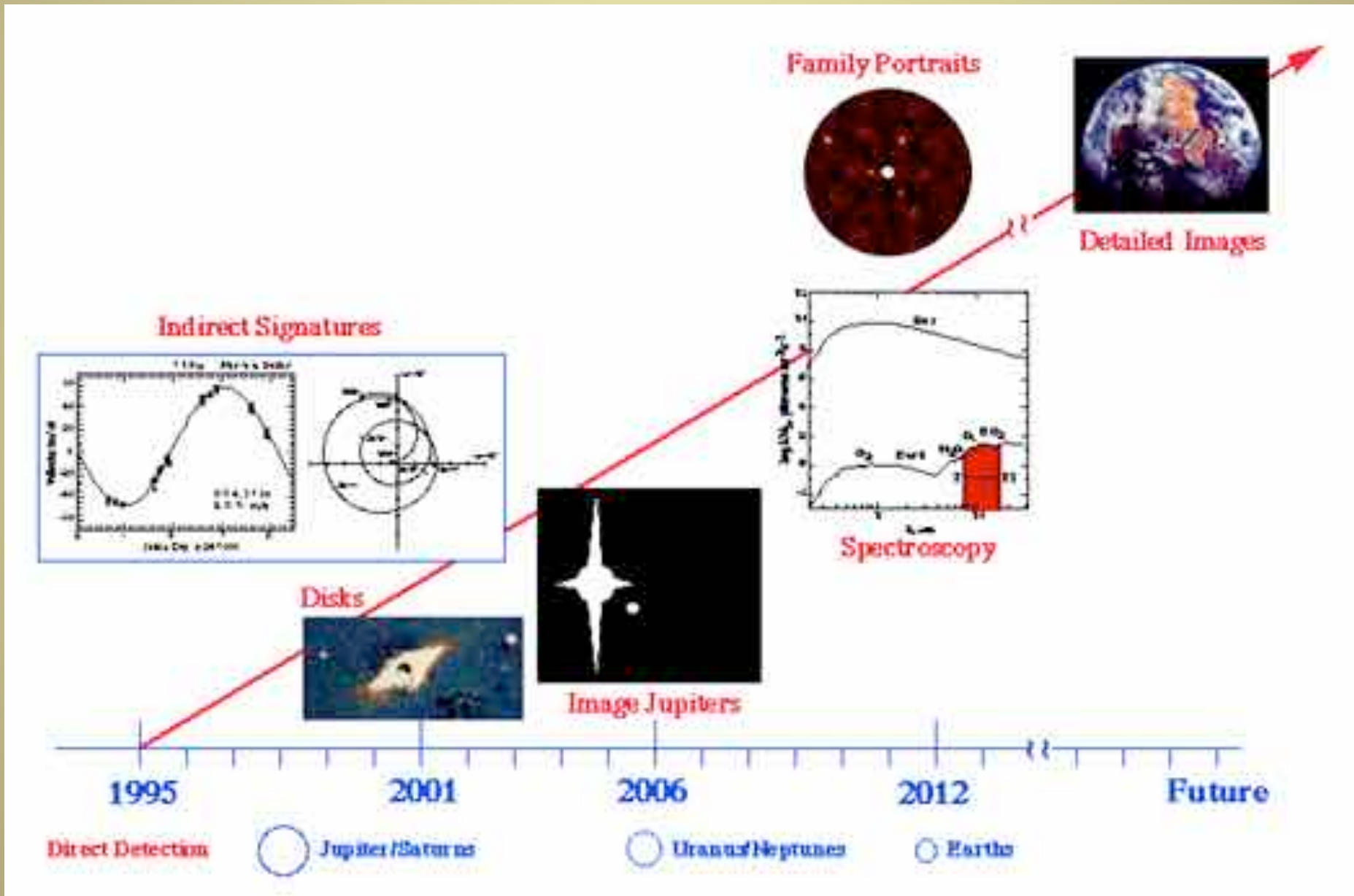
A Road Map for the Exploration of Neighboring Planetary Systems (ExNPS)

 [GL229 B - click to view spectral characterization](#)



NASA's 1995 ExNPS Report

Kepler
A Search for Earth-size
Planets

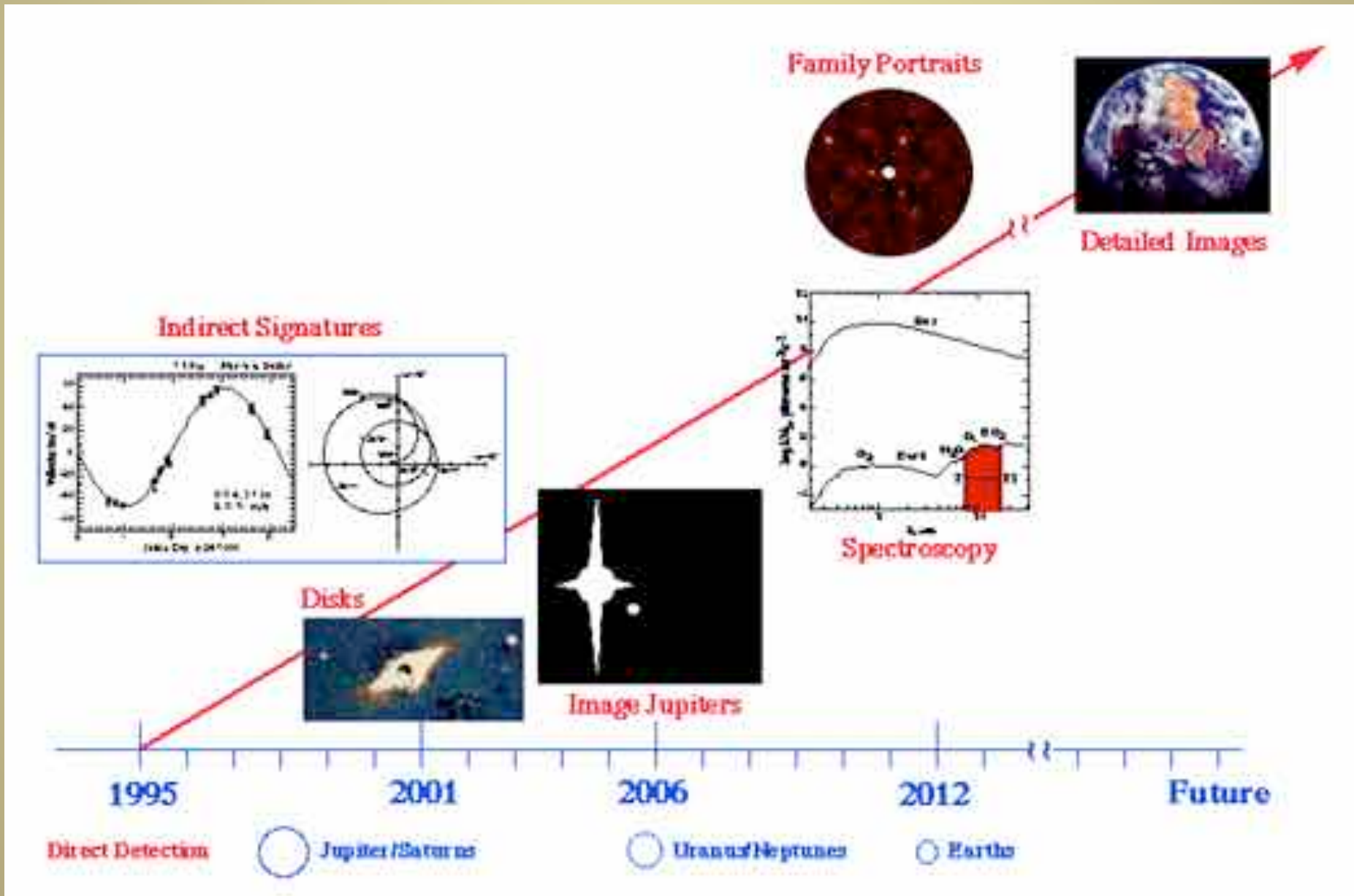




NASA's 1995 ExNPS Report

Kepler
A Search for Earth-size Planets

Transit Photometry not Recommended





Getting Serious about Exo-Earths (1996)

Kepler

*A Search for Earth-size
Planets*

Dreaming of Alien Earths...

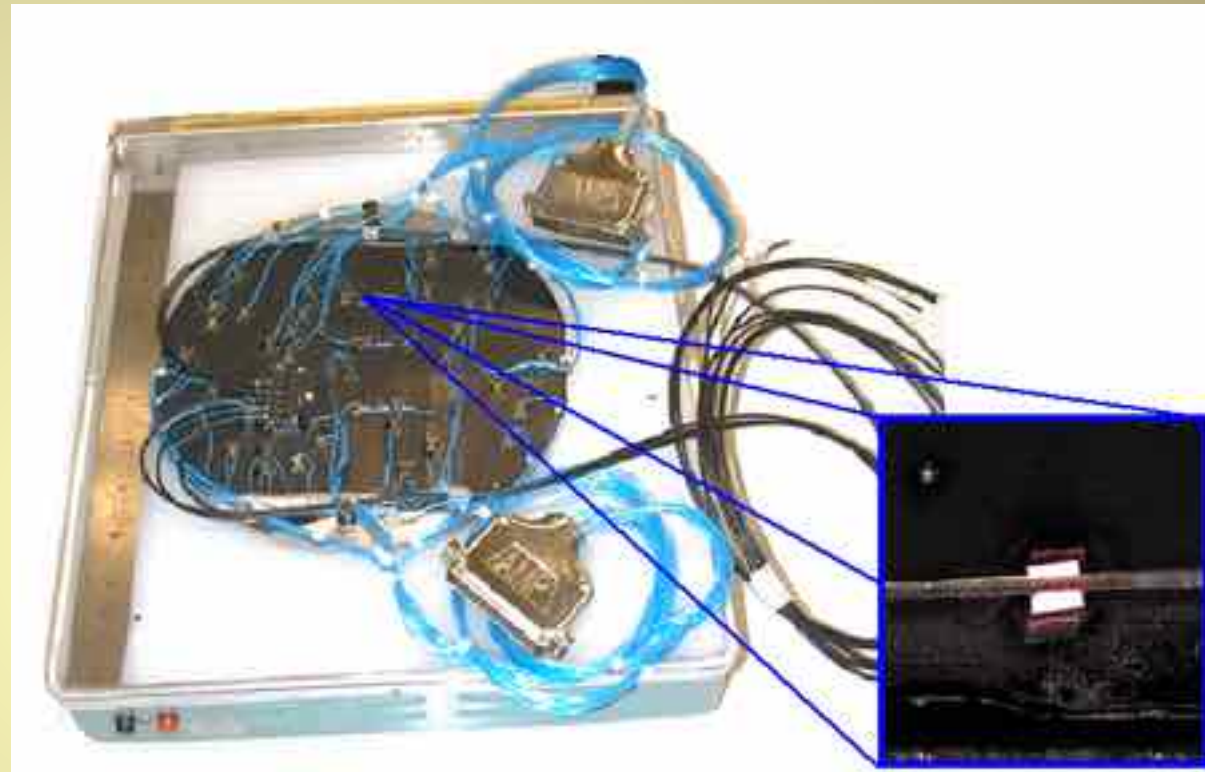




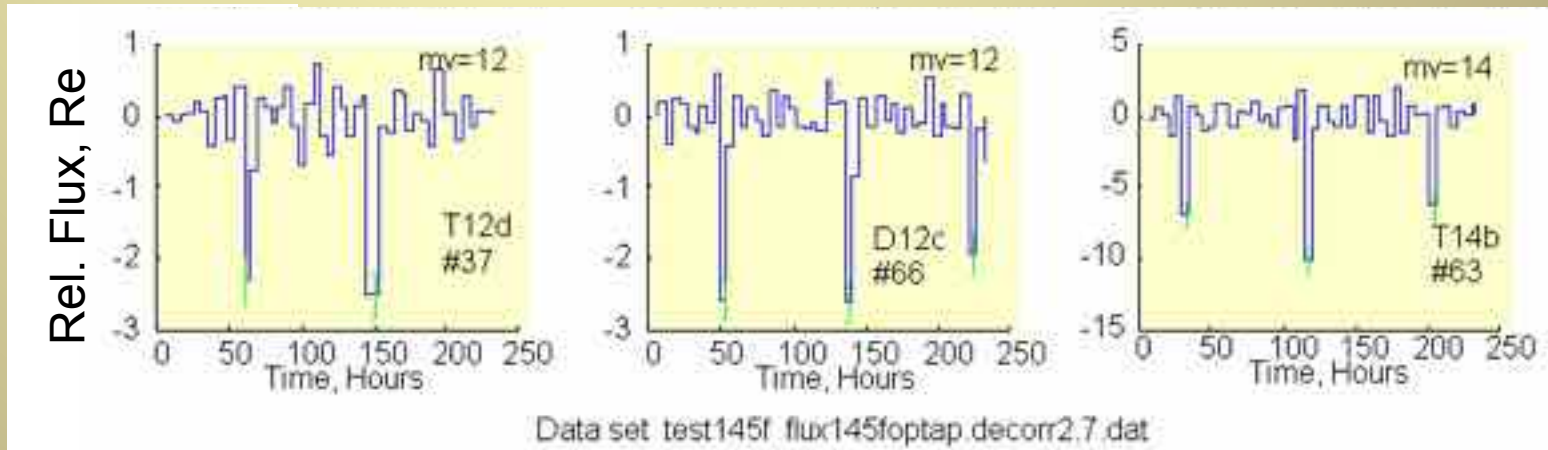
Kepler Tech Demo 1998

Kepler

A Search for Earth-size Planets



David Koch, DPI



Key Science Results



Kepler

A Search for Terrestrial Planets

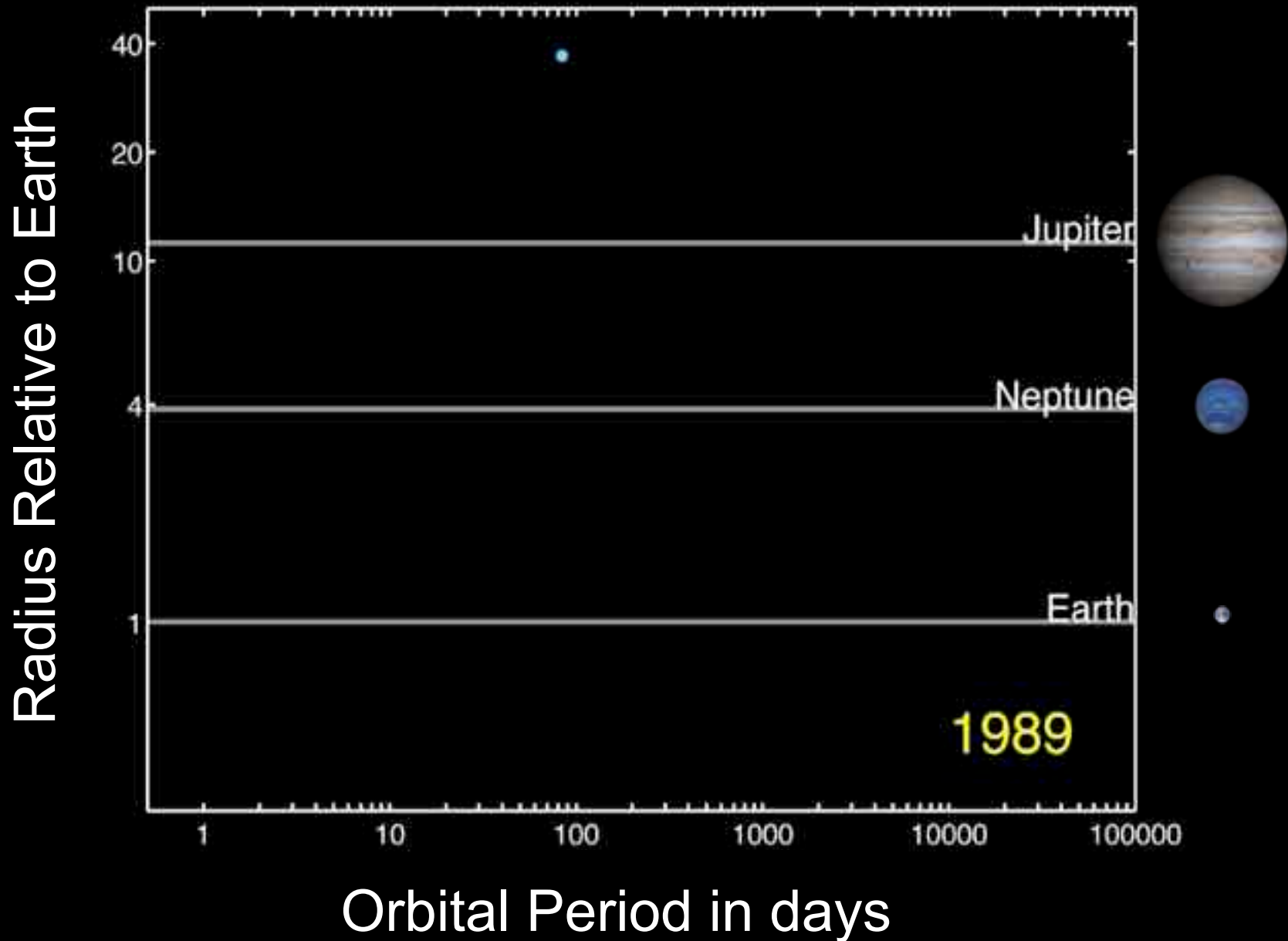
Kepler's Greatest Hits

- Kepler-10b,c
 - Kepler-11b,c,d,e,f,g
 - Kepler-16b
 - Kepler-47c
 - Kepler-22b
 - Kepler-62e,f
 - KIC-12557548
- And Many Others!



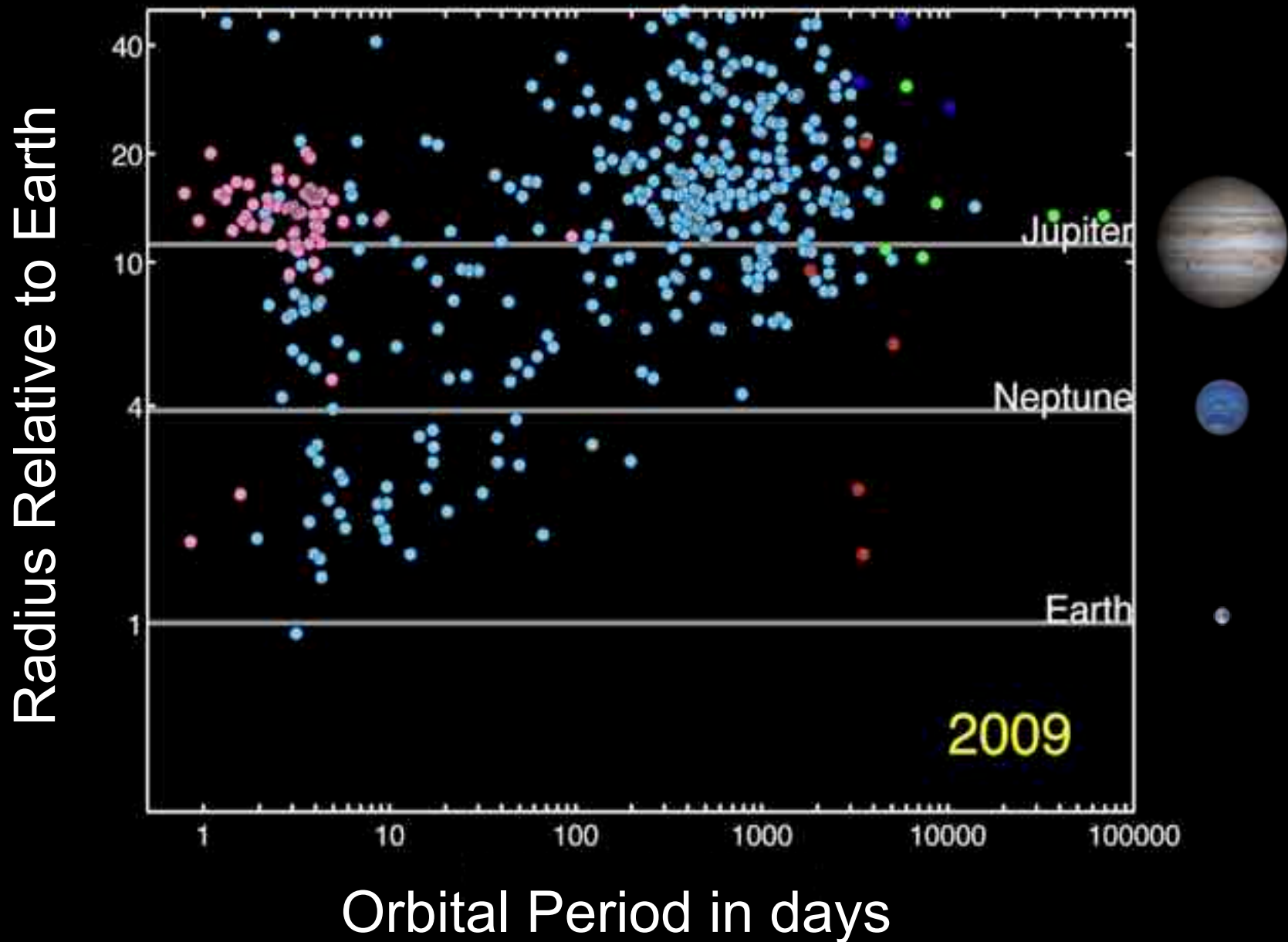
Exoplanet Detections, 1995-2009

● Velocimetry ● Transit ● Imaging ● Eclipse Timing ● Microlensing ● Kepler



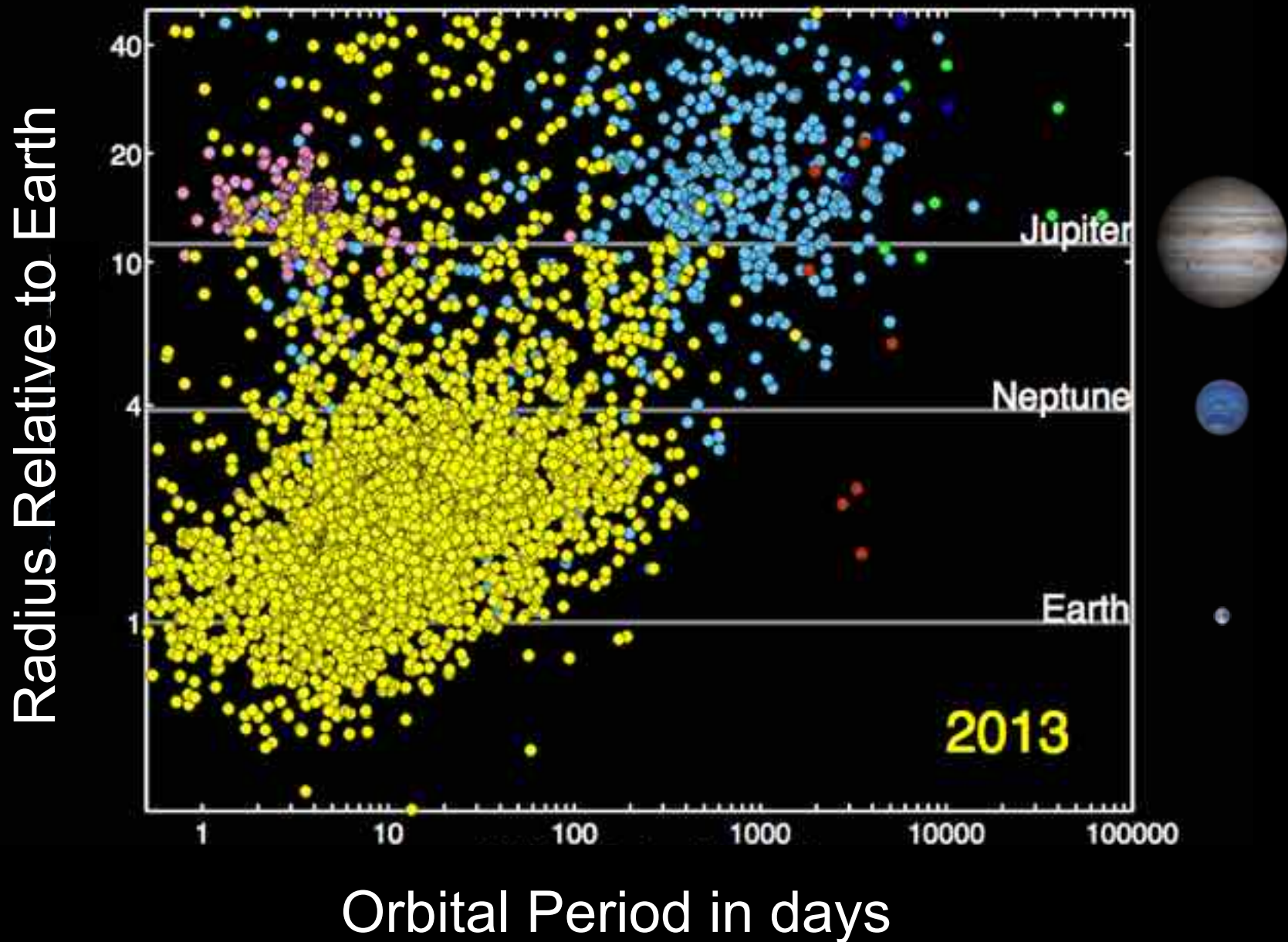
Exoplanet Detections, 1995-2012

● Velocimetry ● Transit ● Imaging ● Eclipse Timing ● Microlensing ● Kepler



Exoplanet Detections, 1995-2013

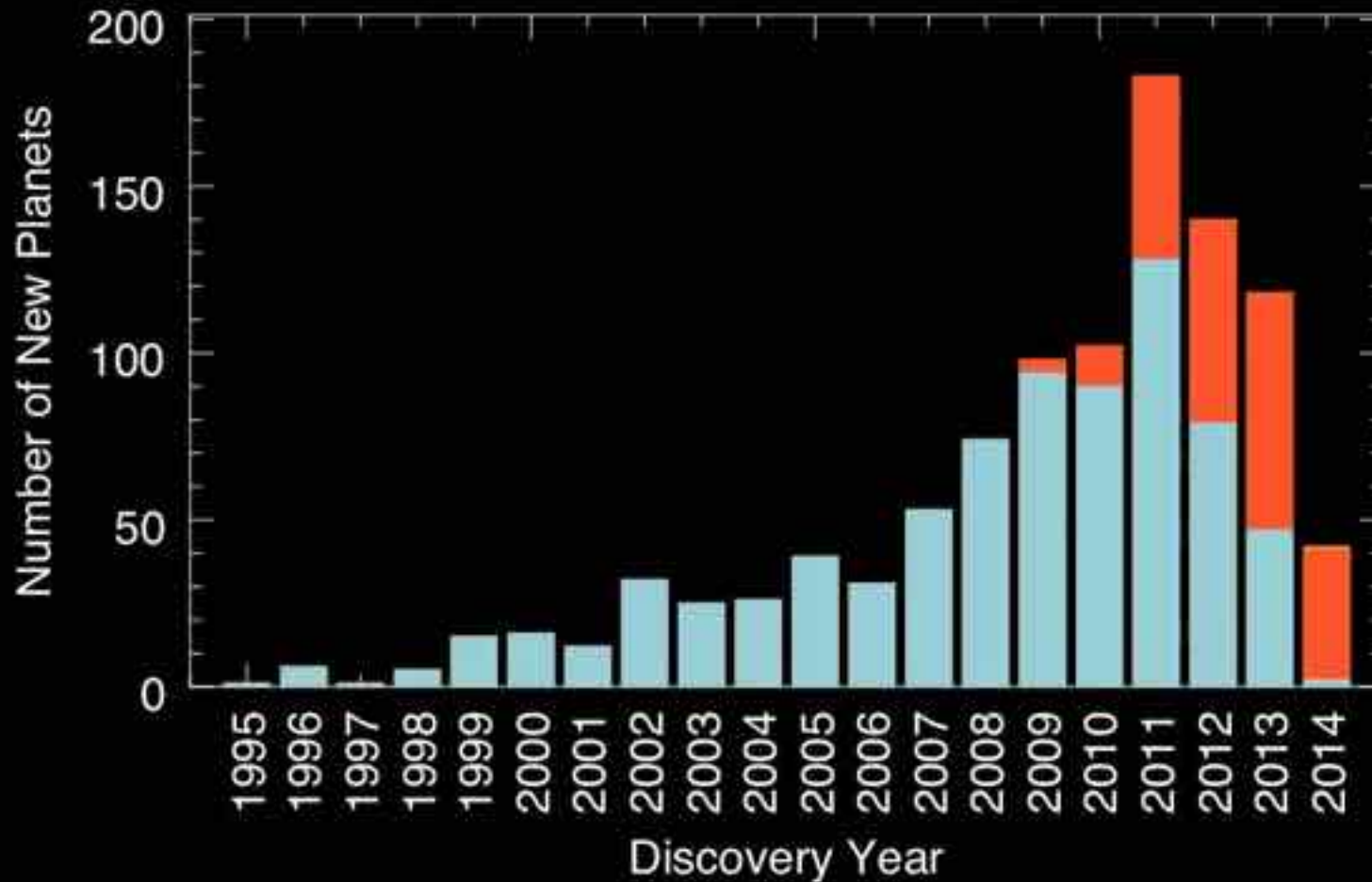
● Velocimetry ● Transit ● Imaging ● Eclipse Timing ● Microlensing ● Kepler





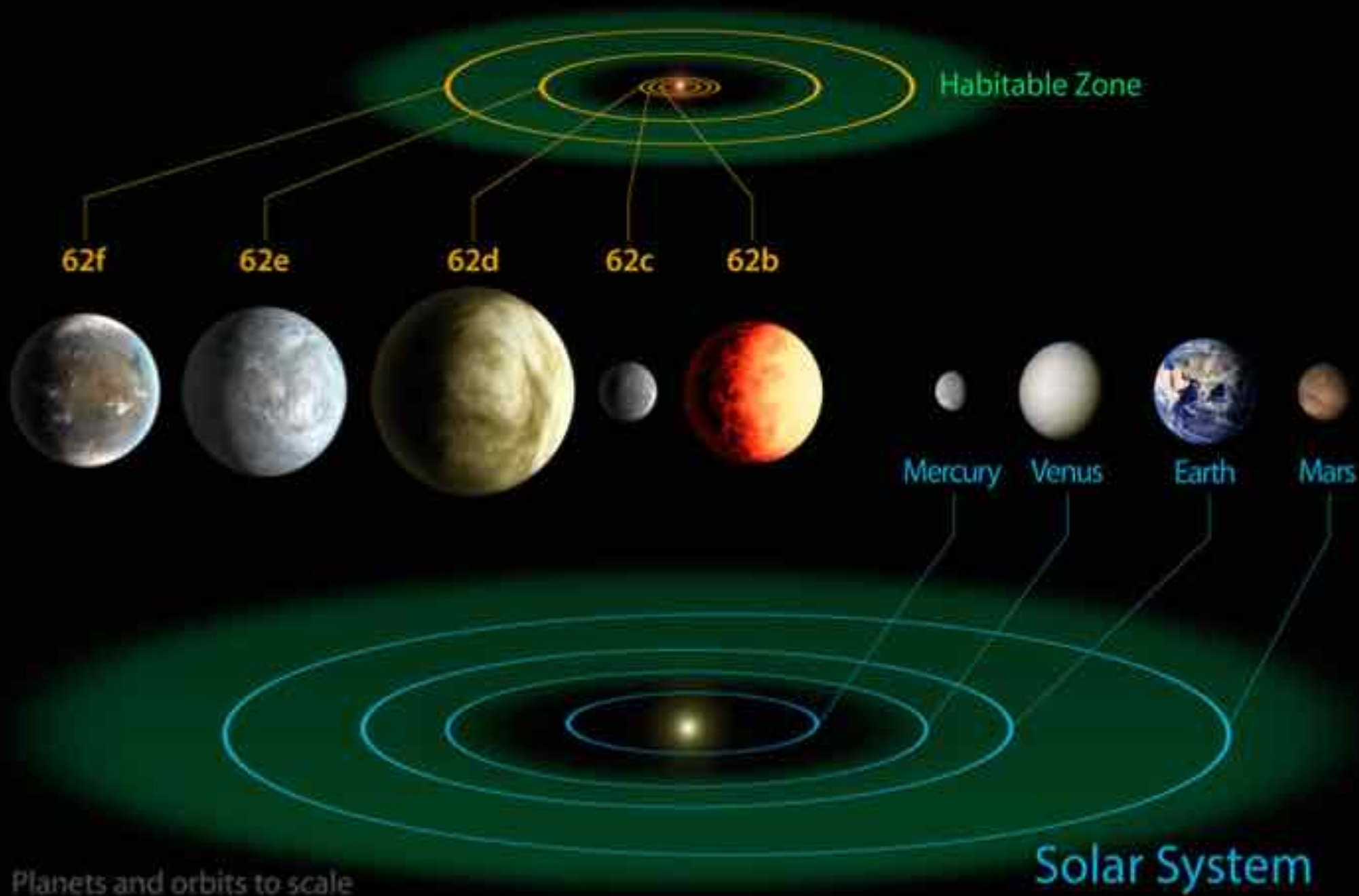
A Bonanza of New Planets

Kepler
A Search for Earth-size
Planets



715 new confirmed planets orbiting 305 stars

Kepler-62 System





Why Do Stars Sing?

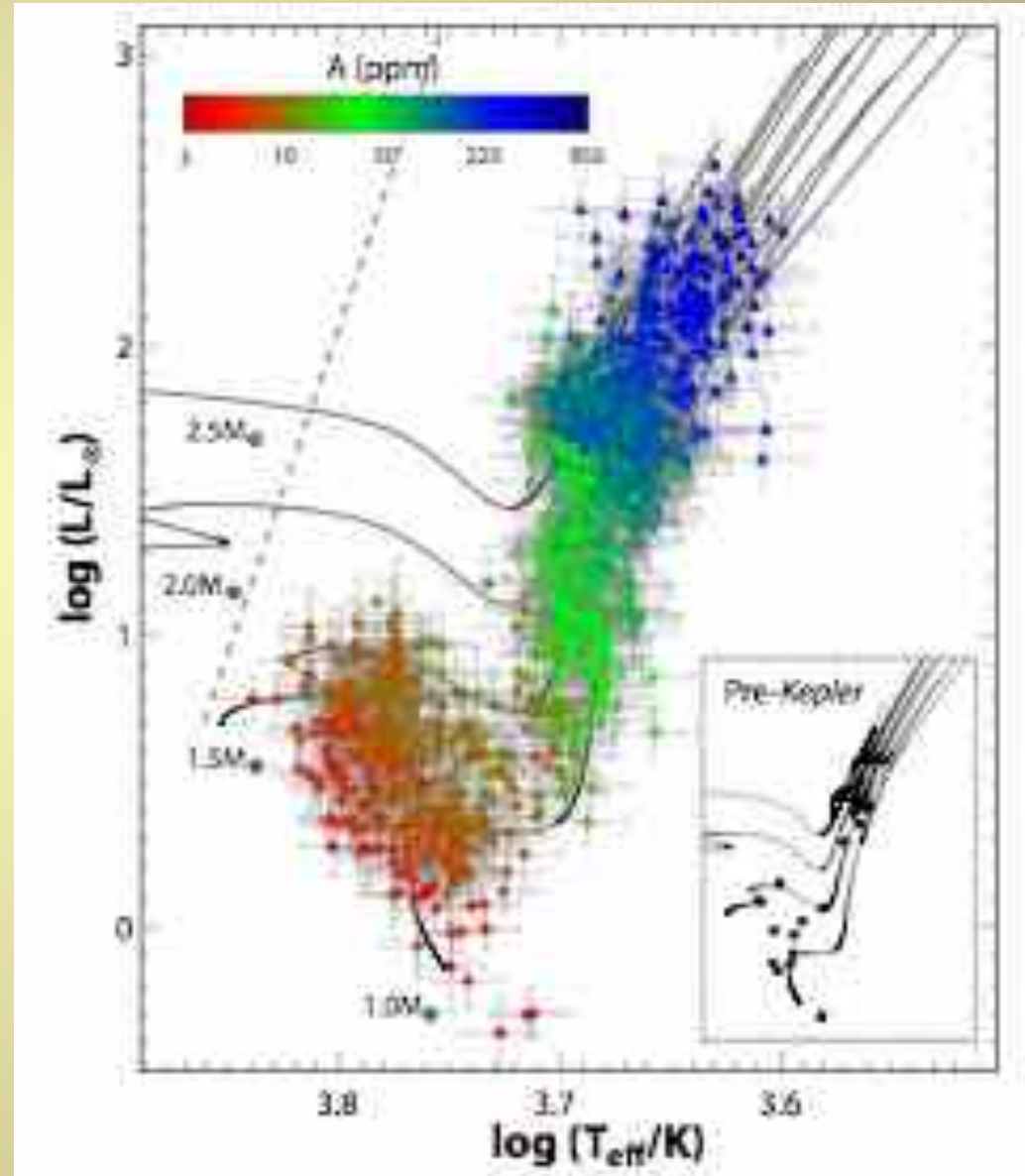
Kepler

A Search for Earth-size Planets

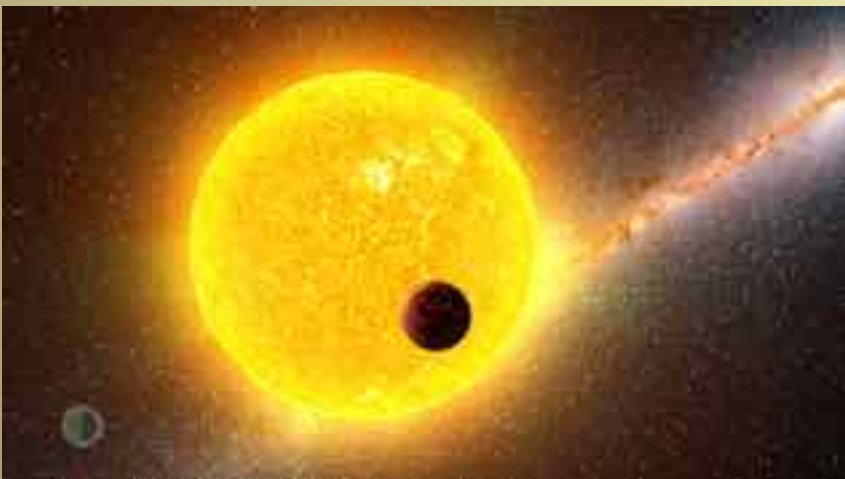
Stars are large resonant cavities that ring like bells

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

Asteroseismology gives unprecedented precision in size, mass of stars



Chaplin et al 2011, Science

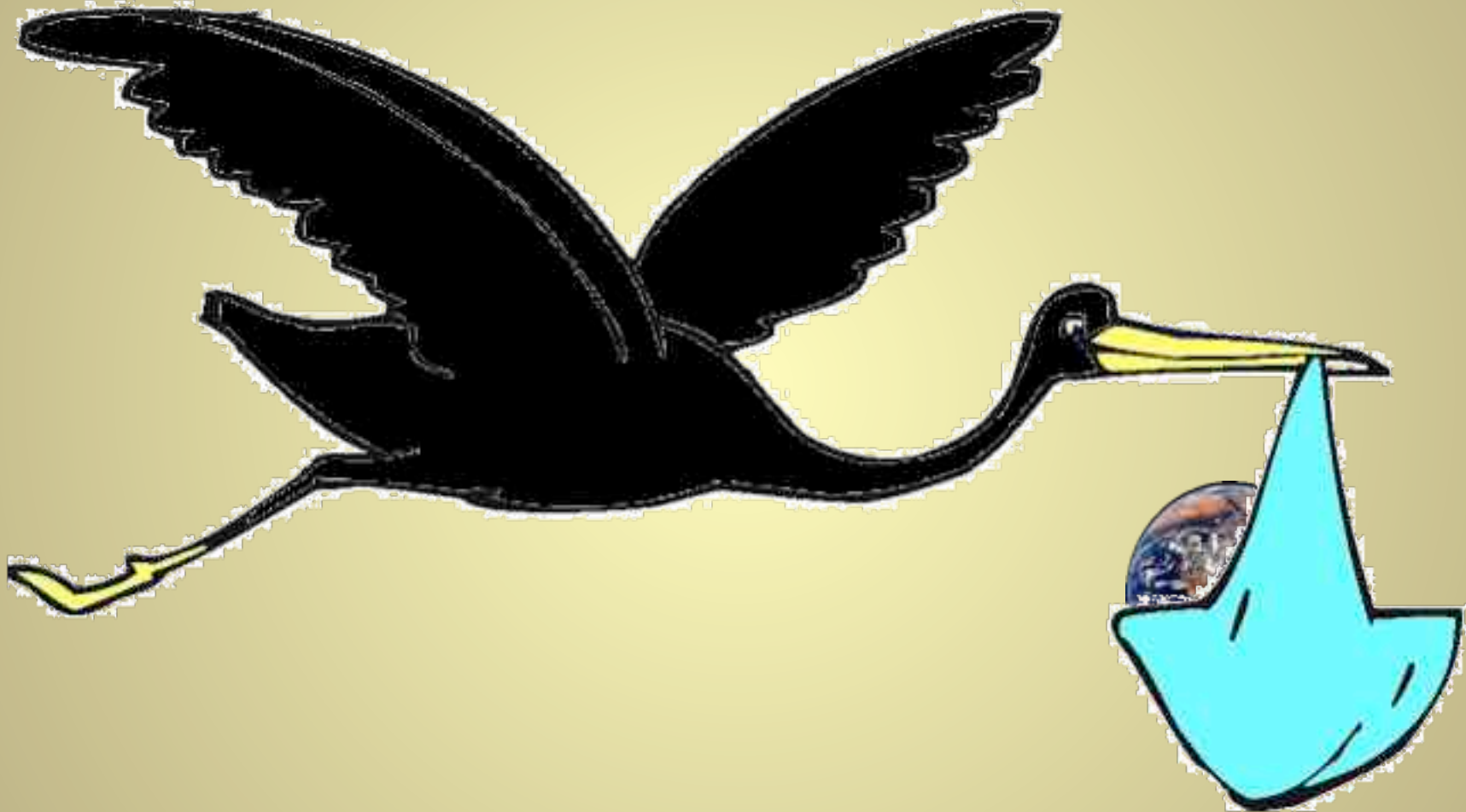




Where Do Planets Come From?

Kepler

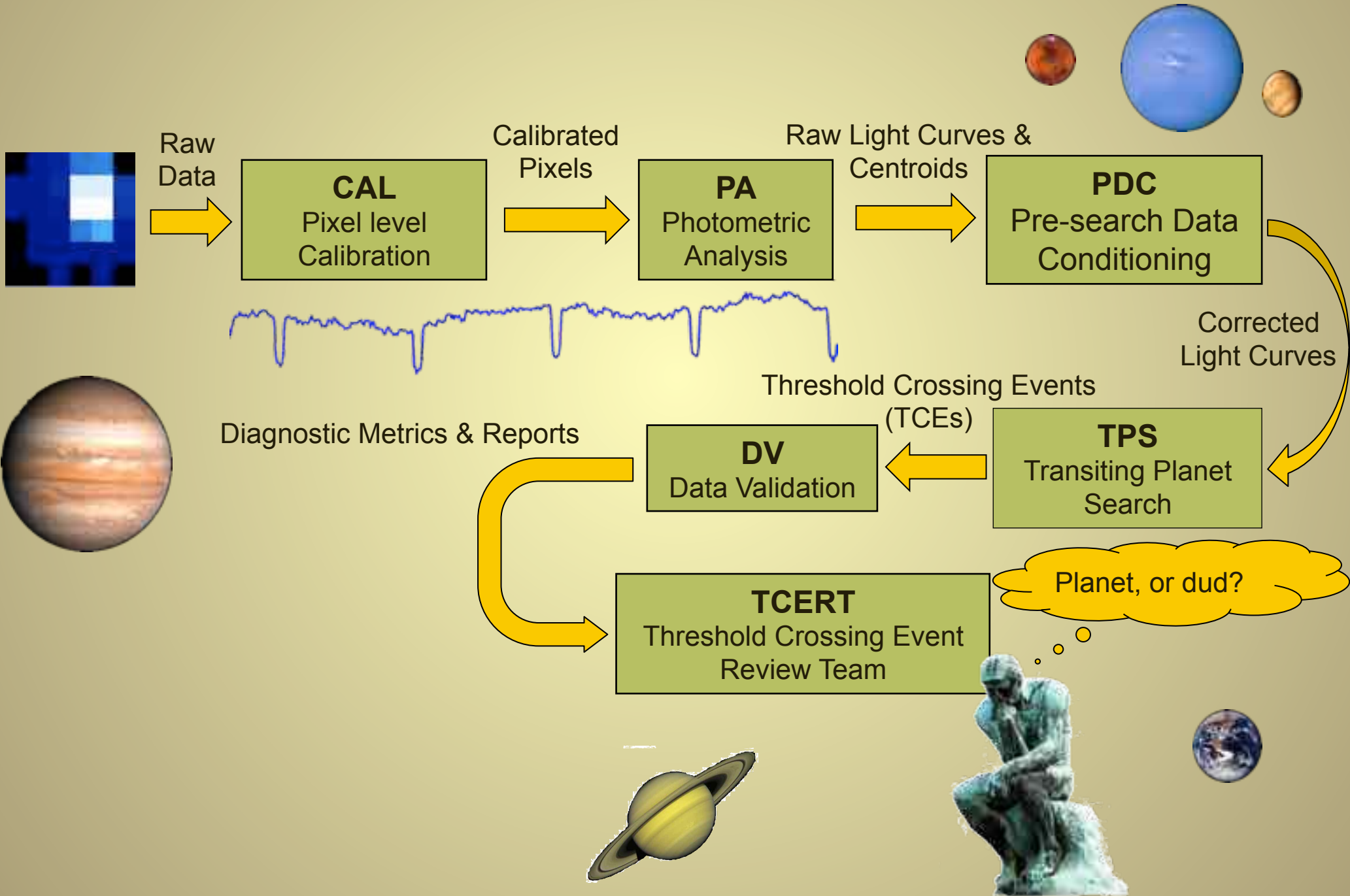
*A Search for Earth-size
Planets*



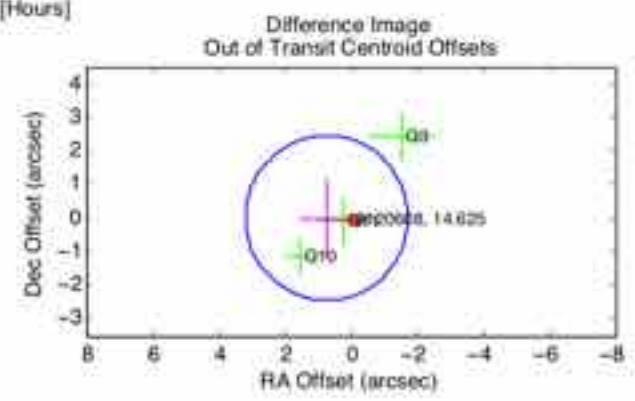
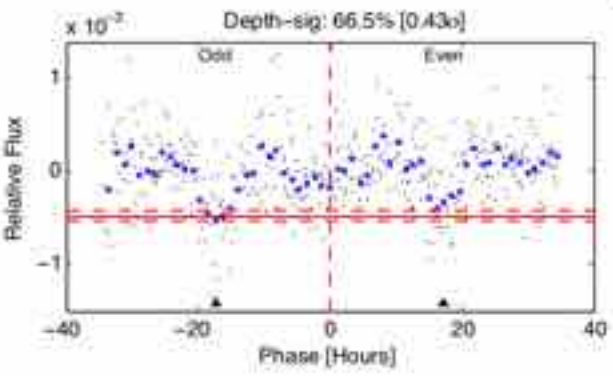
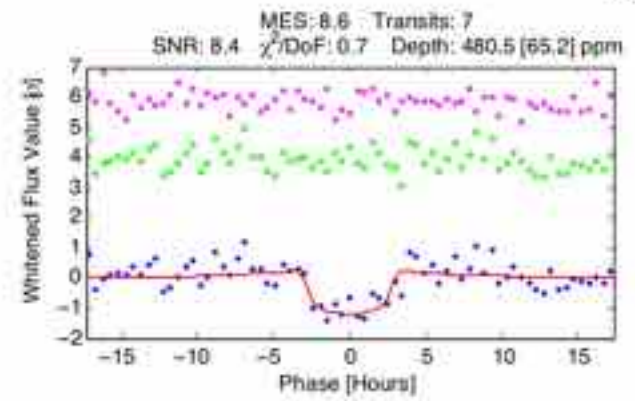
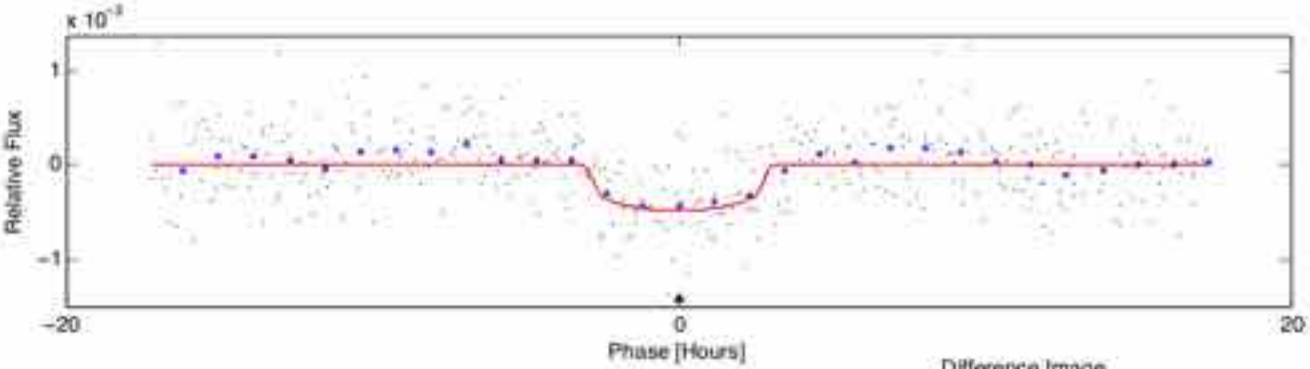
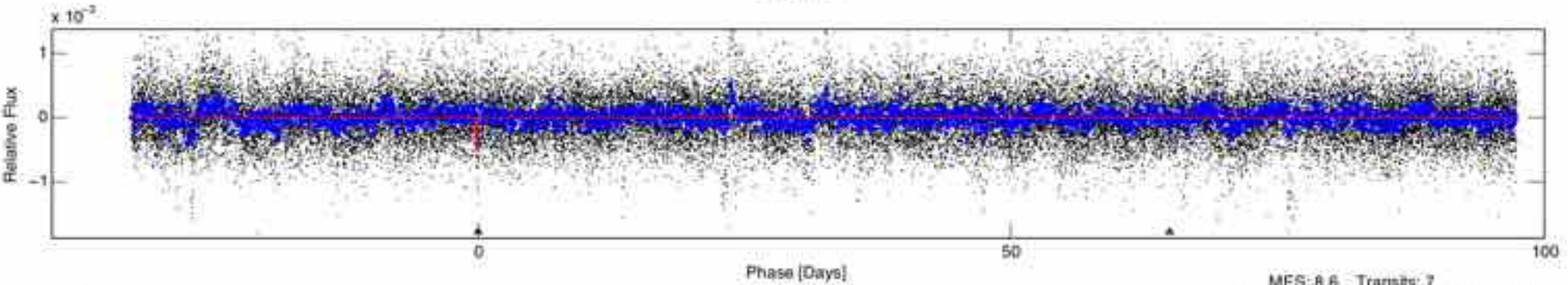
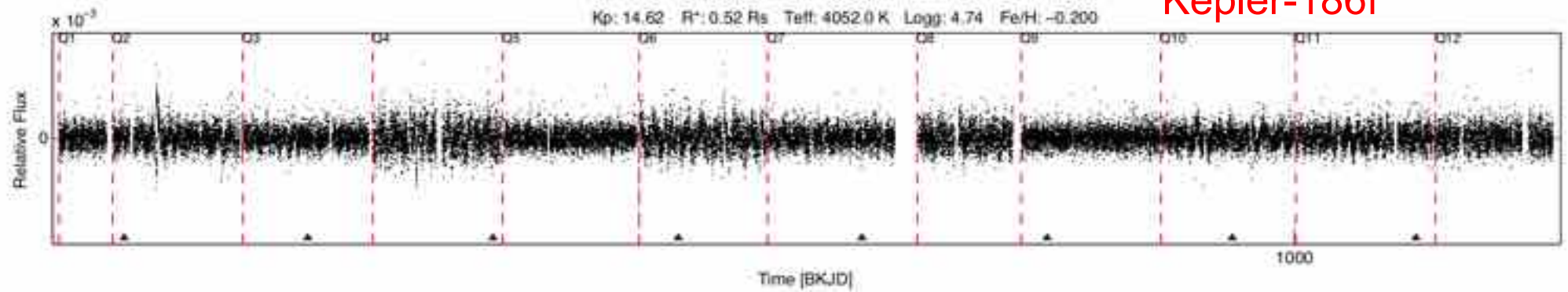


The Kepler Pipeline

Kepler
A Search for Earth-size Planets



Kepler-186f



DV Fit Results:
 Period = 129.94545 [0.00238] d
 Epoch = 178.8272 [0.0115] BKJD
 Rp/R* = 0.0200 [0.0271]
 a/R* = 165.05 [882.88]
 b = 0.34 [13.80]
 Teq = 202 K
 Rp = 1.14 Re
 a = 0.4104 AU

DV Diagnostic Results:
 Epoch-sig: 78.0% [0.28σ]
 ShortPeriod-sig: 100.0% [0.00σ]
 LongPeriod-sig: N/A
 Centroid-sig: 4.6% [1.99σ]
 Bootstrap-pfa: N/A
 OotOffset-rm: 0.735 arcsec [0.90σ]
 KicOffset-rm: 0.869 arcsec [1.17σ]
 OotOffset-bt: N/A
 KicOffset-bf: N/A

A Plague of Planet-like Signatures



Speed up the conveyer belt!

Kepler
TCERT

Kepler
Extended
Mission

Kepler
TCERT

Welcome to the Extended Kepler Mission!





Hardware Architecture

Kepler

*A Search for Earth-size
Planets*



NAS Melades Supercomputer

1.09 Pflop/s

>126,000 cores

191 of TB of RAM

84 hosts, 712 CPUs, 3.7 TB of RAM,

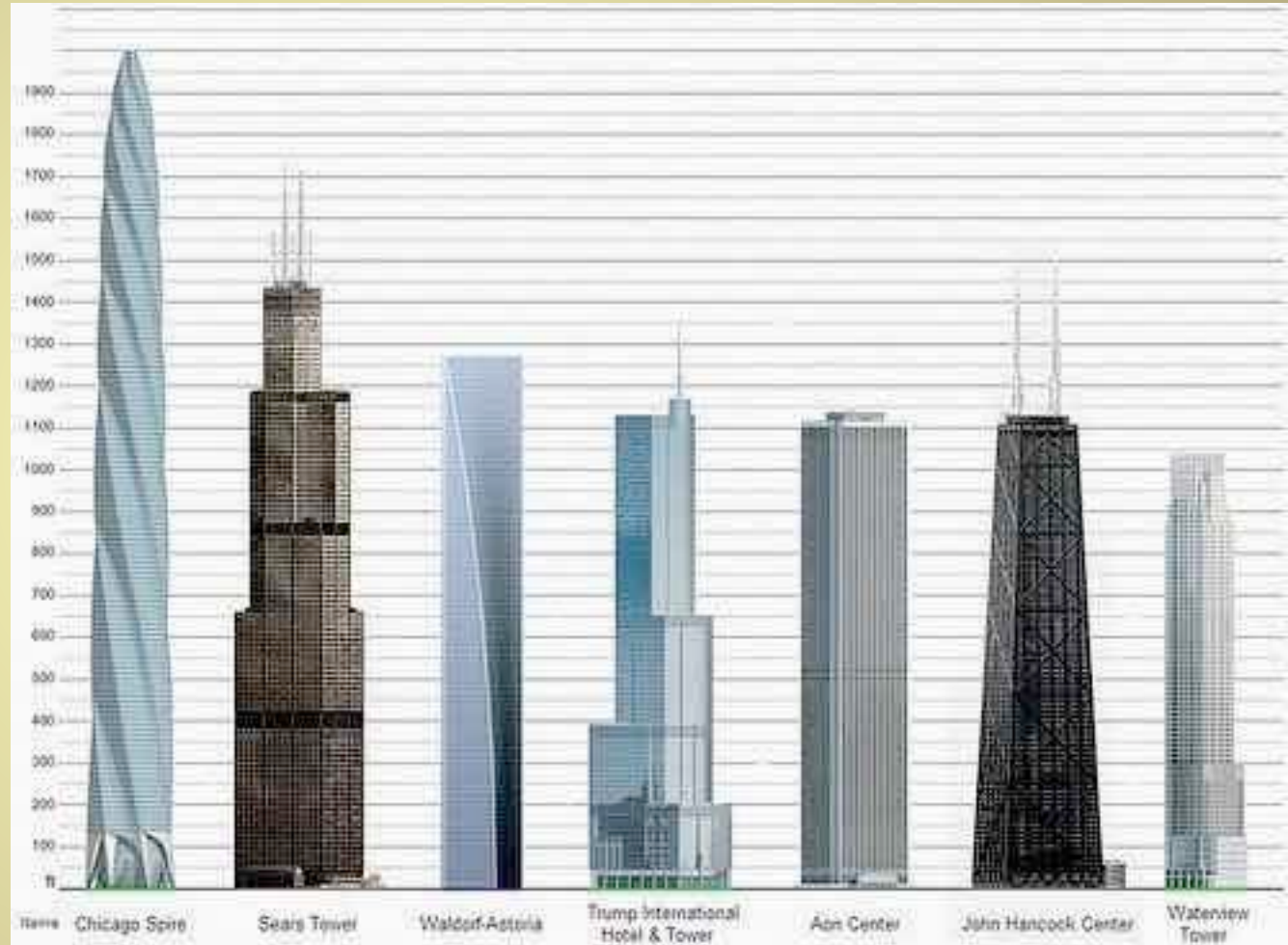
148 TB of raw disk storage





A Stack of DV Reports

Kepler
A Search for Earth-size
Planets

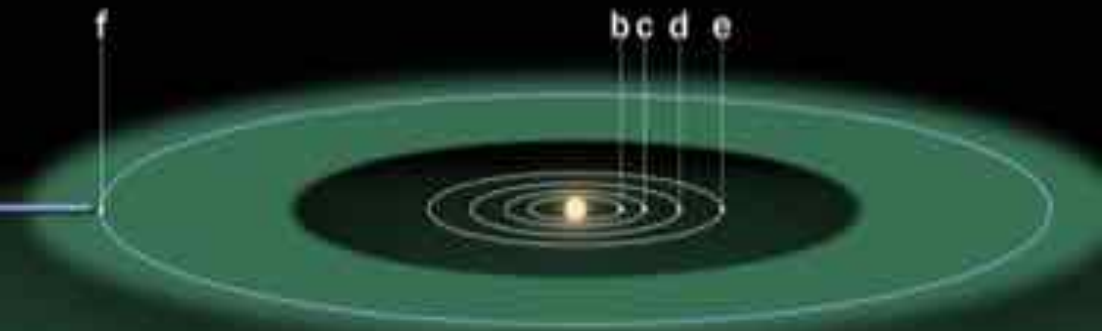


Right size and orbit: Kepler-186f

Artist's concept



Kepler-186 System



Solar System

Earth

Venus

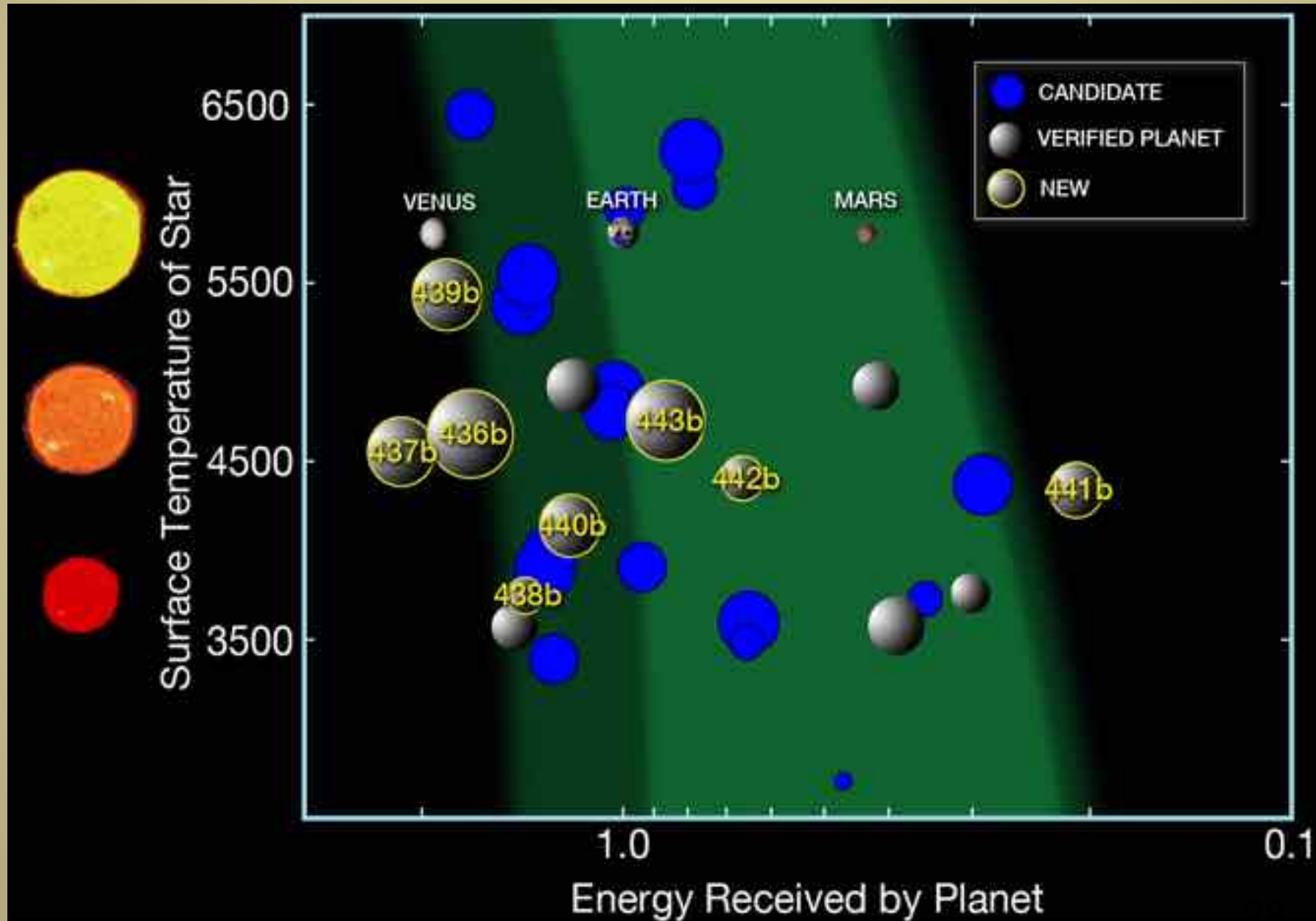
Mercury





New Small Planets

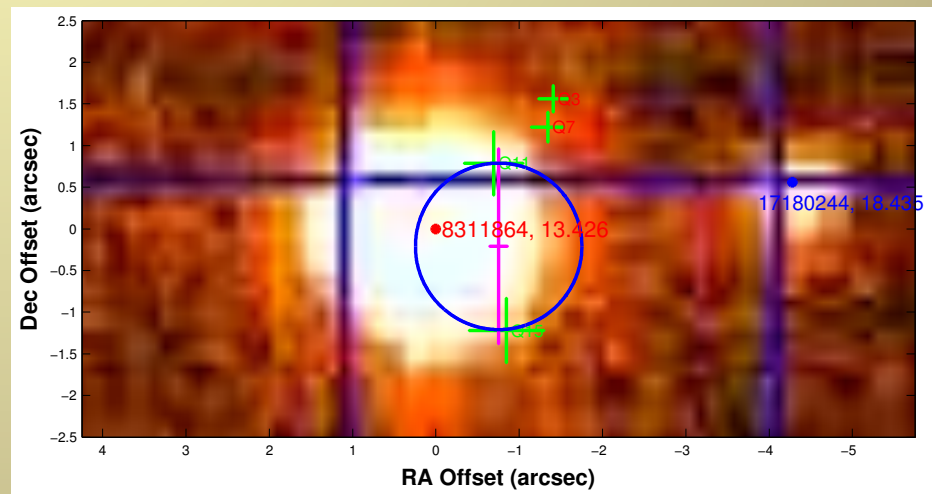
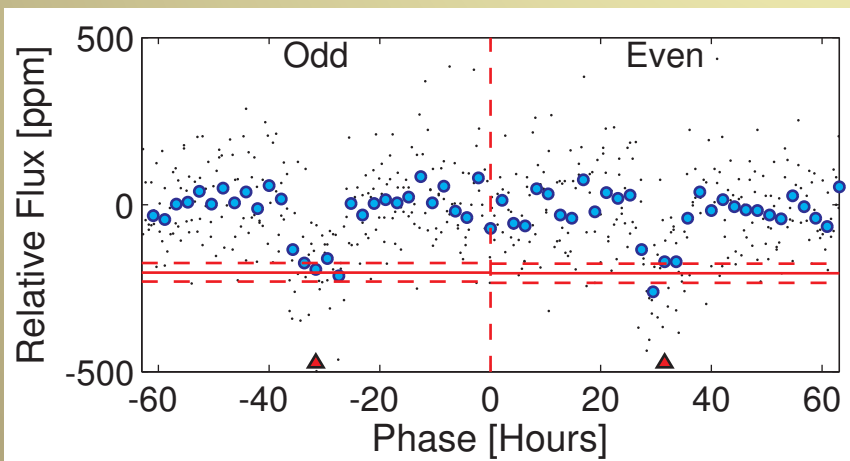
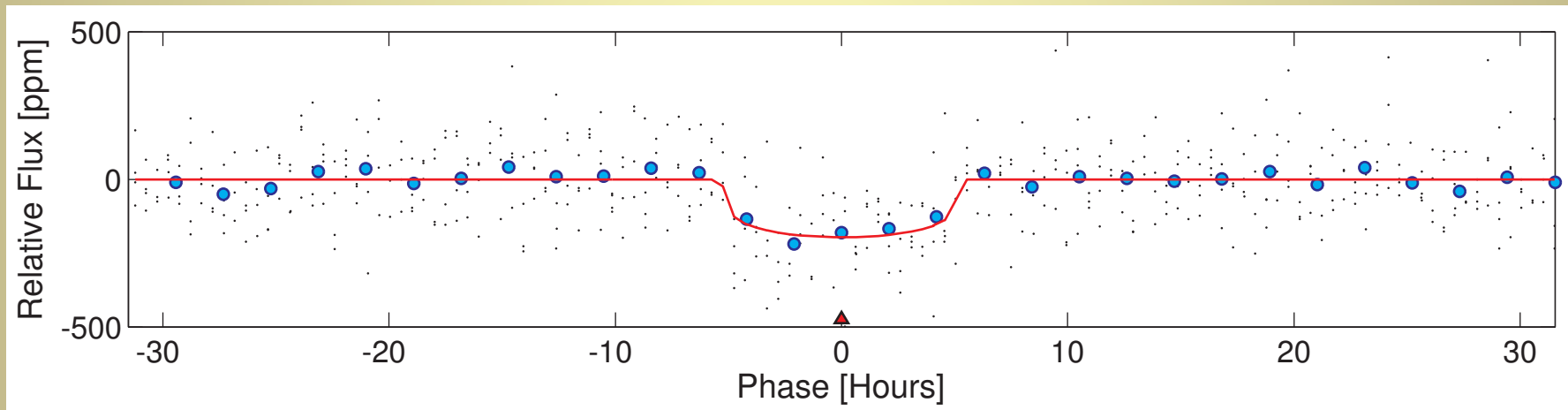
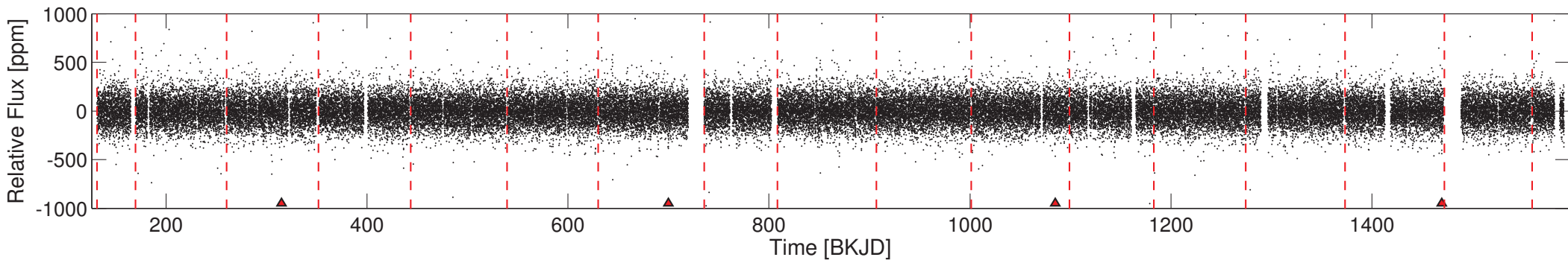
Kepler
A Search for Earth-size
Planets





An Interesting Light Curve

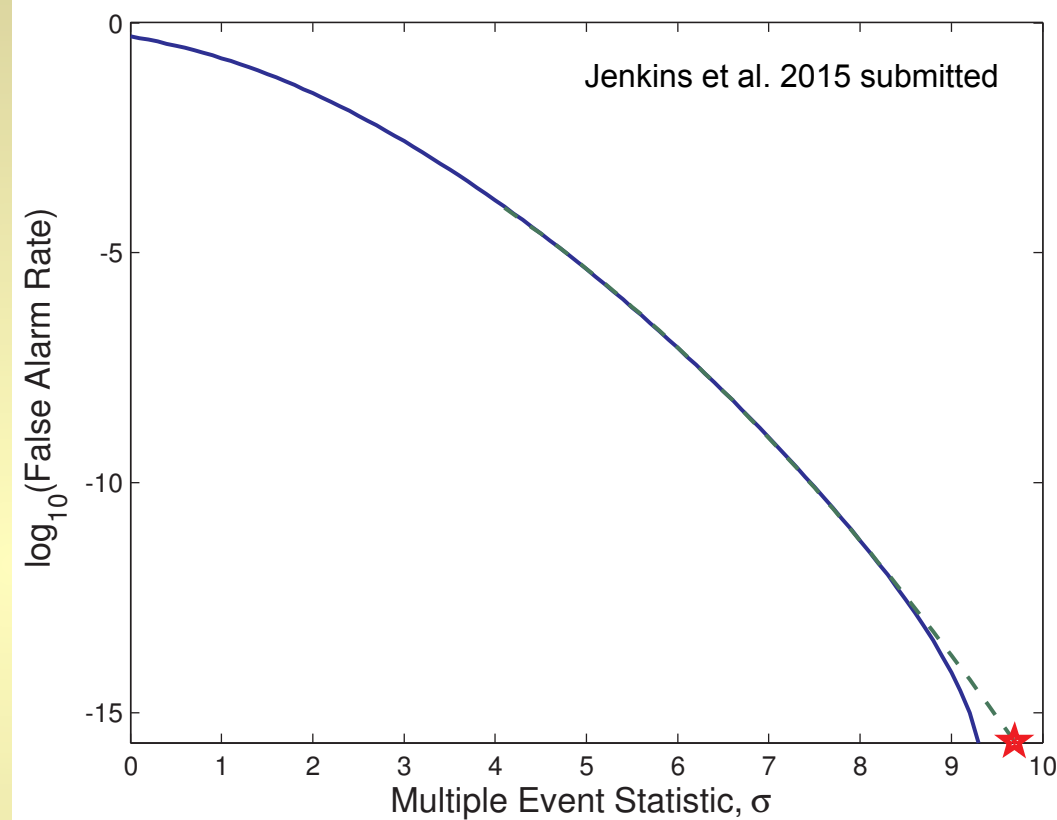
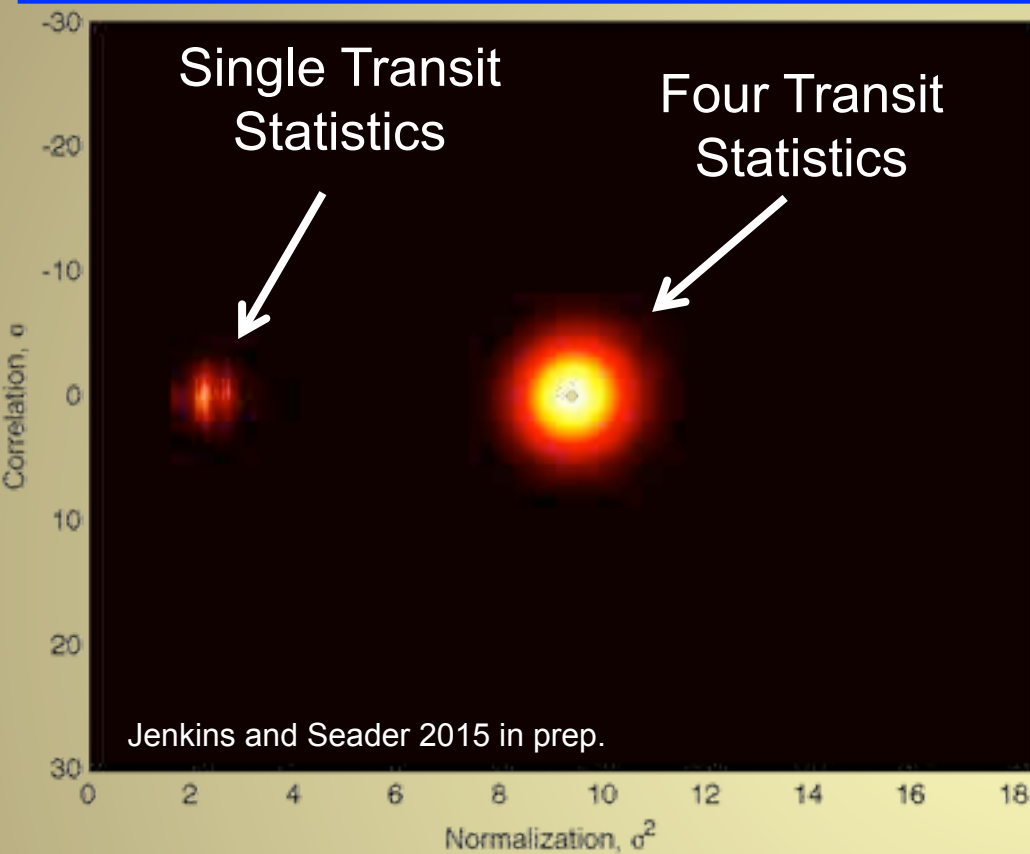
Kepler
A Search for Earth-size
Planets



Jenkins et al. 2015 submitted



Statistical Bootstrap Test



Detection statistic T :

$$T = \sum_i C_i / \sqrt{\sum_i N_i}$$

C is the correlation term

N is the normalization term

Density of m -transit null statistics can be modeled from 1-transit null statistics:

$$p_m(c, n) = p_1(c, n) * p_1(c, n) * \dots * p_1(c, n)$$

In the Fourier domain:

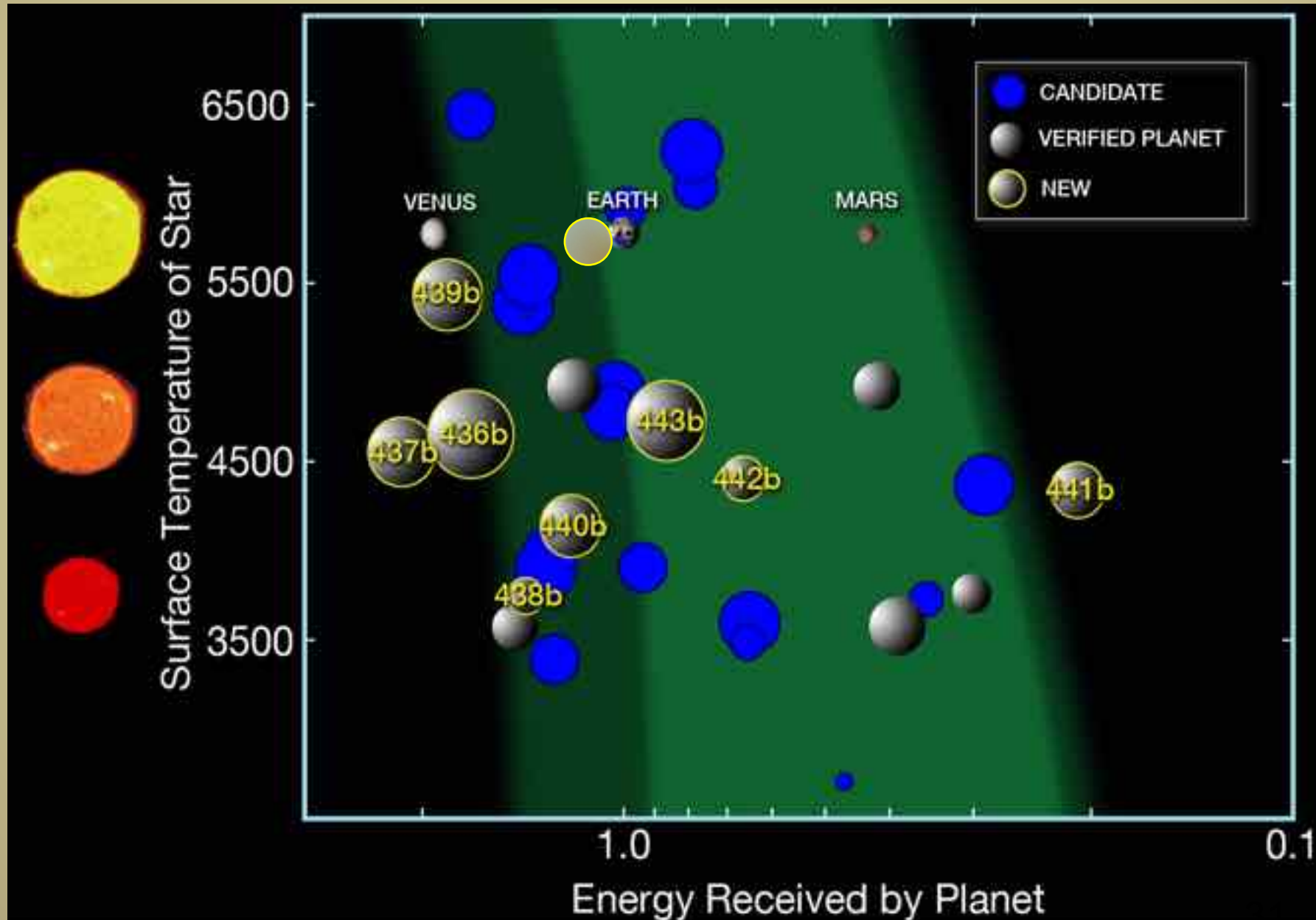
$$P_m(f_c, f_n) = \mathbf{F}\{p_m(c, n)\} = [P_1(f_c, f_n)]^m$$



Another New Planet

Kepler

A Search for Earth-size Planets



The Road to η_{\oplus} : Are We There Yet?

This is no time to fall asleep!





Baking the η_{\oplus} Cake

Kepler
A Search for Earth-size
Planets



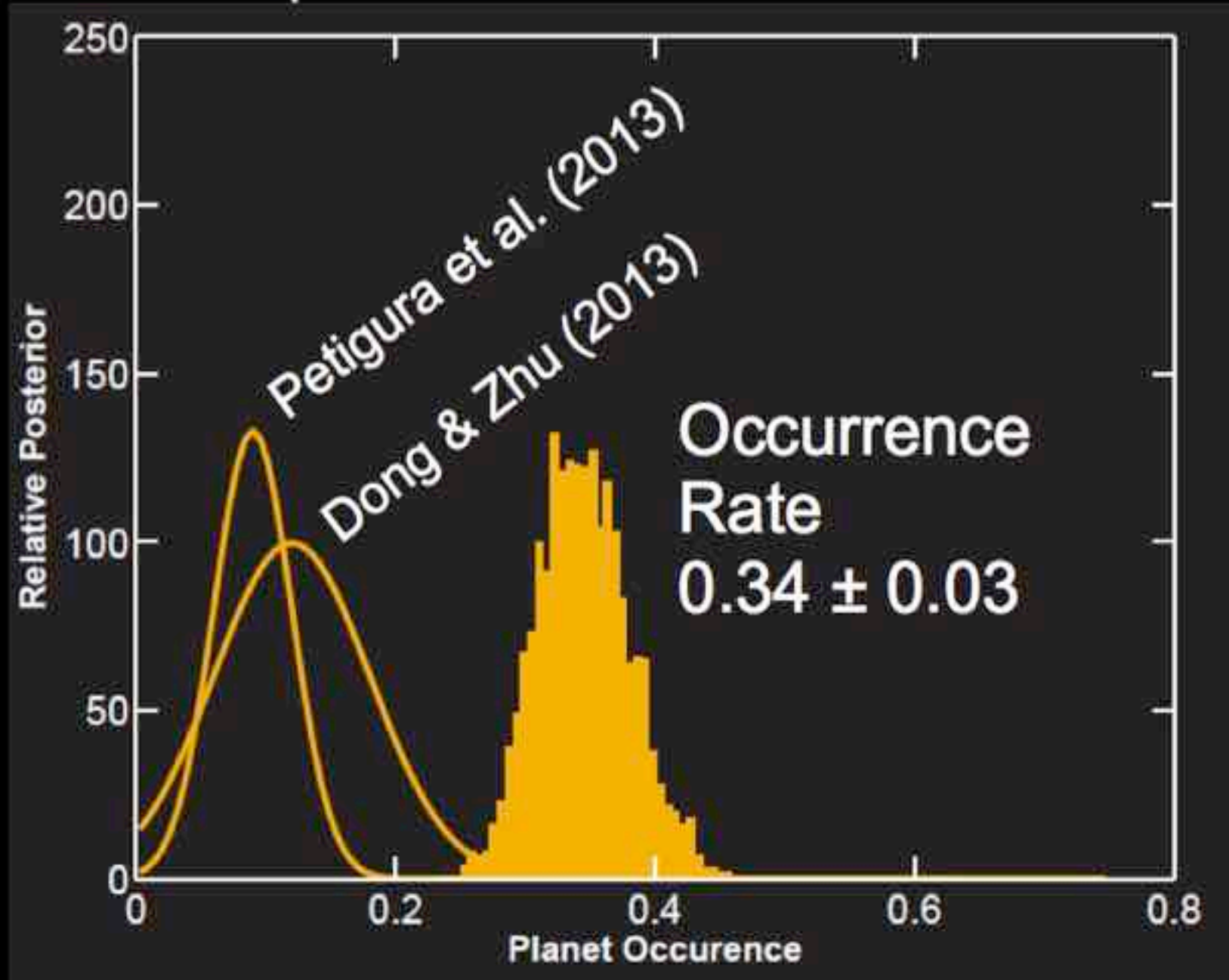
Natalie explains how it's done.

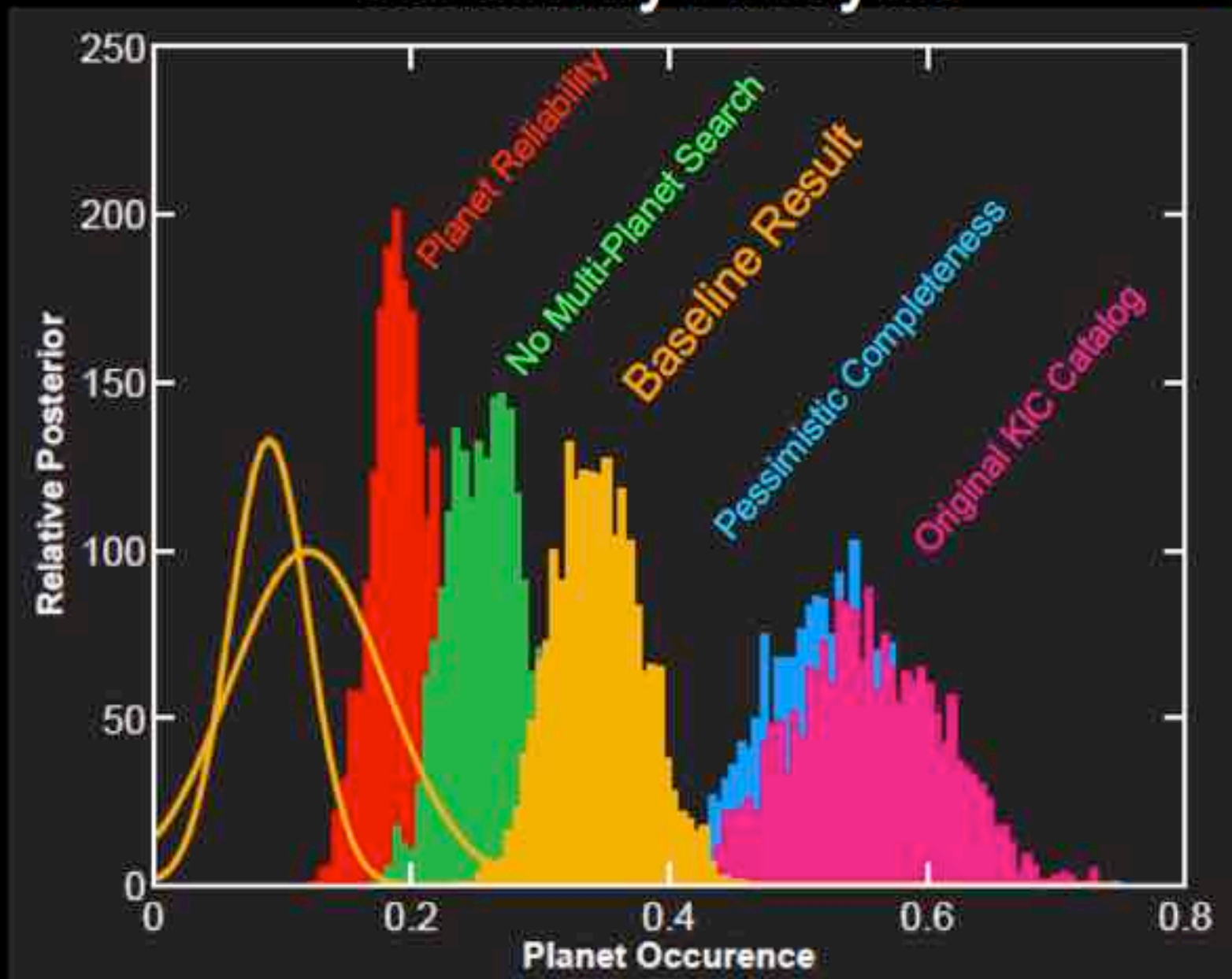
Some Key Ingredients:

1. Planet candidates and confirmed/validated planets
2. Completeness of the *Kepler* planet discovery system
3. Reliability of the *Kepler* planet discovery system
4. Updated stellar properties
5. Knowledge of background eclipsing binary distribution
6. Relation of target sample to general galactic stellar population



Planet Occurrence Comparison: $1 < R_p < 2 R_{\text{earth}}$; $50 < P_{\text{orb}} < 200$ day





Non-negligible Systematic Uncertainty in Occurrence Rates



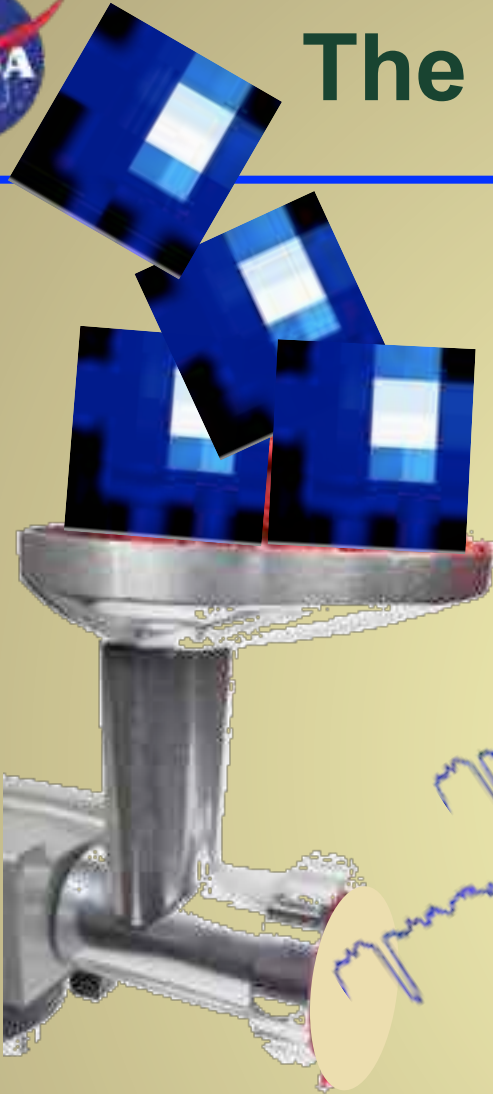
Characterizing the *Kepler* Planet Discovery System



The Kepler Sausage Maker

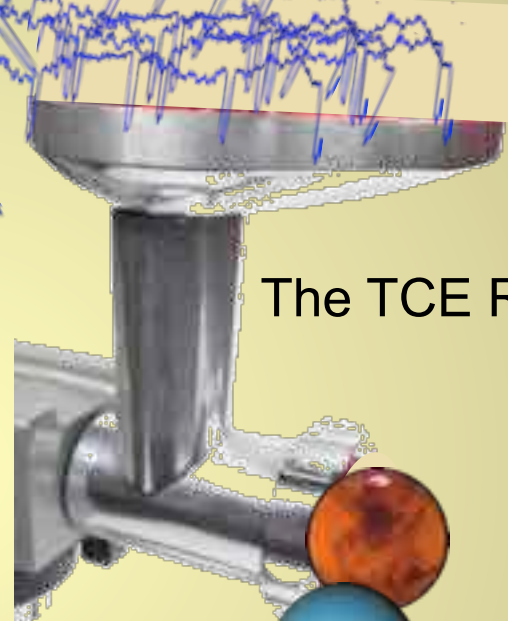
Kepler
A Search for Earth-size
Planets

Raw Data



TCEs and DV Reports

Light Curves



The TCE Review Team

The Pipeline

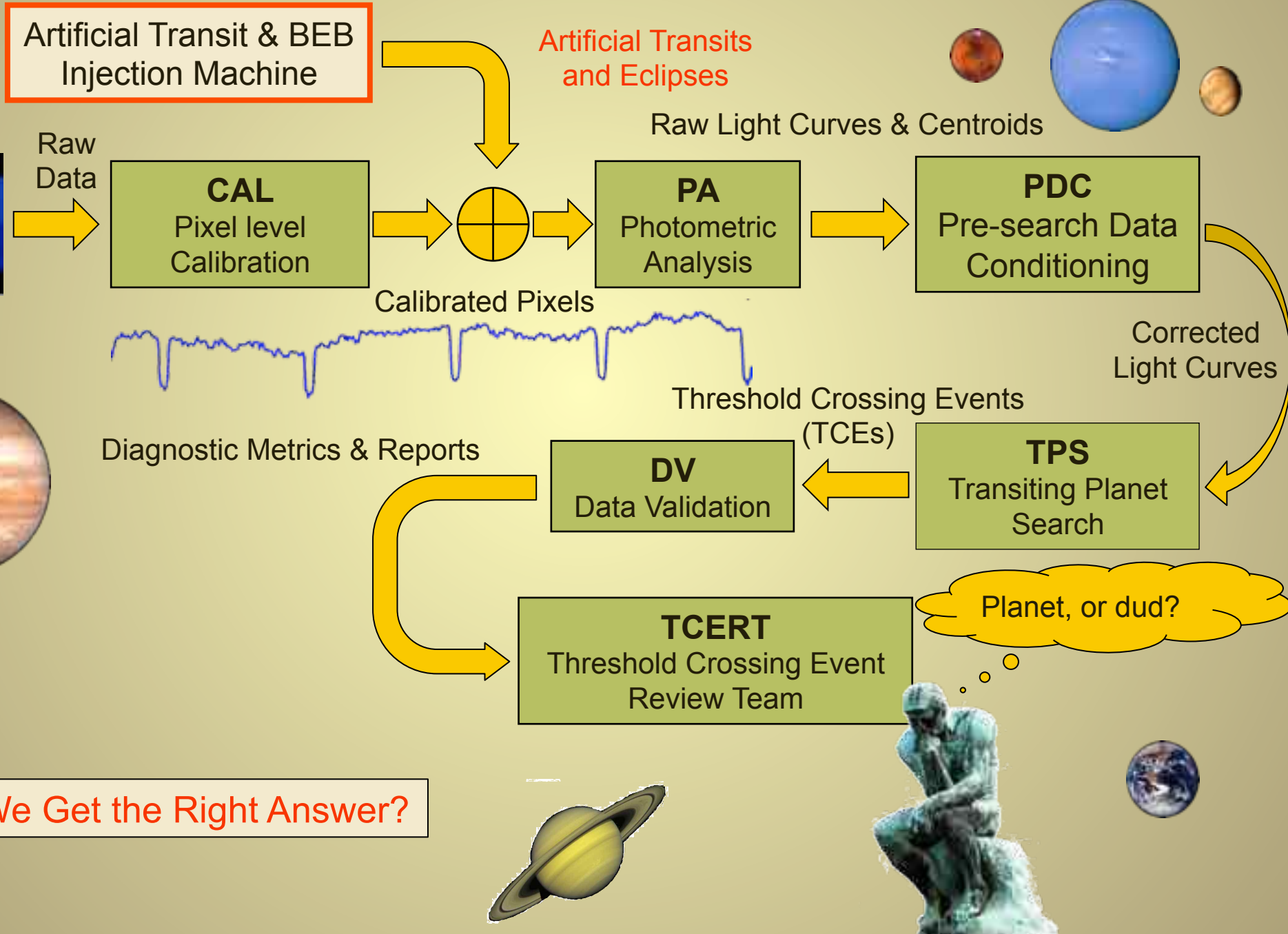


We need to characterize the completeness and reliability of the entire system!



Closing the Loop

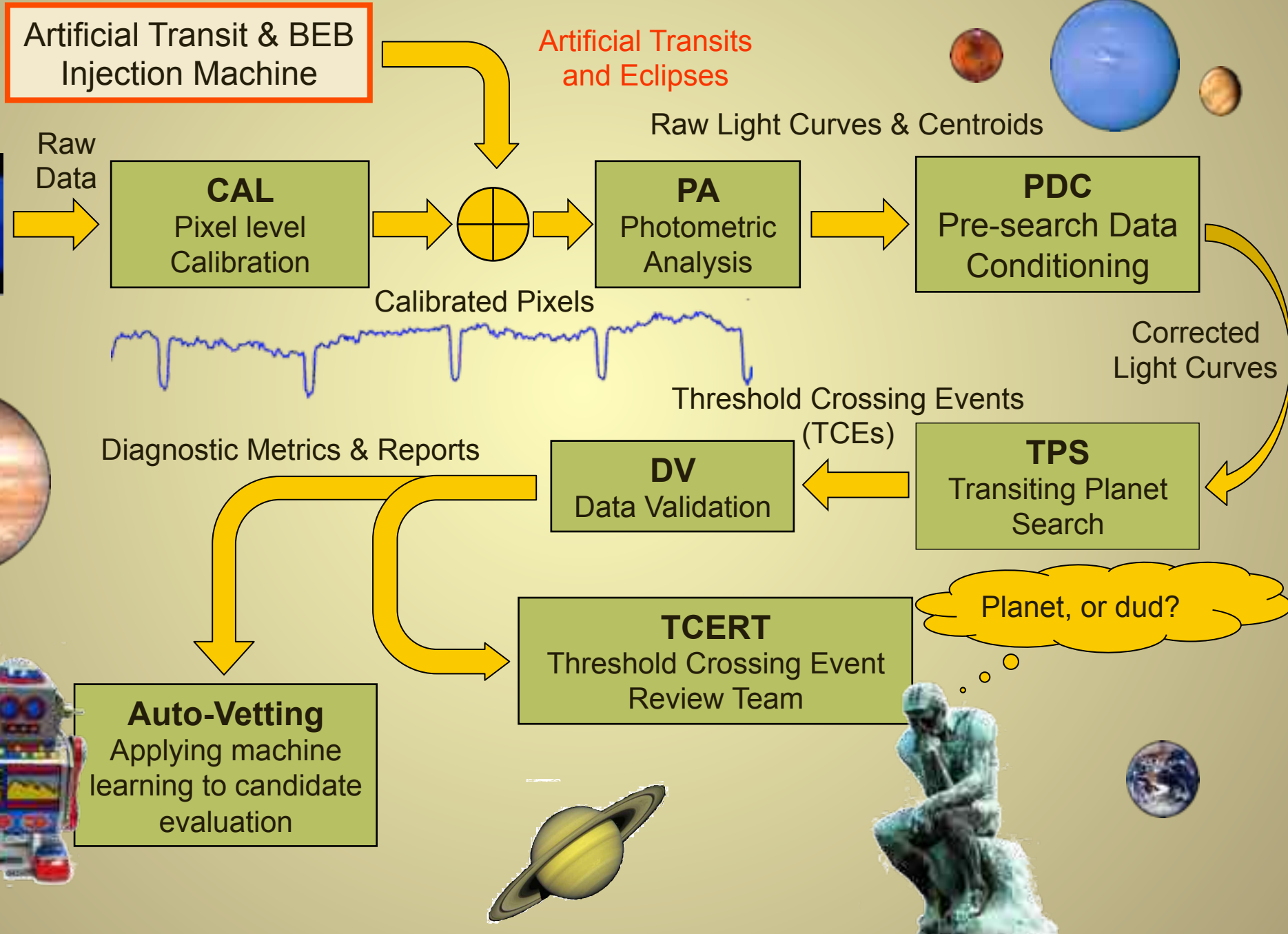
Kepler
A Search for Earth-size Planets





Keeping Up With the Data Avalanche

Kepler
A Search for Earth-size Planets



Random Forests for Auto-vetting

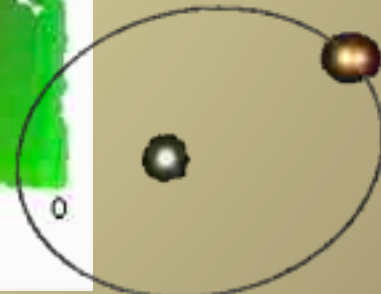
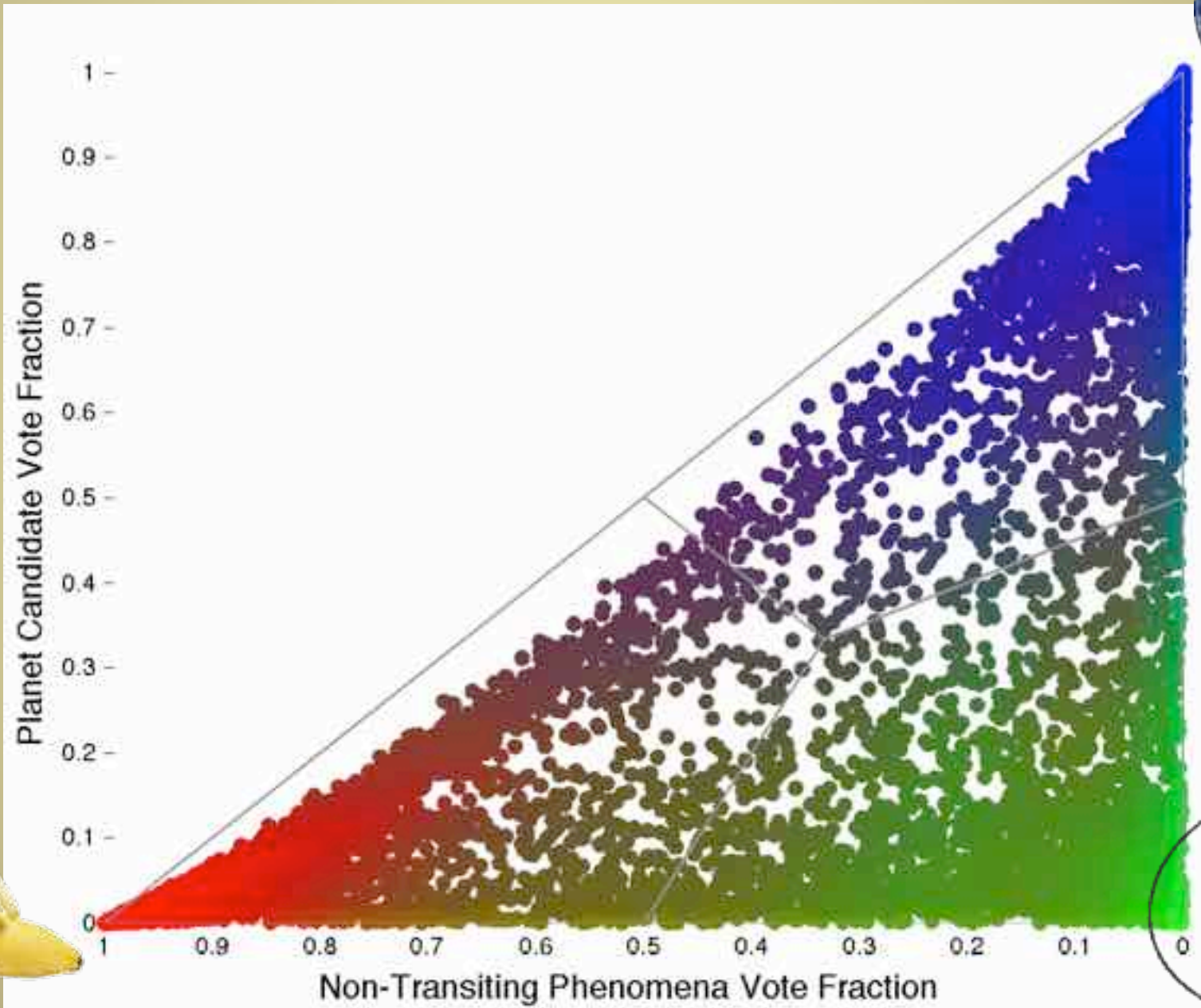




Random Forest Probabilities

Kepler

A Search for Earth-size Planets





TESS Elation!

- All sky transit survey to find Earth's closest cousins
- Selected for flight in Spring 2013
- PDR held in October 2014
- CDR scheduled for August 2015
- Launch in August 2017
- 2 year primary mission

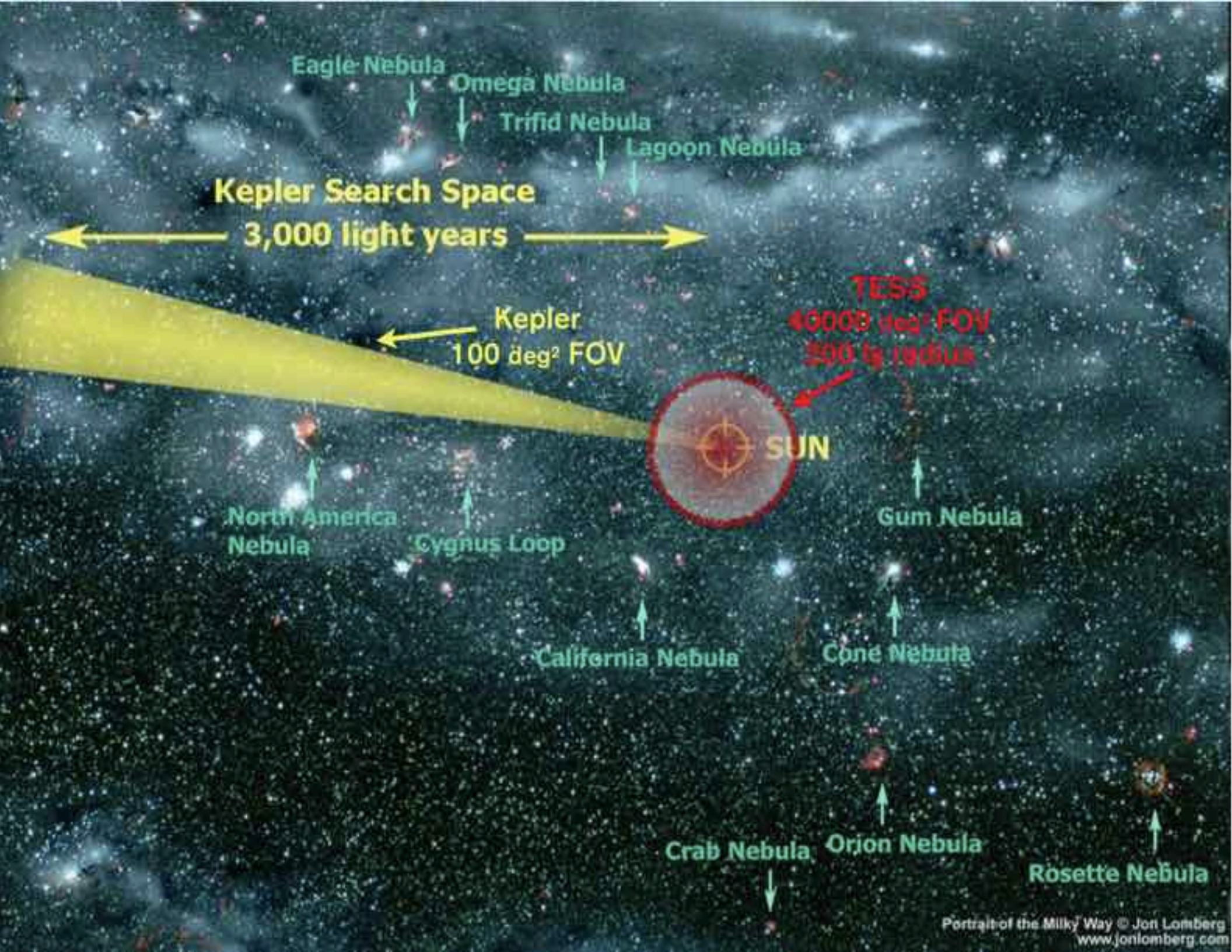
Nominal science data:

- >15,000 10x10 pixel postage stamp targets in each FOV
- 2 min cadence for all stars
- 27 days on each “slice” FOV
- Data processed and archived within 4 months of collection
- >10X the data rate of Kepler at the pixel level

Additional science:

- Full Frame Images at least every 0.5 hours
- will support phenomenal data mining science

Huge opportunities for ground-based follow up for confirmation and characterization of the mass, etc.



Eagle Nebula
Omega Nebula
Trifid Nebula
Lagoon Nebula

Kepler Search Space

3,000 light years

Kepler
100 deg² FOV

TESS
40000 deg² FOV
200 ly radius

SUN

North America
Nebula

Cygnus Loop

Gum Nebula

California Nebula

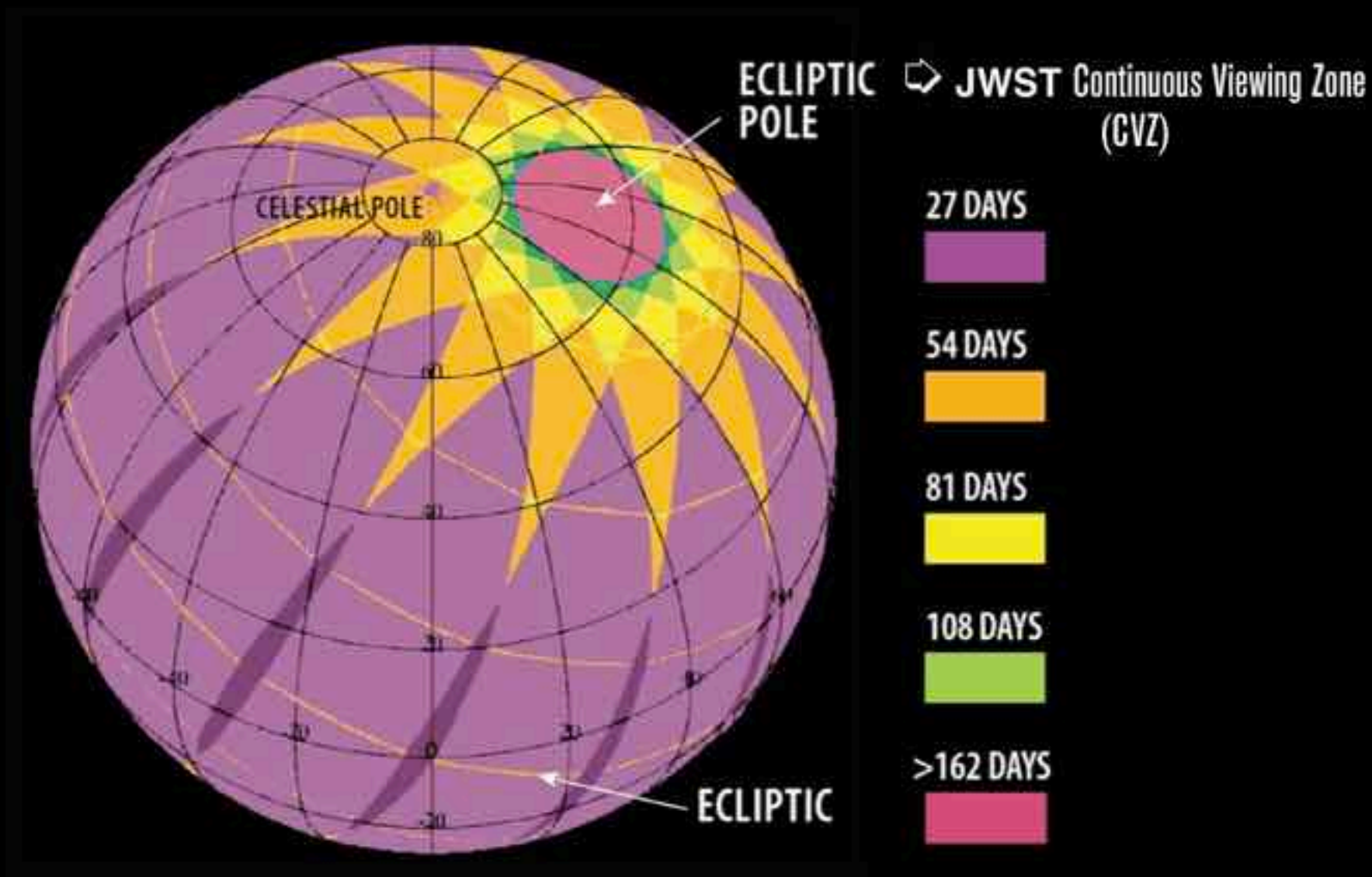
Cone Nebula

Crab Nebula

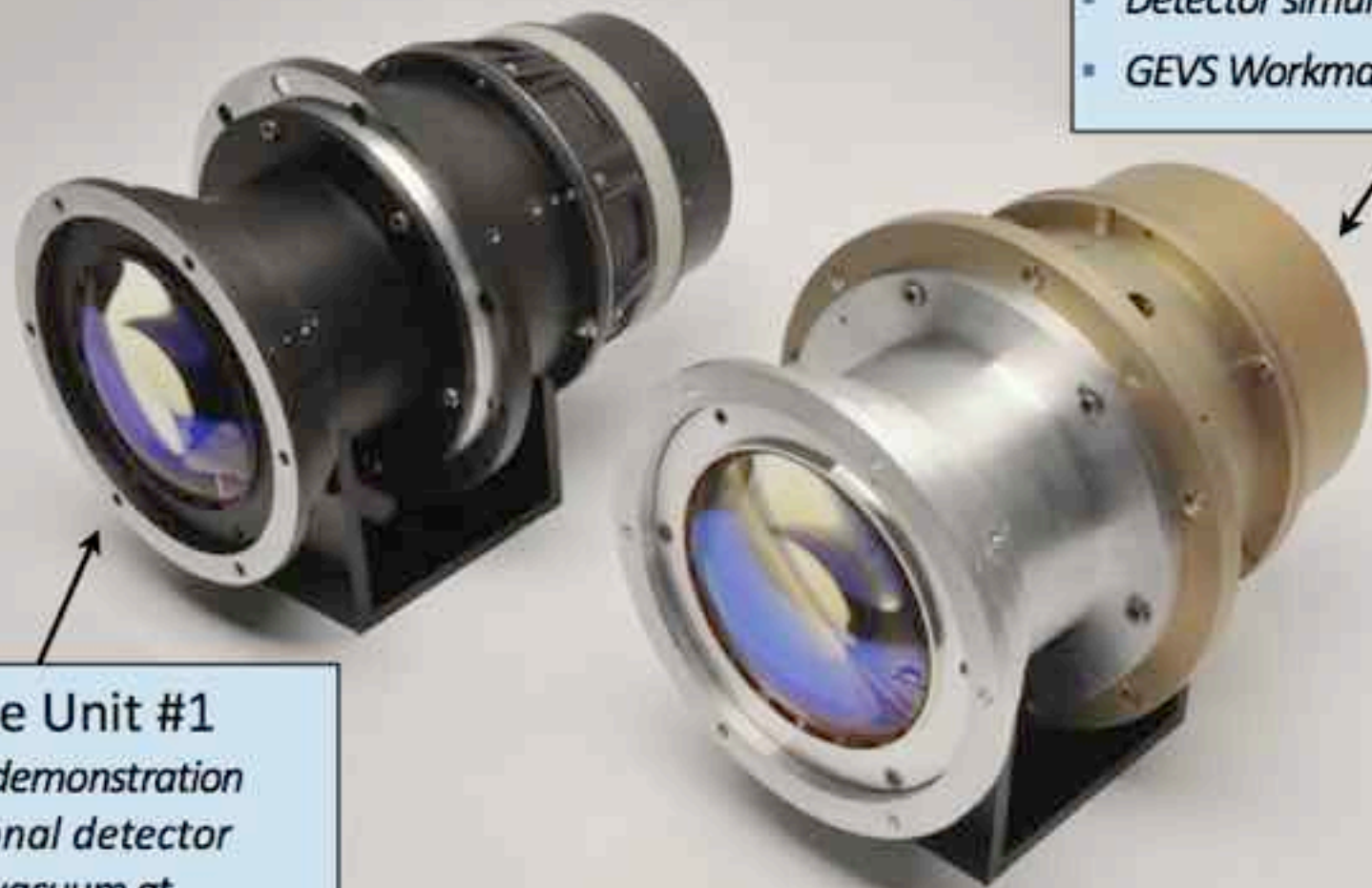
Orion Nebula

Rosette Nebula

TESS Sky Coverage







Prototype Unit #1

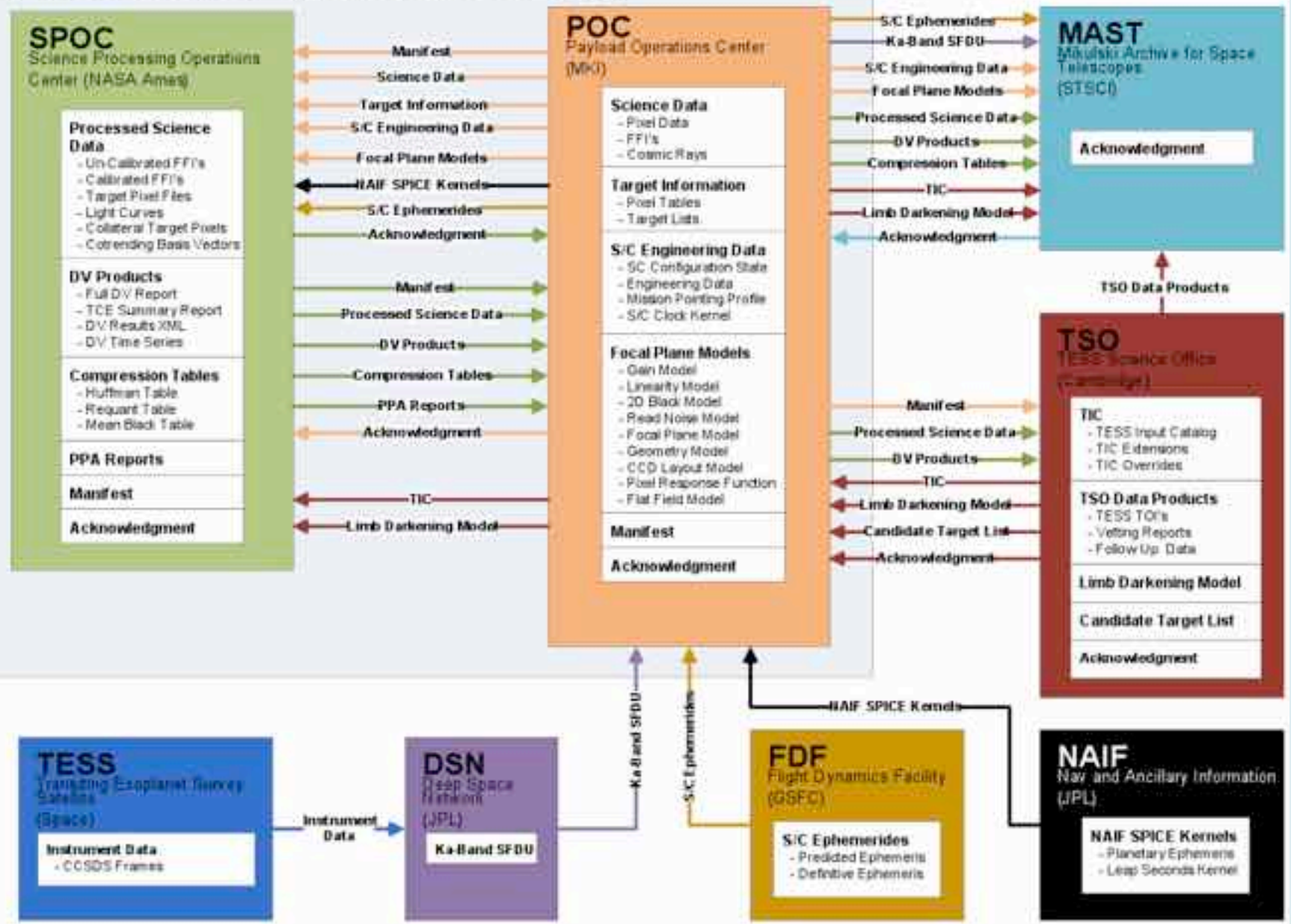
- *Thermal demonstration*
- *Operational detector*
- *Thermal vacuum at operational temperature*

Prototype Unit #2

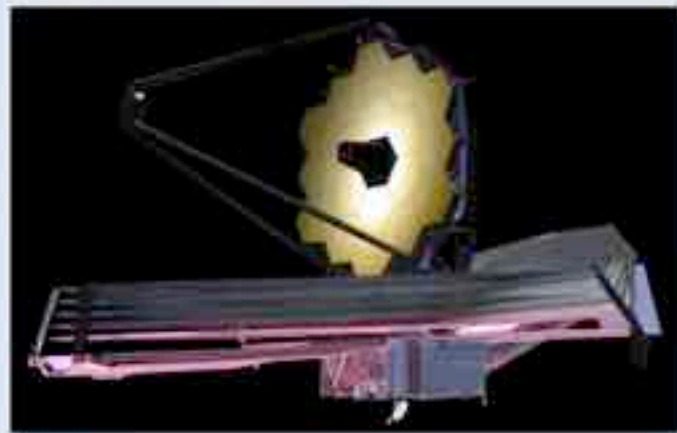
- *Vibration demonstration*
- *Detector simulator*
- *GEVS Workmanship*

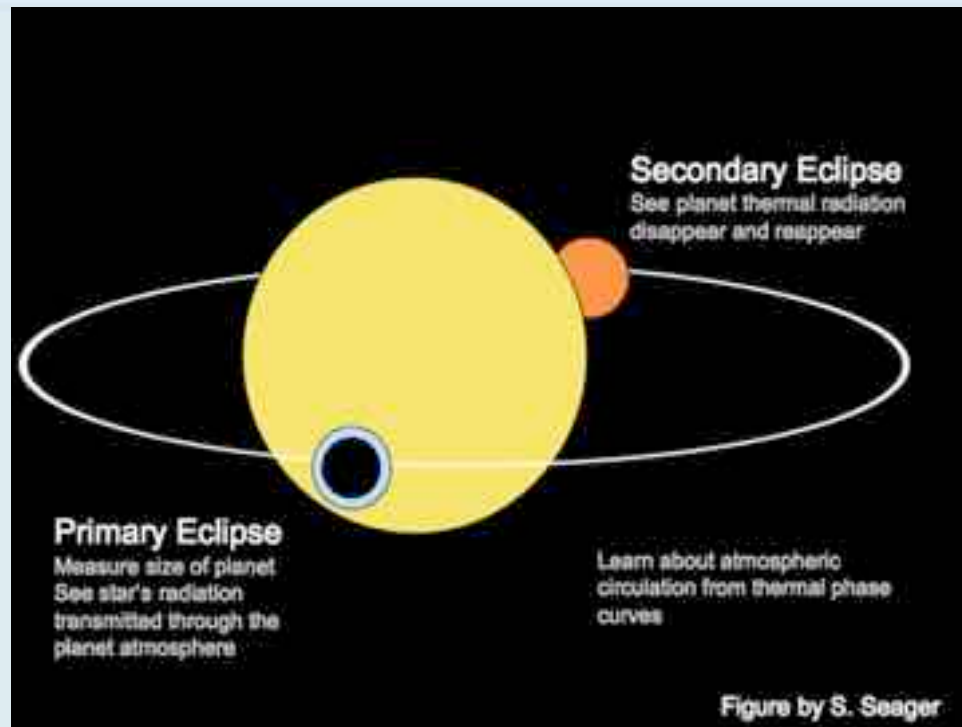


TESS Science Operations Center

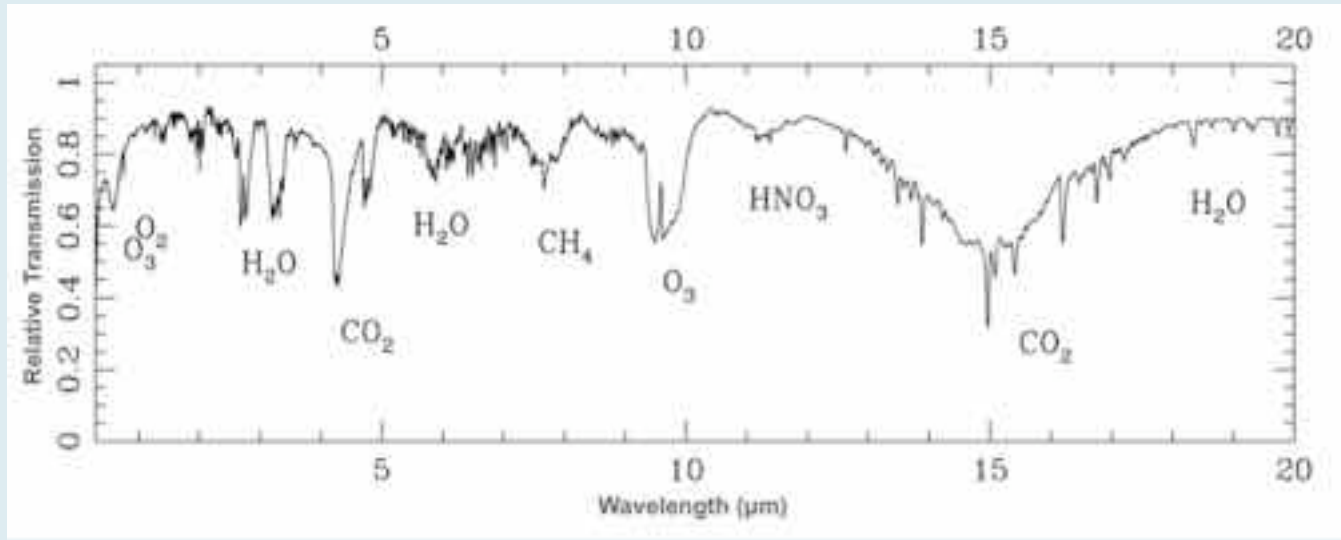


- ◆ TESS will identify the **best and smallest** exoplanet targets for characterization of atmospheres using:
 - *JWST*
 - *Extremely Large Telescopes (ELTs)*
 - *Future Exoplanet Explorers, Probes, and Large Missions*





Transiting planets provide opportunities to determine the bulk planetary density and to characterize their atmospheres



Kaltenegger, L. and Traub, W. (2009) Transits of Earth-Like Planets, ApJ



Summary

Kepler
A Search for Earth-size
Planets

- Kepler has returned a bonanza of planets – far more than any other mission or project
- Characterizing the completeness and reliability of the *Kepler* results are key objectives of the close out mission
- Machine learning promises to significantly reduce the amount of time humans need to spend on “duds” – very important for TESS and PLATO
- K2 should bridge exoplanet science between *Kepler* and TESS
- TESS will fill the sky map with Earth- and super-Earth-size exoplanets starting in 2017

Thank You!



Bill Borucki, David Koch, Natalie Batalha and Doug Caldwell celebrating launch

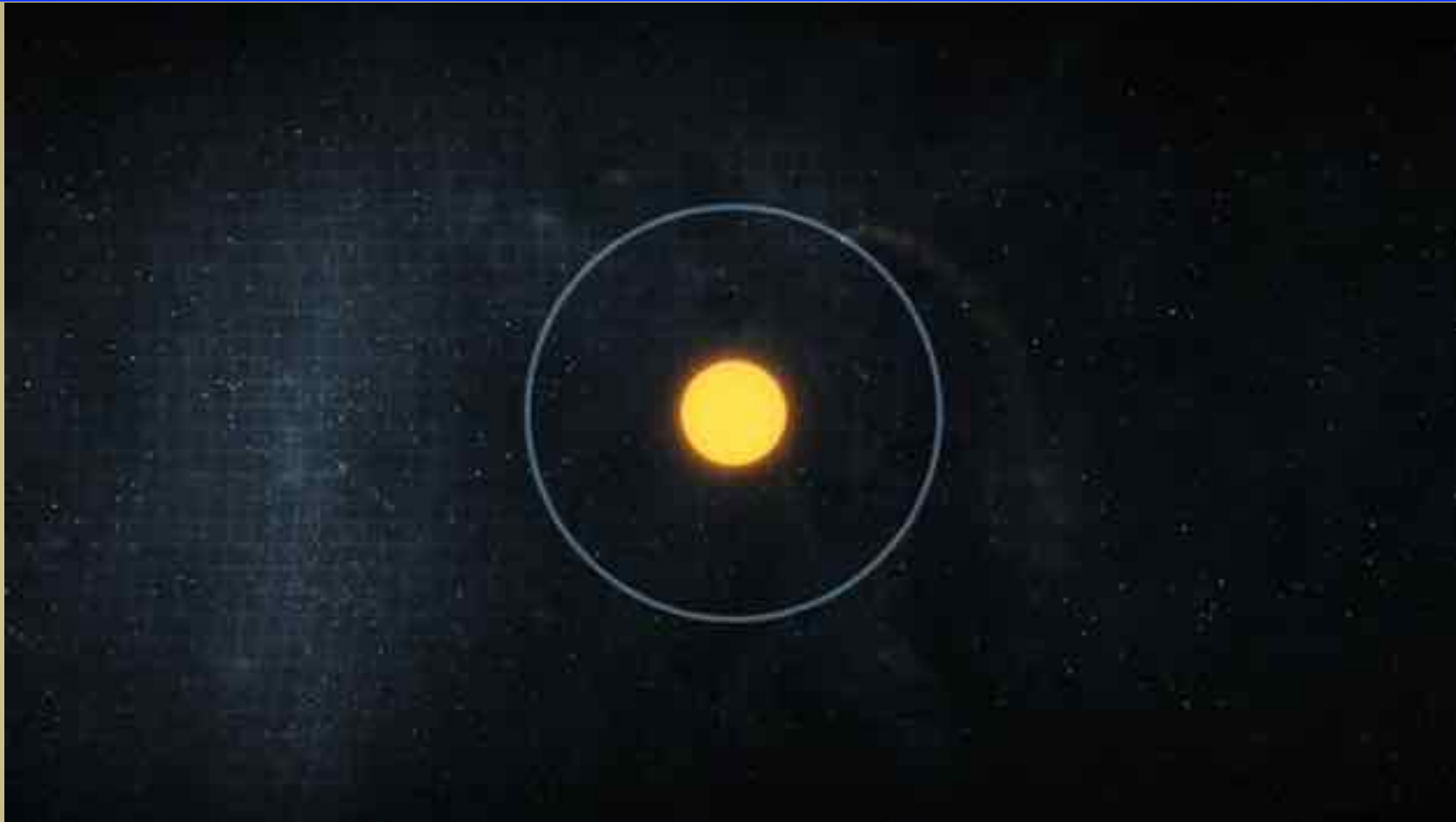


A Disintegrating Sub-Mercury Size Planet

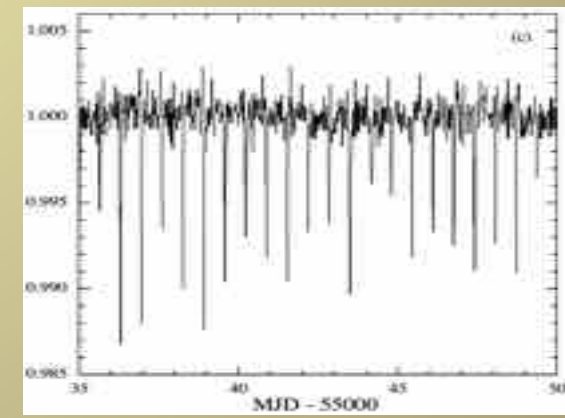
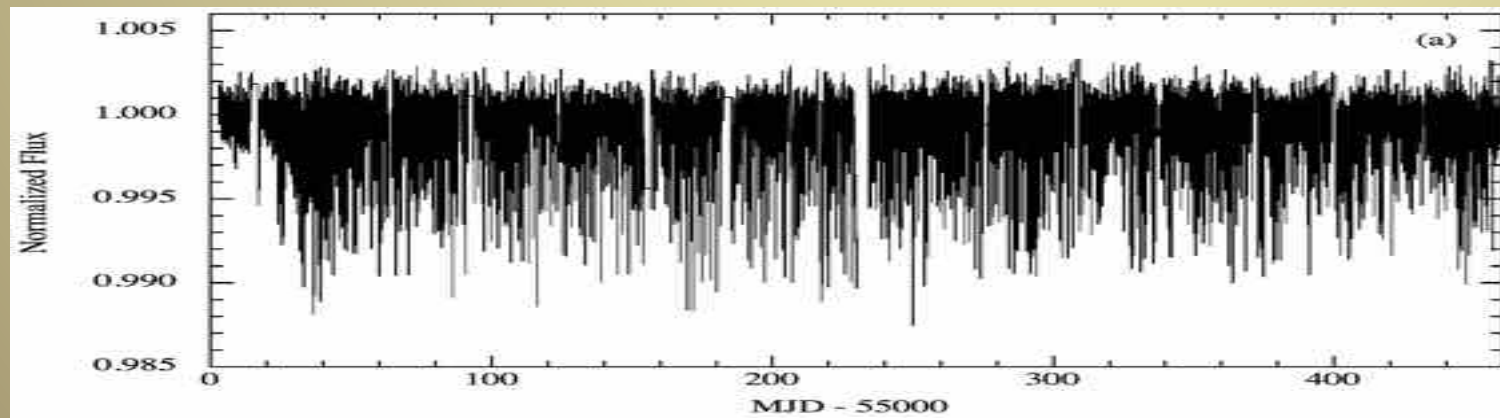
Kepler

A Search for Earth-size Planets

KIC 12557548



Rappaport et al. ApJ 2012





Kepler

*A Search for Earth-size
Planets*

K2

Kepler's Second Mission

K2 - a 2-wheel Kepler mission; The second highest peak in the world, a worthy ascent

Kepler Through the Years



June 2009



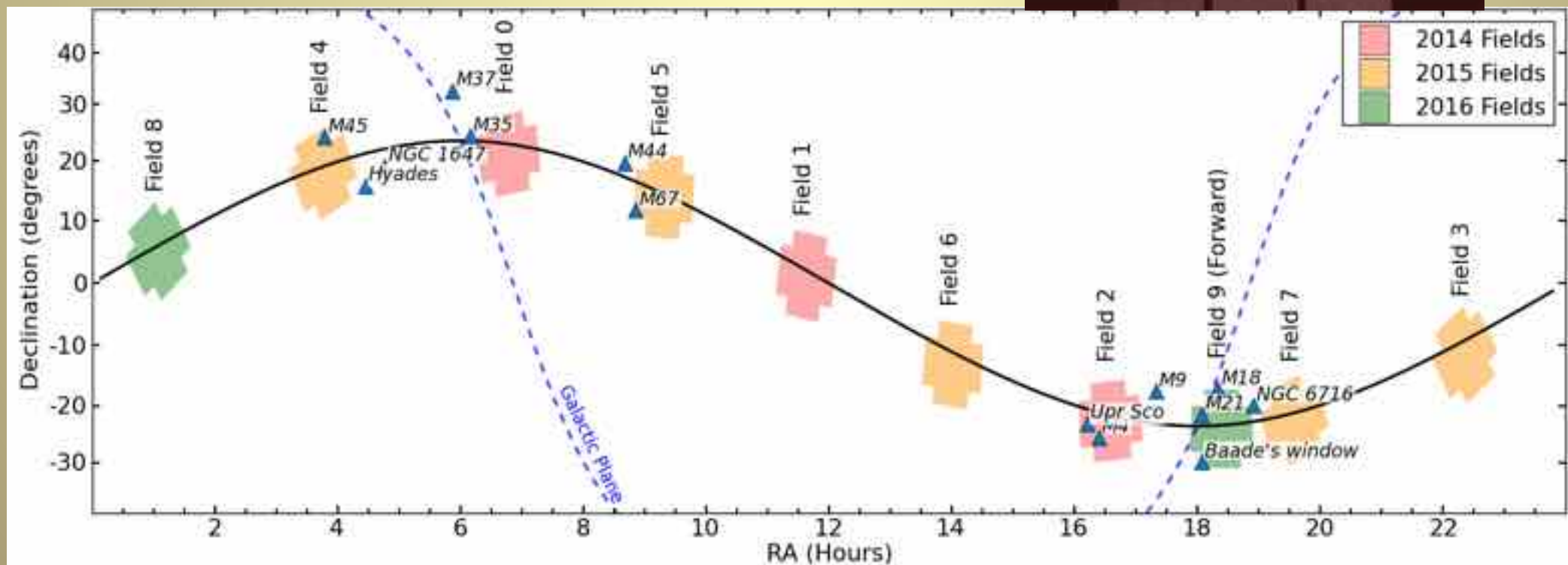
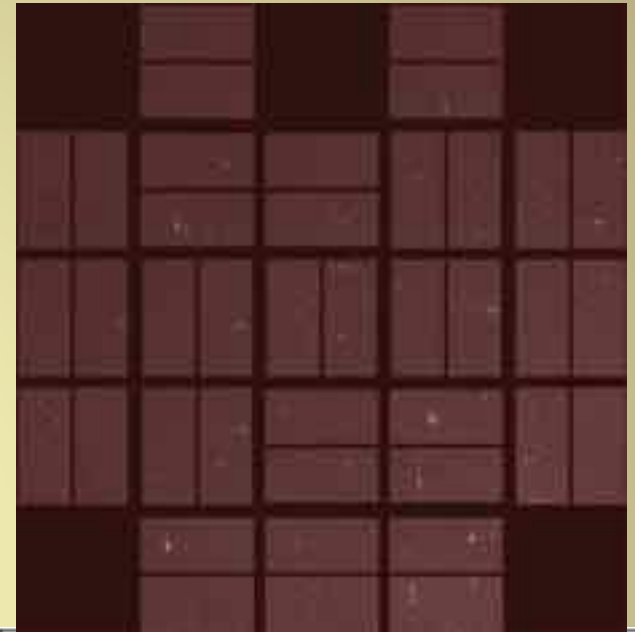


Proposed Campaign Fields

Kepler

A Search for Earth-size Planets

- K2 Mission approved by 2014 Senior Review
- Campaign 4 is underway
- Light curves are on their way

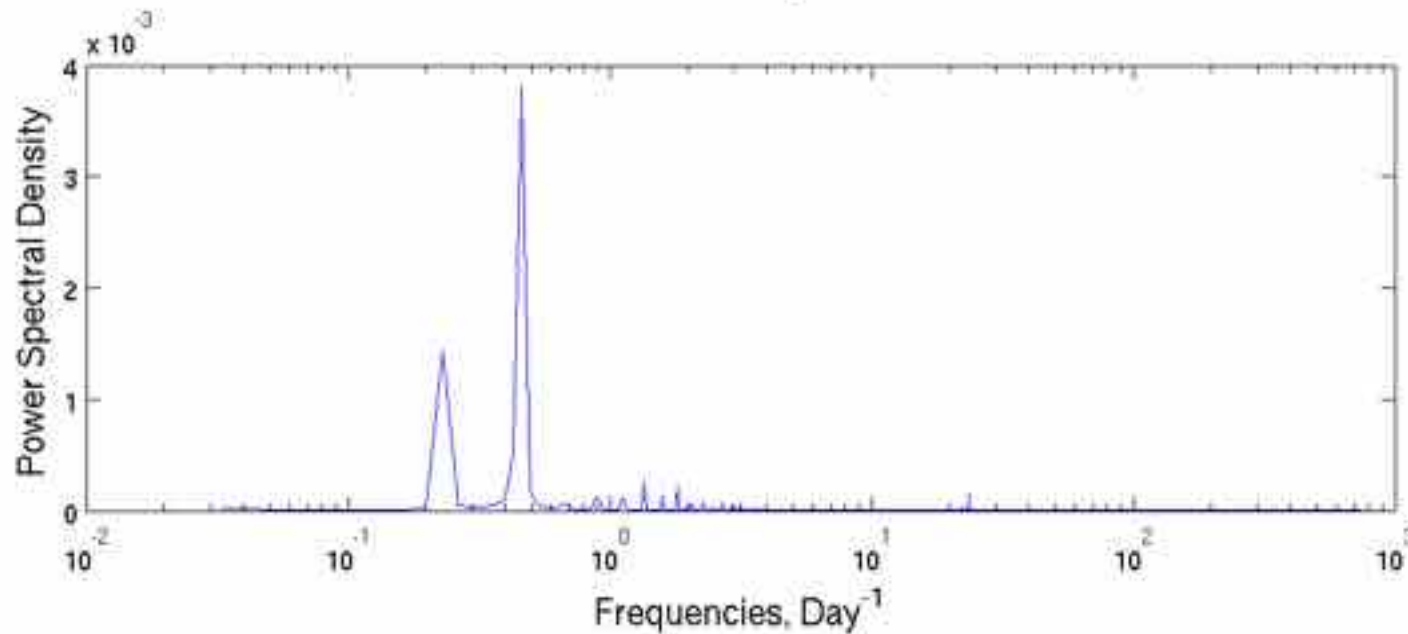
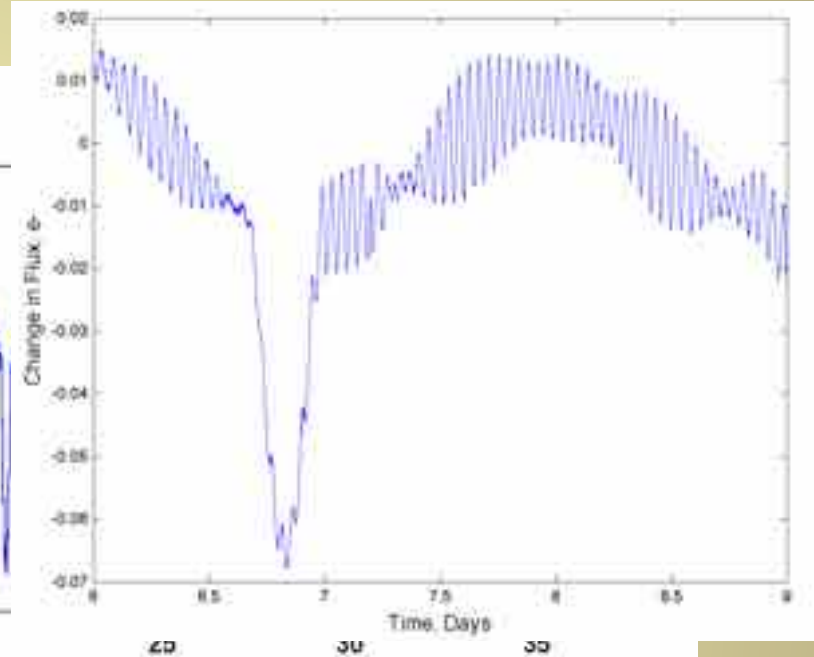
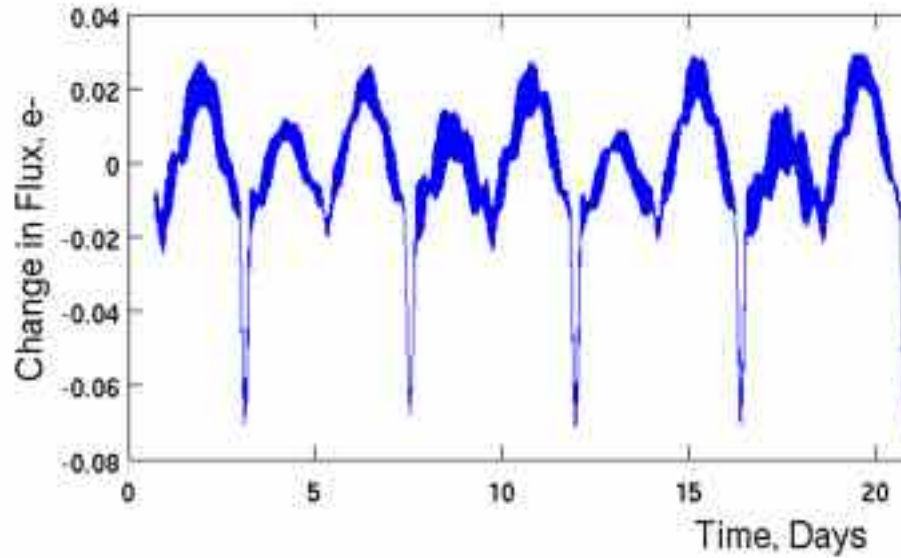




Music From the Stars

Kepler

A Search for Earth-size Planets





Heartbeat Stars: KOI-54

Kepler

A Search for Earth-size Planets

