Prospecting for Habitable Planets

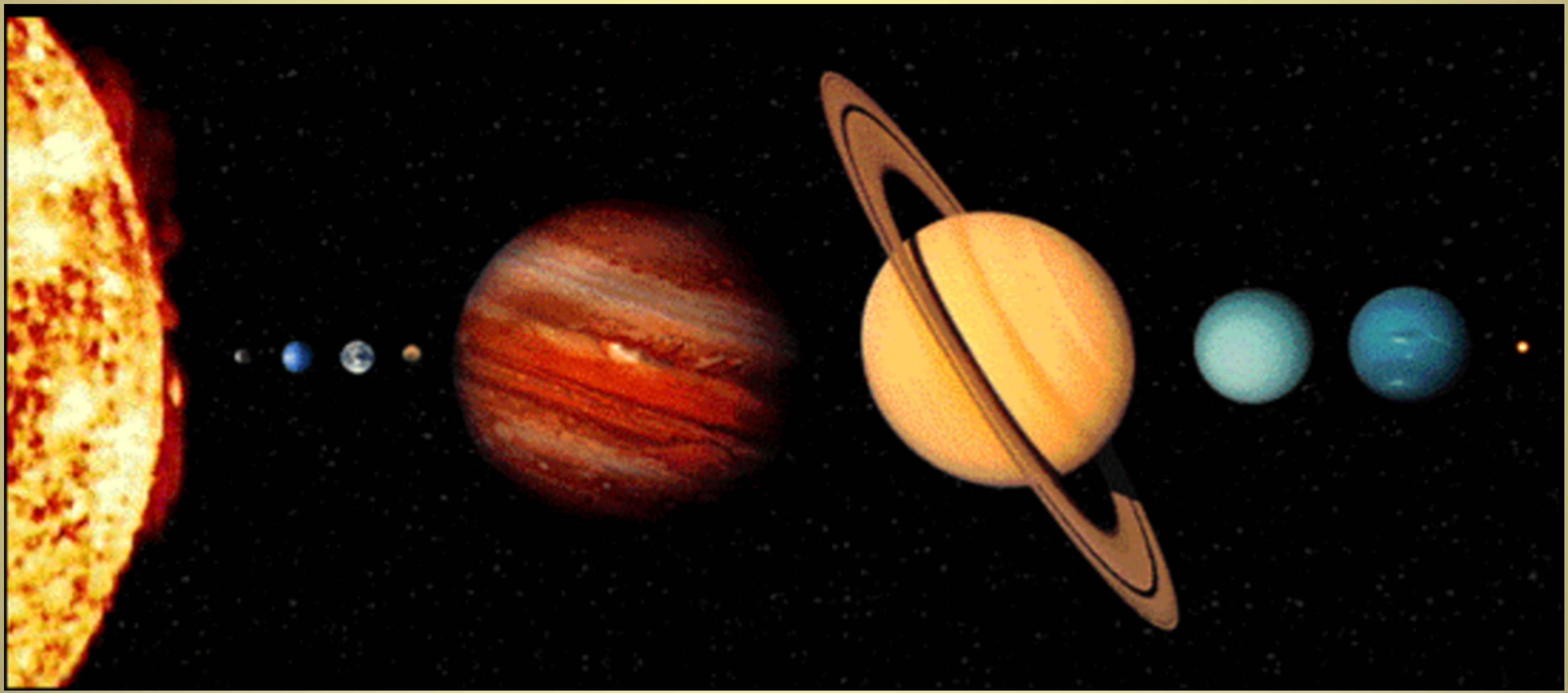
Jon M. Jenkins
NASA Ames Research Center

Monday March 27, 2017

KLA-Tencor Corporation
Milpitas, CA

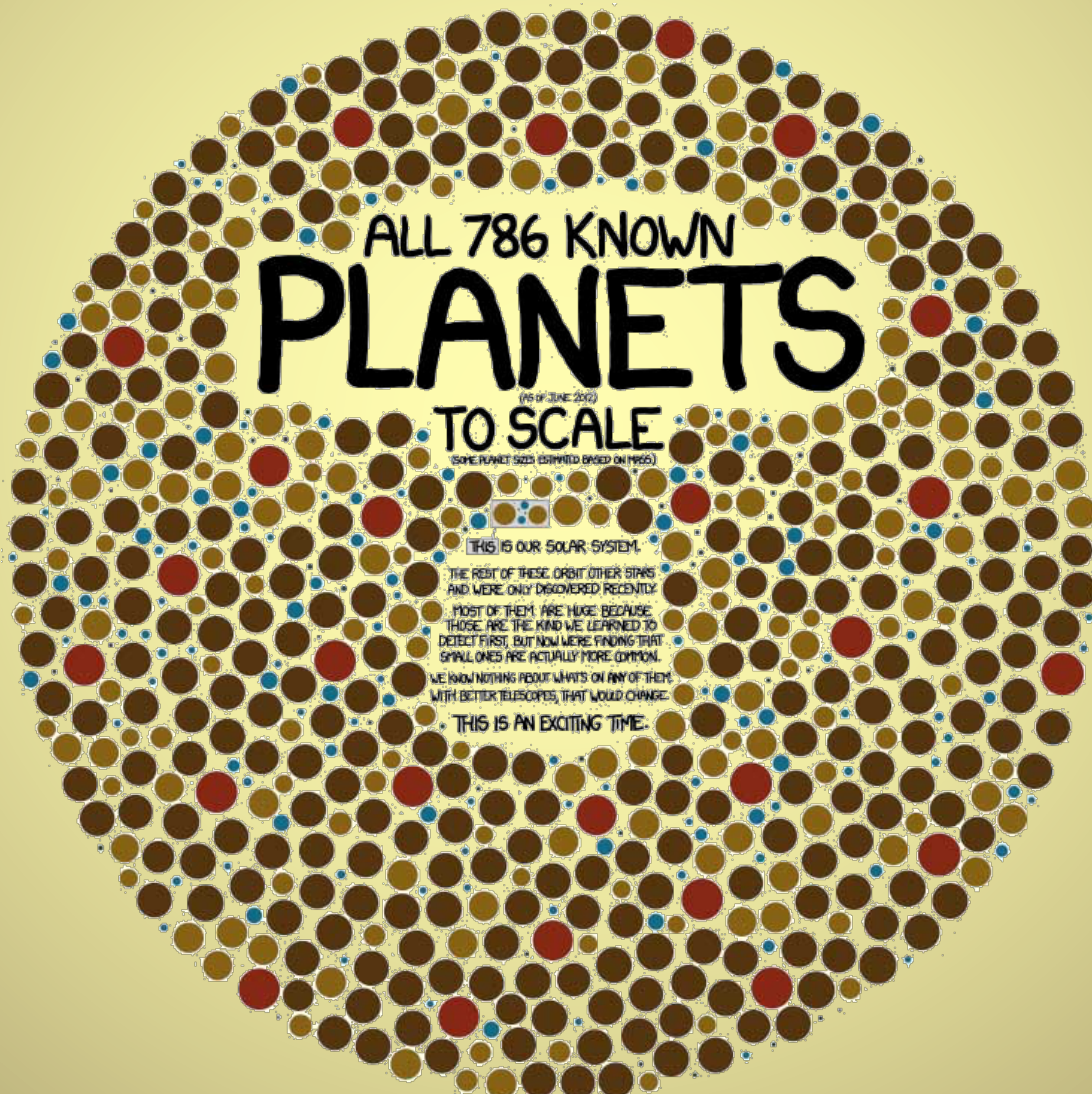
A Search for Earth-size Planets

All the Known Planets In 1994



A More Recent Pictures of Planets

A Search for Earth-size Planets



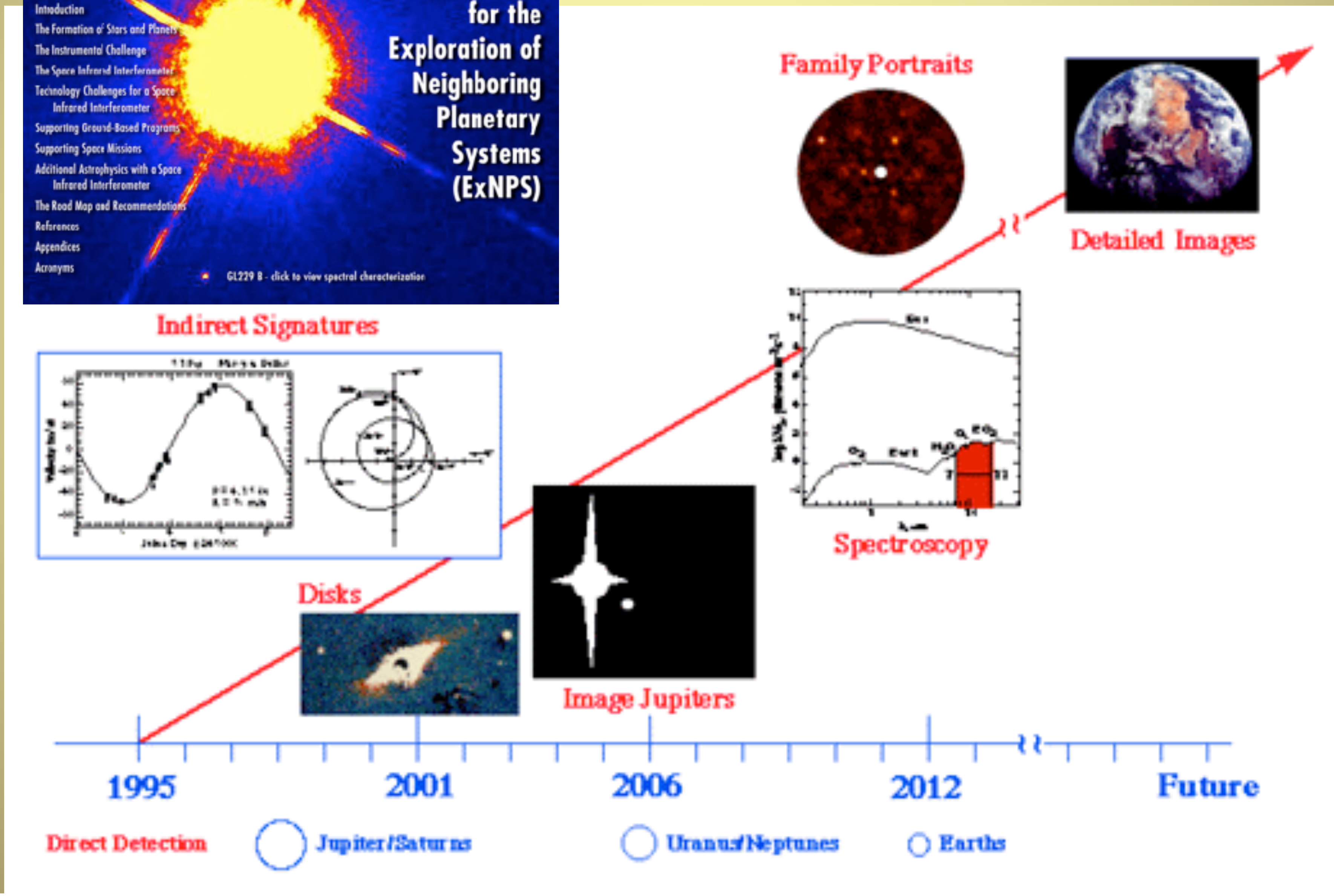
https://xkcd.com/1071/

A Search for Earth-size

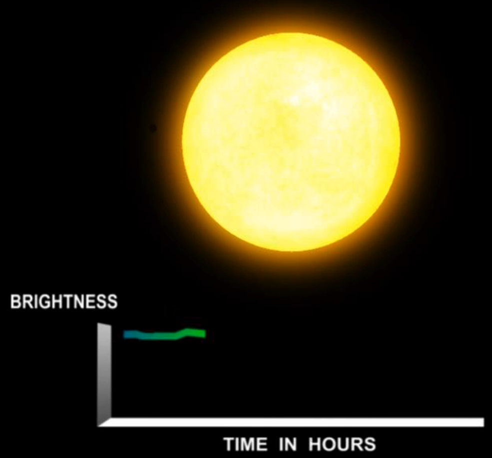
NASA's 1995 ExNPS Report

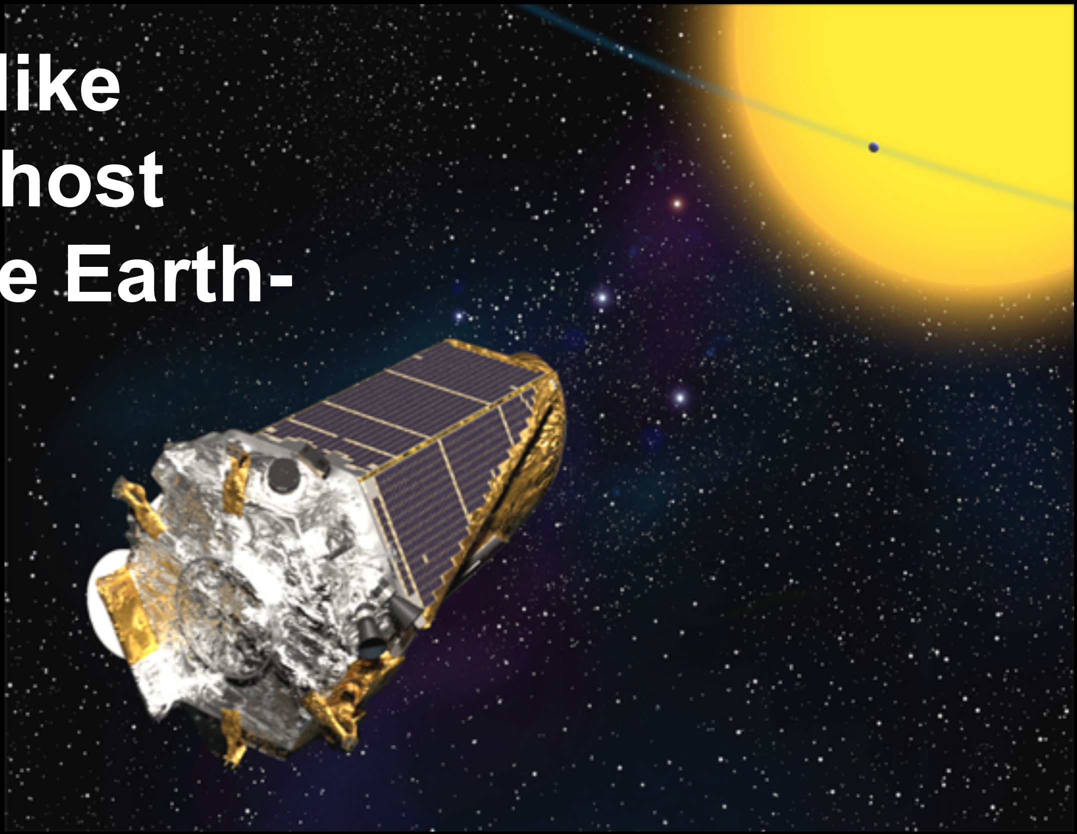
Kepler
A Search for Earth-size Planets

Transit Photometry not Recommended!



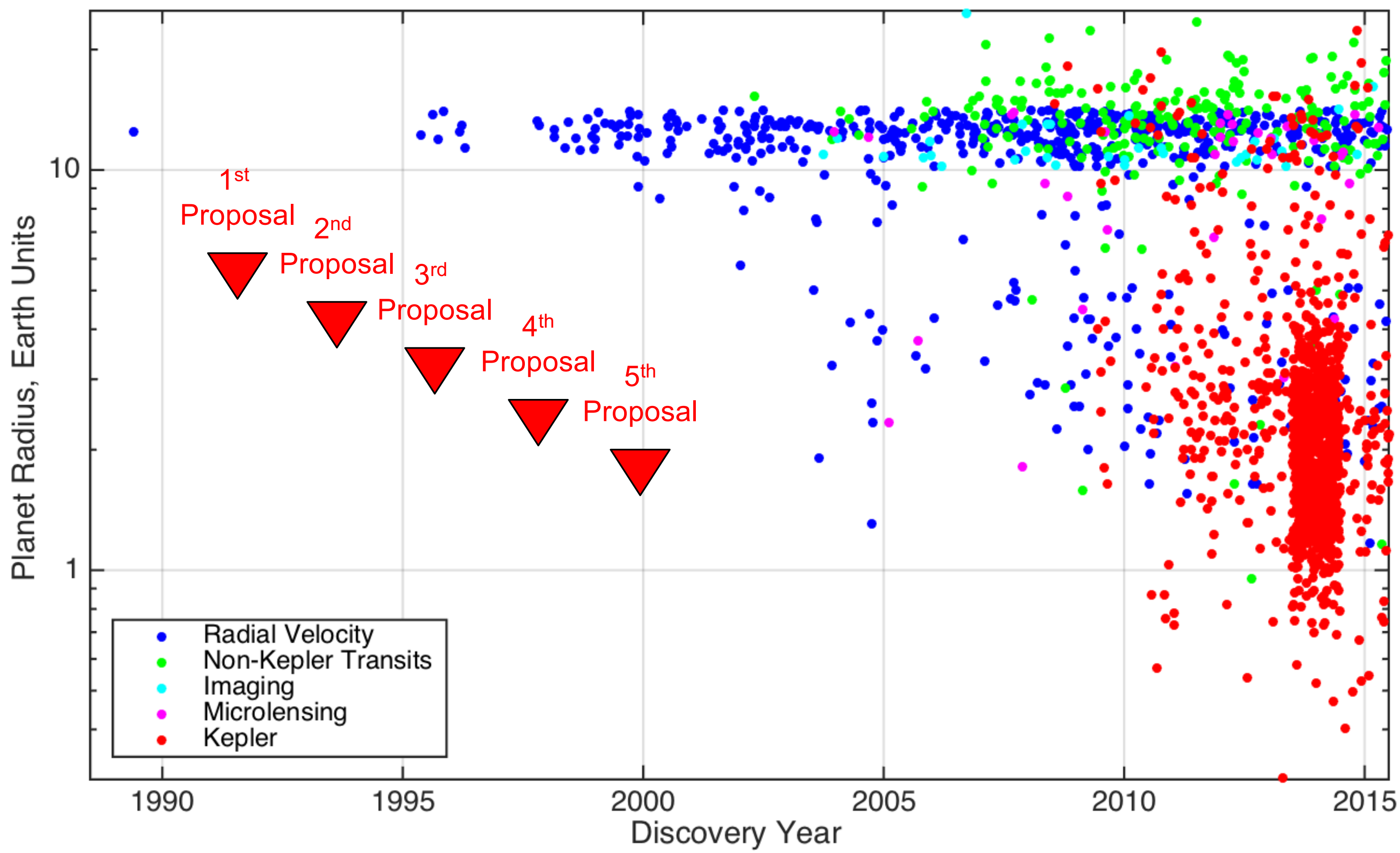
What fraction of sun-like stars in our galaxy host potentially habitable Earth-size planets?





Exoplanet Discoveries Over Time

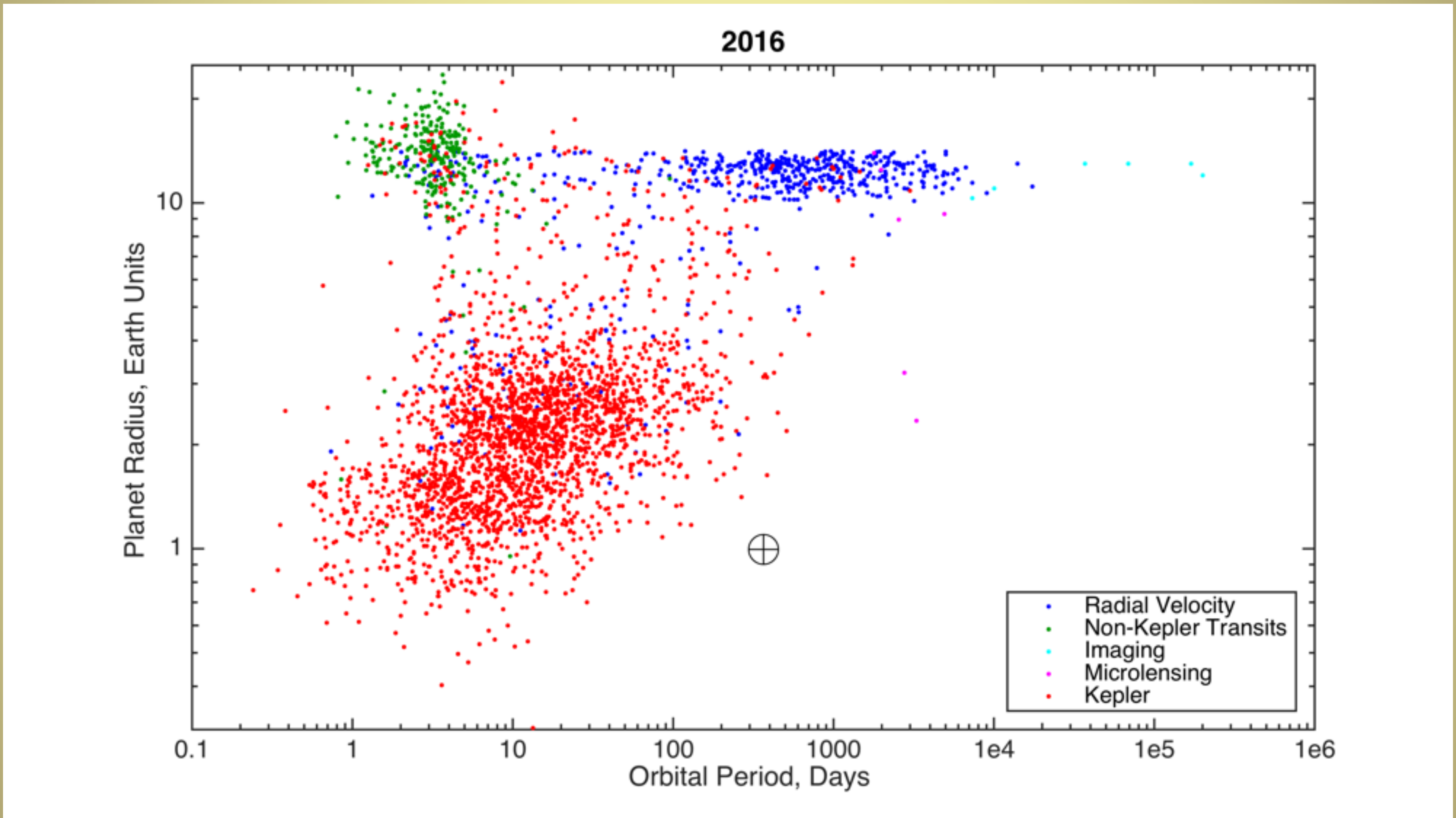
Kepler
A Search for Earth-size Planets



Radii estimated for non-transiting exoplanets
Discovery data dithered randomly within discovery year

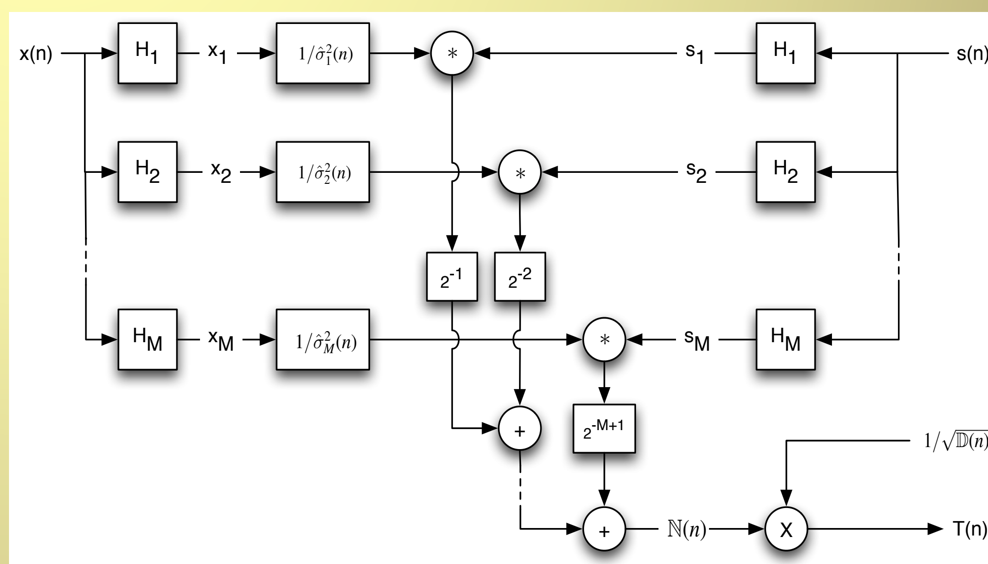
Exoplanet Discoveries

A Search for Earth-size Planets

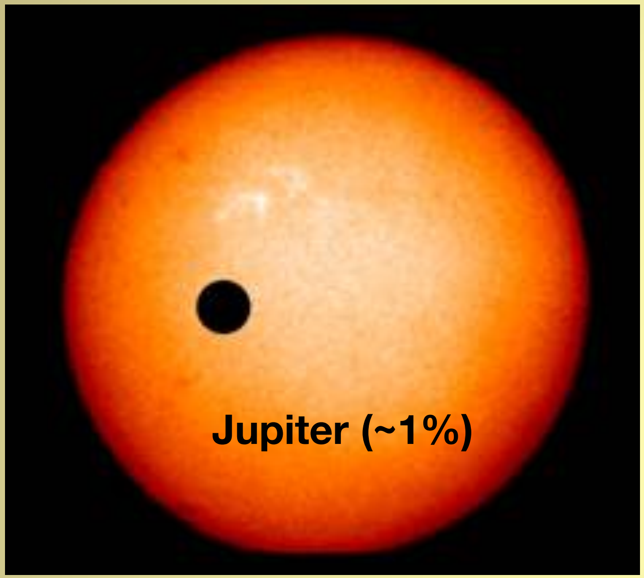


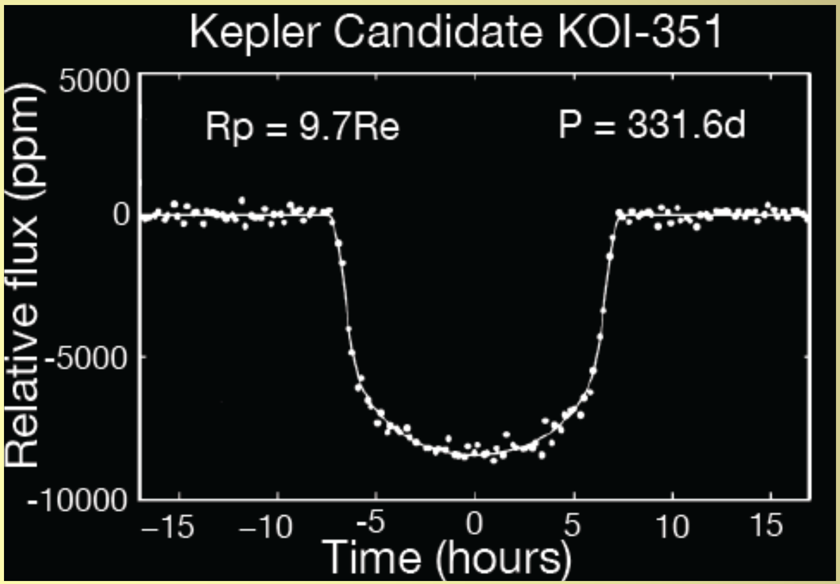
Enabling *Kepler*

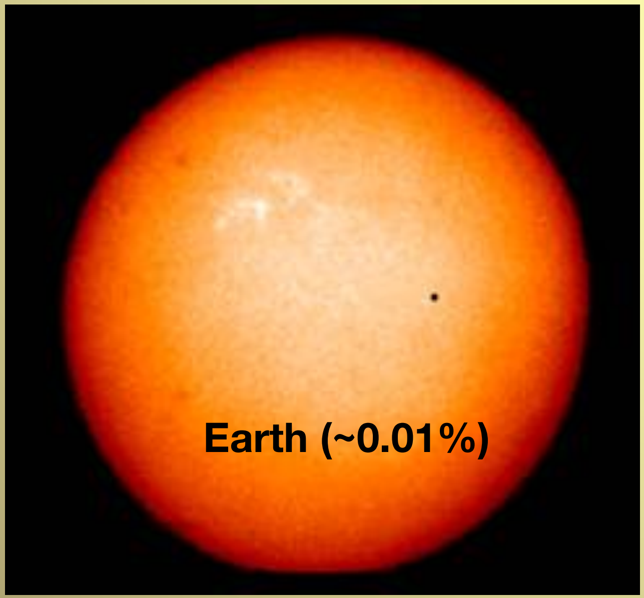
- Back illuminated CCDs (20 ppm photometric precision)
- Sophisticated algorithms
- Computational infrastructure

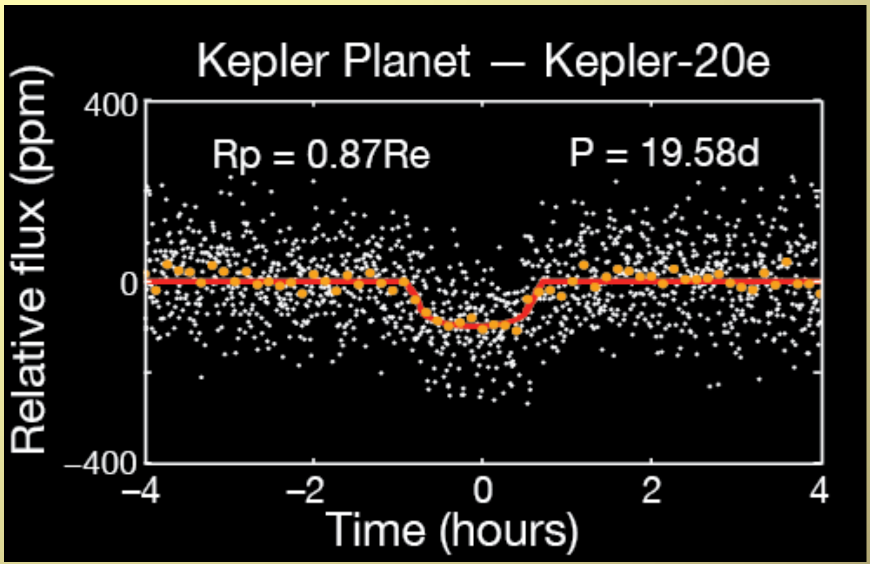


How Hard is it to Find Good Planets?





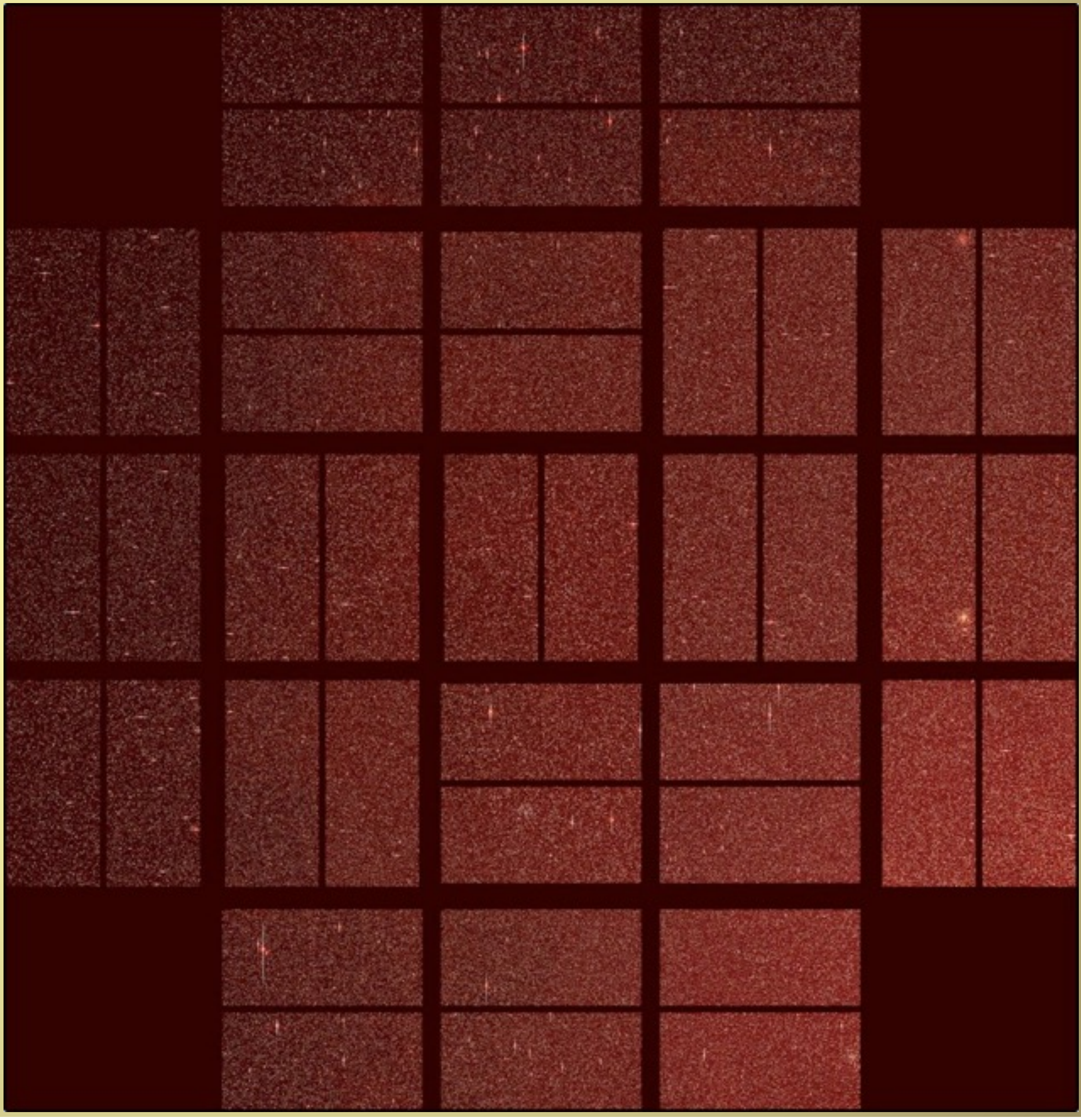




First Light Image

A Search for Earth-size Planets

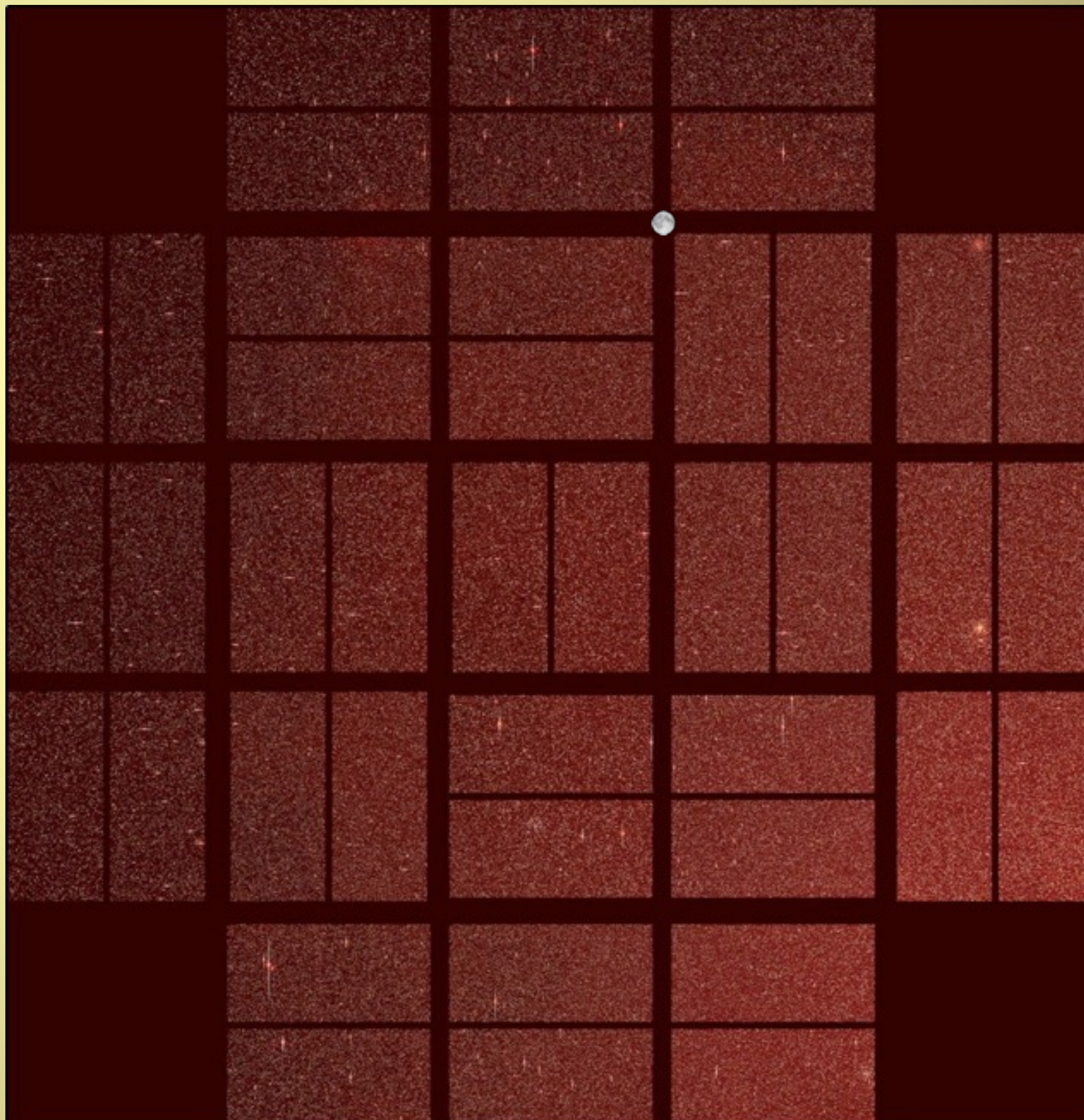
Launched March 7 2009



First Light Image

Kepler
A Search for Earth-size Planets

Launched March 7 2009

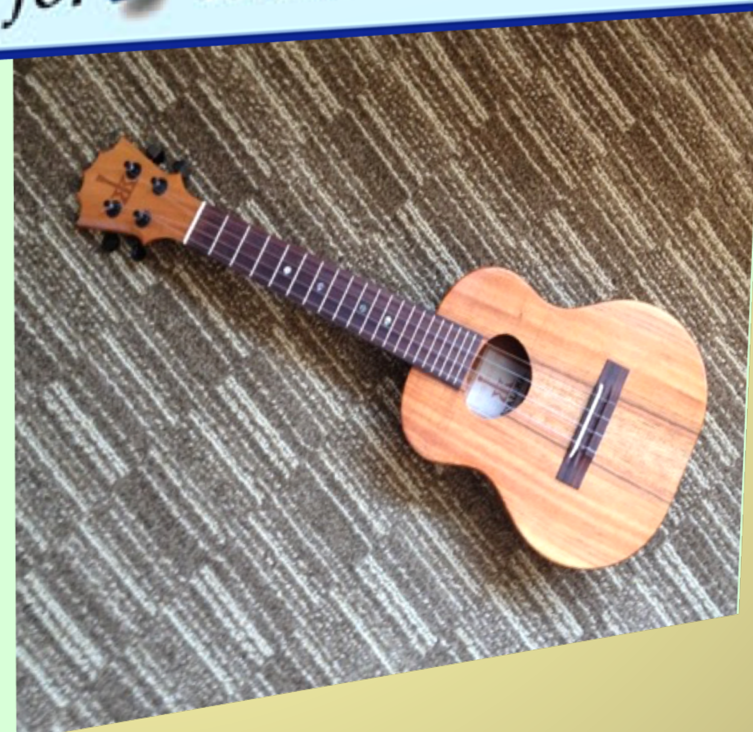


Key Science Results

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

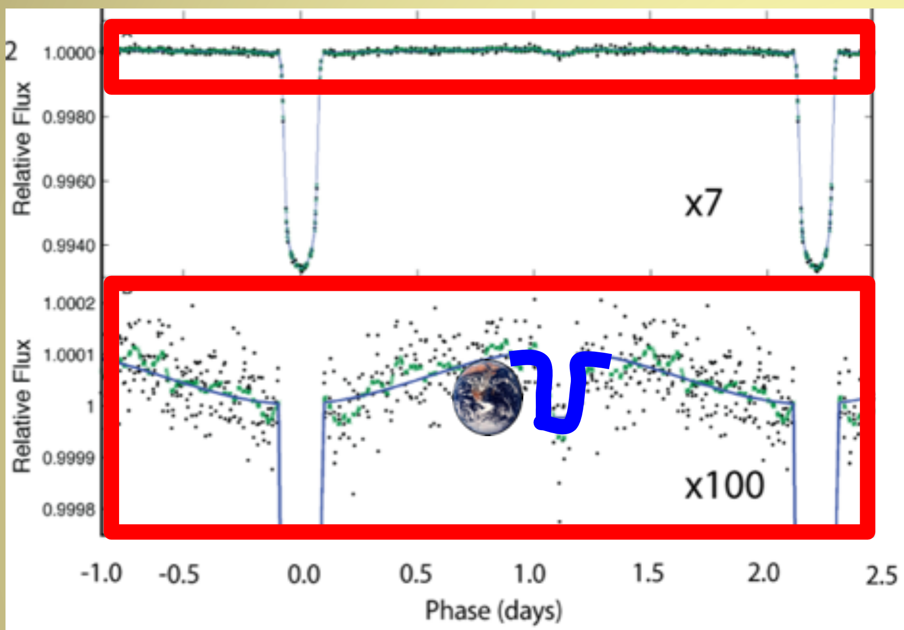
And Many Others!



Kepler's First Science Result

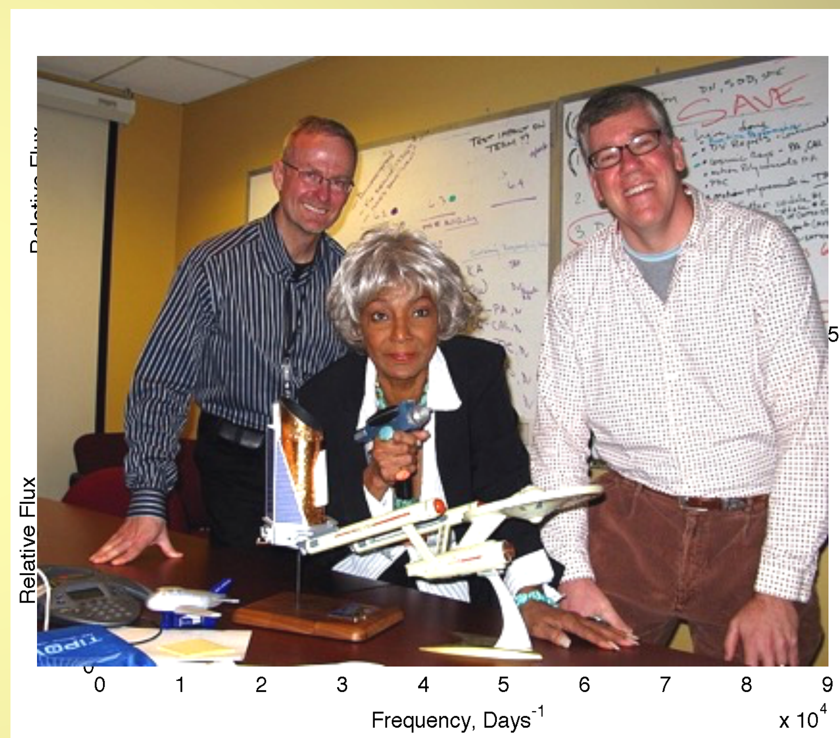
A Search for Earth-size Planets

HAT-P-7B



Kepler Commissioning data (10 days)
W. Borucki et al., 2009

Another Star



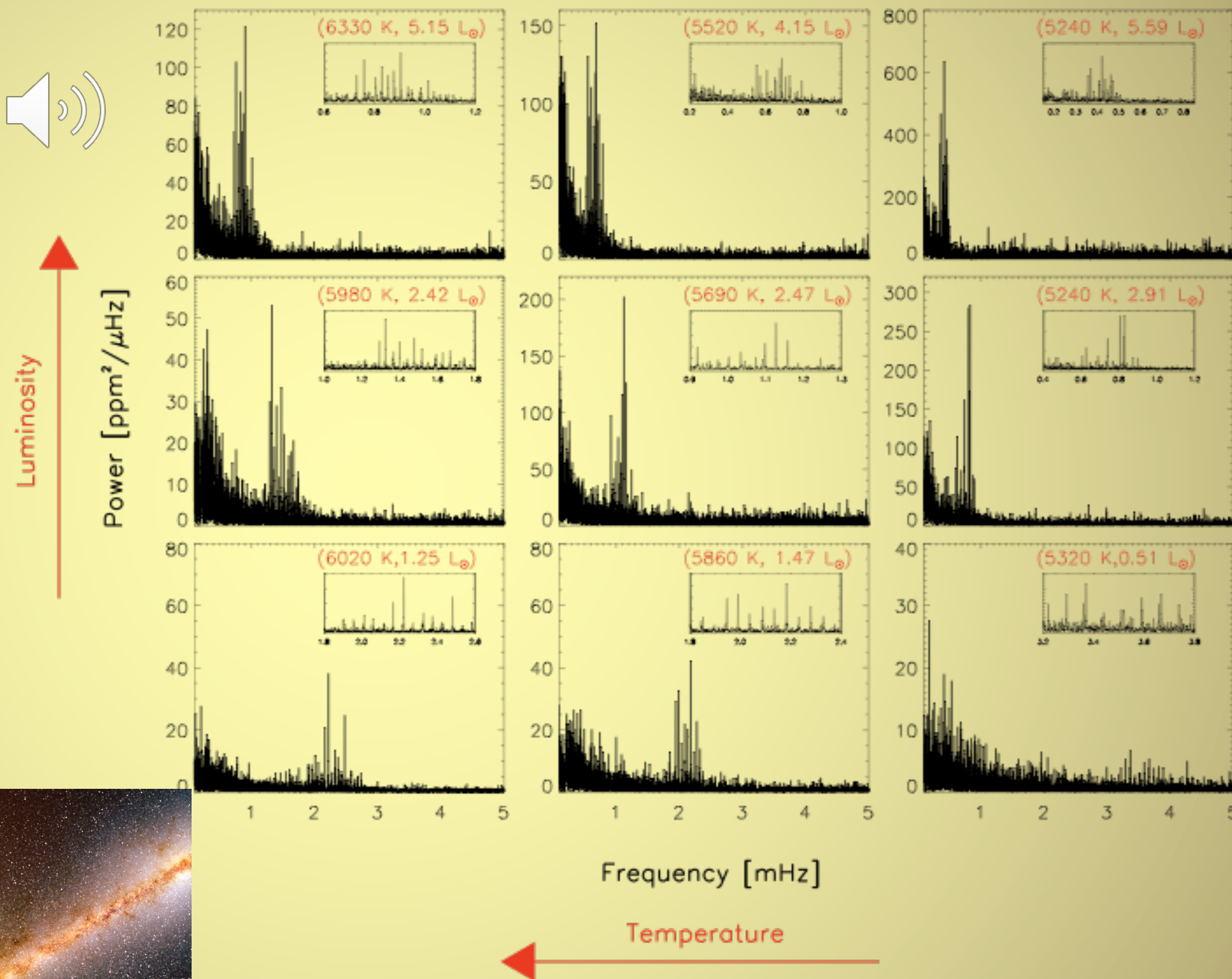
Kepler and Asteroseismology

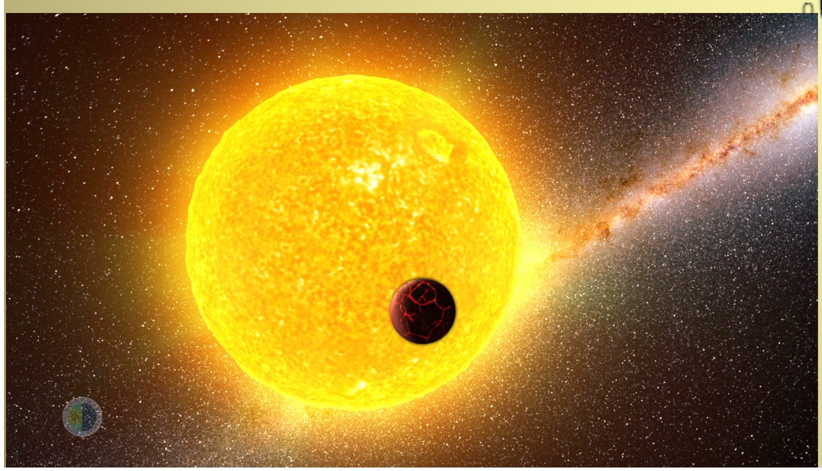
Kepler
A Search for Earth-size Planets

Stars are large resonant cavities that ring like bells

We've measured acoustic modes for >15,000 solar-like stars

Asteroseismology gives unprecedented precision in size, mass of stars

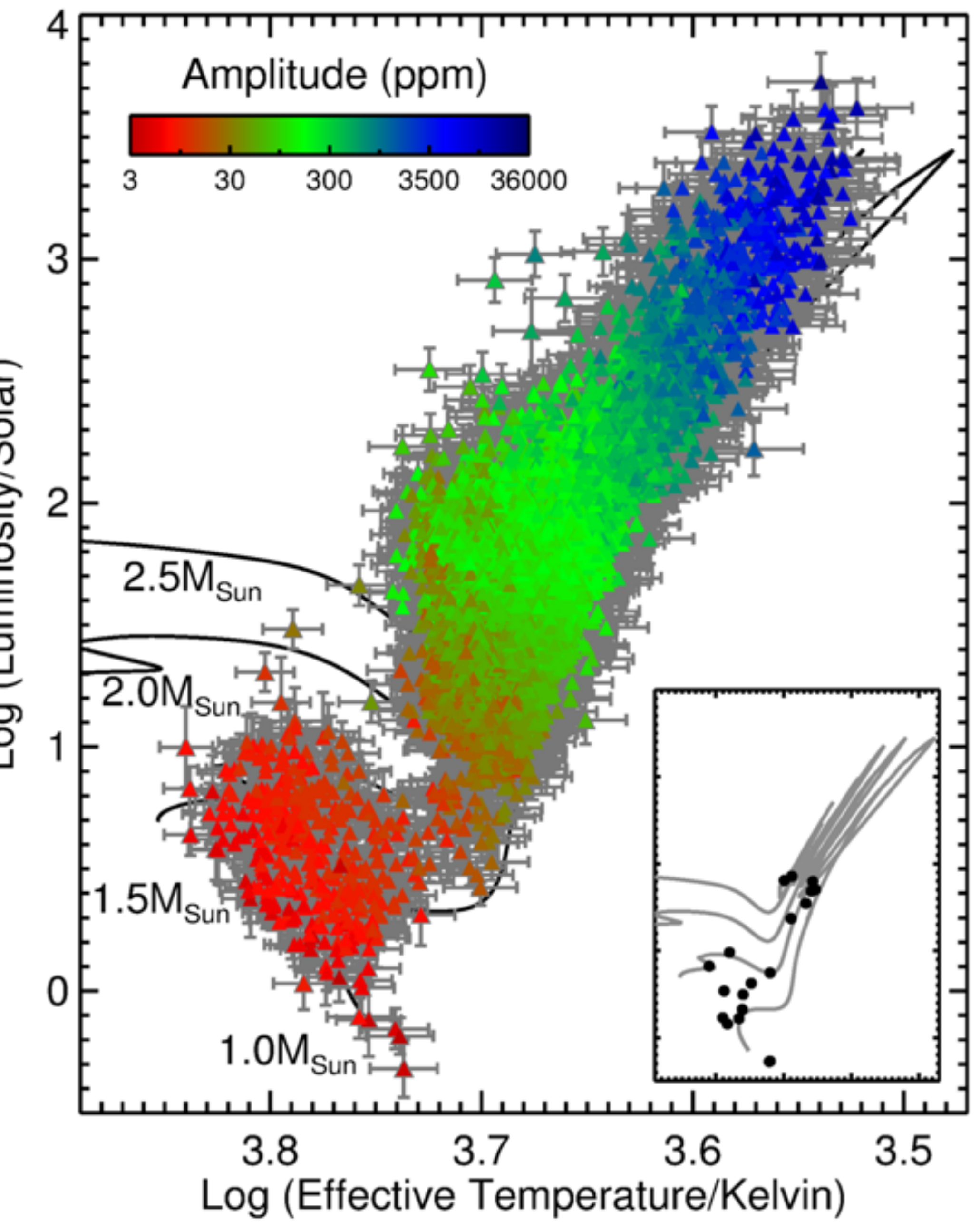




Chaplin et al 2011, Science

Asteroseismology with Kepler

A Search for Earth-size Planets



Huber 2016

Inset – Stellar oscillation Detections before Kepler.

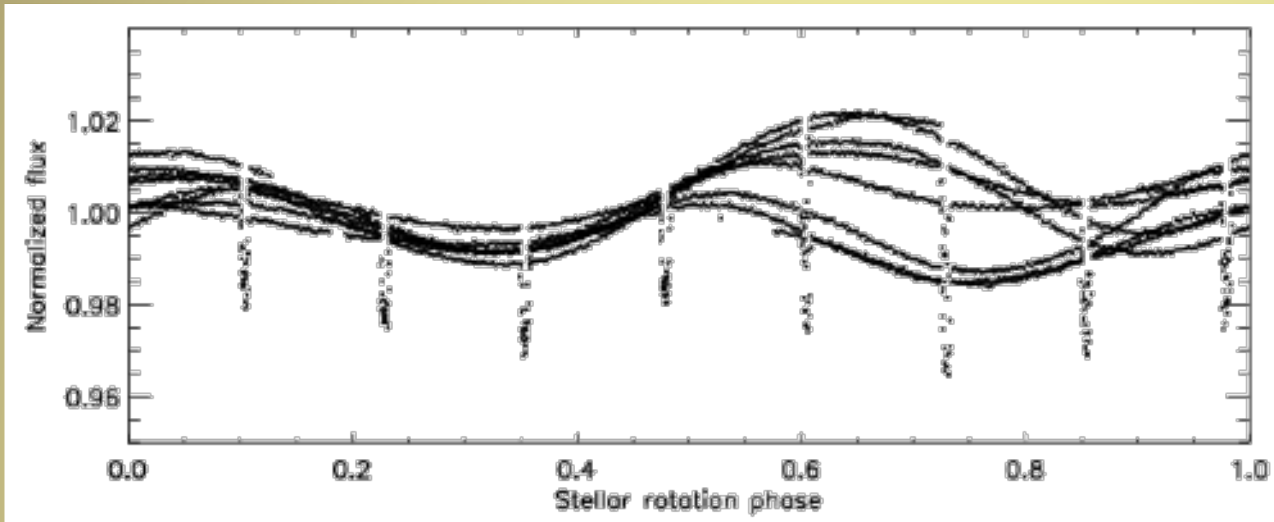
Main: Kepler's 4 years of study show the stars amplitudes (ppm) as color coded points.
Extended study provides –

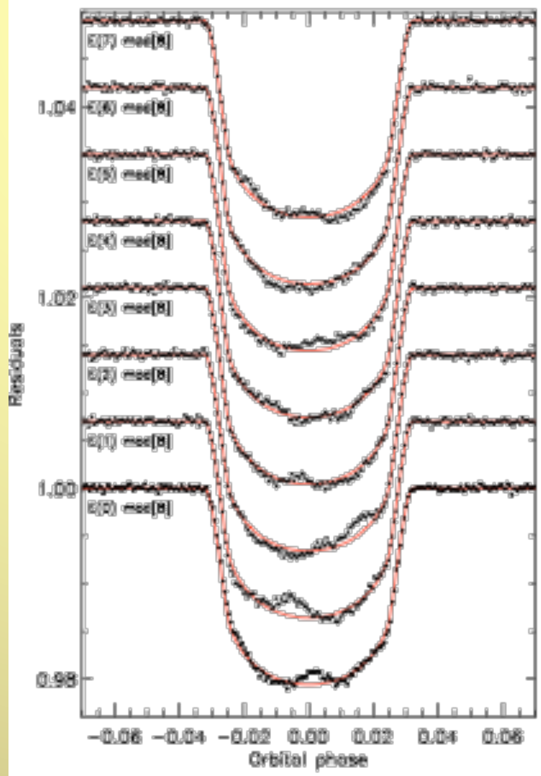
- Stellar ages and radii
- Internal differential rotation
- Convection zone depths ages
- Rotation axis orientation
- Heliophysics-like results

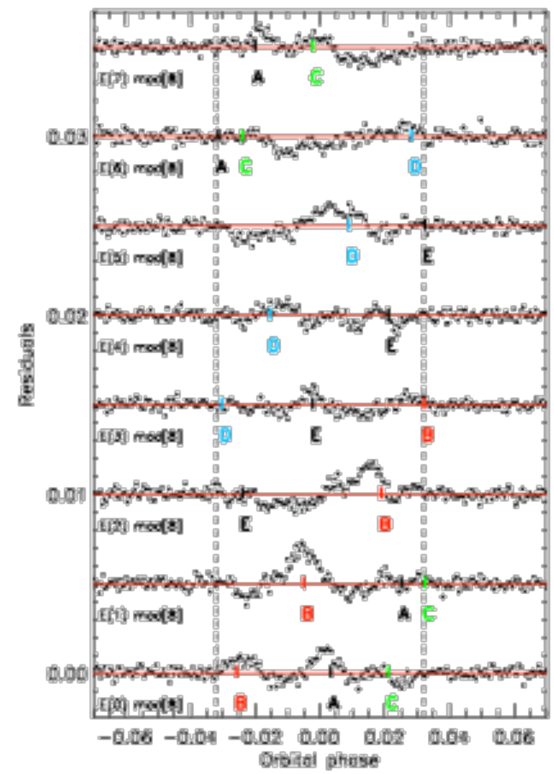
…for many thousands of stars

Kepler-17b: Stroboscopic Spots

A Search for Earth-size Planets



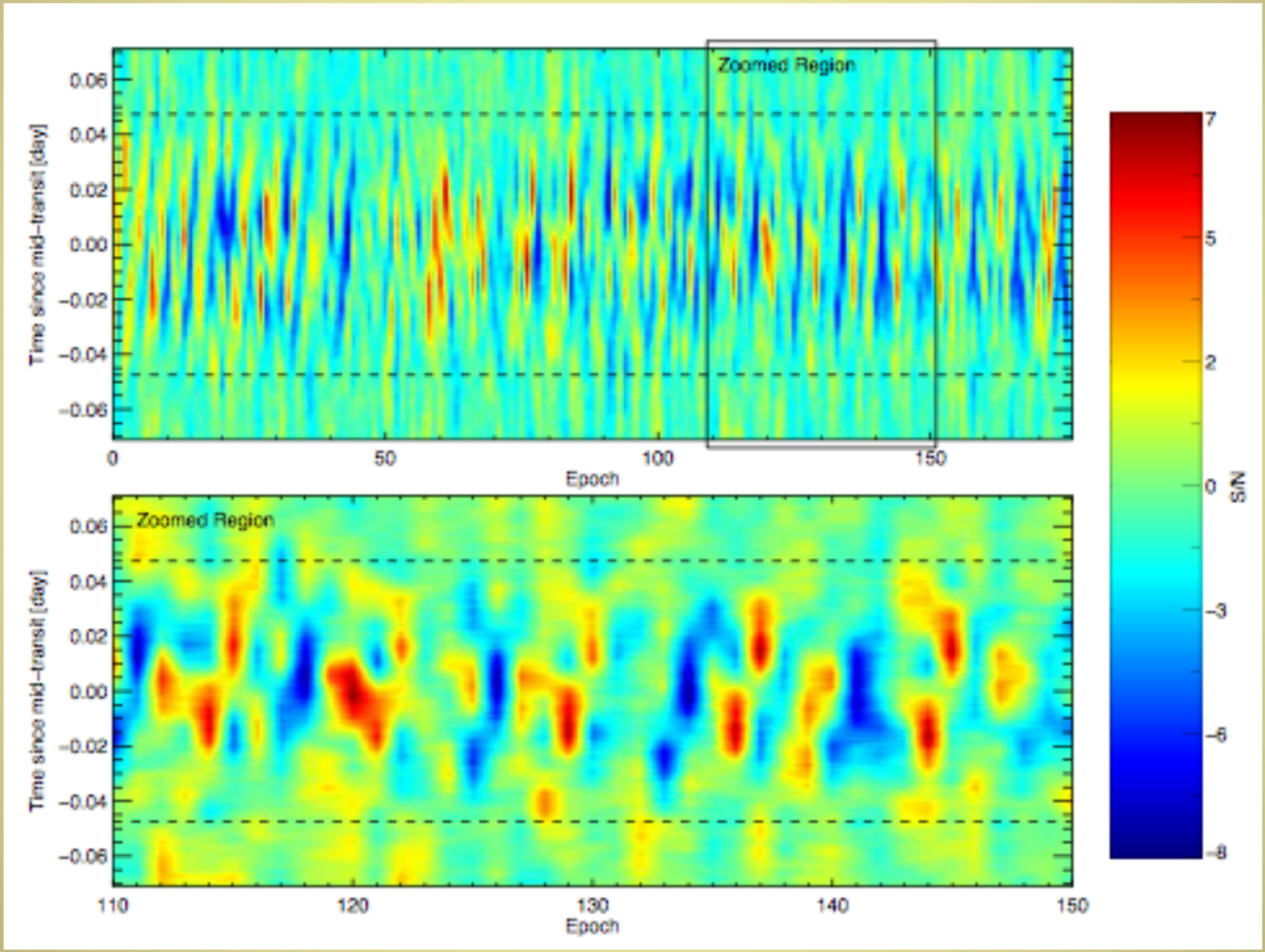




Désert et al. 2011 AJS **197**, 14

Kepler-17b: Spot Lifetime

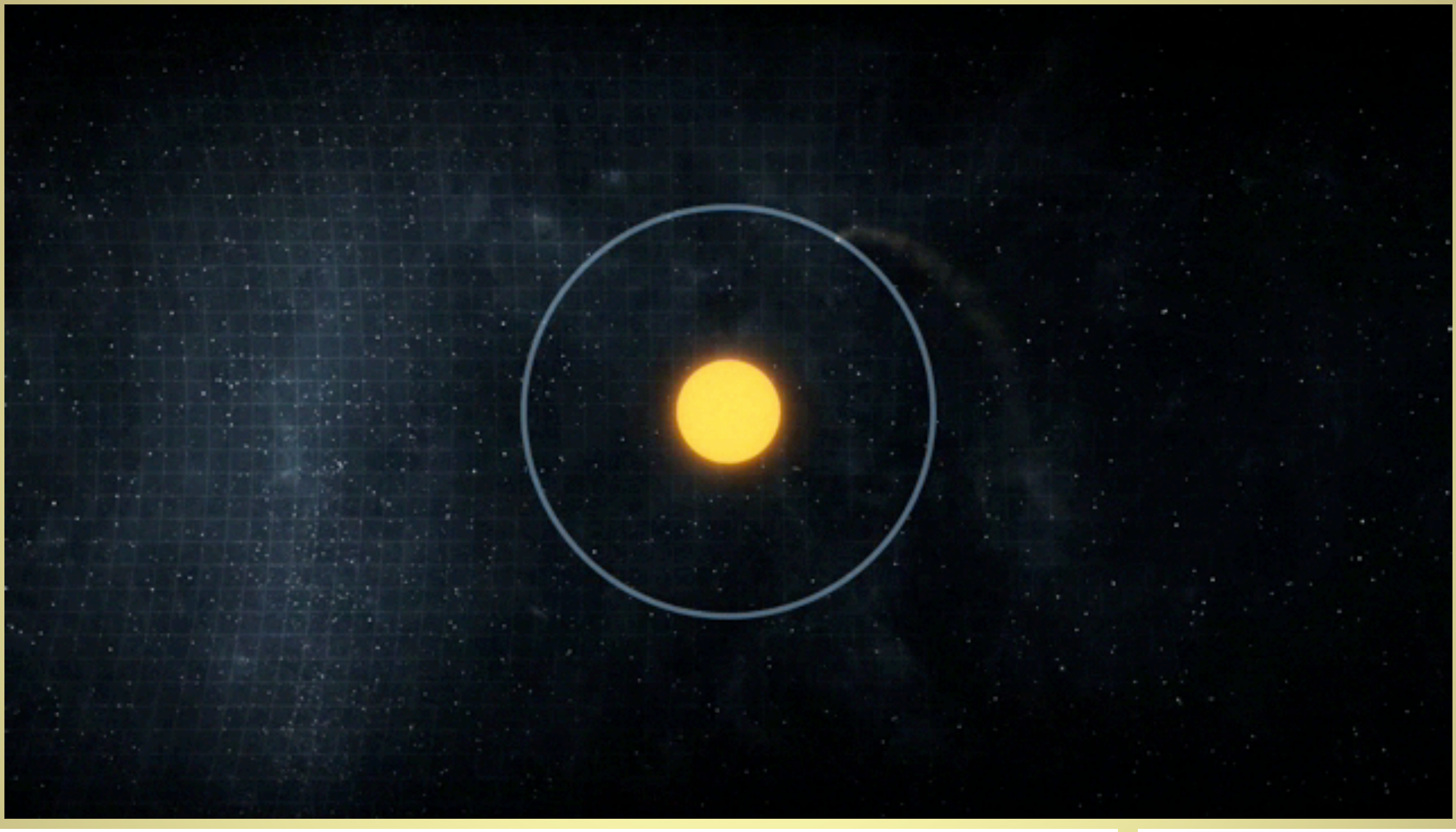
Kepler
A Search for Earth-size Planets

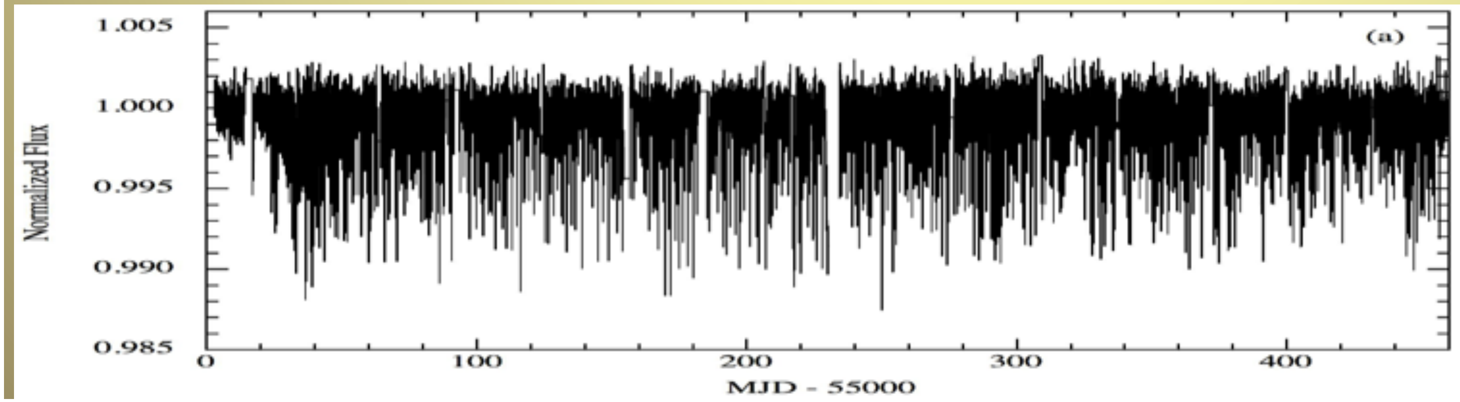


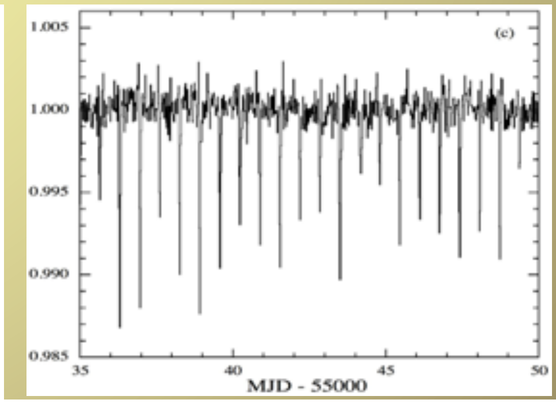
Désert et al. 2011 AJS **197**, 14

A Possibly Disintegrating Planet?

A Search for Earth-size Planets

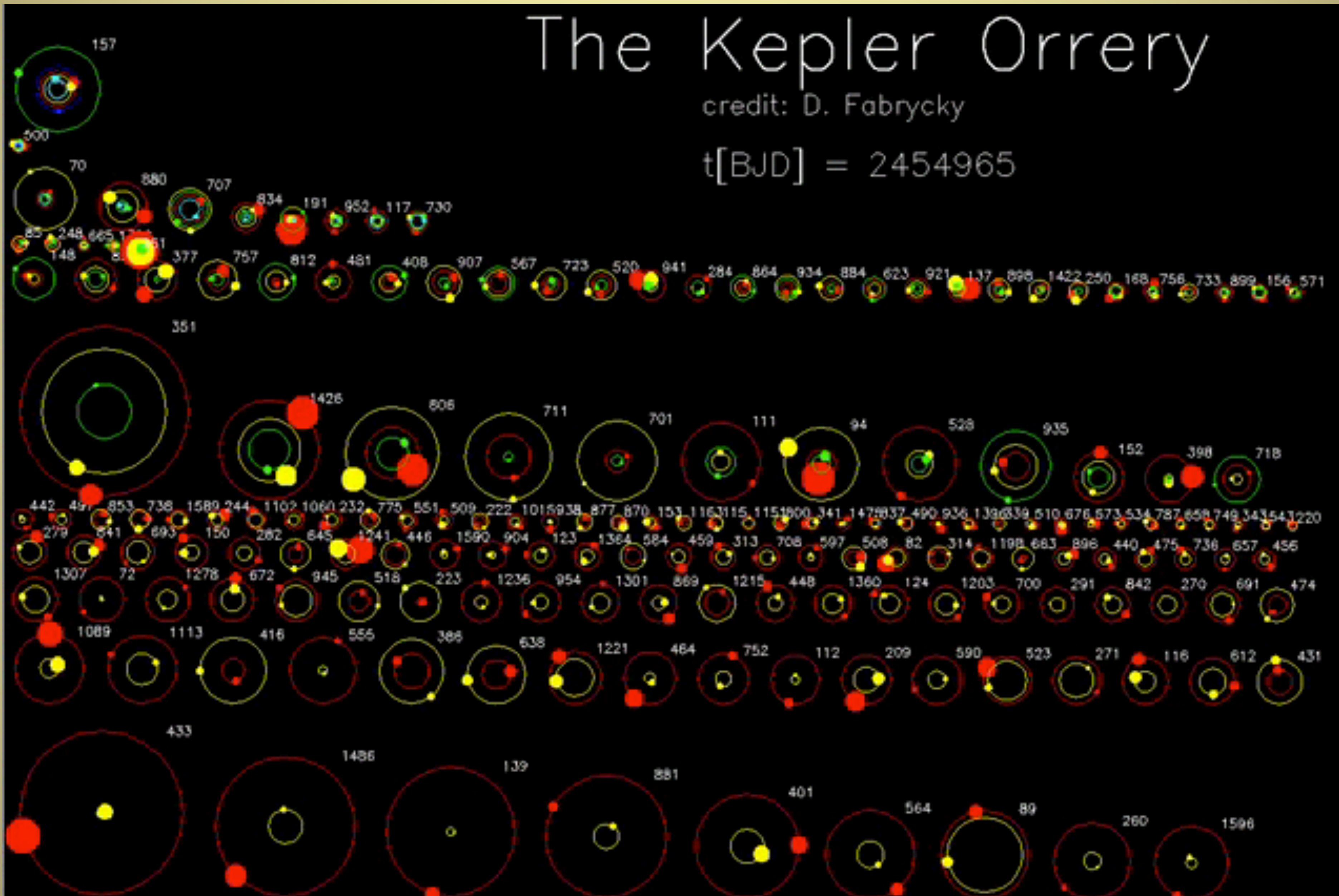






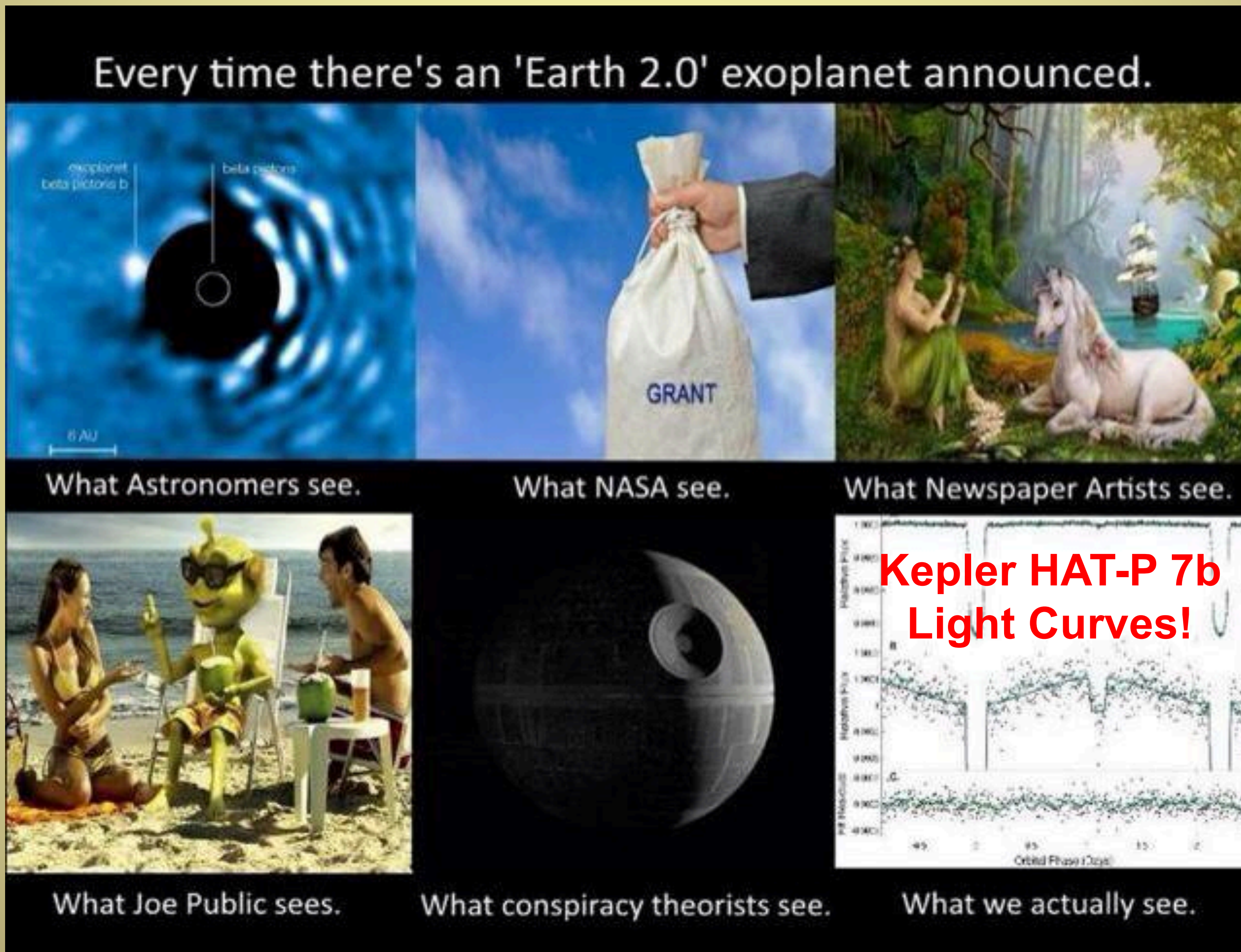
Multiple Transiting Planets

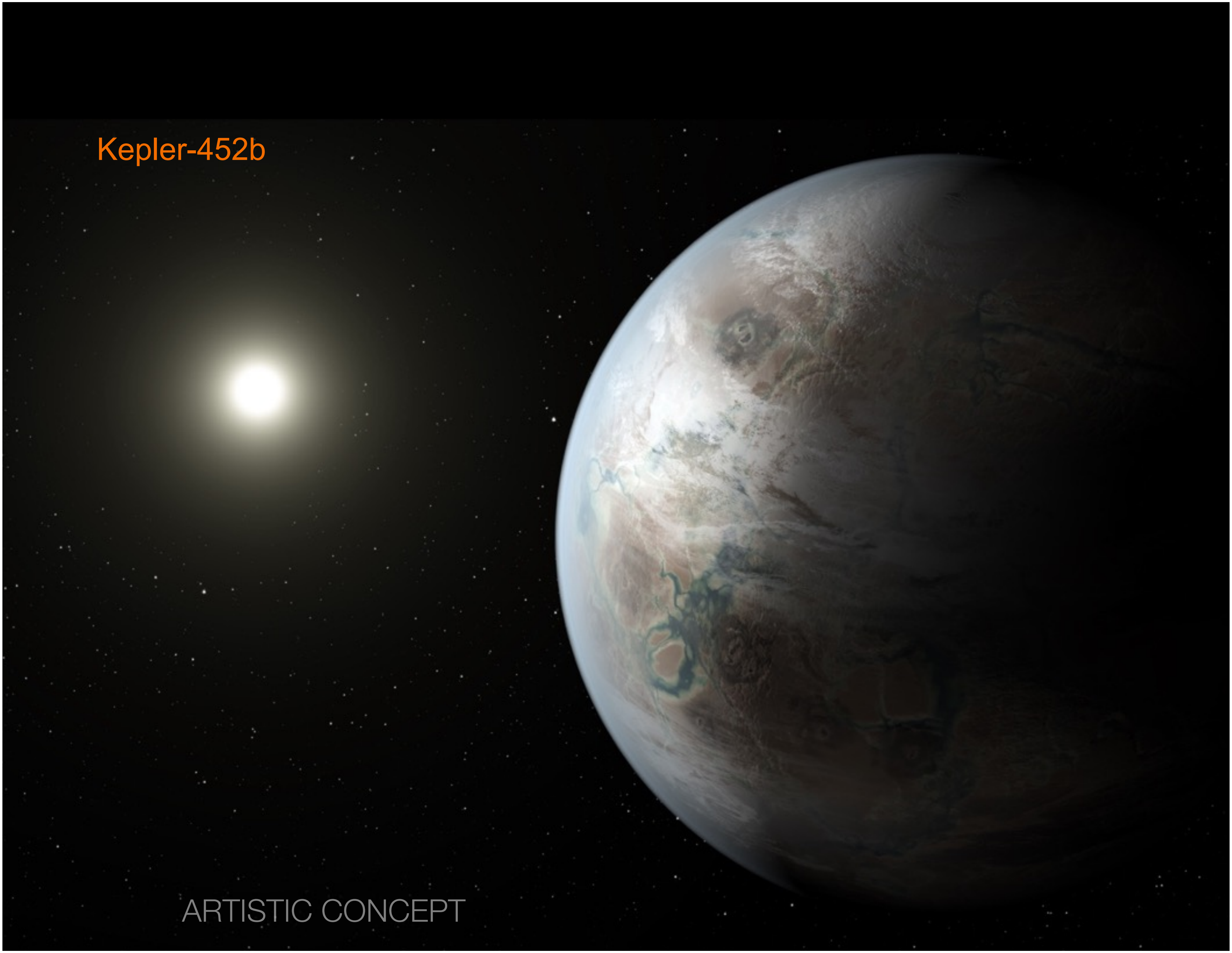
Kepler
A Search for Earth-size Planets



A Funny Thing Happened on the Way to the IAU Meeting

A Search for Earth-size Planets

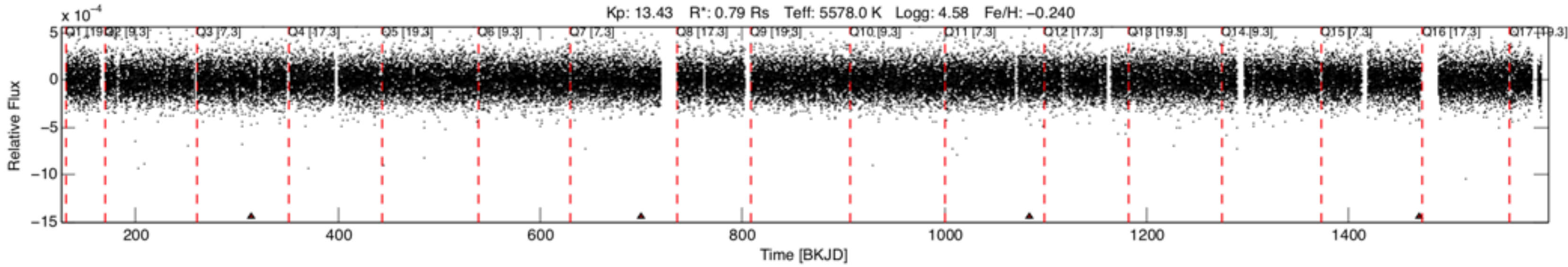


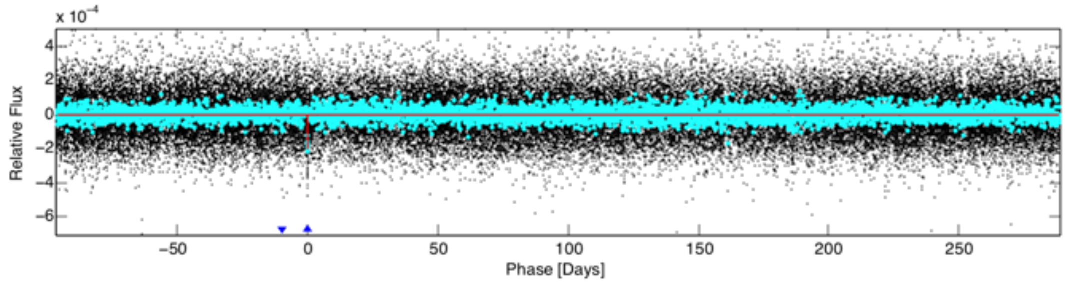

Kepler-452b
ARTISTIC CONCEPT

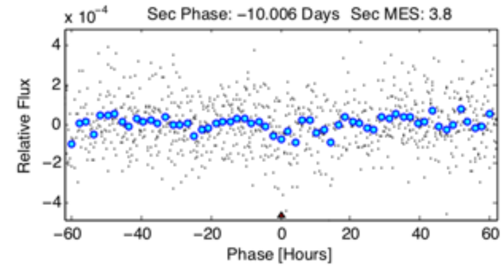
Data Validation Summary

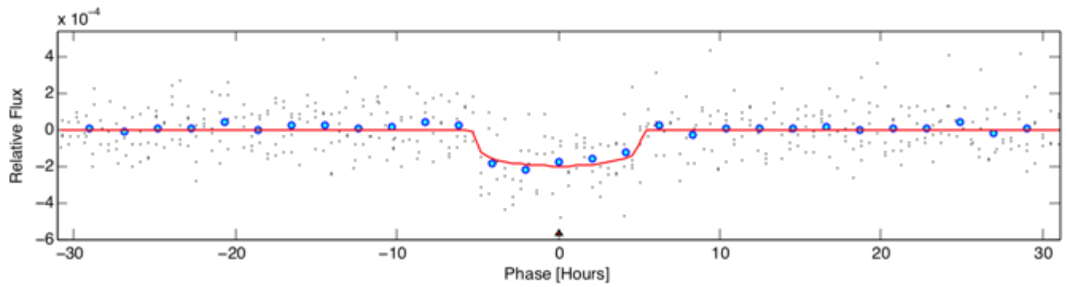
A Search for Earth-size Planets

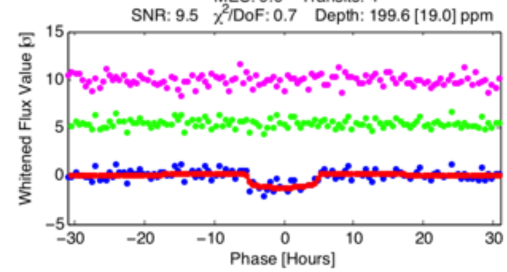
KIC: 8311864 Candidate: 1 of 1 Period: 384.846 d

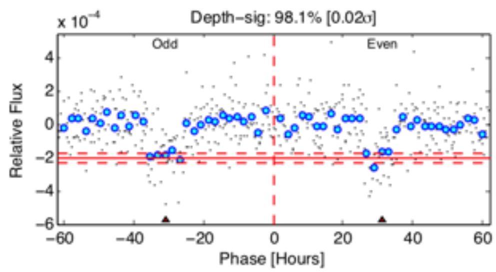


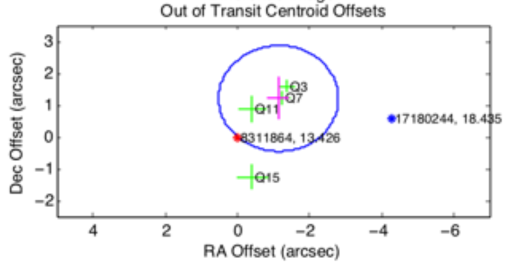












DV Fit Results:

Period = 384.84625 [0.00754] d
Epoch = 314.9787 [0.0146] BKJD
Rp/R* = 0.0129 [0.0248]
a/R* = 274.62 [2265.06]
b = 0.30 [25.06]

Teq = 221 K
Rp = 1.12 Re
a = 0.9888 AU

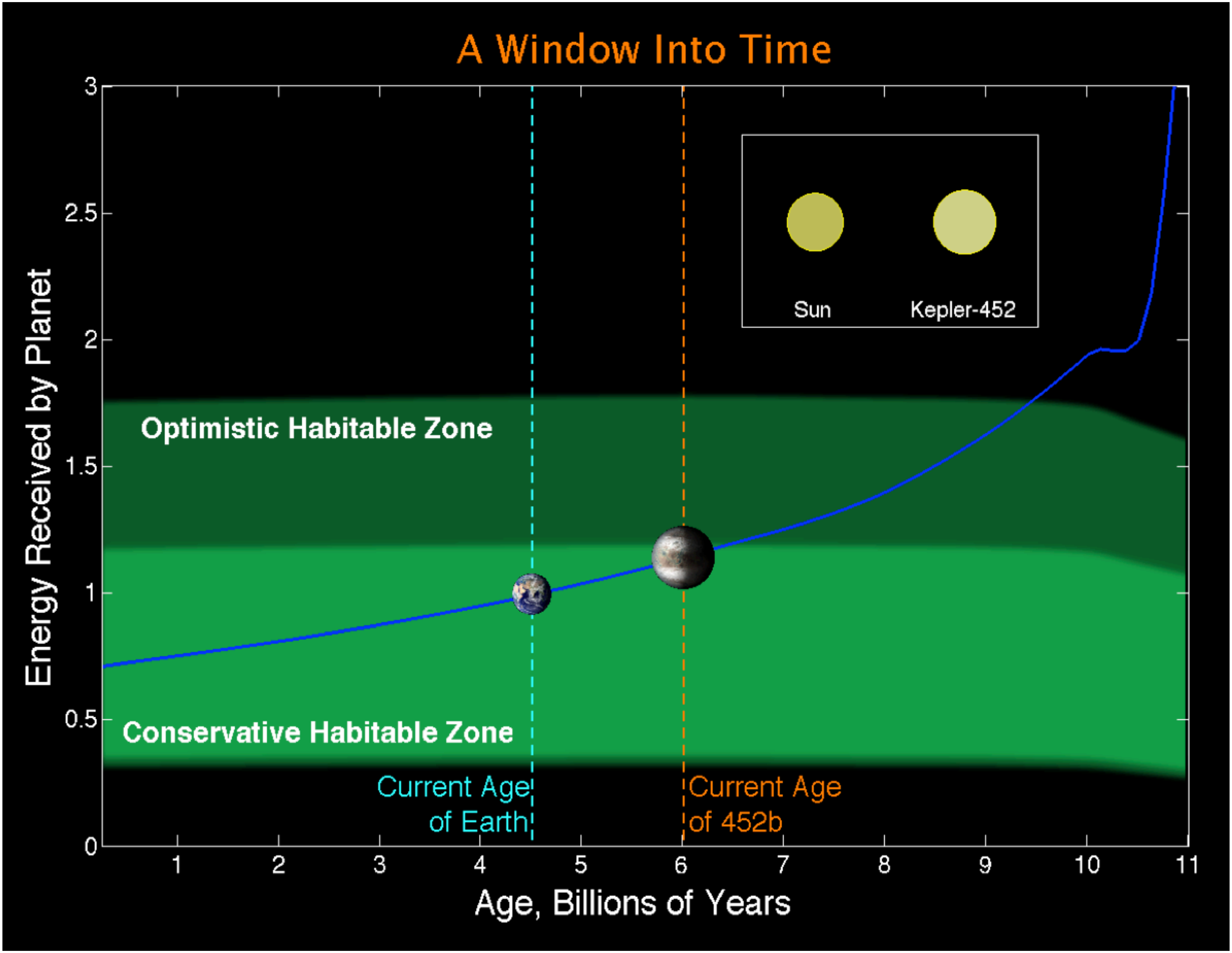
DV Diagnostic Results:

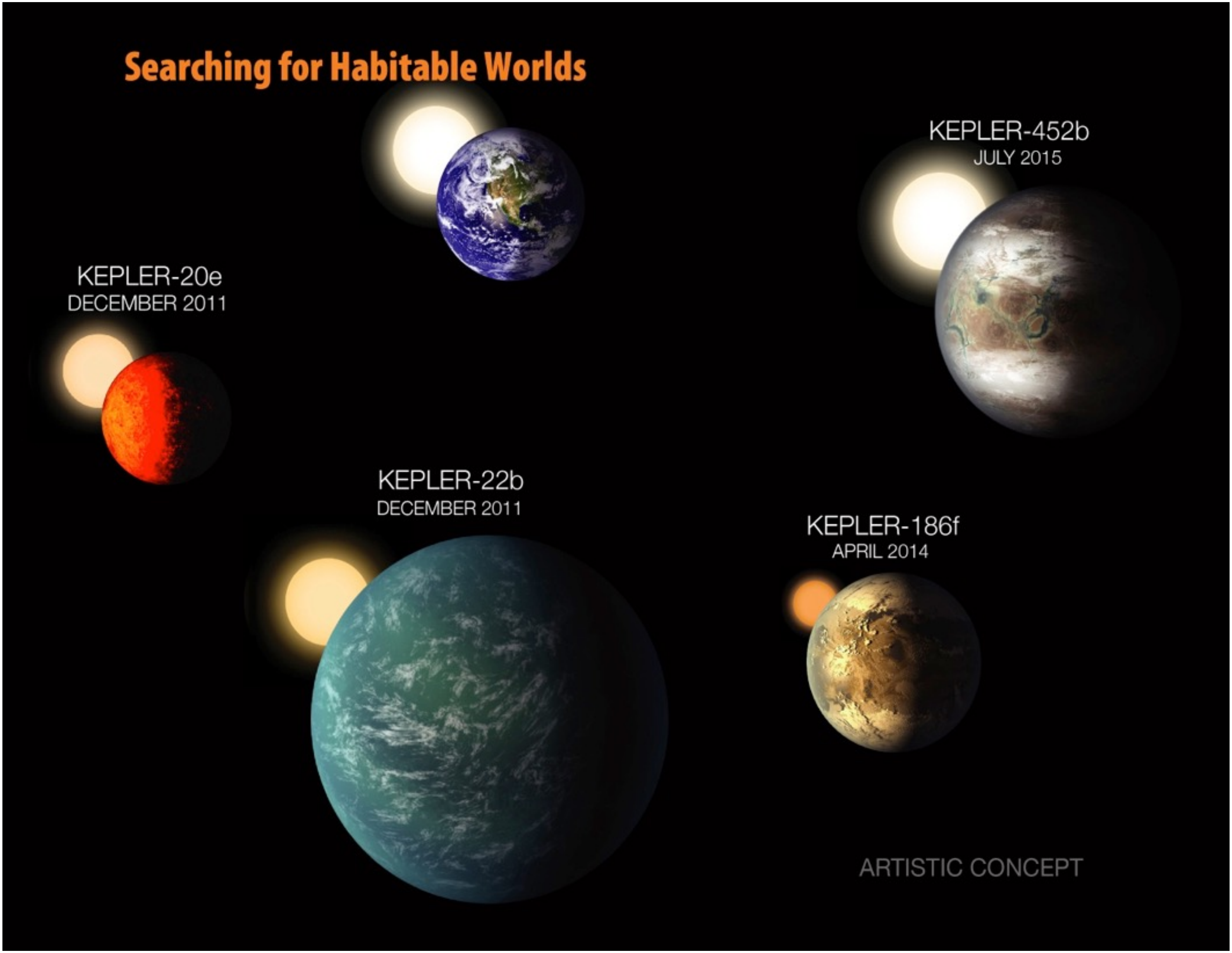
Epoch−sig: 92.0% [0.10σ]
ShortPeriod−sig: N/A
LongPeriod−sig: N/A
ModelChiSquare2−sig: 91.6%
Bootstrap−pfa: 4.79e−14

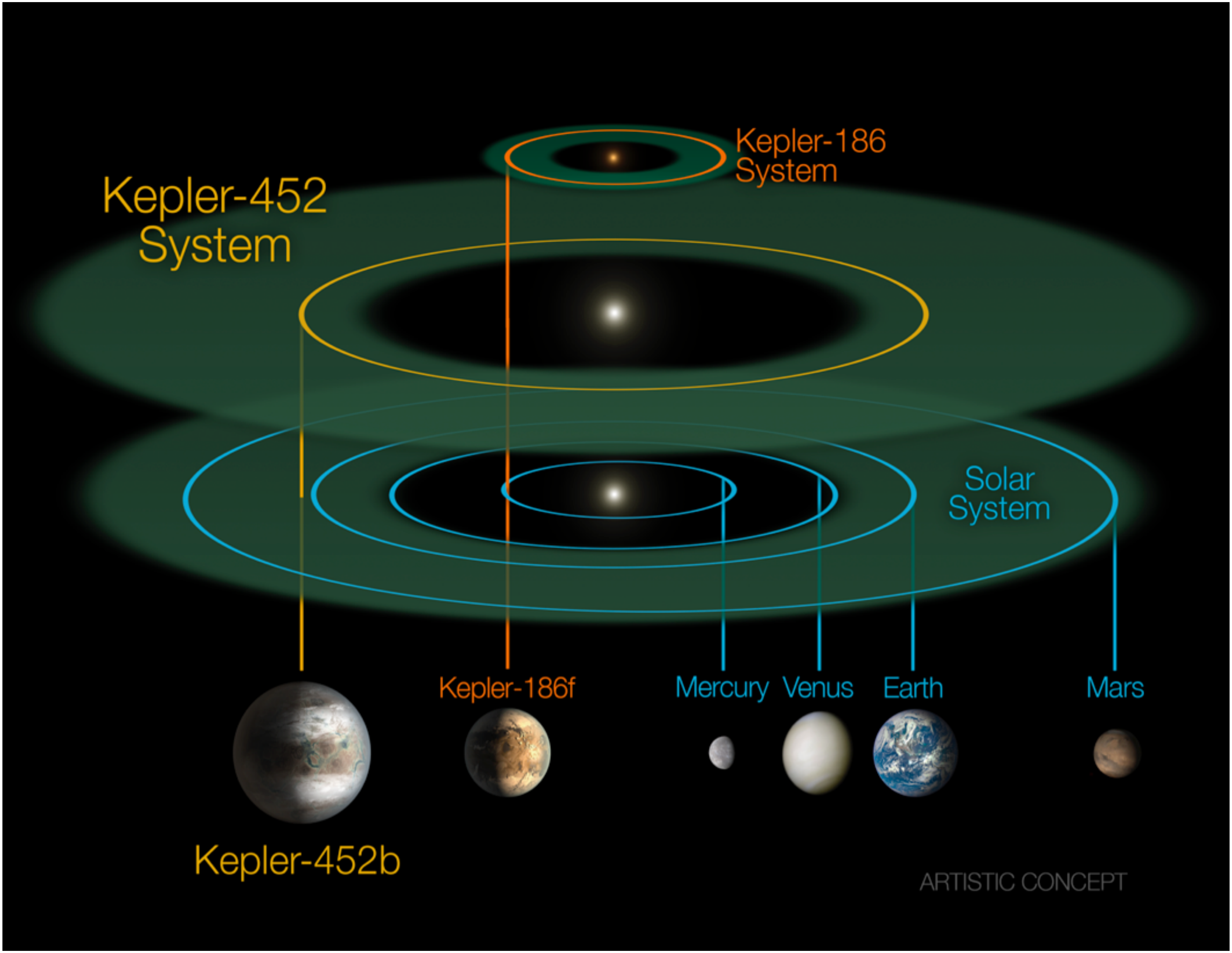
Centroid−sig: 1.1%
Centroid−so: 1.832 arcsec [1.63σ]
OotOffset−rm: 1.664 arcsec [3.00σ]
KicOffset−rm: 1.649 arcsec [3.61σ]
OotOffset−bf: N/A
KicOffset−bf: N/A
OotOffset−st: 0/4/0/0 [4]
KicOffset−st: 0/4/0/0 [4]
DiffImageQuality−fgm: 0.75 [3/4 of 4]

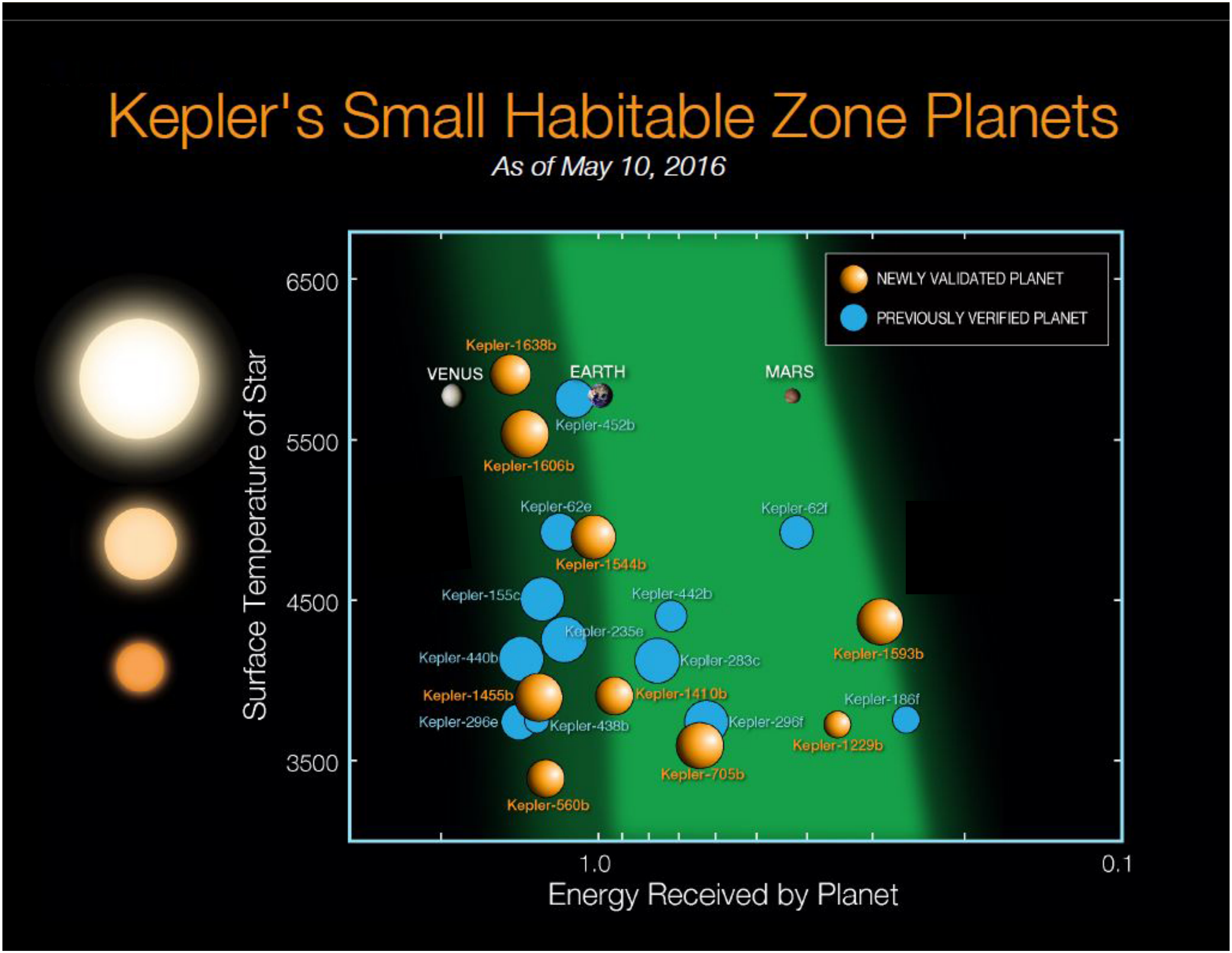
Software Revision: svn+ssh://murzim/repo/soc/branches/integ/ksop−1993@55984 — Date Generated: 11−Jul−2014 01:49:44 Z

This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center


A Window Into Time
Energy Received by Planet
Age, Billions of Years
0
0.5
1
1.5
2
2.5
3
1
2
3
4
5
6
7
8
9
10
11
Optimistic Habitable Zone
Conservative Habitable Zone
Current Age of Earth
Current Age of 452b
Sun
Kepler-452

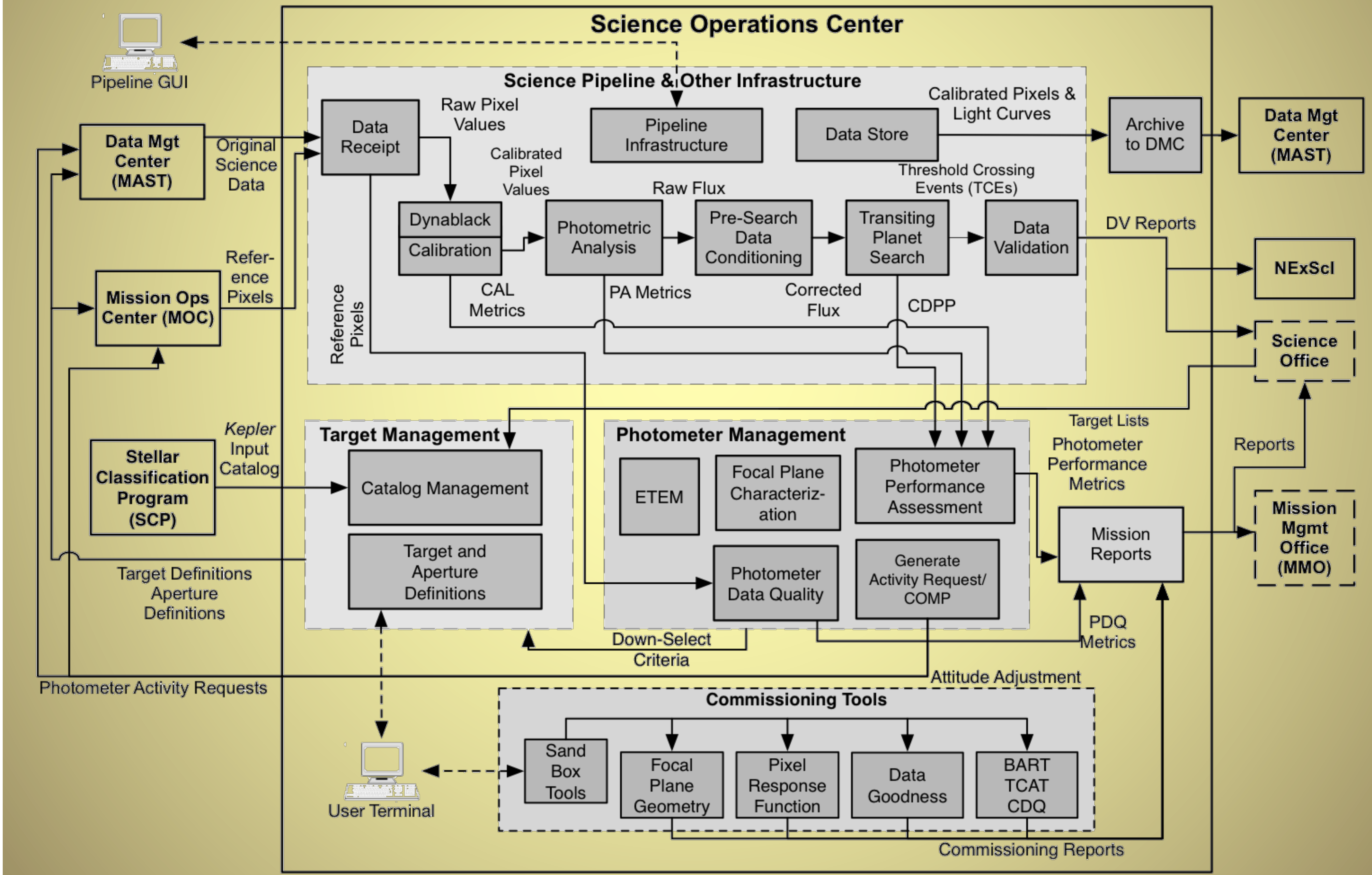

Searching for Habitable Worlds
KEPLER-452b
JULY 2015
KEPLER-20e
DECEMBER 2011
KEPLER-22b
DECEMBER 2011
KEPLER-186f
APRIL 2014
ARTISTIC CONCEPT


Kepler-186
System
Kepler-452
System
Solar
System
Kepler-186f
Mercury
Venus
Earth
Mars
Kepler-452b
ARTISTIC CONCEPT


Kepler's Small Habitable Zone Planets
As of May 10, 2016
NEWLY VALIDATED PLANET
PREVIOUSLY VERIFIED PLANET
6500
5500
4500
3500
Surface Temperature of Star
1.0
0.1
Energy Received by Planet
VENUS
EARTH
MARS
Kepler-1638b
Kepler-452b
Kepler-1606b
Kepler-62e
Kepler-1544b
Kepler-62f
Kepler-155c
Kepler-442b
Kepler-235e
Kepler-440b
Kepler-283c
Kepler-1593b
Kepler-1455b
Kepler-1410b
Kepler-186f
Kepler-296e
Kepler-438b
Kepler-296f
Kepler-1229b
Kepler-705b
Kepler-560b

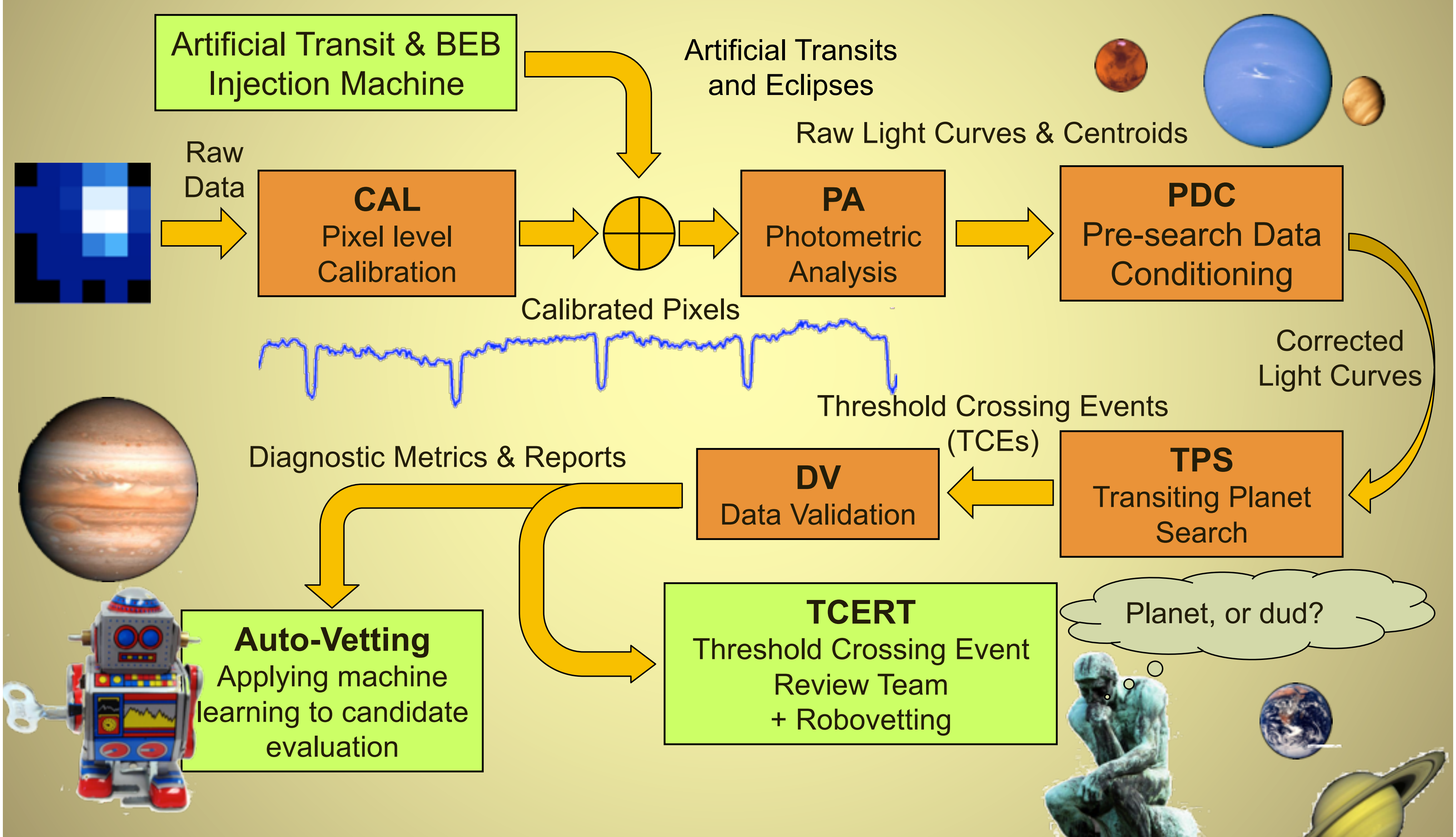

KEPLER
SCIENCE DATA PROCESSING PIPELINE
DYN
OFF
CAL
PA
PDC
TPS
DV

Science Operations Center Architecture



Kepler’s Science Pipeline

Kepler — *A Search for Earth-size Planets*

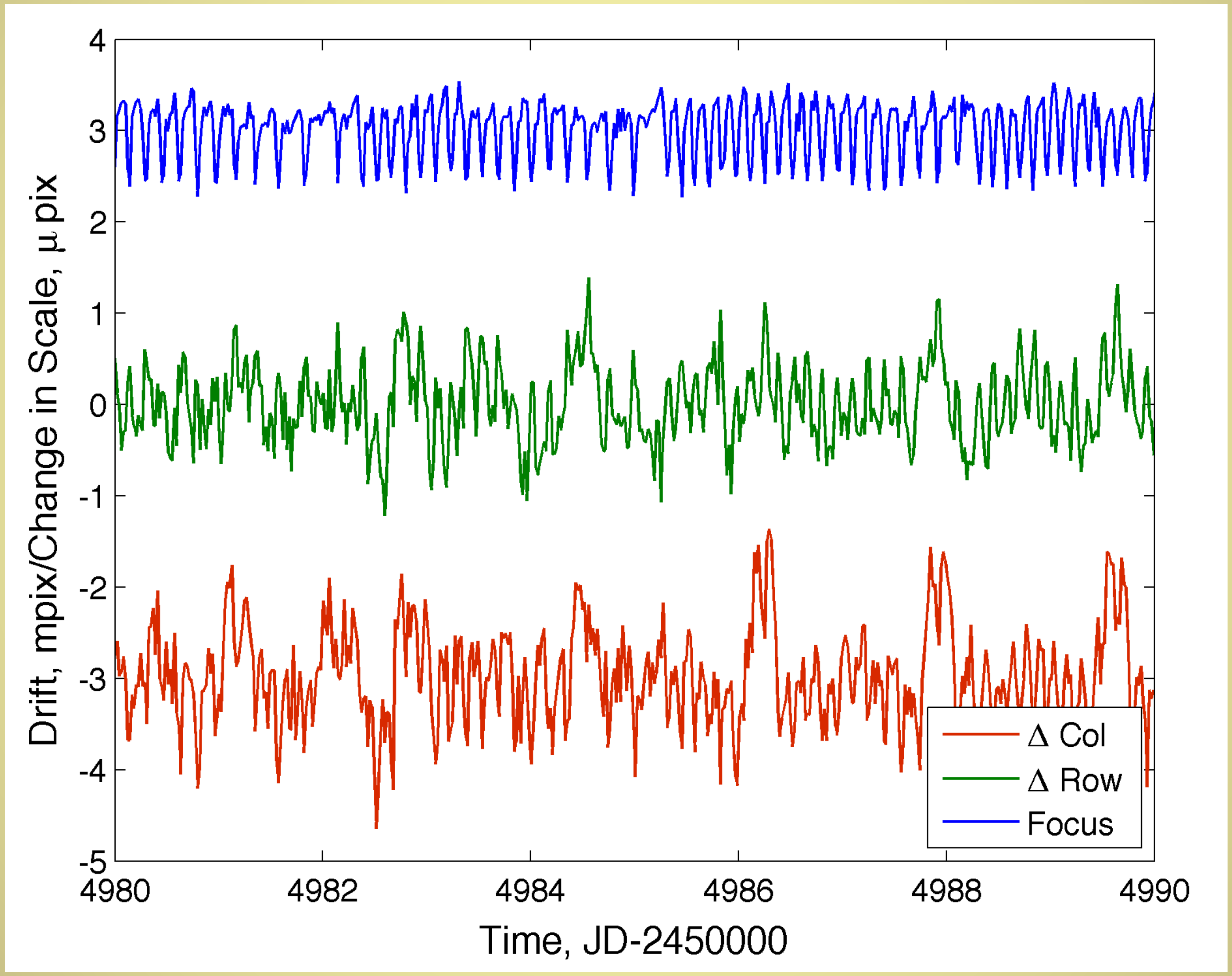


>1,000,000 Lines of Code; 26 different Modules

Short Timescale Instrumental Errors

A Search for Earth-size Planets

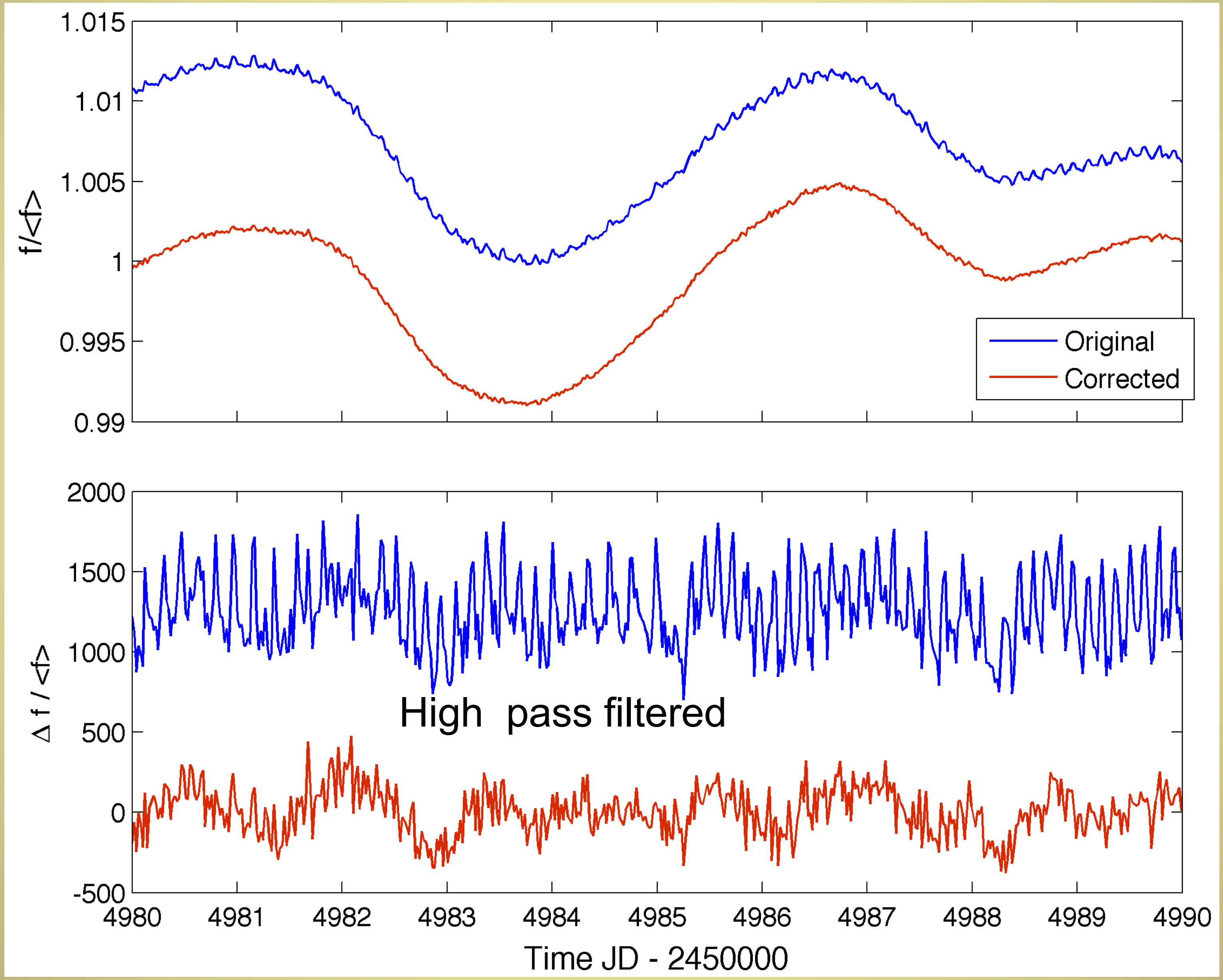
Signature of a heater cycling on the reaction wheels 3/4



Kepler is sensitive to its thermal environment

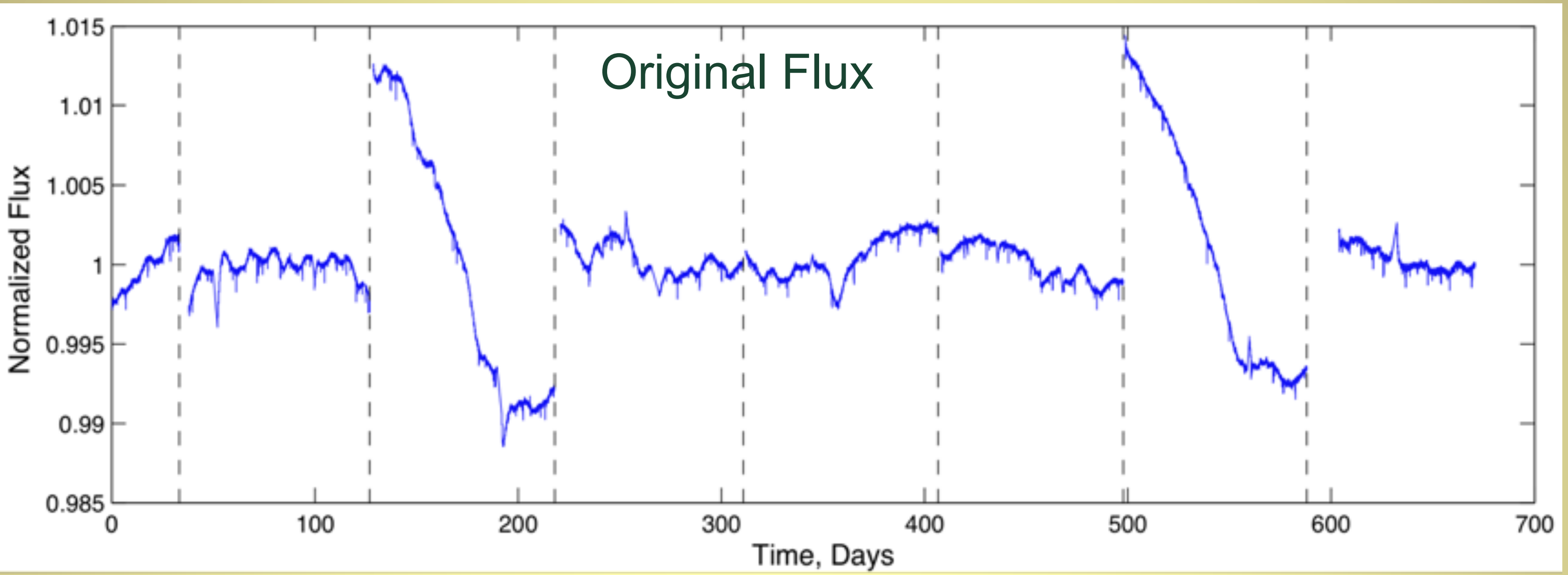
Correcting Instrumental Effects

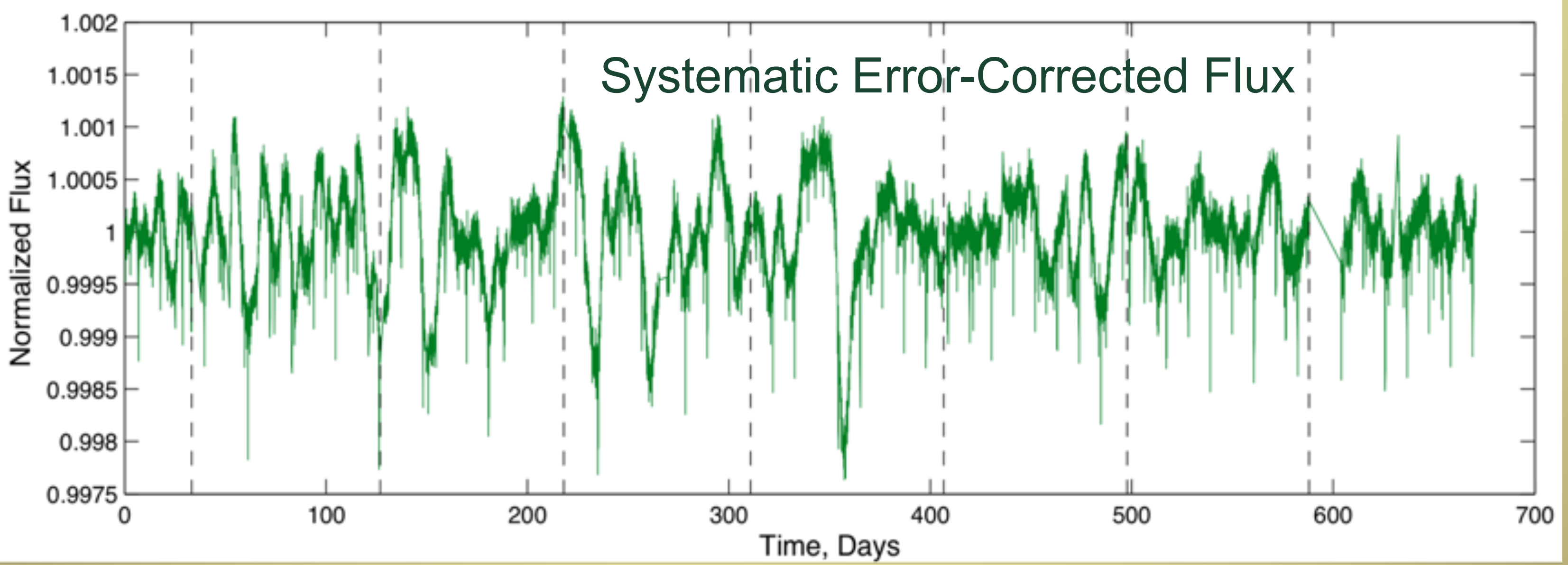
A Search for Earth-size Planets



Correcting Systematic Errors

A Search for Earth-size Planets





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

The Search Problem

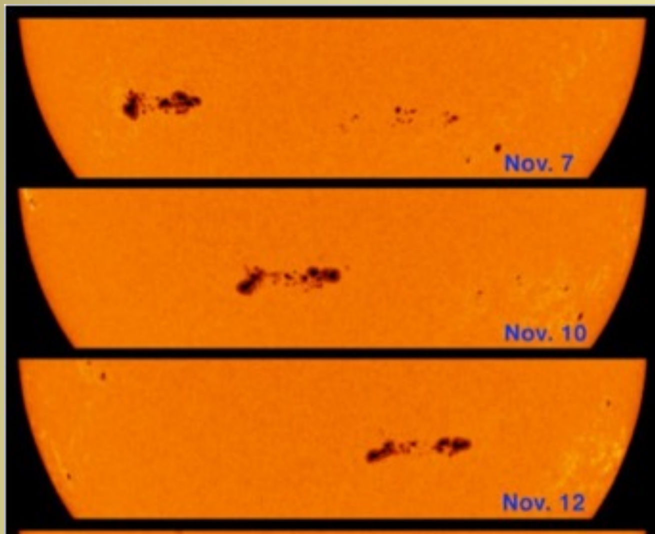
The Search Problem

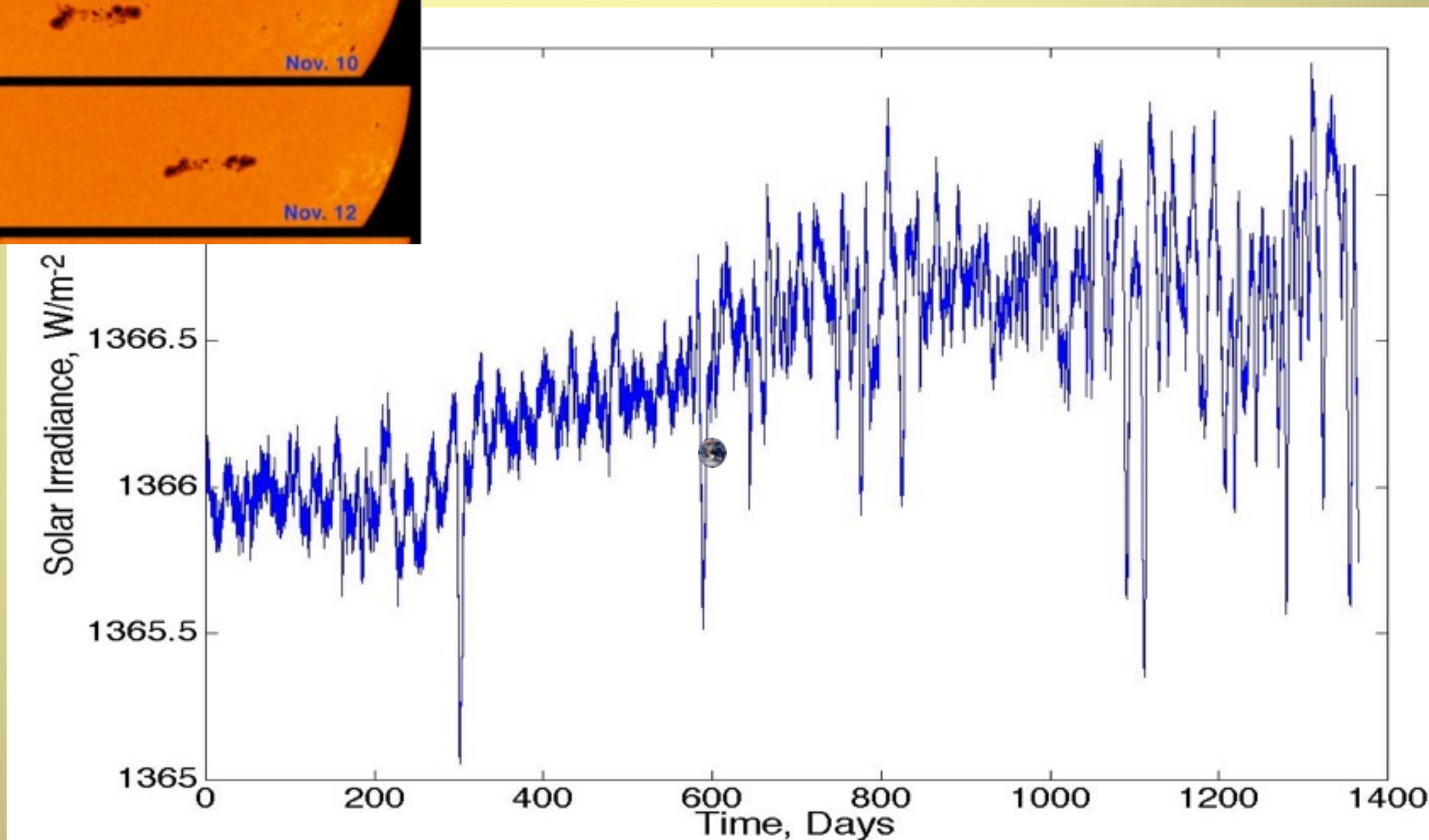
The Search Problem

A Search for Earth-size Planets

Solar Variability

A Search for Earth-size Planets





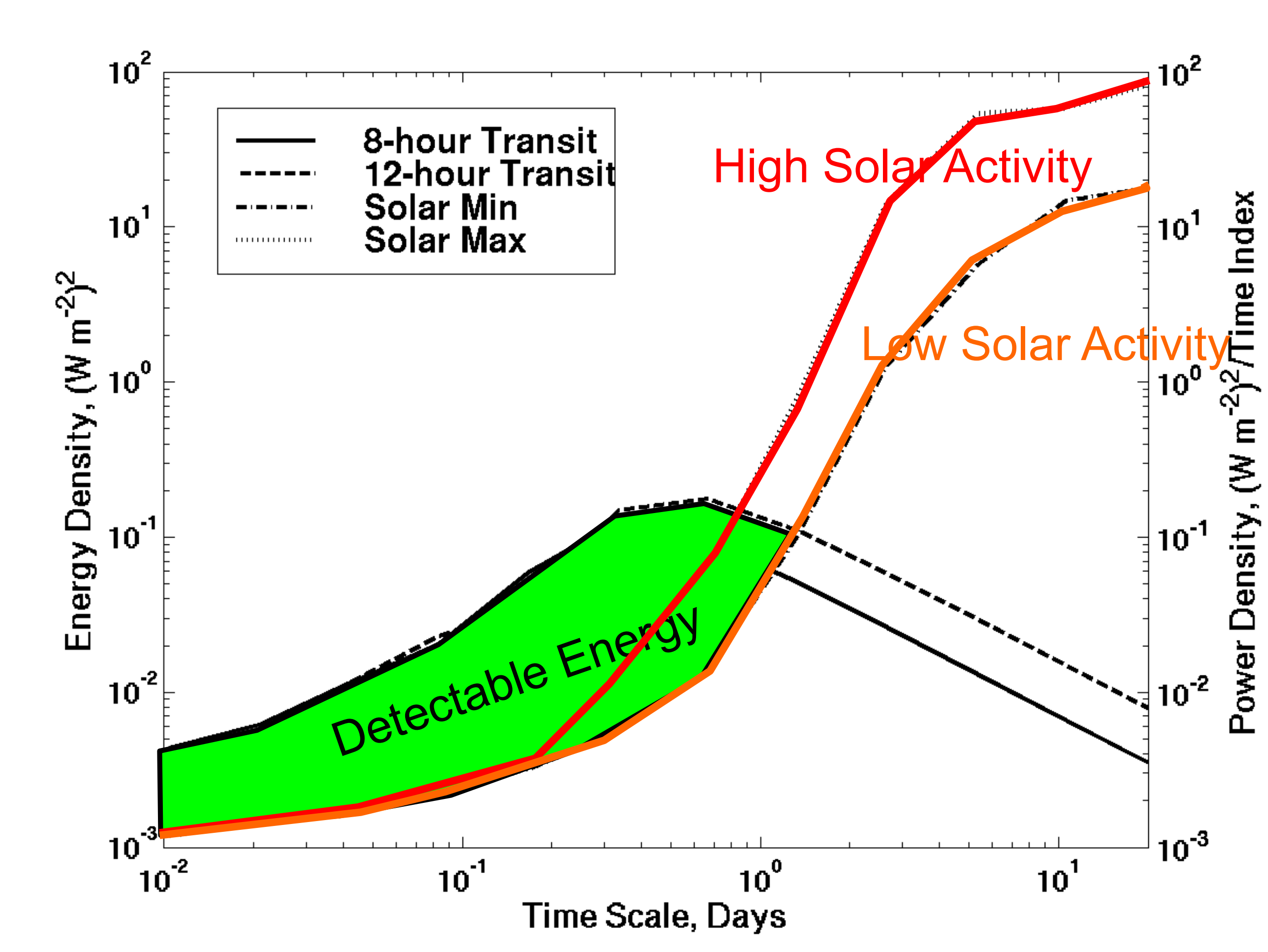
Detecting Transits Against Stellar Variability

Is stellar variability stationary?

No!

We must work in a joint time-frequency domain

Wavelets are a natural choice



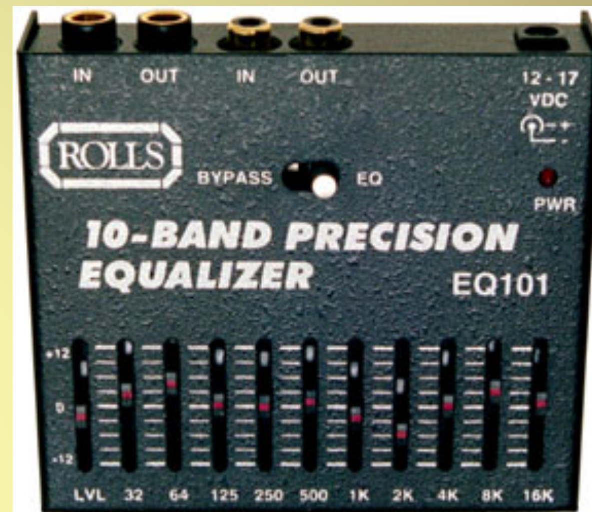
A Wavelet-Based Approach

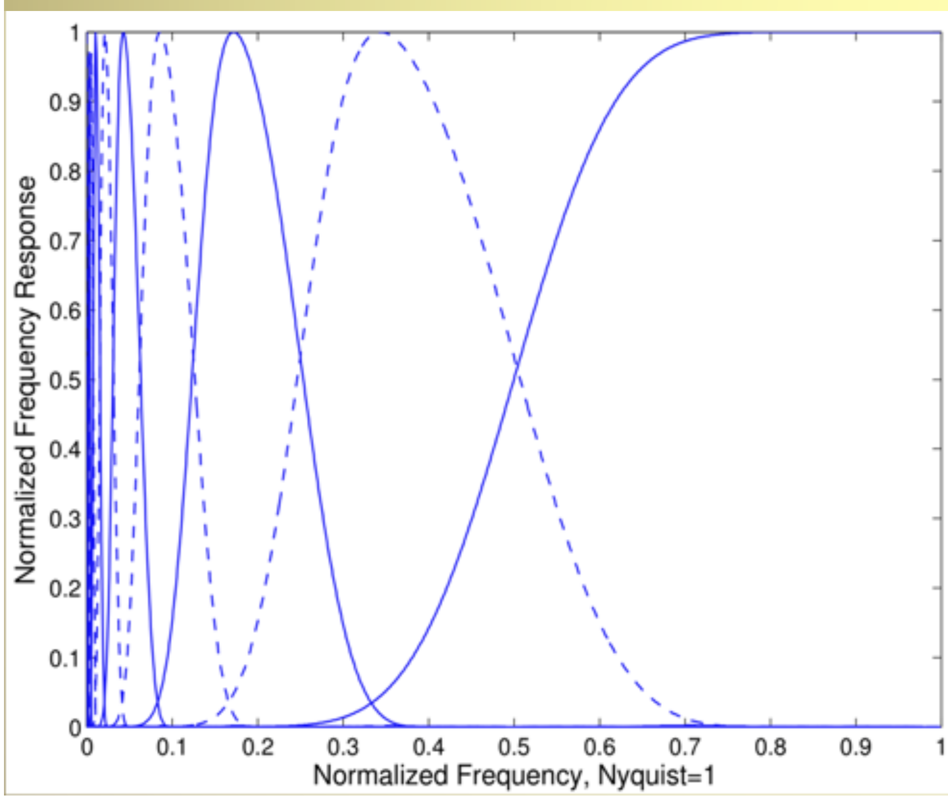
A Search for Earth-size Planets

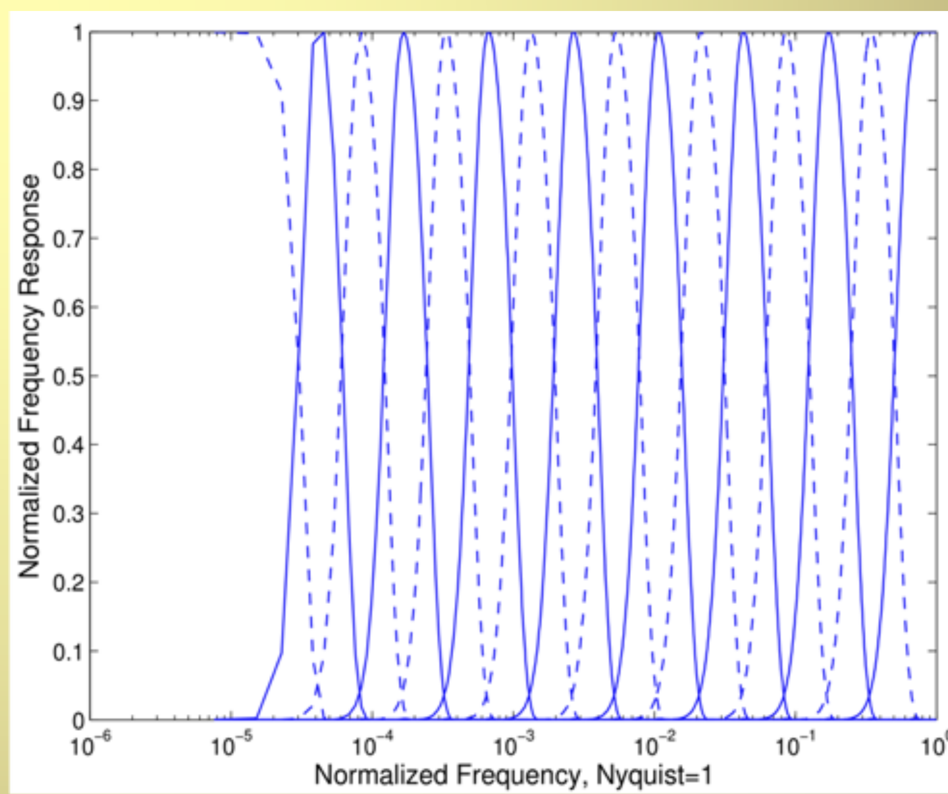
Filter-Bank Implementation of an Overcomplete Wavelet Transform

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

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

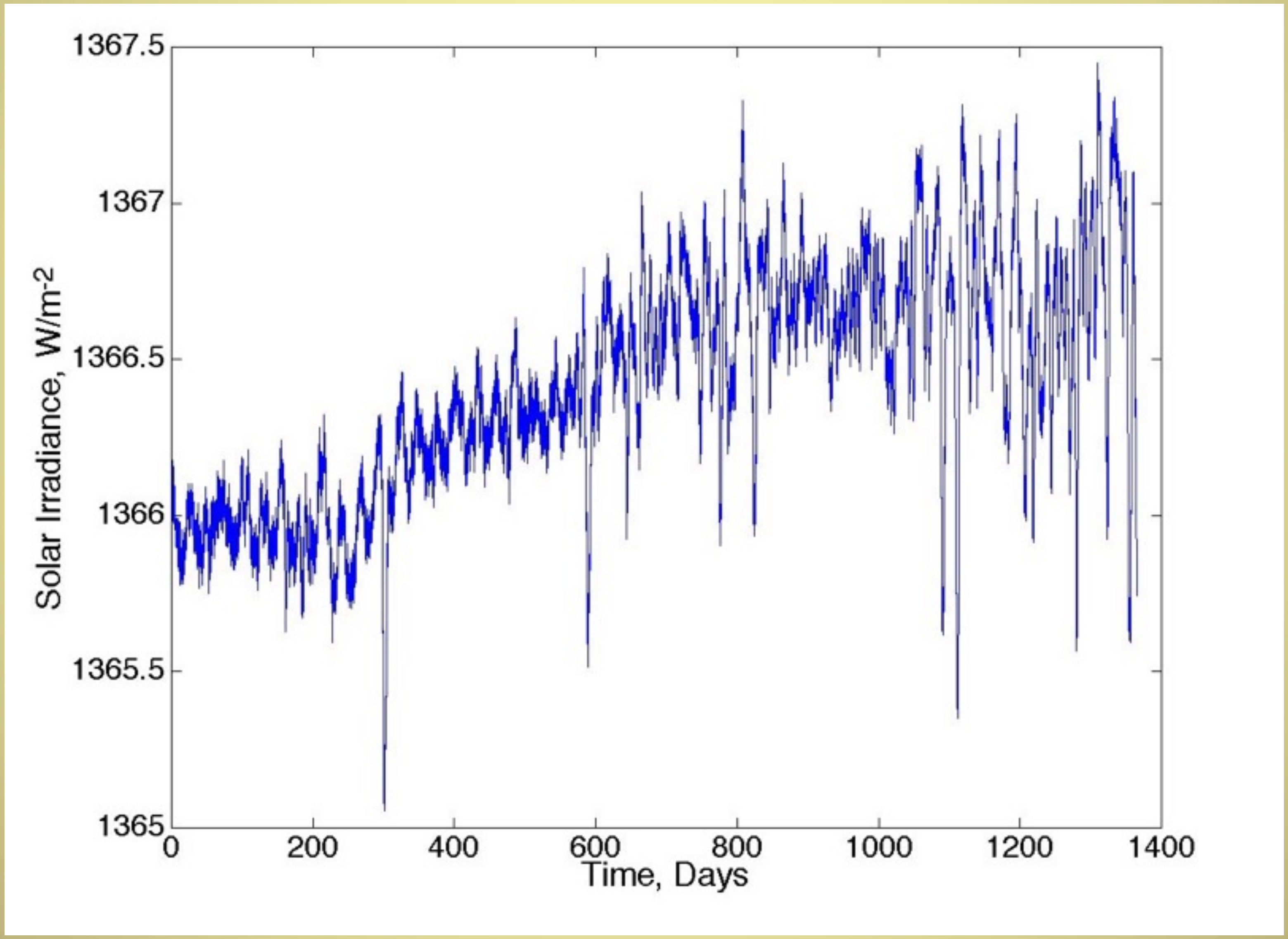






Stellar Variability + Transits

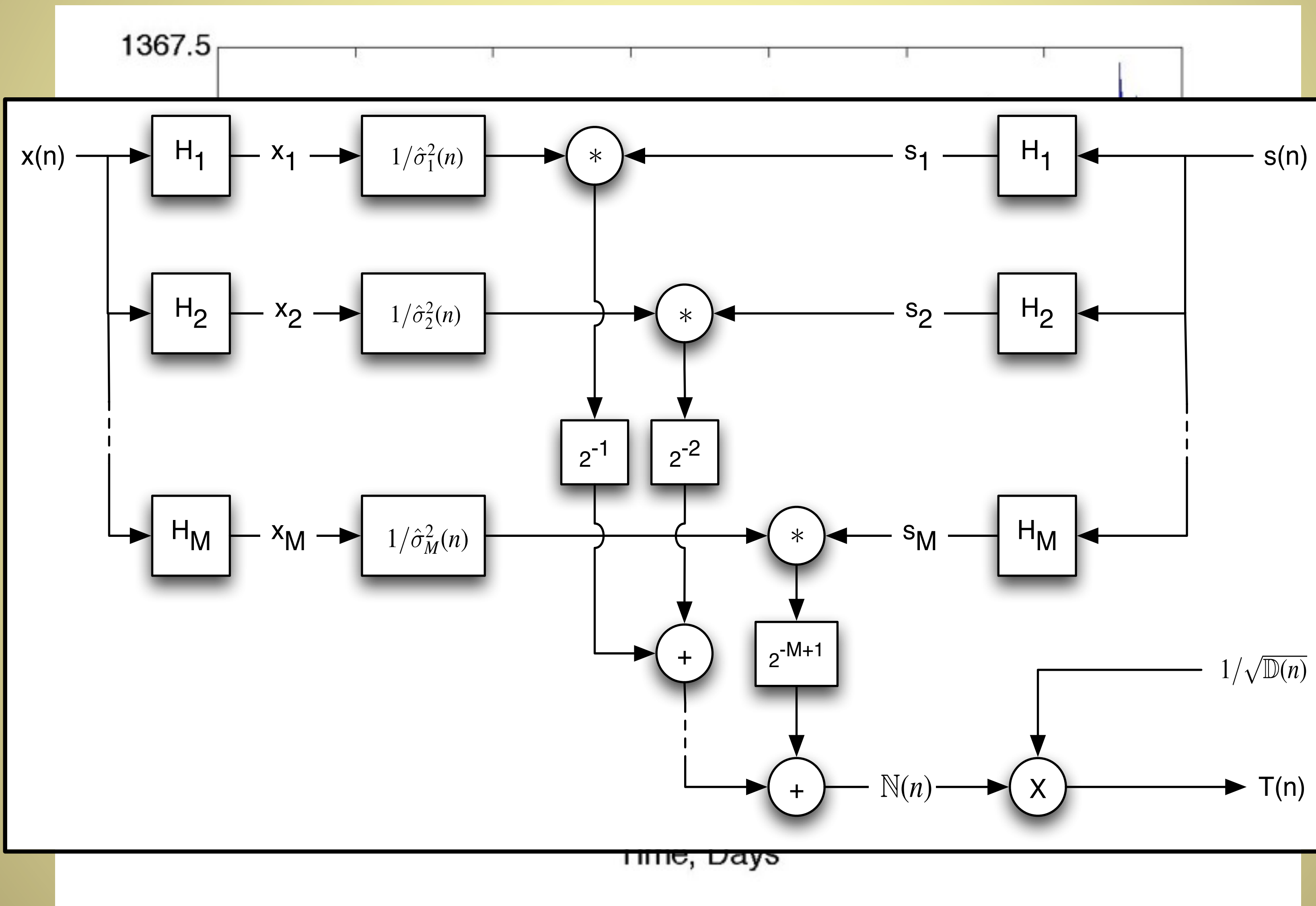
A Search for Earth-size Planets



Stellar Variability + Transits

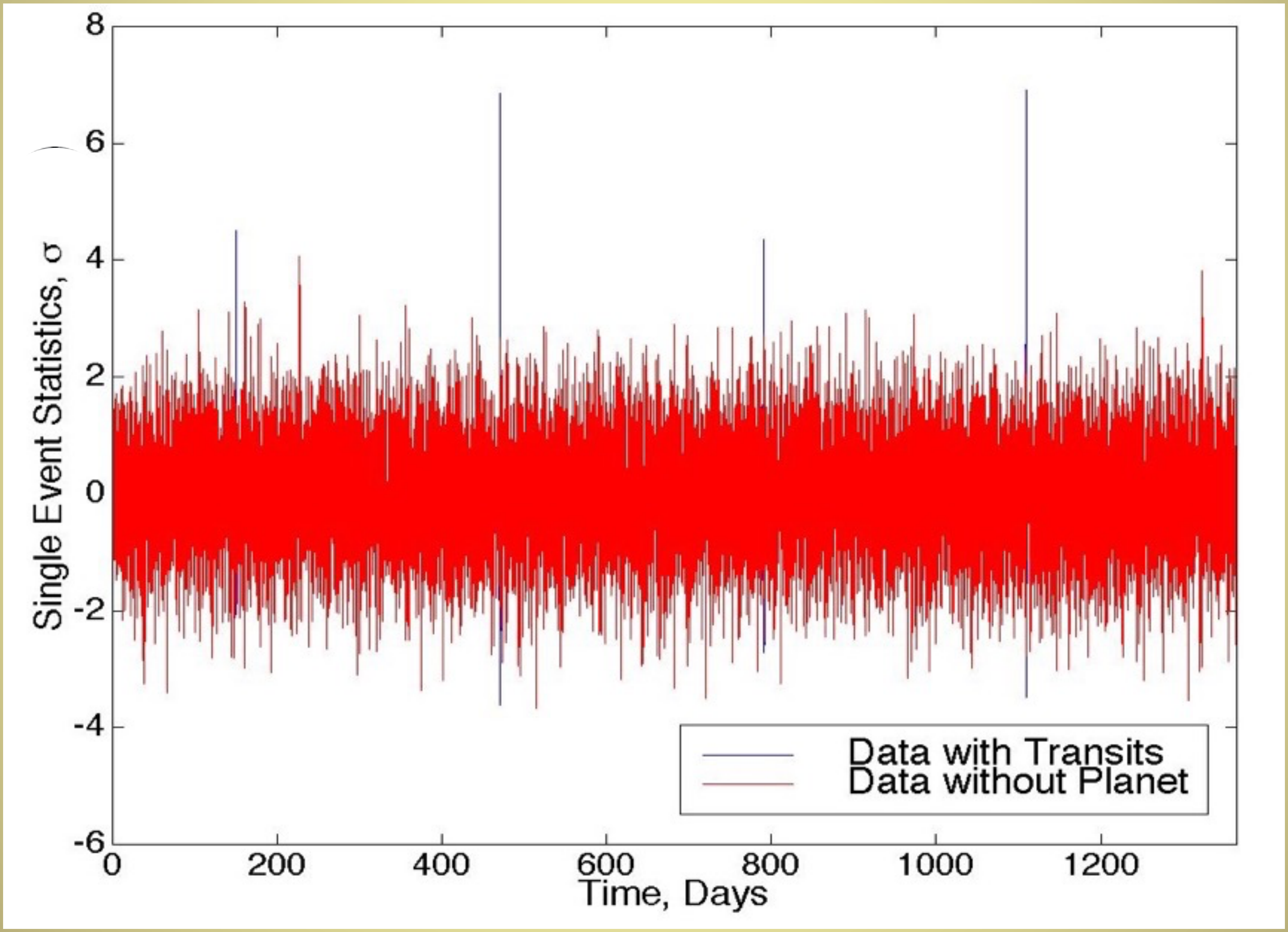
Kepler

A Search for Earth-size Planets



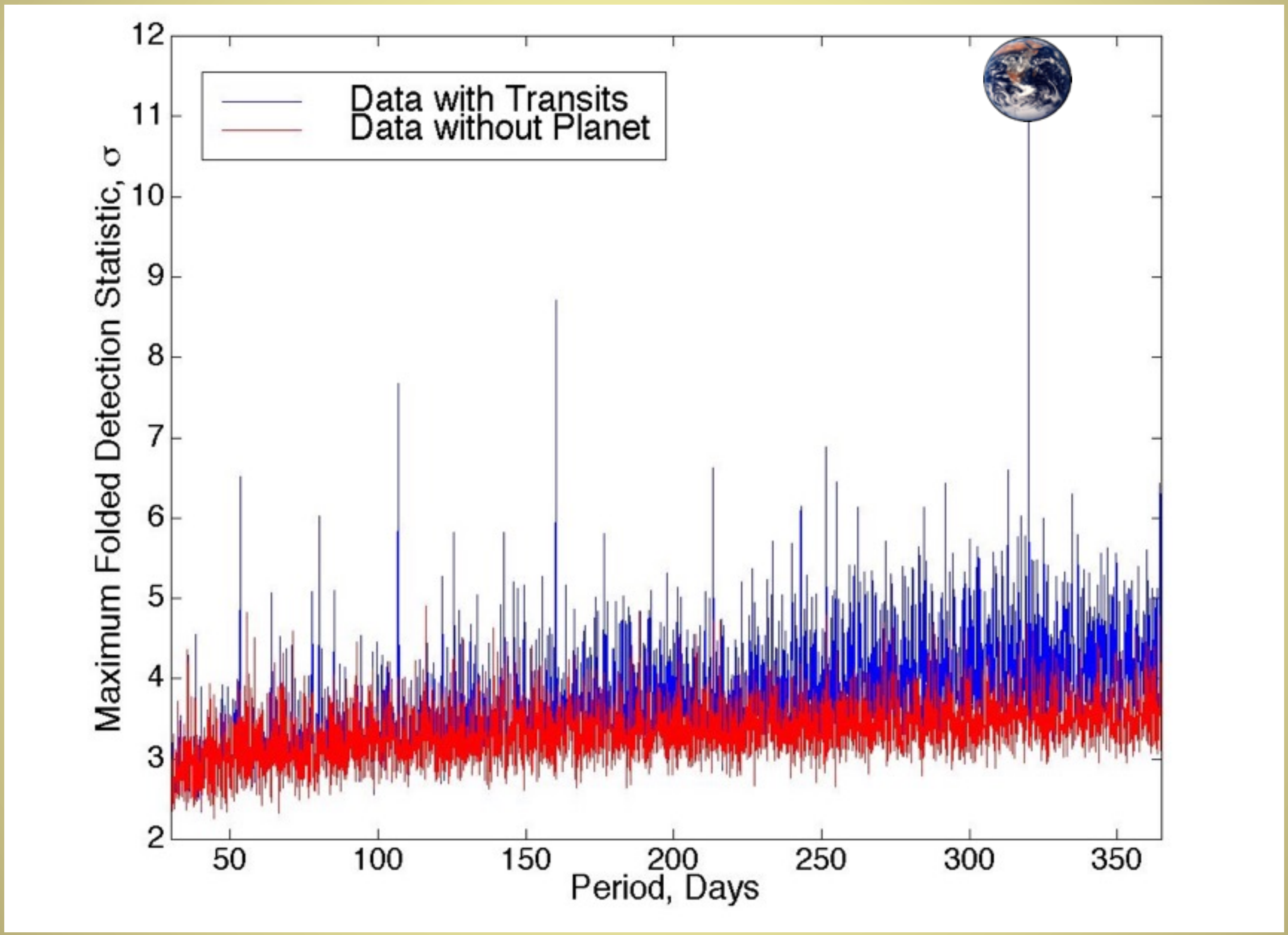
Single Transit Statistics

Kepler
A Search for Earth-size Planets



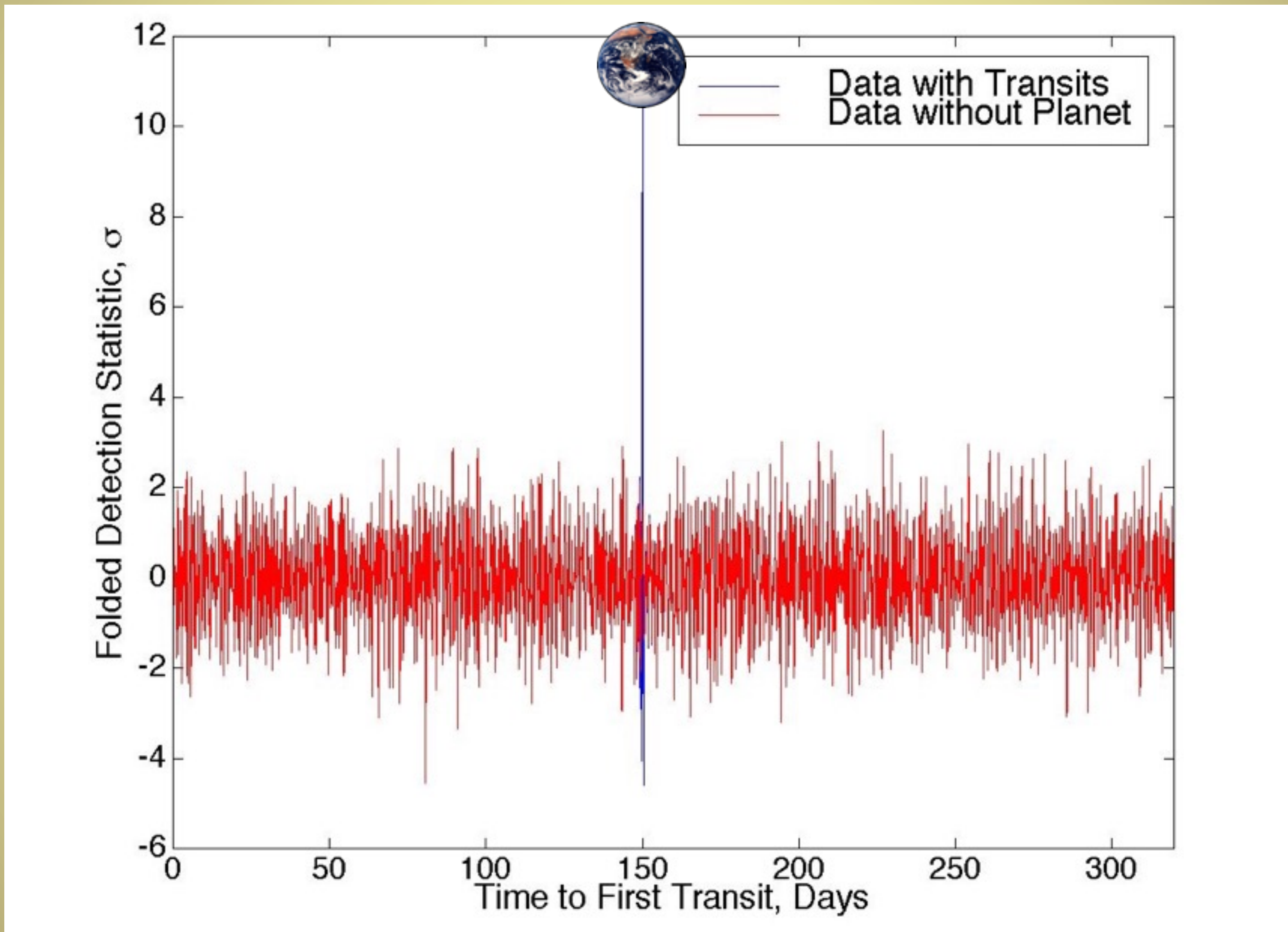
Folded Transit Statistics

Kepler
A Search for Earth-size Planets



Time to First Transit

A Search for Earth-size Planets

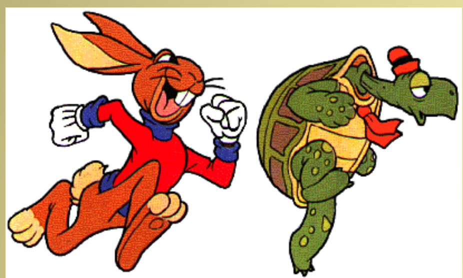


Keeping Up with the Data

A Search for Earth-size Planets

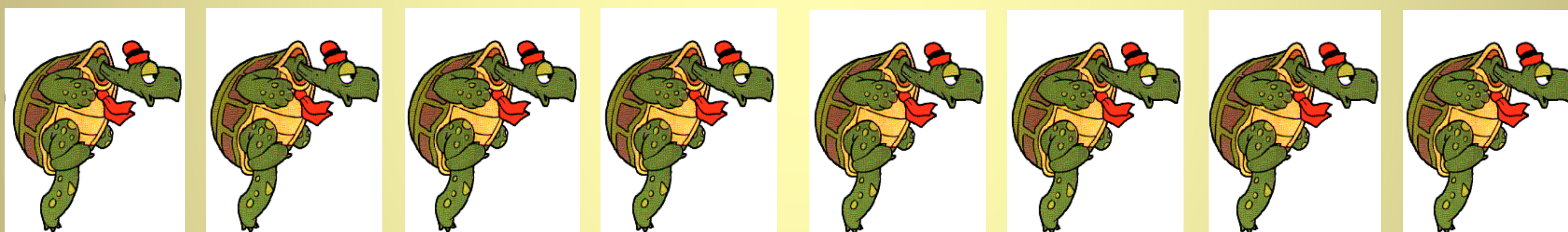
Improving the Throughput of *Kepler's* Science Pipeline

A Search for Earth-size Planets

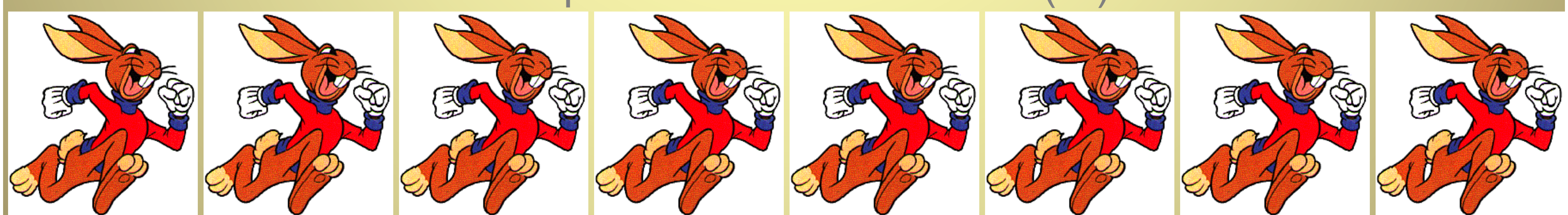


Some fast code; Some slow code

Step 1: Parallelize all code



Step 2: Make slow code fast(er)



Hardware Architecture: Kepler Science Operations Center

64 hosts, 712 CPUs,

3.7 TB of RAM,

148 TB of raw disk storage

Hardware Architecture: NAS Pleiades Supercomputer

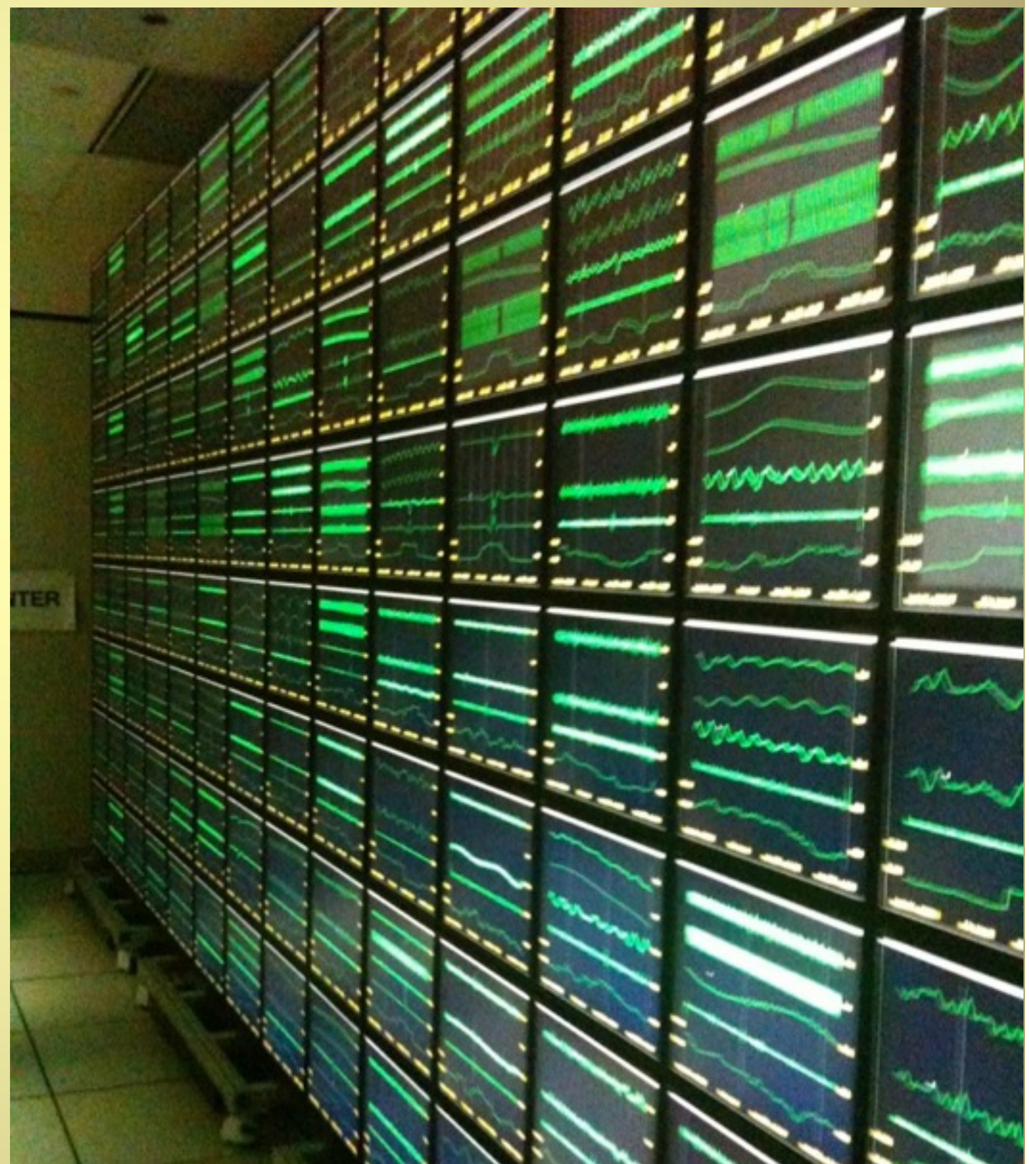
A Search for Earth-size Planets

5.34 Pflop/s peak cluster

211,872 cores

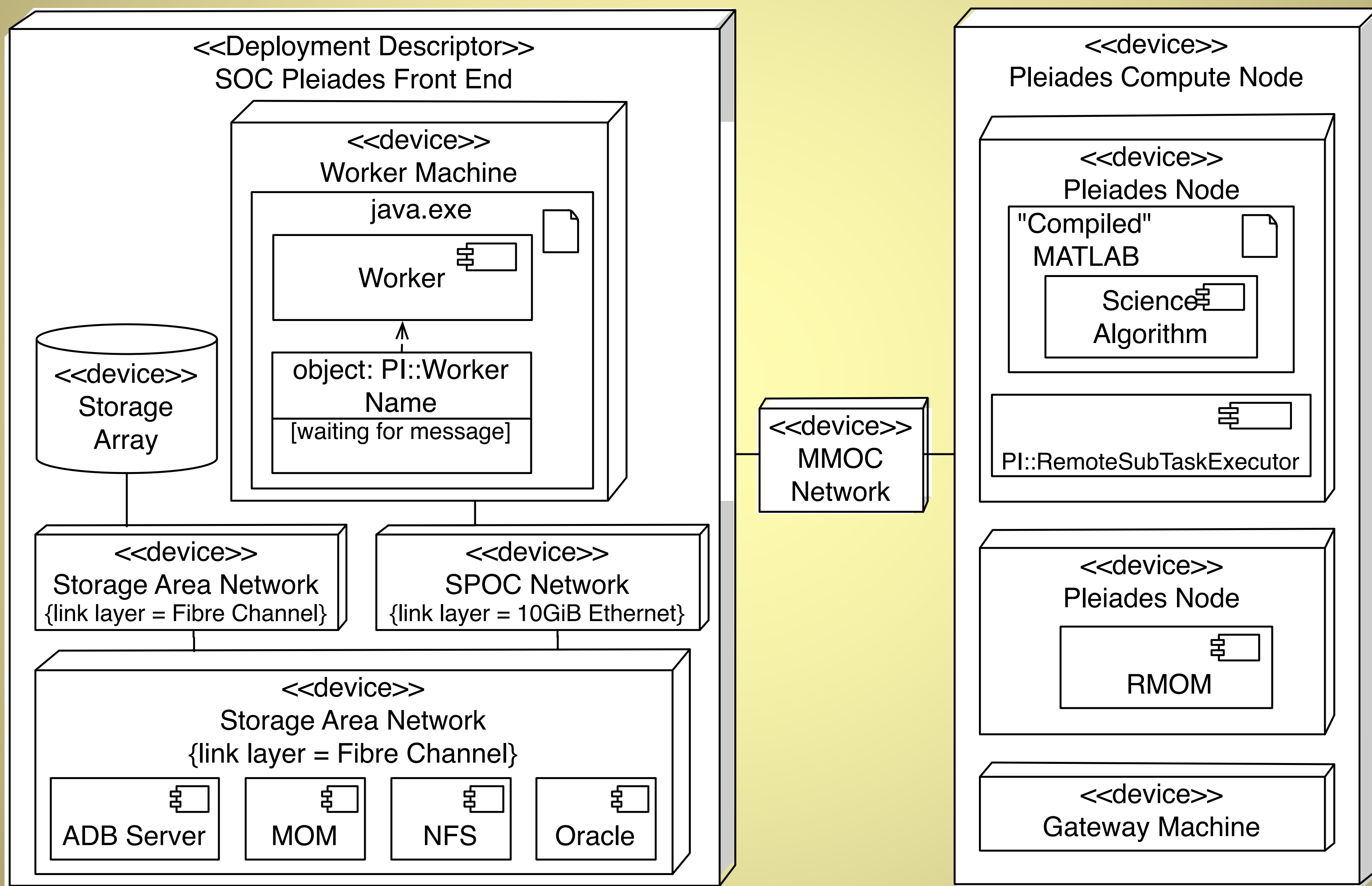
724 TB of memory

15 PB of storage

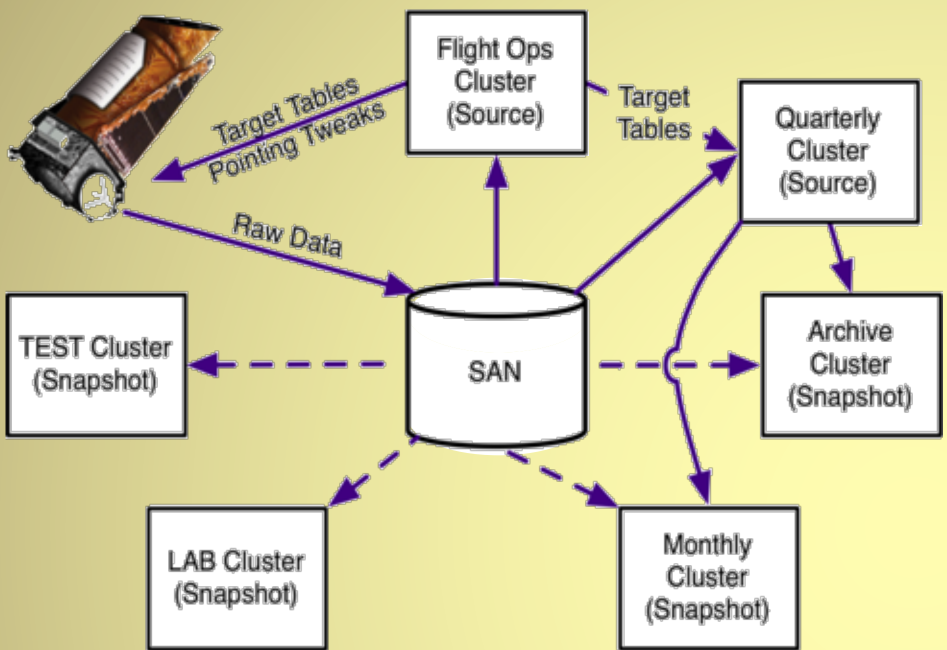


Deploying to the NAS

Kepler
A Search for Earth-size Planets



SOC Cluster Architecture



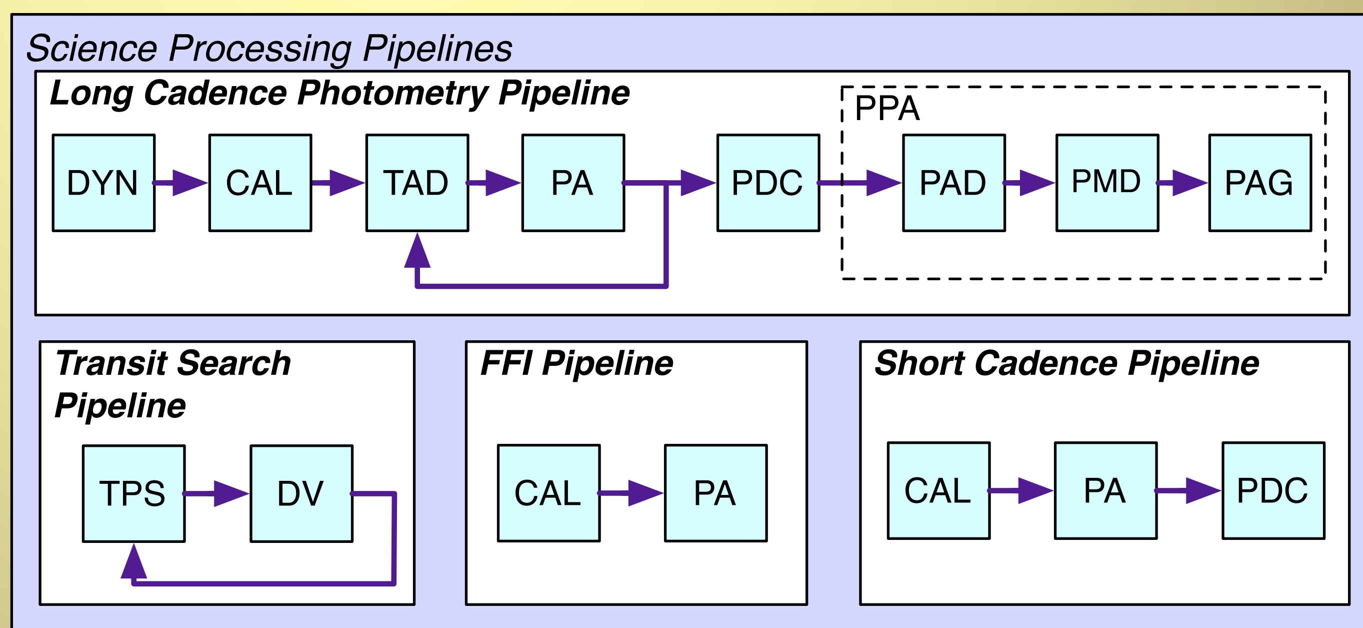
6 Clusters:

4 Operations Clusters:

Flight Ops, Quarterly, Monthly & Archive)

2 Test Clusters:

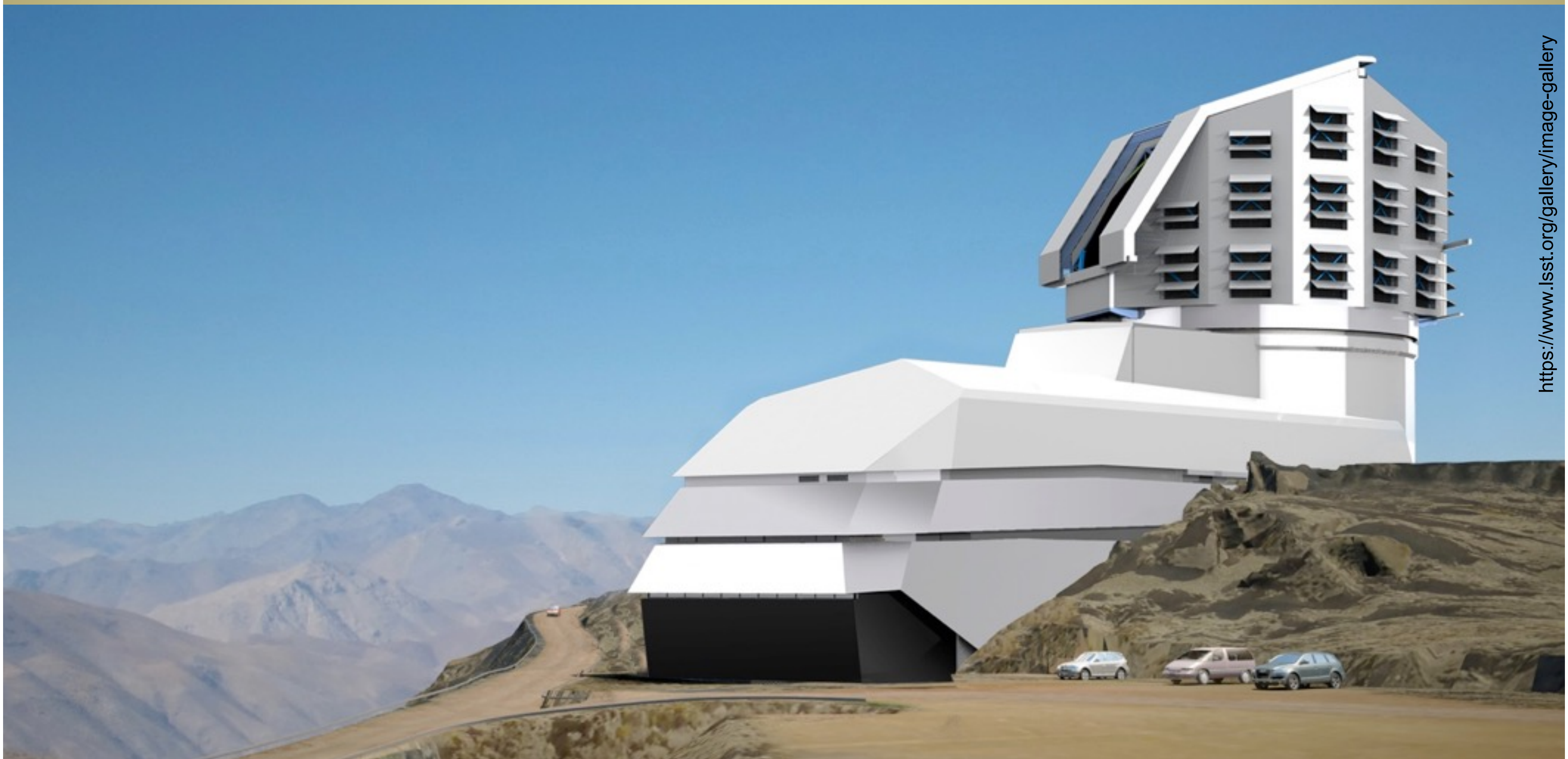
LAB & TEST



The Coming Astronomical Data Storm: LSST

Kepler

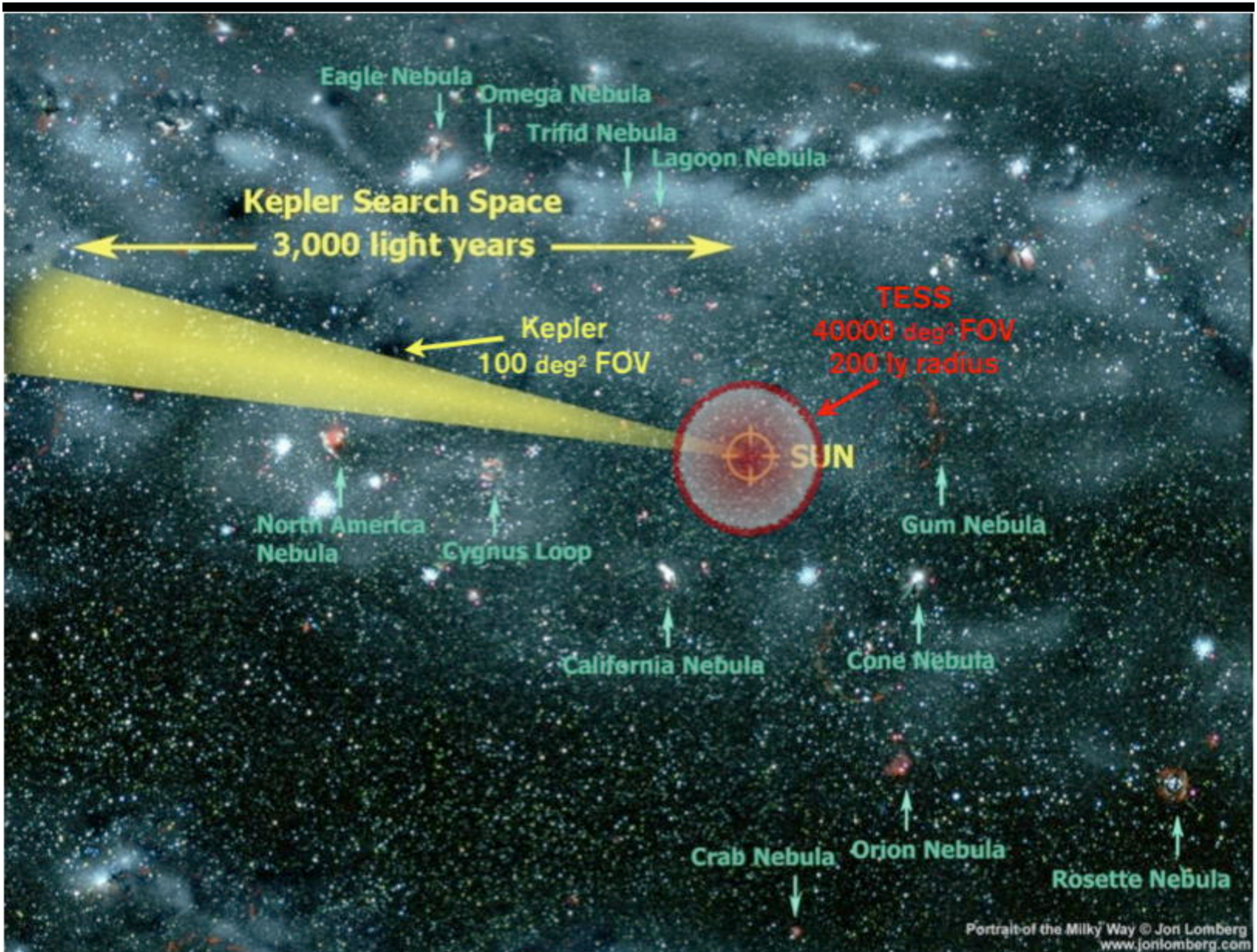
A Search for Earth-size Planets



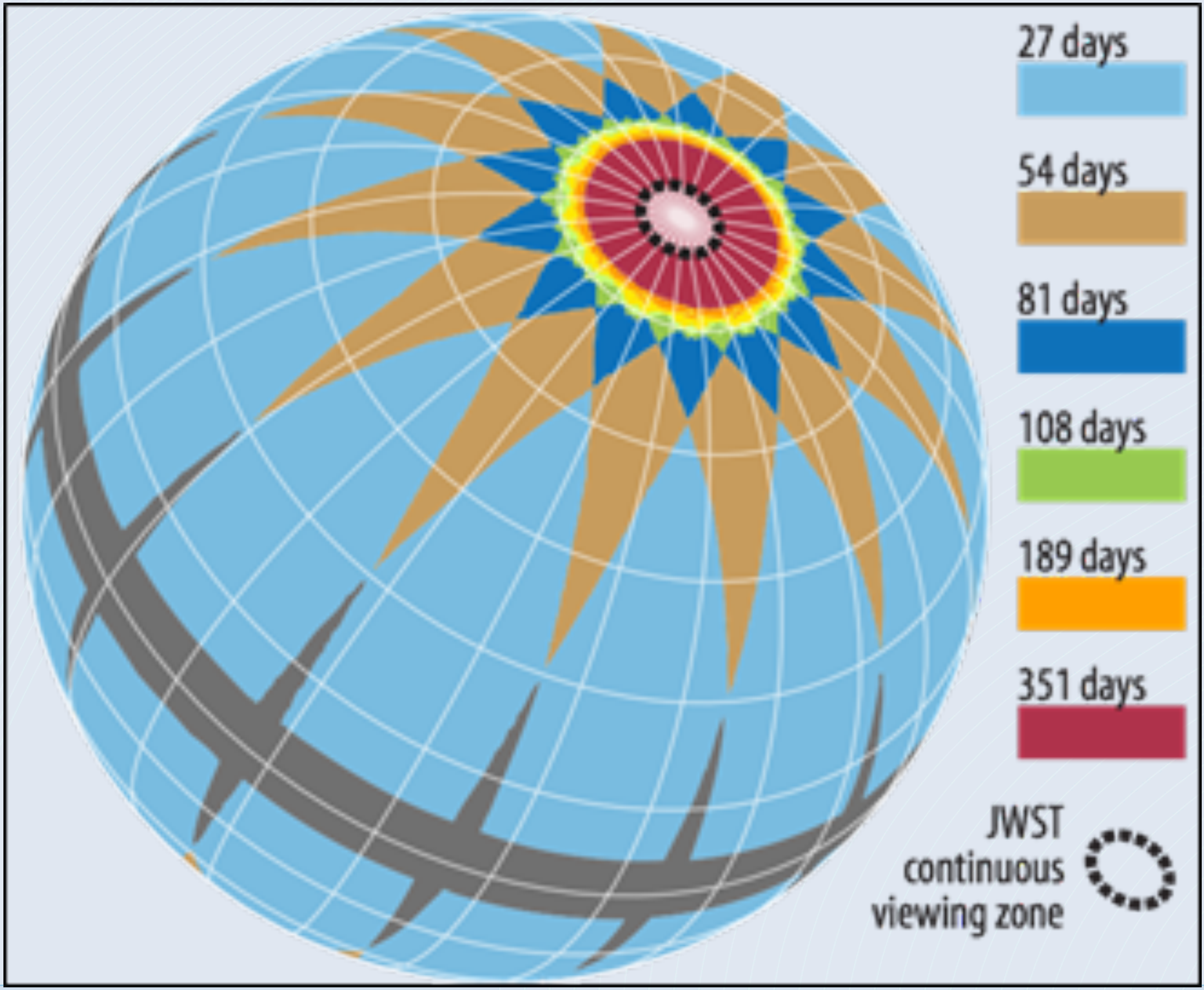
https://www.lsst.org/gallery/image-gallery

Beginning early in the next decade, the LSST will collect over 50 PB of raw data, resulting in over 30 trillion observations of 40 billion astronomical sources. It will measure the positions and properties of over 20 billion stars, or 10% of all stars in the Milky Way.

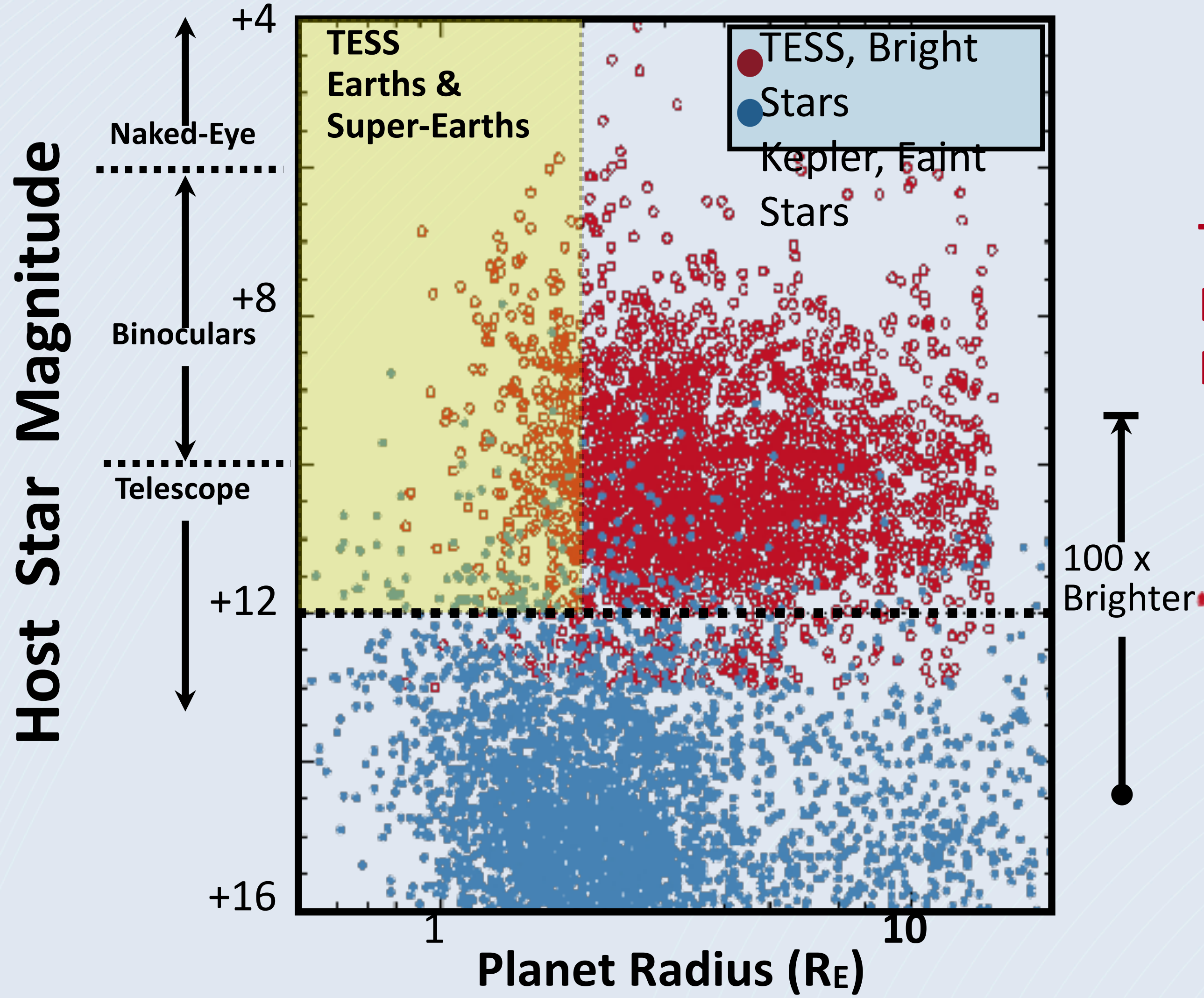

TESS Elation!


Eagle Nebula
Omega Nebula
Trifid Nebula
Lagoon Nebula
Kepler Search Space
3,000 light years
TESS
40000 deg² FOV
200 ly radius
Kepler
100 deg² FOV
SUN
North America
Nebula
Cygnus Loop
Gum Nebula
California Nebula
Cone Nebula
Crab Nebula
Orion Nebula
Rosette Nebula
Portrait of the Milky Way © Jon Lomberg
www.jonlomberg.com

TESS Sky Coverage



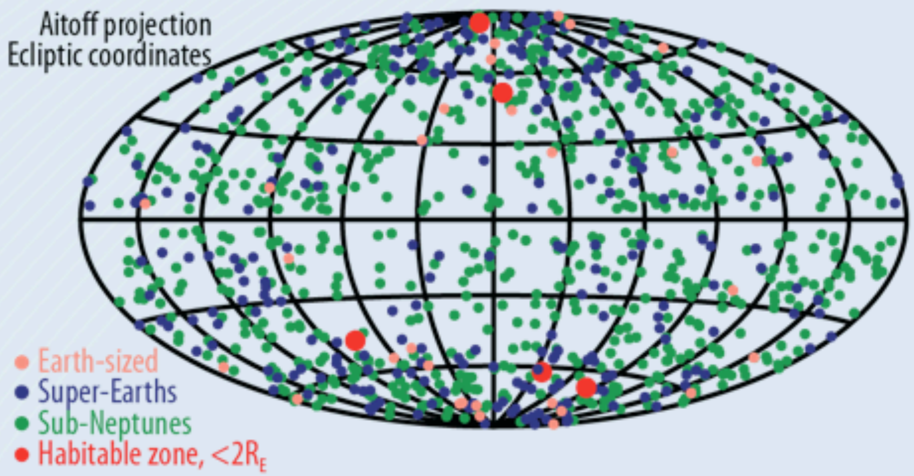
Comparison of Host Star Brightness

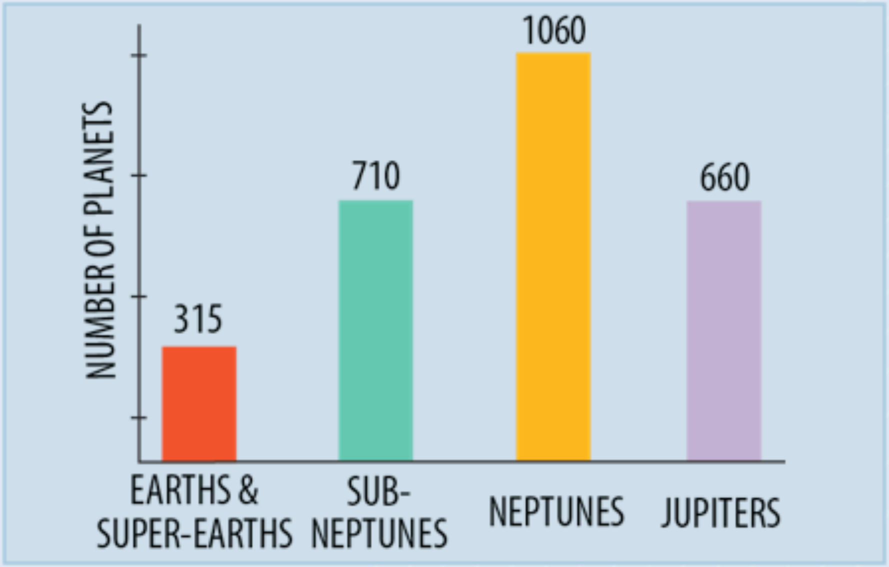


TESS Planets:
Easier to
Followup

TESS Will Discover Earths & Super-Earths Orbiting Bright Stars

Predicted Science Yield from TESS Mission

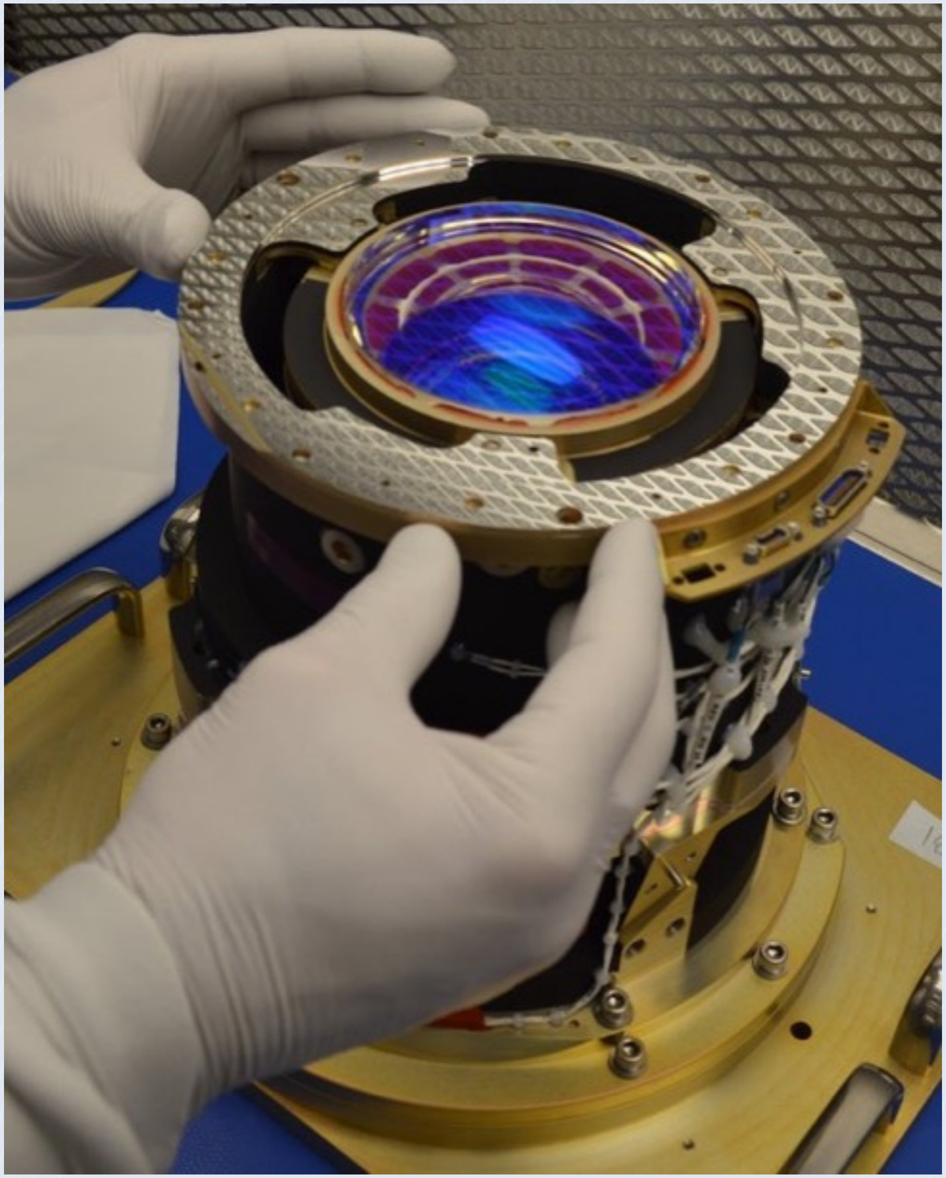


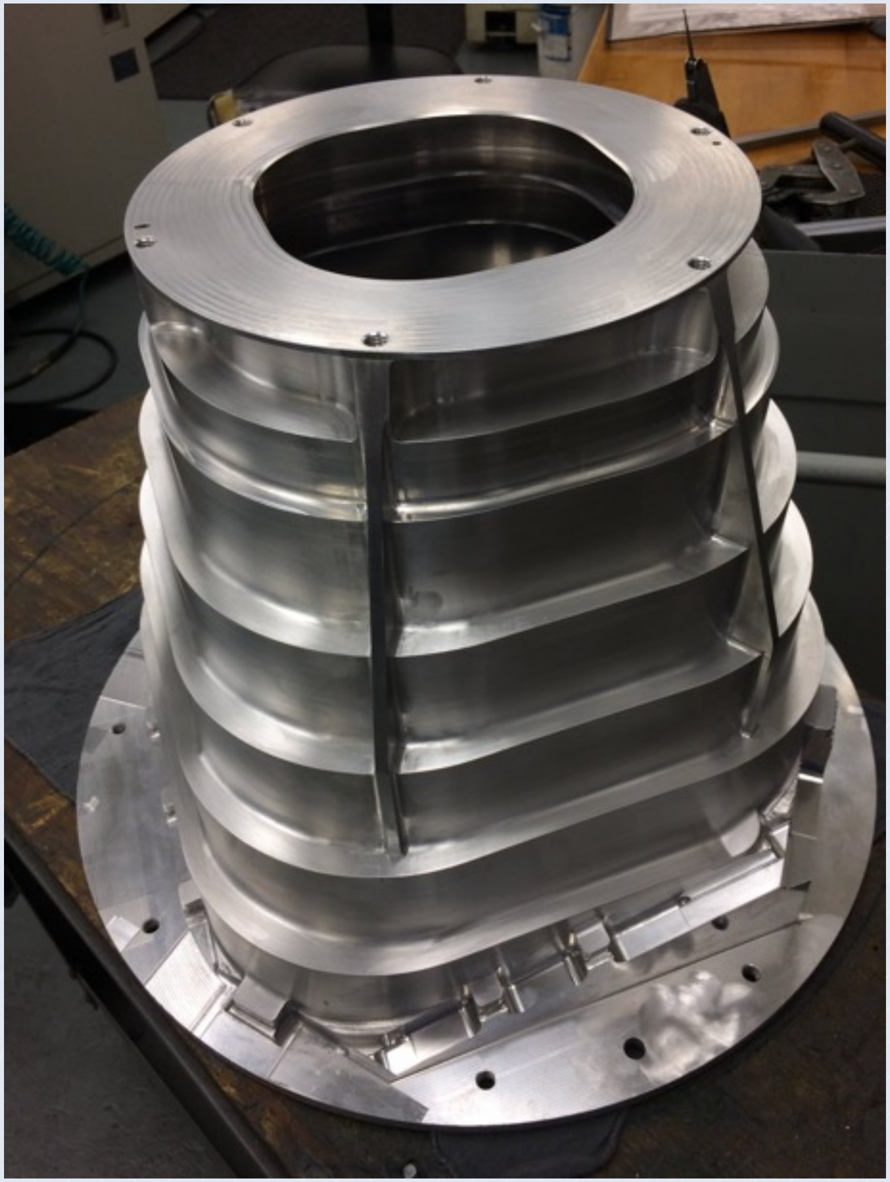


TESS Will Discover ~300 Earths & Super-Earths

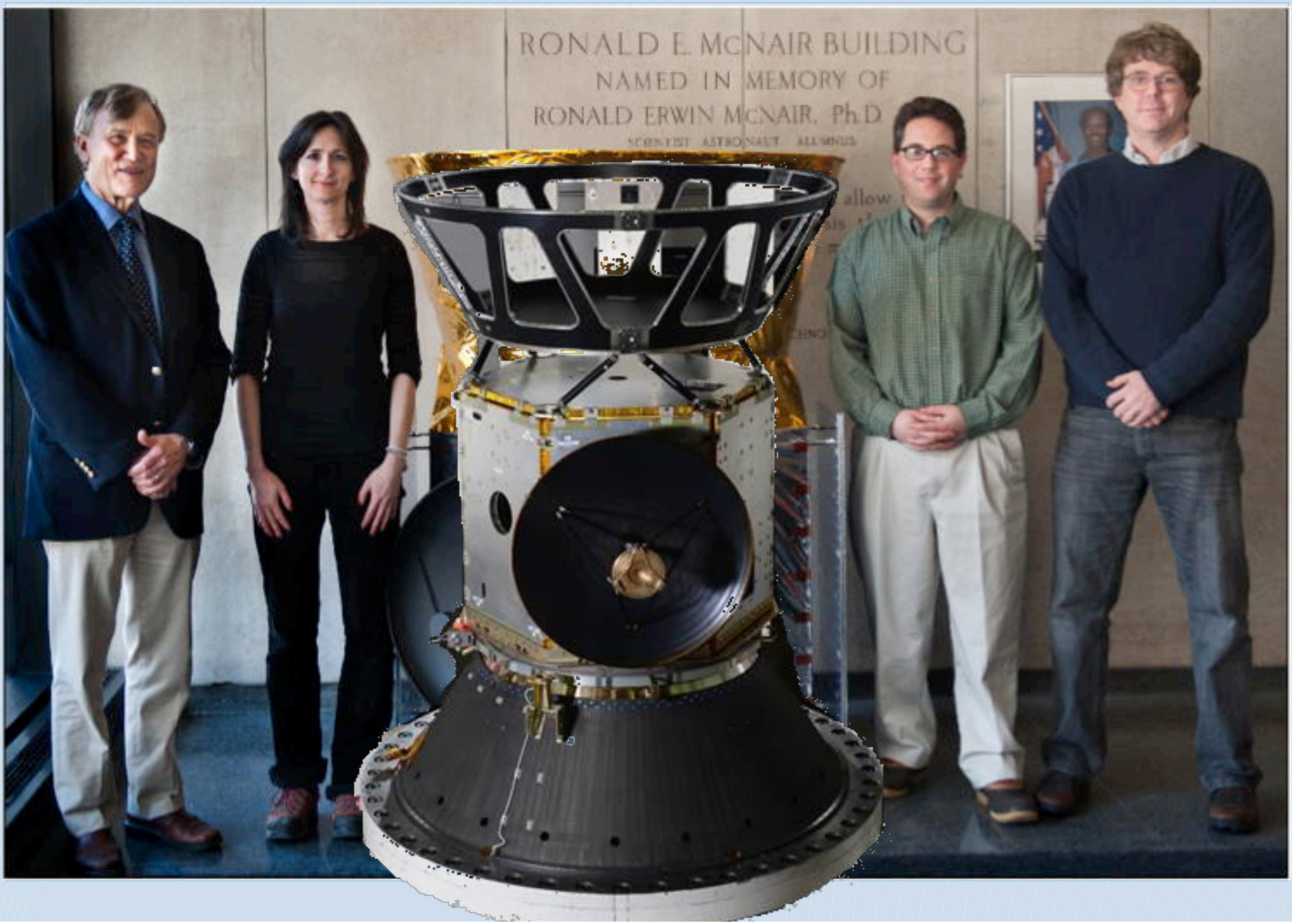
TESS Telescope

TESS Flight Hardware



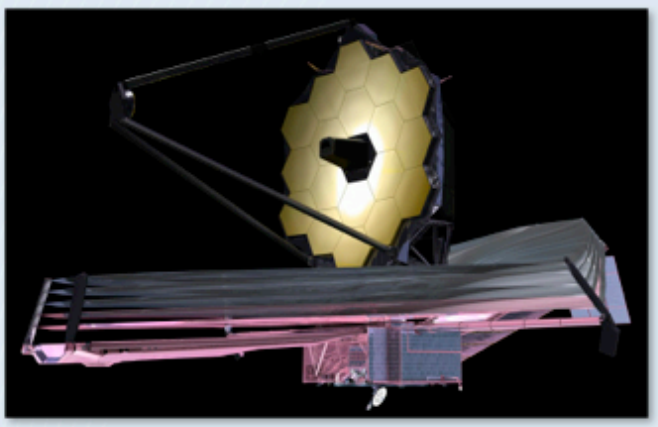
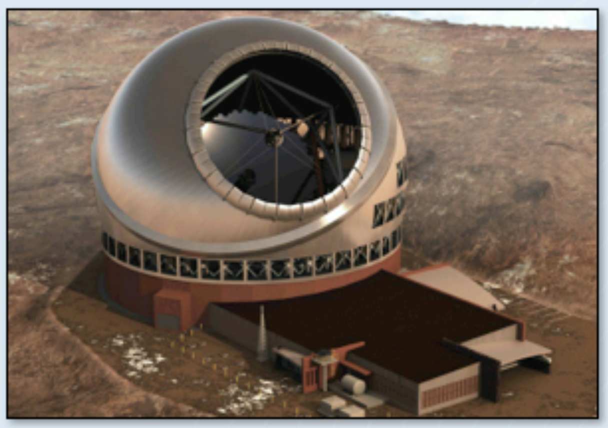


TESS Spacecraft

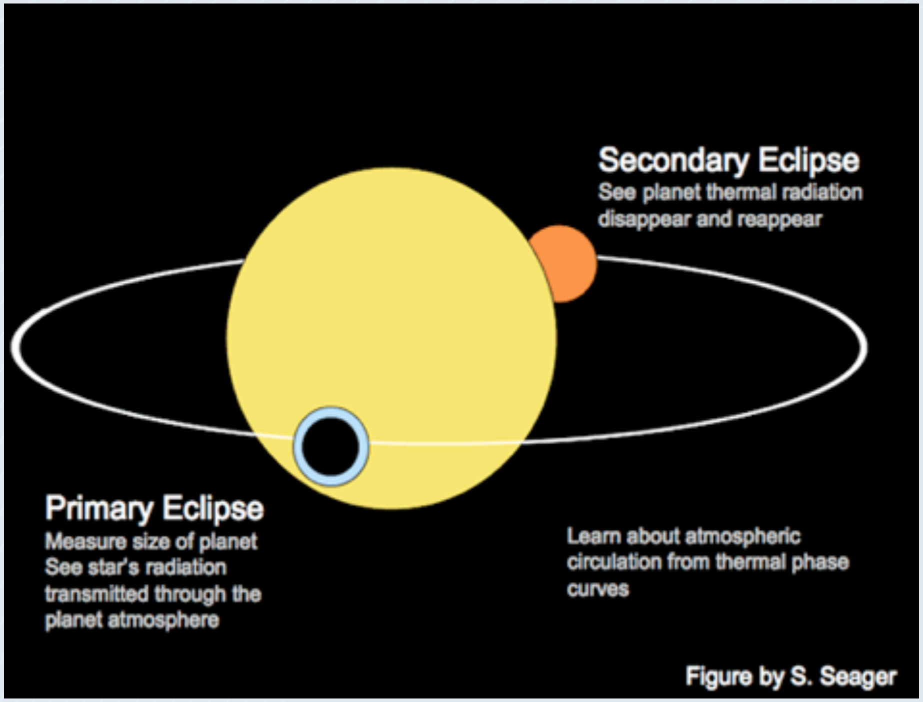


TESS Enables Atmospheric Characterization

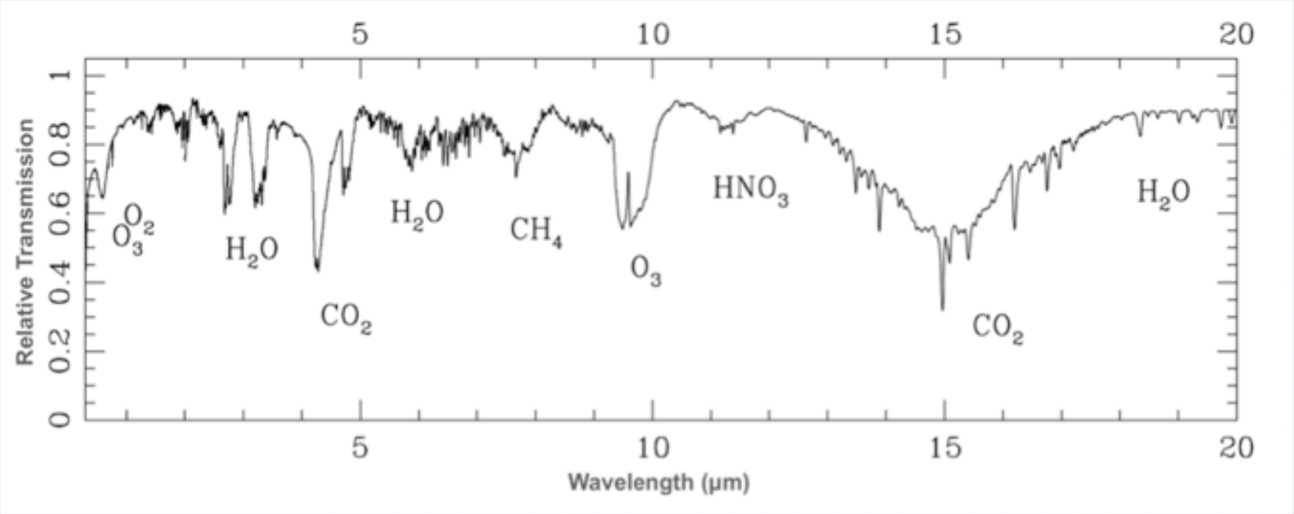
- TESS will identify the **best and smallest** exoplanet targets for characterization of atmospheres using:
  - *JWST*
  - *Extremely Large Telescopes (ELTs)*
  - *Future Exoplanet Explorers, Probes, and Large Missions*


Detecting Biomarkers through Transit Spectroscopy



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


Exoplanet
Missions
JWST
WFIRST-AFTA
TESS
Kepler
New Worlds Telescope
Spitzer
Hubble
Ground-based Observatories
Astronomy and Astrophysics in the New Millennium
2001 Decadal Survey
New Worlds, New Horizons
2010 Decadal Survey

Summary

- We now know of ~2,300 planets orbiting other stars
- ~20 of these planets are less than 2X the size of Earth in the habitable zone of their star
- Kepler-452b is the first small, possibly rocky planet in the habitable zone of a G2 star like the Sun
- TESS is NASA's next mission to find Earth's nearest neighbors