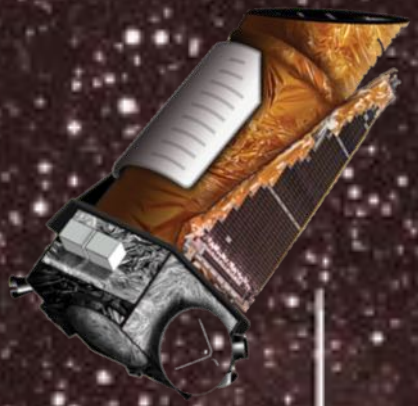
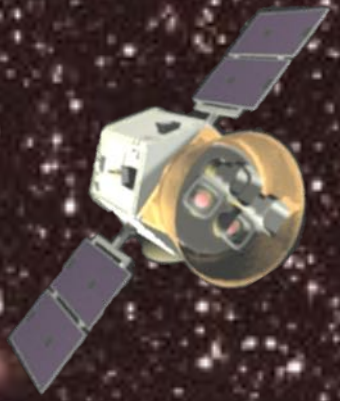
Introduction to Exoplanets and the TESS Planet Finding Pipeline





Jon M. Jenkins
NASA Ames Research Center

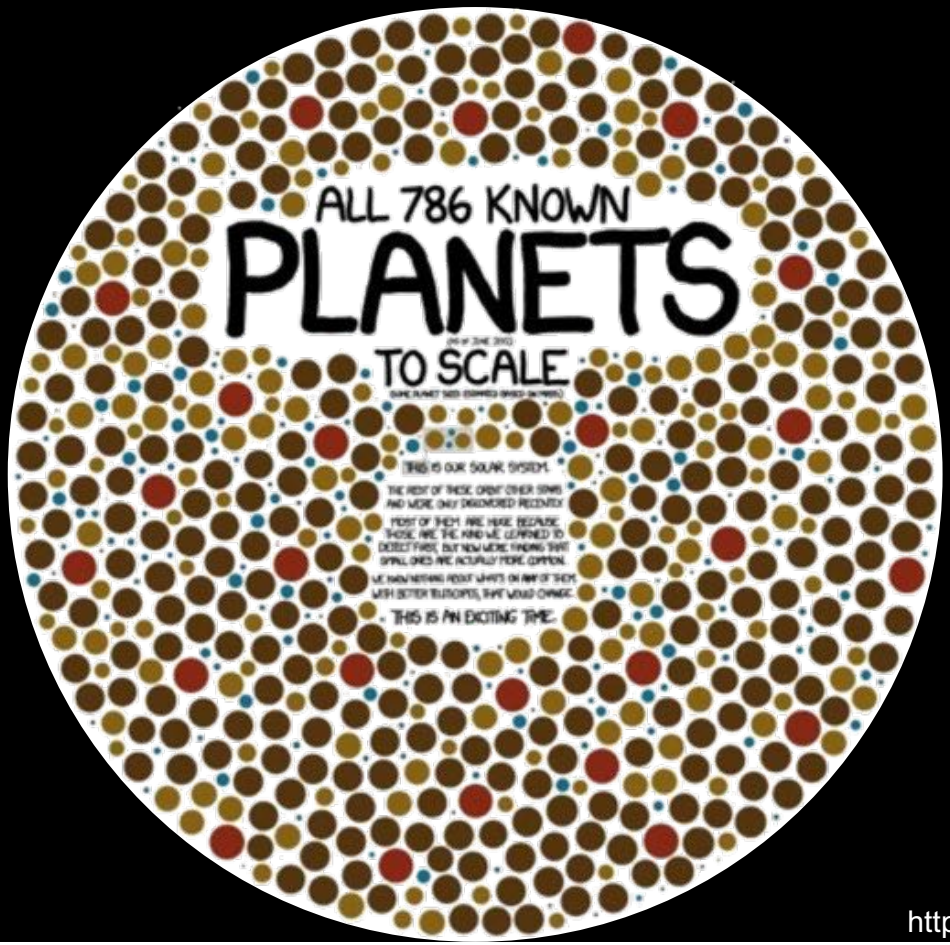
Thursday June 28, 2018
Frontier Development Lab
NVIDEA, Santa Clara CA

All the Known Planets In 1994

Kepler
A Search for Earth-size Planets

A More Recent Pictures of Planets

Kepler
A Search for Earth-size Planets

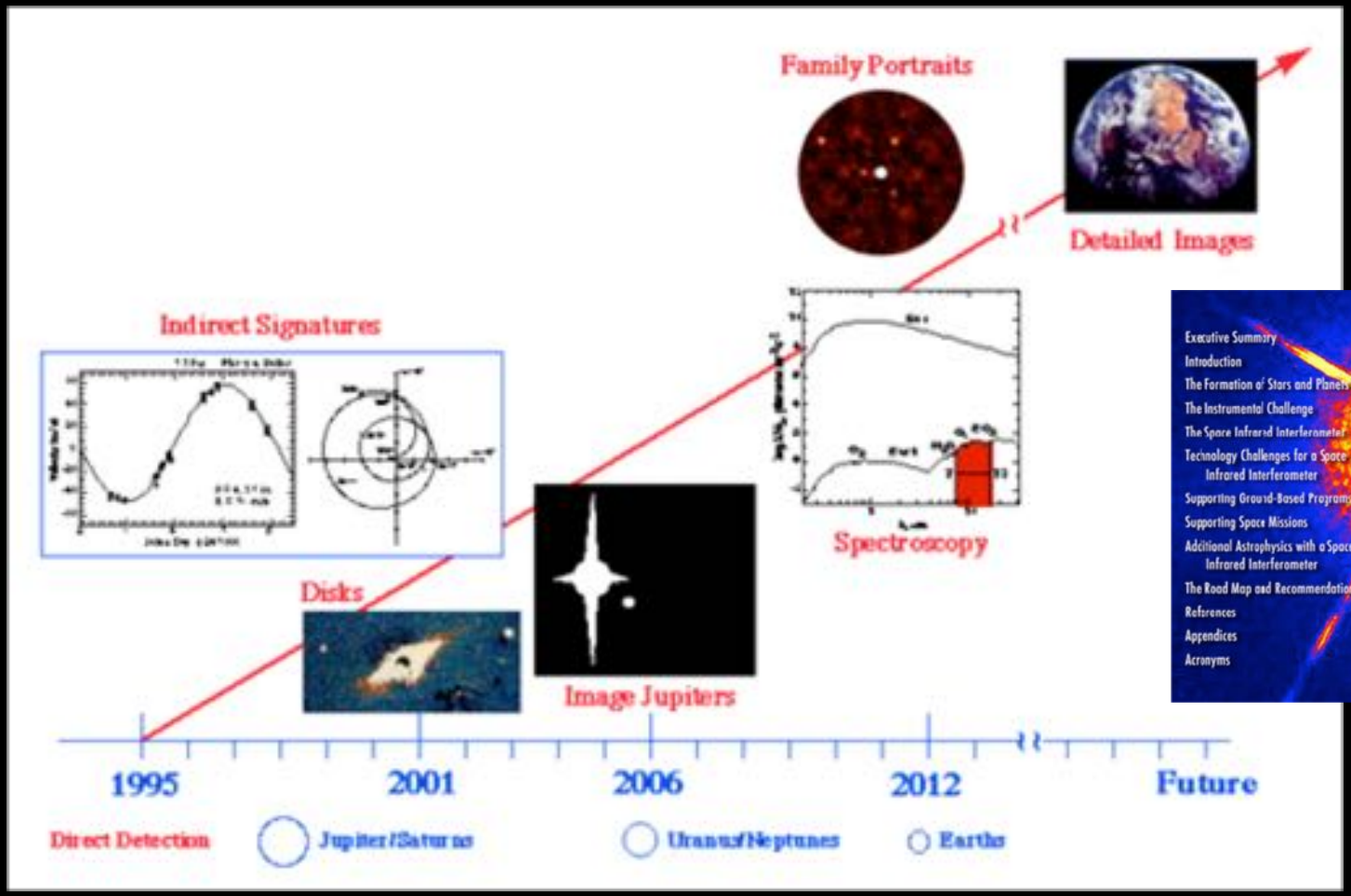


https://xkcd.com/1071/

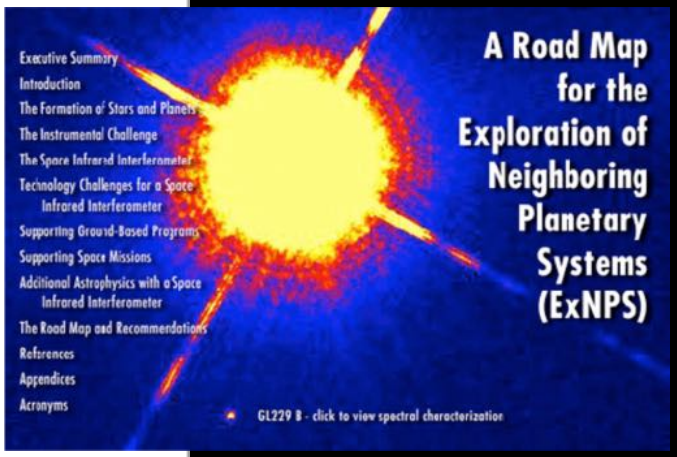

ALL 786 KNOWN
PLANETS
(AS OF JUNE 2012)
TO SCALE
SOME PLANET SIZES EXAGGERATED BASED ON MASS
THIS IS OUR SOLAR SYSTEM.
THE REST OF THESE ORBIT OTHER STARS AND WERE ONLY DISCOVERED RECENTLY.
MOST OF THEM ARE HUGE BECAUSE THOSE ARE THE KIND WE LEARNED TO DETECT FIRST, BUT NOW WE'RE FINDING THAT SMALL ONES ARE ACTUALLY MORE COMMON.

NASA's 1995 ExNPS Report

Kepler
A Search for Earth-size Planets

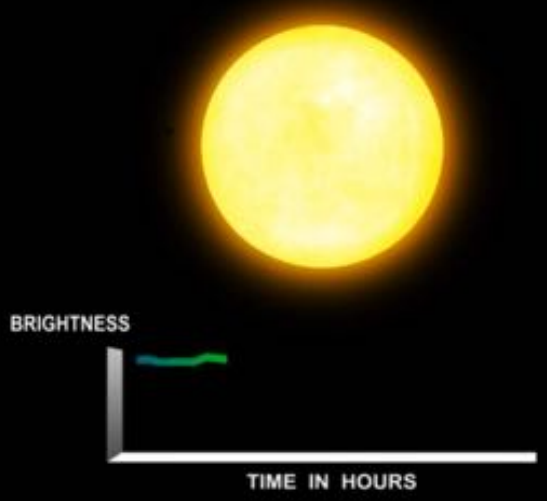


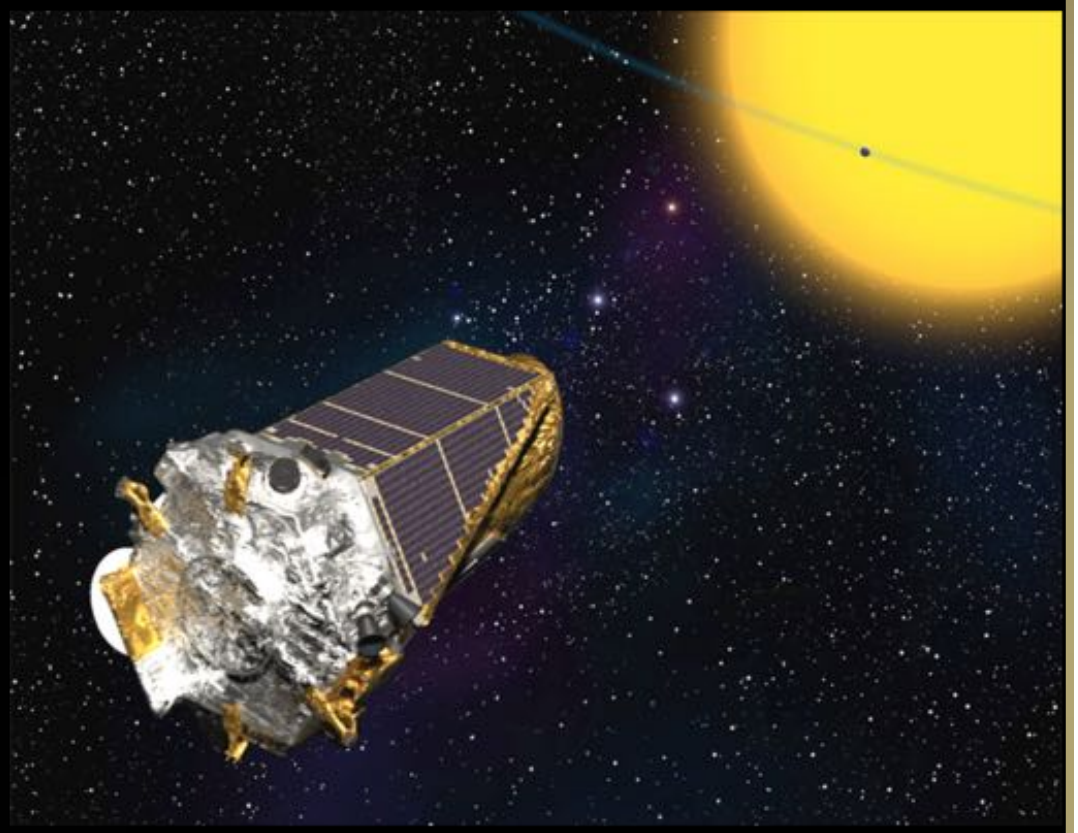
Transit Photometry not Recommended!



The *Kepler* Mission

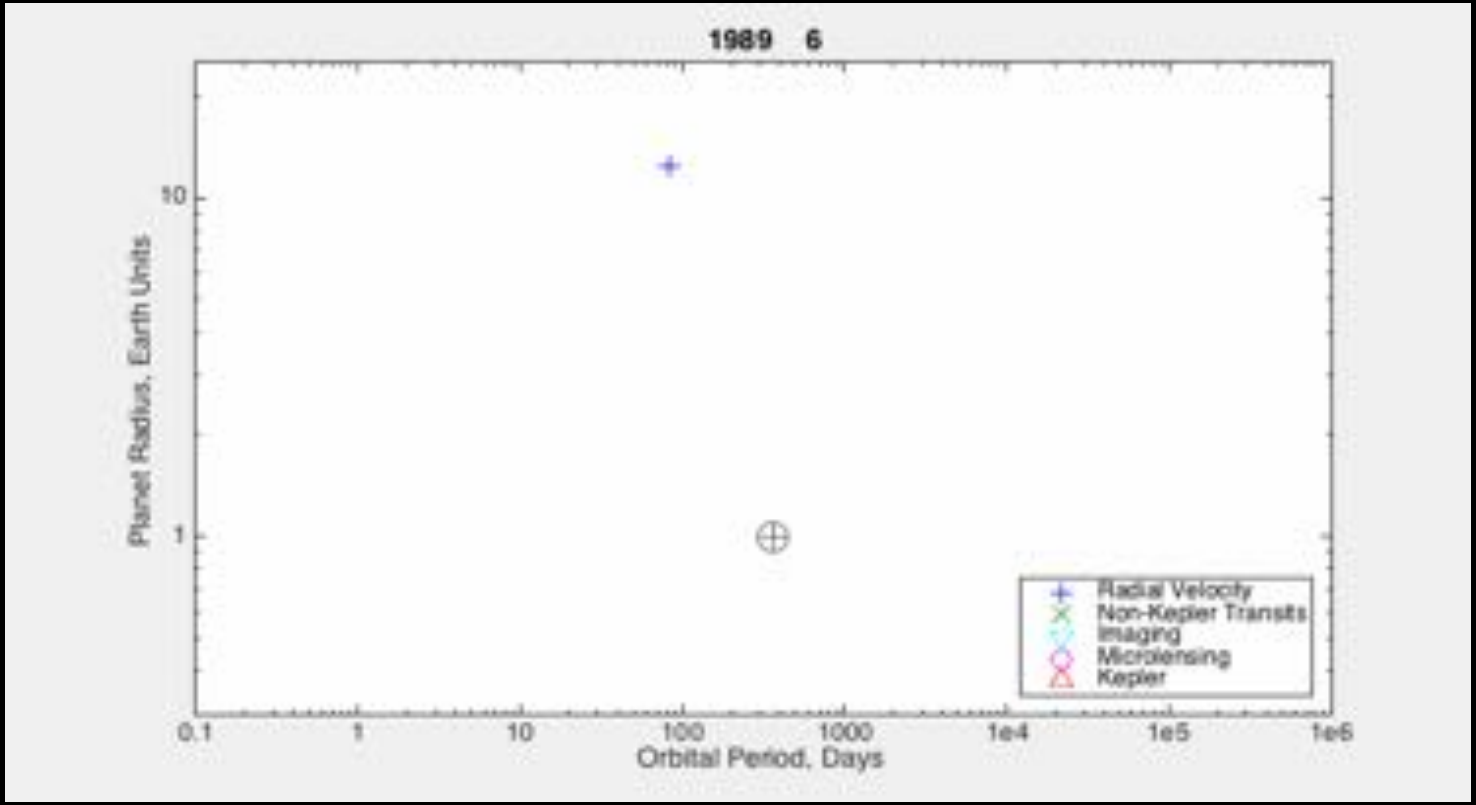
What fraction of sun-like stars in our galaxy host potentially habitable Earth-size planets?





Exoplanet Discoveries Over Time*

Kepler
A Search for Earth-size Planets

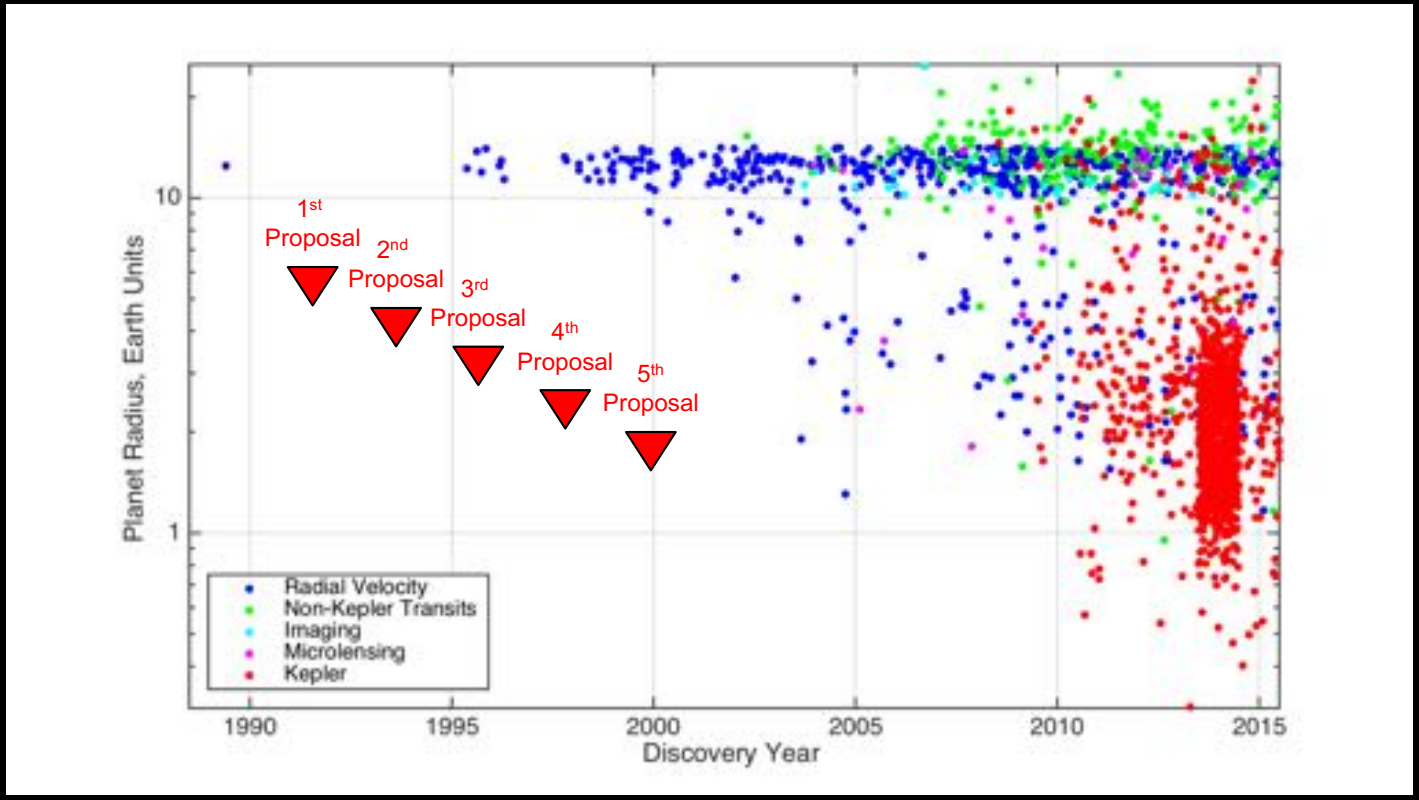


Radii estimated for non-transiting exoplanets
Discovery data dithered slightly

*According to https://exoplanetarchive.ipac.caltech.edu as of 8/29/17

Exoplanet Discoveries Over Time

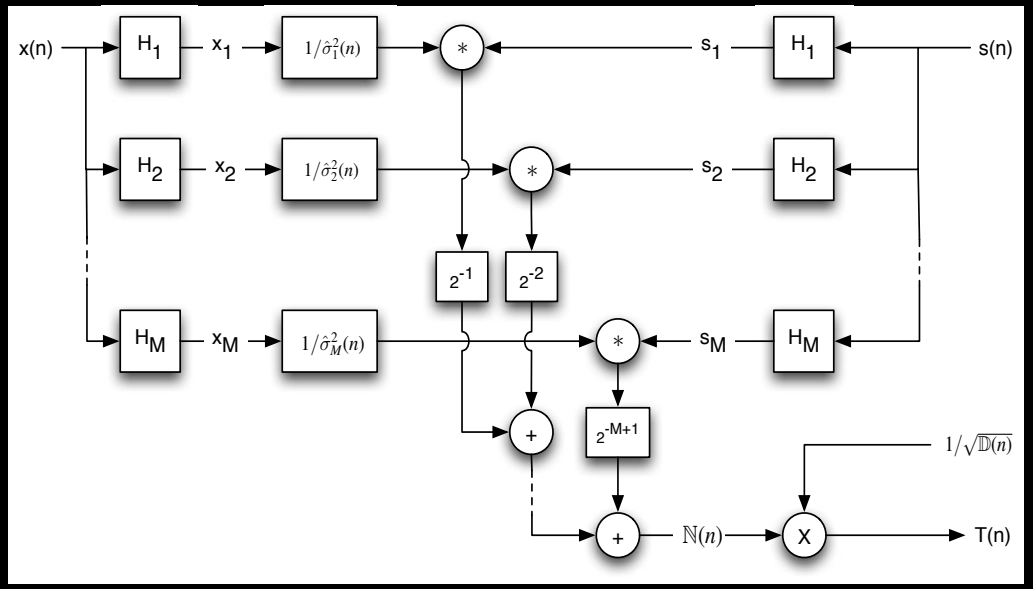
Kepler
A Search for Earth-size Planets



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

Enabling *Kepler*

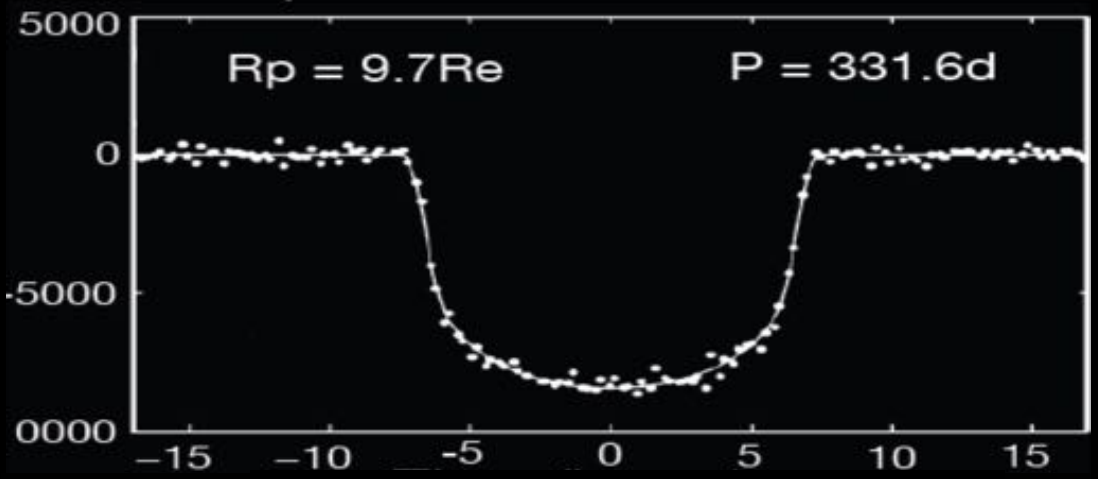
- Back illuminated CCDs (20 ppm photometric precision)
- Sophisticated algorithms
- Computational infrastructure



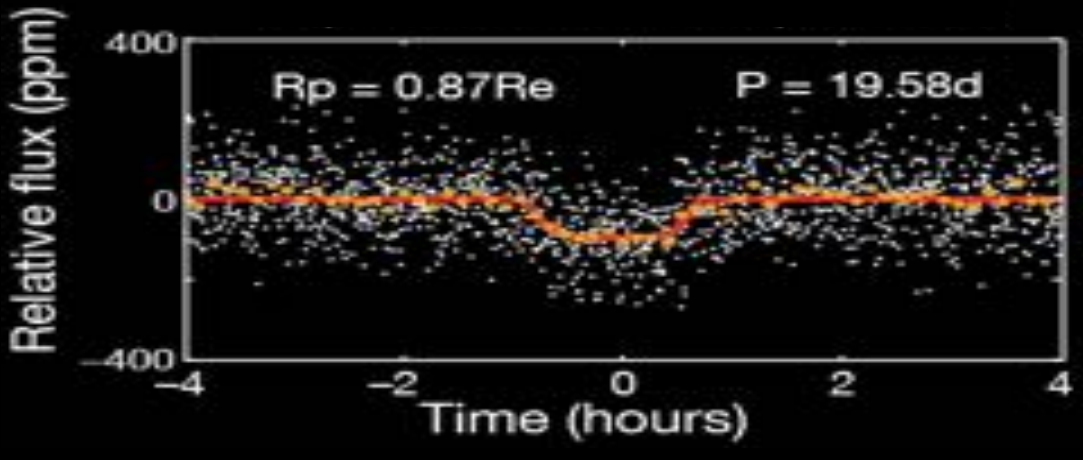
How Hard is it to Find Good Planets?

Kepler
A Search for Earth-size Planets

Jupiter (~1%)

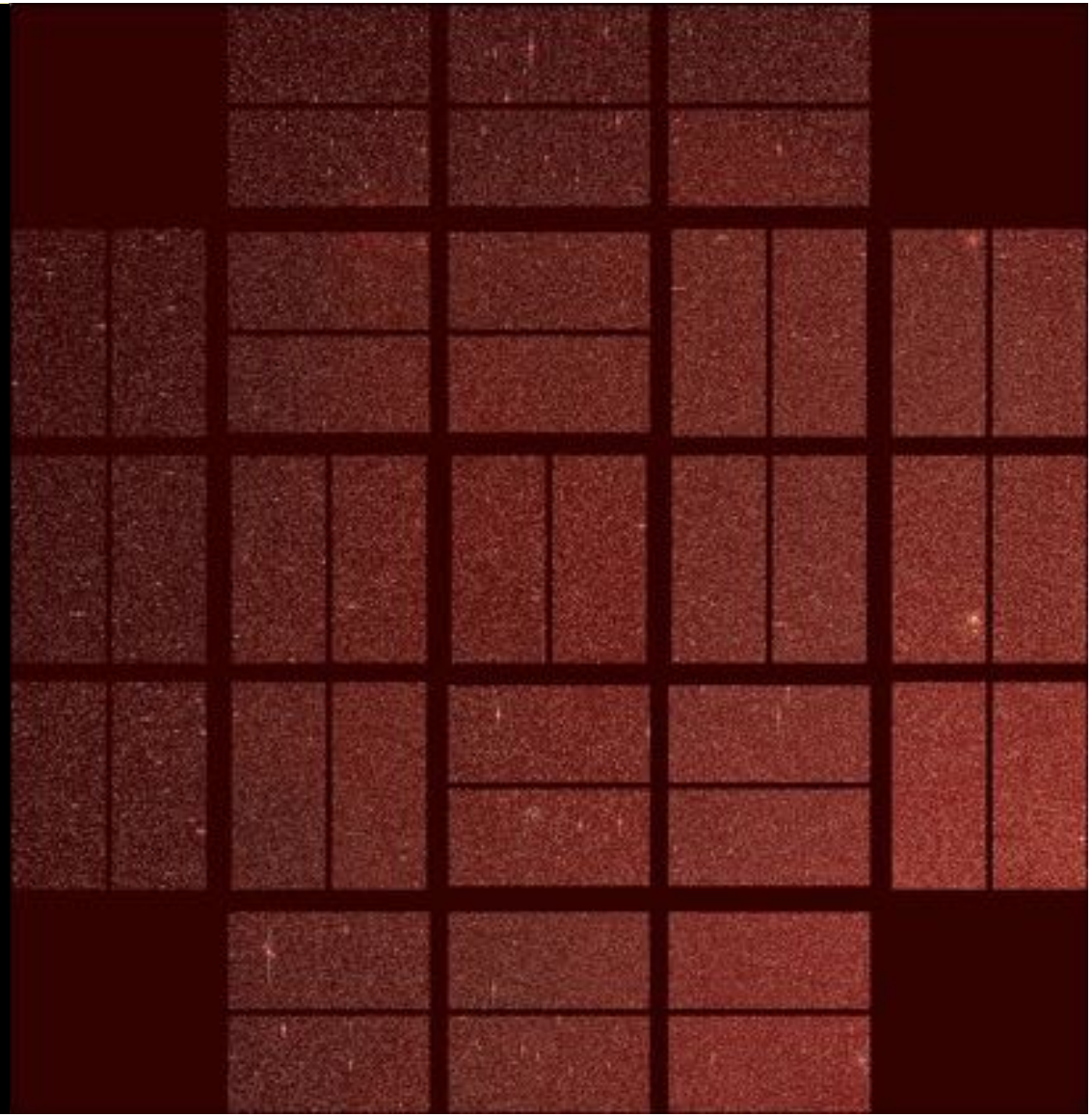


Earth (~0.01%)



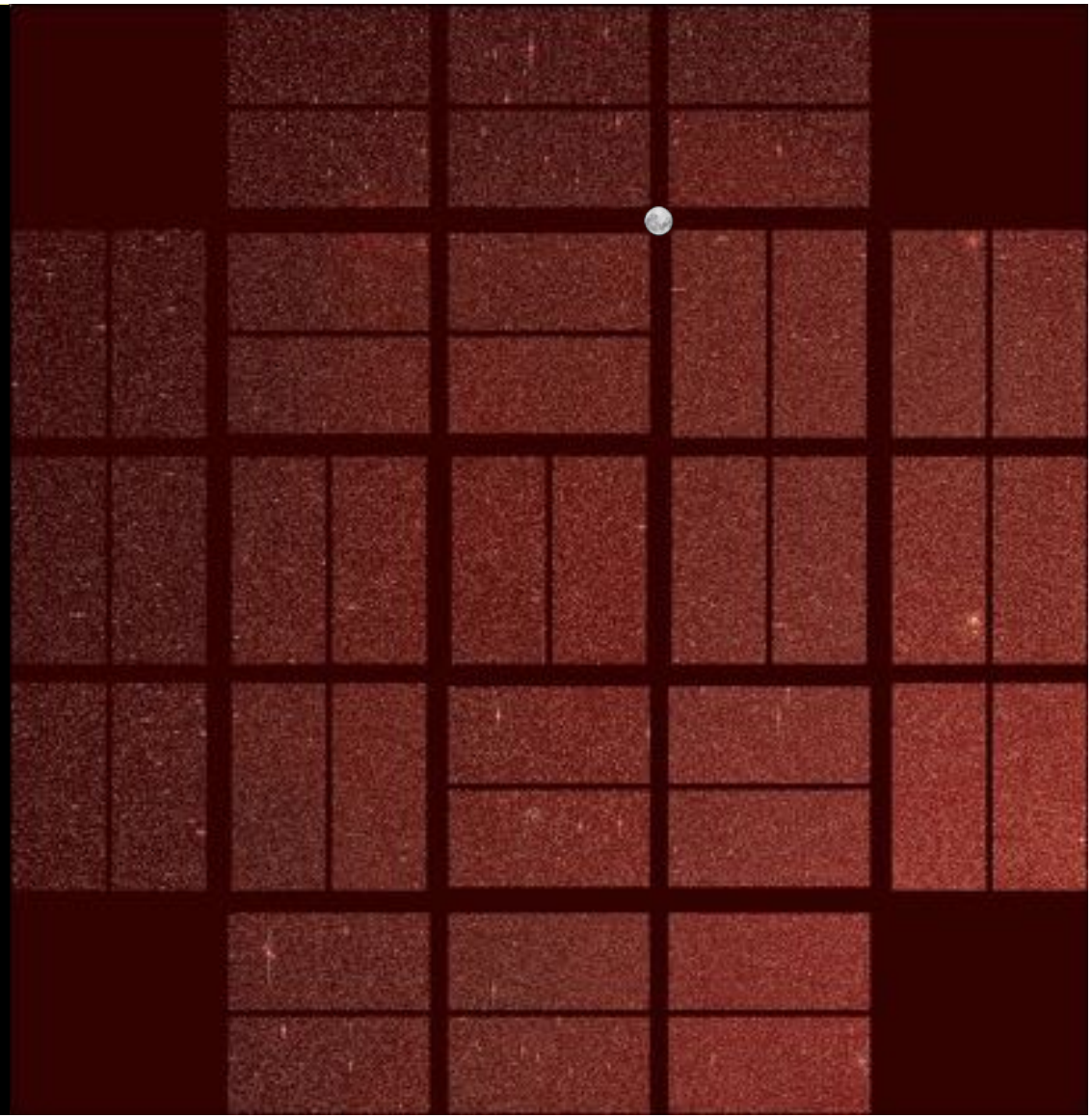
First Light Image

Launched
March 7 2009

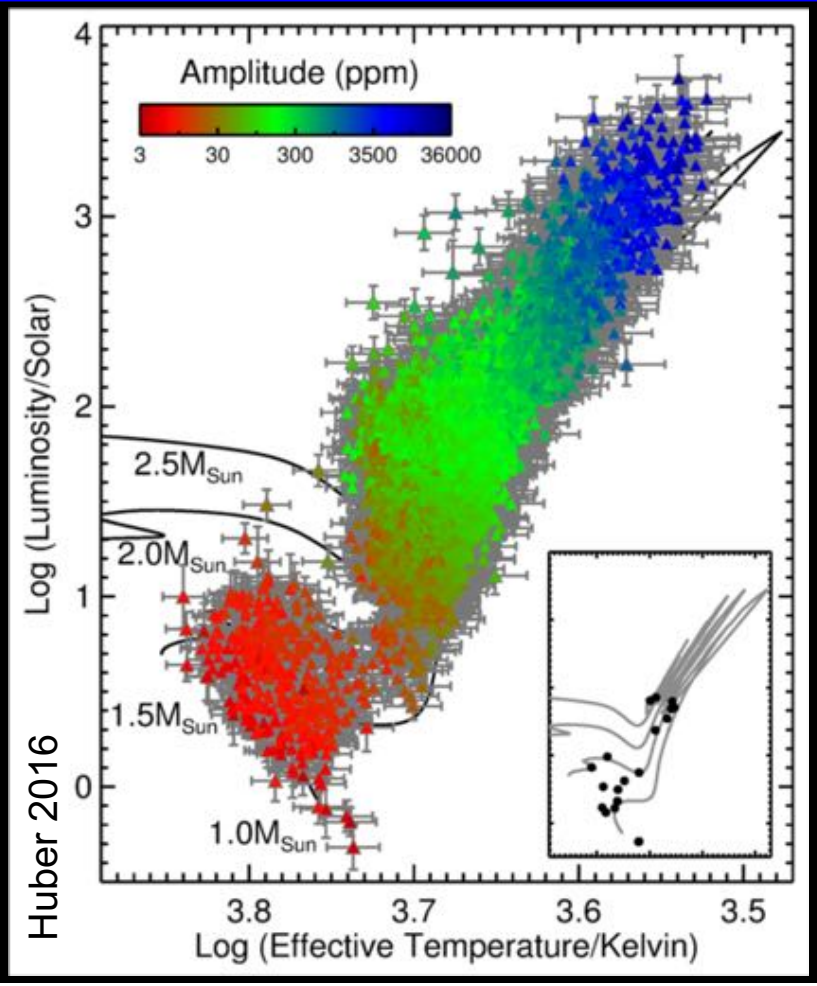


First Light Image

Launched
March 7 2009



Asteroseismology with Kepler

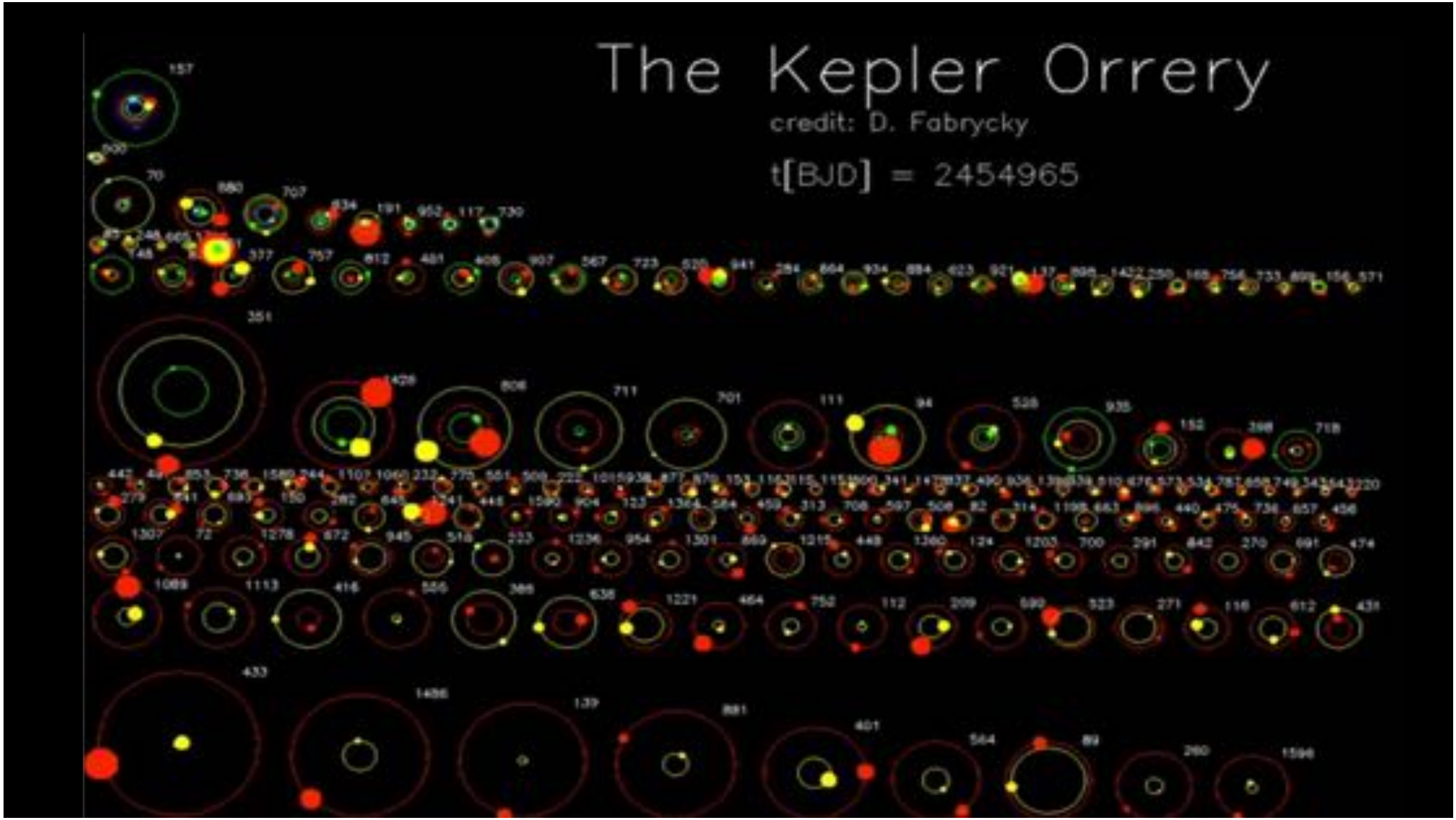


Inset – Stellar oscillation Detections before Kepler.

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

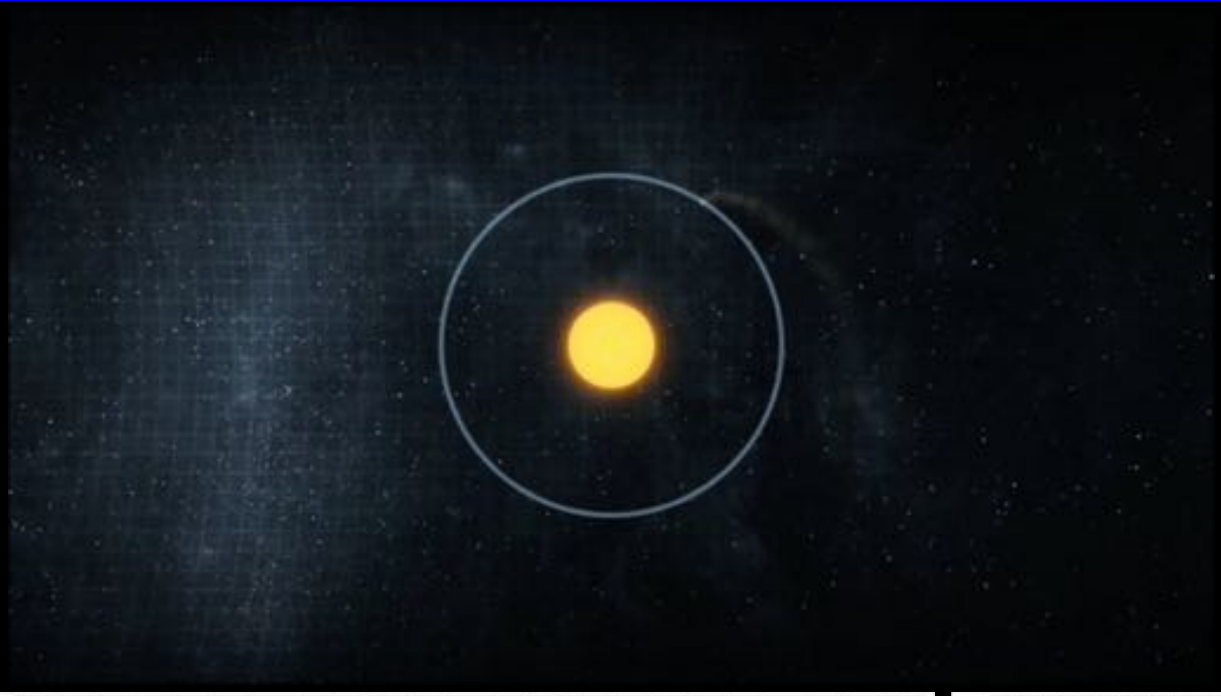
- Stellar ages and radii
- Internal differential rotation
- Convection zone depths ages
- Rotation axis orientation
- Heliophysics-like results

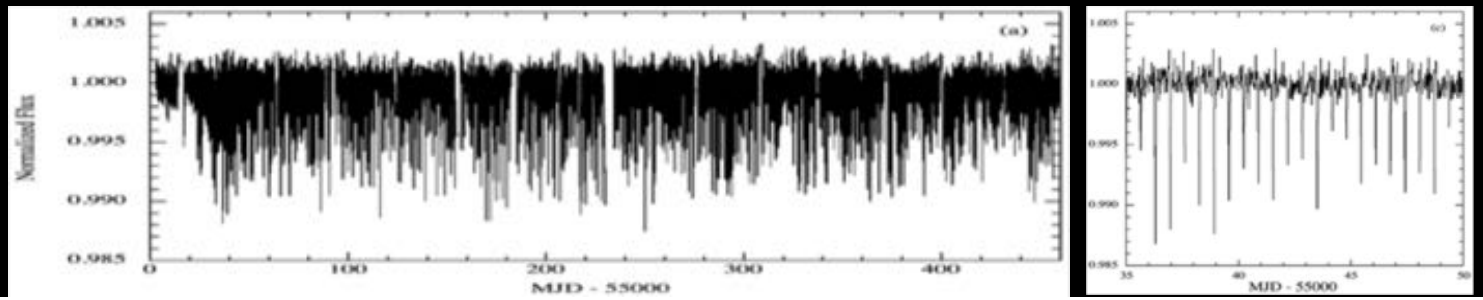
…for 15000+ stars


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

A Disintegrating Sub-Mercury-Size Planet

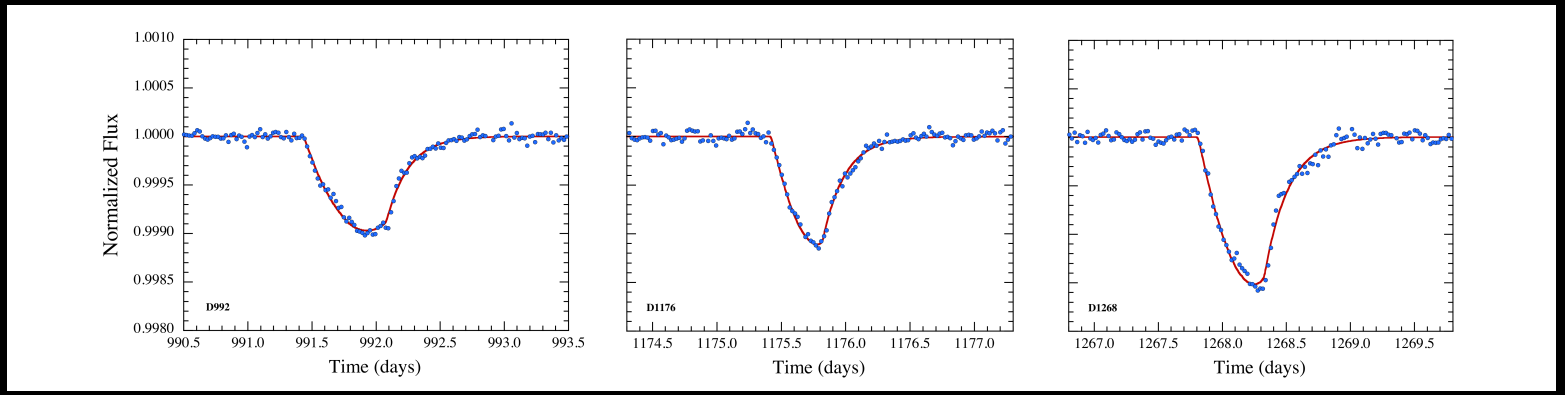
Kepler
A Search for Earth-size Planets

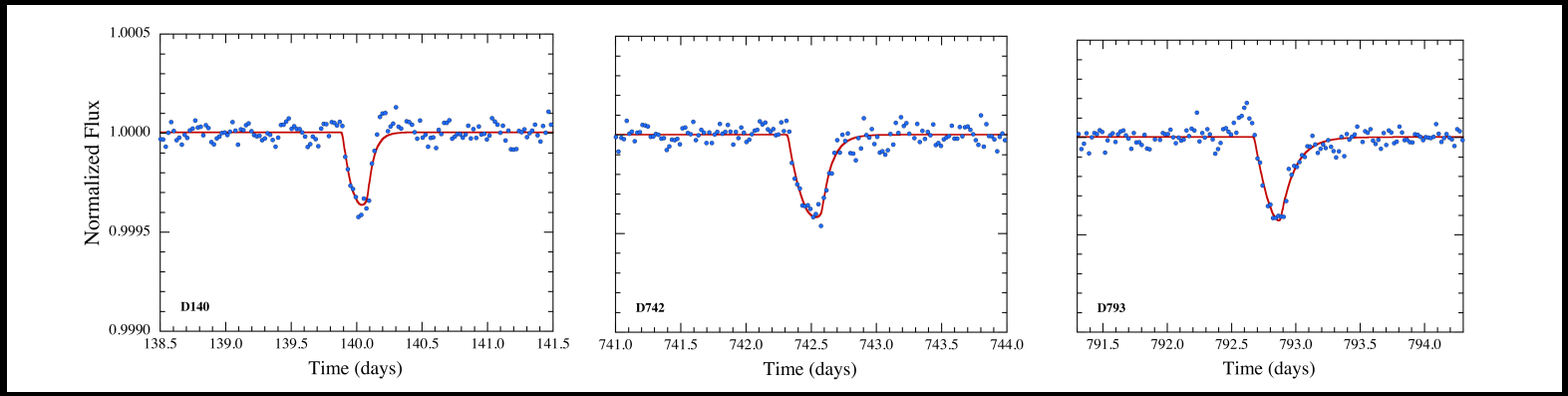




KIC 3542116: An Exocomet Candidate

Kepler
A Search for Earth-size Planets

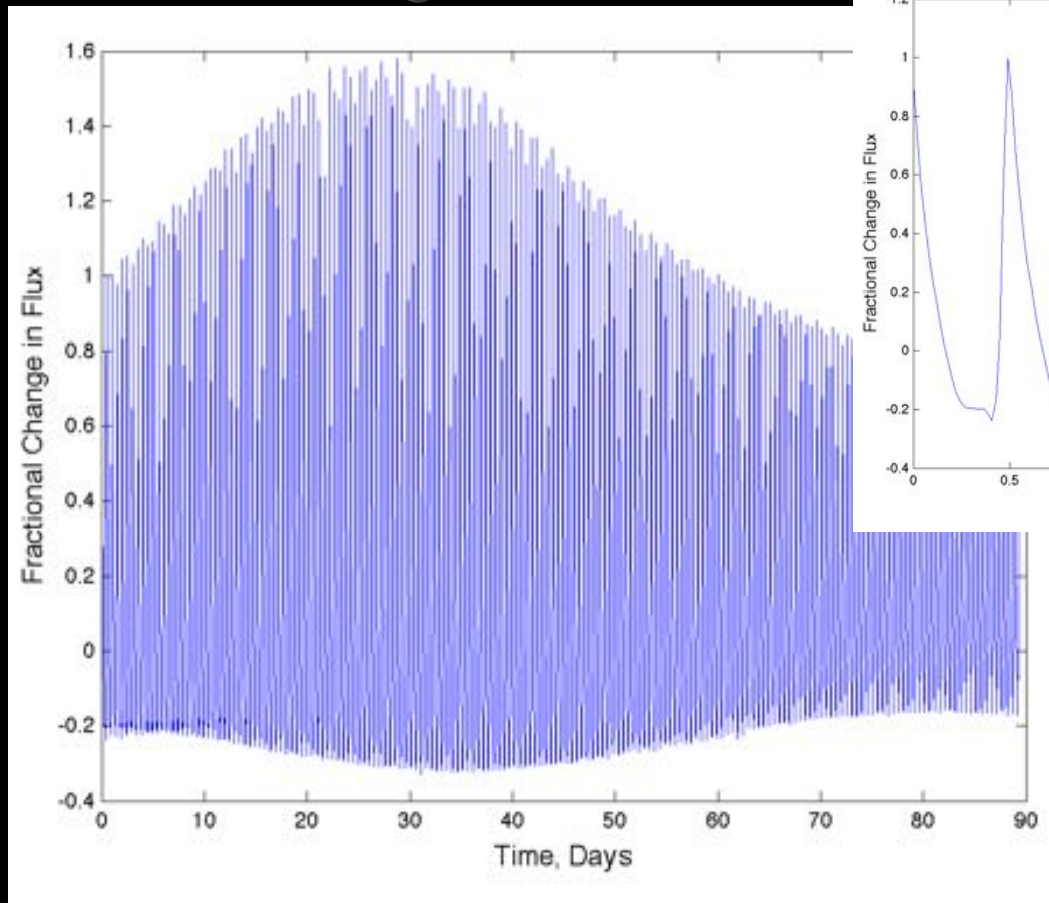


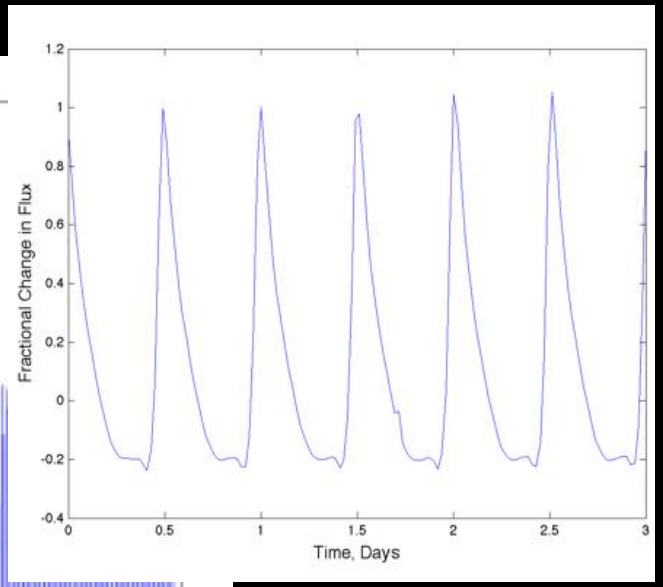


Rappaport et al. 2017, arxiv1708.06069

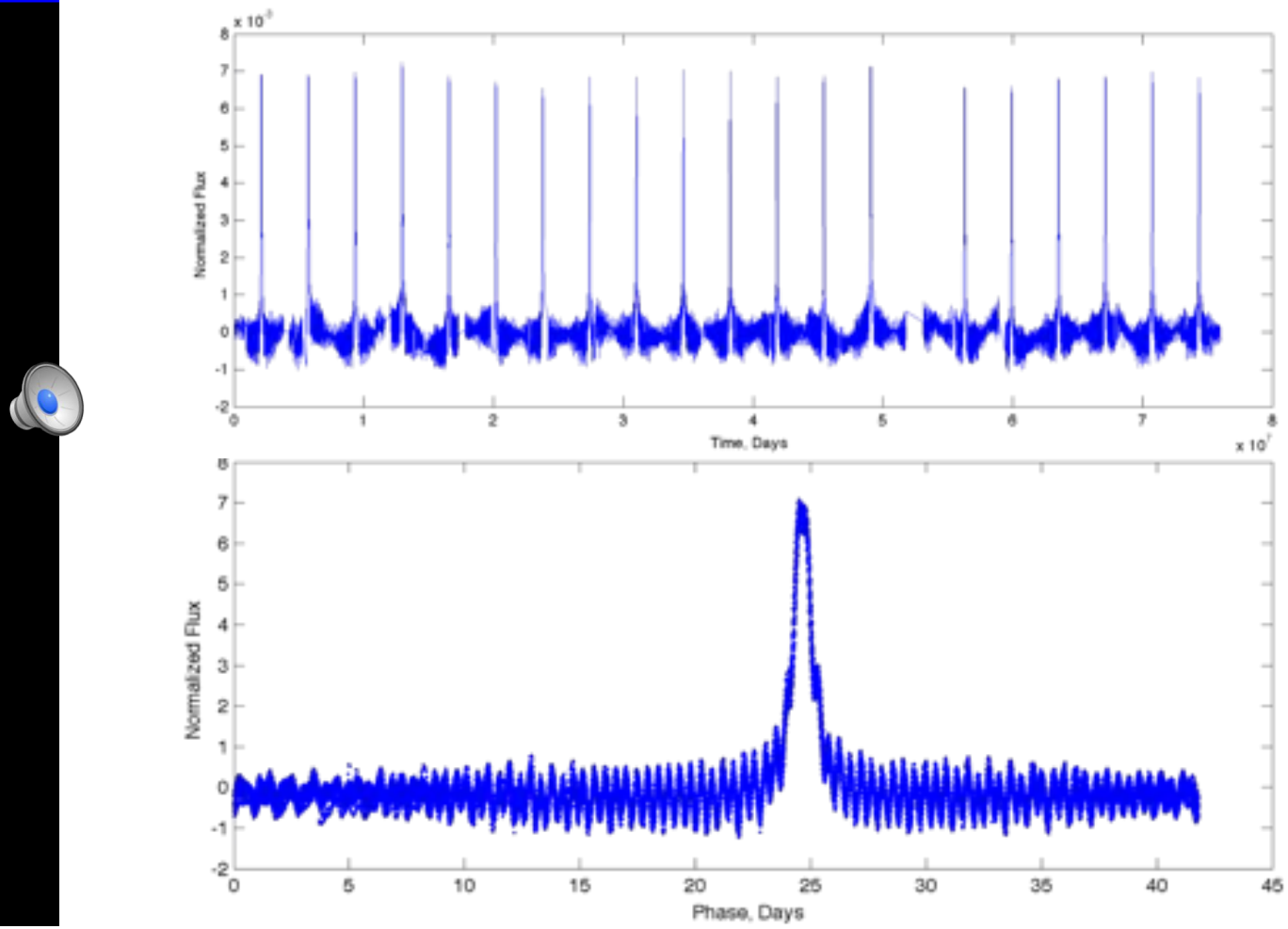
An RR Lyra Star

Kepler
A Search for Earth-size Planets

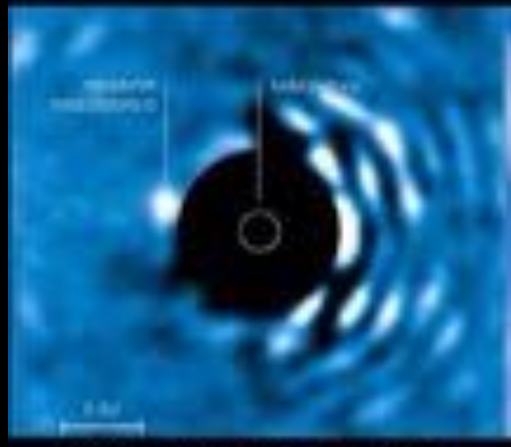




Heartbeat Stars: KOI-54



Every time there's an 'Earth 2.0' exoplanet announced.



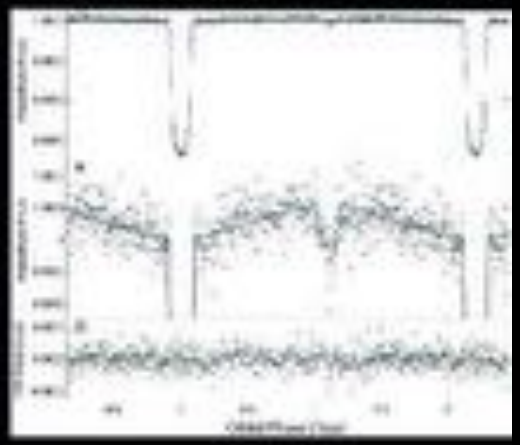
What Astronomers see.

What NASA see.

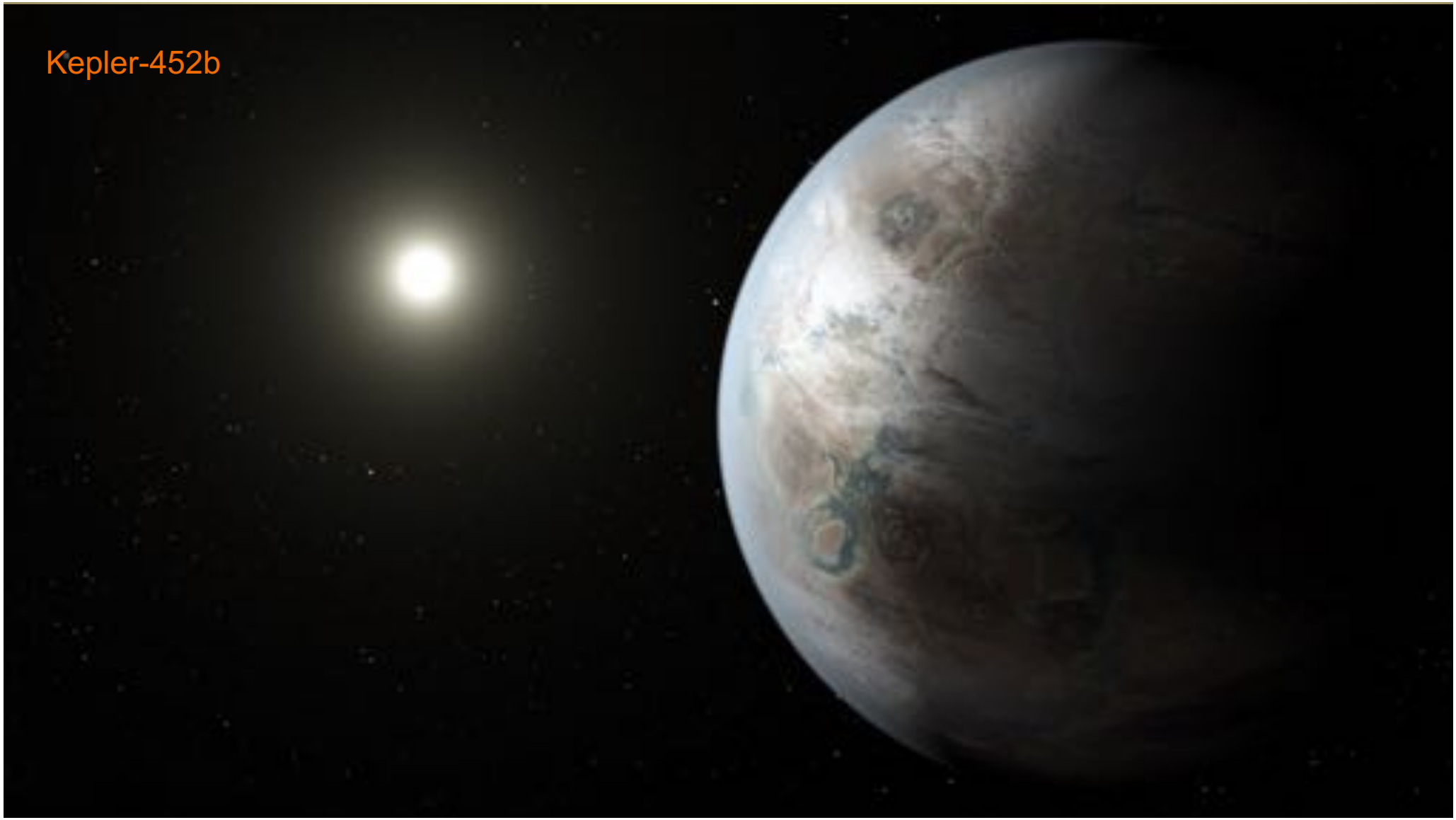
What Newspaper Artists see.

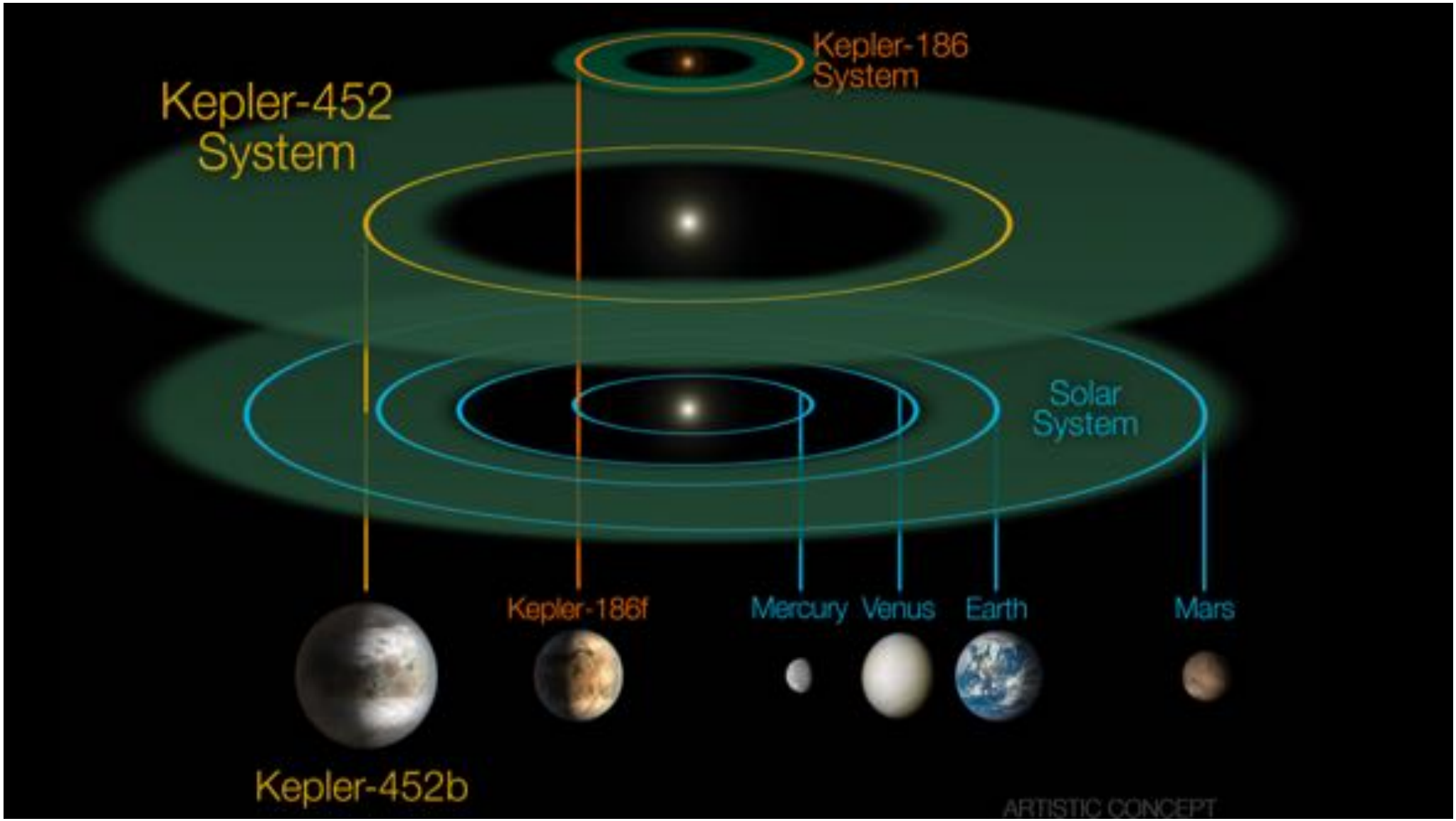
What Joe Public sees.

What conspiracy theorists see.

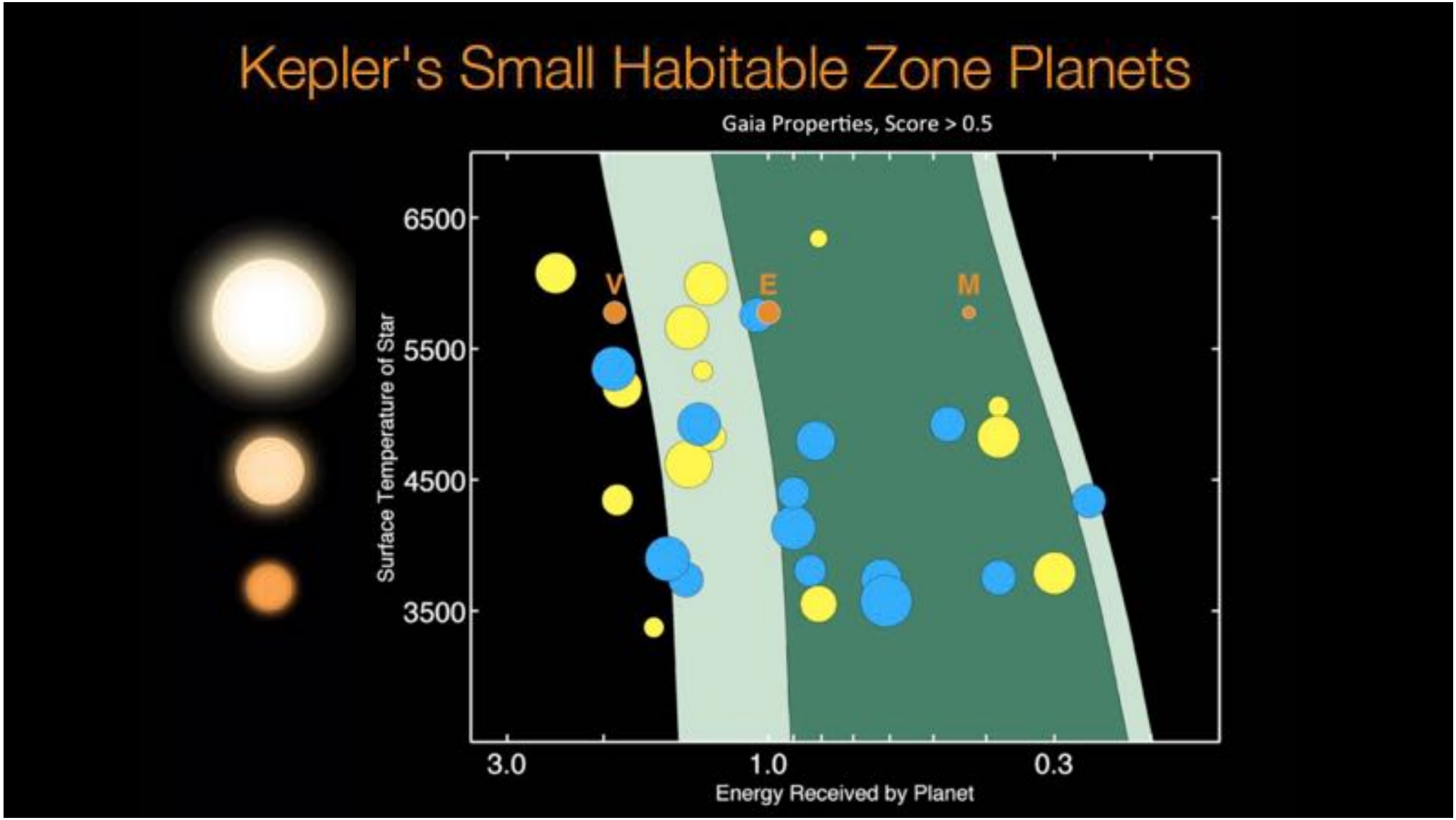


What we actually see.


Kepler-452b

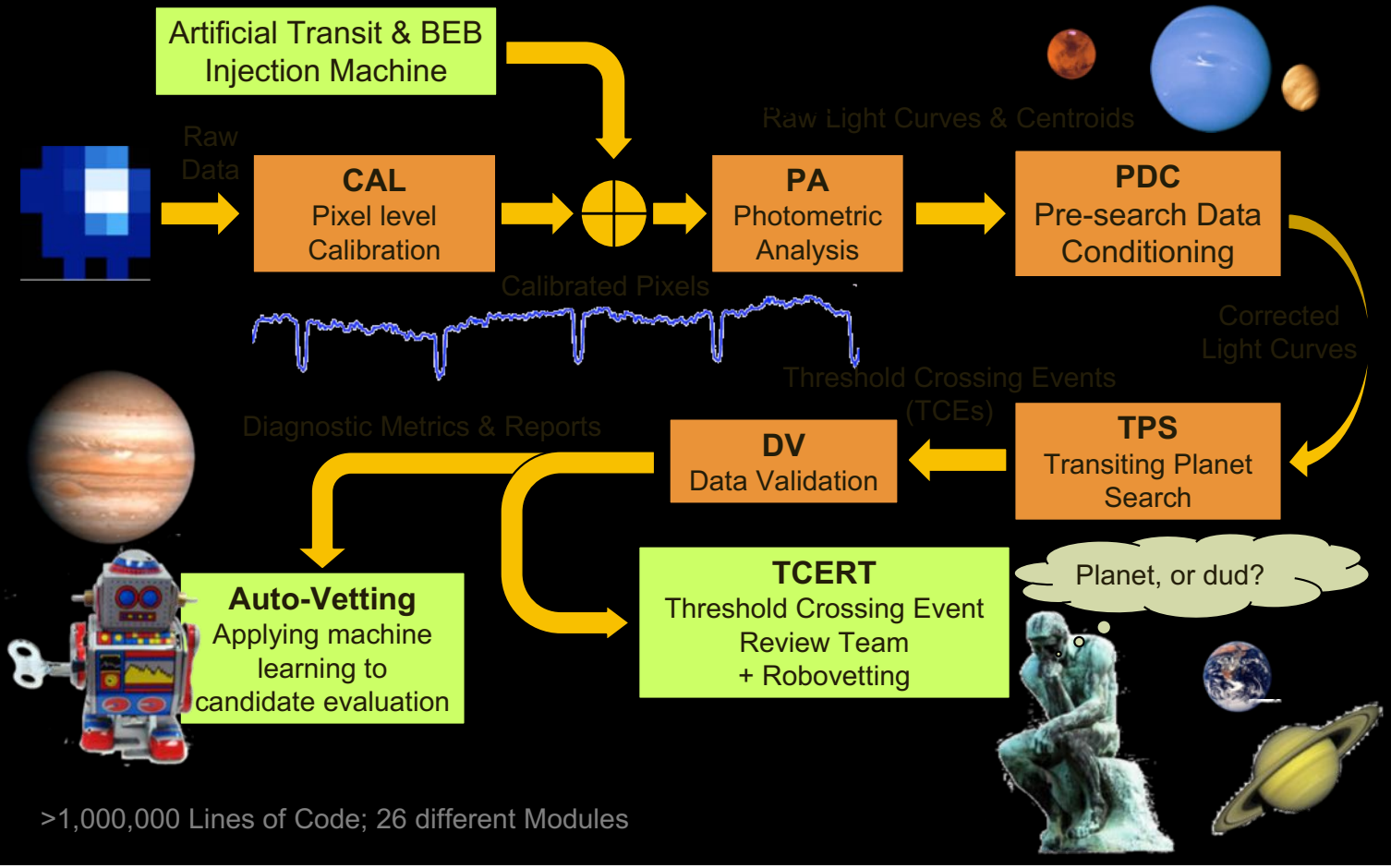

Kepler-186
System
Kepler-452
System
Solar
System
Kepler-186f
Mercury
Venus
Earth
Mars
Kepler-452b
ARTISTIC CONCEPT

Kepler's Small Habitable Zone Planets



Kepler's Science Pipeline

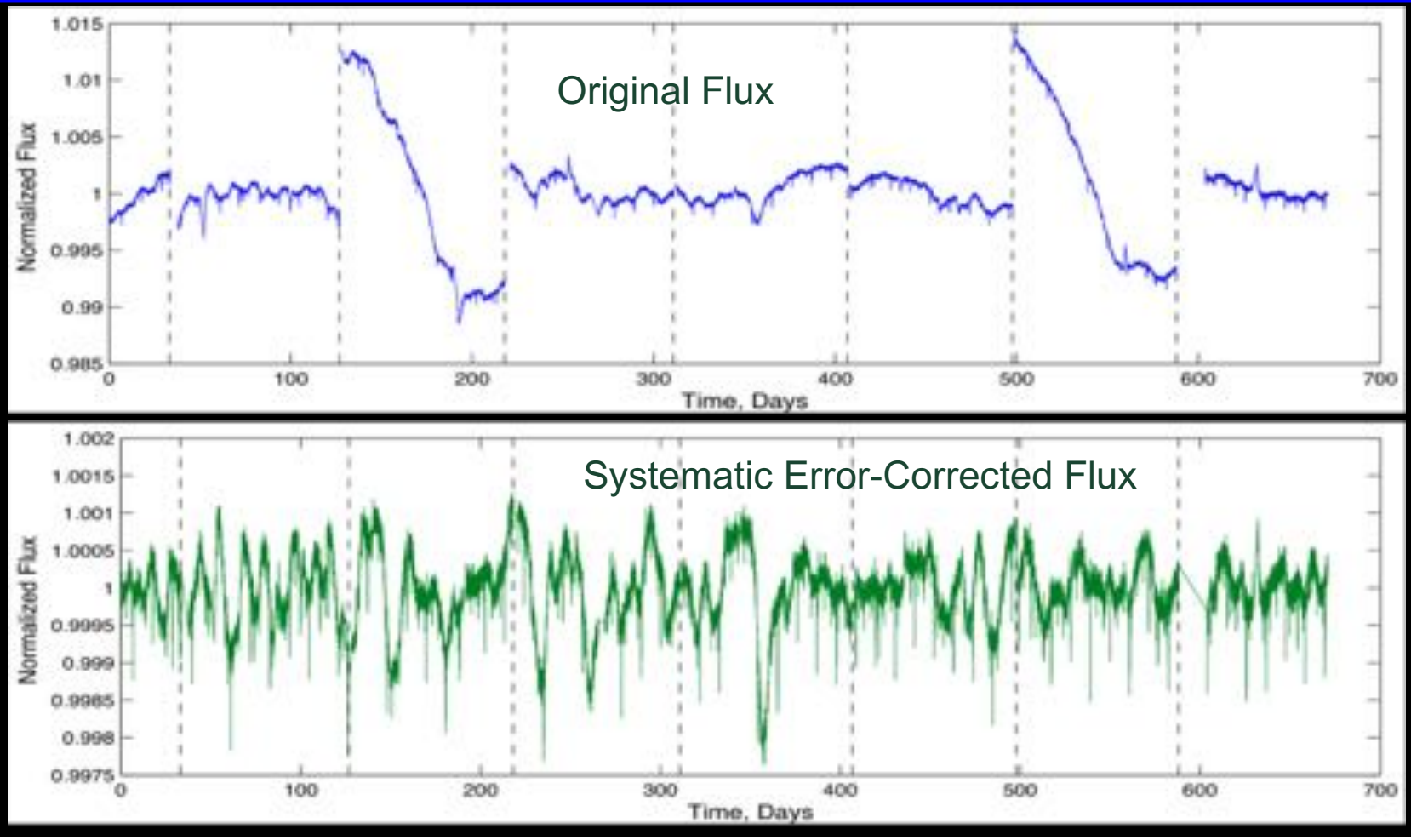
Kepler
A Search for Earth-size Planets



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

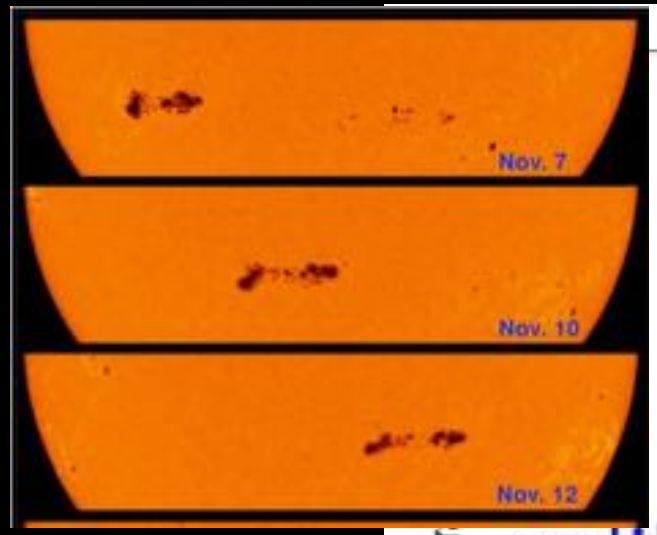
Correcting Systematic Errors

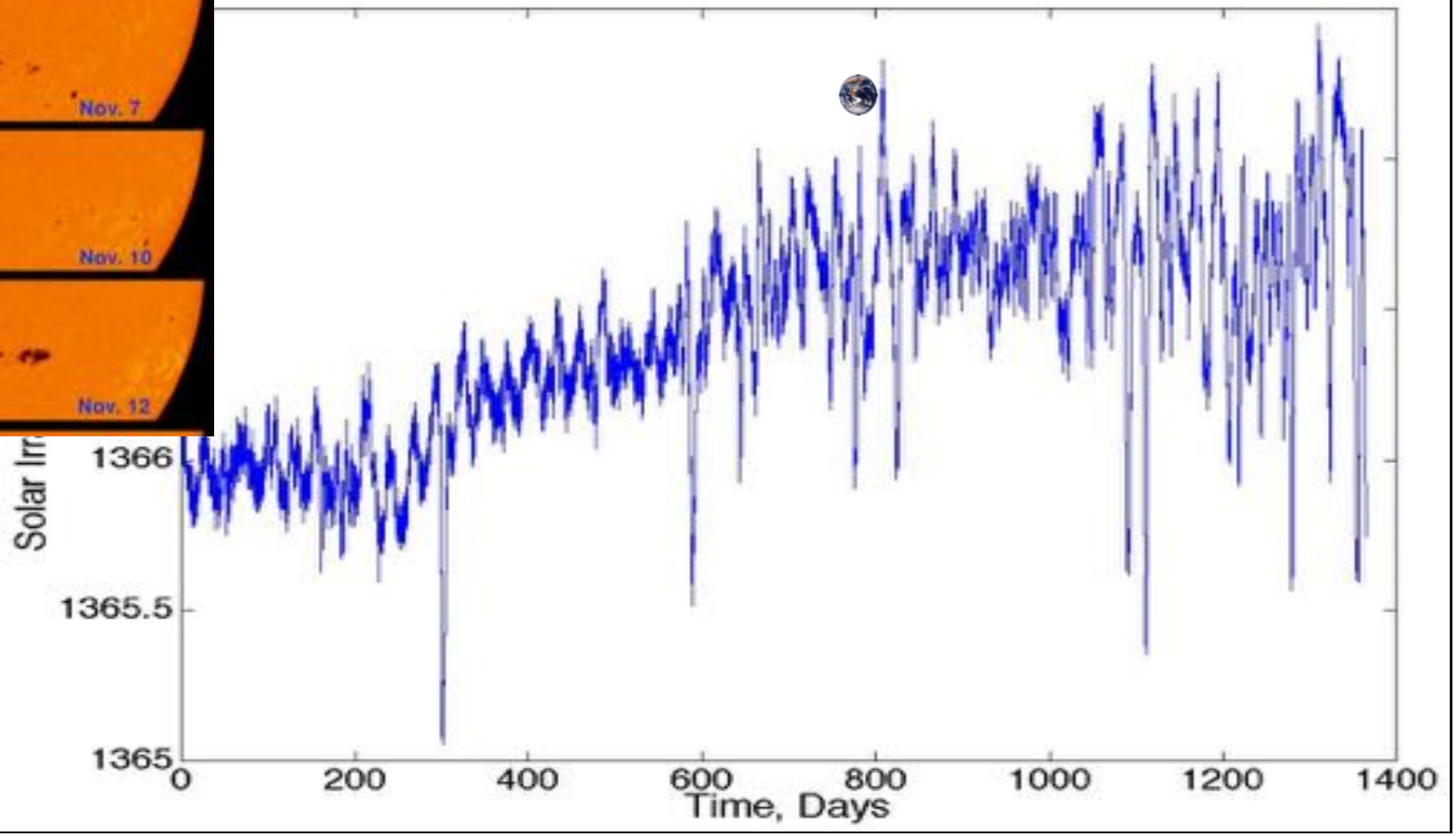
Kepler
A Search for Earth-size Planets



Solar Variability

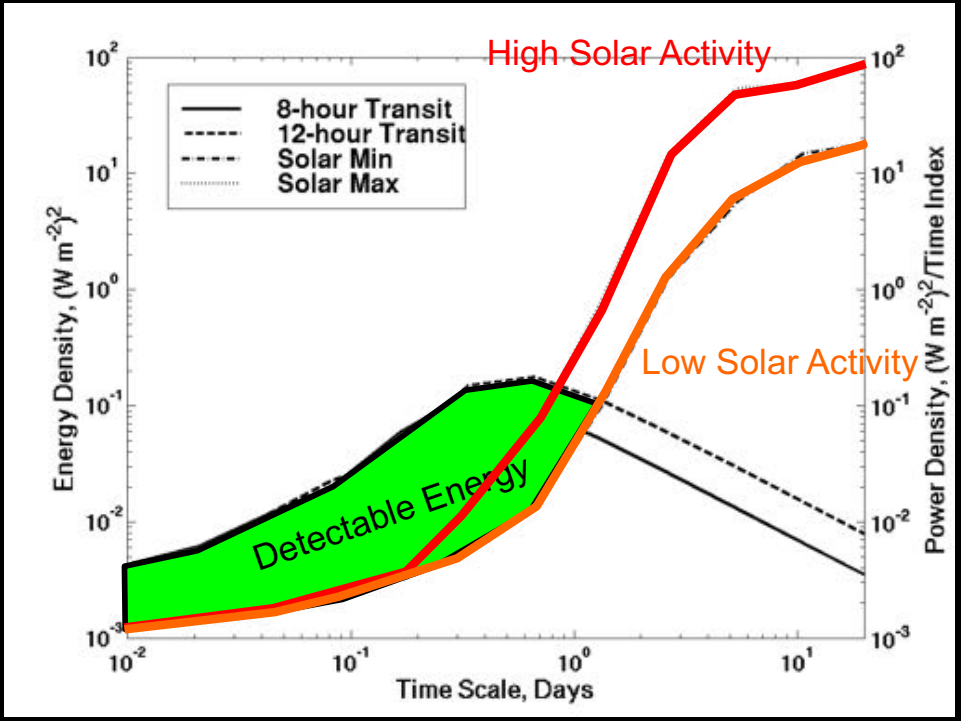
Kepler
A Search for Earth-size Planets





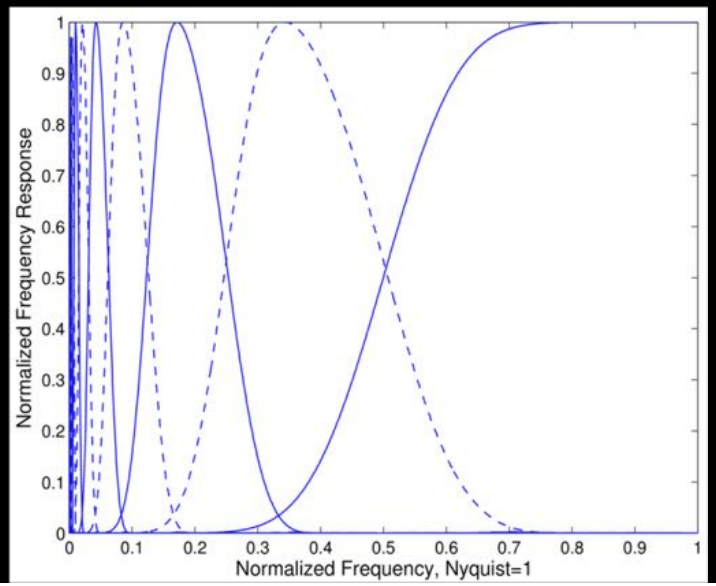
Detecting Transits Against Stellar Variability

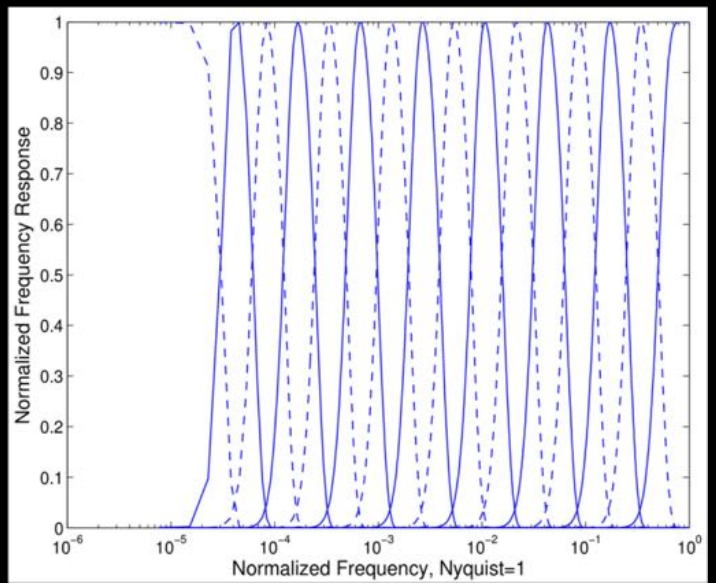
Kepler
A Search for Earth-size Planets



A Wavelet-Based Approach

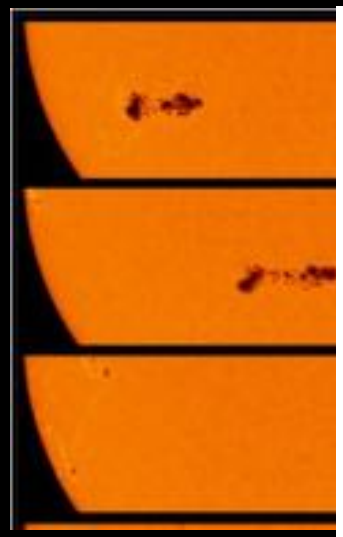
Kepler
A Search for Earth-size Planets

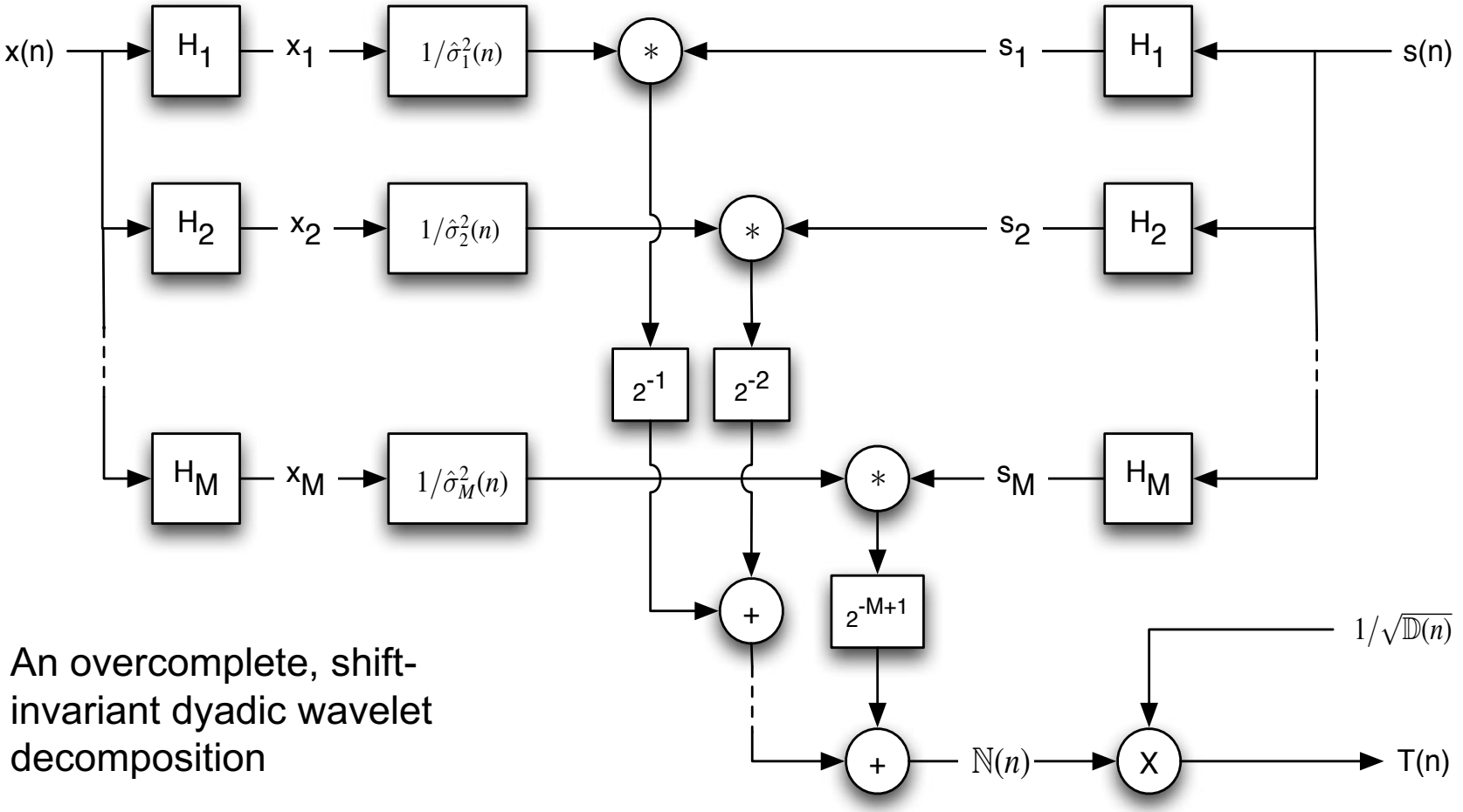




A Wavelet-Based Matched Filter

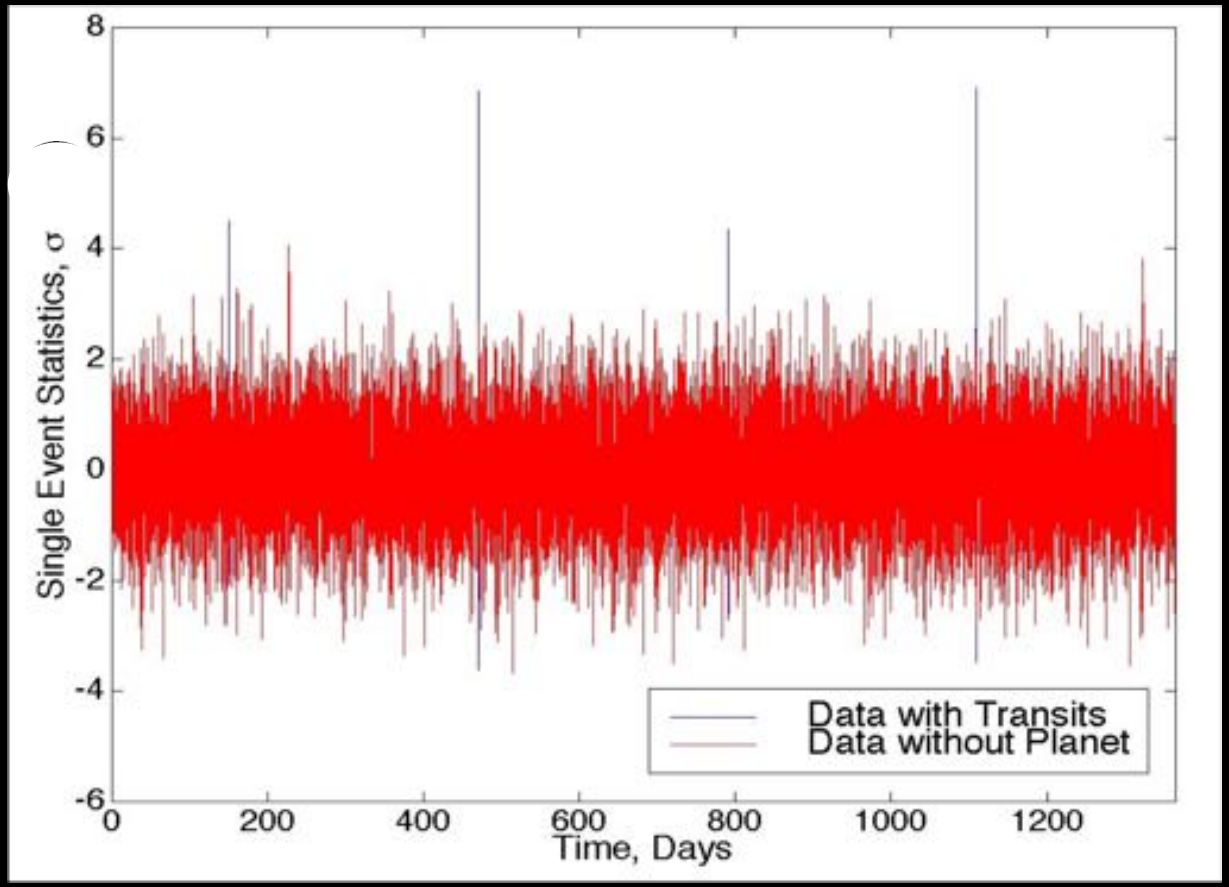
Kepler
A Search for Earth-size Planets





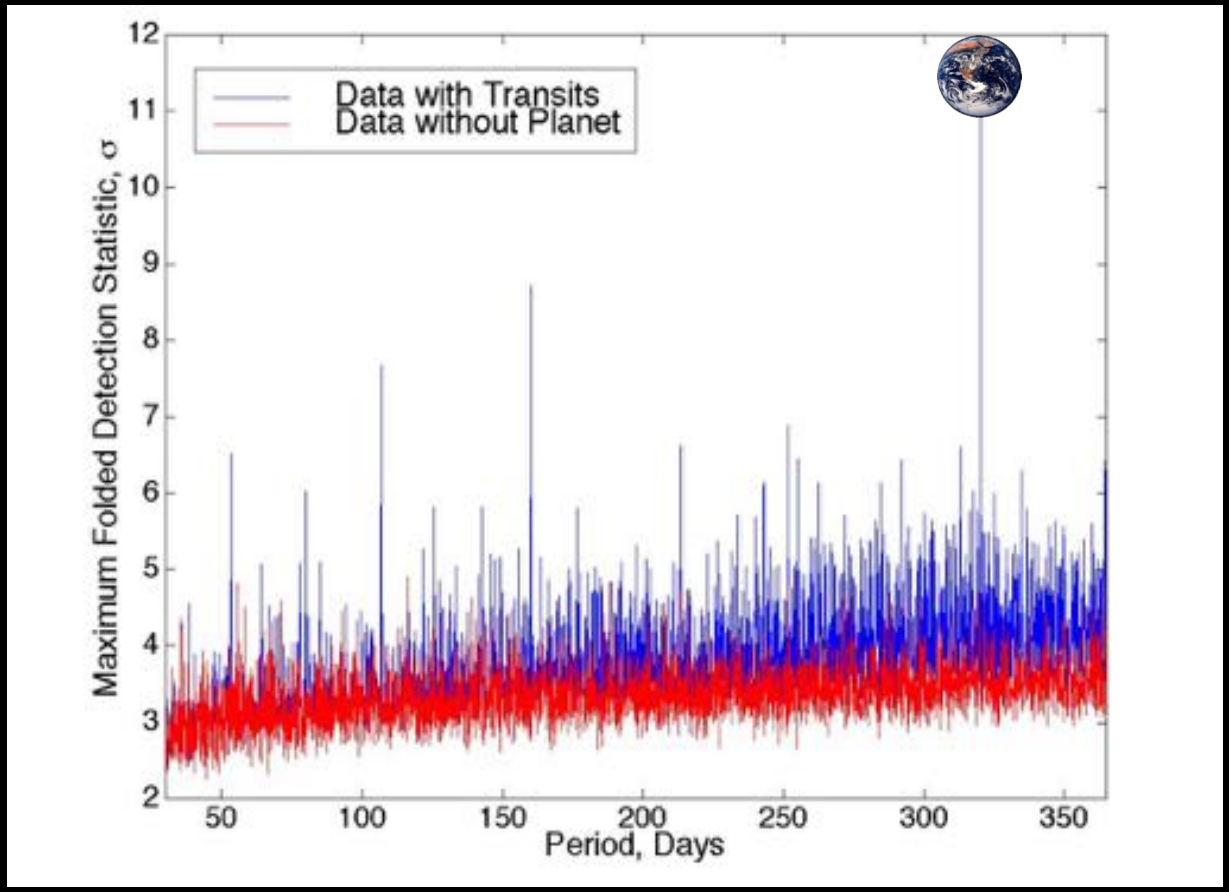
An overcomplete, shift-invariant dyadic wavelet decomposition

Single Transit Statistics

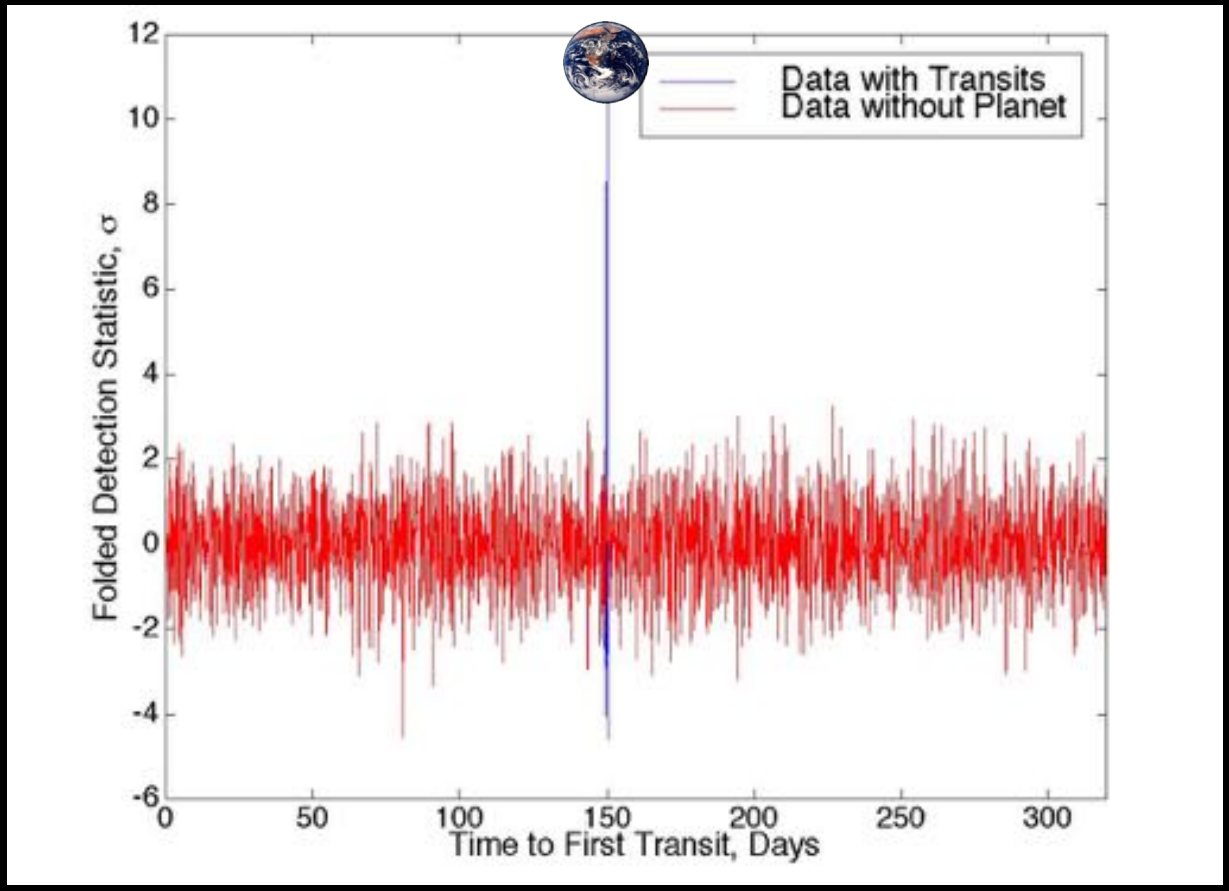


Folded Transit Statistics

Kepler
A Search for Earth-size Planets



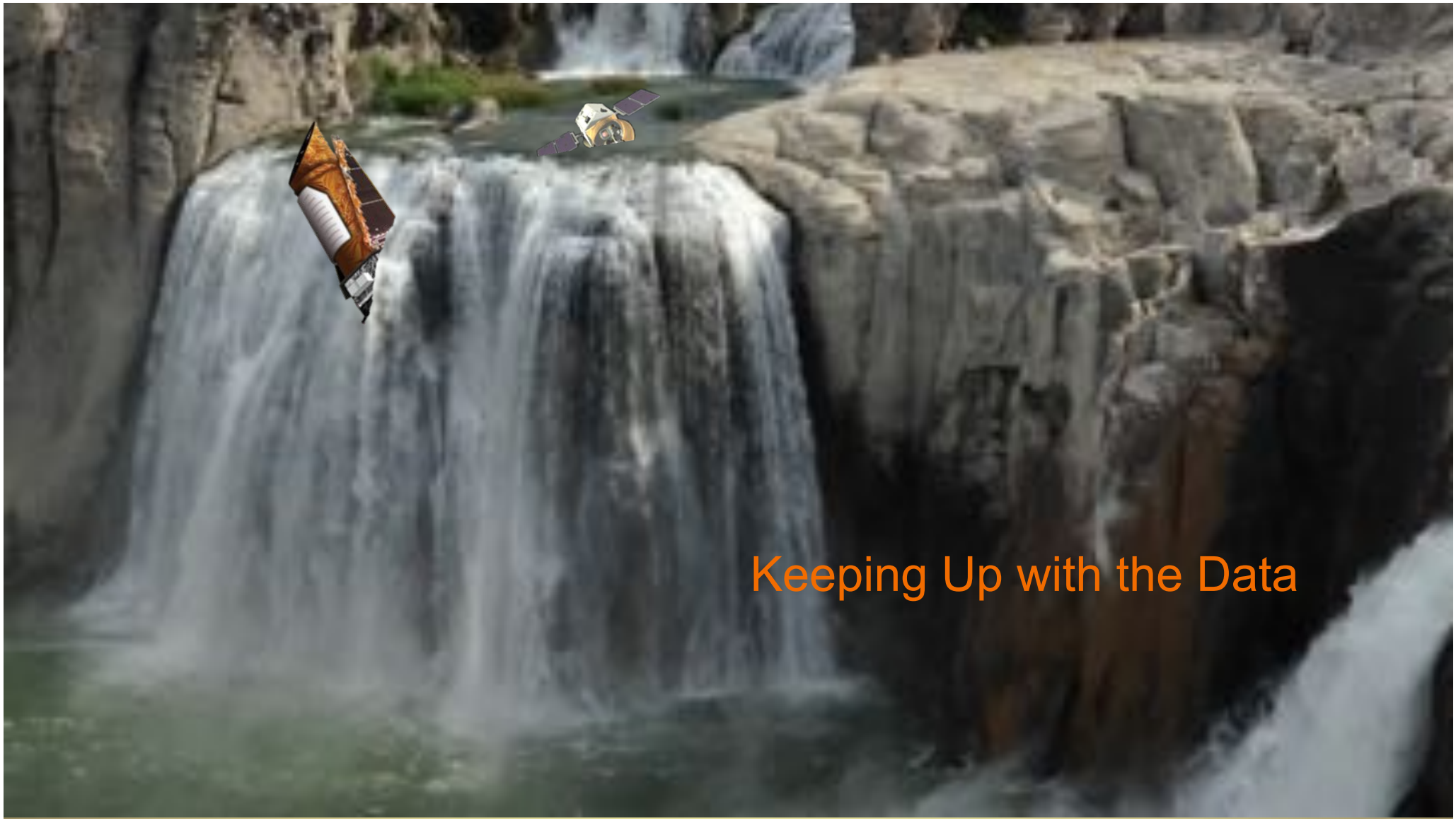
Time to First Transit



The Search Problem

The Search Problem

The Search Problem


Keeping Up with the Data

Hardware Architecture:
Kepler Science Operations Center

Kepler
A Search for Earth-size Planets

64 hosts, 712 CPUs,

3.7 TB of RAM,

148 TB of raw disk storage

Hardware Architecture: NAS Pleiades Supercomputer

Kepler
A Search for Earth-size Planets

7.25 Pflop/s peak cluster

246,048 cores

938 TB of memory

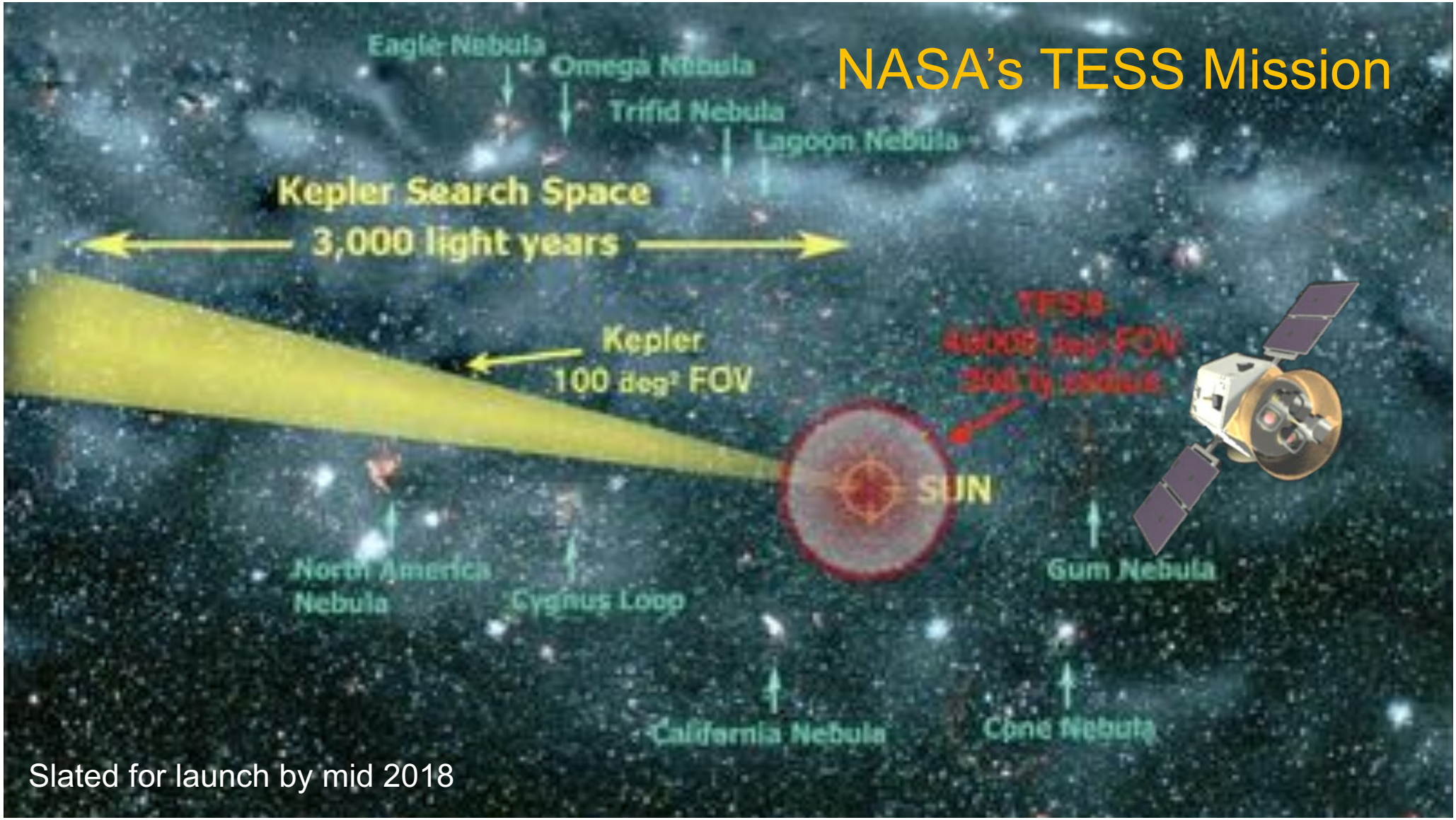
15 PB of storage

Kepler taught us that planets are ubiquitous:

What Next?

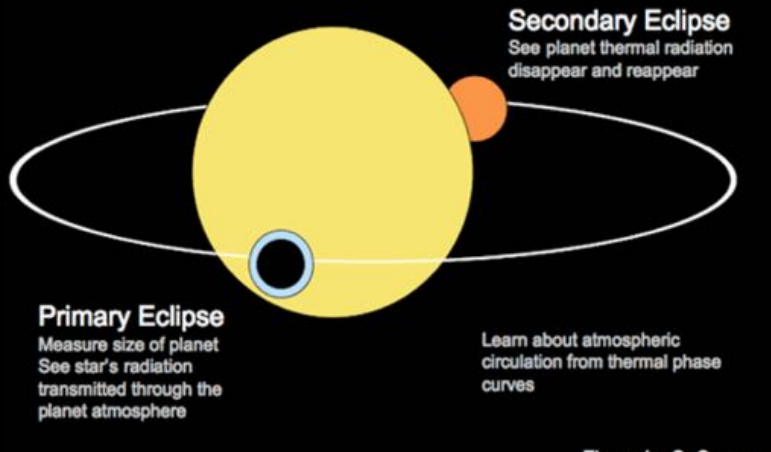

The View from Proxima b
NASA/JPL

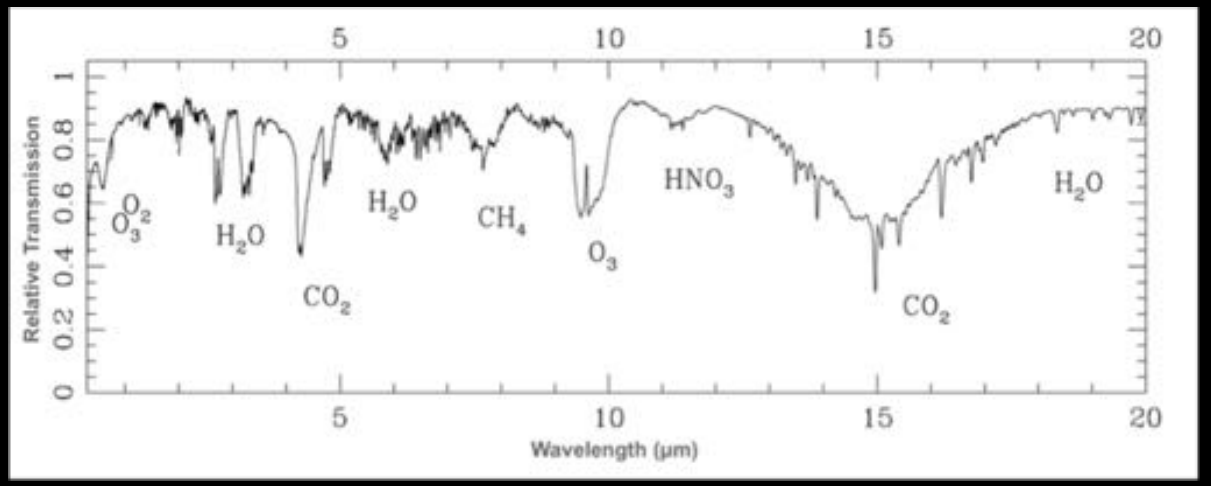
NASA's TESS Mission



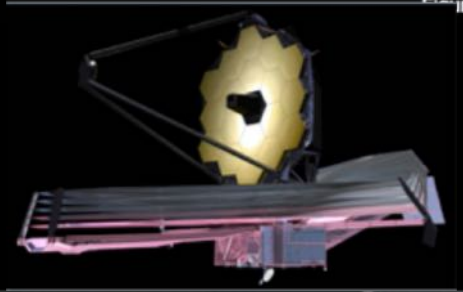
Slated for launch by mid 2018

Detecting Biomarkers through Transit Spectroscopy



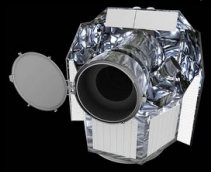


Kaltenegger, L. and Traub, W. (2009) Transits of Earth-Like Planets, ApJ

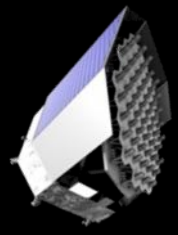


Transiting planets provide opportunities to determine the bulk planetary density and to characterize their atmospheres

+ ESA's CHEOPS (2018)



ESA - C. Carreau



+ ESA's
PLATO Mission (2026)