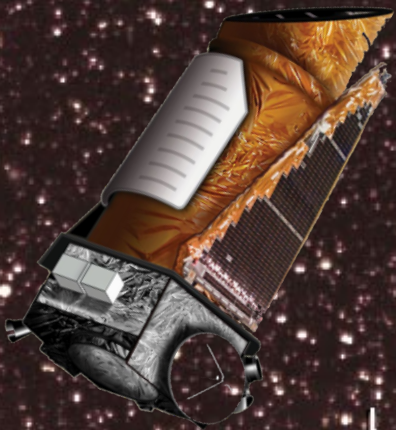


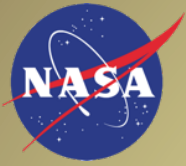
Supercomputing in the Age of Discovering Superearths, Earths and Exoplanet Systems

Jon M. Jenkins
NASA Ames Research Center

Wednesday September 28, 2015

**Ad Hoc Big Data Task Force
of the
NASA Advisory Council Science Committee**

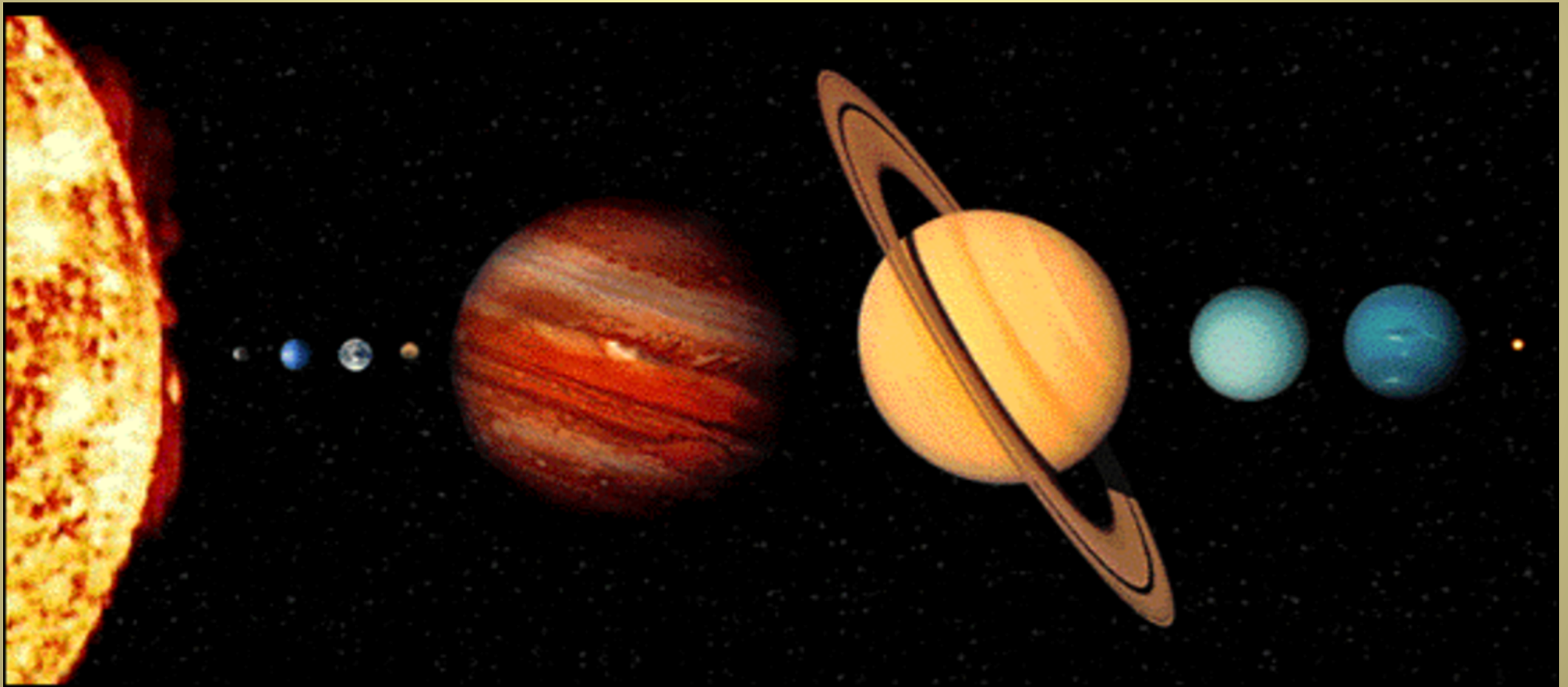


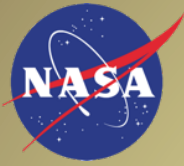


All the Known Planets In 1994

Kepler

*A Search for Earth-size
Planets*

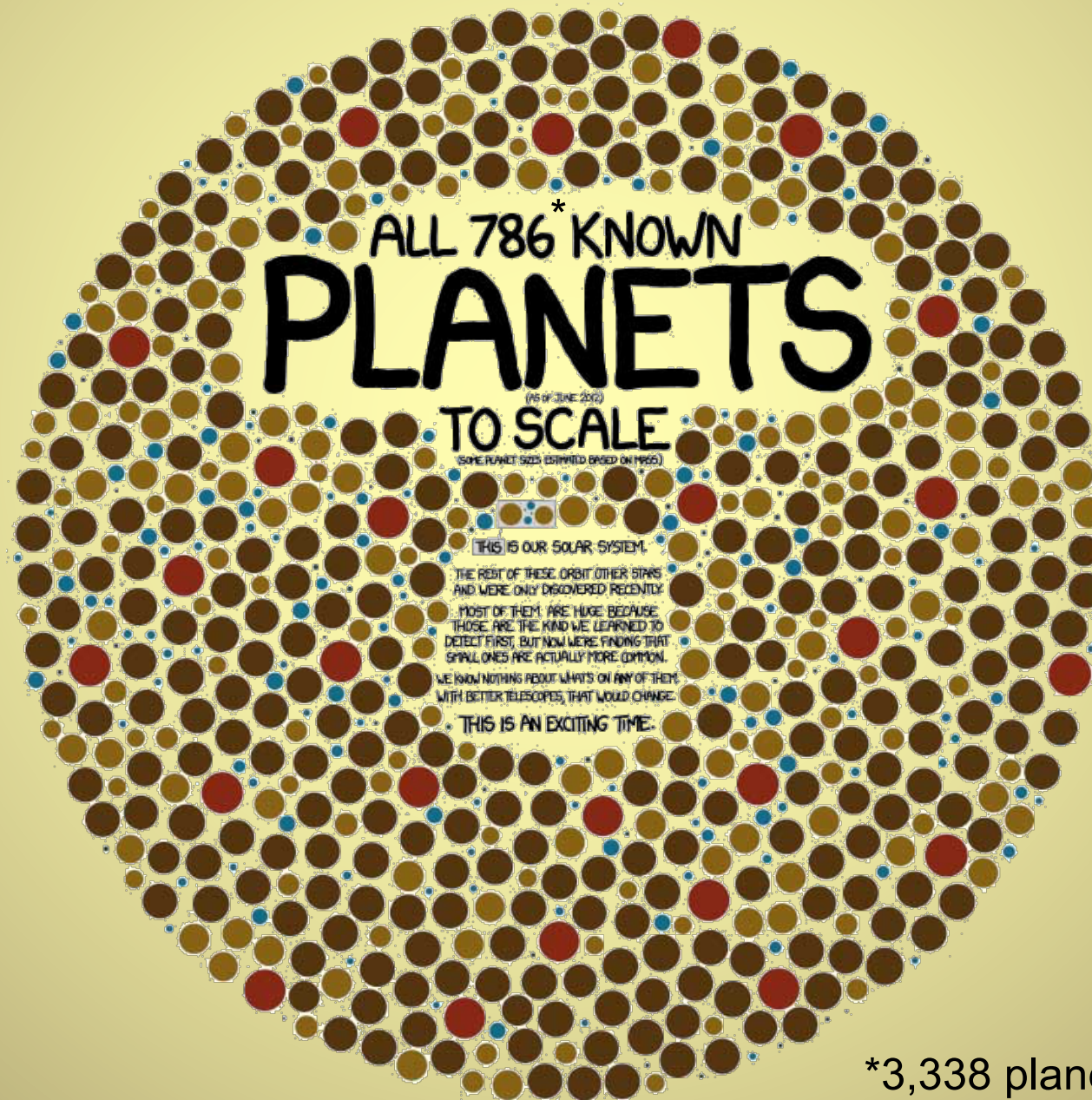




A More Recent Pictures of Planets

Kepler

*A Search for Earth-size
Planets*



*3,338 planets as of 9/28/16

ALL 786 KNOWN PLANETS

Kepler
A Search for Earth-size

(AS OF JUNE 2012)

TO SCALE

(SOME PLANET SIZES ESTIMATED BASED ON MASS)

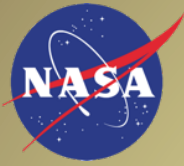


THIS IS OUR SOLAR SYSTEM

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

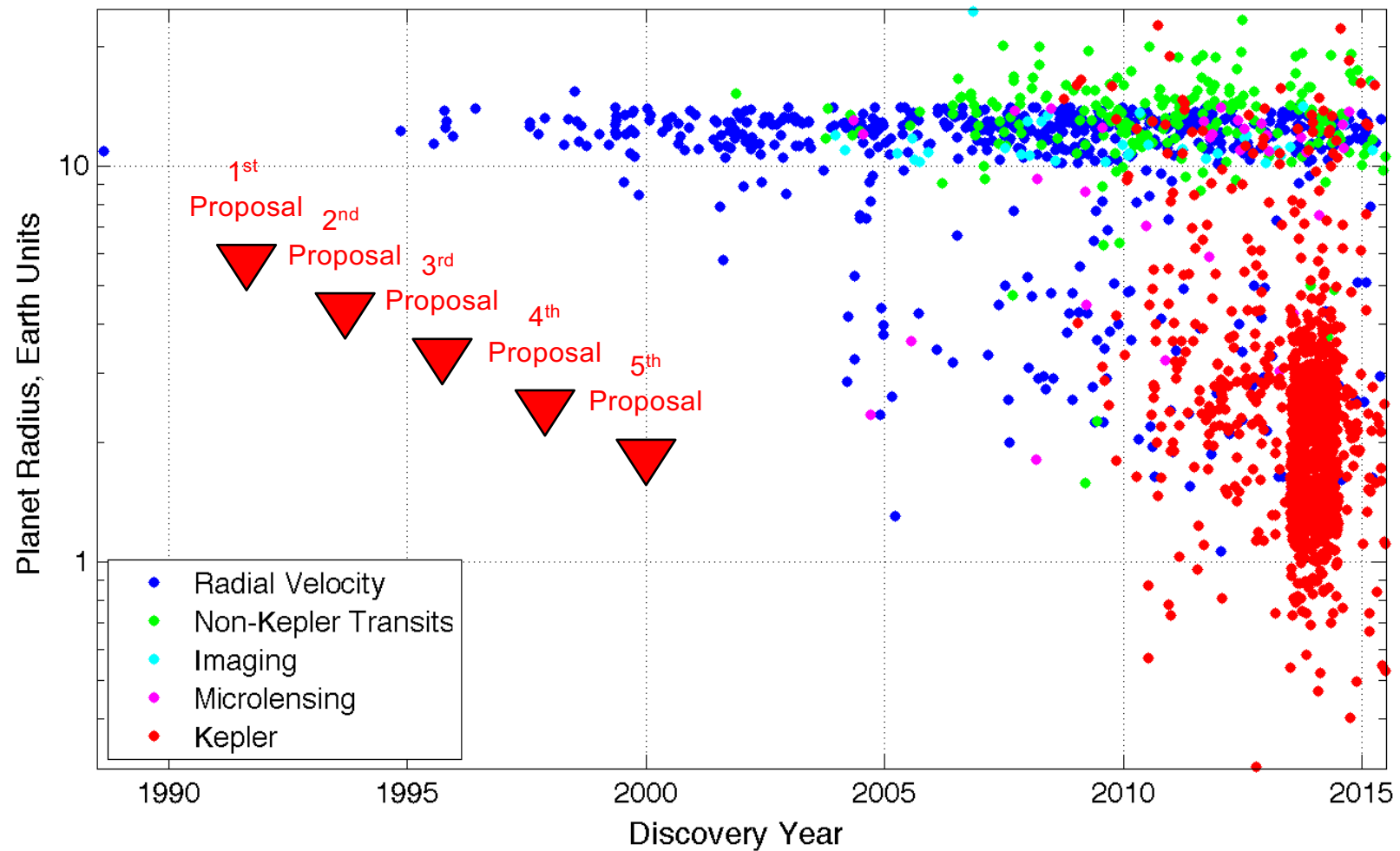
MOST OF THEM ARE HUGE BECAUSE
THOSE ARE THE KIND WE LEARNED TO
DETECT FIRST, BUT NOW WE'RE FINDING THAT
SMALL ONES ARE ACTUALLY MORE COMMON.

WE KNOW NOTHING ABOUT WHAT'S ON ANY OF THEM

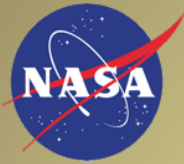


A Search for Earth-size
Planets

Exoplanet Discoveries Over Time



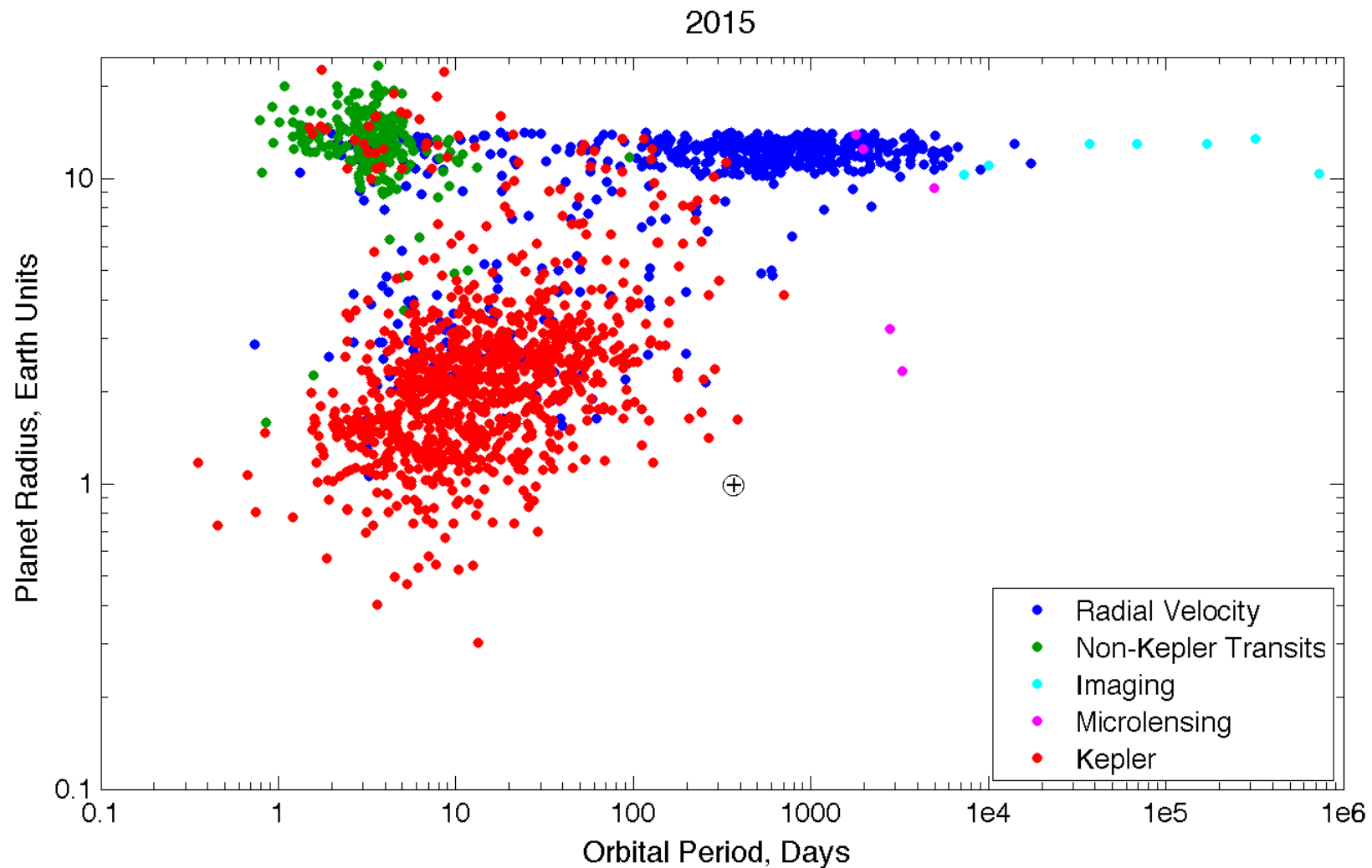
Radii estimated for non-transiting exoplanets
Discovery data dithered randomly within discovery year

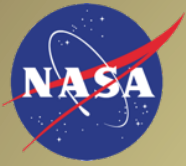


Exoplanet Discoveries

Kepler

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Planets*



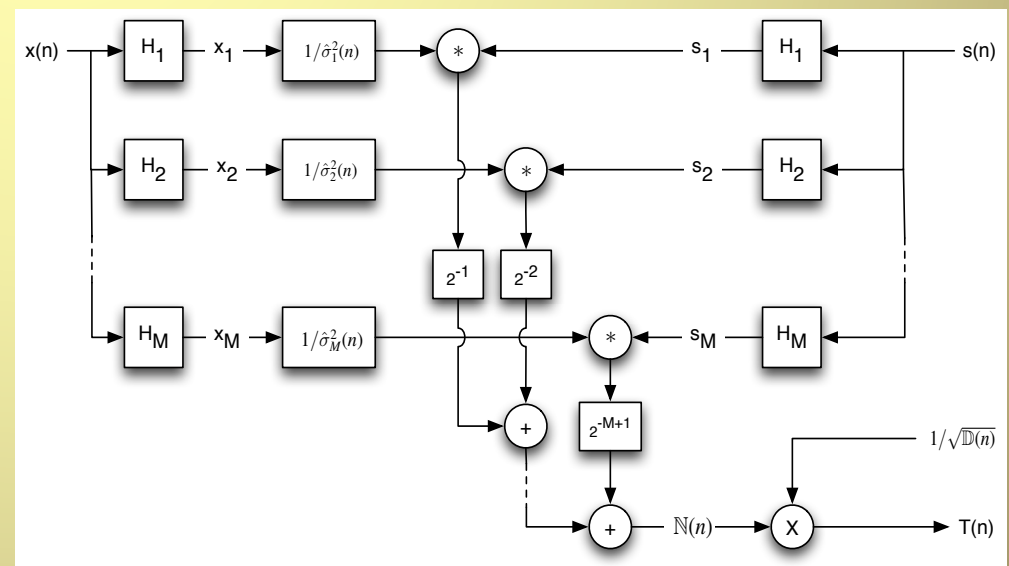


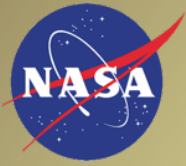
Enabling Kepler

Kepler

A Search for Earth-size Planets

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





How Does Kepler Work?

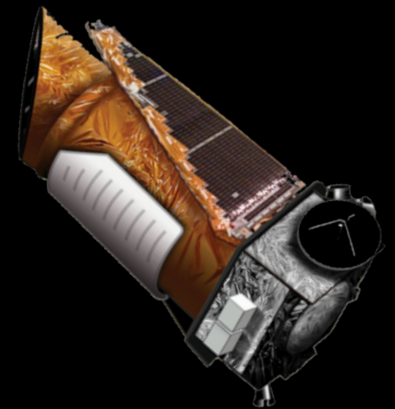
Kepler

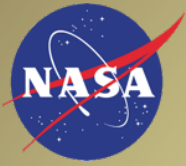
*A Search for Earth-size
Planets*

BRIGHTNESS

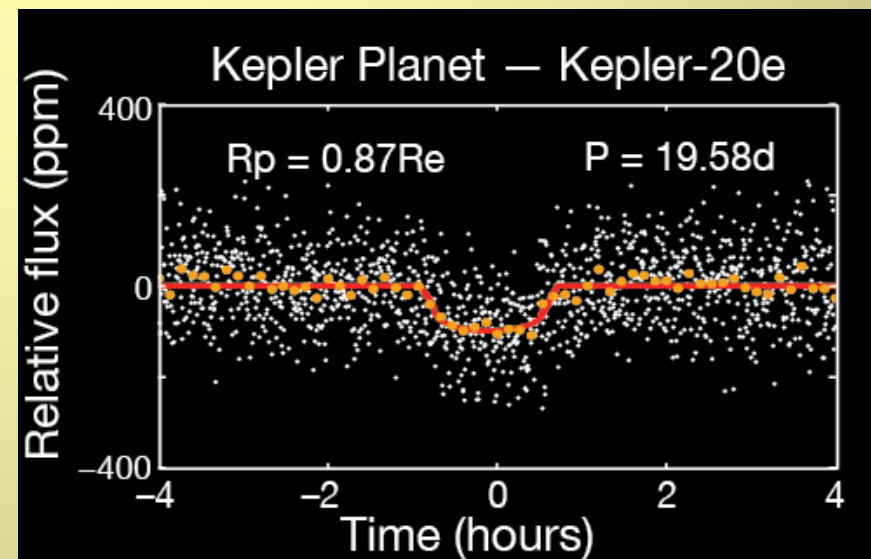
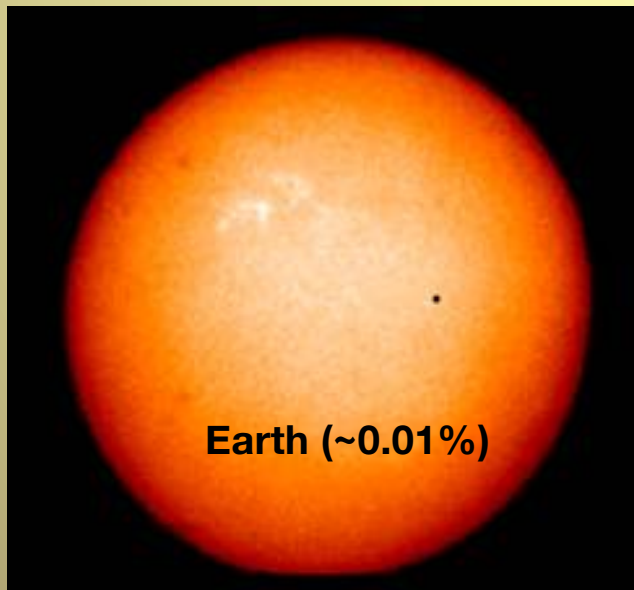
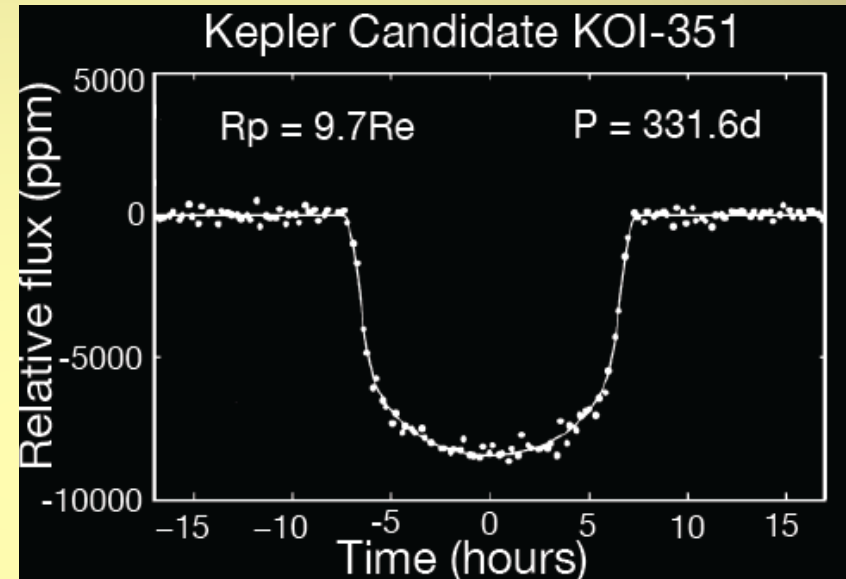
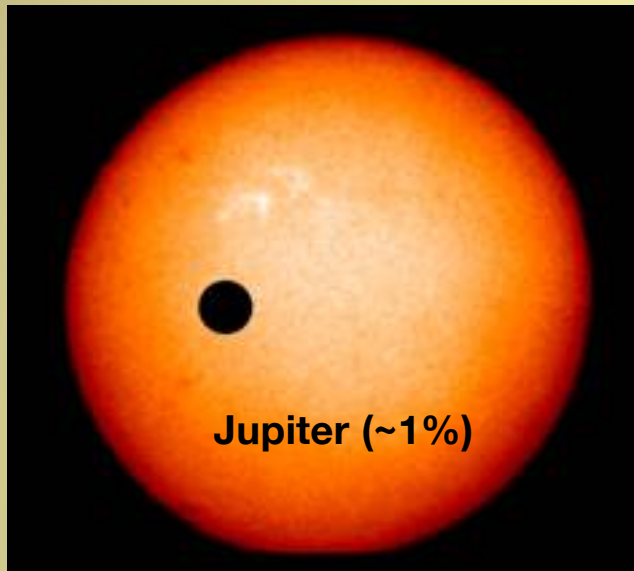


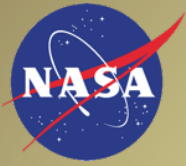
TIME IN HOURS





How Hard is it to Find Good Planets?

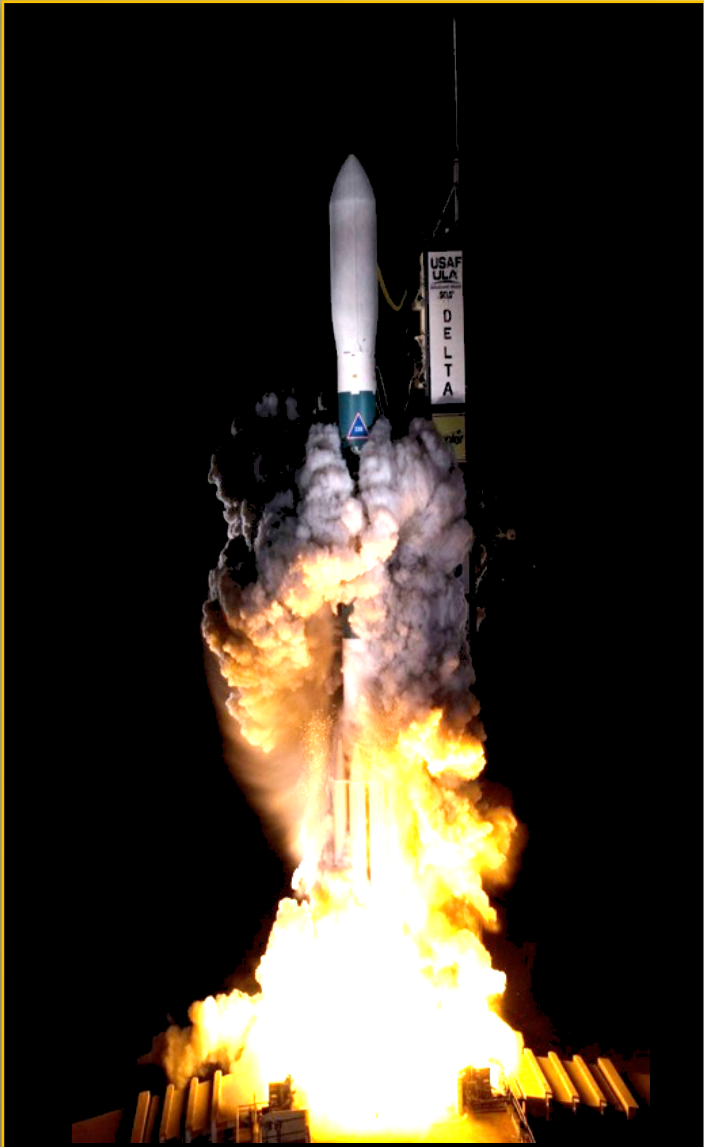




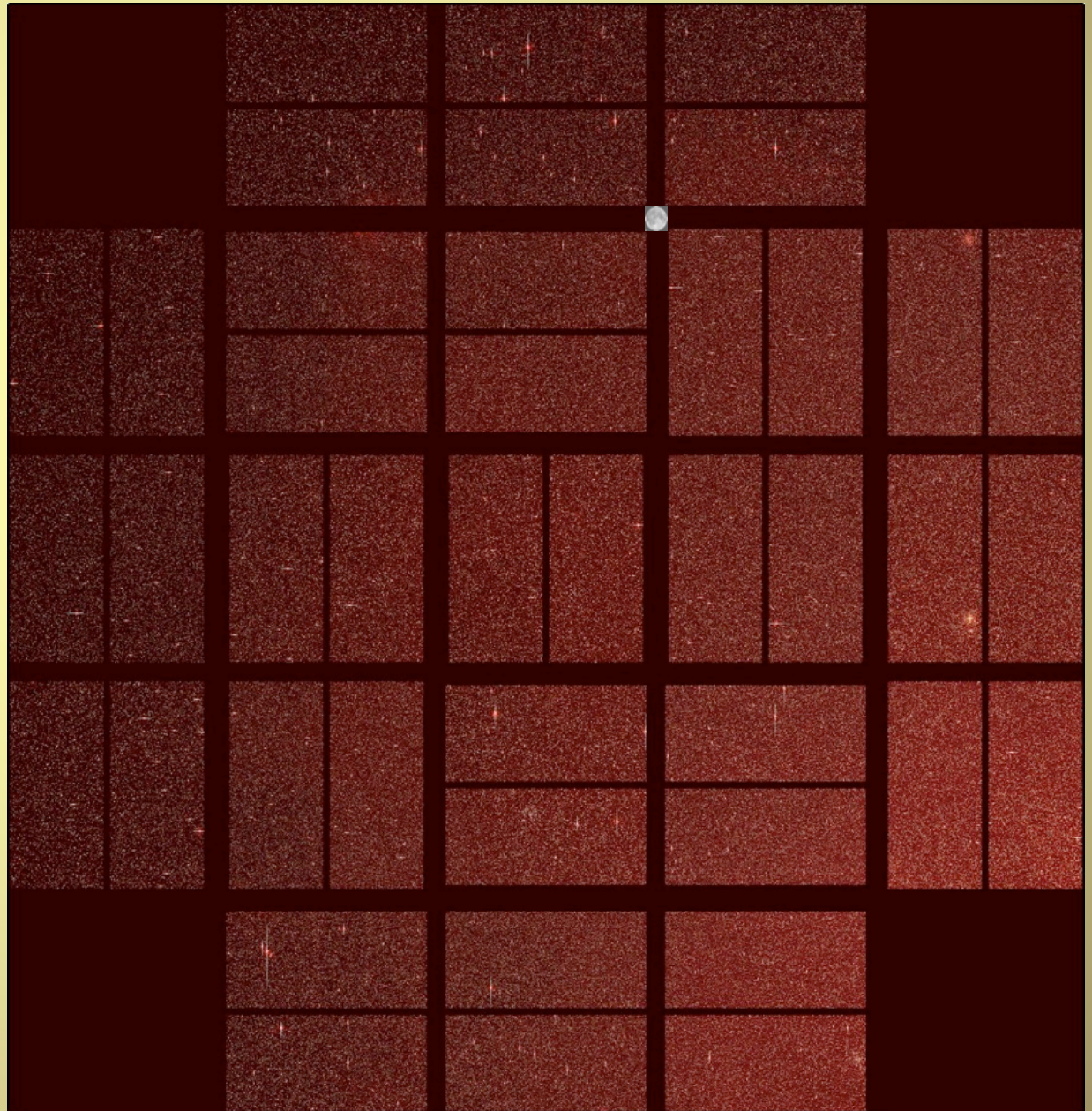
First Light Image

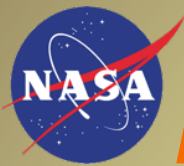
Kepler

*A Search for Earth-size
Planets*



- Launched March 7 2009

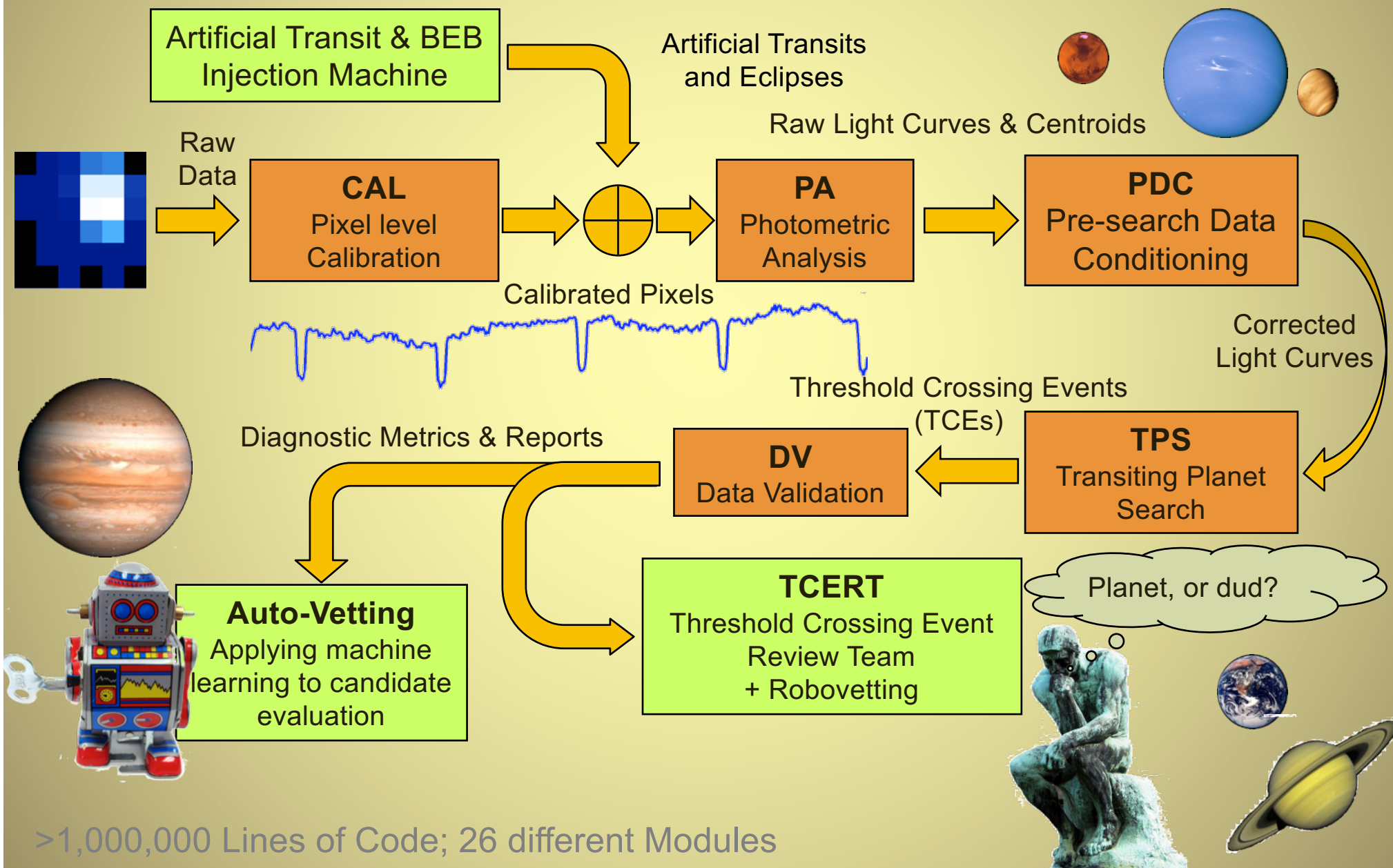




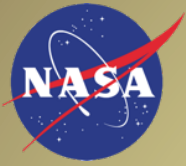
Kepler's Science Pipeline

Kepler

A Search for Earth-size Planets



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

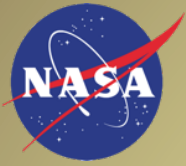


The Search Problem

Kepler

*A Search for Earth-size
Planets*



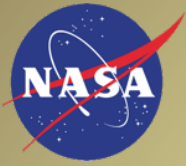


The Search Problem

Kepler

*A Search for Earth-size
Planets*



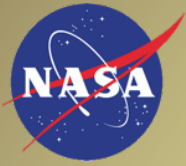


The Search Problem

Kepler

*A Search for Earth-size
Planets*



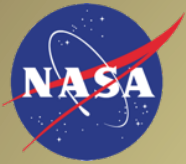


Keeping Up with the Data

Kepler

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Planets*





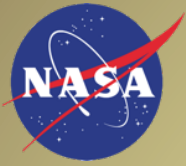
Hardware Architecture: Kepler Science Operations Center

Kepler

*A Search for Earth-size
Planets*



64 hosts, 712 CPUs,
3.7 TB of RAM,
~300 TB of raw disk storage



Hardware Architecture: NAS Pleiades Supercomputer

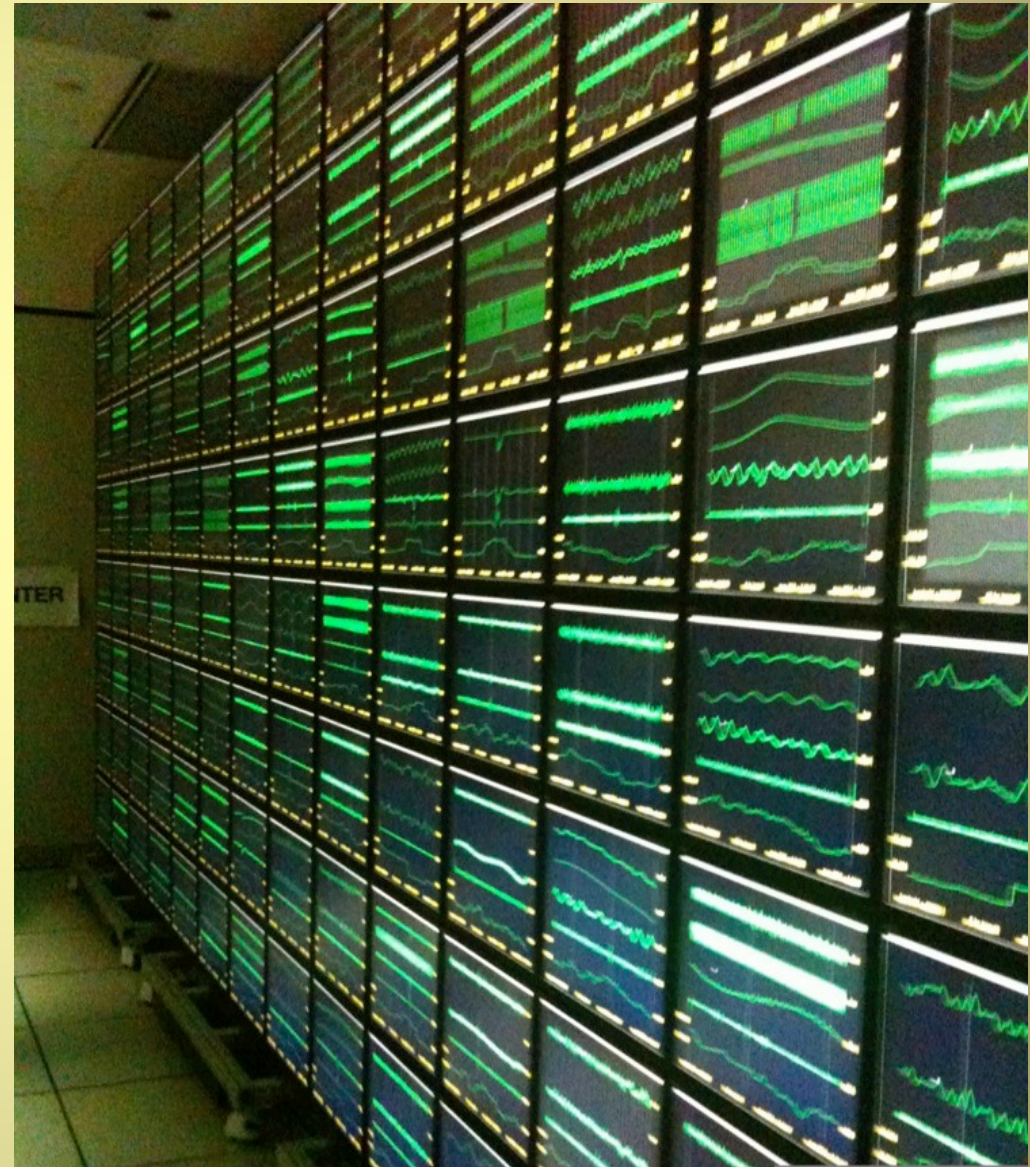
Kepler
A Search for Earth-size
Planets

7.25 Pflop/s peak cluster

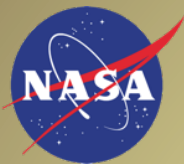
246,048 cores

938 TB of memory

29 PB of storage



Transiting Planet Search Running on Pleiades

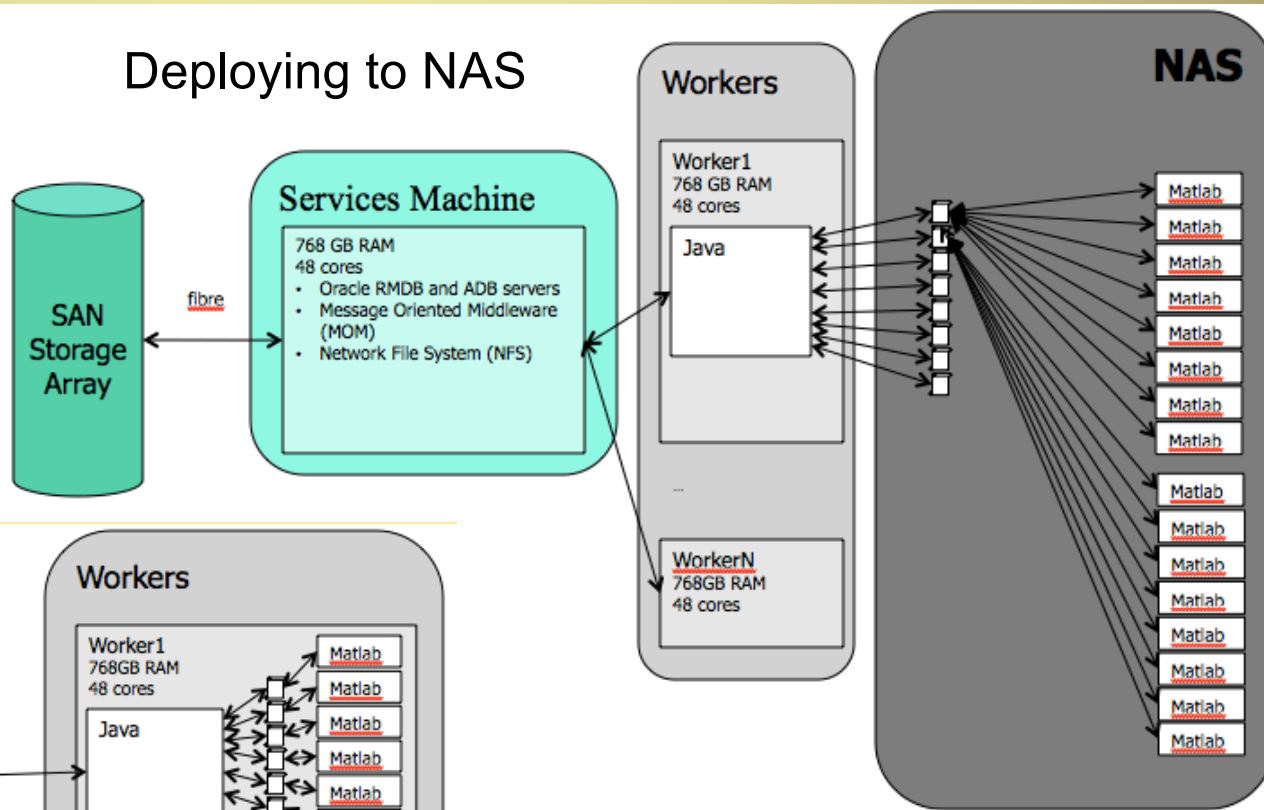


Processing Kepler Data on the NAS Pleiades

Kepler

A Search for Earth-size Planets

Deploying to NAS

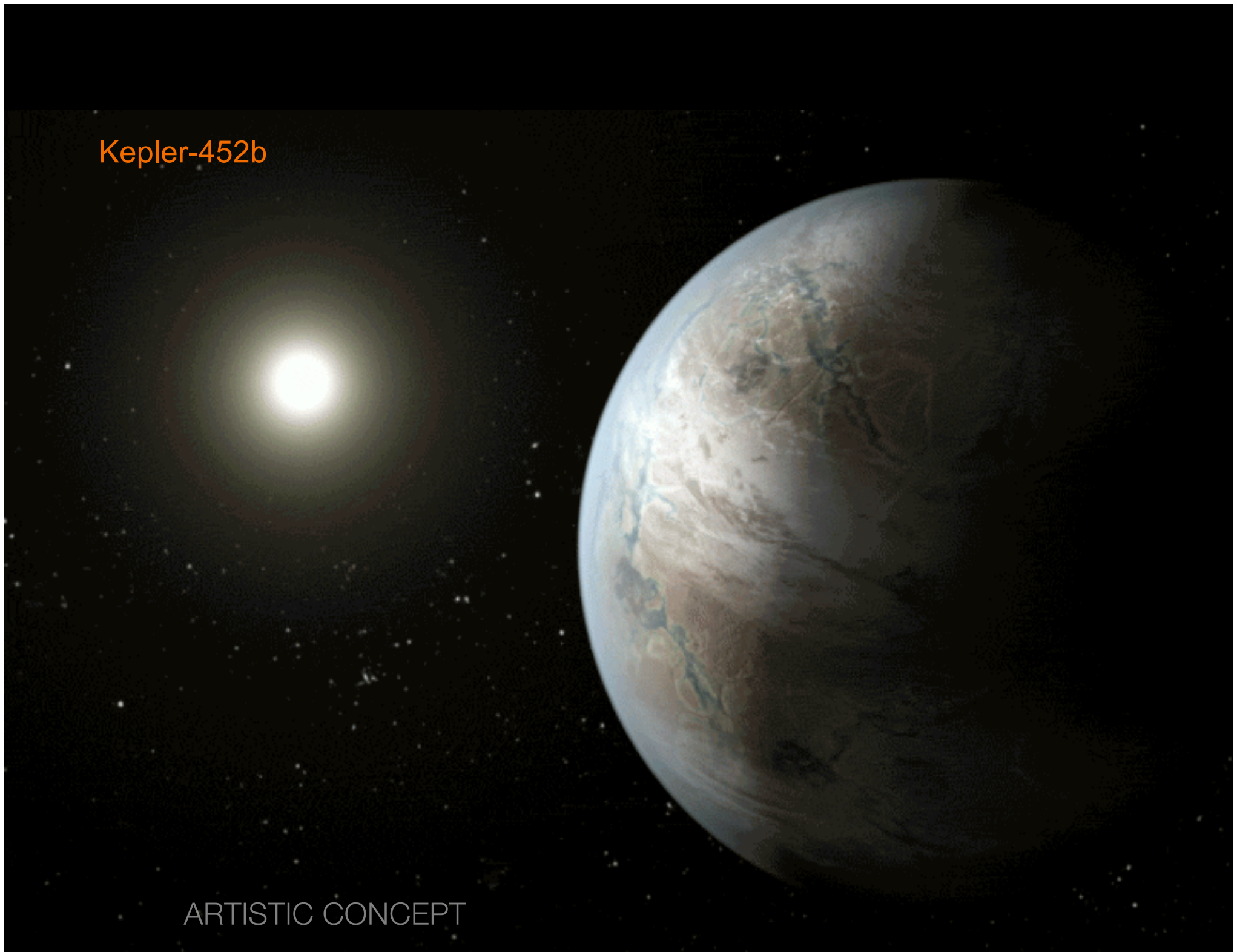


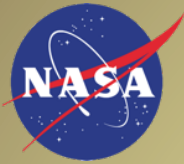
Processing scales from 100s of cores on local cluster to 10s of 1000s of cores on the NAS

Local Clusters

Kepler-452b

ARTISTIC CONCEPT

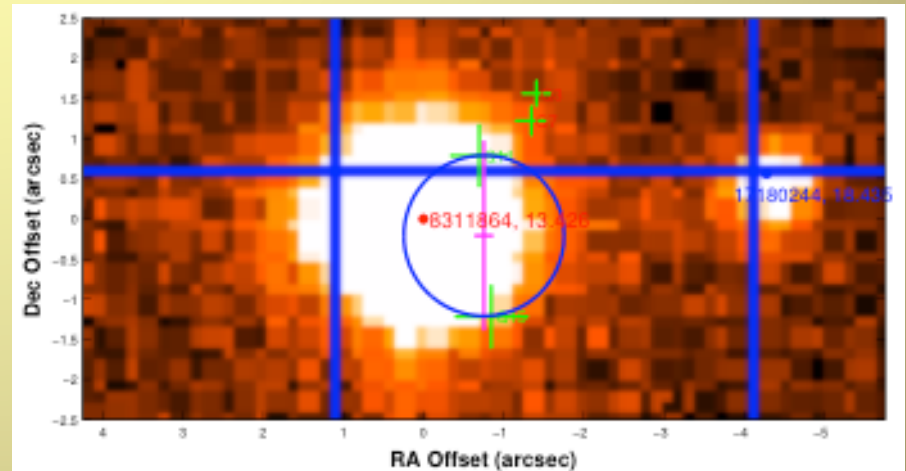
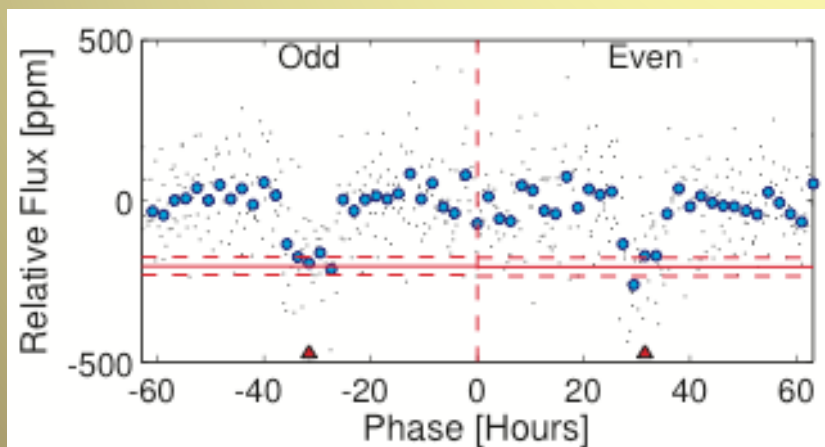
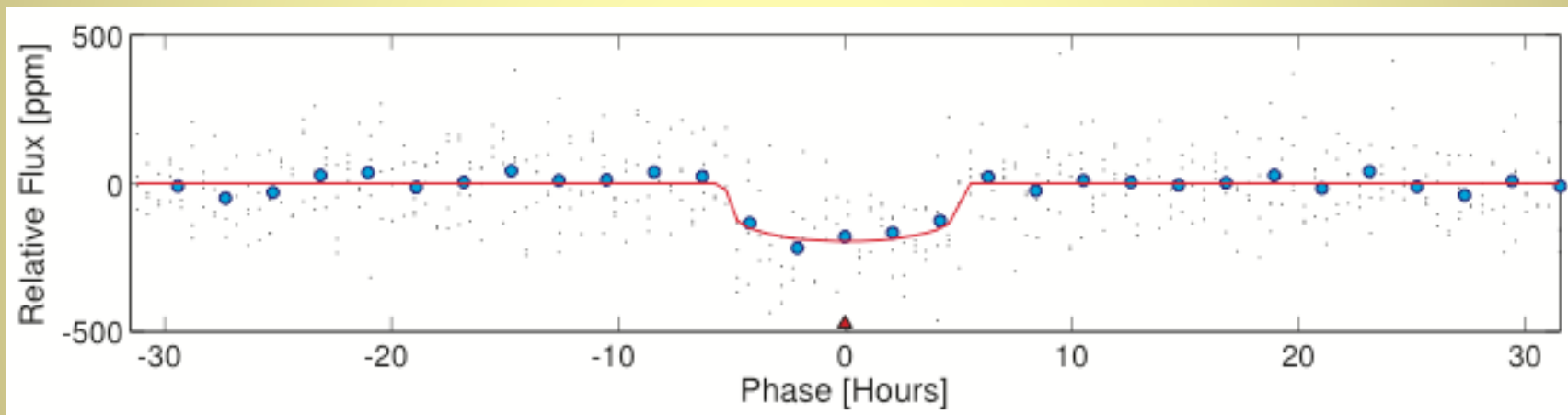
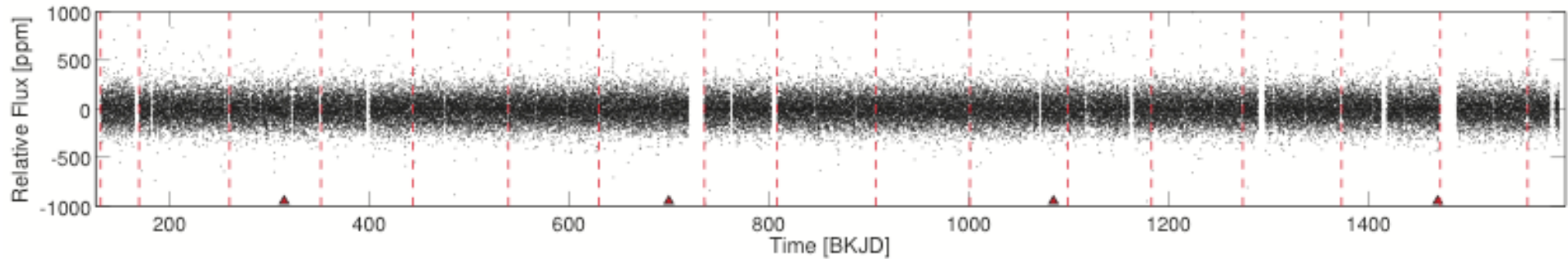


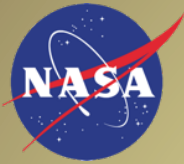


Light Curve

Kepler

A Search for Earth-size Planets





Statistical Validation of Planet Candidates

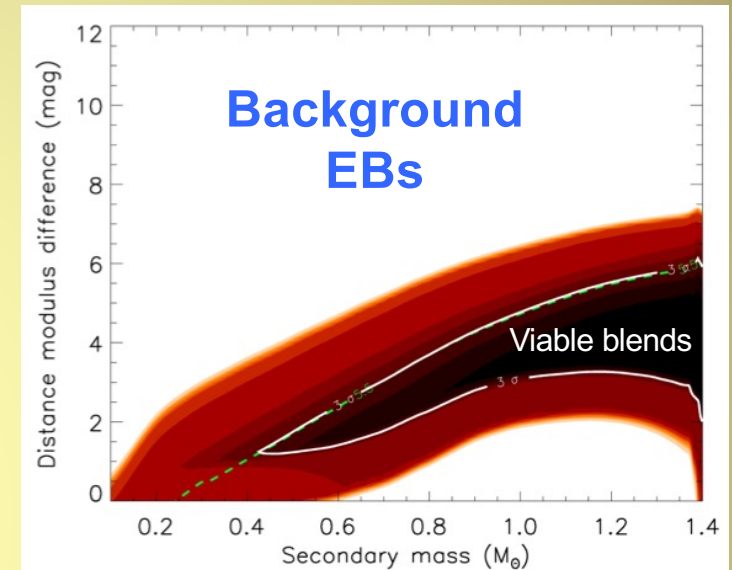
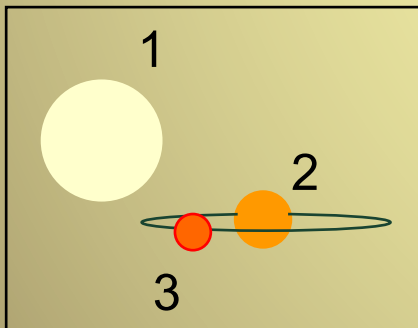
Kepler
A Search for Earth-size
Planets

Transit-like signals can be produced by a number of astrophysical phenomena

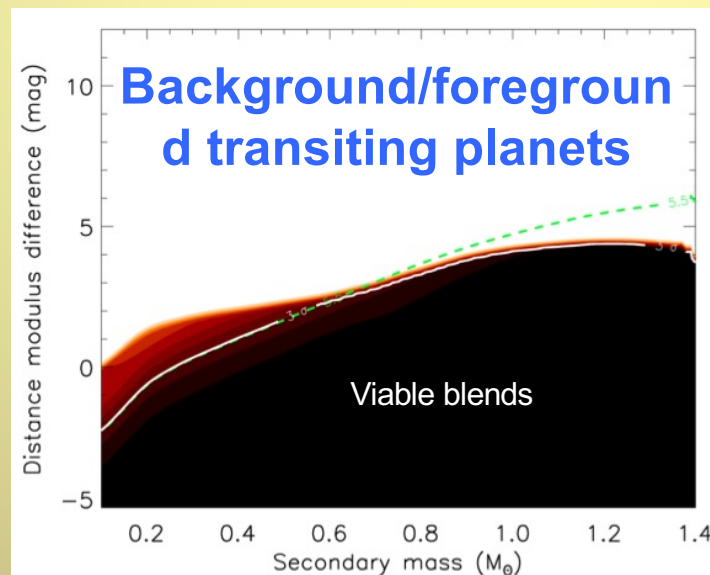
- Background Eclipsing Binaries
- Triple star systems with an EB/planet
- Background/Foreground planet

BLENDER can assess statistical confidence in planetary nature of a candidate

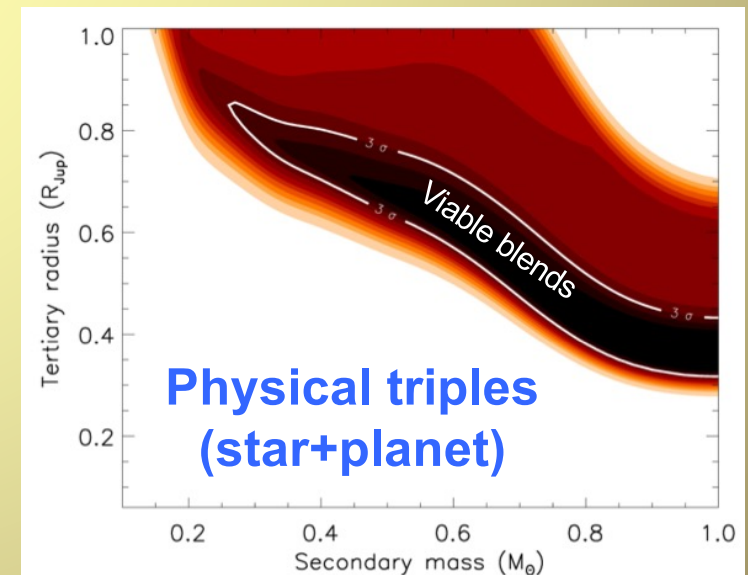
Computationally intensive: Supercomputer essential



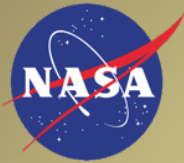
W. Torres 2013



W. Torres 2013



W. Torres 2013



Blender Analysis for Kepler-452b

Kepler
A Search for Earth-size
Planets

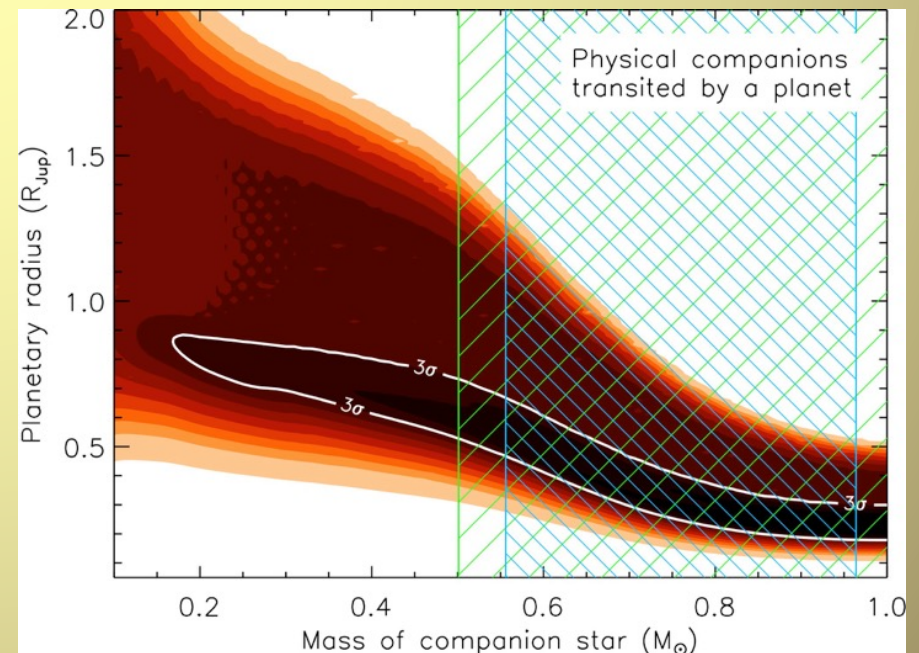
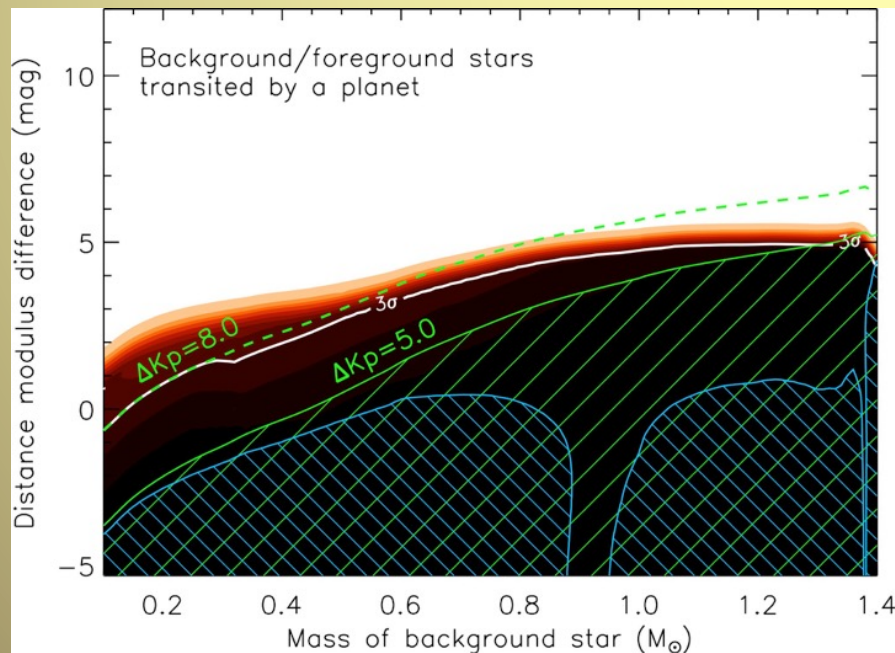
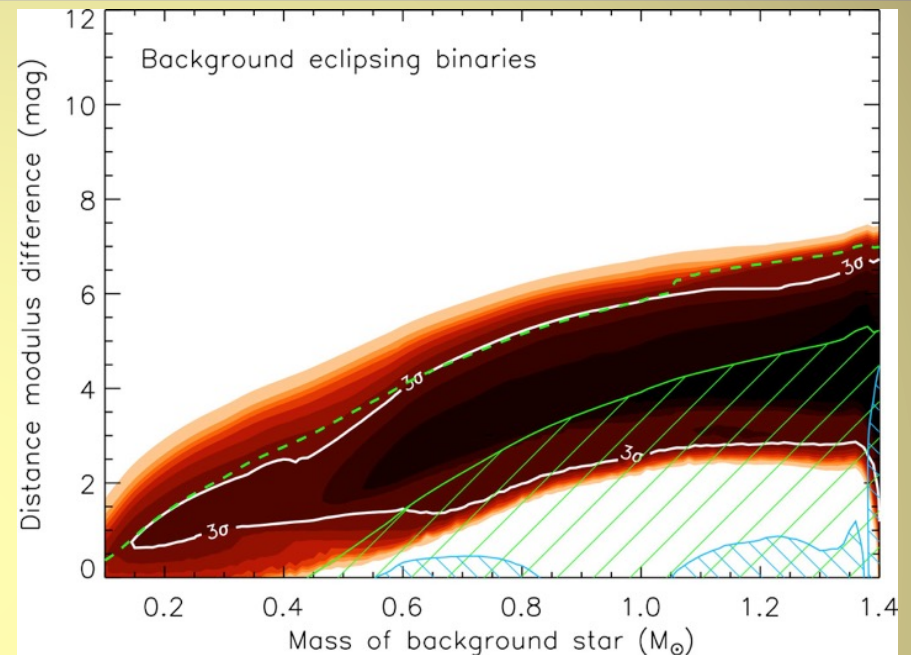
BEB odds: 1.21×10^{-12}

BP odds: 2.56×10^{-10}

HTP odds: 2.35×10^{-6}

Vs: (Expected) Planet odds: 9.97×10^{-4}

Therefore, odds ratio is $\sim 424:1$



Kepler-452
System

Kepler-186
System

Solar
System

Kepler-186f

Mercury

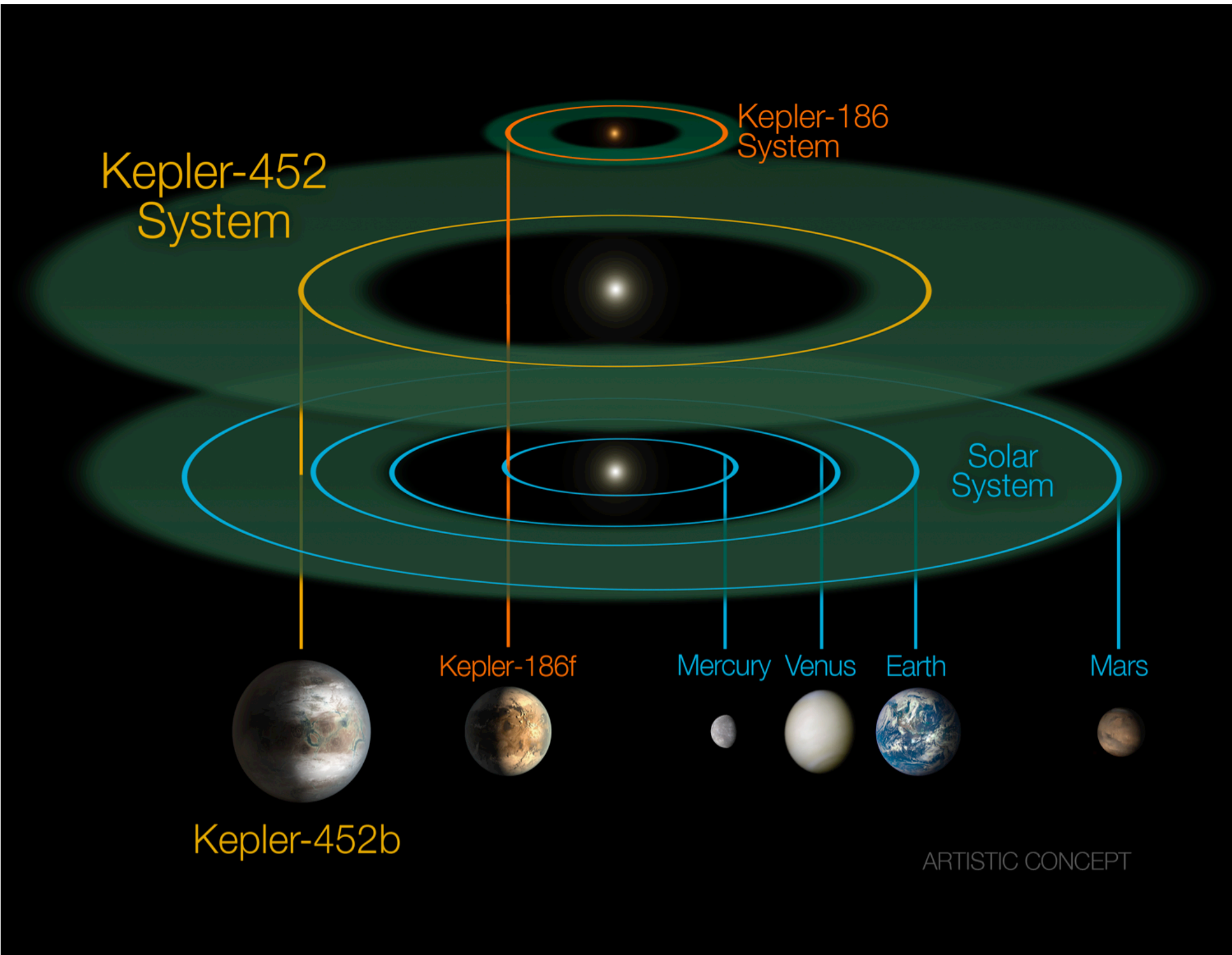
Venus

Earth

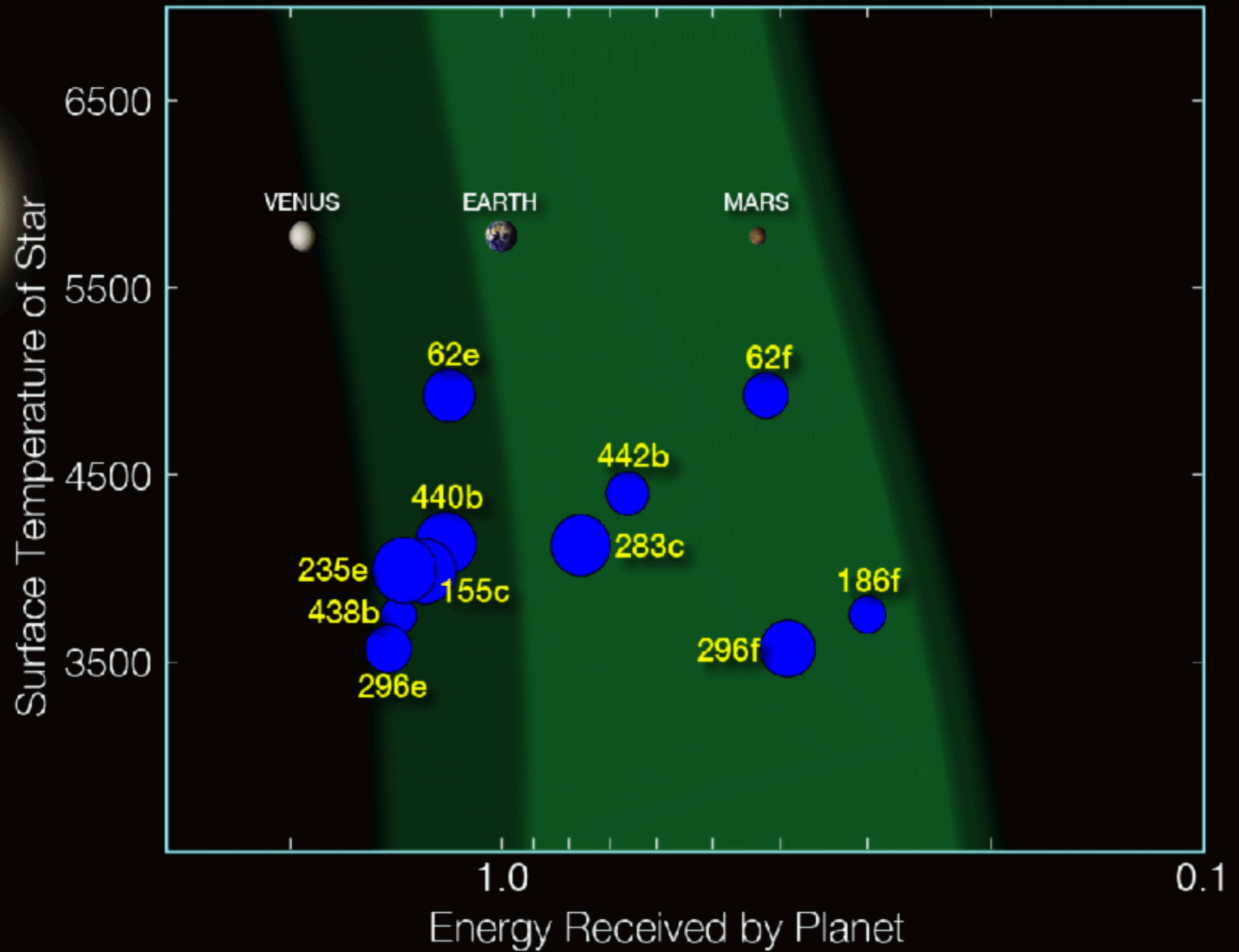
Mars

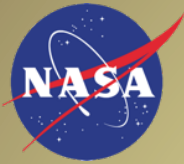
Kepler-452b

ARTISTIC CONCEPT



Kepler Small Habitable Zone Planets Now Include One Orbiting a Sun-Like Star





Searching for Exomoons

Kepler

*A Search for Earth-size
Planets*

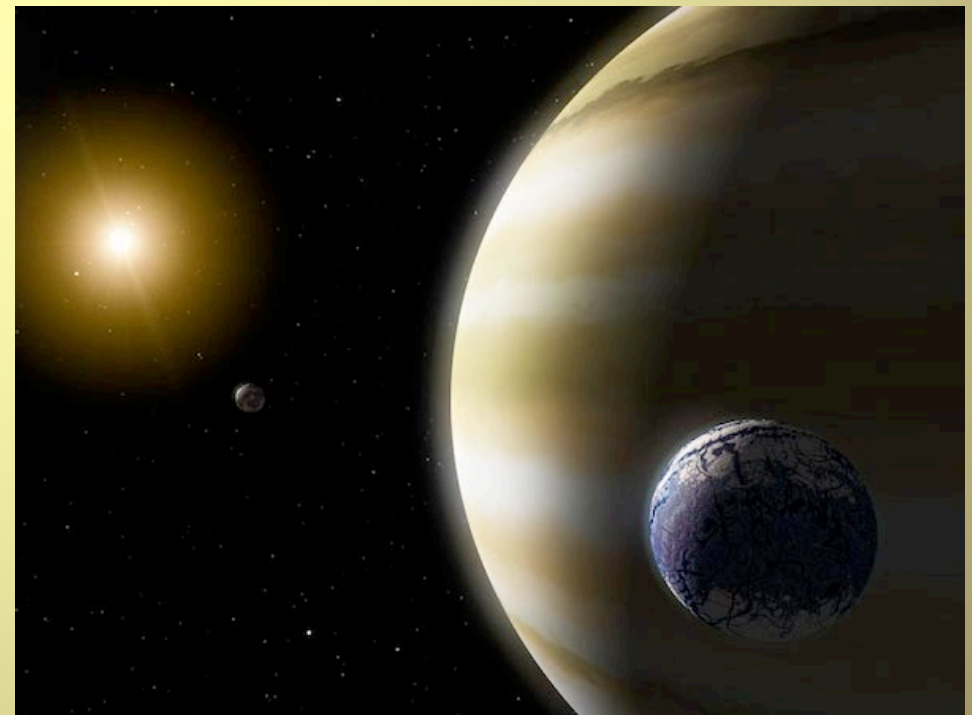
David Kipping and team
have been searching for
exomoons in ~400 light
curves from Kepler on the
NAS Pleiades
supercomputer

Each search consumes
50,000 CPU hours

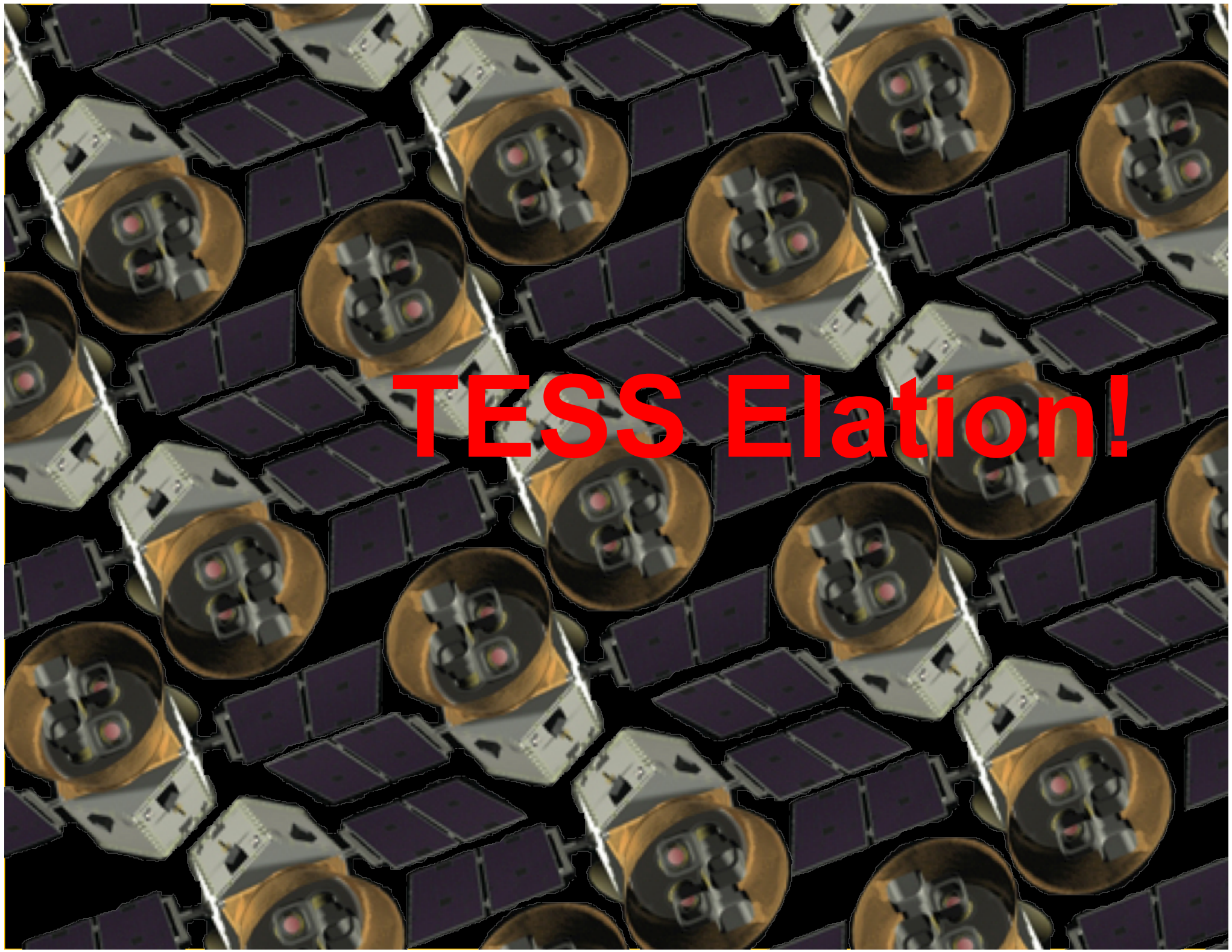
~40 light curves were
searched as of 2014

~300 were search in 2015

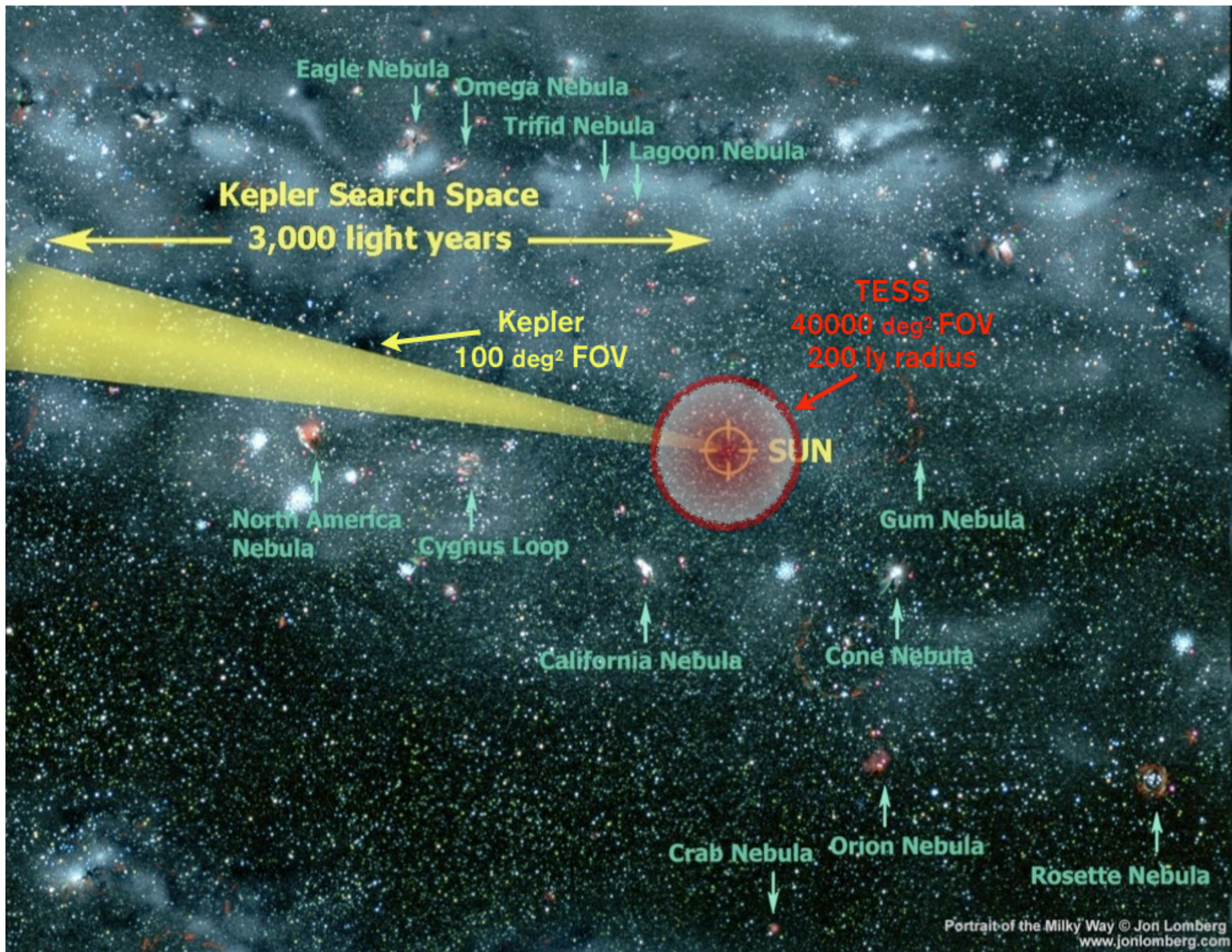
Exomoons remain elusive:
None have been
conclusively discovered



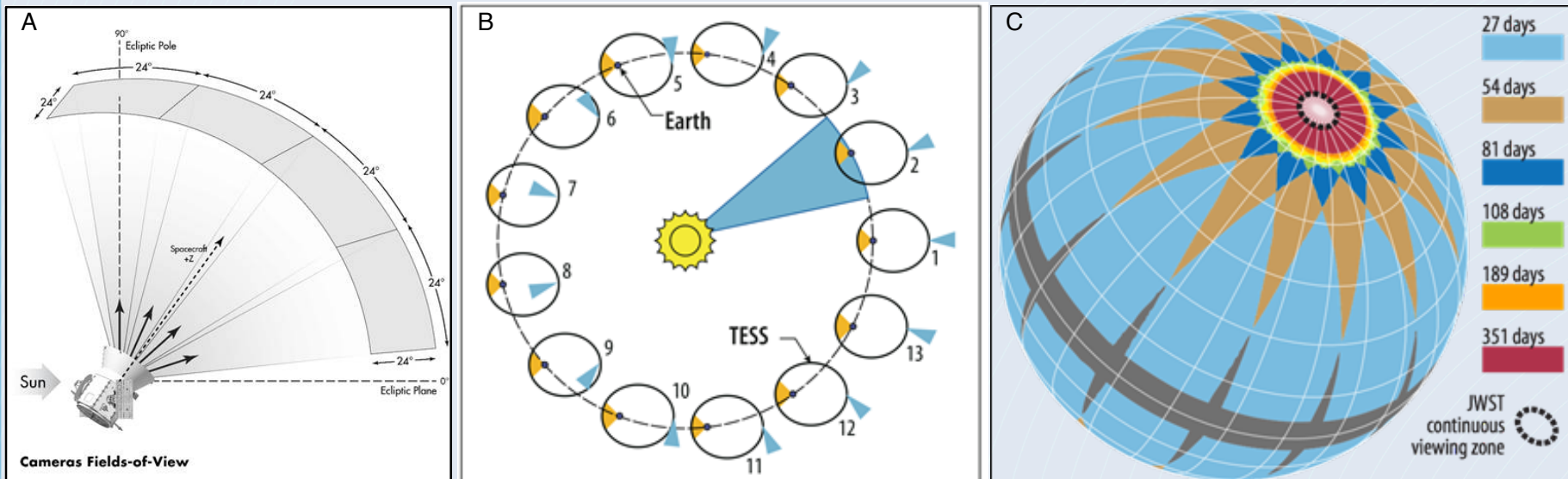
NASA JPL/Caltech



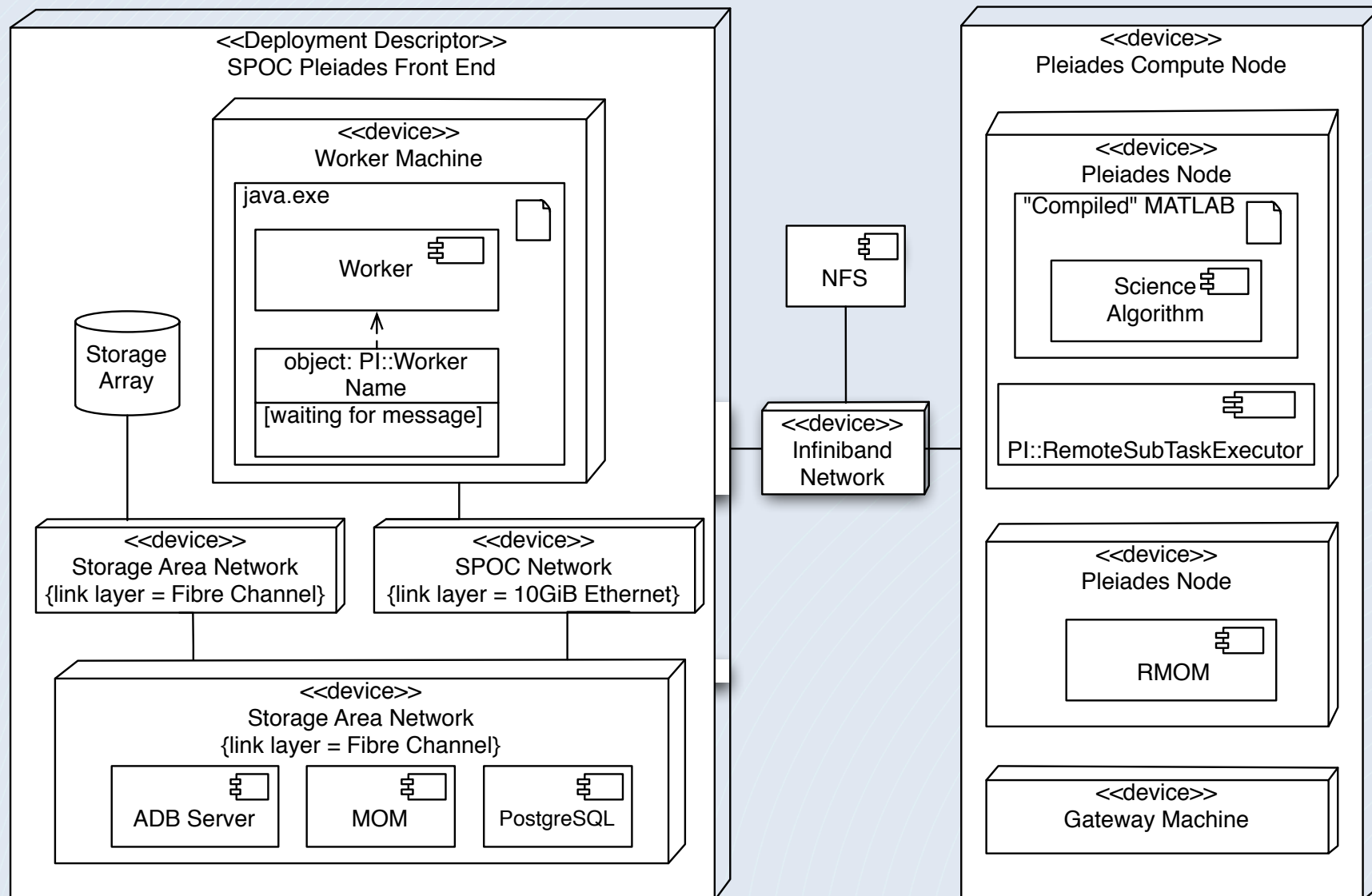
TESS Elation!



- All sky transit survey to find Earth's closest cousins
- 2 year primary mission
- Launch in December 2017 (tentative)
- TESS will identify best planets for follow up and characterization with James Webb and very large telescopes



- Processing TESS data on the NAS



Exoplanet Missions



Hubble

Spitzer

Kepler

TESS

JWST

WFIRST-AFTA

New Worlds Telescope

Ground-based
Observatories

Astronomy and Astrophysics
in the New Millennium



2001
Decadal
Survey

New Worlds,
New Horizons
in Astronomy and Astrophysics



2010
Decadal
Survey

Supercomputing has played an increasingly important role in exoplanet searches, validation and characterization

The Kepler and TESS missions were and are not achievable without supercomputing

The role of supercomputers in exoplanet science is sure to grow in the future as the amount of data and sophistication of the software continue to increase with future missions