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

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NASA Ames Research Center

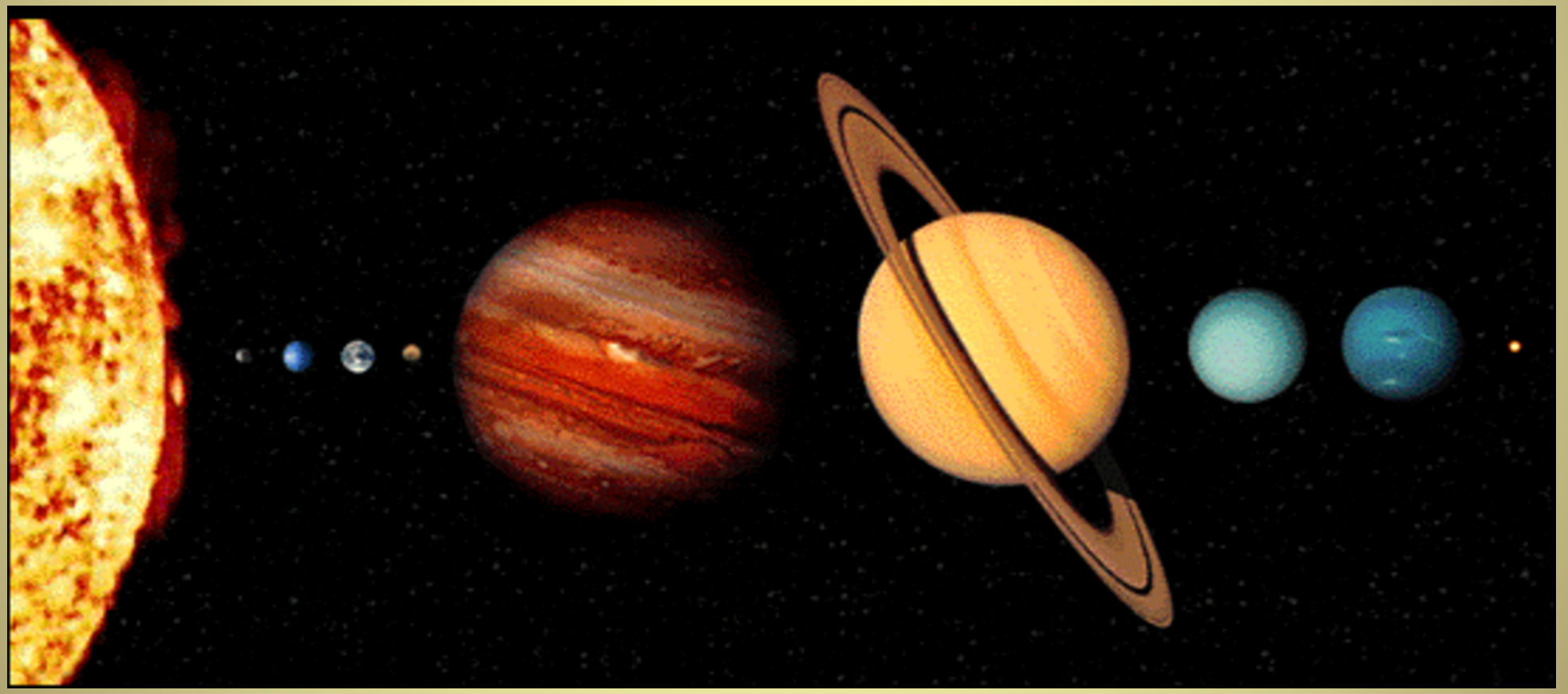
Wednesday September 28, 2015

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

All the Known Planets In 1994

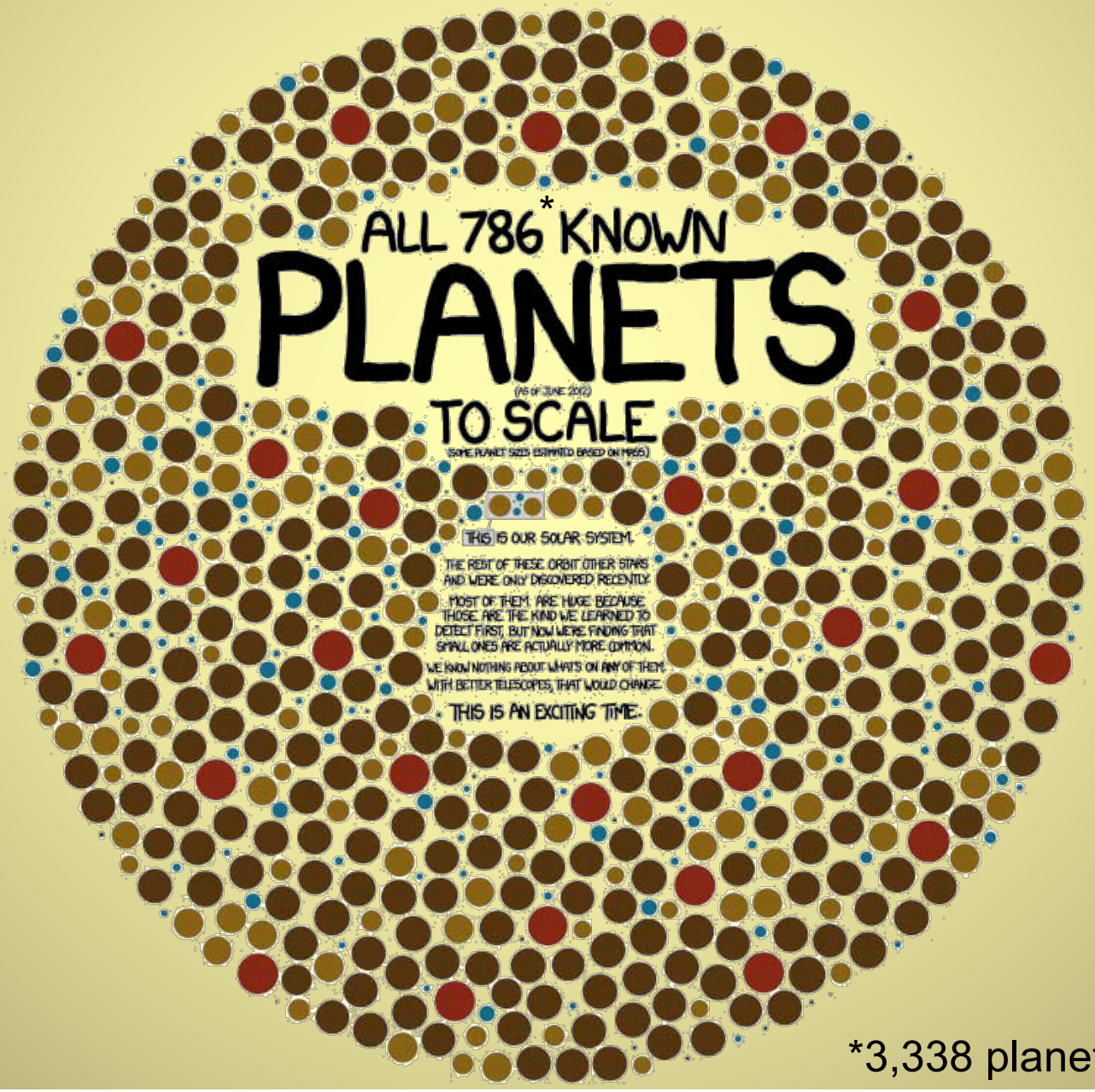
Kepler

A Search for Earth-size Planets



A More Recent Pictures of Planets

Kepler
A Search for Earth-size Planets

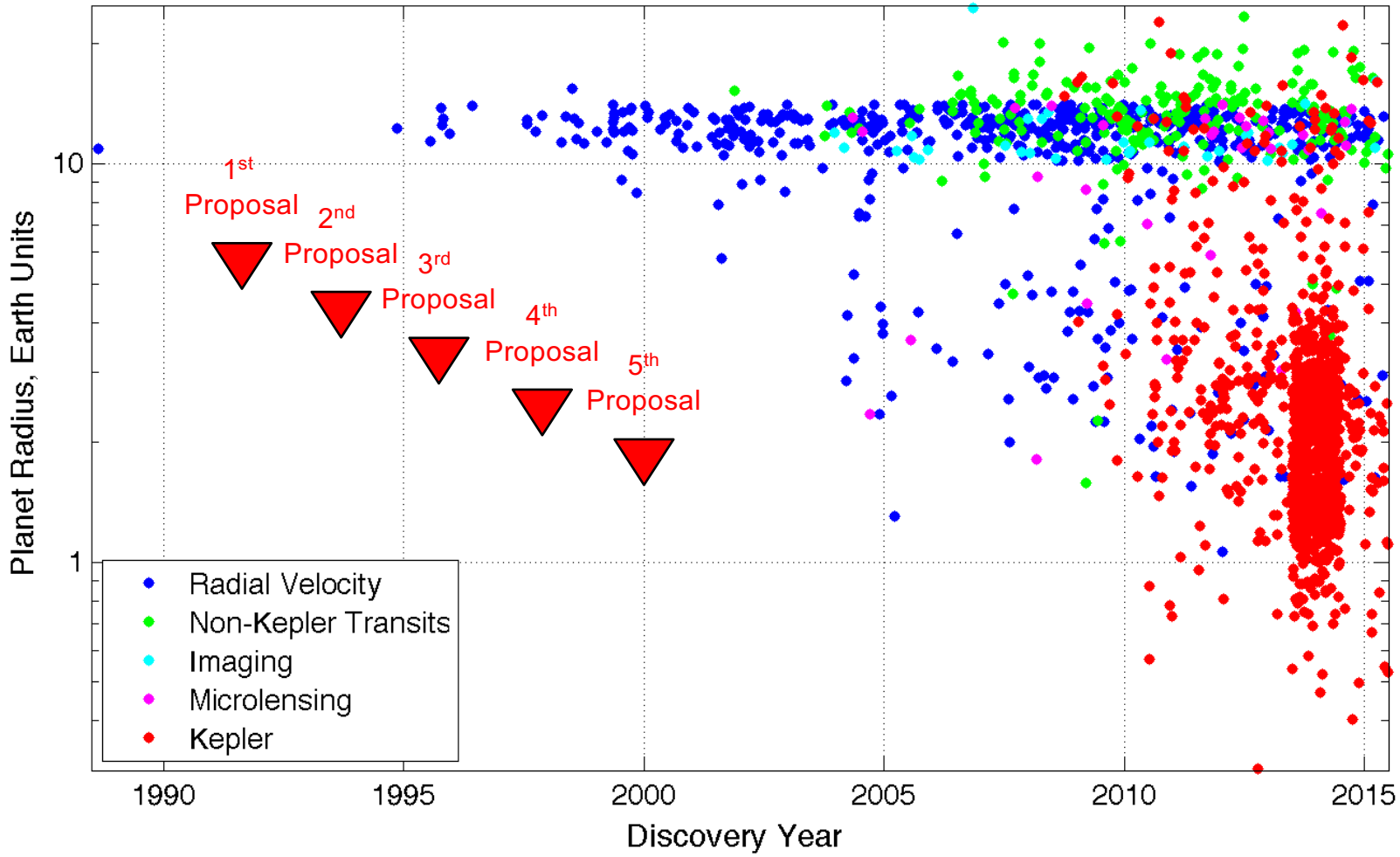


*3,338 planets as of 9/28/16


ALL 786 KNOWN
PLANETS
(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.
Kepler
A Search for Earth-size

Exoplanet Discoveries Over Time

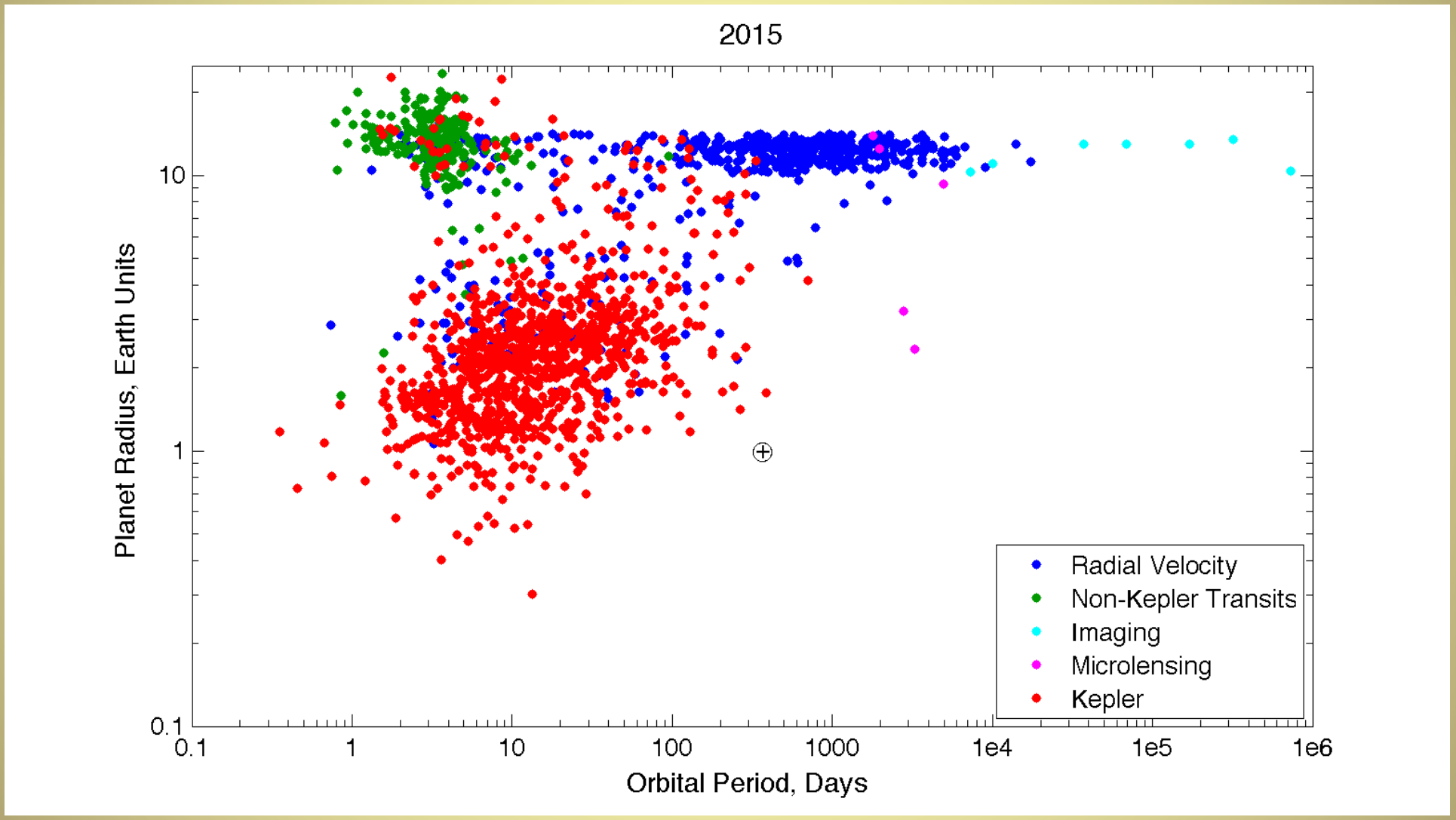
Kepler
A Search for Earth-size Planets



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

Exoplanet Discoveries

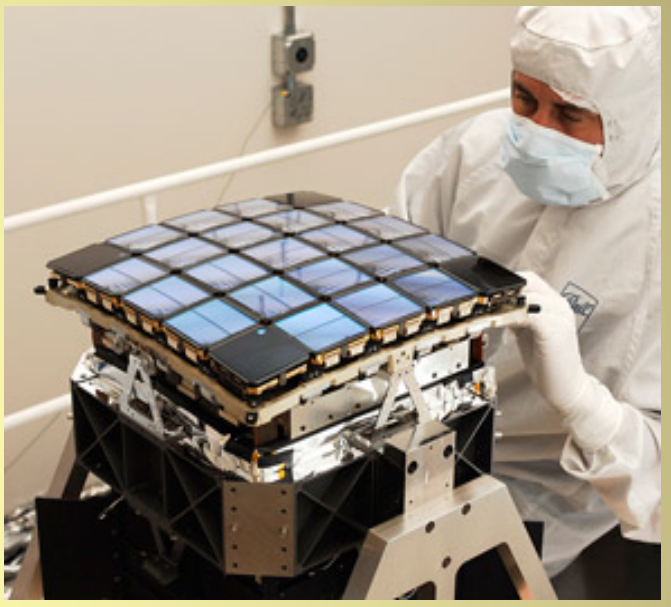
Kepler
A Search for Earth-size Planets

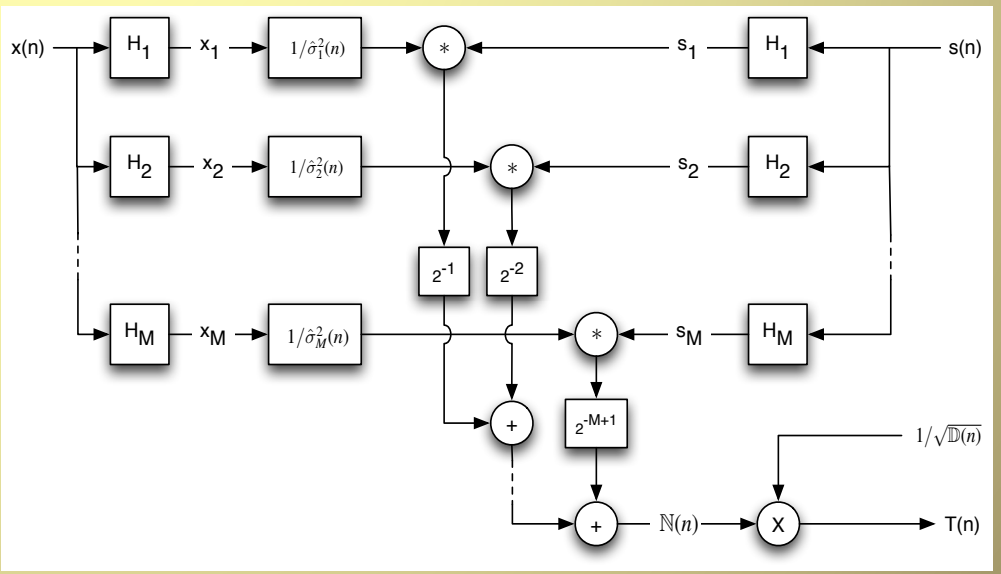


Enabling *Kepler*

Kepler
A Search for Earth-size Planets

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





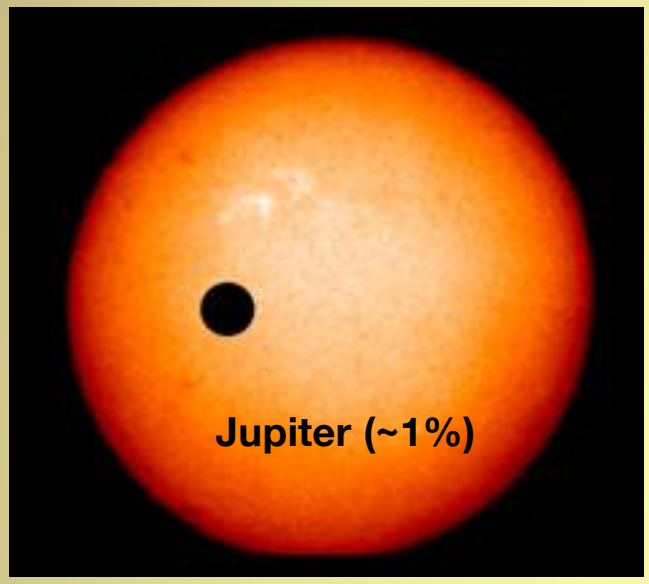
How Does Kepler Work?

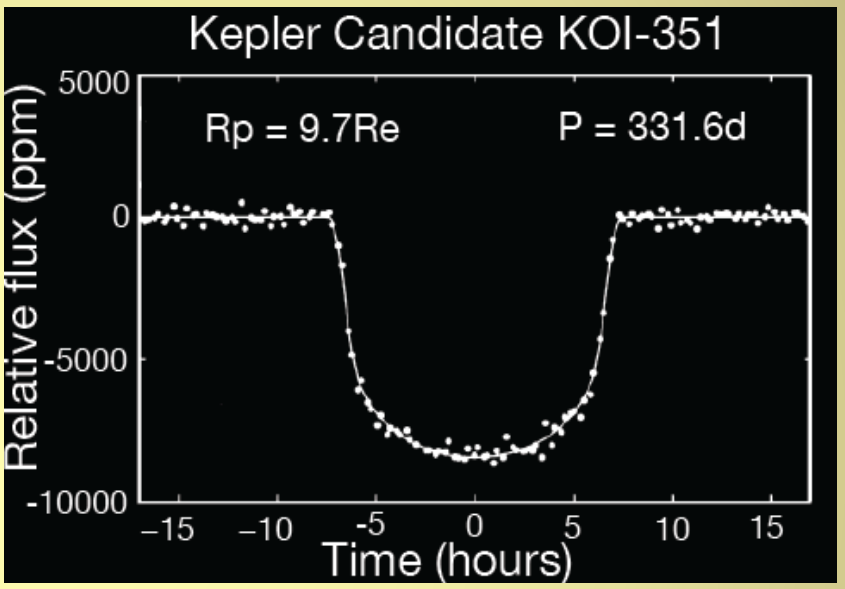
Kepler

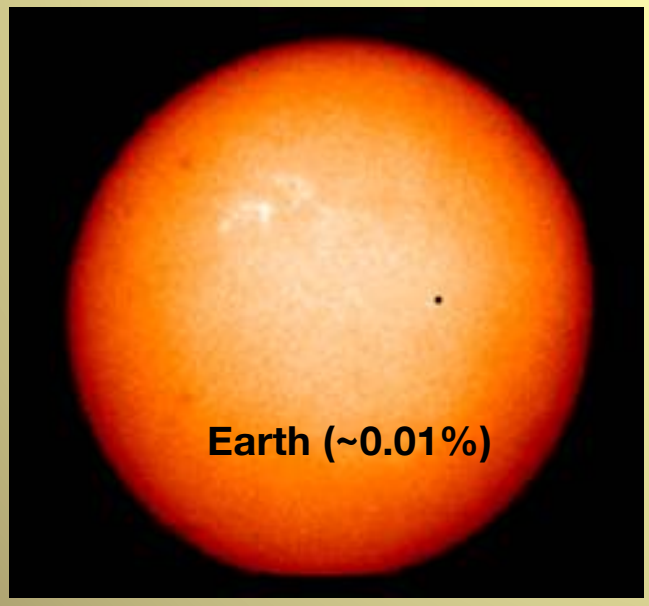
A Search for Earth-size Planets

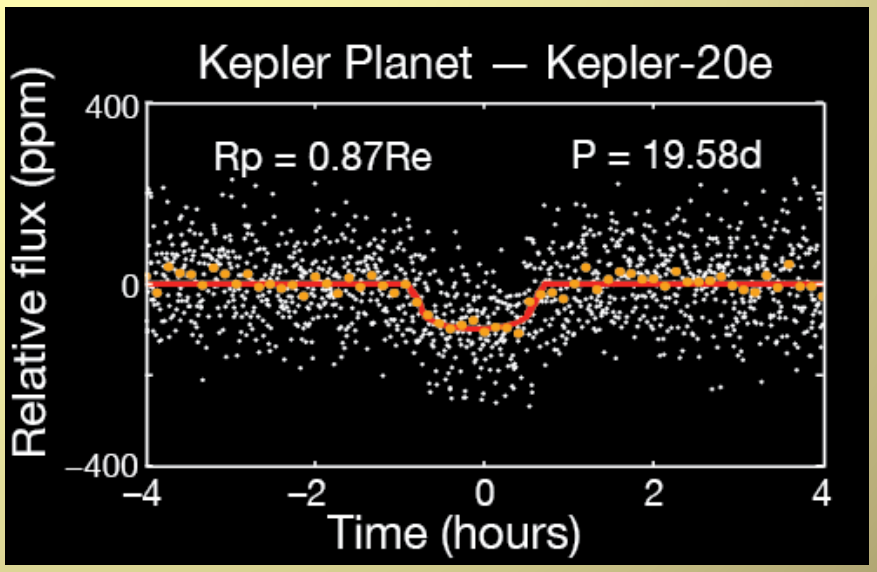
How Hard is it to Find Good Planets?

Kepler
A Search for Earth-size Planets



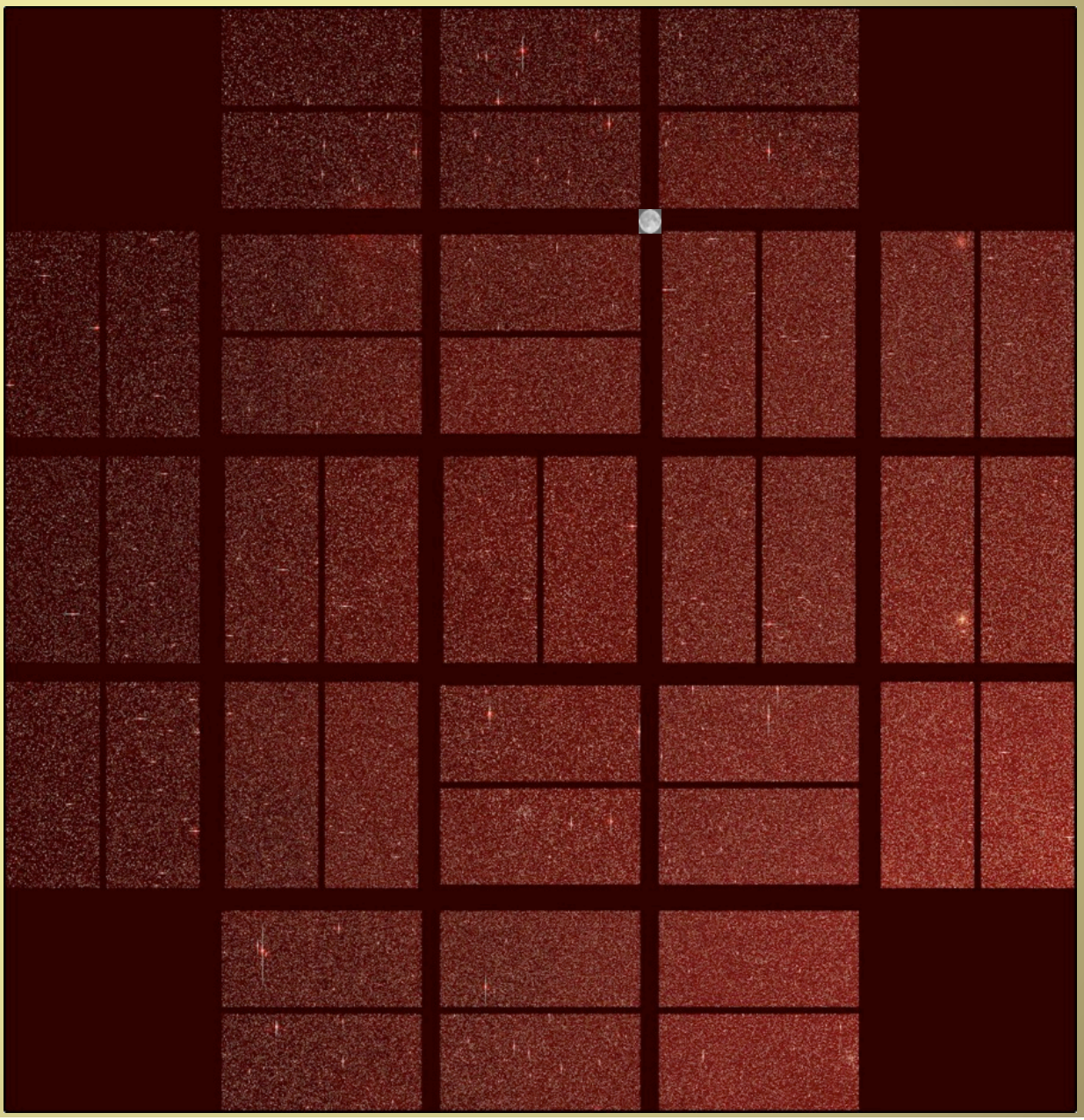






First Light Image

Kepler
A Search for Earth-size Planets



- Launched March 7 2009

Kepler's Science Pipeline

Kepler
A Search for Earth-size Planets

Artificial Transit & BEB Injection Machine

Artificial Transits and Eclipses

Raw Light Curves & Centroids

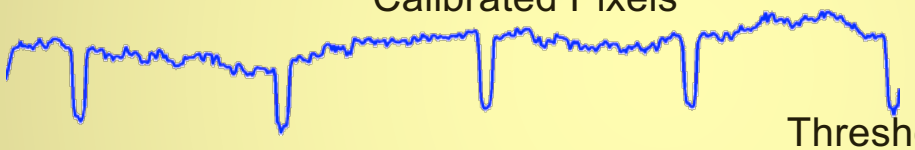
Raw Data

CAL
Pixel level Calibration

PA
Photometric Analysis

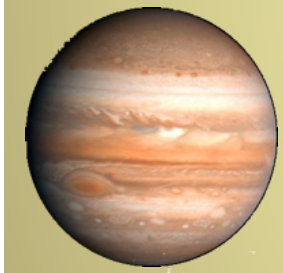
PDC
Pre-search Data Conditioning

Calibrated Pixels



Corrected Light Curves

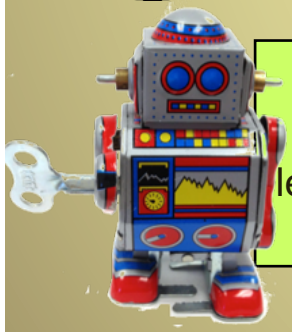
Threshold Crossing Events (TCEs)



Diagnostic Metrics & Reports

DV
Data Validation

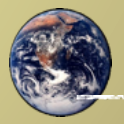
TPS
Transiting Planet Search



Auto-Vetting
Applying machine learning to candidate evaluation

TCERT
Threshold Crossing Event Review Team
+ Robovetting

Planet, or dud?



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

The Search Problem

The Search Problem

Kepler
A Search for Earth-size Planets

The Search Problem

Keeping Up with the Data

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Hardware Architecture: Kepler Science Operations Center

64 hosts, 712 CPUs,

3.7 TB of RAM,

~300 TB of raw disk storage

Hardware Architecture: NAS Pleiades Supercomputer

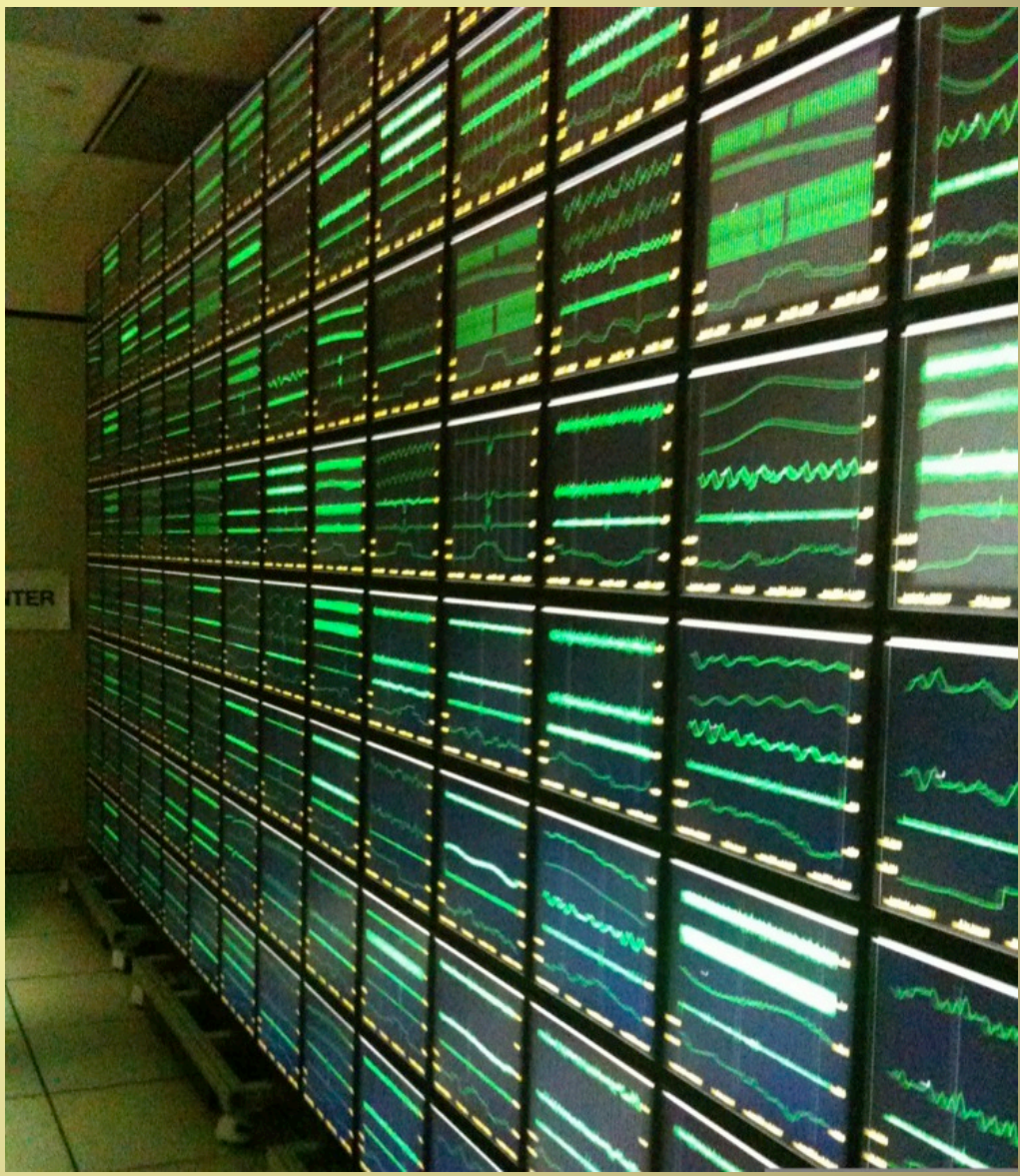
Kepler
A Search for Earth-size Planets

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

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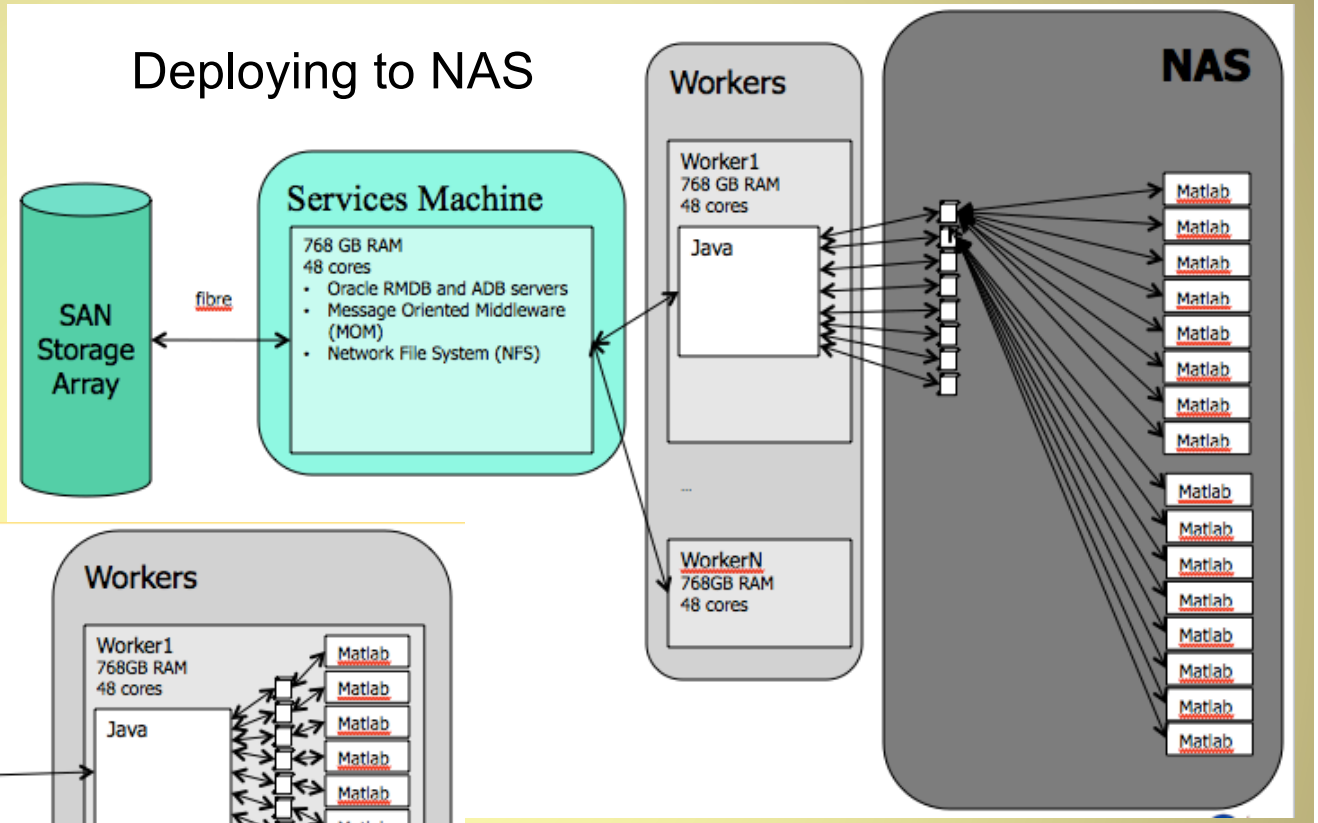
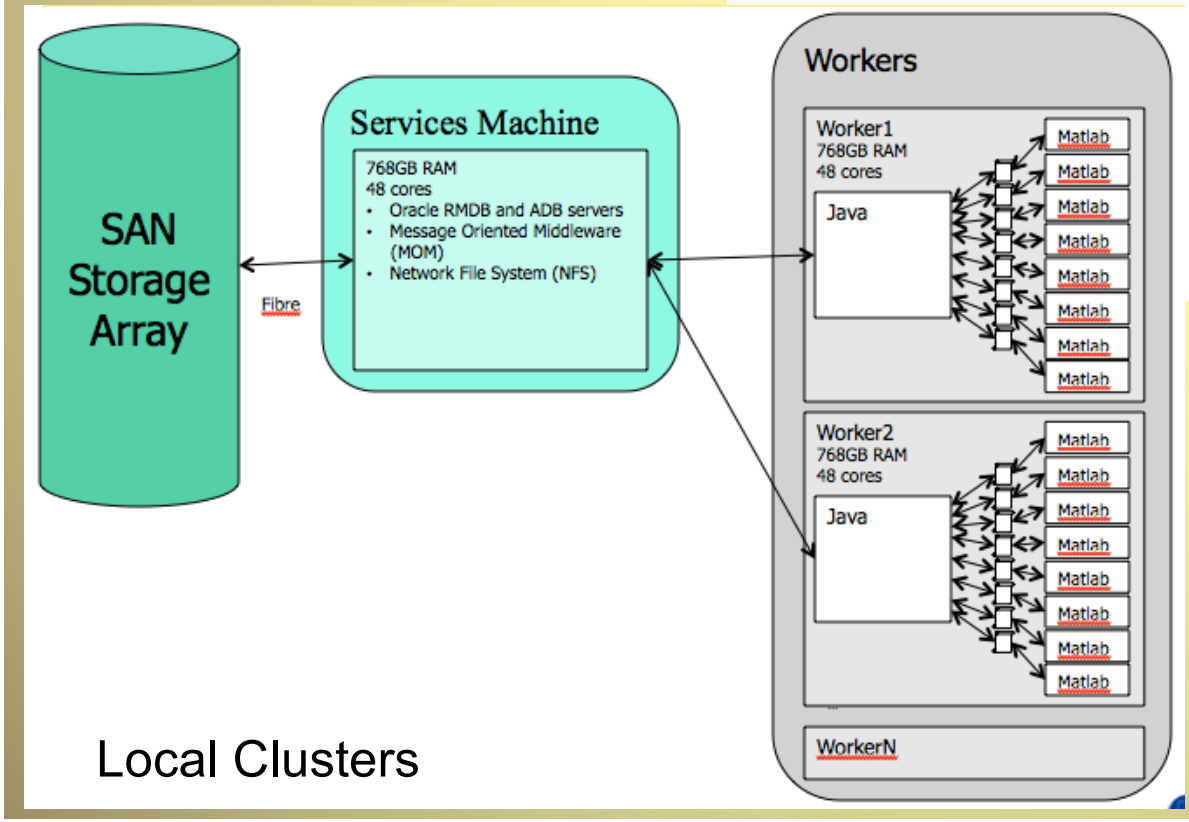
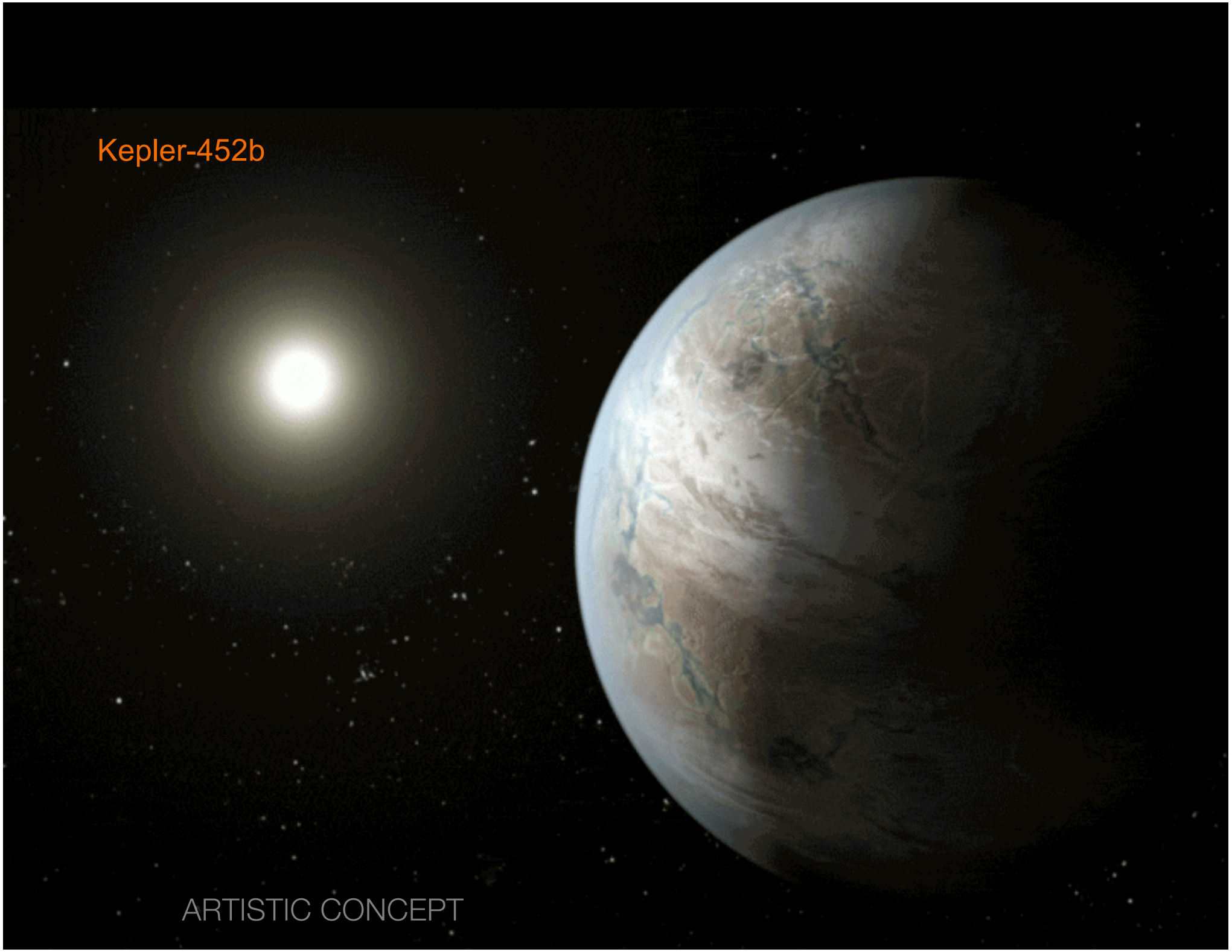
Deploying to NAS





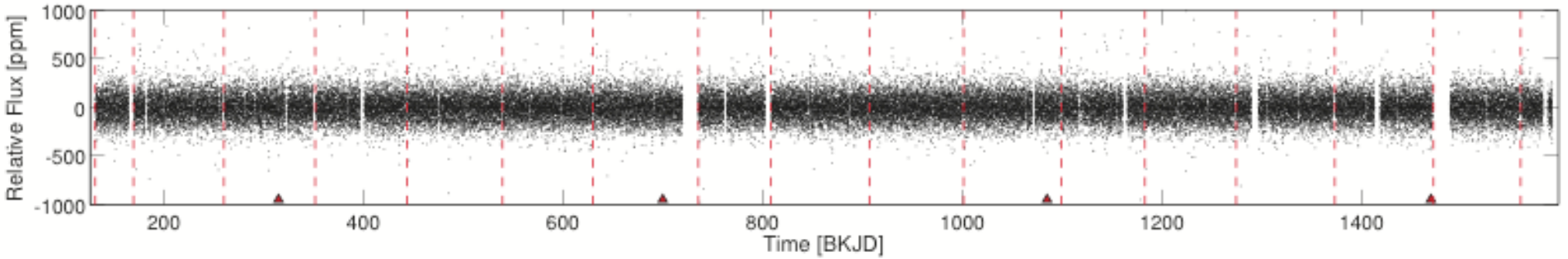
Local Clusters

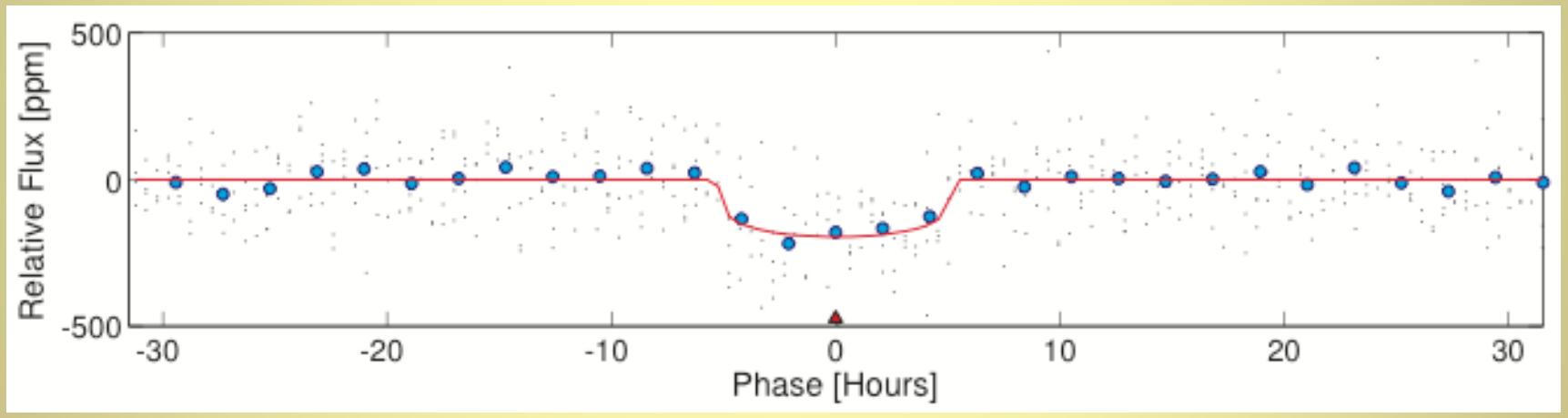
Processing scales from 100s of cores on local cluster to 10s of 1000s of cores on the NAS

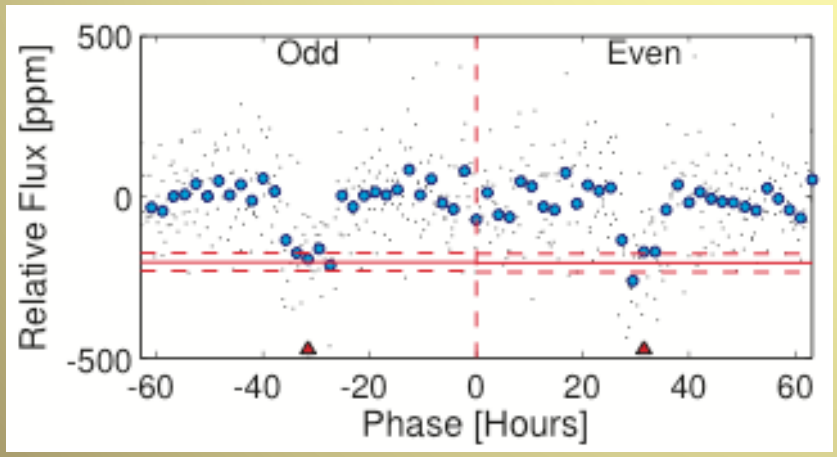

Kepler-452b
ARTISTIC CONCEPT

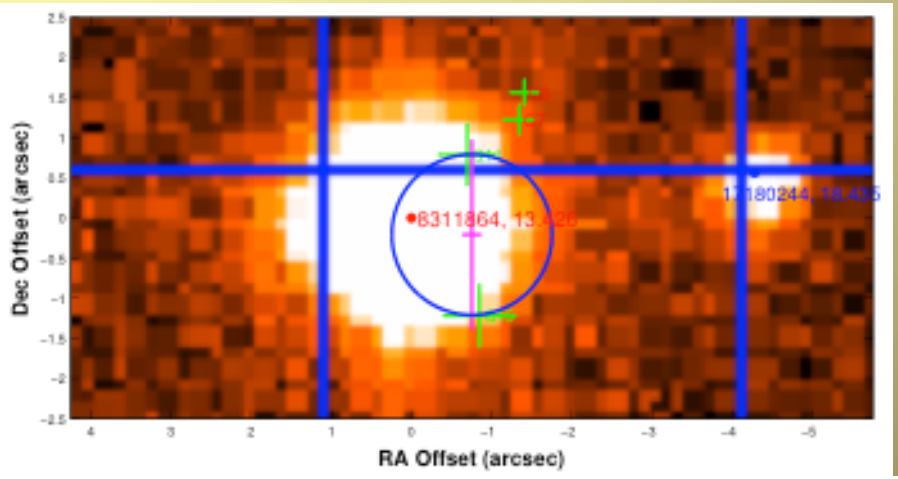
Light Curve

A Search for Earth-size Planets









Statistical Validation of Planet Candidates

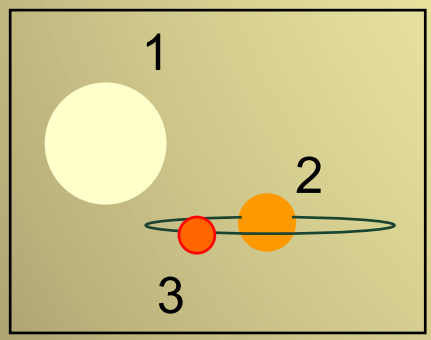
Kepler
A Search for Earth-size Planets

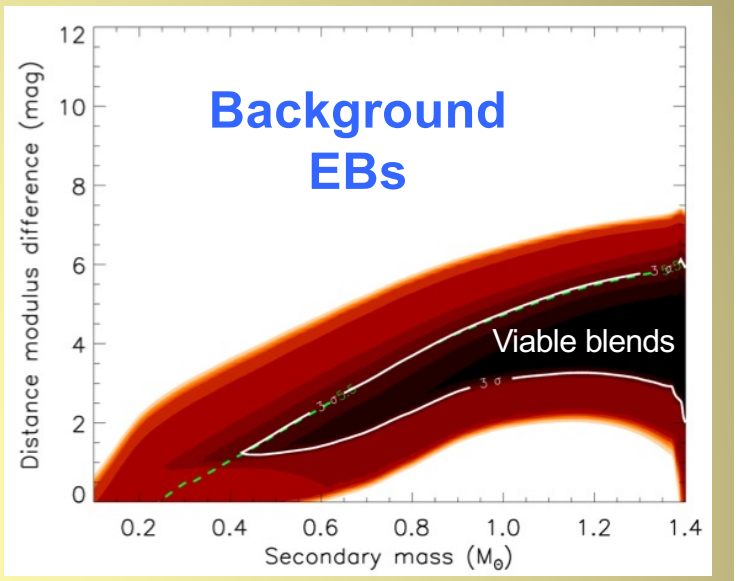
Transit-like signals can be produced by a number of astrophysical phenomena

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

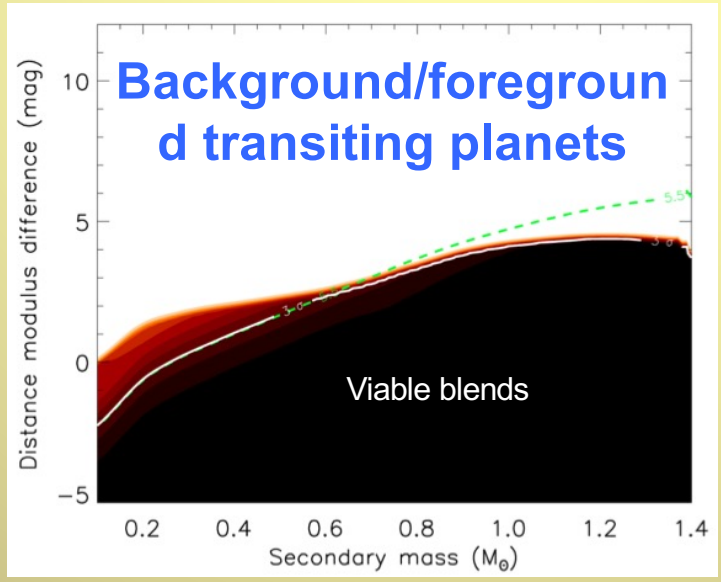
BLENDER can assess statistical confidence in planetary nature of a candidate

Computationally intensive: Supercomputer essential

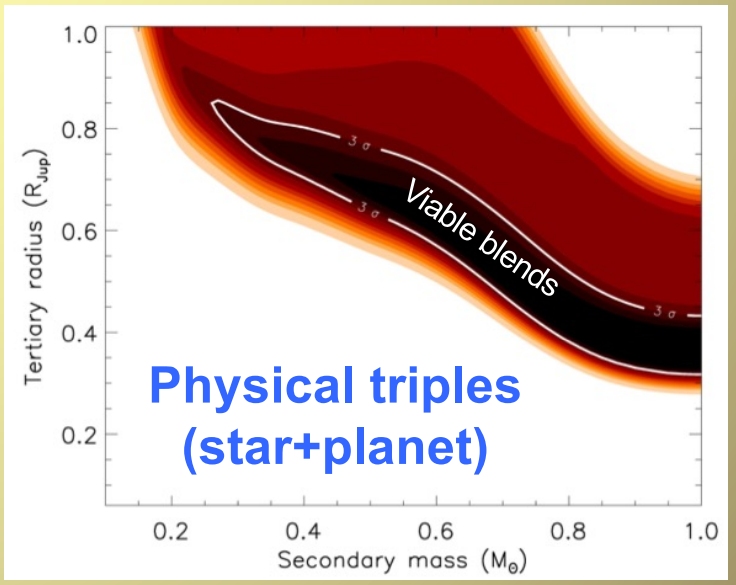




W. Torres 2013



W. Torres 2013



W. Torres 2013

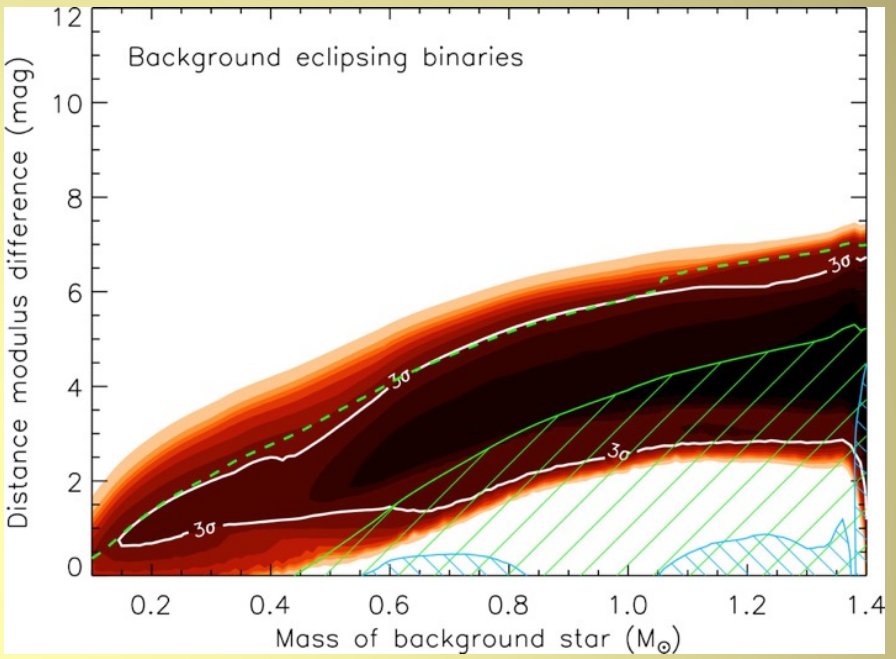
Blender Analysis for Kepler-452b

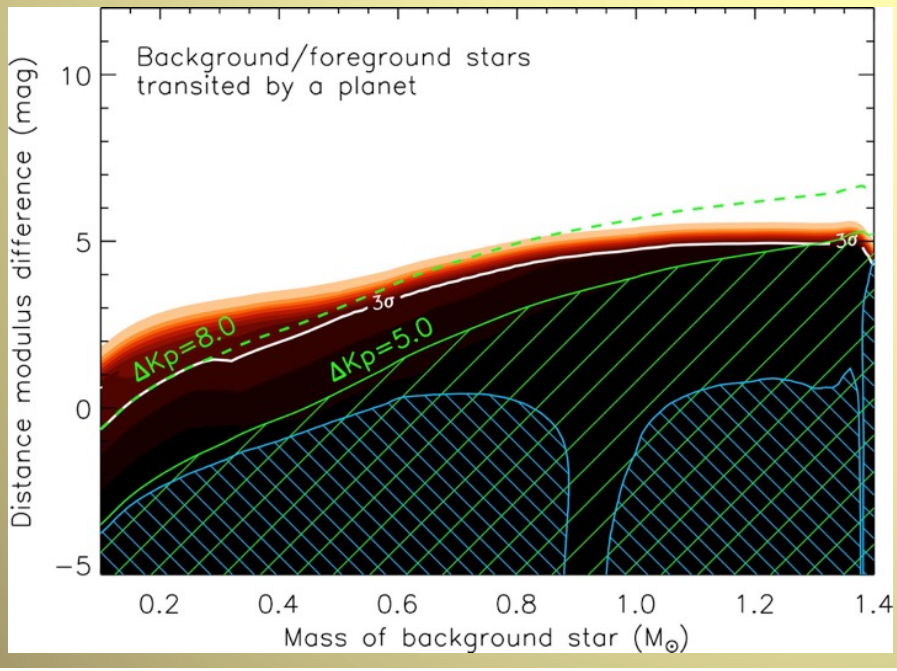
Kepler
A Search for Earth-size Planets

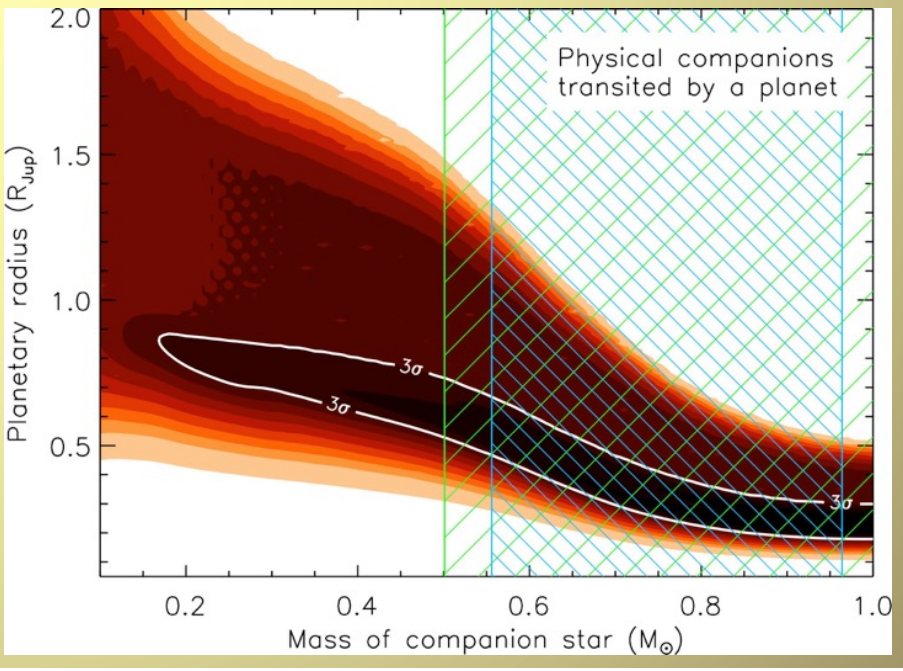
BEB odds: 1.21×10^{-12}
BP odds: 2.56×10^{-10}
HTP odds: 2.35×10^{-6}

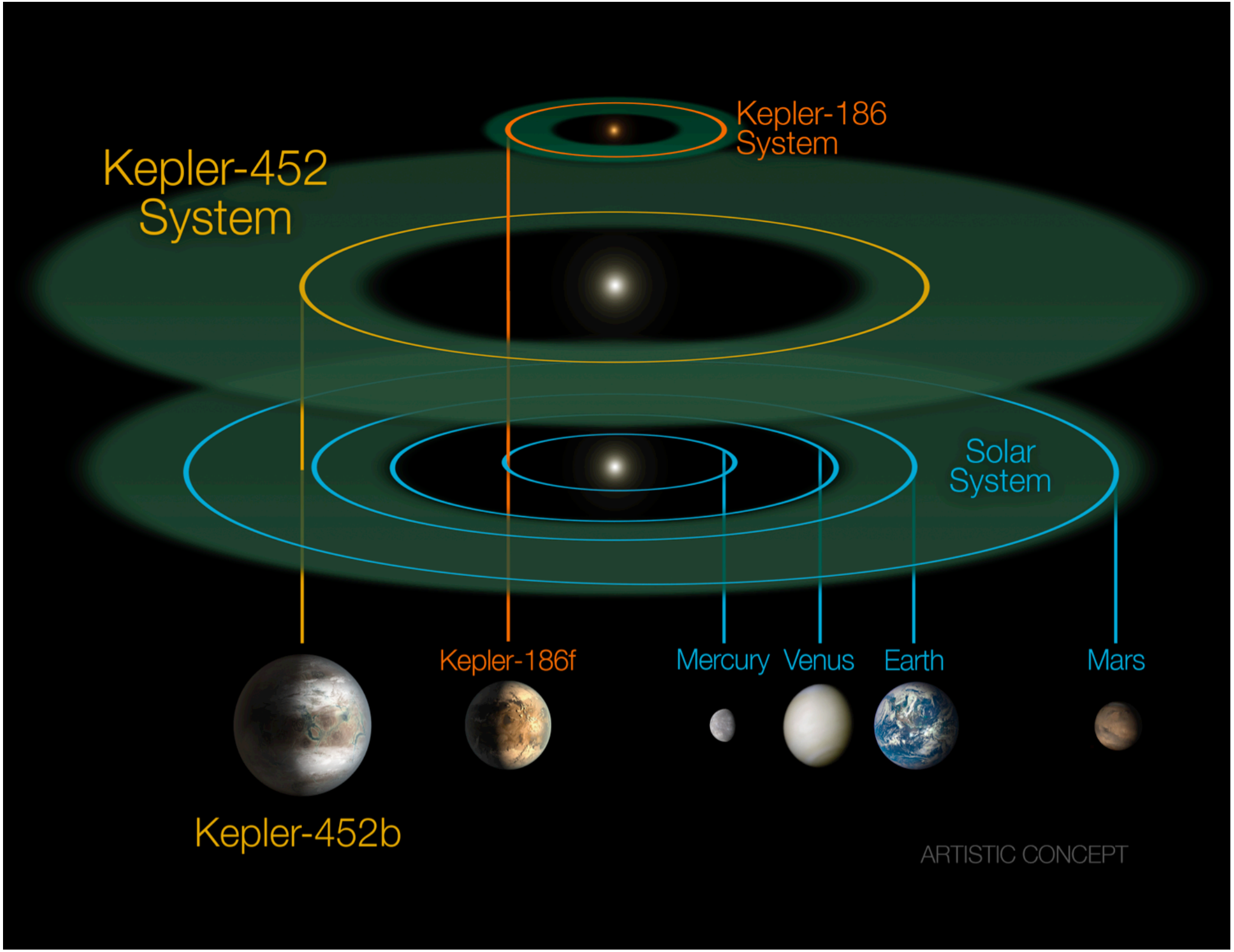
Vs: (Expected) Planet odds: 9.97×10^{-4}

Therefore, odds ratio is ~424:1

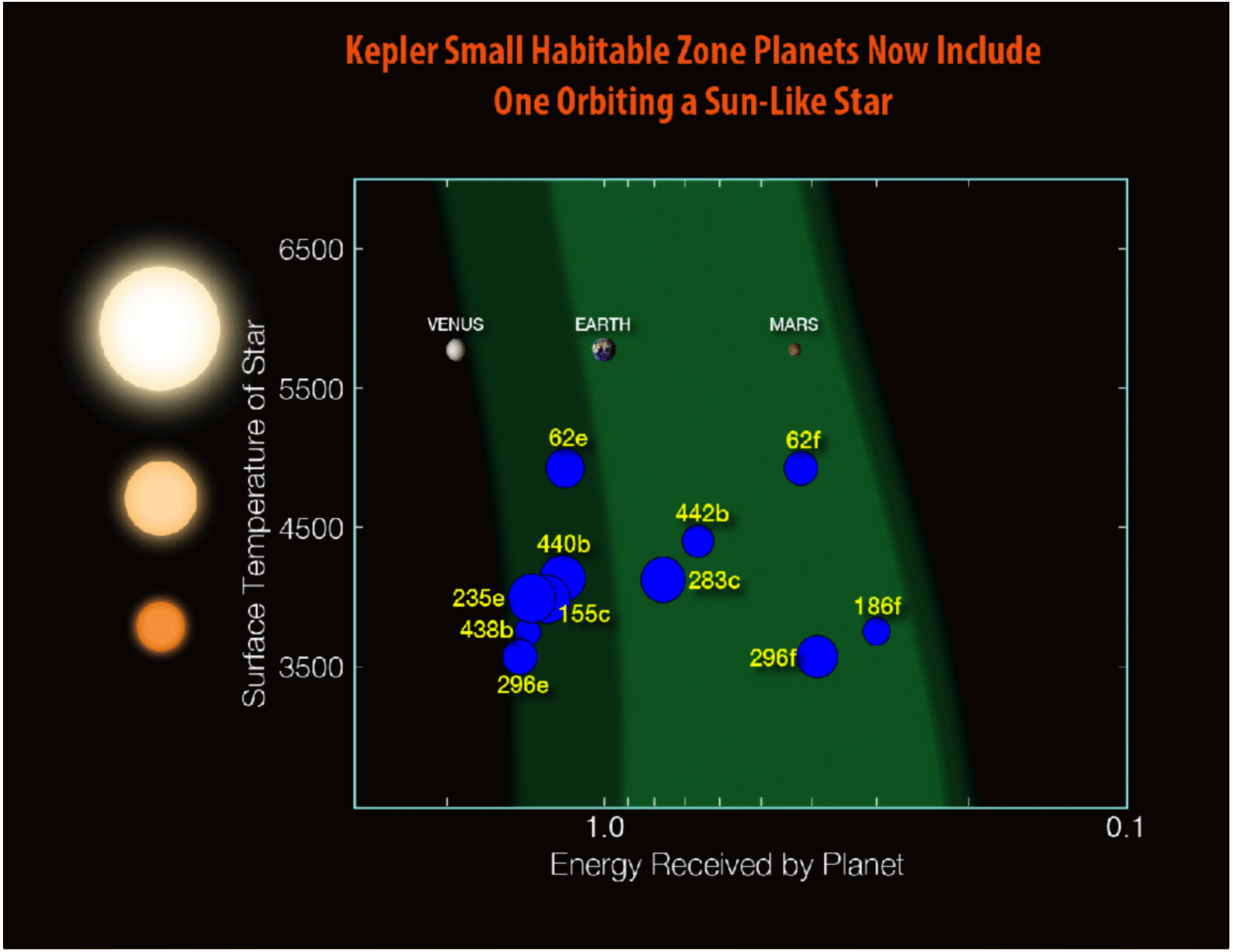







Kepler-452
System
Kepler-186
System
Solar
System
Kepler-452b
Kepler-186f
Mercury
Venus
Earth
Mars
ARTISTIC CONCEPT

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

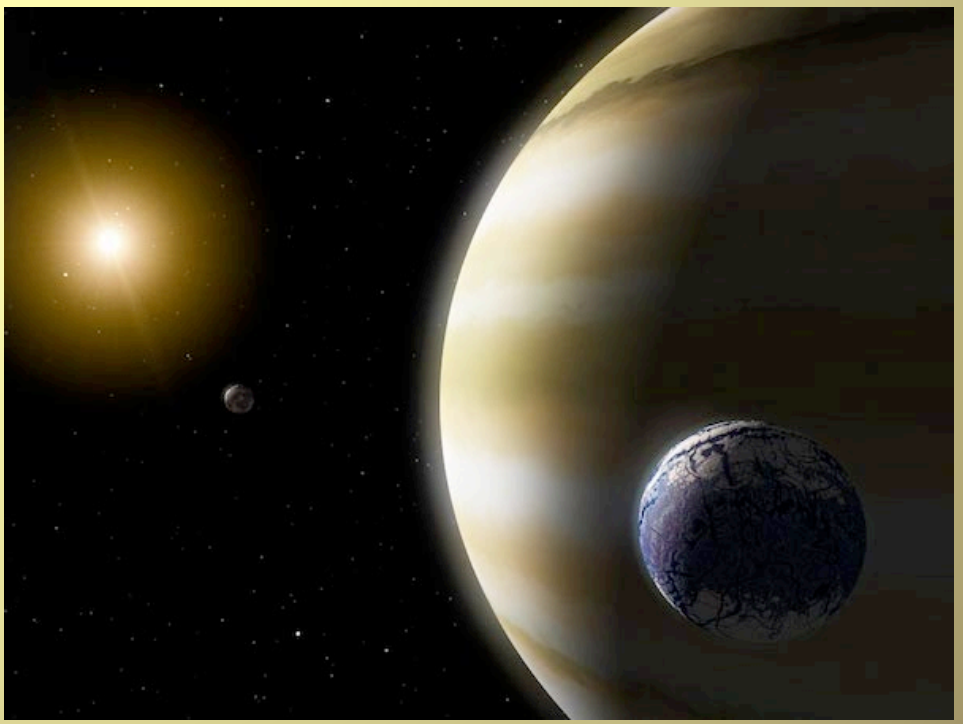
Each search consumes 50,000 CPU hours

~40 light curves were searched as of 2014

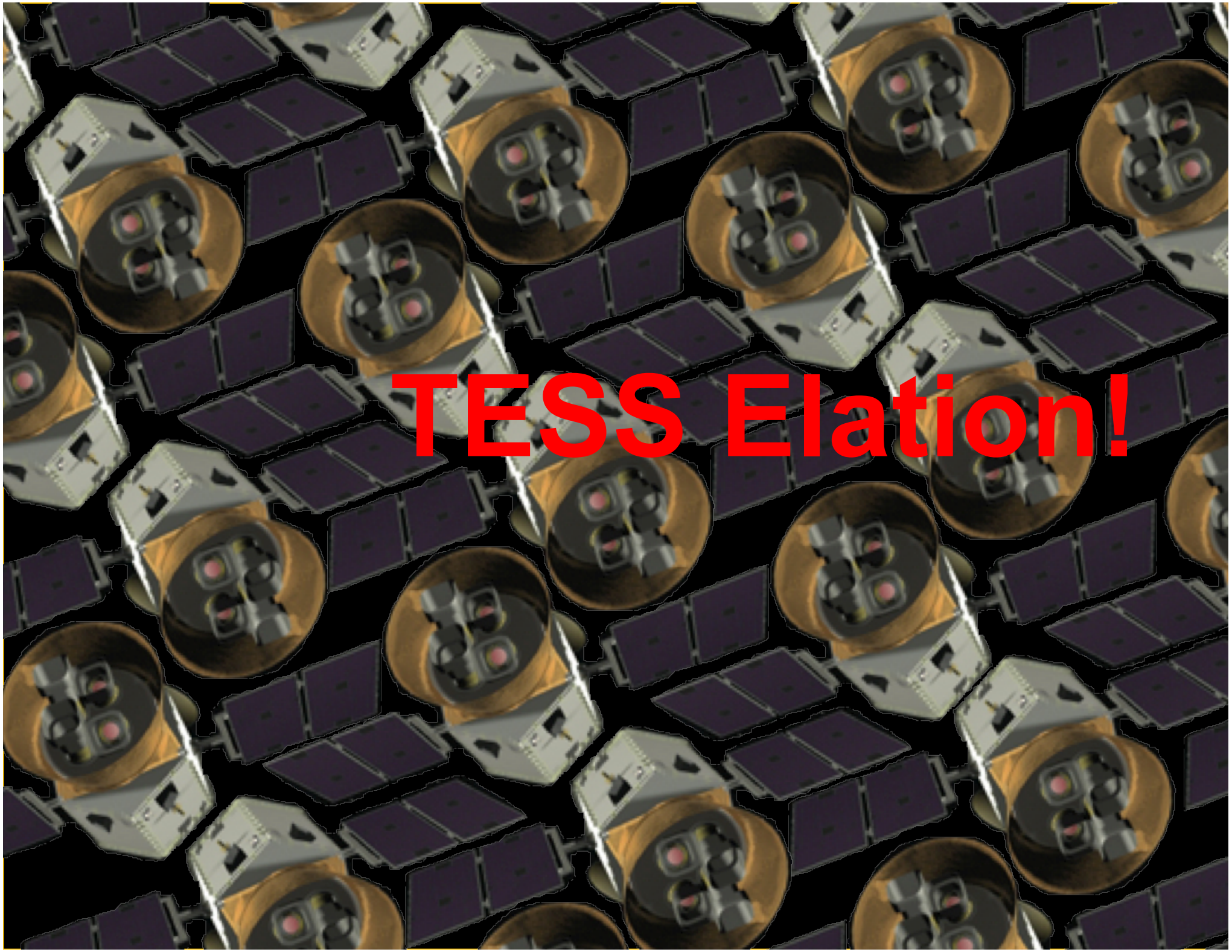
~300 were search in 2015

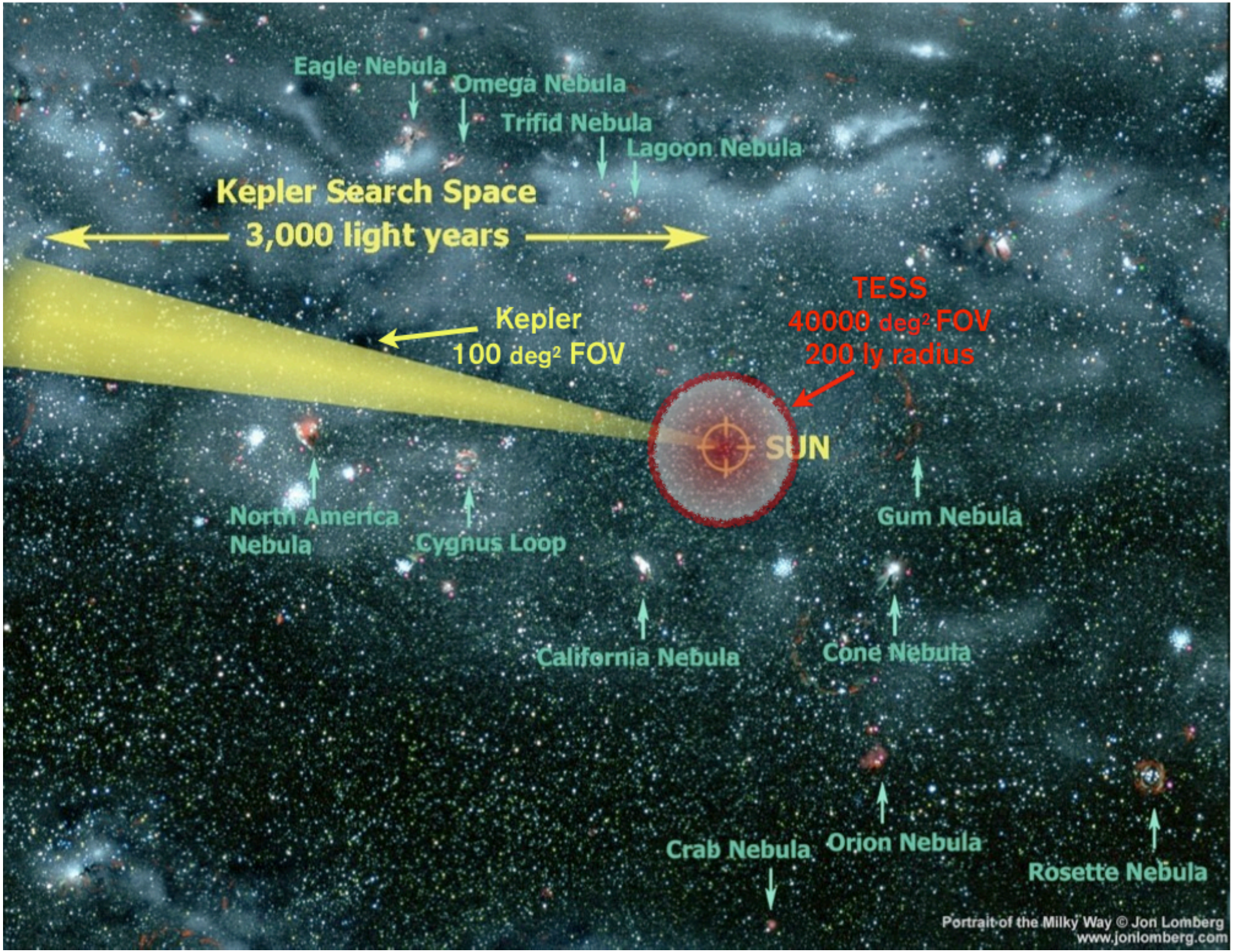
Exomoons remain elusive: None have been conclusively discovered

hek
The Hunt for Exomoons with Kepler



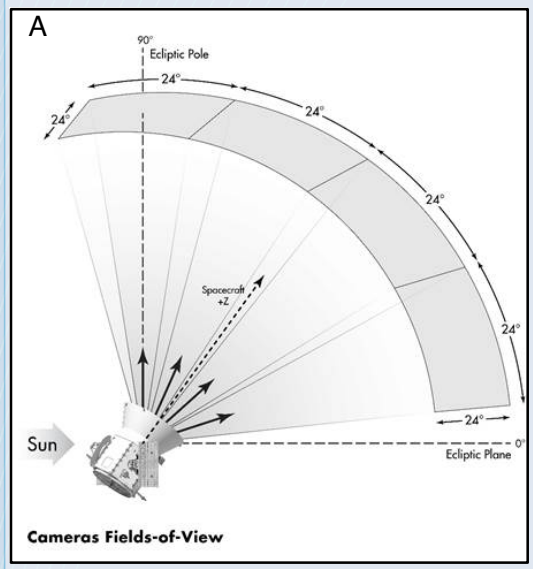
NASA JPL/Caltech

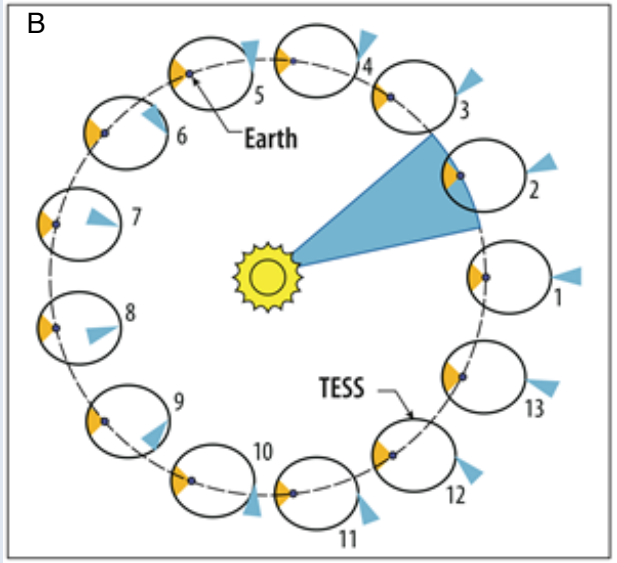

TESS Elation!

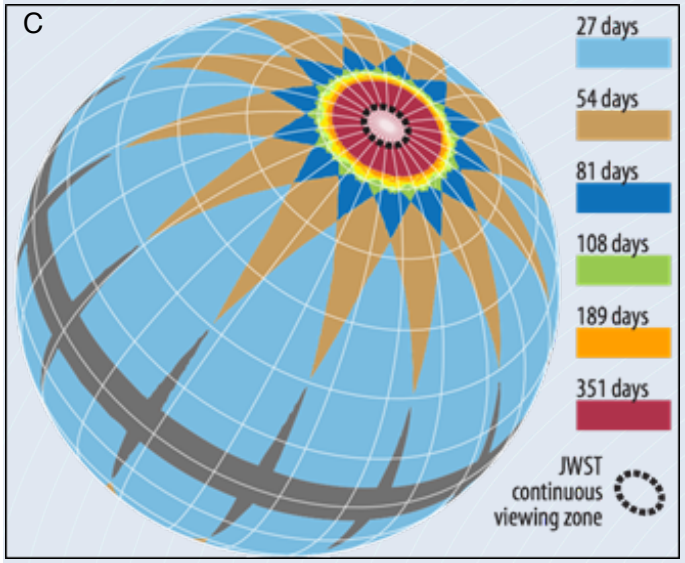

Eagle Nebula
Omega Nebula
Trifid Nebula
Lagoon Nebula
Kepler Search Space
3,000 light years
Kepler
100 deg² FOV
TESS
40000 deg² FOV
200 ly radius
SUN
North America Nebula
Cygnus Loop
Gum Nebula
California Nebula
Cone Nebula
Crab Nebula
Orion Nebula
Rosette Nebula
Portrait of the Milky Way © Jon Lomberg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

TESS Mission

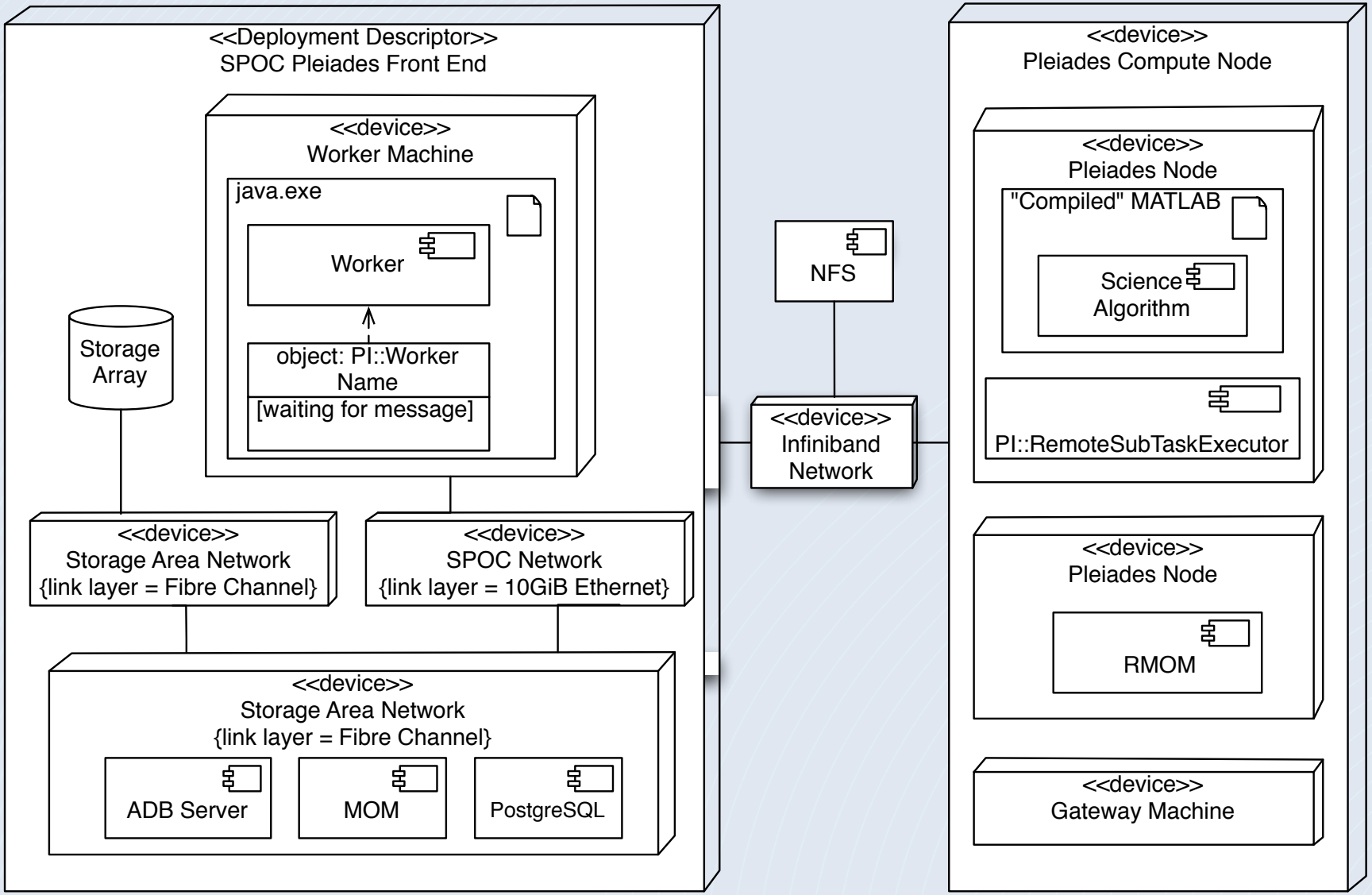
- All sky transit survey to find Earth's closest cousins
- 2 year primary mission
- Launch in December 2017 (tentative)
- TESS will identify best planets for follow up and characterization with James Webb and very large telescopes







- Processing TESS data on the NAS



Exoplanet Missions

JWST

WFIRST-AFTA

TESS

Kepler

New Worlds Telescope

Spitzer

Hubble

Ground-based Observatories

2001 Decadal Survey

2010 Decadal Survey

Conclusions

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