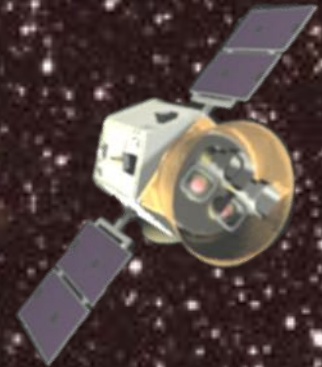
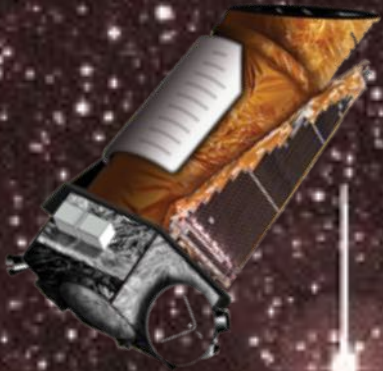


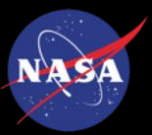
***Passing the Torch: Kepler's Amazing Discoveries Propel NASA's TESS Mission into Orbit to Search for Earth's Closest Cousins***

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

**Thursday May 20, 2019**

**Café Scientifique, Hana House Palo Alto CA**

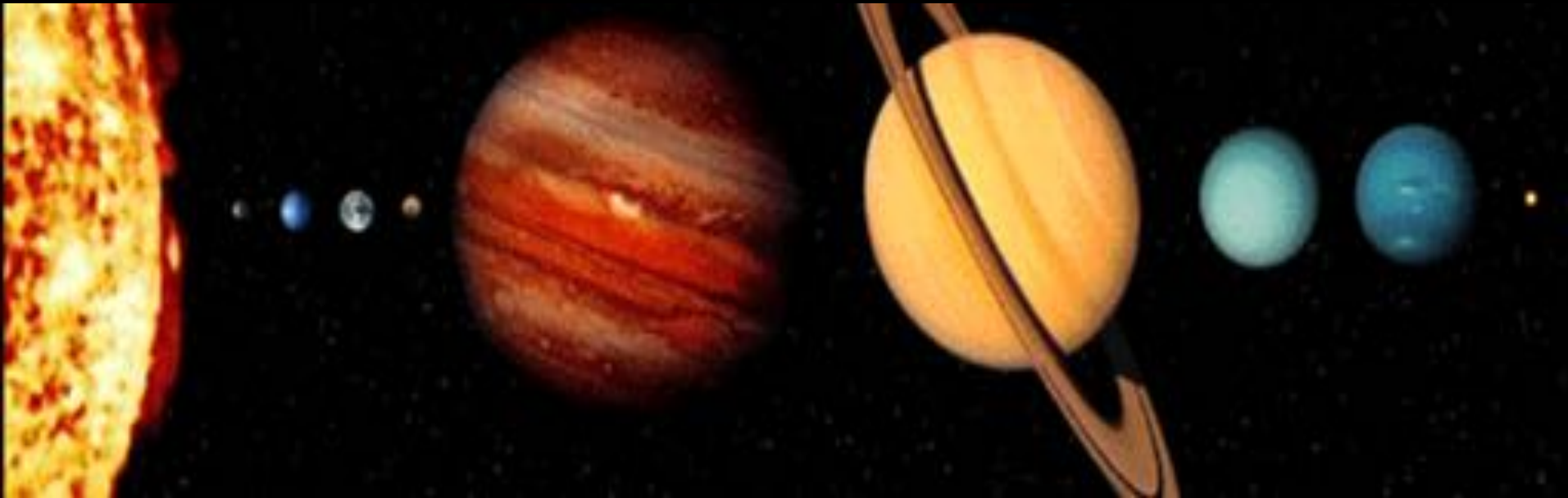




# All the Known Planets In 1994



*A Search for Habitable Planets*



What have we learned in the last 25 years?



# A More Recent Picture of Planets (from June 2012)



*A Search for Habitable Planets*







ALL 786 KNOWN  
**PLANETS**

(AS OF JUNE 2002)

**TO SCALE**

(SOME PLANET SIZES ESTIMATED BASED ON 1966)



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

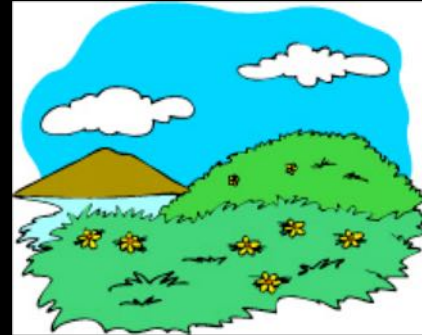


# What Does Habitable Mean To You?



*A Search for Habitable Planets*

- Right temperature
- Air
- Liquid water
- Light
- Radiation shield
- Asteroid protection

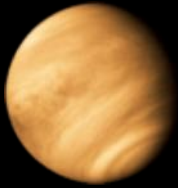




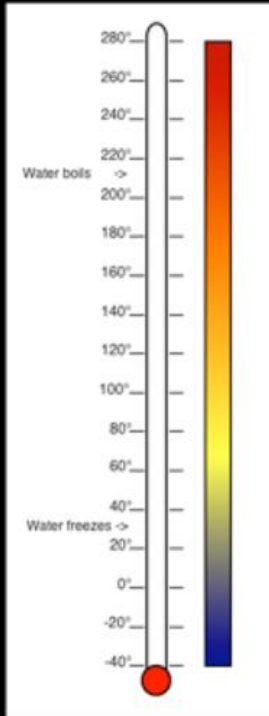
# The Goldilocks Zone



*A Search for Habitable Planets*



Venus: Way too hot!



Mars: Way too cold, and small!



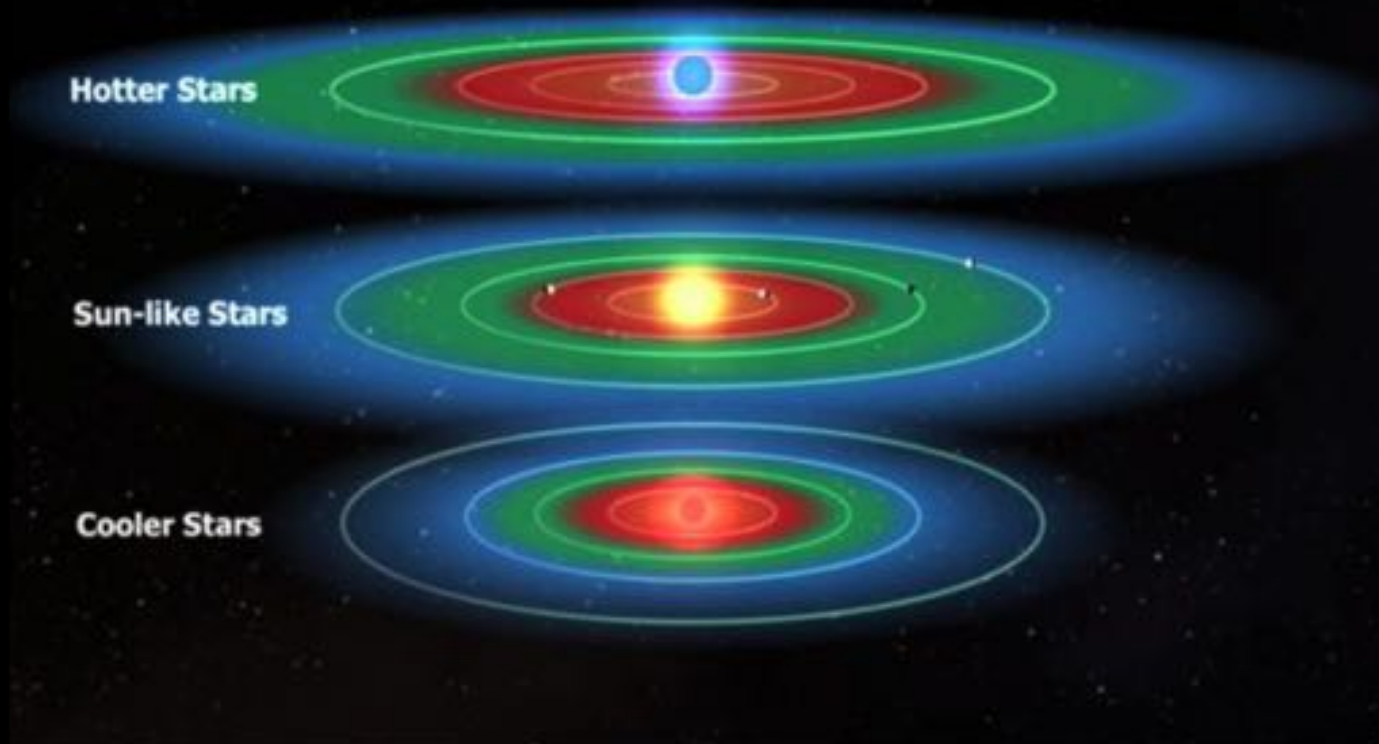
Earth: Just right!



# Habitable Zones



*A Search for Habitable Planets*

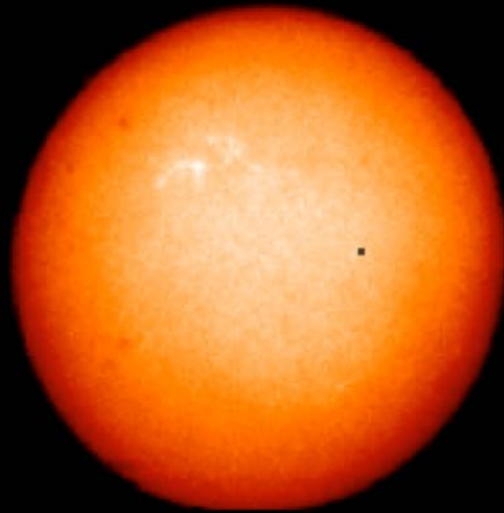




Stars are far away ...



*A Search for Habitable Planets*



Let's move this star away . . .

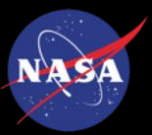




*Kepler*

*A Search for Habitable Planets*





*Kepler*

*A Search for Habitable Planets*

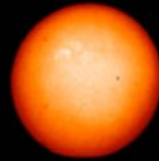


. . .and farther . . .



*Kepler*

*A Search for Habitable Planets*





*Kepler*

*A Search for Habitable Planets*





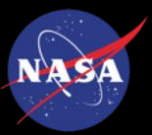


*Kepler*

*A Search for Habitable Planets*



. . .and farther



*Kepler*

*A Search for Habitable Planets*





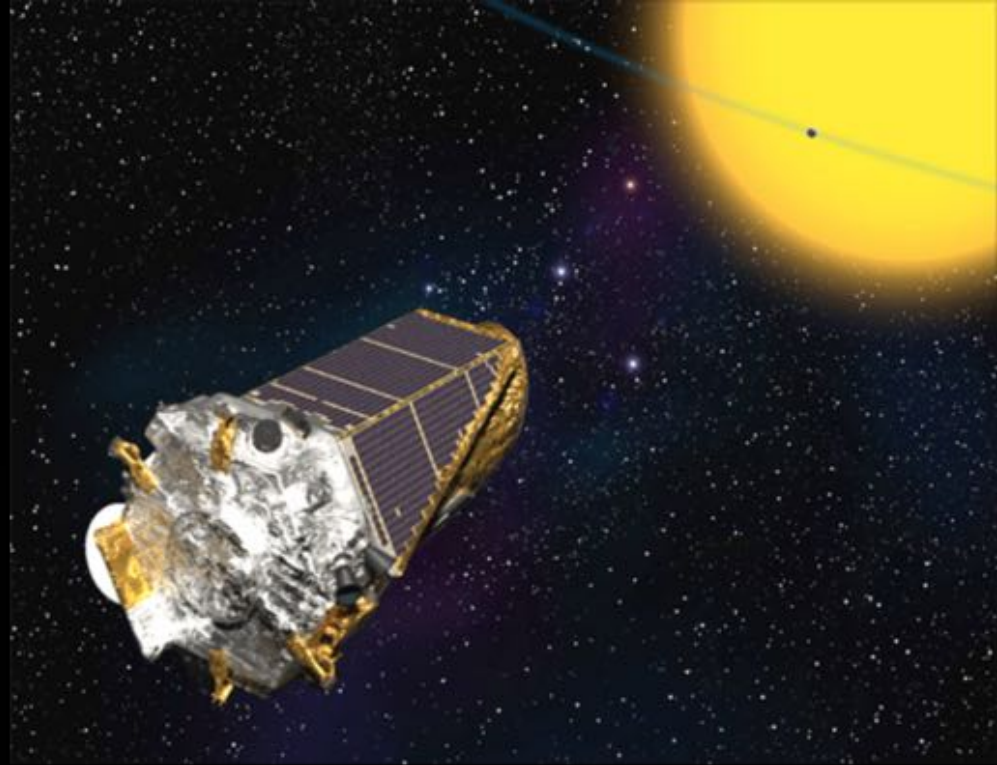
*Kepler*

*A Search for Habitable Planets*

Stars are very far away.  
We cannot see the planet cross in front of the star.

# The *Kepler* Mission

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



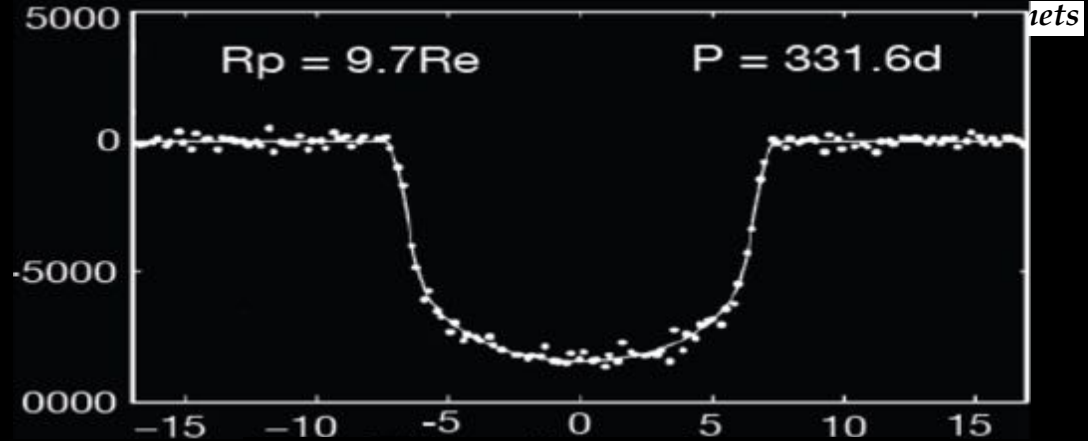




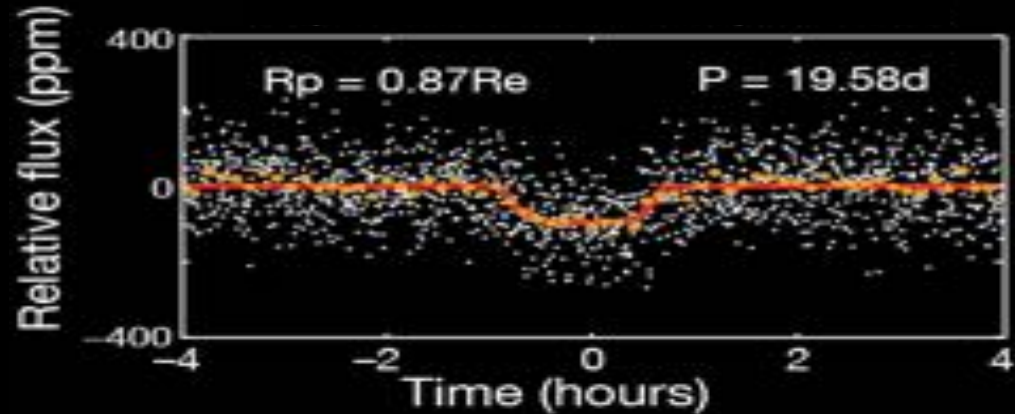
# How Hard is it to Find Good Planets?



Jupiter (~1%)



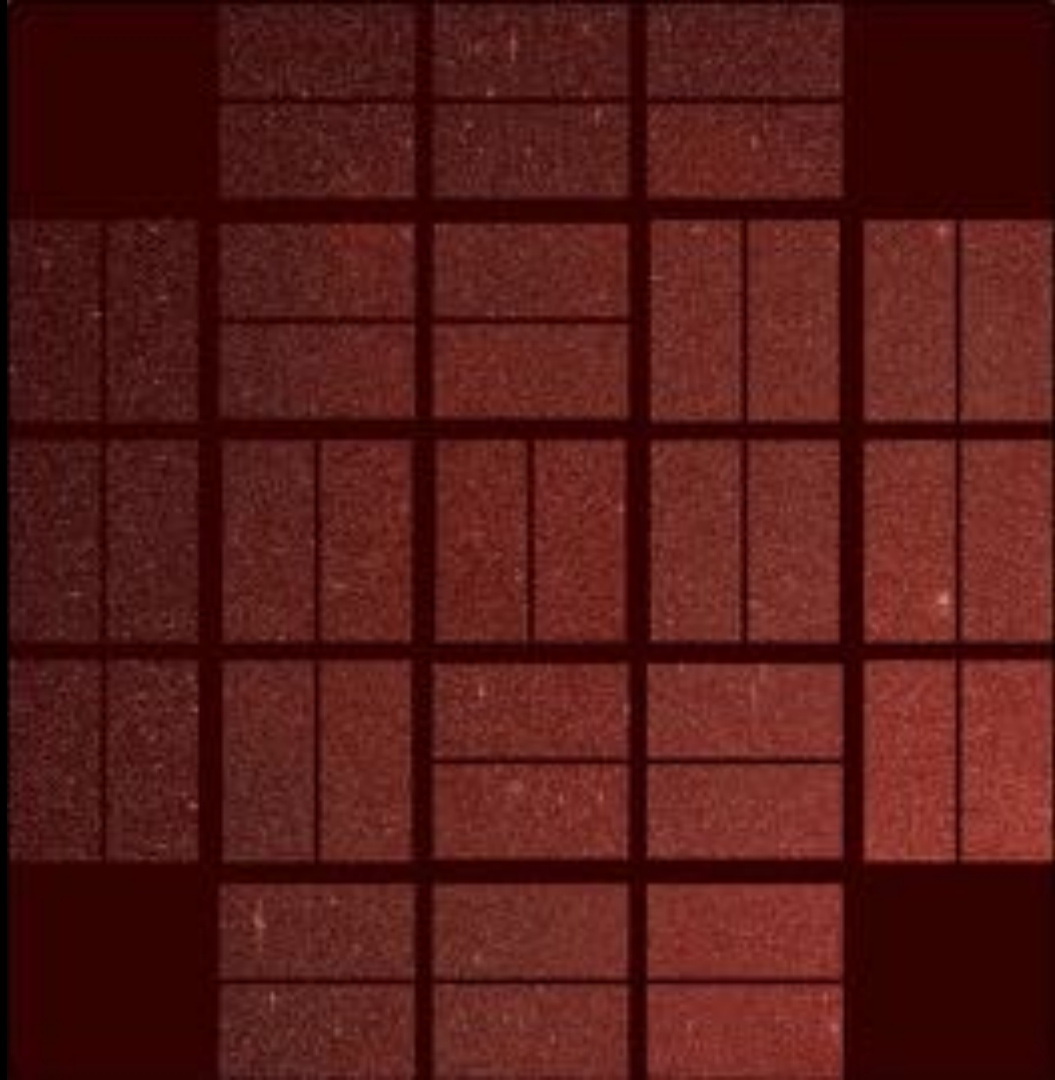
Earth (~0.01%)



# First Light Image



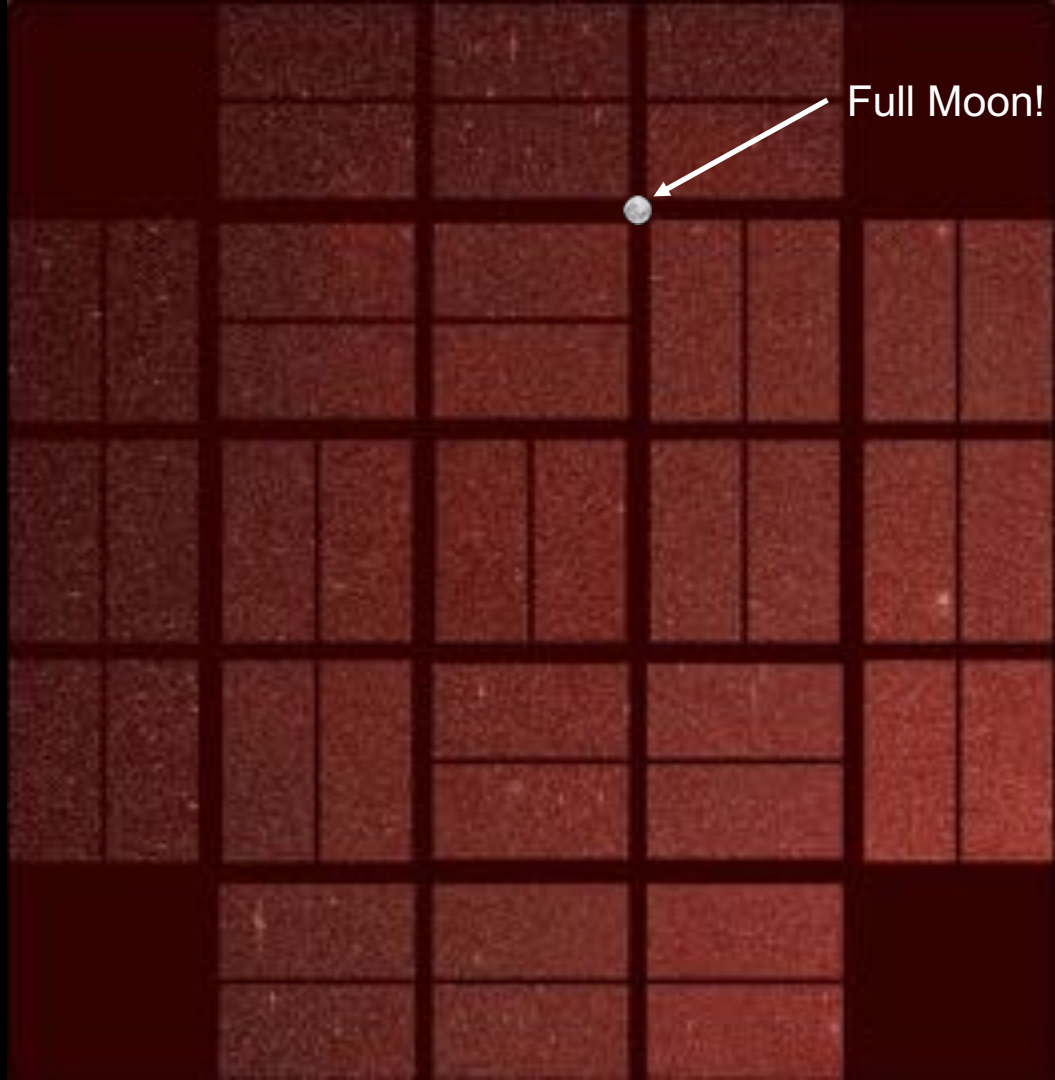
Launched  
March 7 2009



First Light Image



Launched  
March 7 2009



Full Moon!



# Launch Party



*A Search for Habitable Planets*

*Kepler generated a lot of interest*





# Kepler

BY THE NUMBERS

What did *Kepler* Discover?



**9.6** YEARS IN SPACE



**530,506**  
STARS OBSERVED



**2,662**  
PLANETS CONFIRMED



**61** SUPERNOVAE DOCUMENTED

FROM EARLIEST STAGES OF EXPLOSION



**2** MISSIONS COMPLETED

**678 GB** SCIENCE DATA COLLECTED



**2,946** SCIENTIFIC PAPERS PUBLISHED

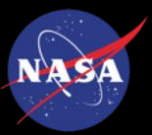
**732,128**  
COMMANDS EXECUTED

**94** MILLION MILES AWAY



**3.12** GALLONS FUEL USED



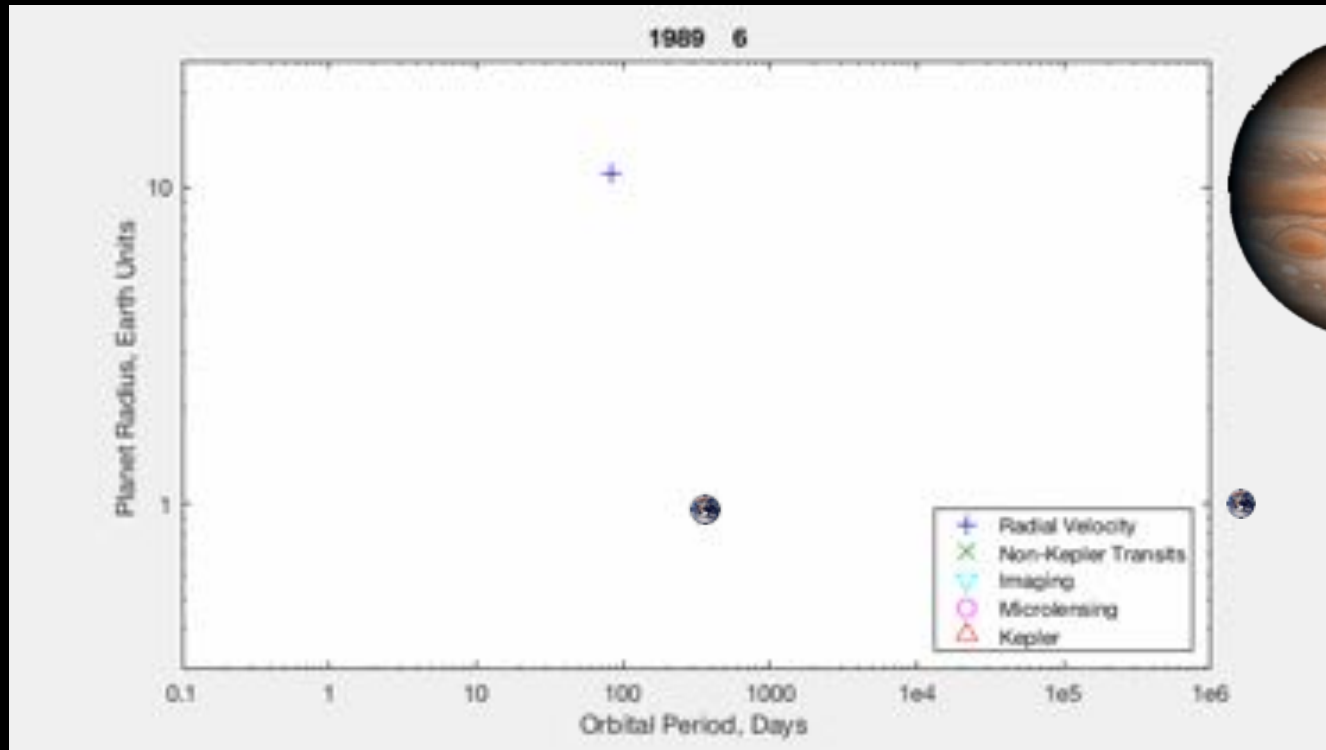


# Exoplanet Discoveries Over Time\*



*A Search for Habitable Planets*

Kepler+K2: 2713  
Other Transit: 366  
RV: 755  
Imaging: 40  
Microlensing: 75  
TESS: 20  
TOTAL: 4003



Radii estimated for non-transiting exoplanets  
Discovery data dithered slightly

\*According to <https://exoplanetarchive.ipac.caltech.edu> as of 9/20/19



# Kepler-20



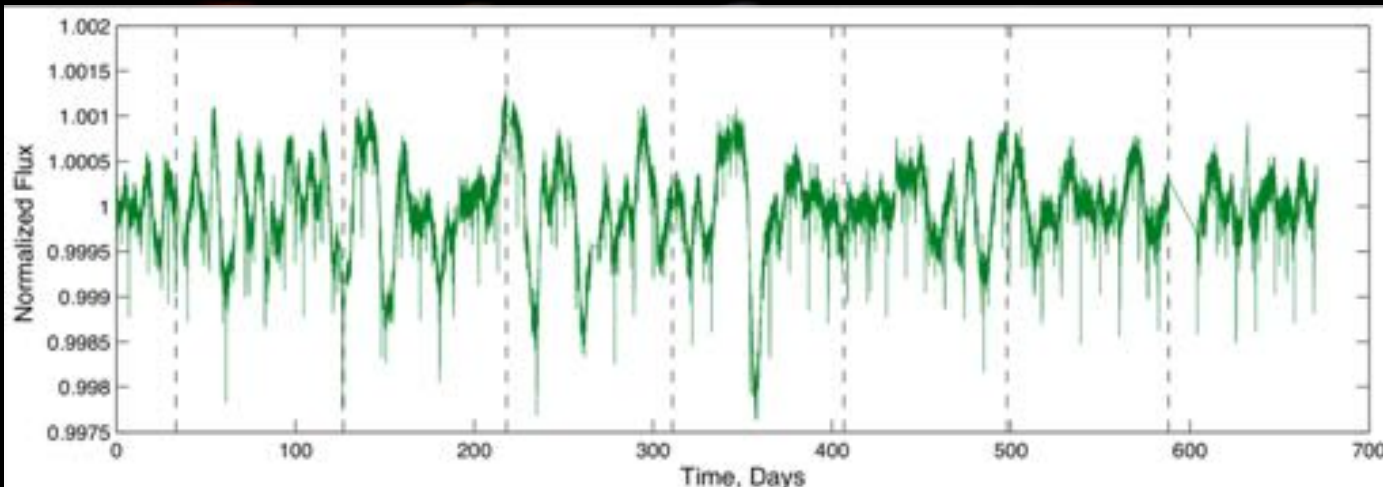
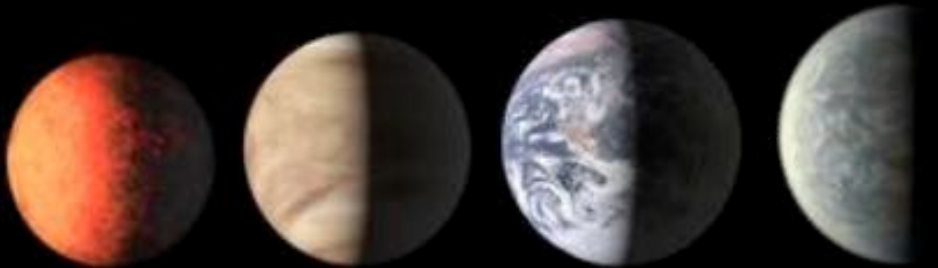
*A Search for Habitable Planets*

Kepler-20e

Venus

Earth

Kepler-20f





## Circumbinary Planets:



## Kepler 35



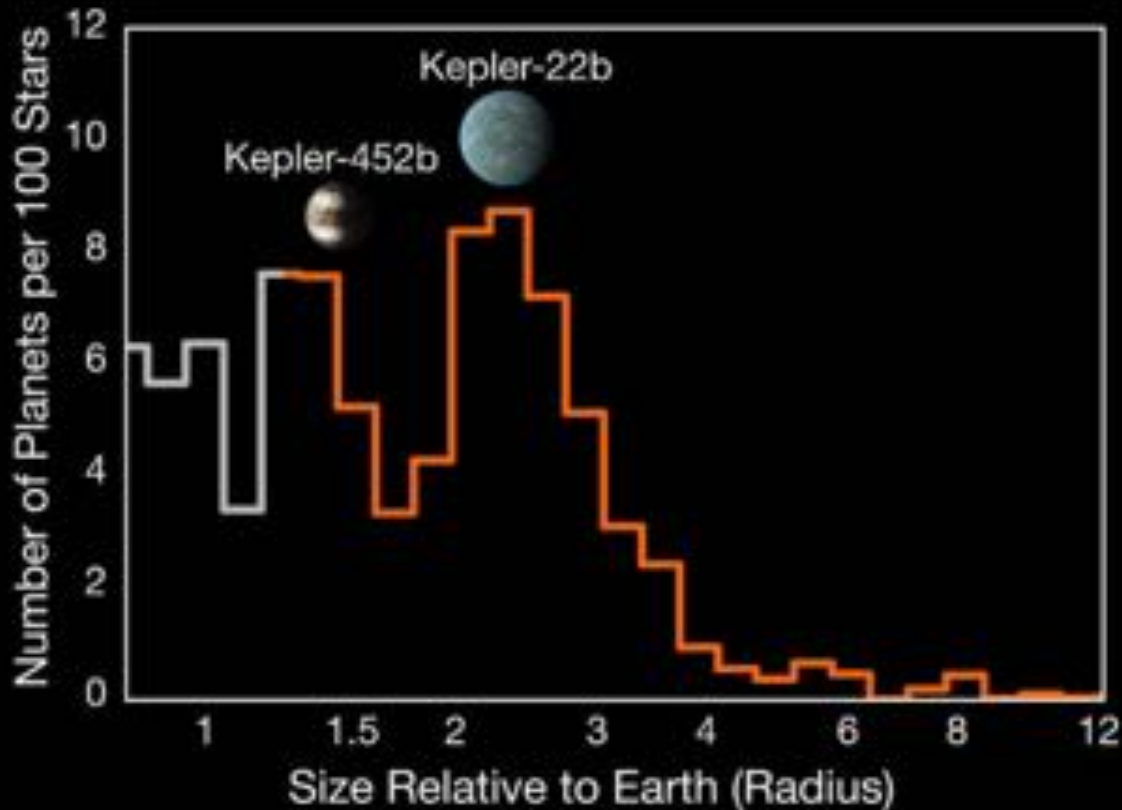


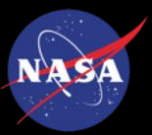


# Small Planets Come in Two Sizes



*A Search for Habitable Planets*





# Kepler and Asteroseismology



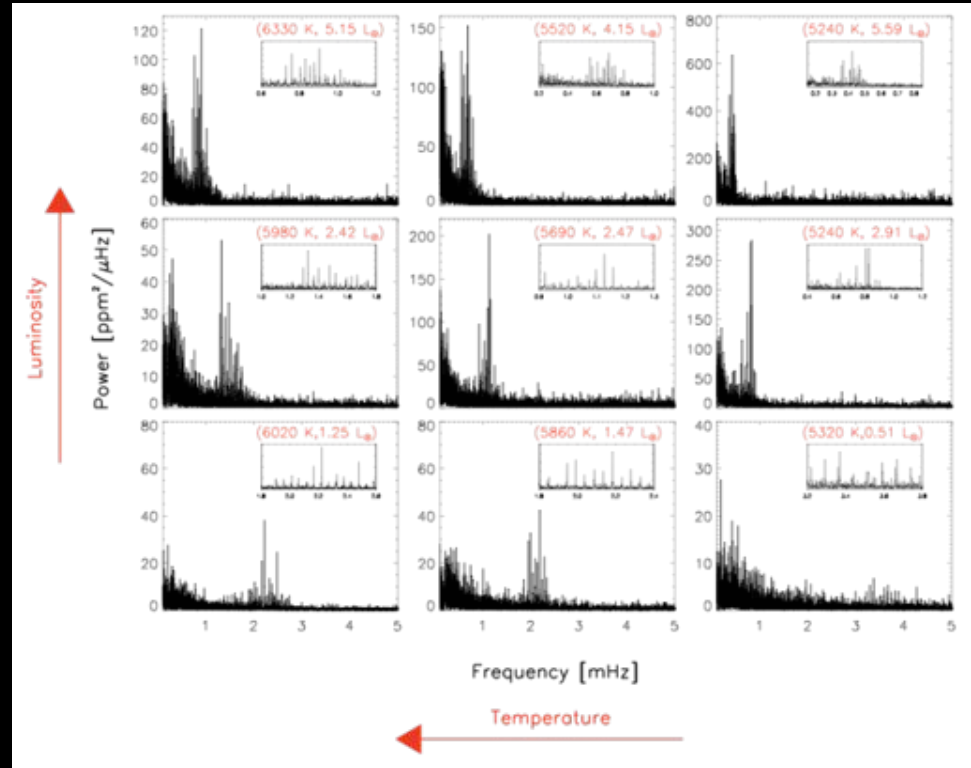
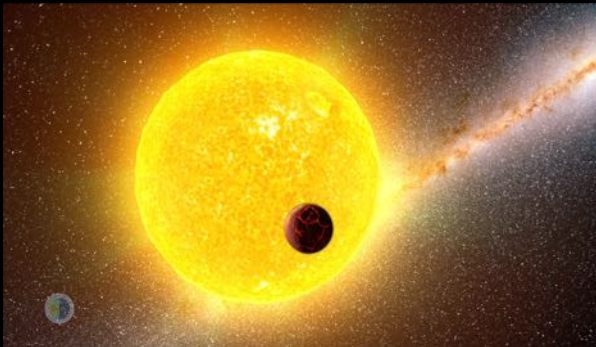
A Search for Habitable Planets

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

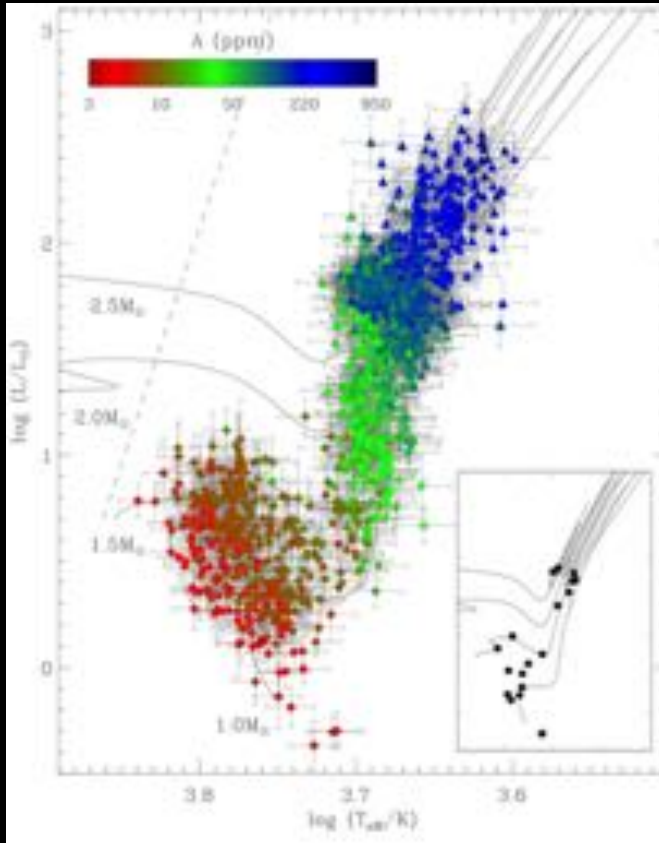




# Kepler Revolutionized Asteroseismology

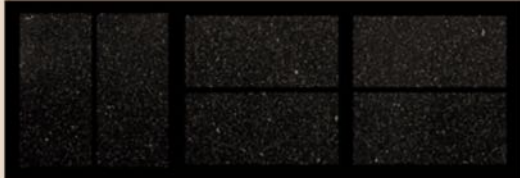


A Search for Habitable Planets



JEFF TALMAN STUDIO - NEW YORK  
*a pioneer of the use of resonance in artworks... Inute, Oxford University*

Berghof Gibacht, Waldmünchen, Germany presents



NATURE OF THE NIGHT SKY (2011)  
Bavarian Forest Sound Installation, May 7 - Sept 18



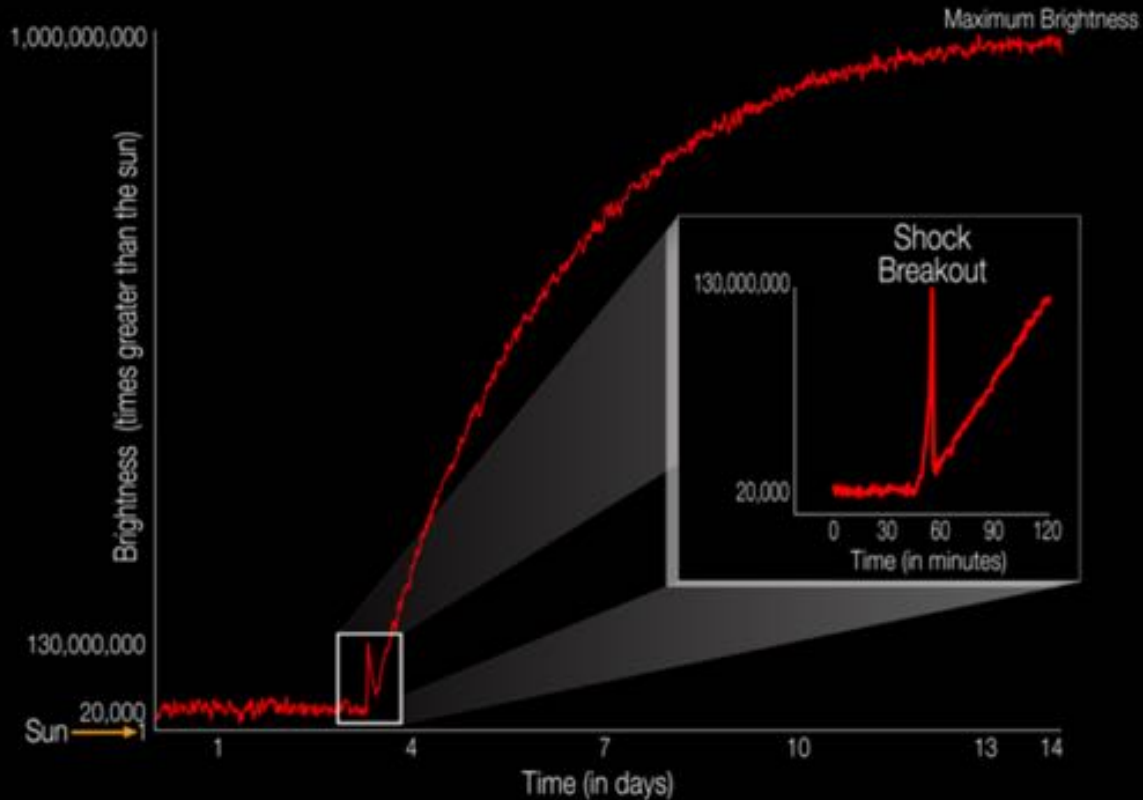
Kepler measured p-mode oscillations for over 15000 stars!



# Shock Breakout of KSN 2011d



*A Search for Habitable Planets*

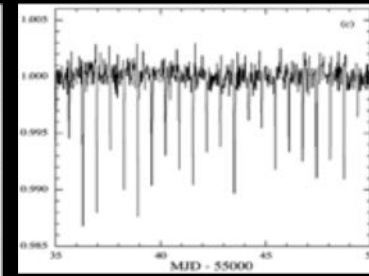
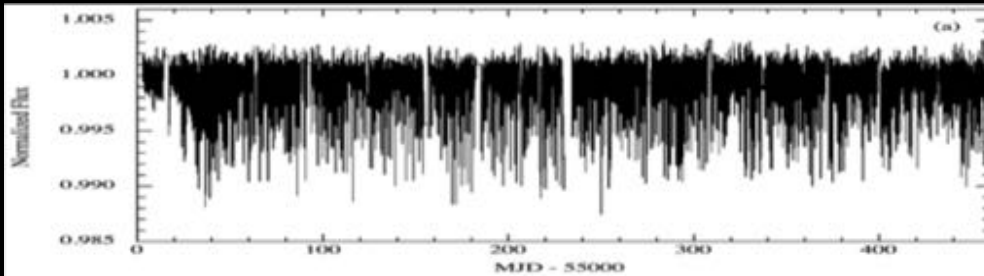
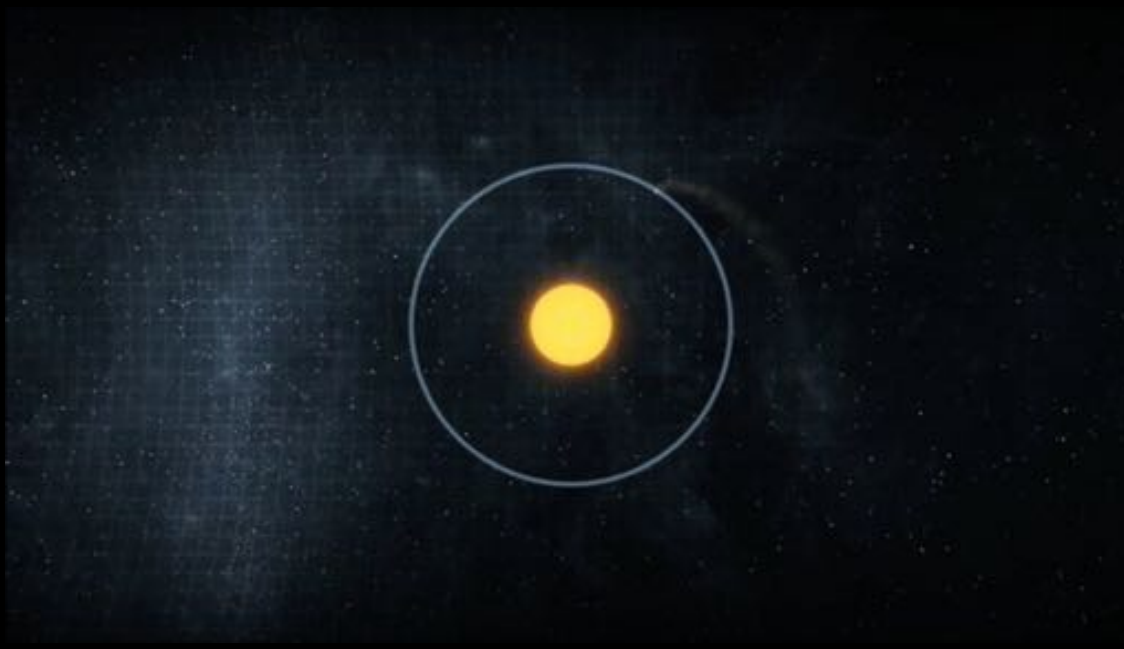




# A Disintegrating Sub-Mercury-Size Planet



Search for Habitable Planets



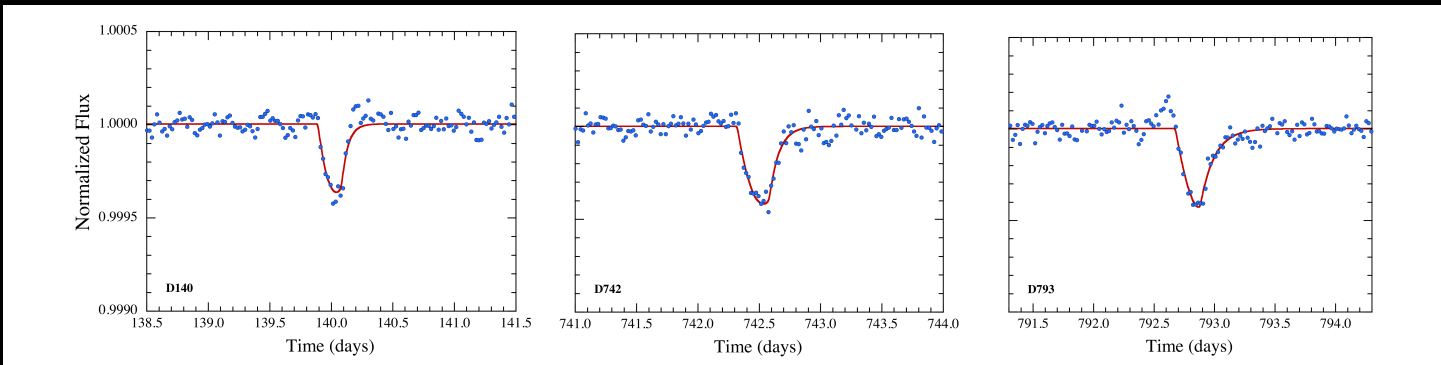
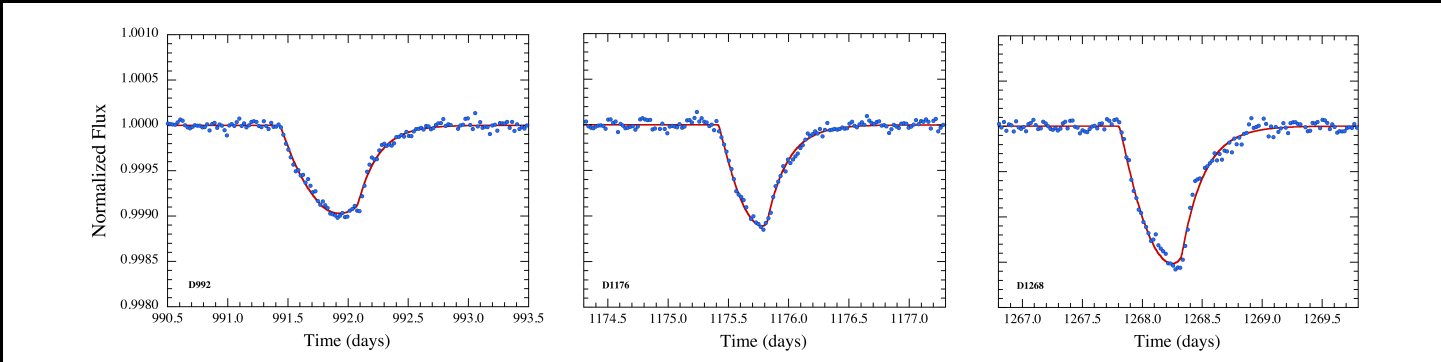


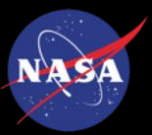


# KIC 3542116: An Exocomet Candidate



*A Search for Habitable Planets*

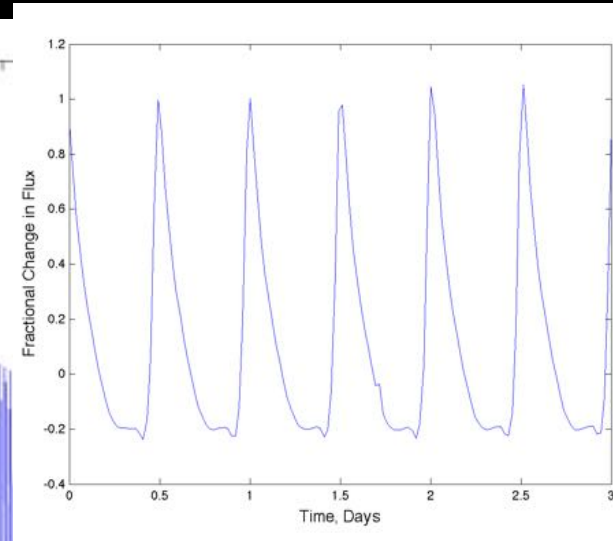
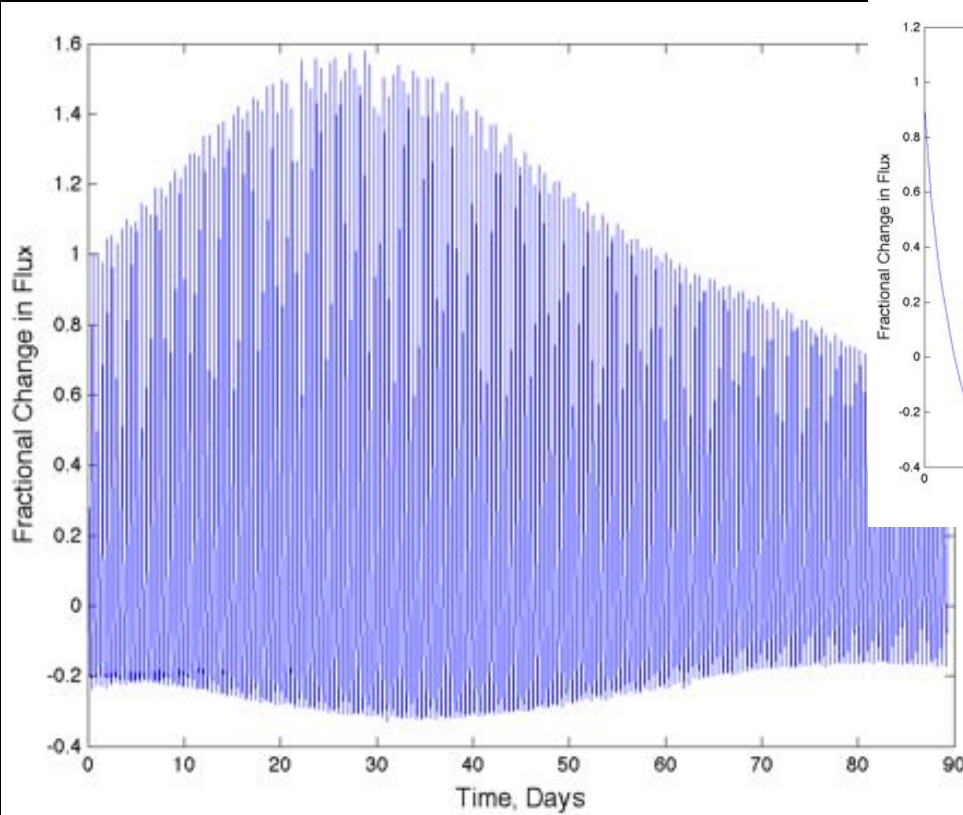




# An RR Lyra Star



*A Search for Habitable Planets*

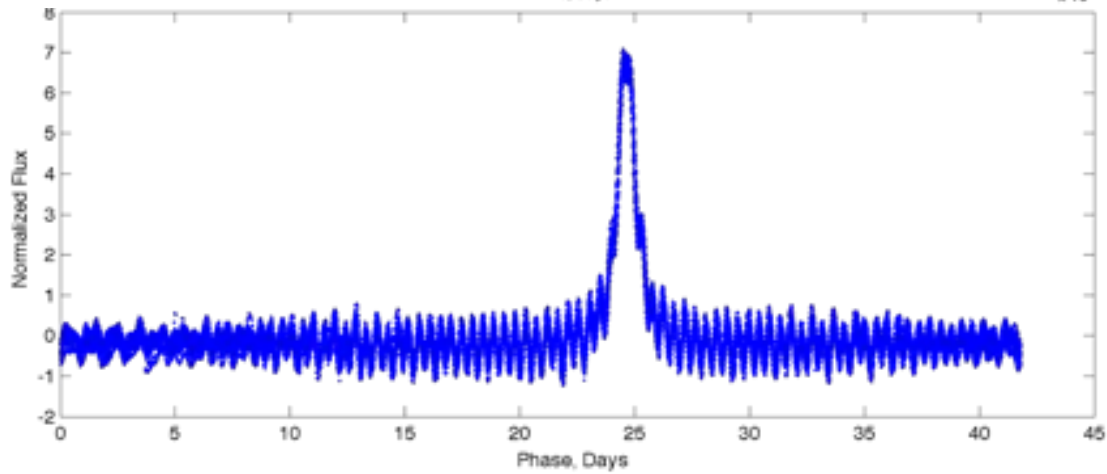
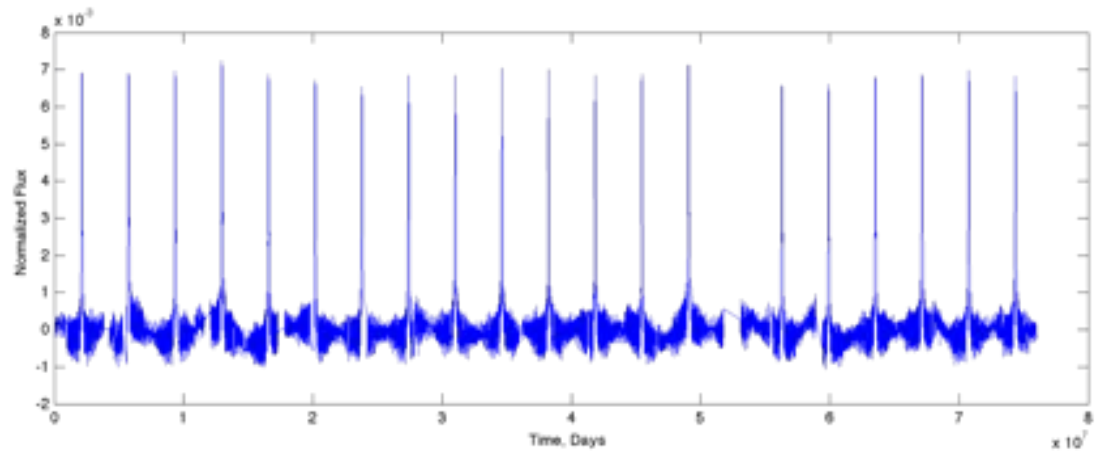




# Heartbeat Stars: KOI-54



*Habitable Planets*





# Multiple Transiting Planet Systems

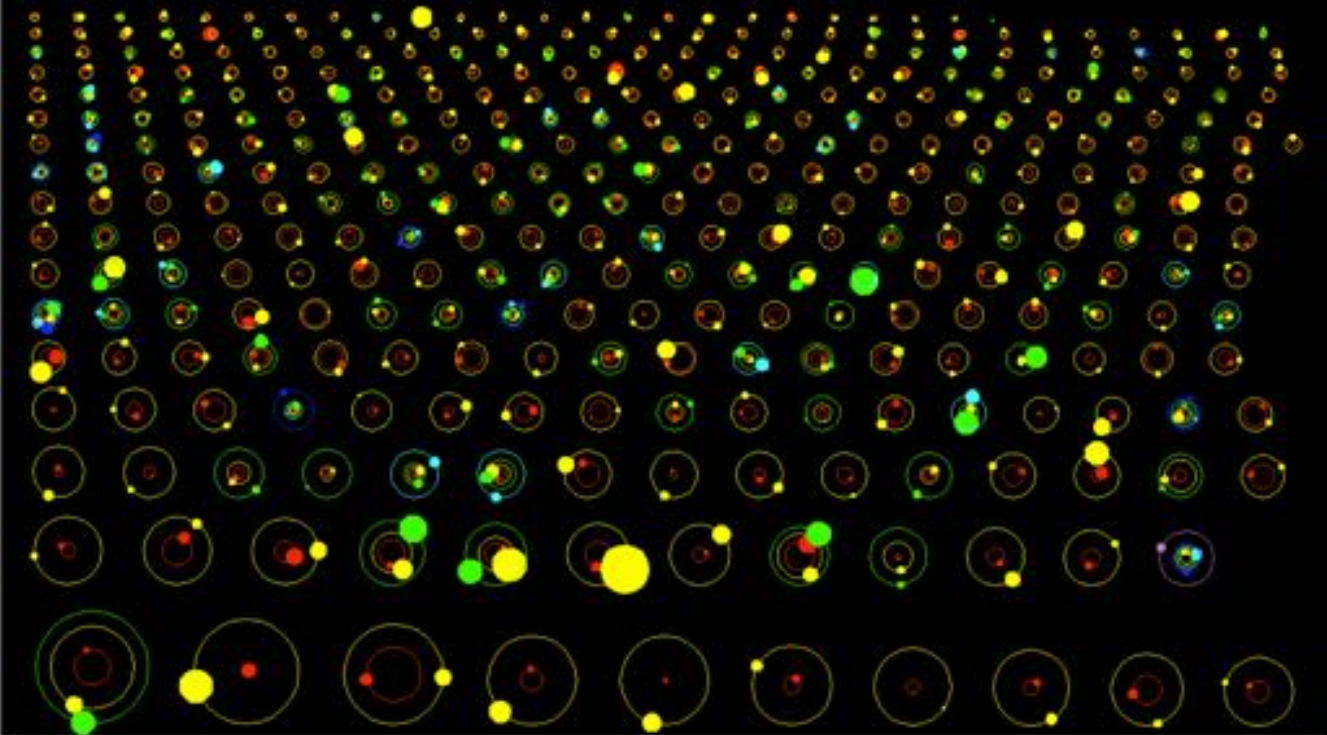


*A Search for Habitable Planets*

## The Kepler Orrery II

t[BJD] = 2454965

D. Fabrycky 2012



Kepler discovered over 500 multiple transiting planet systems!



# Kepler Science Operations Center Architecture



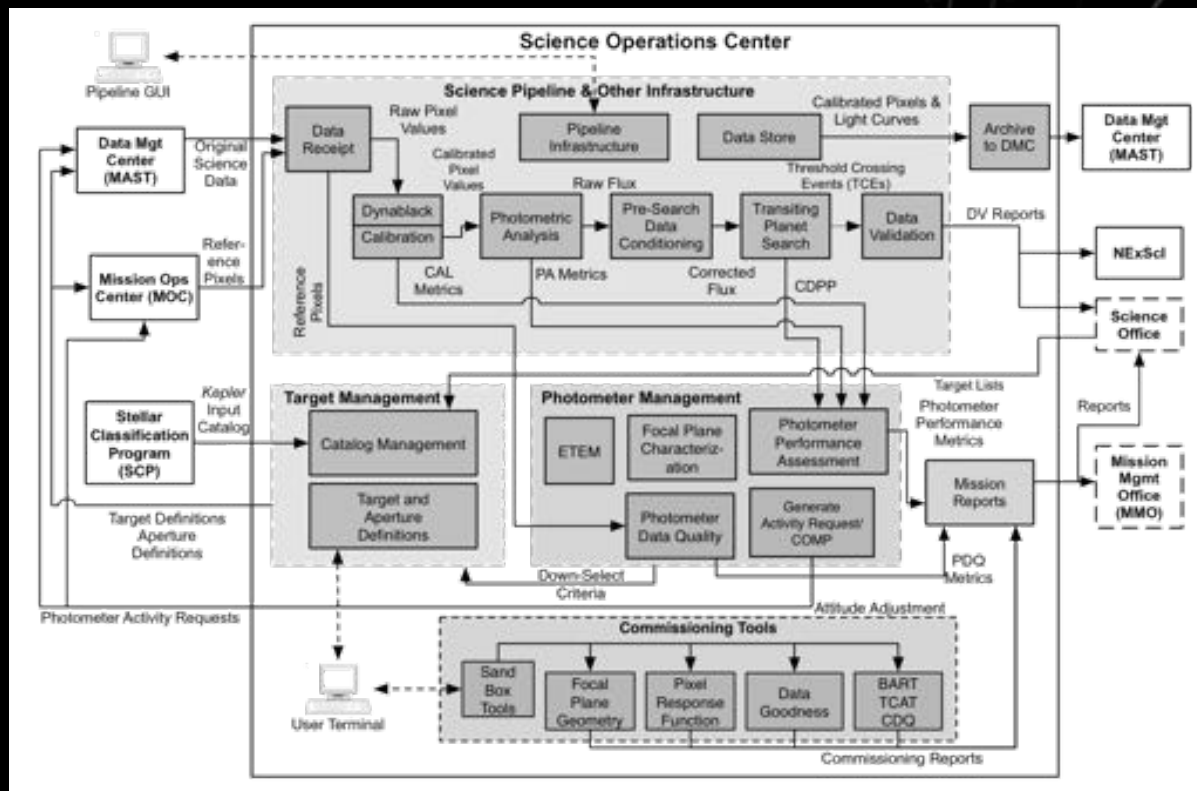
>1,000,000 Lines of Code

26 different Modules

Pipeline can be run on a laptop, workstation, cluster, or supercomputer

Time series photometry is extremely computationally intensive

The SOC was awarded the 2010 NASA Software of the Year Award



The complexity of the Kepler science pipeline and data volume forced us to innovate



# The Search Problem







# The Search Problem





# The Search Problem





# Keeping Up with the Data





# HARDWARE ARCHITECTURE: KEPLER SCIENCE OPERATIONS CENTER



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

**It took 10 months to reprocess 2 years of data on this hardware**





# HARDWARE ARCHITECTURE: NAS PLEIADES SUPERCOMPUTER

**245,536 CPU cores**

**935 TB of memory**

**29 PB of storage**

160 racks (11,440 nodes)

7.24 Pflop/s peak cluster

5.95 Pflop/s LINPACK rating

175 Tflop/s HPCG rating

2 racks (64 nodes)  
enhanced with  
NVIDIA GPUs

184,320 CUDA cores

0.275 Pflop/s total



Kepler used up to 20,000 CPUS on the NAS



Transiting Planet Search Running on Pleiades

The NAS Pleiades supercomputer allowed us to reprocess 4 years of data in a few months

*Kepler* taught us that planets are everywhere!

What next?







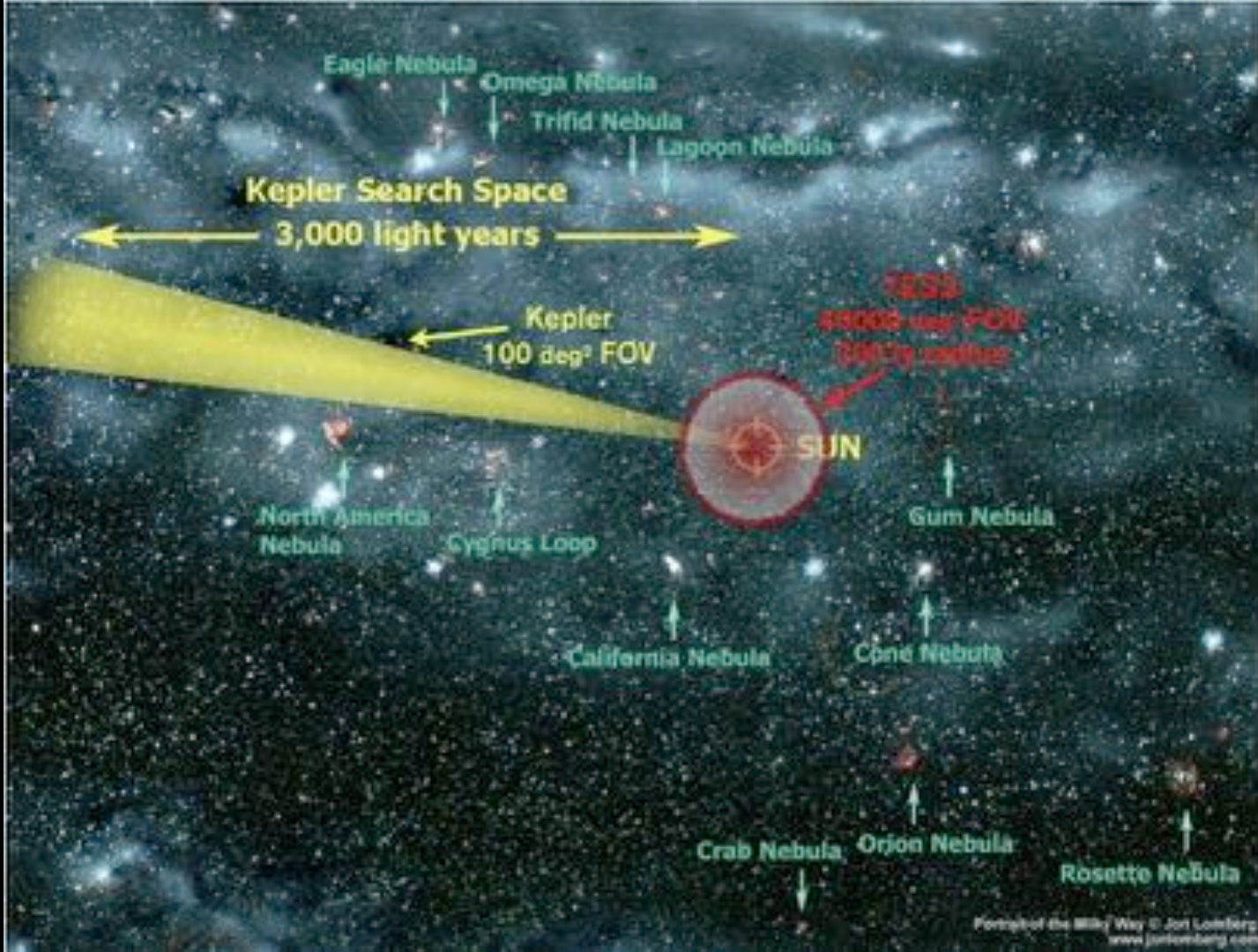
# TRANSITING EXOPLANET SURVEY SATELLITE

*DISCOVERING NEW EARTHS AND SUPER-EARTHS  
IN THE SOLAR NEIGHBORHOOD*

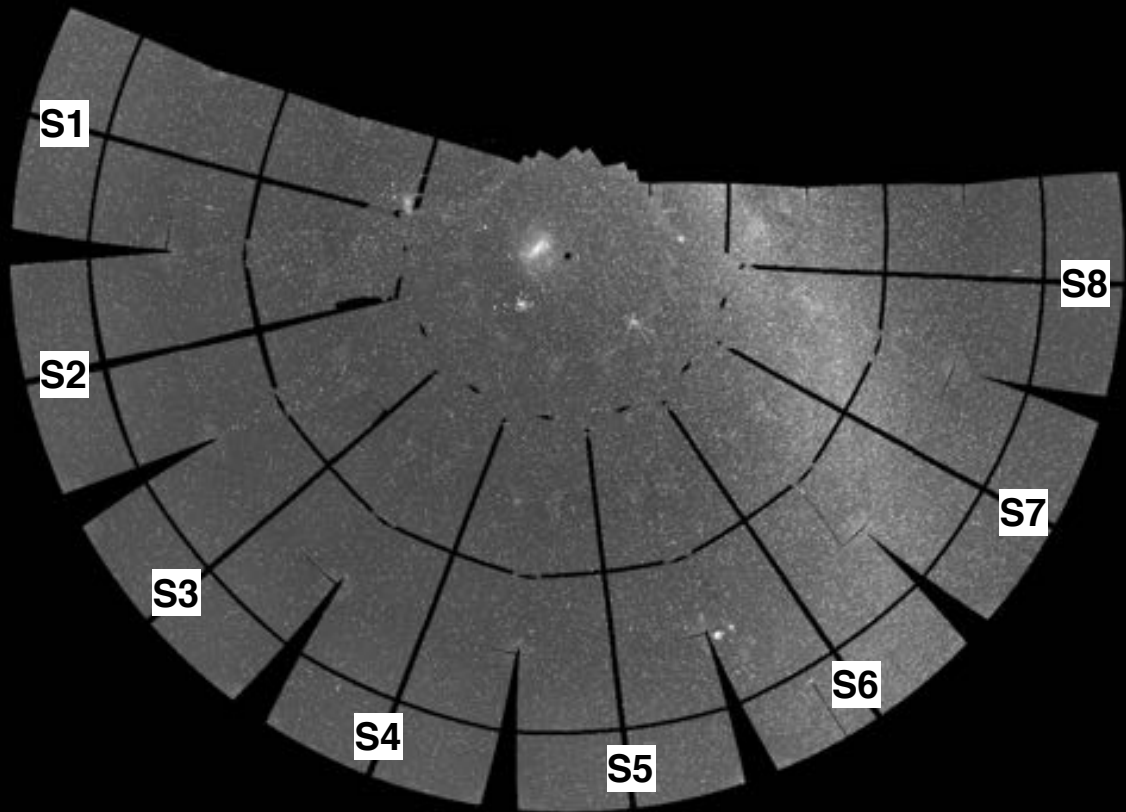
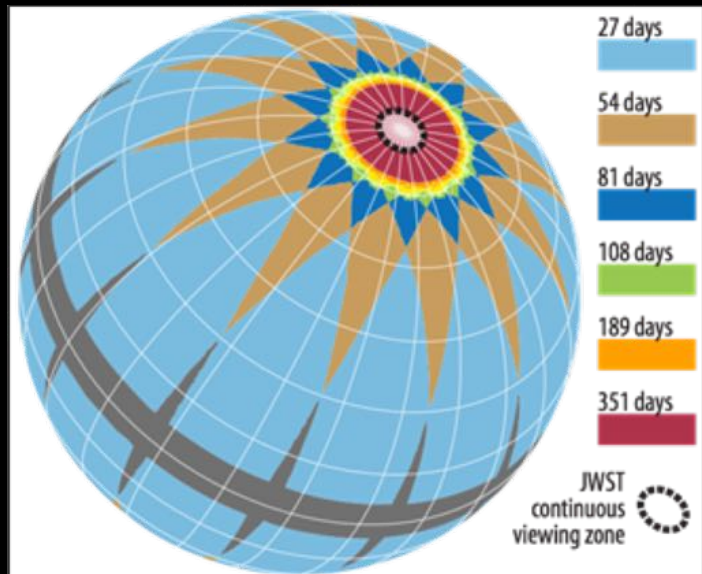
*TESS Launches April 18 2018*







# TESS Sky Coverage



The first eight sectors...



# TESS

Transiting Exoplanet  
Survey Satellite



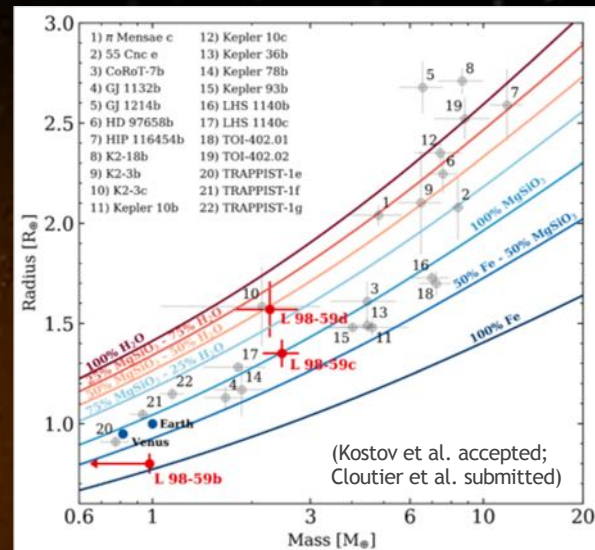
685 planet candidates  
15 confirmed planets

137 publications submitted, 82 through peer-review  
(55% exoplanets, 45% other areas of astrophysics)

## TESS 3-planet system L98-59

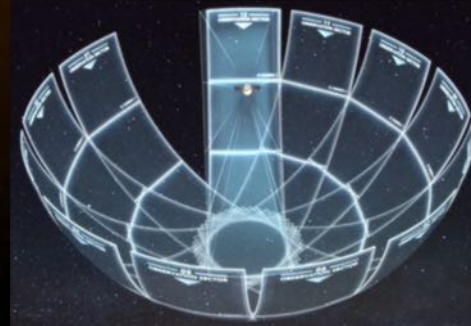
- radii between 0.8 - 1.6 R<sub>Earth</sub>
- mass measurements from HARPS
- M3 dwarf at 10.6 parsec (35 ly)

Exciting system for potential atmosphere  
characterization with HST and JWST



(Kostov et al. accepted;  
Cloutier et al. submitted)

## Observation Sector 12 in progress

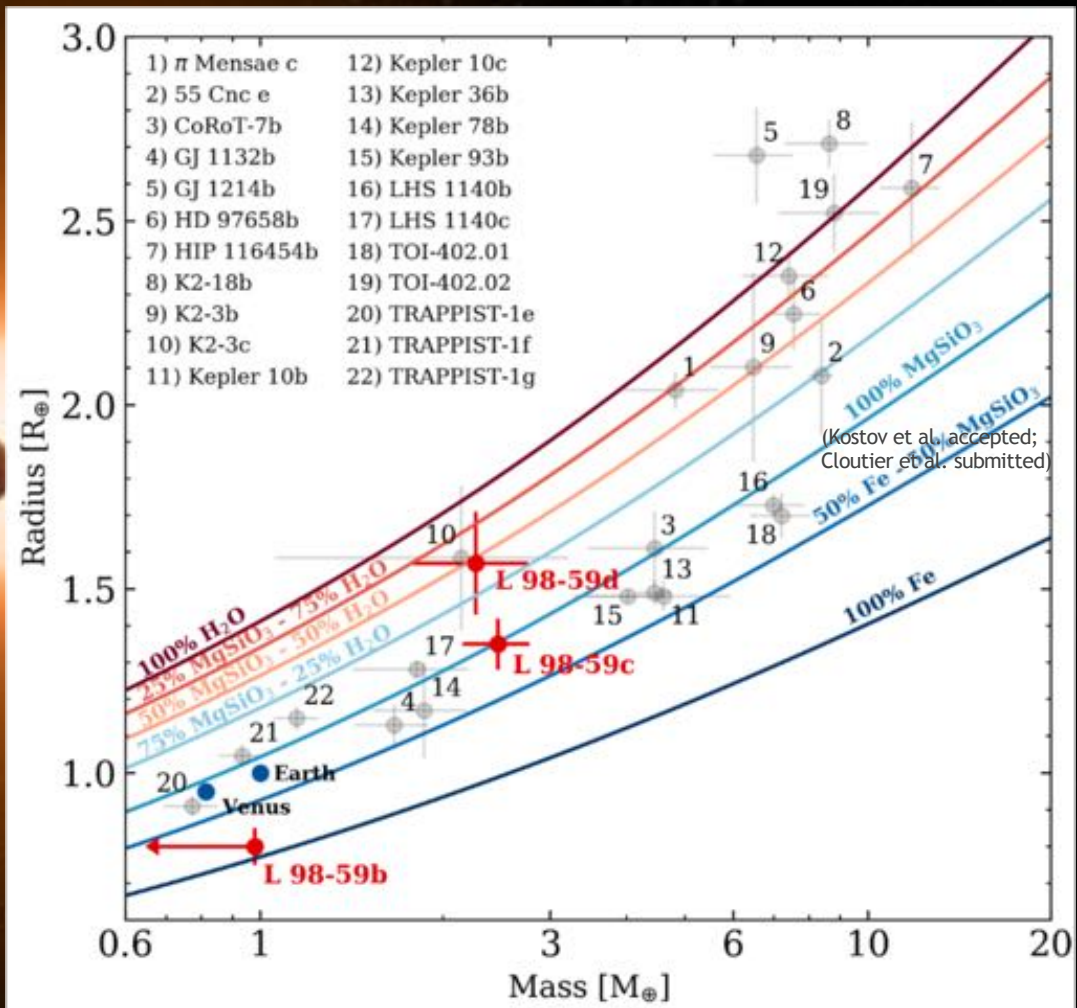


Last update: June 11, 2019

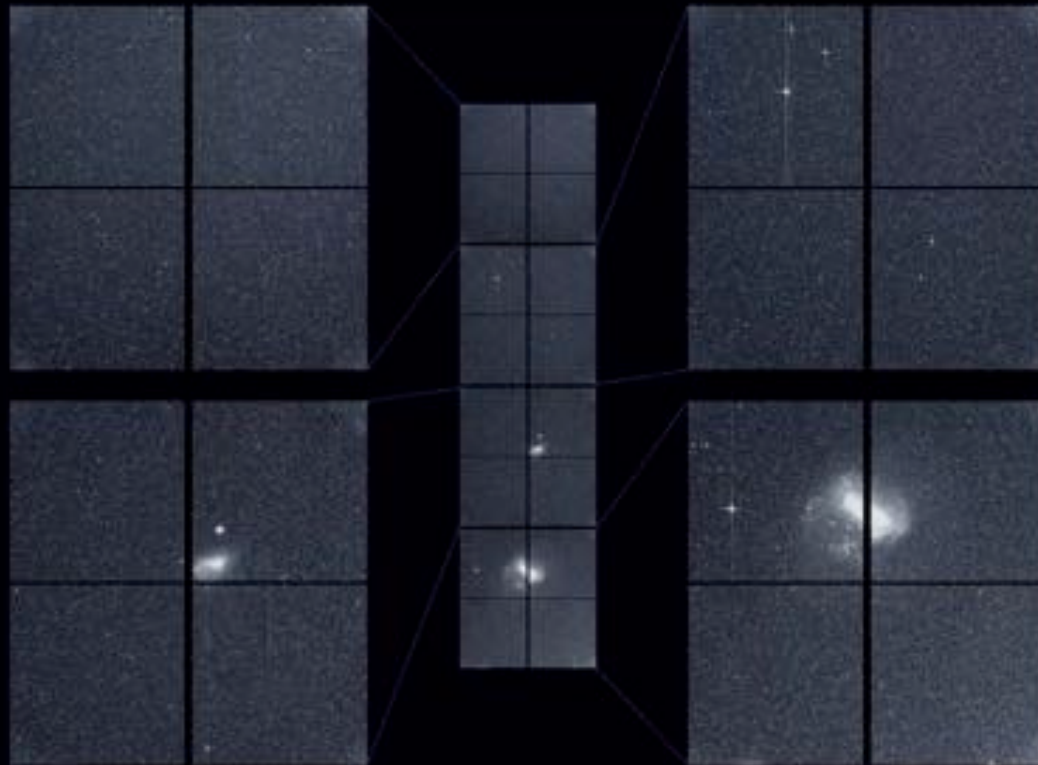
# TESS

Transiting Exoplanet  
Survey Satellite

TESS is starting to fill in the mass-  
radius diagram



# Supernovae Curves in Early TESS Observations



- 53 SNe brighter than 20th magnitude at discovery observed by TESS in the first nine sectors.
- Anticipated detections in 3 years of TESS Observations: ~ 200 SNe

Fausnaugh+ 2019  
arXiv:1904.02171  
Submitted 4/3/19

# Detecting Biomarkers through Transit Spectroscopy

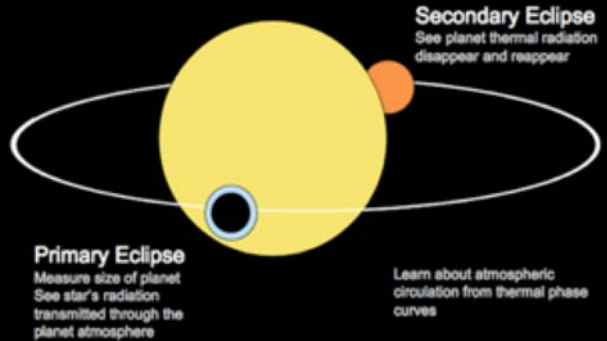
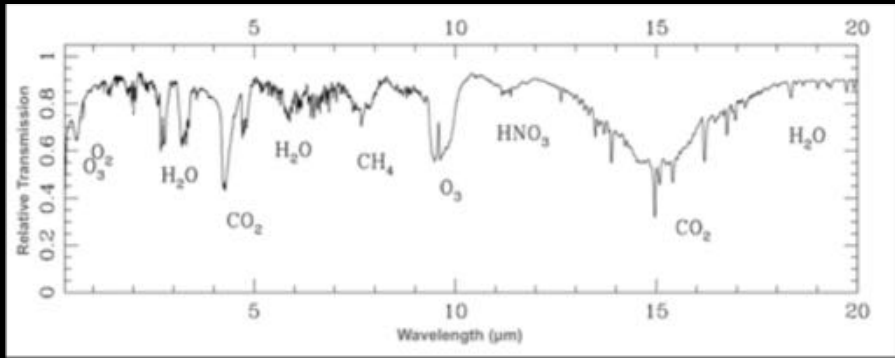


Figure by S. Seager



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



# Exoplanet Missions



Questions?

