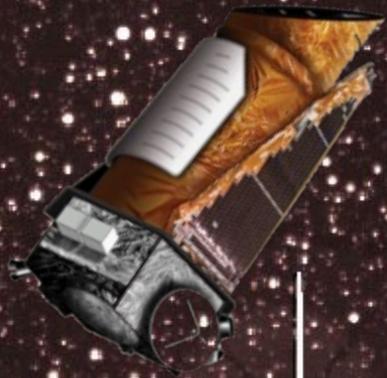


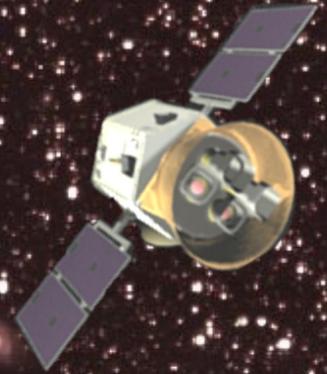


# ***Chasing Shadows in the Night:***

## ***How NASA's Kepler and TESS Missions Are Revolutionizing Exoplanet Science***



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



**Saturday November 19, 2022**

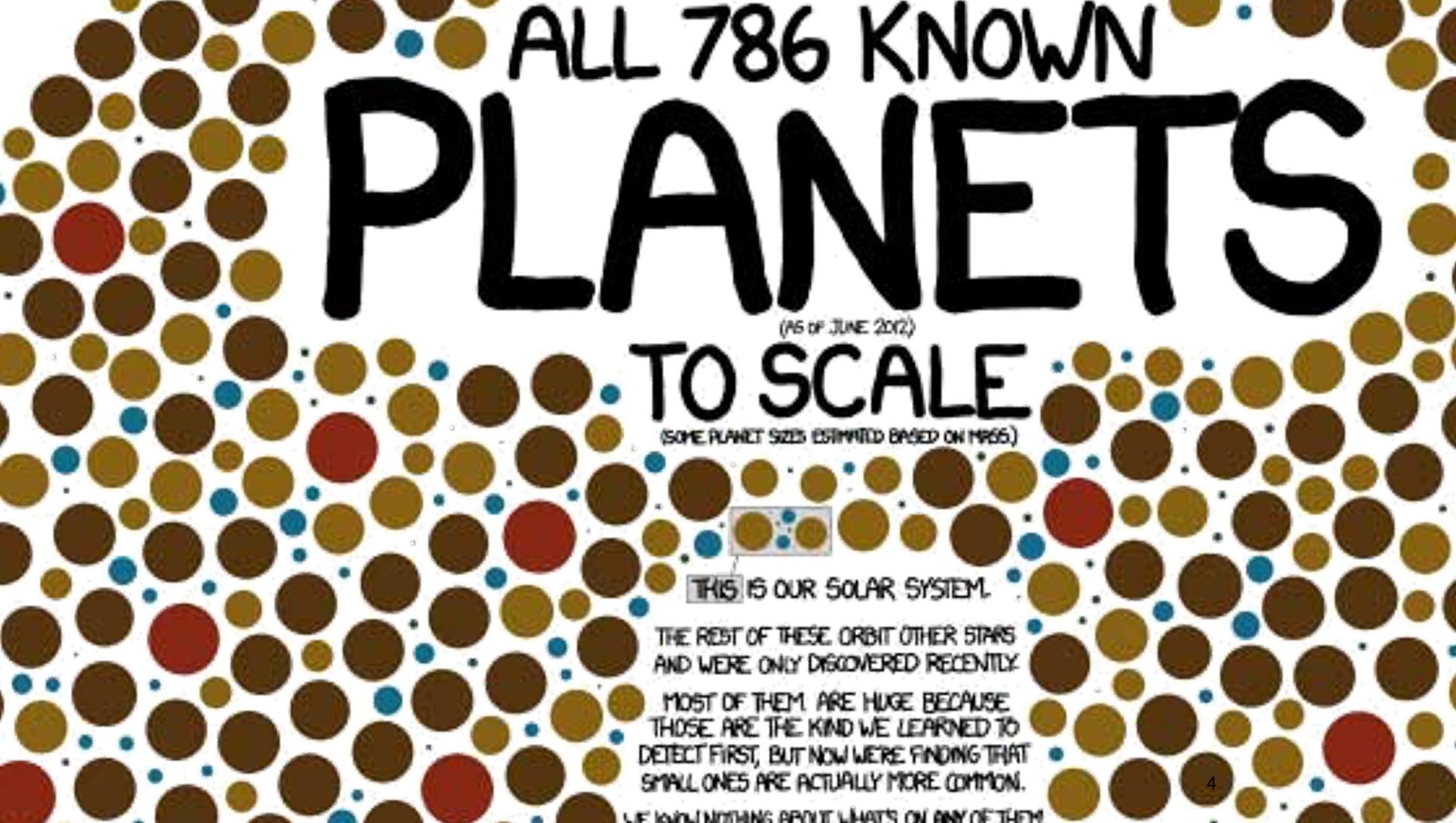
**Eastbay Astronomical Society**



# All the Known Planets In 1994







ALL 786 KNOWN  
**PLANETS**

(AS OF JUNE 2012)

**TO SCALE**

(SOME PLANET SIZES ESTIMATED BASED ON 1995)



**THIS** IS OUR SOLAR SYSTEM.

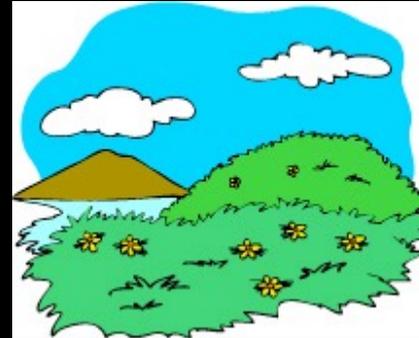
THE REST OF THESE ORBIT OTHER STARS  
AND WERE ONLY DISCOVERED RECENTLY.

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?

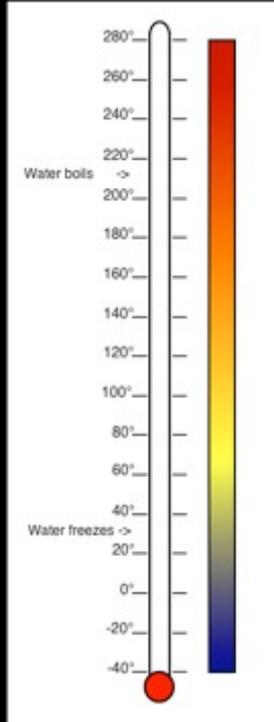
- Right temperature
- Air
- Liquid water
- Light
- Radiation shield
- Asteroid protection



# The Goldilocks Zone



Venus: Way too hot!

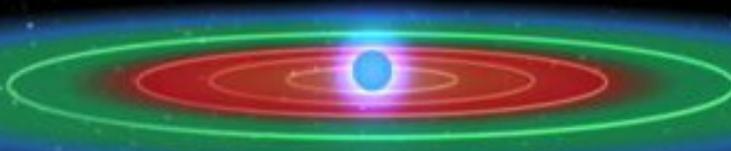


Mars: Way too cold, and small!



Earth: Just right!

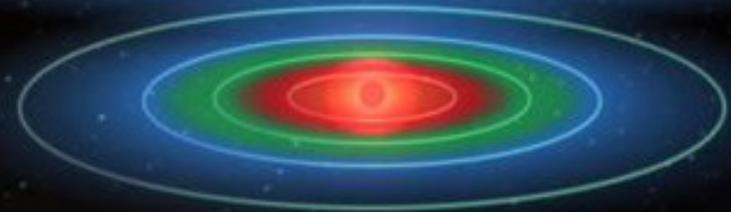
Hotter Stars

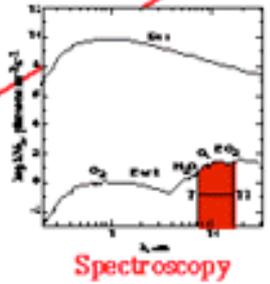
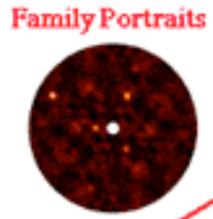
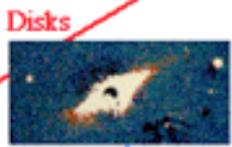
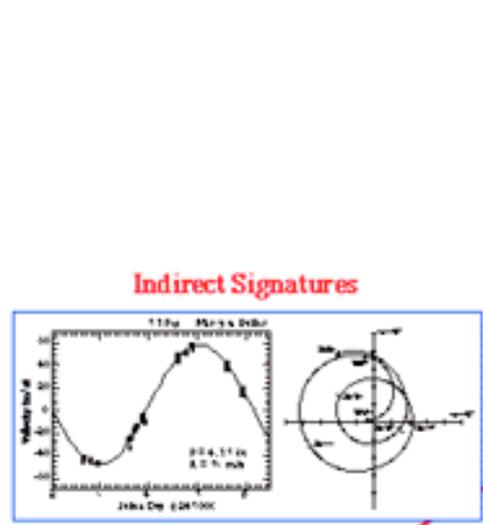


Sun-like Stars



Cooler Stars





**Transit Photometry not Recommended!**

**A Road Map for the Exploration of Neighboring Planetary Systems (ExNPS)**

- Executive Summary
- Introduction
- The Formation of Stars and Planets
- The Instrumental Challenge
- The Space Infrared Interferometer
- Technology Challenges for a Space Infrared Interferometer
- Supporting Ground-Based Programs
- Supporting Space Missions
- Additional Astrophysics with a Space Infrared Interferometer
- The Road Map and Recommendations
- References
- Appendices
- Acronyms

★ GL229 B - click to view spectral characterization

# The *Kepler* Mission

How many stars like the Sun have  
Earth-like planets orbiting them?

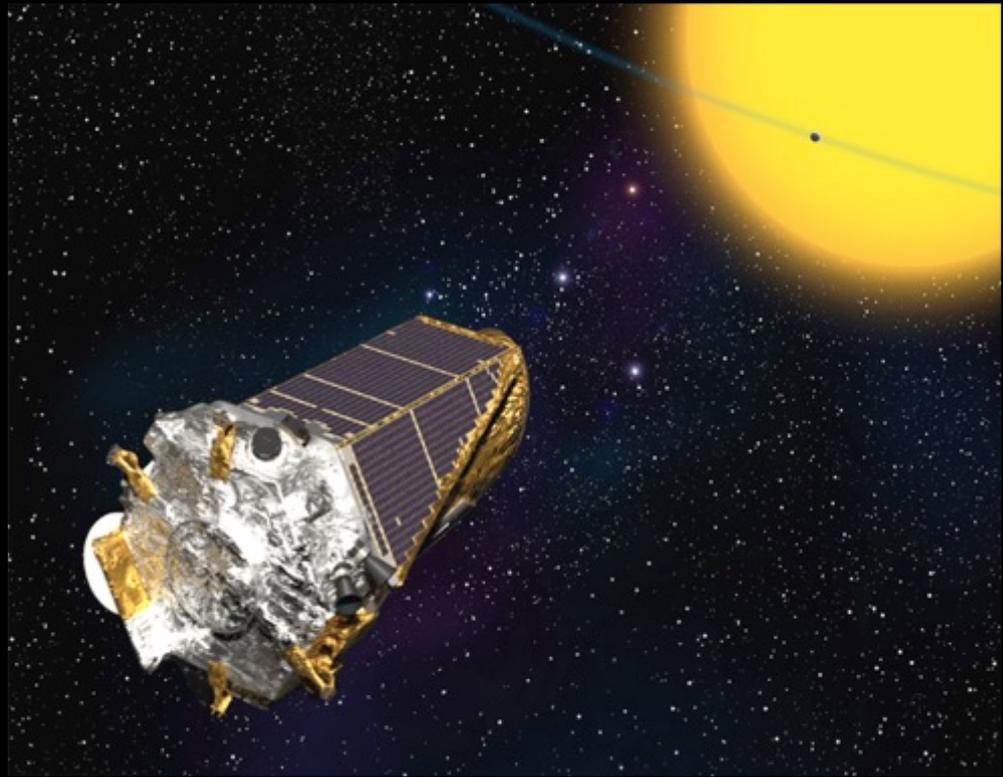
Kepler searches for transiting  
planets



BRIGHTNESS

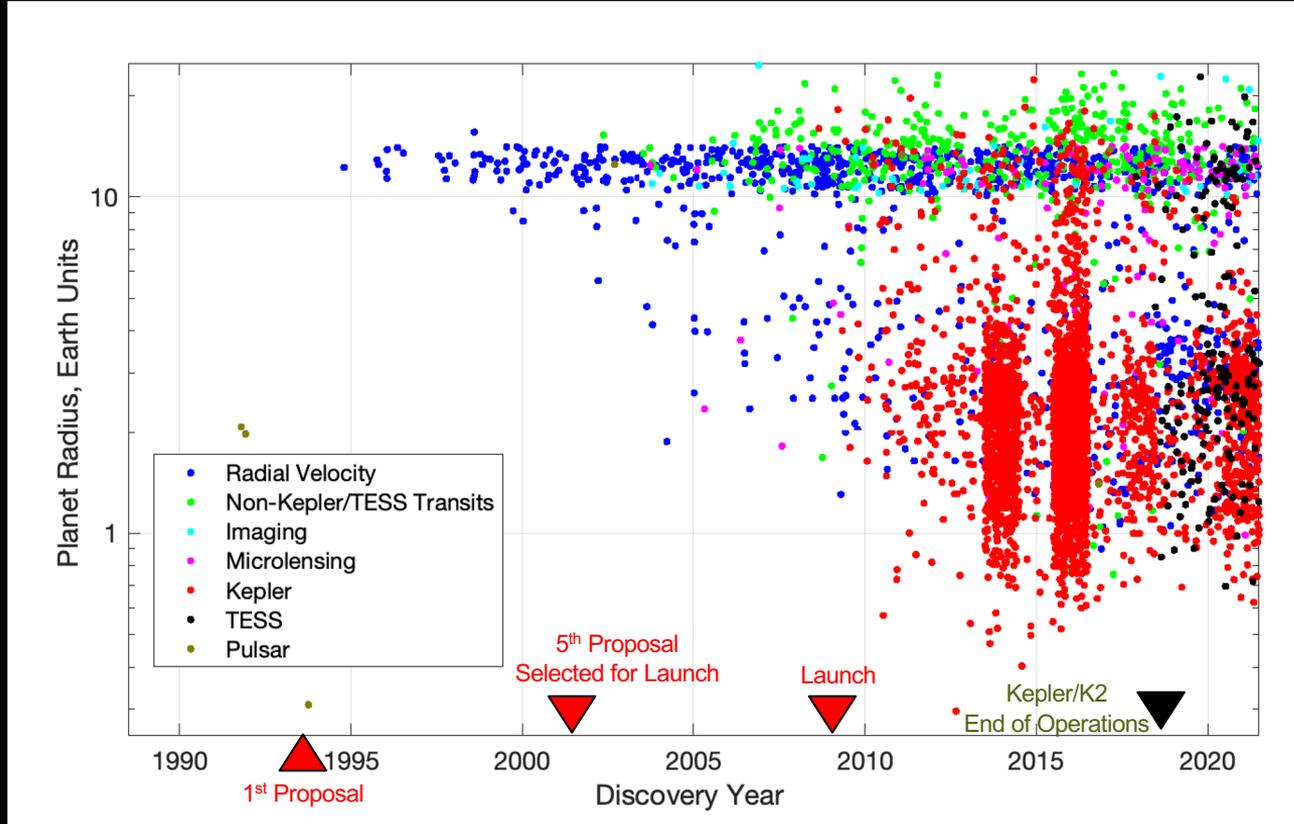
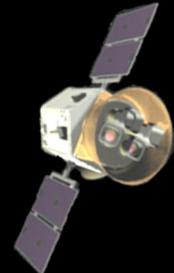
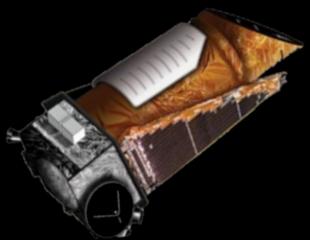


TIME IN HOURS





# Persistence Pays Off: Exoplanet Discoveries Over Time\*

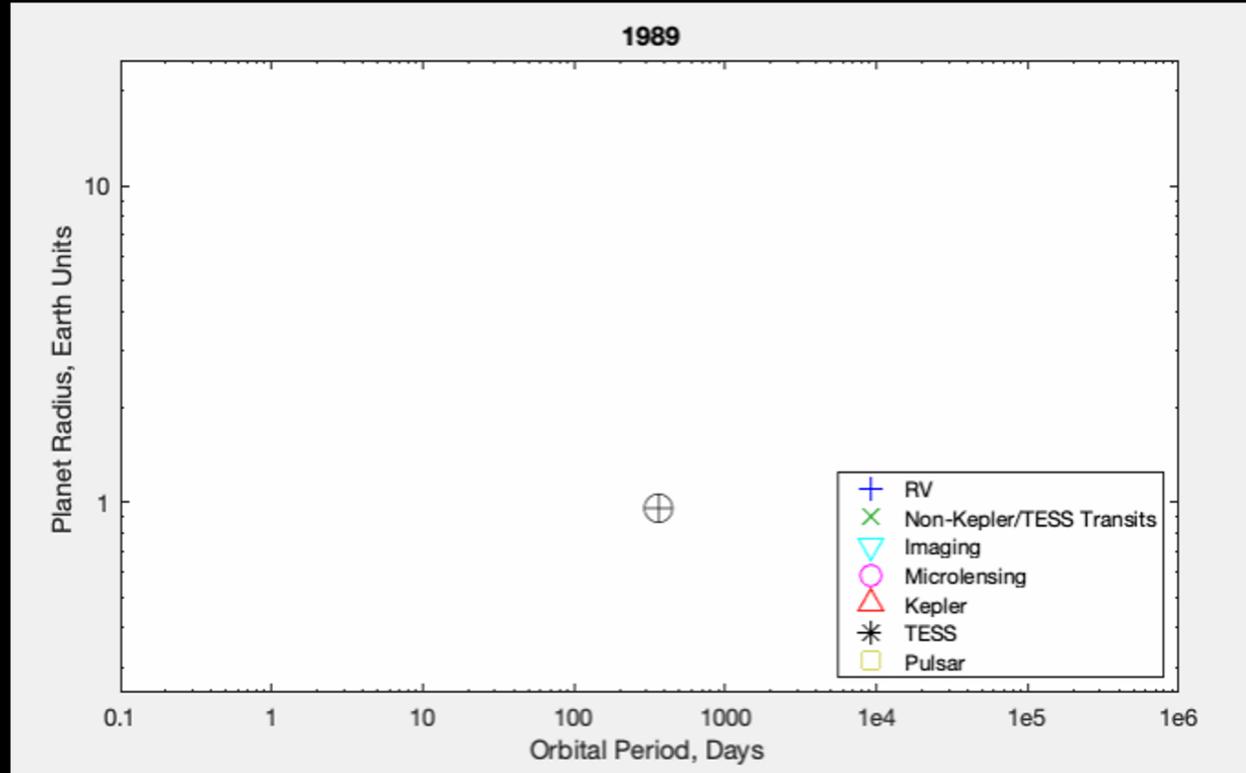


Radii estimated for non-transiting exoplanets  
Discovery date dithered slightly

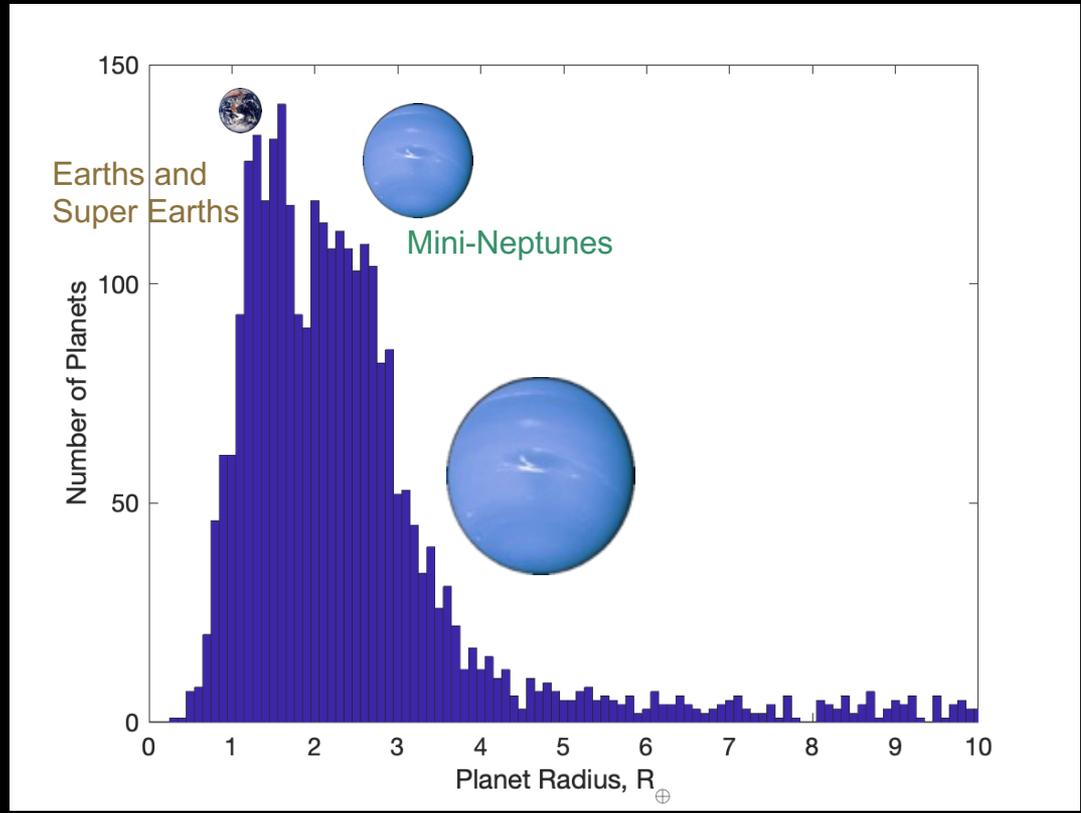
\*According to <https://exoplanetarchive.ipac.caltech.edu> as of 10/4/21

# Exoplanet Discoveries

Kepler+K2:	<b>3234</b>
TESS:	<b>269</b>
Other Transit:	438
RV:	1017
Imaging:	58
μlensing:	141
Pulsar:	7
TOTAL:	5164



\*According to <https://exoplanetarchive.ipac.caltech.edu> as of 11/17/22



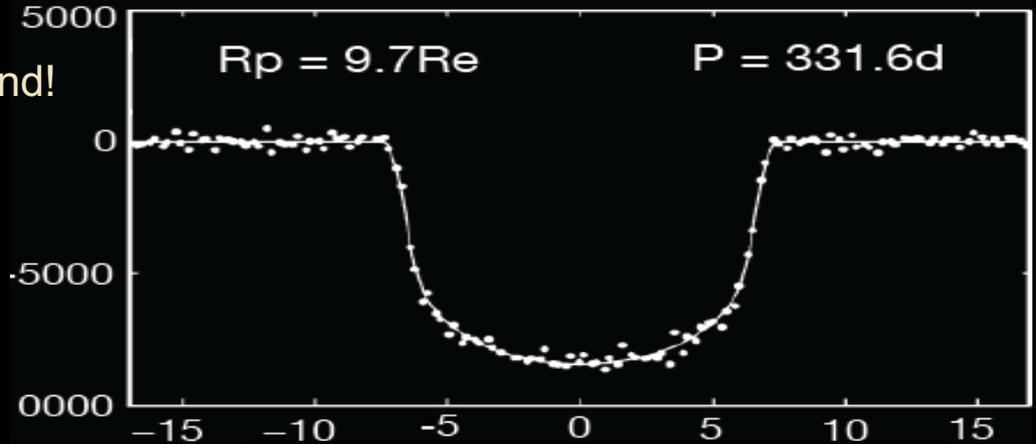
There is a gap between 1.5 and 2  $R_{\text{earth}}$  indicating two populations

# How Hard is it to Find Good Planets?

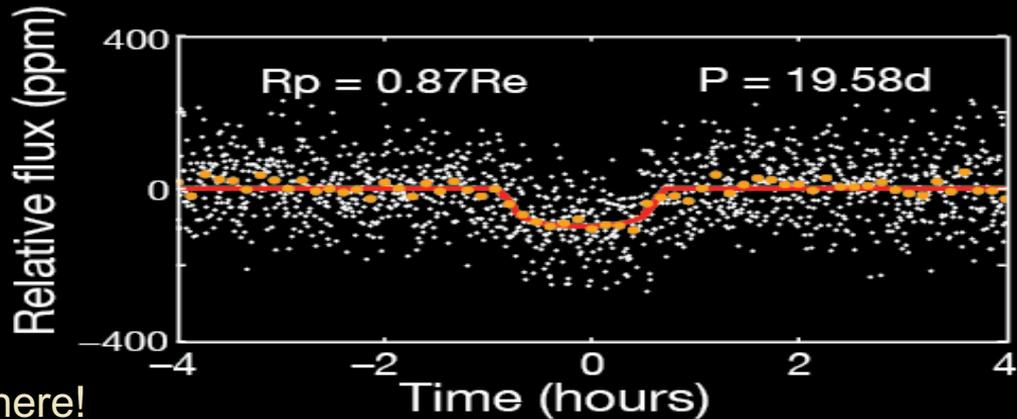


Easy to find from the ground!

Jupiter (~1%)



Earth (~0.01%)

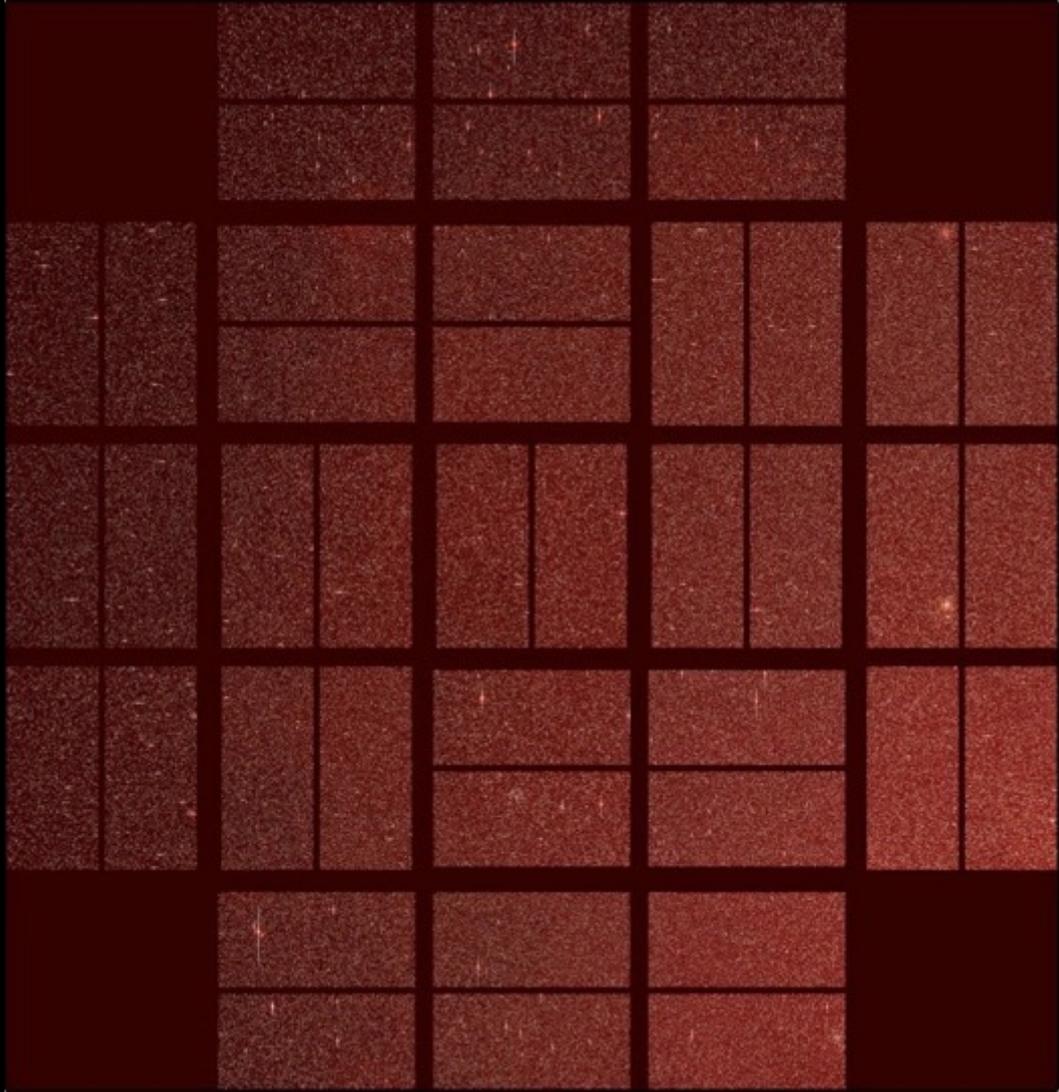


Hard to find from anywhere!

# First Light Image



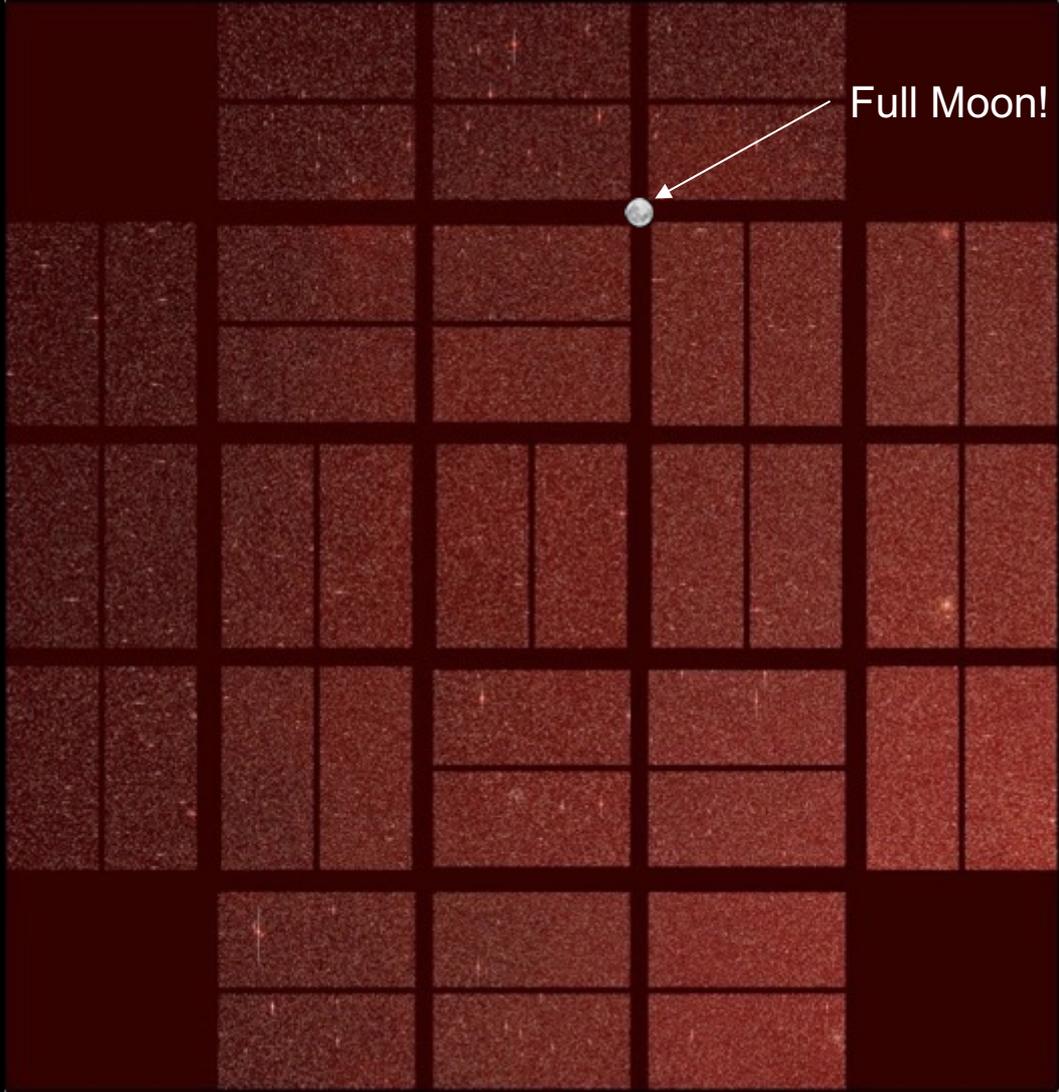
Launched  
March 7 2009



# First Light Image



Launched  
March 7 2009



Full Moon!

Kepler-20e

Venus

Earth

Kepler-20f



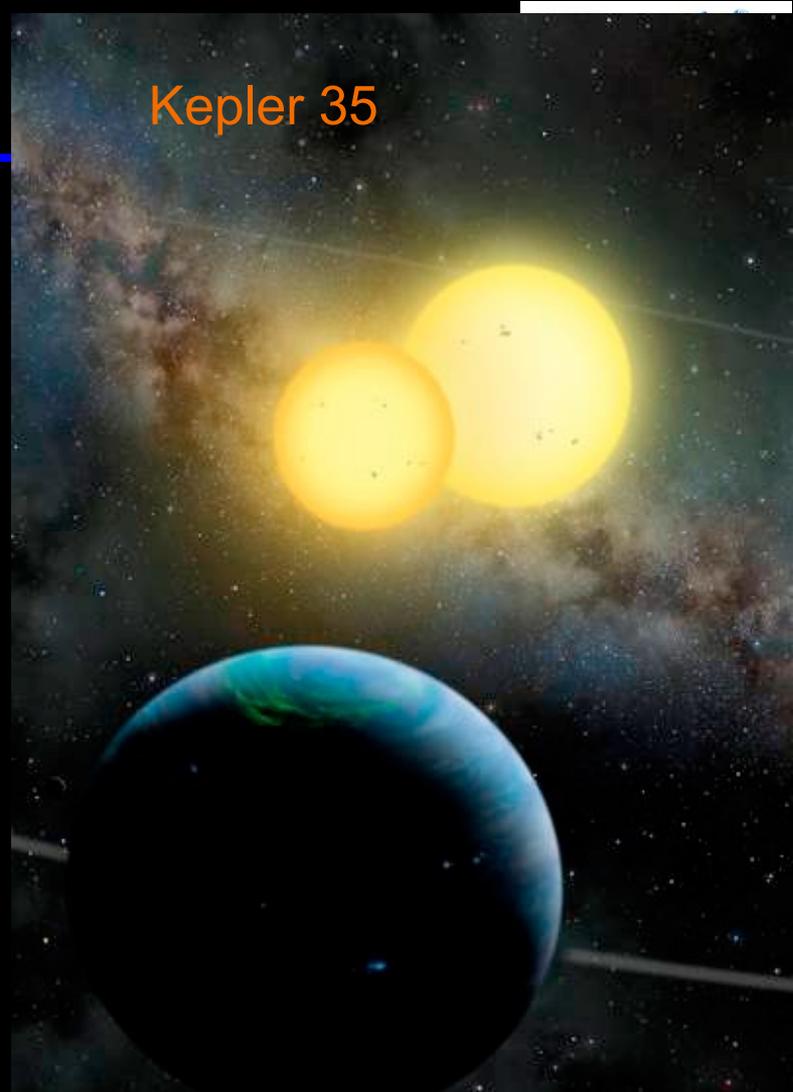
**Kepler discovers two Earth-size planets, which scientists believe are rocky, Kepler-20e and Kepler-20f. These two planets are in the Milky Way galaxy, but not in our solar system. Their solar system also contains larger gas giant planets (like Jupiter) in larger orbits.**



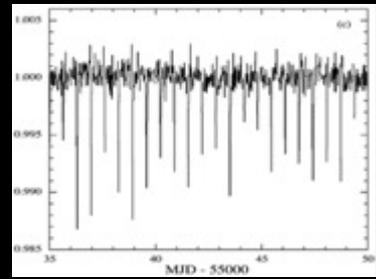
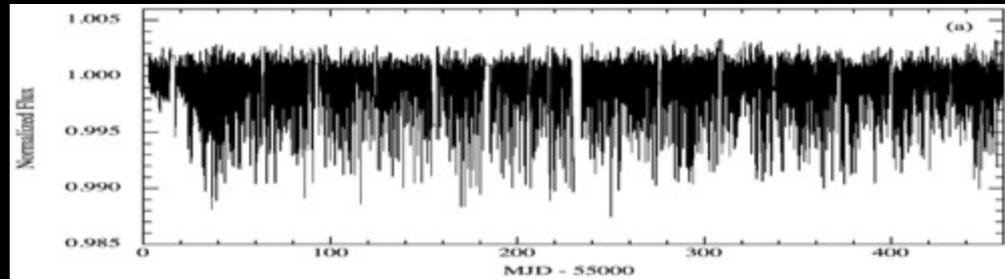
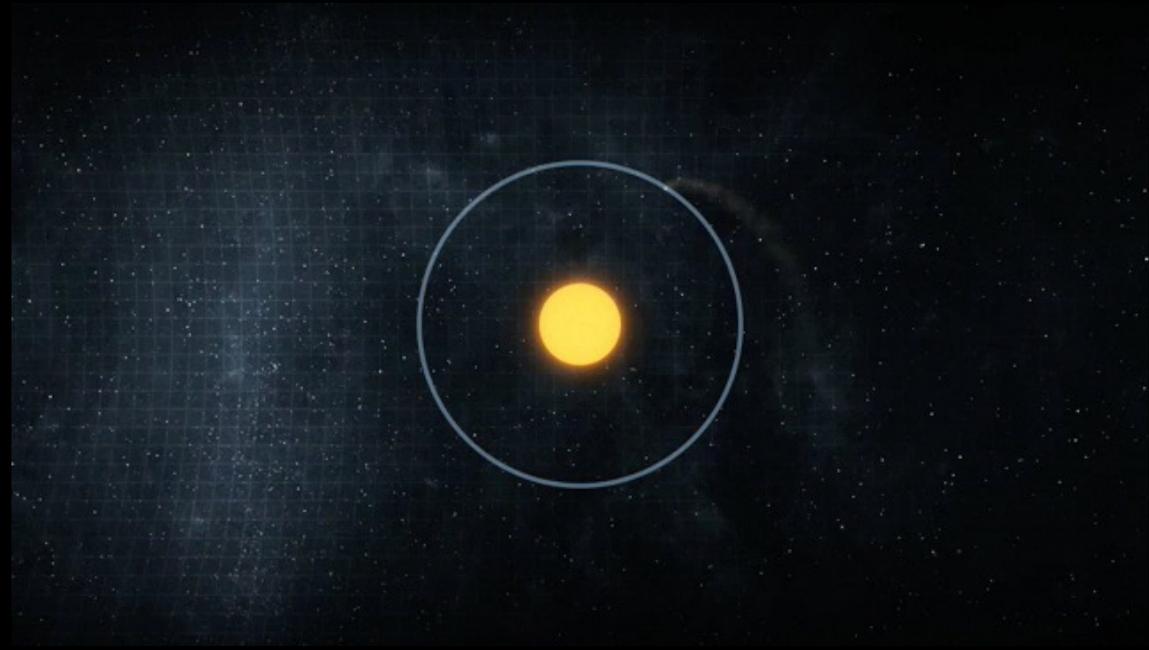
# Circumbinary Planets:



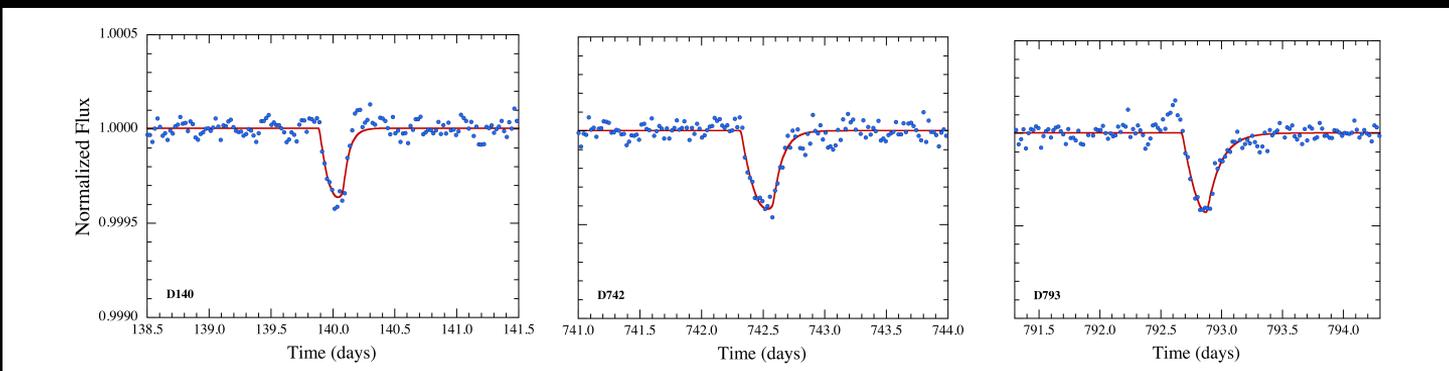
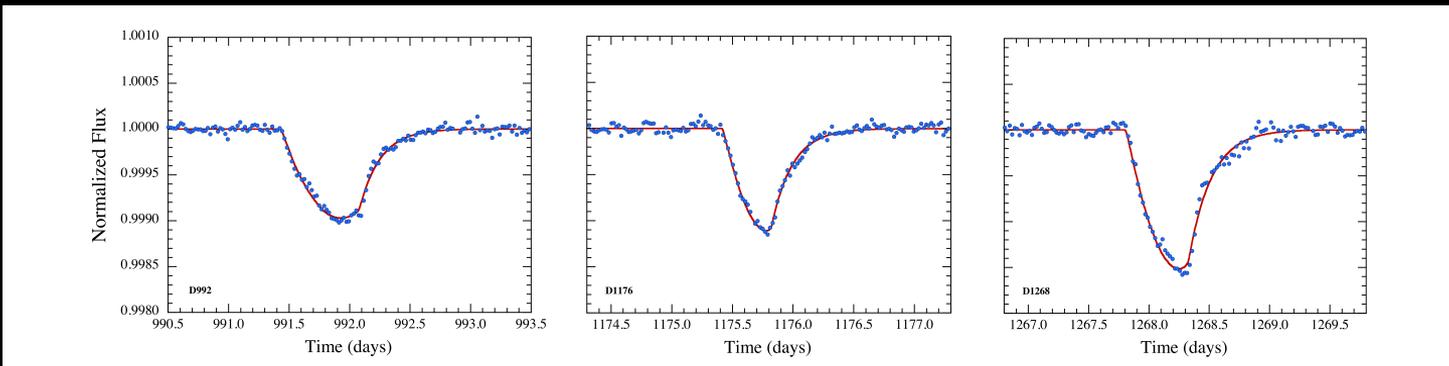
## Kepler 35

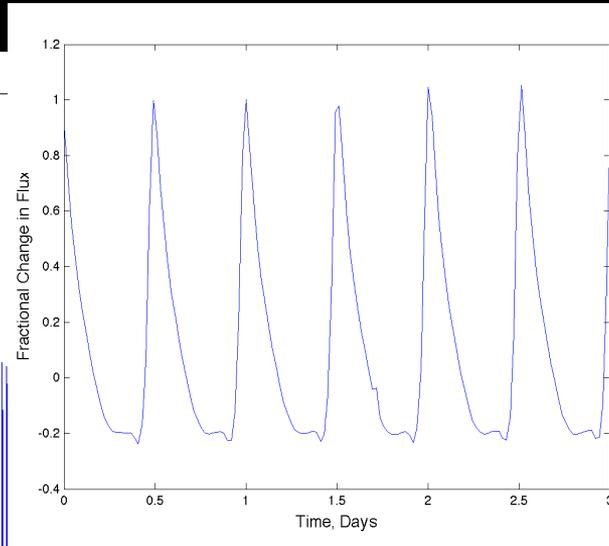
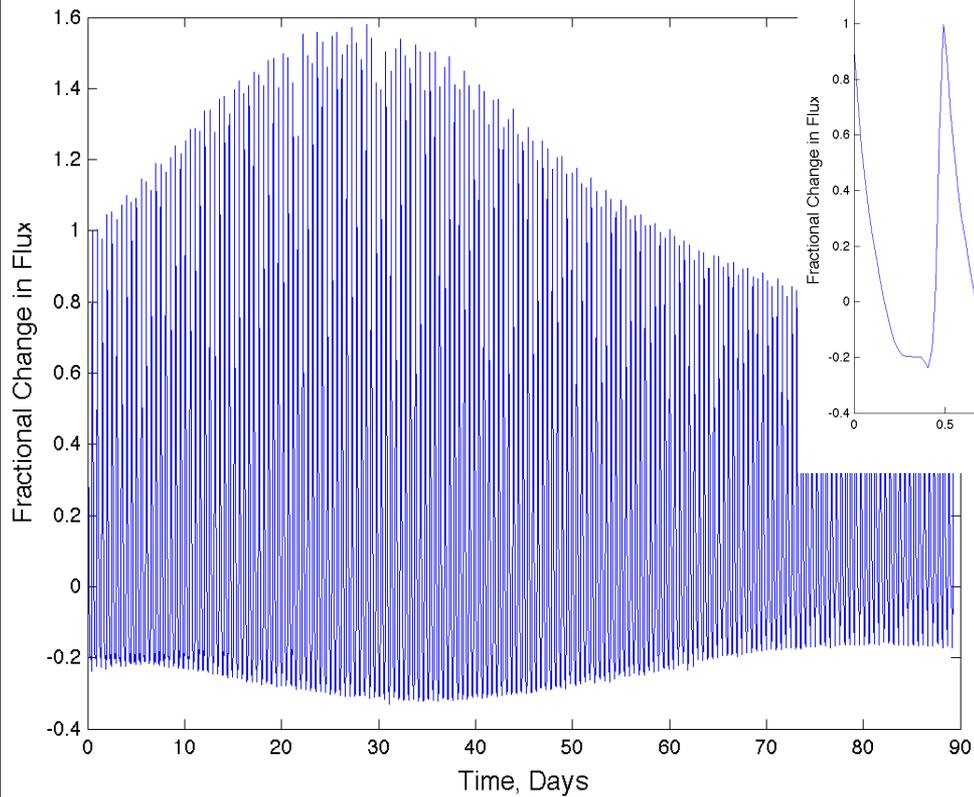


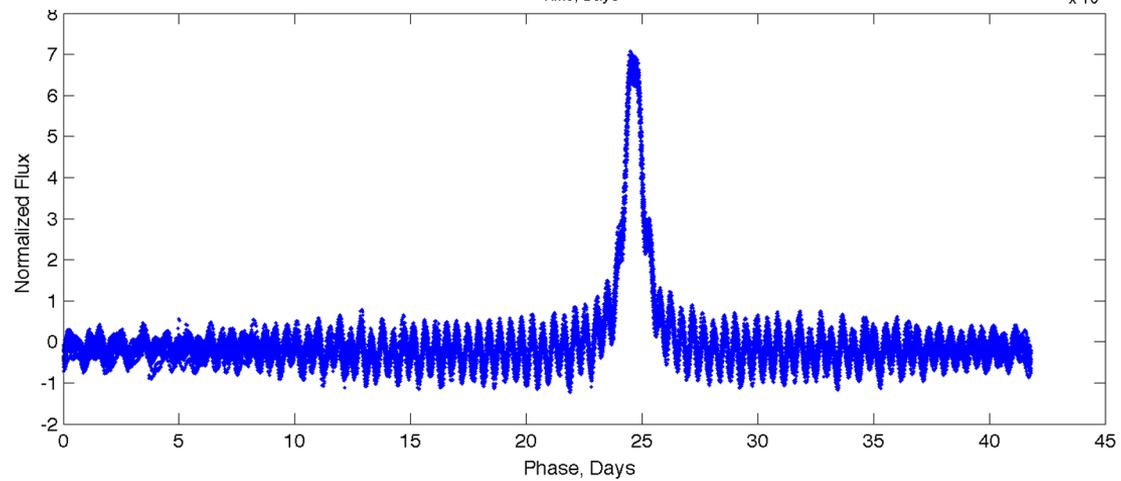
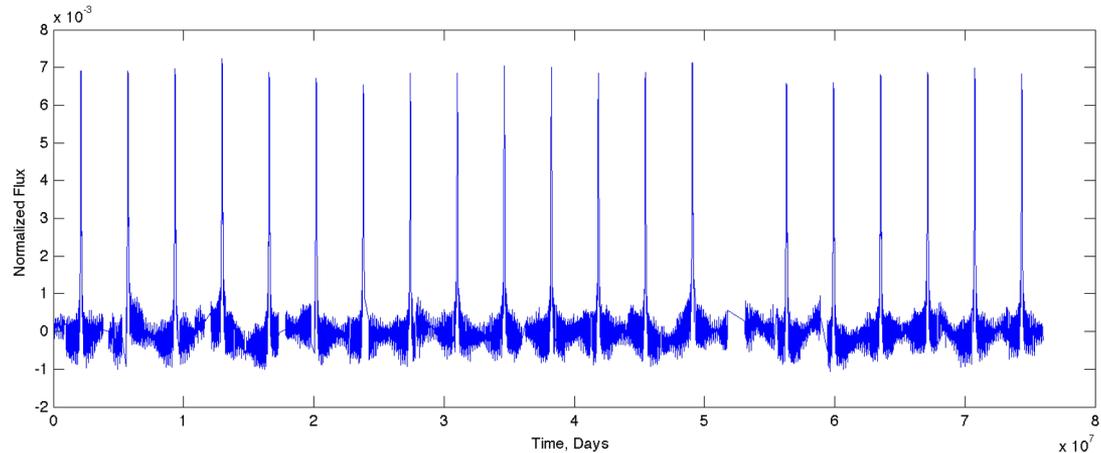
# A Disintegrating Sub-Mercury-Size Planet



# KIC 3542116: An Exocomet Candidate



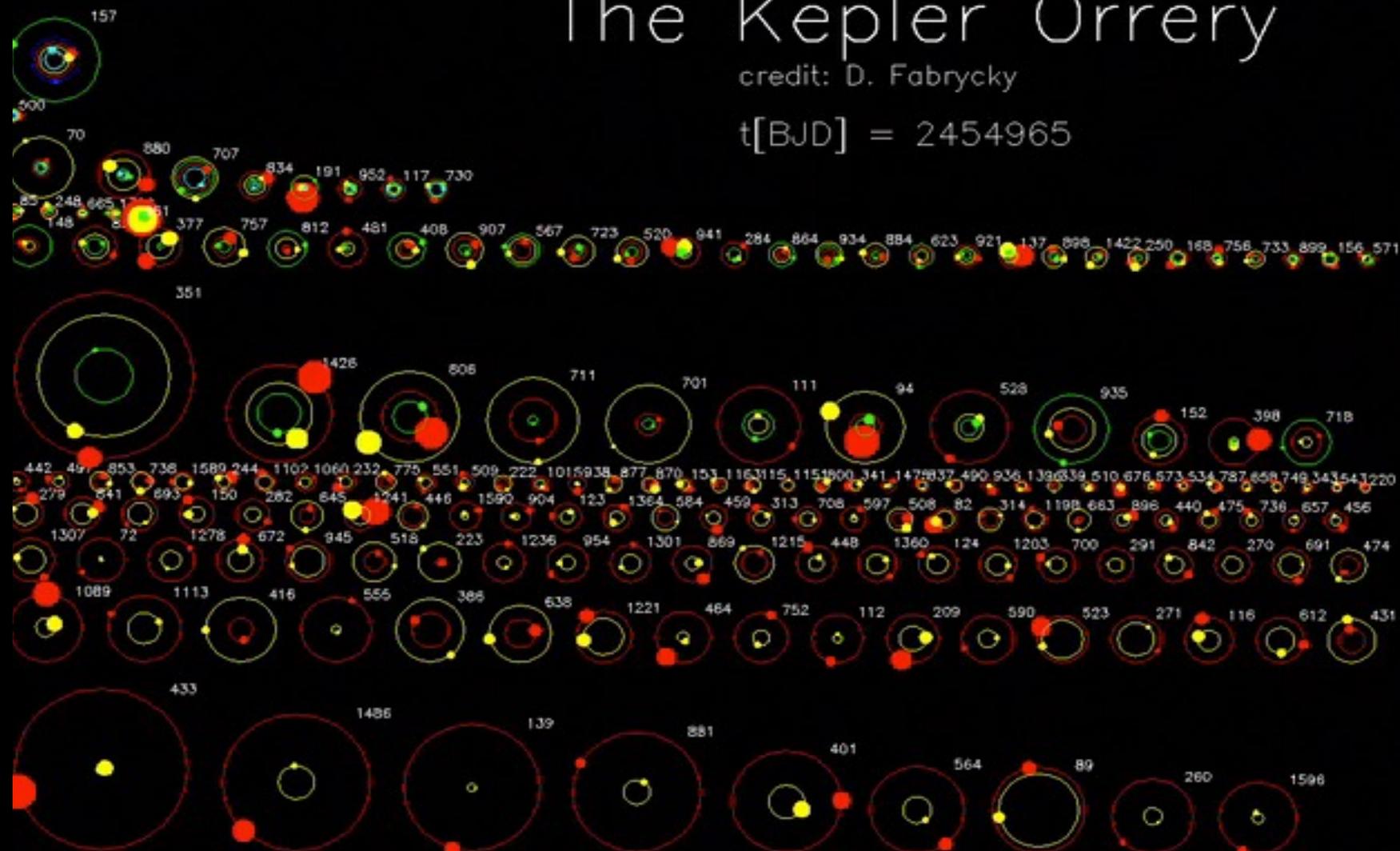




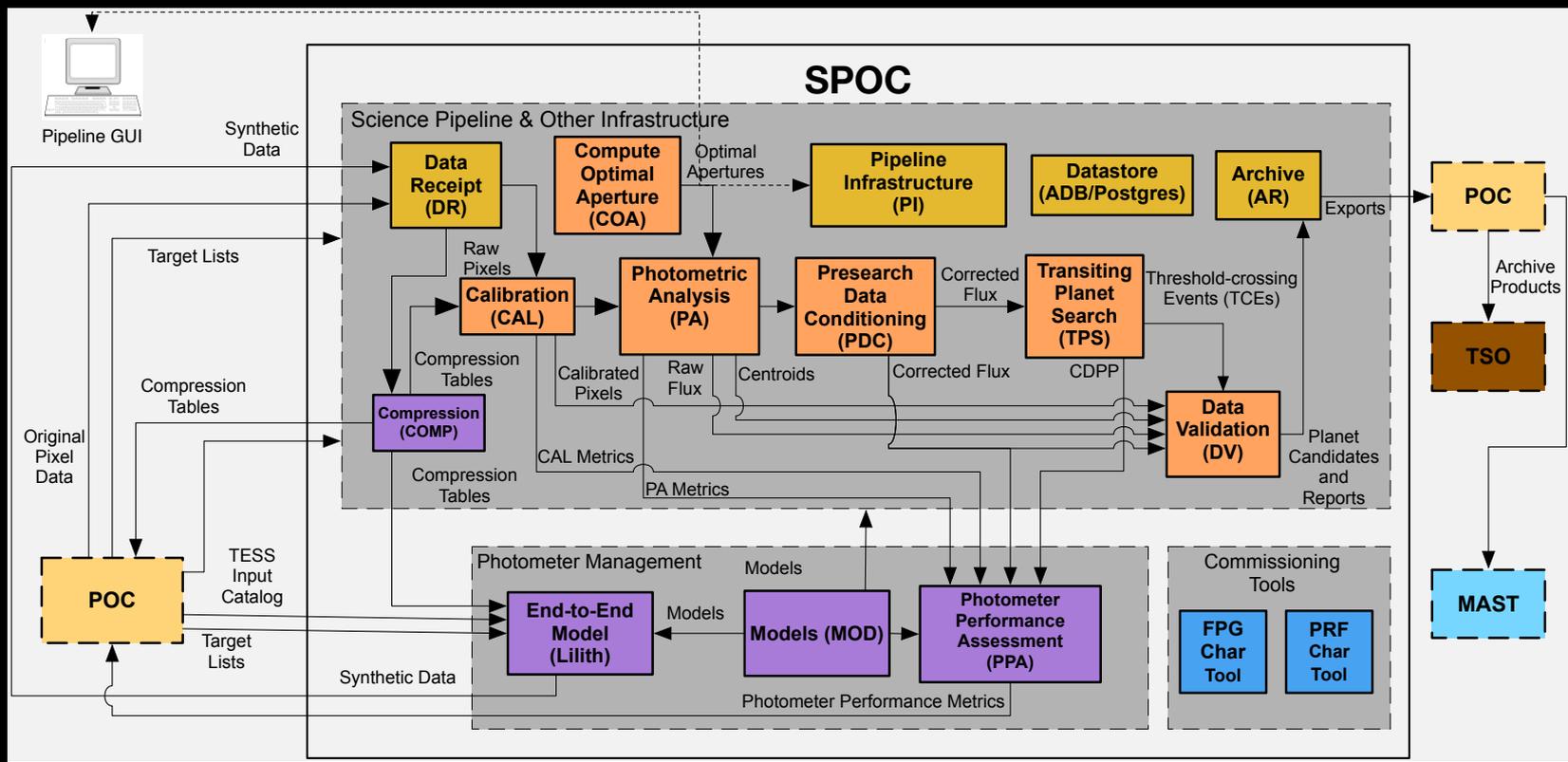
# The Kepler Orrery

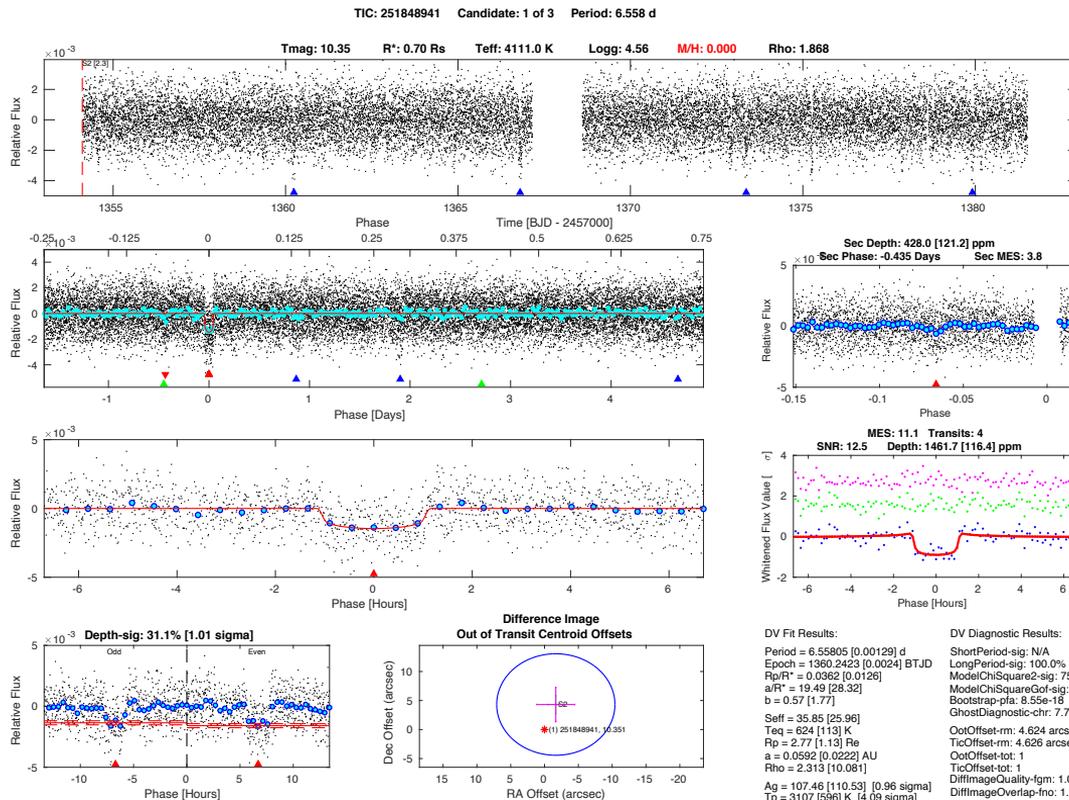
credit: D. Fabrycky

$t[\text{BJD}] = 2454965$



# Science Processing Overview





Kepler taught us that planets are everywhere!

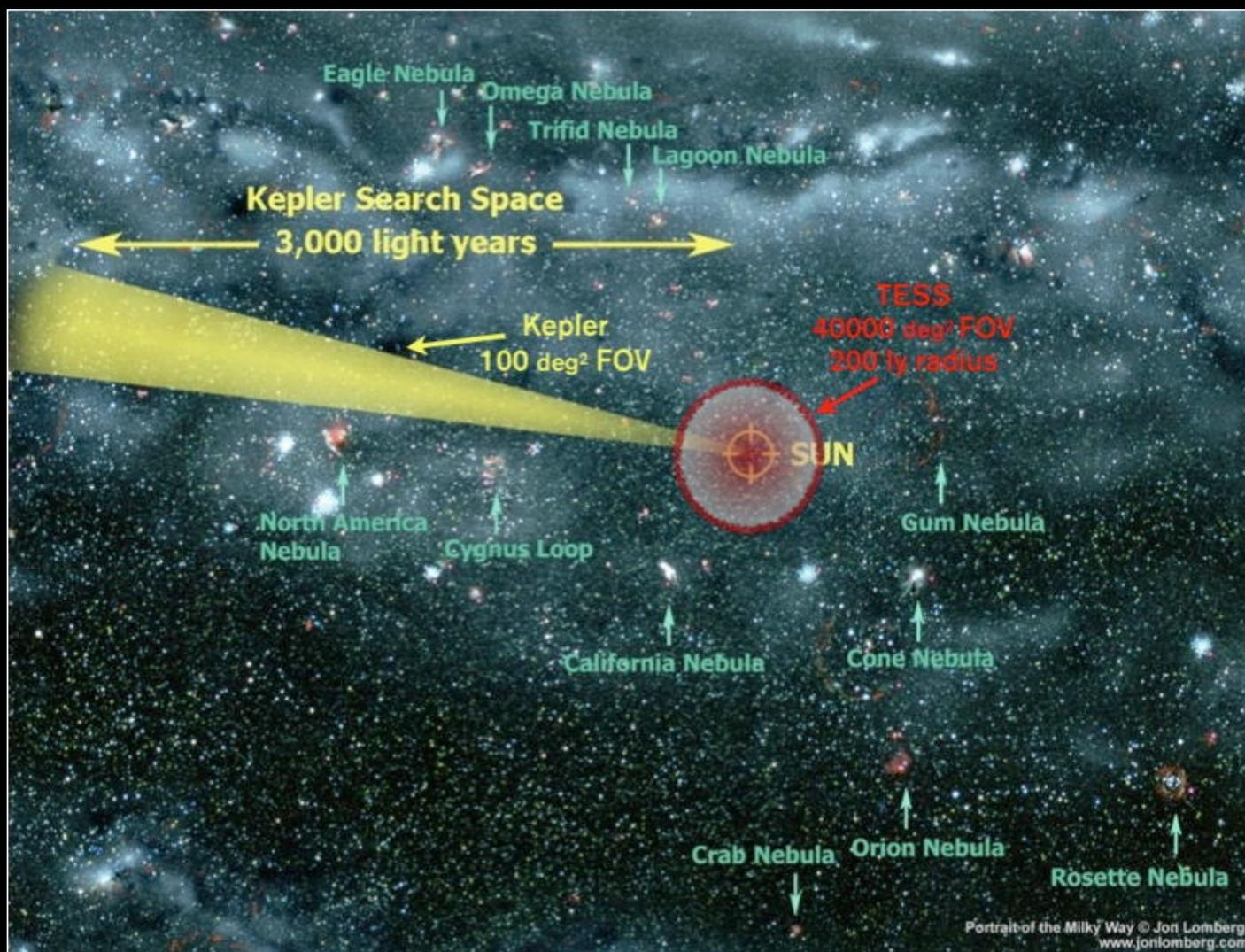
What Next?



# TRANSITING EXOPLANET SURVEY SATELLITE

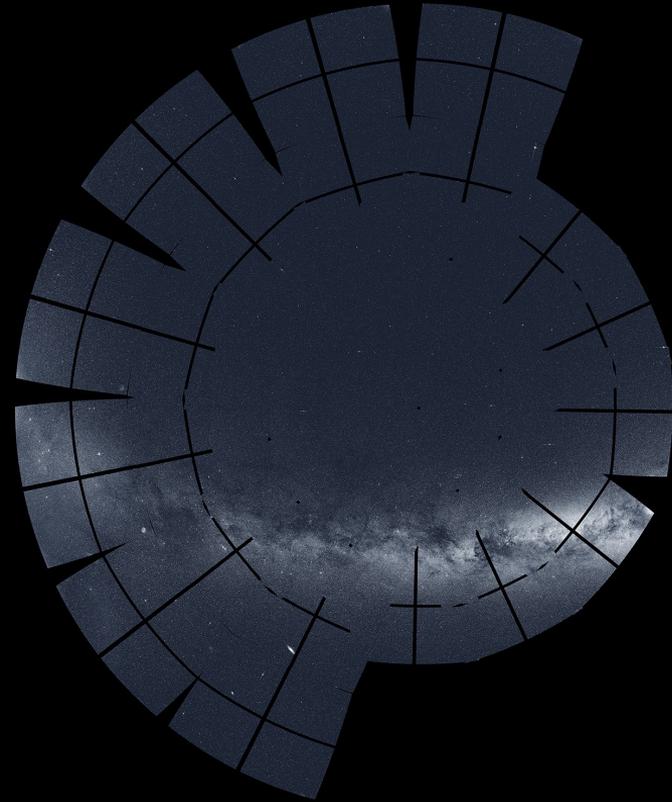
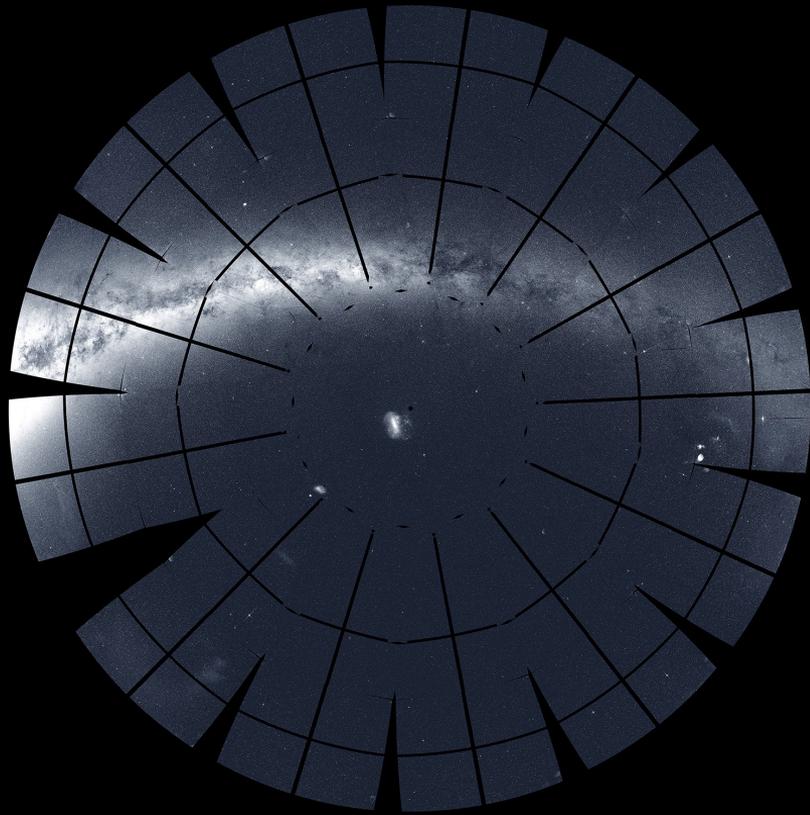
*DISCOVERING NEW EARTHS AND SUPER-EARTHS  
IN THE SOLAR NEIGHBORHOOD*



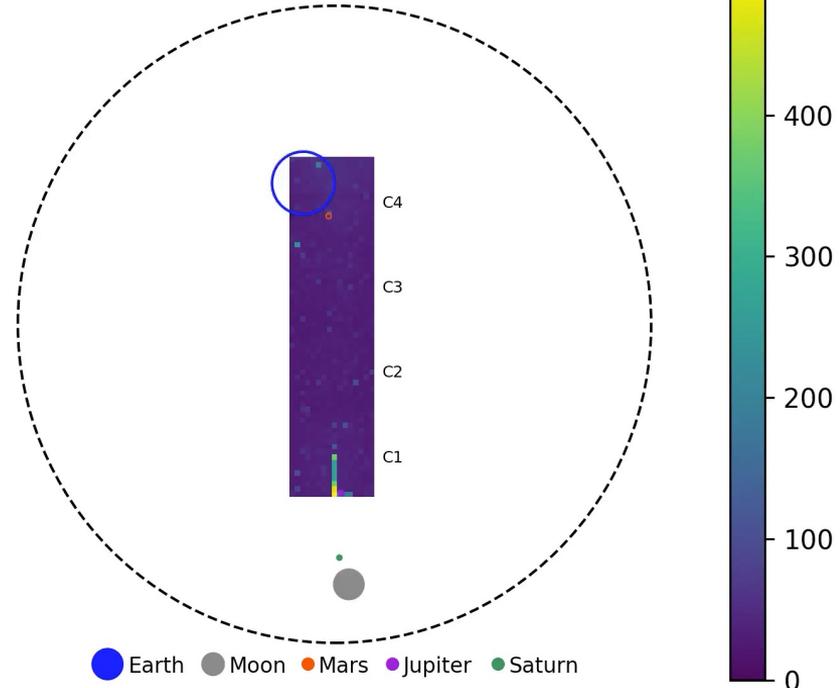


Used with permission of the artist

# TESS Primary Mission Sky Coverage



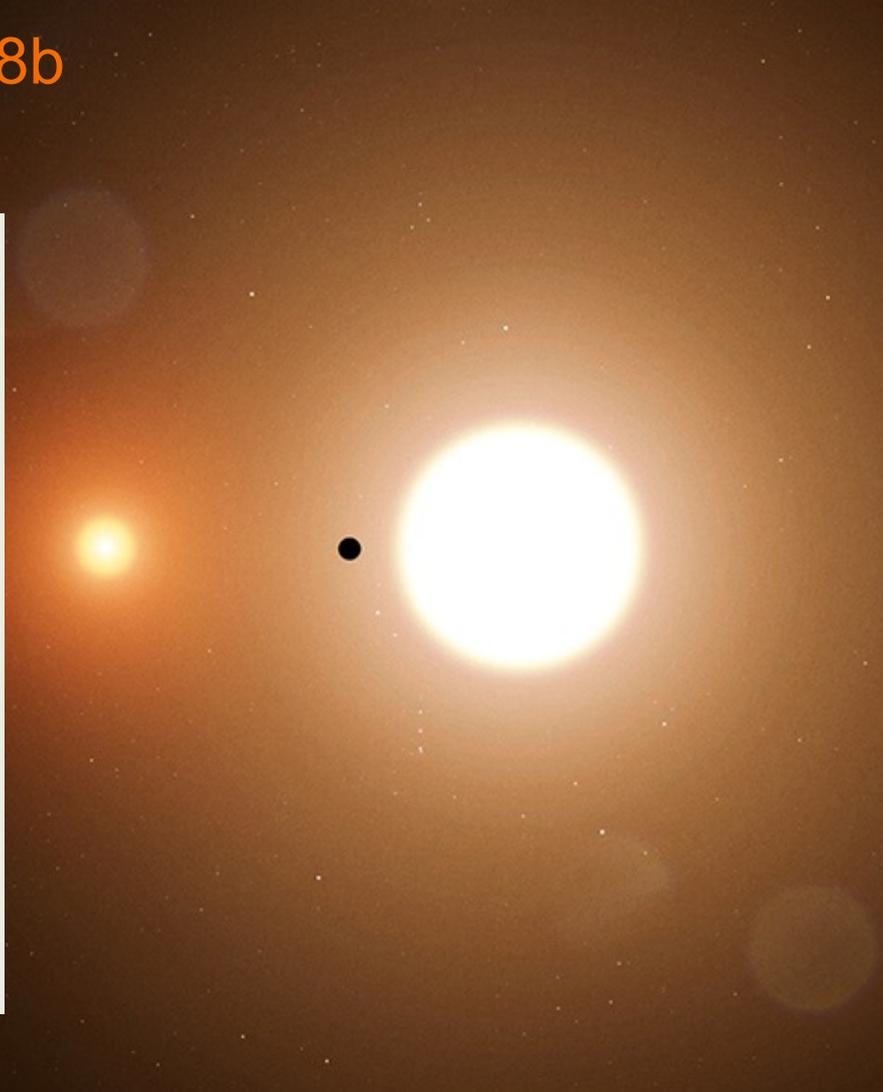
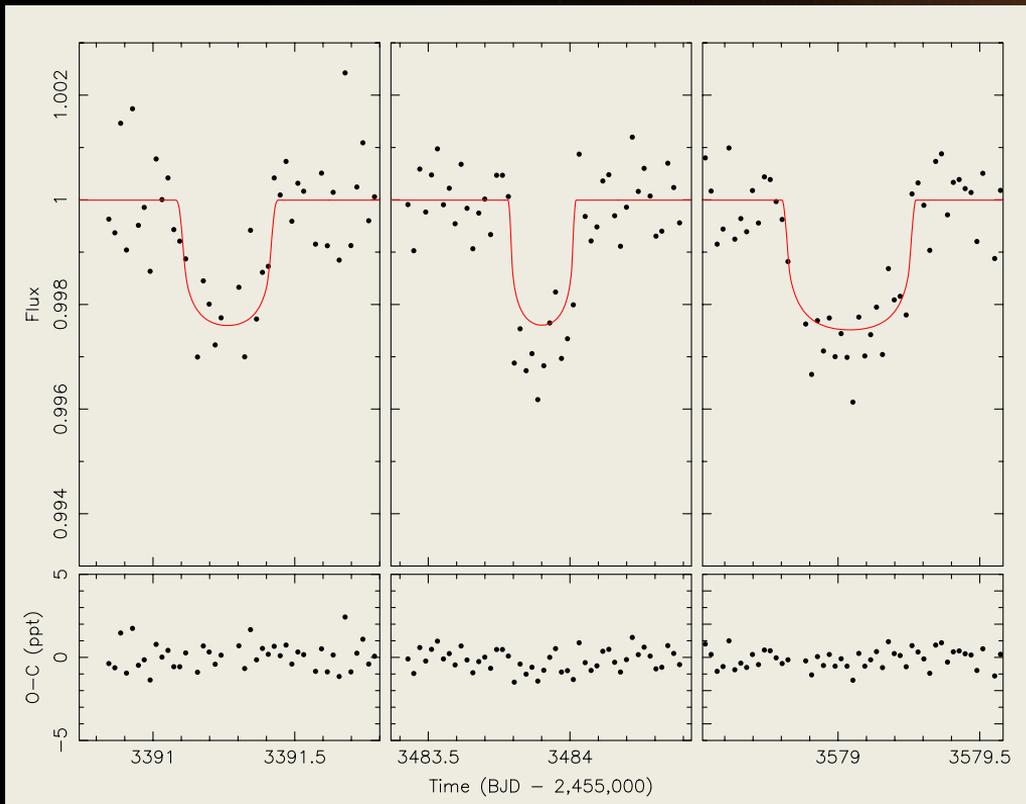
Sky Brightness, Sector 42, Orbit 91  
 FFI 00175715, TJD 2447.702, 2021-08-21 04:49:00 UTC



Polar projection of solar system objects on TESS FOV  
 Dashed line is sunshade. Filled objects are above sunshade, open are below sunshade.  
 Earth/Moon size inversely proportional to distance.

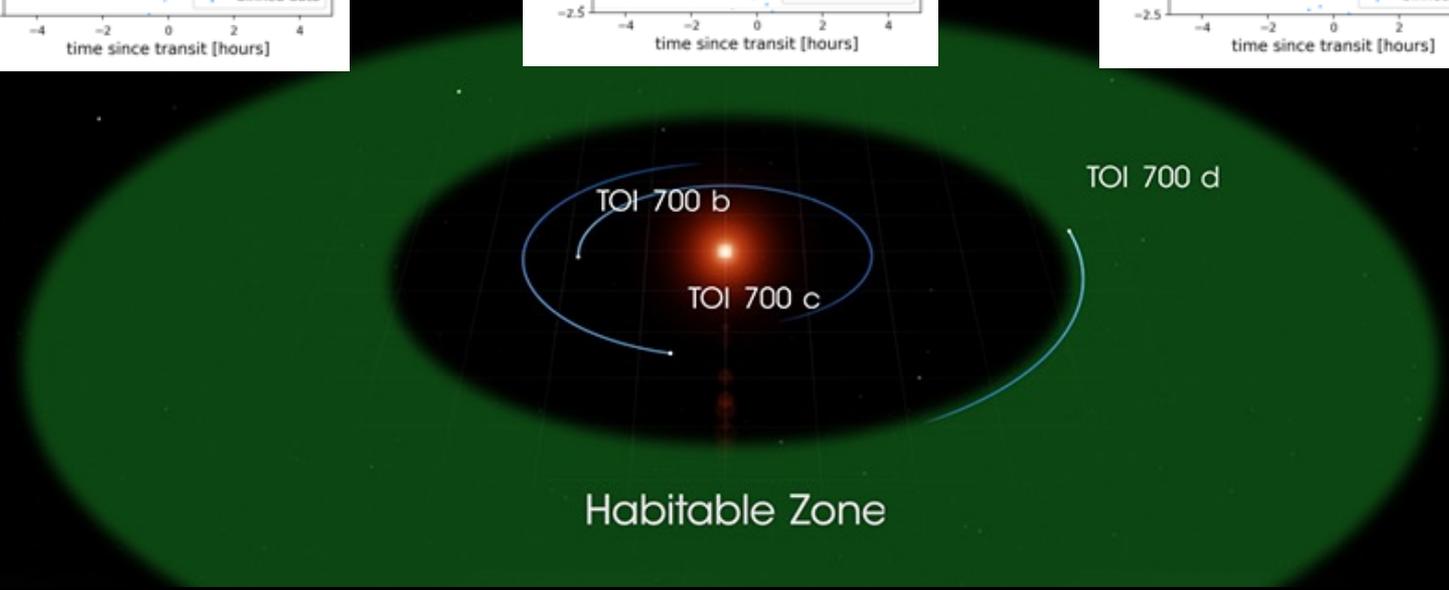
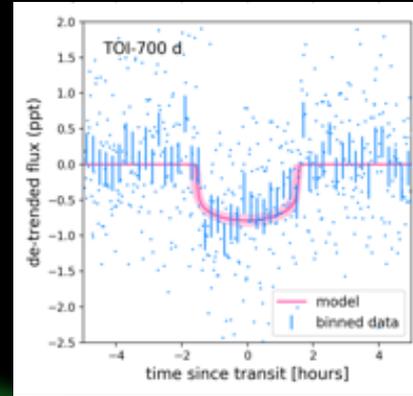
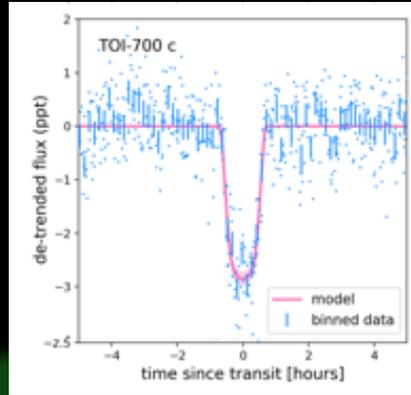
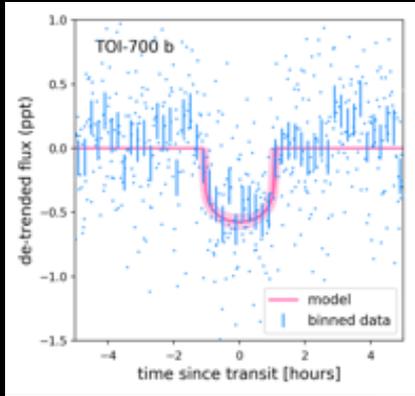
R. Vanderspek, TESS@MIT

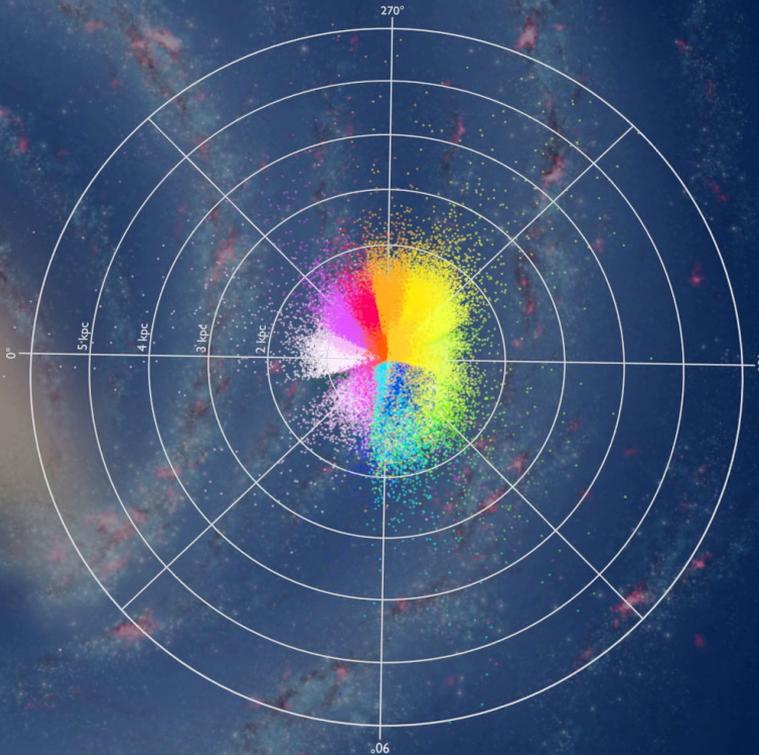
# First Circumbinary Planet: TOI-1338b





# TESS's First Earth-Sized Habitable Zone Planet: TOI-700d





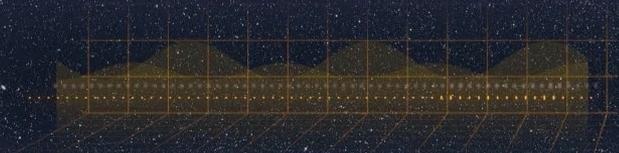
Using observations from NASA's Transiting Exoplanet Survey Satellite (TESS), astronomers have identified an unprecedented collection of pulsating red giant stars all across the sky. These stars, whose rhythms arise from internal sound waves, provide the opening chords of a symphonic exploration of our galactic neighborhood.

The paper is Hon et al.(2021) and has been accepted by the Astrophysical Journal, and is available on astro-ph here: <https://arxiv.org/abs/2108.01241>.



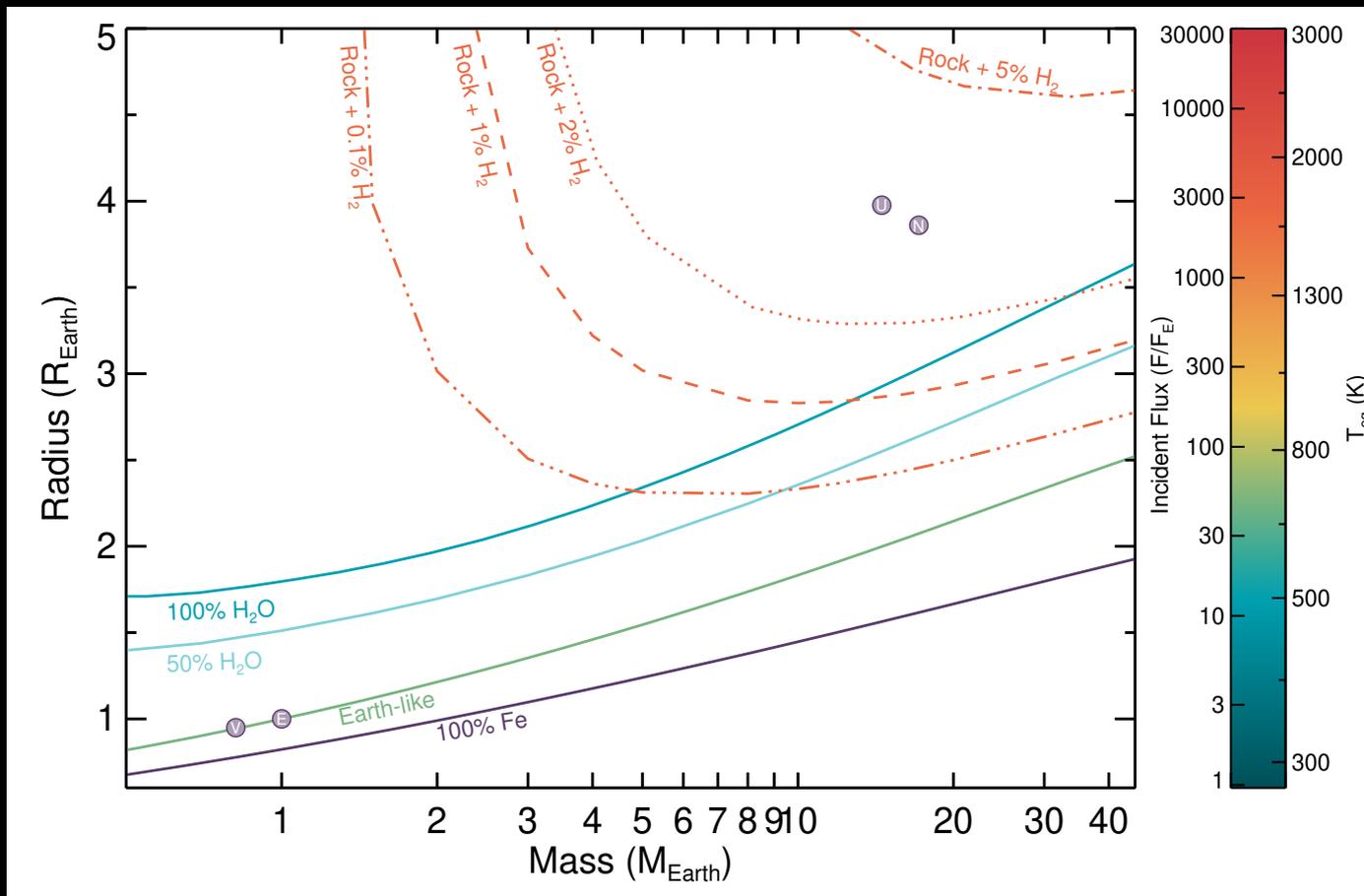


Draco

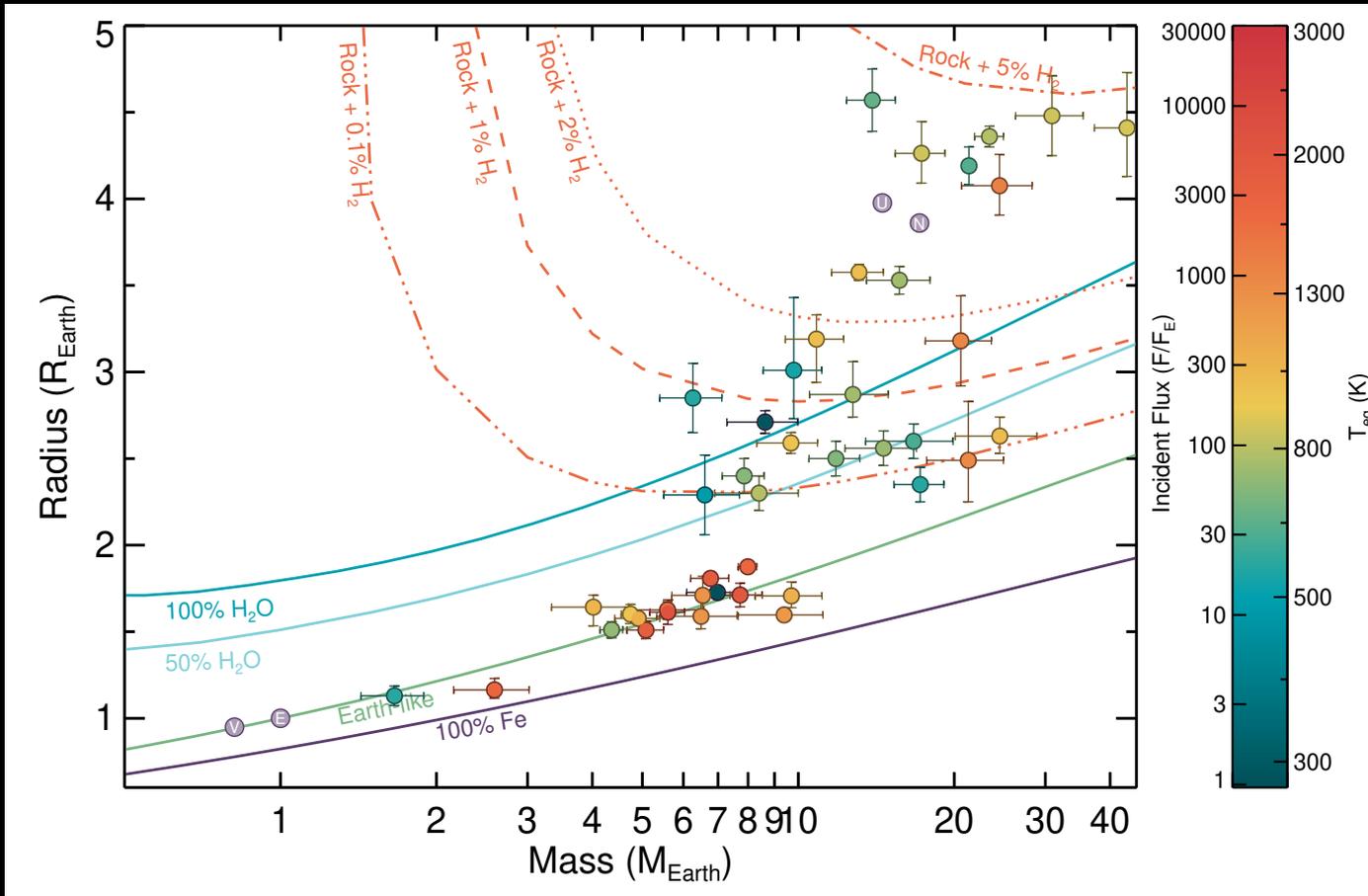


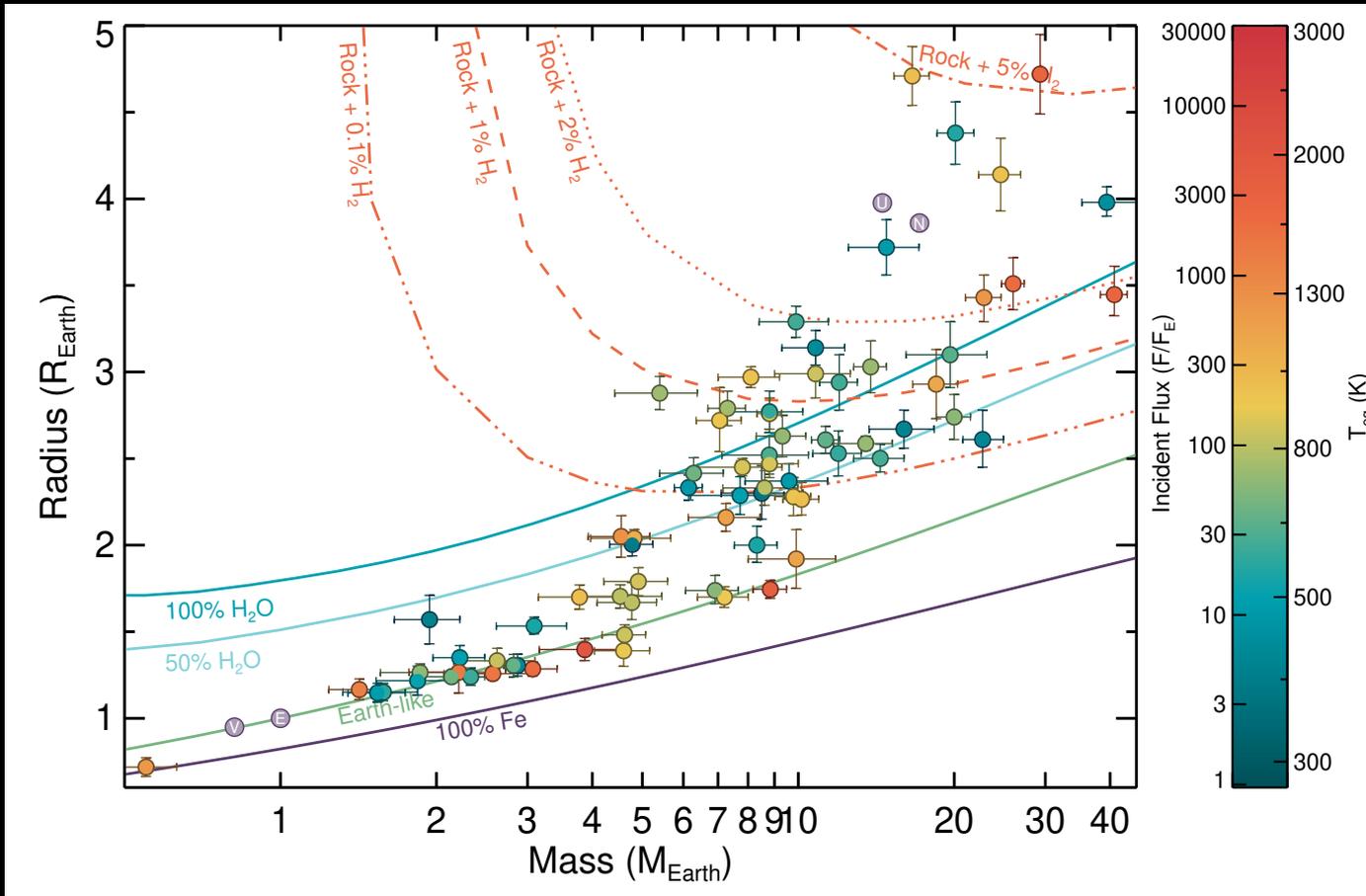
74 Draconis  
5.5 times the Sun's size

Credit: NASA/MIT/TESS and Ethan Kruse (USRA), M. Hon et al., 2021

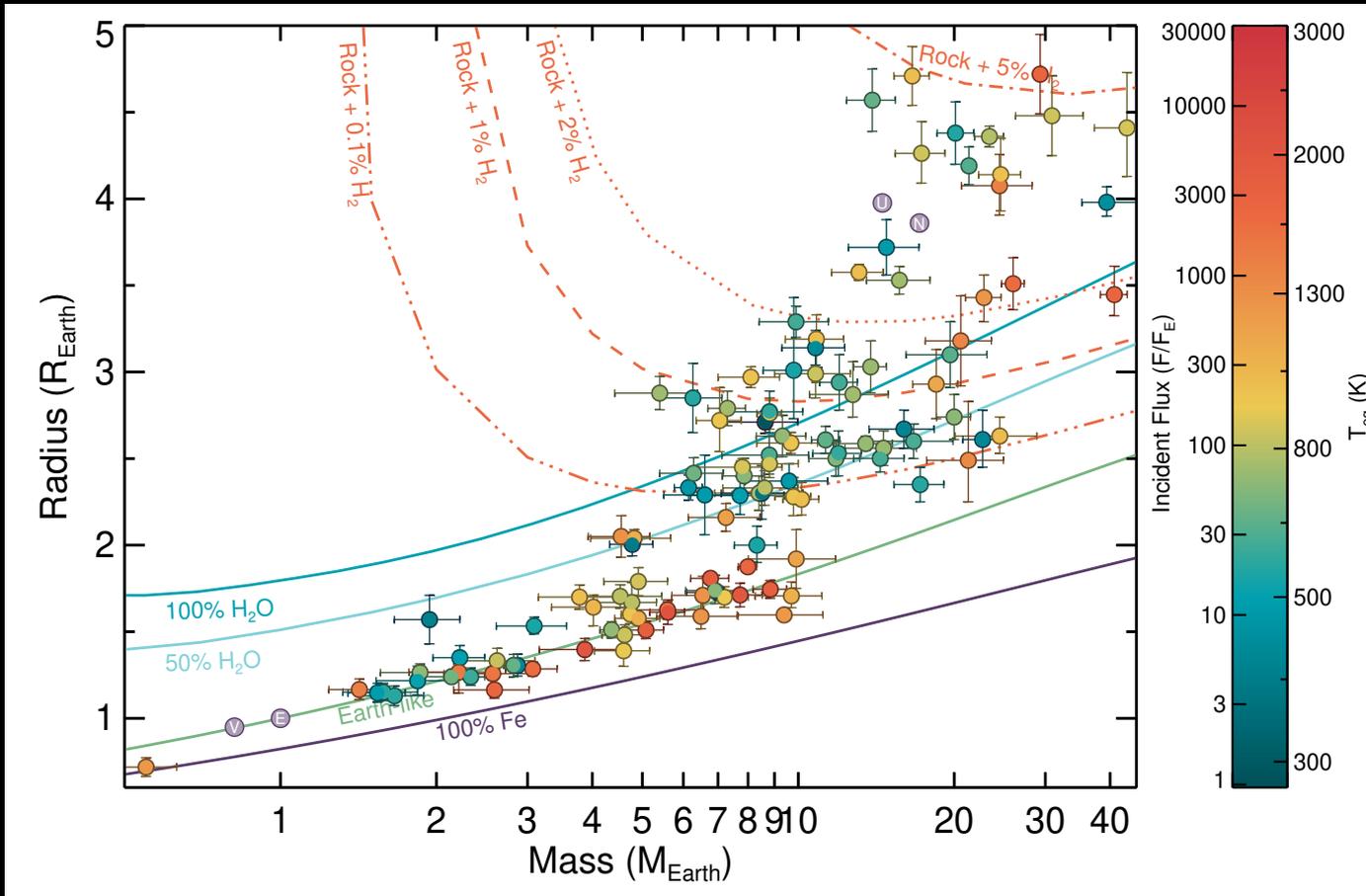


# Precise RV Masses Without TESS

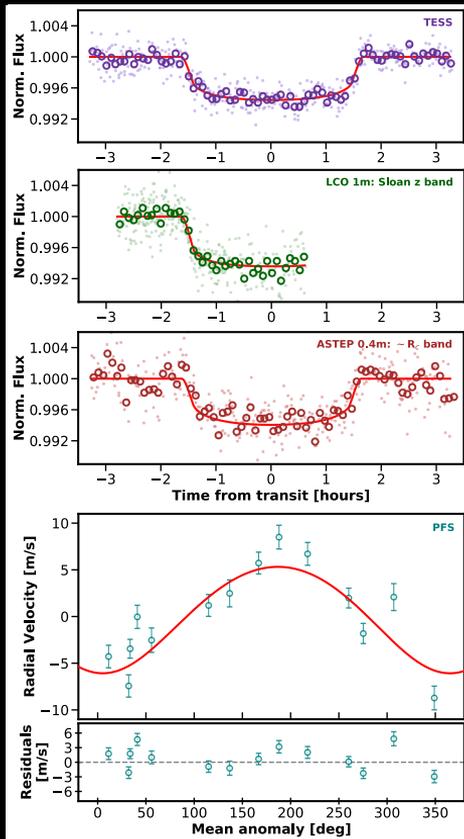




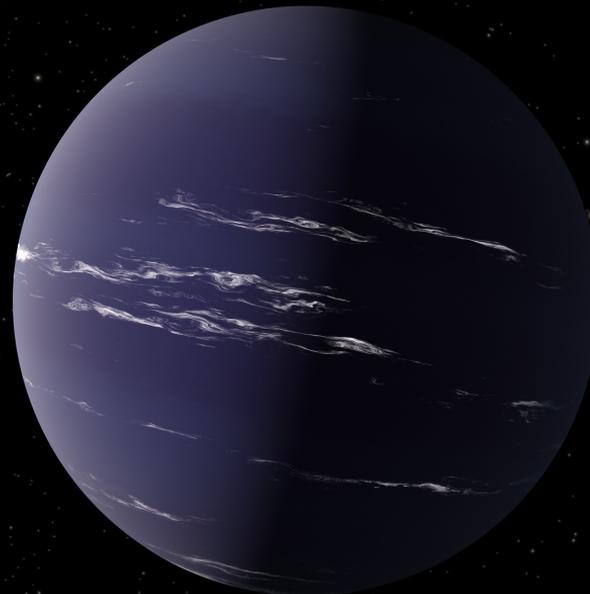
# Precise RV Masses from All Sources



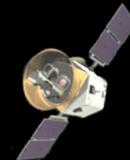
$R_p = 3.65 R_e$ ,  $T_p = 24.246$  days,  $M_p = 15.5 M_e$ ,  $T_{eq} = 330$  K



From Burt et al. 2021



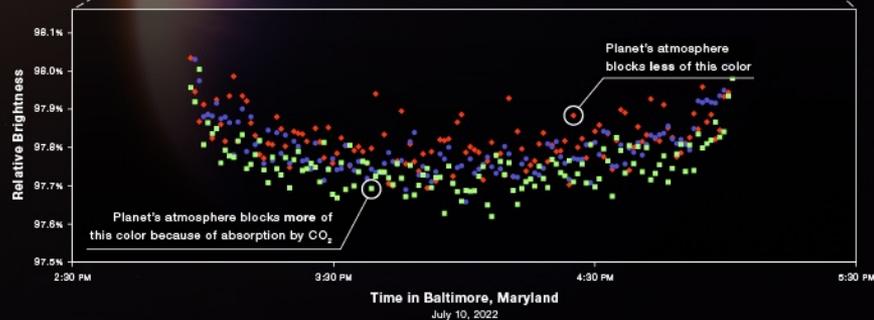
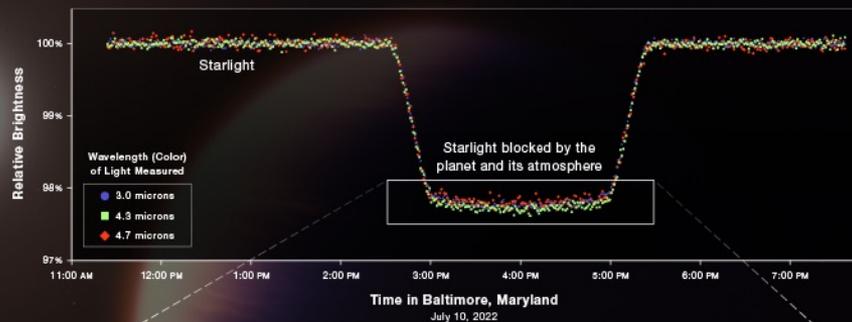
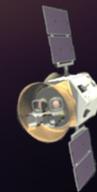
We may be able to detect atmospheric escape via Doppler velocity observations



An exciting target for JWST!

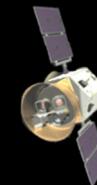
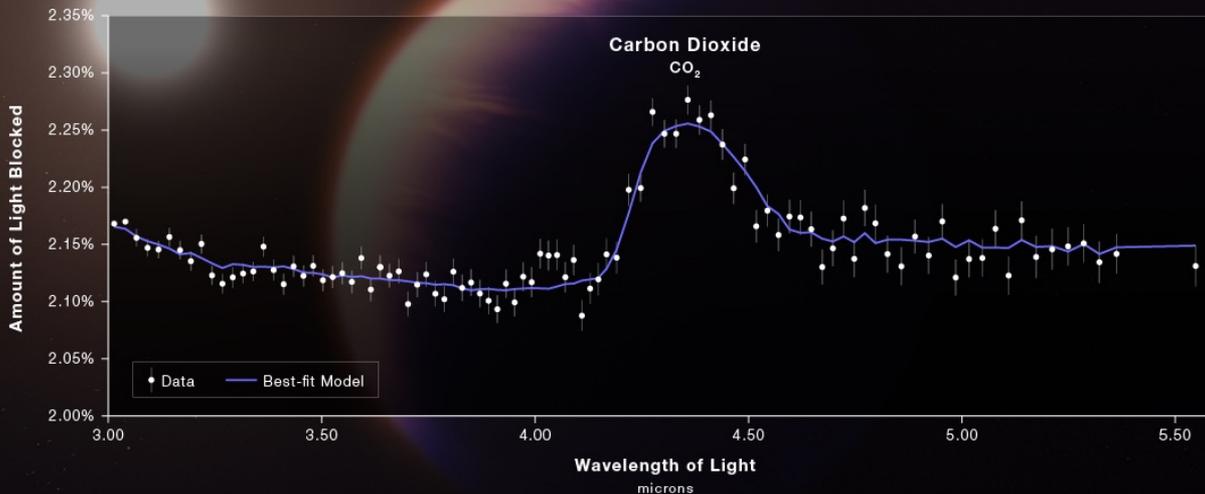
## HOT GAS GIANT EXOPLANET WASP-39 b TRANSIT LIGHT CURVE

NIRSpec | Bright Object Time-Series Spectroscopy



## HOT GAS GIANT EXOPLANET WASP-39 b ATMOSPHERE COMPOSITION

NIRSpec | Bright Object Time-Series Spectroscopy



**WEBB**  
SPACE TELESCOPE

Credits: Illustration: NASA, ESA, CSA, and L. Hustak (STScI); Science: The JWST Transiting Exoplanet Community Early Release Science Team



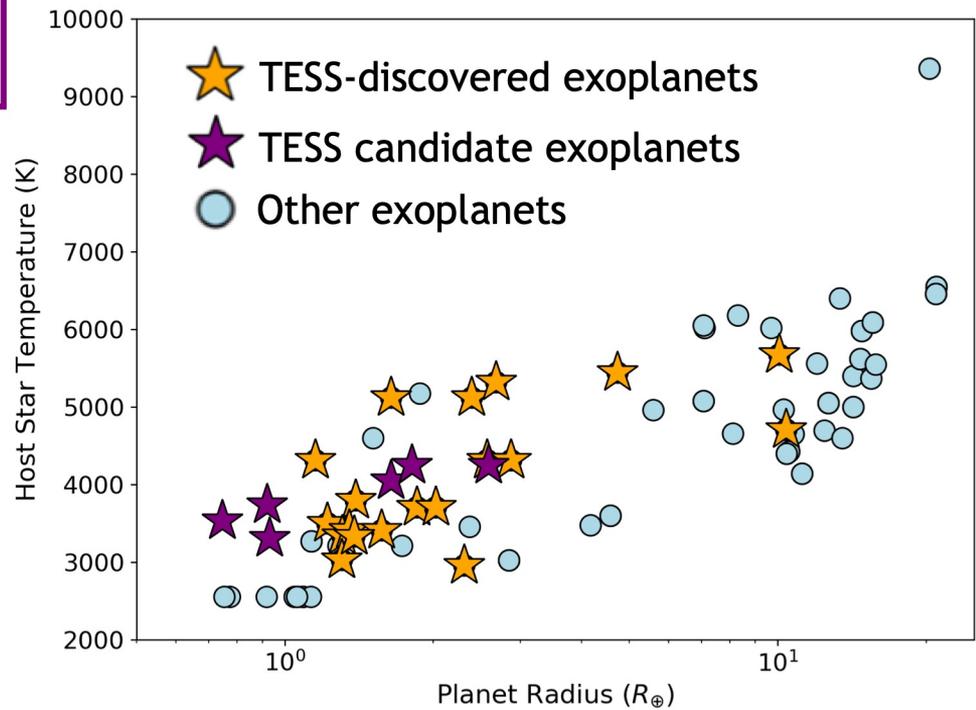
# JWST Cycle 1 Transiting Exoplanet Targets from TESS

A majority of the TESS exoplanets to be observed by JWST are small (< 3 Earth radii) and orbit small, cool stars.

Confirmed TESS Planets on the JWST Cycle 1 List

Candidate TESS Planets on the JWST Cycle 1 List

GJ 357 b	LTT 1445 A b	TOI 260.01
GJ 486 b	LTT 9779 b	TOI 731.01
HD 15337 b	TOI 178 b	TOI 741.01
HD 15337 c	TOI 178 d	TOI 836.01
HIP 67522 b	TOI 178 g	TOI 836.02
L 168-9 b	TOI 421 b	TOI 910.01
L 98-59 c	TOI 776 b	
L 98-59 d	TOI 776 c	
LHS 3844 b	W 1856 b	
LP 791-18 c		



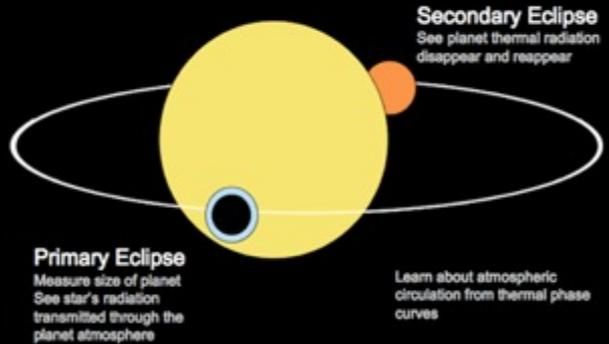
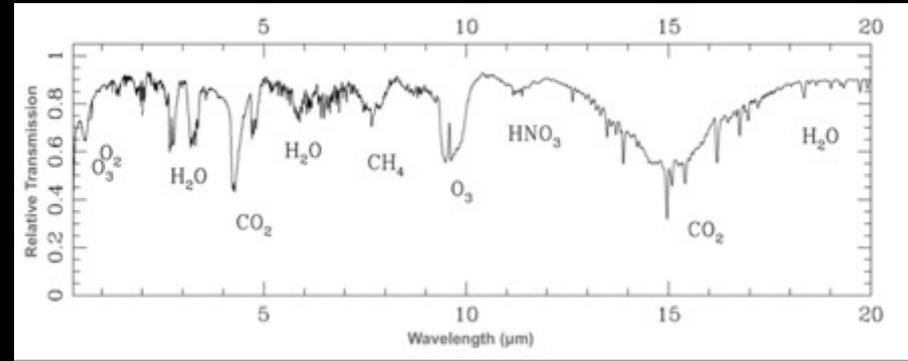


Figure by S. Seager



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

# Exoplanet Missions



W. M. Keck Observatory



Large Binocular Telescope Interferometer



NN-EXPLORE

<sup>1</sup> NASA/ESA Partnership  
<sup>2</sup> NASA/ESA/CSA Partnership  
<sup>3</sup> CNES/ESA

## Ground Telescopes with NASA participation

Do you have questions?

