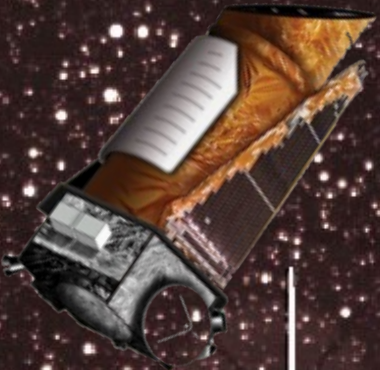
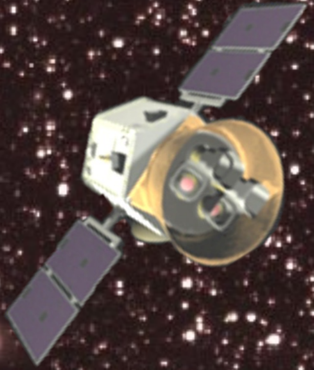
Chasing Shadows in the Night:

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





Jon M. Jenkins

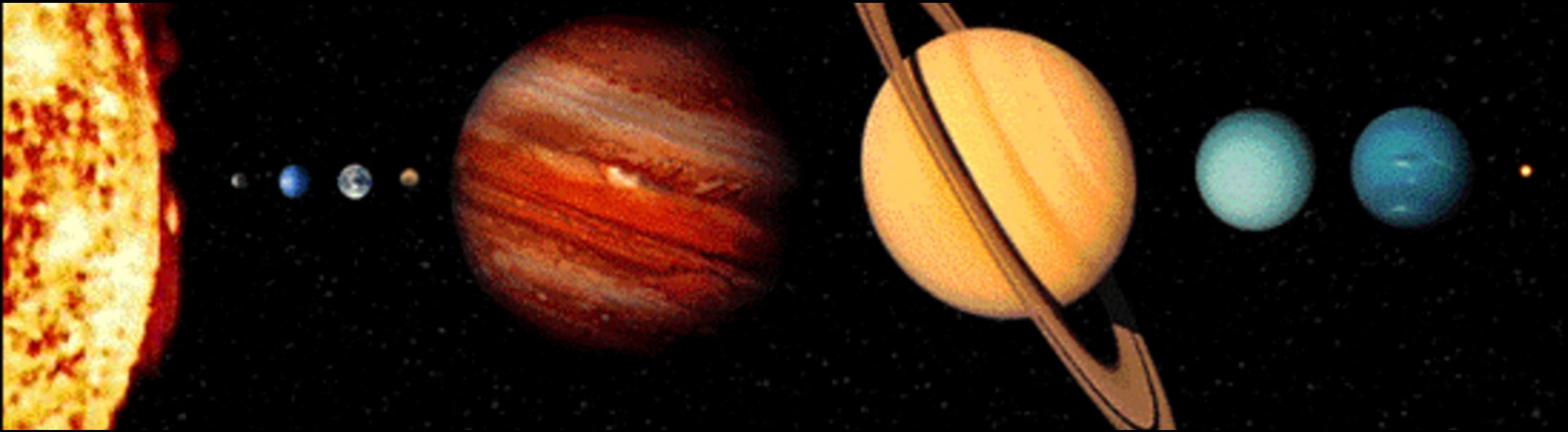
NASA Ames Research Center

Tuesday July 25, 2023

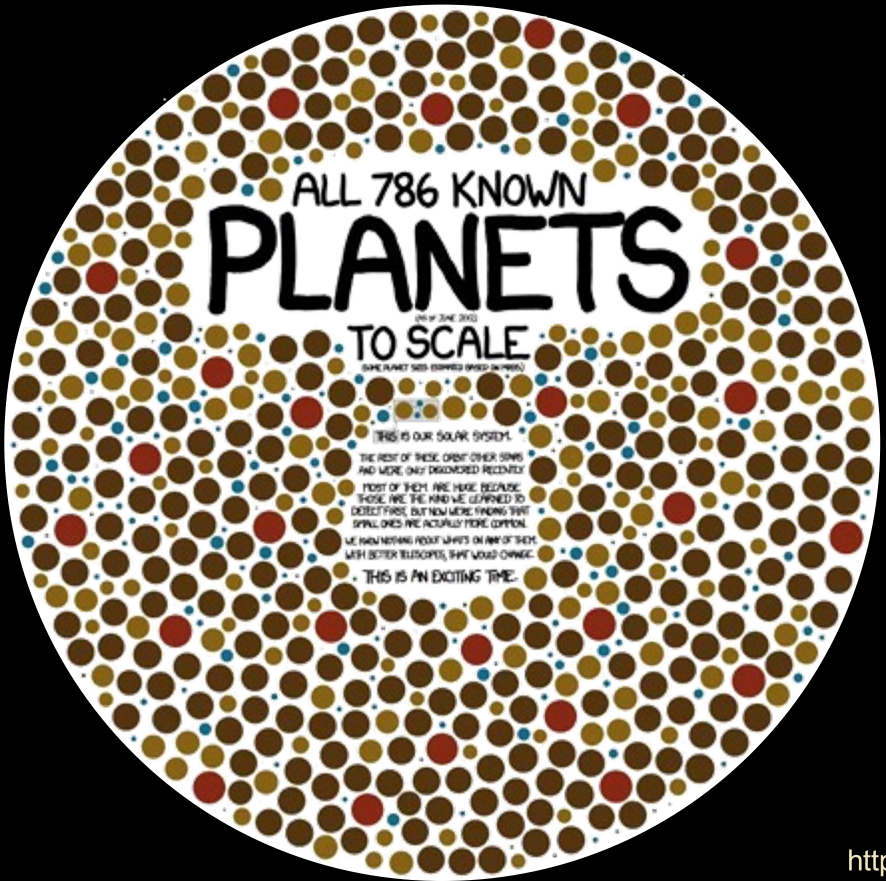
NASA Ames Research Center

Summer Series

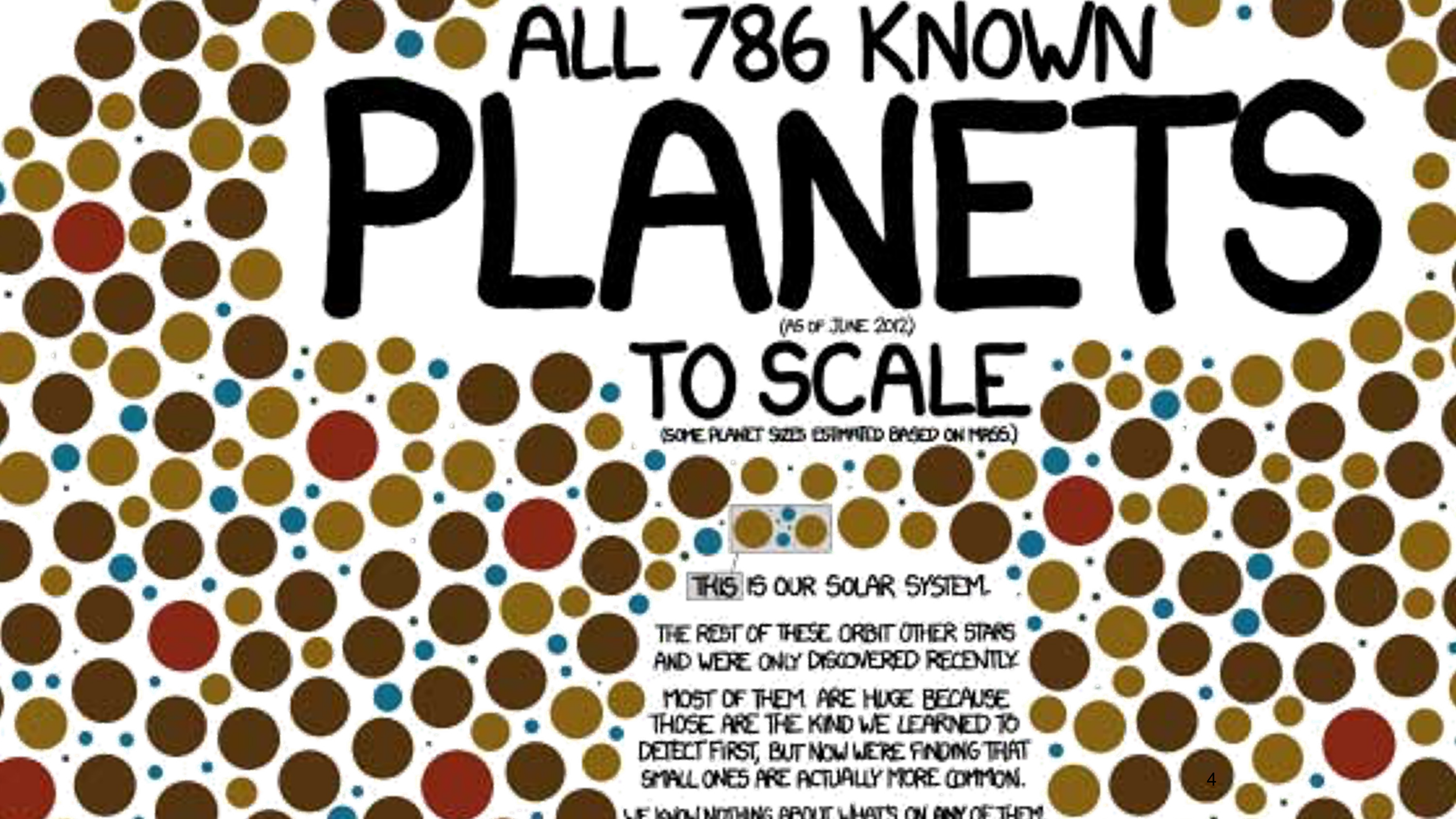
All the Known Planets In 1994



A More Recent Picture of Planets (2012)

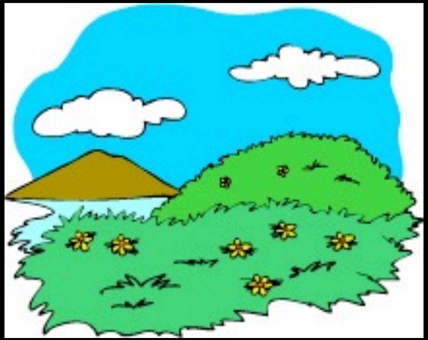


https://xkcd.com/1071/


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.

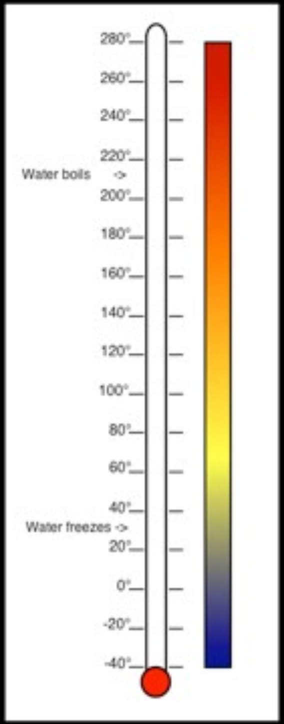
What Does Habitable Mean To You?

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



The Goldilocks Zone

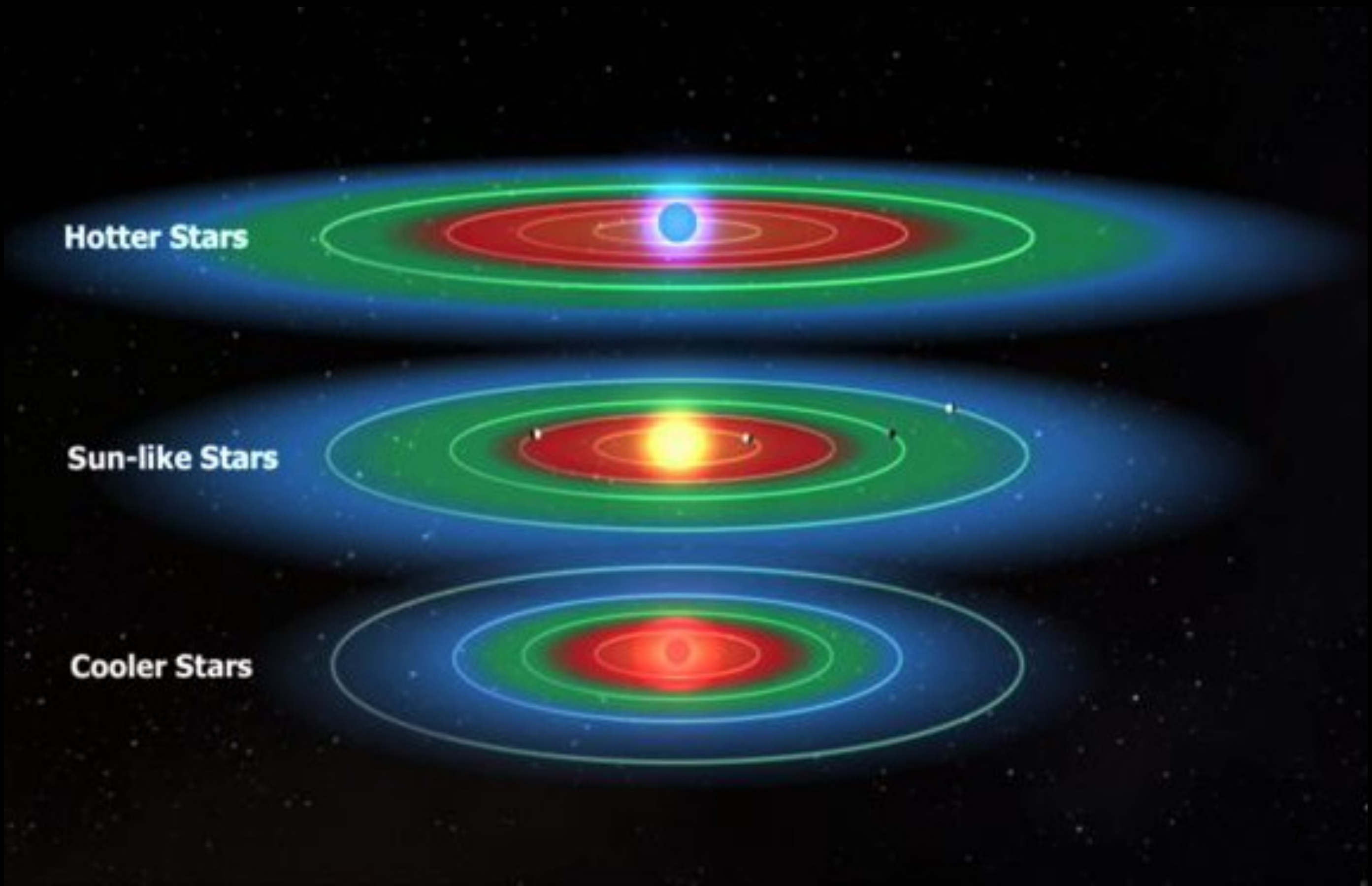
Venus: Way too hot!



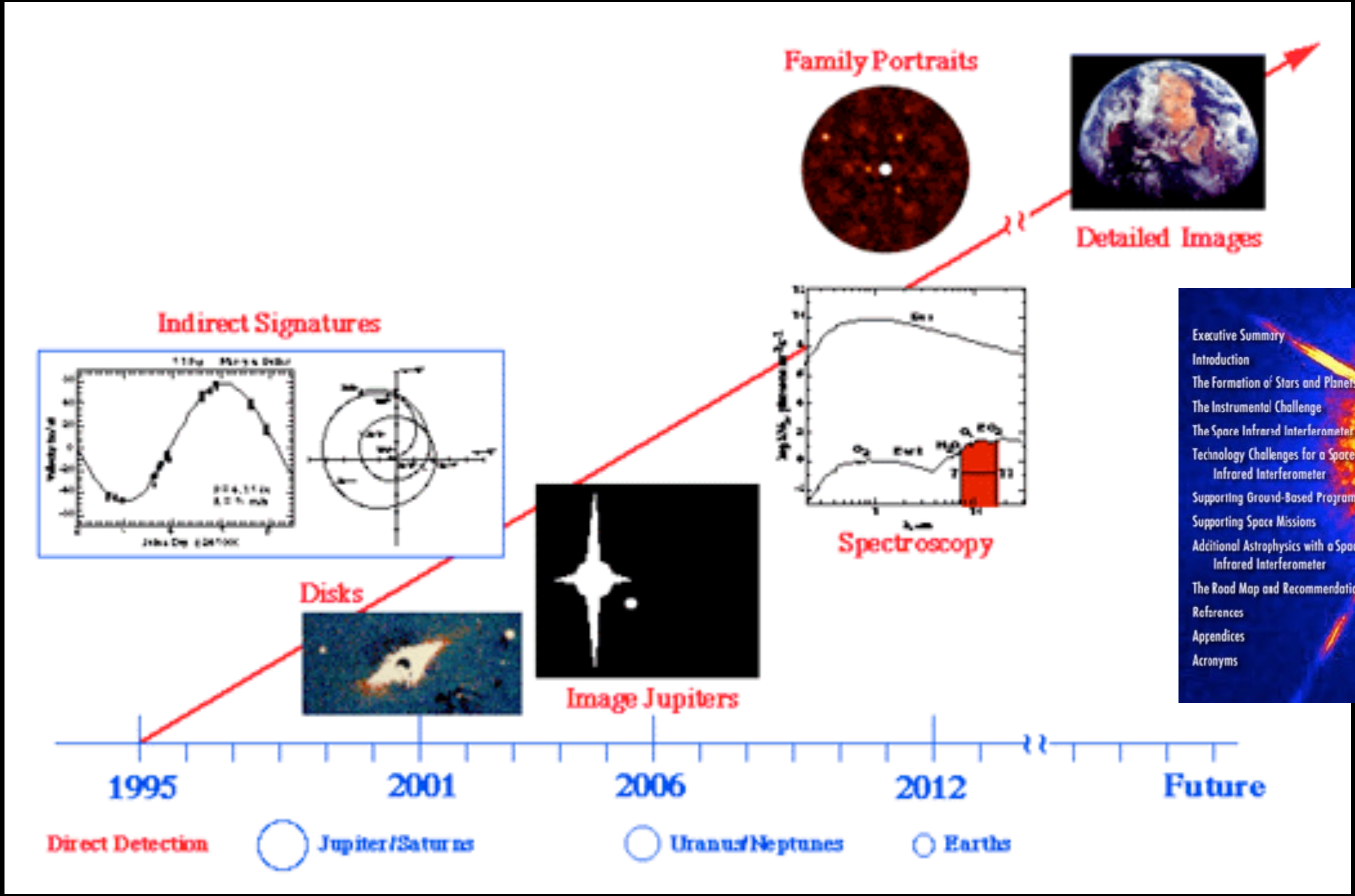
Mars: Way too cold, and small!

Earth: Just right!

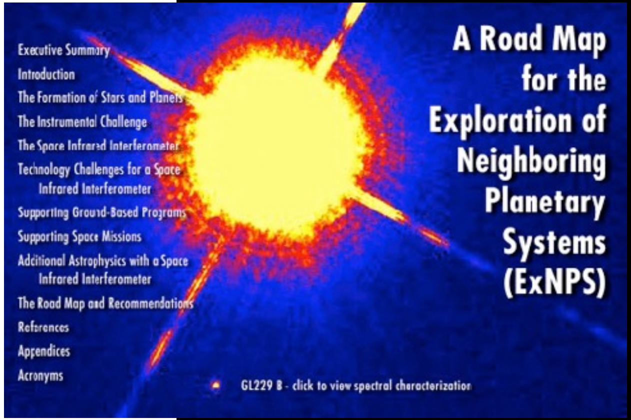
Habitable Zones



NASA's 1995 ExNPS Report



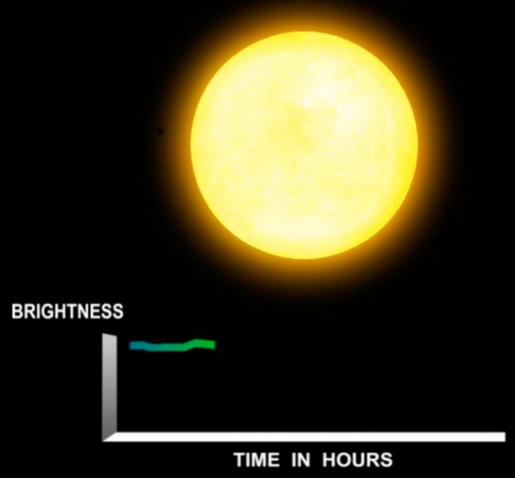
Transit Photometry not Recommended!

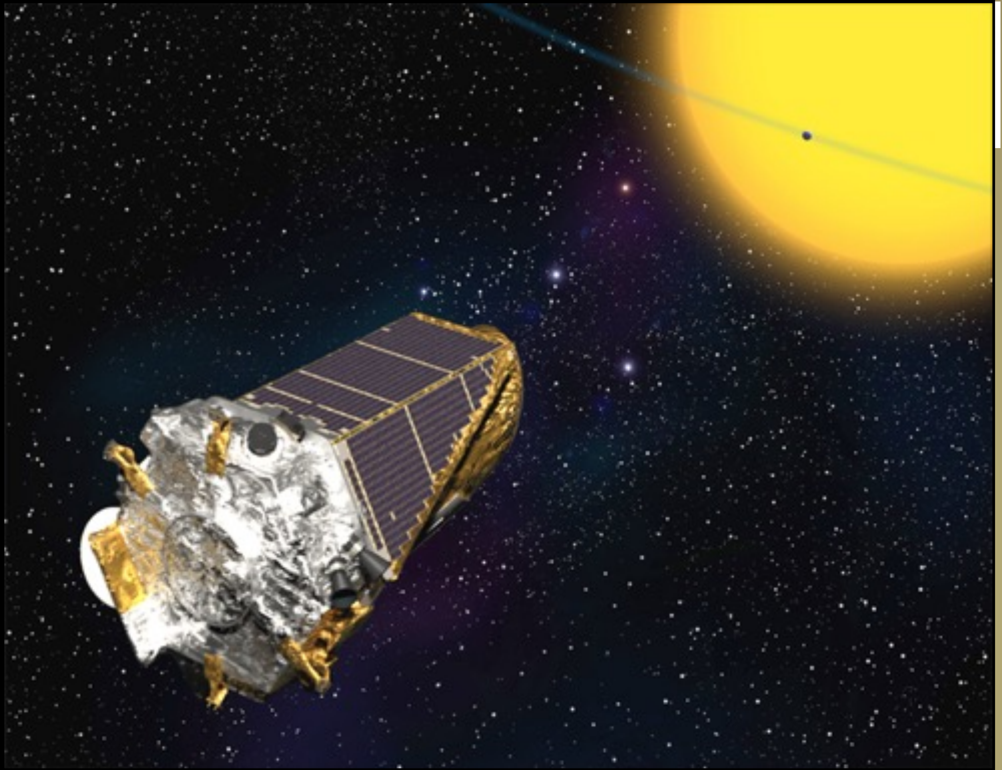


The *Kepler* Mission

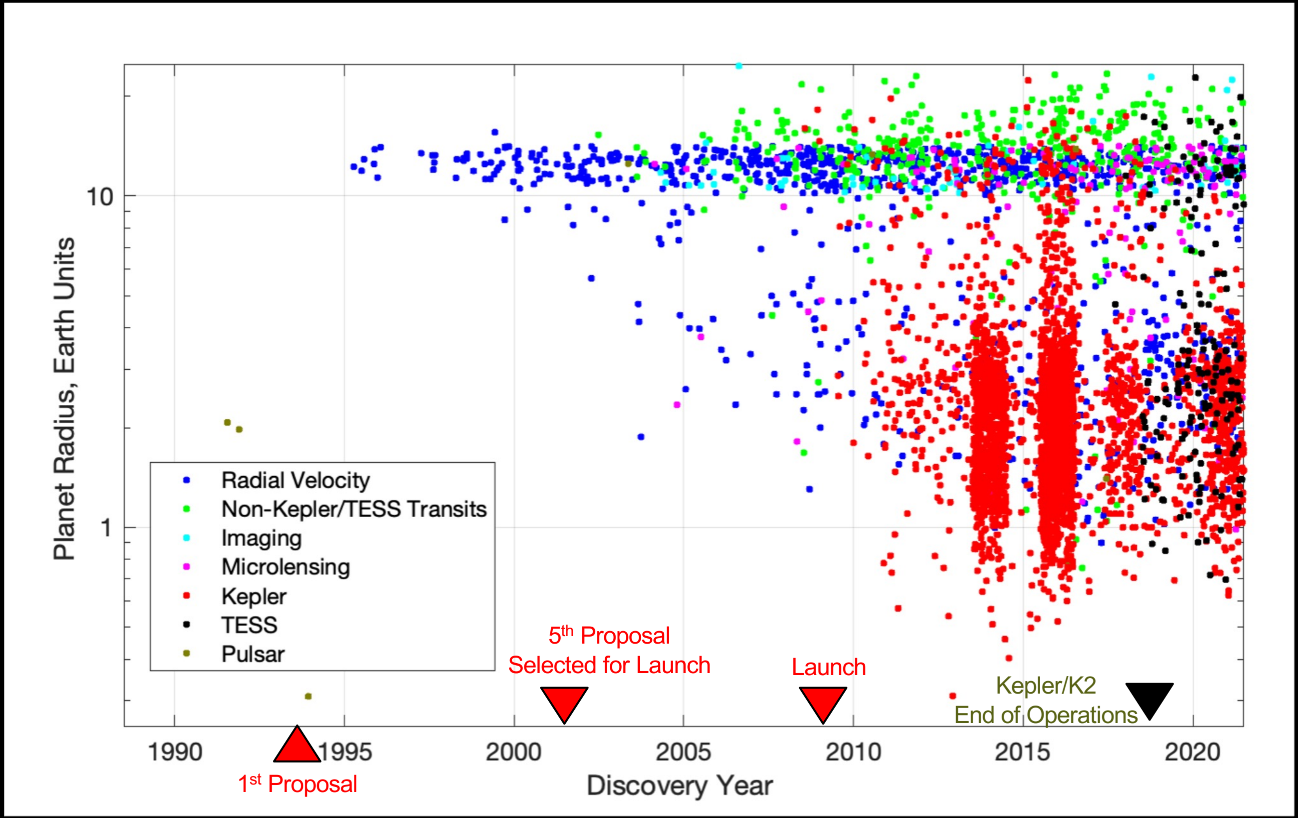
How many stars like the Sun have Earth-like planets orbiting them?

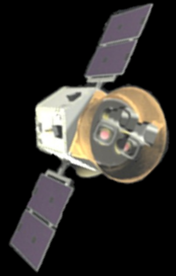
Kepler searches for transiting planets





Persistence Pays Off: Exoplanet Discoveries Over Time*



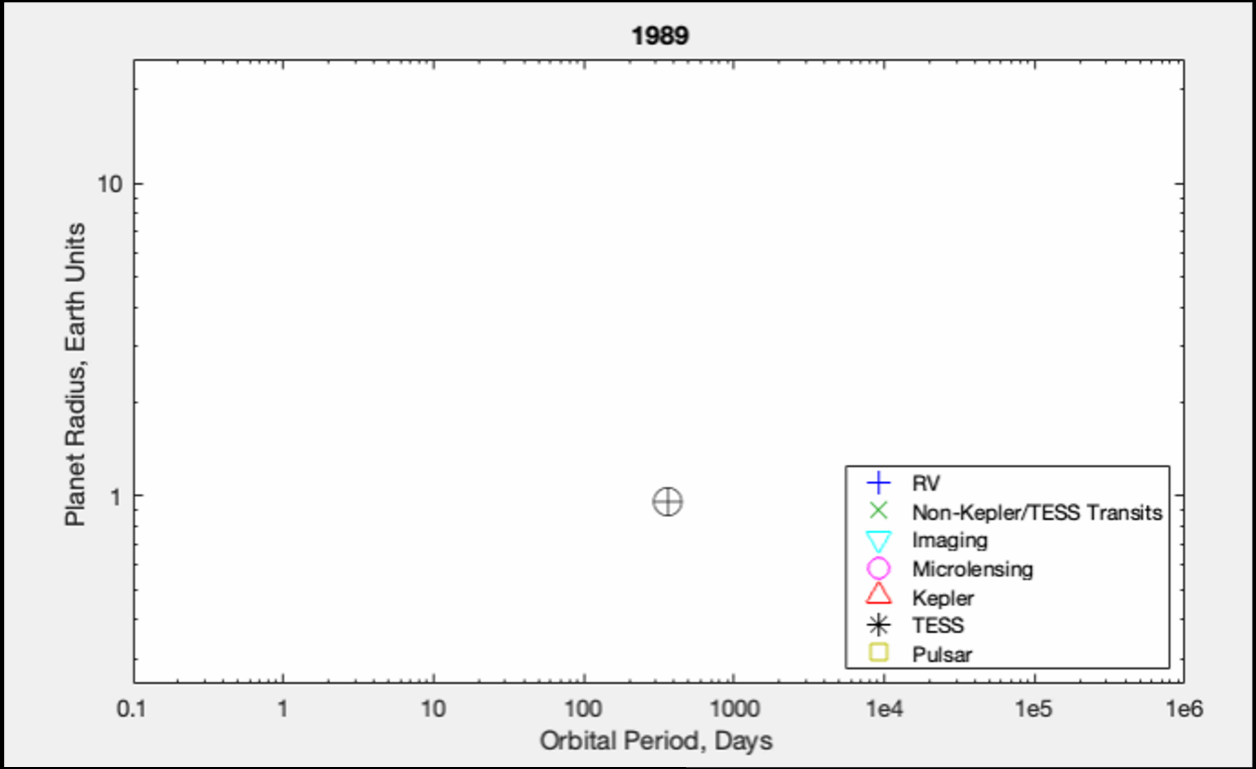


*According to https://exoplanetarchive.ipac.caltech.edu as of 10/4/21

Radii estimated for non-transiting exoplanets
Discovery date dithered slightly

Exoplanet Discoveries

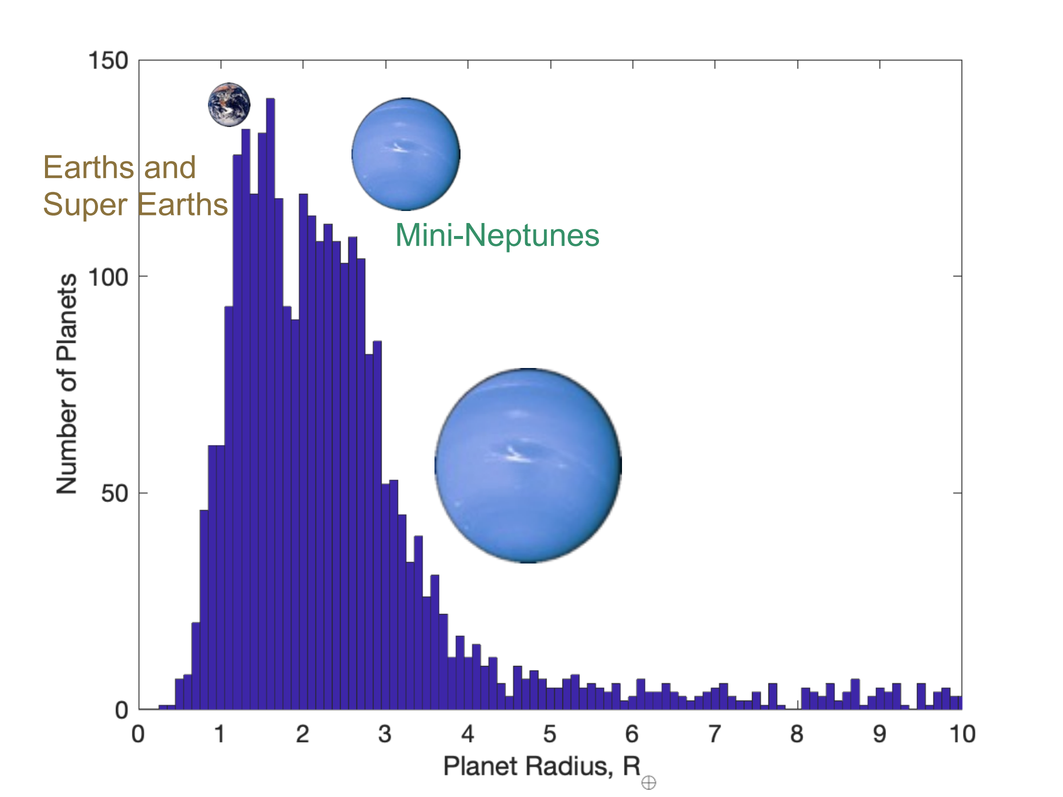
Kepler+K2:	**3306**
TESS:	**359**
Other Transit:	440
RV:	1046
Imaging:	64
μlensing:	200
Pulsar:	7
Other:	48
TOTAL:	5470



*According to https://exoplanetarchive.ipac.caltech.edu as of 7/17/23

75% of exoplanets were discovered using the transit method!

The Radius Valley



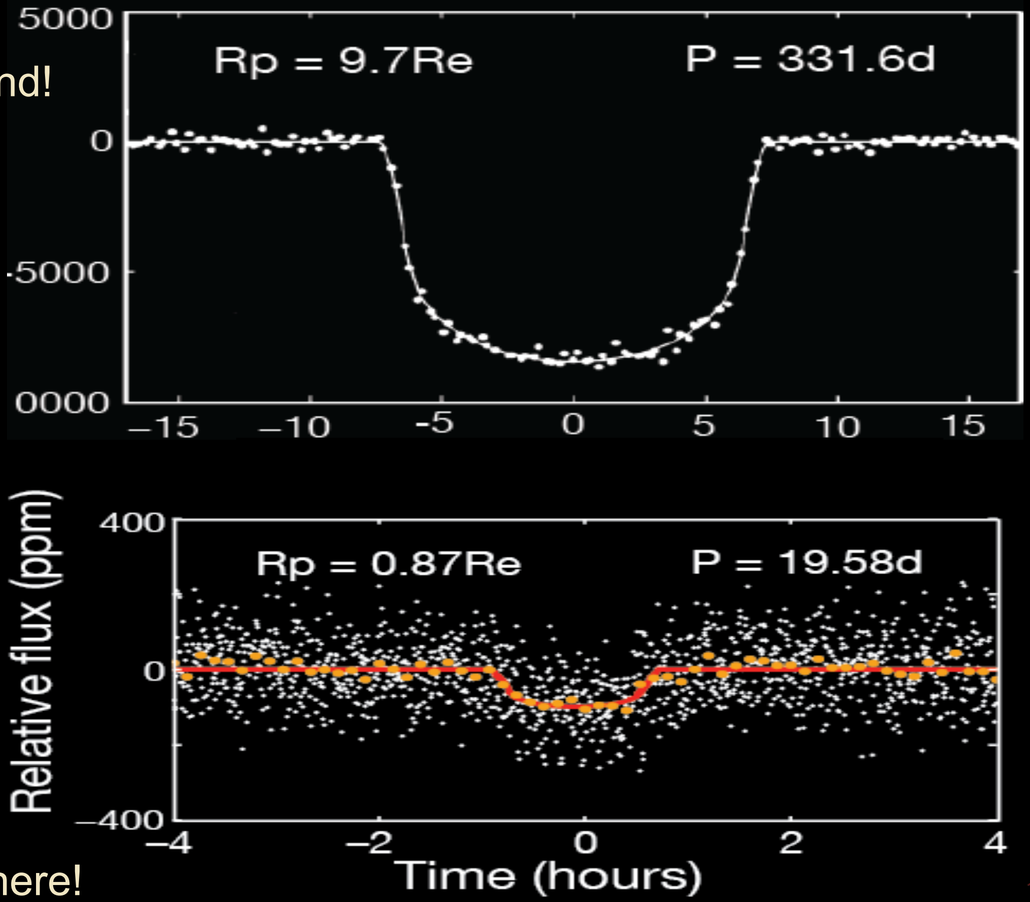
There is a gap between 1.5 and 2 R_{earth} indicating two populations

How Hard is it to Find Good Planets?

Kepler
A Search for Earth-size Planets

Easy to find from the ground!

Jupiter (~1%)

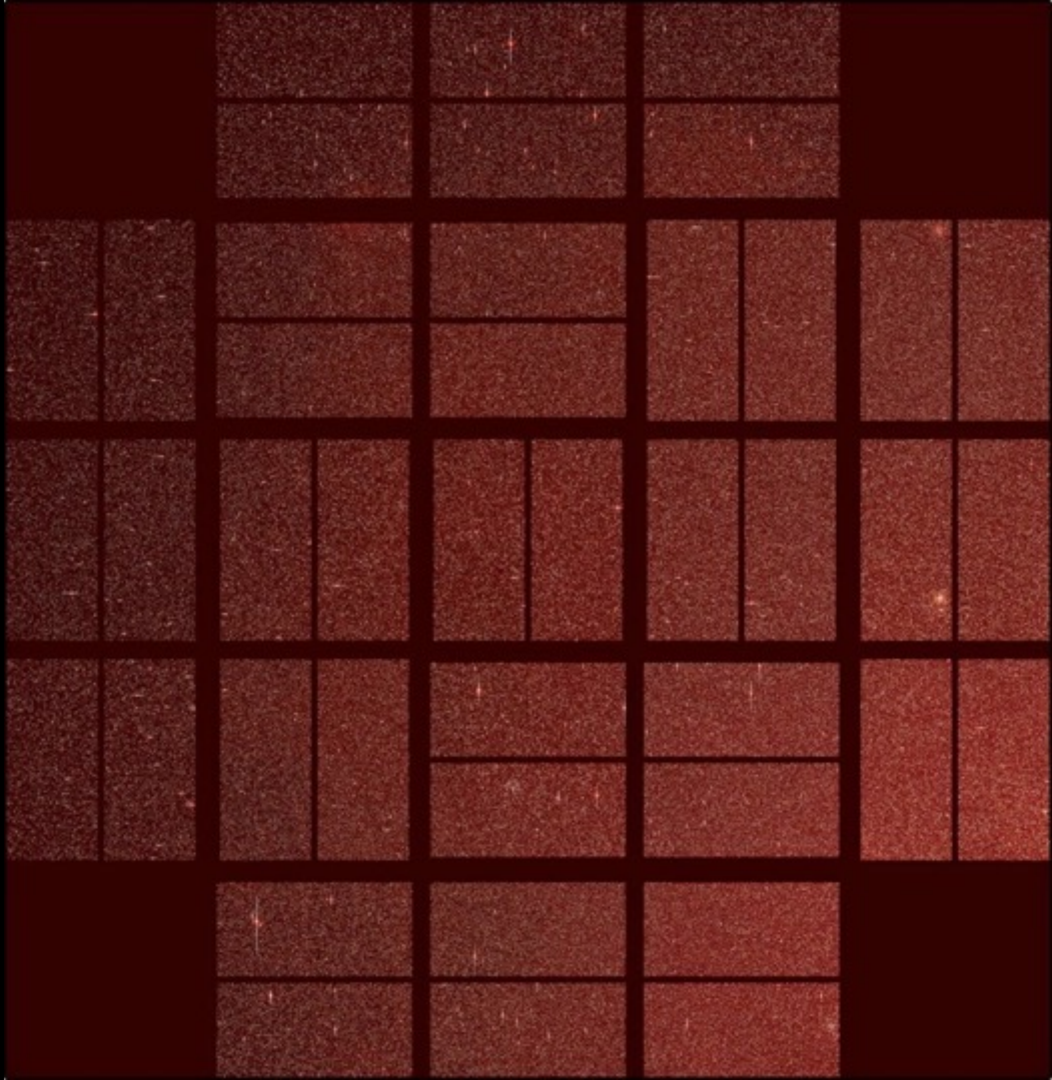


Earth (~0.01%)

Hard to find from anywhere!

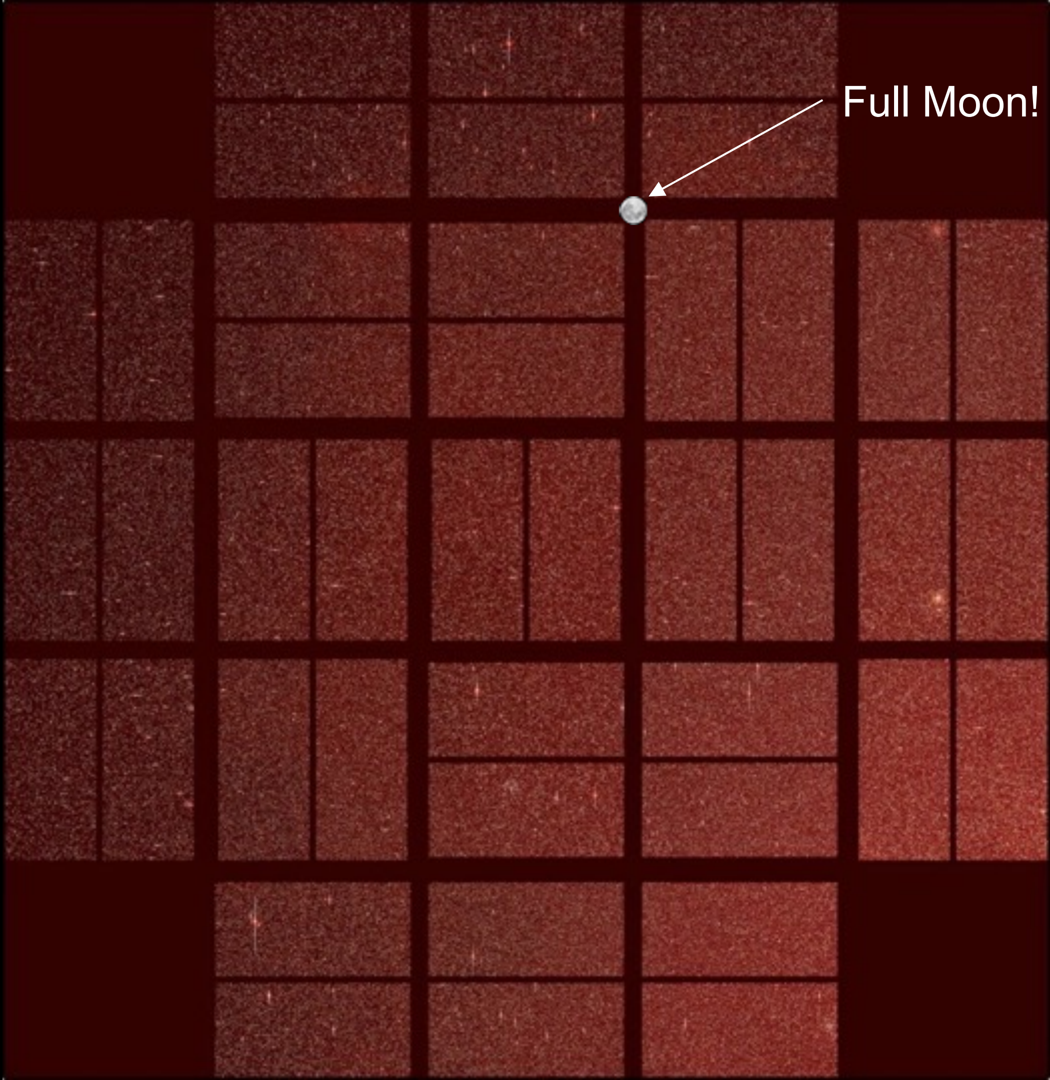
First Light Image

Launched
March 7 2009



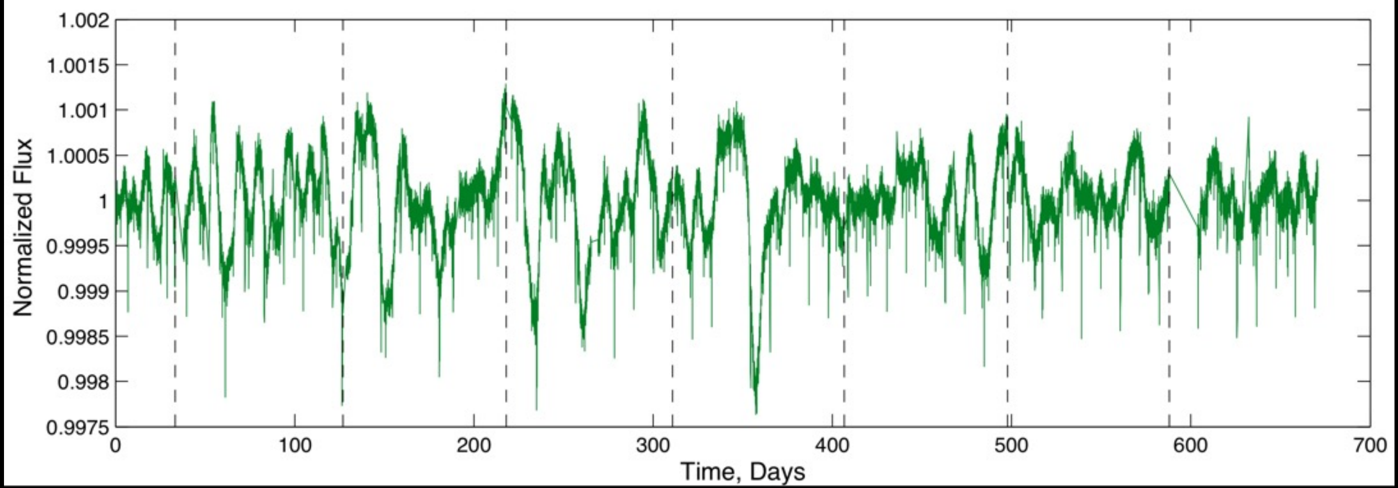
First Light Image

Launched
March 7 2009



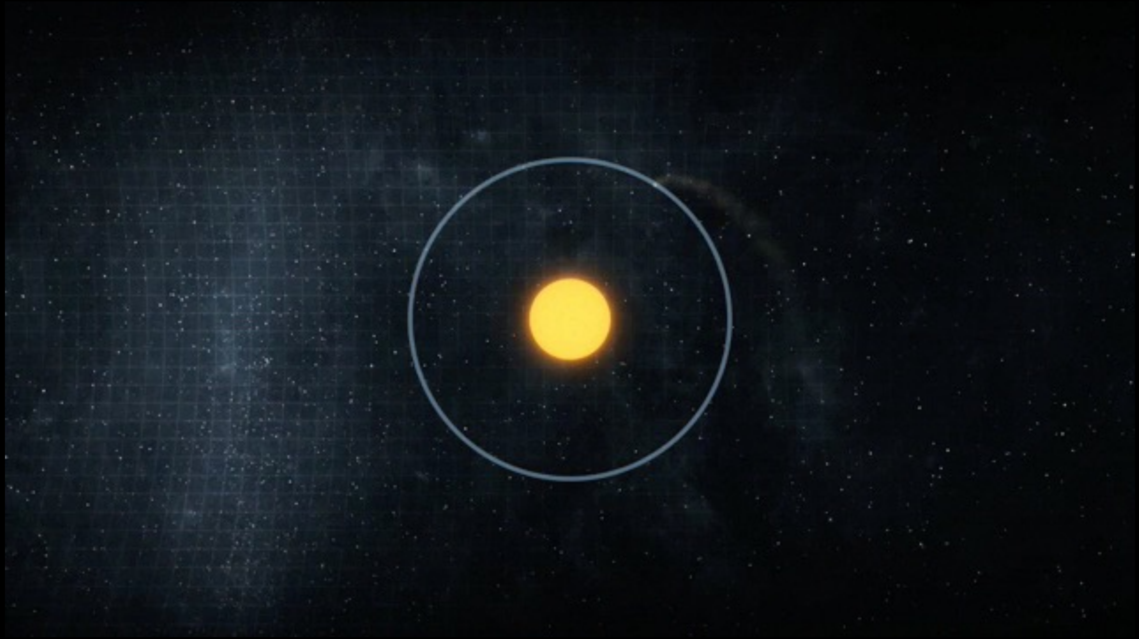
Kepler-20

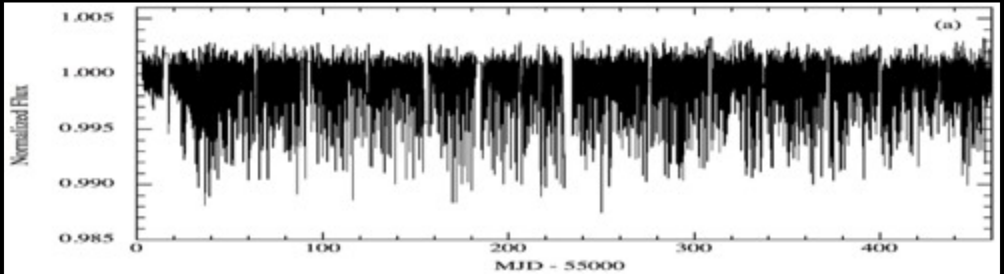
A Search for Habitable Planets

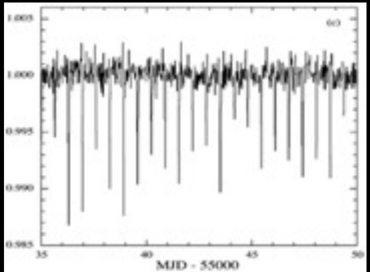


Circumbinary Planets:

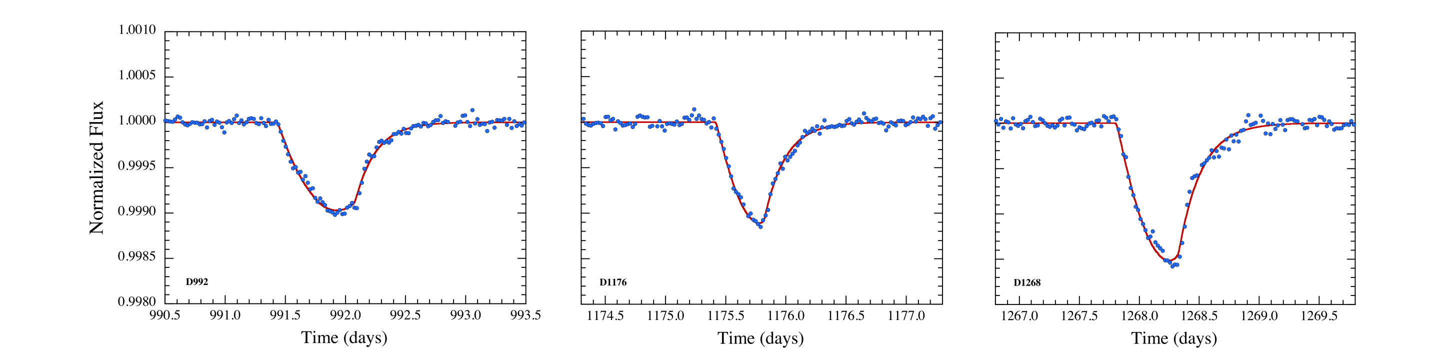
A Disintegrating Sub-Mercury-Size Planet

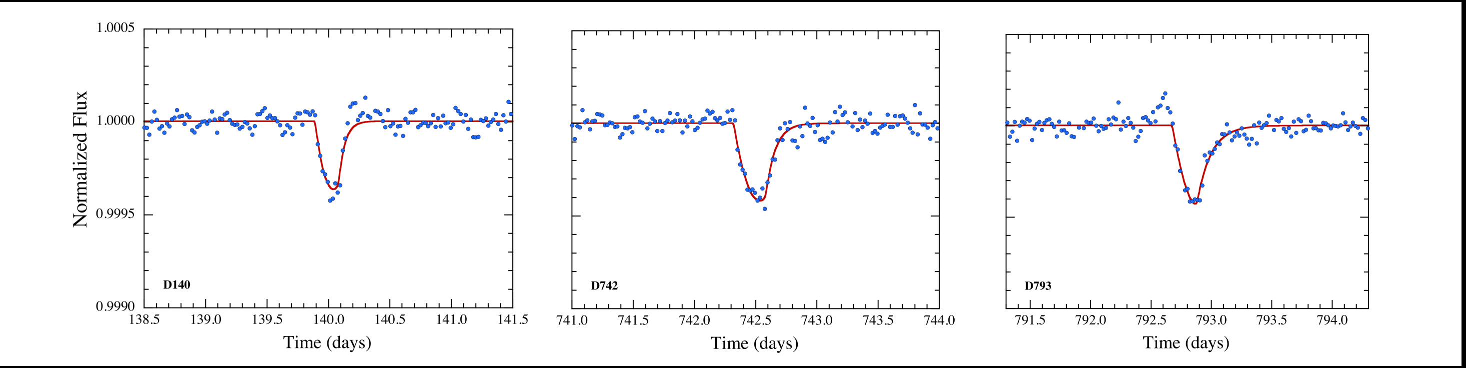






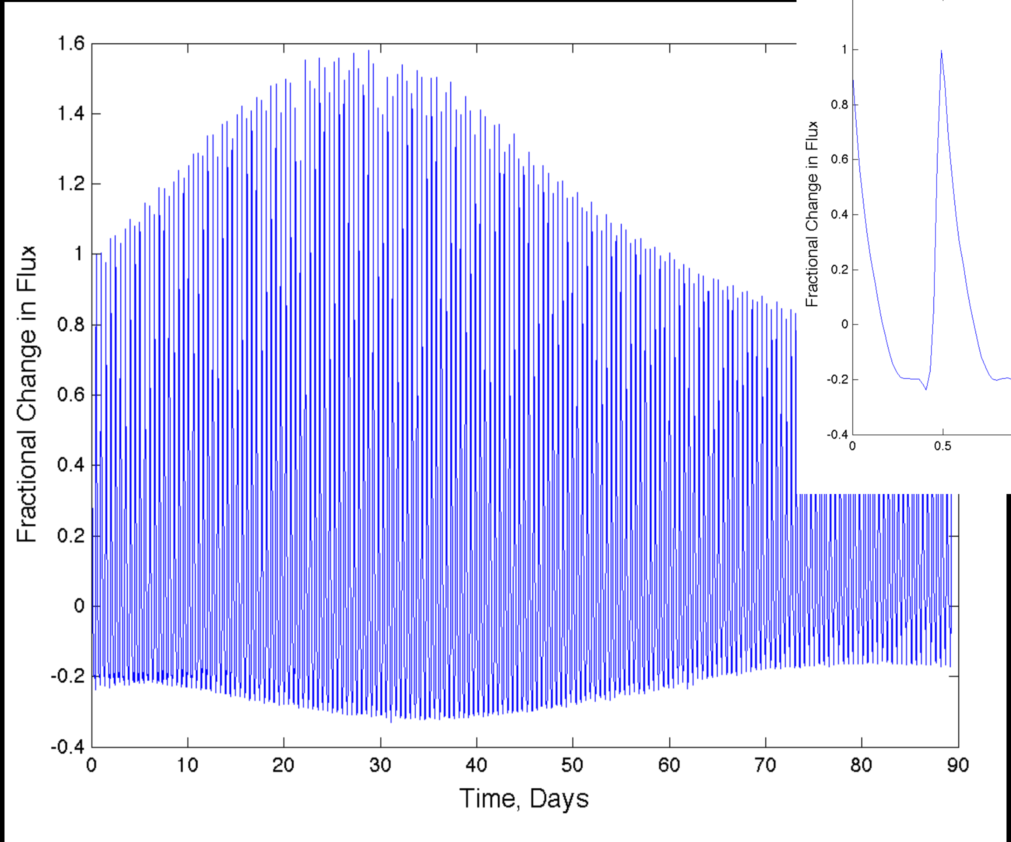
KIC 3542116: An Exocomet Candidate

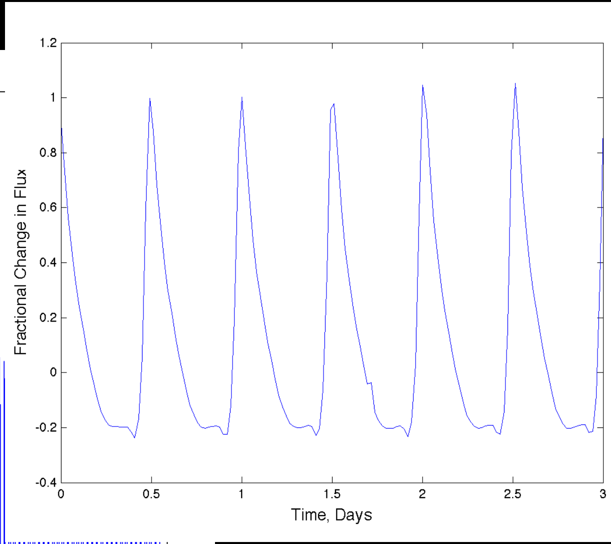




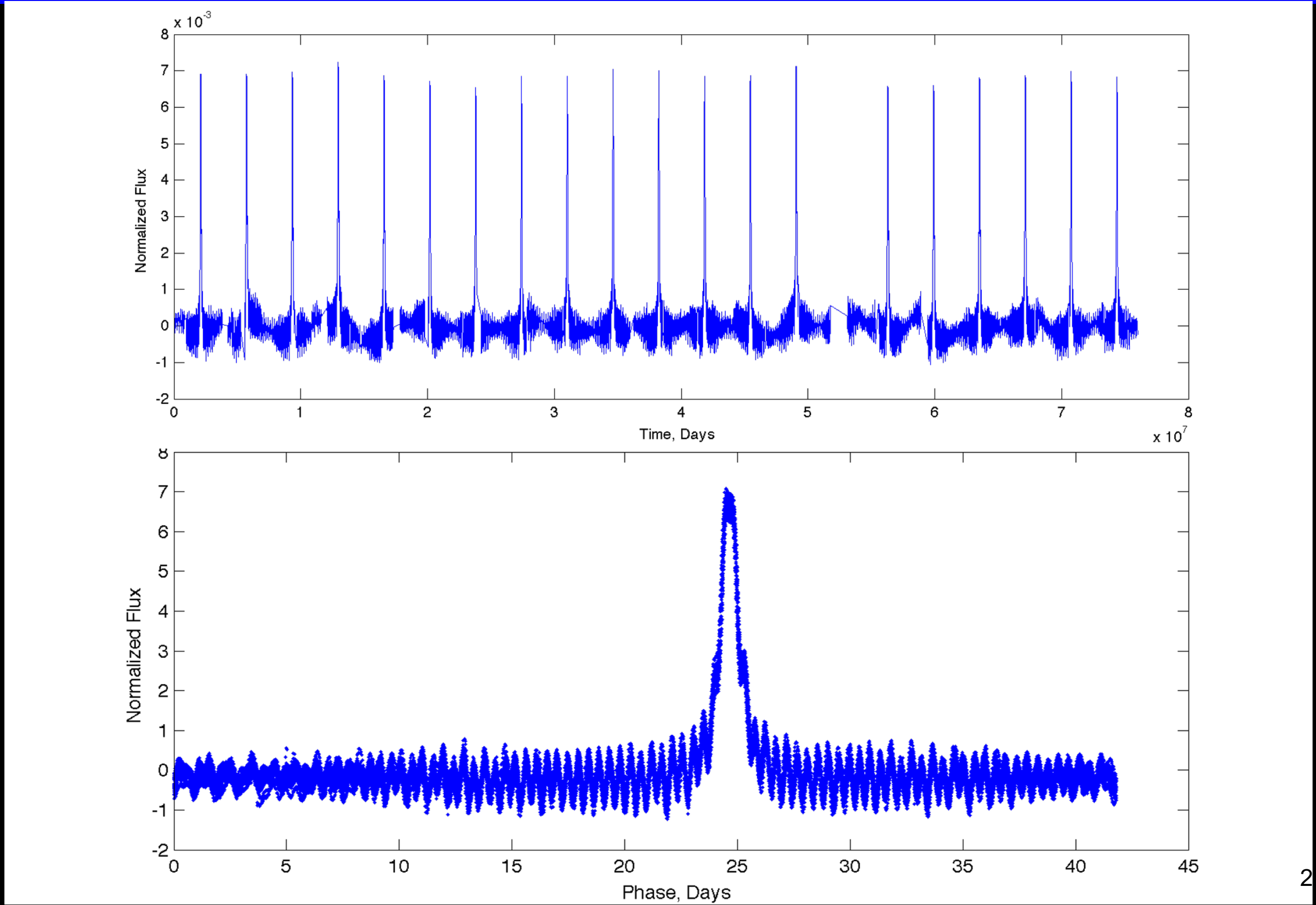
Rappaport et al. 2017, arxiv1708.06069

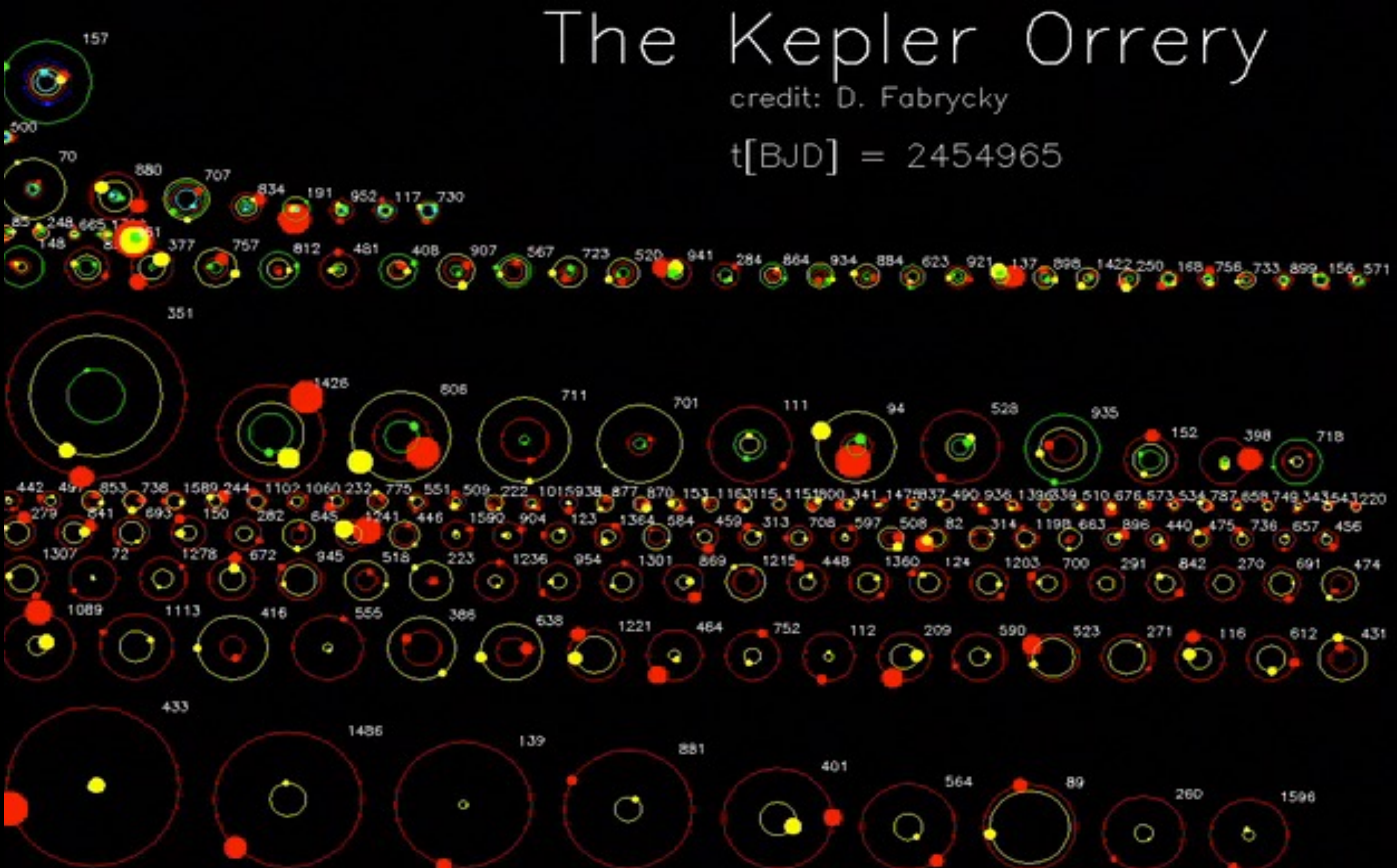
An RR Lyra Star





Heartbeat Stars: KOI-54




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

HECC Overview

NASA Ames' High-End Computing Capability (FY21 Budget: $47M)

- NASA's only cloud-scale private HPC cloud infrastructure
- Similar economics of scale to CSPs who run multiple hyperscale data center
- Robust power infrastructure from aero/windtunnel heritage (each >100MW)
- Current Pad/Power infrastructure can scale out to ~1 Billion SBUs (7.5x)
  - straight forward to double again
- > 620,000 CPU cores > 614,000 GPU cores
- > 17,000 compute nodes - (delivered 110 million SBUs FY21)
- > 100 PB of on-line data storage
- > 350 PB of off-line tape data
- Supplementary analysis systems
- Scientific Consulting for Optimization and Help (significant code speed up)
- Data Analysis and Visualization – as a service

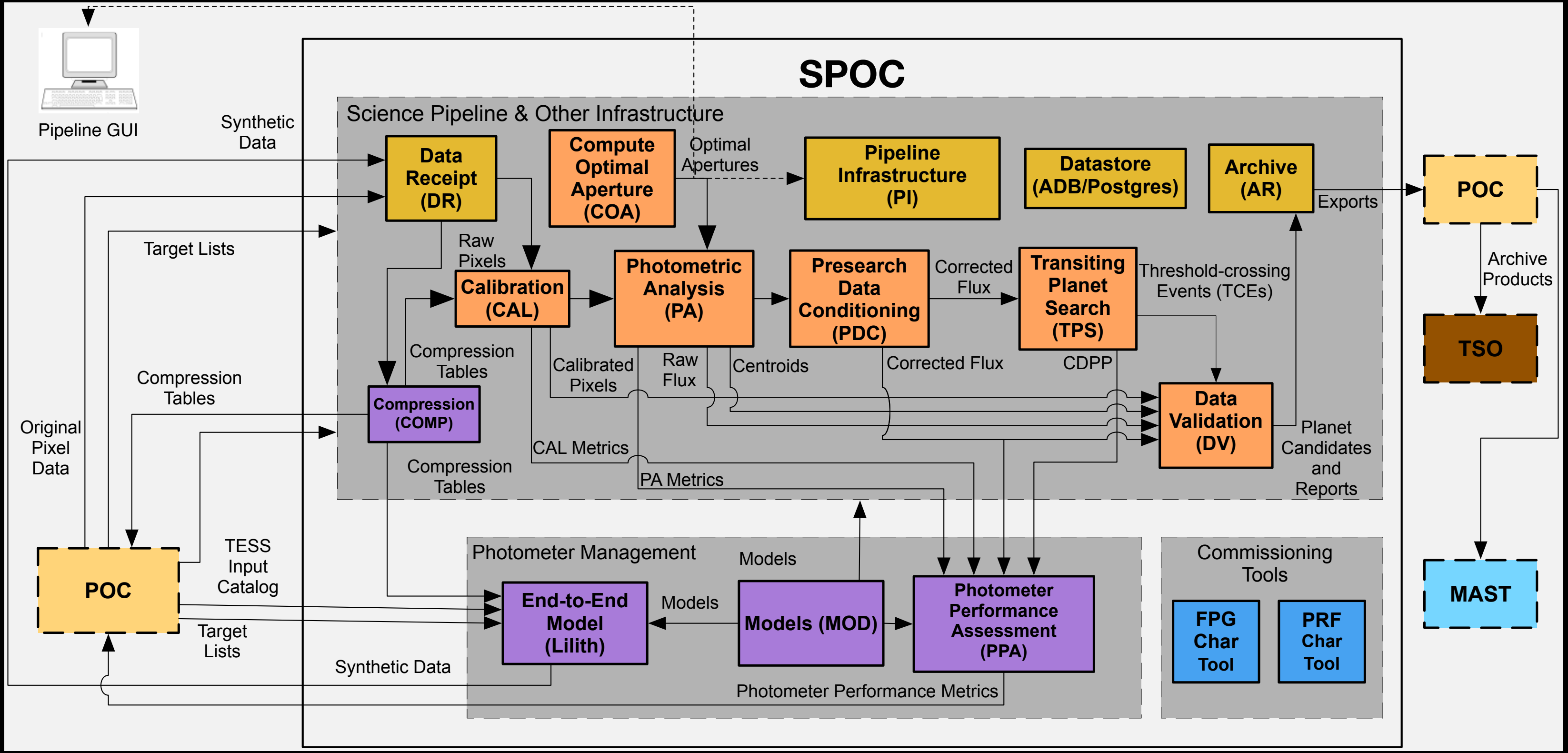
Traditional focus on modeling and simulation (Data Producer)

- Evolving Support for Hybrid Computing (On-prem/Cloud)
- Improvements around Latency (reservations and dedicated systems)

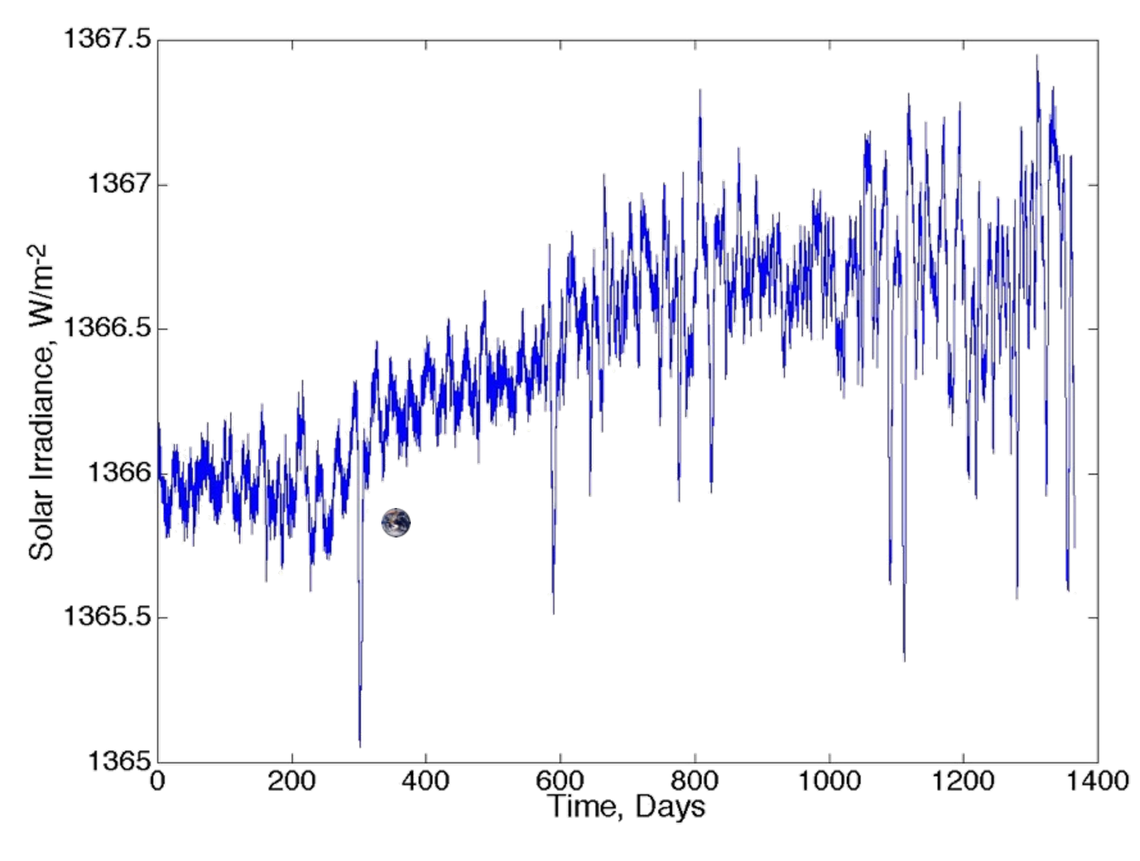
Growth in the size and nature of SMD data sets and SPD-41 motivating changes in HECC

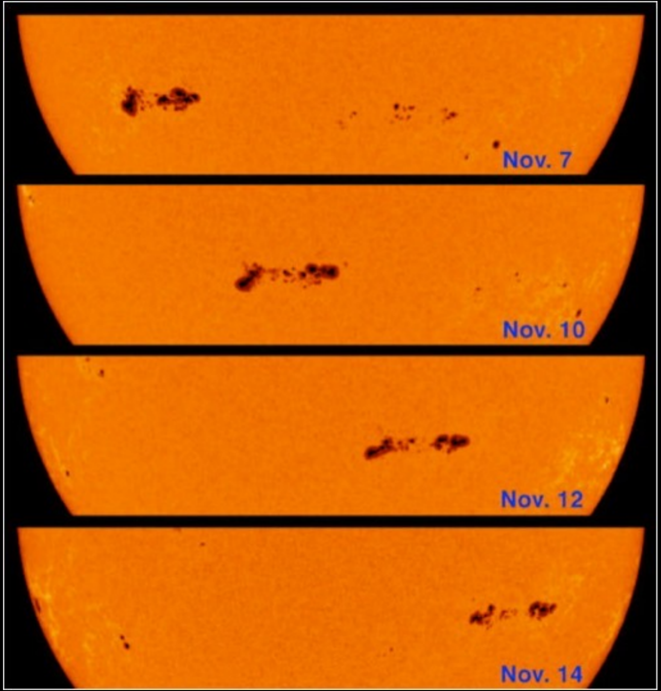
- ECCO (Ocean Only Model Outputs) – 4 PB data set accessible through the NAS Data Portal
- GEOS Coupled – 3 PB of scratch space (https://gmao.gsfc.nasa.gov/GEOS_systems/)
- ECCO with GEOS5 – increased simulation output ~10 – 20 PB
  - Ocean Biology (e.g., predict whale migration/feeding patterns based on food sources estimated from global models)
- NASA's Earth Exchange (NEX) - 5.9 PB of on-line storage, used for data cache based on projects requirements for a given funding cycle.
- SBG is expected to collect 2.4 TB day^{-1} and produce 40 TB day^{-1} of data products

Science Processing Overview



Solar-Like Variability





Data from ESA's SOHO Mission

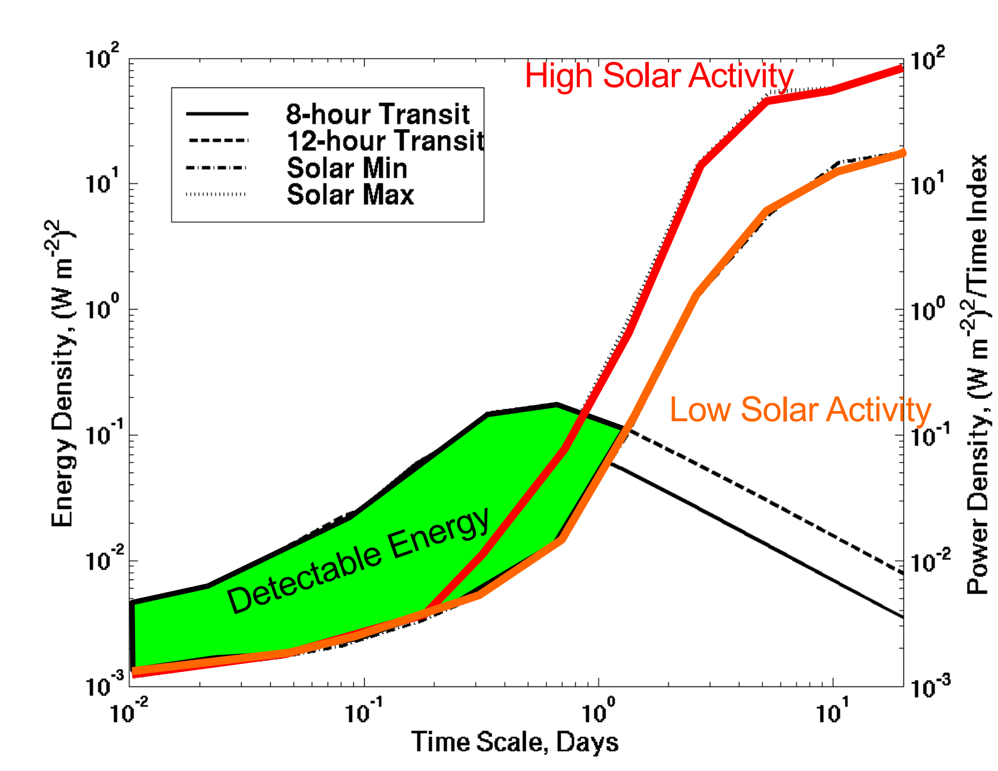
PSDs for Solar-Like Variability

Is stellar variability stationary?

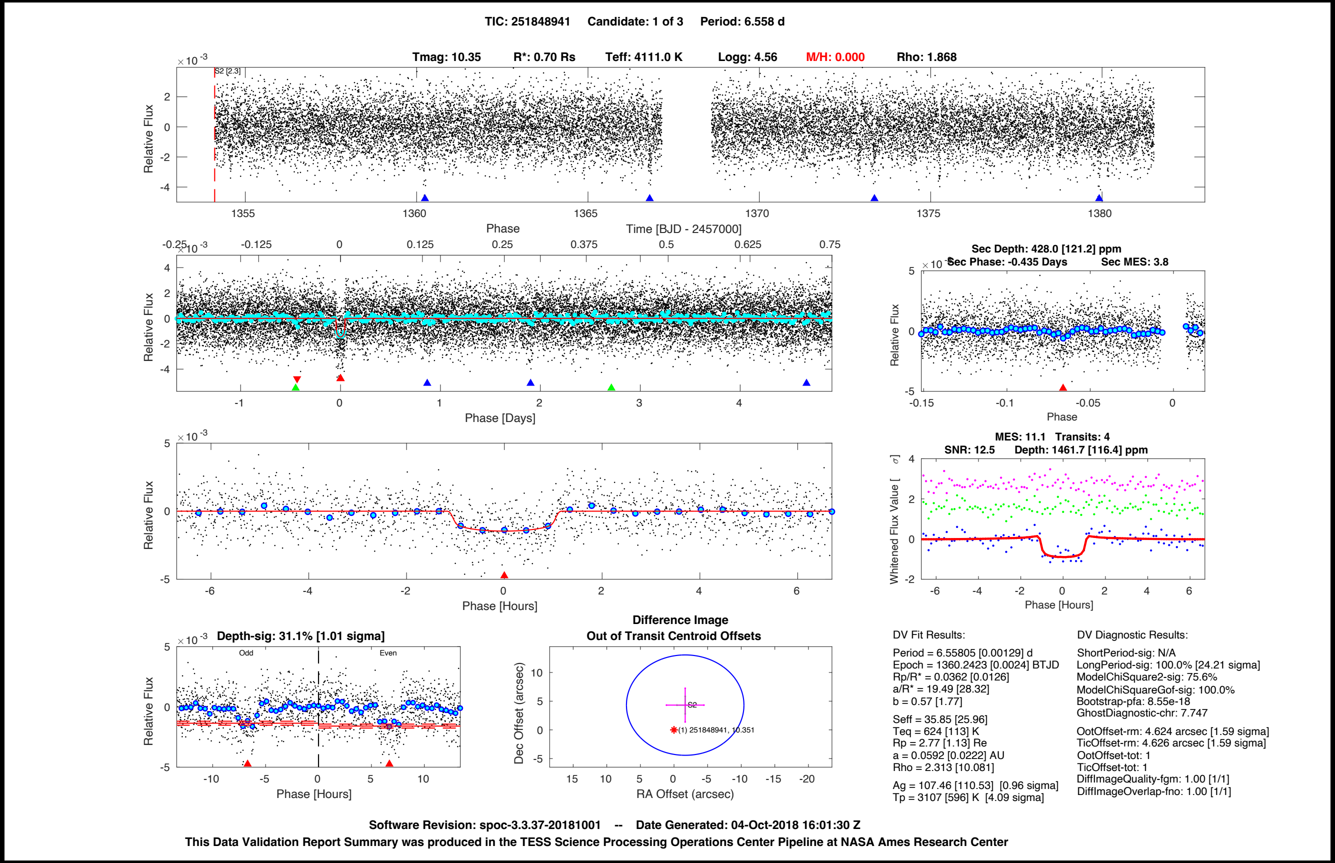
No!

We must work in a joint time-frequency domain

Wavelets are a natural choice

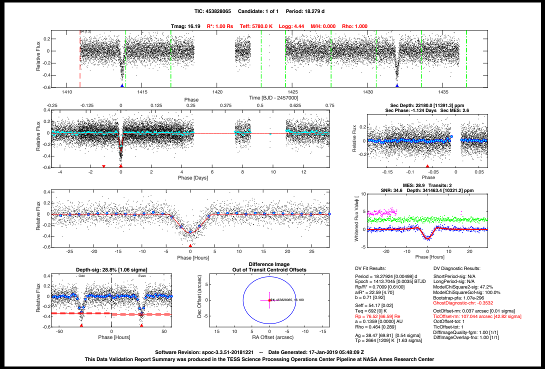


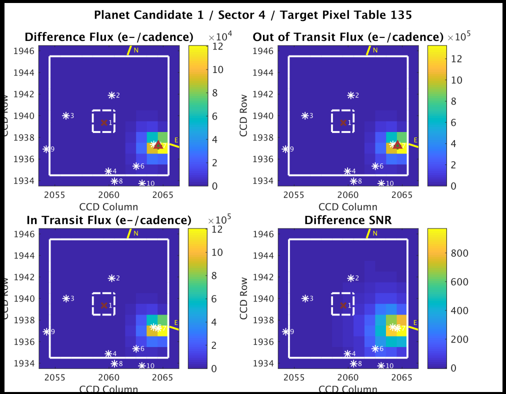
TPS/DV Products

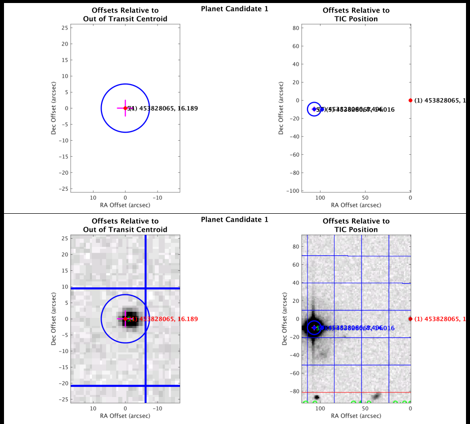


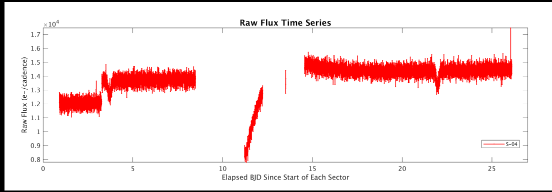
DV Mini-Reports

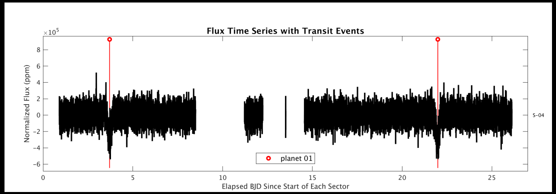
A Search for Earth-size Planets

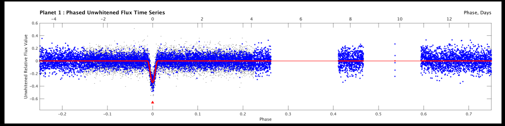


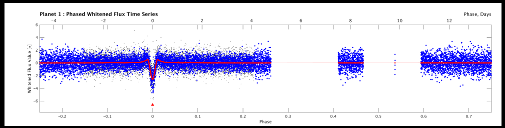


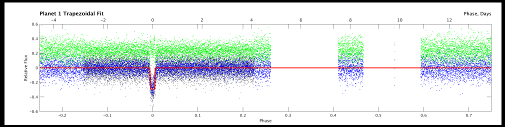




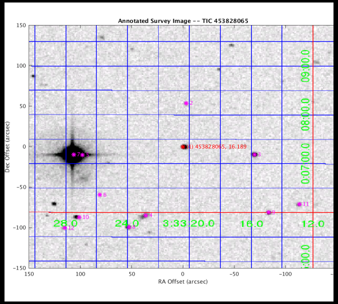








ndex	ID	Mag	(arcsec)
1	0000000453828065	16.19	0.00
2	0000000301423267	18.32	53.78
3	0000000453825823	15.39	70.41
4	0000000301423262	17.74	92.17
5	0000000453828067	14.02	98.39
6	0000000453828068	16.26	100.37
7	0000000453828066	8.50	107.01
8	0000000453828070	16.60	112.20
9	0000000453825819	16.92	116.40
10	0000000453828069	15.62	133.53
11	0000000453825820	18.04	133.69
12	0000000301423260	18.43	152.70



The Challenge of Vetting Exoplanet Candidates

- Discriminating against Instrumental false alarms and astrophysical false positives is challenging, especially for the smallest candidates in or near the habitable zone
- Manual inspection of data/diagnostics is
    - Time consuming and expensive
    - Inconsistent as this is a tedious task so there is often significant turnover as science personnel burn out
- Inconsistencies in human vetting make it difficult if not impractical to quantify completeness and reliability in the process, and to support occurrence rate studies
- Machine Learning can be brought to bear on this classification problem to identify high priority exoplanet candidates for follow up and characterization and to statistically validate candidate exoplanets

Applying ML to Vetting Exoplanet Candidates

A number of ML approaches have been applied to the problem of classifying candidate transiting planet signals:

- The Kepler Autovetter: A Random Forest Approach (Jenkins et al. 2014, McCauliff et al. 2014; 2015)
- The Kepler Robovetter: a decision tree approach with manual tuning/optimization (Coughlin et al. 2016)
- Deep Learning:
  - AstroNet (Shallue & Vanderburg 2018, Datillo et al. 2019, Yu et al, 2019),
  - ExoNet (Ansdell et al. 2018, Osborn 2020)
- Non-DNN models: Armstrong et al. (2020)
- ExoMiner: a DNN with an explainability framework (Valizadegan et al. 2020)

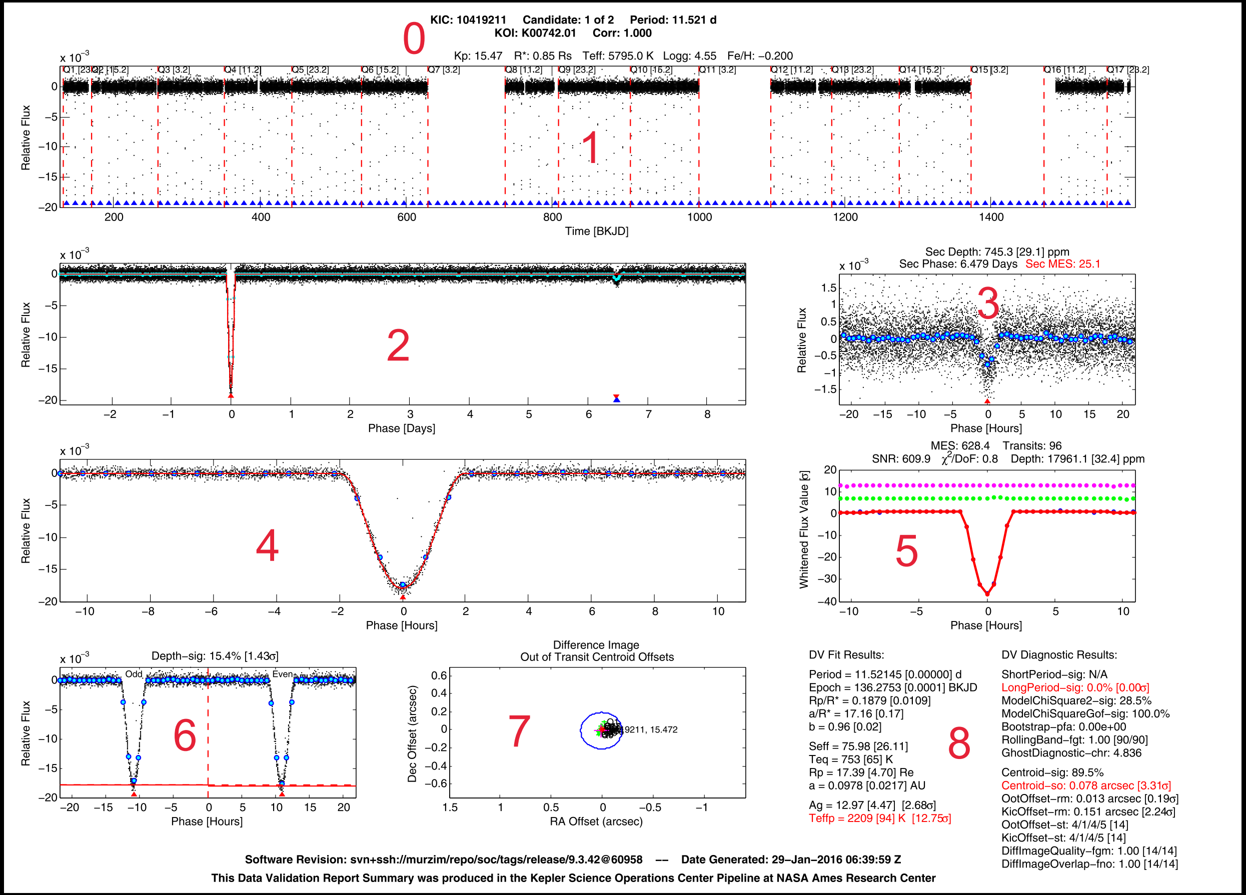
A Search for Earth-size Planets

ExoMiner Inputs

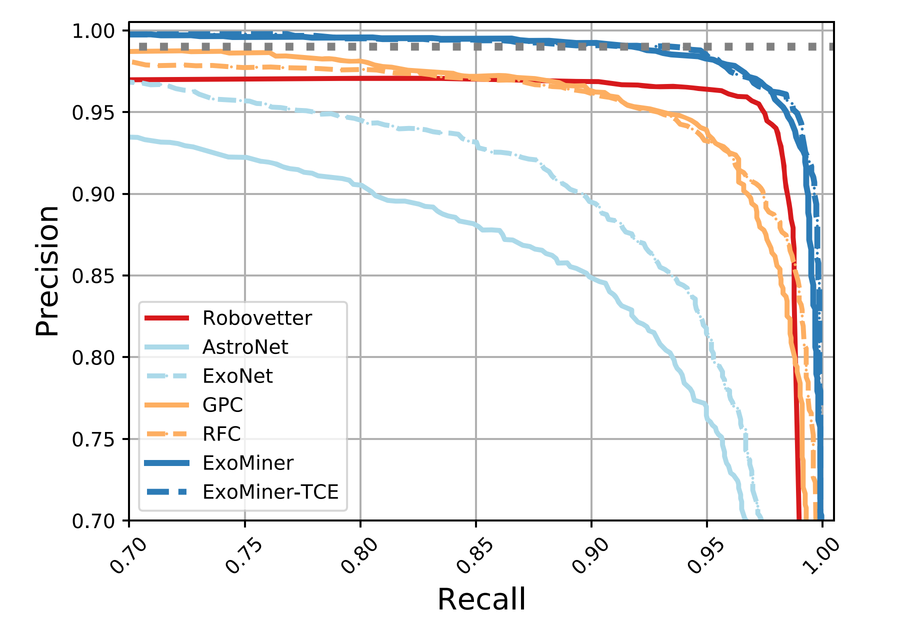
ExoMiner inputs are inspired by the 1-page DV Summary Reports

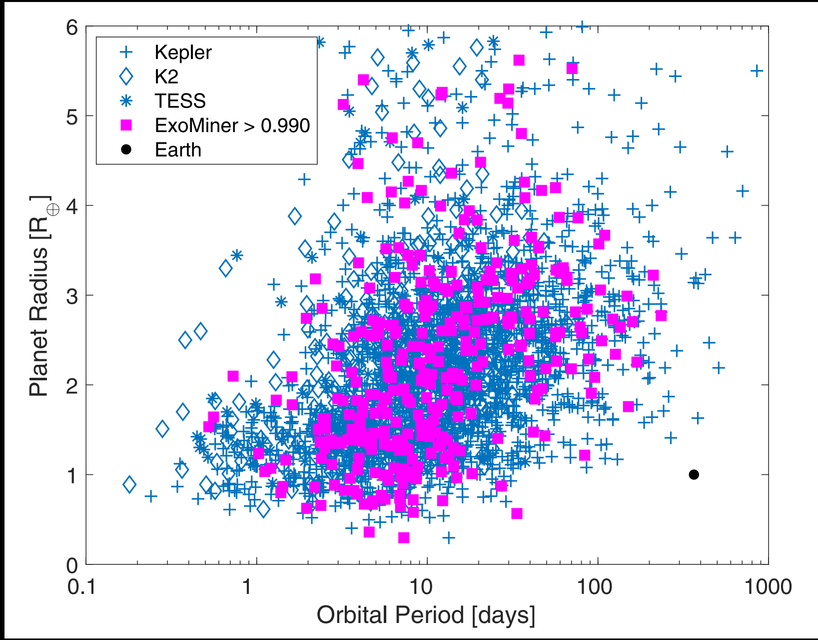
The inputs include:

- Stellar parameters
- Full flux time series
- Full-orbit phase-folded flux
- Folded secondary flux
- Zoomed folded flux
- Folded whitened flux
- Odd/even transit views
- Difference image centroiding
- Diagnostic metrics



ExoMiner Performance



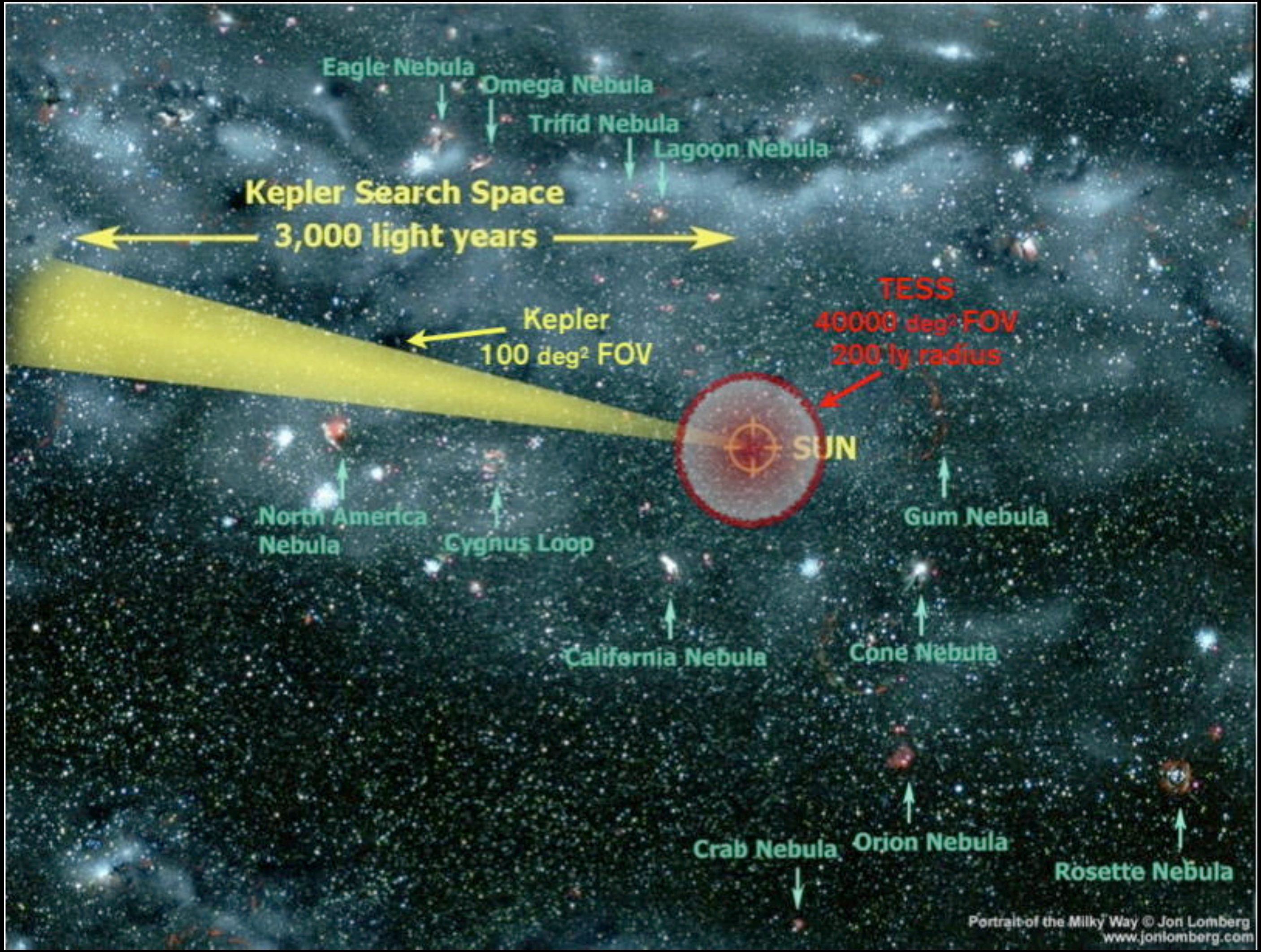


Kepler taught us that planets are everywhere!

What Next?

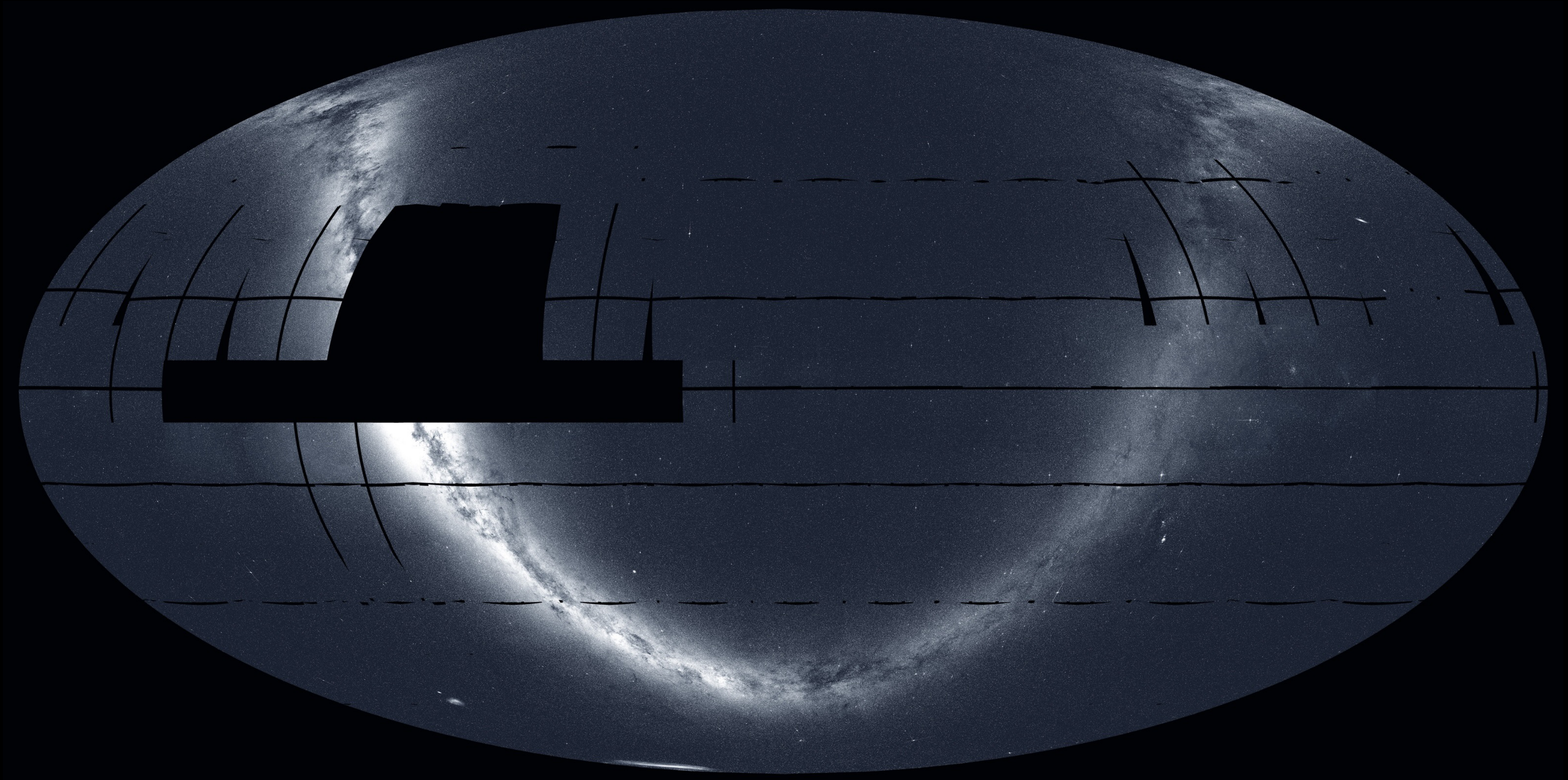
TRANSITING EXOPLANET SURVEY SATELLITE

DISCOVERING NEW EARTHS AND SUPER-EARTHS IN THE SOLAR NEIGHBORHOOD

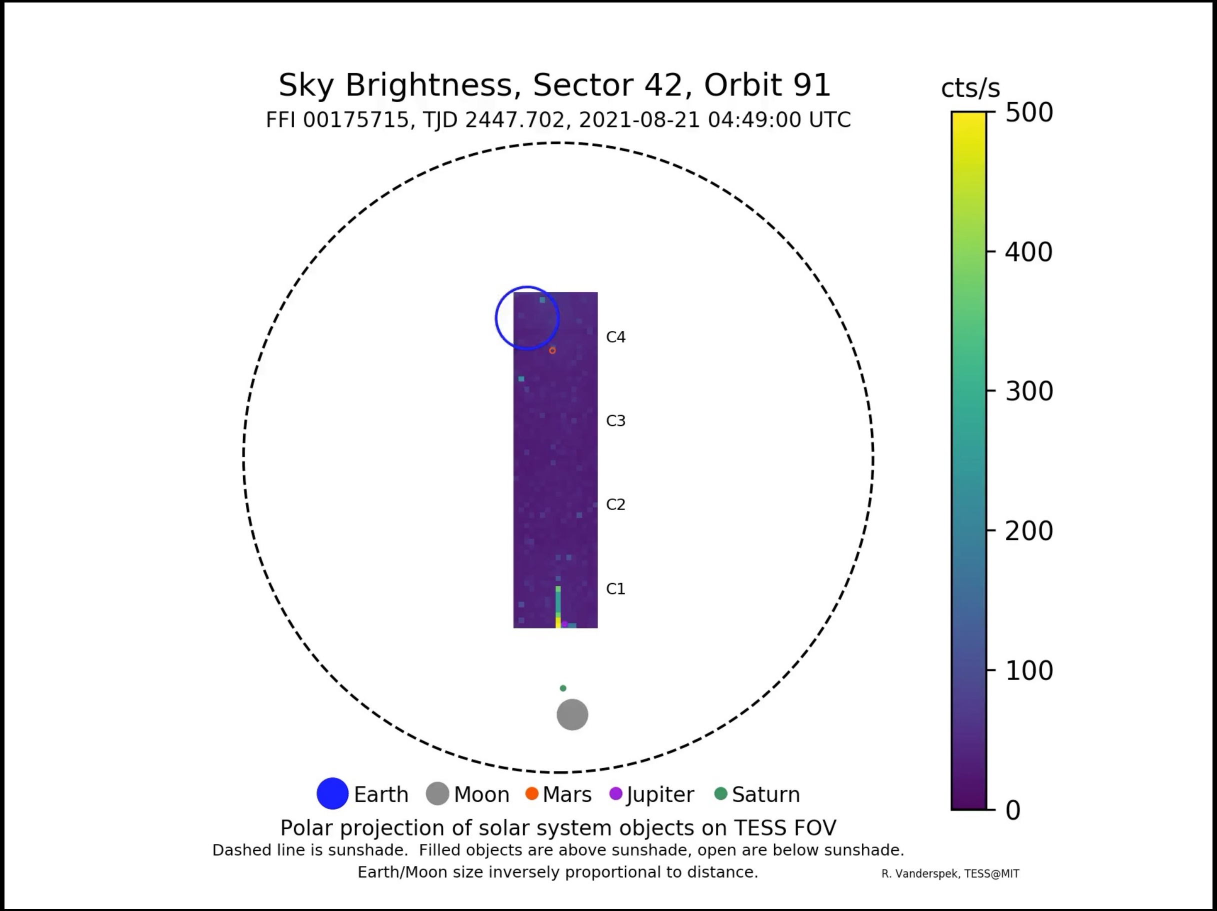


Used with permission of the artist

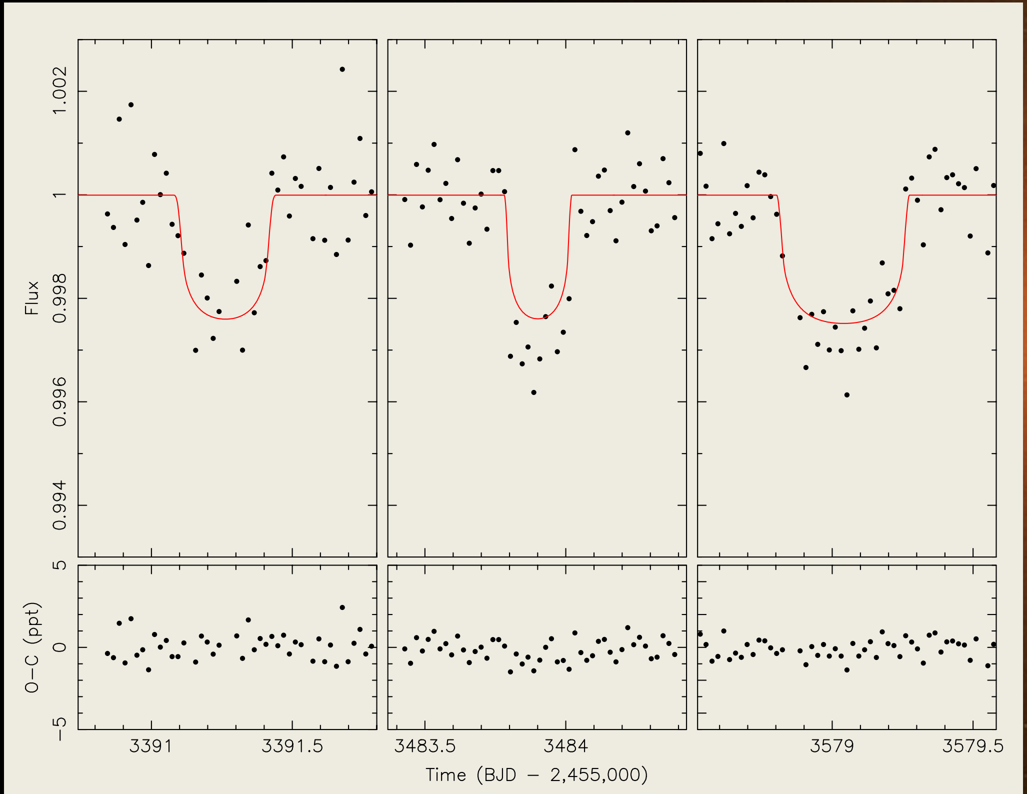
TESS Sky Coverage through October 2022

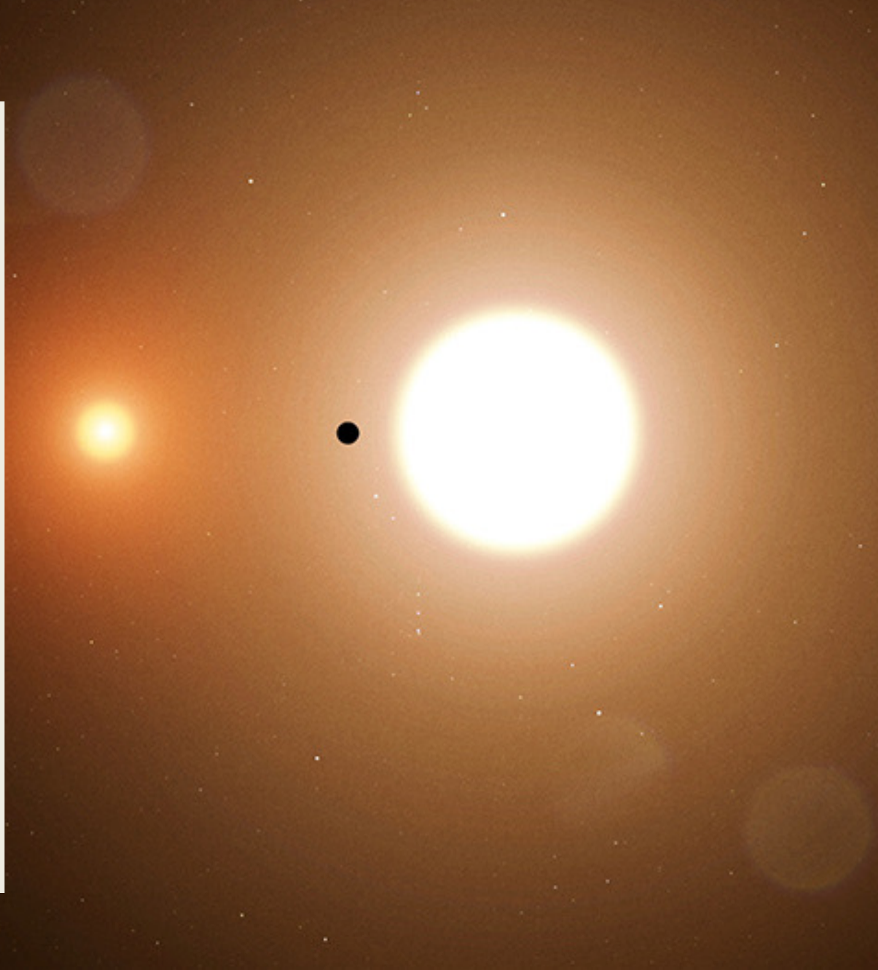


Observing from TESS is Interesting!



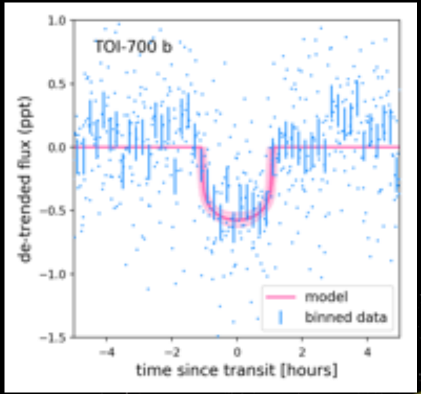
First Circumbinary Planet: TOI-1338b

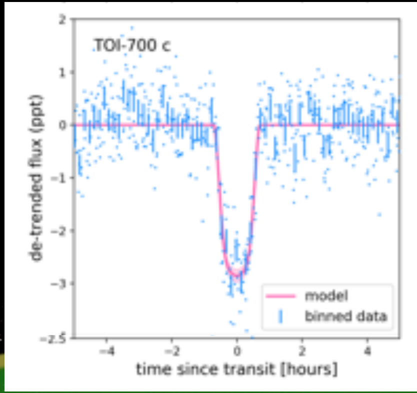


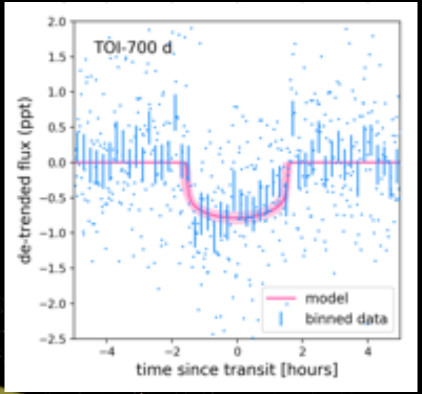


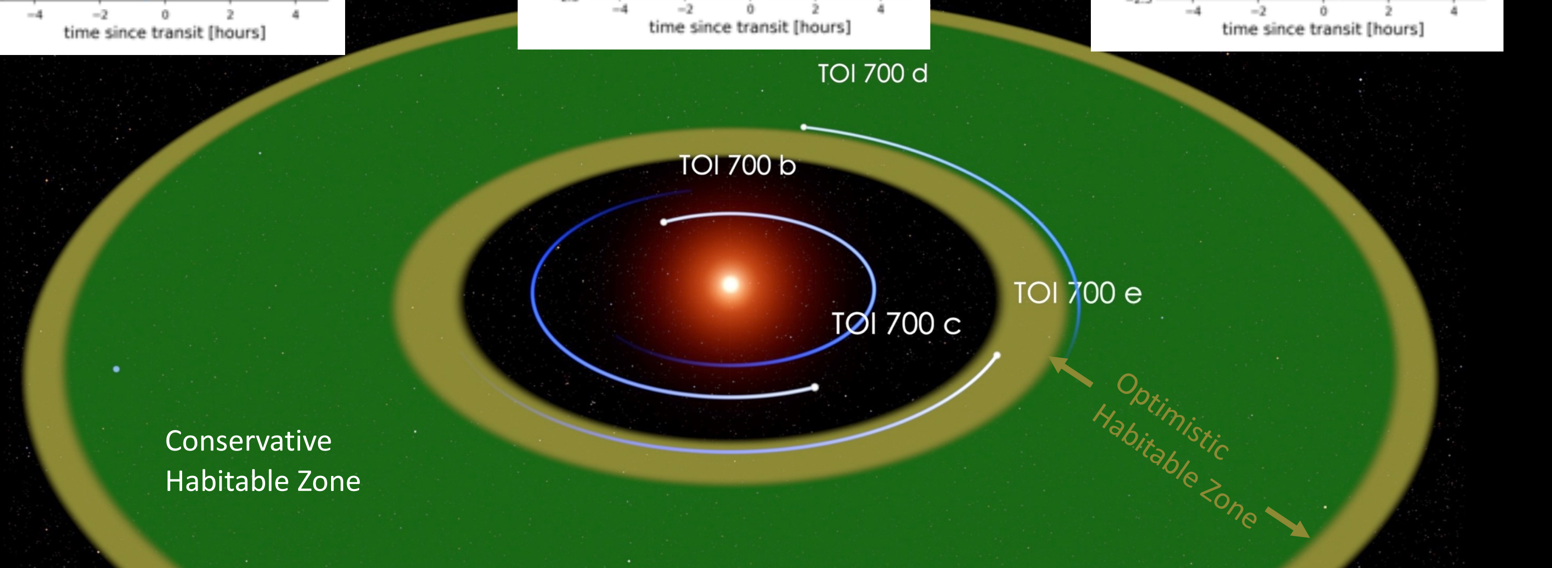
TESS's First Two Earth-Sized Habitable Zone Planets: TOI-700d and TOI-700e

Kepler
A Search for Earth-size Planets







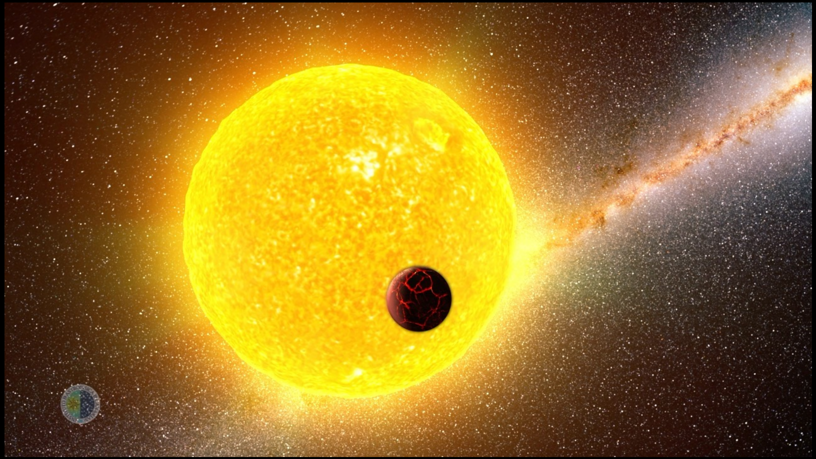


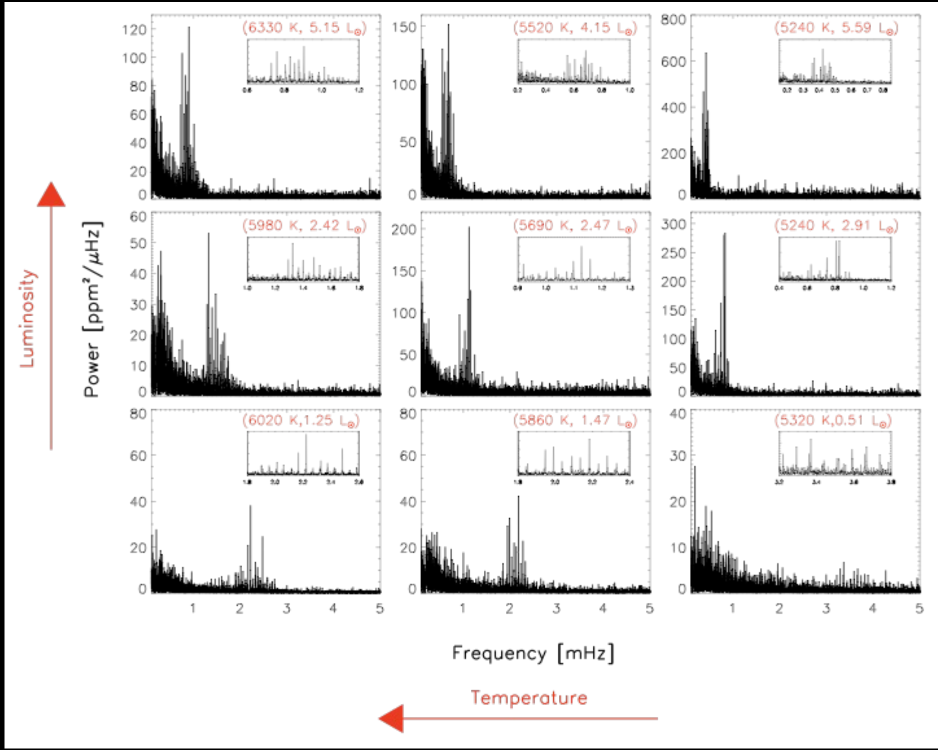
Why Do Stars Sing?

Stars are large resonant cavities that ring like bells

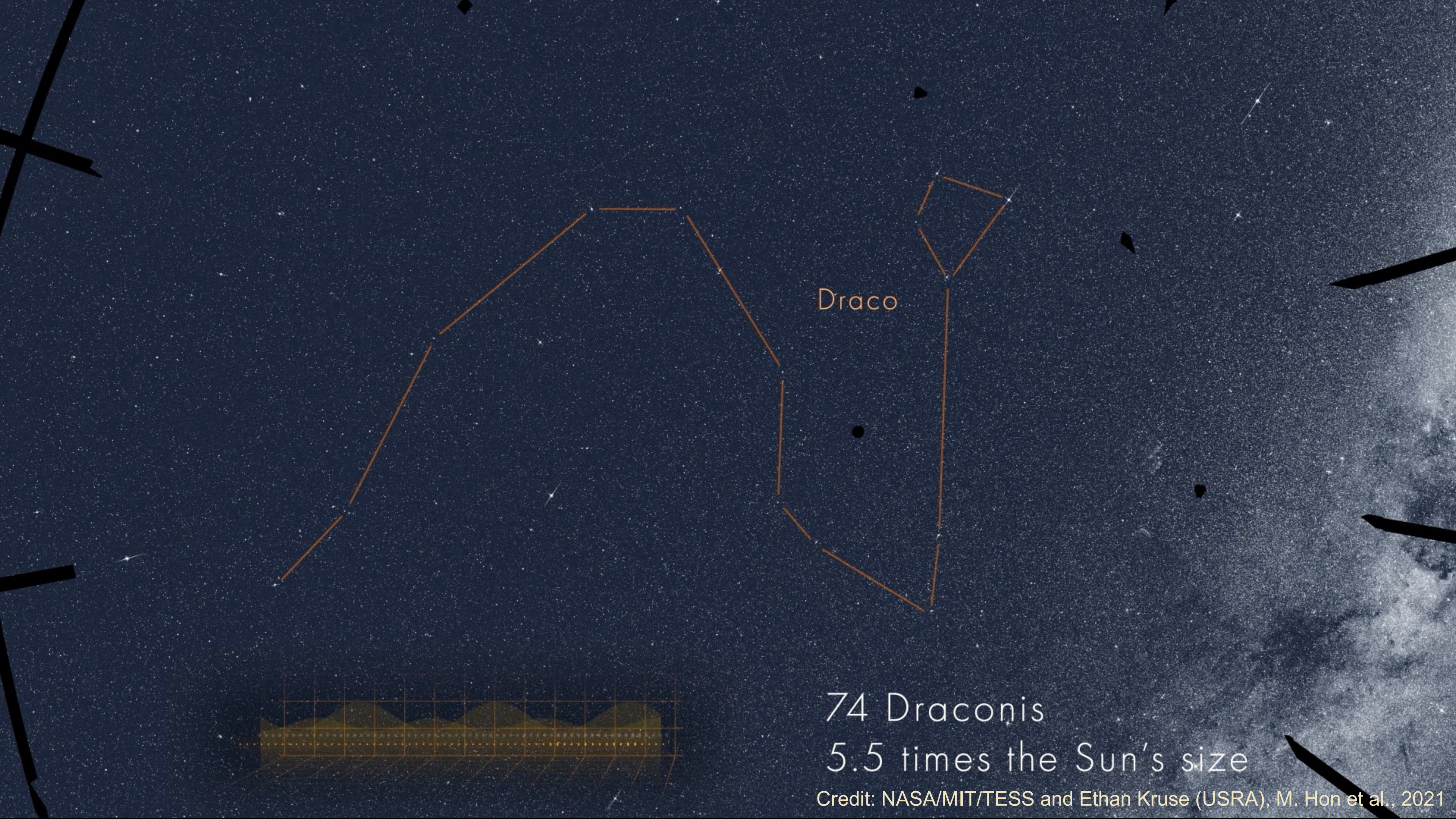
We've measured acoustic modes for >500 solar-like stars

Asteroseismology gives unprecedented precision in size, mass of stars



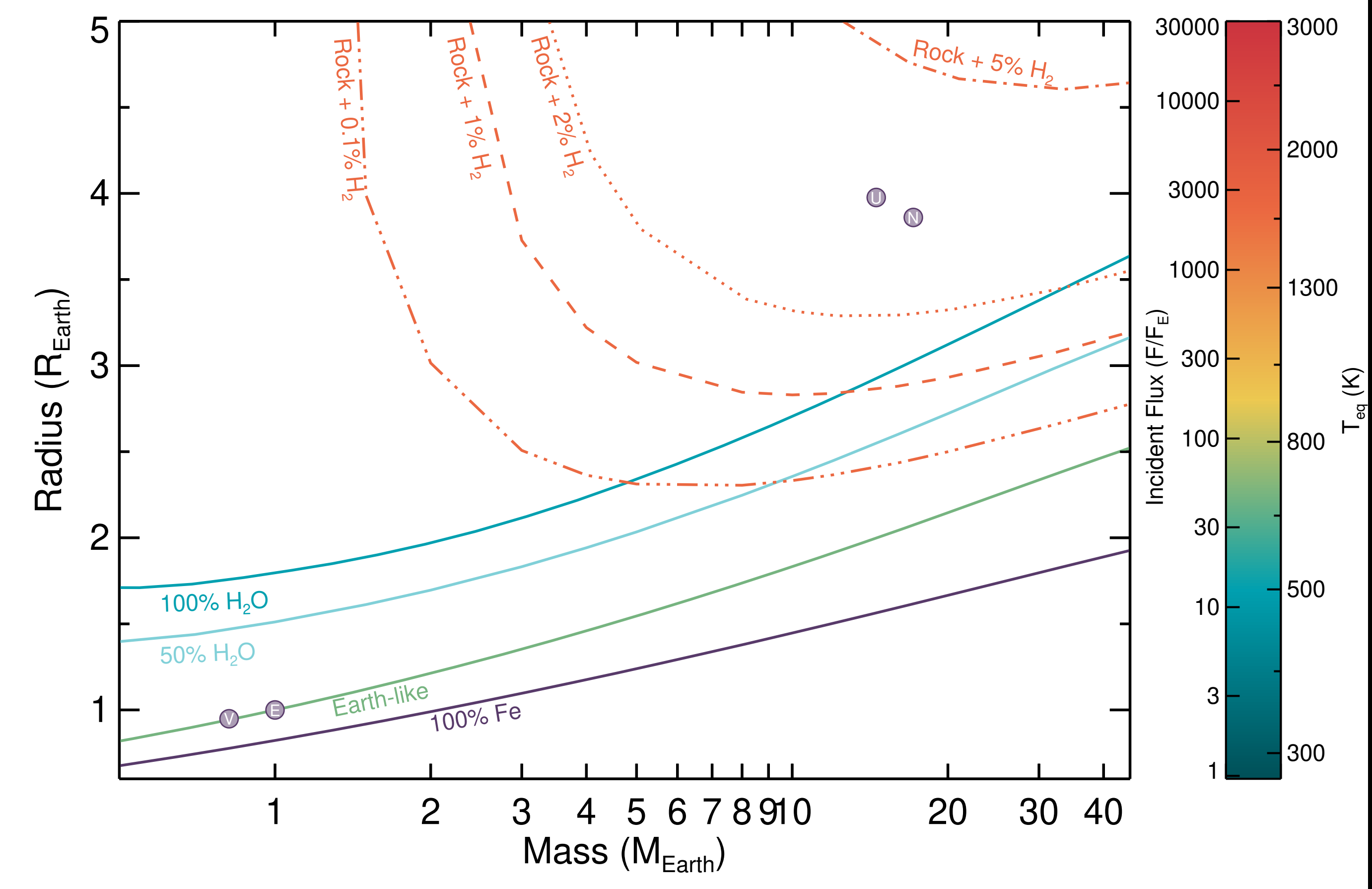


Chaplin et al 2011, Science.



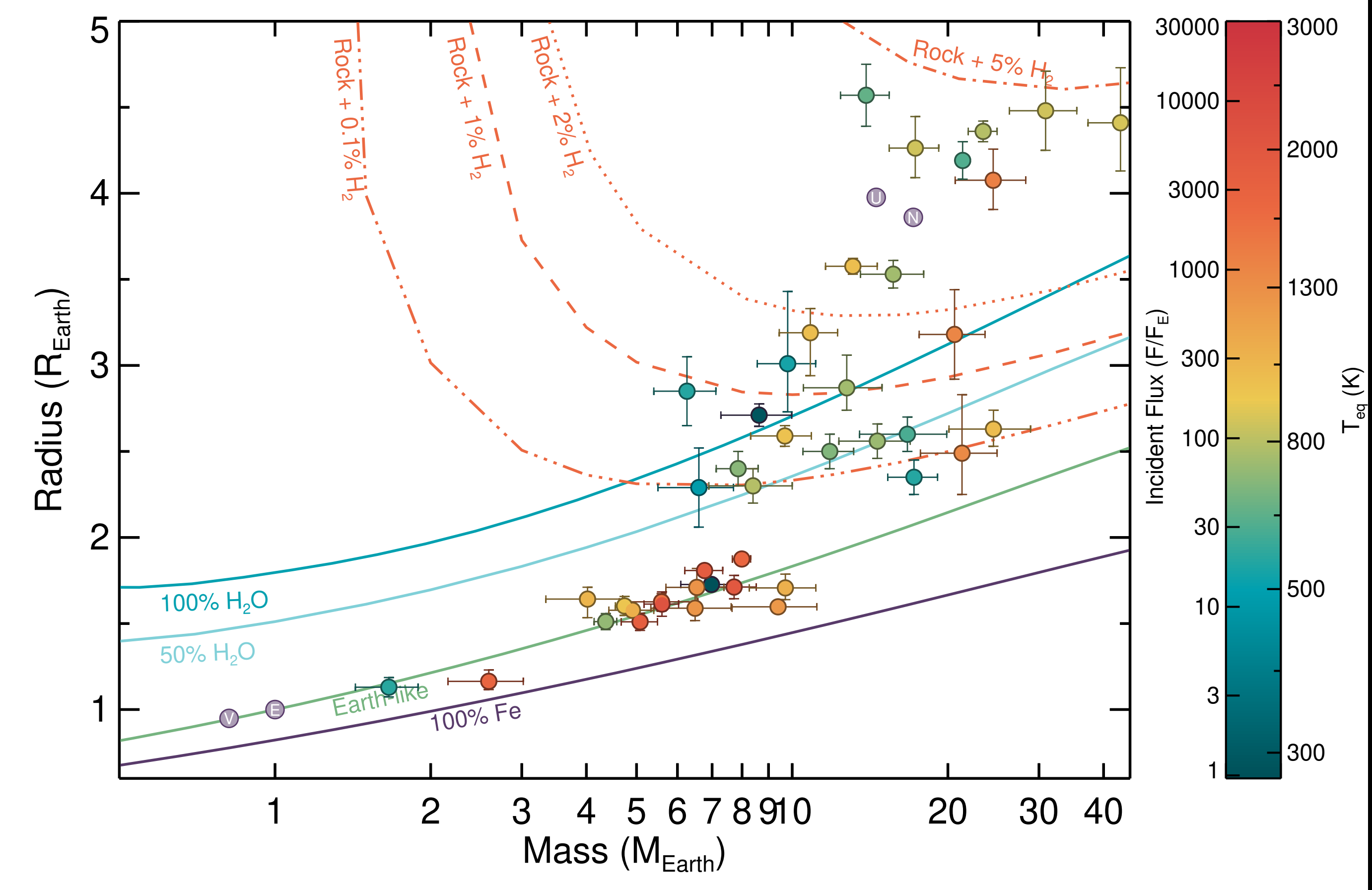
Credit: NASA/MIT/TESS and Ethan Kruse (USRA), M. Hon et al., 2021

Precise RV Masses



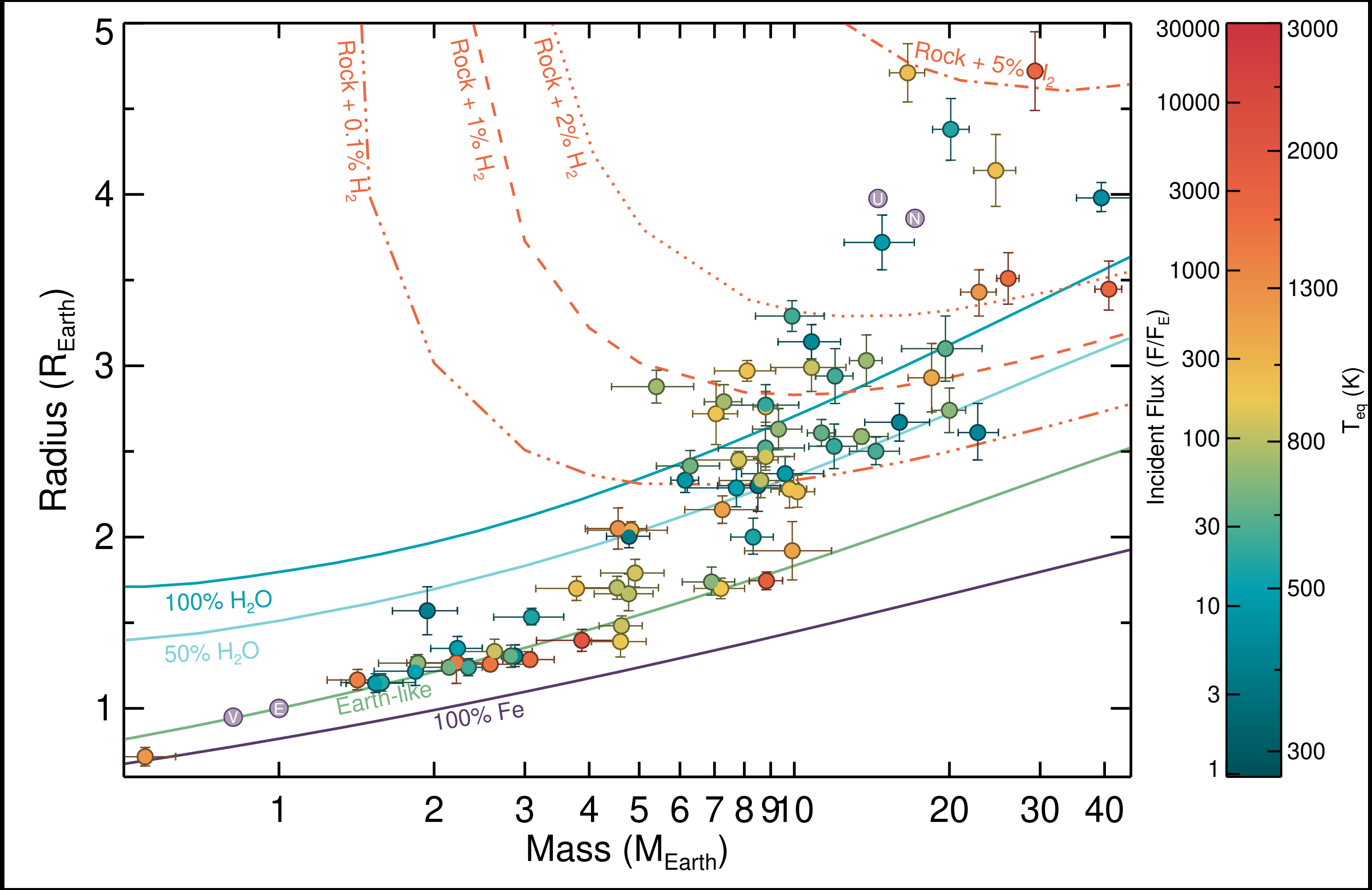
Credit: Sam Quinn

Precise RV Masses Without TESS



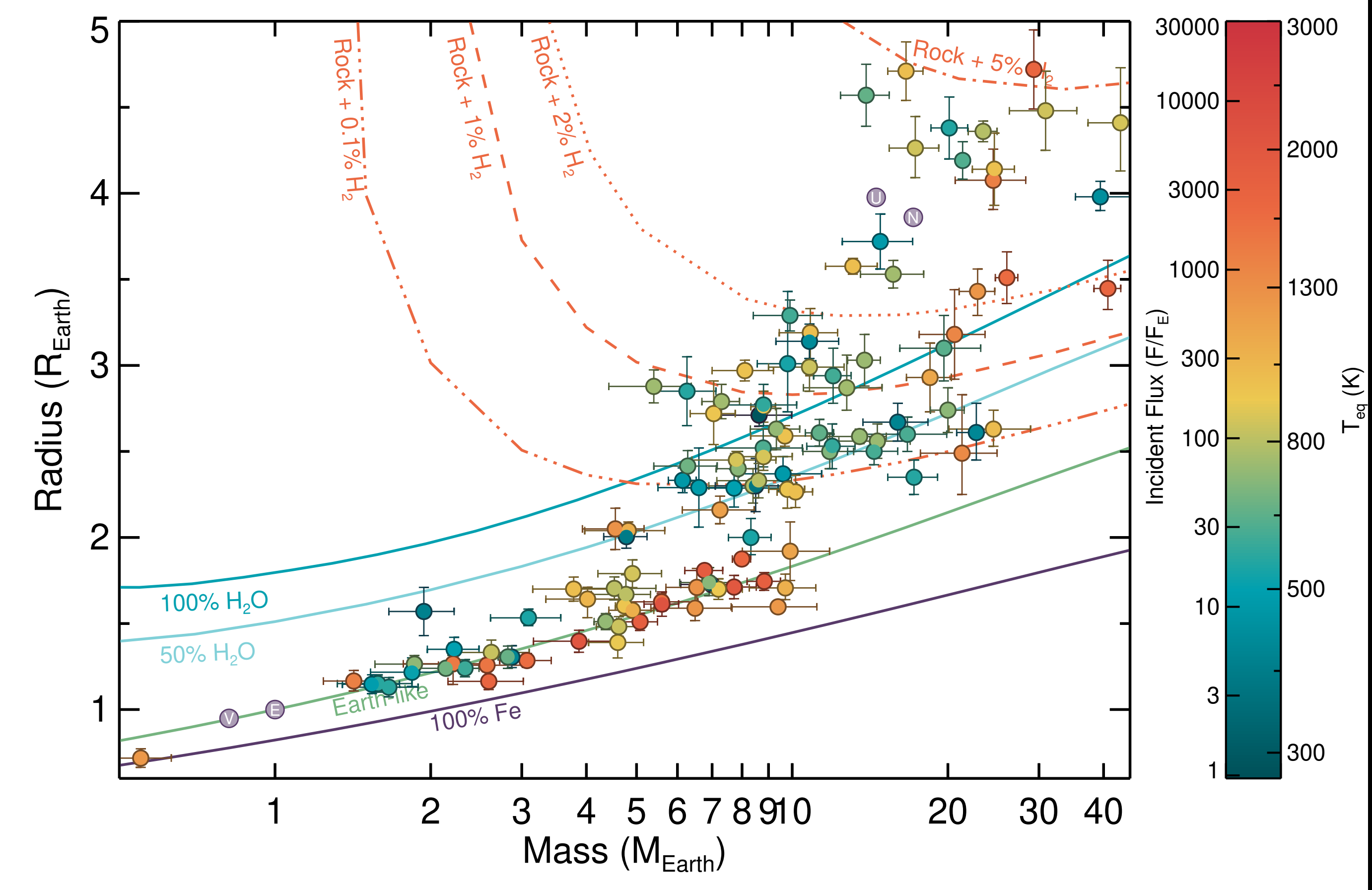
Credit: Sam Quinn

Precise RV Masses from TESS



Credit: Sam Quinn

Precise RV Masses from All Sources

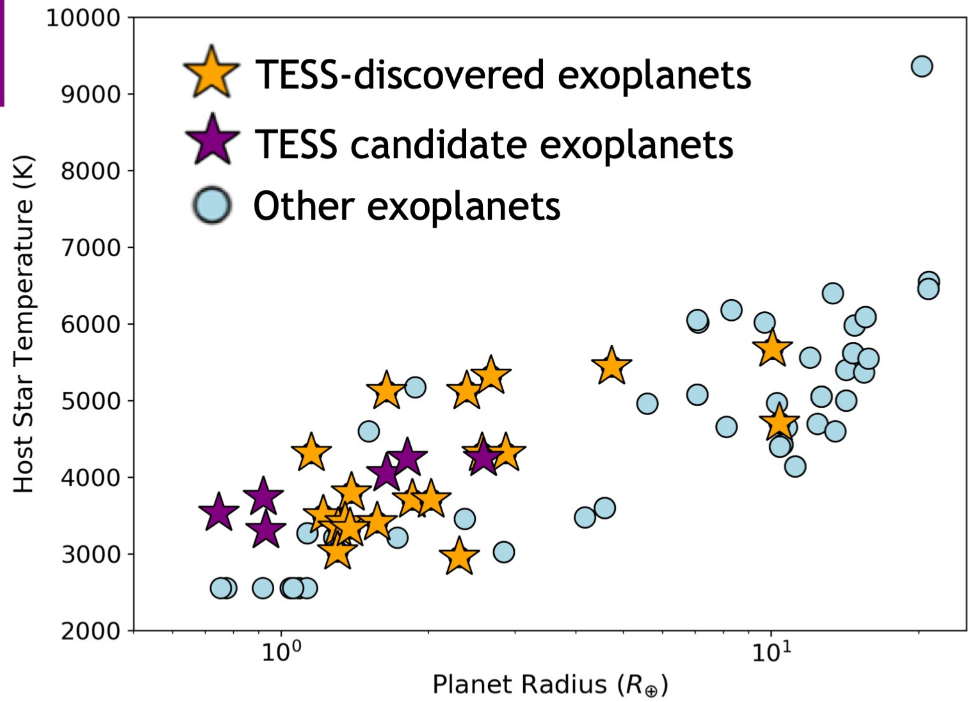


Credit: Sam Quinn

JWST Cycle 1 Transiting Exoplanet Targets from TESS

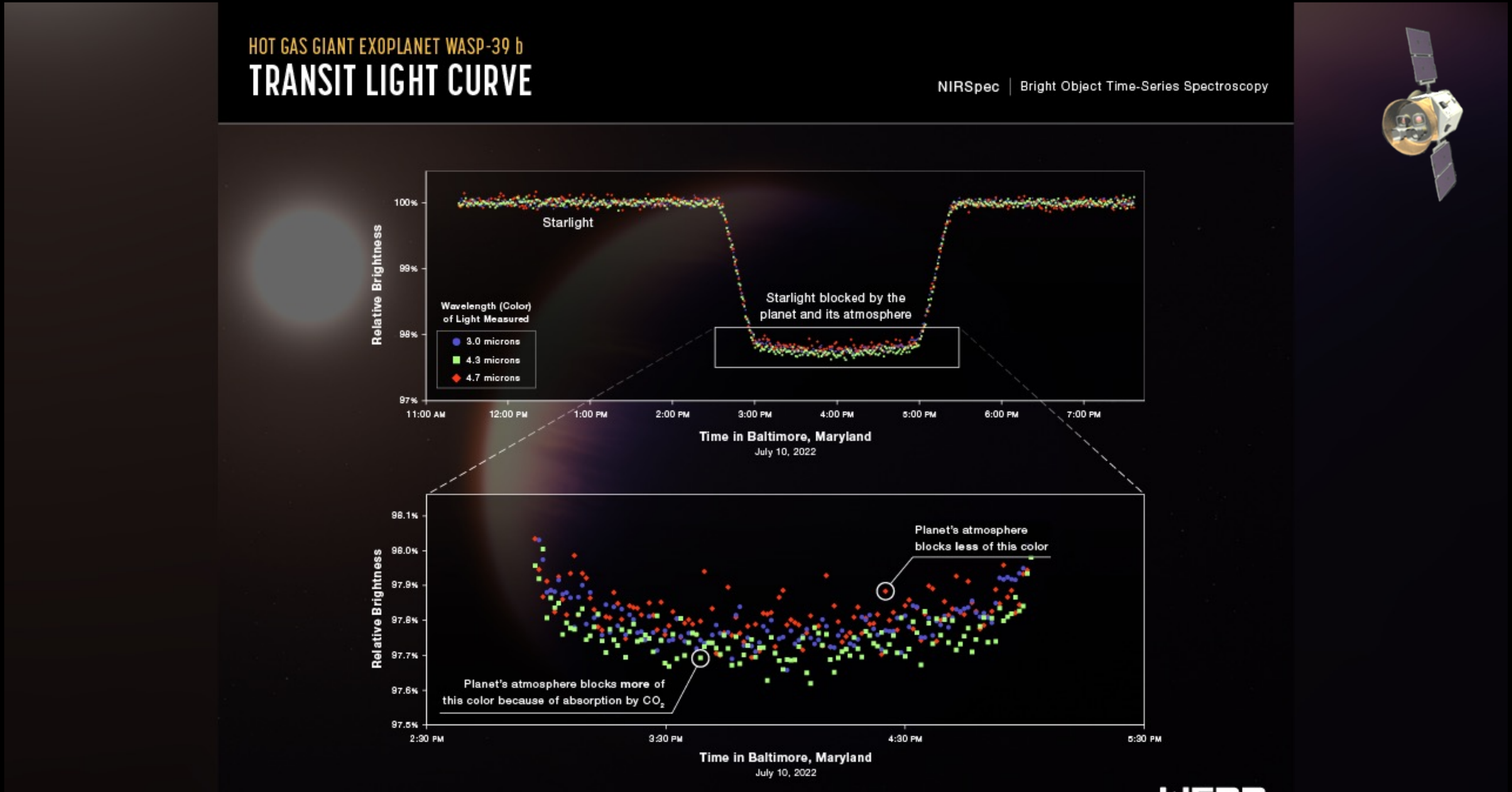
A majority of the TESS exoplanets to be observed by JWST are small (< 3 Earth radii) and orbit small, cool stars.

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		



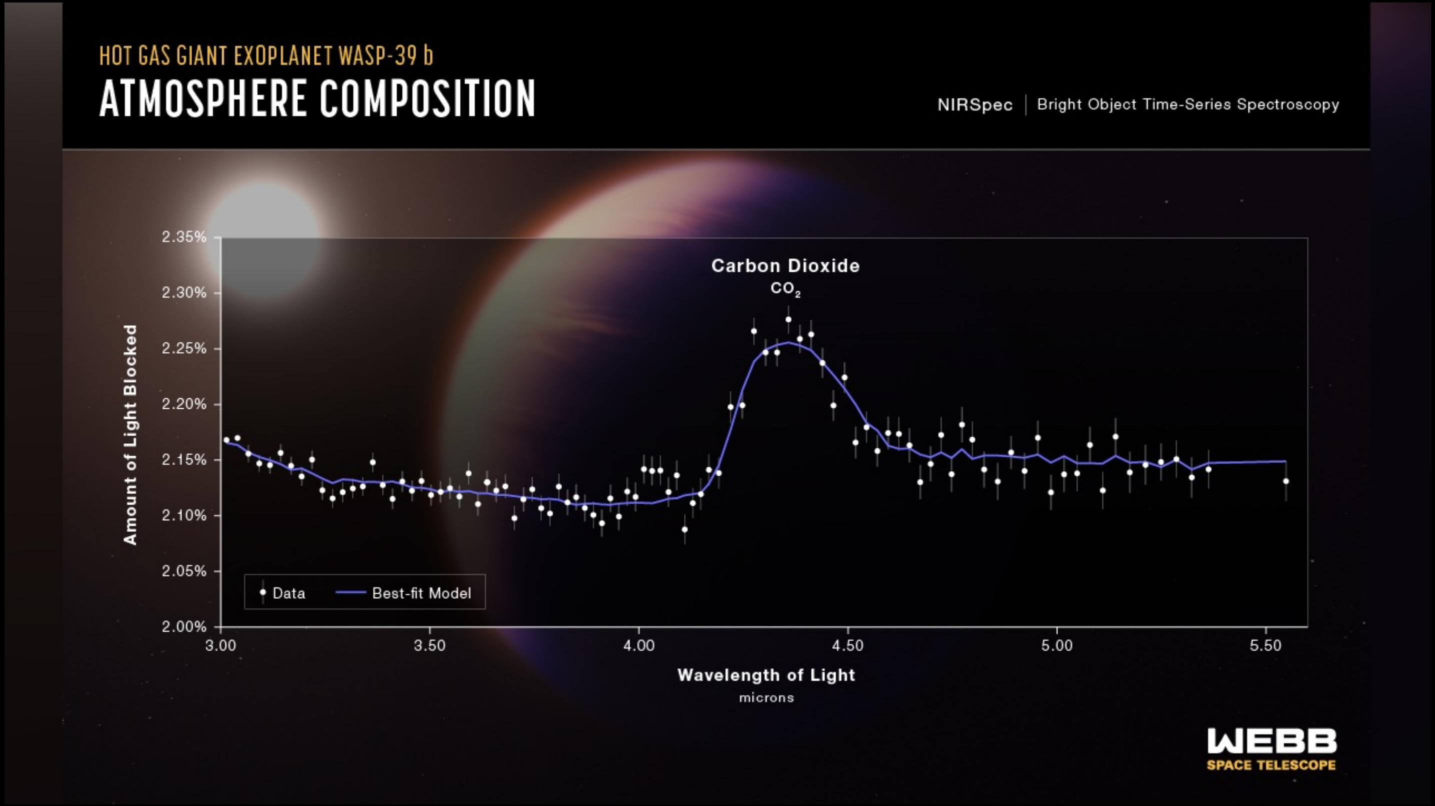
K. Colón (2021 April 16)

JWST Detects CO_2 in the Atmosphere of WASP-39b!



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

JWST Detects CO in the Atmosphere of WASP-39b!



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

Detecting Biomarkers through Transit Spectroscopy

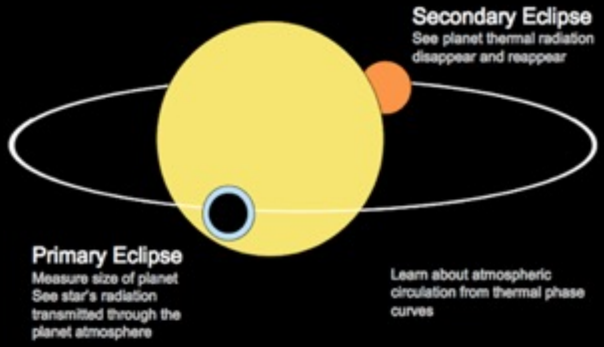
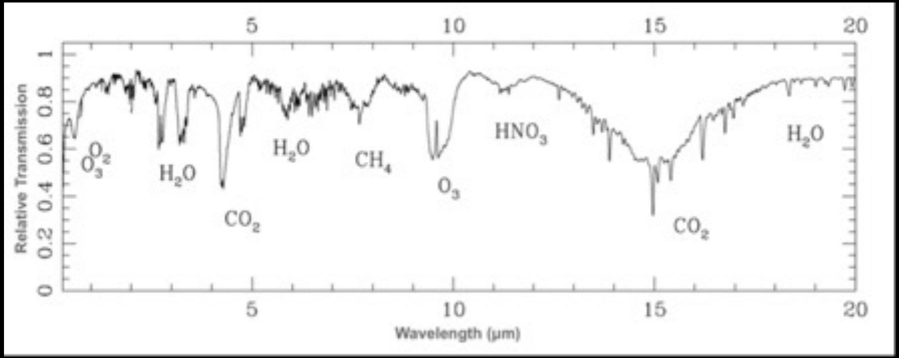
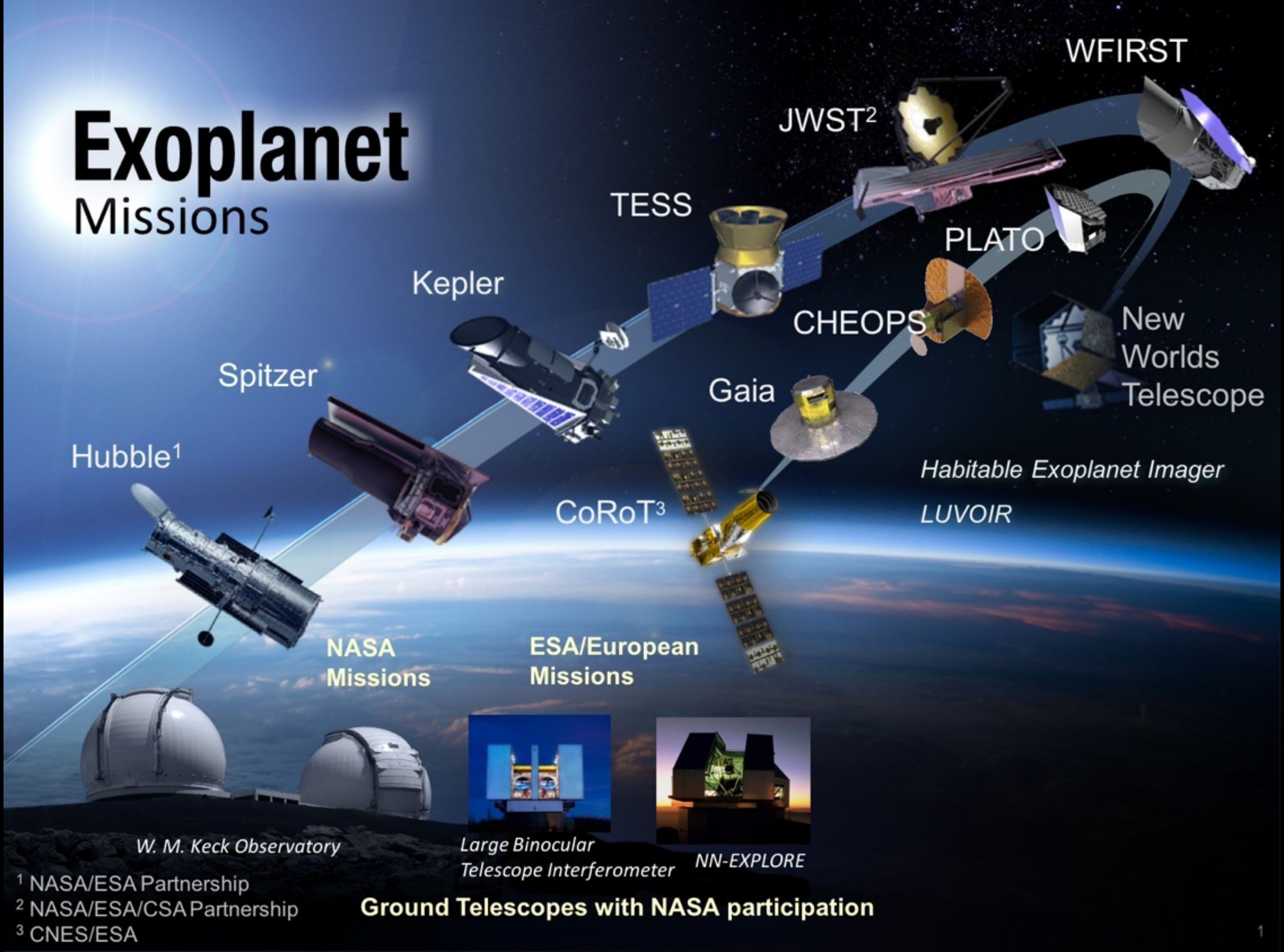


Figure by S. Seager



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



Exoplanet
Missions
WFIRST
JWST2
TESS
PLATO
Kepler
CHEOPS
New
Worlds
Telescope
Spitzer
Gaia
Hubble1
Habitable Exoplanet Imager
CoRoT3
LUVOIR
NASA
Missions
ESA/European
Missions
W. M. Keck Observatory
Large Binocular
Telescope Interferometer
NN-EXPLORE
1 NASA/ESA Partnership
2 NASA/ESA/CSA Partnership
3 CNES/ESA
Ground Telescopes with NASA participation
1

Do you have any questions?