TESS and the Search for Rocky Planets

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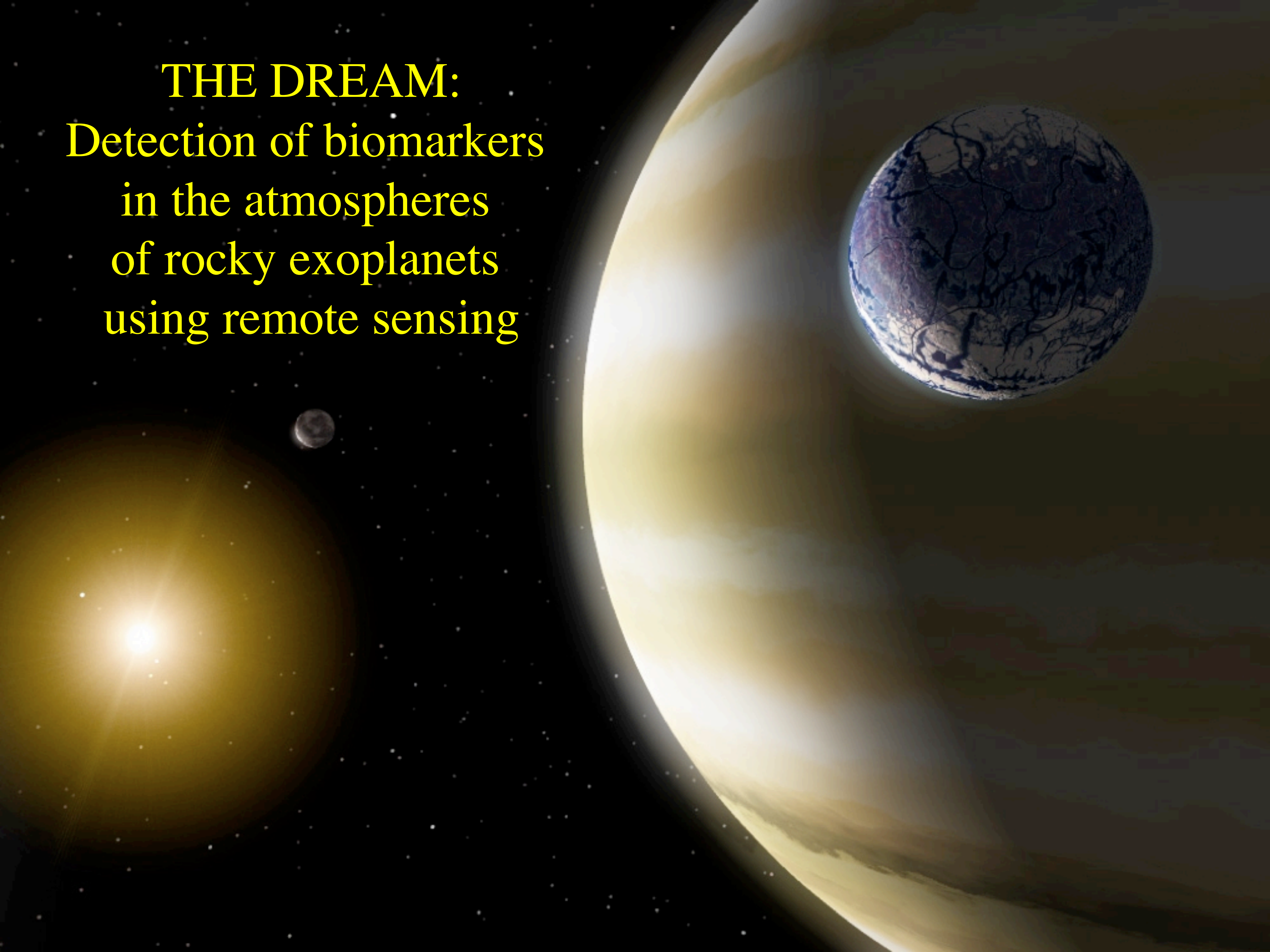
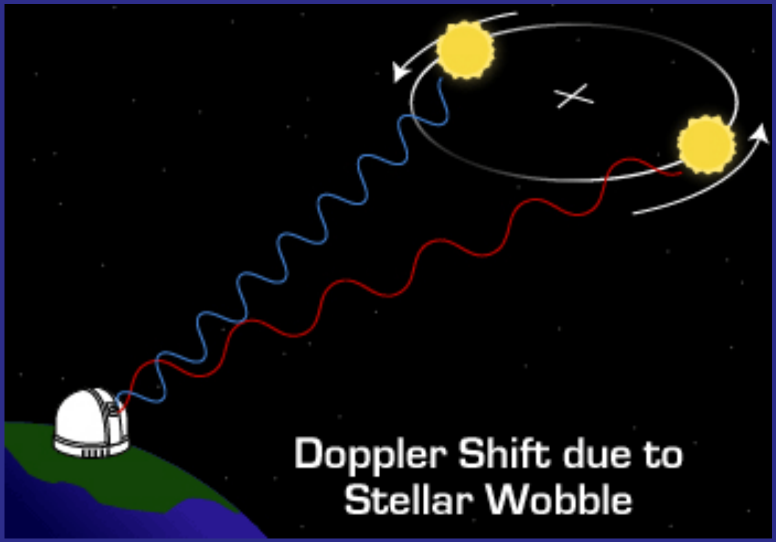
Center for Astrophysics | Harvard & Smithsonian

LIneA Webinar - 25 March 2021

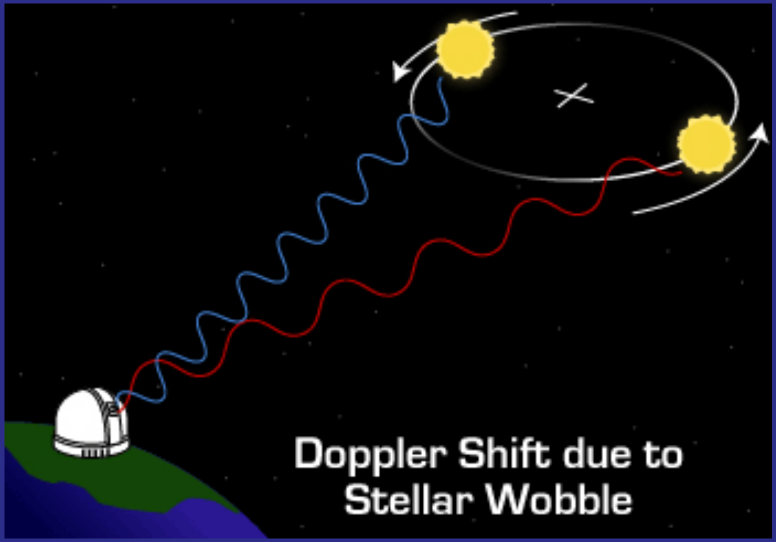

THE DREAM:
Detection of biomarkers
in the atmospheres
of rocky exoplanets
using remote sensing

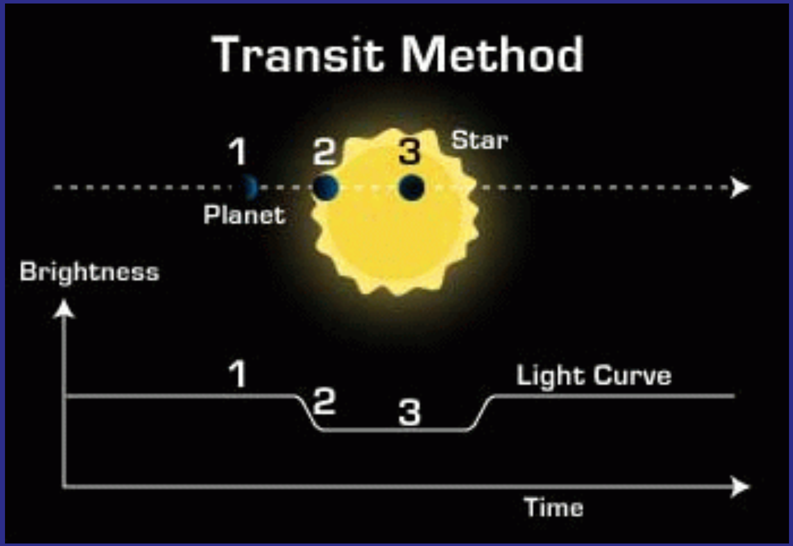
Astronomers have developed two clever *(but indirect)* methods to find exoplanets



Doppler Method
Determine Planet Mass

Astronomers have developed two clever *(but indirect)* methods to find exoplanets

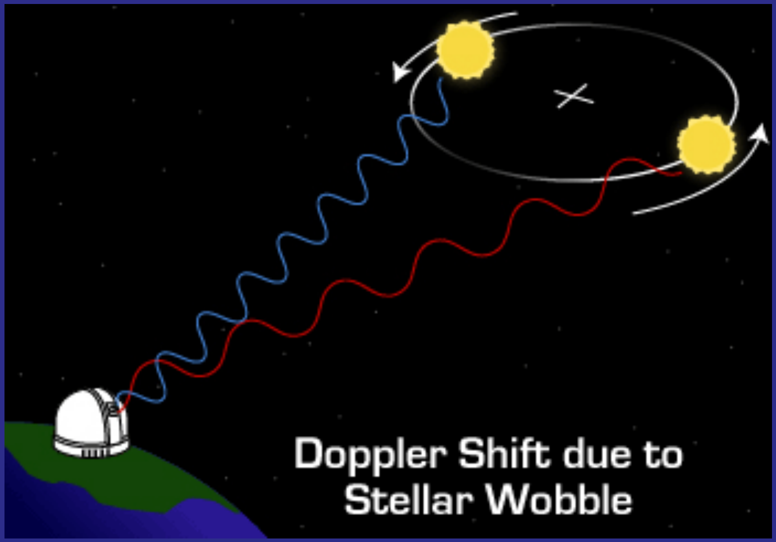


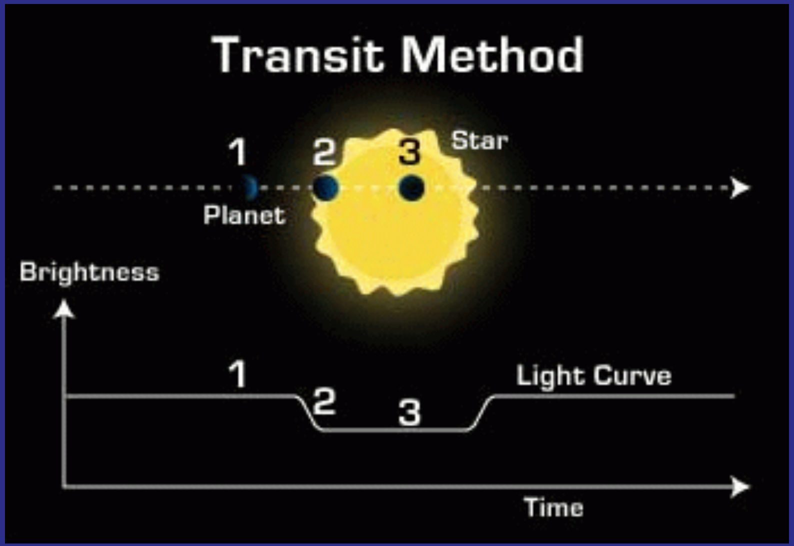


Doppler Method
Determine Planet Mass

Transit Method
Determine Planet Diameter

Together, Doppler orbits and transit light curves yield the actual planetary mass

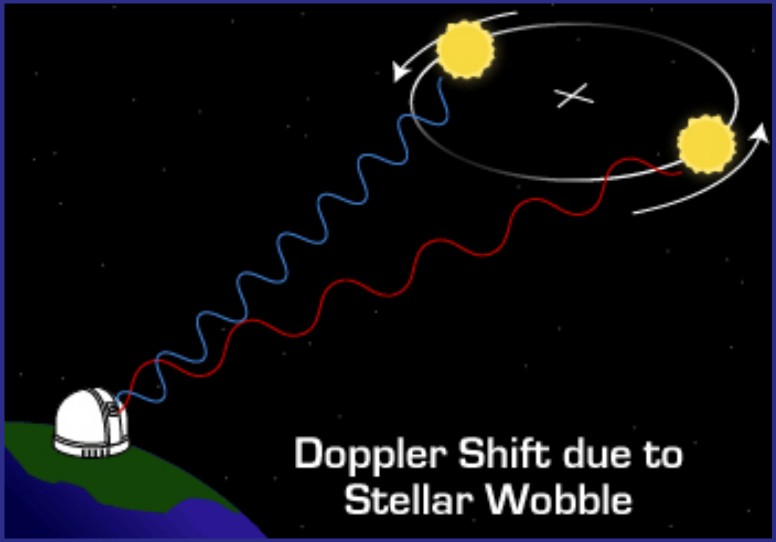


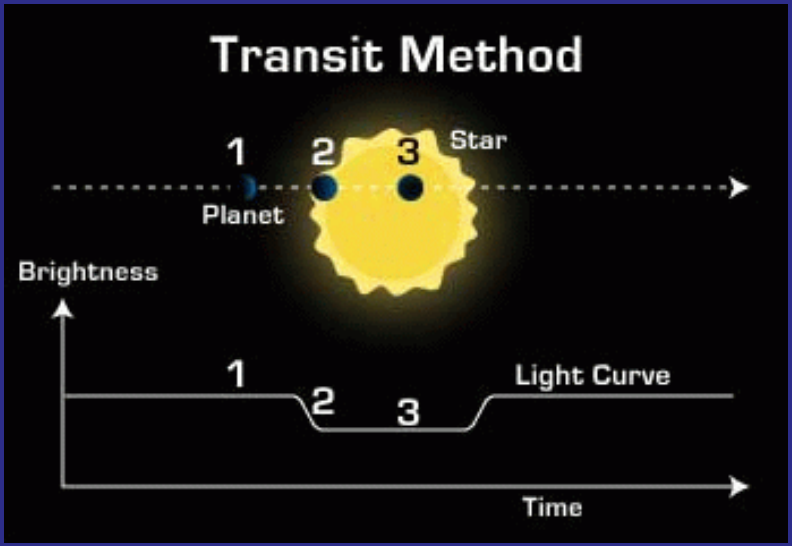


Doppler Method
Determine Planet Mass
Remove sin(*i*) ambiguity

Transit Method
Determine Planet Diameter
AND orbital inclination

Together, Doppler orbits and transit light curves yield the actual planetary mass





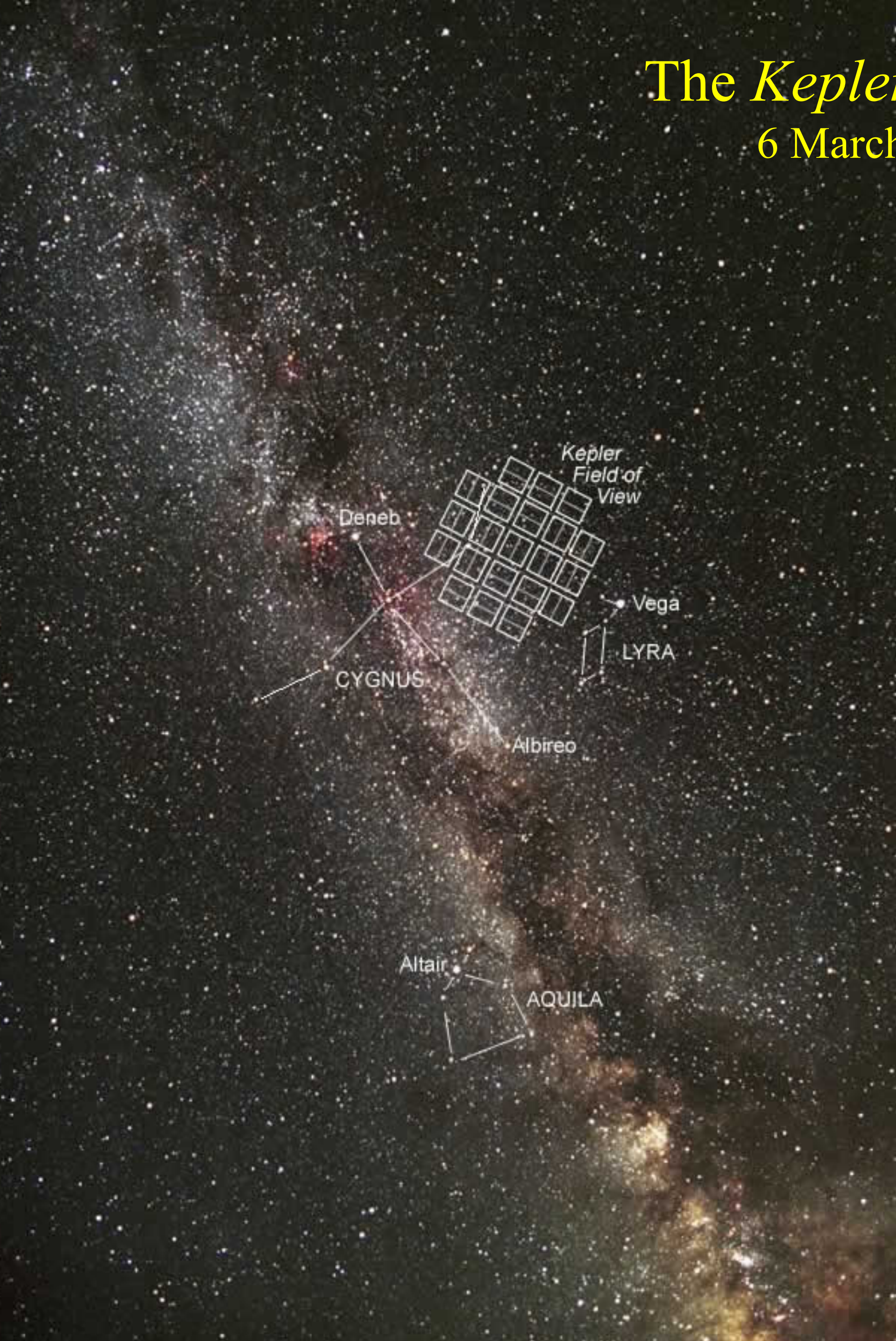
Doppler Method
Determine Planet Mass
Remove sin(*i*) ambiguity

Transit Method
Determine Planet Diameter
AND orbital inclination

Calculate Planet Density and Infer Composition:
Gas giant (Jupiter), or Ice giant (Neptune), or Rocky planet (Earth)?
or Water worlds, or Super Earths? Also get surface gravity.

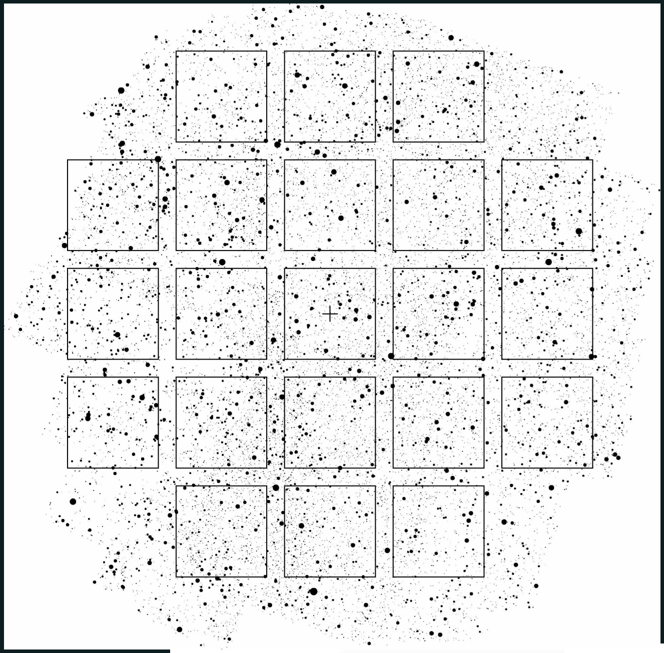
The *Kepler* Mission

6 March 2009

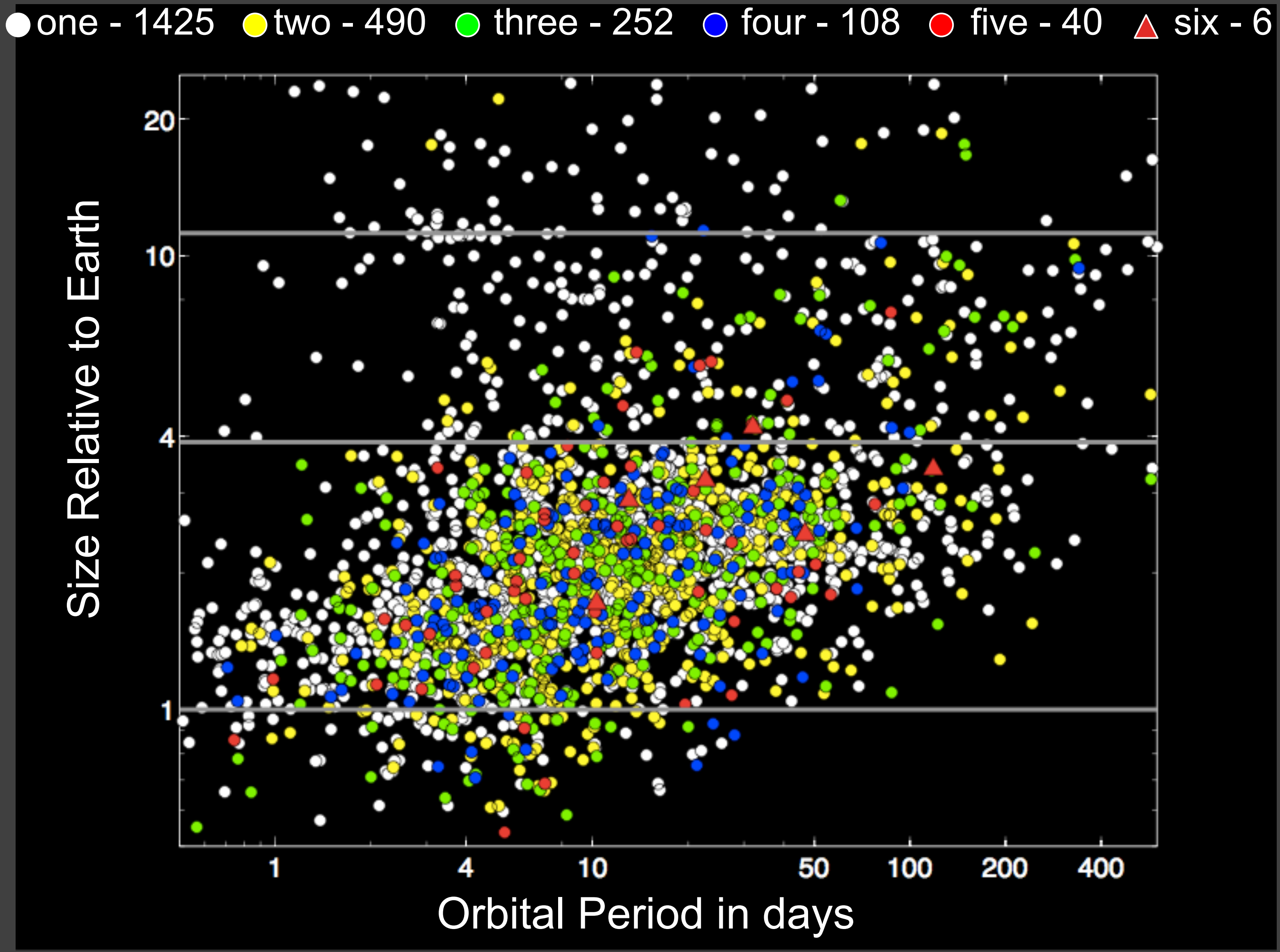


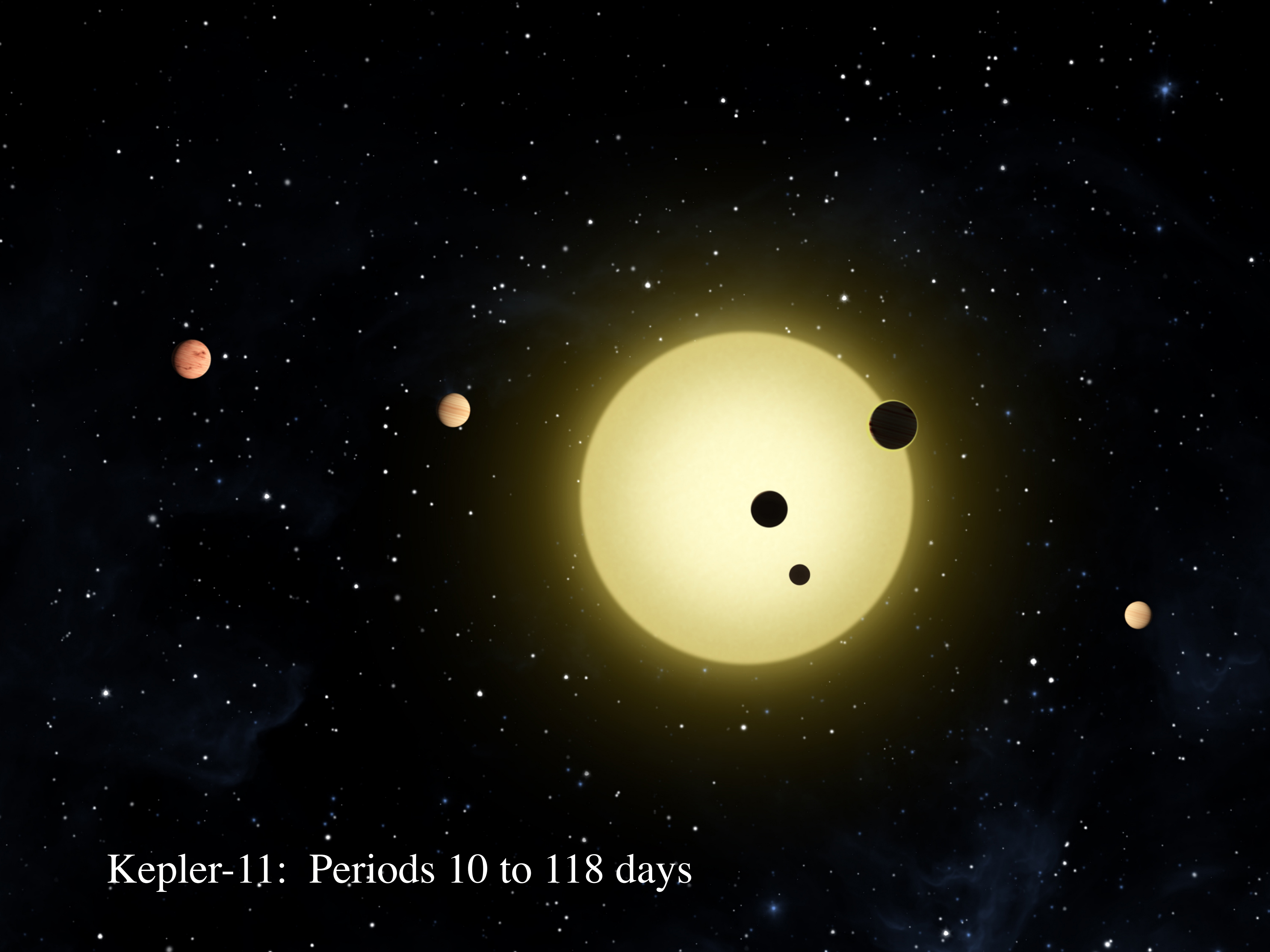
Kepler Mission Concept

- *Kepler* was optimized to find transiting Earth-like planets
  - Radius down to 1 R_{earth}
  - Sun-like host stars
  - Orbits out to 1 AU = 1 year
- Mission characteristics
  - Stare at one FOV for 4 years
  - 150,000 Sun-like targets
  - Earth-trailing orbit for stability and continuous light curves



Planet Radius vs. Orbital Period from *Kepler*

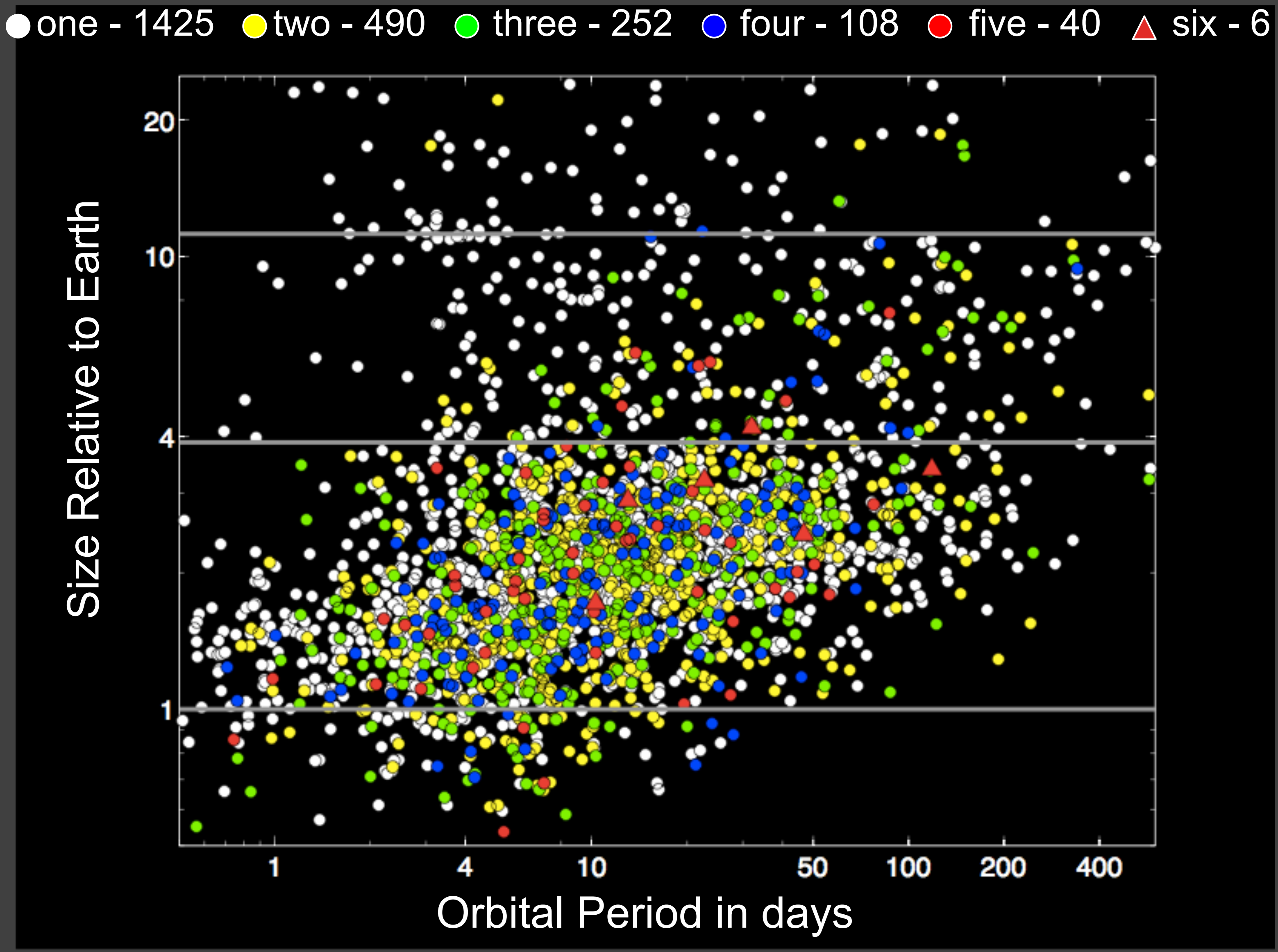




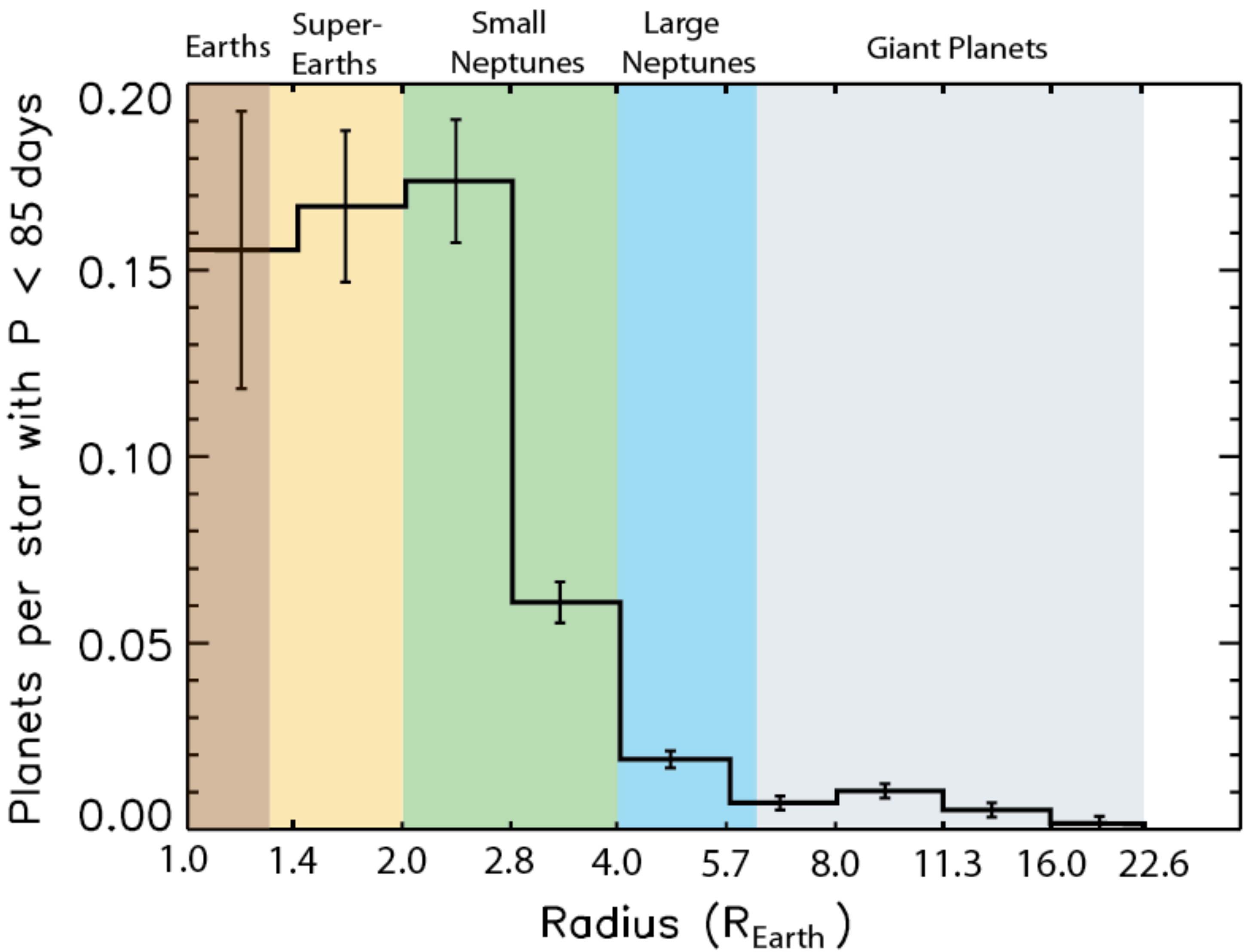
Kepler-11: Periods 10 to 118 days

Two Legacies of Kepler

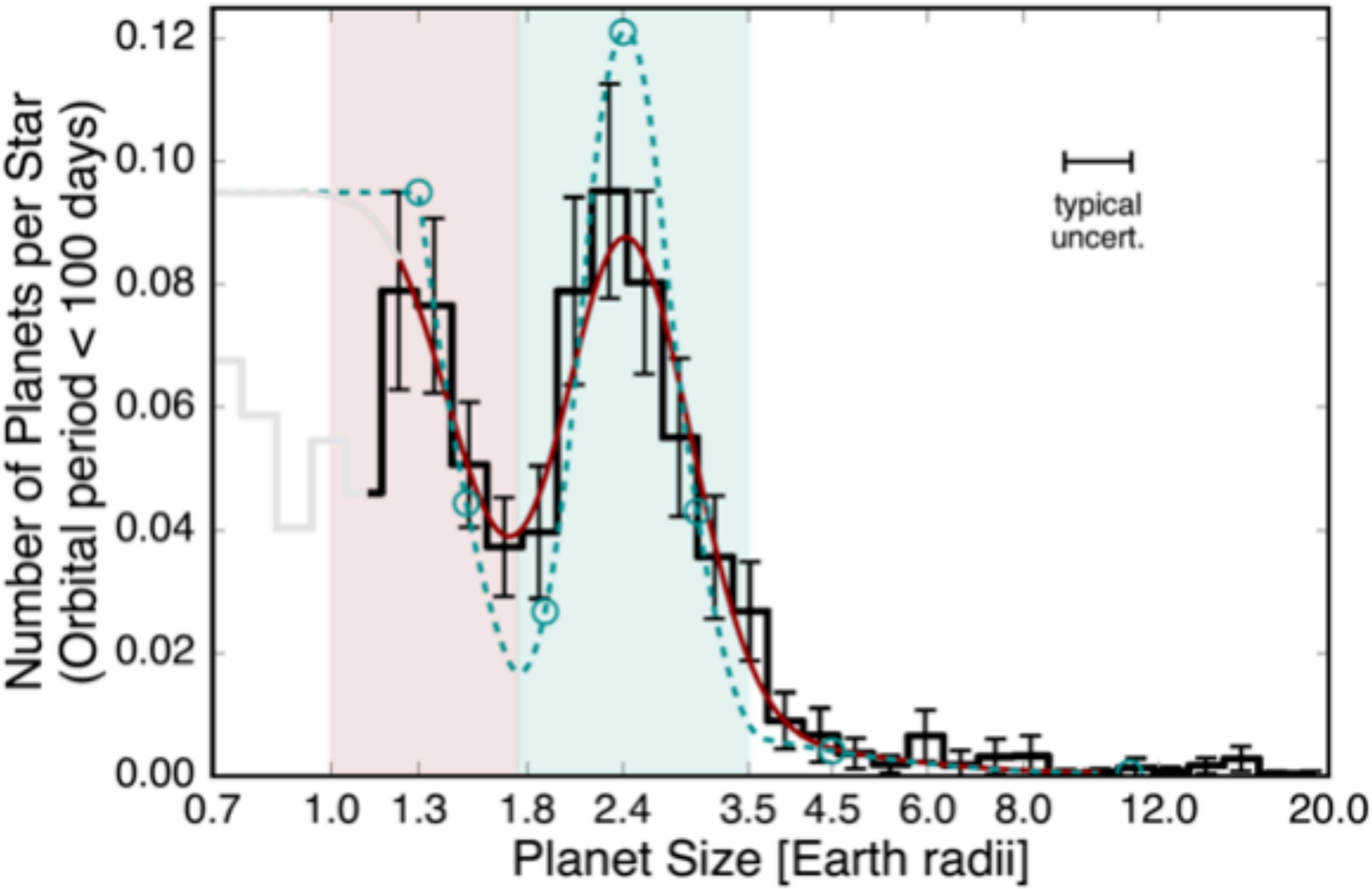
- Planets smaller than 4 Earth radii orbiting close to their host stars are common (most stars host at least one)
- Compact systems of multiple small planets orbiting in the same plane are also common



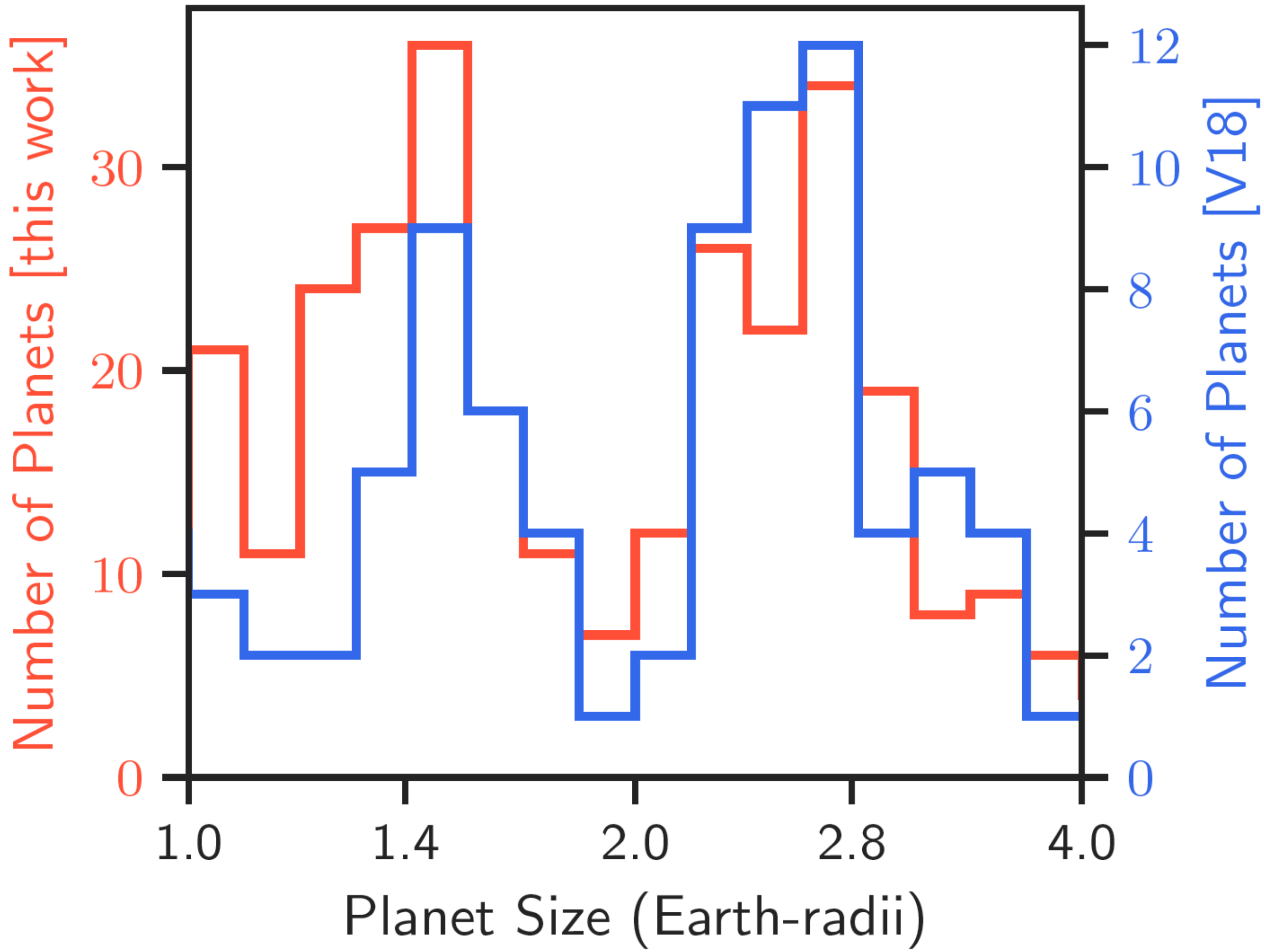
one - 1425
two - 490
three - 252
four - 108
five - 40
six - 6
Size Relative to Earth
20
10
4
1
Orbital Period in days
1
4
10
50
100
200
400



Exoplanet Occurrence Rates, Fressin et al. 2013



With Improved Stellar Radii, Fulton, et al. 2017

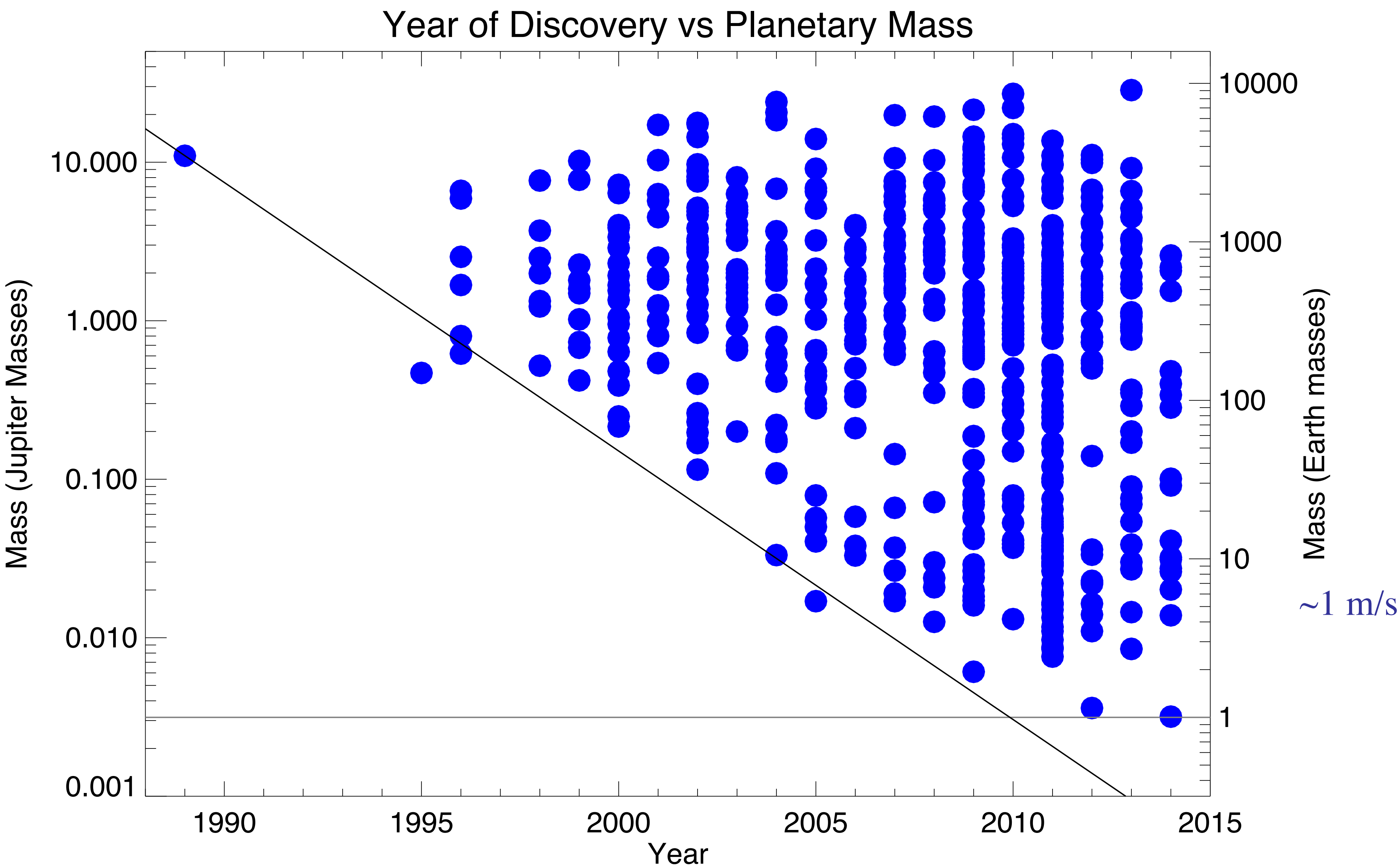


Are planets smaller than 1.8 Earth radii all rocky?

Van Eylen + (2018, MNRAS, 479, 4786)

Petigura (2020, AJ, 160, 89)

Masses are needed to distinguish rocky planets



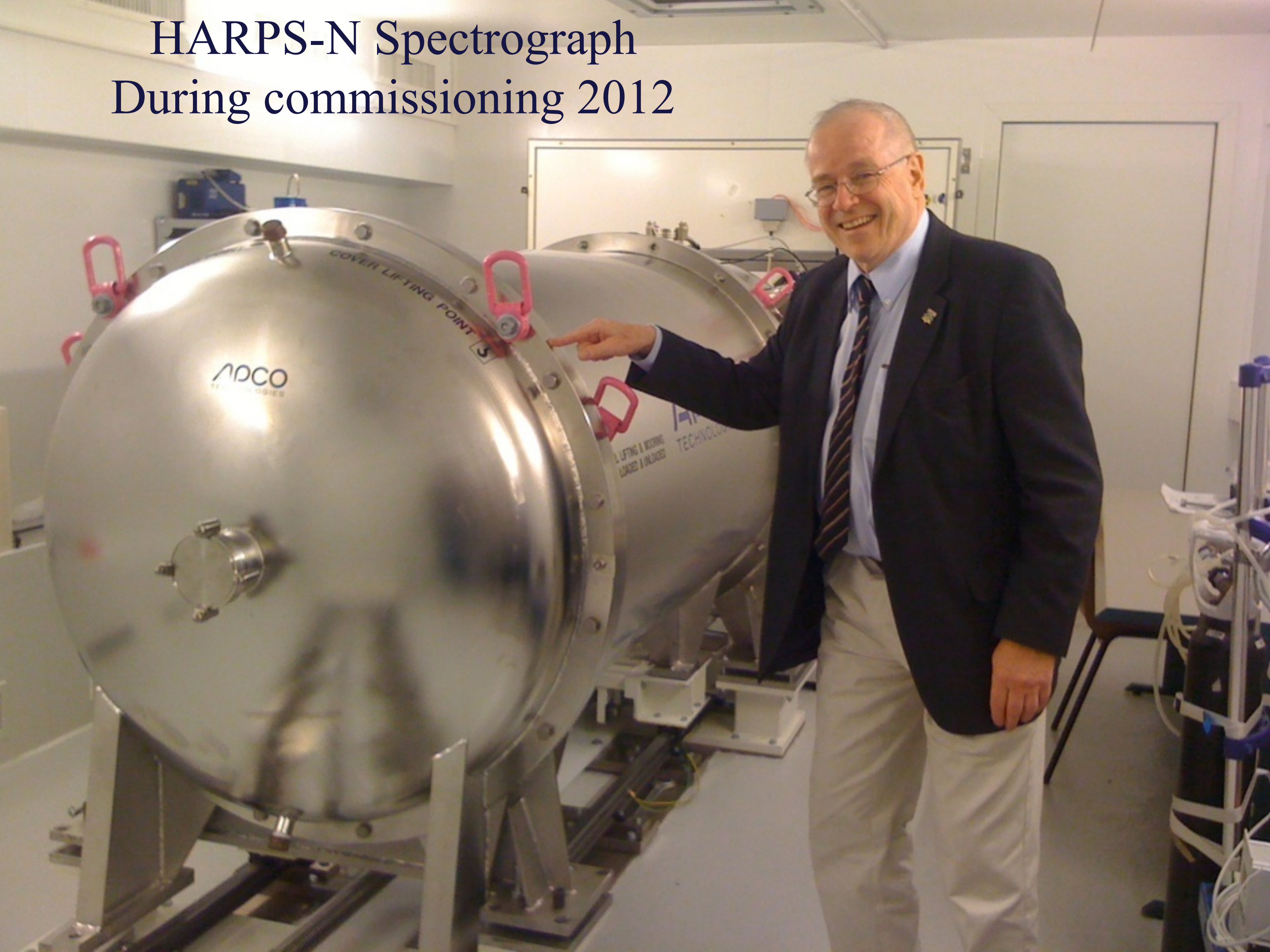
HARPS-N Collaboration

Francesco Pepe, Andrew Collier Cameron, David W. Latham, Ennio Poretti, Stéphane Udry; François Bouchy, David Charbonneau, John Johnson, Mercedes Lopez-Morales, Christophe Lovis, Michel Mayor, Giusi Micela, Emilio Molinari, David Phillips, Giampaolo Piotto, Ken Rice, Dimitar Sasselov, Damien Ségransan, Alessandro Sozzetti, Chris A. Watson, and many collaborators ...

HARPS-N Collaboration

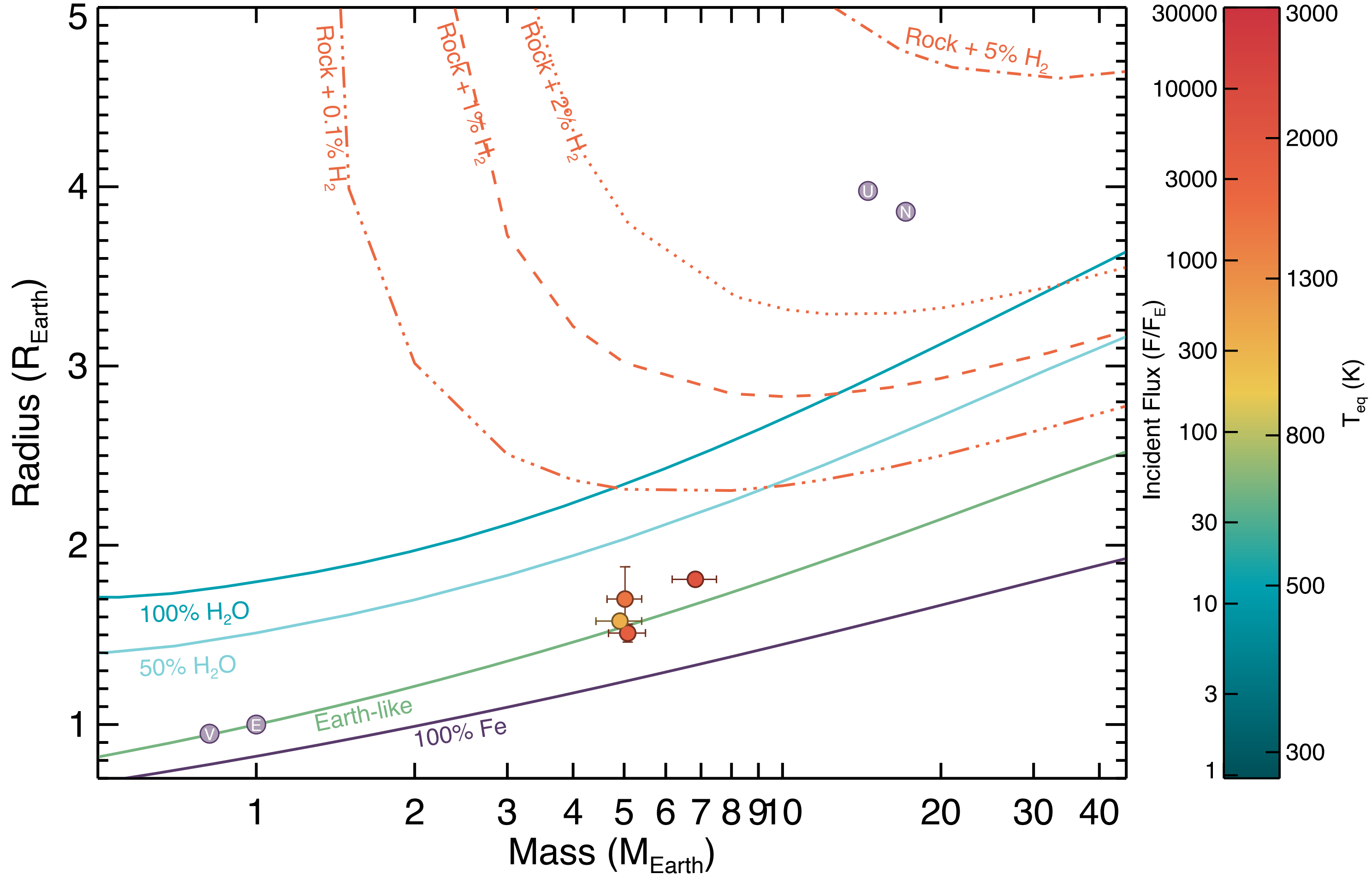
- 2005 Geneva & HUOLI & CfA establish the project
  - Improved version of the original HARPS at ESO
- 2008 Recession put Harvard funding on hold
- 2010 Additional partners, new funding, new host (INAF)
- 2012 Science operations started on TNG, 80 nights/year
  - Kepler and K2 follow-up (CfA); Rocky Planet Search (Geneva)
- 2015 Solar telescope installed
  - Sun observed as a star every clear day
- 2017 Collaboration extended for five more years
  - TESS Follow-up

HARPS-N Spectrograph
During commissioning 2012



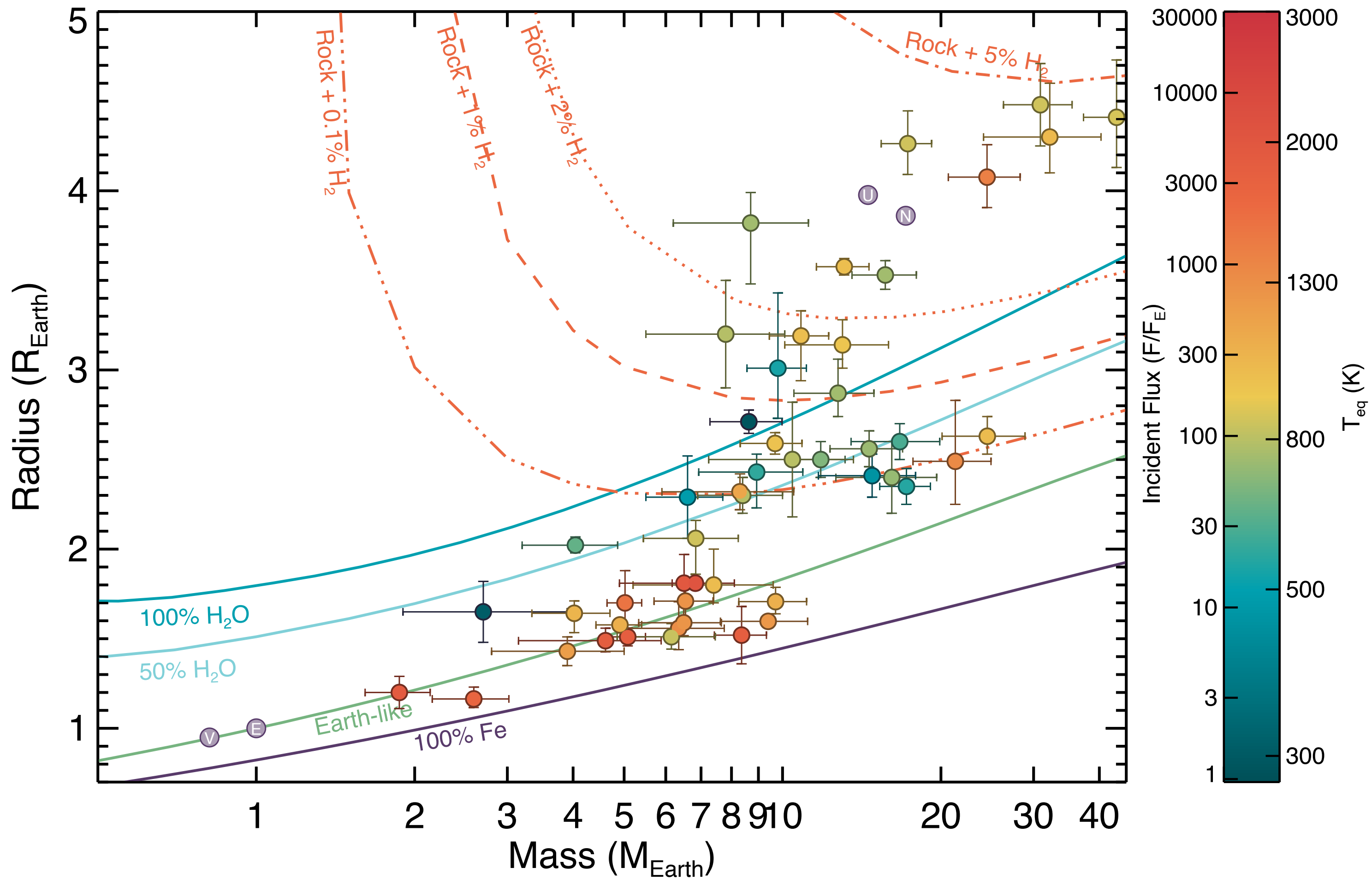
Radius vs. Mass Diagram

10-σ masses from Kepler

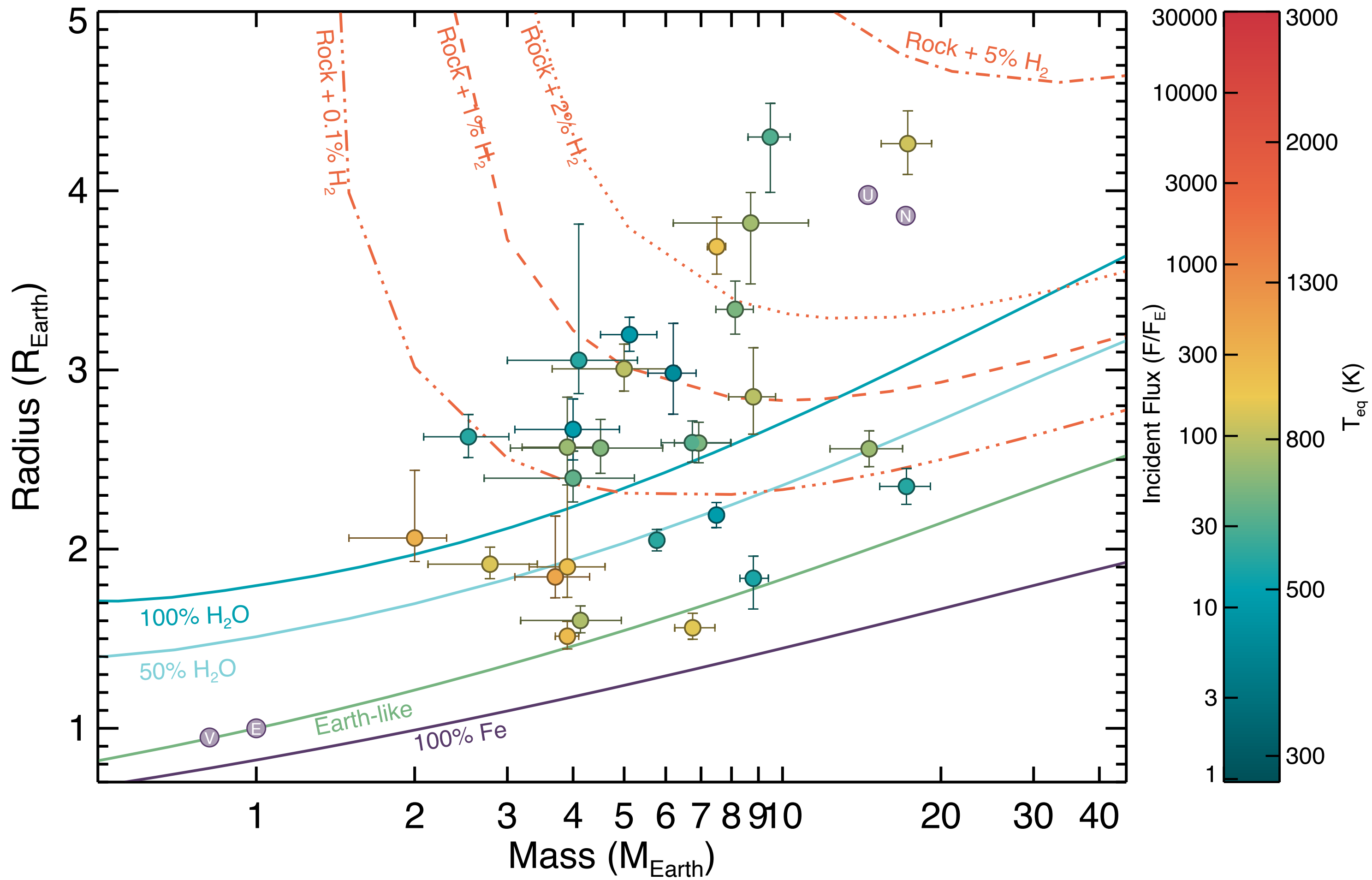


Models by Li Zeng et al. 2019; Plots by Sam Quinn

3-σ RV masses from Kepler + K2



3-σ TTV masses from Kepler + K2



Kepler's Un-fulfilled Promise

- No true Earth twins – no confirmed rocky planets with measured masses in one year orbits around a star like the Sun in orbits where water might be liquid on the surface.
- Velocity jitter in quiet stars is at the m/s level.

Lessons Learned

- Correcting for stellar jitter the main challenge
  - Correlations with activity indicators not perfect
  - Gaussian processes can help sometimes
    - Often need intense campaigns over consecutive nights
- Missing planets can distort the results
  - e.g. non-transiting intermediate planets
- Solar observations are revealing
  - Help understand the instrument performance
  - Reveal spectral lines less sensitive to activity

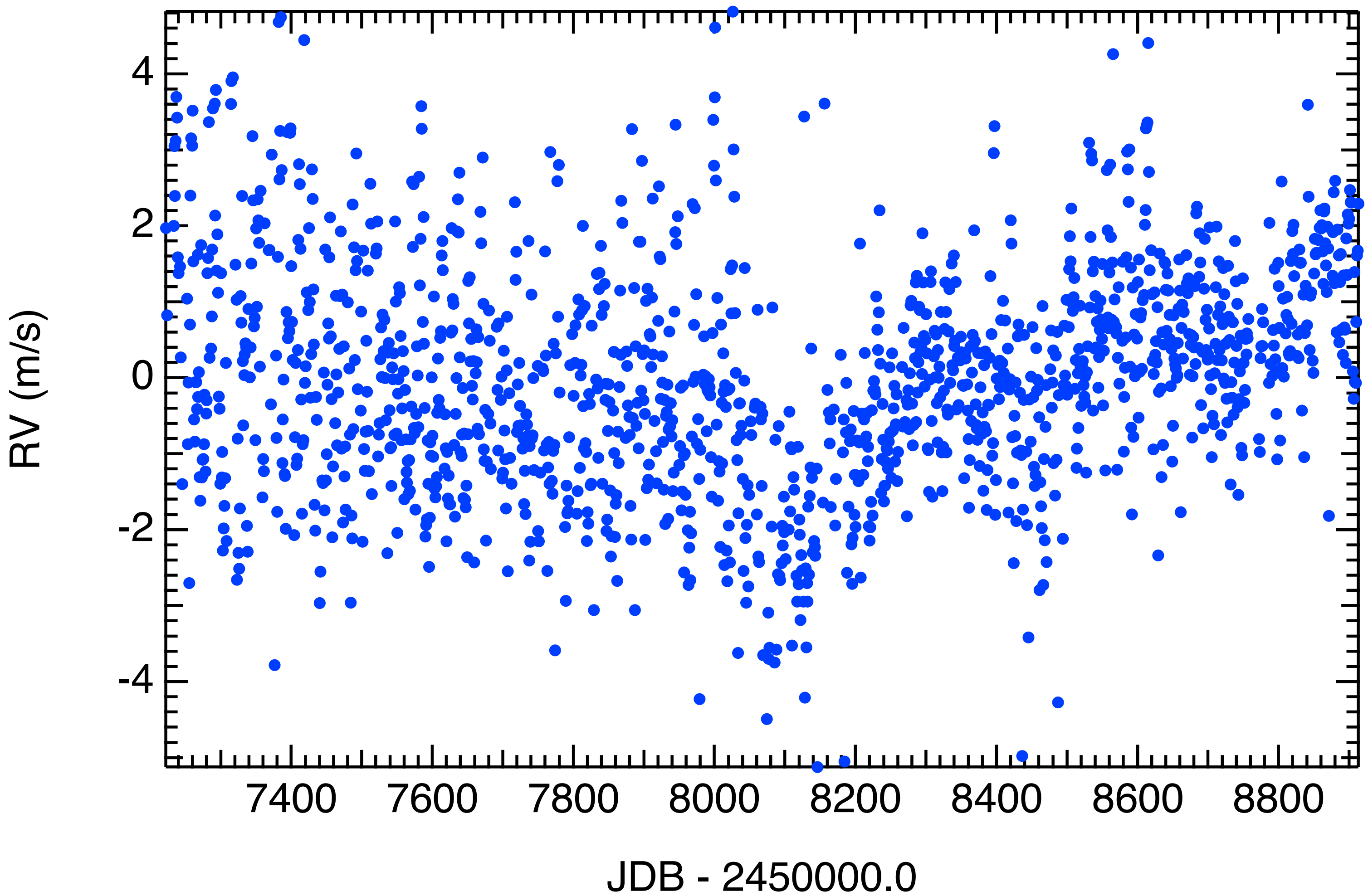
The HARPS-N Solar Telescope

Credit: A. Glenday

X. Dumusque, D. F. Phillips, A. Glenday, A. Collier Cameron, D. Charbonneau,
D. W. Latham, C. Lovis, G. Micela, E. Molinari, J. Maldonado, F. Pepe, R. H. Haywood, S. Udry

HARPS-N Solar Telescope

Daily averages, 79,670 Solar velocities on 1400 days



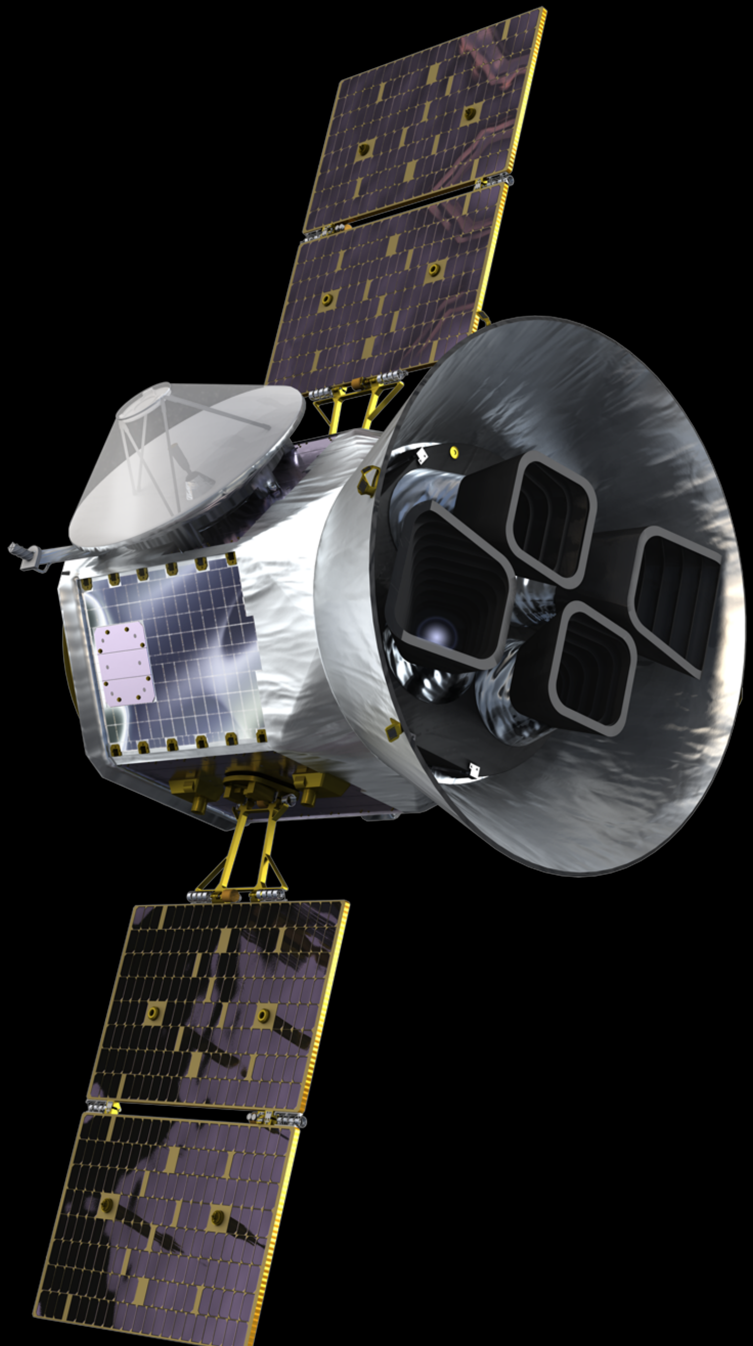
Courtesy of David Phillips, SAO

Beyond Kepler

- Kepler provided radii for thousands of planets around fainter stars
- Doppler orbits and masses are rarely available for planets smaller than $4R_{Earth}$
- Need an all-sky survey to find nearby bright transiting systems with rocky planets that are easier to characterize
- More emphasis on small cool dwarf stars

Geneology of TESS

- 2005: Conversations at the AMA in Chicago
- 2006: Proposal to monitor bright stars for hot Jupiters
  - Mission of opportunity to re-use the HETE-2 optical camera
- 2007: Re-structured as a privately-funded small mission
  - Efforts to convince donors failed
- 2008: Re-configured as a NASA Small Explorer (SMEX)
  - Selected for Phase A (1 of 3 Astrophysics Missions), lost
- 2010: Re-proposed as a NASA Explorer ($200M cap)
  - Selected for Phase A (1 of 2 Astrophysics Missions)
- 2013: Selected for formulation (April 5, 2013)
- 2018: 18 April launch



NASA's TESS Mission

George Ricker (MIT)

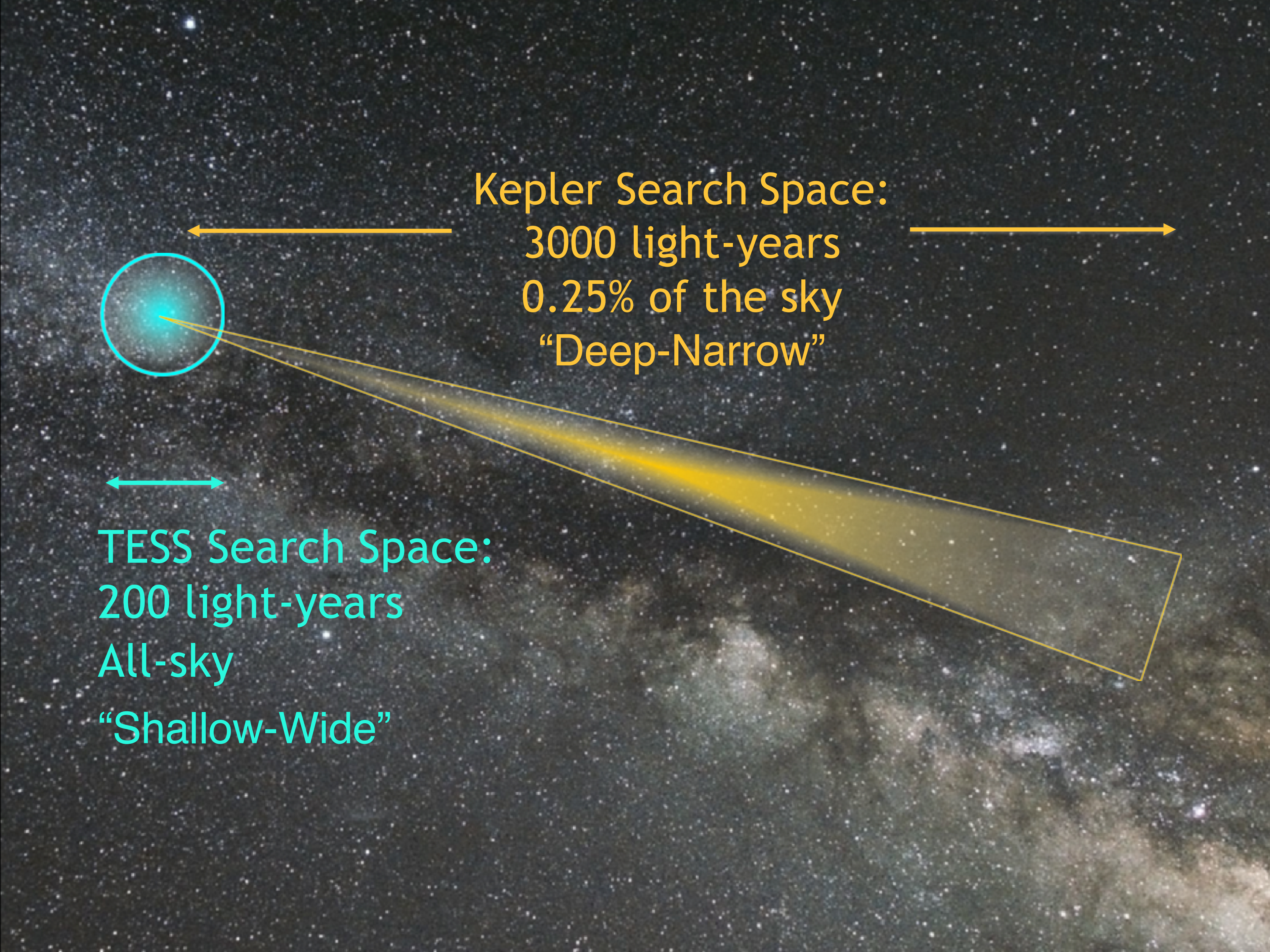
TESS Principal Investigator

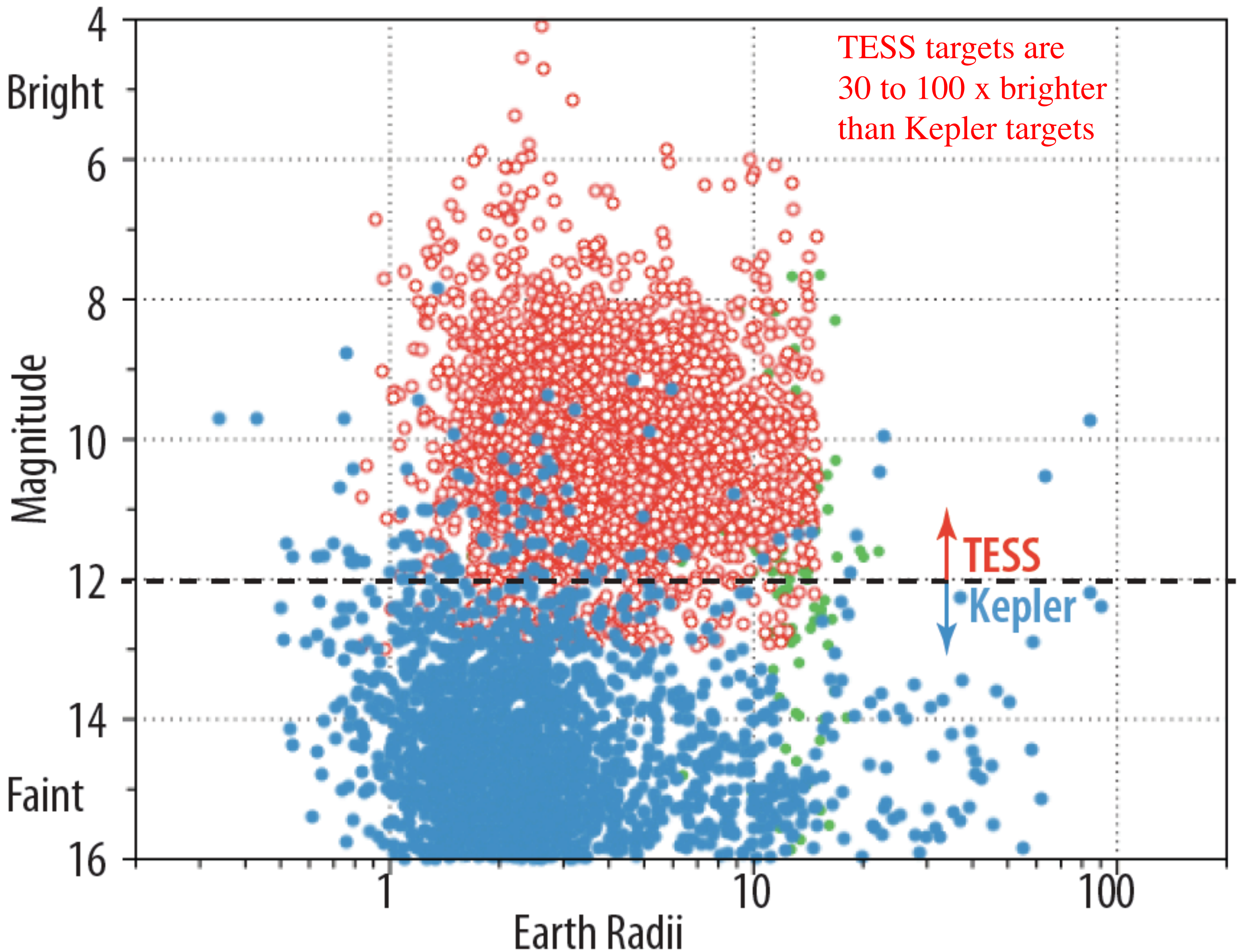
David Latham (CfA)

TESS Director of Science

TESS is a collaboration including:

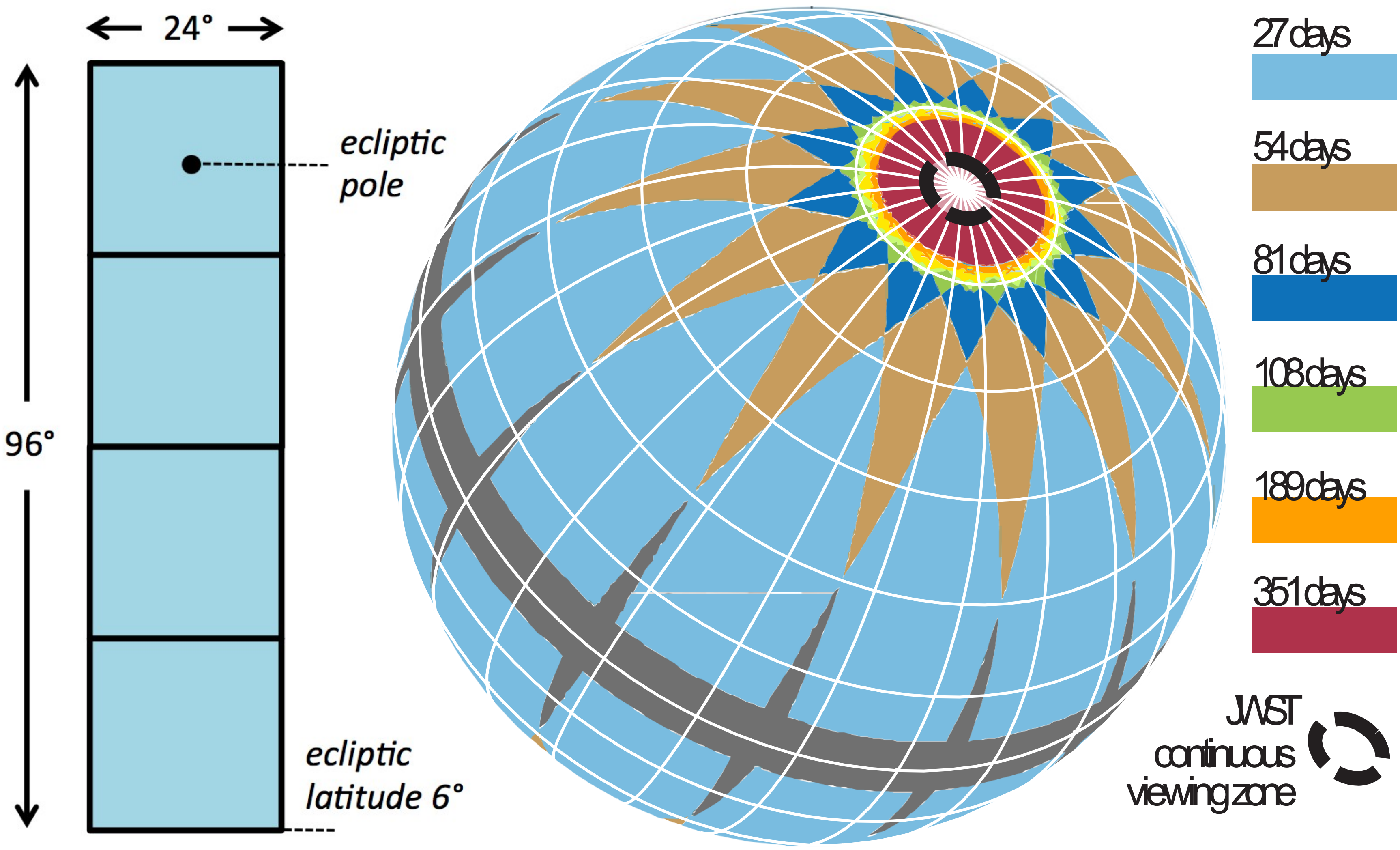
MIT/MKI, MIT/LL, NASA Goddard, NASA Ames, NGIS, SpaceX, STScI, SAO, MPIA-Germany, Las Cumbres Observatory, Geneva Observatory, OHP-France, University of California, University of Florida, Aarhus University-Denmark, Harvard College Observatory, Princeton University, Vanderbilt University...

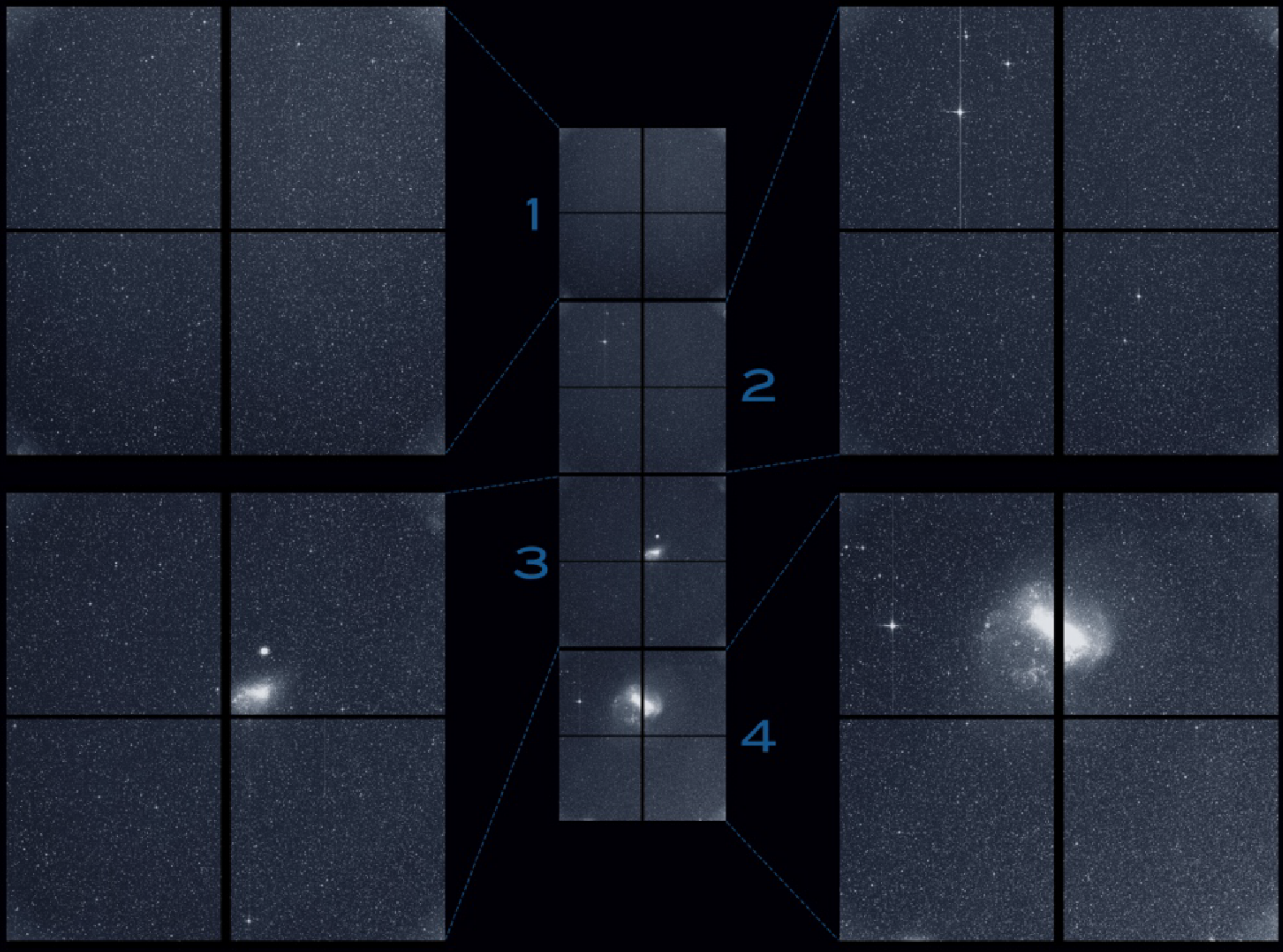

Kepler Search Space:
3000 light-years
0.25% of the sky
“Deep-Narrow”
TESS Search Space:
200 light-years
All-sky
“Shallow-Wide”


TESS targets are
30 to 100 x brighter
than Kepler targets
Bright
Faint
Magnitude
4
6
8
10
12
14
16
1
10
100
Earth Radii
TESS
Kepler

TESS Observatory During Integration and Testing

TESS's 2300 deg^2 FOV and 2 Year Survey Plan

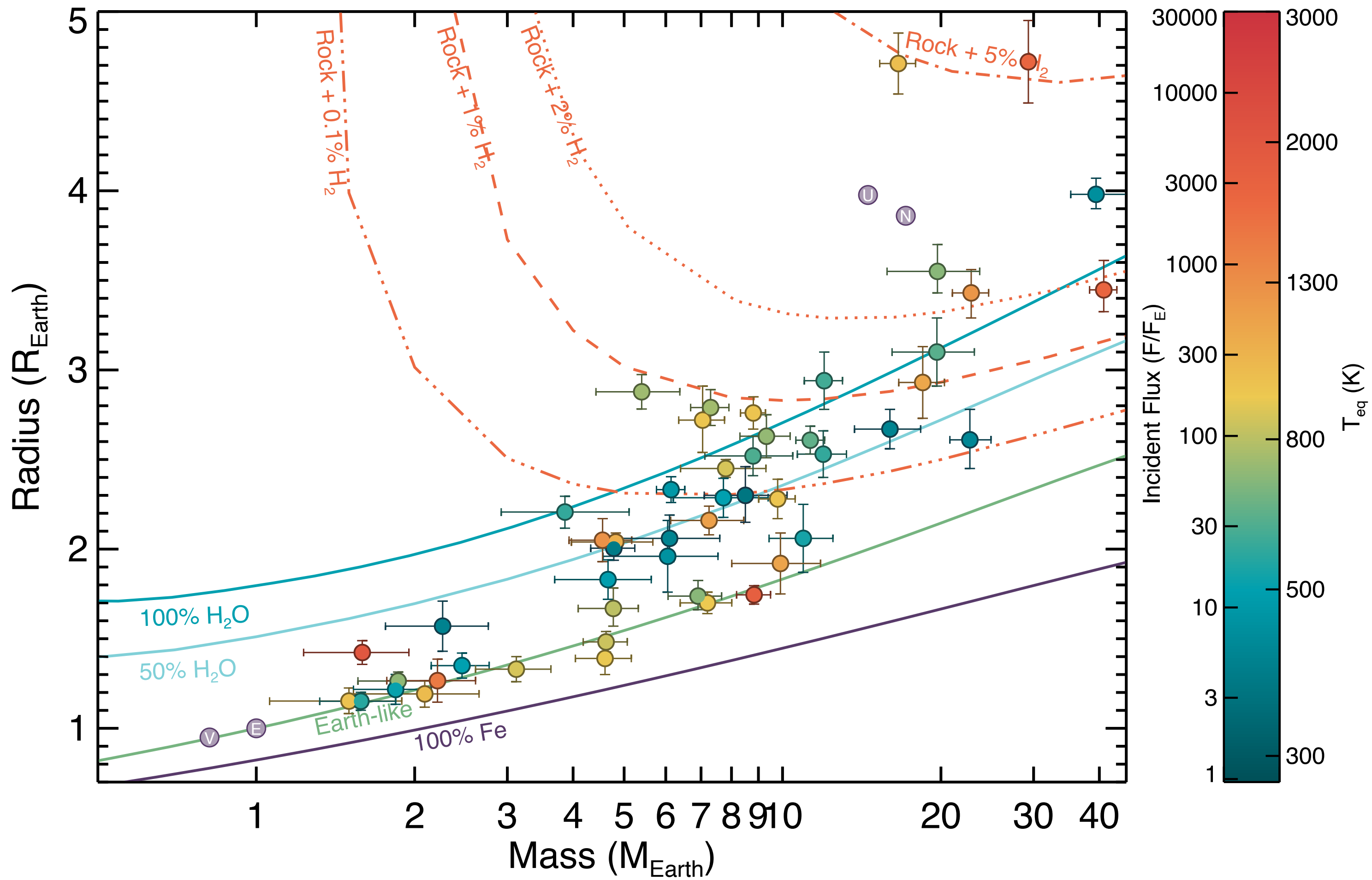



1
2
3
4

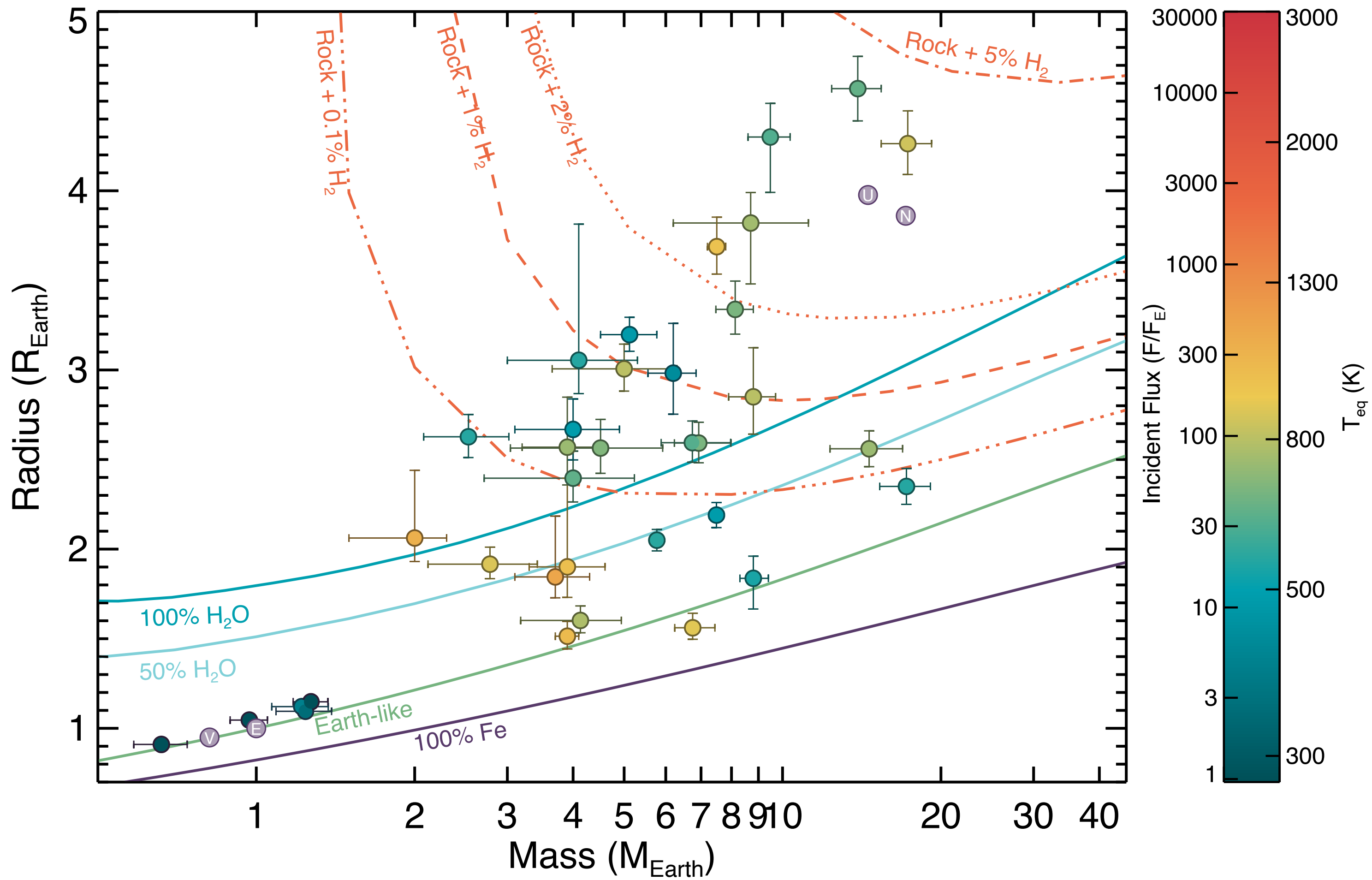
TESS Status Report

- 36 moonths (sectors) of data on the ground
- 2487 candidate planet-hosting stars released
- Follow-up observations in full swing
- More than 47 masses for planets smaller than 4 Earth radii already published, many more in the pipeline

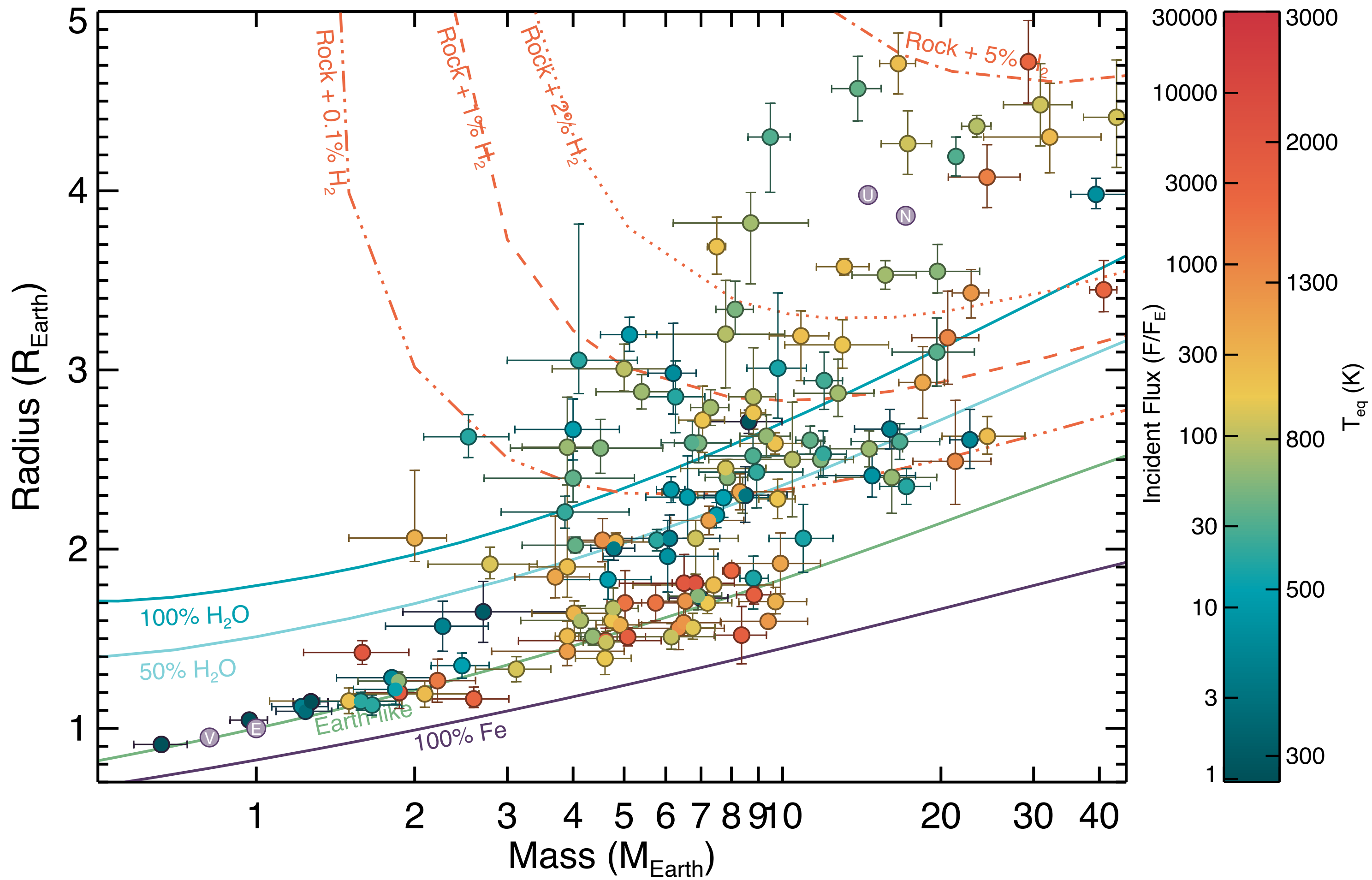
3-σ RV masses from TESS



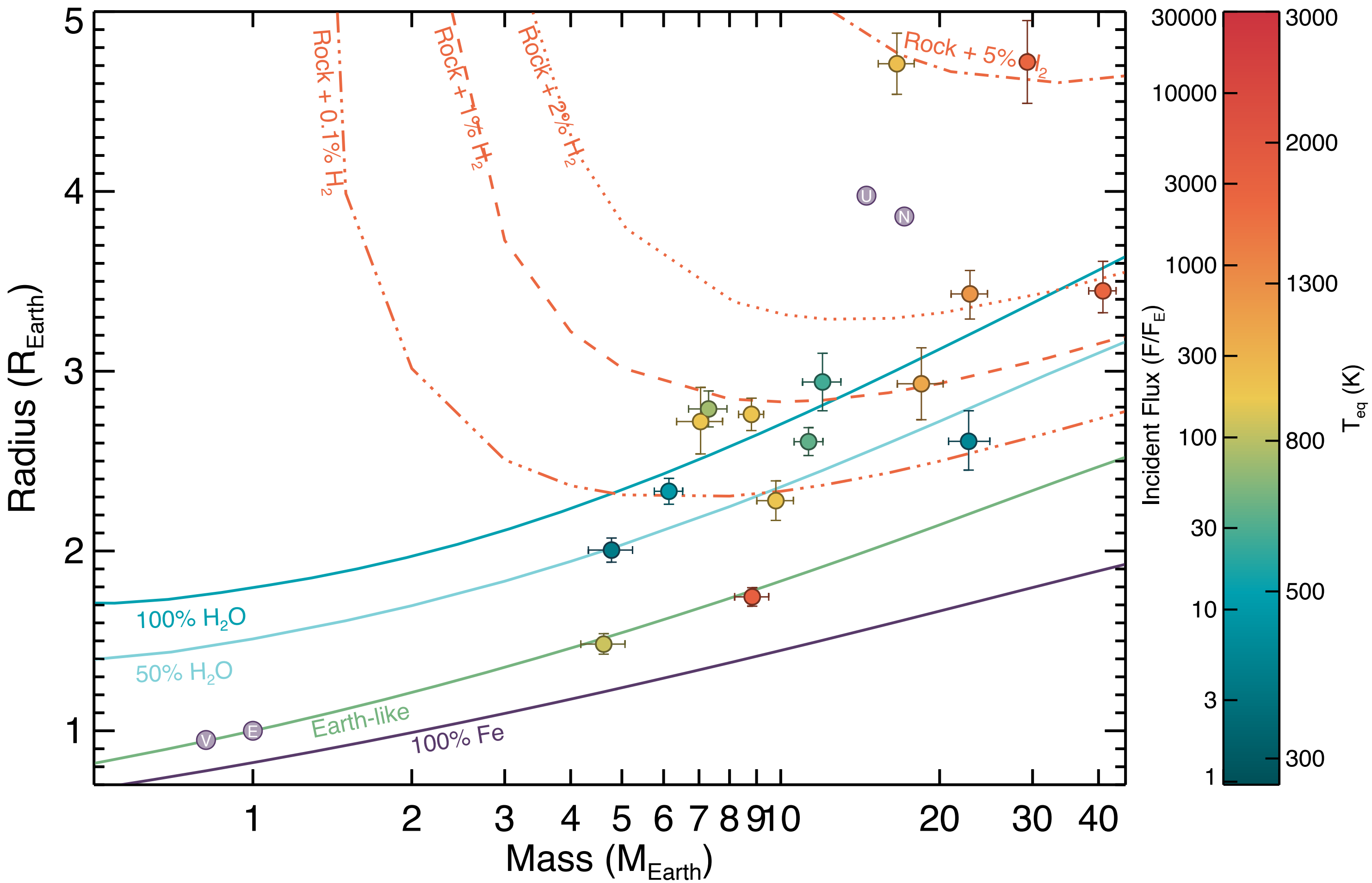
3-σ TTV masses, mostly from Kepler + K2



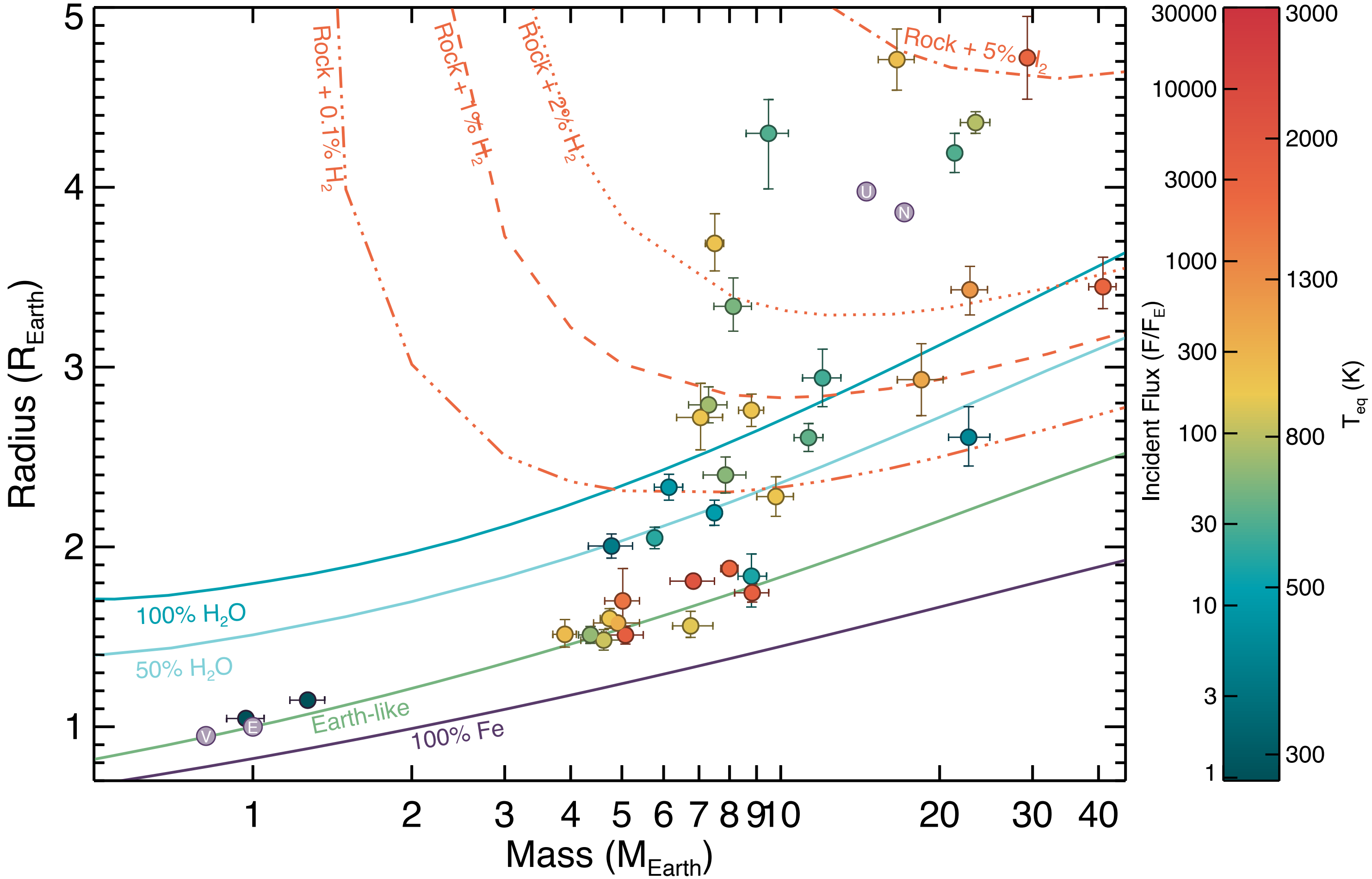
3-σ masses from all sources



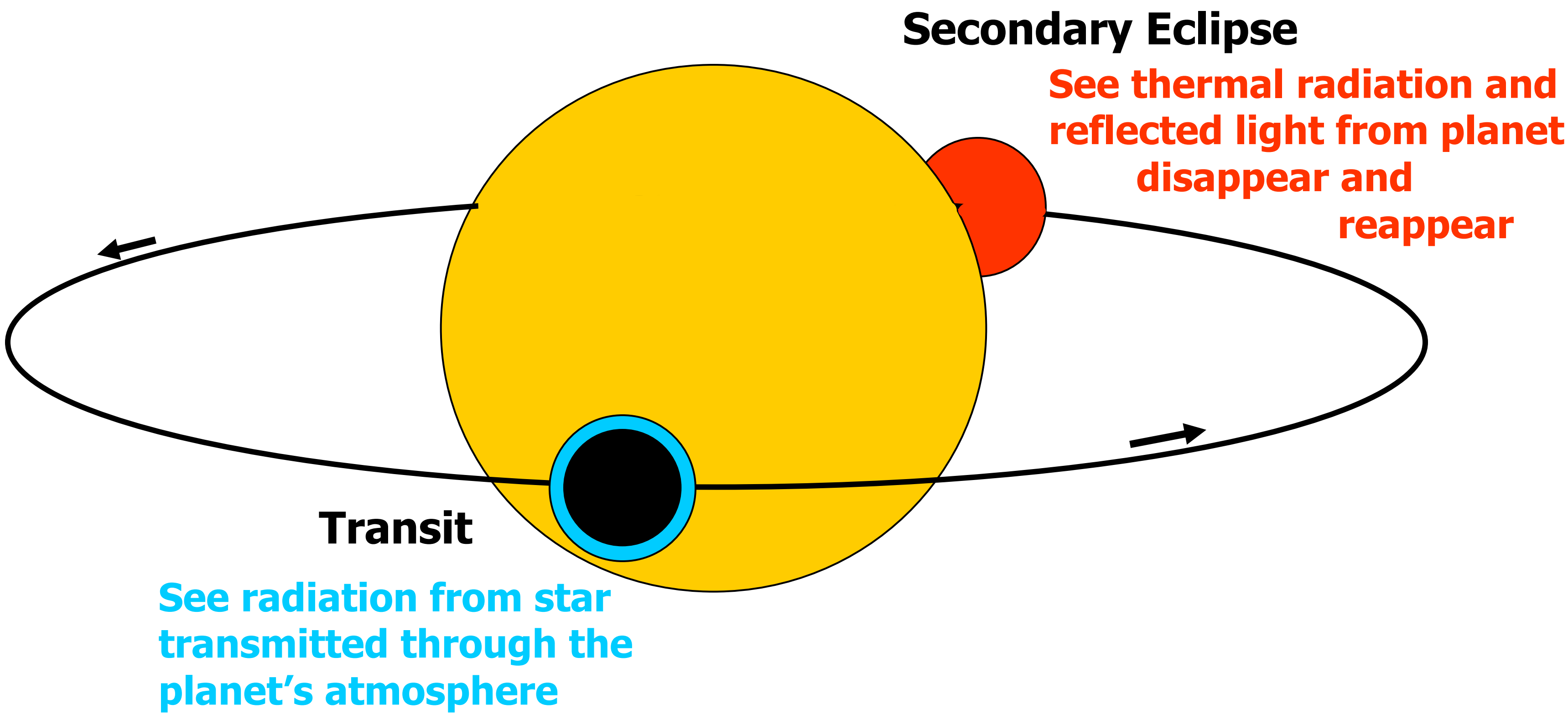
10-σ masses from TESS



10-σ masses from all sources



Transits Allow Studies of the Atmospheres That Are Not Yet Feasible for Non-Transiting Planets



After a diagram by Tim Brown

Secondary eclipse of TOI-136 in the IR with Spitzer:
Temperature of permanent nightside
indicates no heat redistribution, therefore no atmosphere

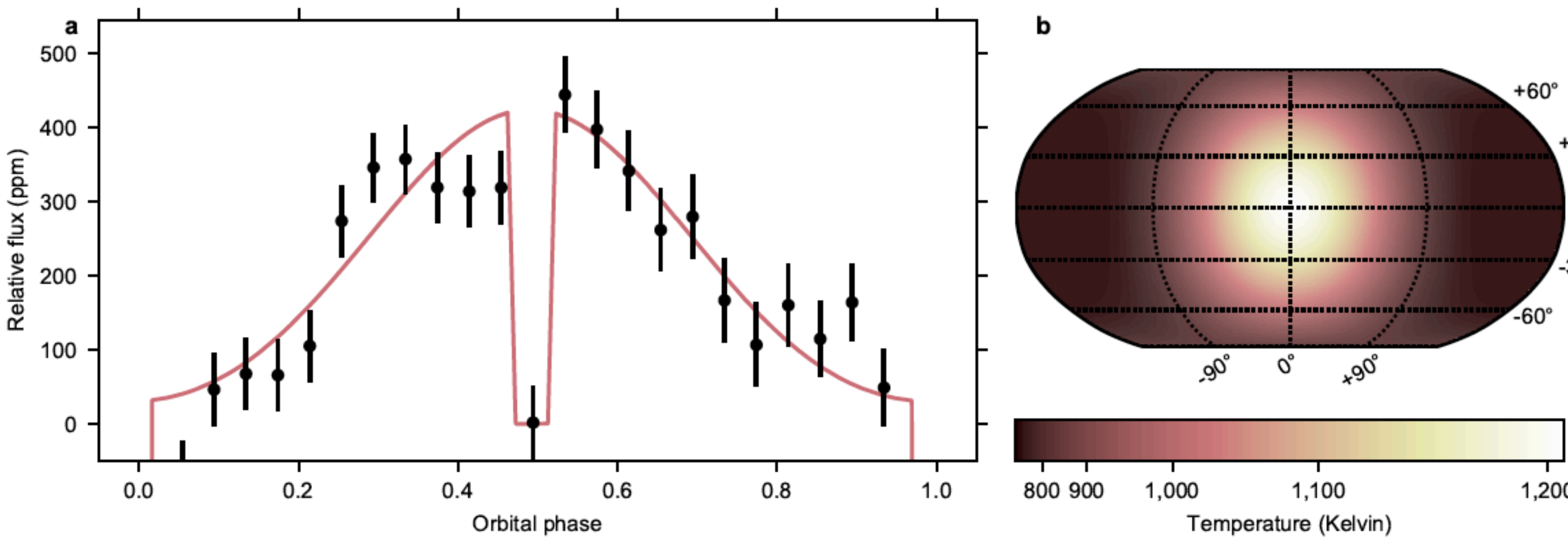
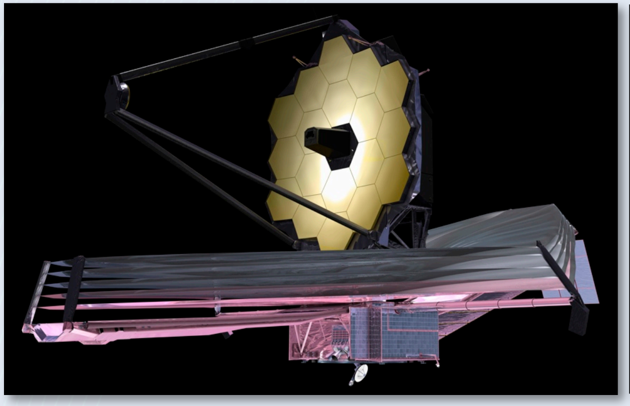


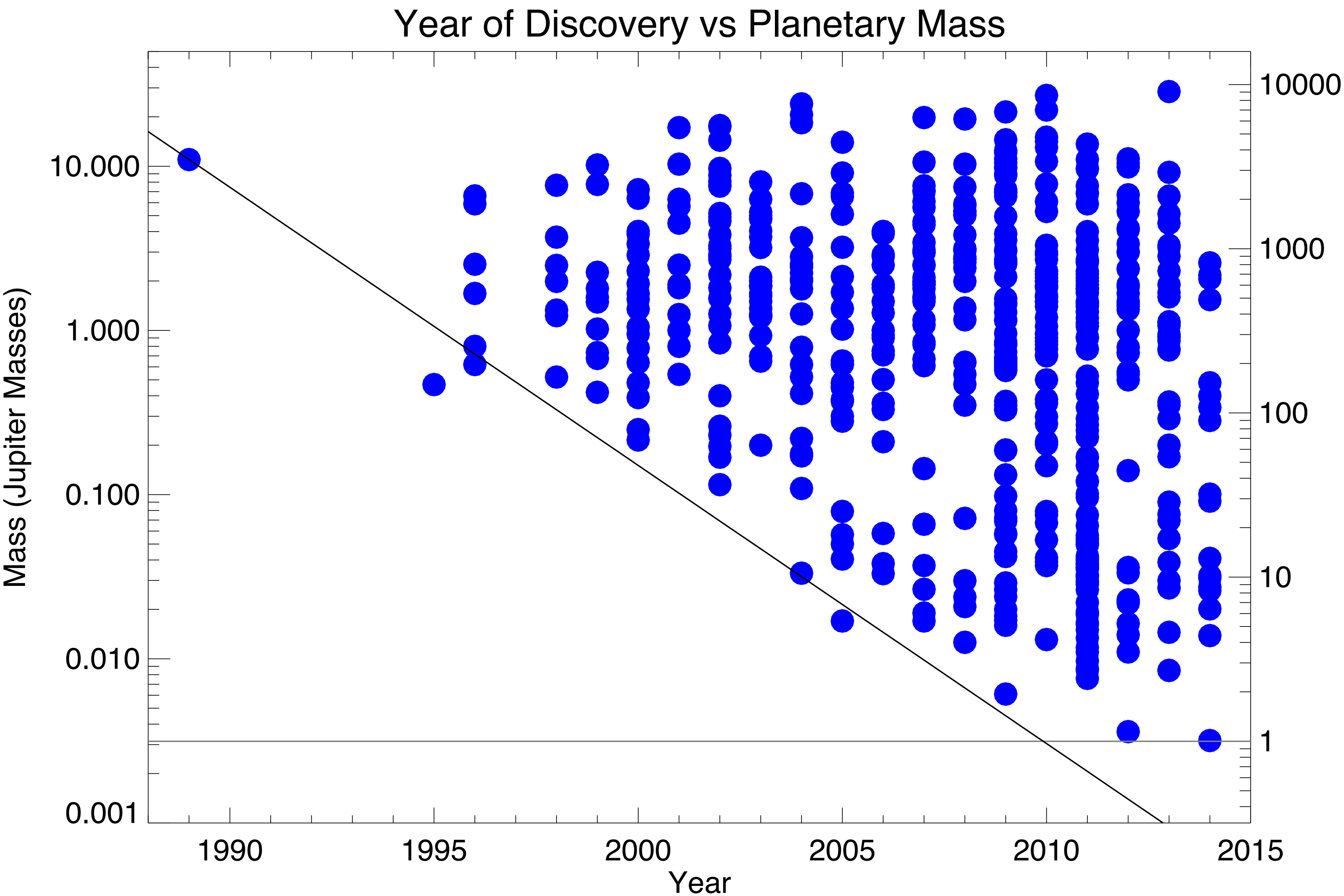
Figure 1: **The 4.5 μm thermal phase curve of LHS 3844b and best fit temperature map. a,** Planet-to-star flux binned over 25 equally spaced intervals over the planet's 11.1-hour orbital period (points with 1 σ uncertainties) compared to the best fit phase curve (line). The data are normalized such that the relative flux is zero when the planet is eclipsed by the star at orbital phase

Kreidberg et al. 2019, Nature

TESS Enables Atmospheric Characterization

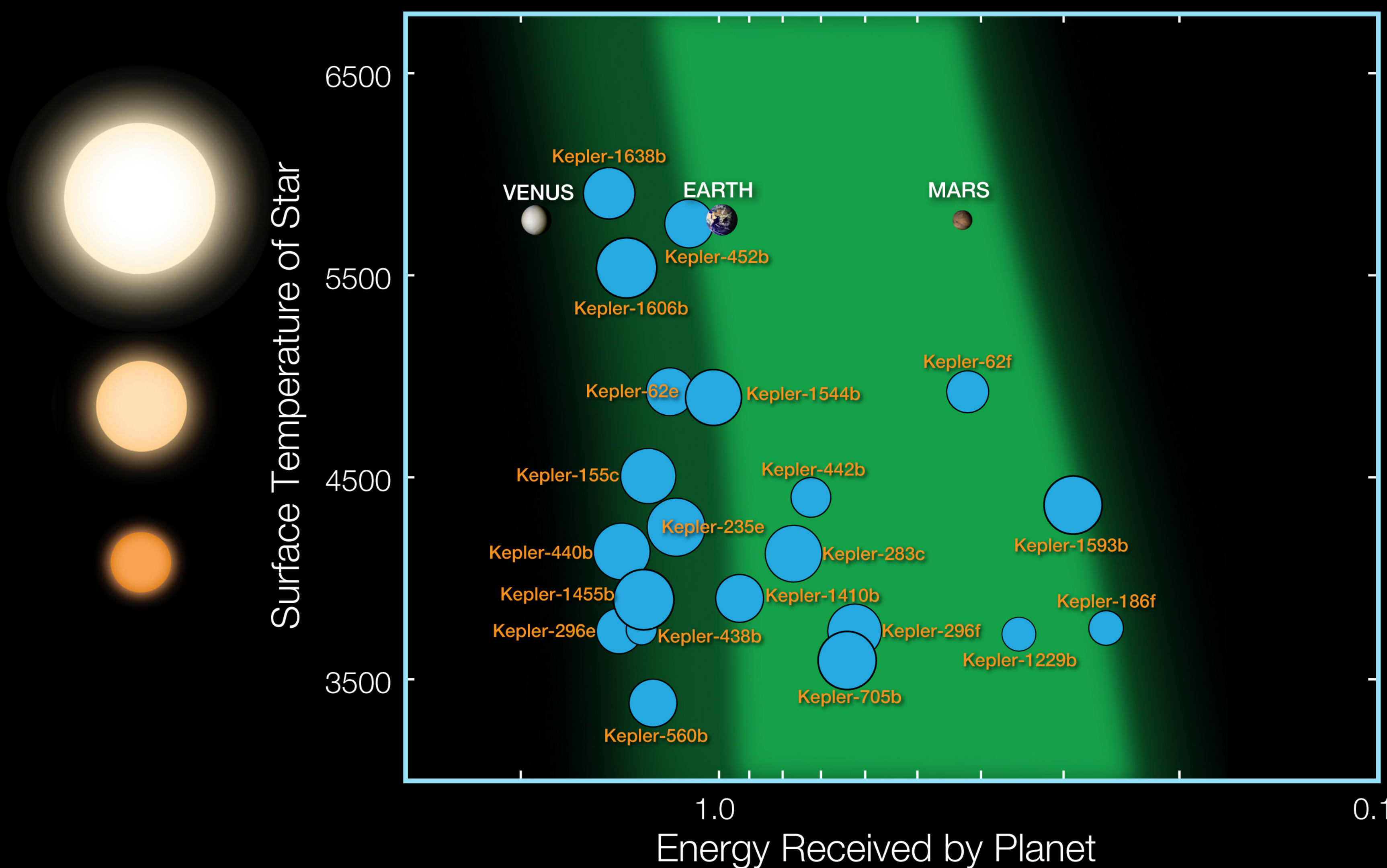
- TESS will identify the best and smallest exoplanet targets for characterization of atmospheres using:
  - *James Webb Space Telescope*
  - *Extremely Large Telescopes (ELTs)*
  - *Future Exoplanet Explorers, Probes, and Large Missions*

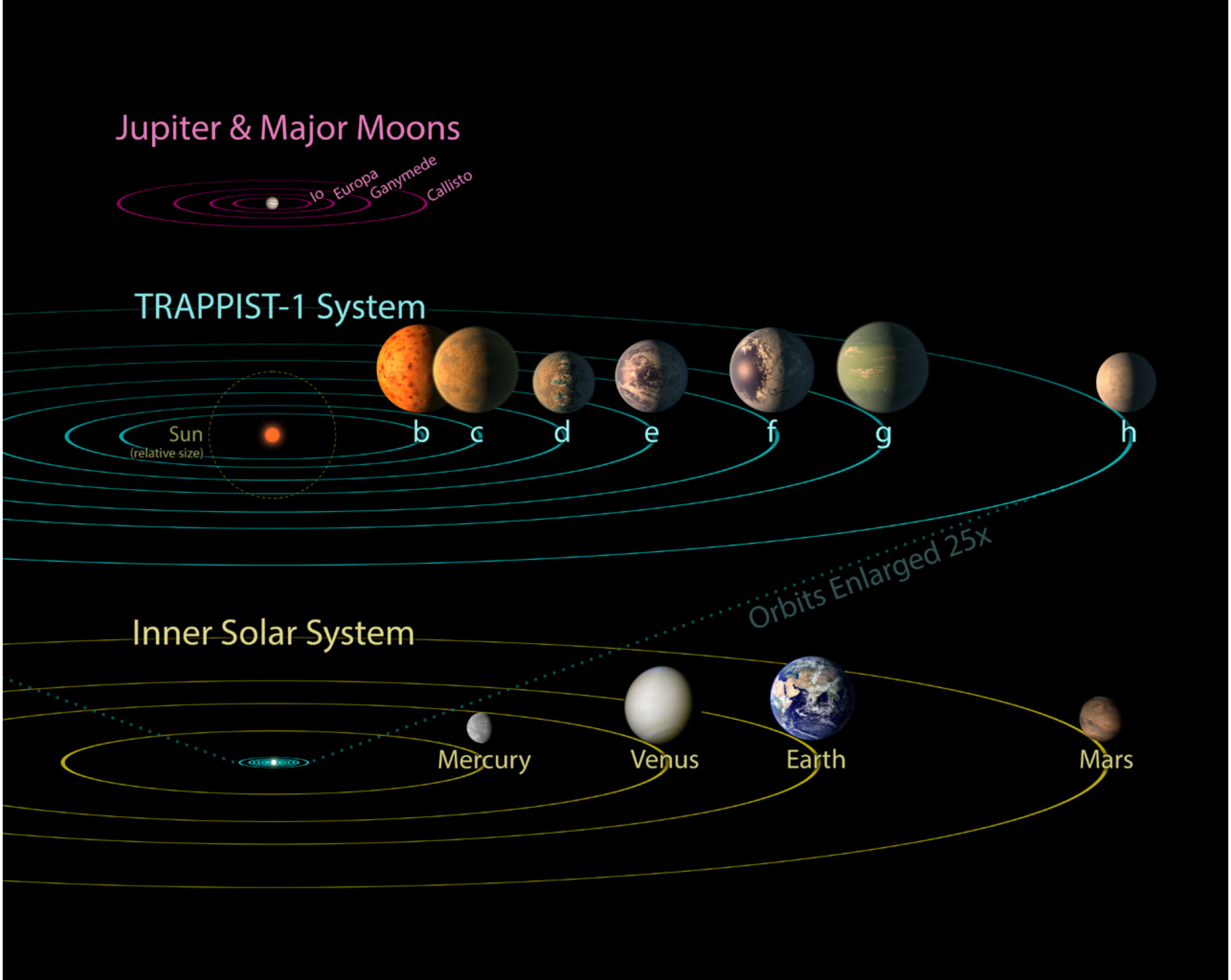



Year of Discovery vs Planetary Mass
Mass (Jupiter Masses)
10.000
1.000
0.100
0.010
0.001
Mass (Earth masses)
10000
1000
100
10
1
1990
1995
2000
2005
2010
2015
Year

Kepler's Small Habitable Zone Planets

As of May 10, 2016




Jupiter & Major Moons
Io
Europa
Ganymede
Callisto
TRAPPIST-1 System
Sun
(relative size)
b
c
d
e
f
g
h
Orbits Enlarged 25x
Inner Solar System
Mercury
Venus
Earth
Mars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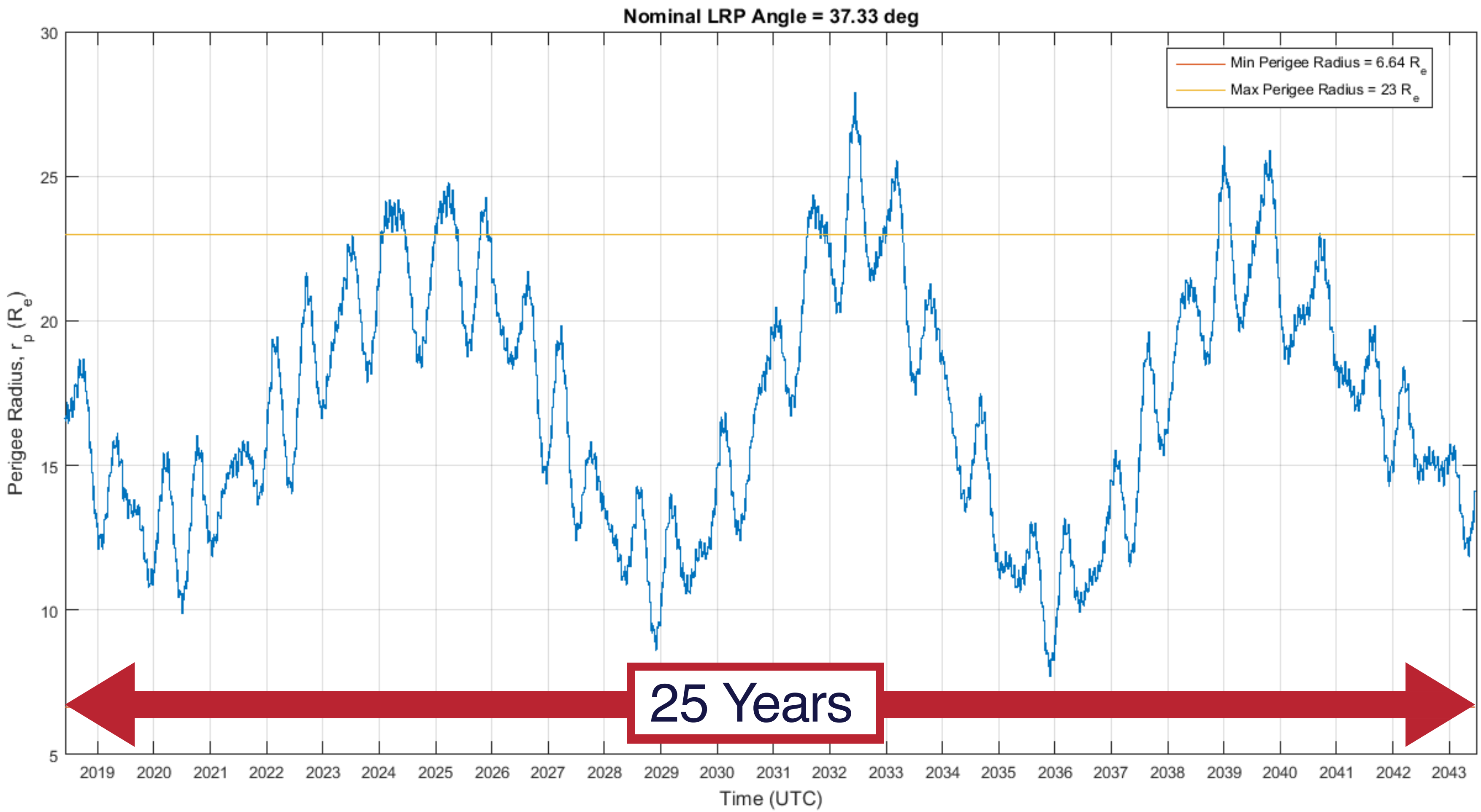
SPACEX

P/2 Lunar Resonant Orbit



- Orbit is stable with respect to Kozai oscillations, as planned
- **Stable TESS orbit behavior is anticipated for >25 years**