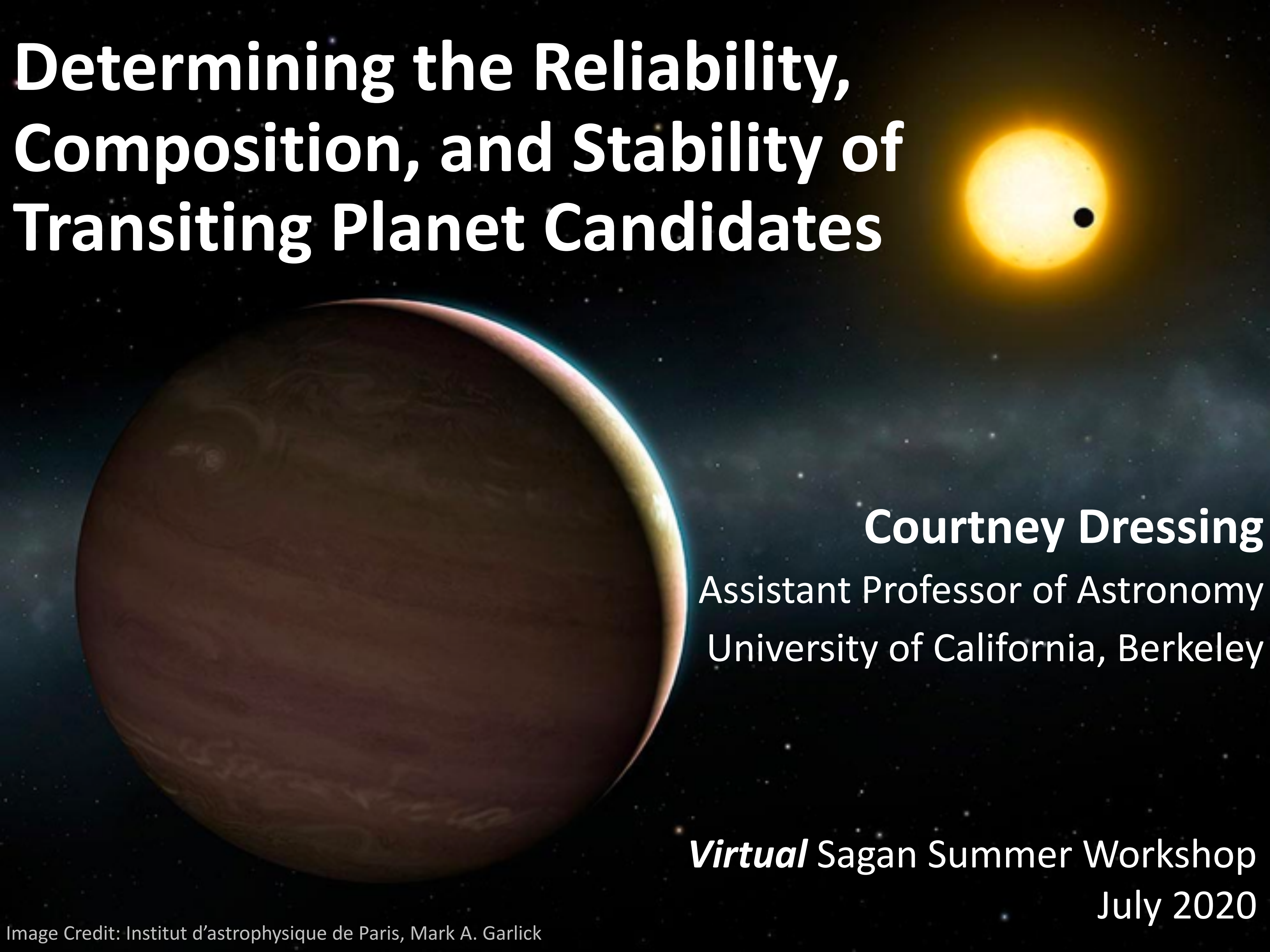
Determining the Reliability, Composition, and Stability of Transiting Planet Candidates



Courtney Dressing
Assistant Professor of Astronomy
University of California, Berkeley

Virtual Sagan Summer Workshop
July 2020

Image Credit: Institut d’astrophysique de Paris, Mark A. Garlick

Questions Addressed in This Talk

- What are **transiting planets**, how are they detected, and what planetary characteristics can be determined?
- What **follow-up data** are needed to determine which candidate transiting planets are real planets?
- How do astronomers determine the **compositions** of planets and what have we learned so far?
- What are the three-dimensional **orientations** of planetary systems and how stable are they?

Streamlined Outline

1. Transiting planets

2. Follow-up observations

3. Planetary compositions

4. System orientations

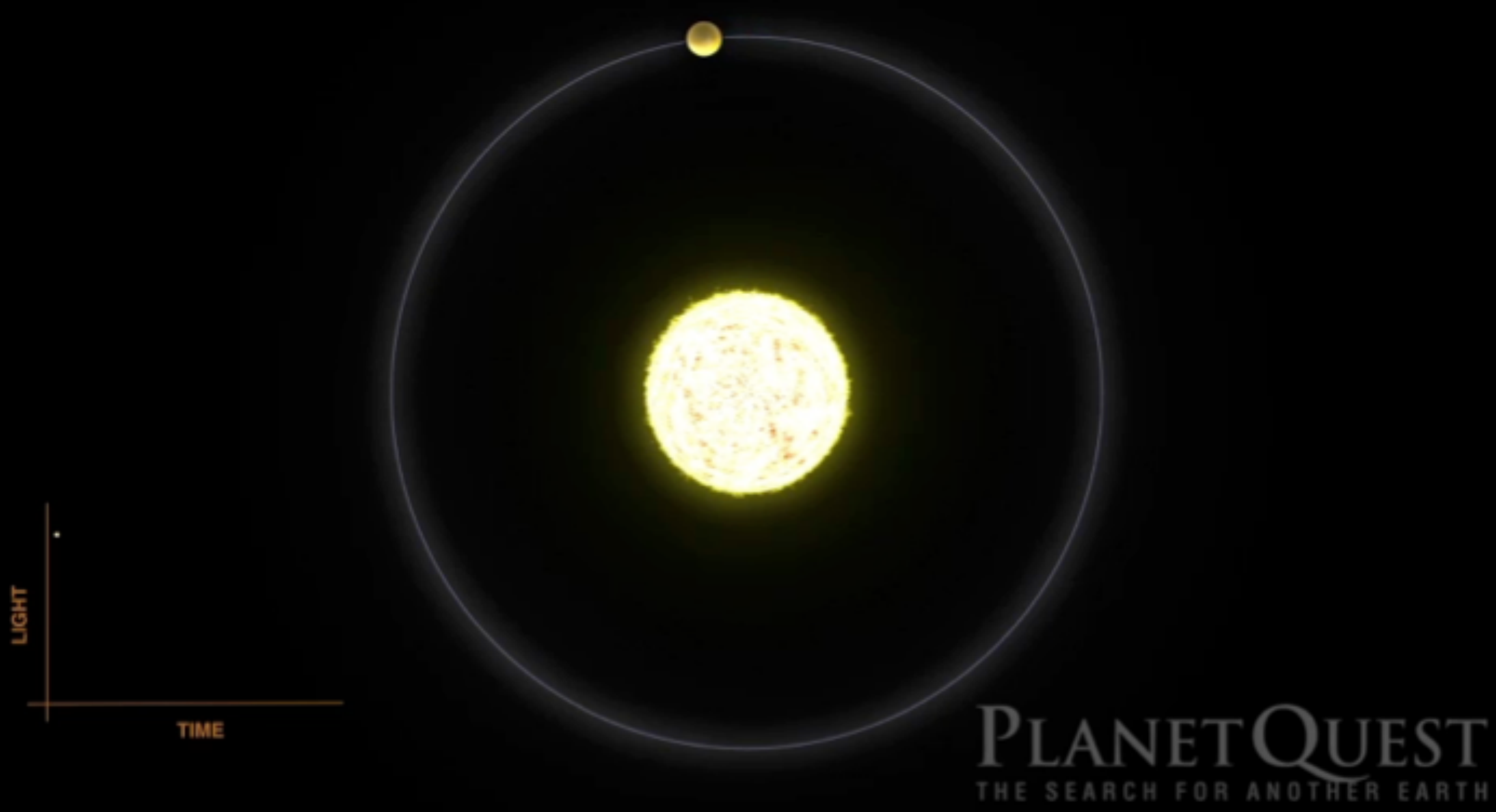
Part 1. *Transiting Planets*

Radial Velocity Observations Reveal Planet Masses

Image credit: NASA/SDO, Scientific American

Transit Observations Reveal Planet Sizes

We detect transiting planets by monitoring the brightness of their host stars and looking for periodic decreases in brightness.



Transit Light Curves Reveal Planet Properties

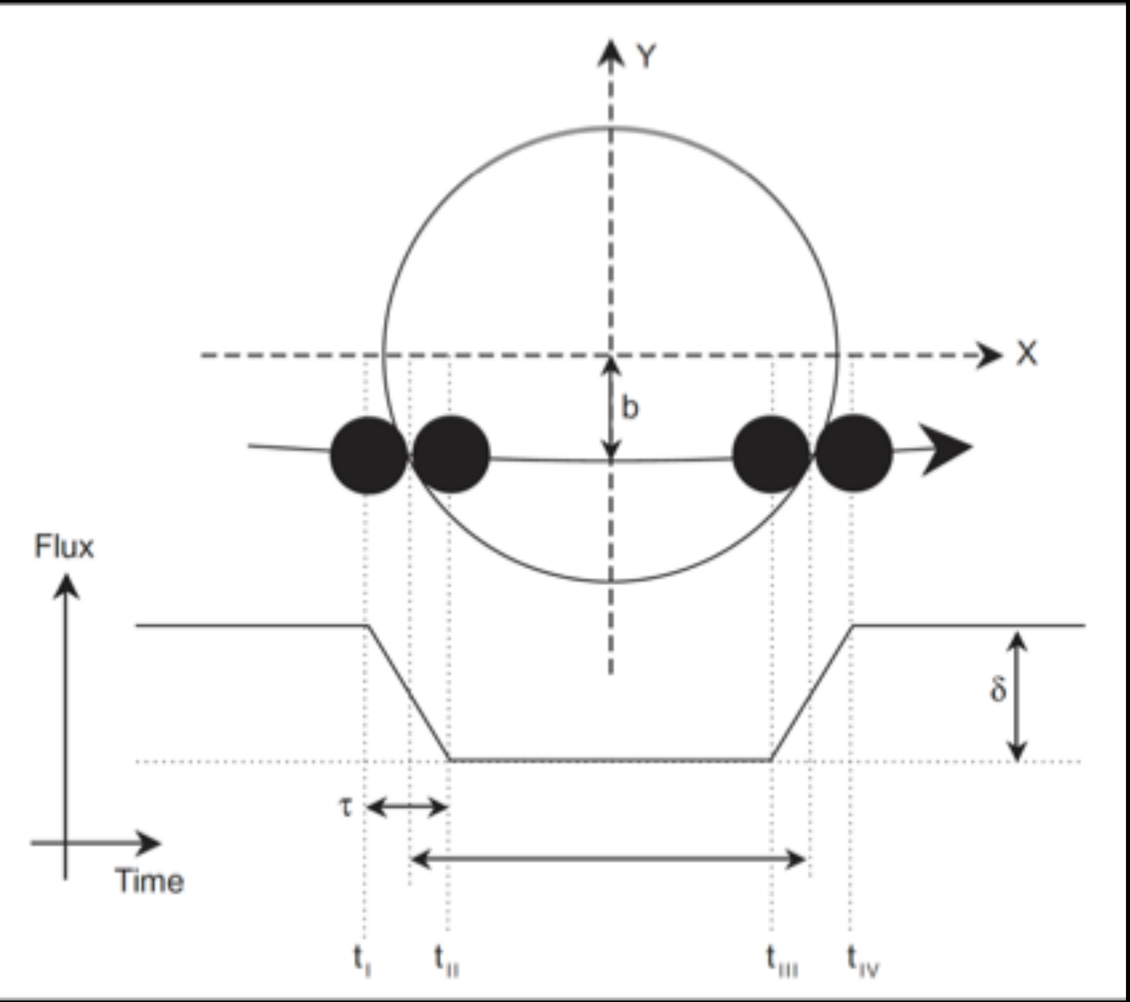
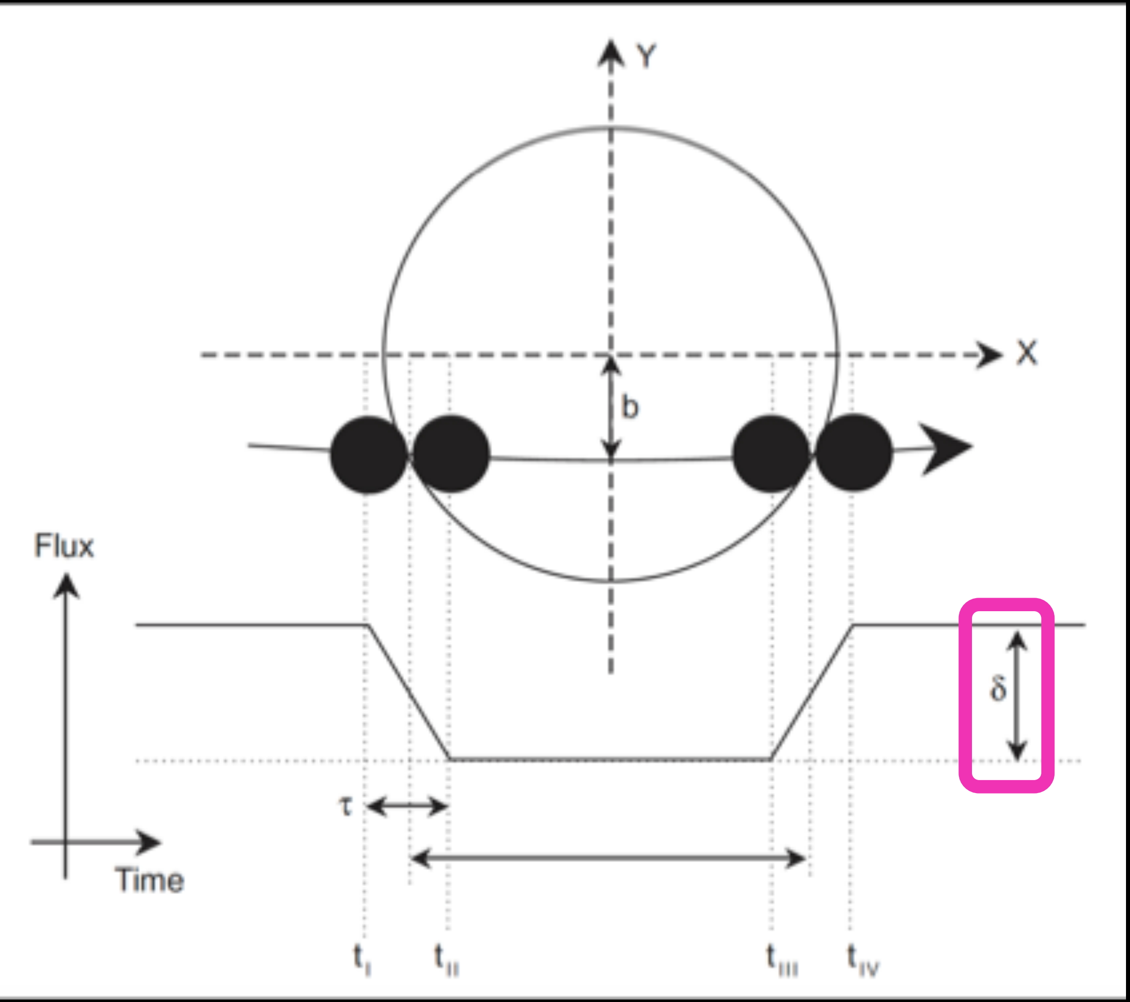


Figure 2 from Transits & Occultations by Winn (2010)

Transit Light Curves Reveal Planet Properties

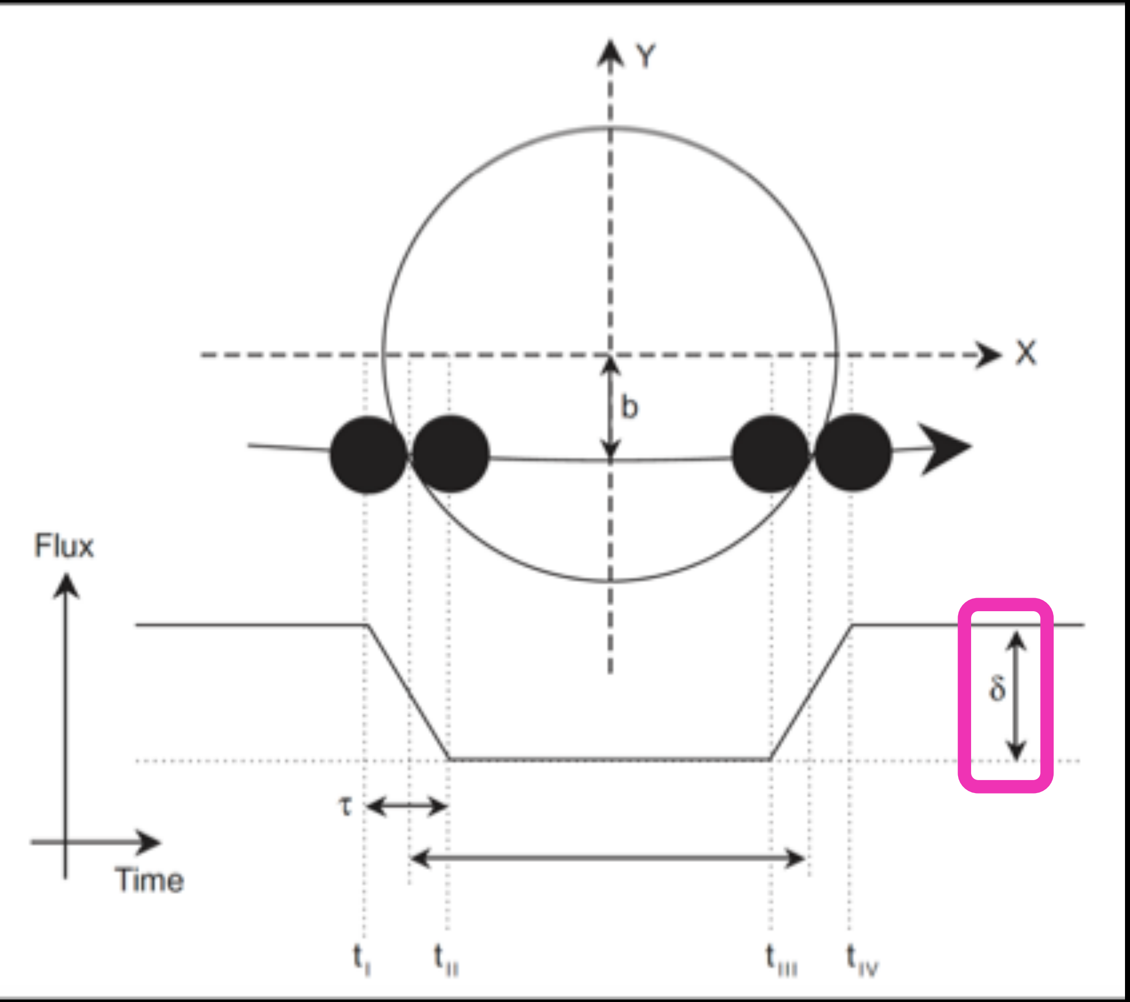


Transit Depth:

$$\delta \approx \left(\frac{R_p}{R_\star}\right)^2$$

Figure 2 from Transits & Occultations by Winn (2010)

Transit Light Curves Reveal Planet Properties



Transit Depth:

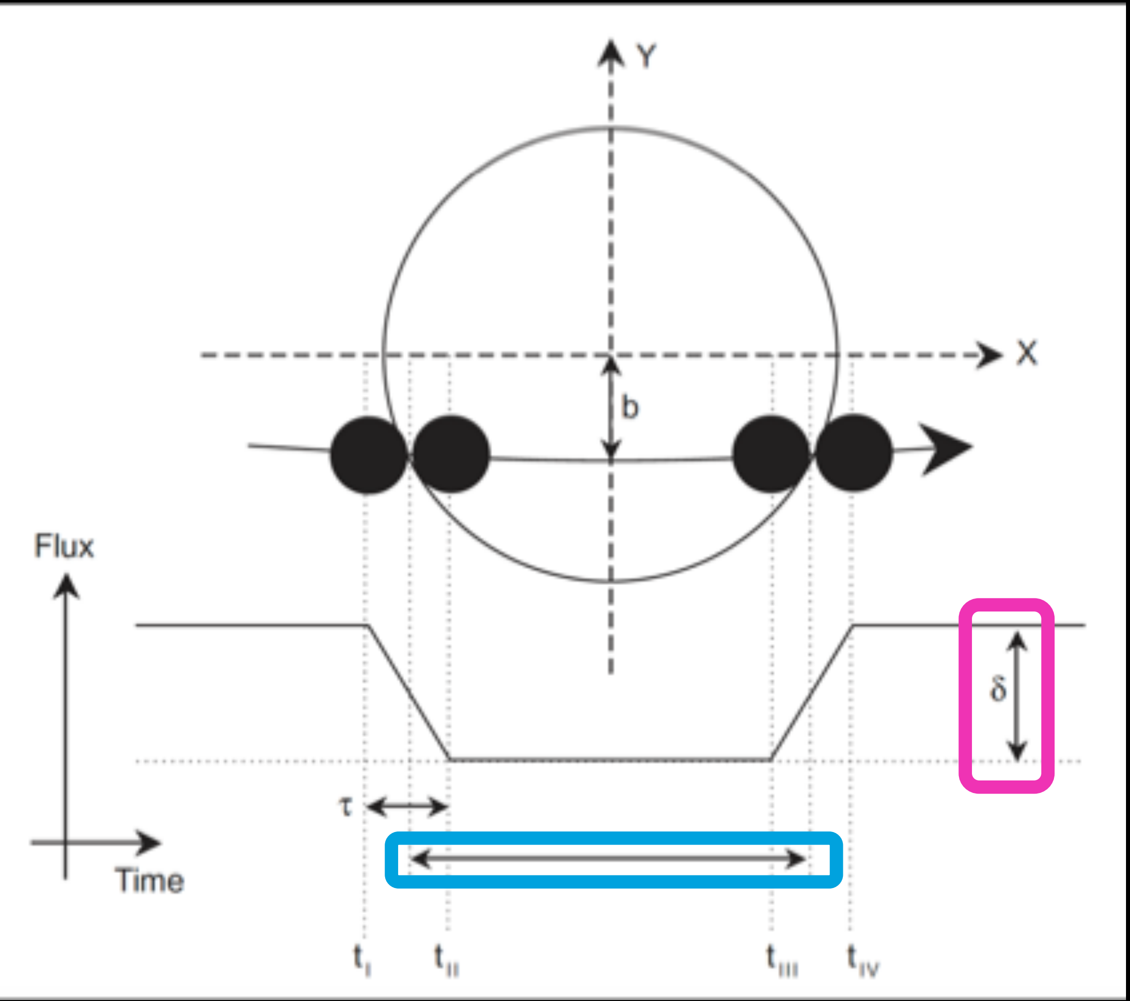
$$\delta \approx \left(\frac{R_p}{R_\star}\right)^2$$

Characteristic Timescale:

$$T_0 \equiv \frac{R_\star P}{\pi a} \approx 13\ \mathrm{h} \left(\frac{P}{1\ \mathrm{yr}}\right)^{1/3} \left(\frac{\rho_\star}{\rho_\odot}\right)^{-1/3}$$

Figure 2 from Transits & Occultations by Winn (2010)

Transit Light Curves Reveal Planet Properties



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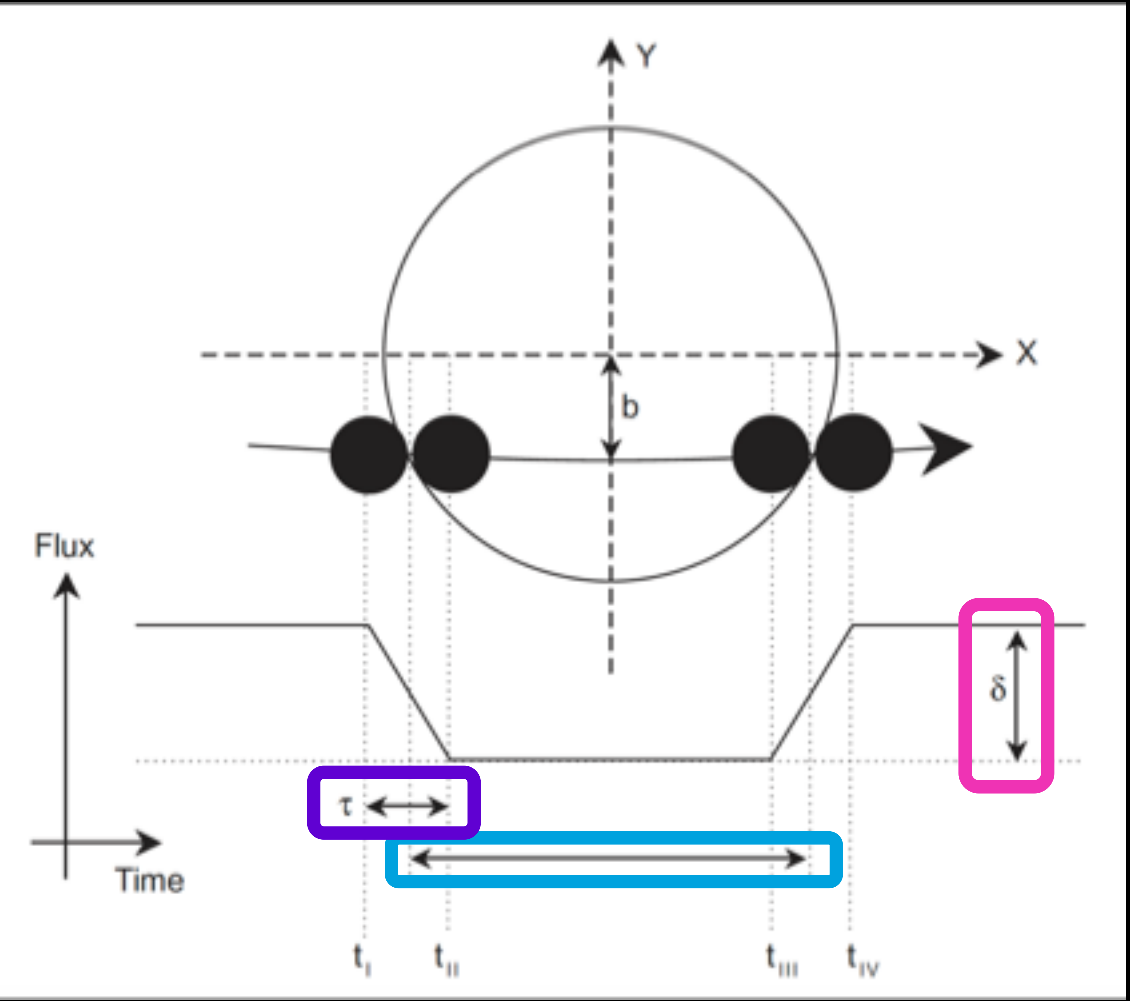
Transit Duration:

$$T \approx T_0\sqrt{1-b^2}$$

Figure 2 from Transits & Occultations by Winn (2010)

Transit Light Curves Reveal Planet Properties



Transit Depth:

$$\delta \approx \left(\frac{R_p}{R_\star}\right)^2$$

Characteristic Timescale:

$$T_0 \equiv \frac{R_\star P}{\pi a} \approx 13\text{ h}\left(\frac{P}{1\text{ yr}}\right)^{1/3}\left(\frac{\rho_\star}{\rho_\odot}\right)^{-1/3}$$

Transit Duration:

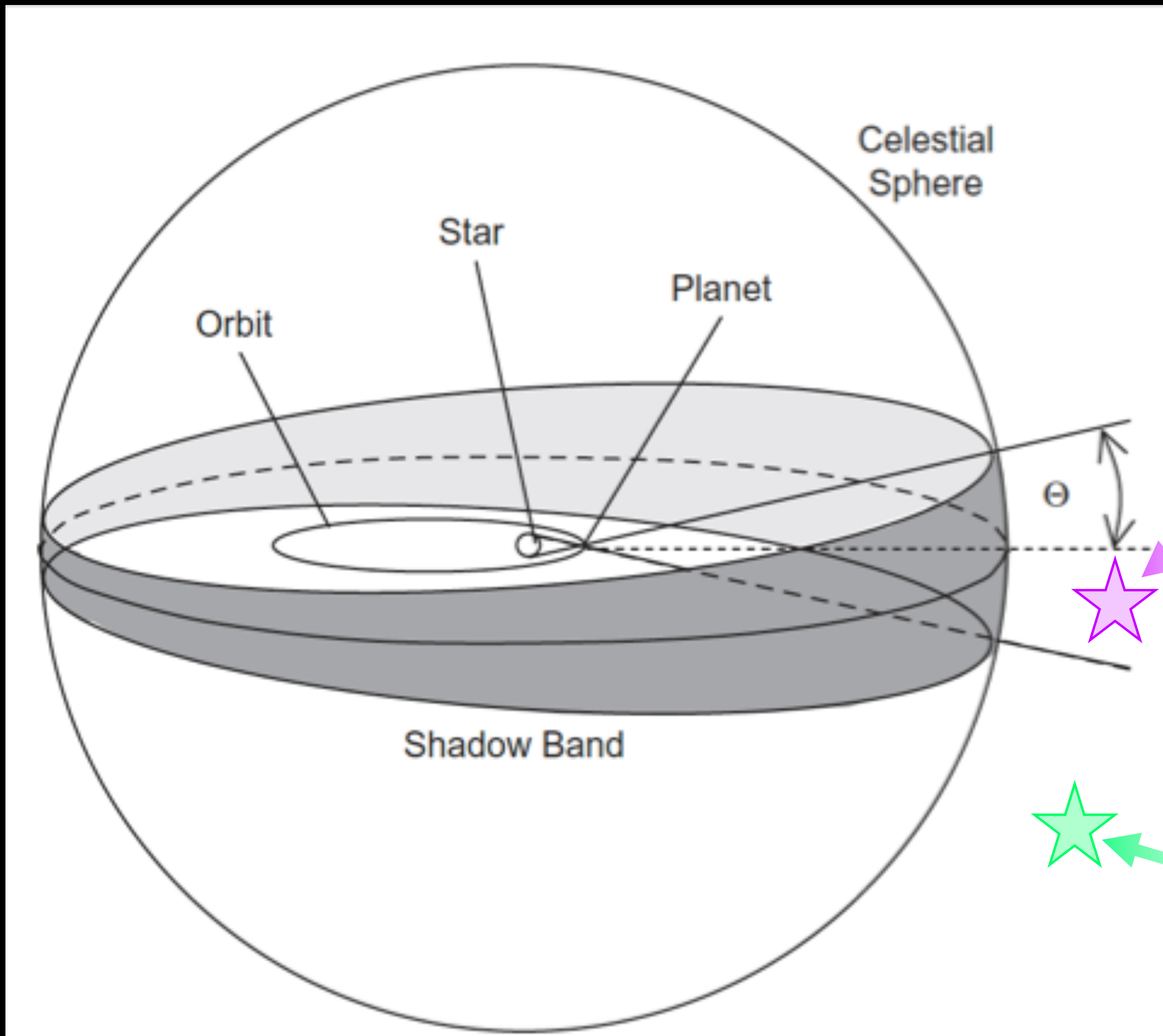
$$T \approx T_0\sqrt{1-b^2}$$

Ingress Duration:

$$\tau \approx \frac{T_0}{\sqrt{1-b^2}}\frac{R_p}{R_\star}$$

Figure 2 from Transits & Occultations by Winn (2010)

Most Planets Do Not Transit

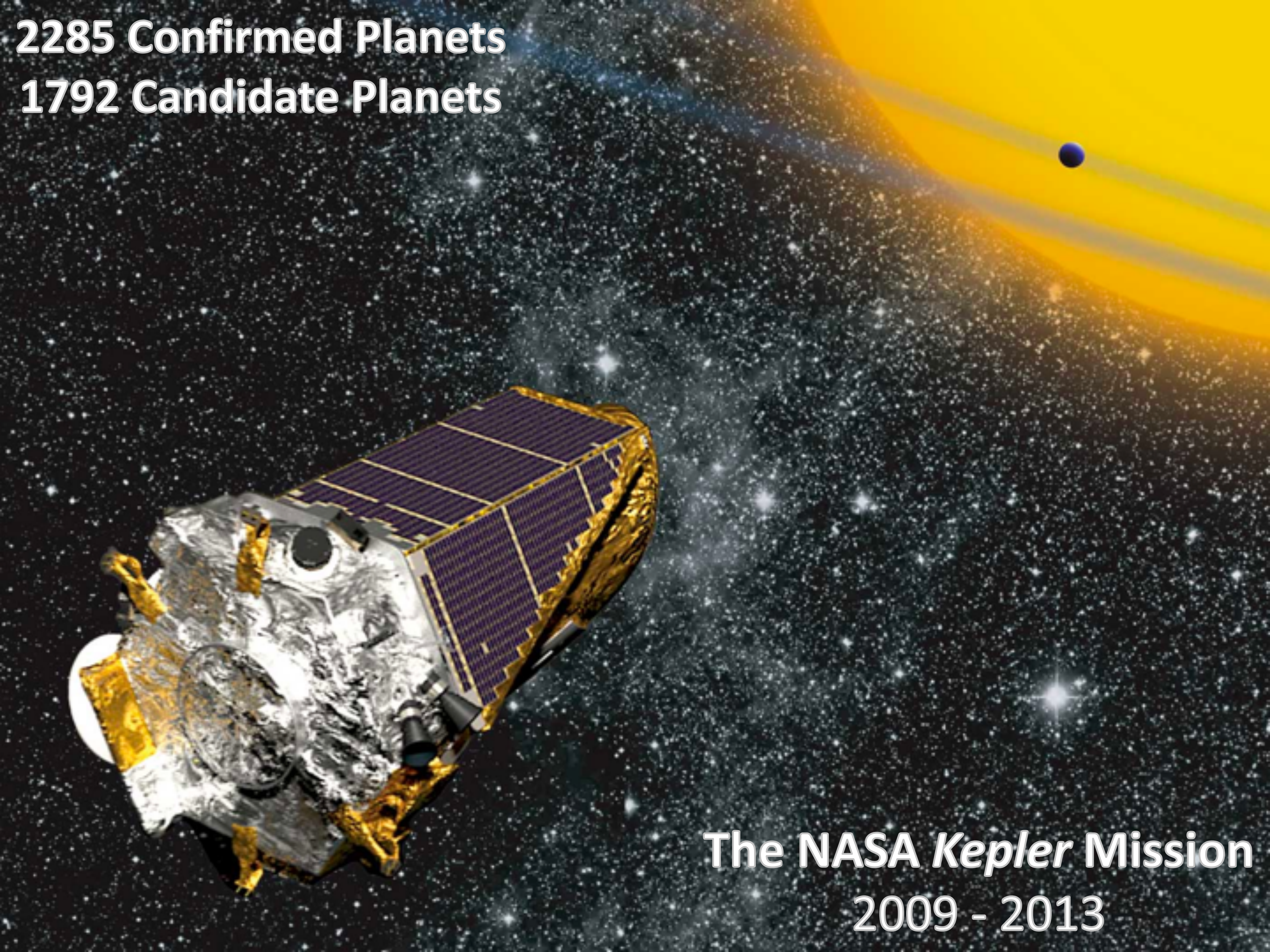


An observer here would see a transit

Transits not visible from here

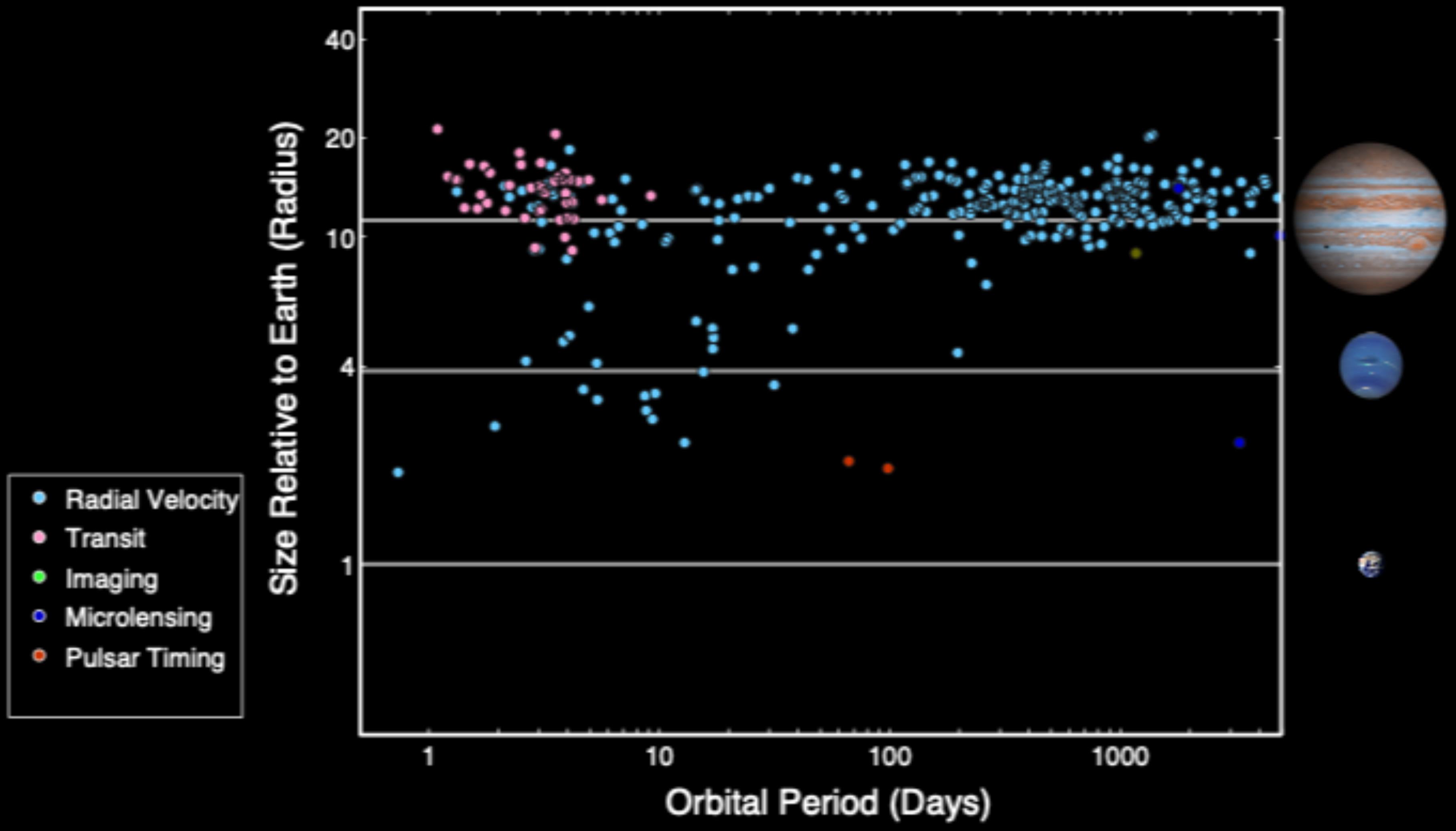
Figure 3 from Transits & Occultations by Winn (2010)

Space-Based Surveys for Transiting Planets


2285 Confirmed Planets
1792 Candidate Planets
The NASA *Kepler* Mission
2009 - 2013

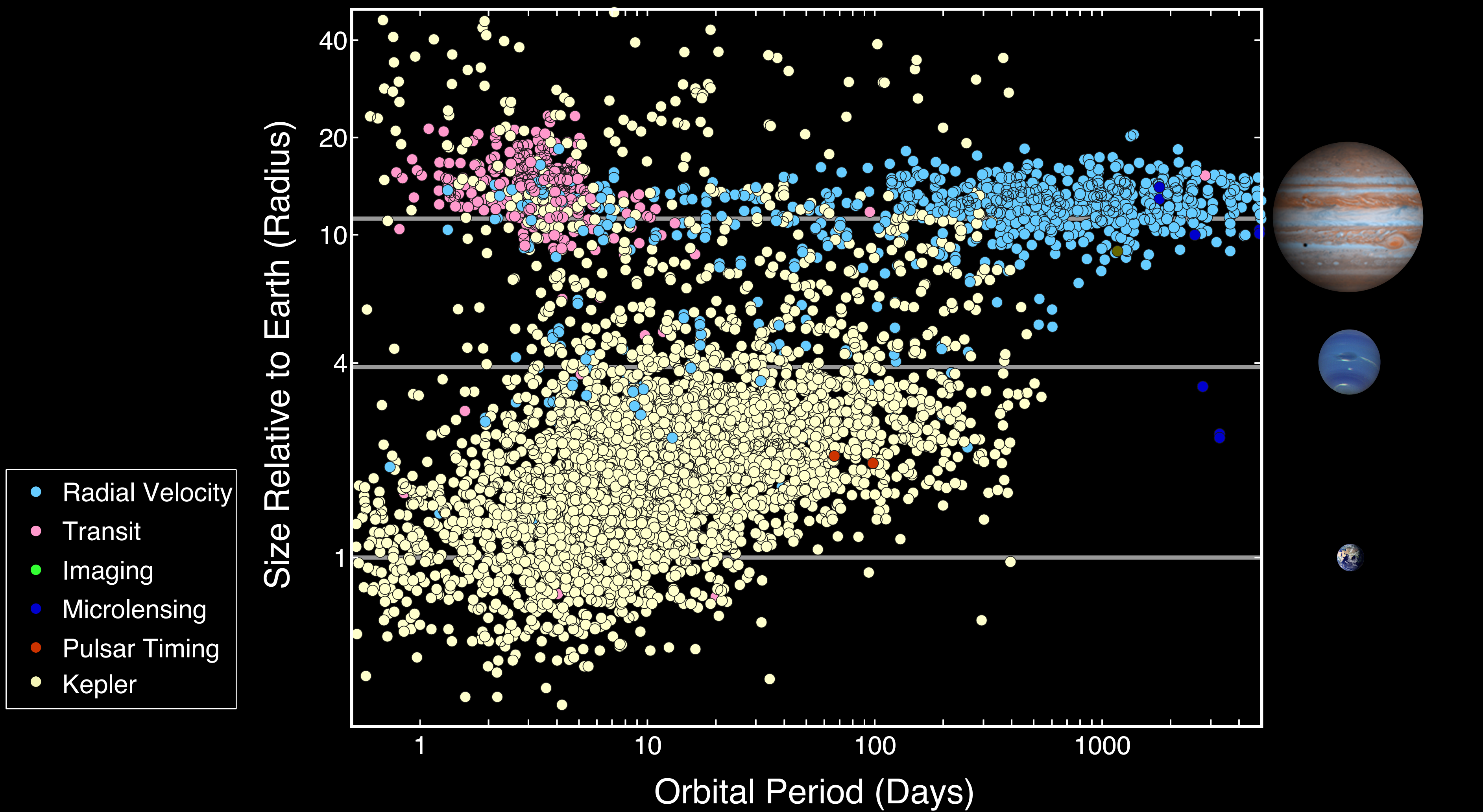
Exoplanet Populations

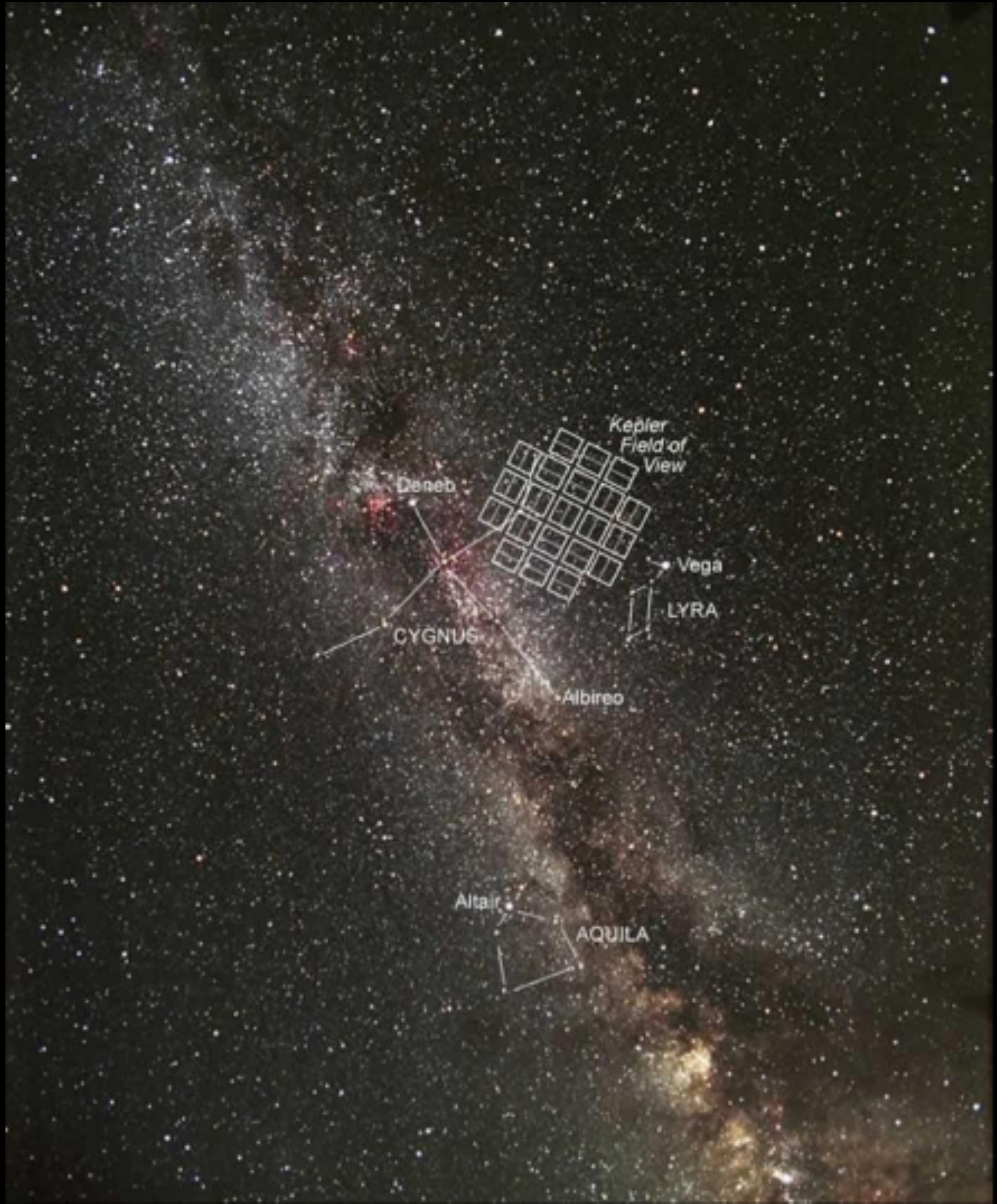
Non-Kepler Discoveries



Exoplanet Populations

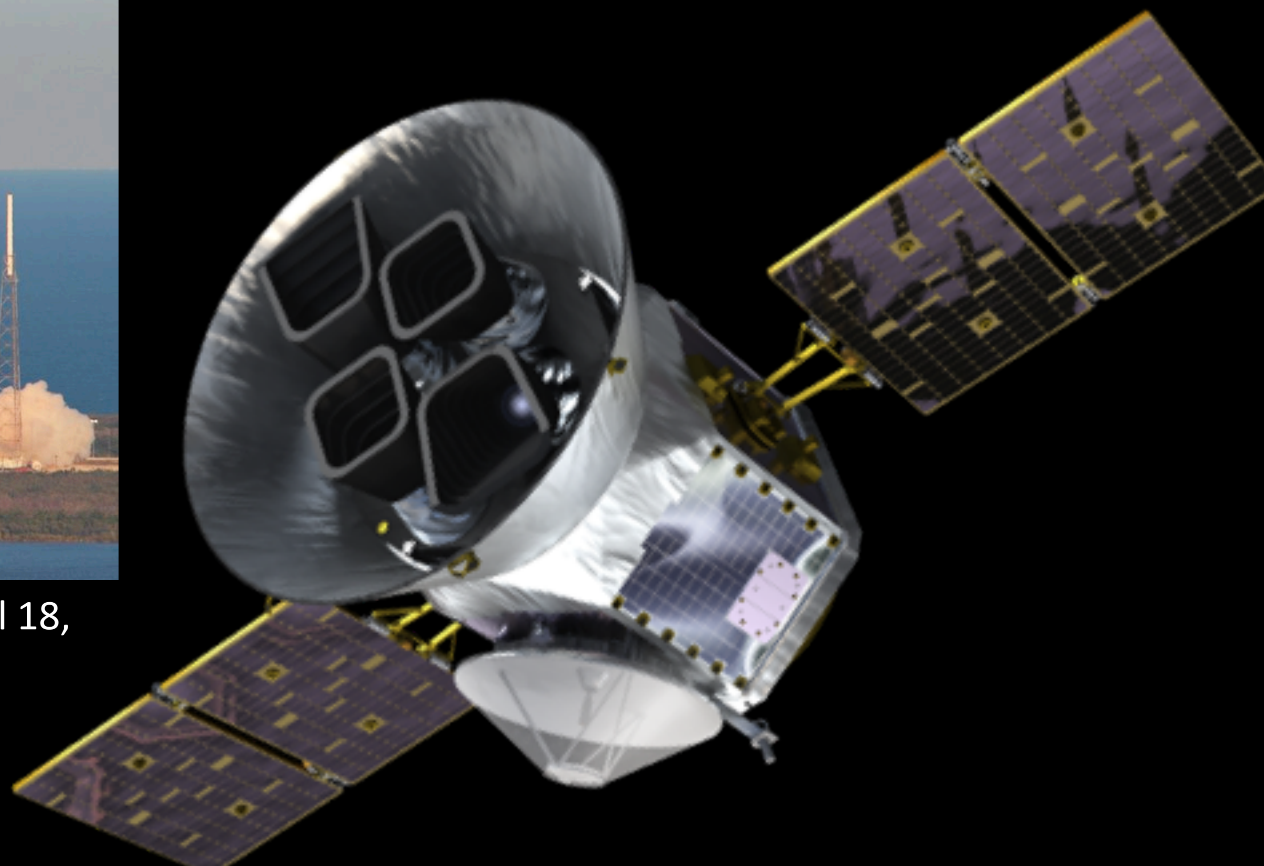
Non-Kepler and Kepler Discoveries



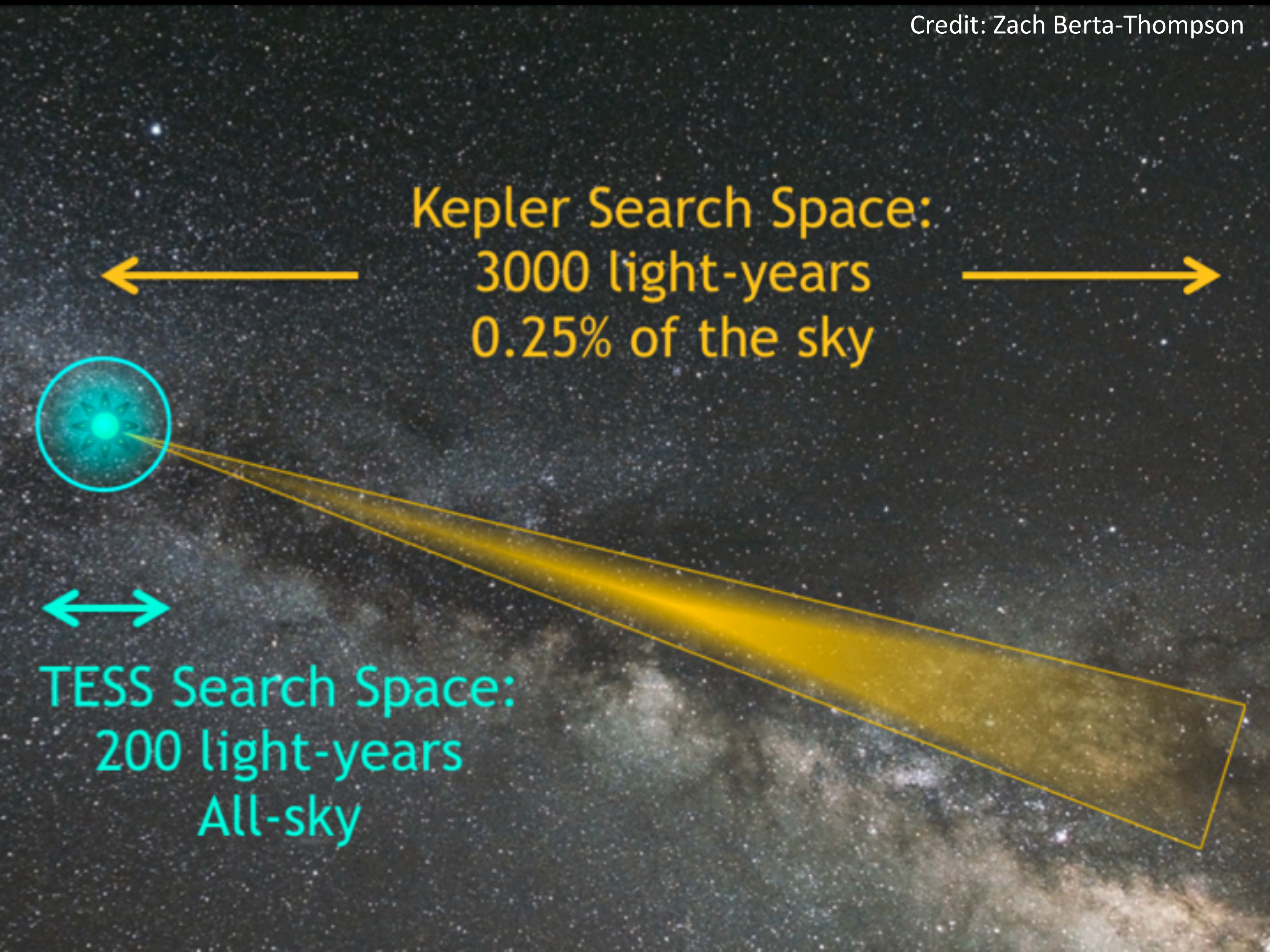

Kepler
Field of
View
Deneb
Vega
LYRA
CYGNUS
Albireo
Altair
AQUILA

NASA's *TESS* Mission is conducting an all-sky search for transiting planets orbiting bright nearby stars

TESS launching into space on April 18, 2018. (Credit: Michael Deep / SpaceFlight Insider)



TESS Spacecraft (Credit: NASA)


Credit: Zach Berta-Thompson
Kepler Search Space:
3000 light-years
0.25% of the sky
TESS Search Space:
200 light-years
All-sky

TESS is finding excellent targets for future study

- Probe **interior structures** of exoplanets
- Determine **atmospheric composition**
- Investigate the **demographics** of planetary populations

Important Caveat: Not all transit-like events are caused by transiting planets

Not All Candidate Signals will be Planets

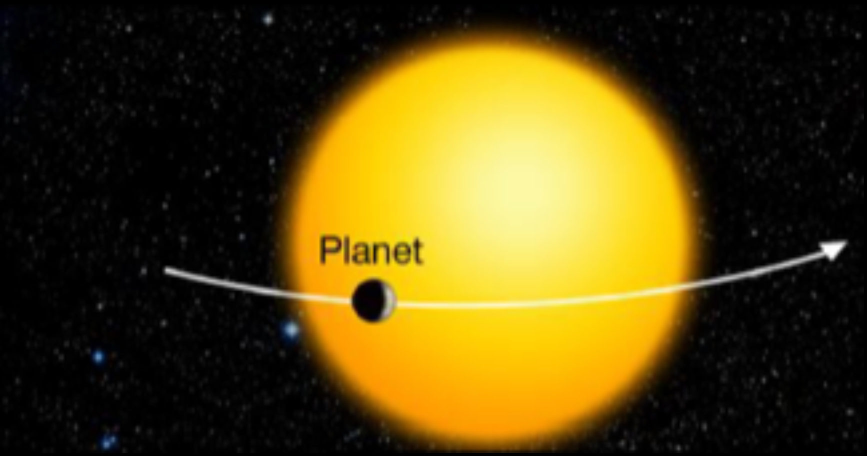
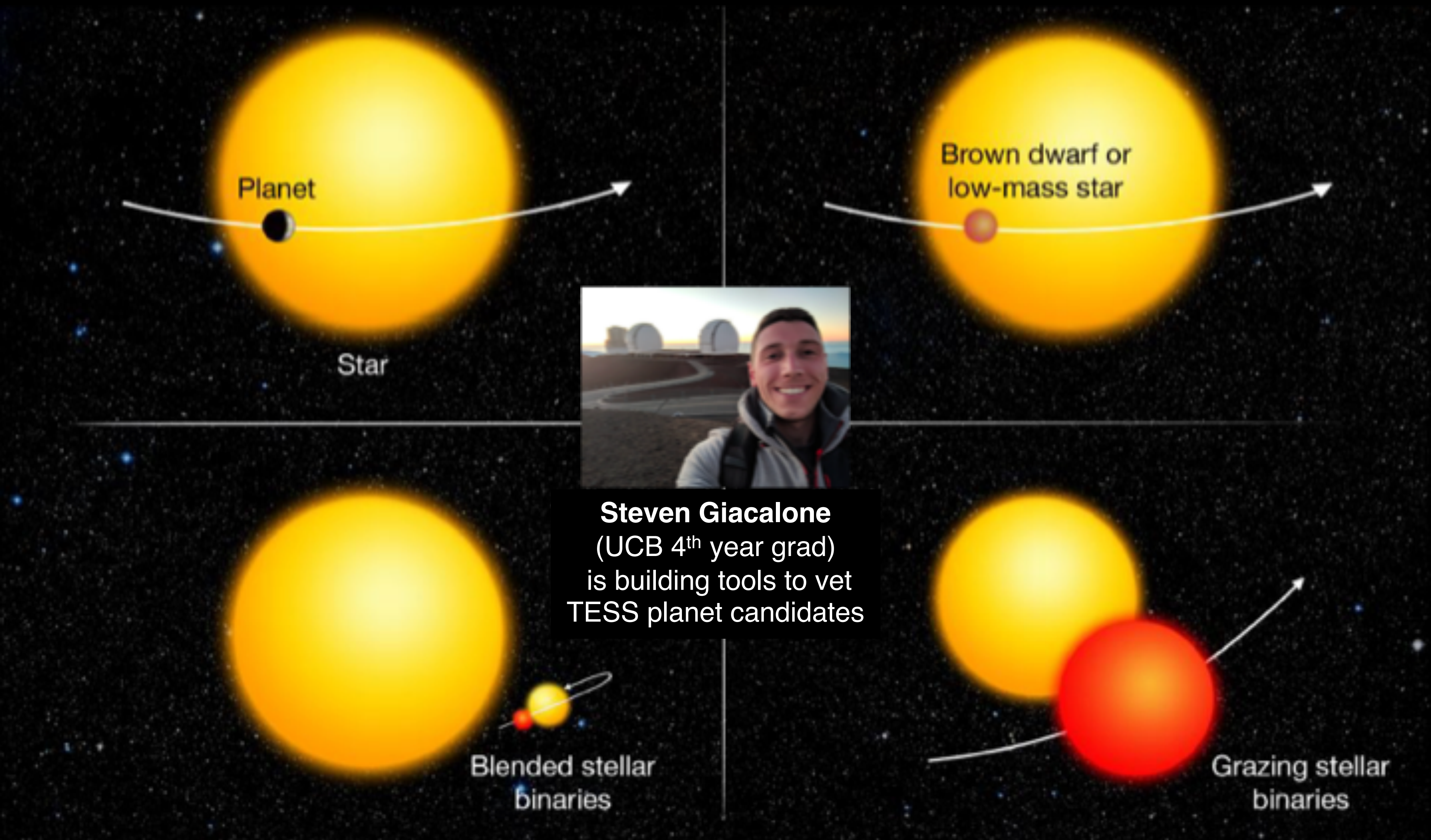


Image Credit: NASA

Not All Candidate Signals will be Planets



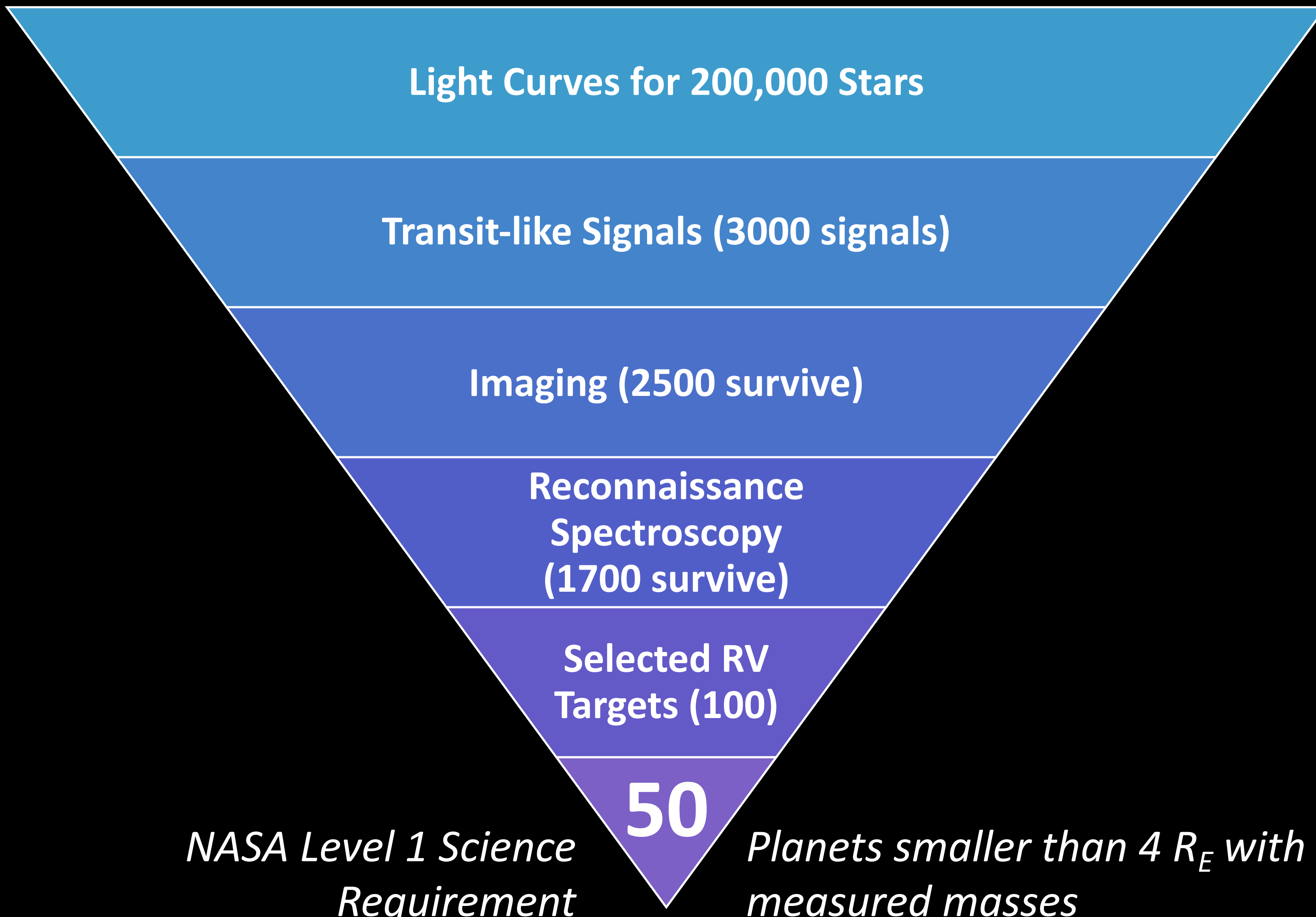
Steven Giacalone
(UCB 4th year grad)
is building tools to vet
TESS planet candidates

Image Credit: NASA

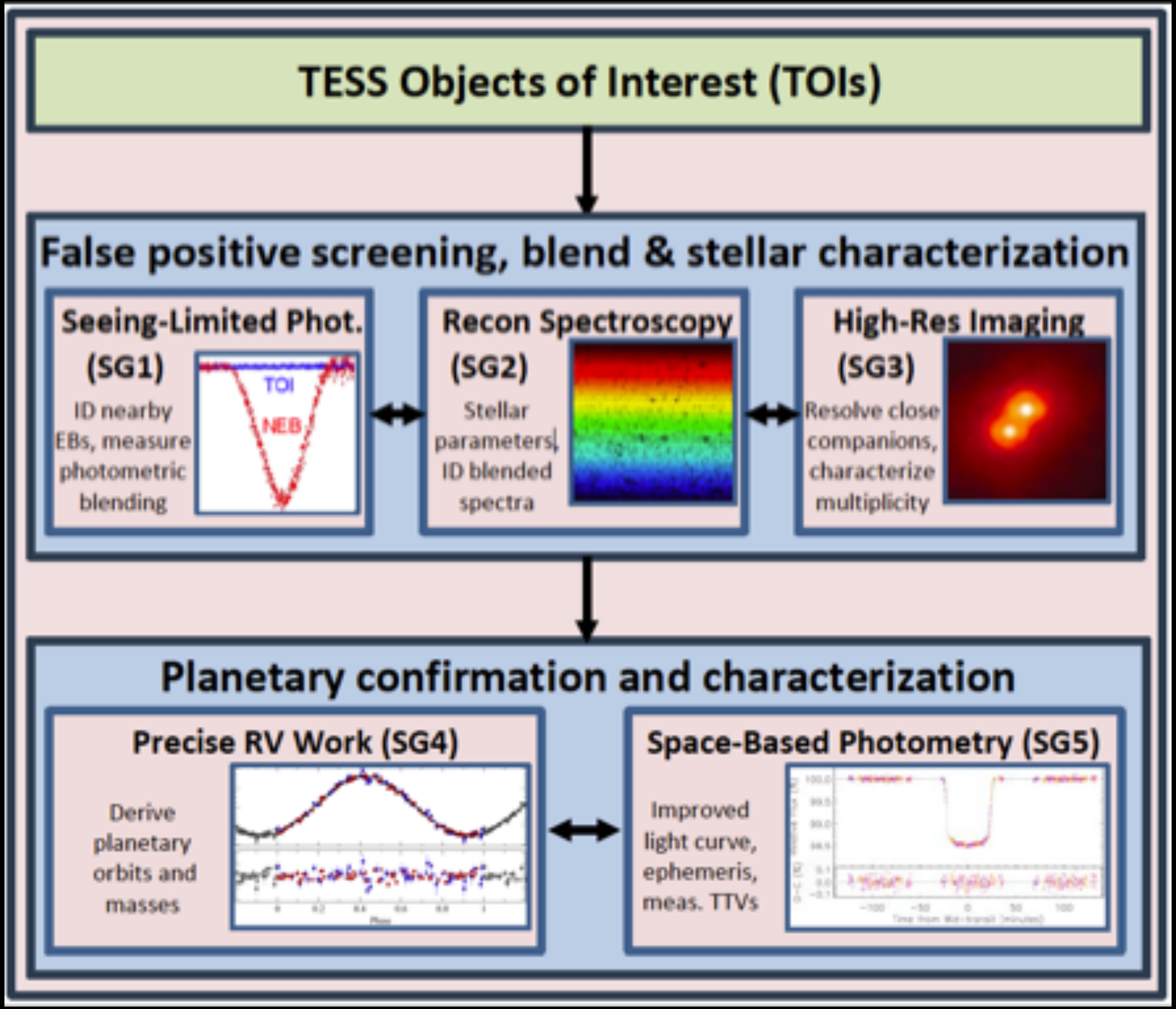
TRICERATOPS pipeline described in Giacalone & Dressing
(under review at AAS journals, arXiv:2002.00691)

Part 2. *Follow-up Observations*

Follow-up Observations Are Essential For Identifying False Positives



TFOP (TESS Follow-up Observing Program) Systematically Vets TESS Planet Candidates



Graphic from https://tess.mit.edu/followup/ Image credits (clockwise from top left): KELT Survey, NOAO/AURA/NSF, Buchhave et al. (2011), Berta et al. (2012), Malavolta et al. (2016).

TFOP Subgroup 1: ***Seeing-limited Imaging***

- Produce ***higher-resolution map*** of the scene
- Monitor brightness of ***candidate host star***
- Identify ***nearby eclipsing binaries***
- Determine transit times to improve ***ephemerides*** (when transits occur) and measure ***transit timing variations*** (whether transits occur early or late)

For more details about TFOP, see https://tess.mit.edu/followup/

TFOP Subgroup 2: *Reconnaissance Spectroscopy*

- Determine ***stellar parameters*** (T_{eff}, log g, [Fe/H])
- Improve estimates of ***planetary properties***
- Identify ***spectroscopic binaries***
- Constrain ***stellar rotation rates*** to screen targets for future precise RV spectroscopy

For more details about TFOP, see https://tess.mit.edu/followup/

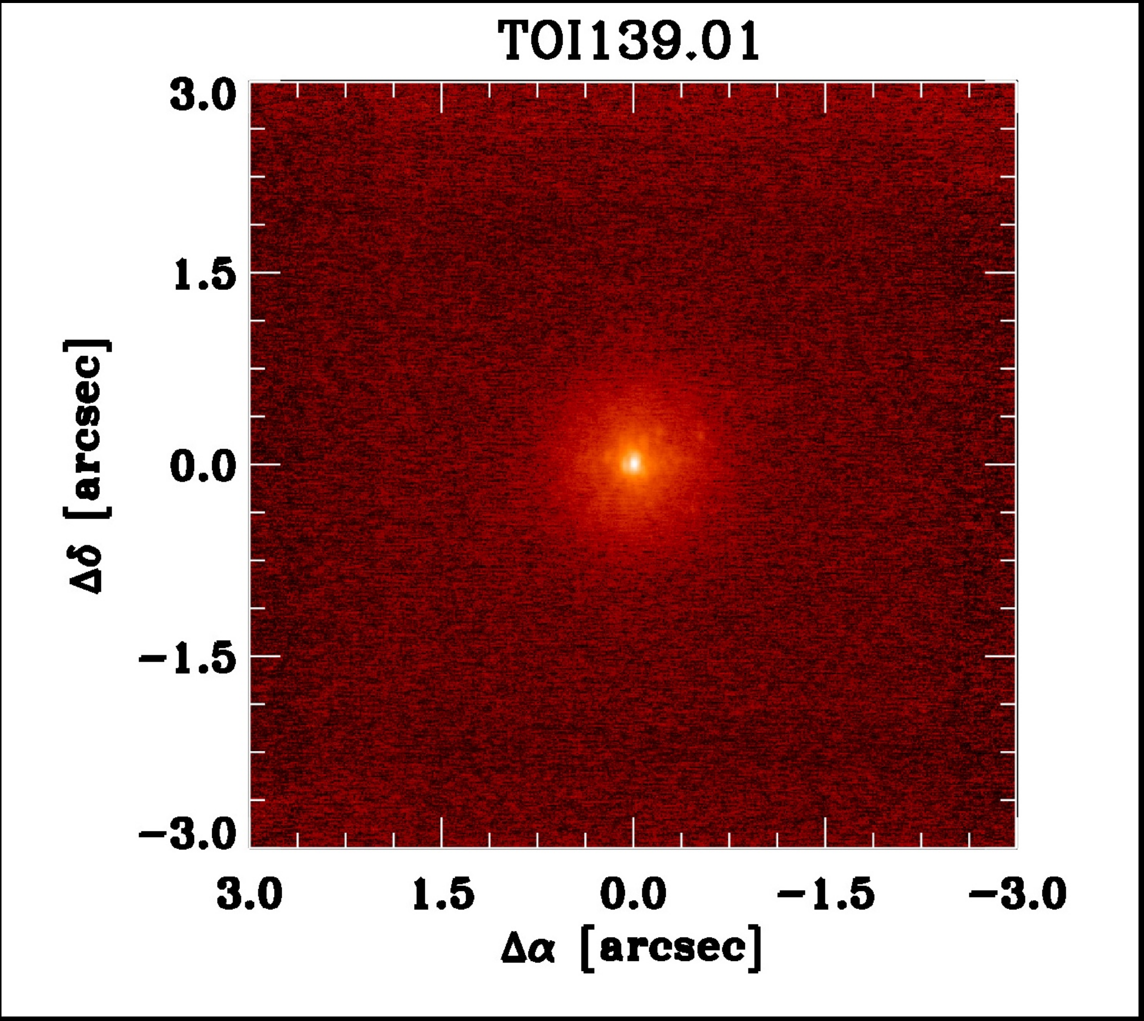
TFOP Subgroup 3: *High-Resolution Imaging*

- Map the scene at even ***higher resolution***
- Detect ***nearby stellar companions***
- Correct estimates of ***planetary properties***
- Assess whether candidate stellar companions are ***physically bound*** to the target star
- Techniques include ***adaptive optics imaging***, ***speckle imaging***, and ***lucky imaging***

For more details about TFOP, see https://tess.mit.edu/followup/

Follow-up observations can help distinguish between TESS planets & false positives

No companion star detected. ***Stronger*** support for transiting planet?

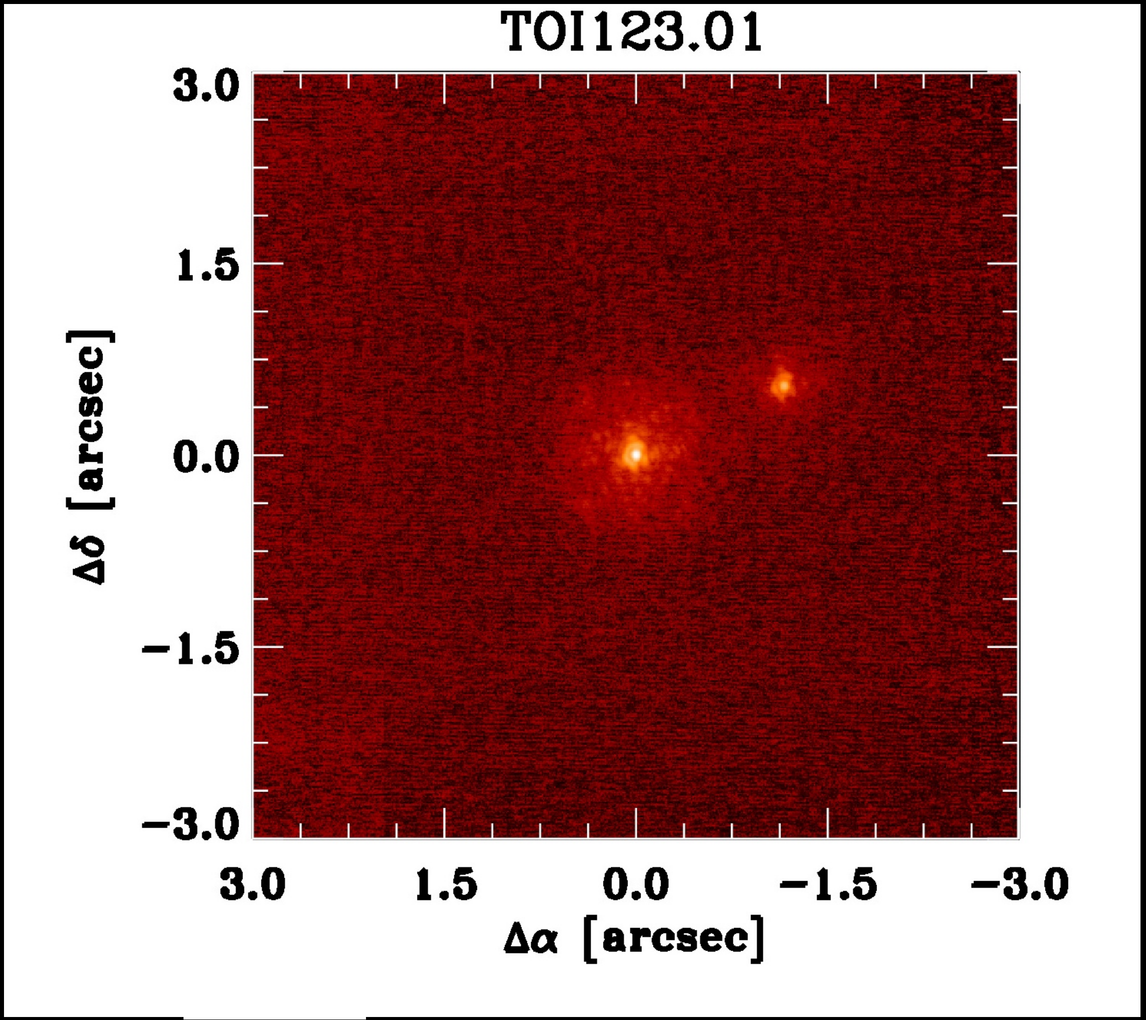


Keck/TESS ToO Program (PI: Beichman)

Figure by D. Ciardi

Follow-up observations can help distinguish between TESS planets & false positives

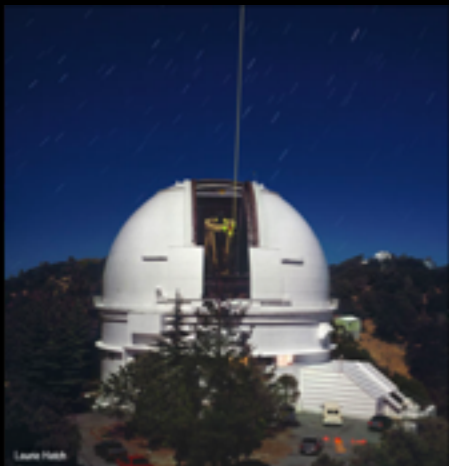
Companion star detected. ***Weaker*** support for transiting planet?

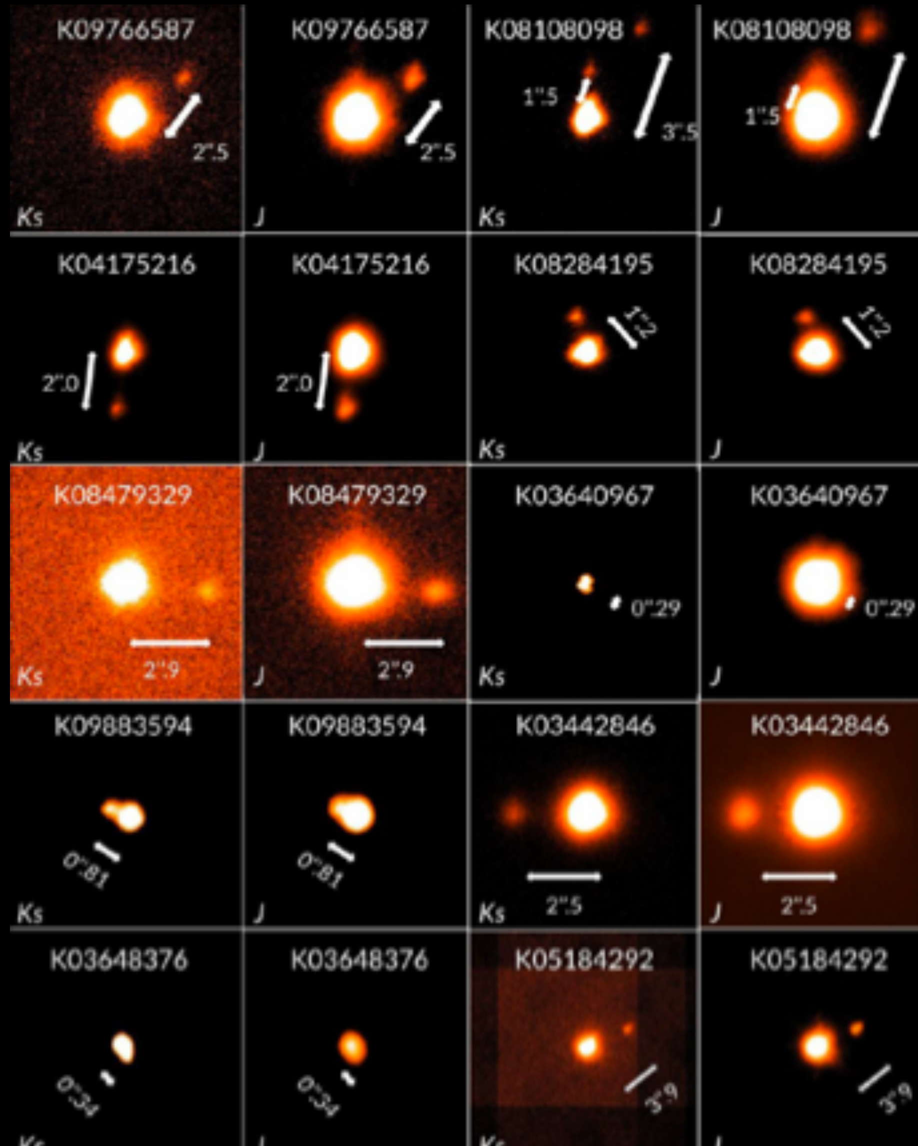


Keck/TESS ToO Program (PI: Beichman)

Figure by D. Ciardi

Determining the Multiplicity of *Kepler* Target Stars to Revise Estimates of the Frequency of Earth-like Planets





Arjun Savel
(UCB 2020 grad; now 1st year grad student at UMD)

Imaged 71 *Kepler* target stars with Lick/ShARCS

Detected 14 companions within 4” of 13 stars

Savel, Dressing et al. (under review at *AAS Journals*)

TFOP Subgroup 5: *Space-Based Photometry*

- Obtain ***high-cadence photometry*** of the target star
- Improve estimates of ***planetary properties***
- Determine transit times to improve ***ephemerides*** and measure ***transit timing variations***
- Facilities include ***HST***, ***Spitzer, CHEOPS, and JWST***

For more details about TFOP, see https://tess.mit.edu/followup/

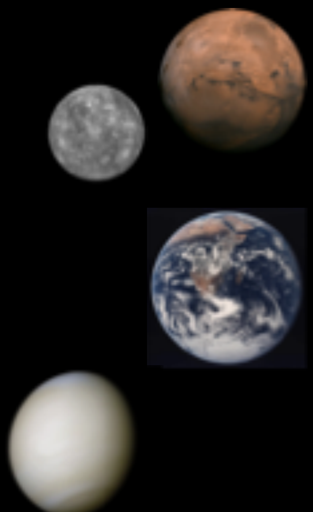
TFOP Subgroup 4: *Precise RV Spectroscopy*

- Obtain ***highly precise radial velocities*** of the target star
- Measure ***planet masses***
- Constrain ***planet densities***

For more details about TFOP, see https://tess.mit.edu/followup/

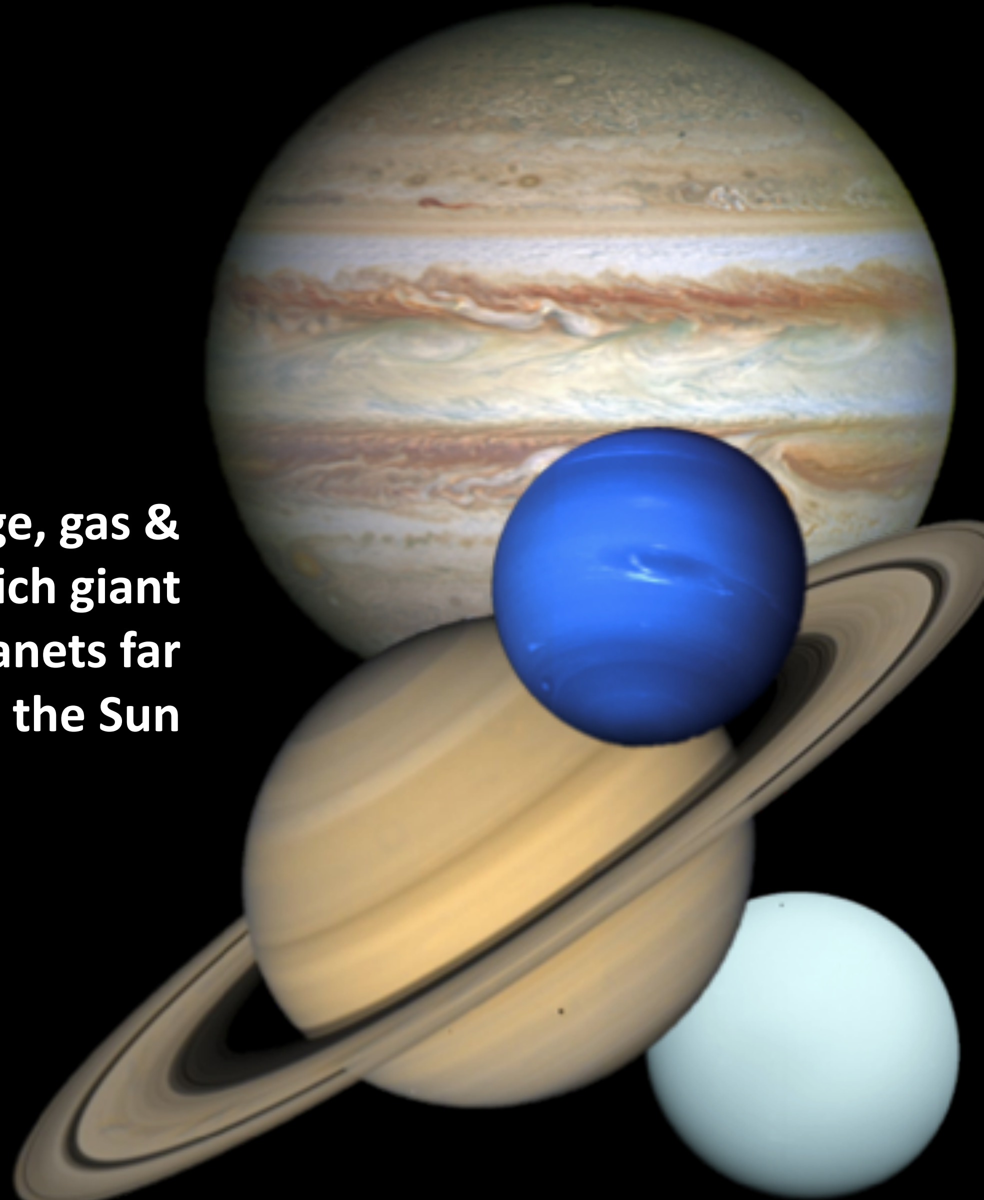
Part 3. *Planetary Compositions*

Our Solar System has Two Types of Planets



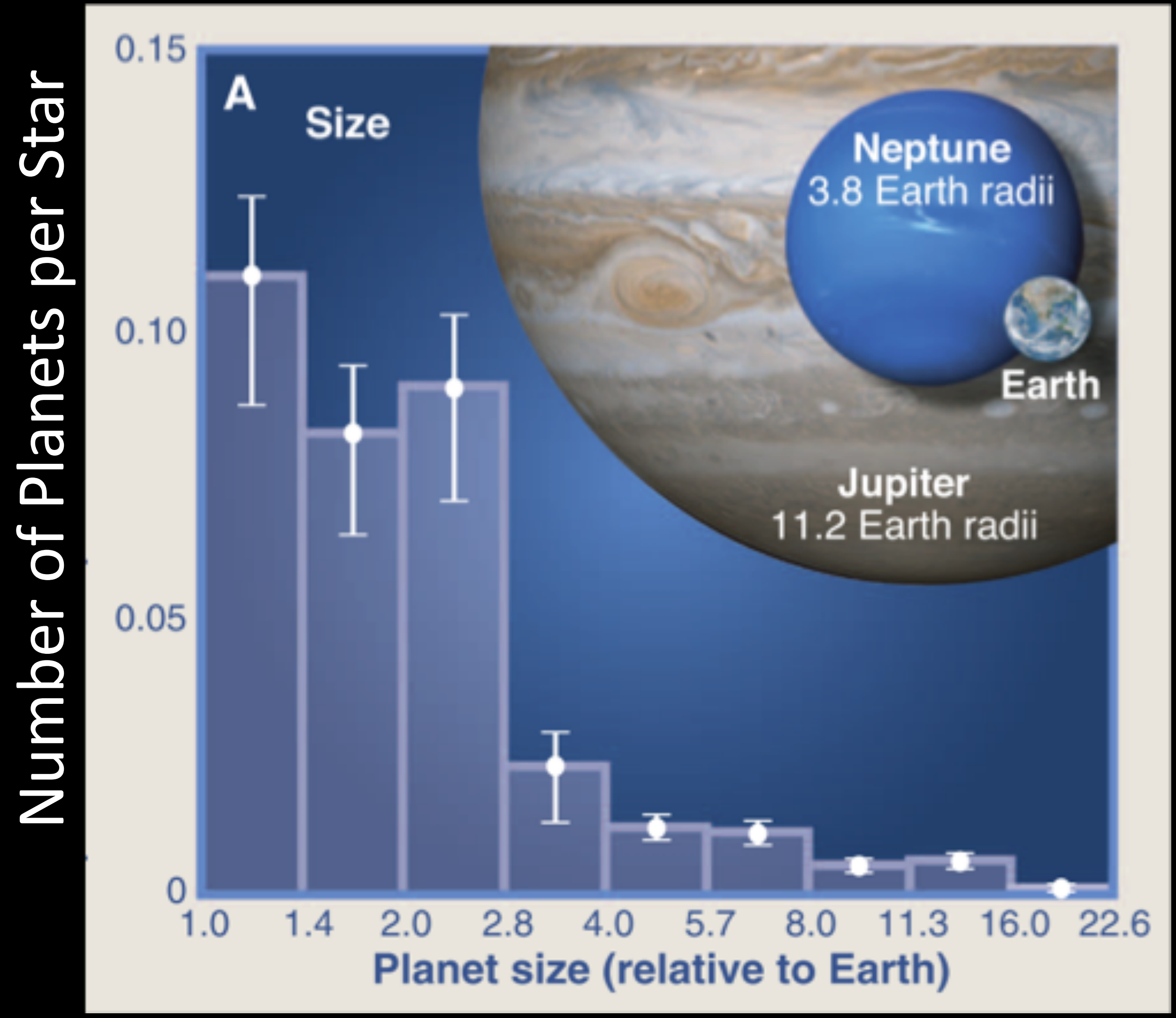
Small, terrestrial (rocky) planets close to the Sun

large, gas & ice-rich giant planets far from the Sun



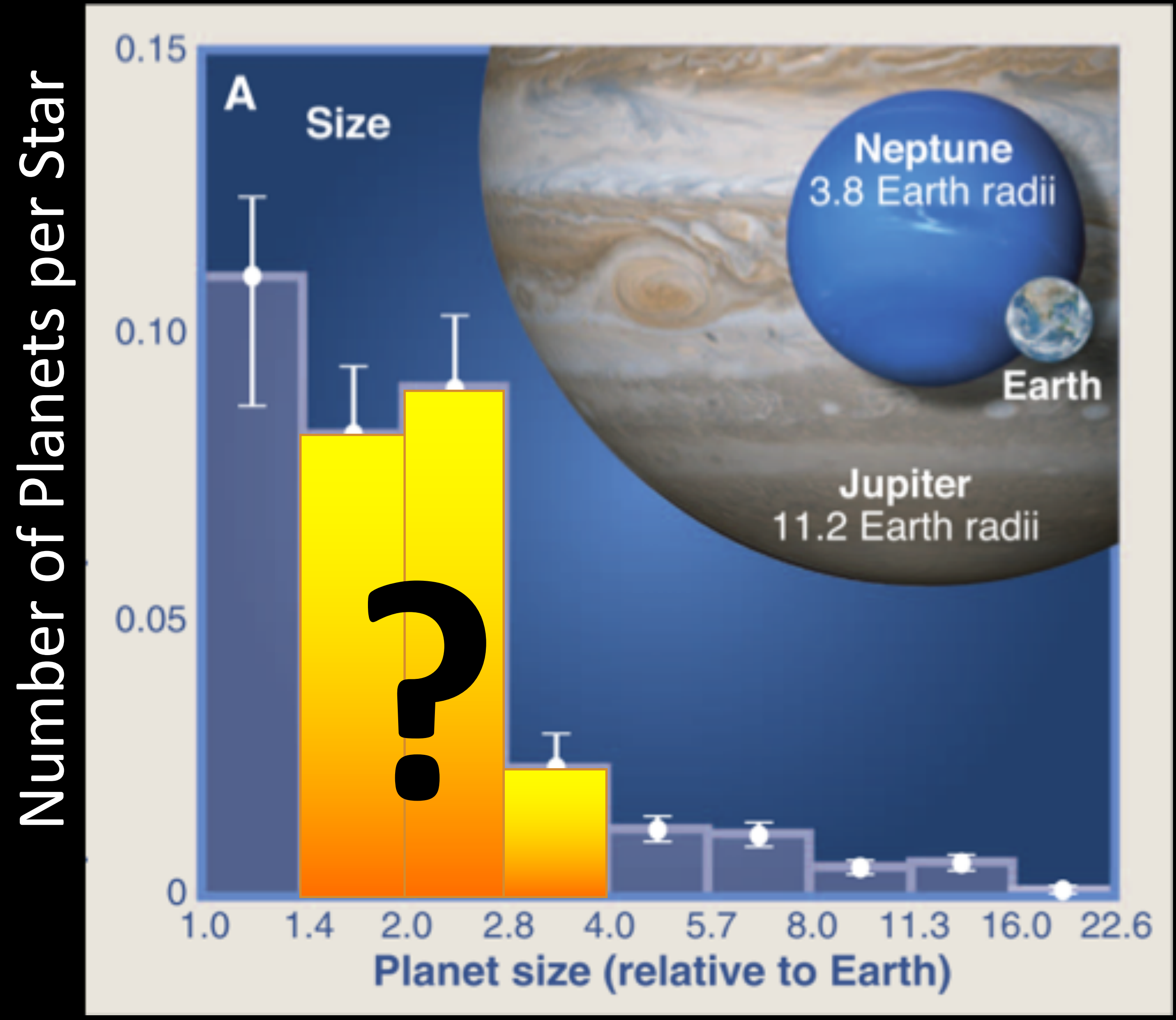
Not to scale

Planets 2-4x Larger than Earth are Common



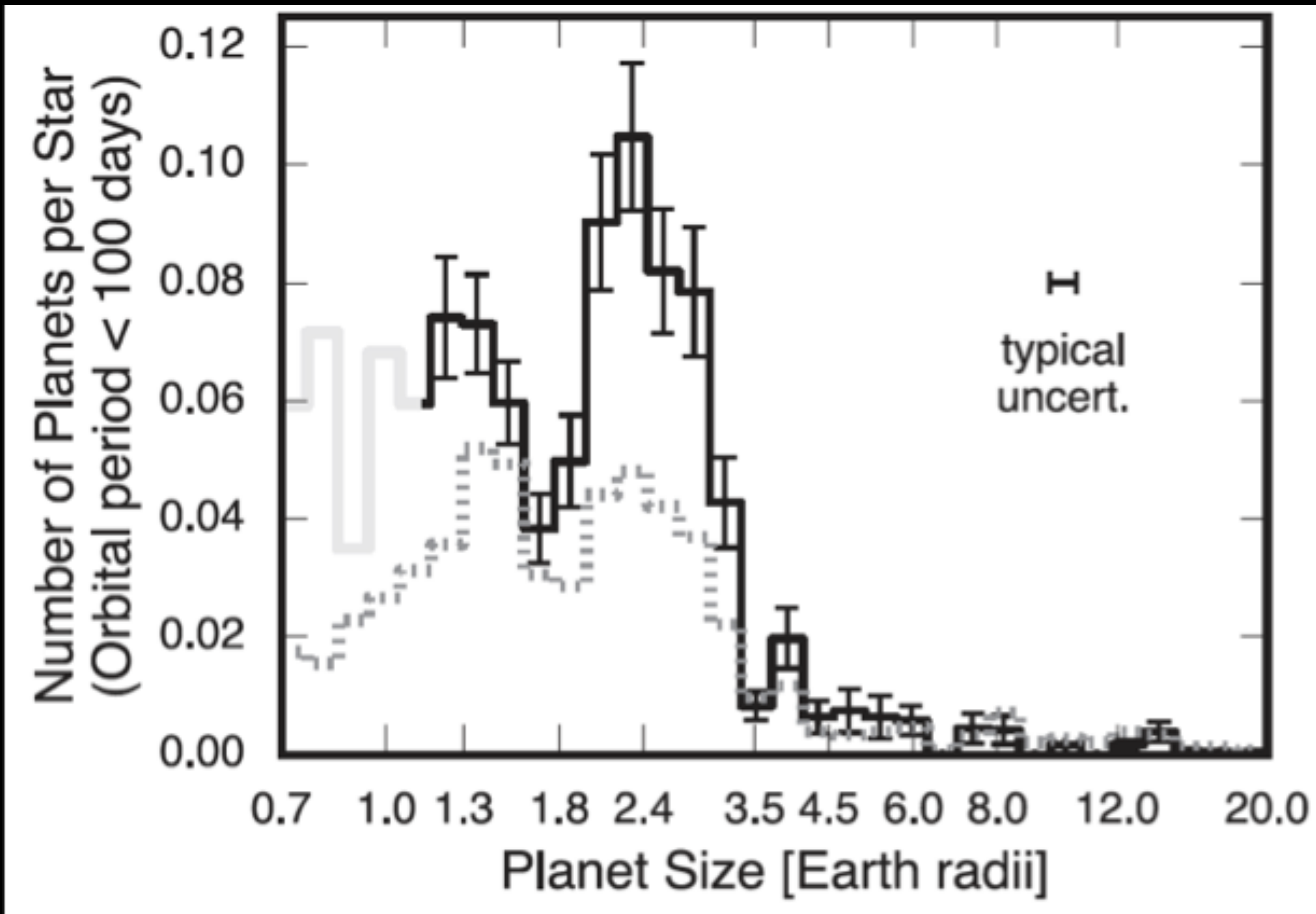
Howard 2013, Science, 340, 572

Planets 2-4x Larger than Earth are Common



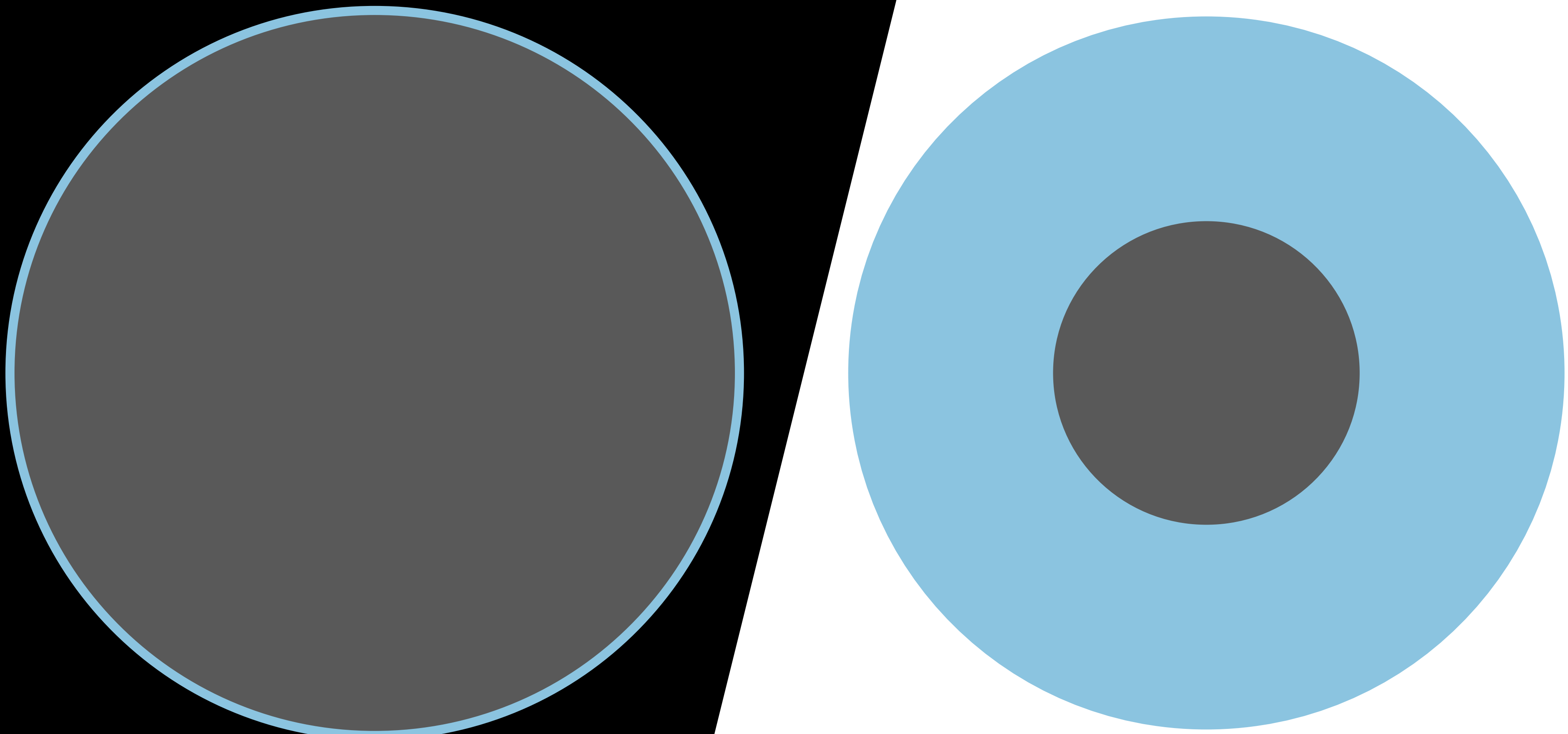
Howard 2013, Science, 340, 572

There is a Gap in the Planet Radius Distribution



Fulton & Petigura 2018

Are small planets rocky?



Or volatile-rich?

We need to measure densities to find out!

Density = Mass/Volume so we need planet masses and planet radii

Use the radial velocity method!

Use the transit method!

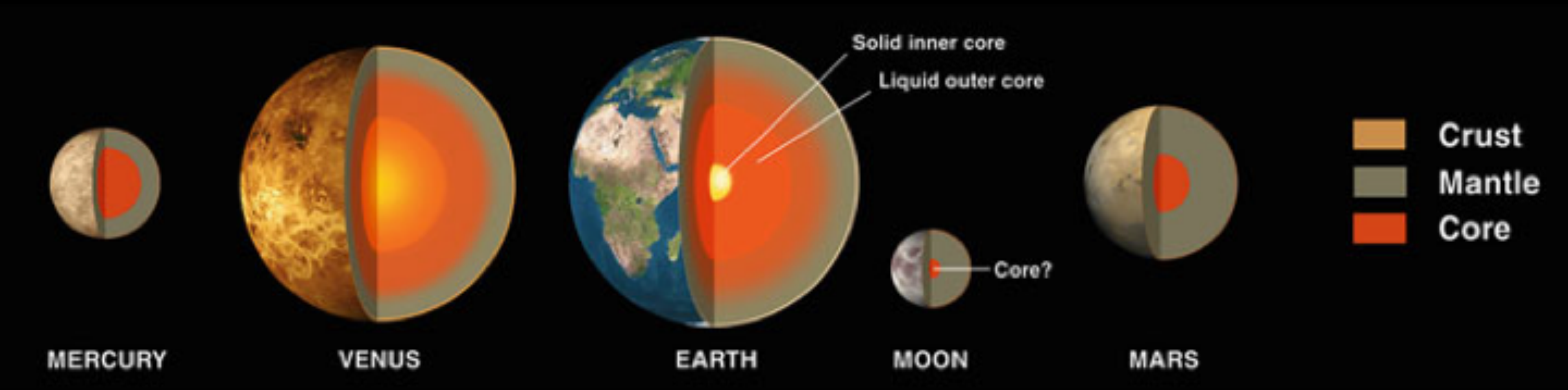
The Terrestrial Planets of the Solar System

0.06 Earth Masses	0.82 Earth Masses	1 Earth Mass	0.11 Earth Masses

0.383 Earth Radii	0.95 Earth Radii	1 Earth Radius	0.53 Earth Radii

Credit: Lunar and Planetary Institute

The Interiors of Terrestrial Worlds

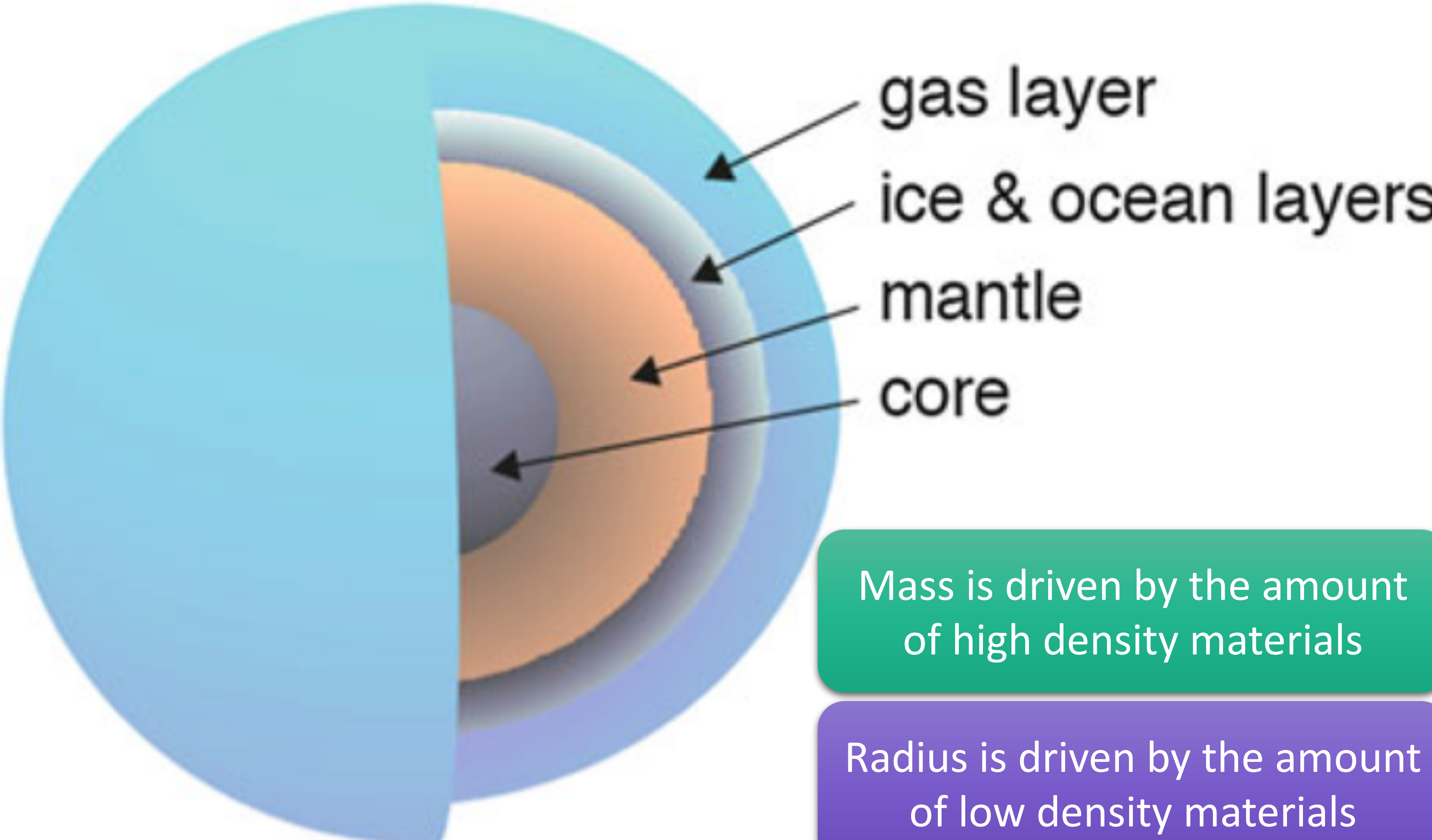


Credit: NASA

The Interiors of Large Moons

Credit: NASA

Cross-Section of a "Generic" Exoplanet



Mass is driven by the amount of high density materials

Radius is driven by the amount of low density materials

Dorn et al. (2018)

Modeling Planetary Interiors

Dorn (2018)

$$\frac{dm(r)}{dr} = 4\pi r^2 \rho(r)$$

Mass Conservation

$$\frac{dP(r)}{dr} = -\frac{Gm(r)\rho(r)}{r^2}$$

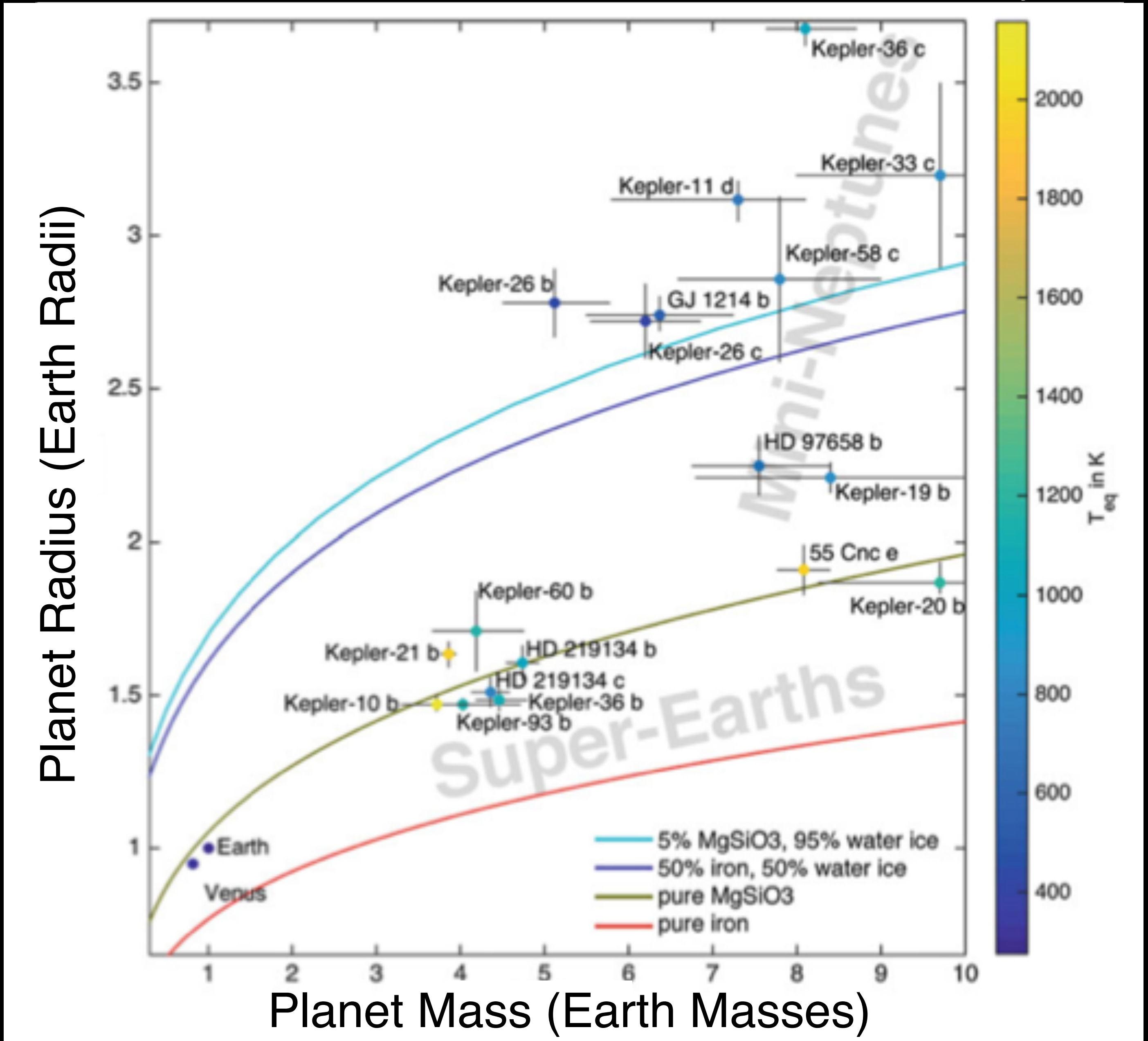
Hydrostatic Equilibrium

$$\rho(r) = f(P(r), T(r))$$

Equation of State

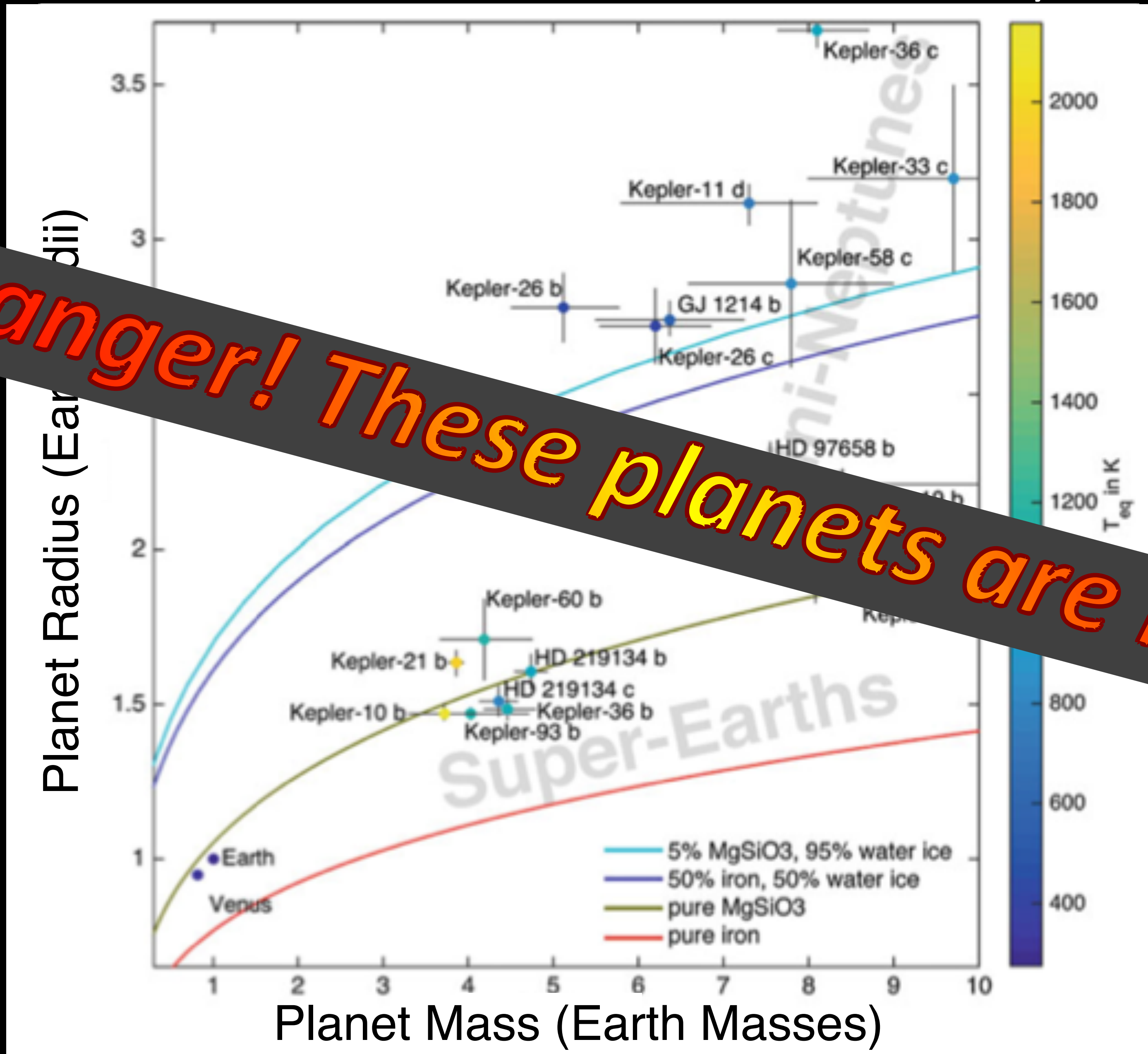
Need to know the temperature gradient T(r)

Few Small Planets Have Precise Density Estimates

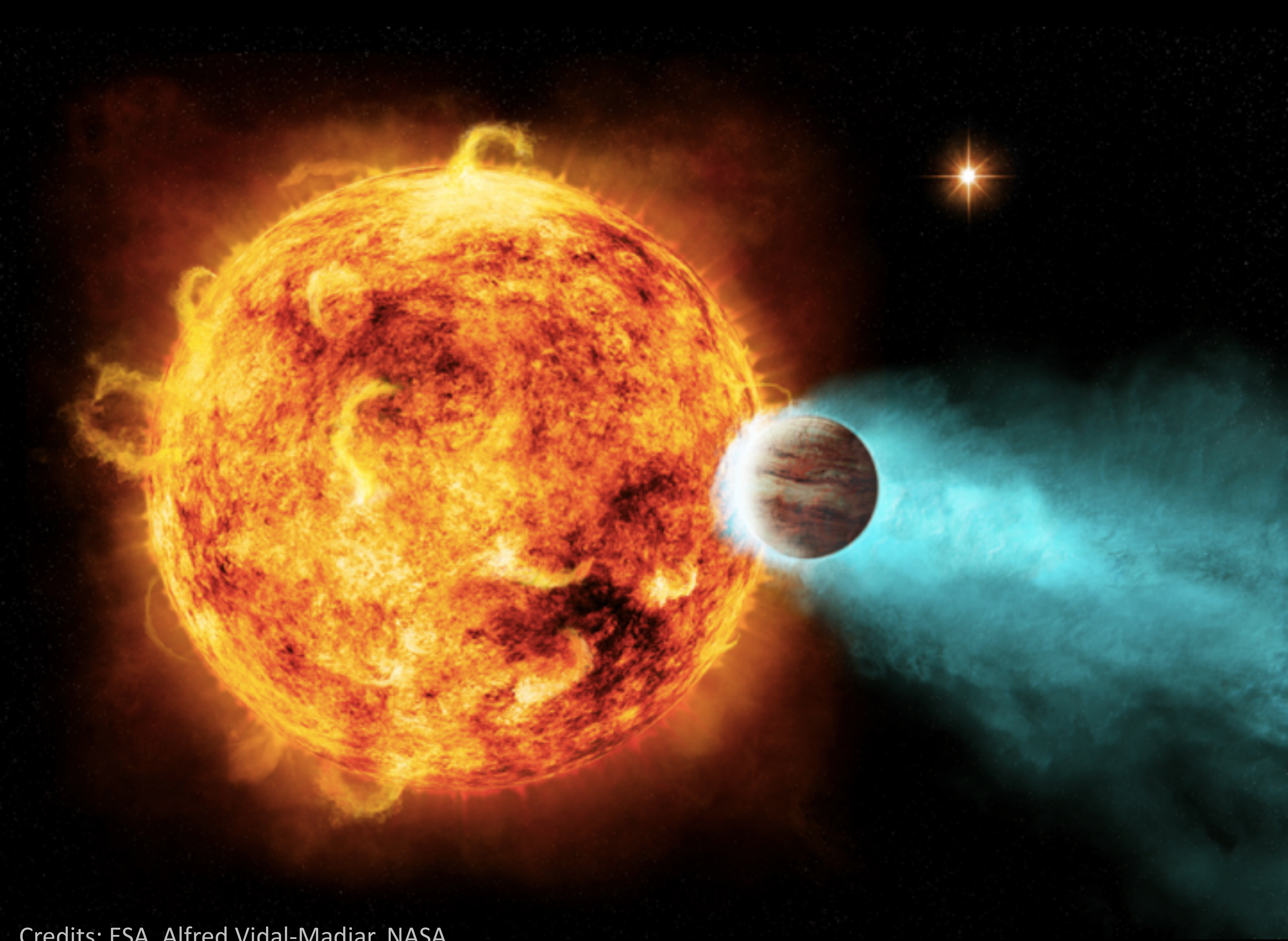


Dorn et al. 2018

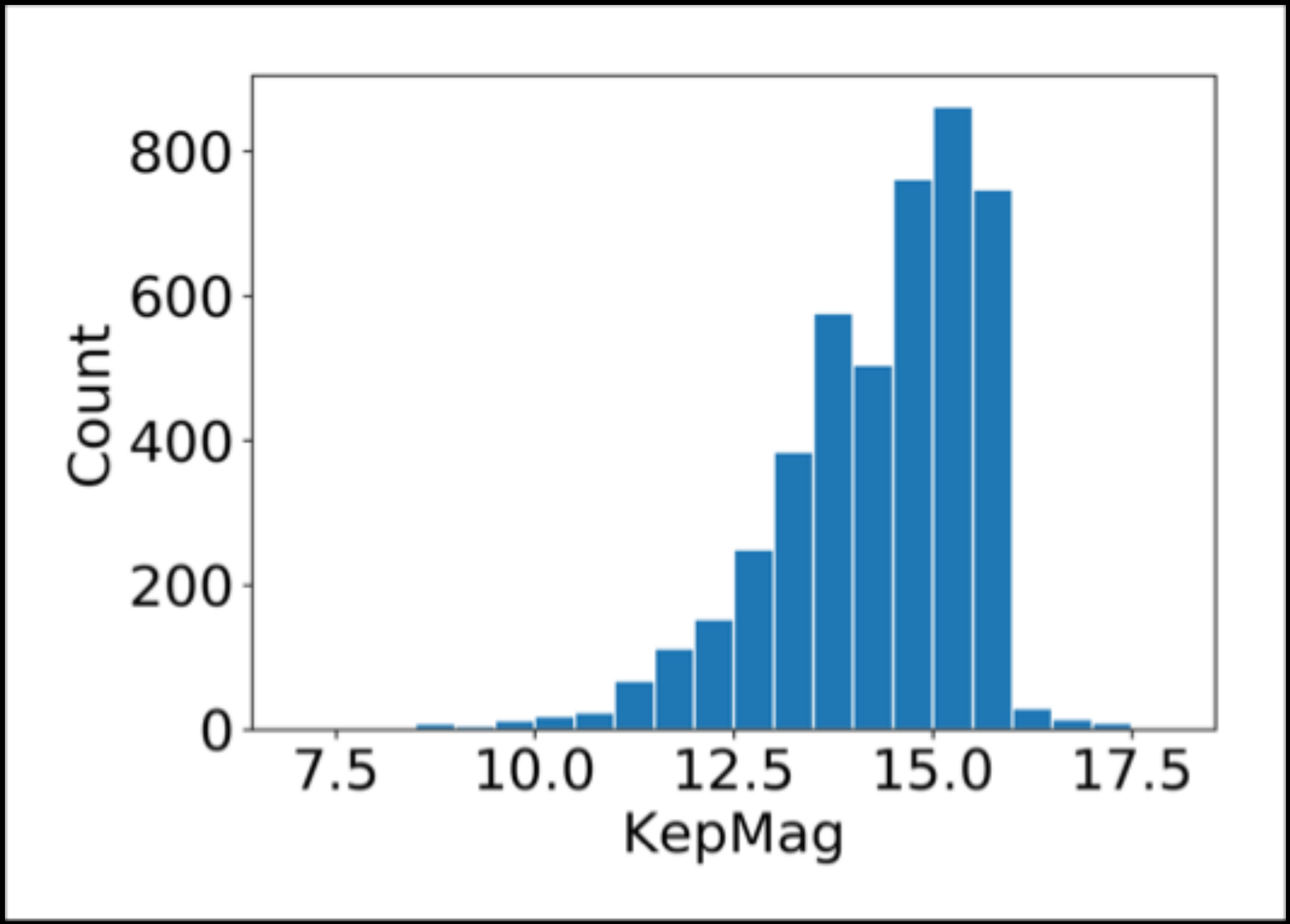
Few Small Planets Have Precise Density Estimates



Dorn et al. 2018

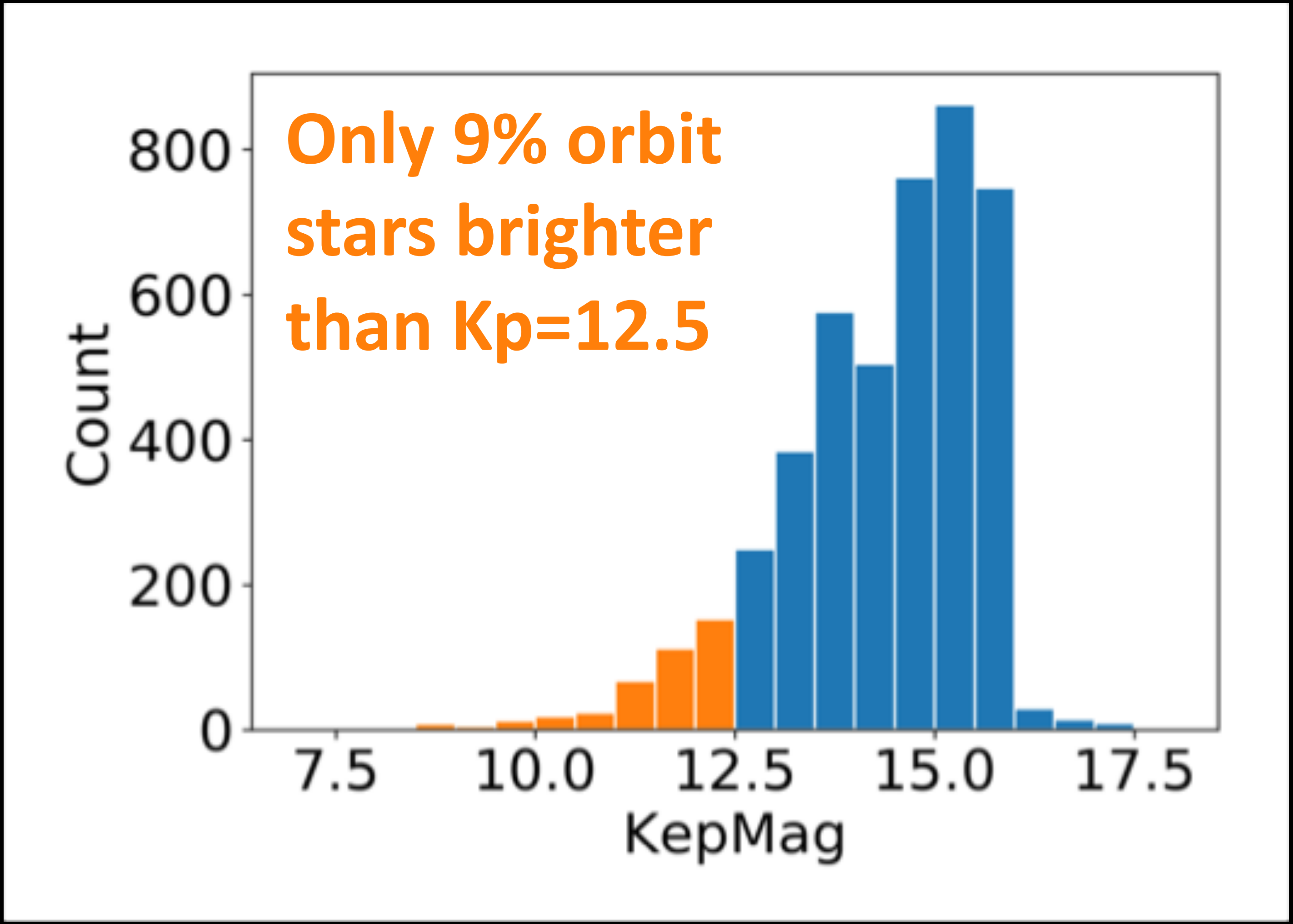

Credits: ESA, Alfred Vidal-Madjar, NASA

Most *Kepler* planet candidates orbit stars that are too faint for RV follow-up



Data from the NASA Exoplanet Archive

Most *Kepler* planet candidates orbit stars that are too faint for RV follow-up



Data from the NASA Exoplanet Archive

TESS planets are ideal targets for RV mass measurement

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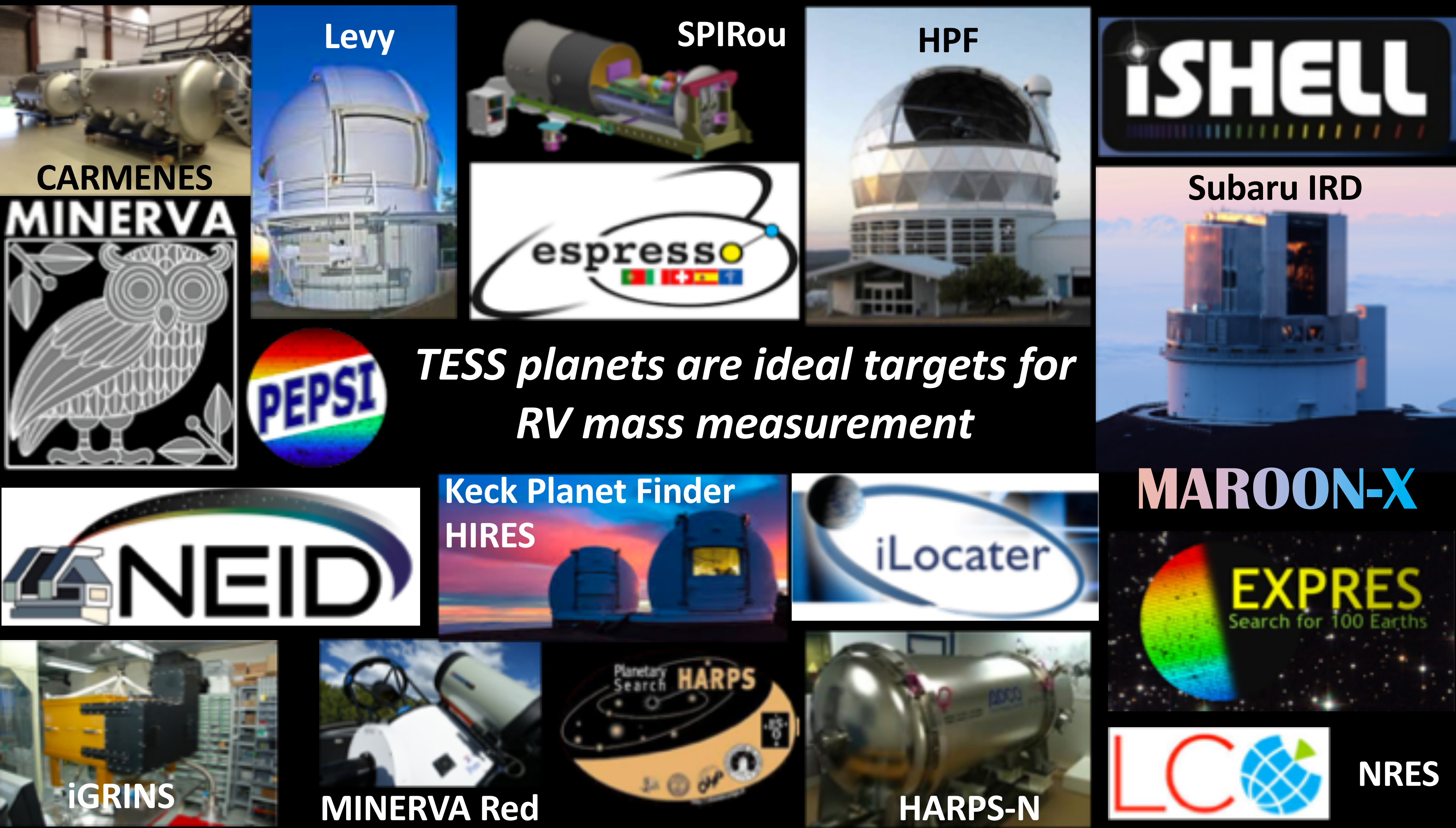


The Exoplanet Census is Substantially Incomplete

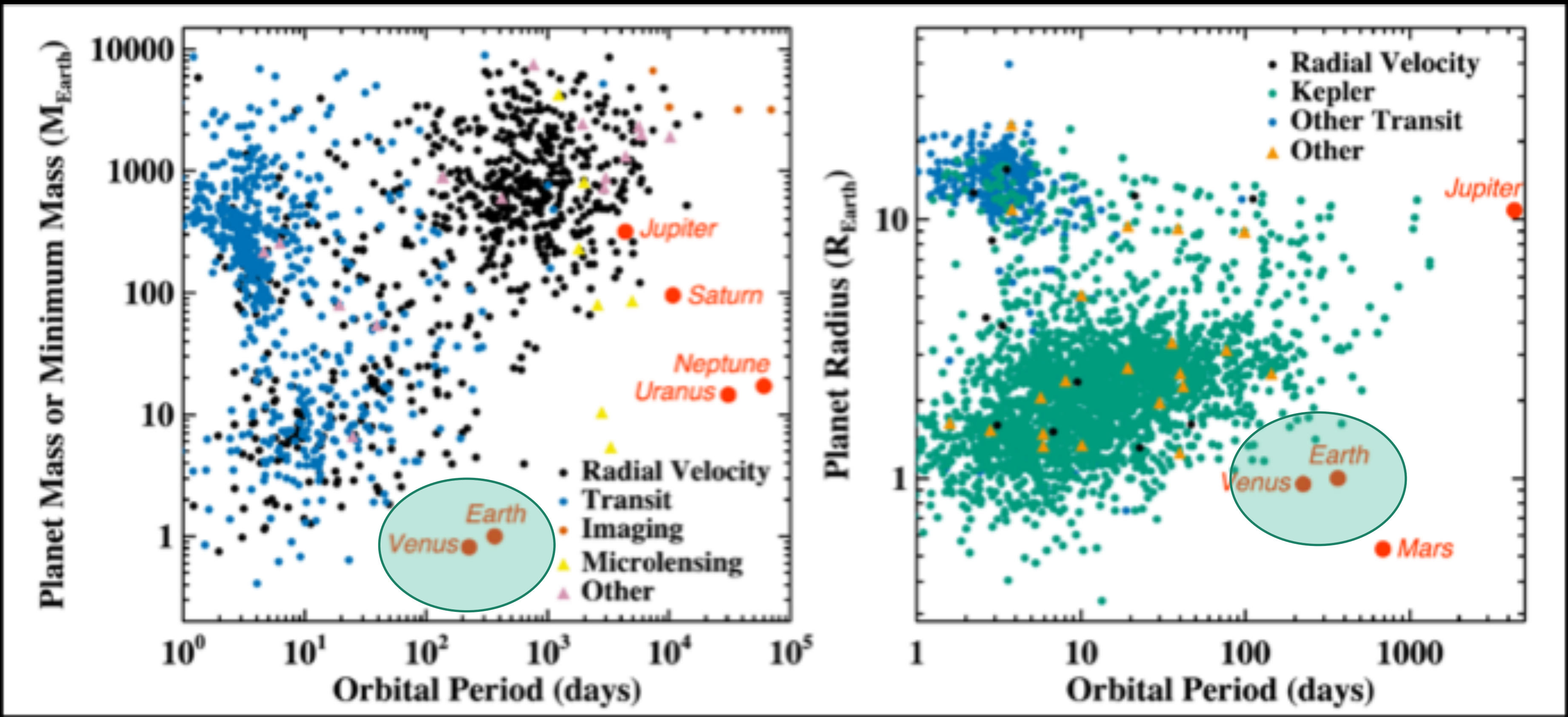
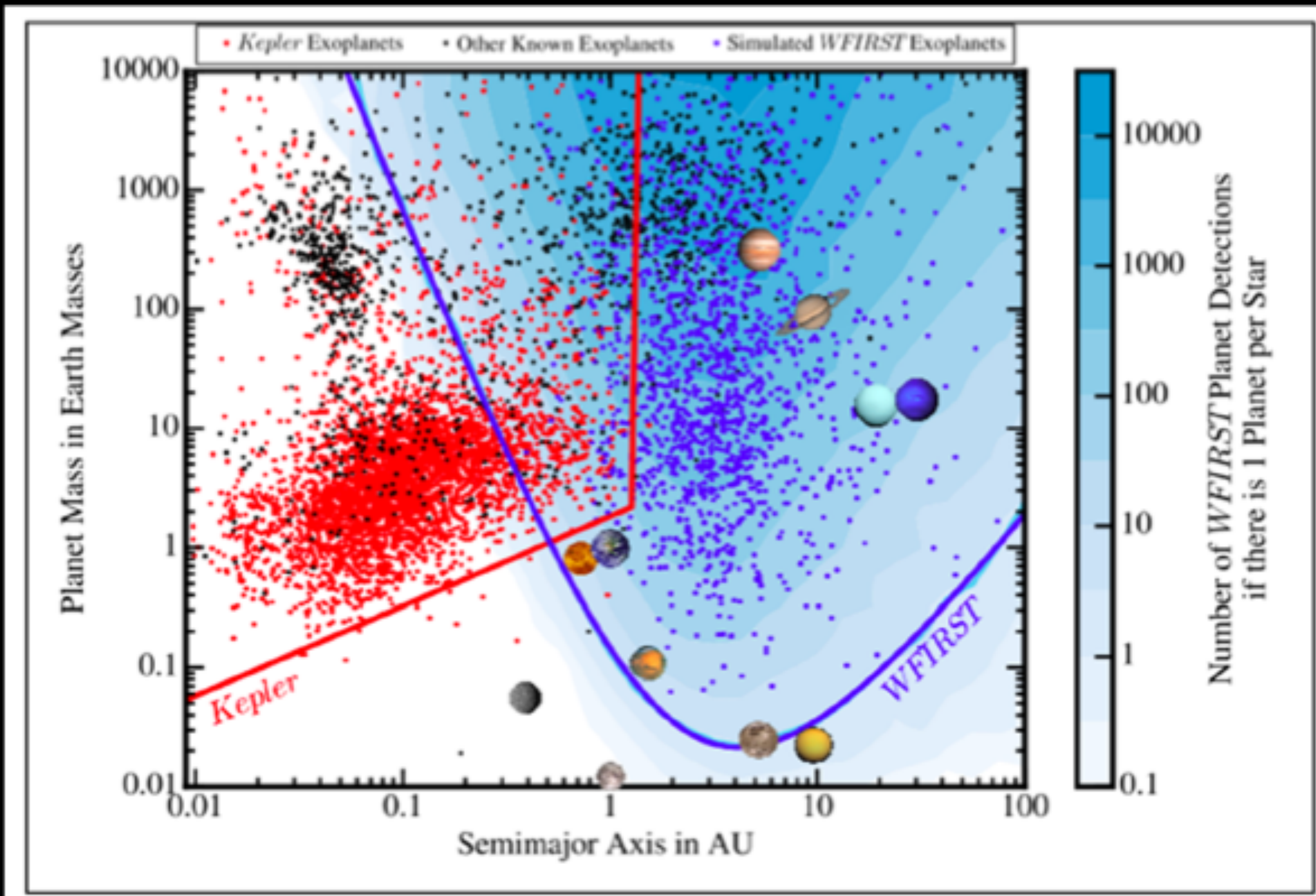


Figure from ESS Report. Produced by A. Weinberger using data from the NASA Exoplanet Archive

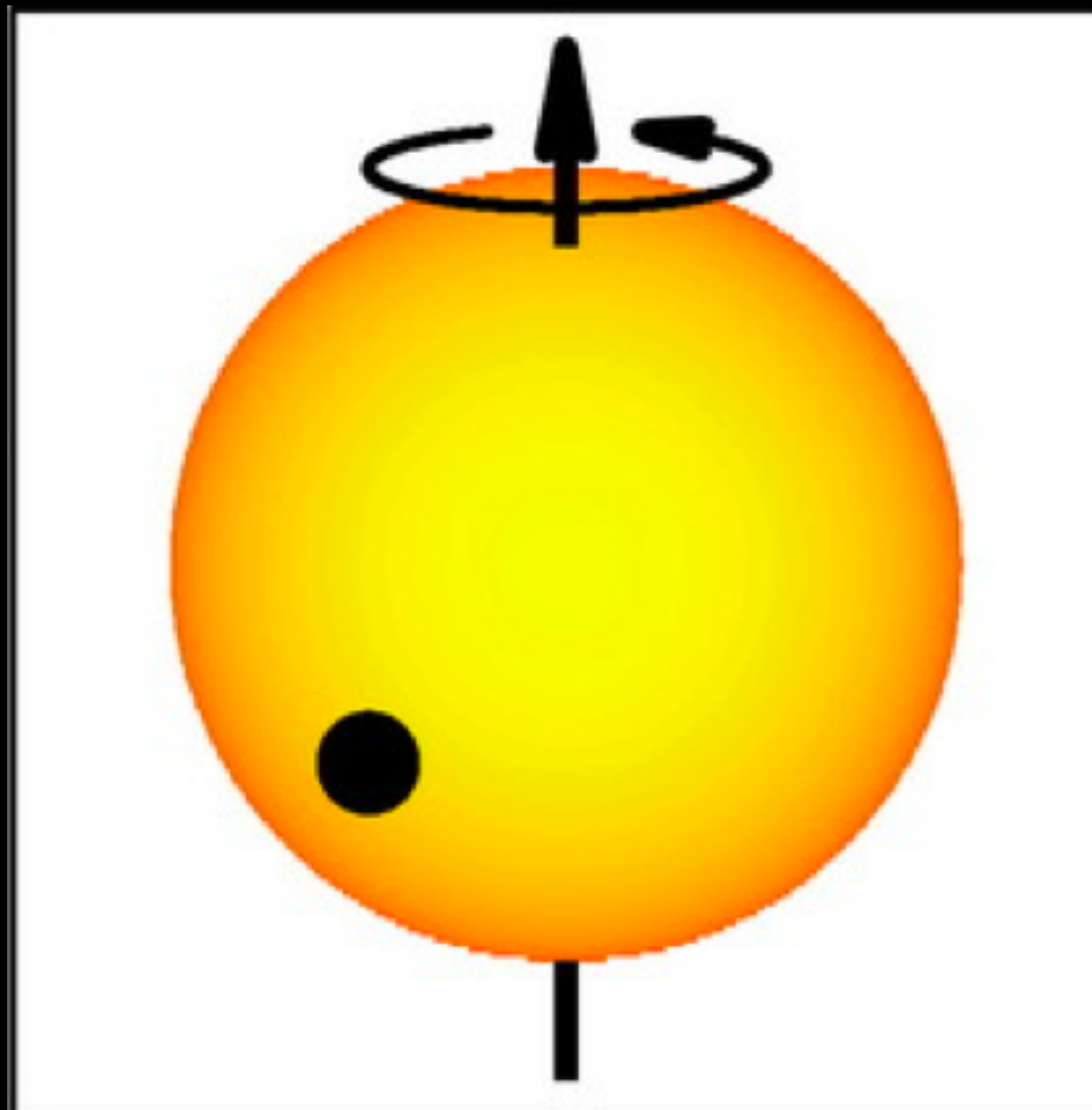
WFIRST Will Dramatically Expand the Exoplanet Census



Penny et al. 2018

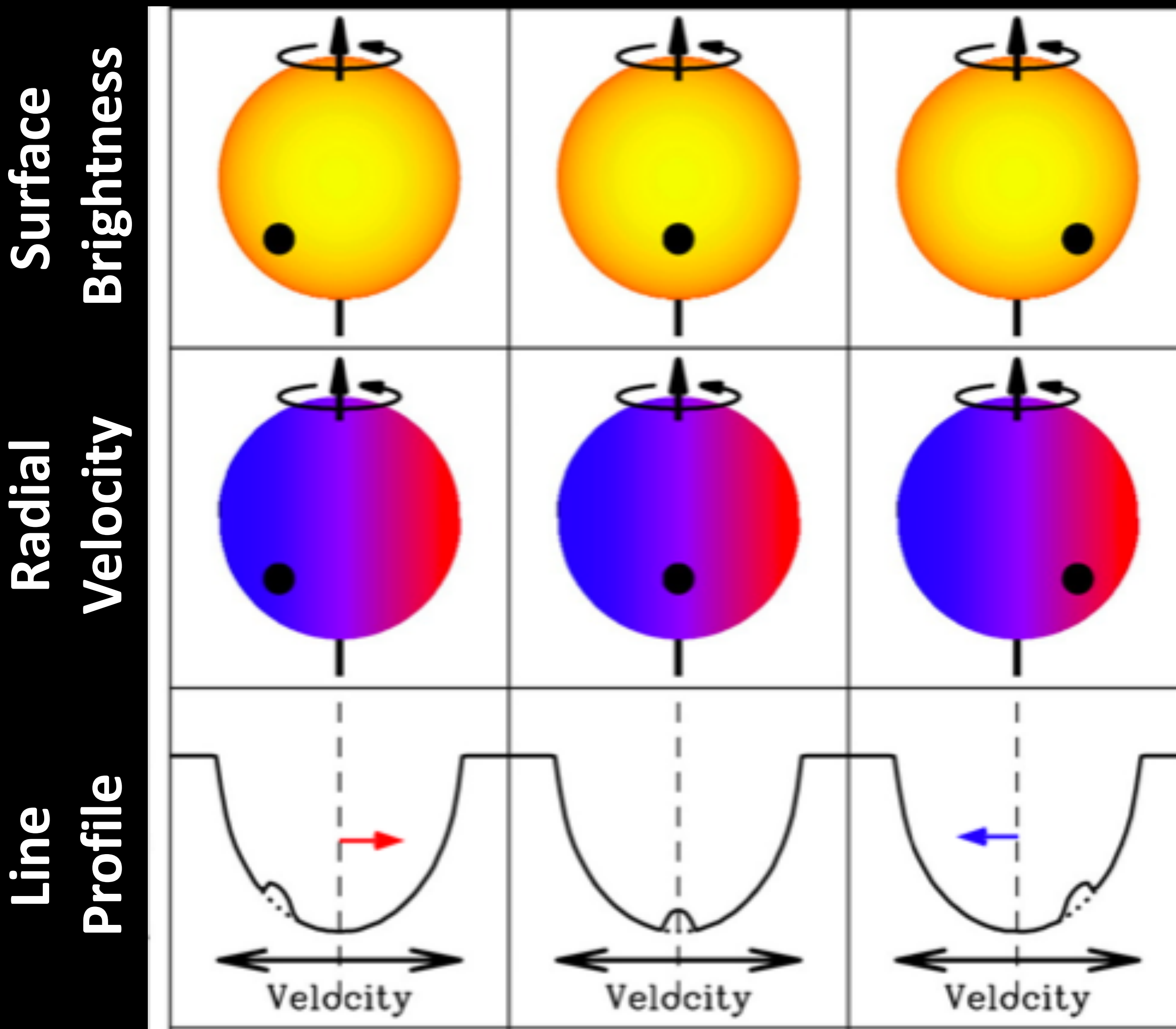
Part 4. *System Orientations*

The Rossiter-McLaughlin Effect: RV Observations During Transit Probe Orbital Inclination



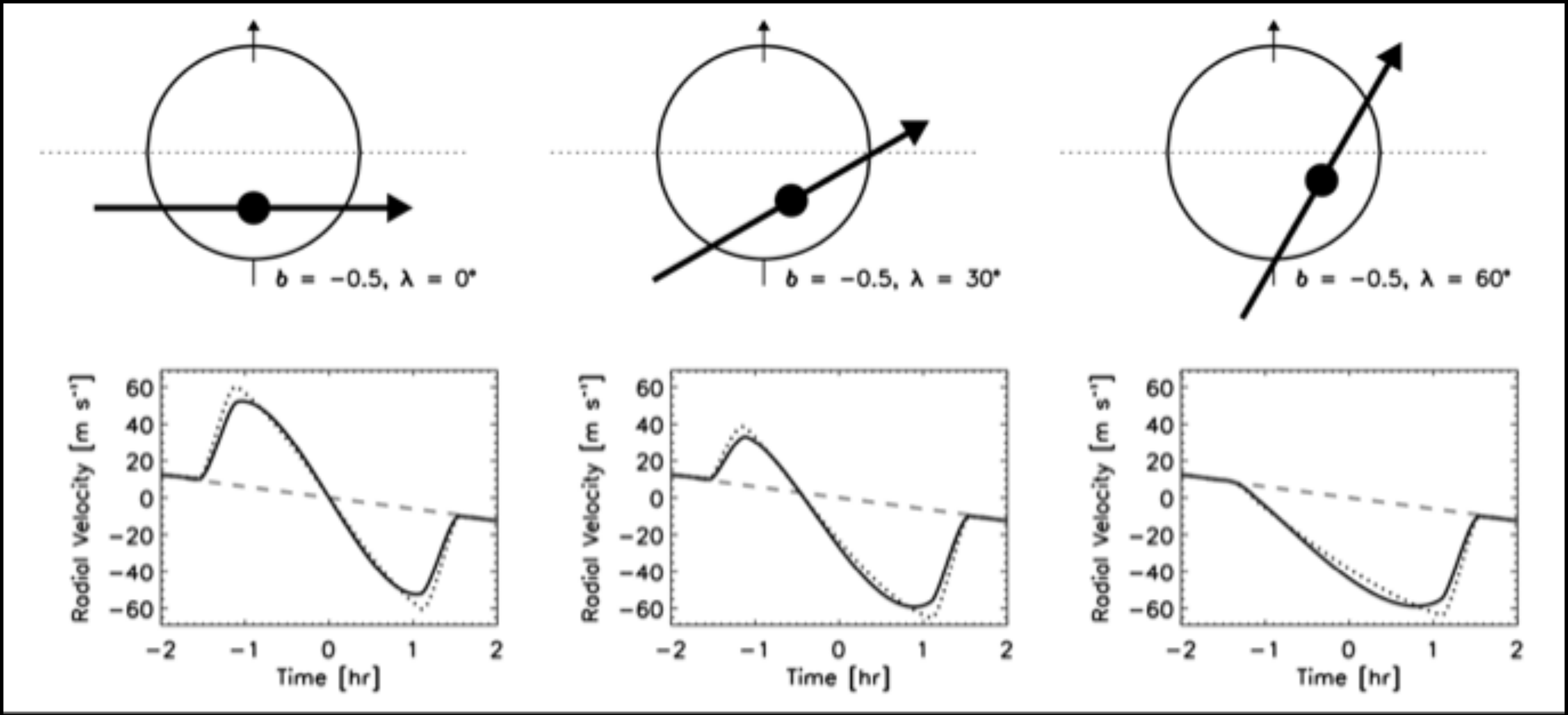
Gaudi & Winn (2007)

The Rossiter-McLaughlin Effect: RV Observations During Transit Probe Orbital Inclination



Gaudi & Winn (2007)

The Rossiter-McLaughlin Effect: RV Observations During Transit Probe Orbital Inclination



Gaudi & Winn (2007)

Wrapping Up: Topics Listed in Outline

1. Transiting planets
2. Follow-up observations
3. Planetary compositions
4. System orientations

Summary

- ***Transiting planets*** are planets that cross in front of their stars.
  - Periodic decreases in stellar brightness reveal transiting planets.
  - Transit light curves reveal the relative size of the planet relative to the host star and the orbital period of the planet.
- ***Follow-up data*** can be used to determine which candidate transiting planets are real planets.
  - **Seeing-limited imaging** can screen out nearby eclipsing binaries.
  - **Reconnaissance spectroscopy** can reveal spectroscopic binaries and improve stellar (and planetary) parameters.
  - **High-resolution imaging** reveals nearby stellar companions that can dilute the depth of stellar eclipsing binaries and transiting planets.
  - **Space-based imaging** can refine transit ephemerides and reveal transit timing variations.
  - **Precise RVs** can determine planet masses, thereby constraining planet compositions.

Summary

- Planetary ***compositions*** can be estimated by measuring both radius and mass.
  - Radii can be estimated from transit light curves.
  - Masses can be estimated from radial velocity observations and/or transit timing variations.
  - Small planets tend to have higher densities consistent with Earth-like compositions while larger planets require more volatiles.
  - Most planets with compositional constraints are either much hotter or much more massive than the Earth.
- Planetary systems have a variety of three-dimensional ***orientations***.
  - Some planets have orbits aligned with the spin axis of their host star.
  - Other planets orbit in the opposite direction.

A Selection of Useful References (Part 1 of 2)

- Previous Sagan Summer Workshops
  - *Did I Really Just Find an Exoplanet?* (2018; https://nexsci.caltech.edu/workshop/2018)
  - *Is There a Planet in My Data? Statistical Approaches to Finding and Characterizing Planets in Astronomical Data* (2016; https://nexsci.caltech.edu/workshop/2016/)
  - *Working with Exoplanet Light Curves* (2012; https://nexsci.caltech.edu/workshop/2012/)
- Textbook Chapters
  - Transits & Occultations by Winn (2010, arXiv:1001.2010, from *Exoplanets* ed:Seager)
  - Handbook of Exoplanets (2018, ed: Deeg & Belmonte; check your university library for free electronic access)

A Selection of Useful References (Part 2 of 2)

- Journal Articles & Reports
  - The Occurrence and Architecture of Exoplanetary Systems (Winn & Fabrycky 2015, *Annual Review of Astronomy & Astrophysics*, 53, 409)
  - Statistical Trends in the Obliquity Distribution of Exoplanet Systems (Muñoz & Perets 2018, AJ, 156, 253)
  - The Compositional Diversity of Low-Mass Exoplanets (Jontof-Hutter 2019, Annual Review of Earth and Planetary Sciences 47, 141)
  - Resources Needed for Planetary Confirmation and Characterization (Ciardi et al. 2018, arXiv:1810.08689)
  - The Kepler Follow-up Observation Program. I. A Catalog of Companions to Kepler Stars from High-Resolution Imaging (Furlan et al. 2017, AJ, 153, 71)
- Websites
  - Kepler & K2 missions (https://www.nasa.gov/mission_pages/kepler/overview/index.html)
  - TESS mission (https://www.nasa.gov/tess-transiting-exoplanet-survey-satellite)