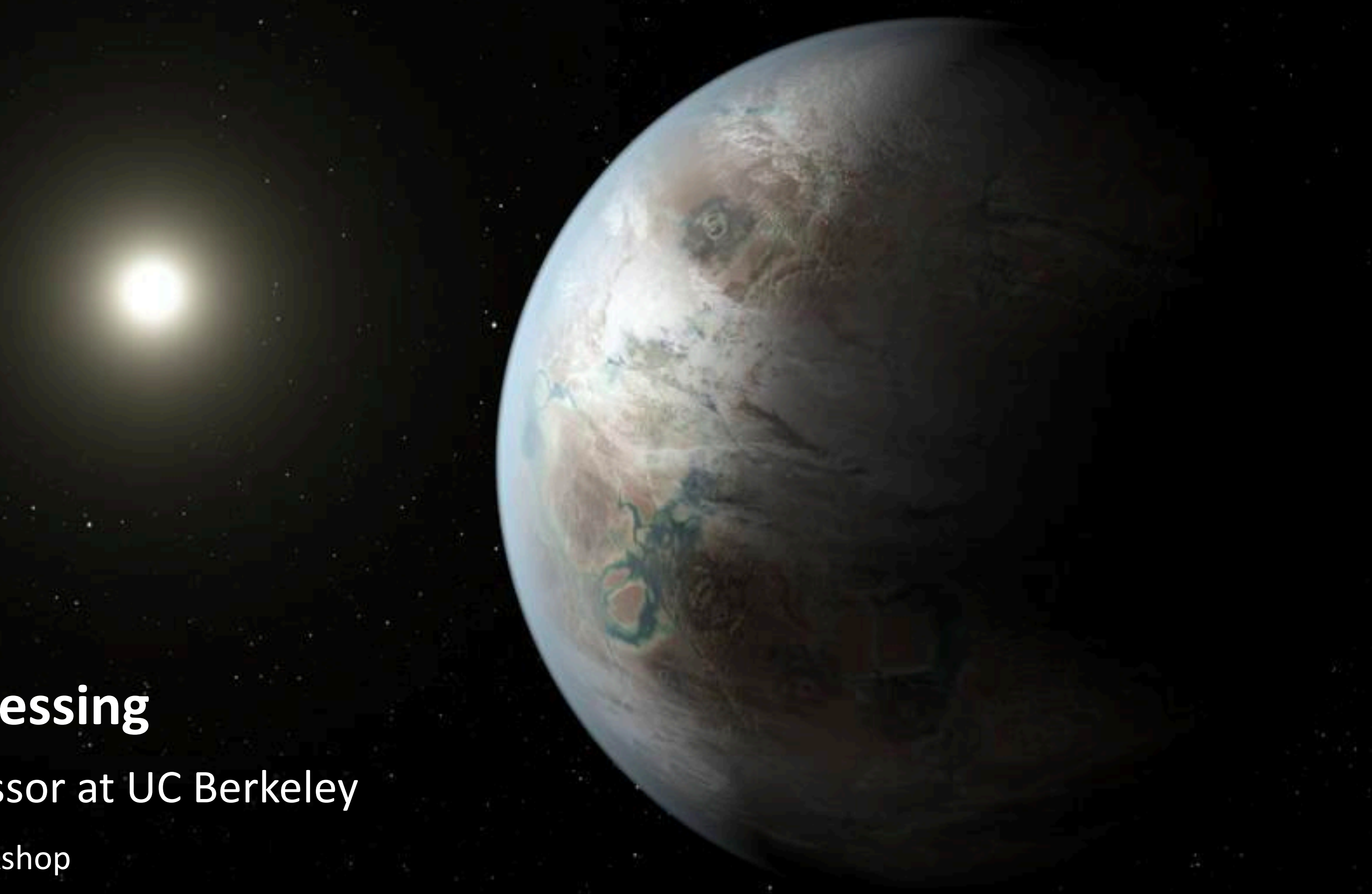
Exo-Earths:

Discovery, Demographics, & Characterization



Courtney Dressing

Assistant Professor at UC Berkeley

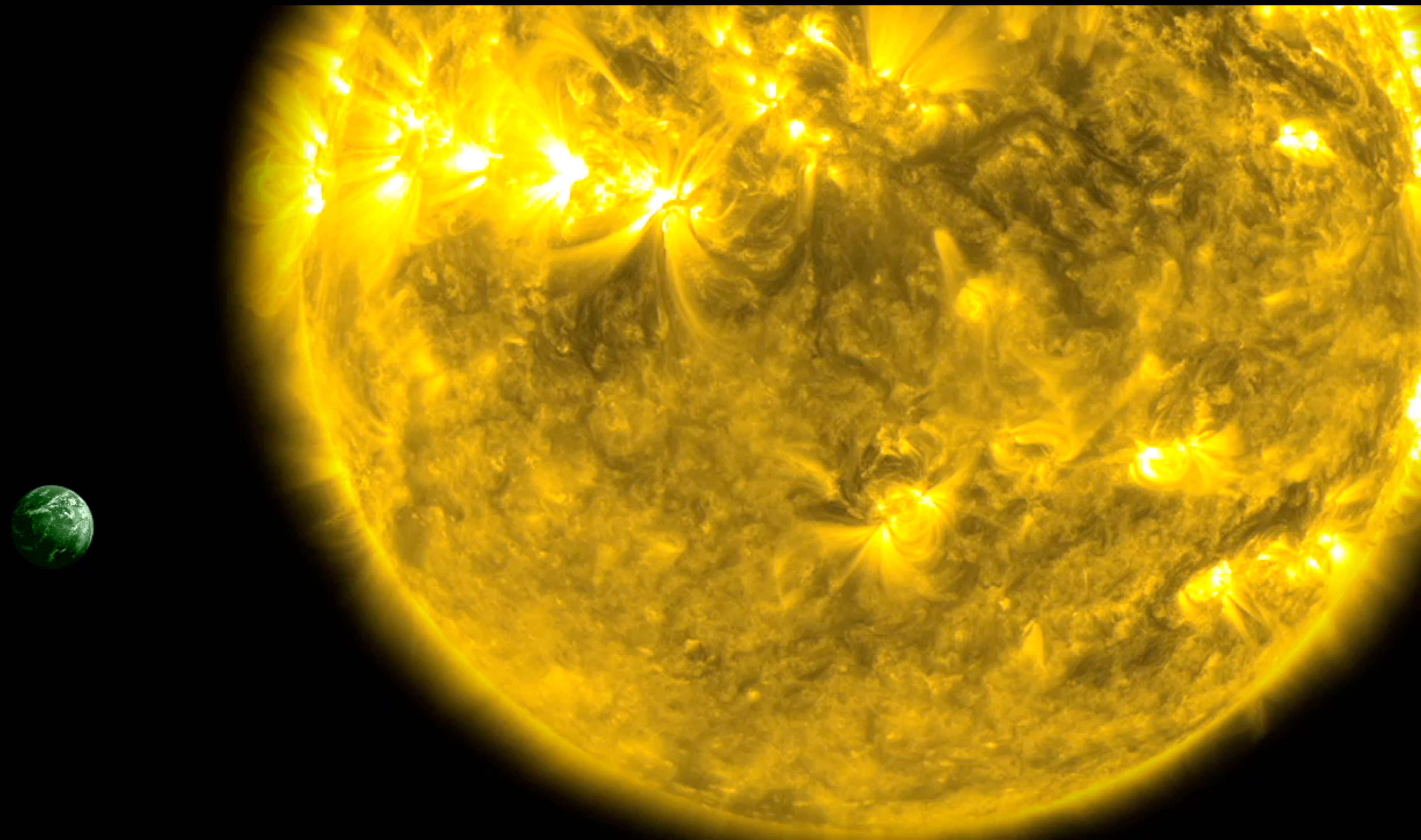
Sagan Summer Workshop

July 17, 2019

Credit: NASA

Discovery

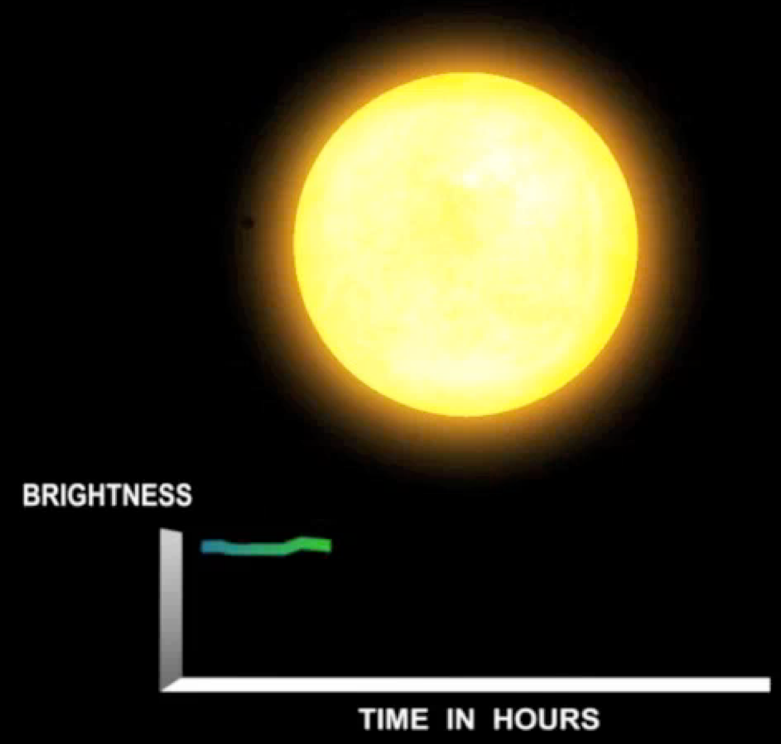
Right now, exoplanets are small black shadows to us



How exoplanets are detected today

Transits

observe star = indirect method



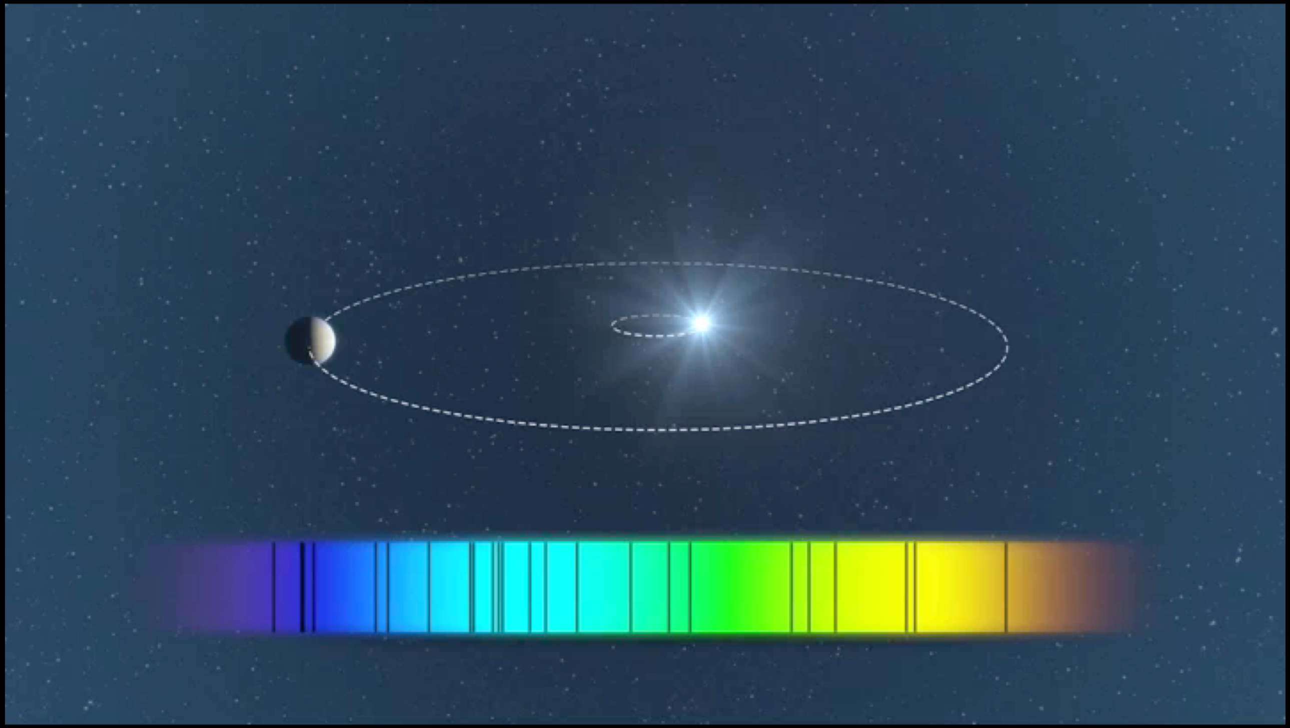
What can you learn?

Planet distance from star and Δ flux = $(R_{planet} / R_{star})^2$

How exoplanets are detected today

Radial velocity

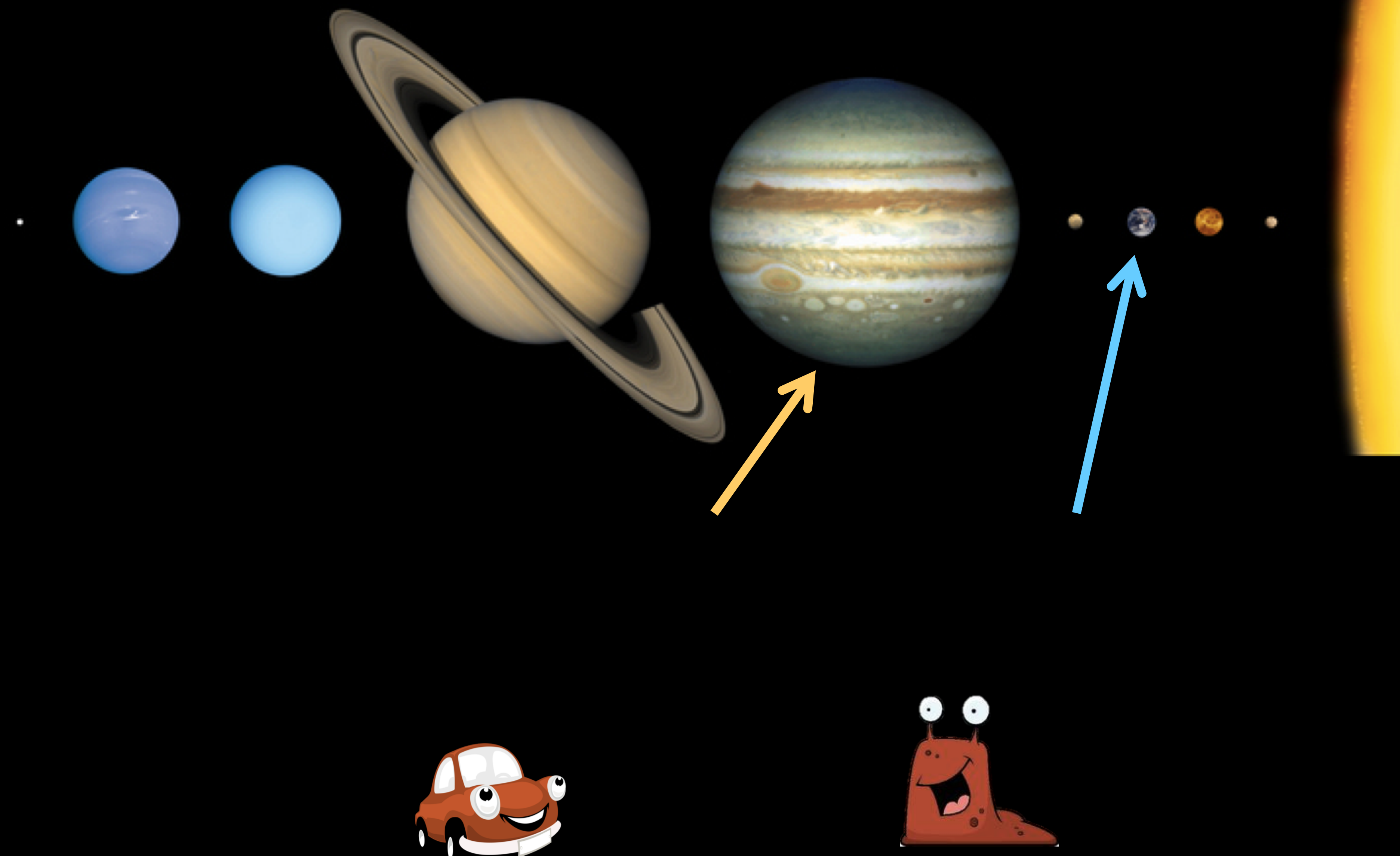
observe the star = indirect method

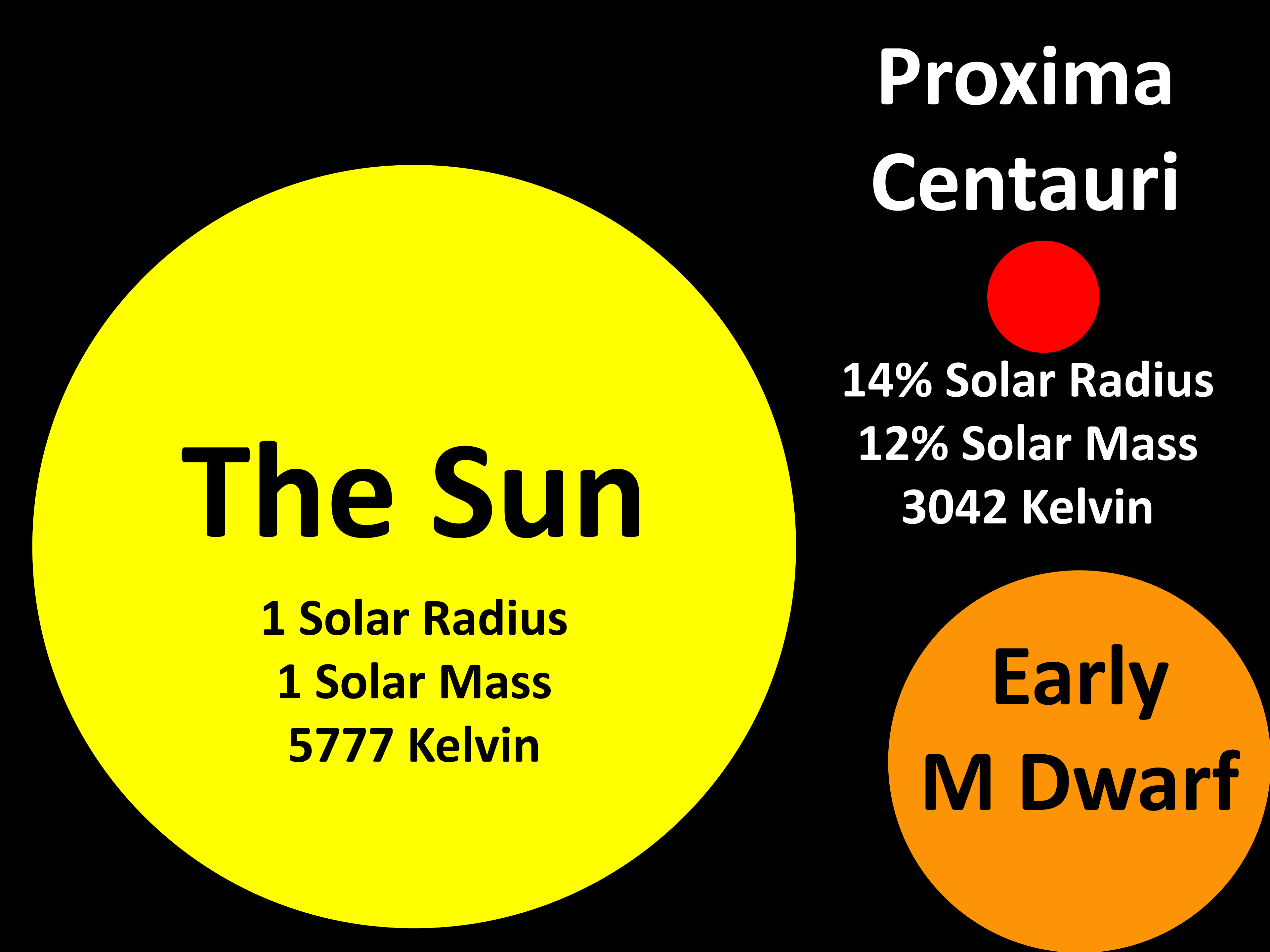


What can you learn?

Planet distance from star and minimum planet mass

How detectable are these signals?




Proxima
Centauri
14% Solar Radius
12% Solar Mass
3042 Kelvin
The Sun
1 Solar Radius
1 Solar Mass
5777 Kelvin
Early
M Dwarf

Exoplanets:
Cumulative Detections by Discovery Year

1989-2018

Plots generated Sept. 27, 2018

The Exoplanet Census is Substantially Incomplete

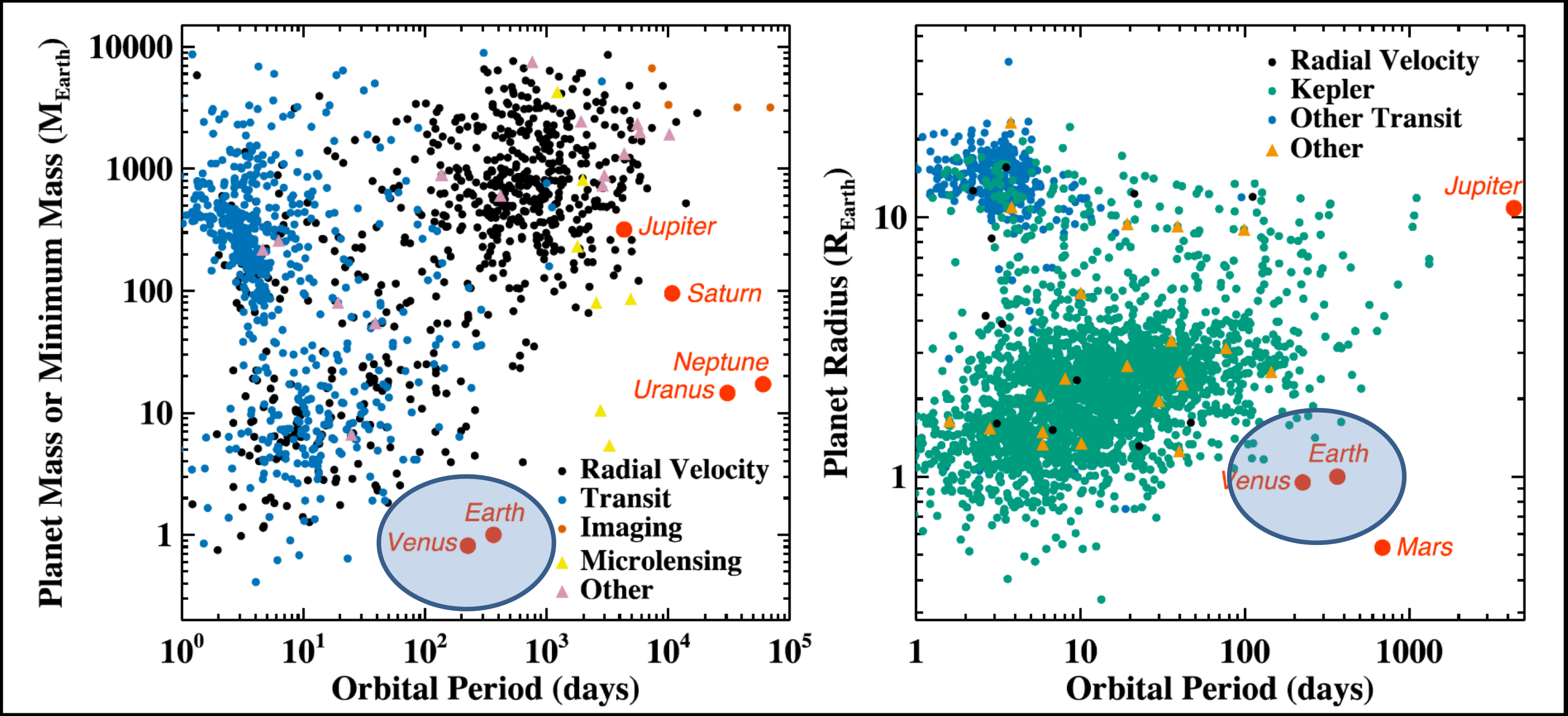
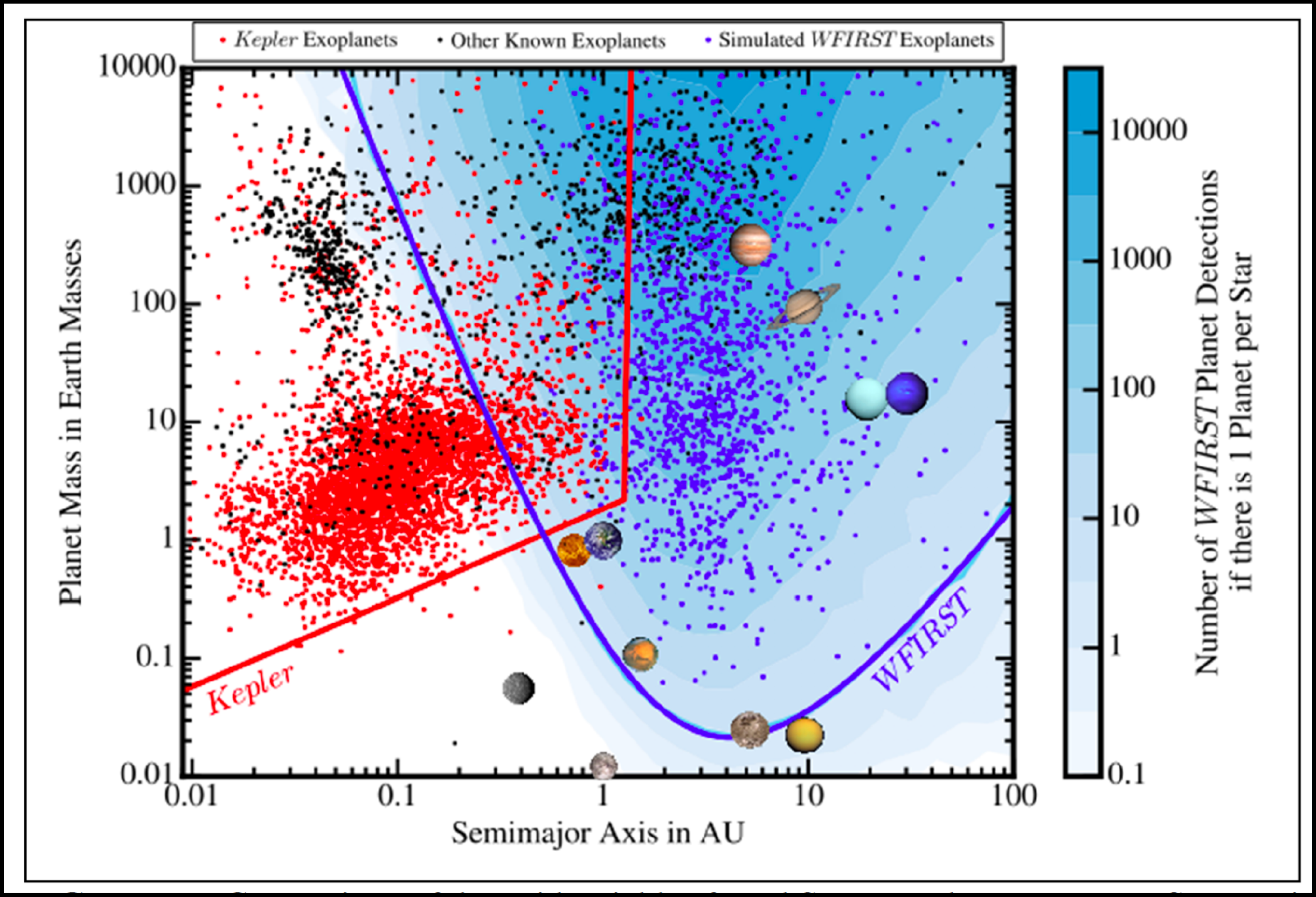
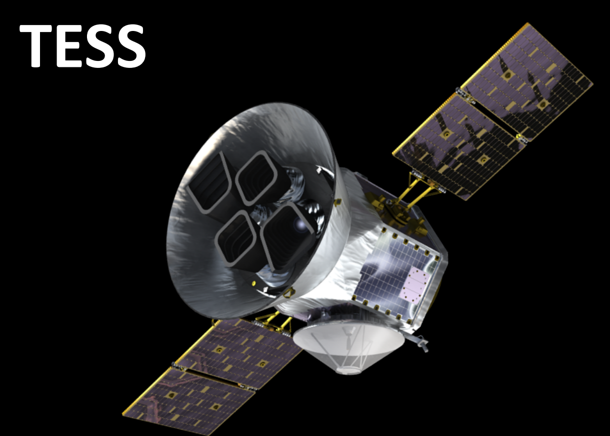


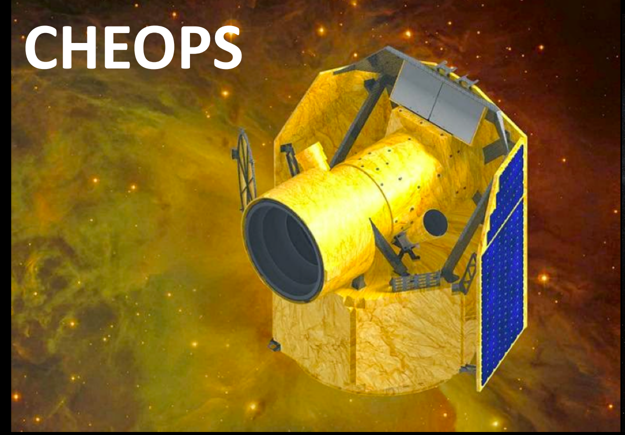
Figure from ESS Report. Produced by A. Weinberger using data from the NASA Exoplanet Archive

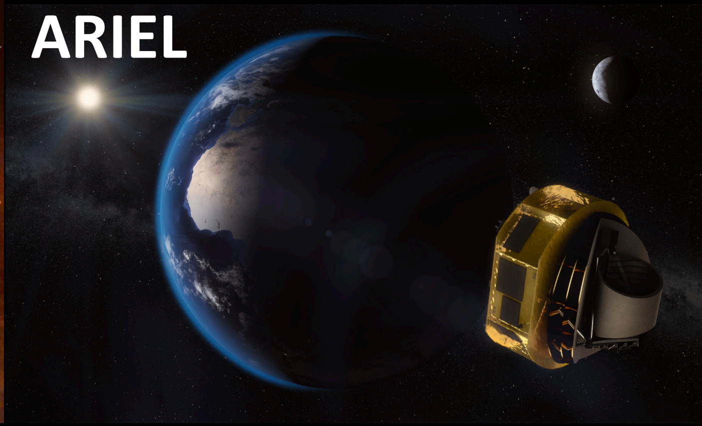
WFIRST Will Dramatically Expand the Exoplanet Census



Penny et al. 2018







Transiting Planets are Convenient Targets for Probing Bulk and Atmospheric Compositions

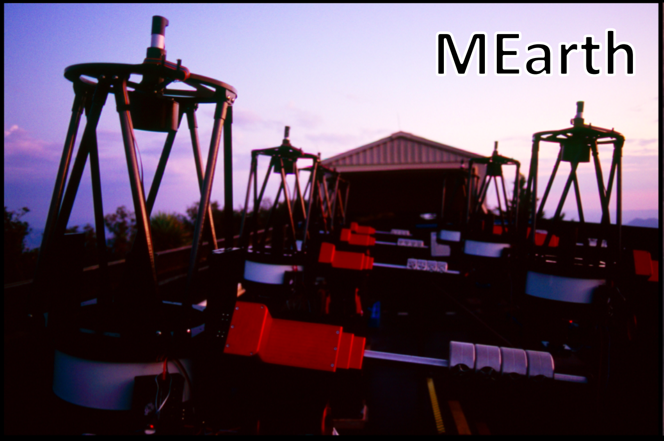


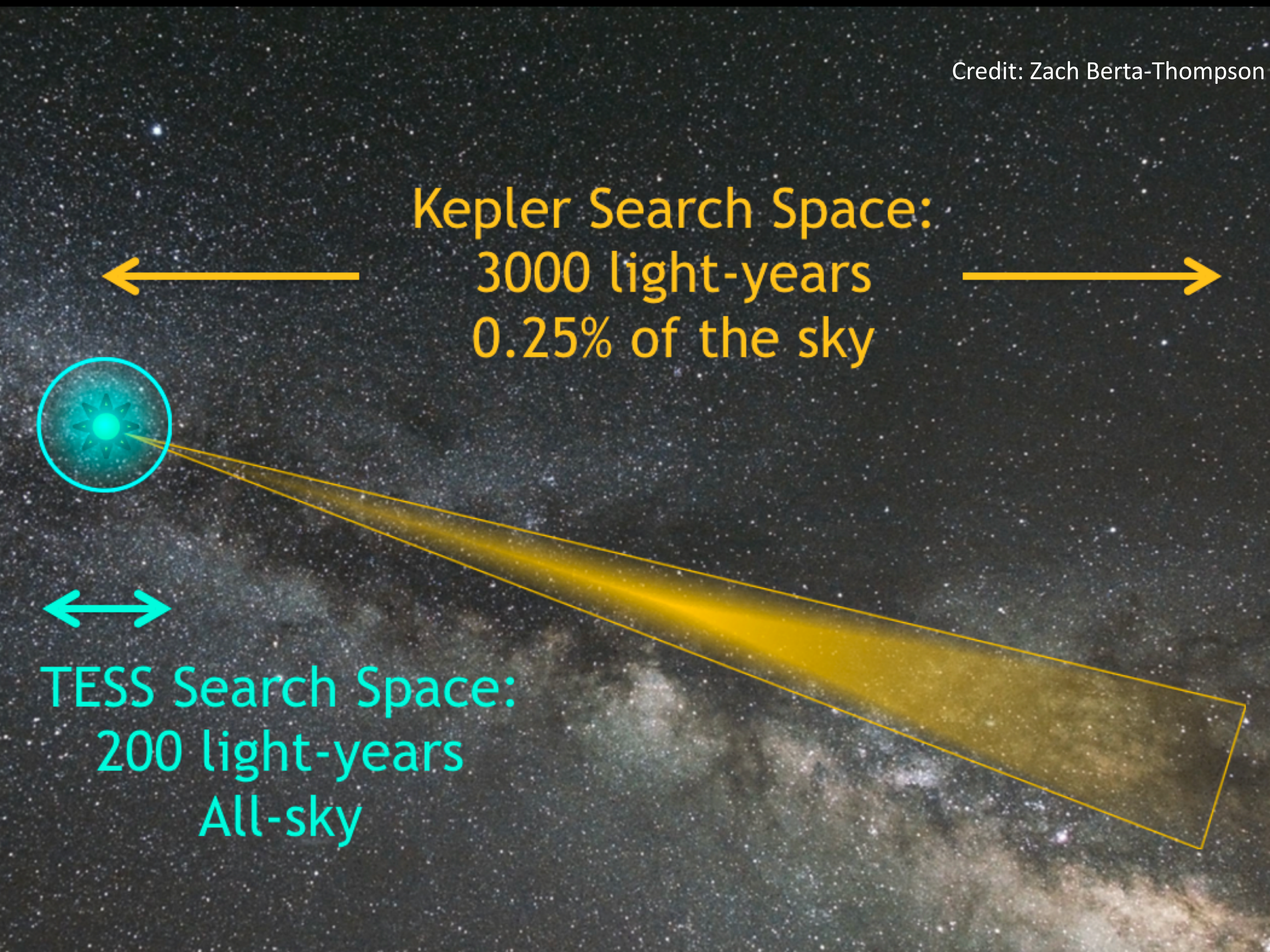
Image credit: NASA TV

TESS

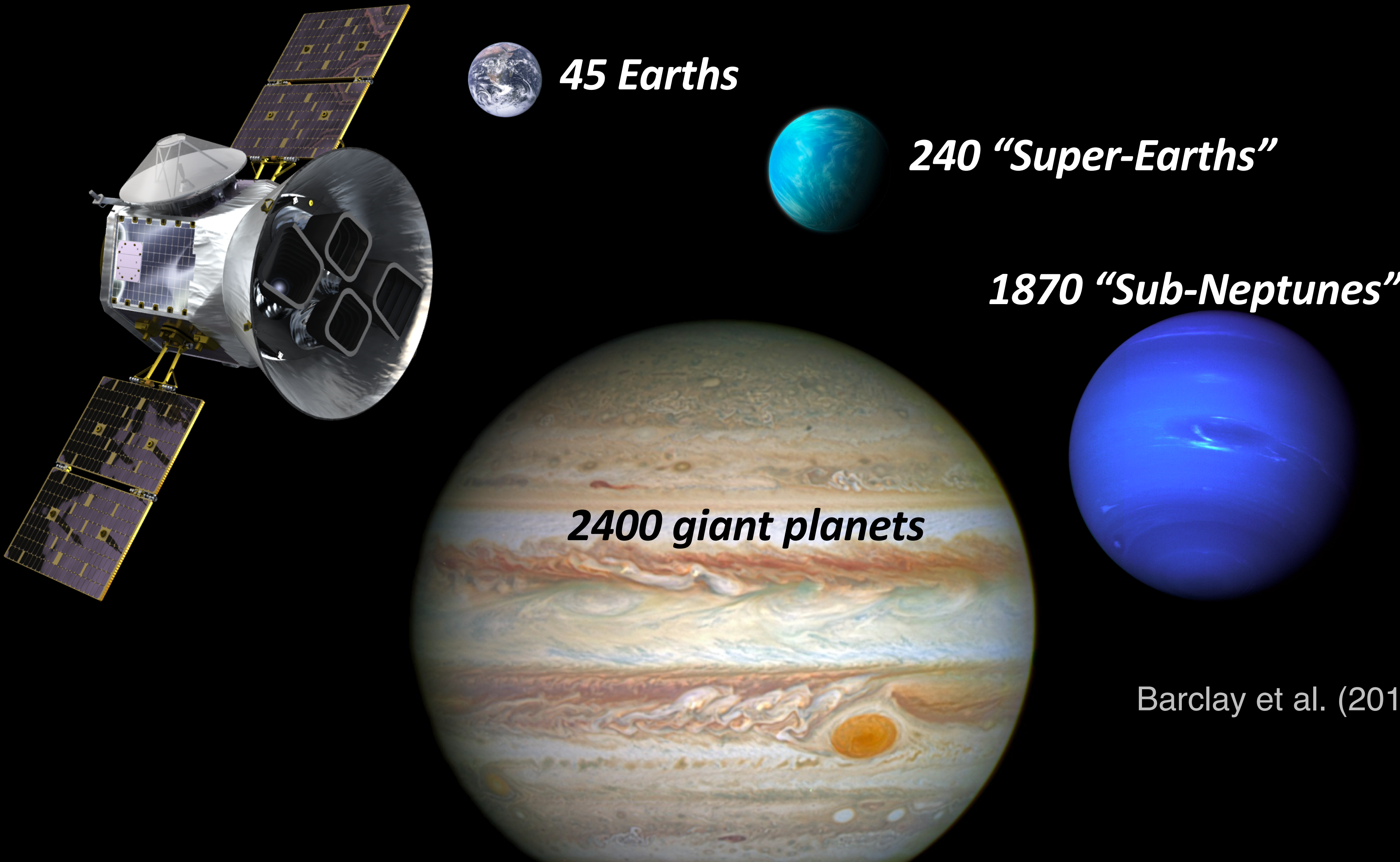
Explorer Mission

launched in 2018
to find hundreds of nearby small exoplanets amenable to detailed characterization

Ricker et al., JATIS, (2014)


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

TESS Will Find Thousands of Planets



Barclay et al. (2018)

TESS Has Already Found Hundreds of Candidates

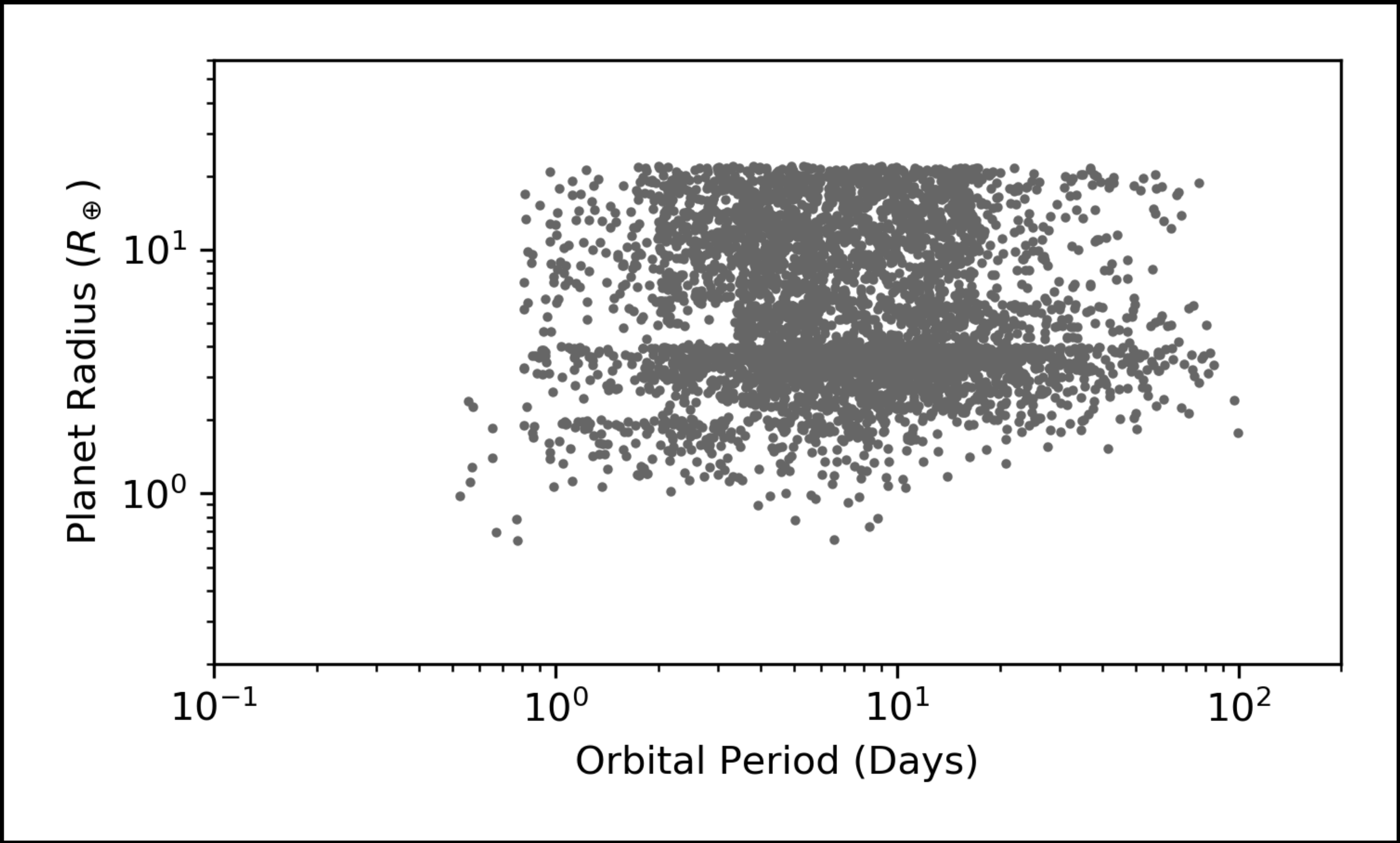


Figure by Dressing

Yield Simulation by Barclay et al. (2018)

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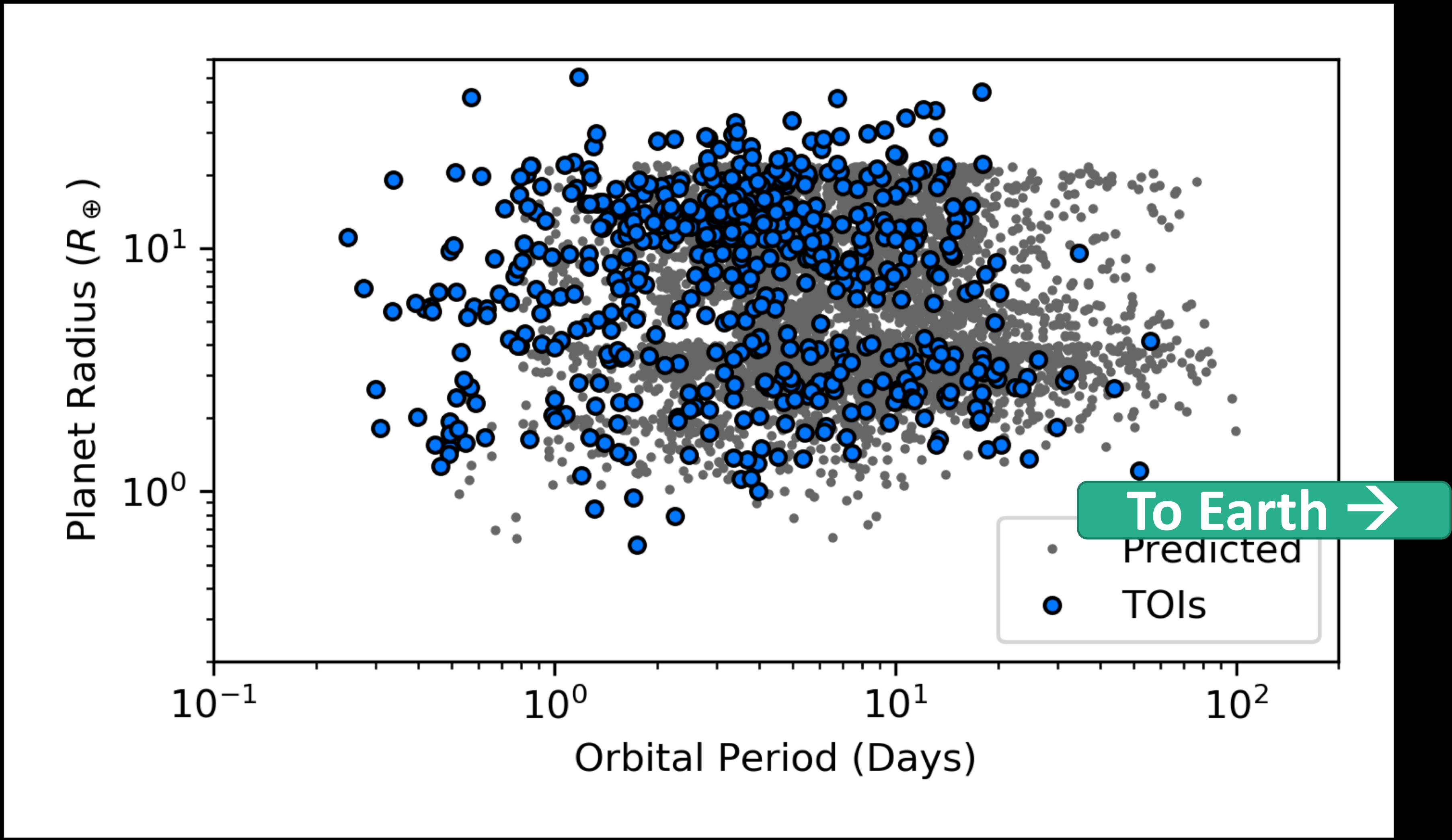


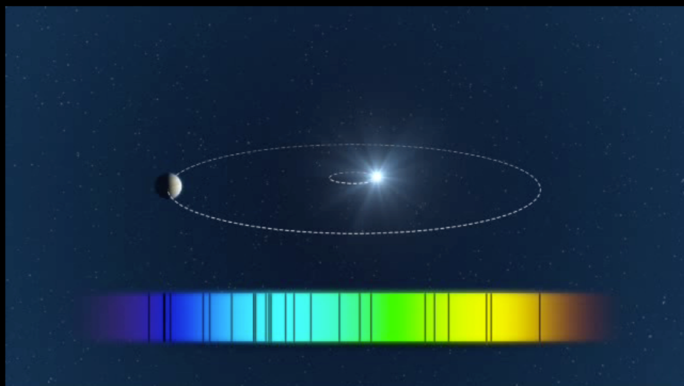
Figure by Dressing

TOIs from NASA Exoplanet Archive

Yield Simulation by Barclay et al. (2018)

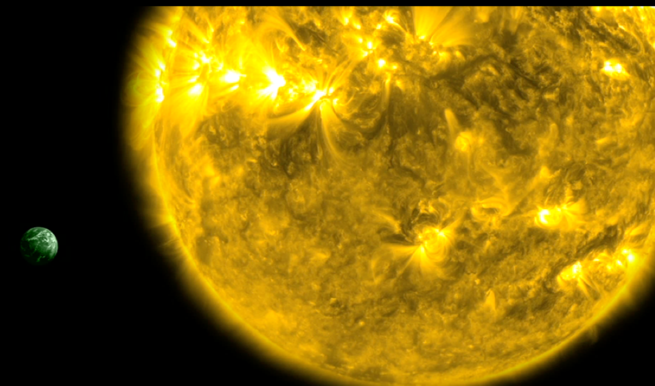
Radial Velocity

Animation by European Southern Observatory

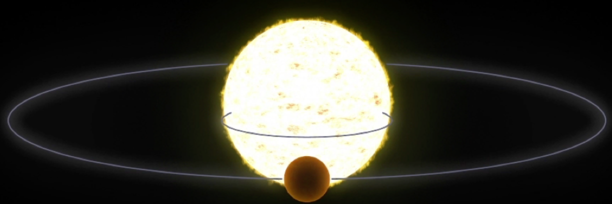


Transit

Animation by NASA Goddard Media Studios

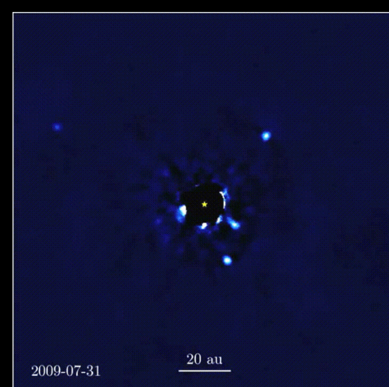


Which methods are most likely to find Exo-Earths?



Astrometry

Animation by Exoplanet Exploration Office at NASA JPL



Direct Imaging

Animation by Jason Wang

Microlensing

Animation by Exoplanet Exploration Office at NASA JPL

How Will We Find Exo-Earths?

The M-Dwarf Opportunity

the G-Dwarf Case

Table 1: Challenges and opportunities for HZ planets around M dwarfs and FGK dwarfs.

	Challenges	**Opportunities**
Potentially habitable planets orbiting M dwarfs	Multiple barriers to habitability possible; e.g. desiccation during super-luminous pre-main sequence phase, stellar activity-driven atmospheric loss. Apparent high potential for false positive oxygen biosignatures. Challenging to observe via direct imaging due to the small planet-star angular separation. Even nearest planets require ELTs (Crossfield 2013).	Most common type of stars (~75%). Planets with significantly different histories to Earth valuable for comparative planetology. Transits of HZ planets more easily observed due to shorter orbital periods and deeper transit depths. May be possible with JWST and/or ELTs. Moderate planet-star contrast ratio (10^{-8} in reflected light). Nearest planets may be within reach of ELTs (Crossfield 2013).
Potentially habitable planets orbiting FGK dwarfs	Less common types of stars. Transit spectroscopy prohibitively difficult due to long orbital periods, small transit depths, lower transit probability. Challenging planet-star contrast ratio (10^{-10} for a Sun-Earth twin in reflected light) demands starlight suppression advances.	Less significant barriers to habitability due to moderate stellar evolution and activity. Understand Earth in the context of planets with similar histories. Is Earth typical? Observable with potential future space-based telescopes in direct imaging due to larger planet-star angular separation. Known that life can flourish on such planets. May be best opportunity for high-confidence detection of biosignatures.

The Sun-like Stars Opportunity (Arney et al. 2019, Astro2020 White Paper)

How Will We Find Exo-Earths?

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The M-Dwarf Opportunity

and

the G-Dwarf Case

can be explored together!

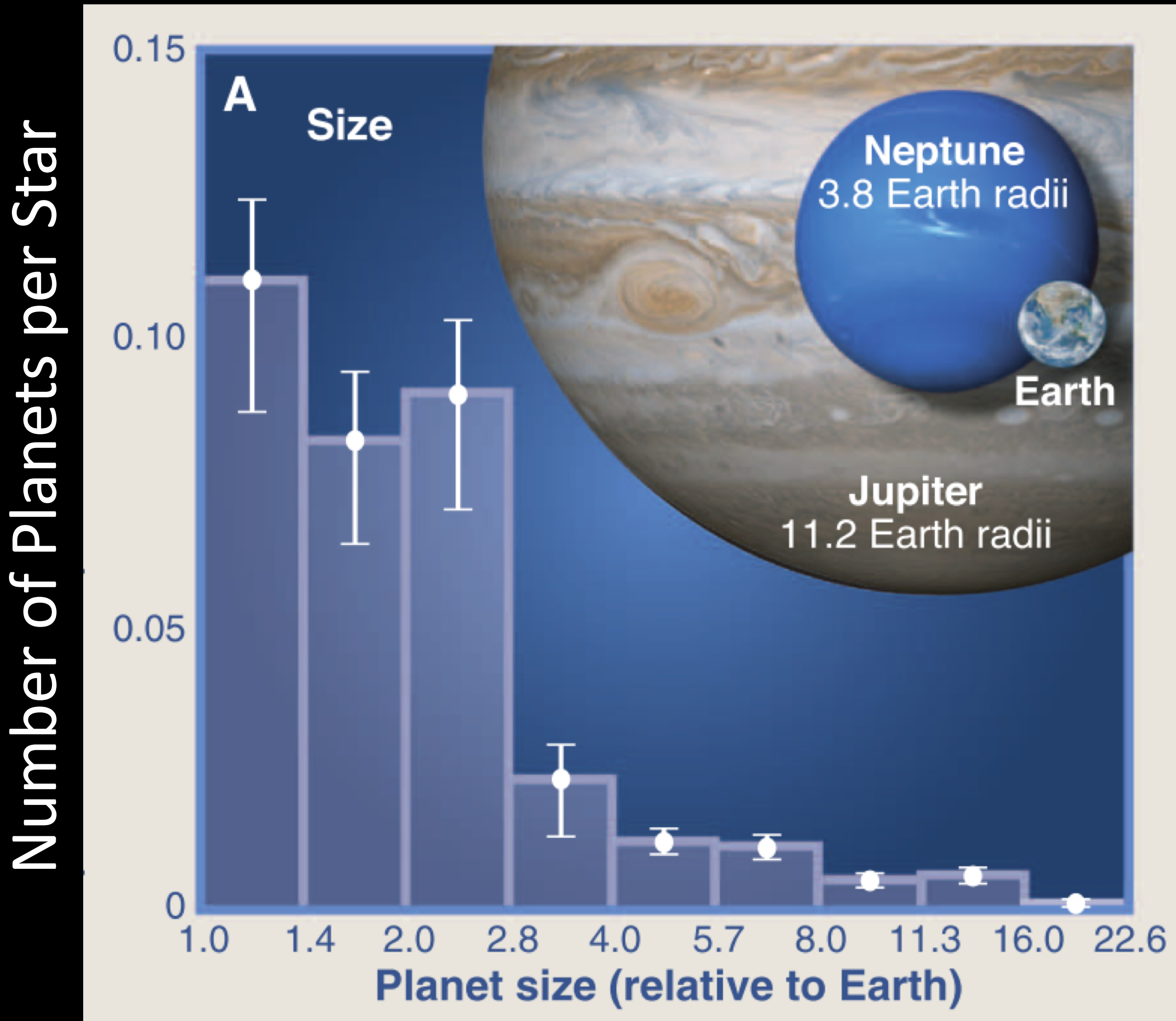
The Sun-like Stars Opportunity (Arney et al. 2019, Astro2020 White Paper)

Demographics

How Common are Exo-Earths?

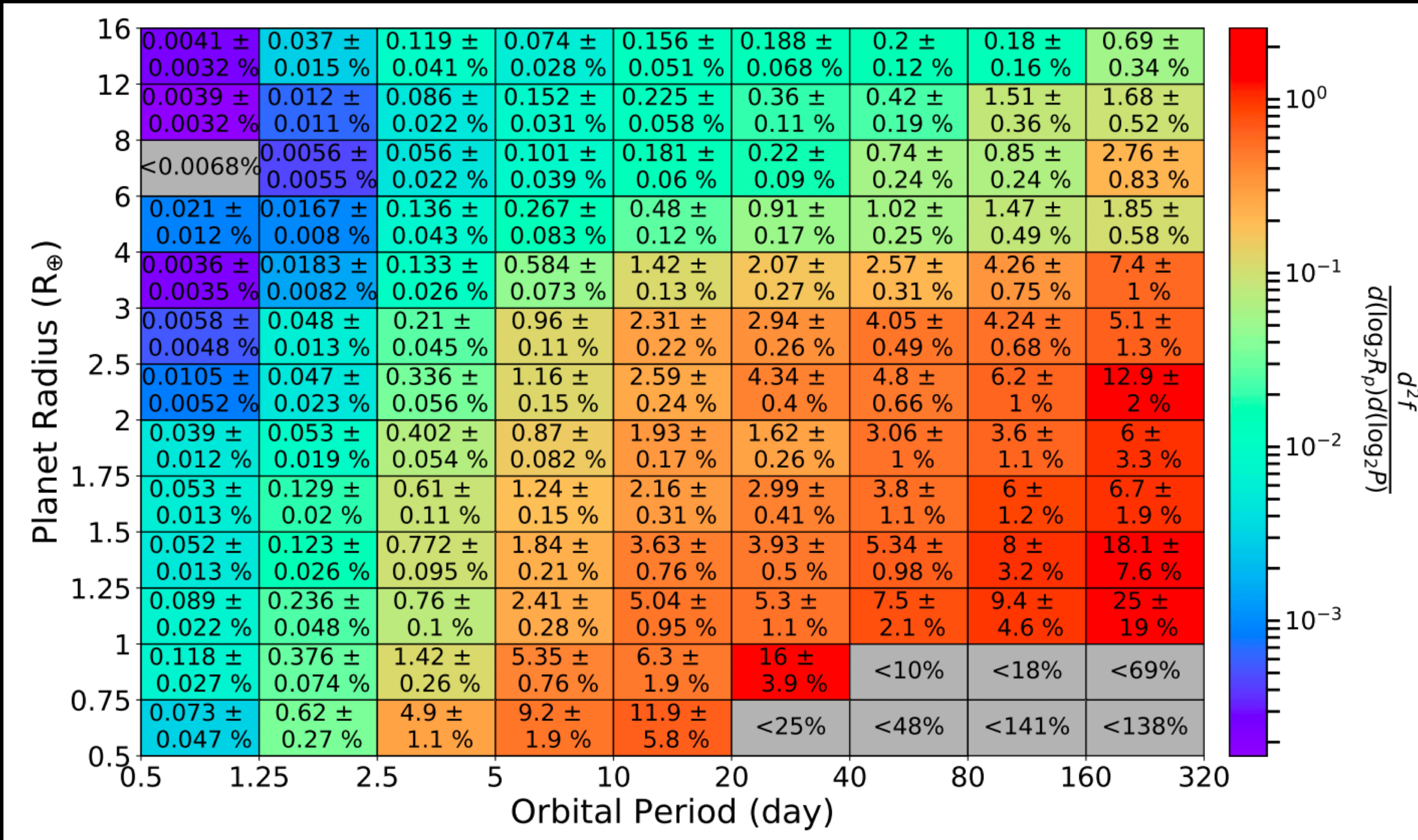
How Common are Exo-Earths?

How Common are Small Planets?



Howard 2013, Science, 340, 572

How Common are Small, Cool Planets?

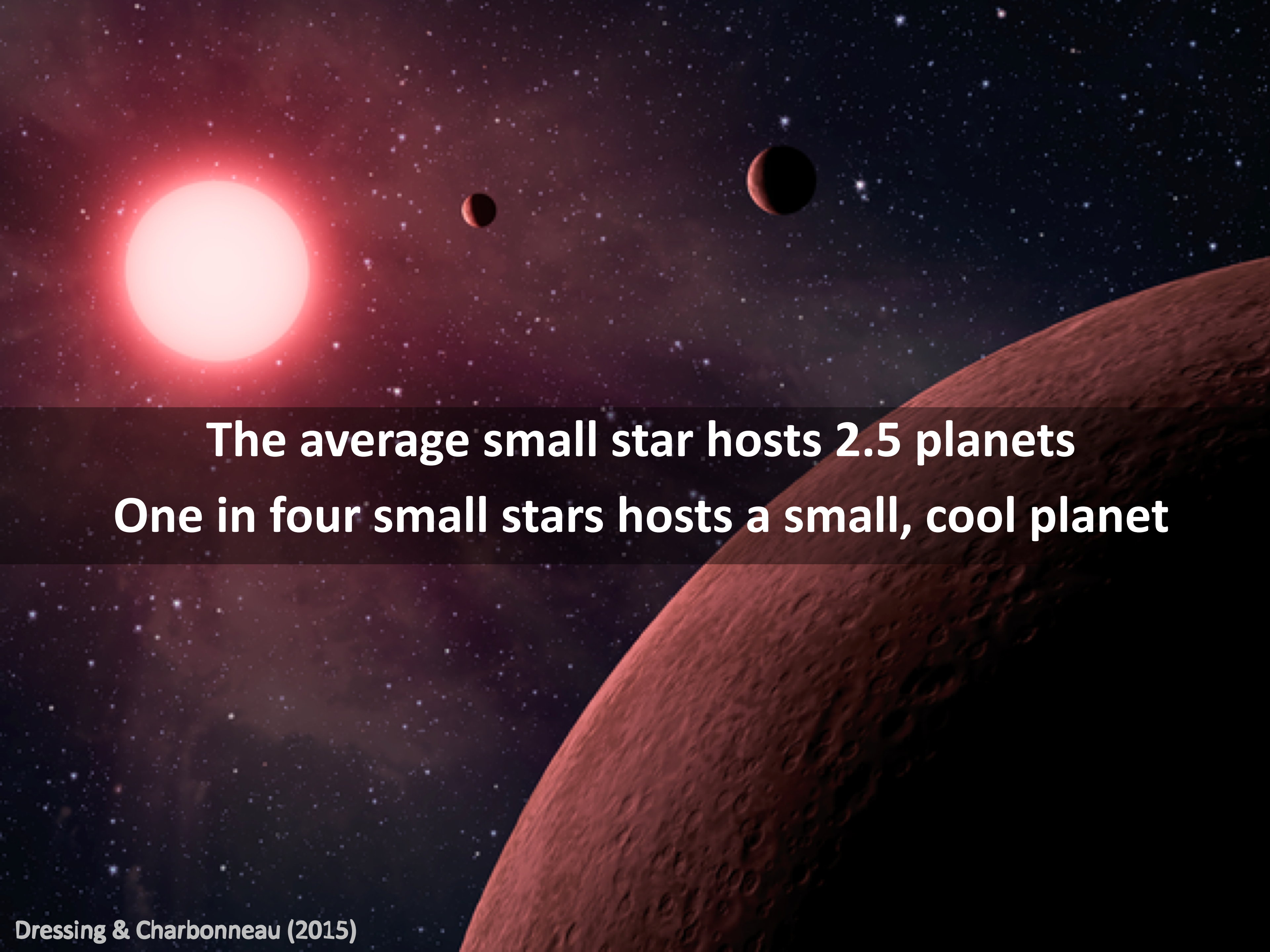


0.41 (+0.29/-0.12) **planets per star**

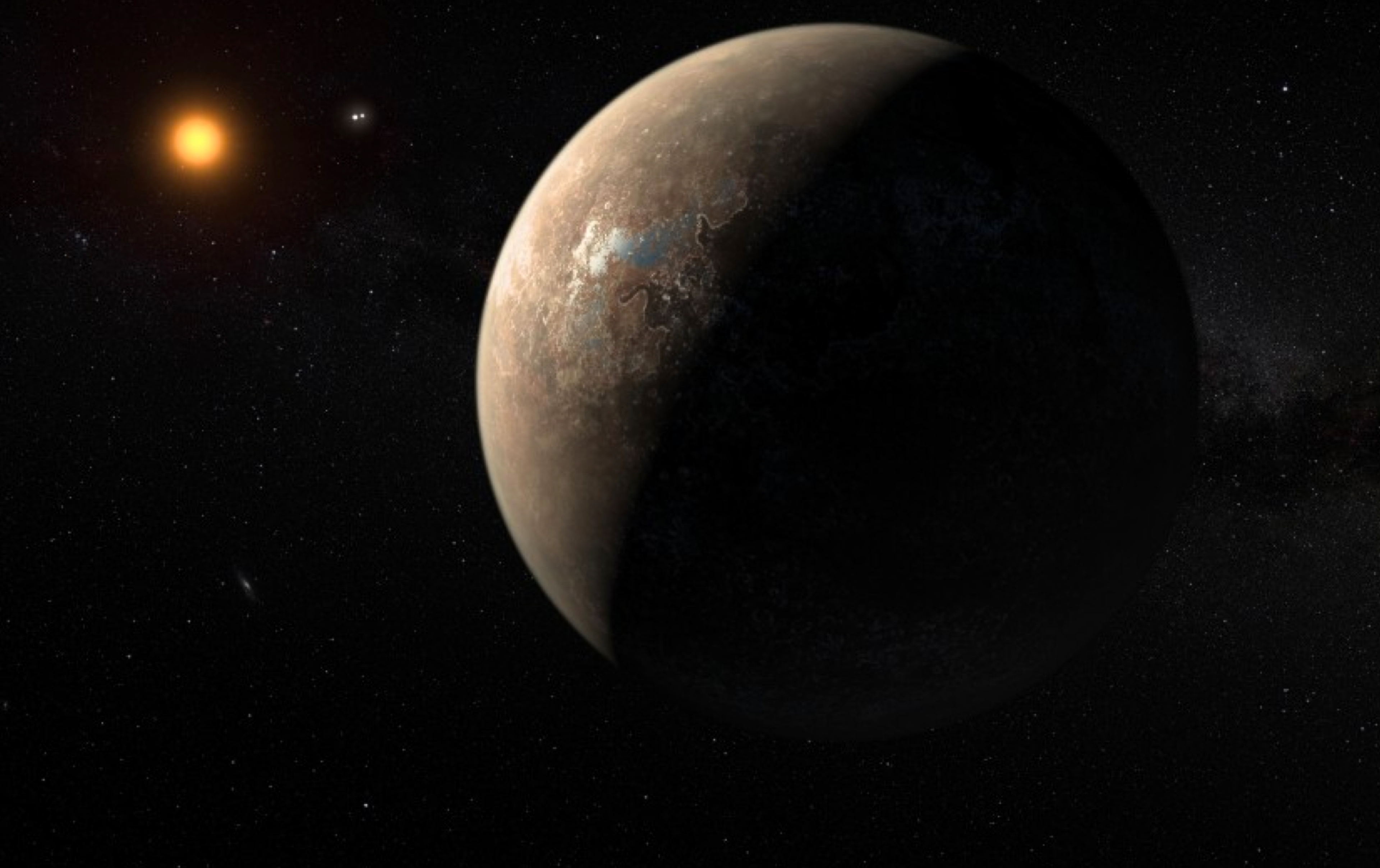
for Rp = 1-1.5 R_{Earth} & P = 237 – 320 days

Hsu et al. 2018

See also Burke et al. 2015, Belikov et al. 2017

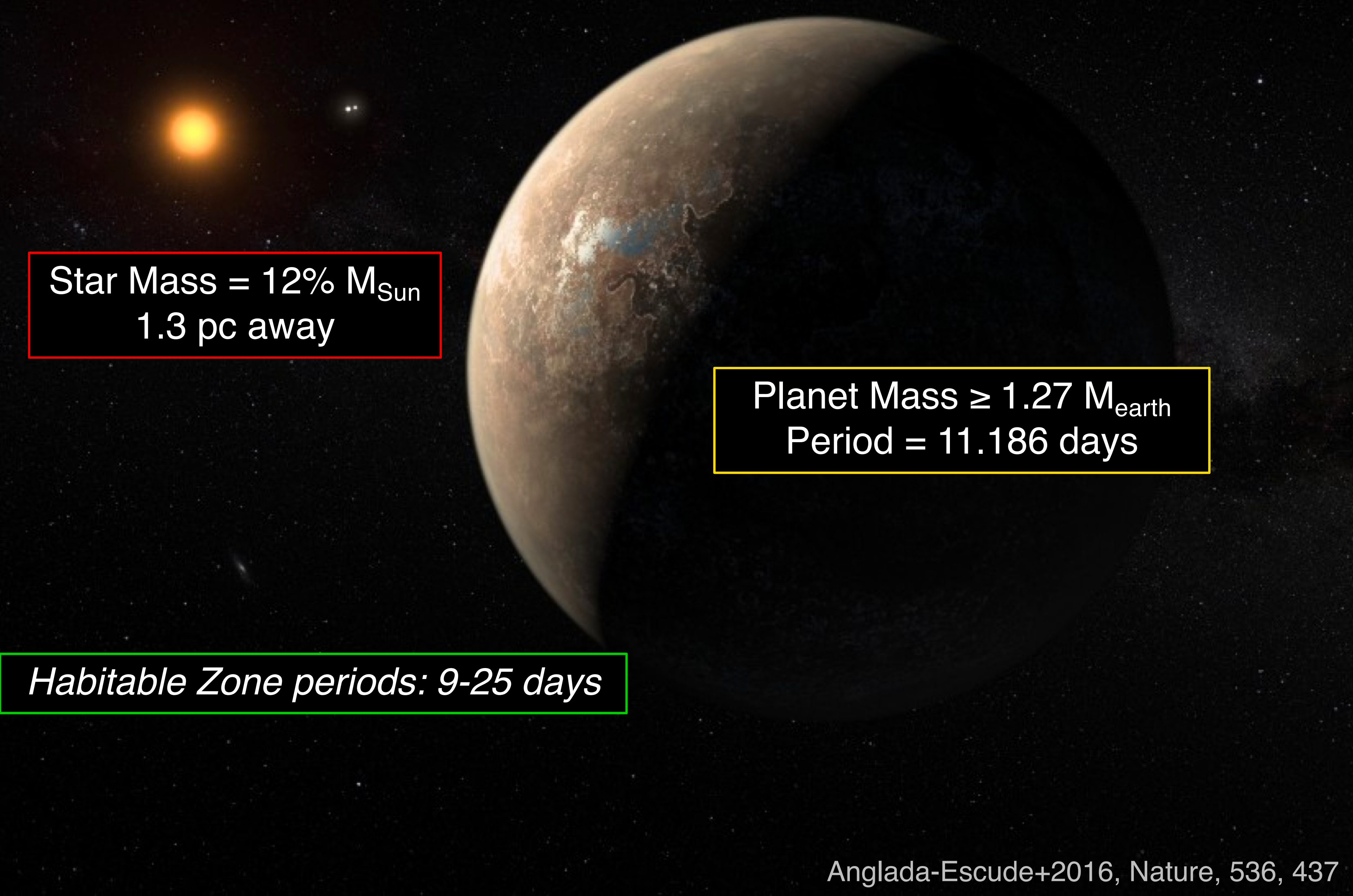

The average small star hosts 2.5 planets
One in four small stars hosts a small, cool planet
Dressing & Charbonneau (2015)

An Artist’s Rendition of Proxima Cen b



Anglada-Escude+2016, Nature, 536, 437

An Artist's Rendition of Proxima Cen b



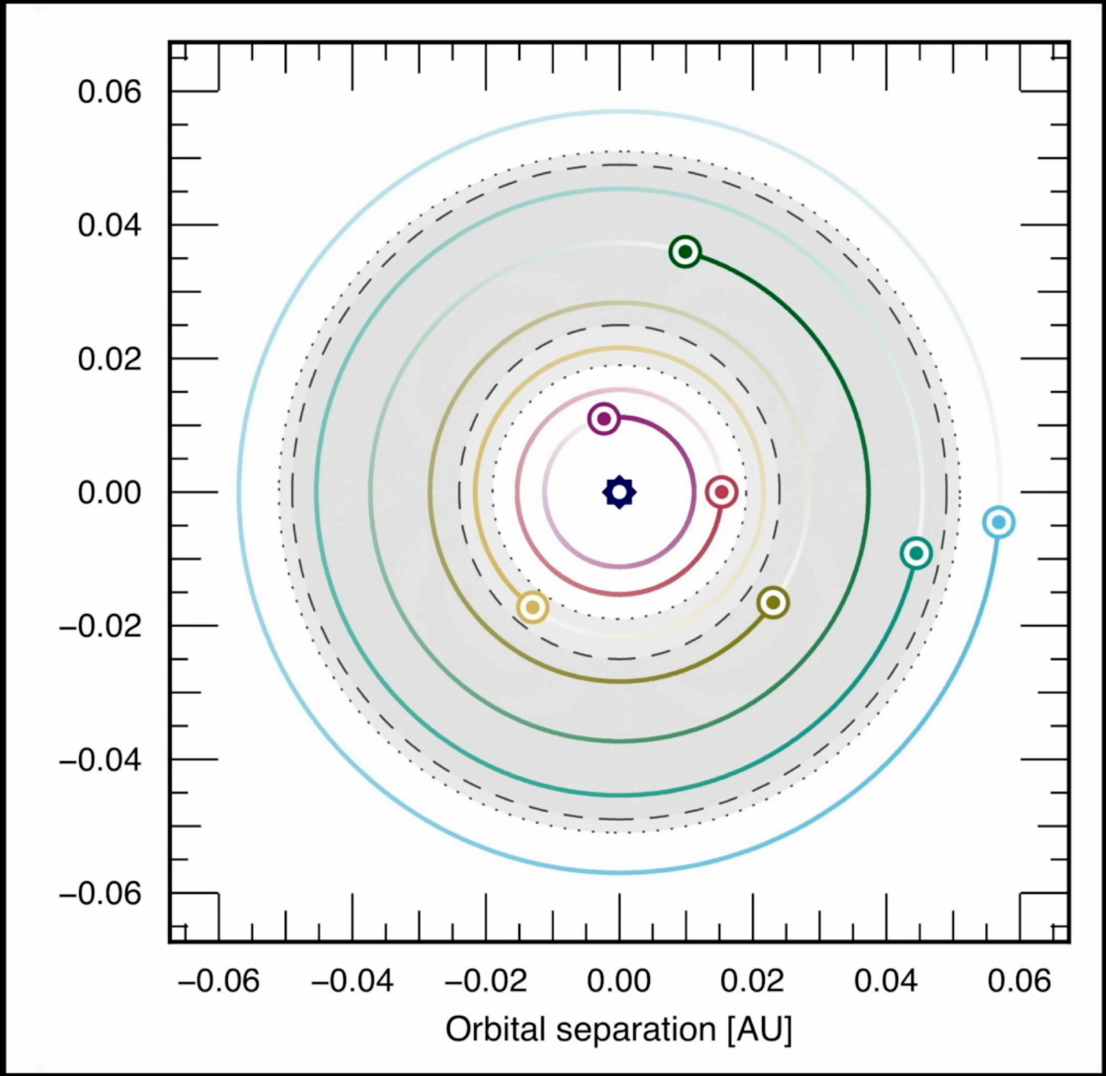
TRAPPIST-1 hosts 7 planets!

Planet b
1.5d
$1.1R_{Earth}$

Planet c
2.4d
$1.1R_{Earth}$

Planet d
4.0d
$0.8R_{Earth}$

Planet e
6.1d
$0.9R_{Earth}$



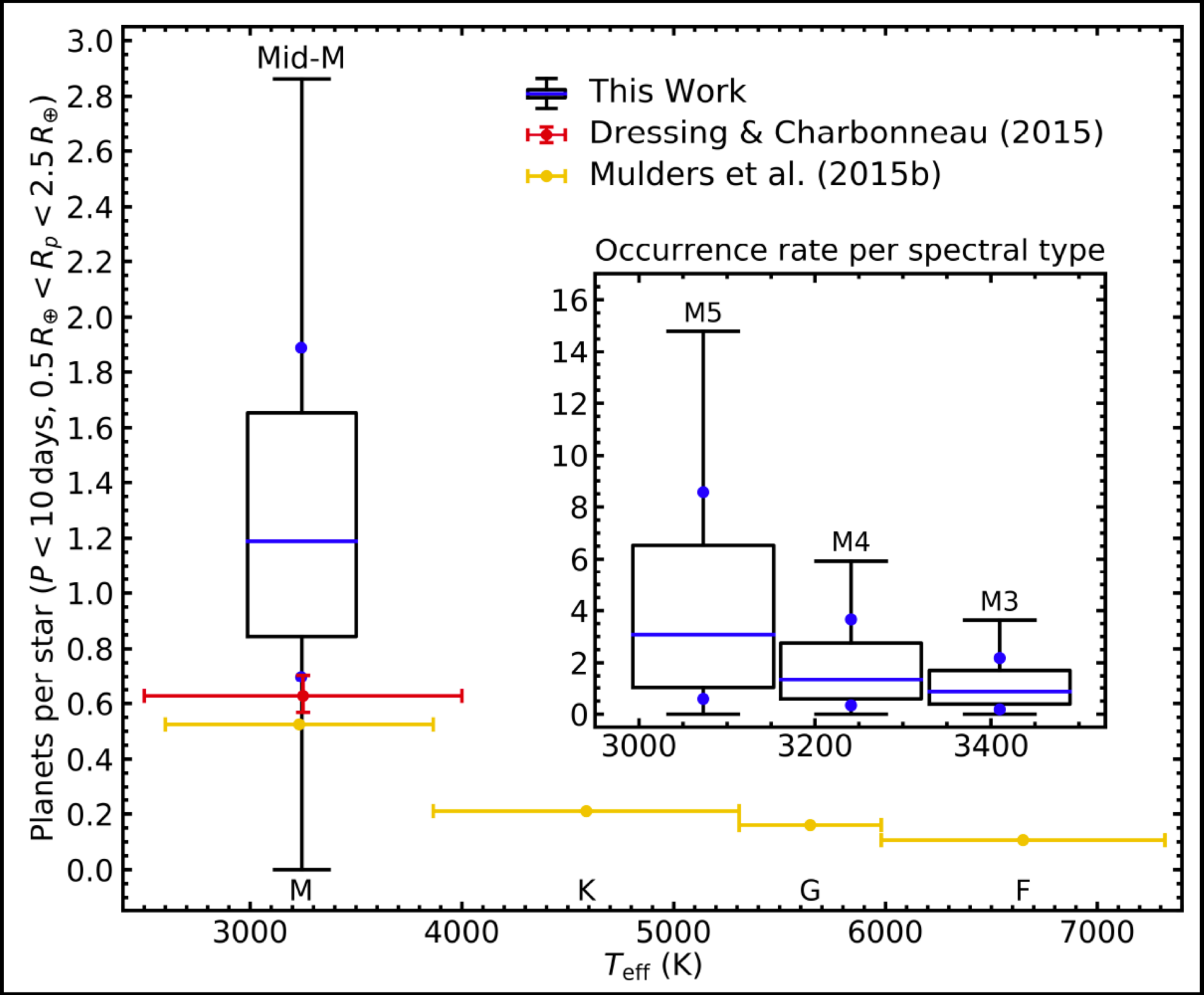
Planet f
9.2d
$1.0R_{Earth}$

Planet g
12.4d
$1.1R_{Earth}$

Planet h
18.8d
$0.8R_{Earth}$

Gillon+2016, 2017

The Smallest Stars Host Even More Close-in Planets

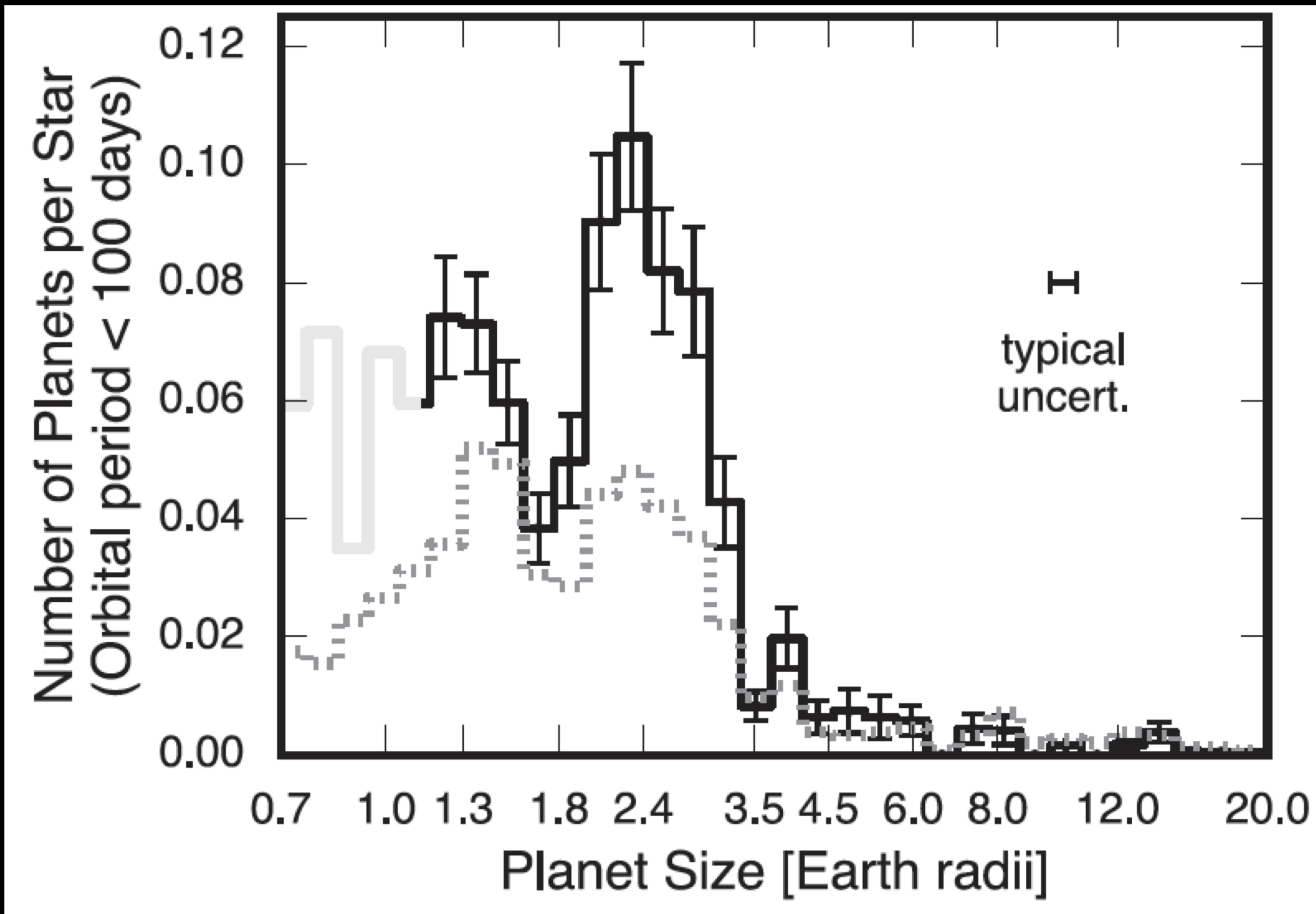


Hardegree-Ullman et al. 2019, arXiv: 1905.05900

How Common are Exo-Earths?

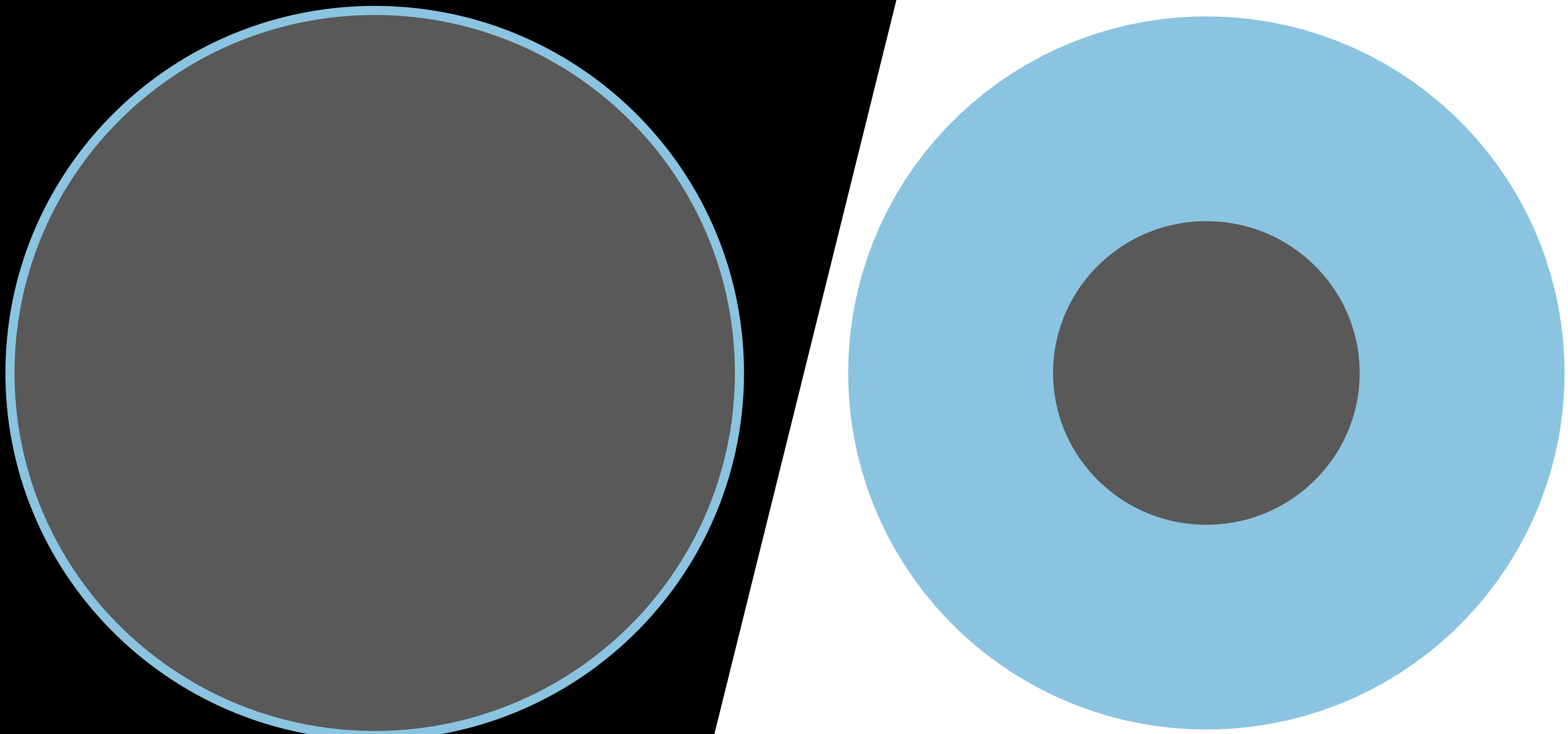
How Common are Exo-Earths?

There is a Gap in the Planet Radius Distribution



Fulton & Petigura 2018

Are small planets rocky?



Or volatile-rich?

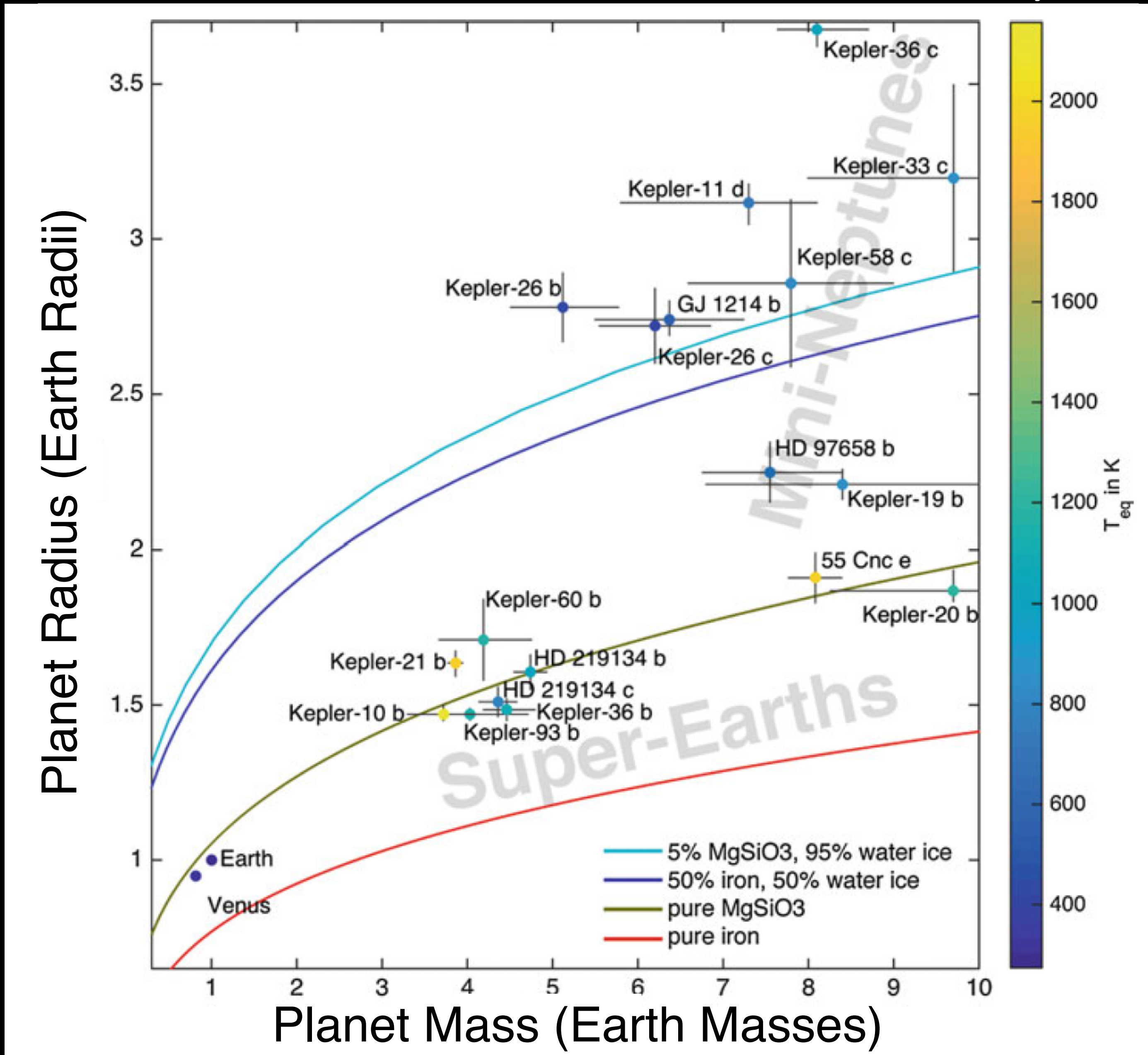
We need to measure densities to find out!

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

Use the radial velocity method!

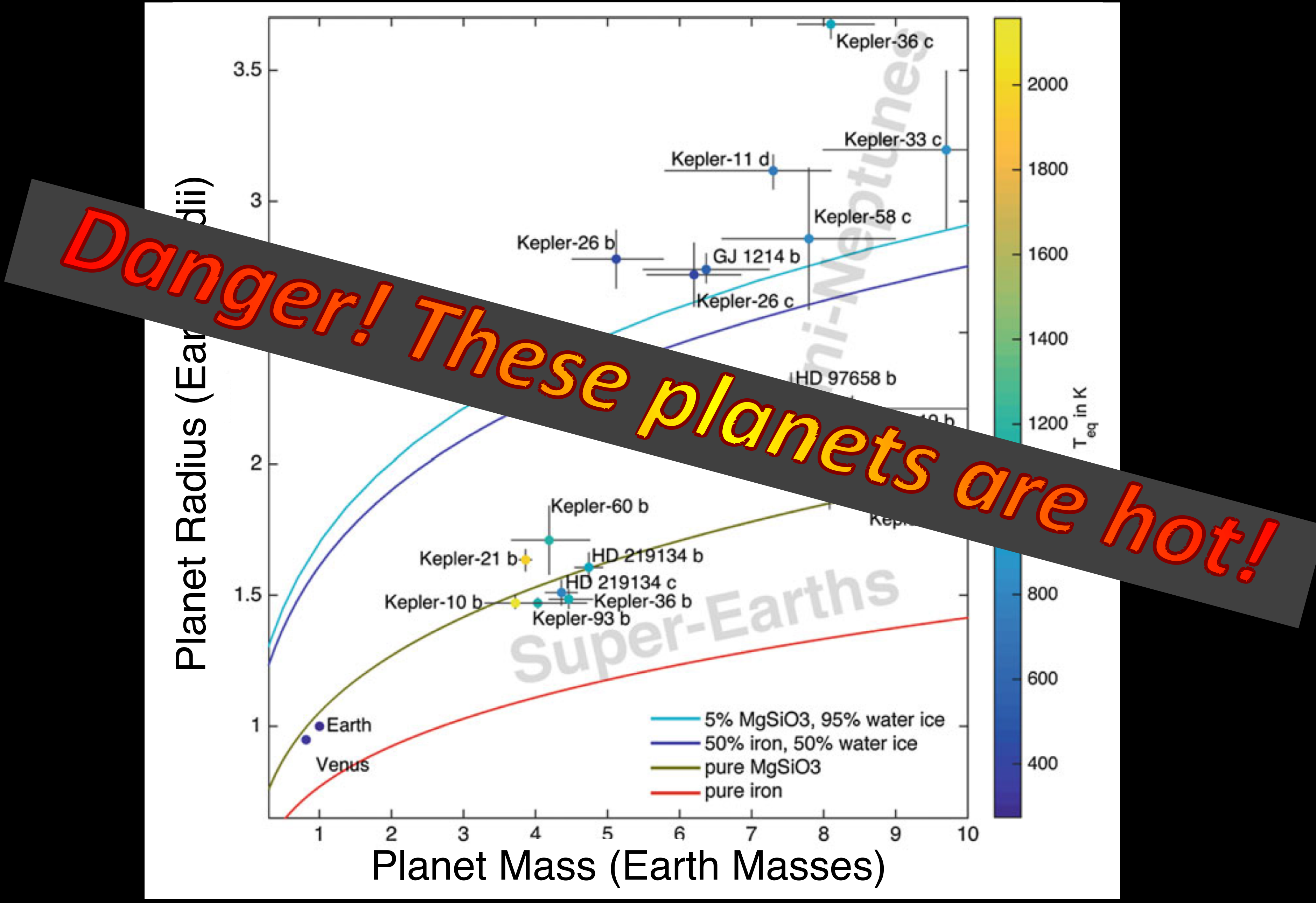
Use the transit method!

Few Small Planets Have Precise Density Estimates

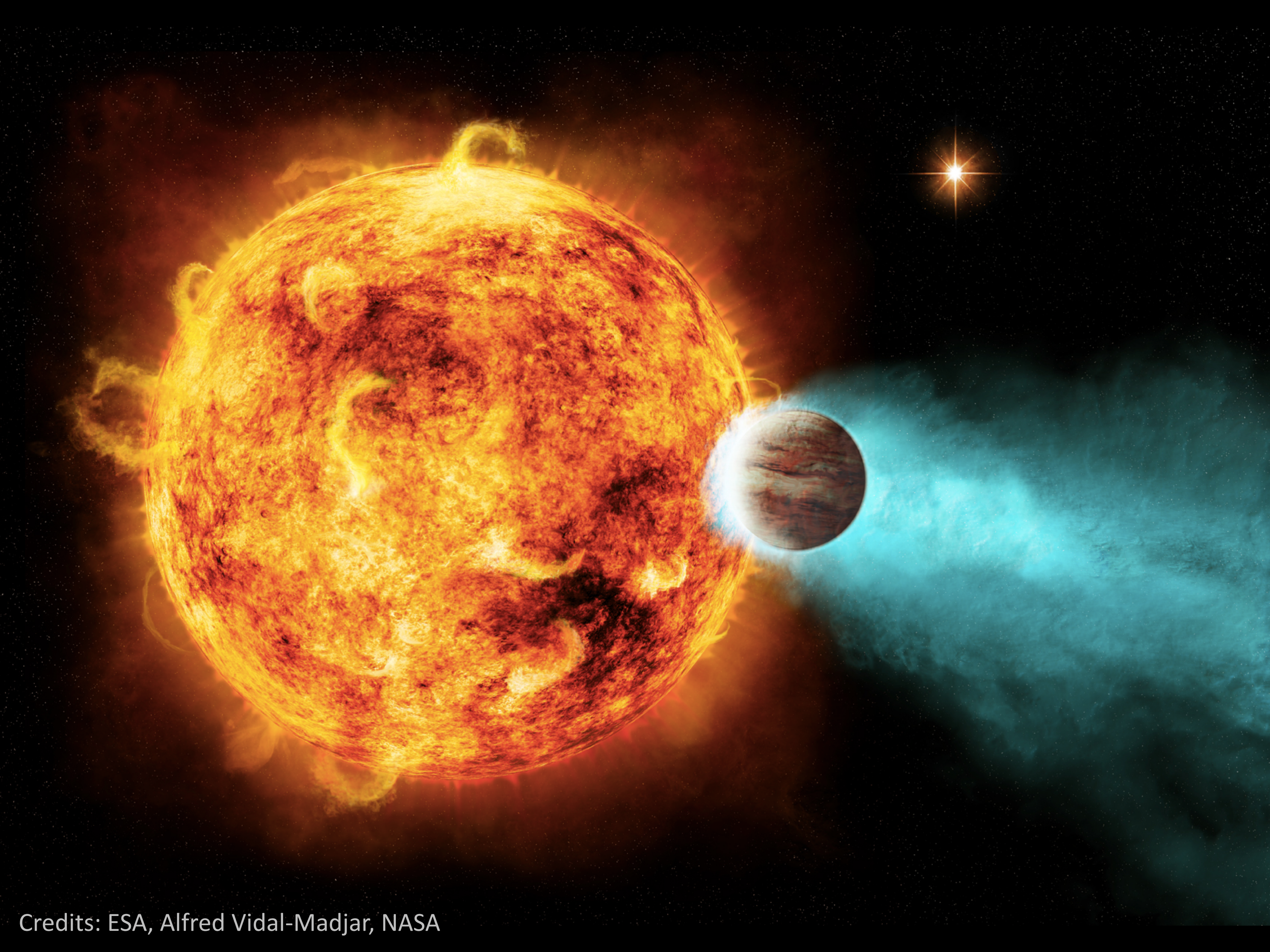


Dorn et al. 2018

Few Small Planets Have Precise Density Estimates

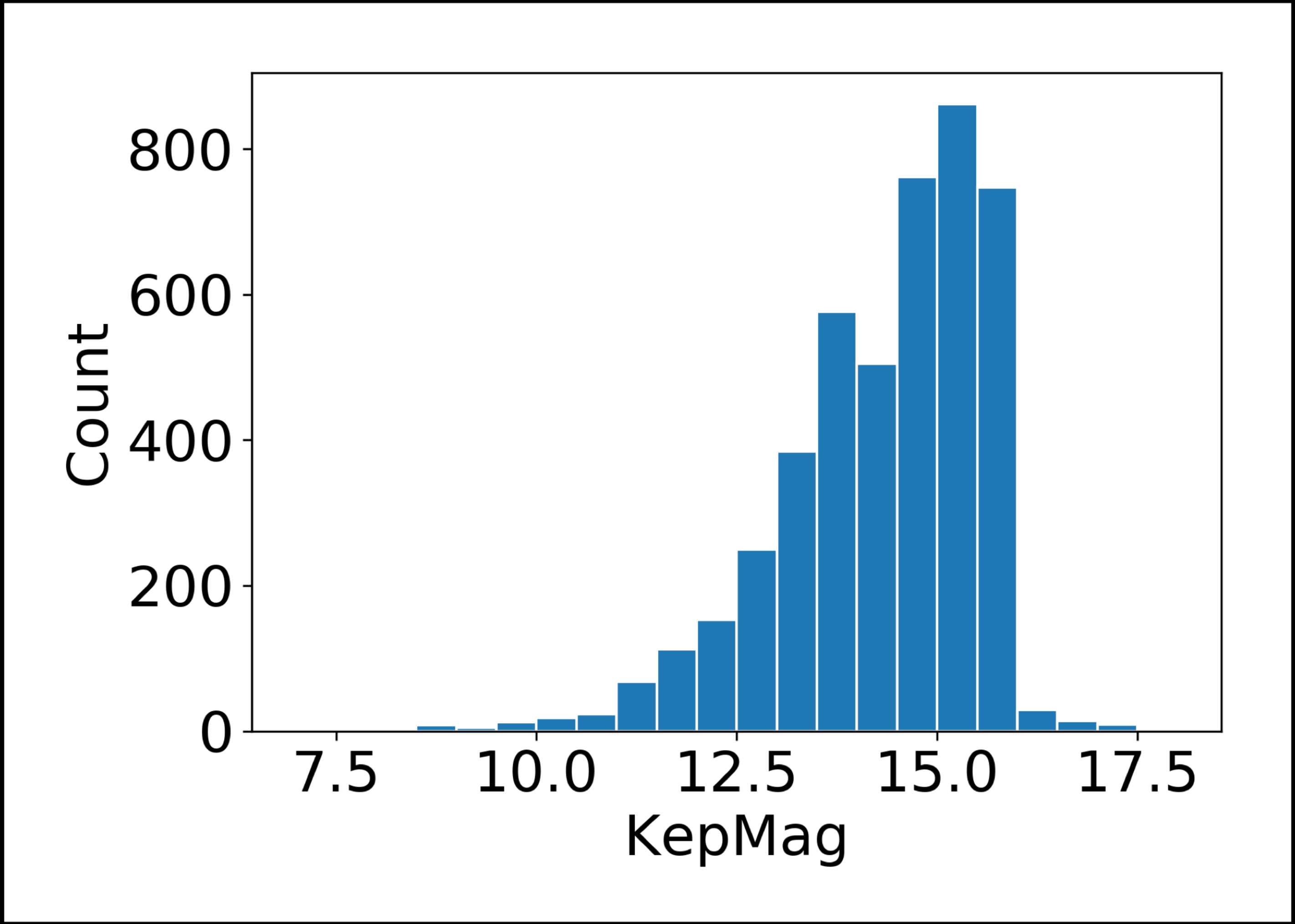


Dorn et al. 2018



Credits: ESA, Alfred Vidal-Madjar, NASA

Most *Kepler* planet candidates orbit stars that are too faint for Keck/HIRES



Data from the NASA Exoplanet Archive

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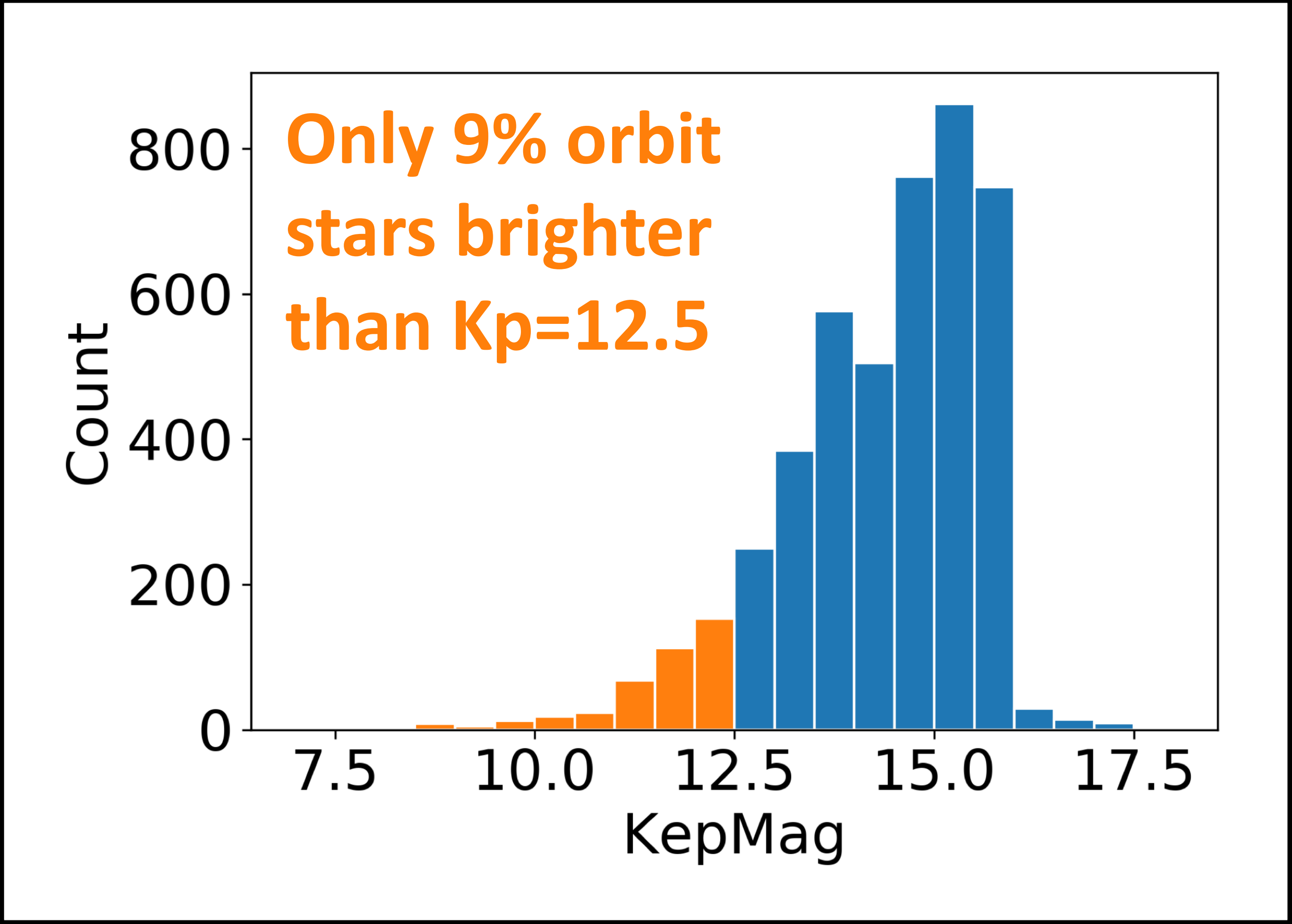
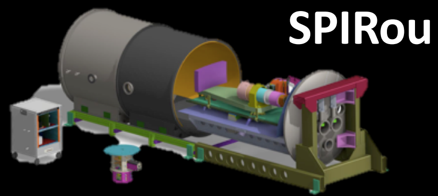


Data from the NASA Exoplanet Archive

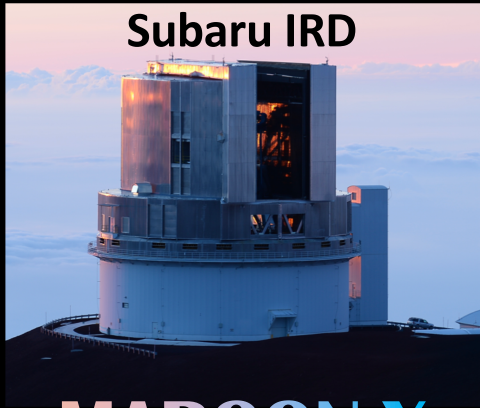
TESS planets are ideal targets for RV mass measurement



iSHELL

MINERVA

espresso



PEPSI

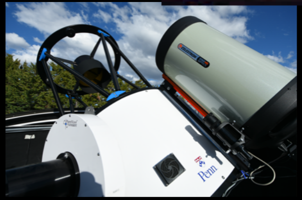
TESS planets are ideal targets for RV mass measurement

MAROON-X

NEID

iLocater

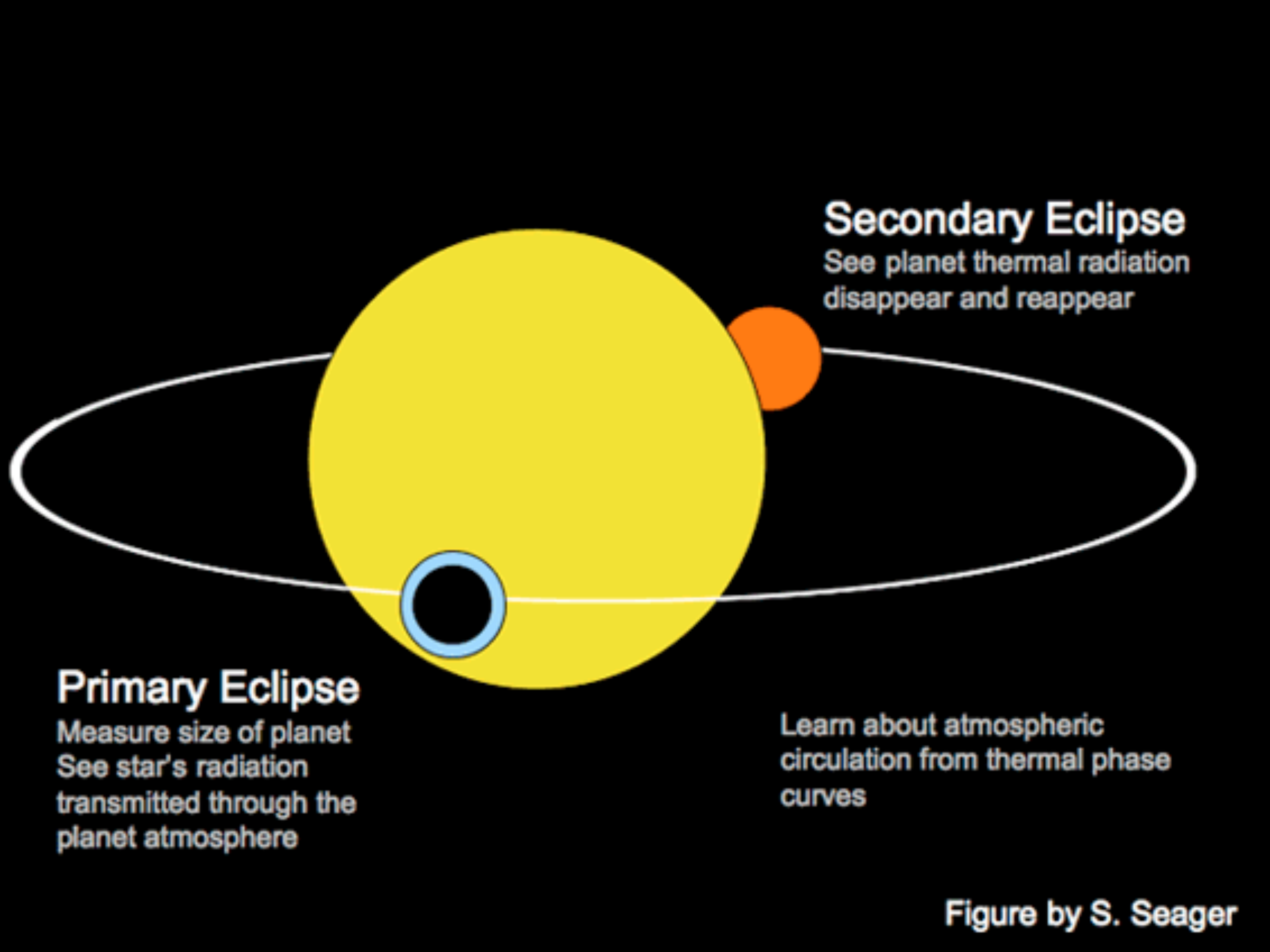
EXPRES
Search for 100 Earths


MINERVA Red

Planetary Search HARPS

LCO NRES

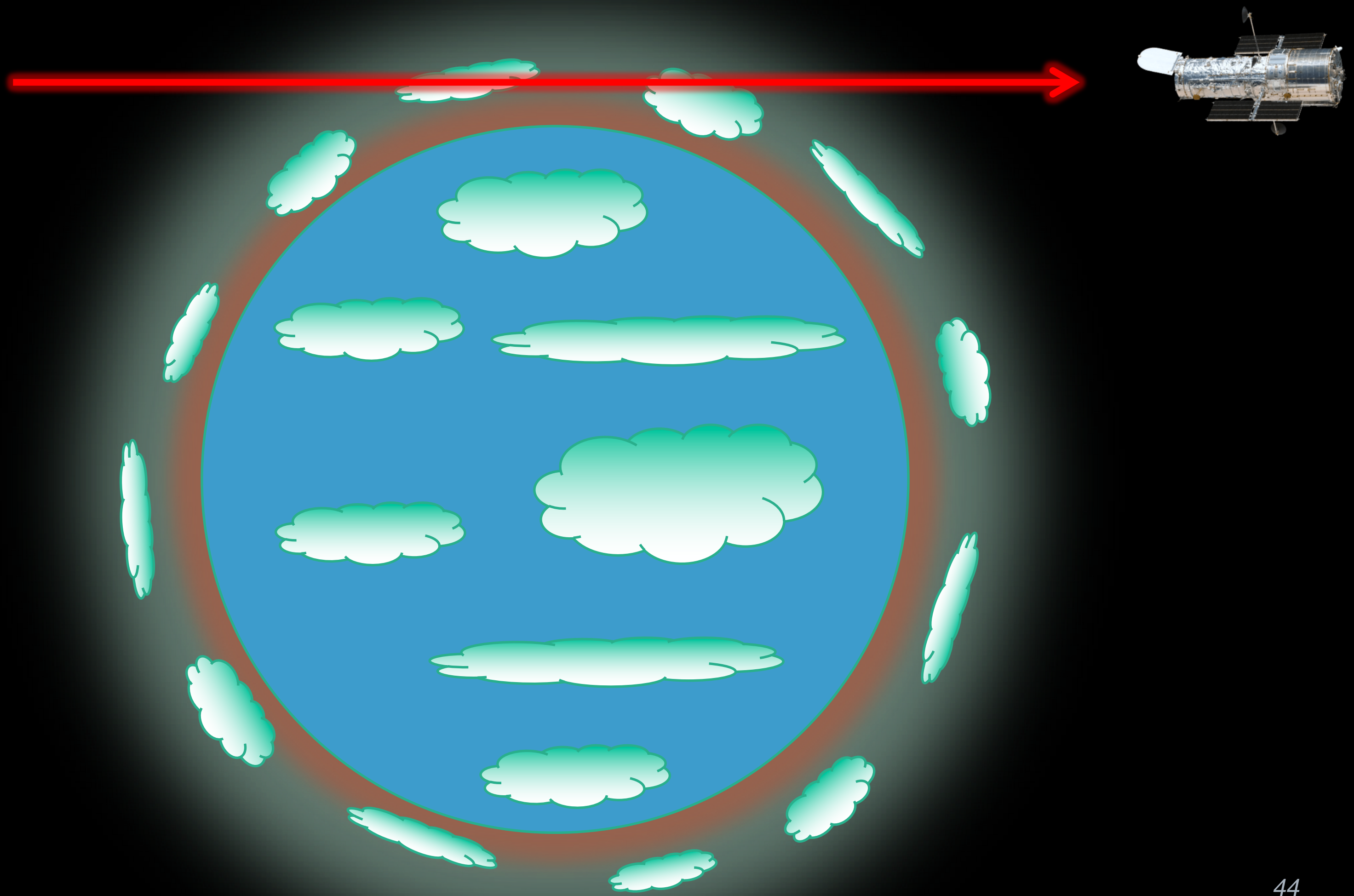
Characterization


Secondary Eclipse
See planet thermal radiation disappear and reappear
Primary Eclipse
Measure size of planet
See star's radiation transmitted through the planet atmosphere
Learn about atmospheric circulation from thermal phase curves
Figure by S. Seager

Challenges of transmission spectroscopy

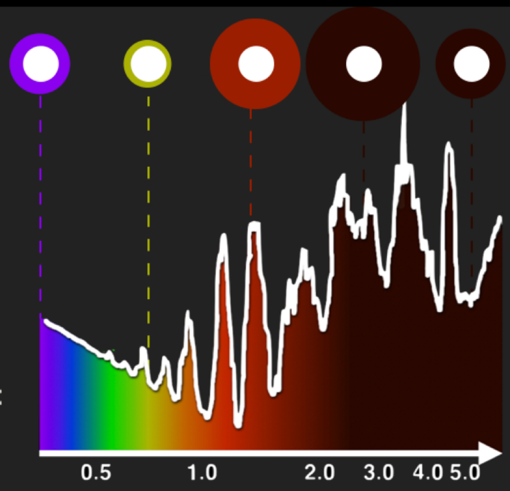
Transit spectroscopy probes upper atmosphere

Sensitive to clouds & hazes



TRANSIT TRANSMISSION SPECTRA

$$\alpha_\lambda = \left(\frac{R_p + z_\lambda}{R_*}\right)^2 =$$



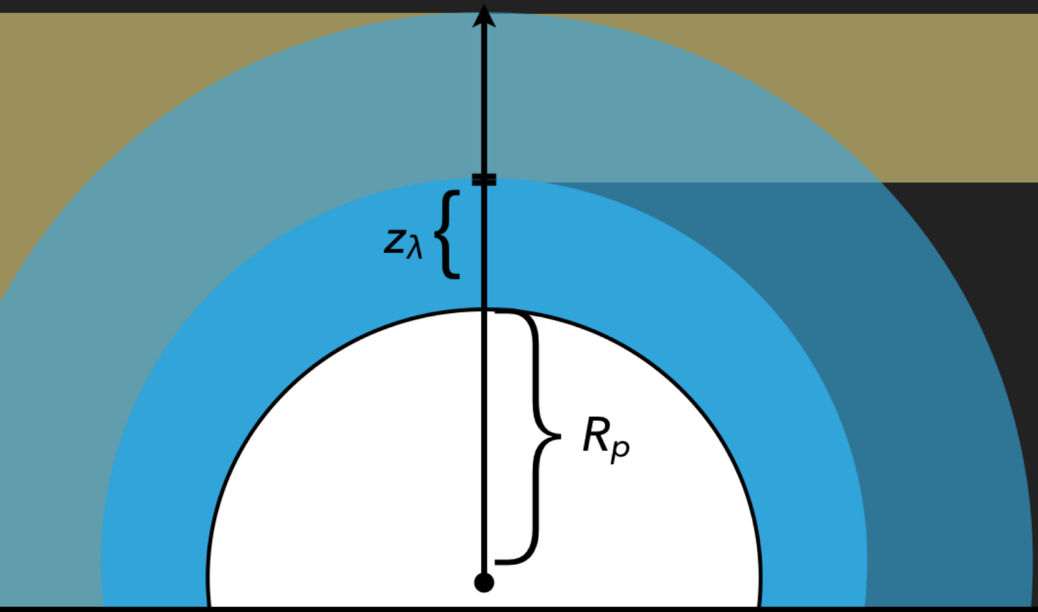
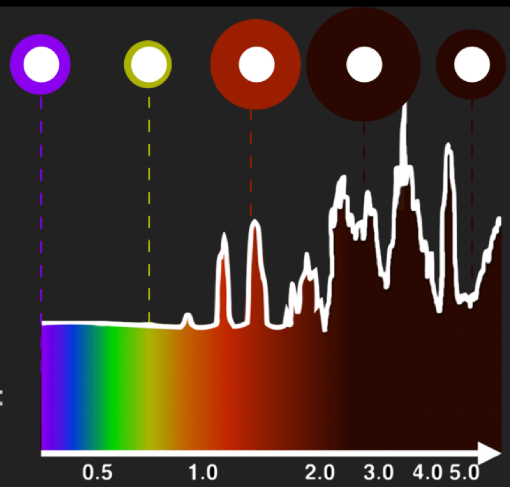


Image Credit: Batalha, NE

TRANSIT TRANSMISSION SPECTRA & CLOUDS

$$\alpha_\lambda = \left(\frac{R_p + z_\lambda}{R_*}\right)^2 =$$



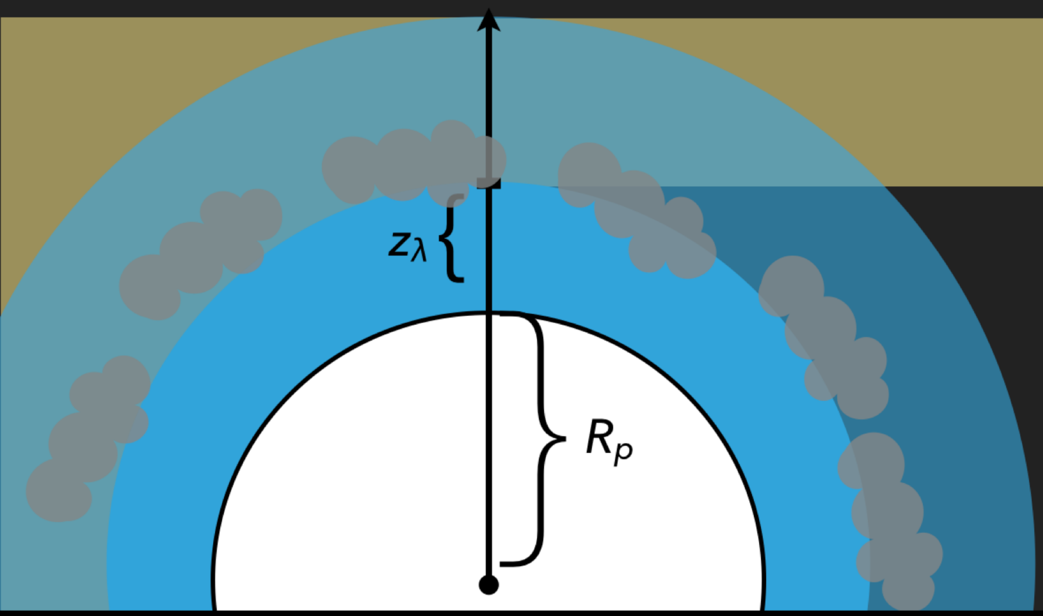
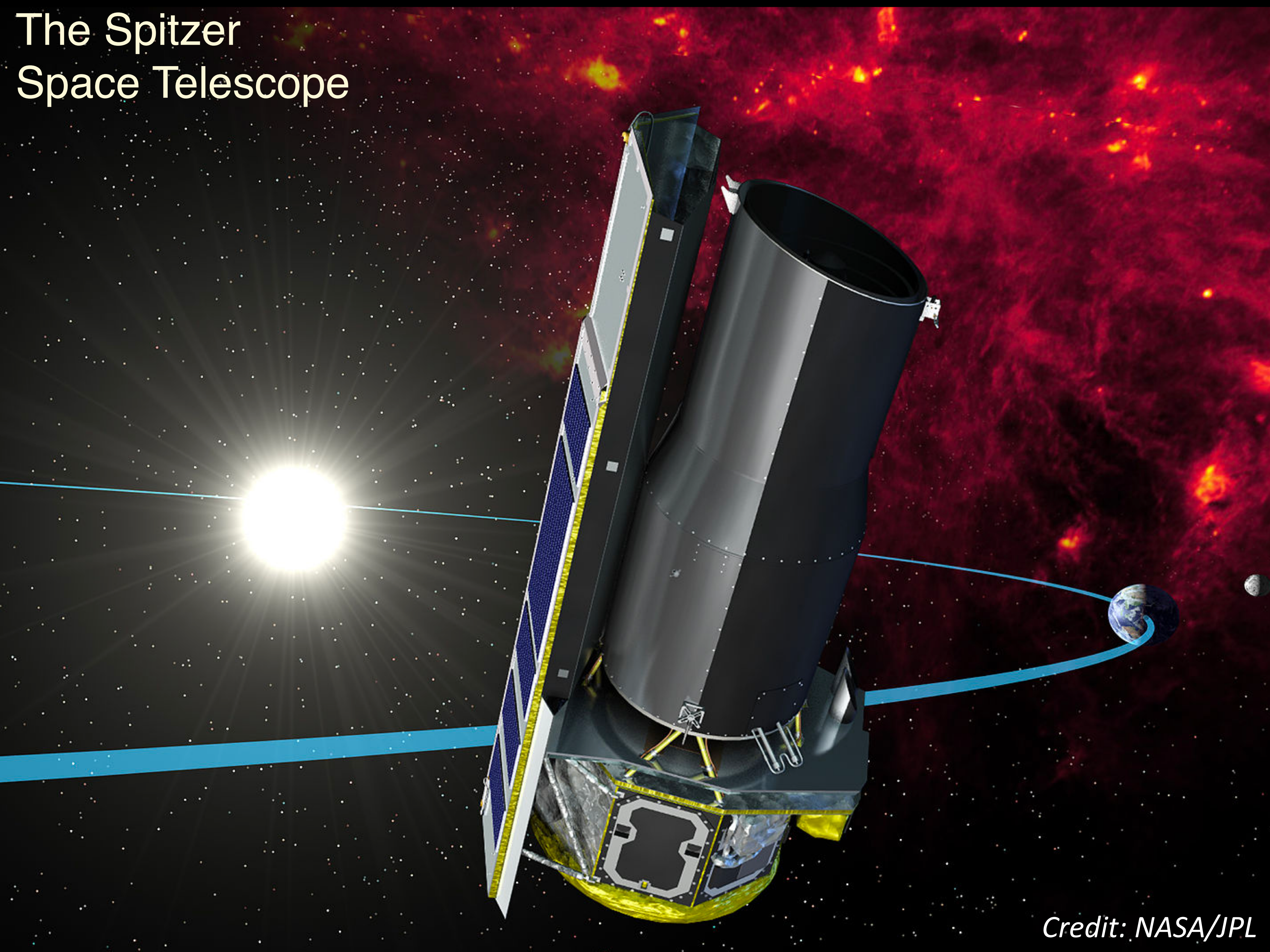
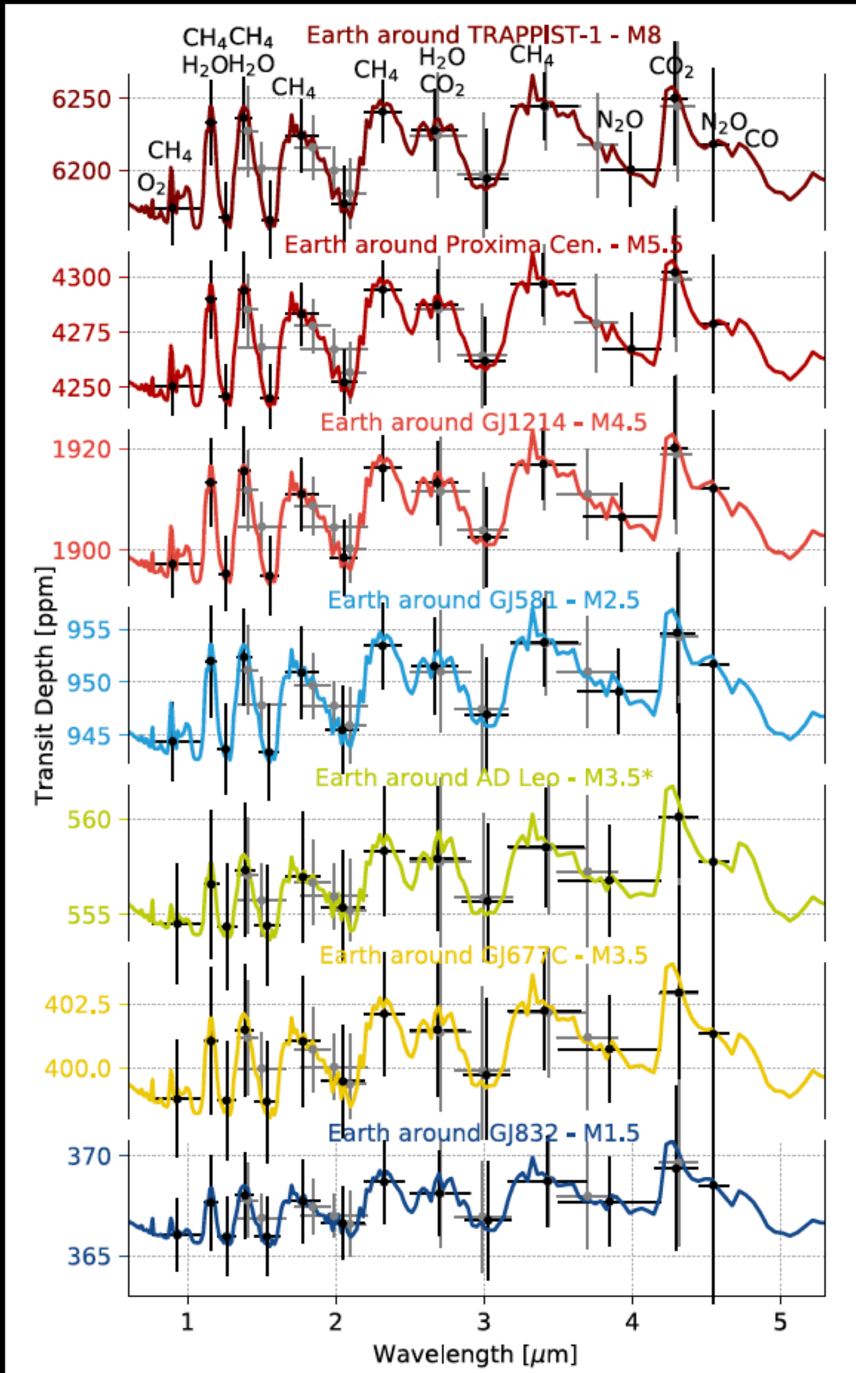


Image Credit: Batalha, NE

The Hubble Space Telescope


The Spitzer
Space Telescope
Credit: NASA/JPL

Transit spectroscopy of large planets with James Webb Space Telescope



Simulating JWST Observations of Potentially Habitable Planets Orbiting Nearby M Dwarfs

Number of Transits Needed for Detection

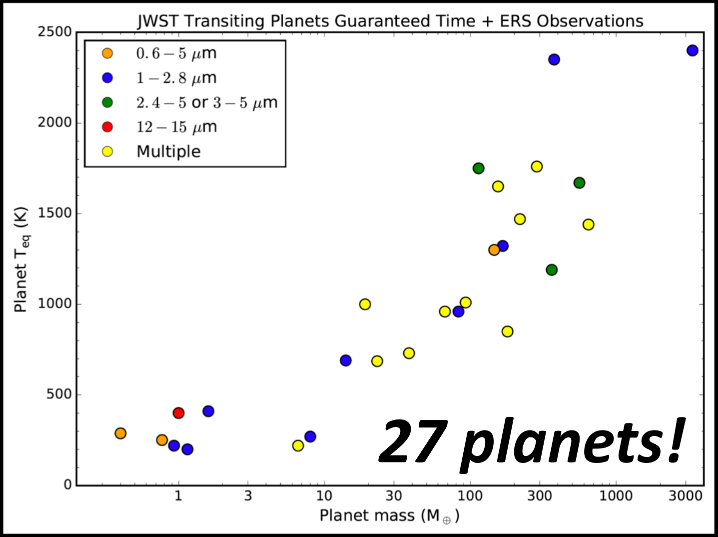
Host star	H_2O	CH_4	CO_2	O_3
GJ 436	31	10	30	209
GJ 1132	14	4	13	142
TRAPPIST-1	12	3	10	172
GJ 1214	17	4	15	171
LHS 1140	25	5	21	354
GJ 3470	91	17	80	792
NLTT 41135	47	9	41	711
K2-18	93	18	80	824
LHS 6343	167	33	140	1332
Kepler-42	168	30	106	2880
K2-25	233	42	184	5887

Wunderlich et al. (2019)

The Exoplanet Community Has Developed a Plan to Optimize JWST Observations of Transiting Planets

Table 1: **Approved GTO and ERS Transiting Planet Programs**

ID	Title and Science Instrument	Team Lead	Hours
1177	MIRI observations of transiting exoplanets	T. Greene	75
1185	Transit Spectroscopy of Mature Planets (NIRCam)	T. Greene	140
1201	NIRISS Exploration of the Atmospheric Diversity of Transiting Exoplanets	D. Lafrenière	201
1224	Transiting Exoplanet Characterization with JWST/NIRSPEC	S. Birkmann	50
1274	Extrasolar Planet Science with *JWST* (NIRCam)	J. Lunine	74
1279	Thermal emission from Trappist1-b (MIRI)	P.-O. Lagage	25
1280	MIRI Transiting Observation of WASP-107b	P.-O. Lagage	11
1281	MIRI and NIRSPEC Transit Observations of HAT-P-12 b	P.-O. Lagage	32
1312	Transit and Eclipse Spectroscopy of a Warm Neptune (NIRISS+NS+MIRI)	N. Lewis	36
1331	Transit Spectroscopy of TRAPPIST-1e (NIRSpec)	N. Lewis	22
1353	Transit and Eclipse Spectroscopy of a Hot Jupiter (NIRISS+NS+MIRI)	N. Lewis	72
1366	The Transiting Exoplanet Community ERS Program (all SIs)	N. Batalha	78
	TOTAL		816



Characterizing Transiting Exoplanets with JWST Guaranteed Time and ERS Observations
(Greene et al. 2019)

Engaging Citizen Scientists to Keep Transit Times Fresh and Ensure the Efficient Use of Transiting Exoplanet Characterization Missions
(Zellem et al. 2019)

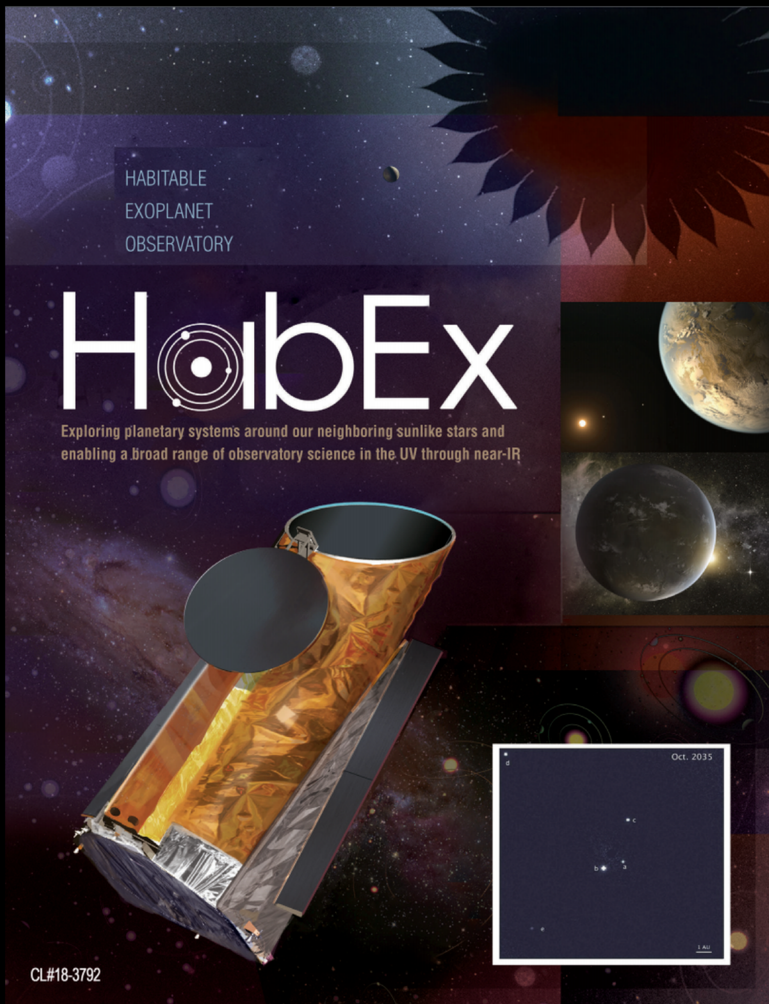
Probing Earth-like atmospheres

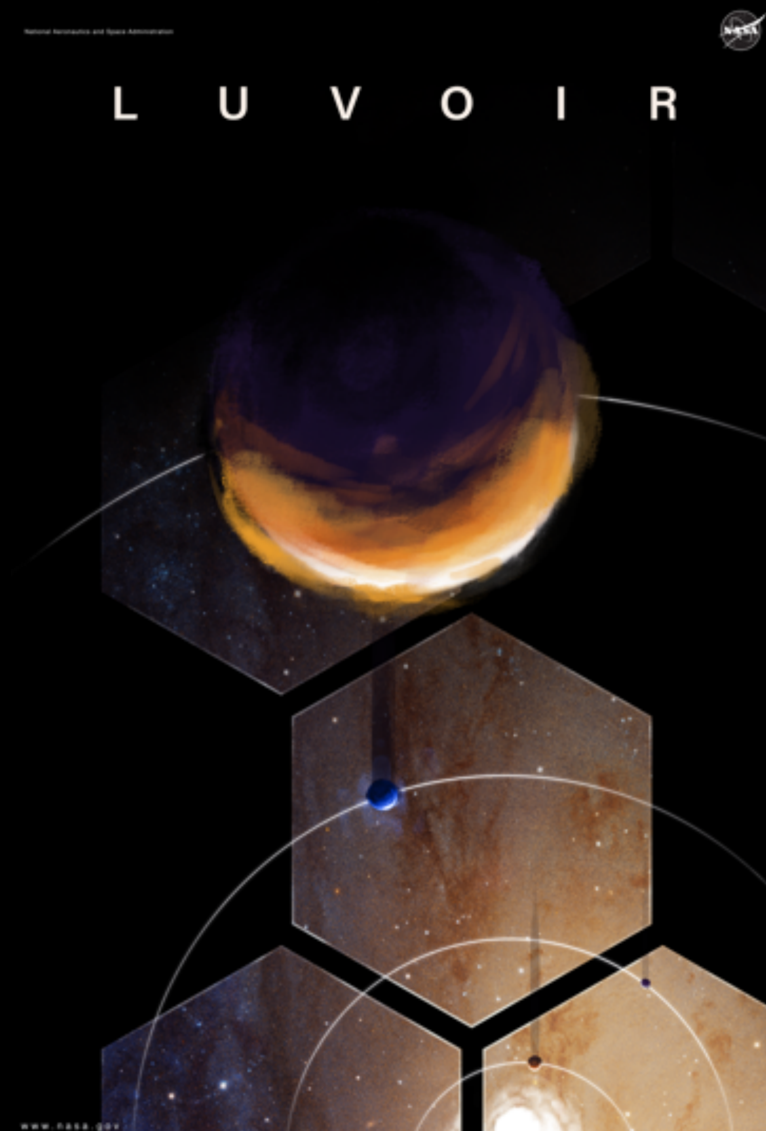
Four ways to make transit depths too small

- Larger star / smaller planet
- Less puffy atmosphere (colder / heavier)
- Clouds or hazes
- Refraction

Spectroscopy of Earth-like planets around Sun-like stars needs a different technique …

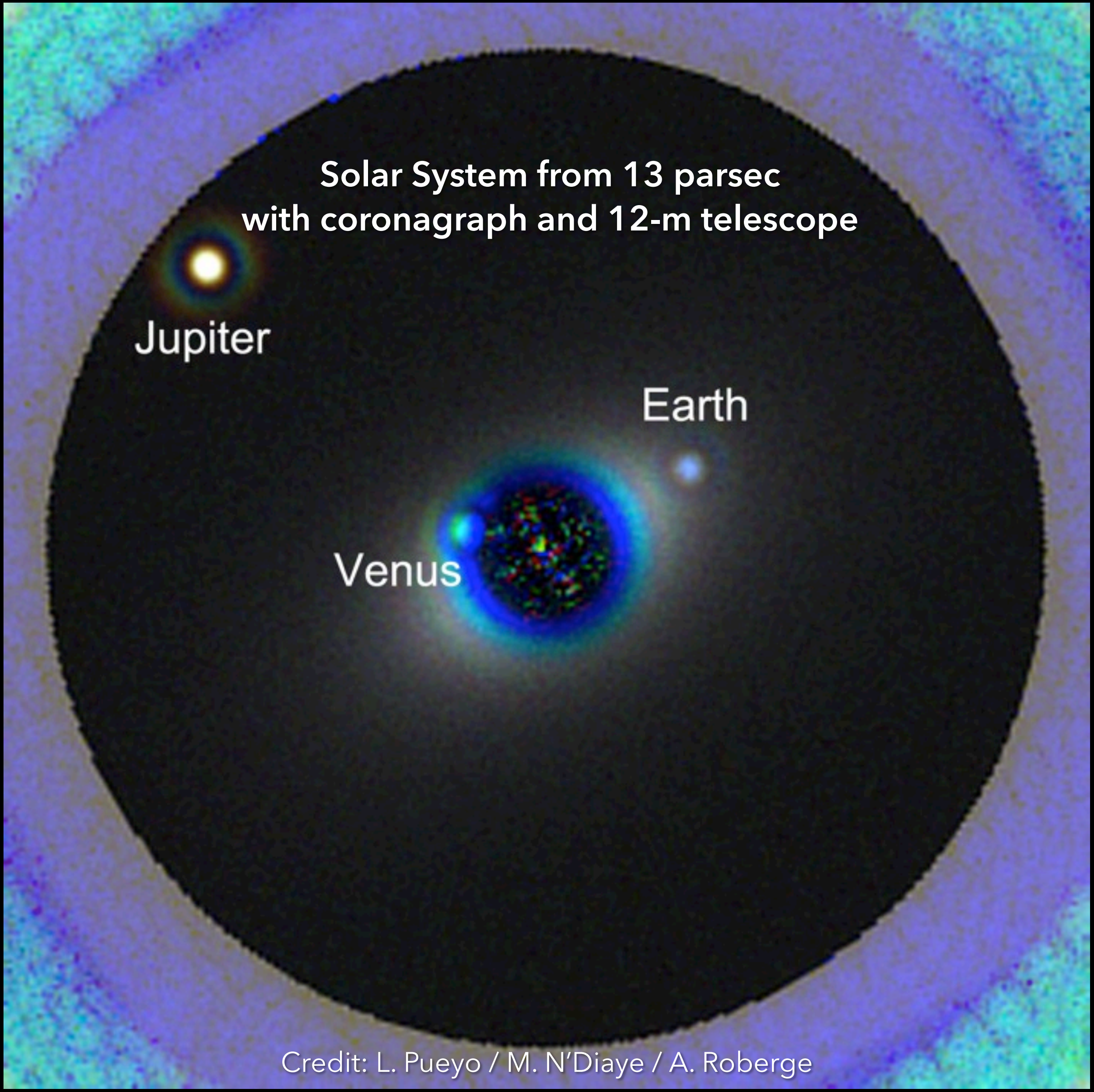
Collect photons from a planet alone with little or no starlight blended in = direct observations


HABITABLE
EXOPLANET
OBSERVATORY
HabEx
Exploring planetary systems around our neighboring sunlike stars and enabling a broad range of observatory science in the UV through near-IR
Oct. 2035
d
c
b
a
1 AU
CL#18-3792


L U V O I R
www.nasa.gov

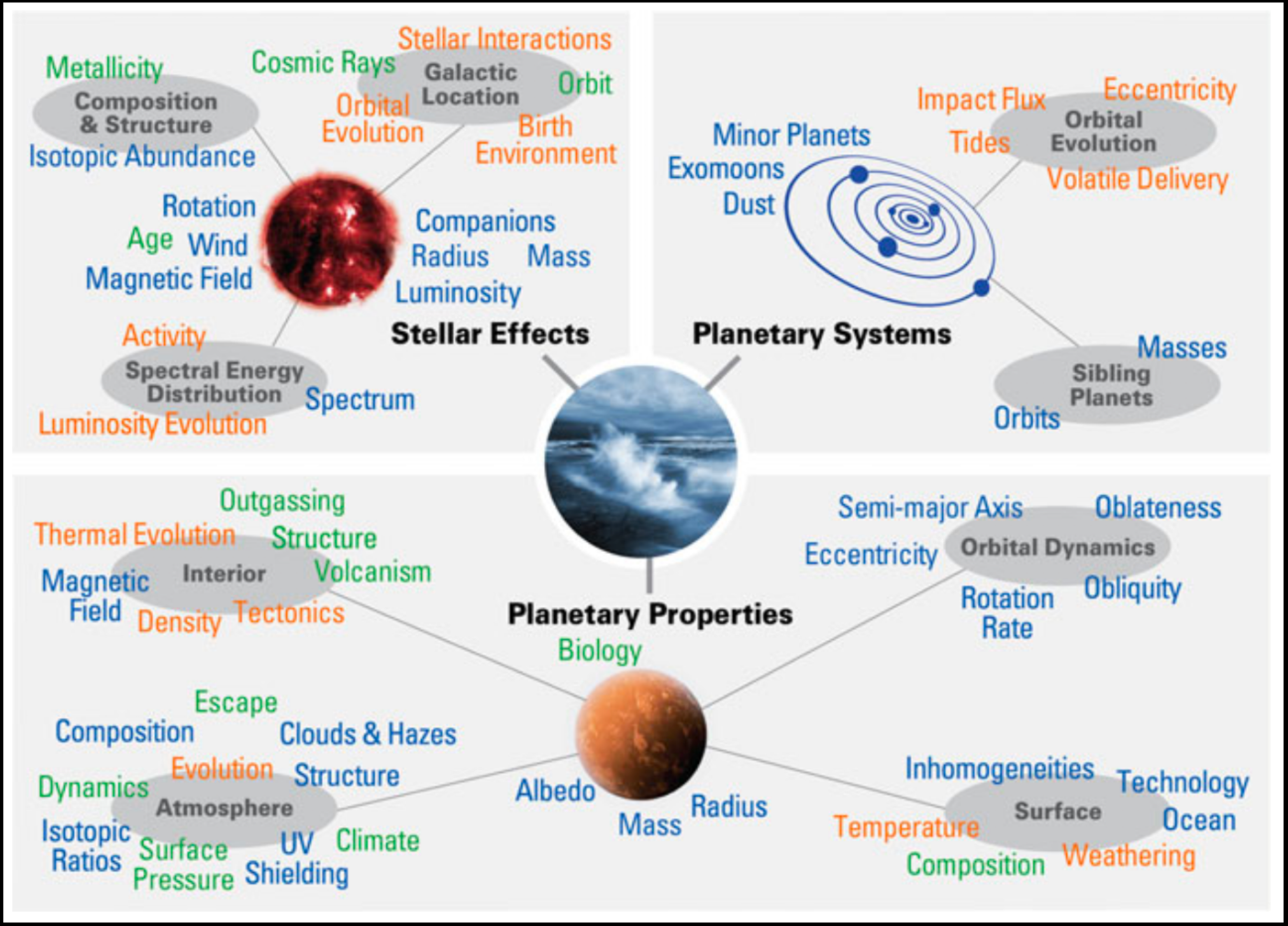

Cosmic Origins
&
the Ultra-Faint
Universe
Exotic Worlds
The Search
for Life
Our Dynamic
Solar System
LUVOIR

Imaging Earthlike Planets



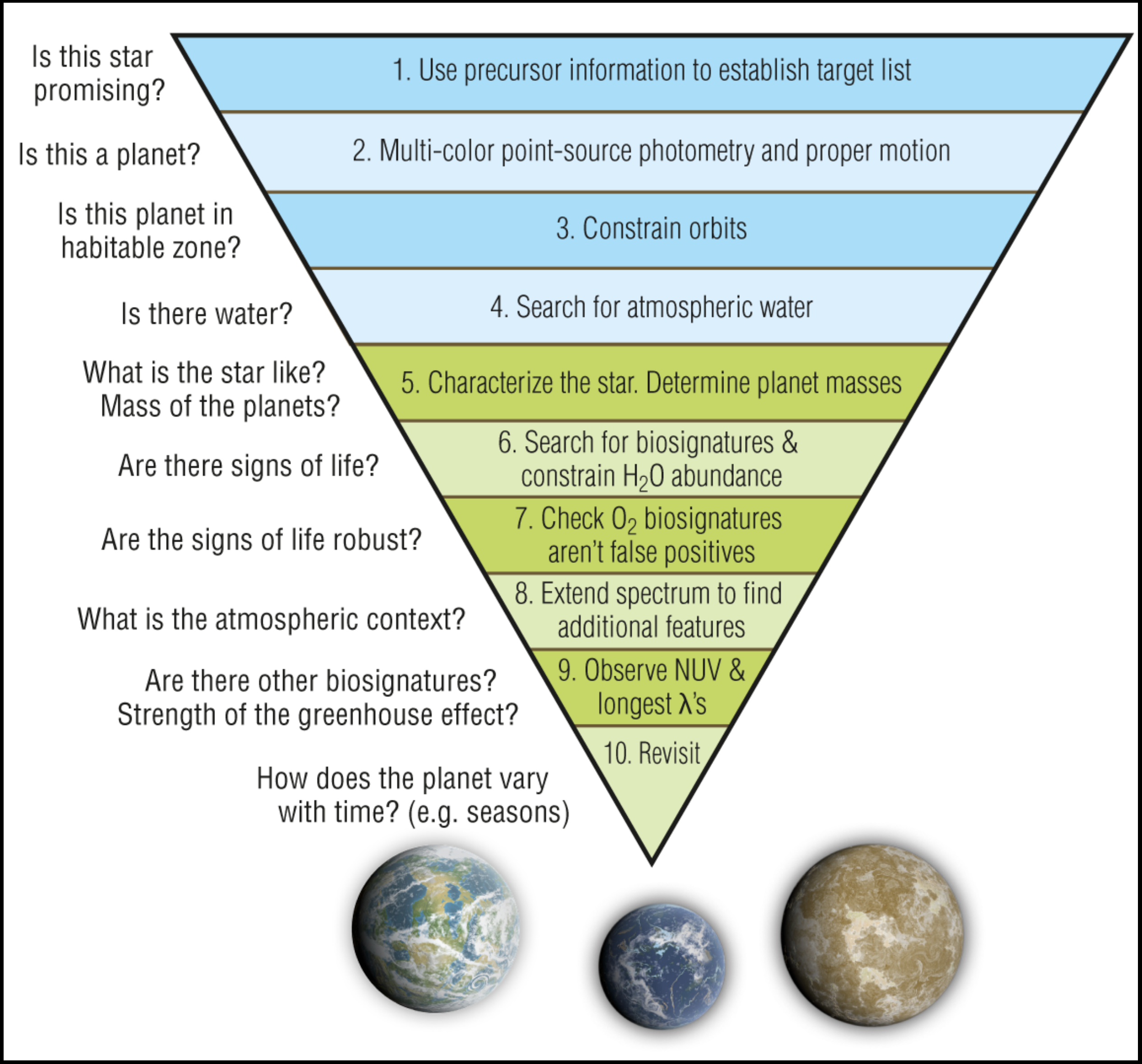
Searching for Signs of Life

Habitability is Complicated



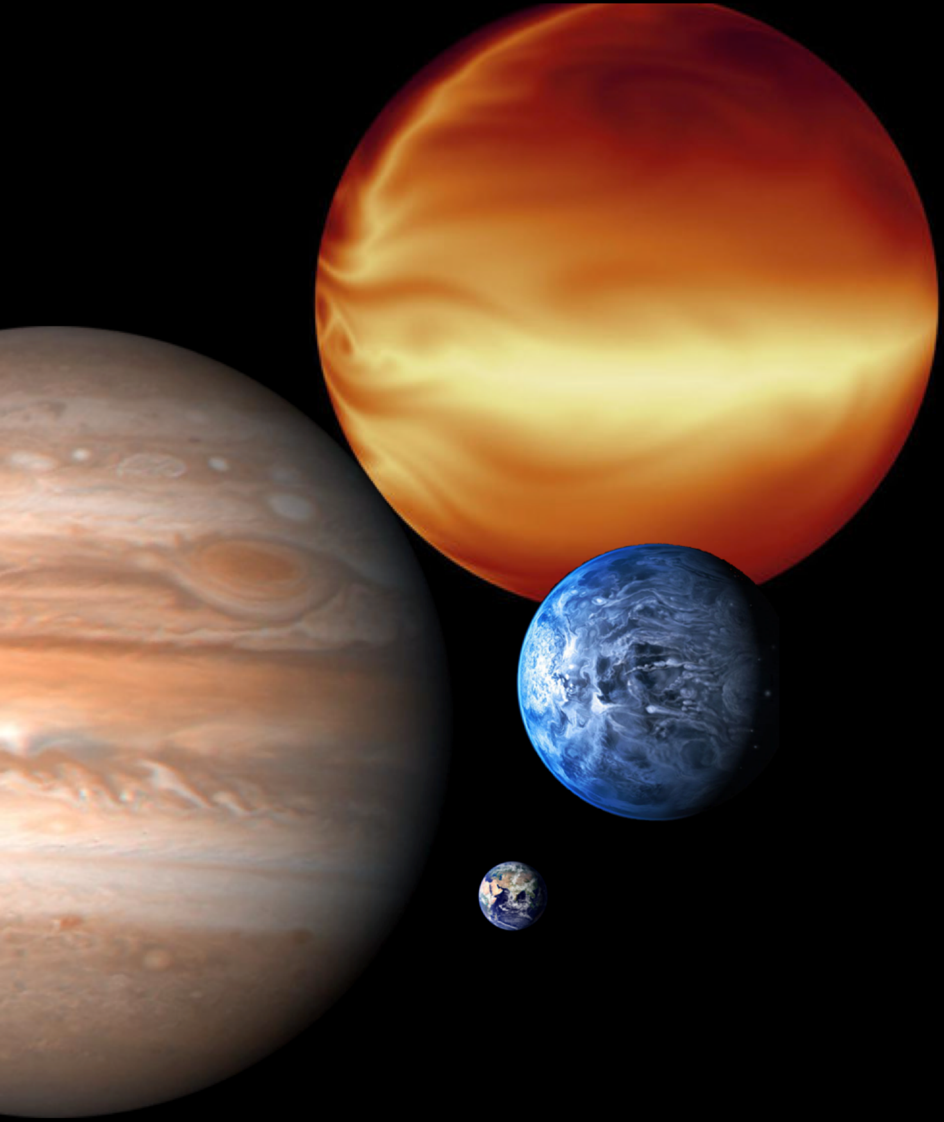
Meadows & Barnes (2018)

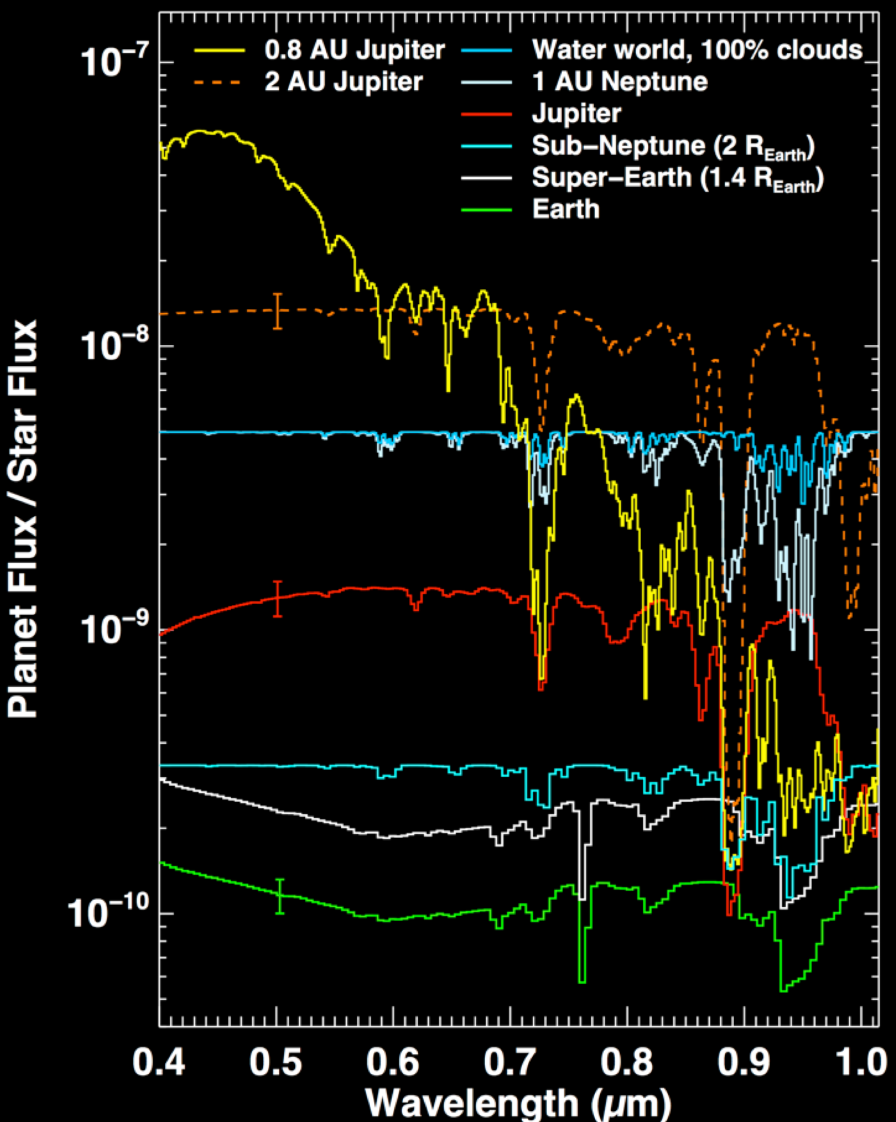
Finding & Interpreting Biosignatures with LUVOIR



Credit: T. Griswold (NASA GSFC)

LUVOIR Enables Exoplanetology





Exoplanet
Missions
NASA
JWST
WFIRST
TESS
Kepler &
K2
New Worlds
Telescope
Spitzer
Hubble
Ground-based
Observatories
Astronomy and Astrophysics
in the New Millennium
National Research Council
2001
Decadal
Survey
New Worlds,
New Horizons
in Astronomy and Astrophysics
Book-share
2010
Decadal
Survey

Ground-based observations will complement space-based observations

Giant Magellan Telescope

Credit: GMT, rendering by Mason Media

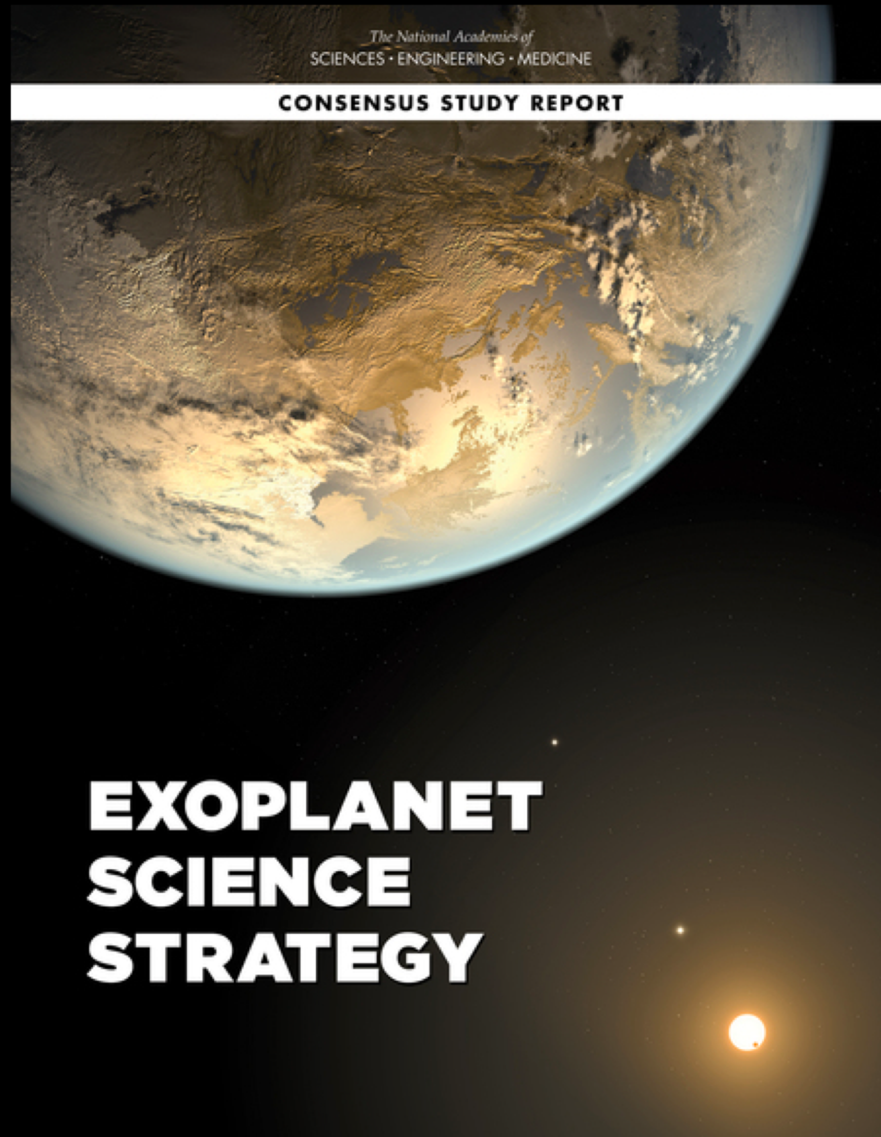
Thirty Meter Telescope

Credit: TMT

Extremely Large Telescope

Credit:ESO/L. Calçada

Recommendations



David Charbonneau (Co-Chair), **Scott Gaudi** (Co-Chair), Fabienne Bastien, Jacob Bean, Justin Crepp, Eliza Kempton, Chryssa Kouveliotou, Bruce Macintosh, Dimitri Mawet, Victoria Meadows, Ruth Murray-Clay, Evgenya Shkolnik, Ignas Snellen, Alycia Weinberger

Astro 2020

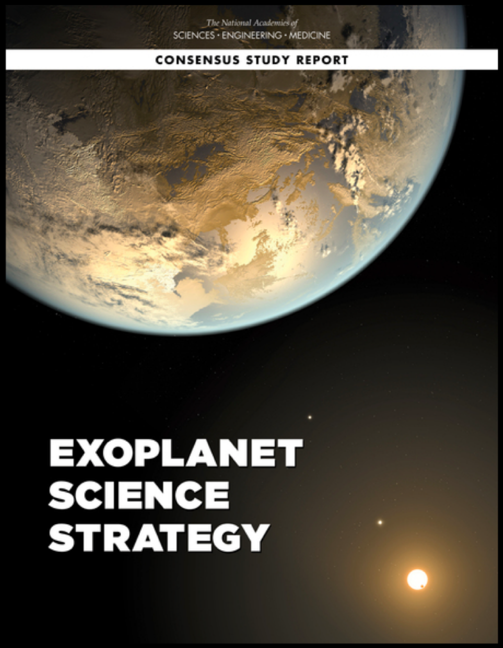
Decadal Survey on Astronomy and Astrophysics

The National Academies of SCIENCES ENGINEERING MEDICINE

What Do We Know Today?

(Statements from the ESS Report)

- "Planetary systems are **ubiquitous** and surprisingly **diverse**, and many **bear no resemblance to the Solar System**."
- "A significant fraction of planets appear to have **undergone large-scale migration** from their birthsites."
- "**Most stars have planets**, and **small planets are abundant**."
- "Large numbers of **rocky planets** [have] been identified and **a few habitable zone examples** orbiting nearby small stars have been found."
- "**Massive young Jovians** at large separations have been imaged."
- "**Molecules** and **clouds** in the atmospheres of large exoplanets have been detected."
- "The identification of potential false positives and negatives for atmospheric biosignatures has improved the **biosignature observing strategy and interpretation framework**."

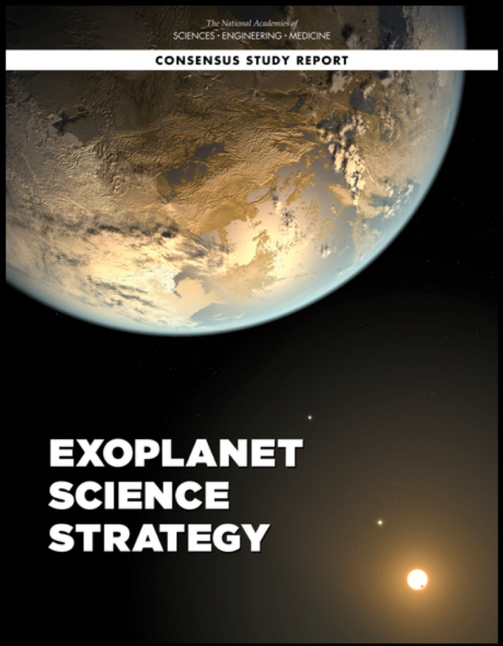


Finding: The GMT and TMT will enable profound advances in imaging and spectroscopy of entire planetary systems, over a wide range of masses, semimajor axes, and wavelengths, potentially including temperate Earth-size planets orbiting M-type stars.

Finding: The technology roadmap to enable the full science potential of GMT and TMT in exoplanet studies is in need of investments, leveraging the existing network of U.S. centers and laboratories and current 8-10 meter class facilities.

Finding: GMT and TMT, equipped with high-resolution optical and infrared spectrographs, will be powerful tools for studying the atmospheres of transiting and nontransiting close-in planets, and have the potential to detect molecular oxygen in temperate terrestrial planets transiting the closest and smallest stars.

Finding: The detection of young planets in disks will provide the ground truth for the time scale of planet formation and permit studies of the dynamical interaction between disks and planets. With the high spatial resolution of the GMT and TMT, researchers will be able to search the inner parts of planet-forming systems.

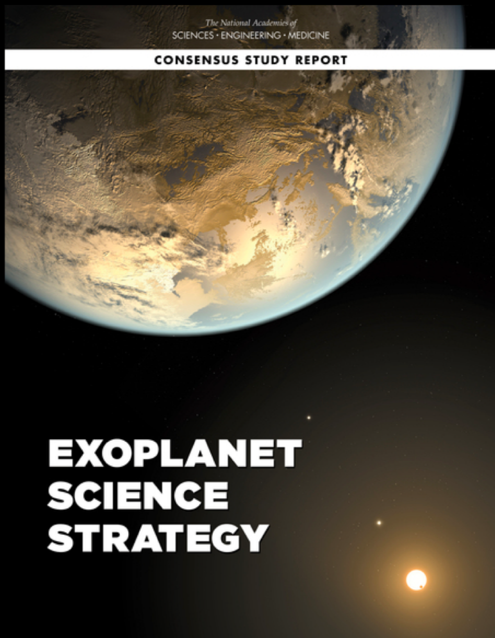


Finding: GMT and TMT will transform exoplanet science.

Finding: The GSMT technology roadmap requires investment.

Finding: GSMTs will probe planetary atmospheres & search for biosignatures (for M dwarf planets).

Finding: GSMTs could detect planets forming in disks.



Detecting Earth-like Biosignatures on Rocky Exoplanets around Nearby Stars with Ground-based Extremely Large Telescopes
(Lopez-Morales et al. 2019)

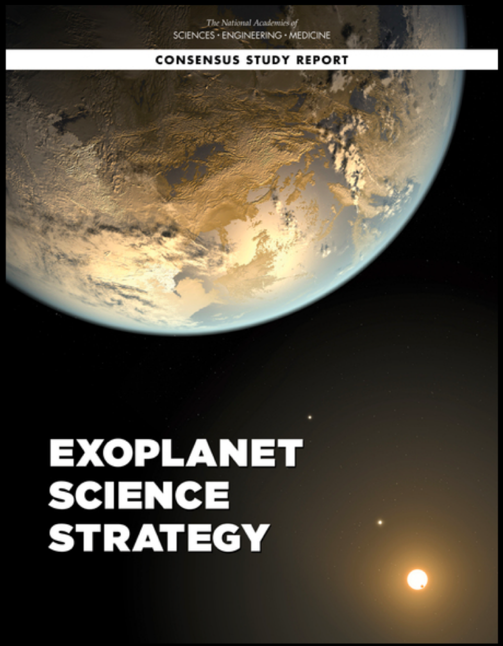
The Critical, Strategic Importance of Adaptive Optics-Assisted Ground-Based Telescopes for the Success of Future NASA Exoplanet Direct Imaging Missions
(Currie et al. 2019)

New Frontiers for Terrestrial-sized to Neptune-sized Exoplanets in the Era of Extremely Large Telescopes
(Wong & Meyer et al. 2019)

The Demographics and Atmospheres of Giant Planets with the ELTs
(Bowler et al. 2019)

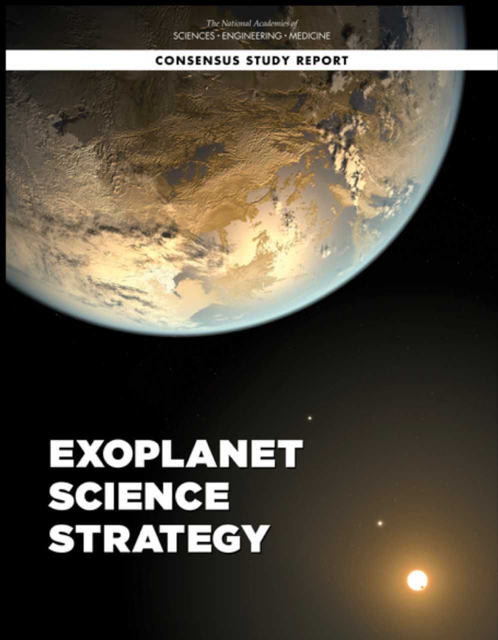
Directly Imaging Rocky Planets from the Ground
(Mazin et al. 2019)

Recommendation: The National Science Foundation (NSF) should invest in both the GMT and TMT and their exoplanet instrumentation to provide all-sky access to the U.S. Community.



Finding: A coronagraphic or starshade-based direct imaging mission is the only path currently identified to characterize Earth-size planets in the habitable zones of a large sample of nearby Sun-like stars in reflected light.

Finding: Recently acquired knowledge of the frequency of occurrence of small planets, and advances in the technologies needed to directly image them, have significantly reduced uncertainties associated with a large direct imaging mission.



Finding: A large direct imaging mission is required to detect Earth-like planets orbiting Sun-like stars in reflected light.

Finding: We have the required knowledge and technology.

Recommendation: NASA should lead a large strategic direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars.

Summary

- **Exo-Earth Detection**
  - Hundreds of Earth-sized planets have been detected
  - A few dozen planets are both small & cool
- **Exo-Earth Demographics**
  - Small planets are extremely common
  - On the order of 10-20% of stars host small & cool planets
- **Exo-Earth Characterization**
  - Transmission spectroscopy probes the upper atmosphere
  - Direct spectroscopy can look closer to the surface
  - A large space-based observatory could search for life on Earth-like planets orbiting Sun-like stars