Recent Advances and Near-Future Opportunities in the Study of Planets Orbiting Other Stars

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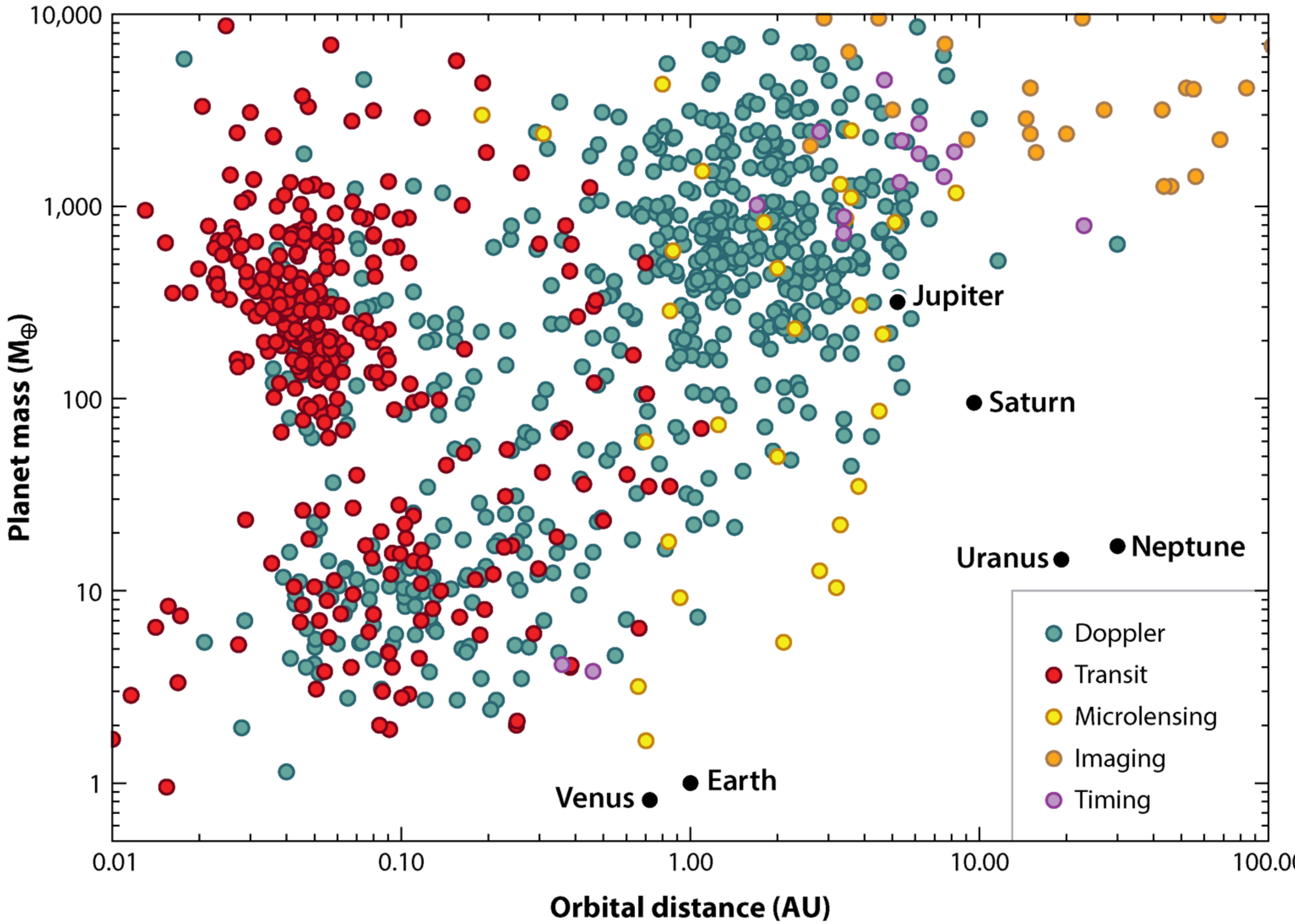
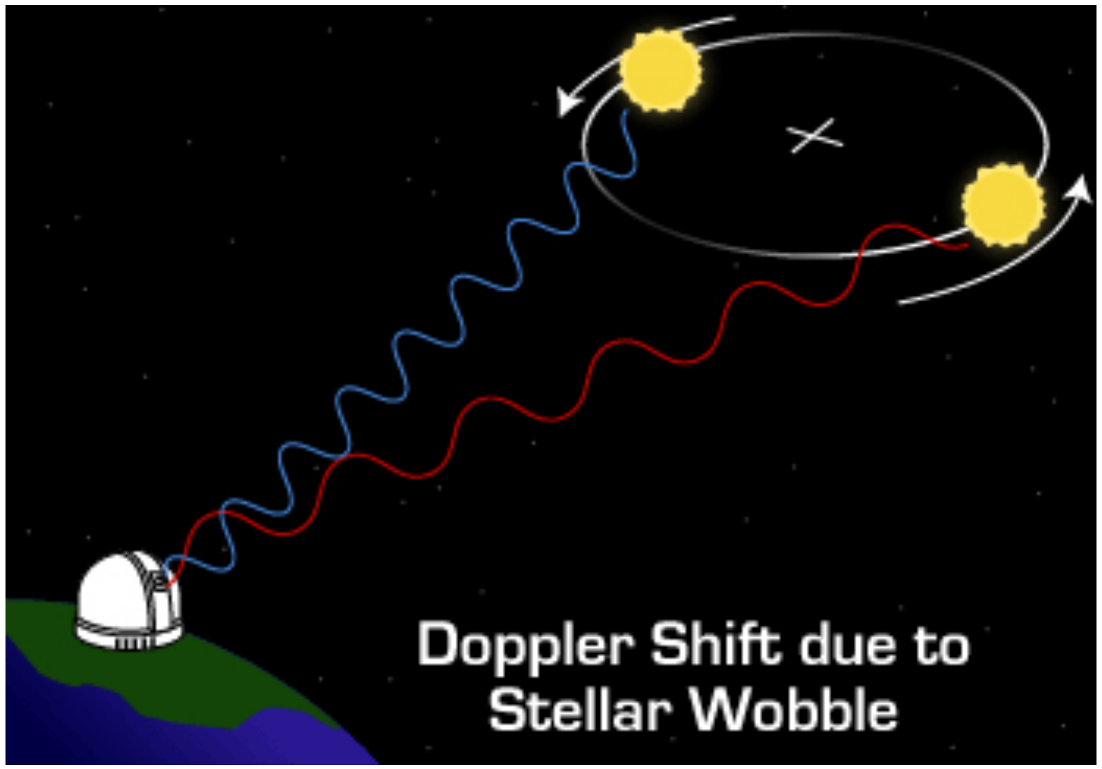
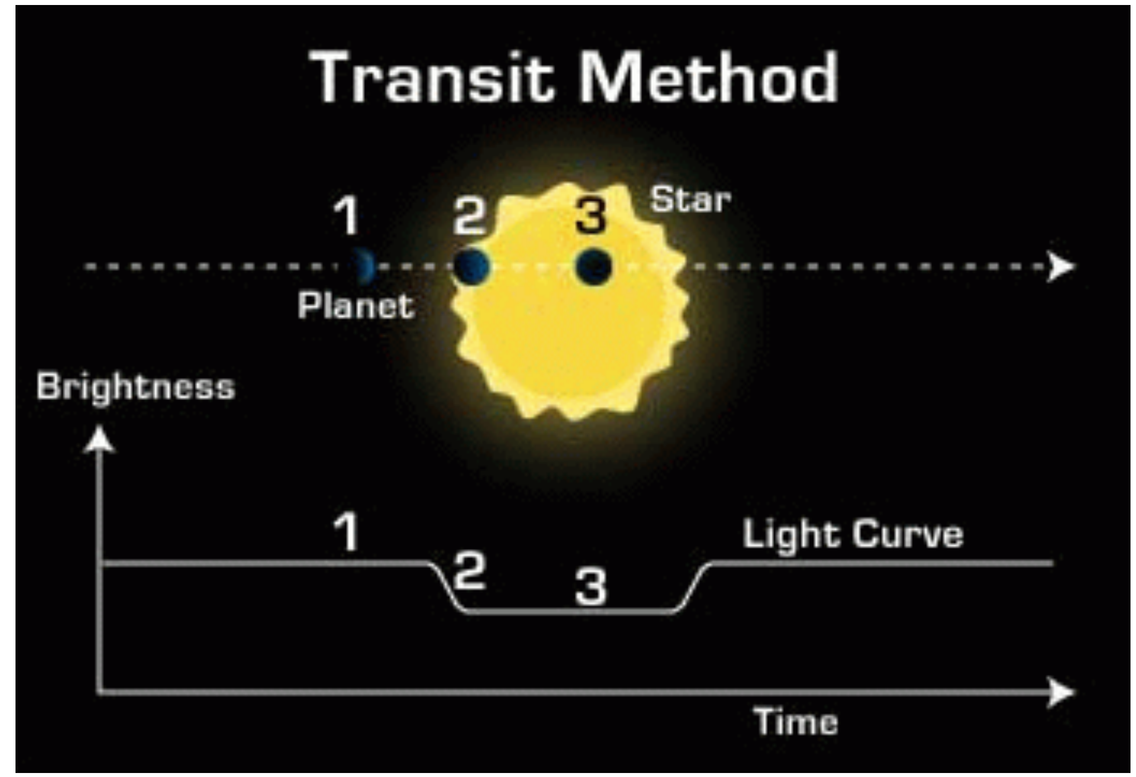
The Observed Population of Exoplanets: *Complementarity of Four Methods*



AR Winn JN, Fabrycky DC. 2015.
Annu. Rev. Astron. Astrophys. 53:409–47

Radial Velocity and Transits:
Population Statistics and Bulk Densities





Doppler Method

Determine Planet Mass

Transit Method

Determine Planet Diameter

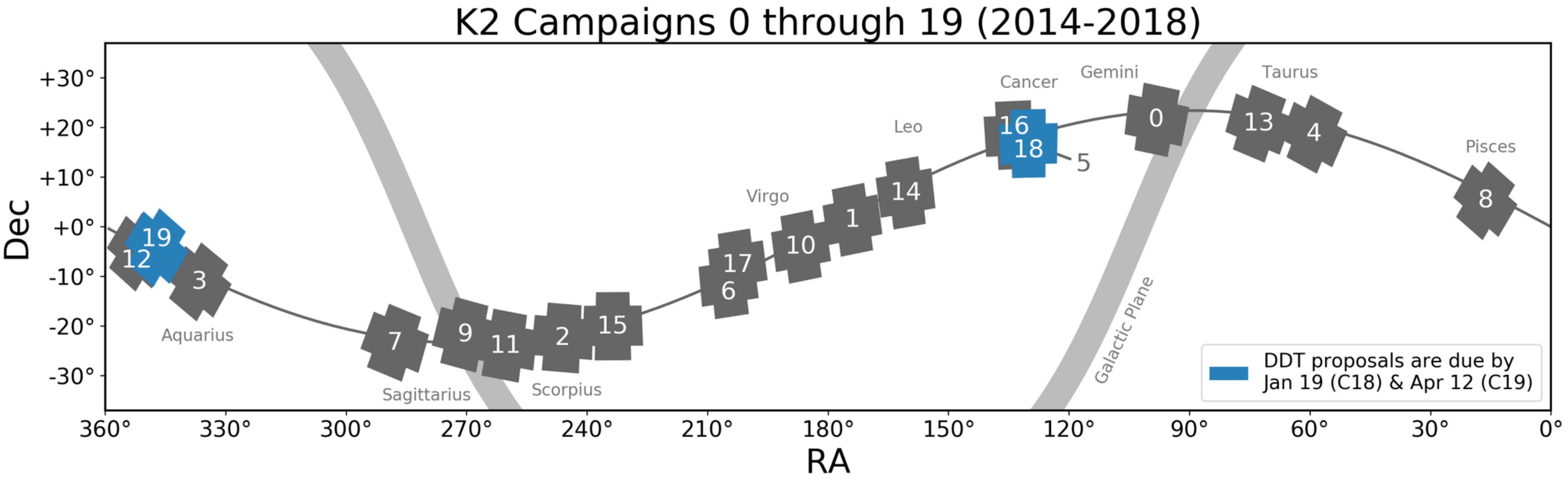
Calculate Planet Density and Infer Composition:

Gas giant (Jupiter) or Rocky planet (Earth)

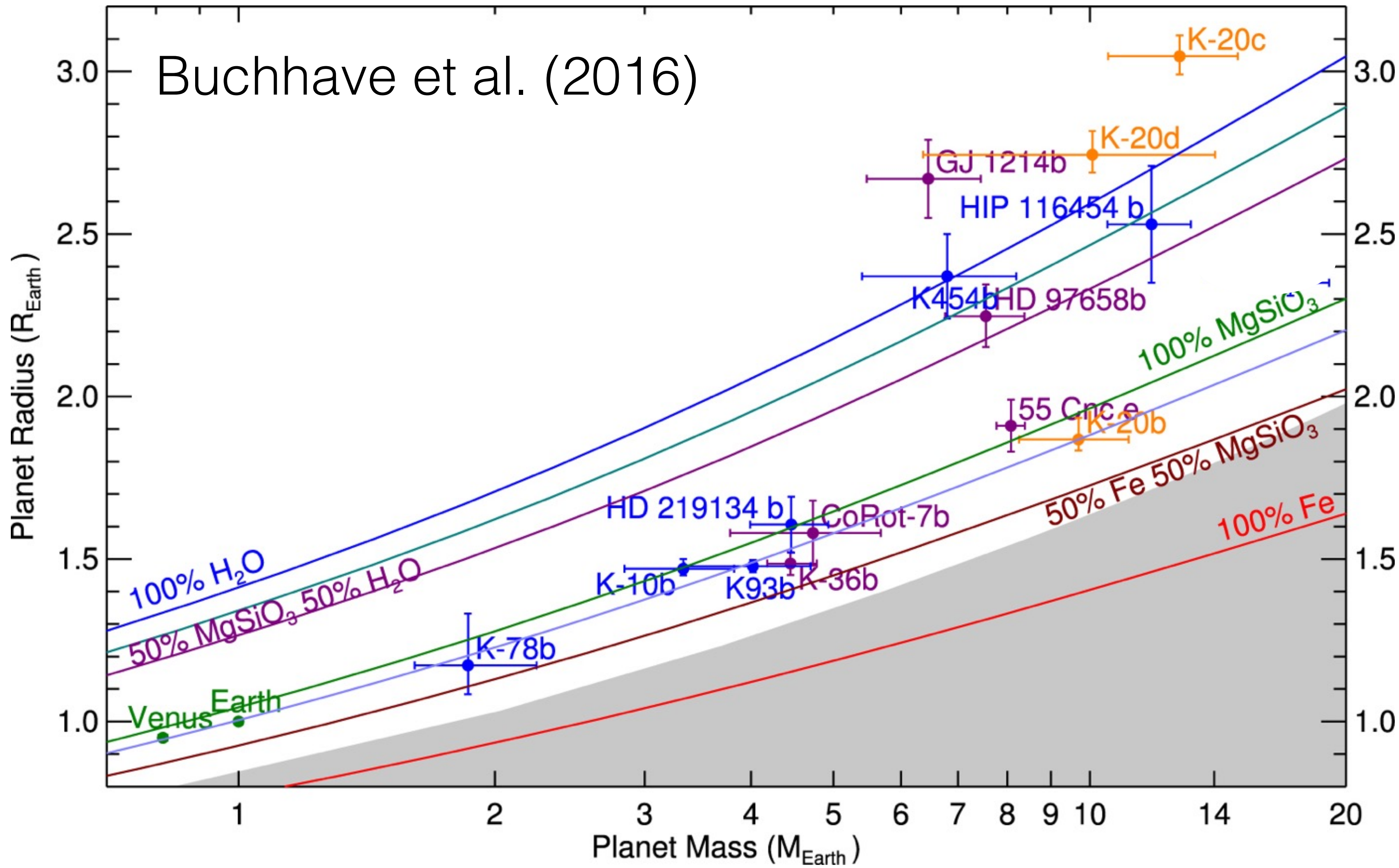
NASA Kepler Mission
2009 – 2013

Failure of reaction wheel resulted in an opportunity:

NASA K2 Mission
2014 - 2018



Inferred Bulk Compositions from Kepler & Radial Velocity Follow-Up



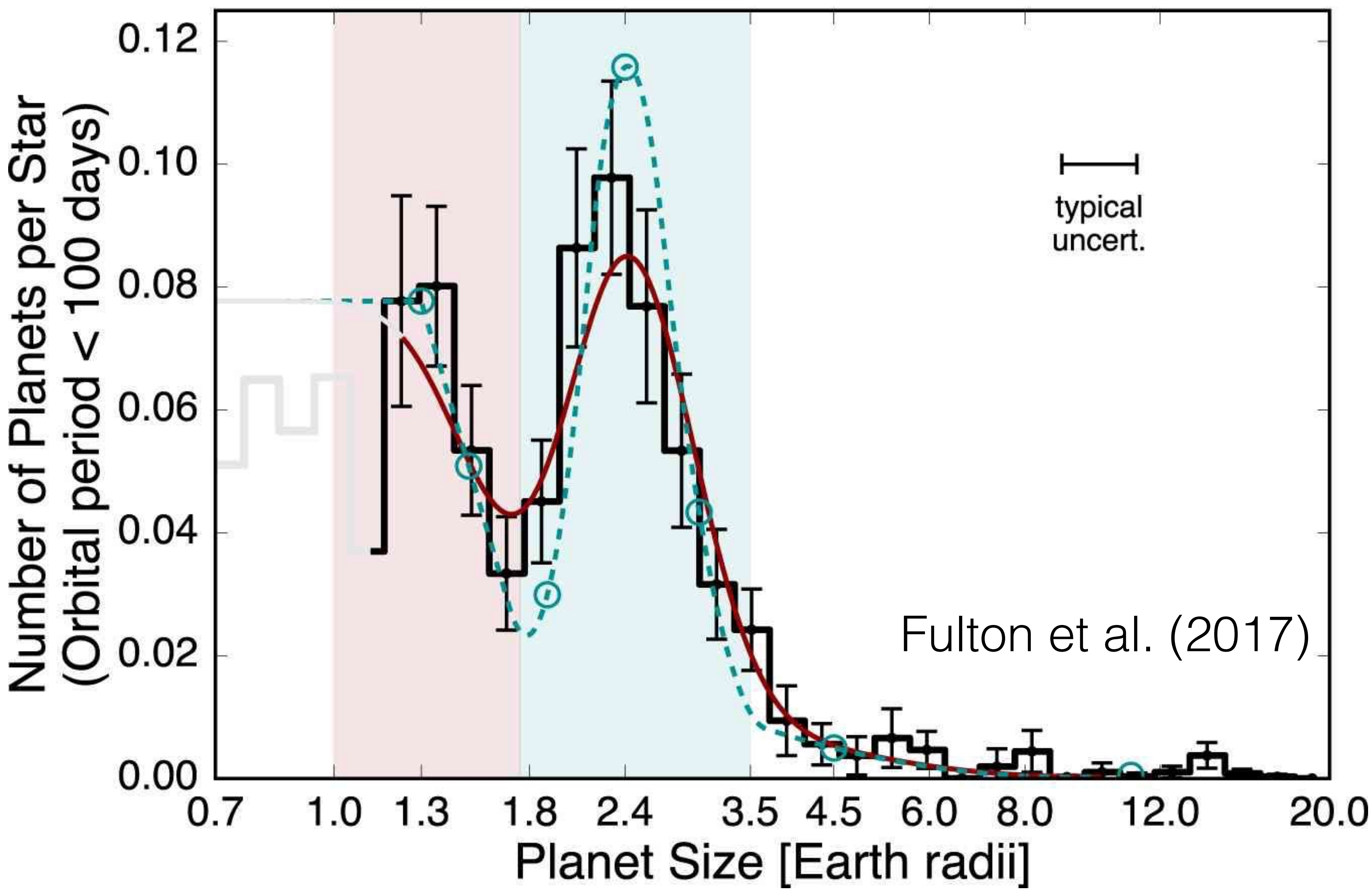
RV follow-up of short period small planets + Transit Timing Variations (TTVs) of cooler small planets show that these have densities consistent with Earth composition.

There are no* rocky planets > 10 M_{Earth} & There are no* super-Mercuries.

Discovery of gas dwarfs, i.e. low-mass, low-density planets w/ no Solar sys counterpart.

**Although candidates exist, the uncertainties are sufficiently large to preclude definitive conclusions.*

Population Statistics from Kepler & Ground-based Follow-Up



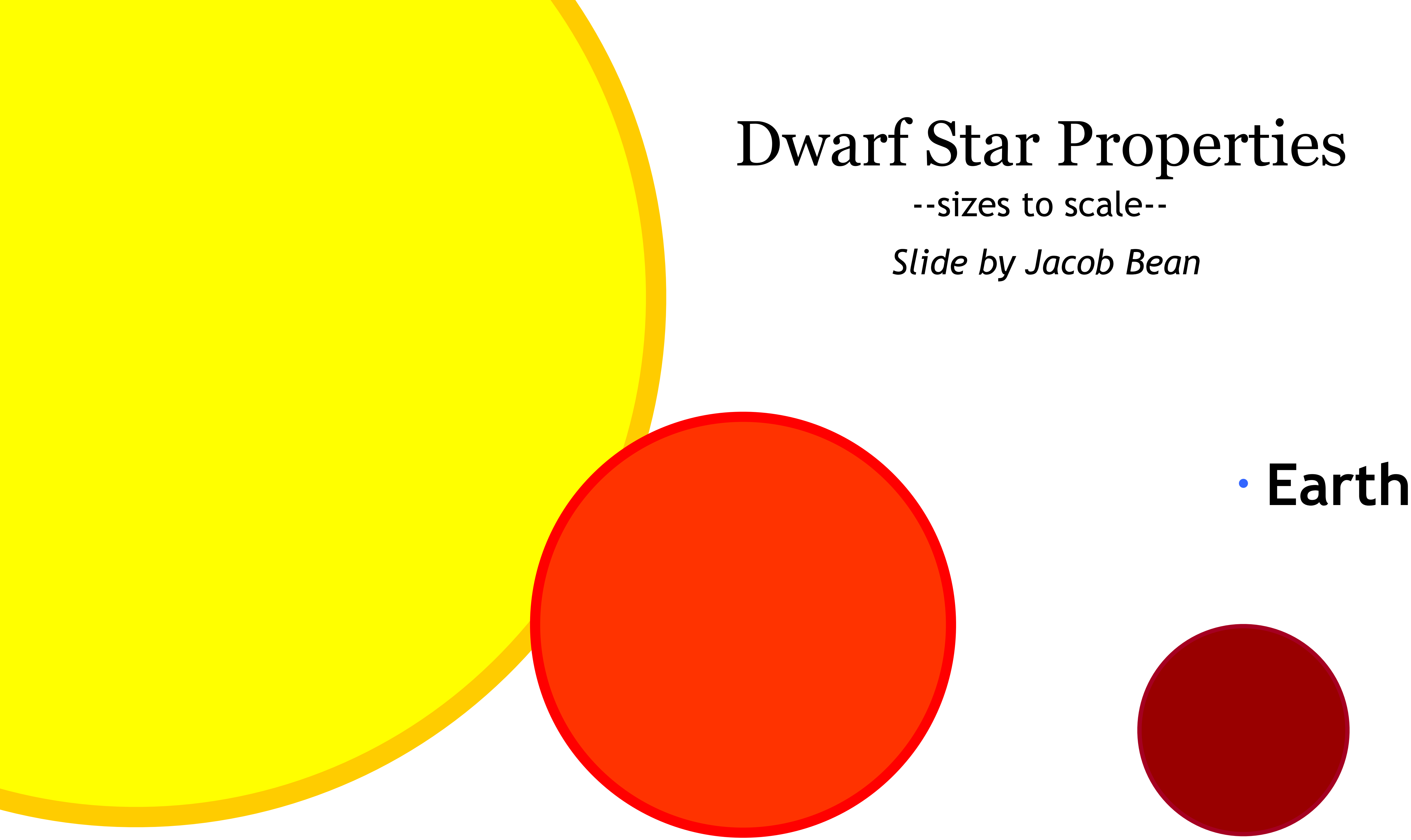
At P < 100d, per Sun-like star:

0.25 large terrestrials (1.1-1.7 R_{Earth})
0.43 gas dwarfs (1.8-5 R_{Earth}): Likely rock+iron cores w/ small H/He envelope

Dwarf Star Properties

--sizes to scale--

Slide by Jacob Bean



G2

M = 1 M_{sun}

R = 1 R_{sun}

T = 5800 K

M3

M = 0.45 M_{sun}

R = 0.45 R_{sun}

T = 3500 K

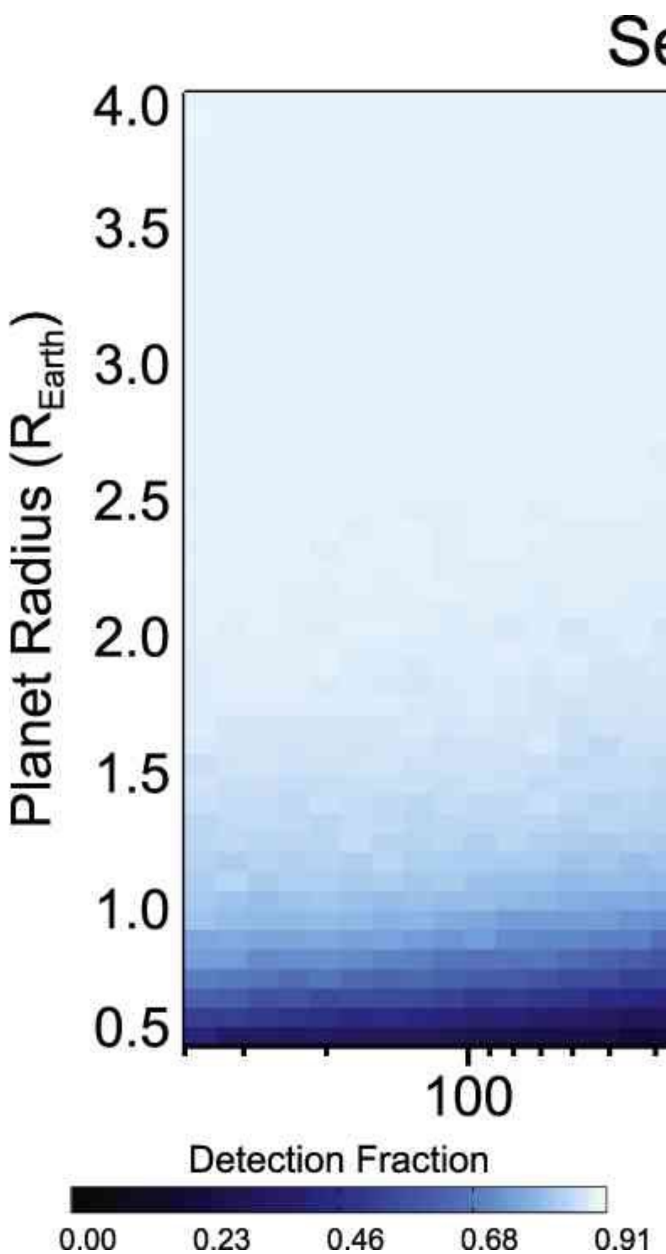
M6

M = 0.12 M_{sun}

R = 0.18 R_{sun}

T = 2900 K

The Number of Earth-sized Planets per Habitable Zone: **Small Stars**



Dressing & Charbonneau (2015)

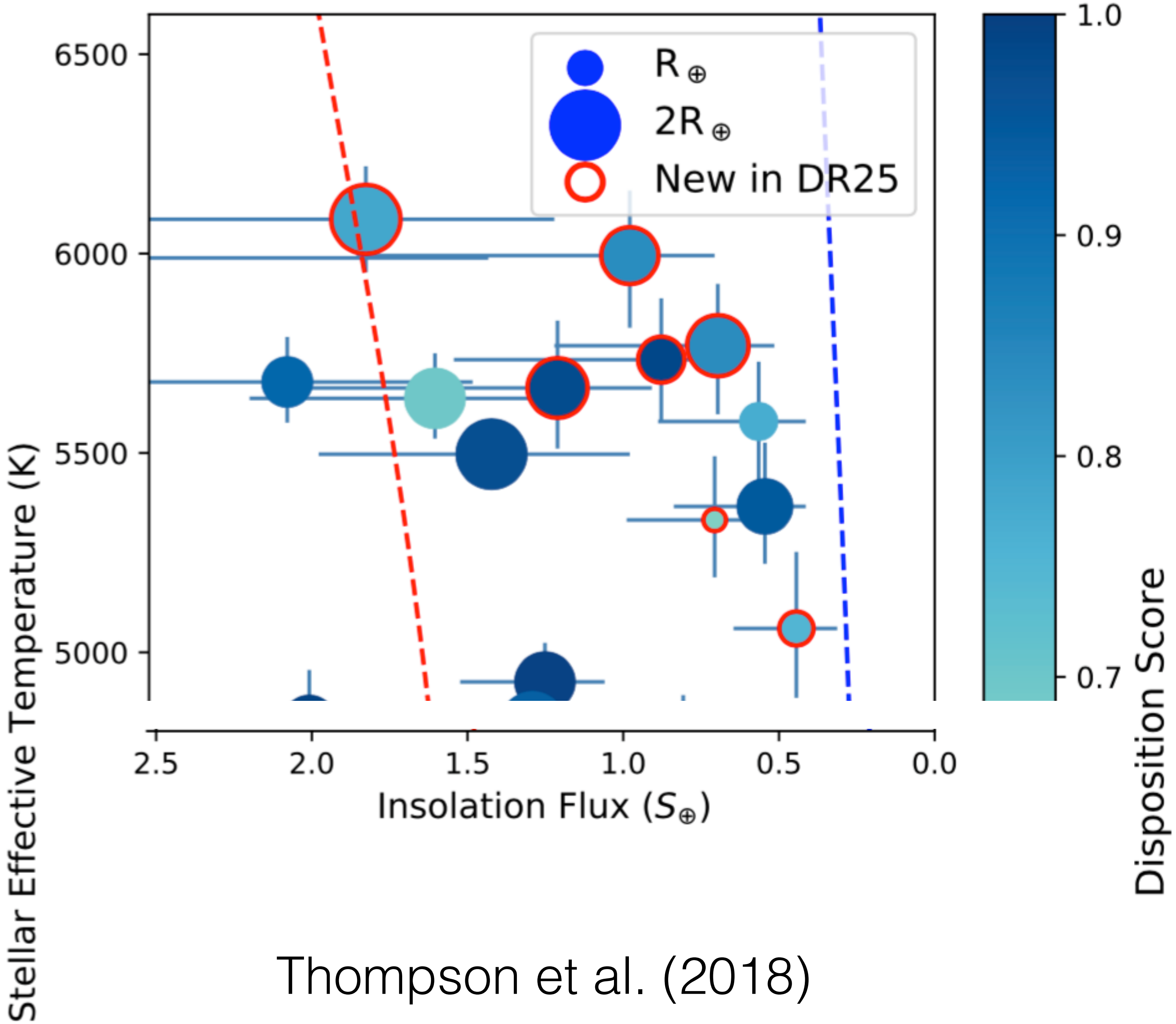
Owing to their deep transits and short orbital periods, the rate of occurrence of HZ Earth-sized planets is well determined:

2.5 (± 0.2) **small** (1-4 R_E) **planets** with **P<200 days**

Empirical Venus/Mars Habitable Zone:

- **0.24** (+0.18/-0.08) **terrestrials** (1-1.5 R_E)
- **0.21** (+0.11/-0.06) larger planets (1.5-2 R_E)

The Number of Earth-sized Planets per Habitable Zone: **Sun-like Stars**



Thompson et al. (2018)

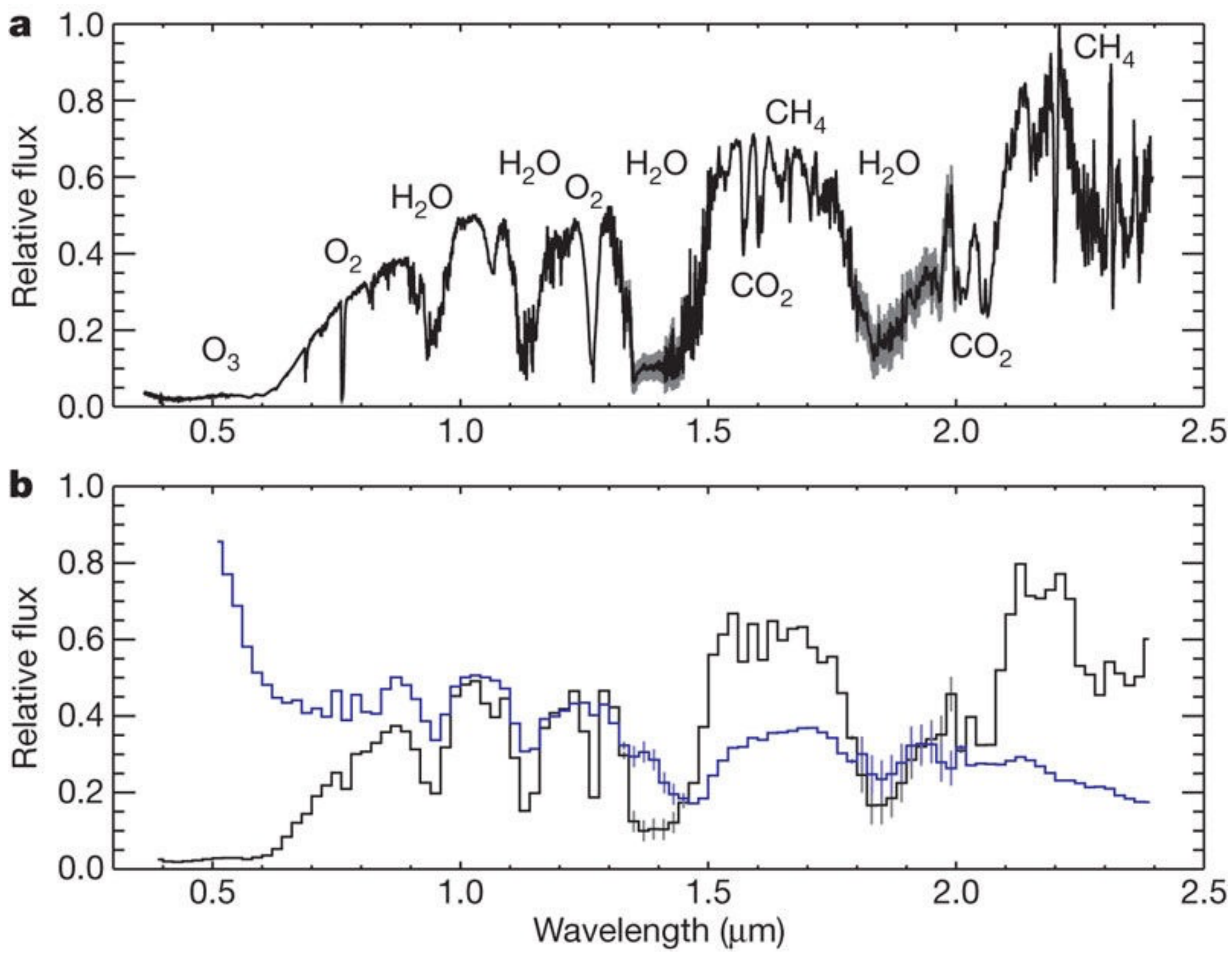
Earth-Sun analog has a **84 ppm** transit and presents **3 transits** during the Kepler baseline: A very challenging detection!

Until recently, no Earth analogs had been founded, so estimates of the rate of occurrence were extrapolated from hotter, larger planets, and range from 1-20%.

Final list of Kepler candidates (DR25) just released and contains more objects, which should reduce the uncertainty in the rate of occurrence.

The Central Tenet of Current Strategic Planning for Searches for Life Outside the Solar System:

There exists a set of spectroscopic features that can be observed remotely and, along with contextual information, attributed uniquely to life.



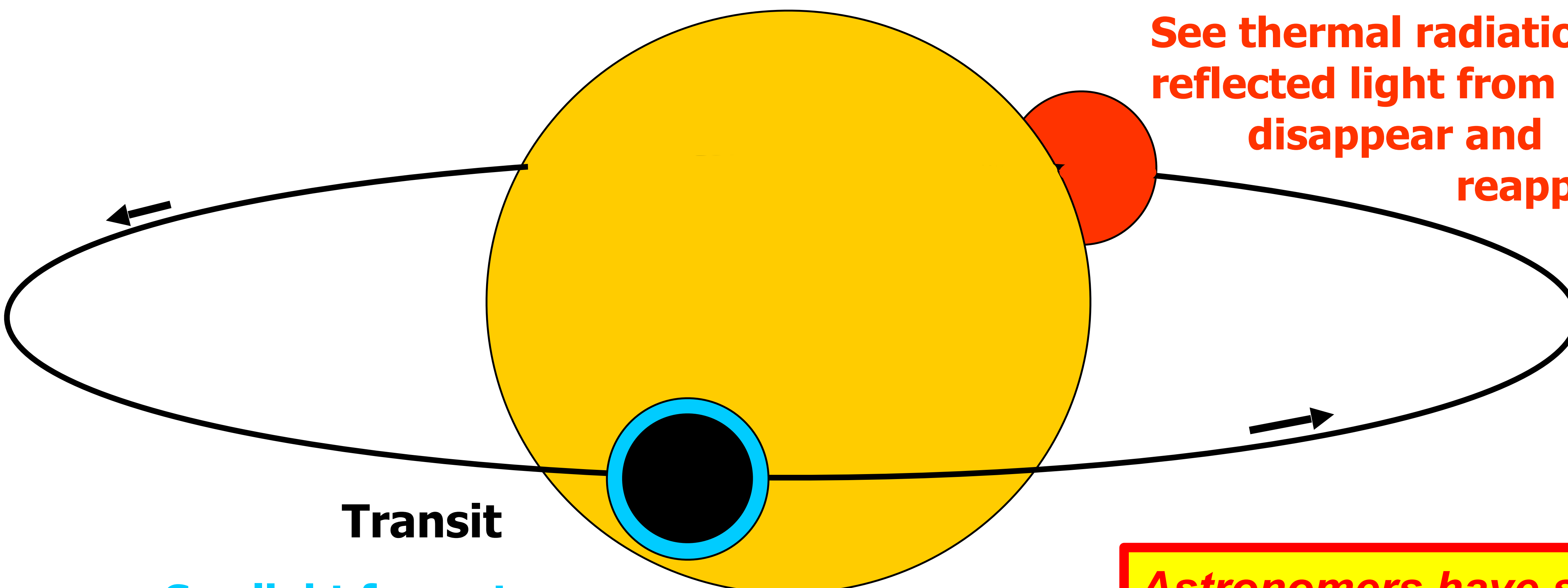
Observed Transmission and Reflectance Spectrum of Earth
Palle et al. (2009)

Temperate terrestrial planets are small (10^{-4}) and faint (10^{-6} - 10^{-10}) relative to their Sun-like parent stars, hence attempts to study their atmospheres are enormously challenging.

Transits Allows Studies of the Atmospheres That Are Not Possible for Non-Transiting Planets

Secondary Eclipse

See thermal radiation and reflected light from planet disappear and reappear

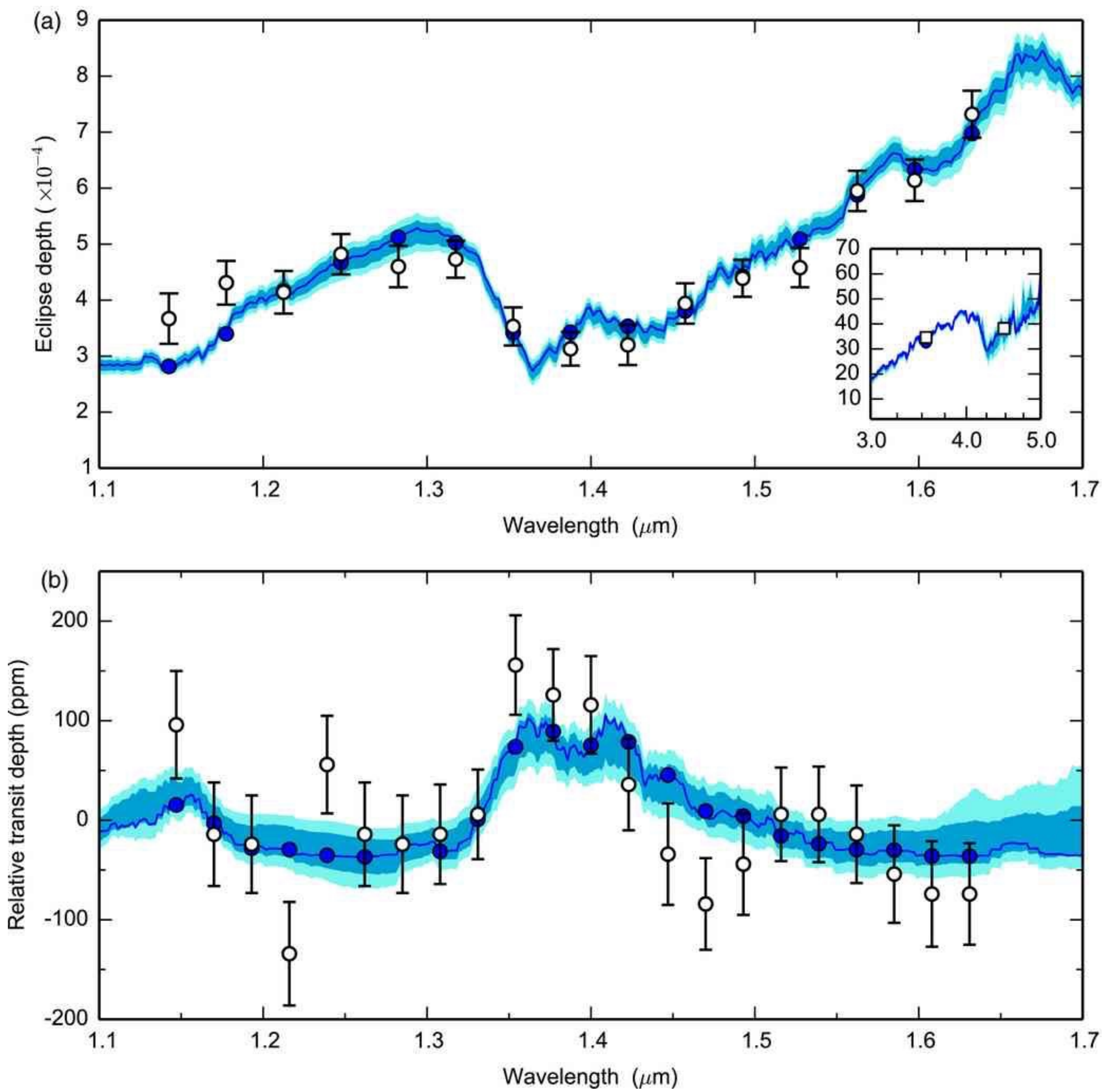


Transit

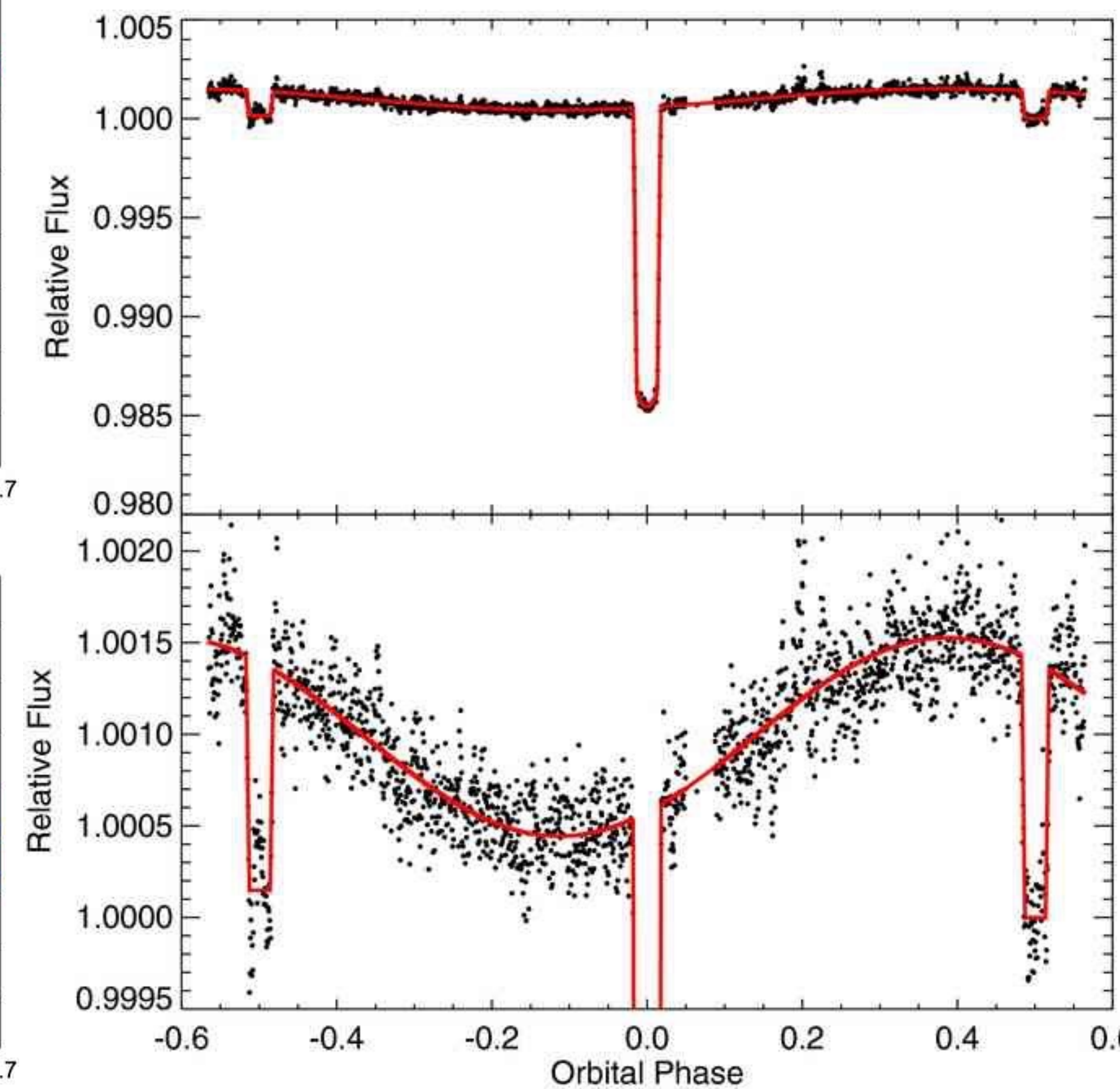
See light from star transmitted through the planet's atmosphere

<u>Astronomers have studied</u>
-Atoms & Molecules
-Clouds
-Winds

Transmission and Emission Spectroscopy of Gas Dominated Worlds with Spitzer and Hubble

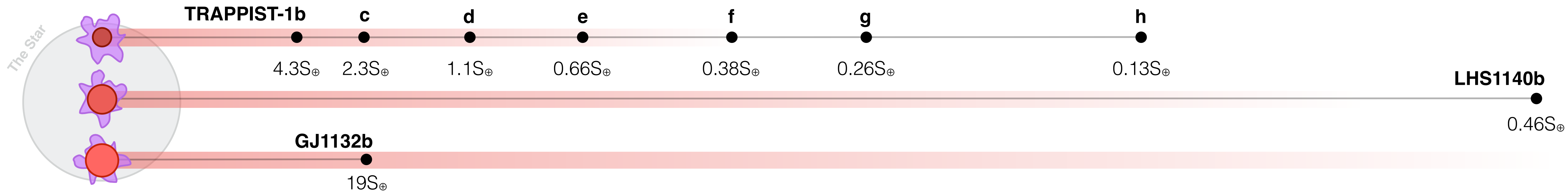


Kreidberg et al. (2014)

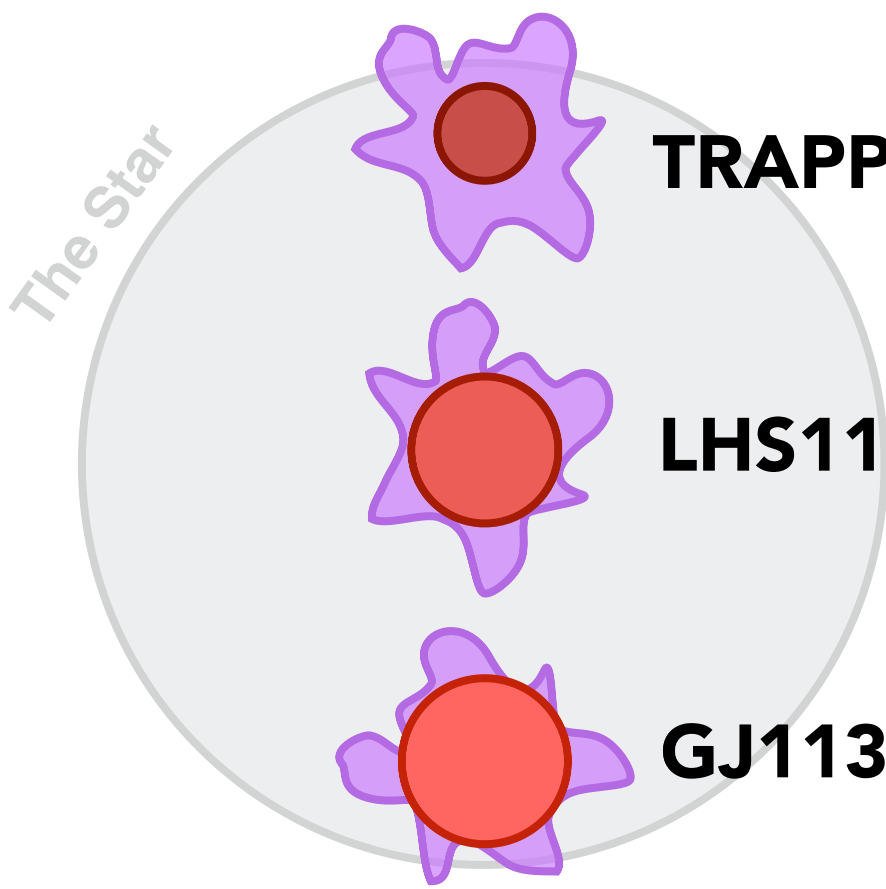


Zellem et al. (2014)

The spectroscopically accessible transiting terrestrial planets



offer laboratories to explore the influence of different M dwarf environments on planetary atmospheres.



TRAPPIST-1 = moderately active $0.08M_{\odot}$

Wheatley et al. (2017), Luger et al. (2017)

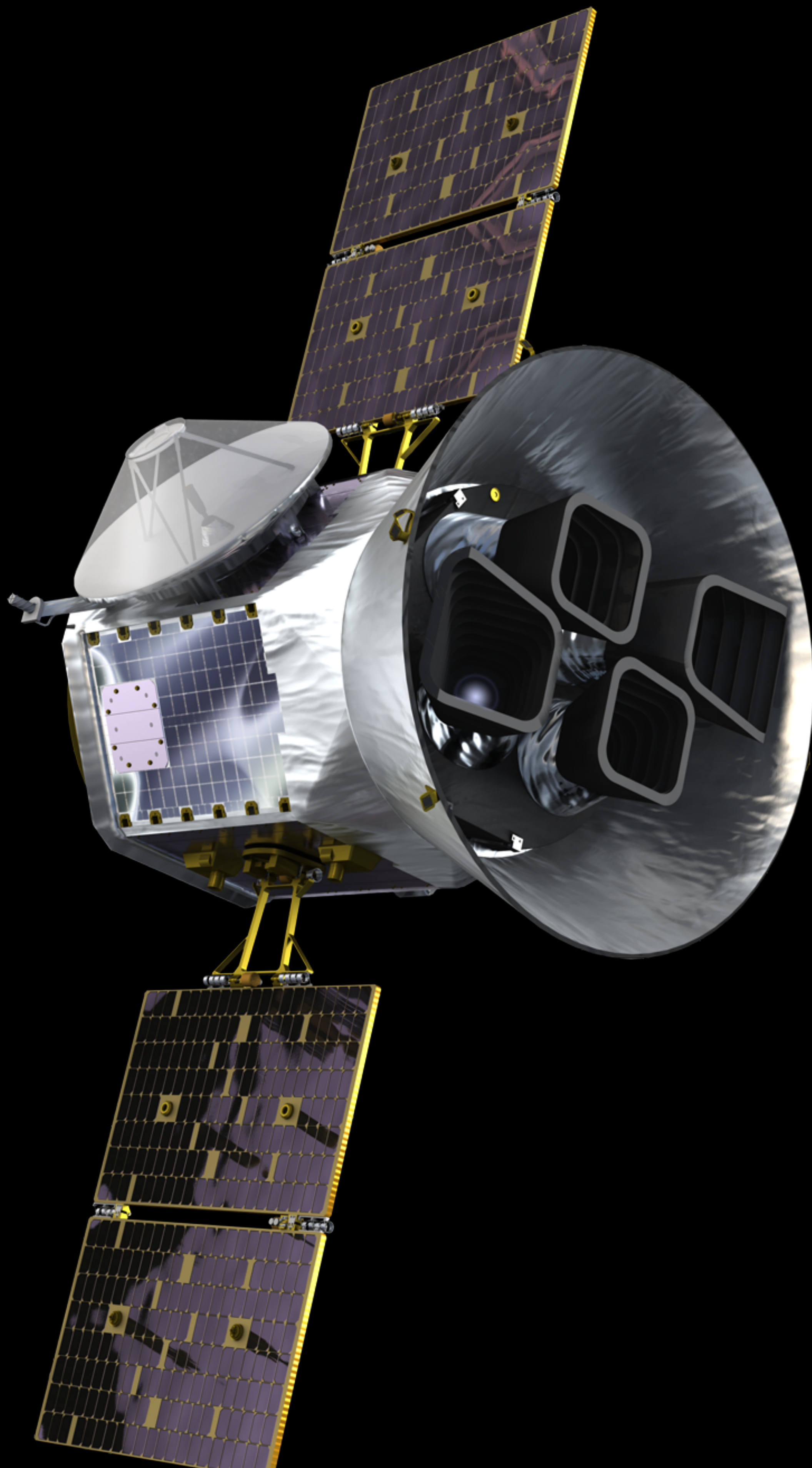
LHS1140 = currently inactive $0.15M_{\odot}$

Dittmann et al. (2017)

GJ1132 = currently inactive $0.18M_{\odot}$

Berta-Thompson et al. (2017)

this slide and the following two are courtesy Z. Berta-Thompson

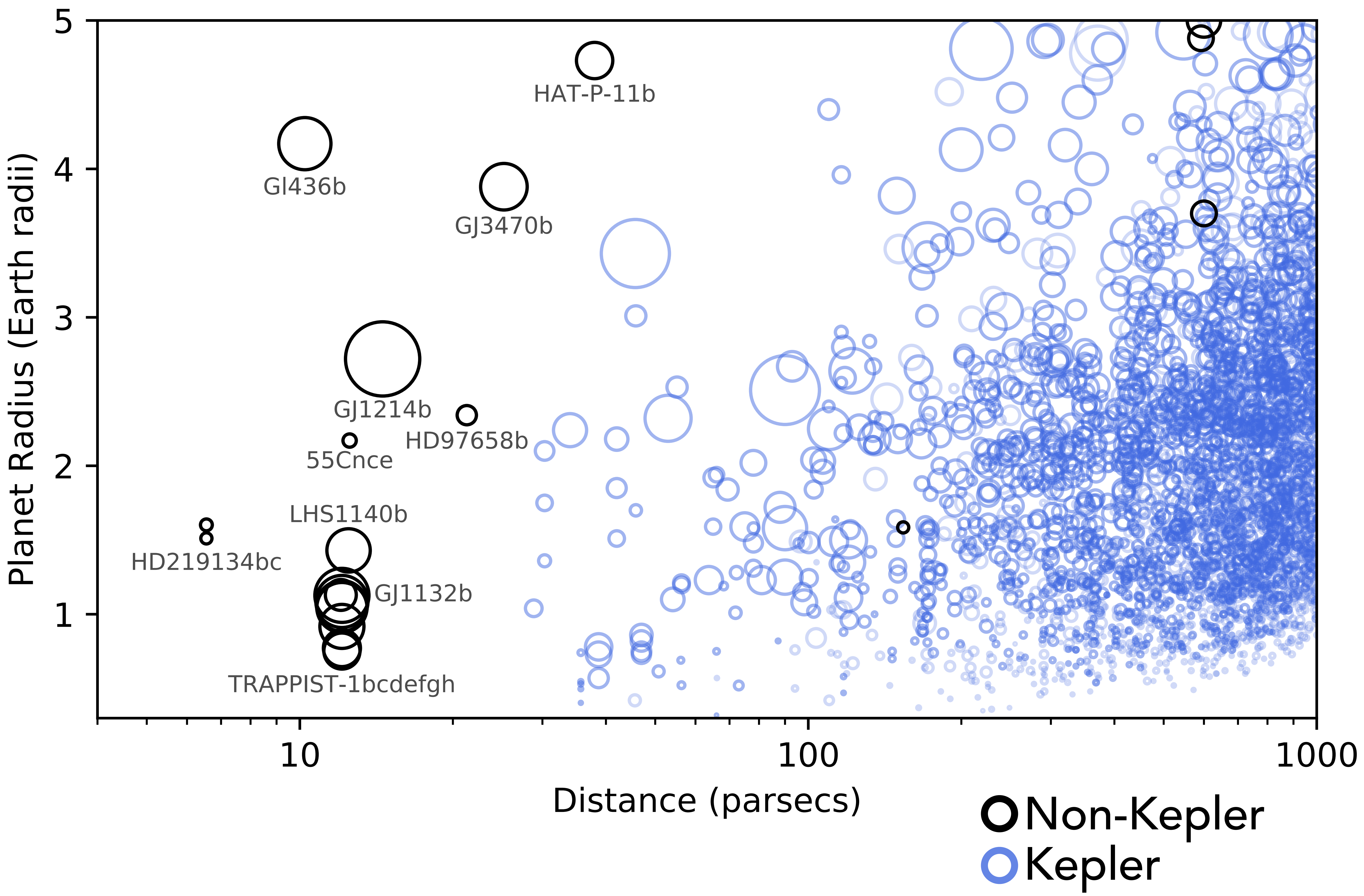


TESS

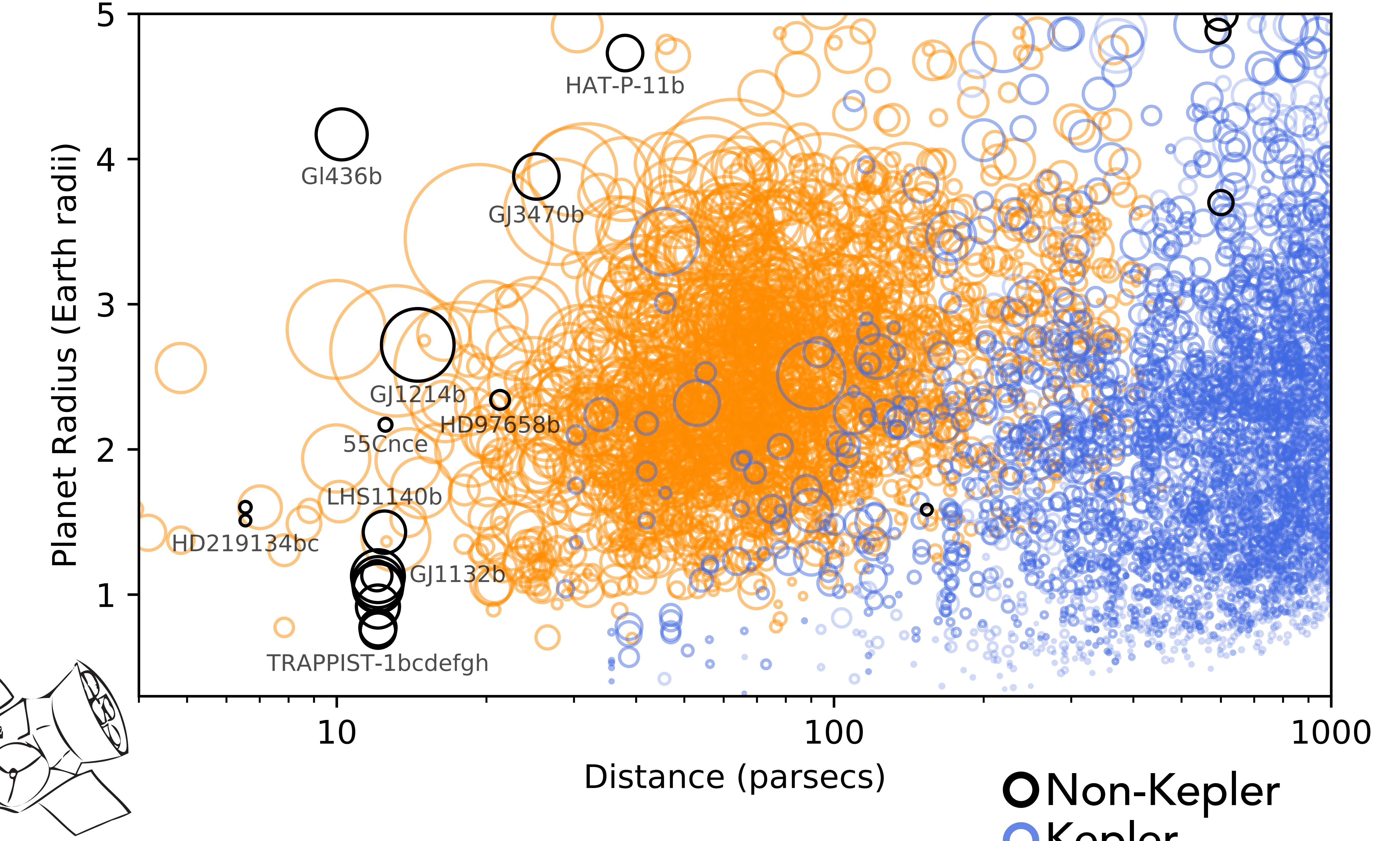
Explorer Mission

*launch in **2018**,*
to find hundreds of
nearby small exoplanets
amenable to detailed
characterization

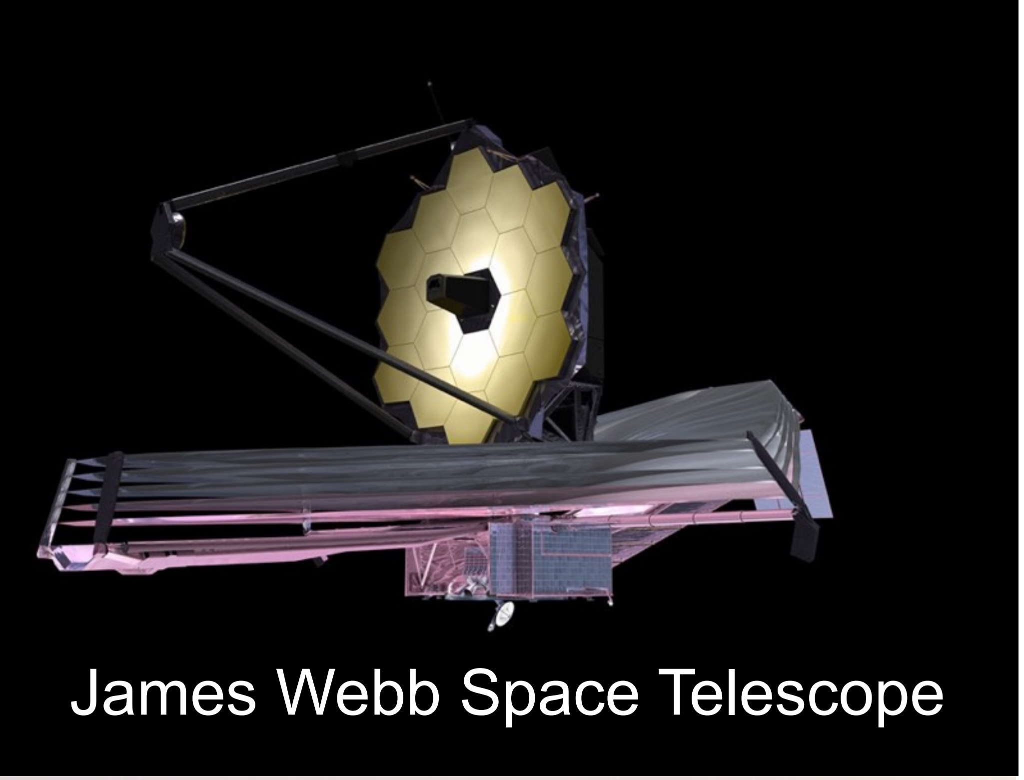
Ricker et al., *JATIS*, (2014)

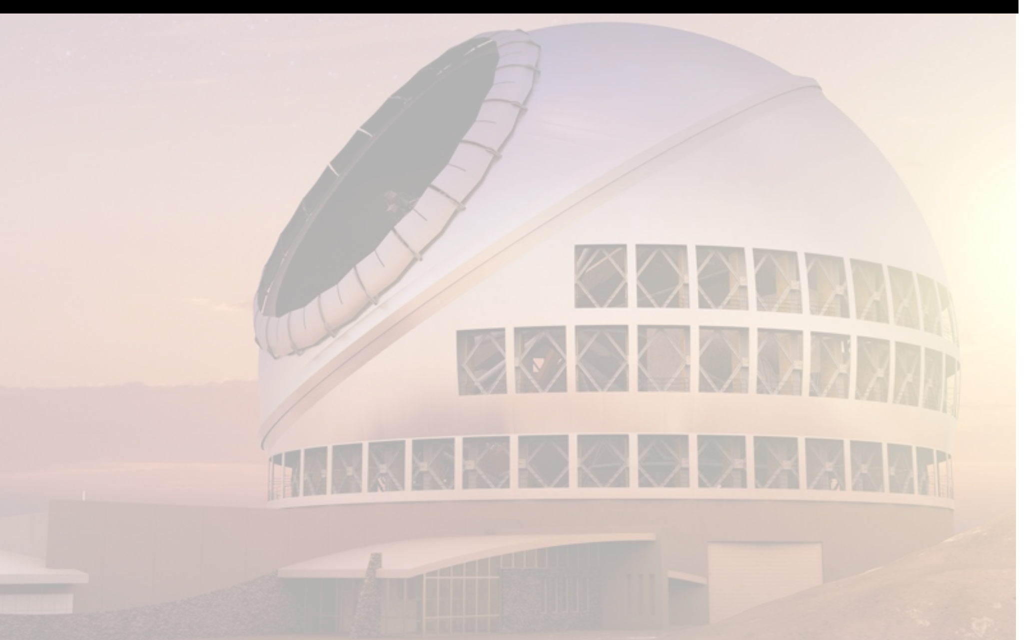


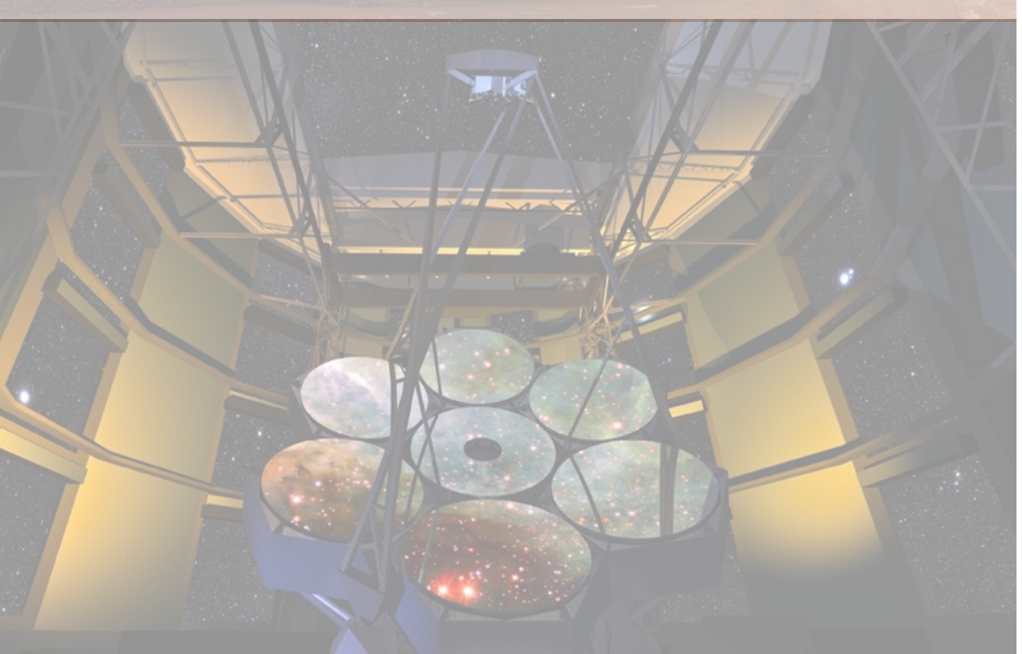
HAT-P-11b
Gl436b
GJ3470b
GJ1214b
HD97658b
55Cnce
LHS1140b
HD219134bc
GJ1132b
TRAPPIST-1bcdefgh
Planet Radius (Earth radii)
Distance (parsecs)
1
2
3
4
5
10
100
1000
Non-Kepler
Kepler



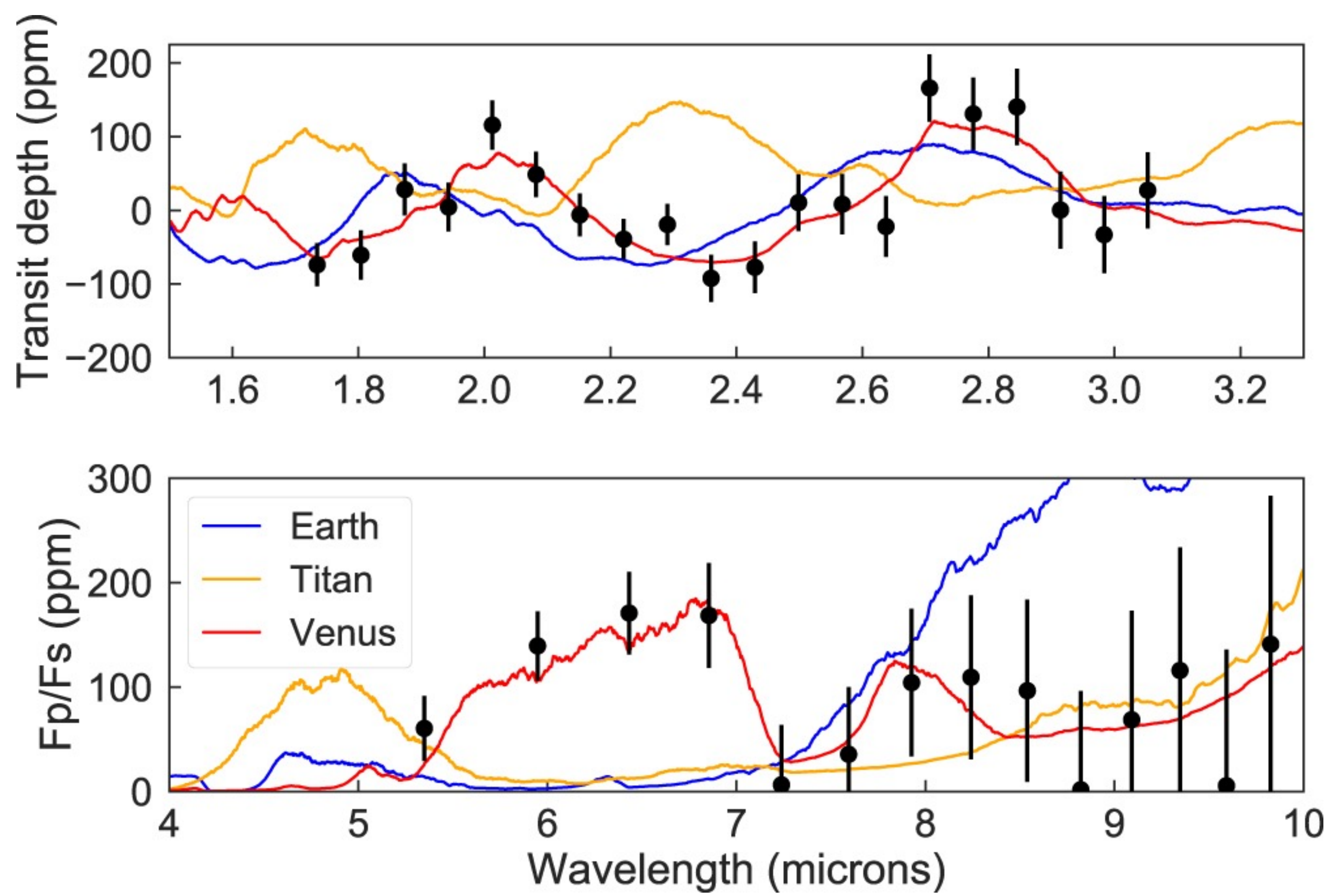
TESS simulated yield from Sullivan et al. (2015)



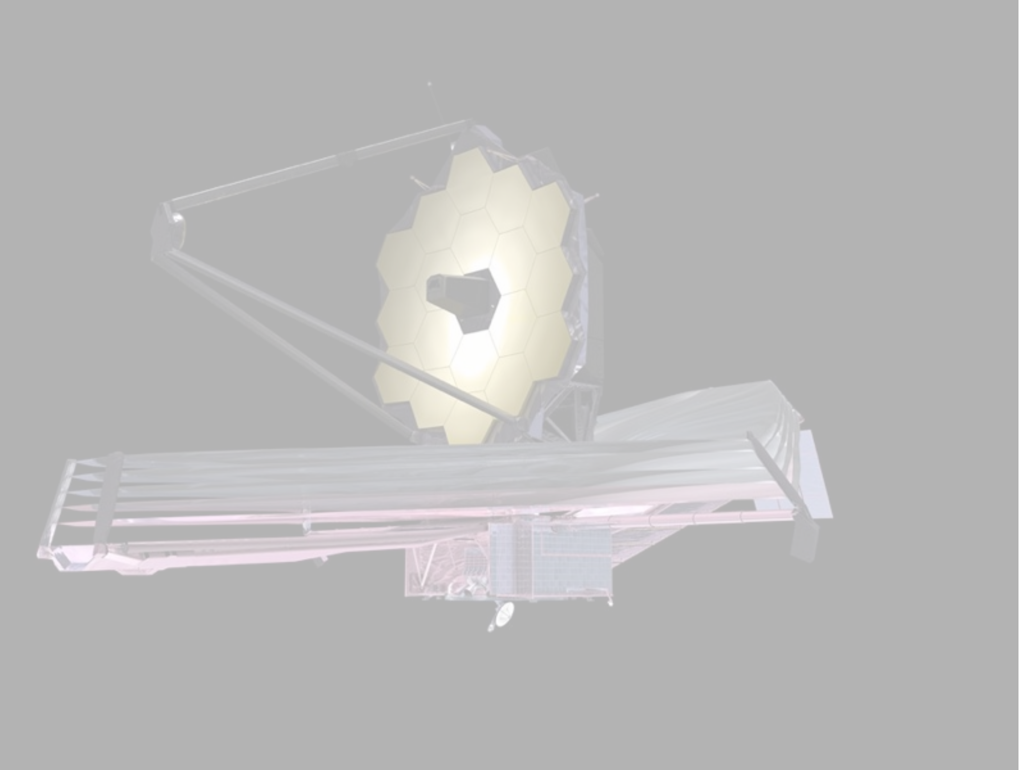


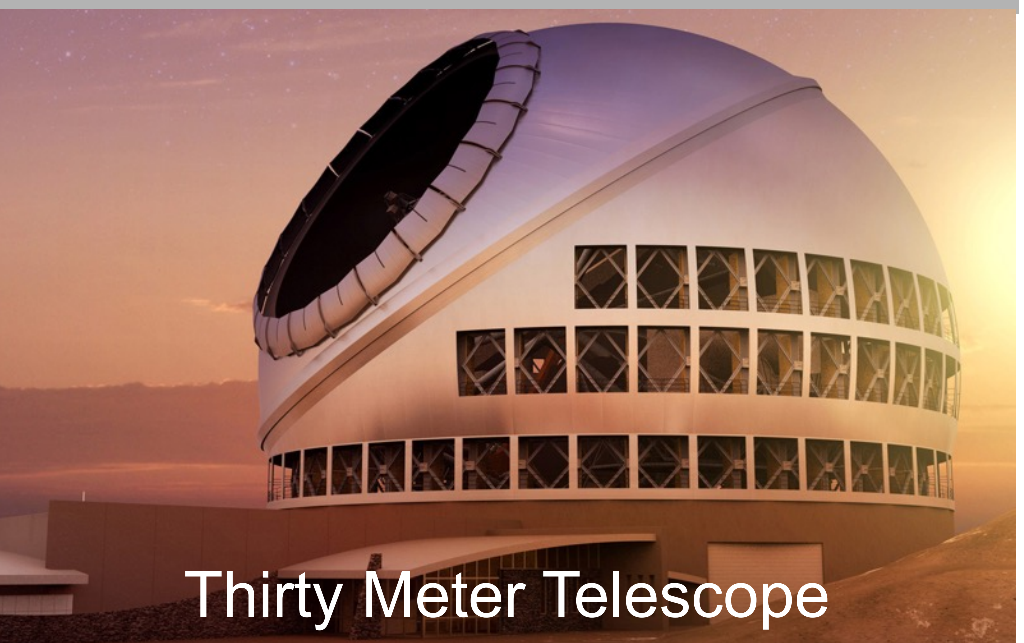


SNR Predictions for JWST Observations of TRAPPIST-1b

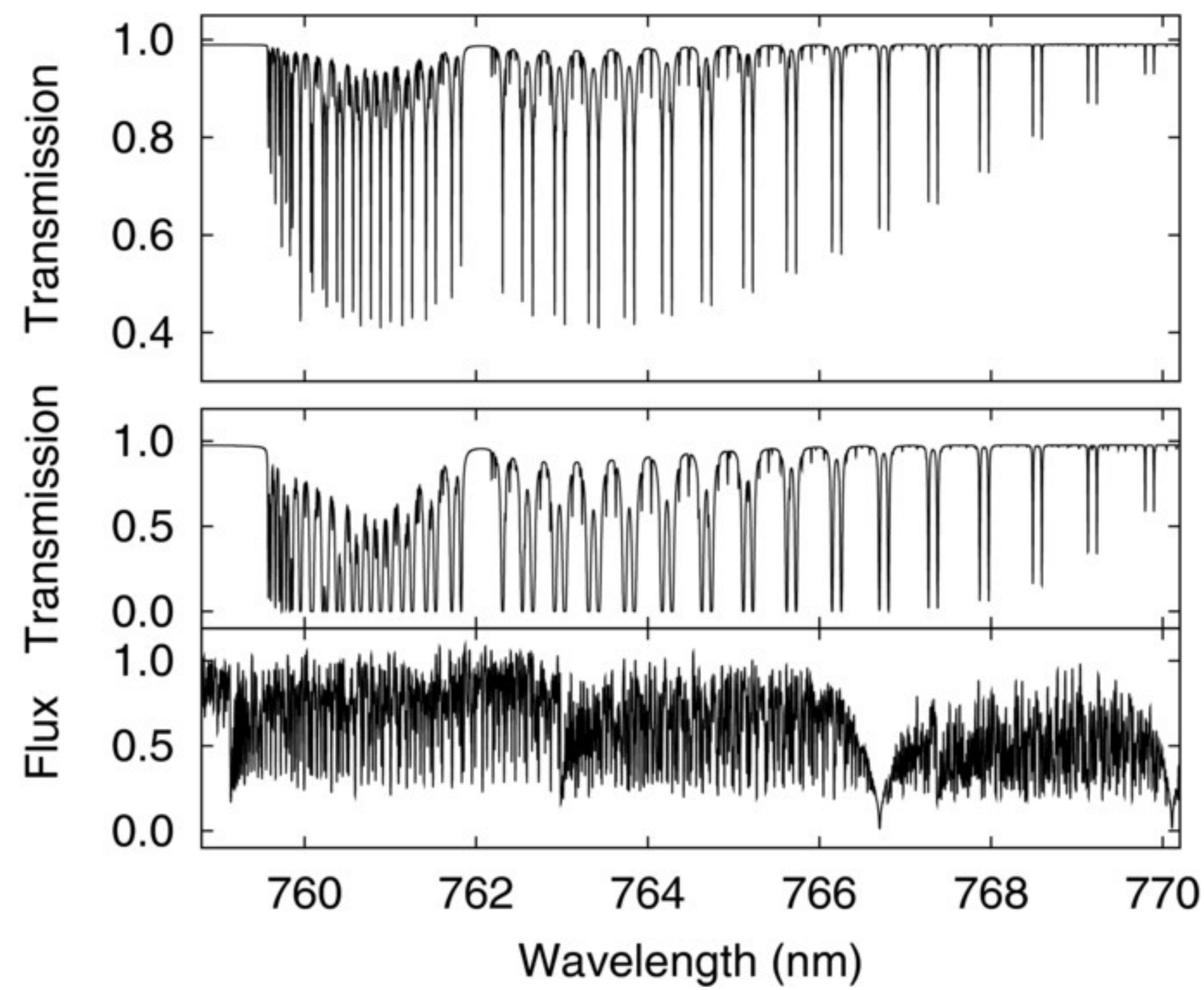


Morley et al. 2017

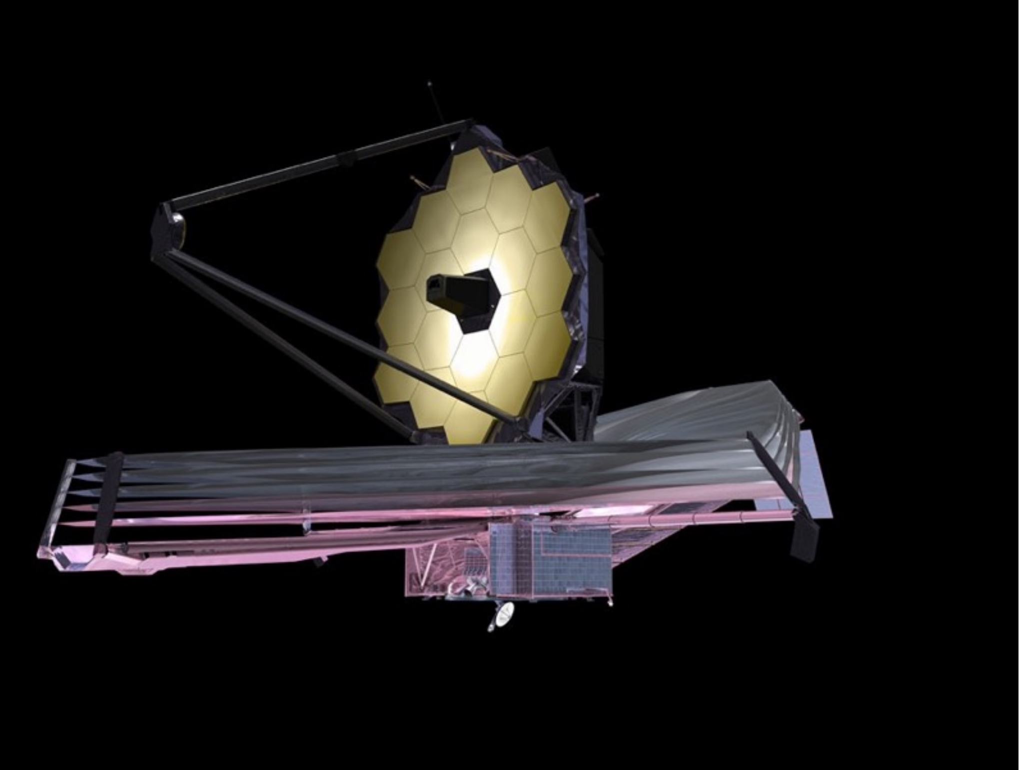


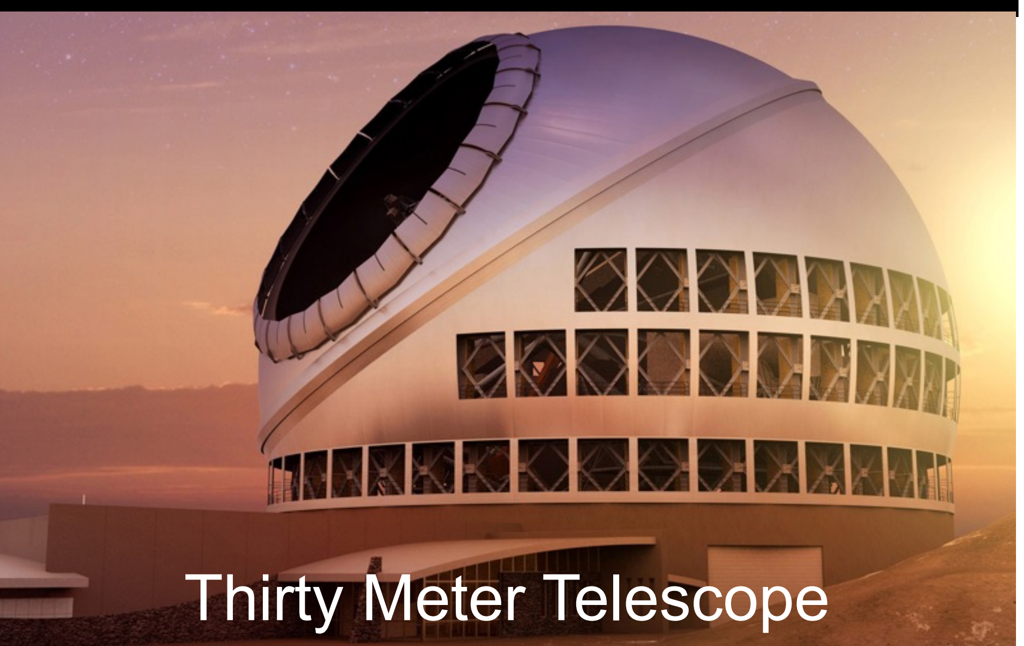


Transmission Spectroscopy at High Spectral Resolution



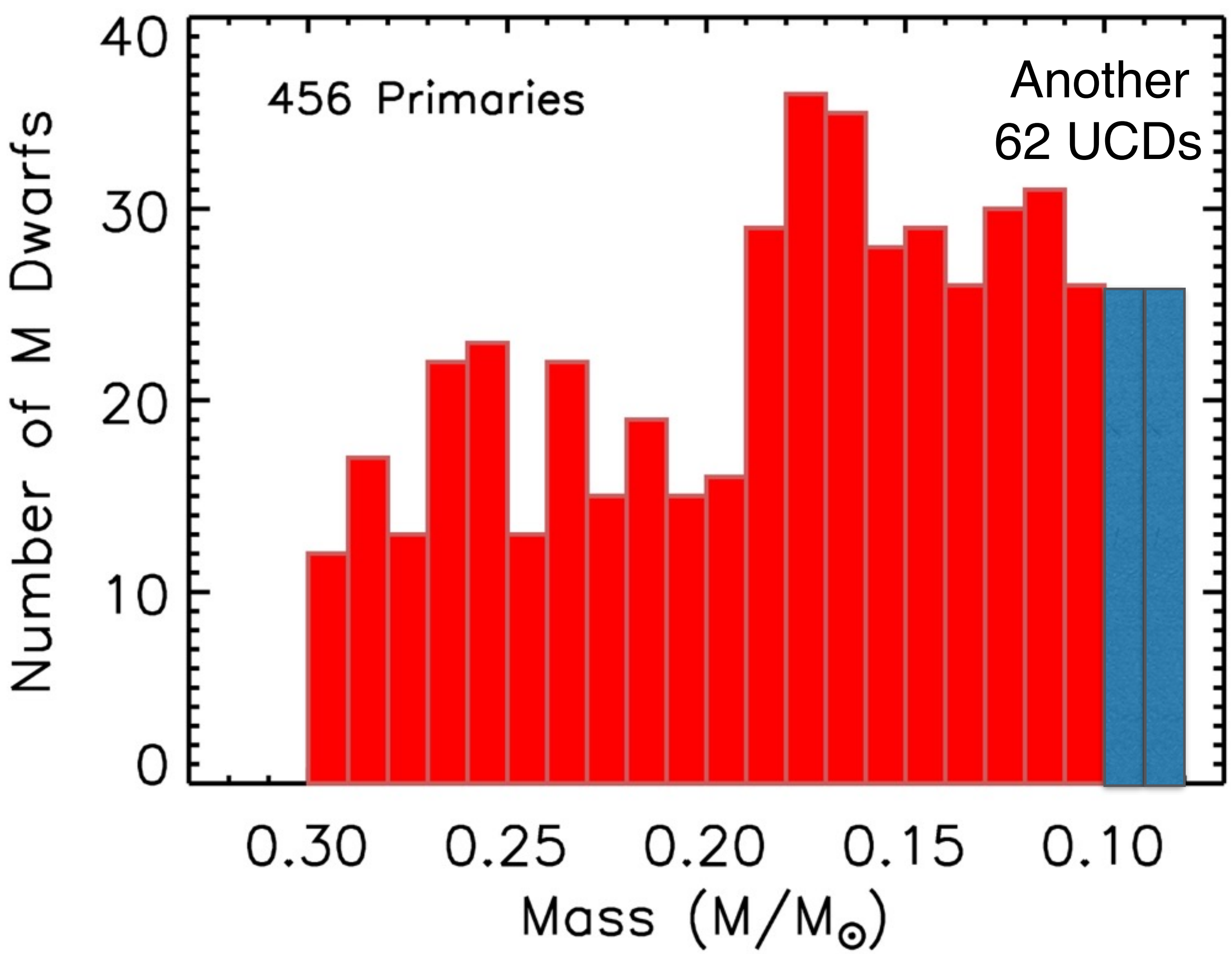
Rodler & Lopez-Morales (2014)





The only temperate, terrestrial planet atmospheres that we will study in the next 15 years will be for planets that orbit M dwarfs.

This idea works for only nearby stars with masses < 0.3 M_{Sun}.



Jennifer Winters

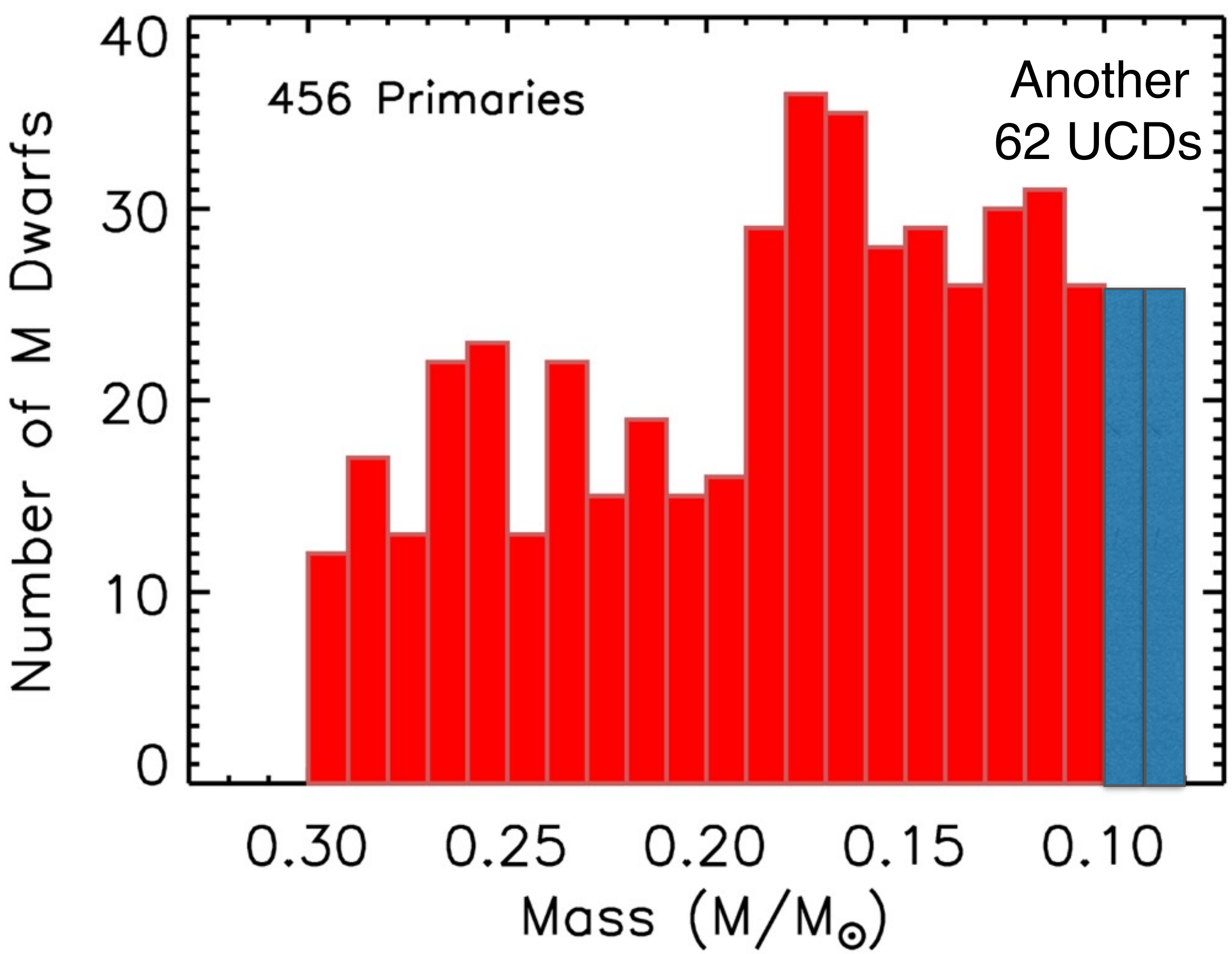
Some Reasons to Think M-Dwarfs May Not Host Inhabited Planets:

Planets would spend the first 100-1000 Myr experiencing much stronger bolometric irradiation due to extended stellar pre-main-sequence phase.

Planets would be tidally locked.

Planets would receive too much UV light throughout their lifetime.

This idea works for only nearby stars with masses < 0.3 M_{Sun}.



Jennifer Winters

Some Reasons to Think M-Dwarfs May Not Host Inhabited Planets:

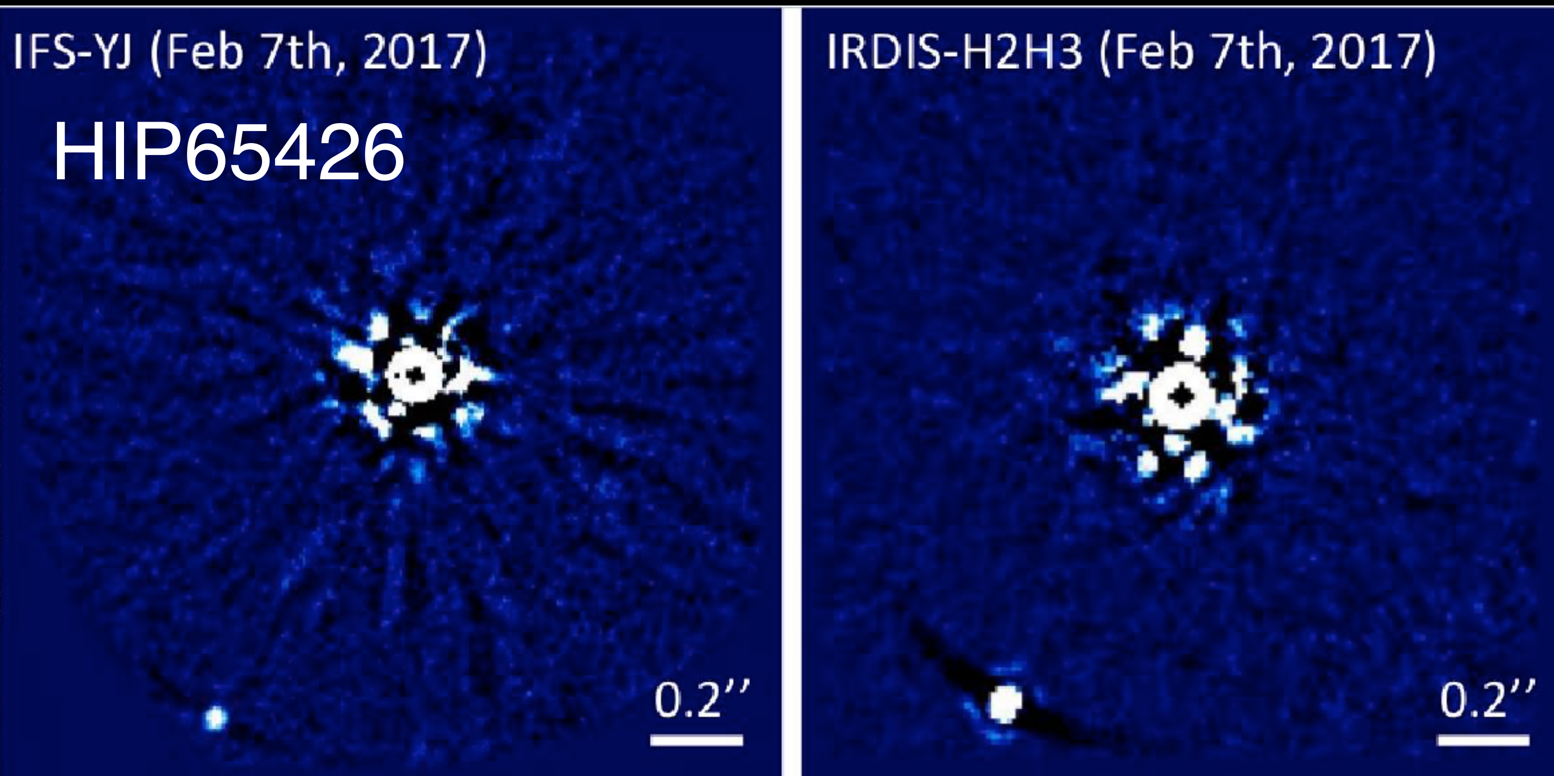
Such planets would spend the first 100-1000 Myr experiencing much stronger bolometric irradiation due to extended stellar pre-main-sequence phase.

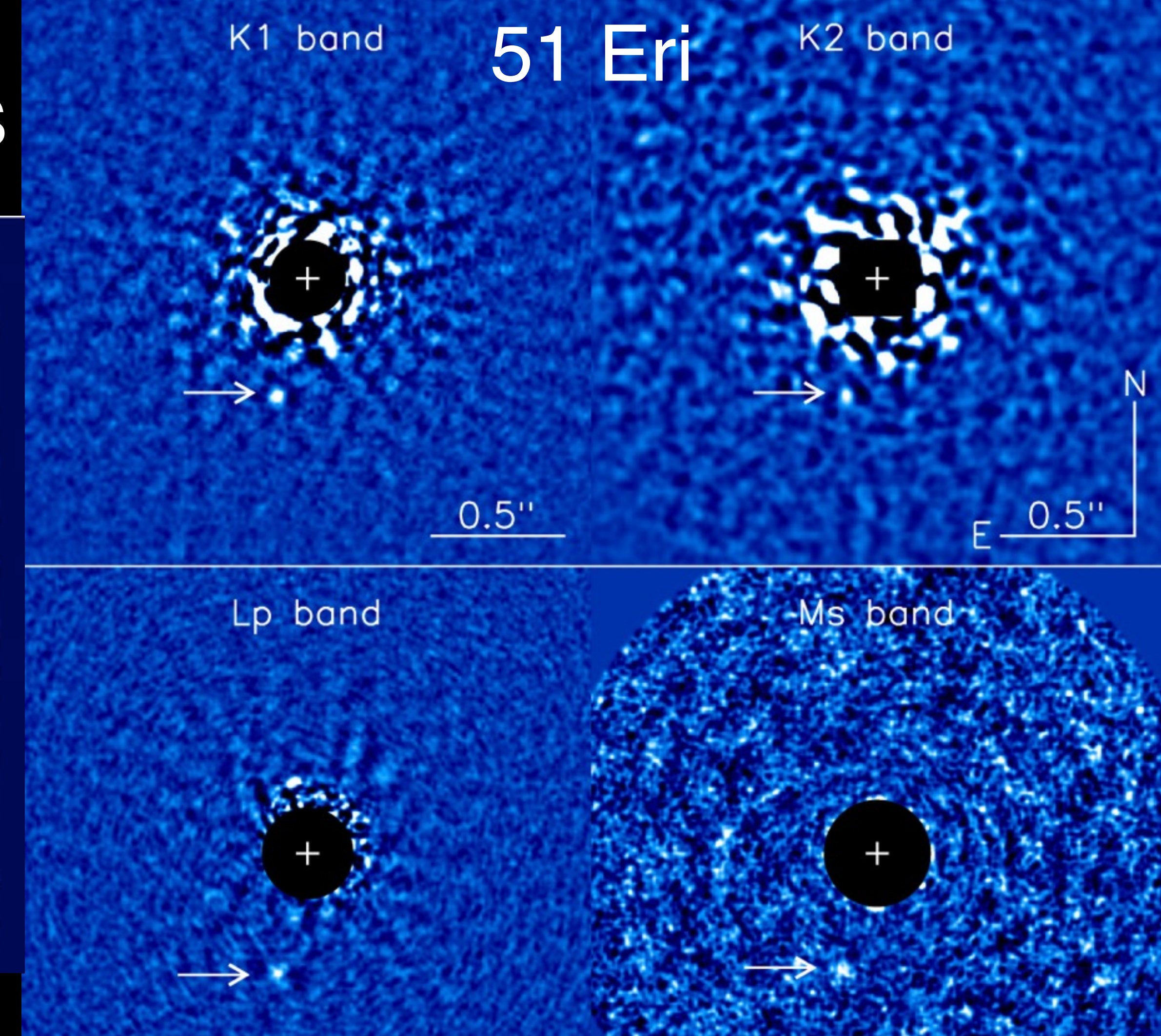
Such planets would be tidally locked.

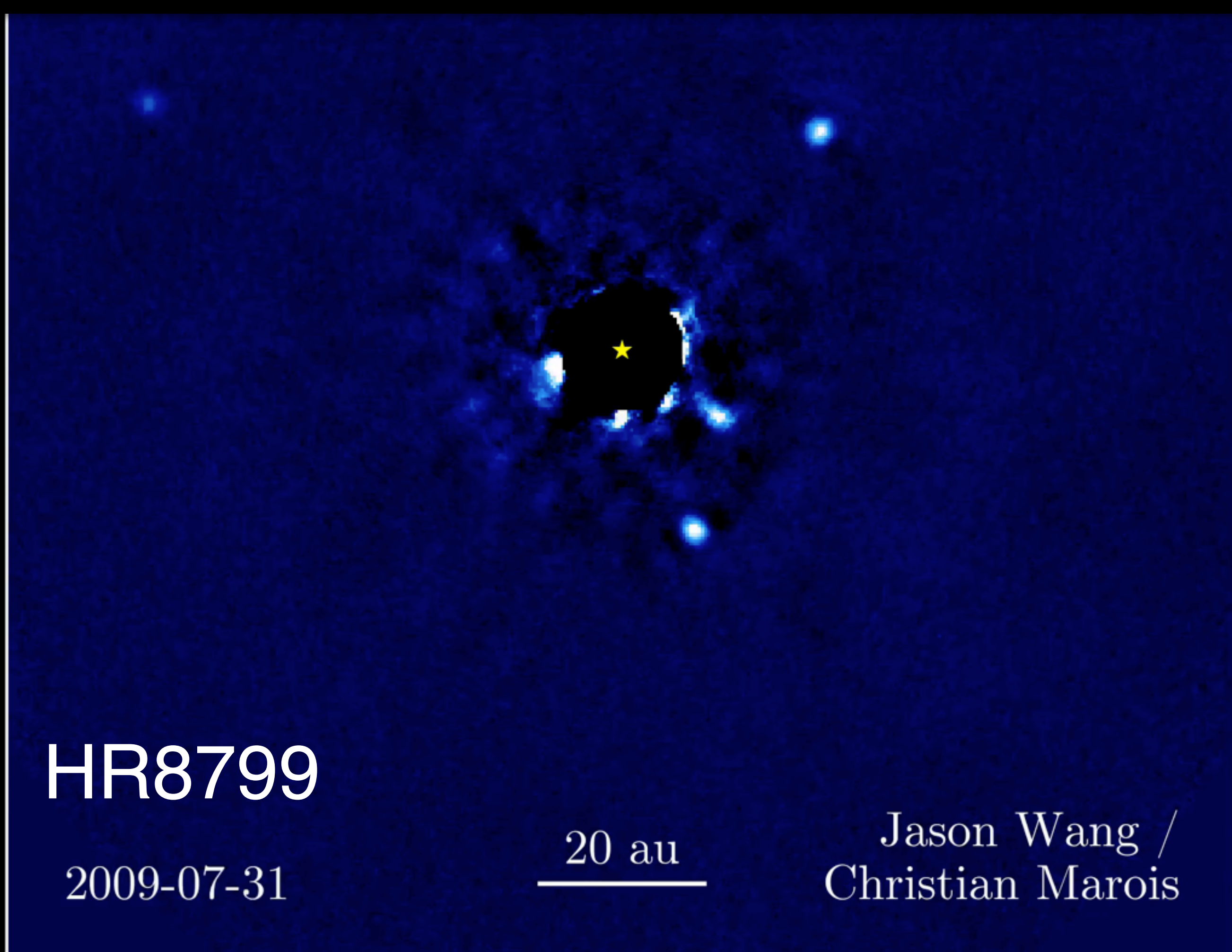
Such planets would receive too much UV light throughout their lifetime.

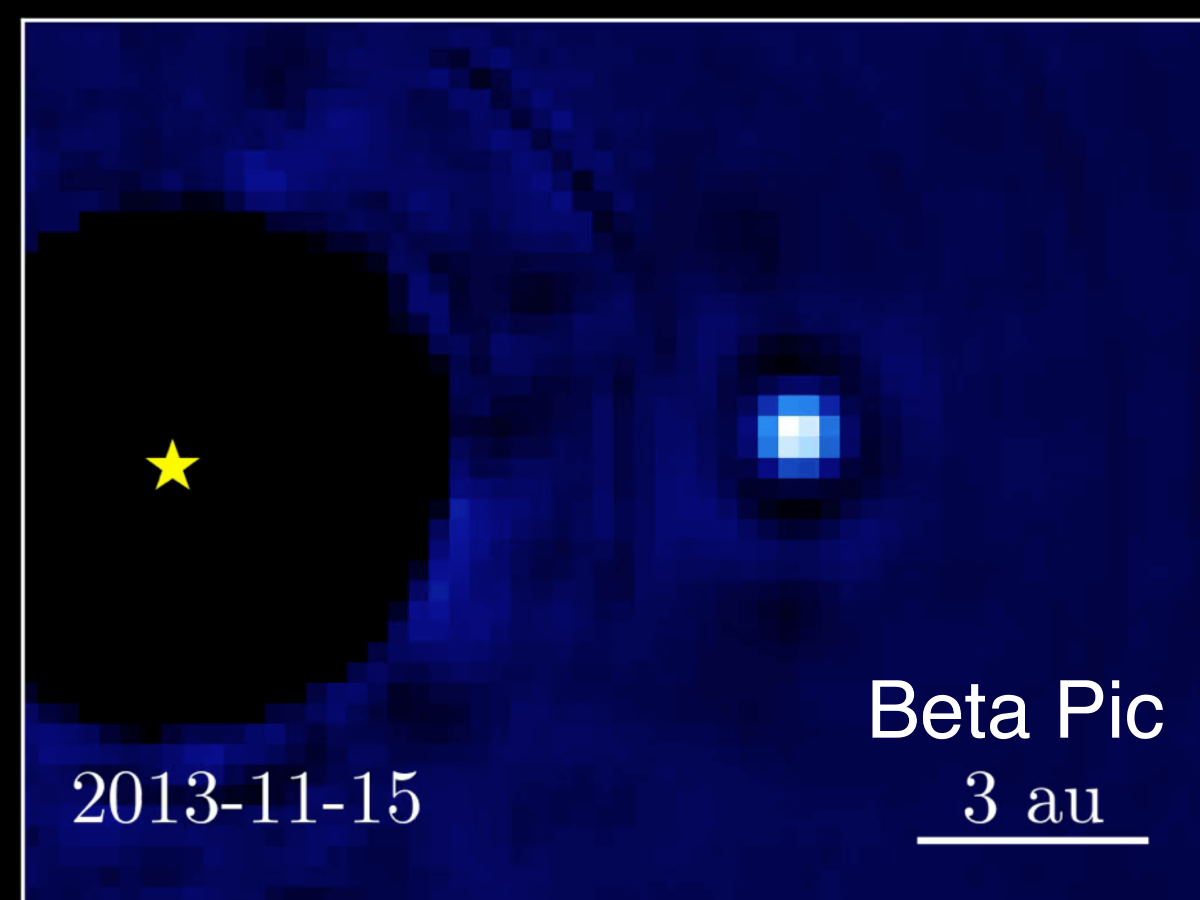
Given these concerns, and the fact that at least one Sun-like star supports life, astronomers are pursuing a separate path to study terrestrial worlds around Sun-like stars.

A Gallery of Directly Imaged Planets







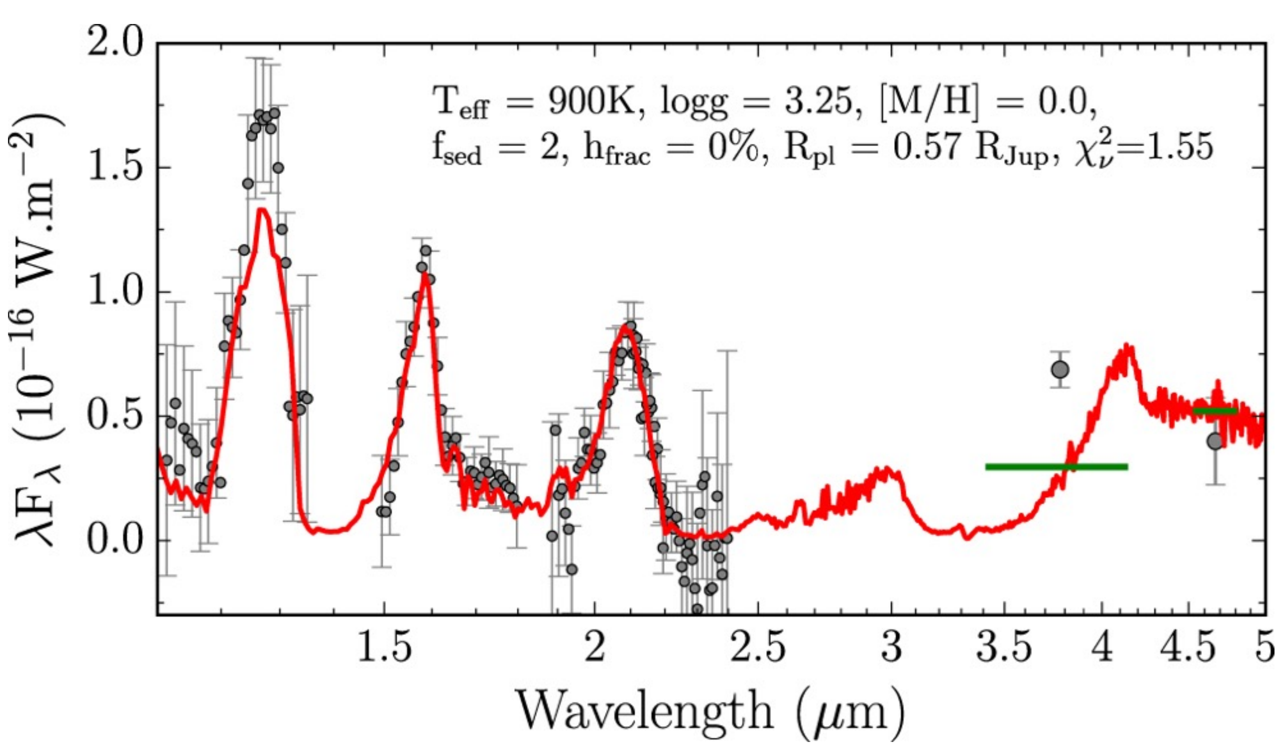


Spectroscopy of Directly Imaged Planets

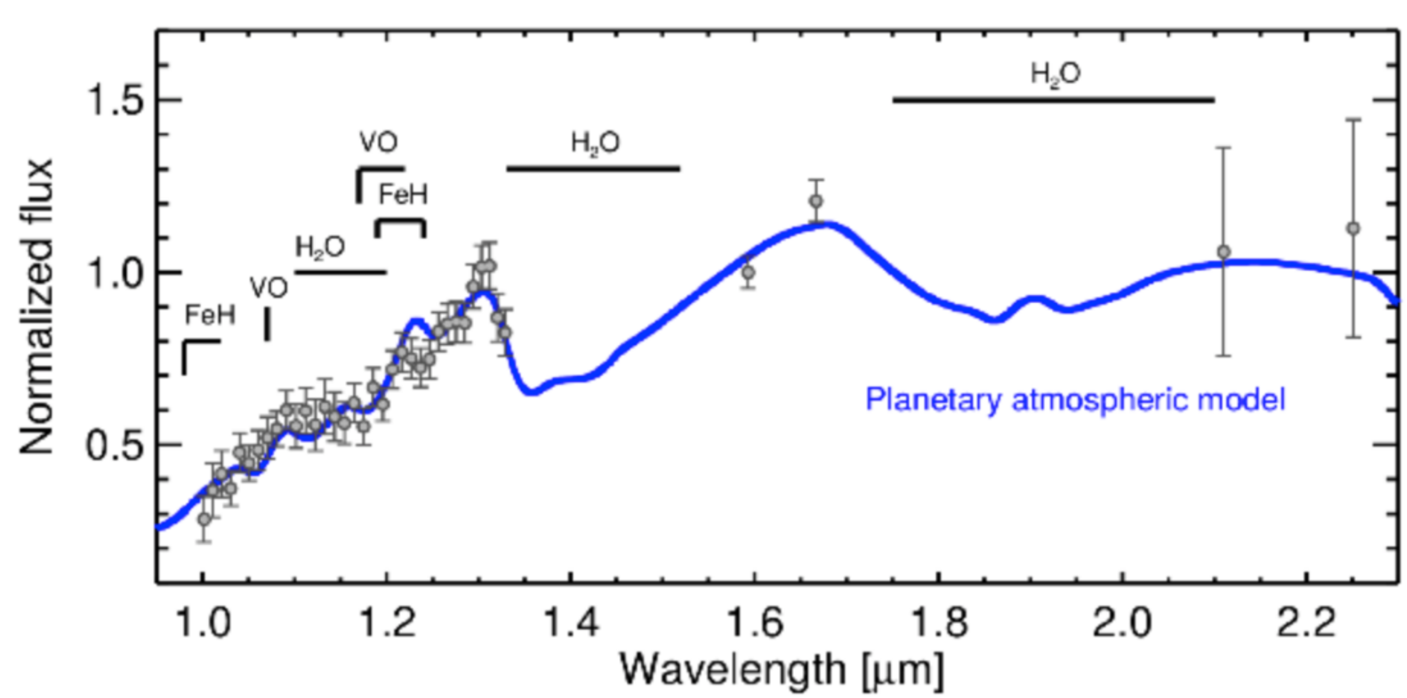
The handful of directly imaged planets are all young gas giants at large orbital separations. The heat and orbital separation permit spectroscopy with current 8m class telescopes.

The diffraction limit of the ELTs will naturally move the probed region in from 20 AU to 5 AU, enabling detection of solar system analogs.

Imaging temperate terrestrial planets orbiting Sun-like stars will likely not be possible with the ELTs.



51 Eri B: Rajan et al. 2017



HIP65426b: Chauvin al. 2017

In 2015, Paul Hertz established Large Mission Concept Studies to provide input into the Astrophysics Decadal Survey:

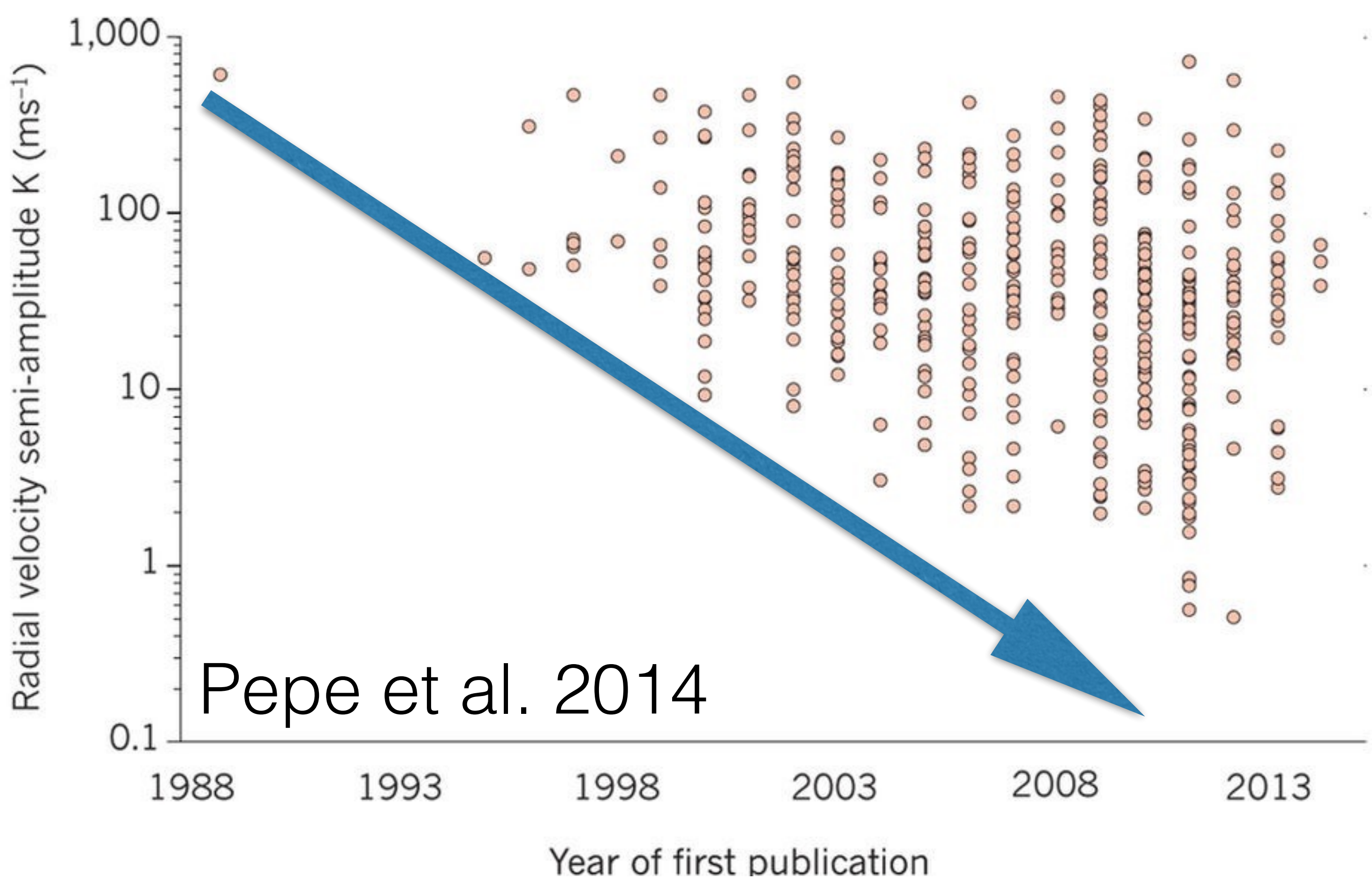
	Brief description	Lead Center
Far Infrared Surveyor **OST**	The Astrophysics Visionary Roadmap identifies a Far IR Surveyor with improvements in sensitivity, spectroscopy, and angular resolution.	Goddard Space Flight Center
Habitable-Exoplanet Imaging Mission **HabEx**	The 2010 Astrophysics Decadal Survey recommends that a habitable-exoplanet imaging mission be studied in time for consideration by the 2020 Astrophysics Decadal Survey.	Jet Propulsion Laboratory
UV/Optical/IR Surveyor **LUVOIR**	The Astrophysics Visionary Roadmap identifies a UV/Optical/IR Surveyor with improvements in sensitivity, spectroscopy, high contrast imaging, astrometry, angular resolution and/or wavelength coverage. The 2010 Astrophysics Decadal Survey recommends that NASA prepare for a UV mission to be considered by the 2020 Astrophysics Decadal Survey.	Goddard Space Flight Center
X-ray Surveyor **LYNX**	The Astrophysics Visionary Roadmap identifies an X-ray Surveyor with improvements in sensitivity, spectroscopy, and angular resolution.	Marshall Space Flight Center

Large Mission Concept Studies: Leadership and Timeline

	Community STDT Chairs	Center Study Team	Study Lead Center
Far IR Surveyor	Asantha Cooray Margaret Meixner	David Leisawitz Ruth Carter	GSFC
Habitable Exoplanet Imaging Mission	Scott Gaudi Sara Seager	Bertrand Mennesson Keith Warfield	JPL
Large UV/Optical/IR Surveyor	Debra Fischer Bradley Peterson	Aki Roberge Julie Crooke	GSFC
X-ray Surveyor	Feryal Ozel Alexey Vikhlinin	Jessica Gaskin Karen Gelmis	MSFC

Interim Reports: March 2018
Final Reports: Summer 2019

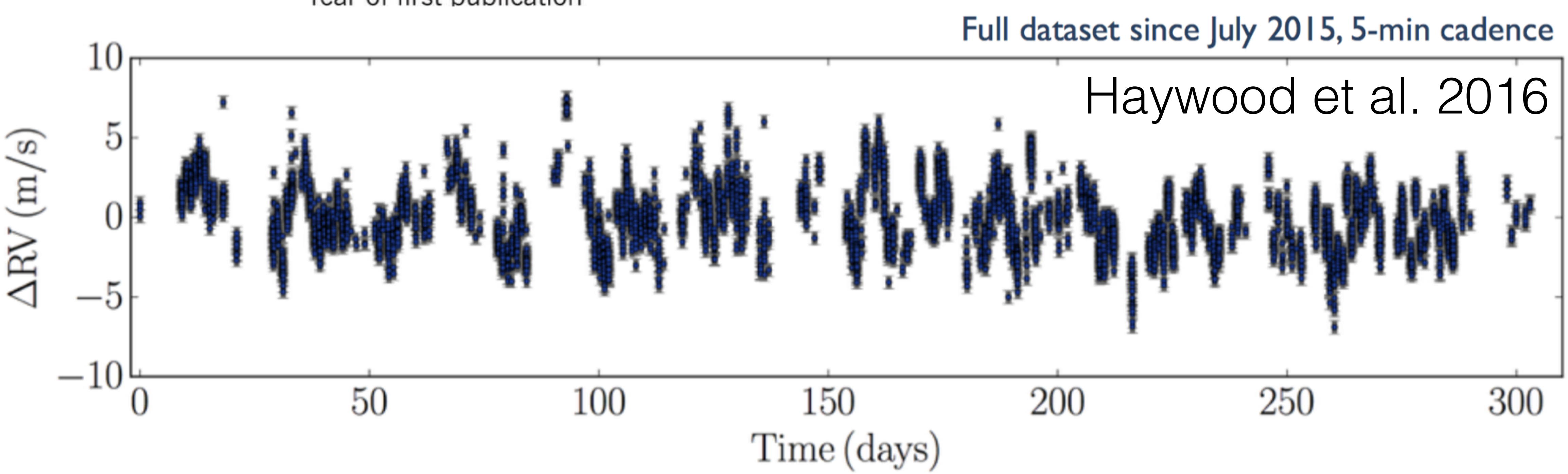
The Need for More Precise Radial Velocities



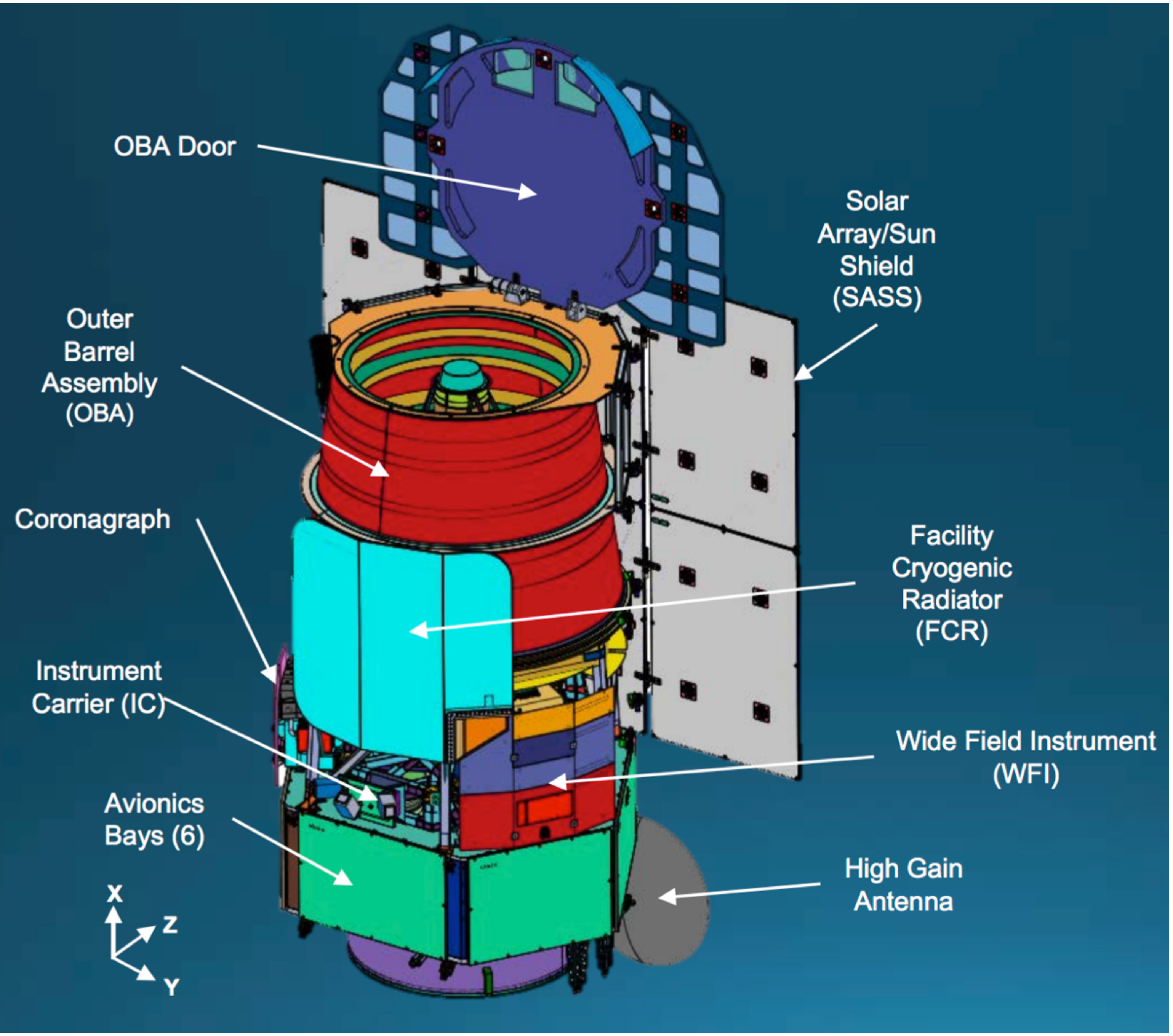
Earth-Sun analog presents 9 cm/s.

Enable discovery of targets around nearby stars, and mass measurements of know planets.

Enable enormous scientific return from current & planned missions.



Wide Field Infrared Survey Telescope



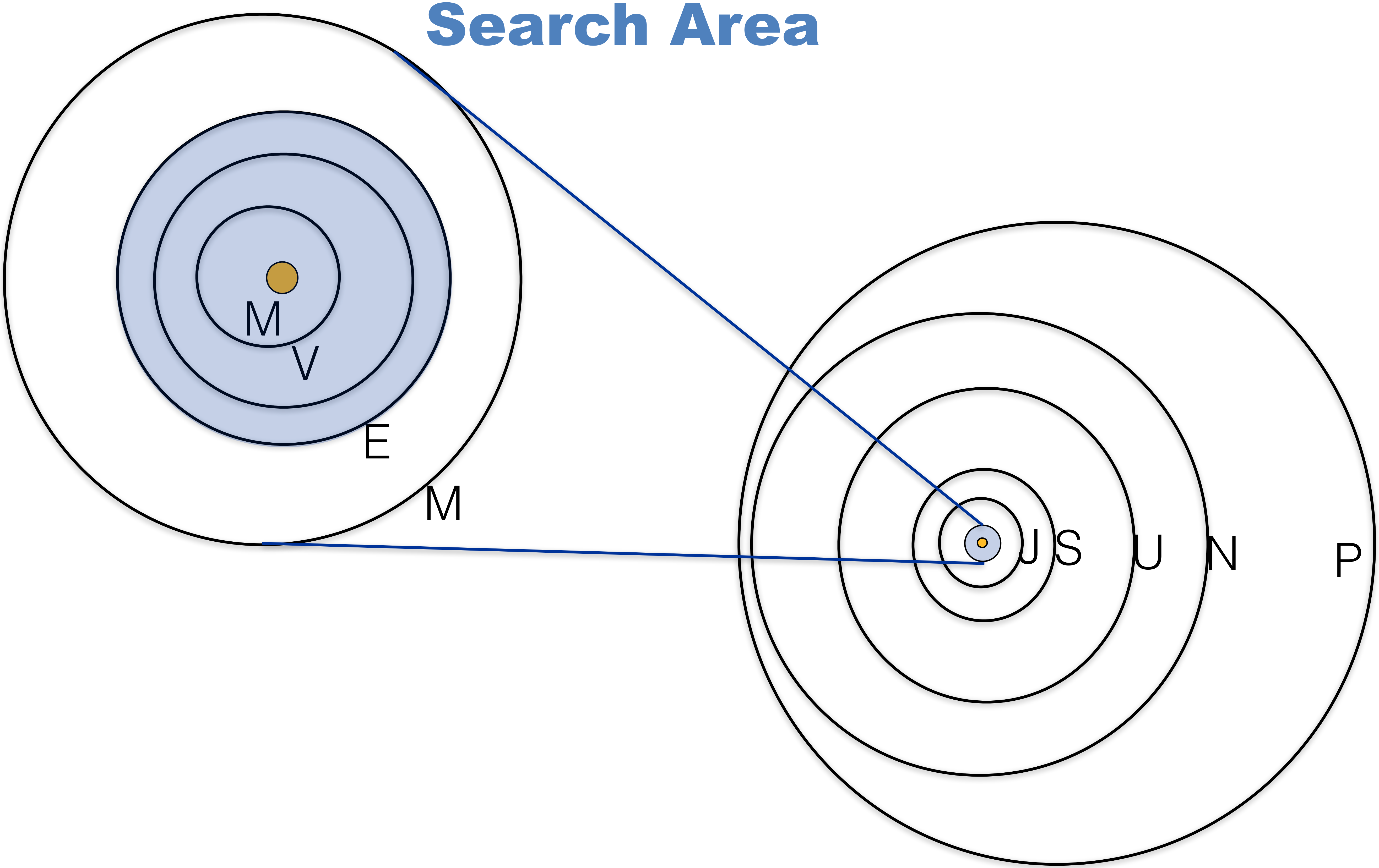
Coronagraphic Instrument

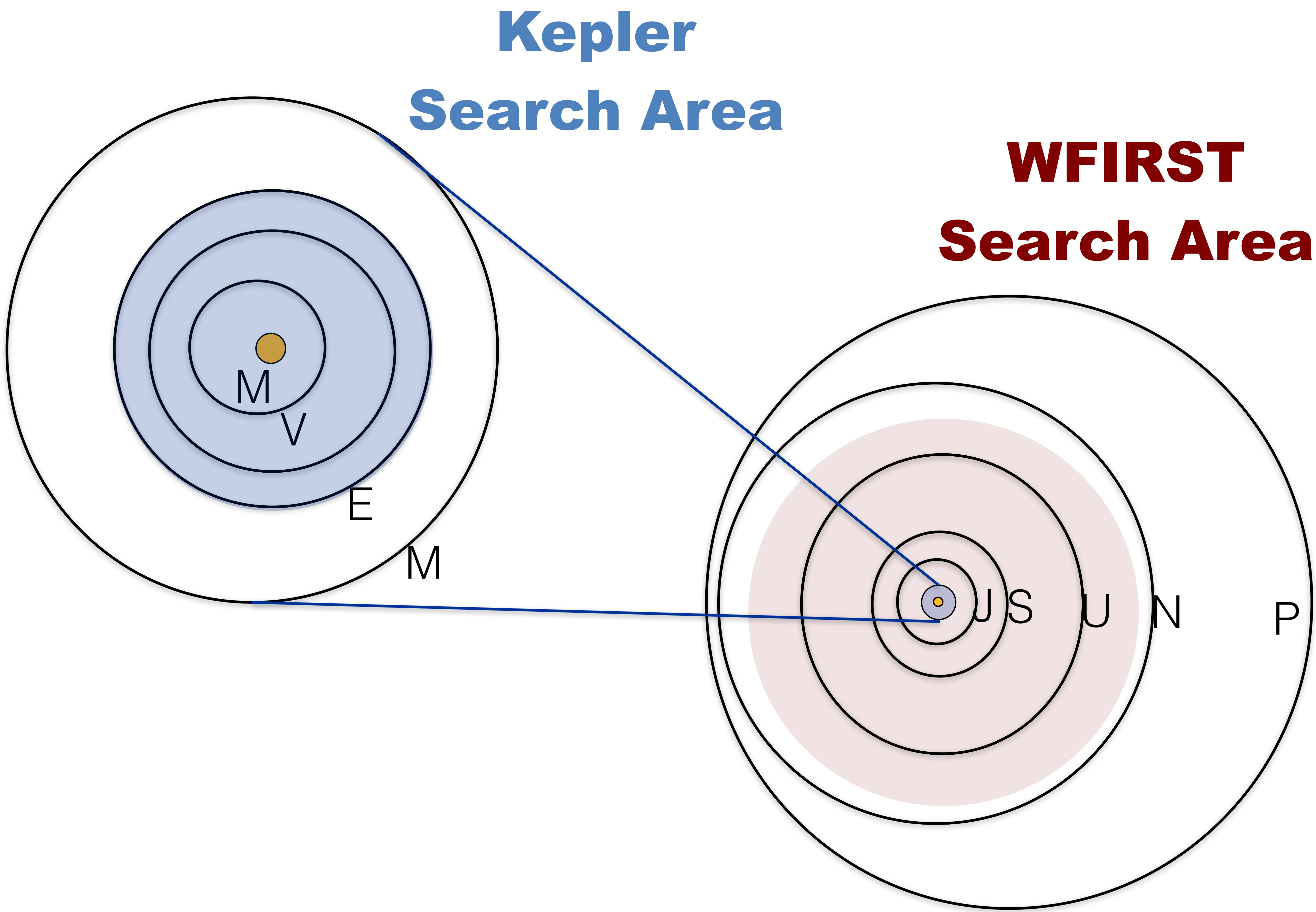
Requirements recently sharpened to serve as technology demonstration instrument. This should significantly advance technology readiness and reduce risk for HabEx and LUVOIR.

Gravitational Lensing Survey

to complete the census of exoplanets beyond the ice line.

Kepler Search Area




Kepler
Search Area
WFIRST
Search Area
M
V
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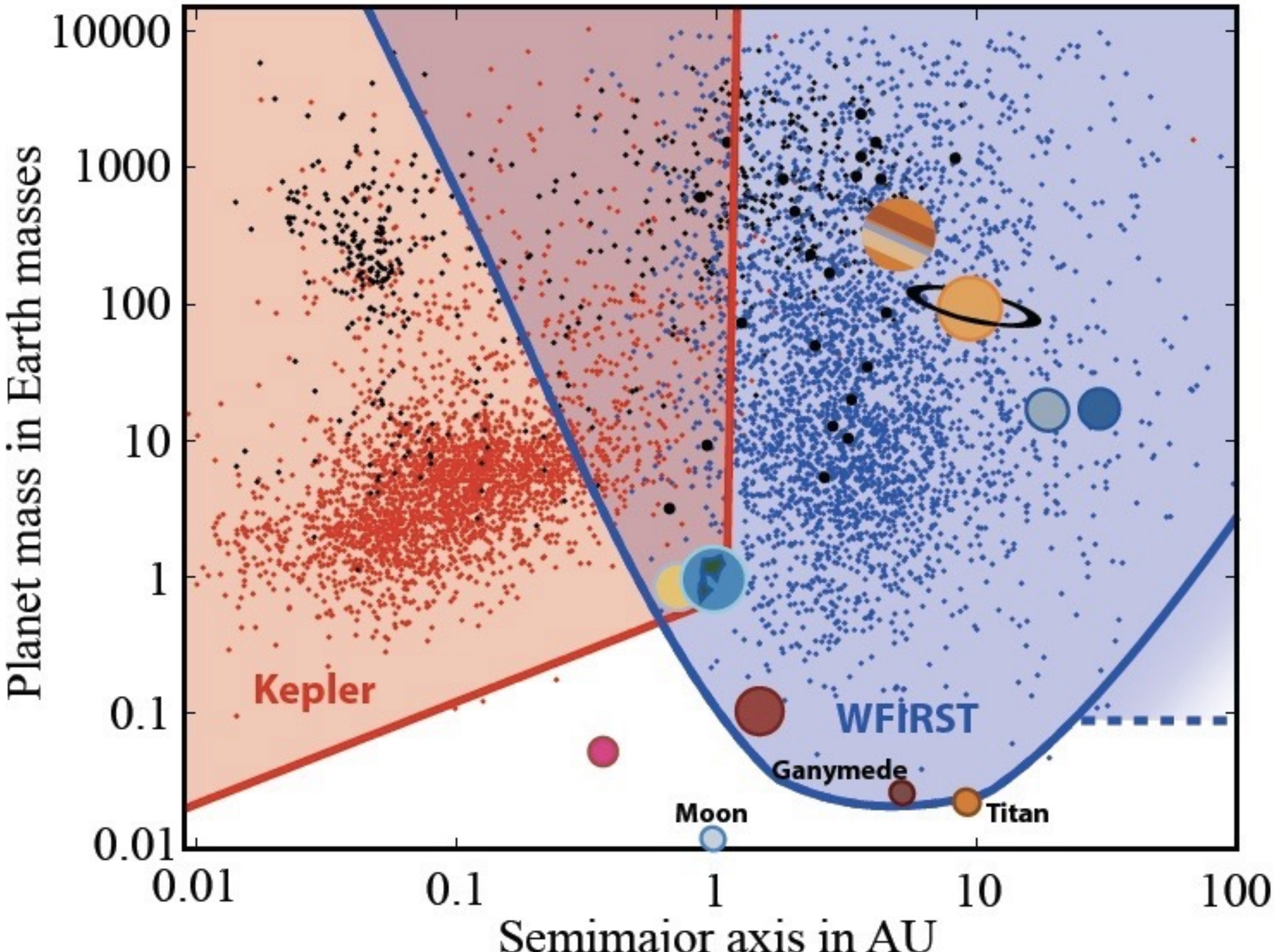
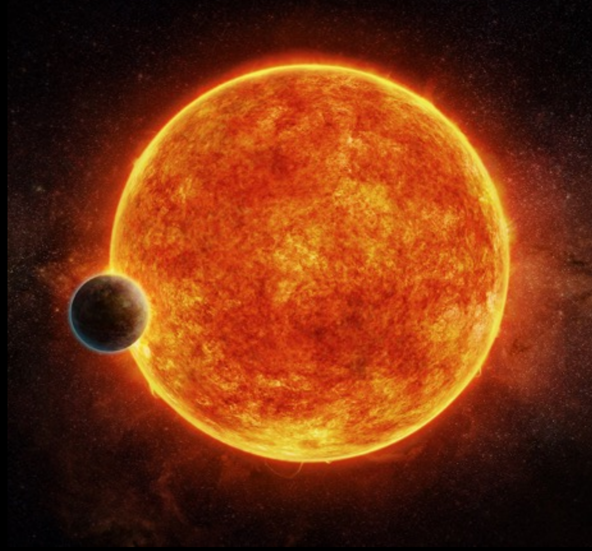
WFIRST's Census of Planets Beyond the Snow Line is Essential to Understand Planet Formation



Penny & Gaudi (2014)

Summary



Atmospheric study of gas giant exoplanets is underway. Kepler and ground astronomy have provided a census of terrestrial exoplanets and their densities.

TESS will find the closest examples for characterization, and WFIRST will complete the census beyond the snow line. Precise RV is essential to reap the scientific return from current & future missions.

There is at least one terrestrial planet per low-mass star habitable zone. Two nearby transiting systems are known. TESS will find more. JWST & the ELTs could search for atmospheric molecules, including biogenic ones.

Recent Kepler HZ planet candidates around Sun-like stars may permit the determination of their rate of occurrence. Atmospheric spectroscopy likely requires space imaging. WFIRST CGI tech demo, and ongoing mission studies will permit an informed consideration of ideas to image Earth analogs.