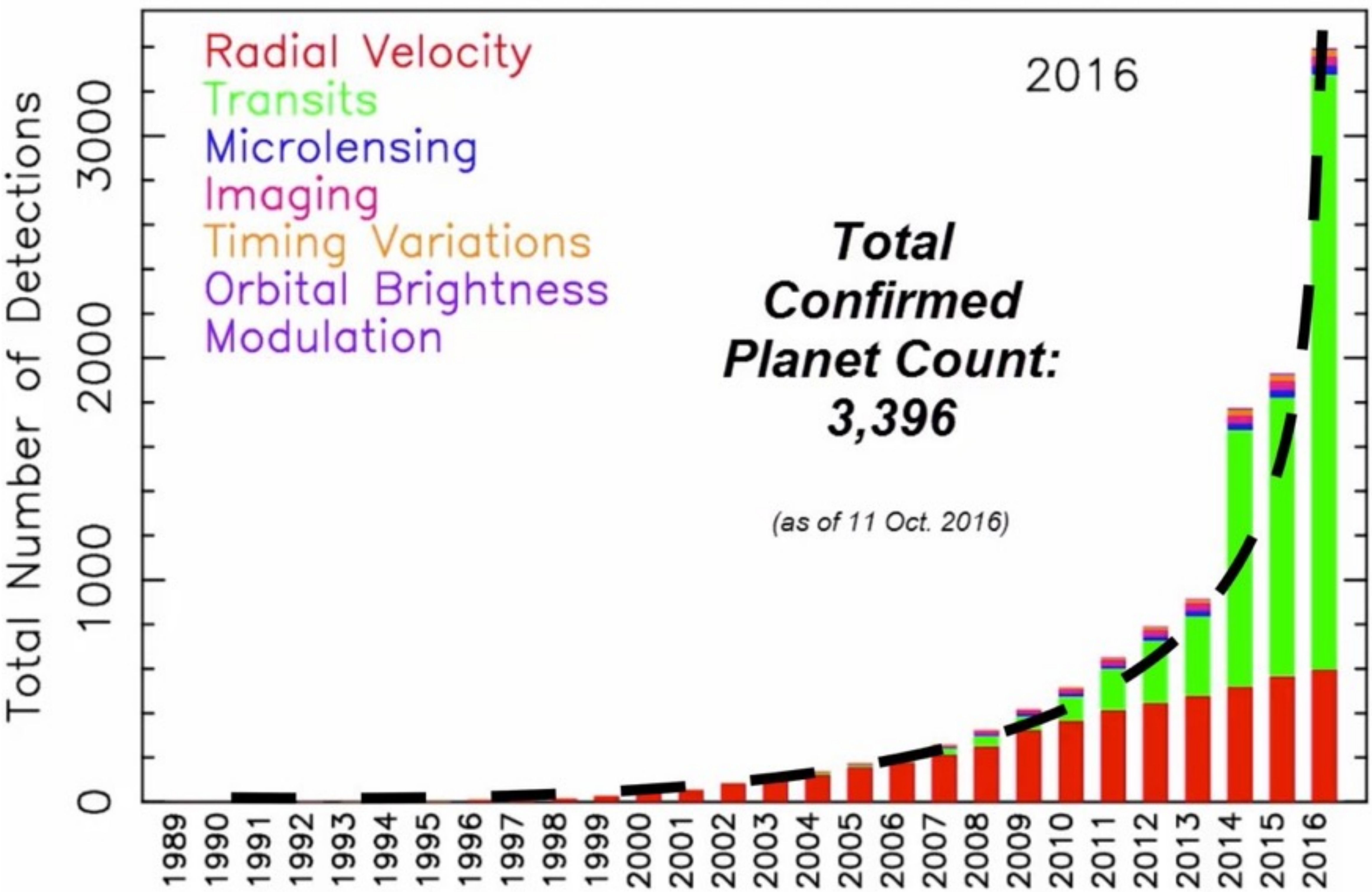
Exoplanet Syzygy: A Star, A Planet, & JWST

David Charbonneau (Harvard)

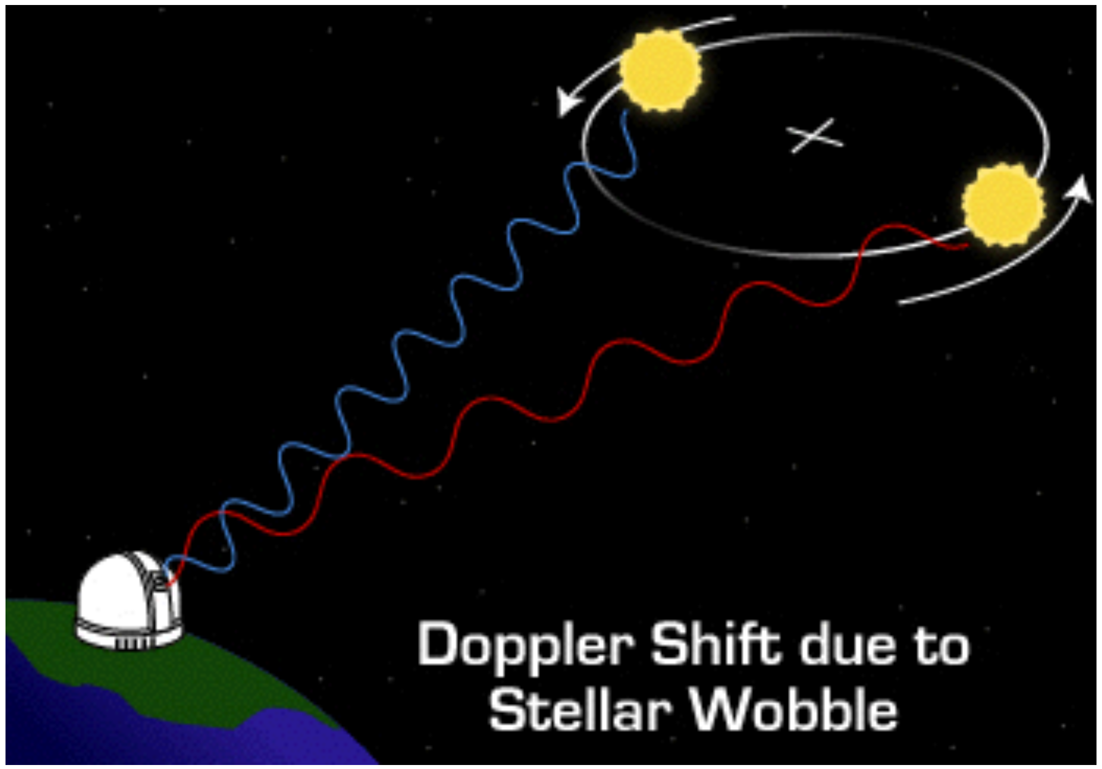
25 October 2016

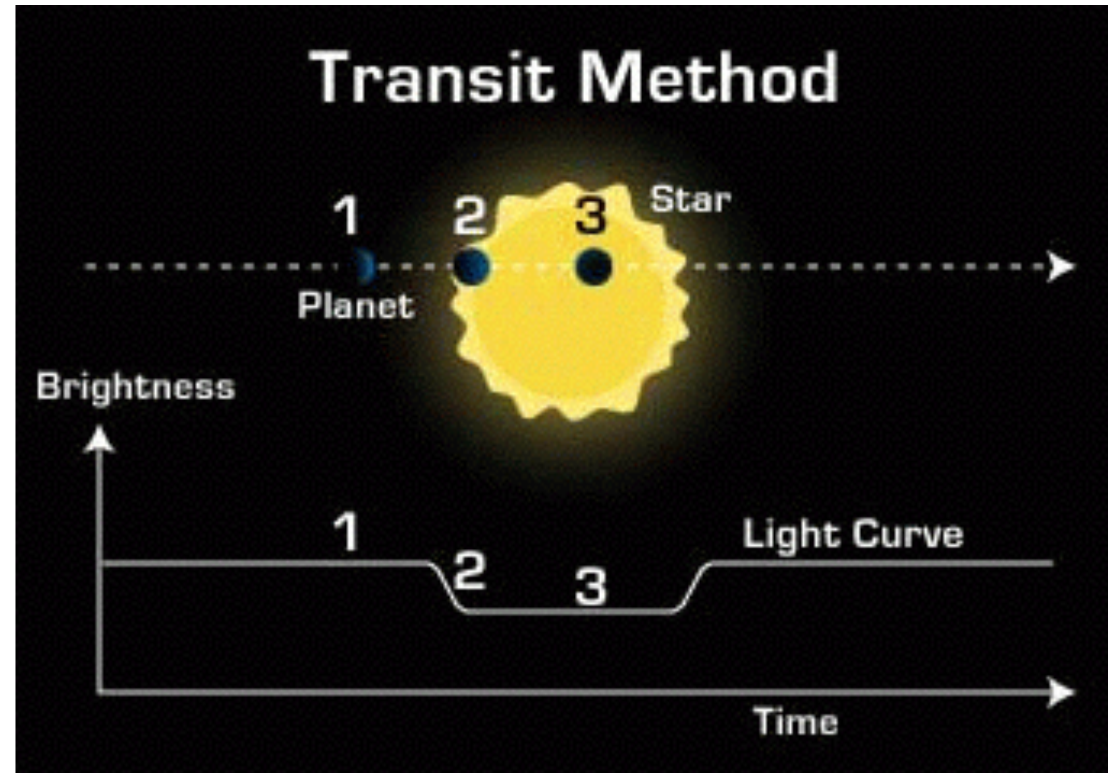
A Special Moment in Human History, and the Right Time to Launch JWST…



courtesy @aussiastronomer (Jessie Christiansen)

Transiting Planets Alone
Grant Access to their Masses and Radii





Doppler Method

Determine Planet Mass

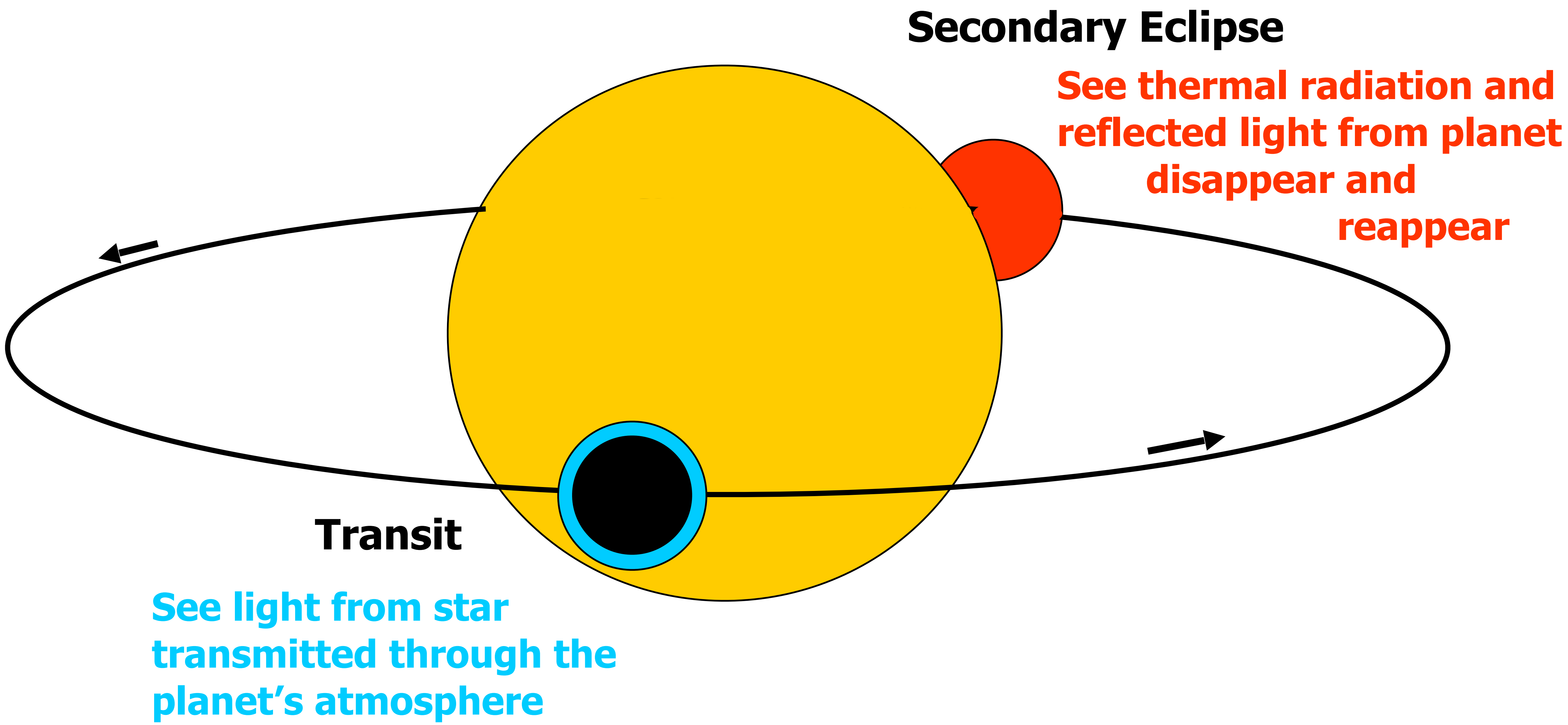
Transit Method

Determine Planet Diameter

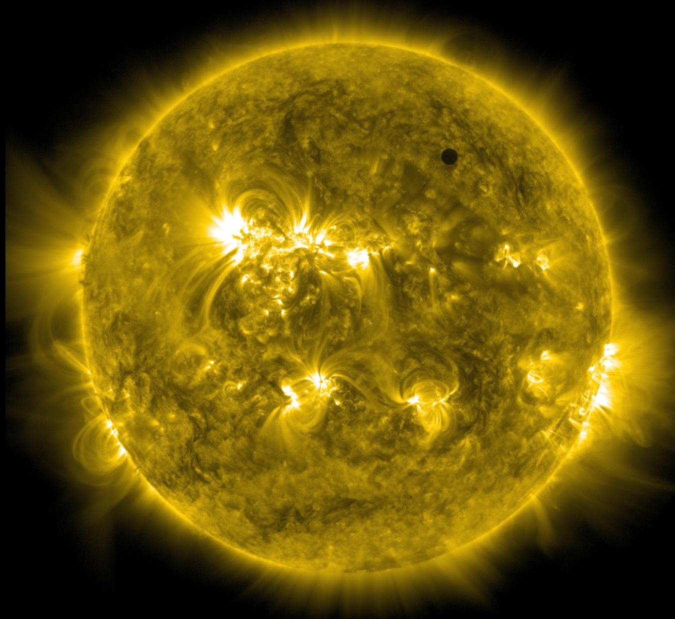
Calculate Planet Density and Infer Composition:

Gas giant (Jupiter) or Rocky planet (Earth)

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



My Plan for Today



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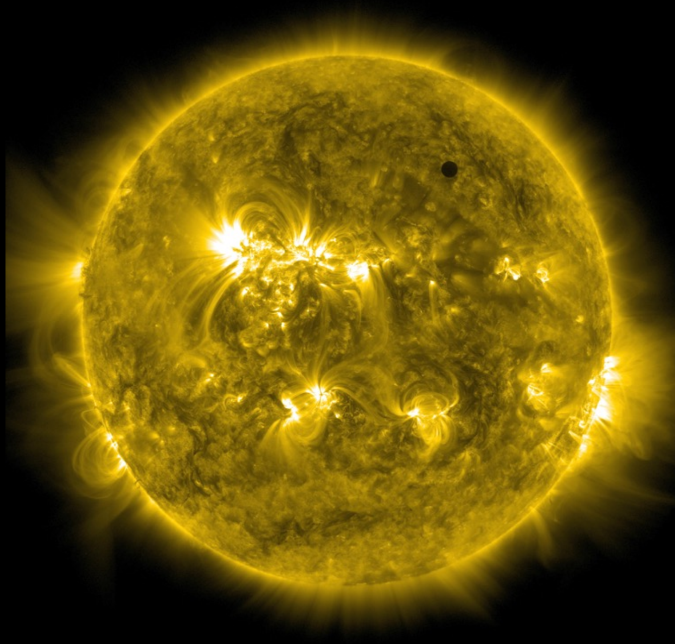

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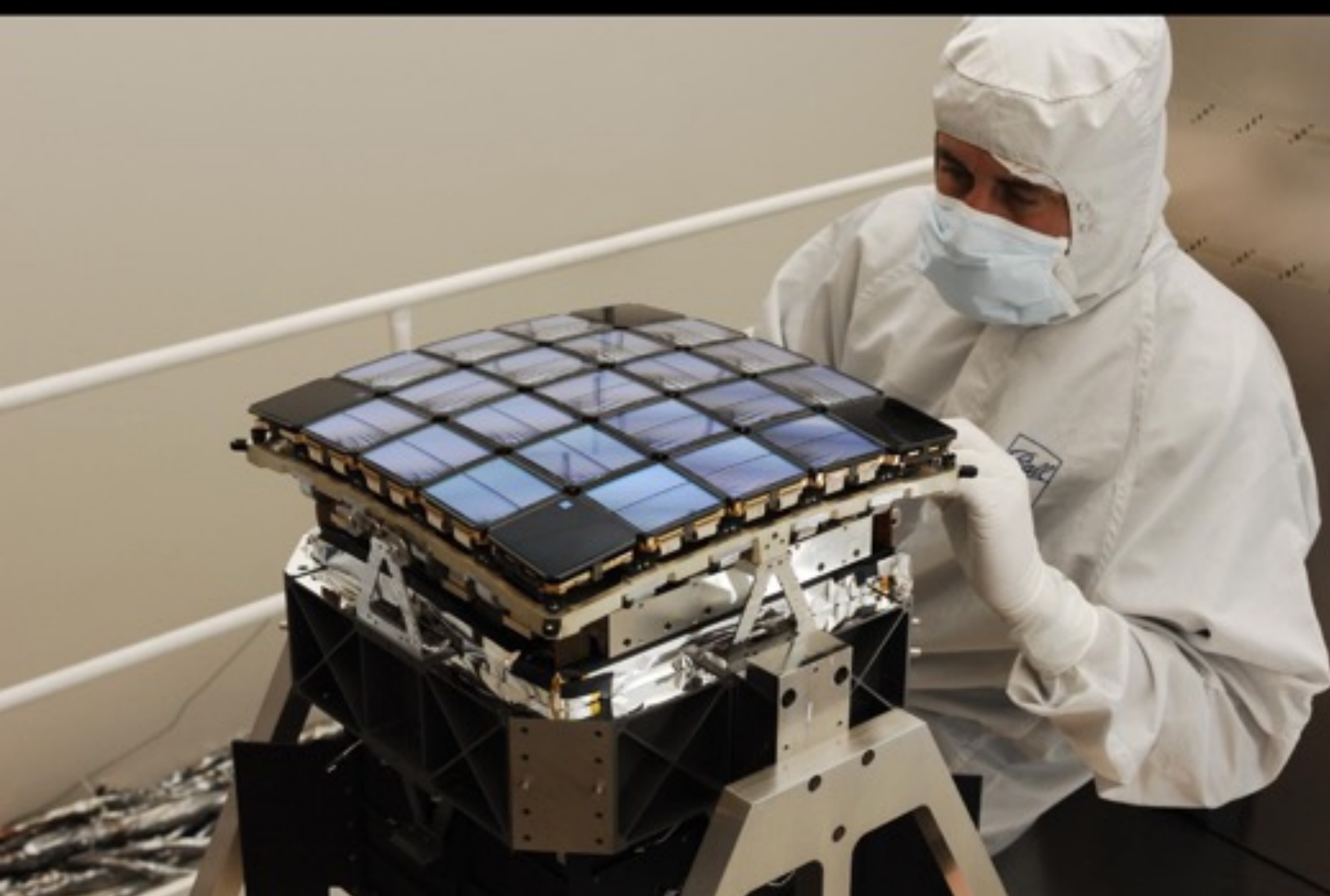
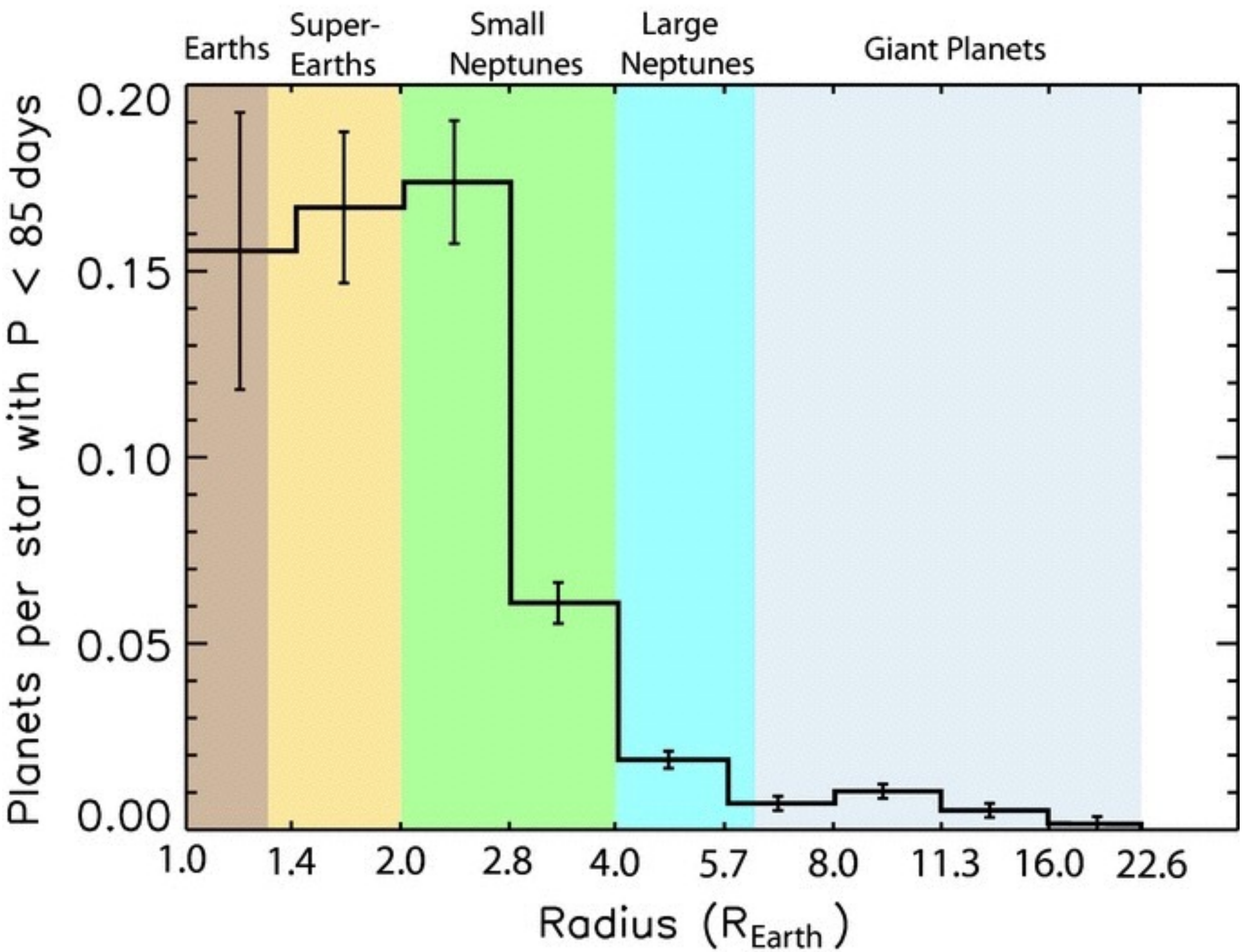
NASA Kepler Mission
2009 – 2013
(now reborn as the K2 Mission, 2014+)



The Planet Radius Distribution for Sun-Like Stars



Fressin, Torres, Charbonneau et al. (2013); see also Petigura+(2013), Burke+(2015)

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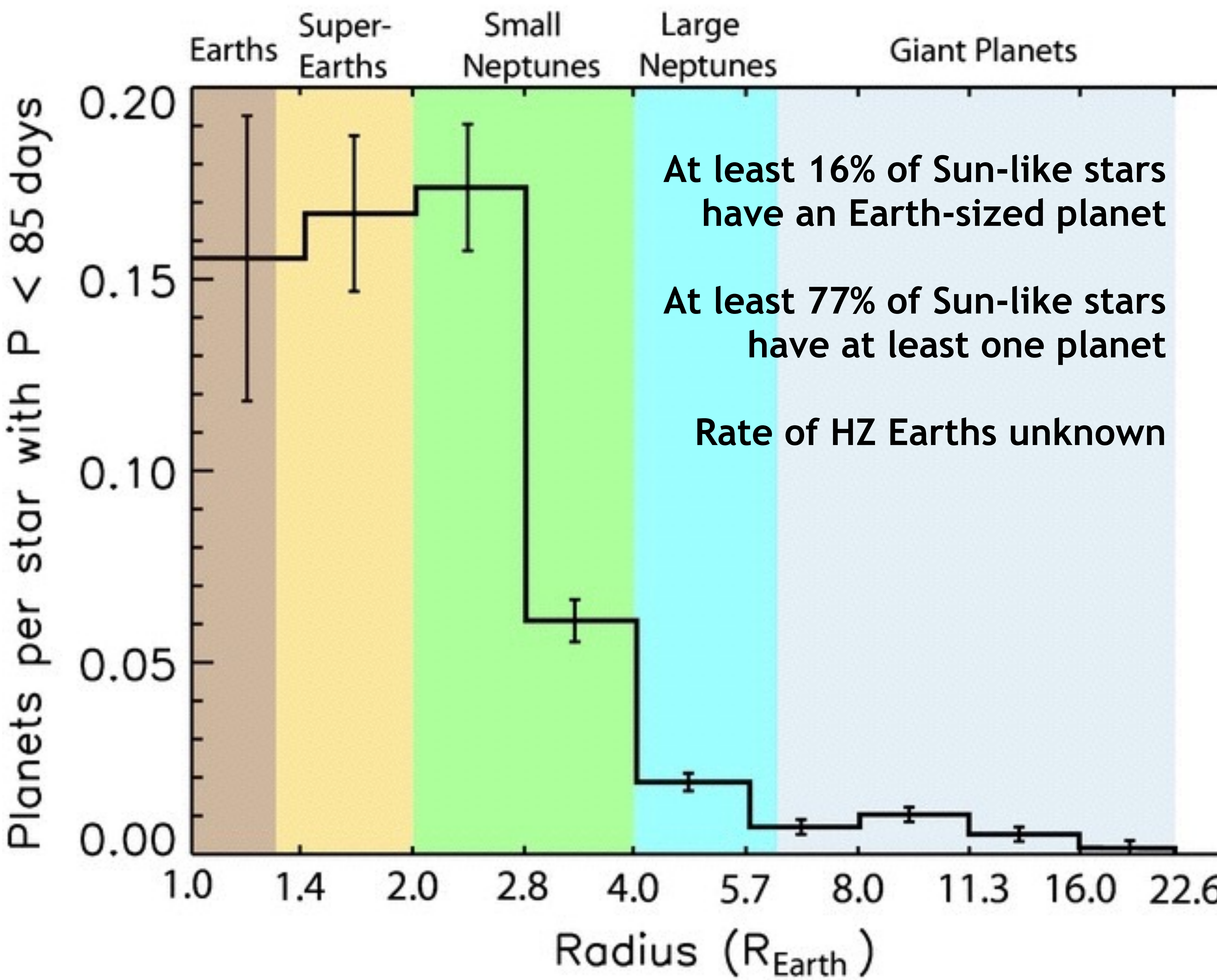
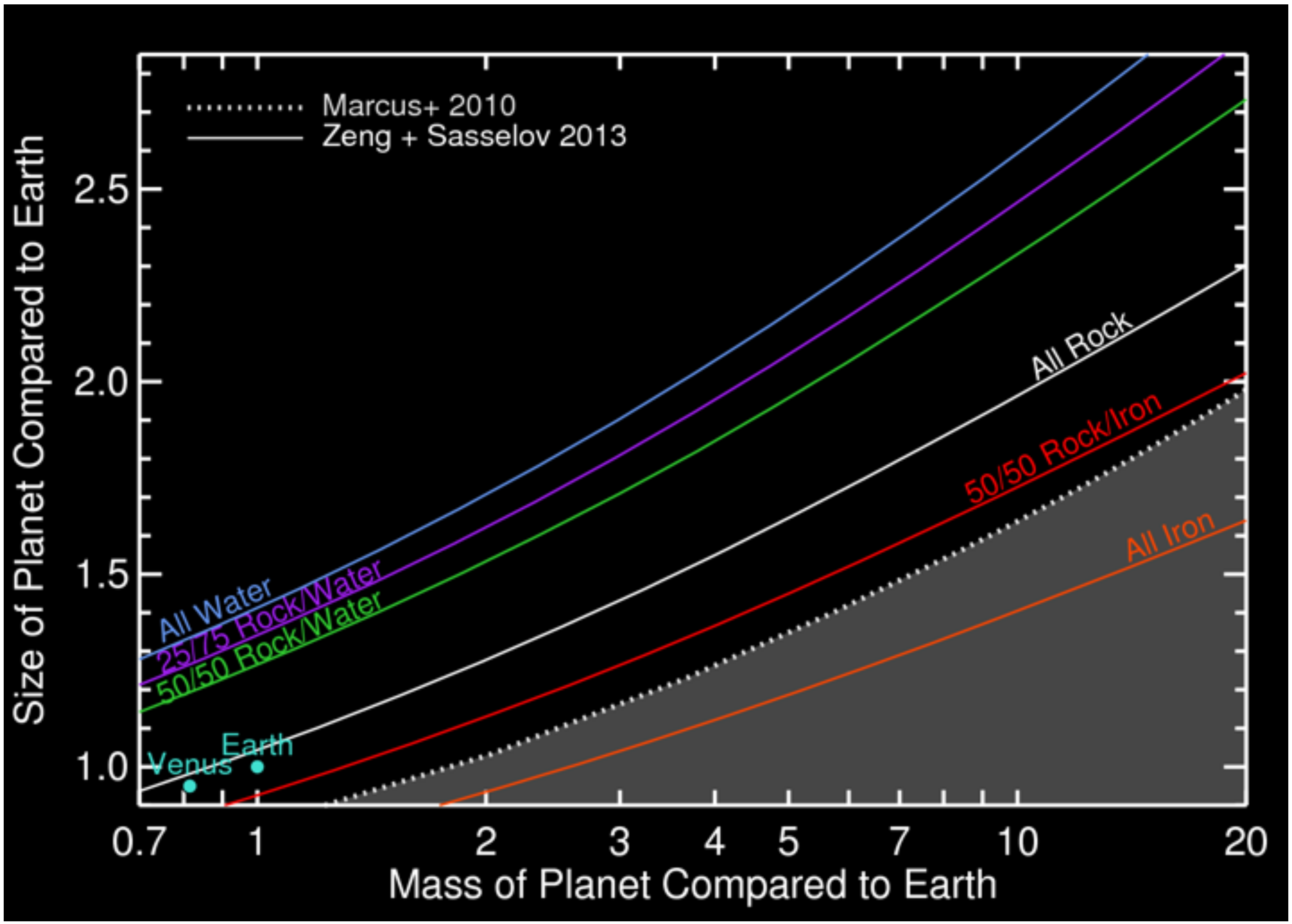


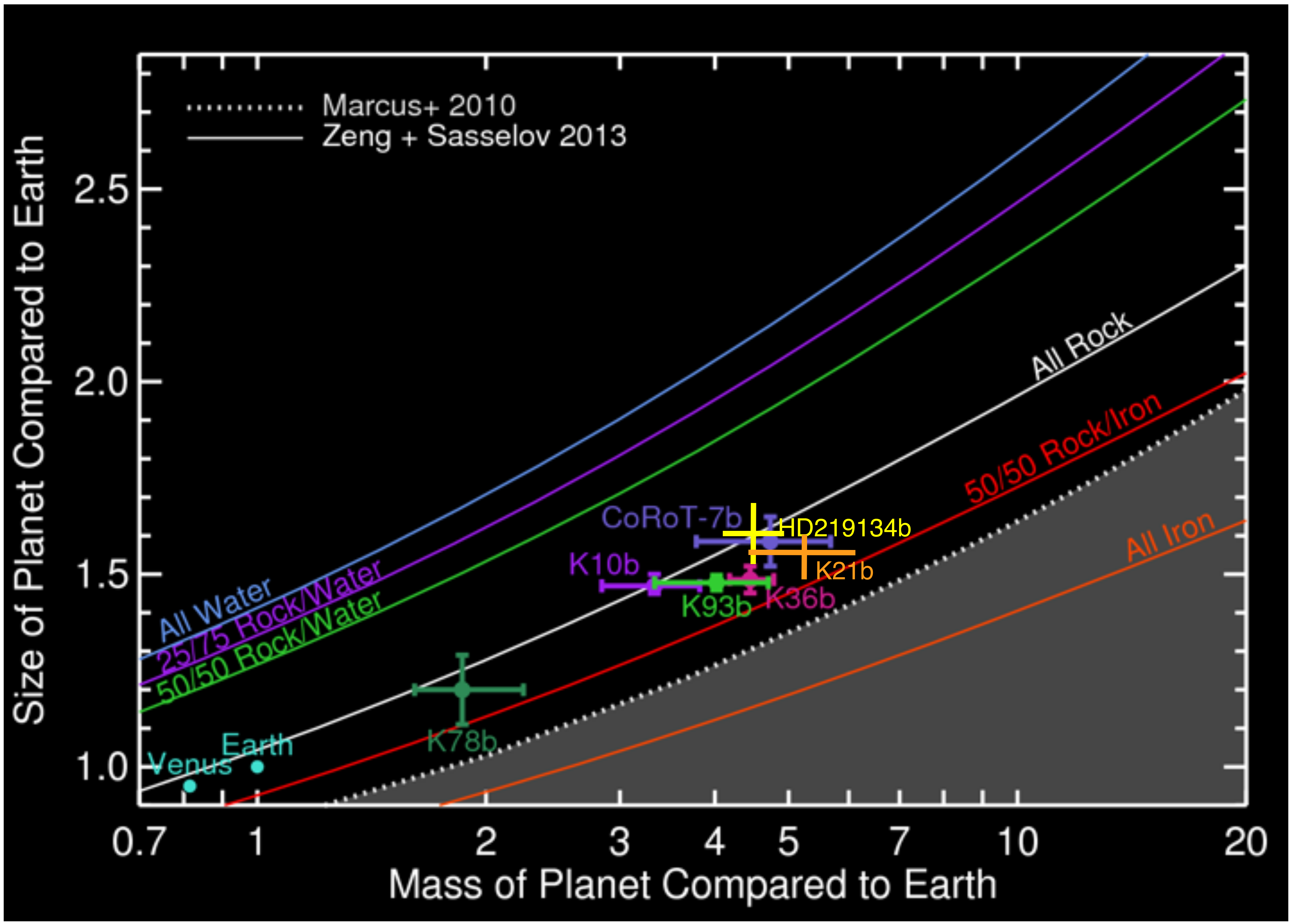
Fressin, Torres, Charbonneau et al. (2013); see also Petigura+(2013), Burke+(2015)

Towards Precise Constraints on the Mass-Radius Diagram below 2.8 Earth Radii



Dressing, Charbonneau, et al. ApJ (2015)

Small Planets Have Densities Consistent with the Rock-Iron Ratio of the Earth



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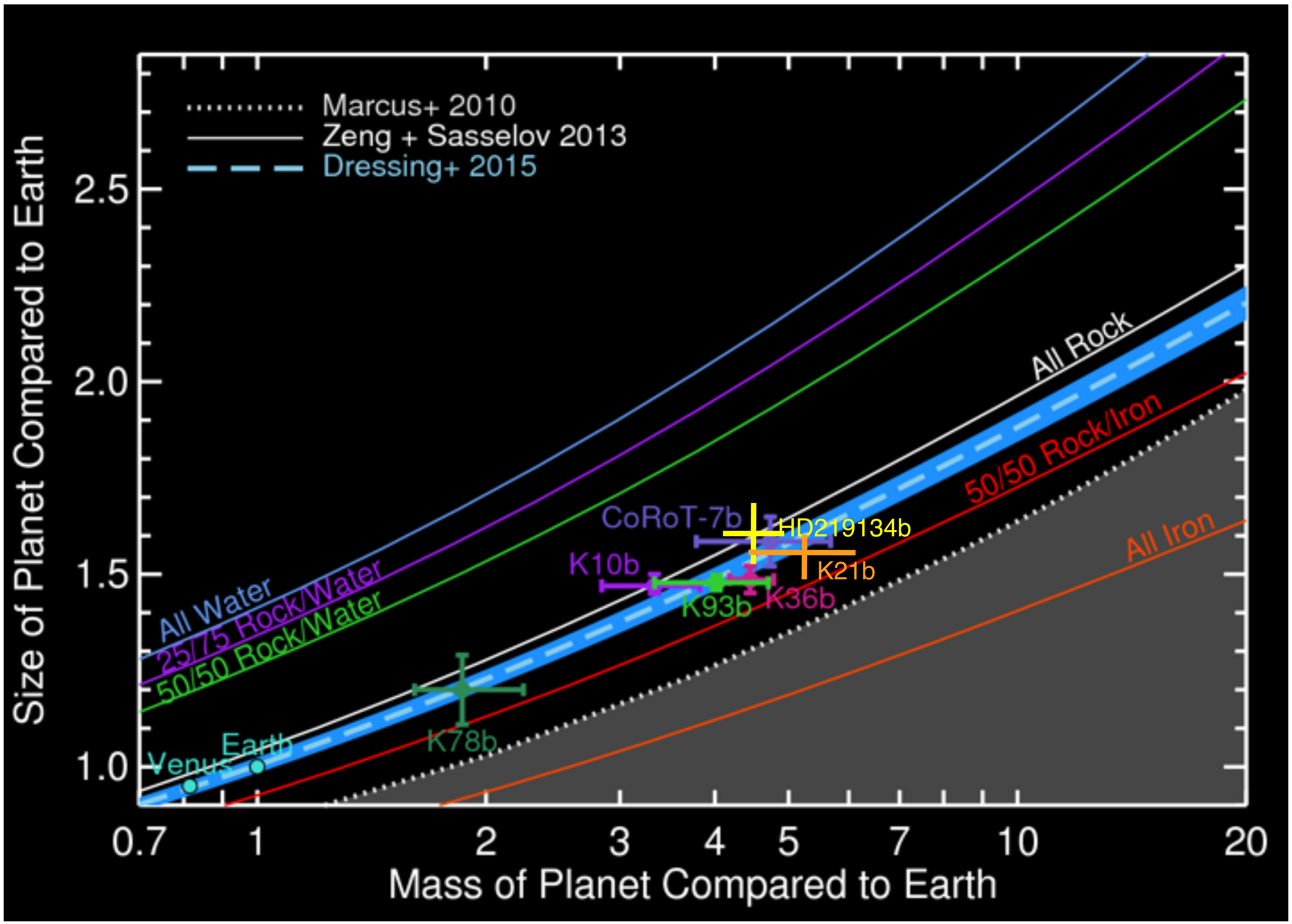
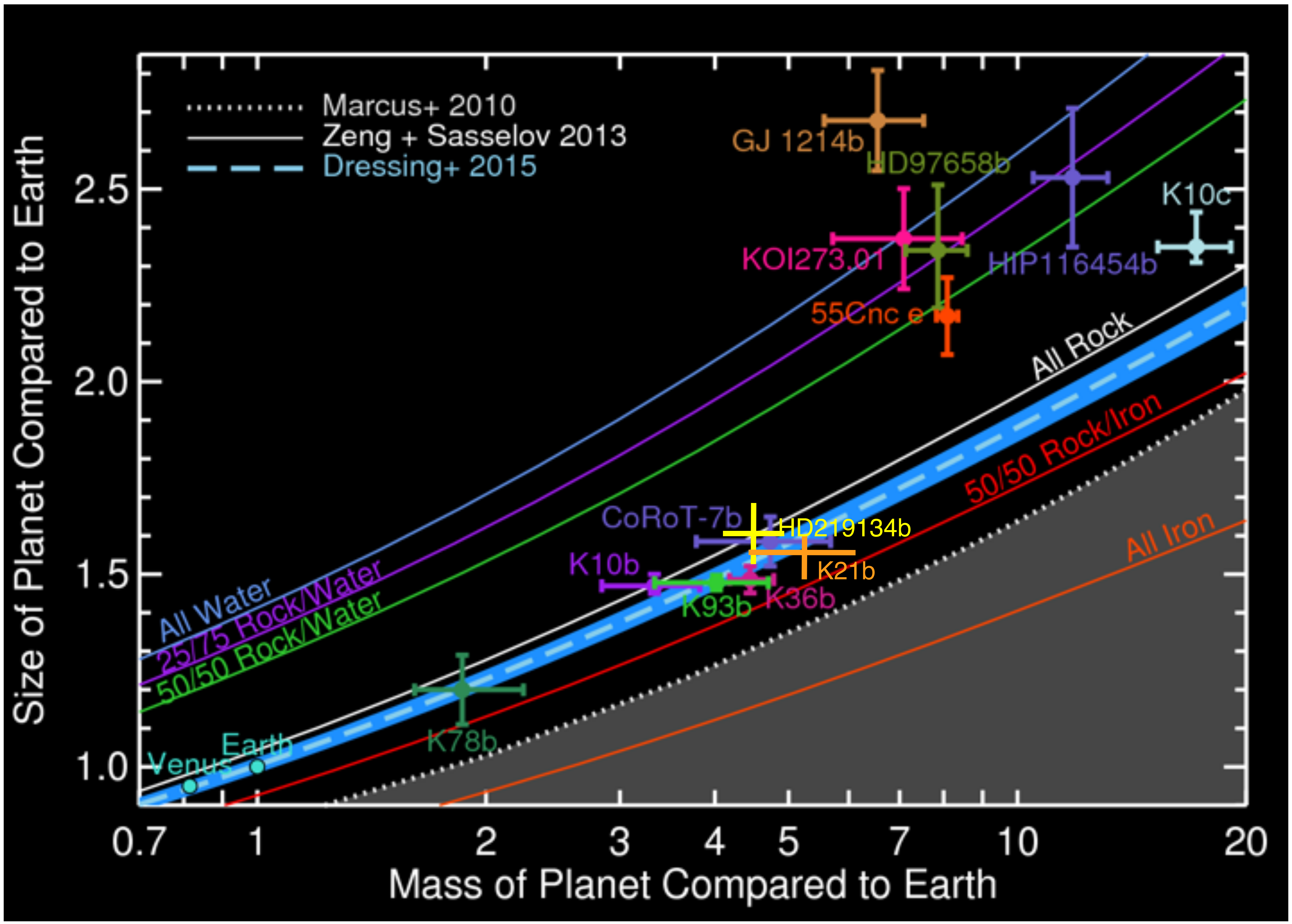
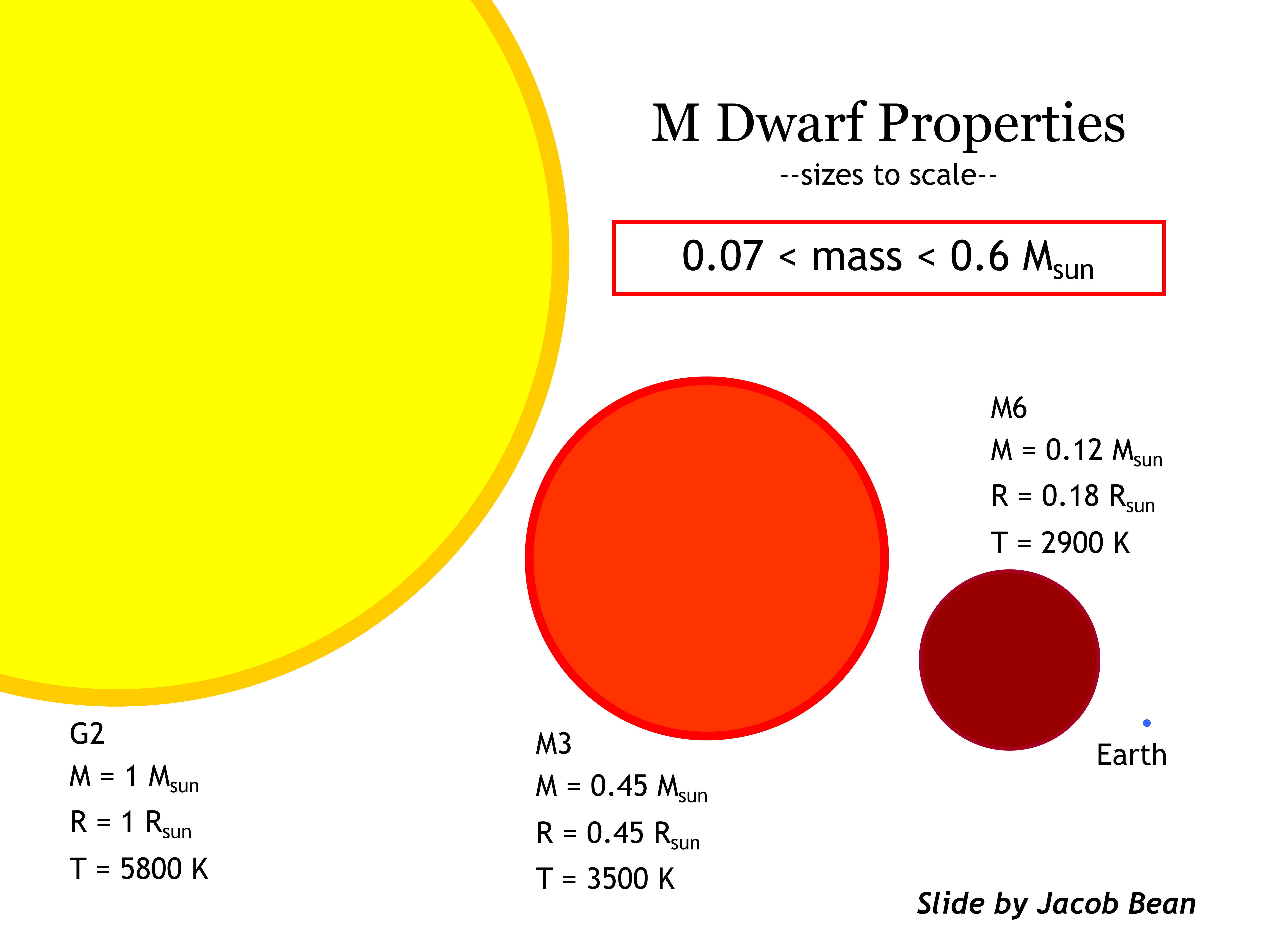


Dressing, Charbonneau, et al. ApJ (2015)

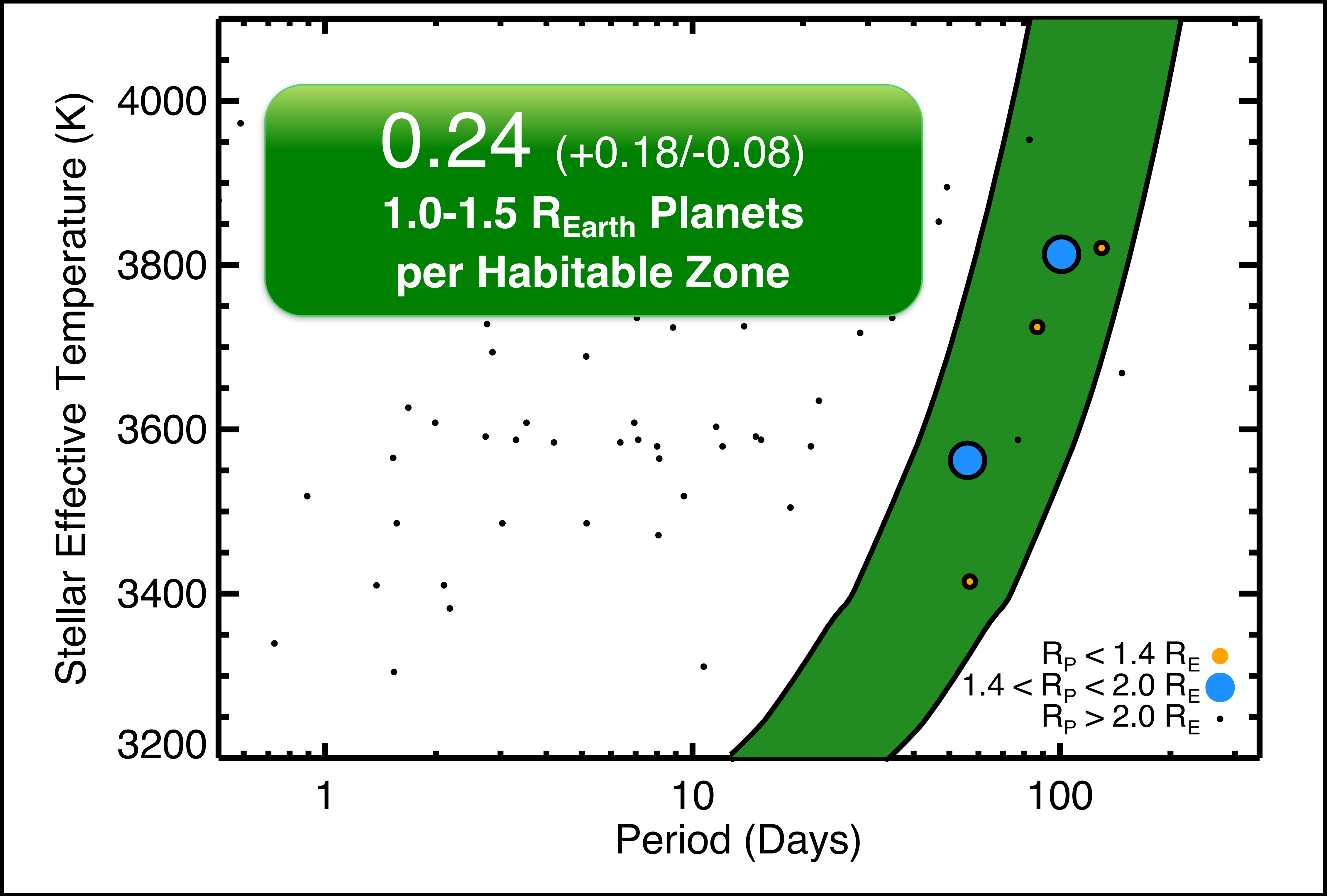
Most planets more massive than 7 M_{Earth} require a H/He envelope



Dressing, Charbonneau, et al. ApJ (2015)


M Dwarf Properties
--sizes to scale--
0.07 < mass < 0.6 M_{sun}
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
Earth
Slide by Jacob Bean

What is the Occurrence Rate of Planets that are both Earth-size and Earth-temperature?



Dressing & Charbonneau 2015

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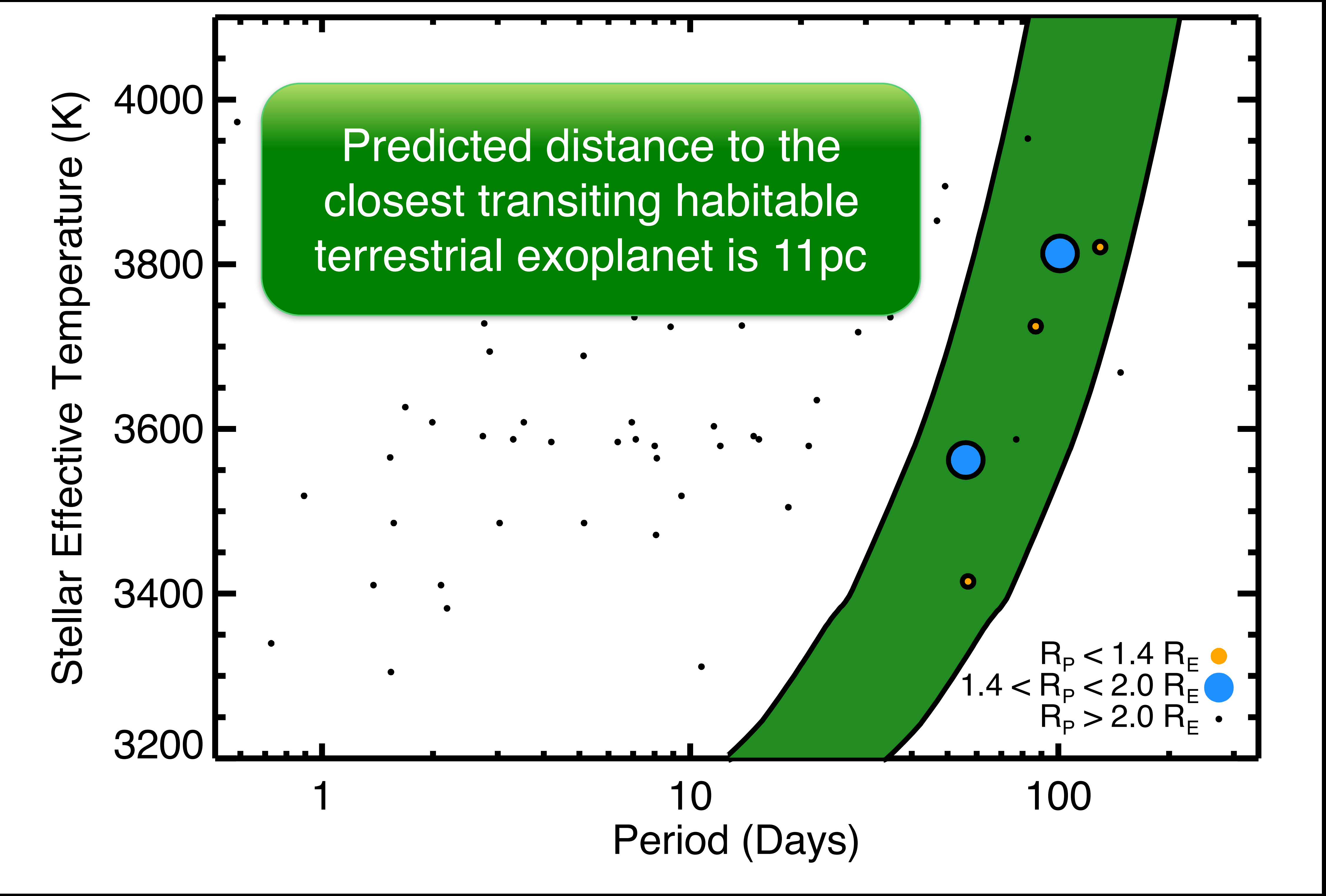
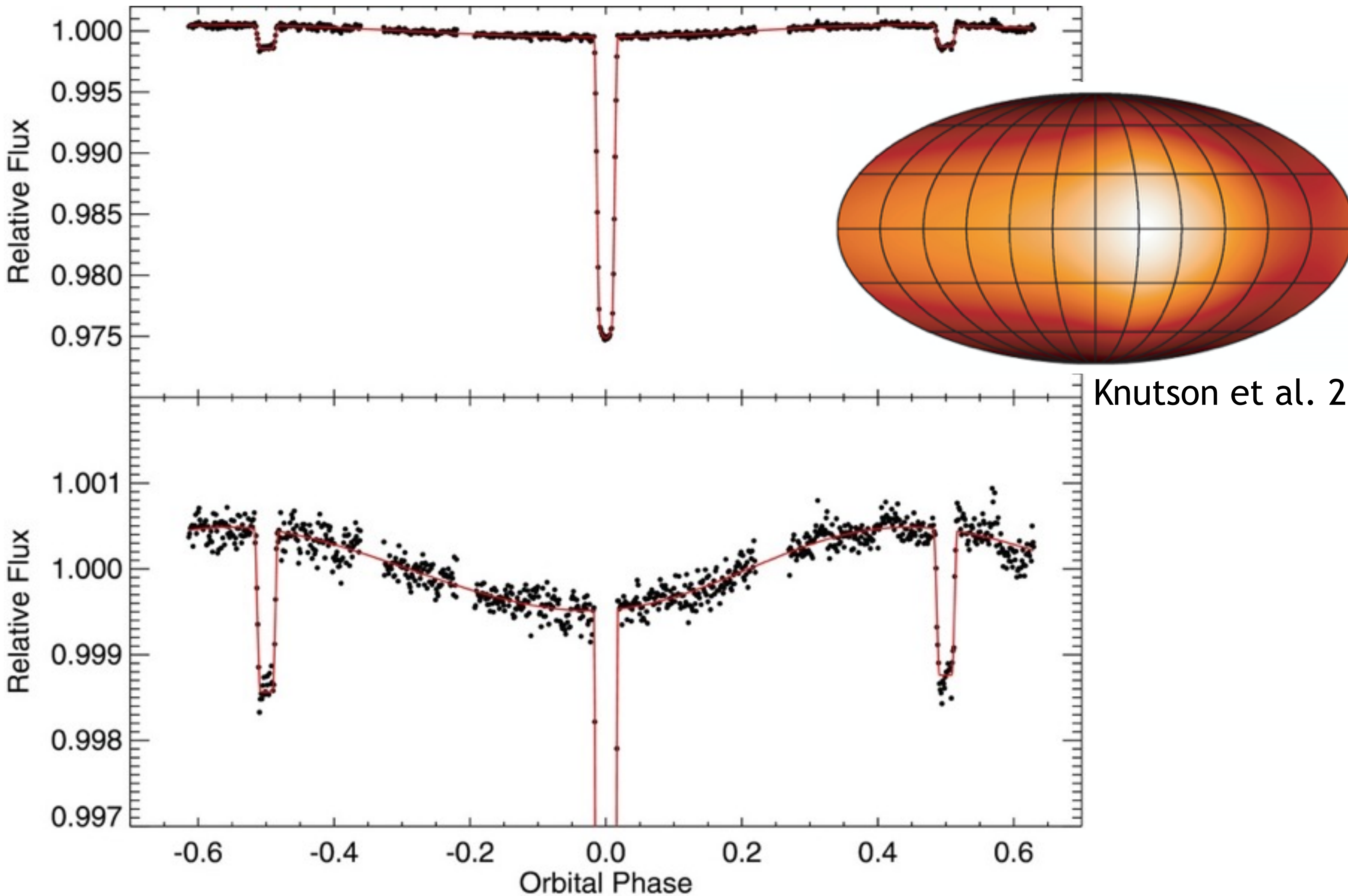
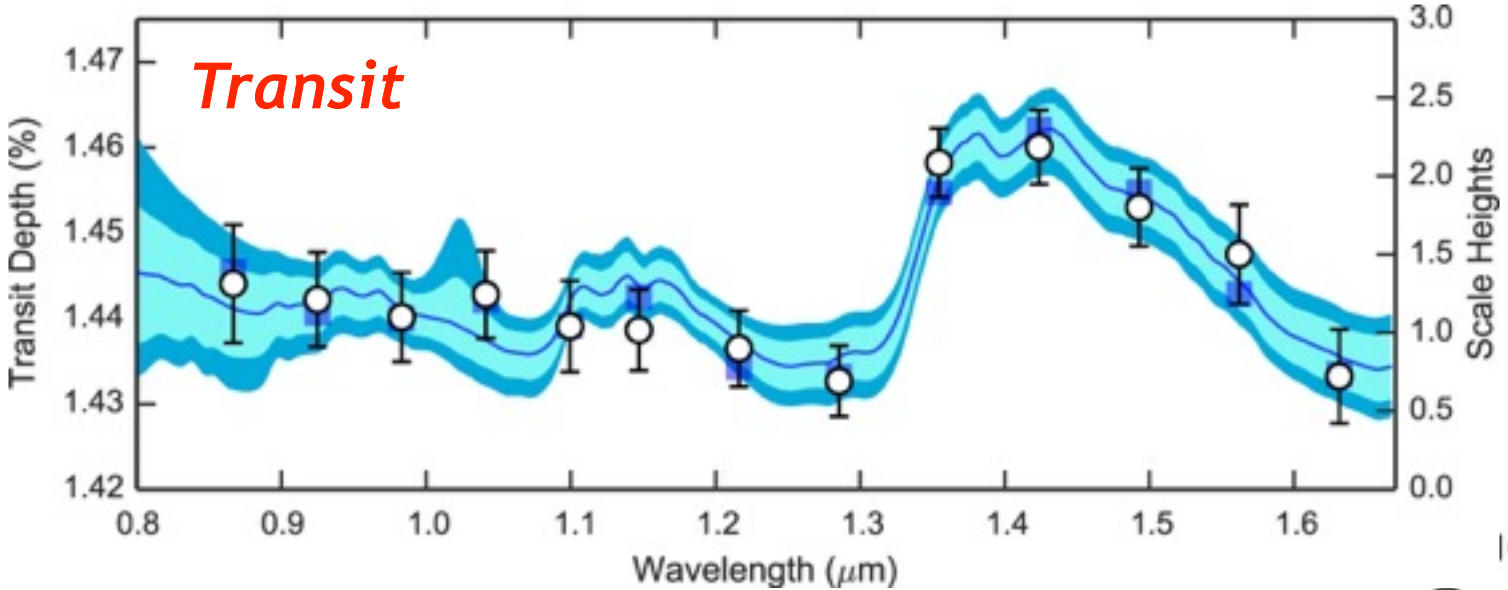


Dressing & Charbonneau 2015

Maps and Atmospheric Dynamics



Knutson et al. 2012

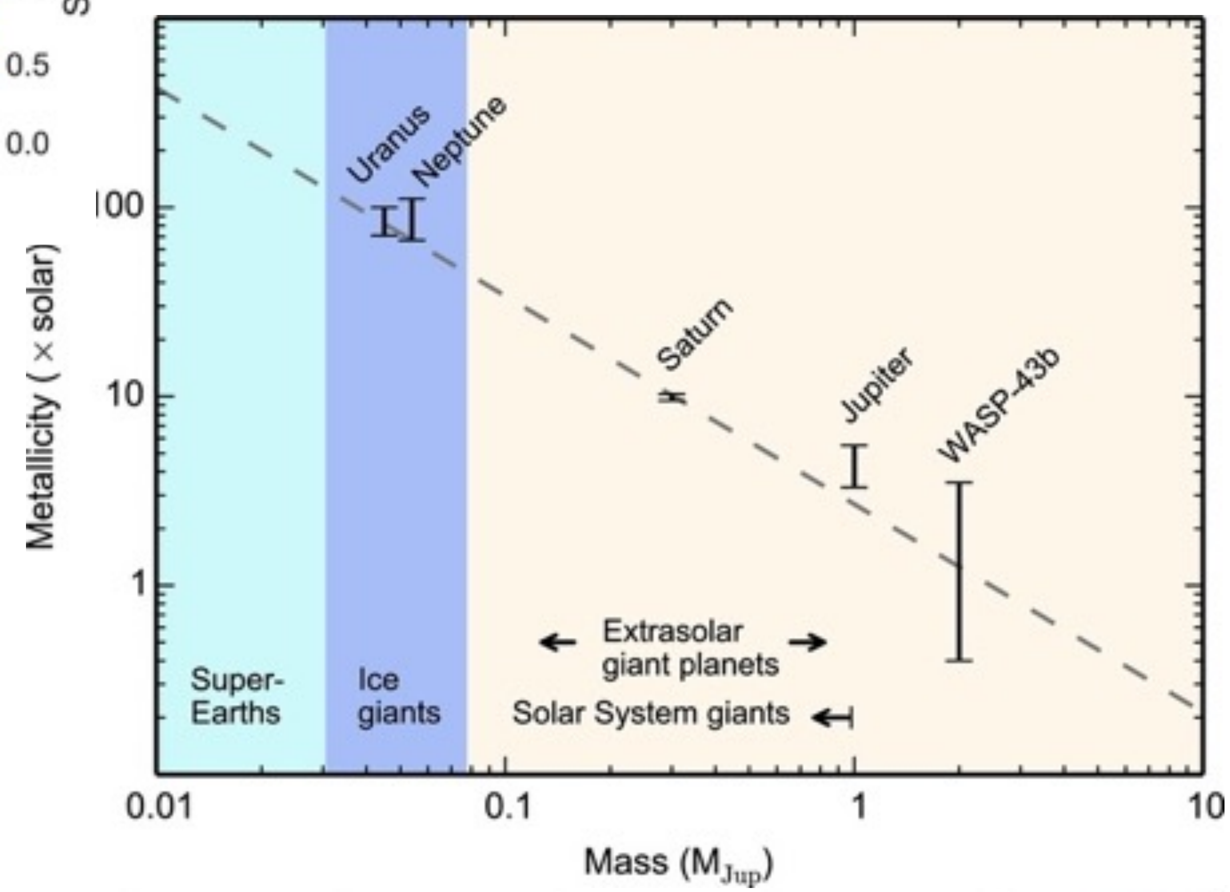


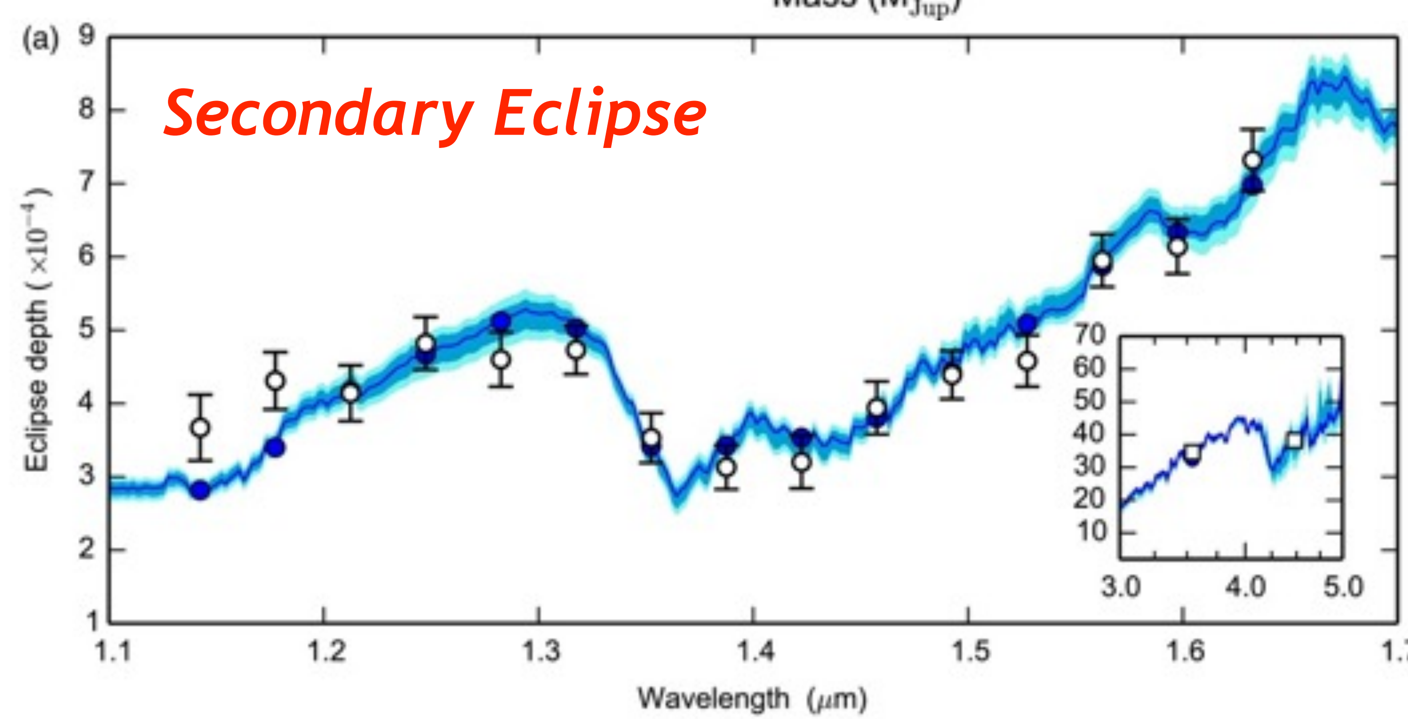
Detection of Molecules

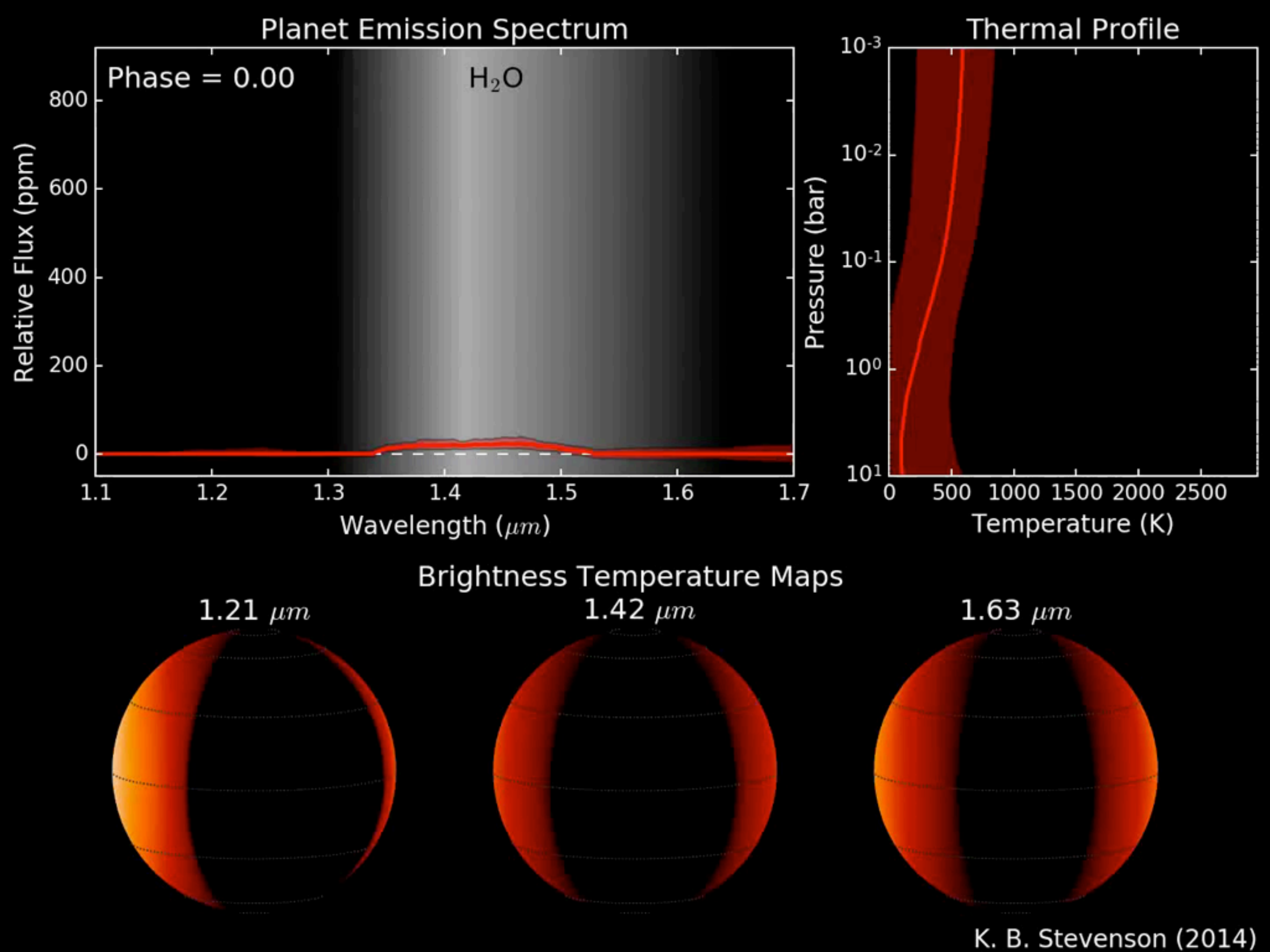
Constraints on Metallicity

Non-Equilibrium Chemistry

Kreidberg et al. 2014, 2015



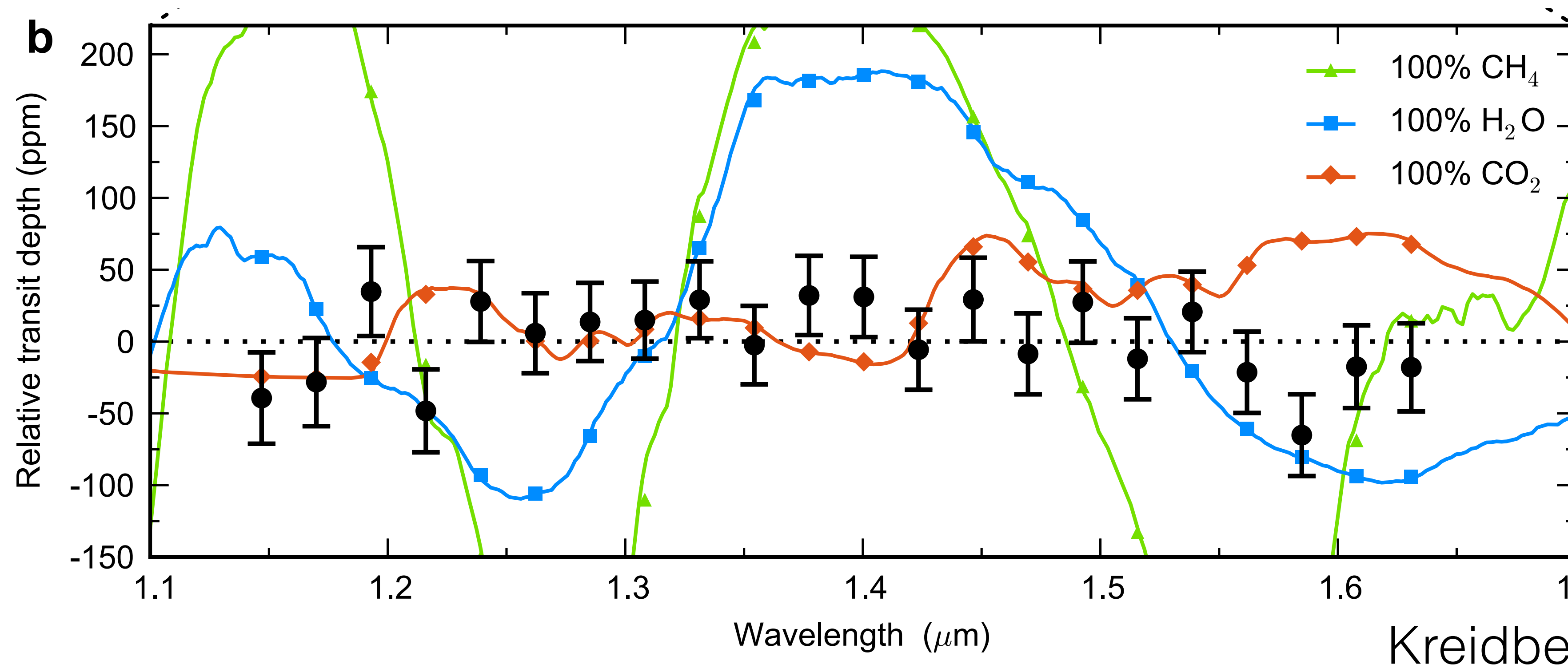




Planet Emission Spectrum
Phase = 0.00
H_2O
Relative Flux (ppm)
800
600
400
200
0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Wavelength (μm)
Thermal Profile
Pressure (bar)
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
0
500
1000
1500
2000
2500
Temperature (K)
Brightness Temperature Maps
1.21 μm
1.42 μm
1.63 μm
K. B. Stevenson (2014)

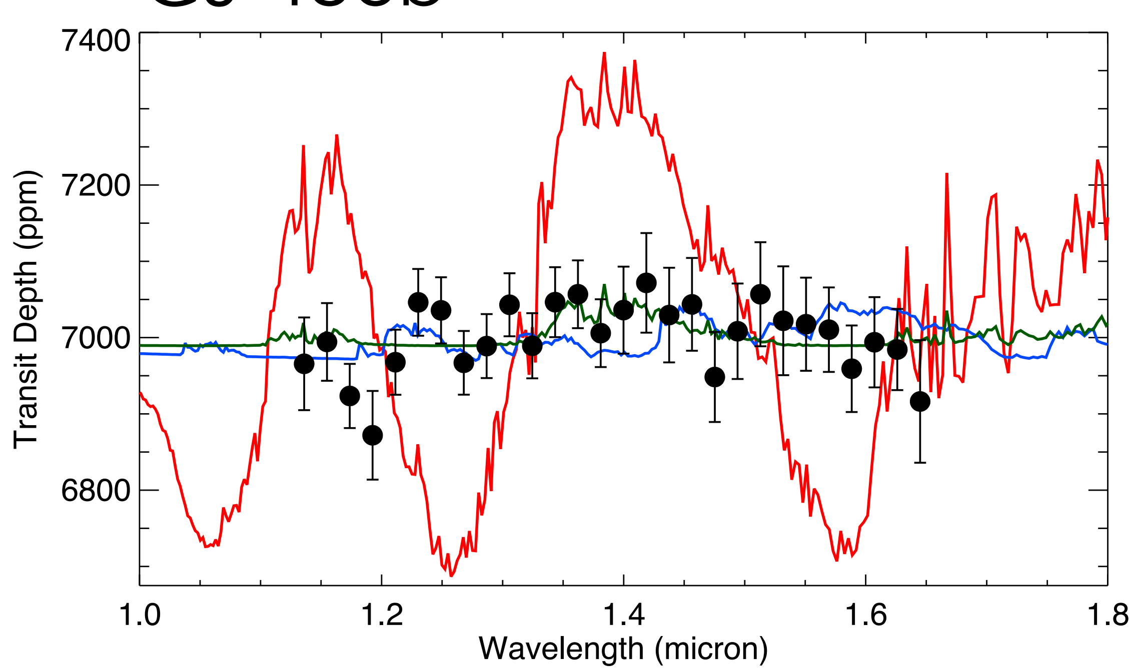
We have not detected a molecular feature in any planet smaller than Neptune.

GJ 1214b



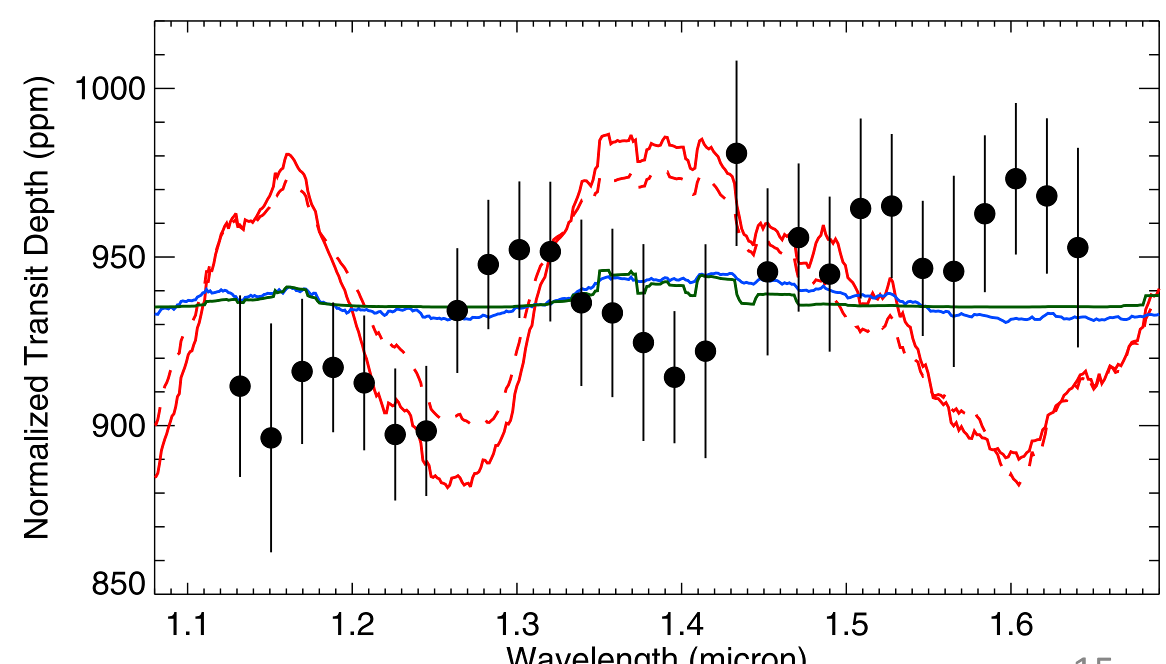
Kreidberg et al. 2014

GJ 436b



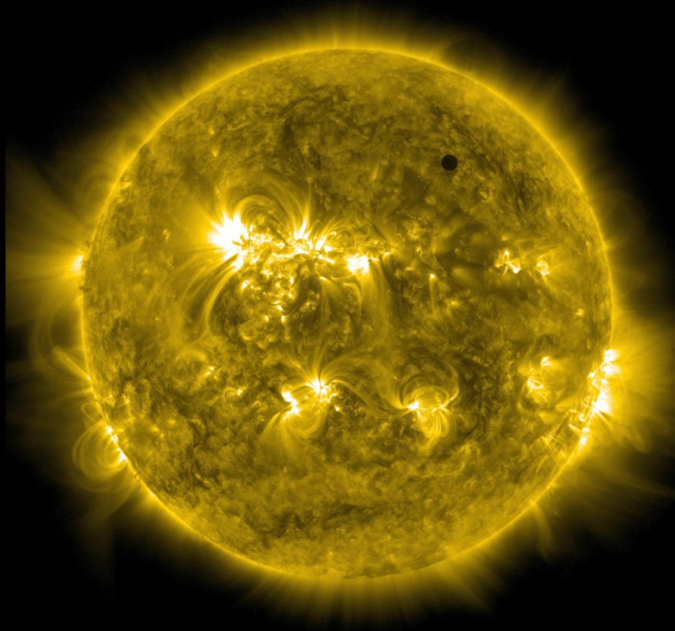
Knutson et al. 2014a

HD 97658b



Knutson et al. 2014b

My Plan for Today



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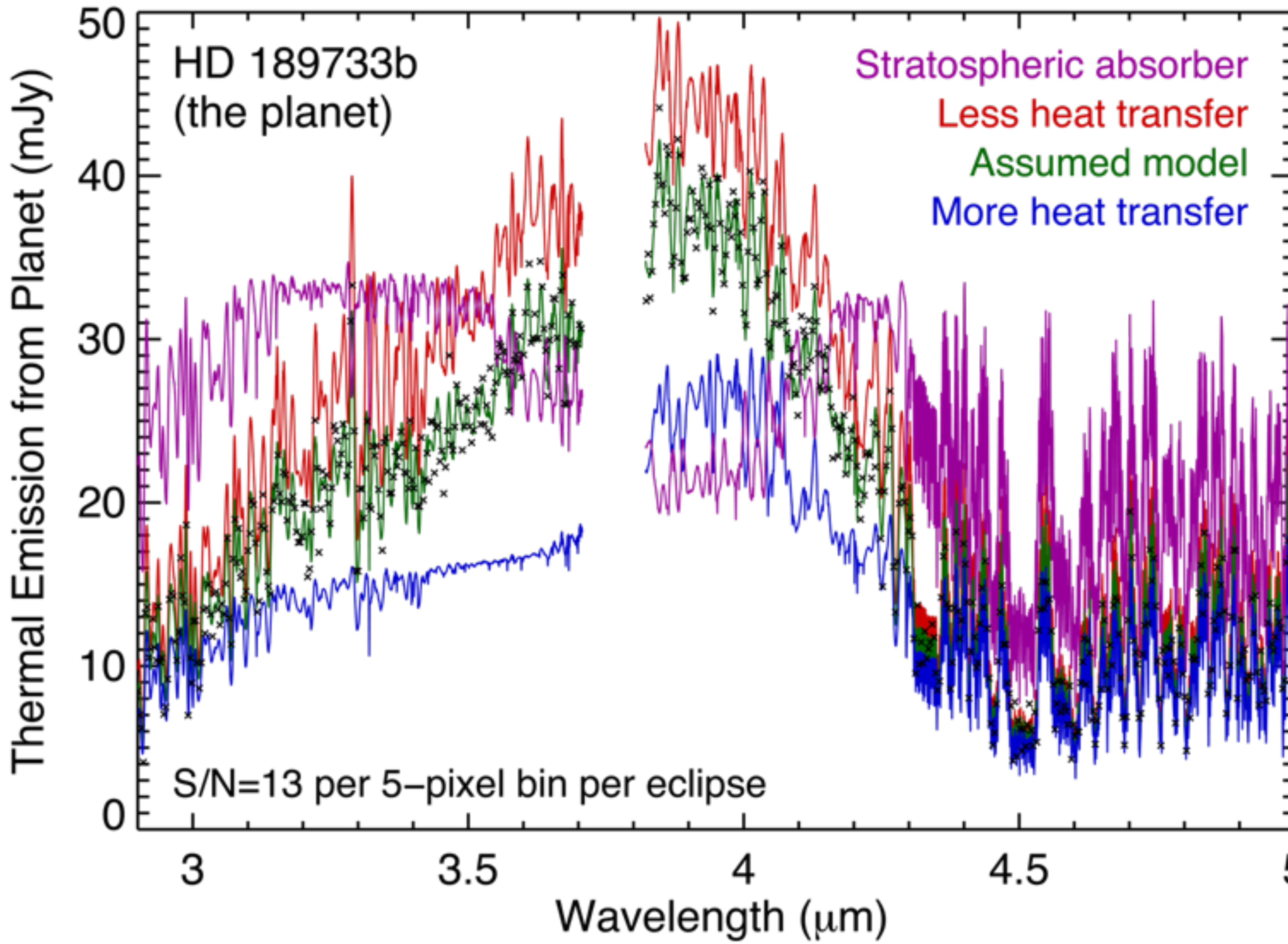
Spectroscopic modes for exoplanets

Mode	Instrument	Wavelength (micron)	#	Resolution ($R=\lambda/\Delta\lambda$)	Field of View
Single Object Spectroscopy	NIRISS	0.6-2.5	1	700	2.2x2.2′ slitless
	NIRCam	2.4-5.0	2	1700	2.2x2.2′ slitless
	NIRSpec	0.6-5.2	9	100, 1000, 2700	1.6x1.6″
	MIRI	5.0-12.0	1	100	slitless
Integral Field Spectroscopy	MIRI	5.0-7.7	3	3500	3.0x3.9″
		7.7-11.9		2800	3.5x4.4″
		11.9-18.3		2700	5.2x6.2″
		18.3-28.8		2200	6.7x7.7″

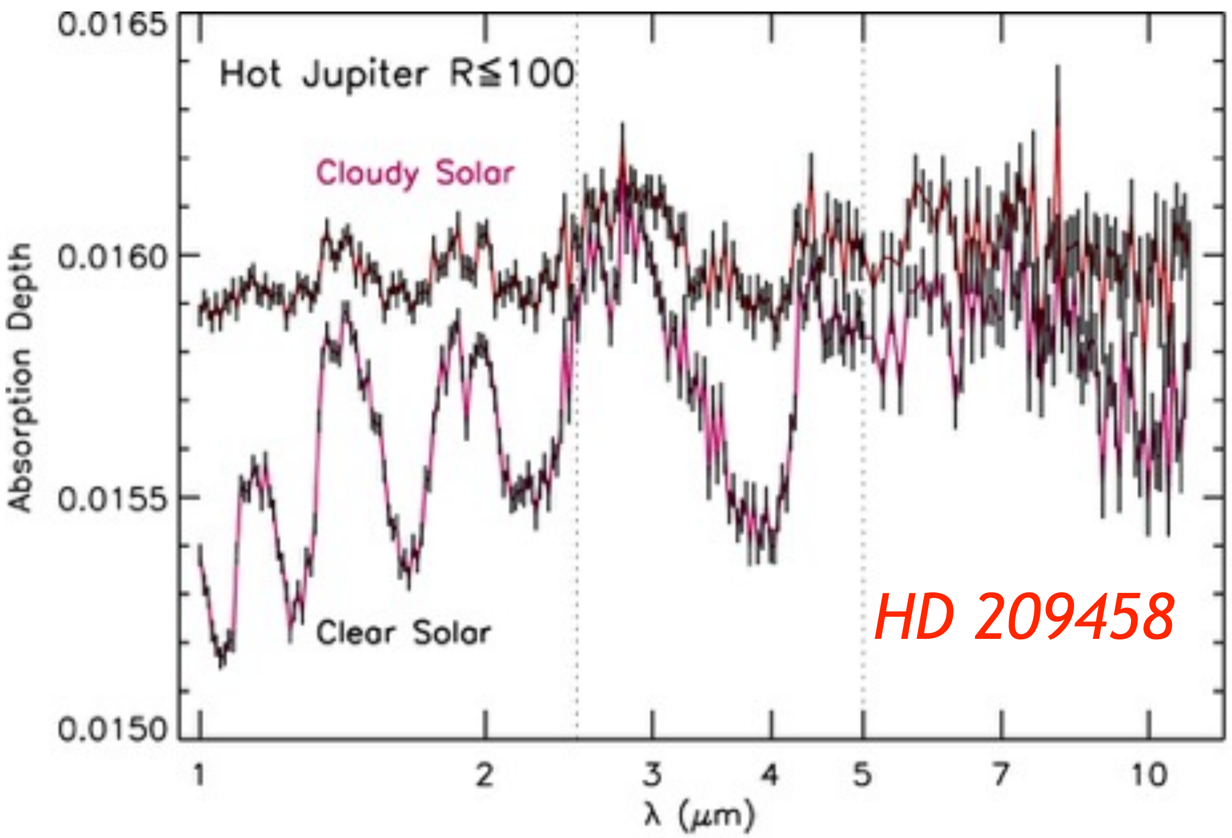
Slide courtesy Jeff Valenti

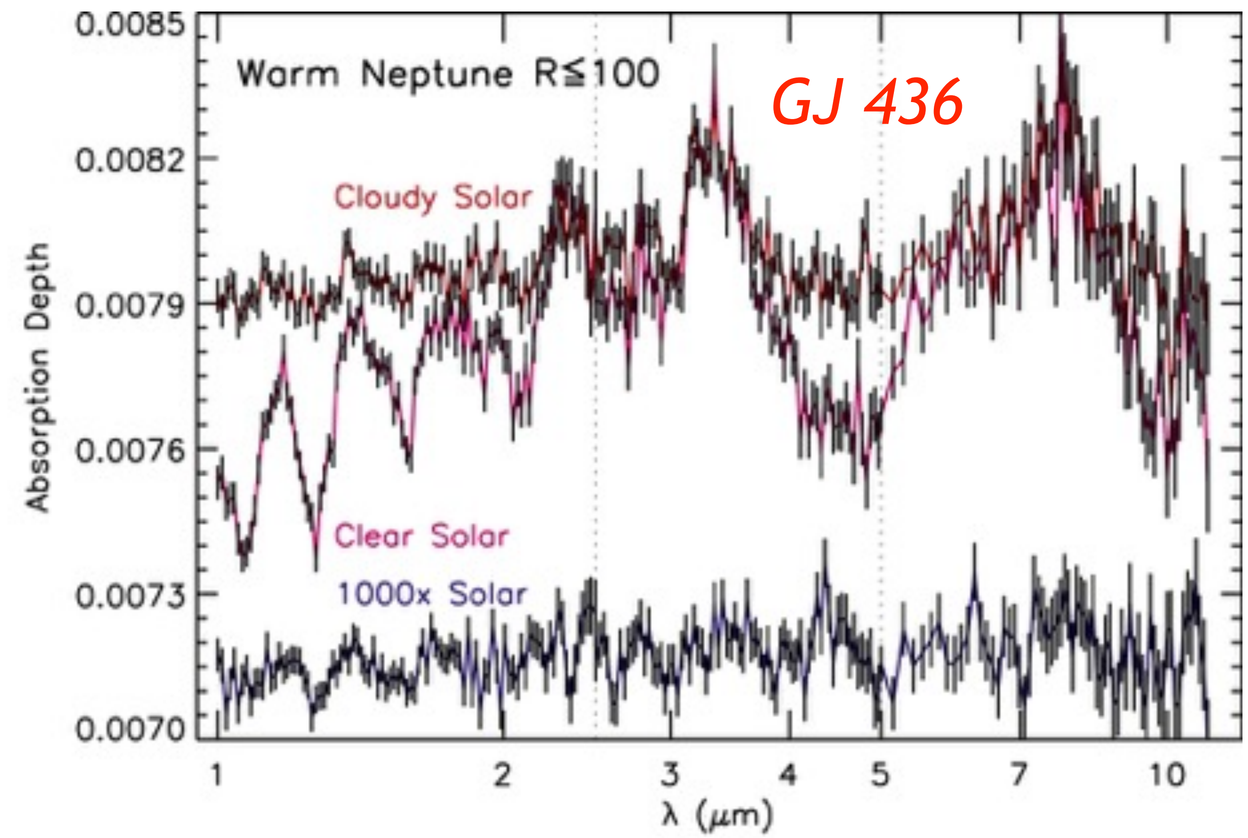
Data quality for a single eclipse

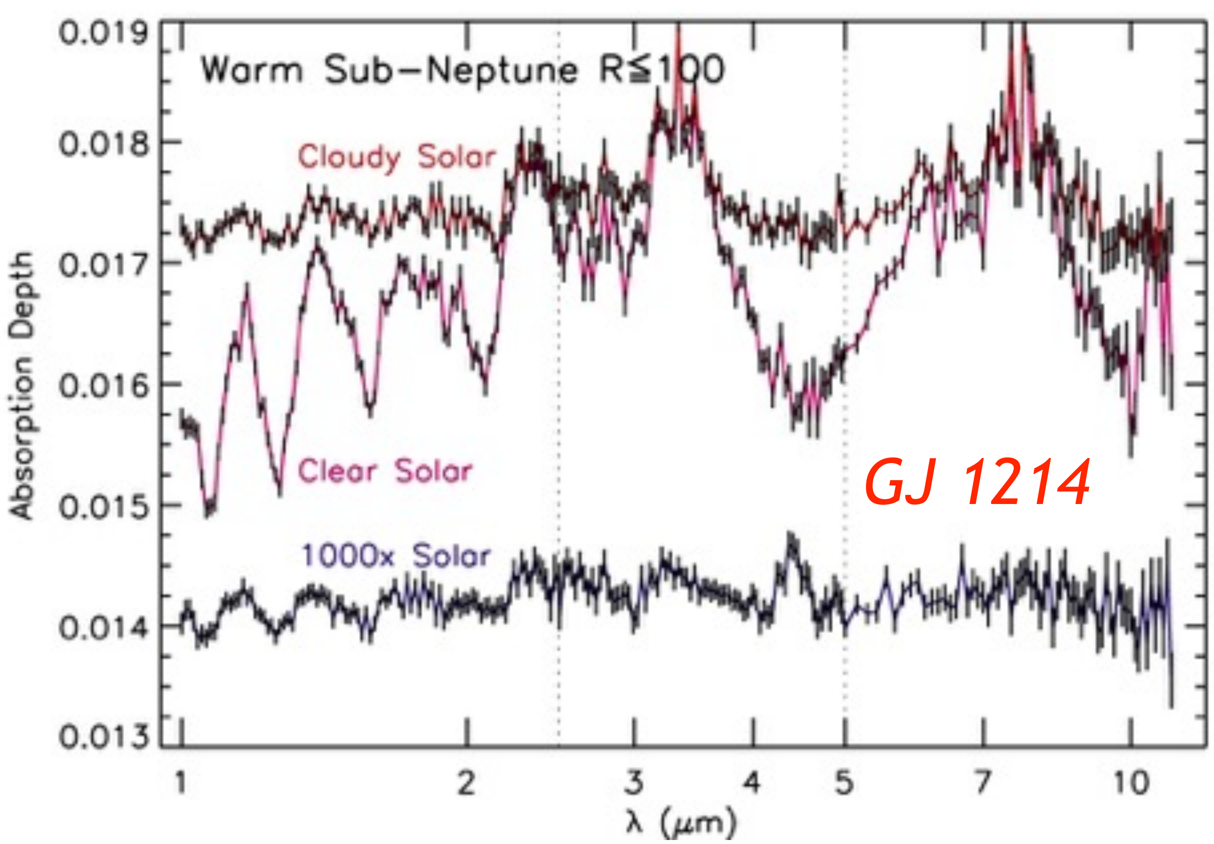


Models from Figure 4b of Burrows et al. 2008

Slide courtesy Jeff Valenti





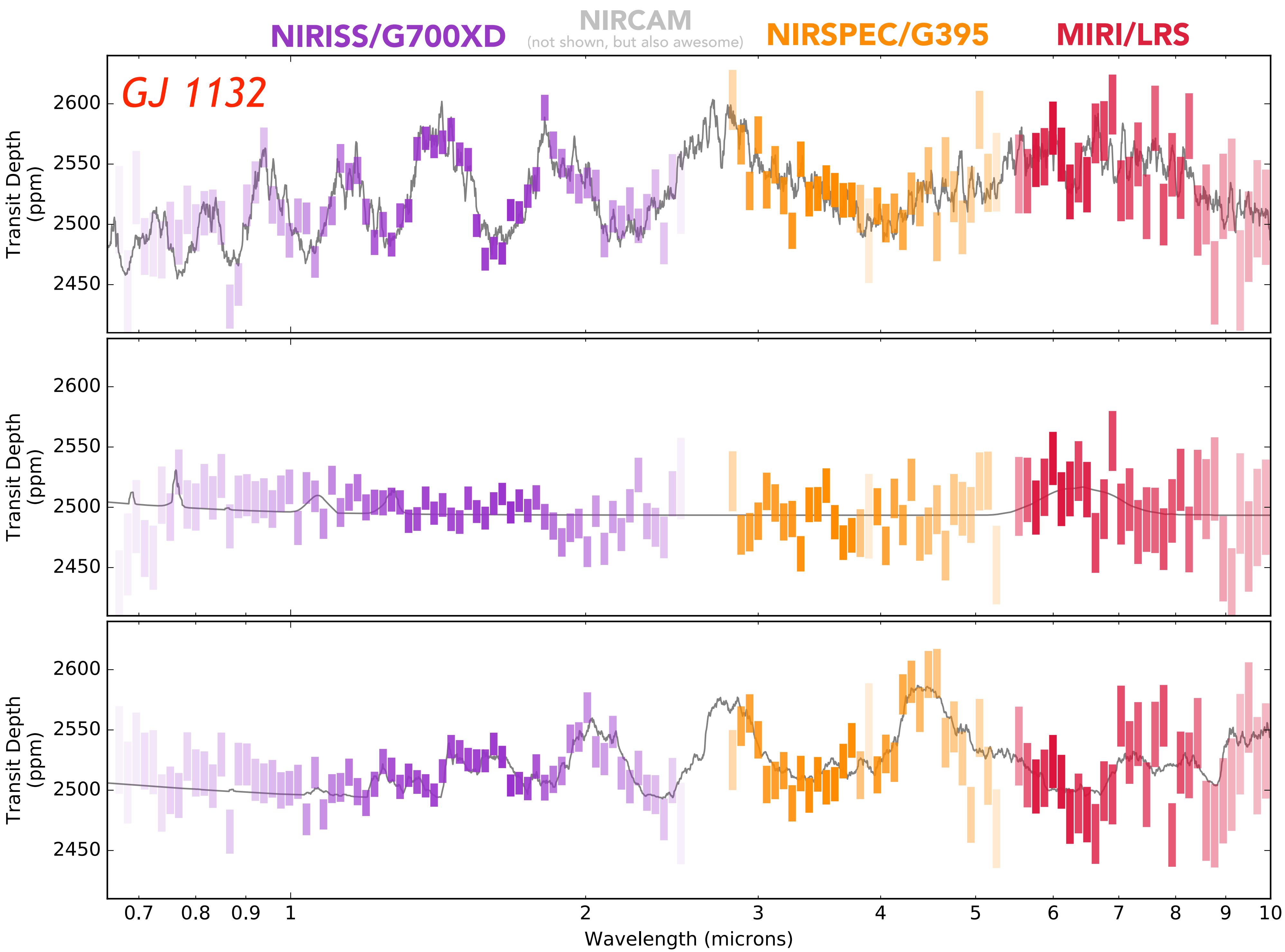


Single Transit in each of NIRISS, NIRCam, and MIRI, displayed at R=100.

Constrain major molecular constituents (CH_4, CO, CO_2, H_2O, NH_3), temperature inversions, overall metallicity, and in some cases the C/O ratio.

Greene et al. (2016)

JWST will be able to observe some high-μ atmospheres on terrestrial exoplanets.



cloudless atmospheres, 15 transits with each instrument:

H_2O

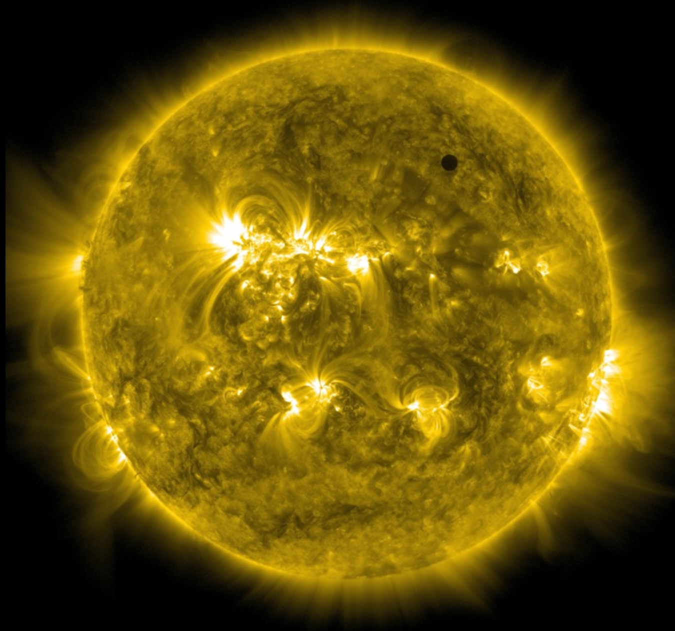
O_2

CO_2

Slide courtesy Zach Berta-Thompson

JWST noise estimates from Natasha Batalha; model atmospheres from Eliza Kempton's `Exo-Transmit`

My Plan for Today



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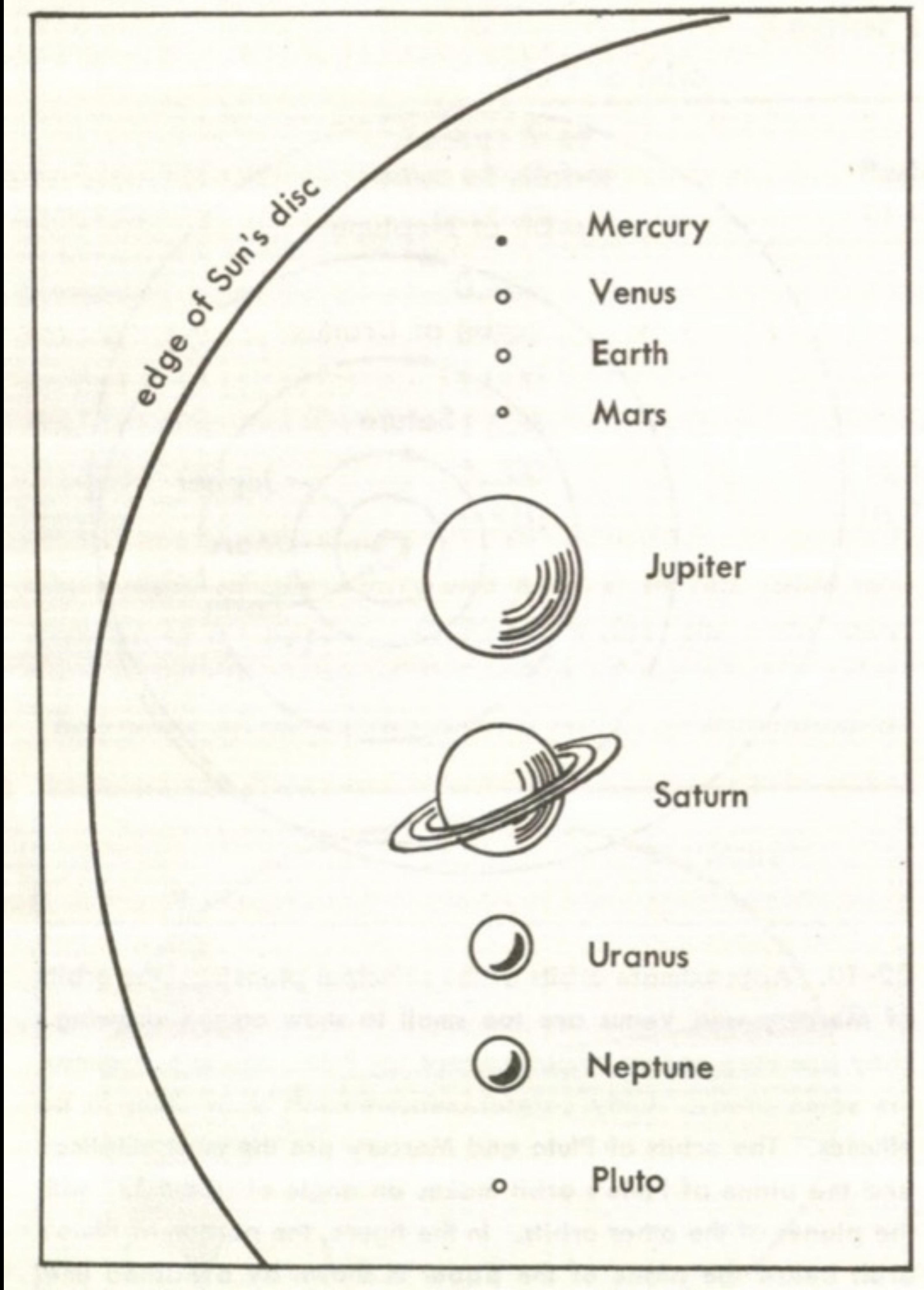
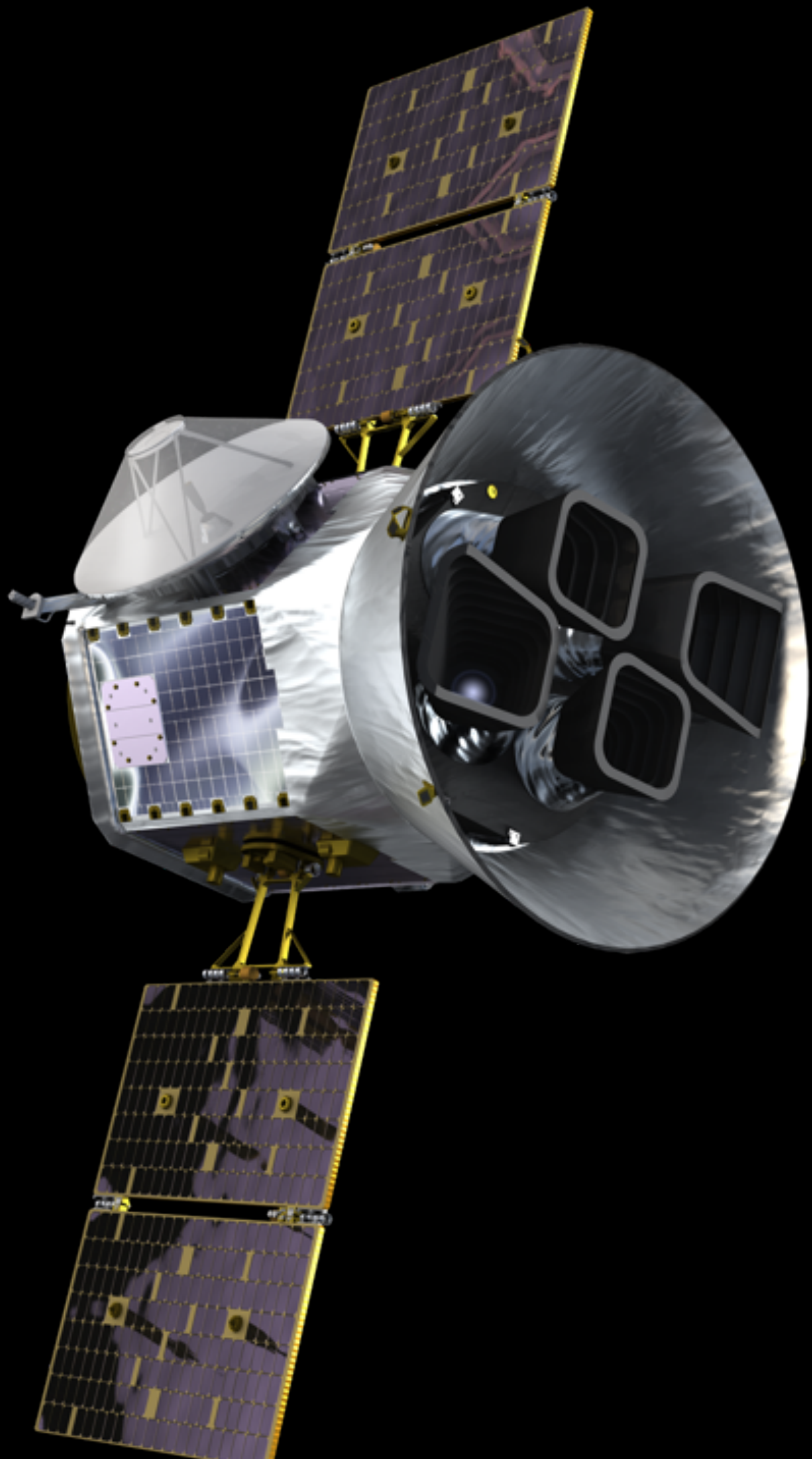


Characterization requires photons.

Images: PHYSICS by Physical Science Study Committee; NASA

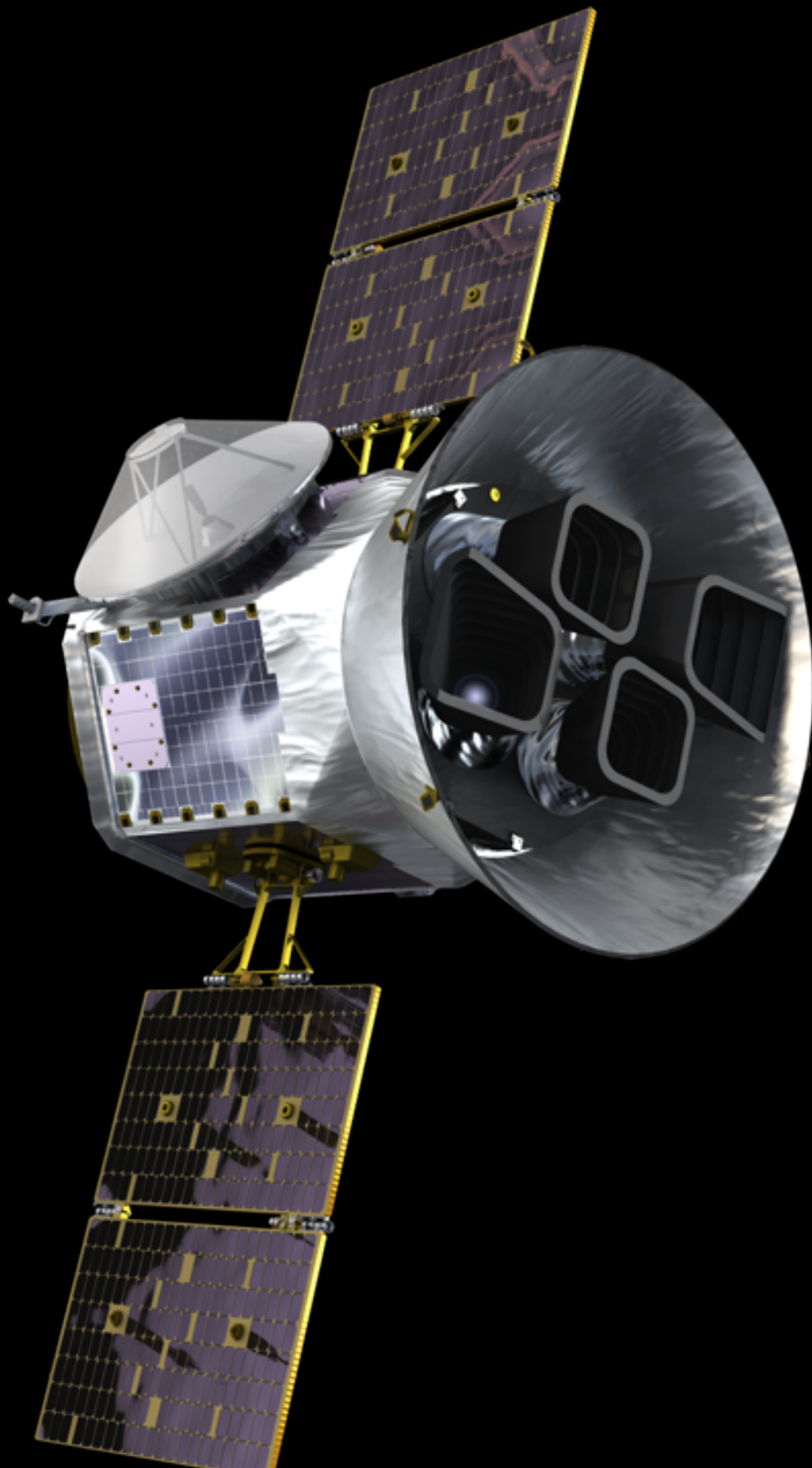


TESS

Explorer Mission

*launch in **2017**,*
to find hundreds of
nearby small exoplanets
amenable to detailed
characterization

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



TESS

George Ricker (P.I.)
Roland Vanderspek (Deputy P. I.)
Massachusetts Institute of Technology

science center shared between
MIT + Harvard/Smithsonian CfA

collaboration including:
NASA Goddard, NASA Ames, MIT Lincoln Lab, Orbital Sciences, STScI, SAO, MPIA-Germany, Las Cumbres Observatory, Geneva Observatory, OHP-France, University of Florida, Aarhus University-Denmark, Harvard College Observatory, Vanderbilt University,

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

TESS

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Massachusetts Institute of Technology

All the TESS slides are courtesy Zach Berta-Thompson

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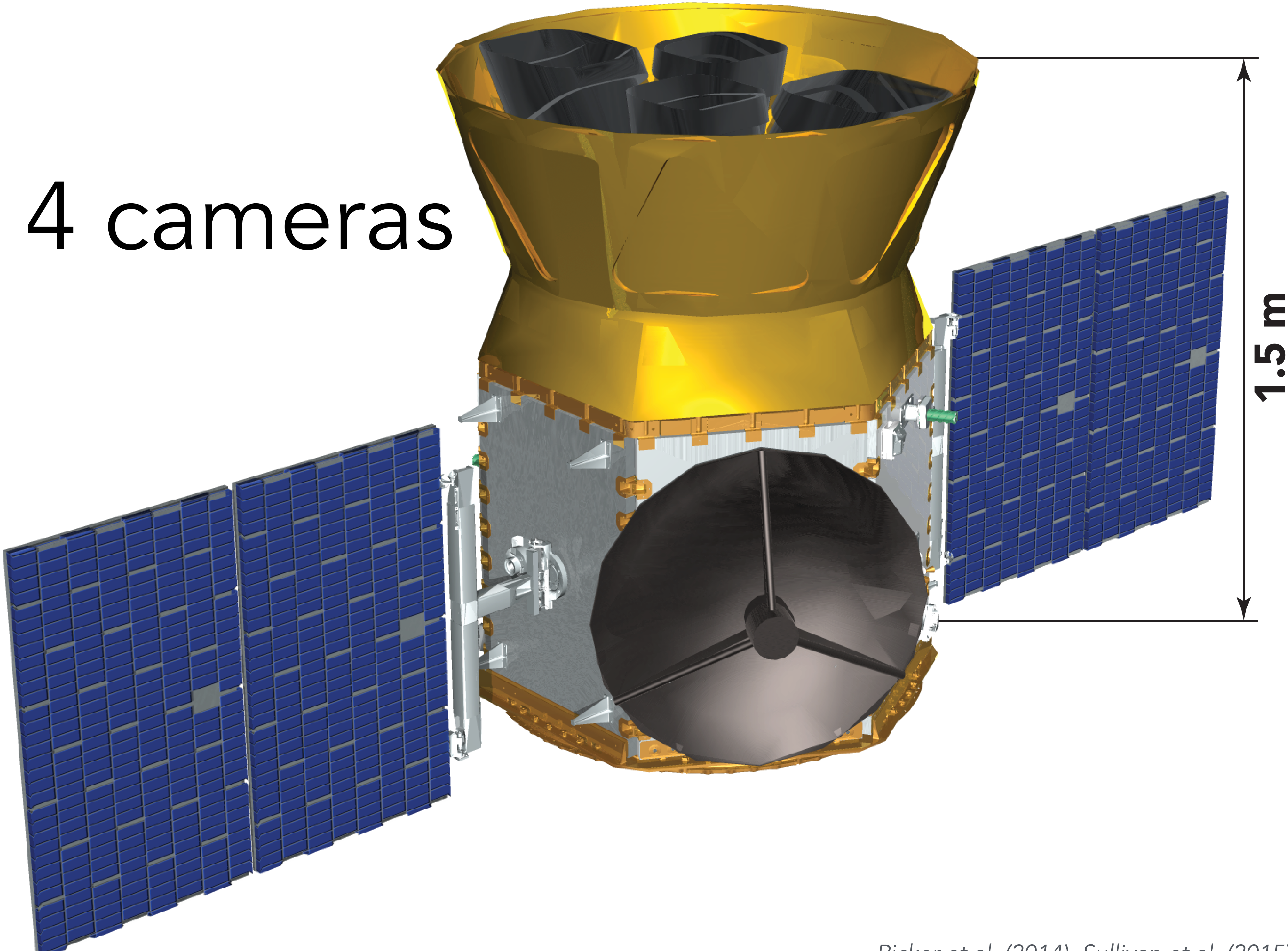
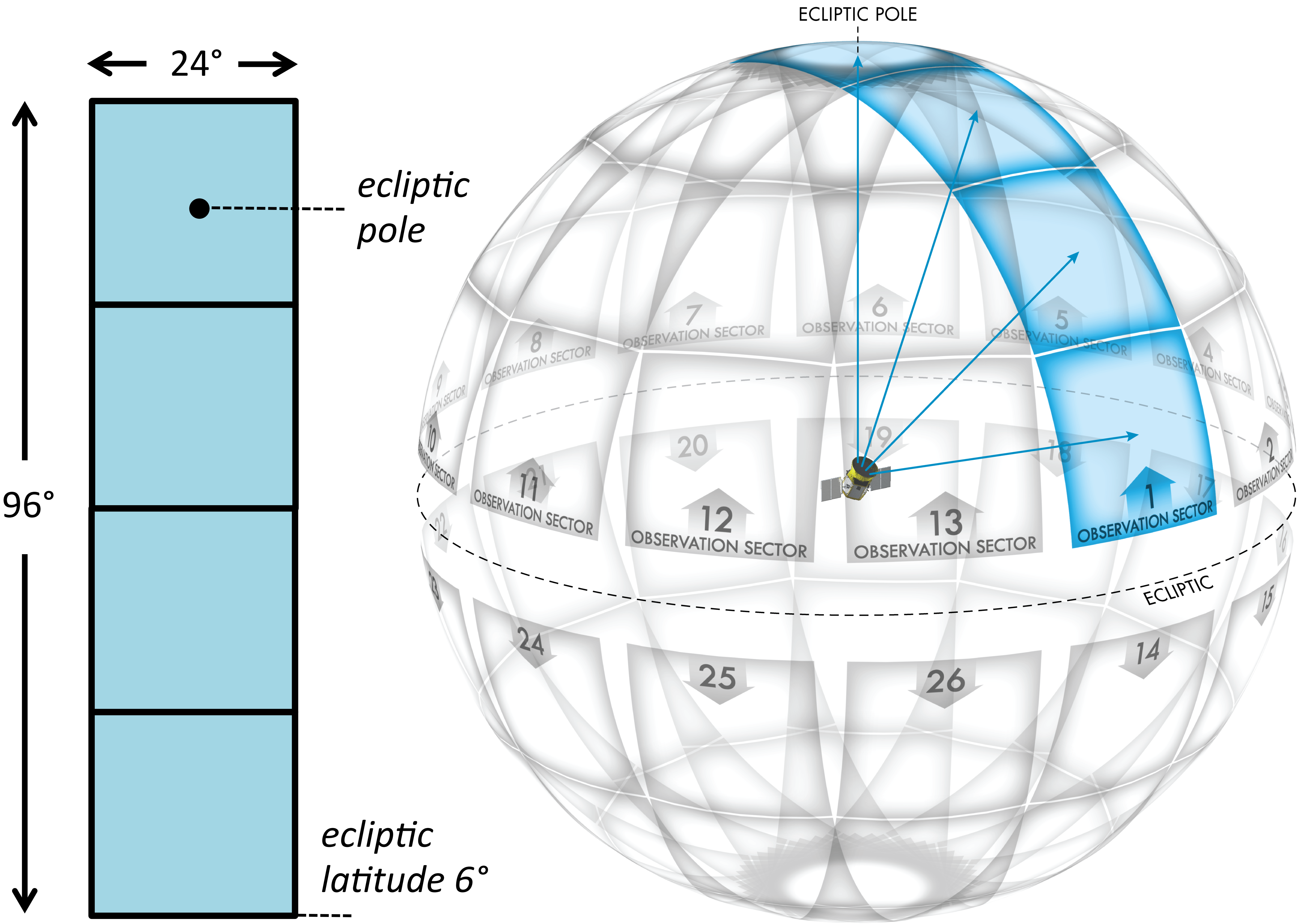


Ricker et al. (2014), Sullivan et al. (2015)



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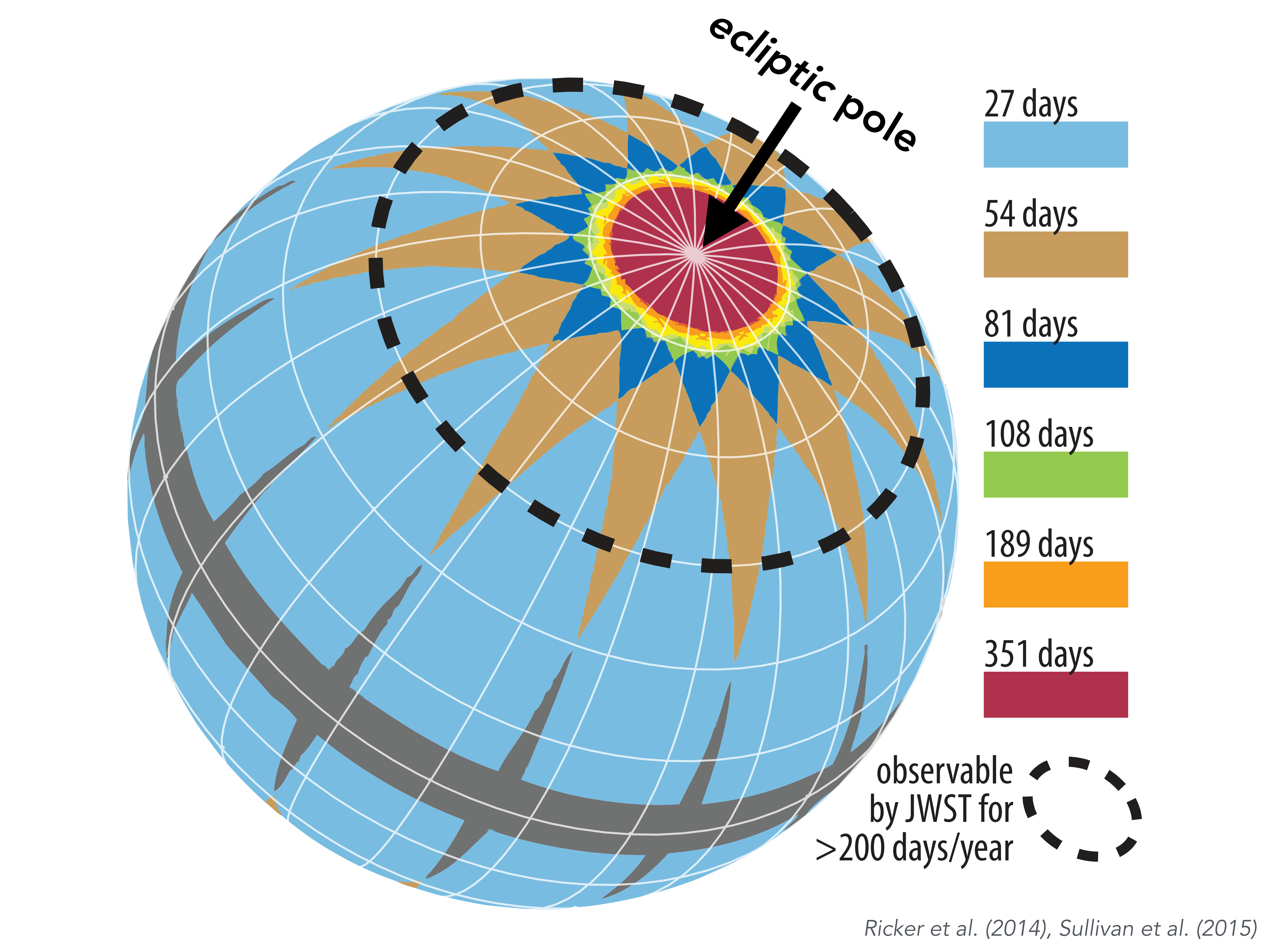


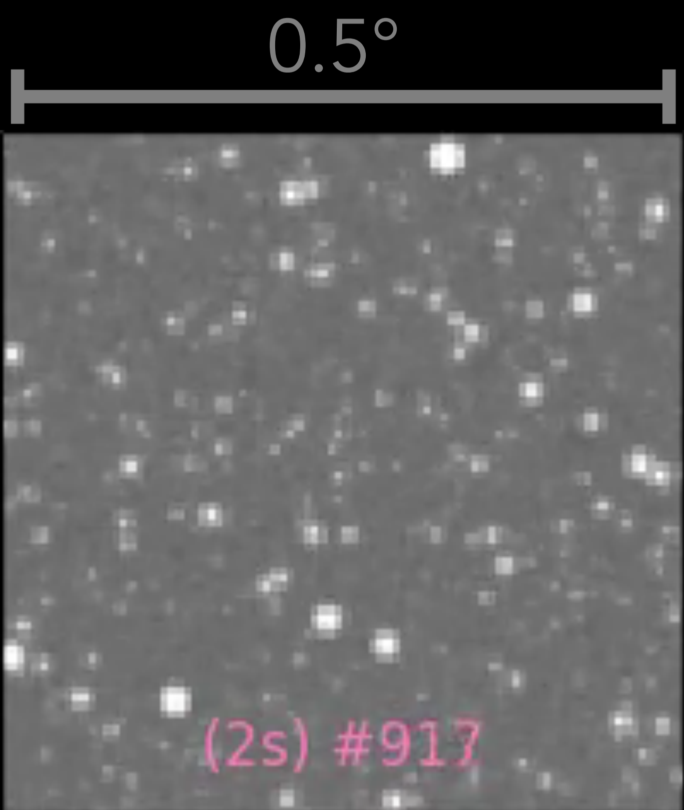
ecliptic pole
27 days
54 days
81 days
108 days
189 days
351 days
observable
by JWST for
>200 days/year
Ricker et al. (2014), Sullivan et al. (2015)

0.5°

(60X speed)

The TESS CCDs take **2 second** exposures. These data are used for guiding, but not downloaded.

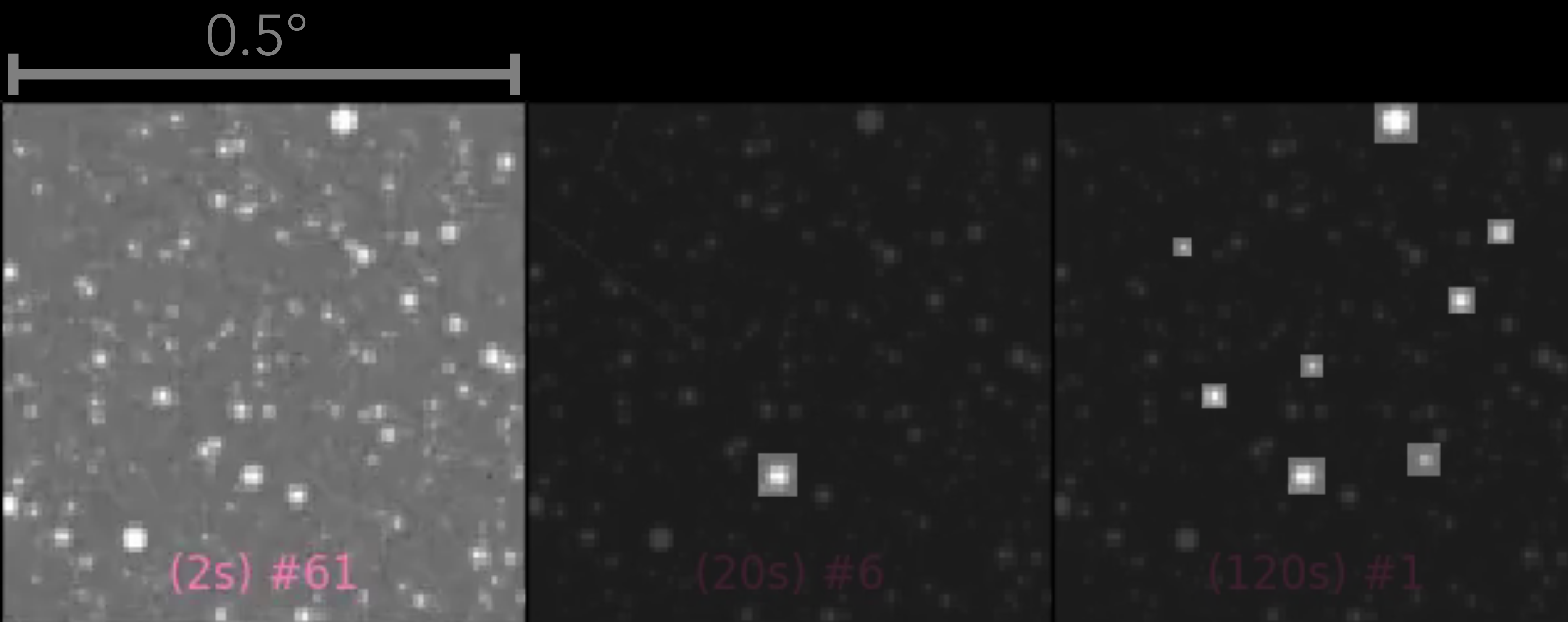
(60X speed)



The TESS CCDs take **2 second** exposures. These data are used for guiding, but not downloaded.

Postage stamps will be downloaded at **20 second** cadence for 1,000 bright **asteroseismology** targets.

(60X speed)



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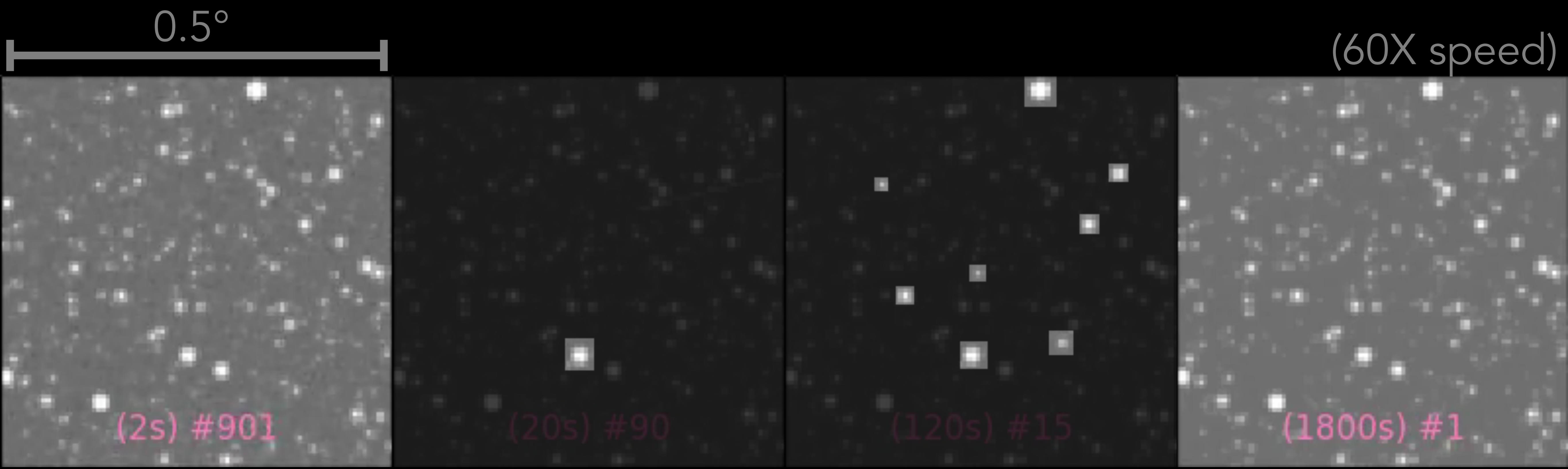
Postage stamps will be downloaded at **20 second** cadence for 1,000 bright **asteroseismology** targets.

Postage stamps will be downloaded at **2 minute** cadence for 200,000 stars, primarily good **planet-search** hosts.



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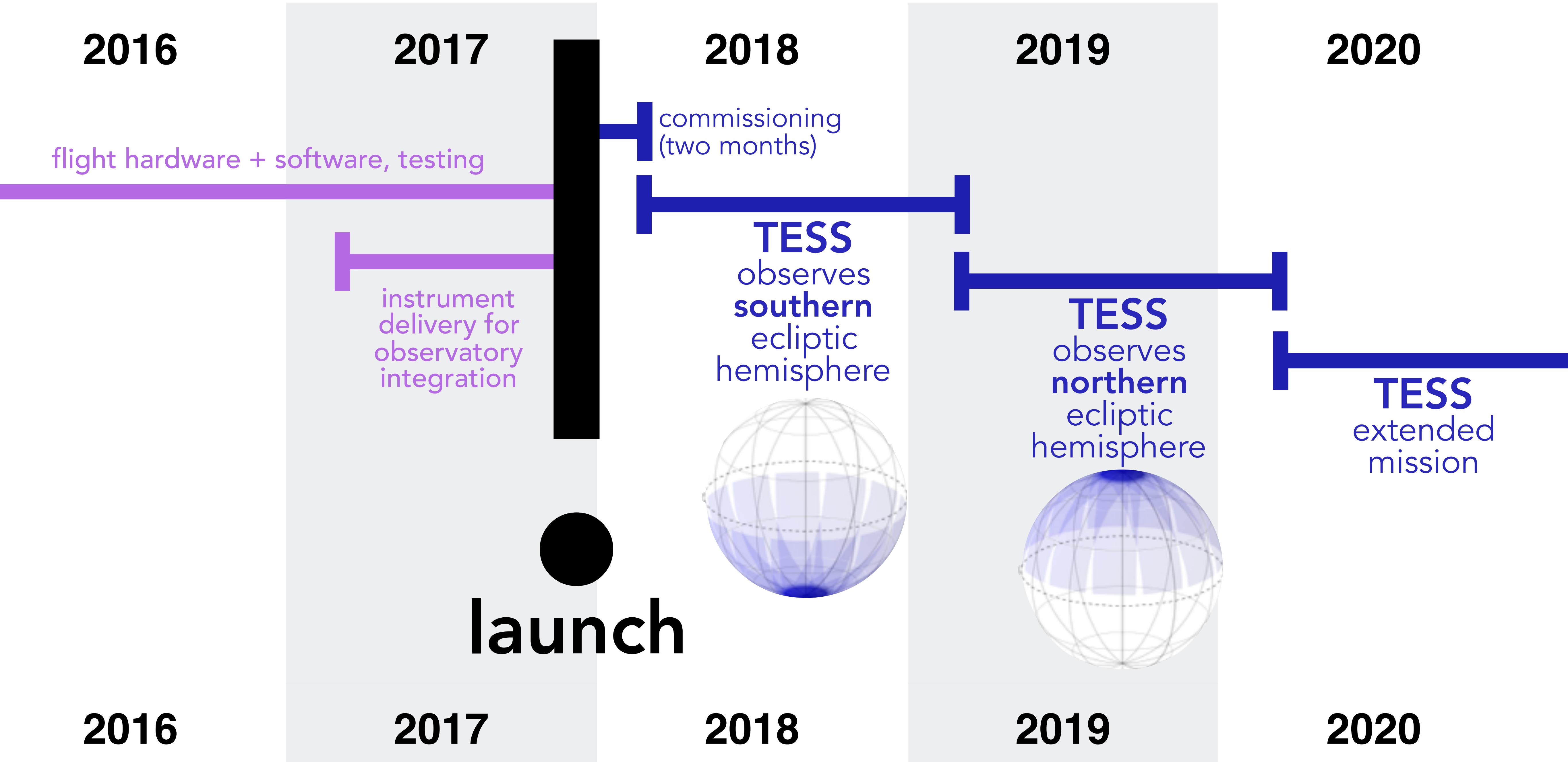
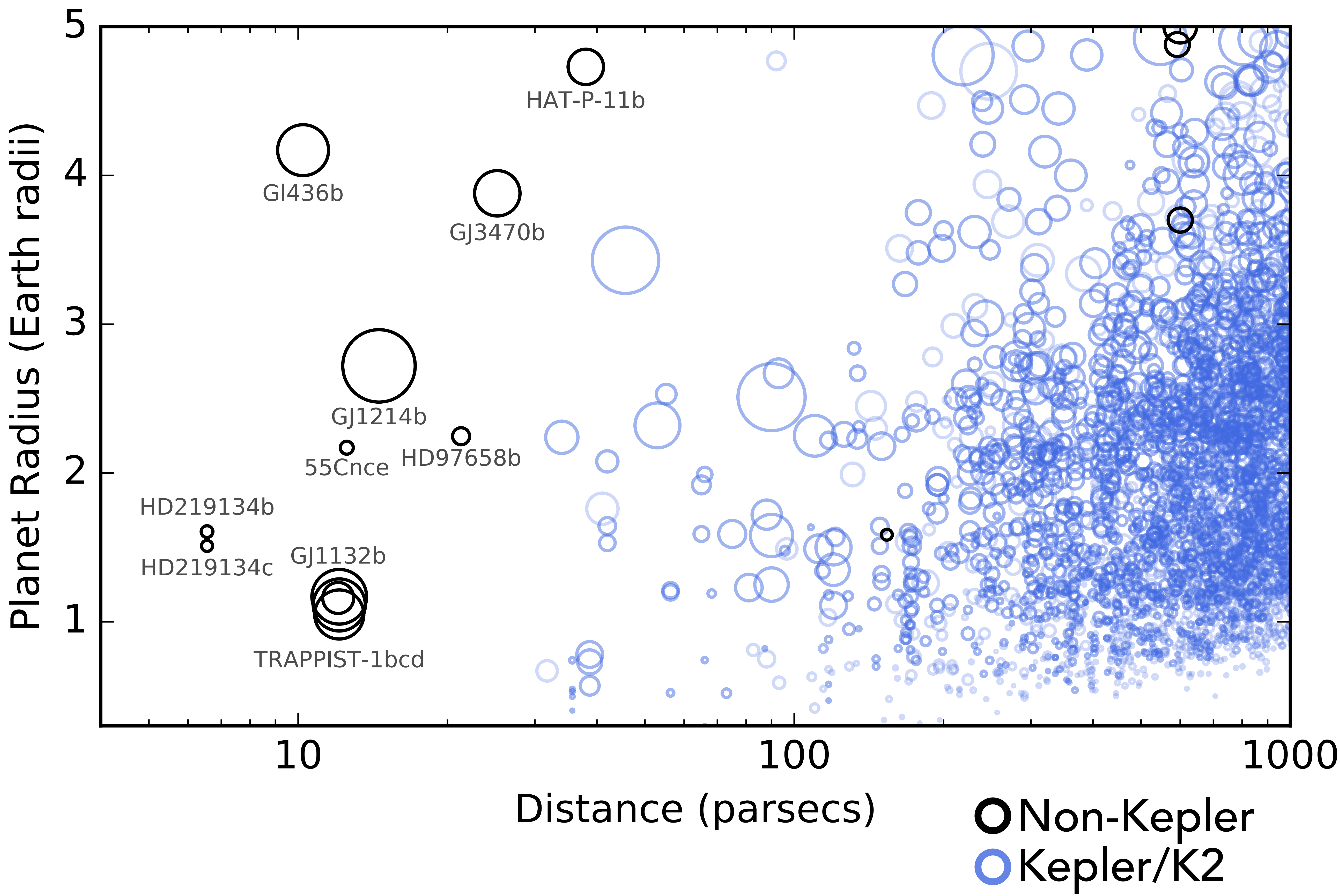
Postage stamps will be downloaded at **2 minute** cadence for 200,000 stars, primarily good **planet-search** hosts.

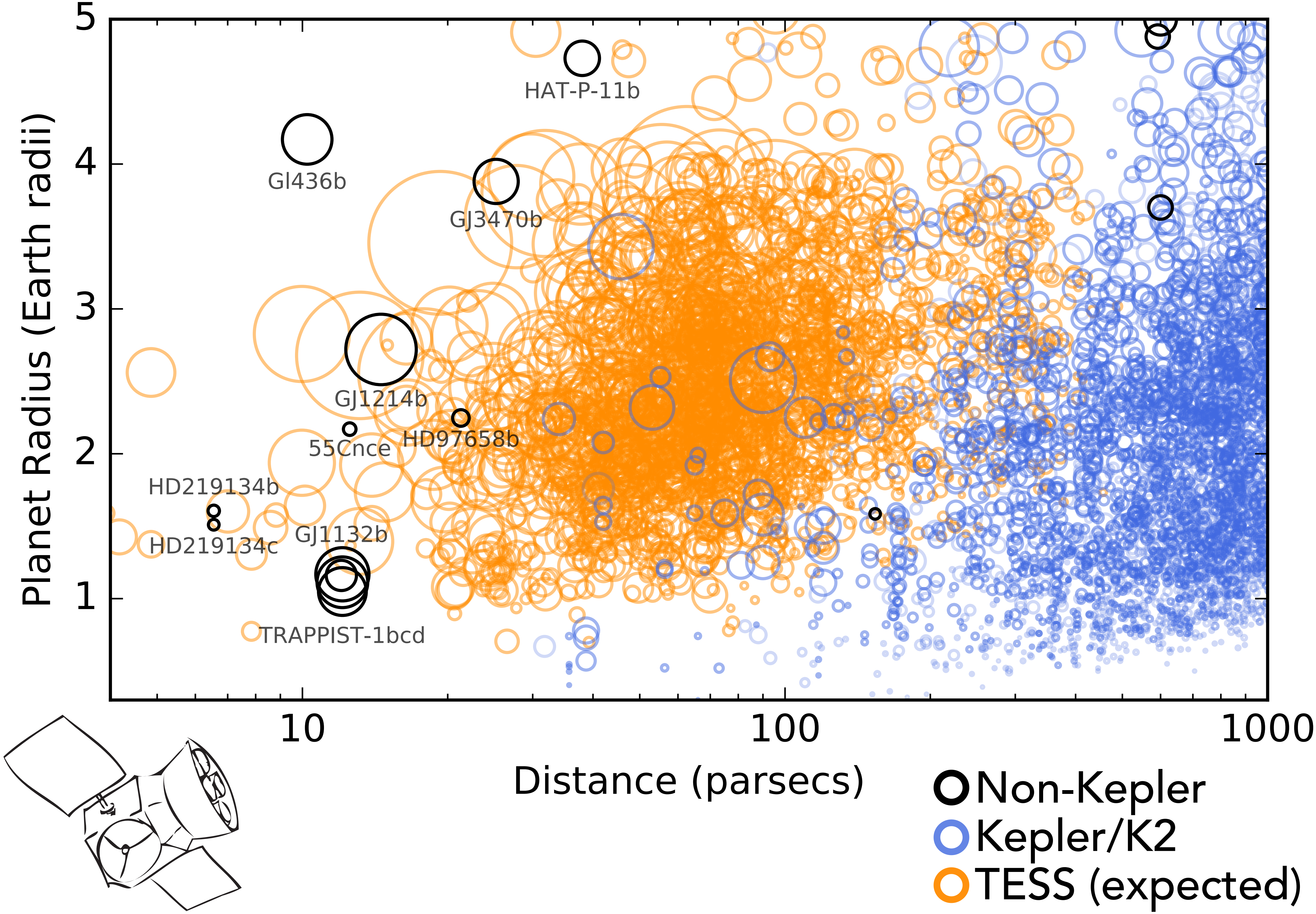
Full frame images will be downloaded at **30 minute** cadence.

TESS timeline:





5
4
3
2
1
Planet Radius (Earth radii)
10
100
1000
Distance (parsecs)
HAT-P-11b
Gl436b
GJ3470b
GJ1214b
HD97658b
55Cnce
HD219134b
HD219134c
GJ1132b
TRAPPIST-1bcd
Non-Kepler
Kepler/K2



Planet Radius (Earth radii)
Distance (parsecs)
5
4
3
2
1
10
100
1000
HAT-P-11b
Gl436b
GJ3470b
GJ1214b
HD97658b
55Cnce
HD219134b
HD219134c
GJ1132b
TRAPPIST-1bcd
Non-Kepler
Kepler/K2
TESS (expected)

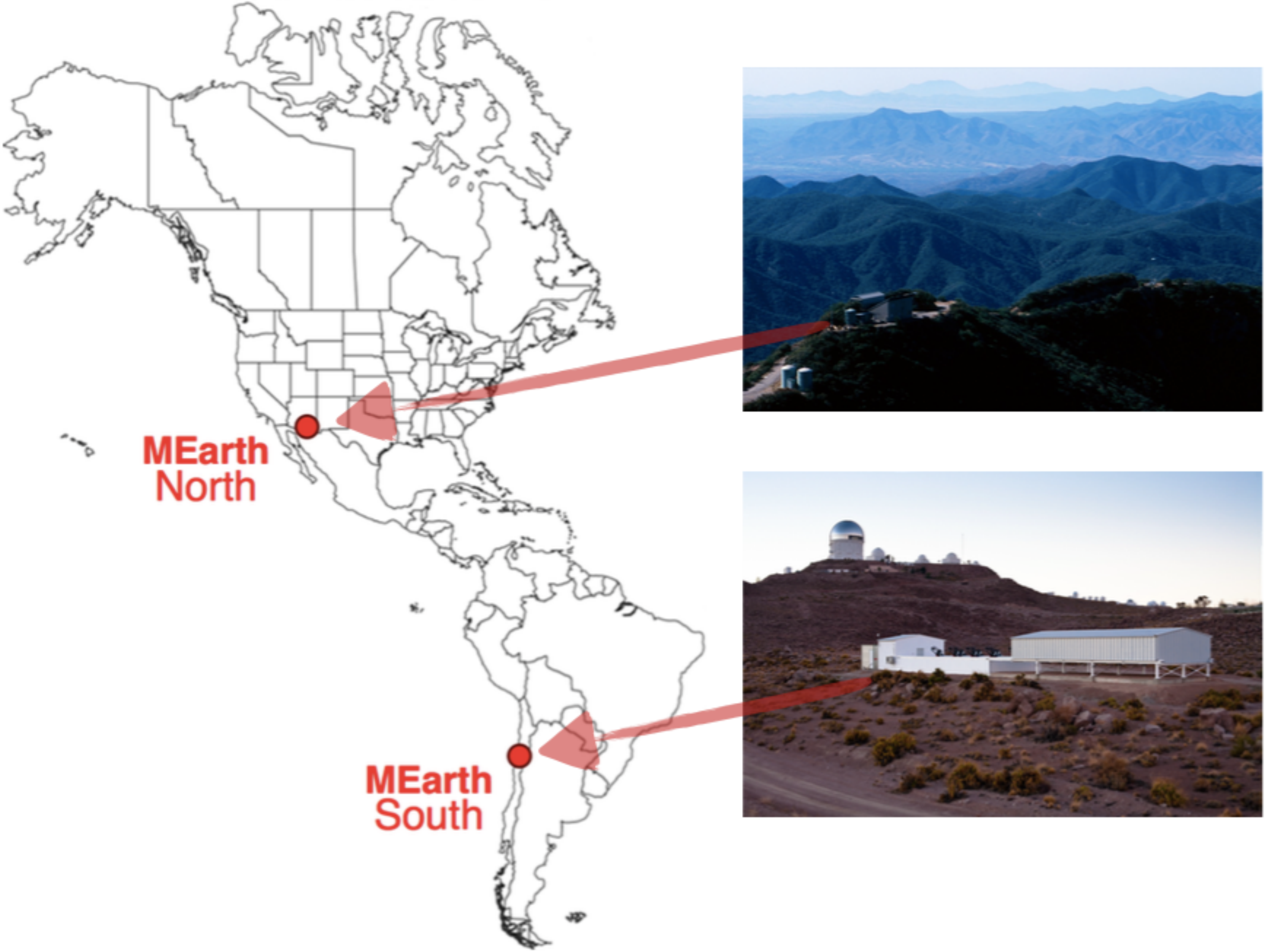
Many Ongoing / Upcoming Dedicated M-dwarf Planet Surveys

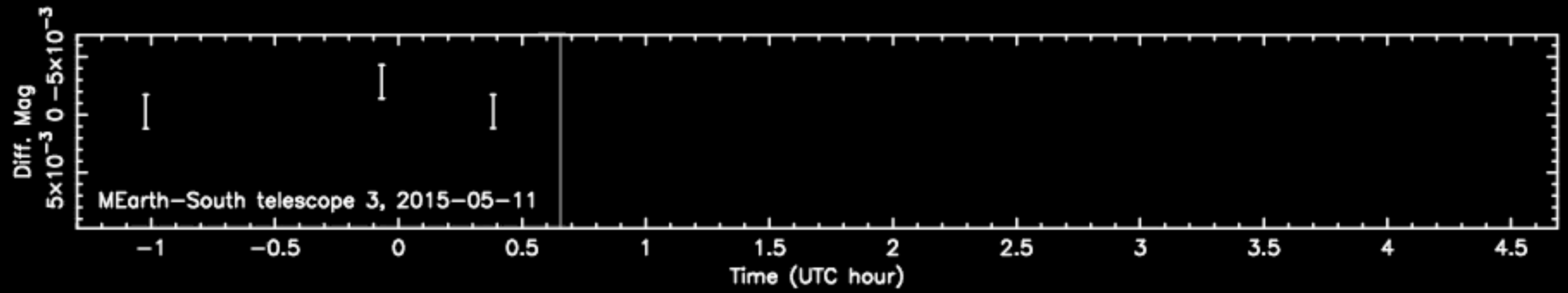
- SPIROU (RV, CFHT)
- CARMENES (RV, Calar Alto Observatory)
- HPF (RV, Hobby Eberly Telescope)
- APACHE (Transit, Italy)
- MEarth-N and MEarth-S (Transit, Arizona + Chile)
- SPECULOOS (Transit, Chile)
- EXTRA (Transit, Chile)

- Also, NGTS, HARPS, HARPS-N, HIRES, and others…

The MEarth Project

David Charbonneau, Jonathan Irwin,
Zachory Berta-Thompson,
Elisabeth Newton & Jason Dittmann

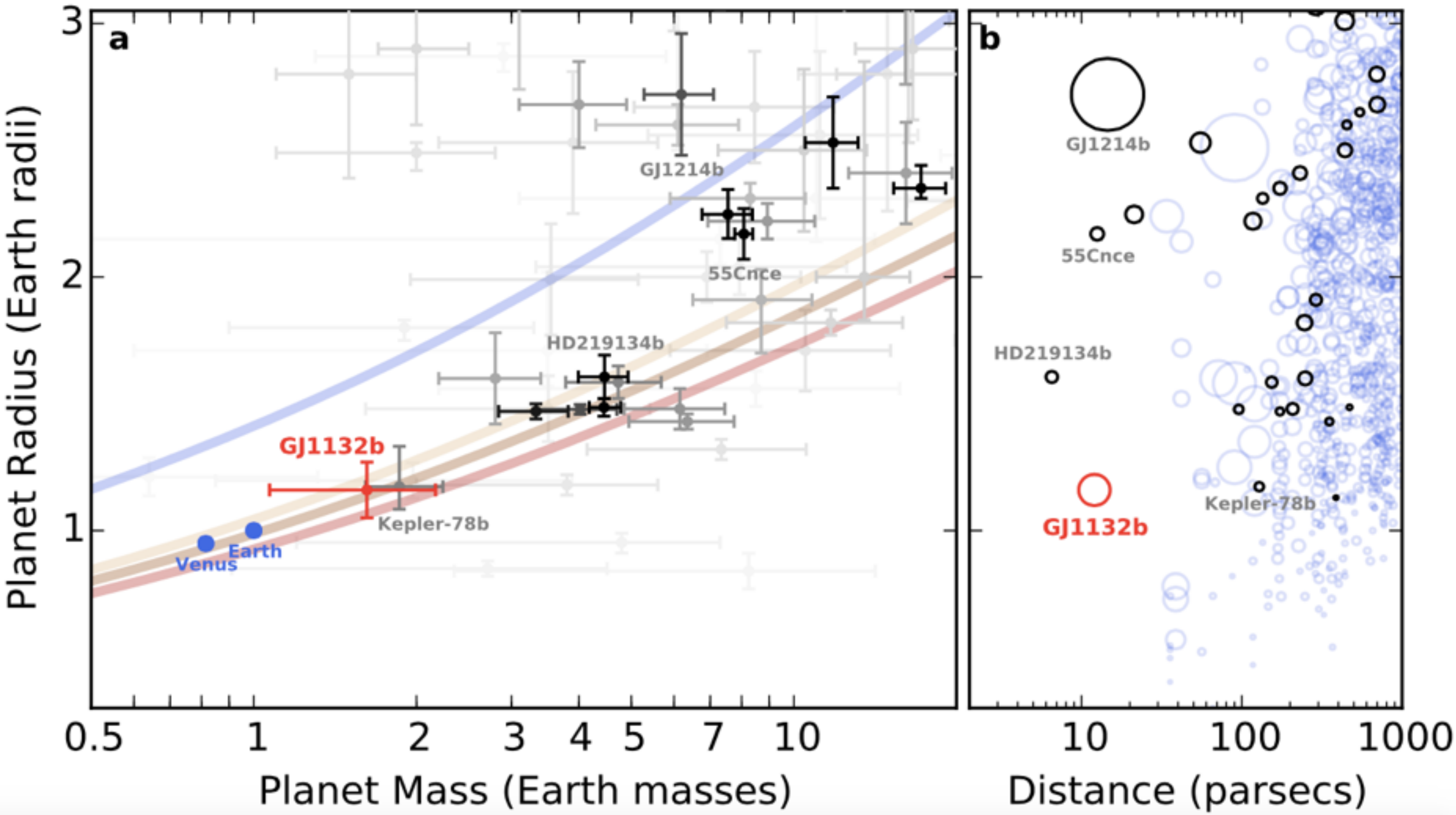

MEarth
North
MEarth
South



MEarth Discovers GJ1132b – 11 May 2015

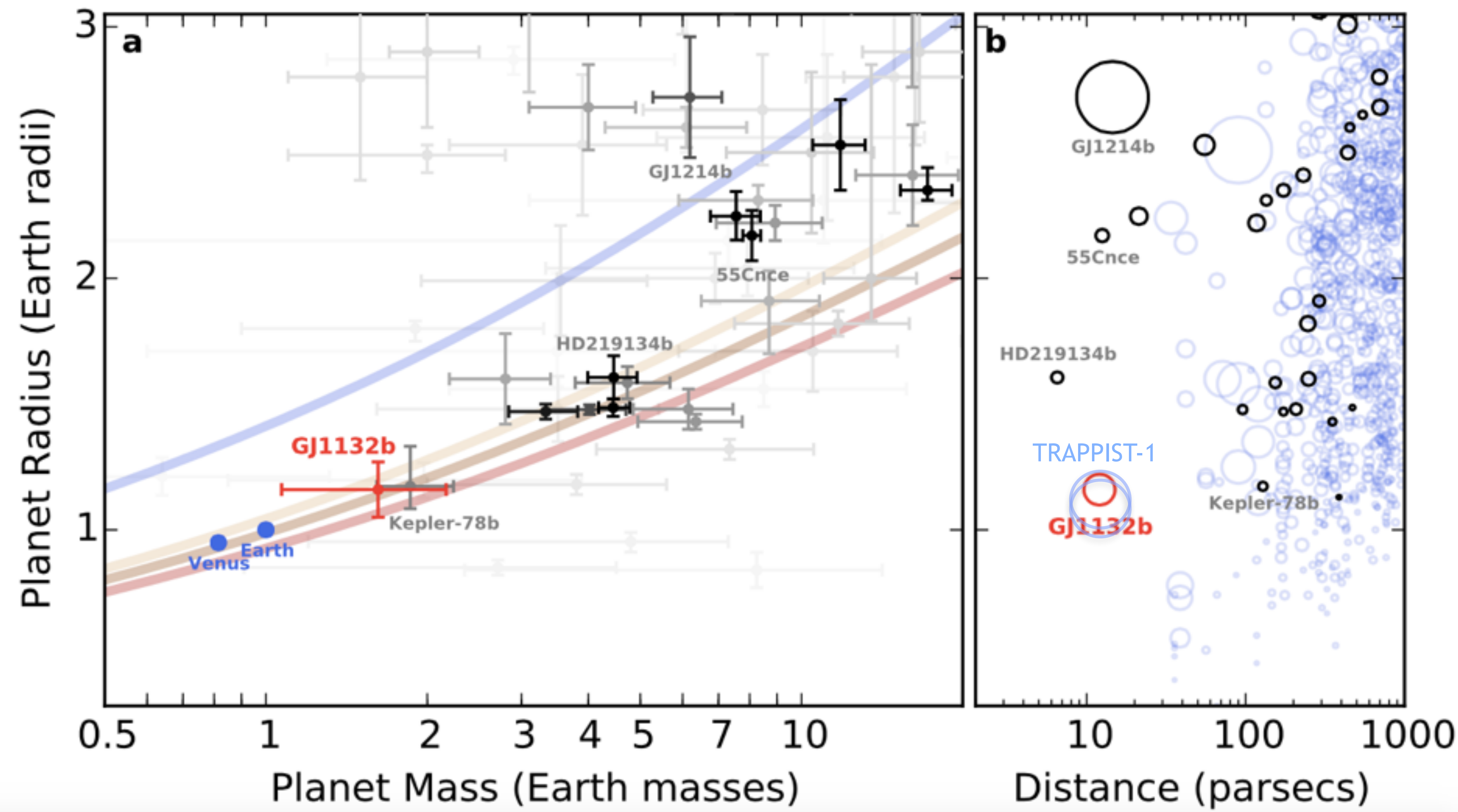
Movie & Observatory by Jonathan Irwin (Harvard-Smithsonian CfA)

The First Terrestrial Exoplanet Available for Atmospheric Study



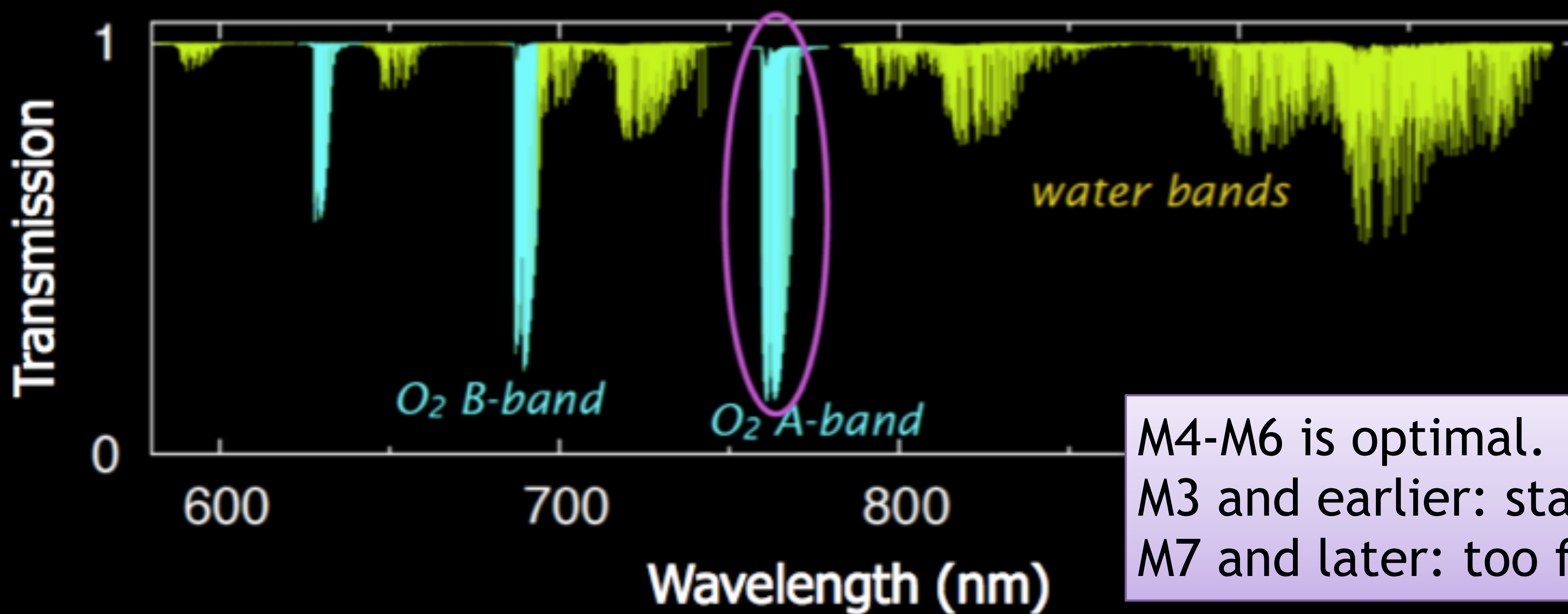
Berta-Thompson et al. Nature Nov 2015

The First Terrestrial Exoplanet Available for Atmospheric Study

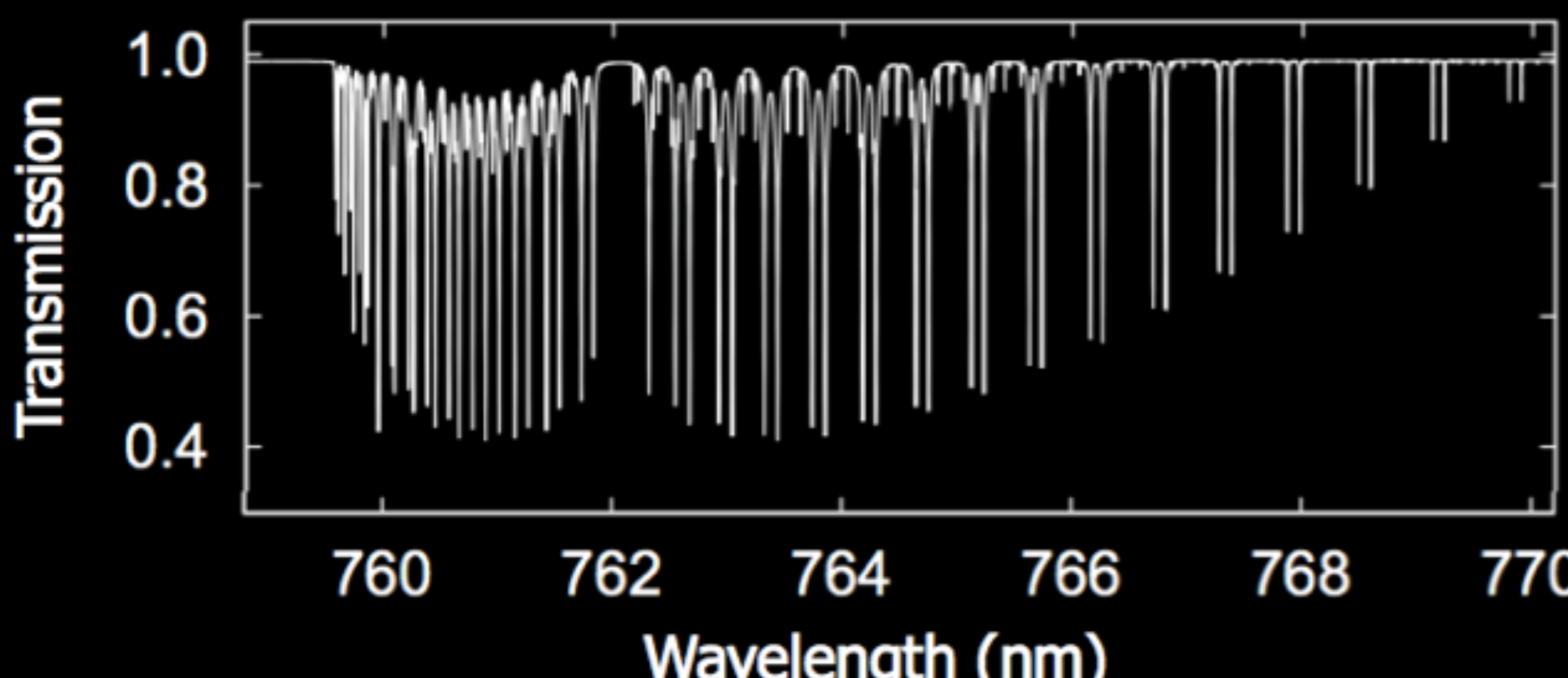


Berta-Thompson et al. Nature Nov 2015

Humanity's First Credible Attempt to Detect an Alien Biomarker Gas is to Use the ELTs to Search for Oxygen at High Resolution (Snellen et al.; Rodler & Lopez-Morales)

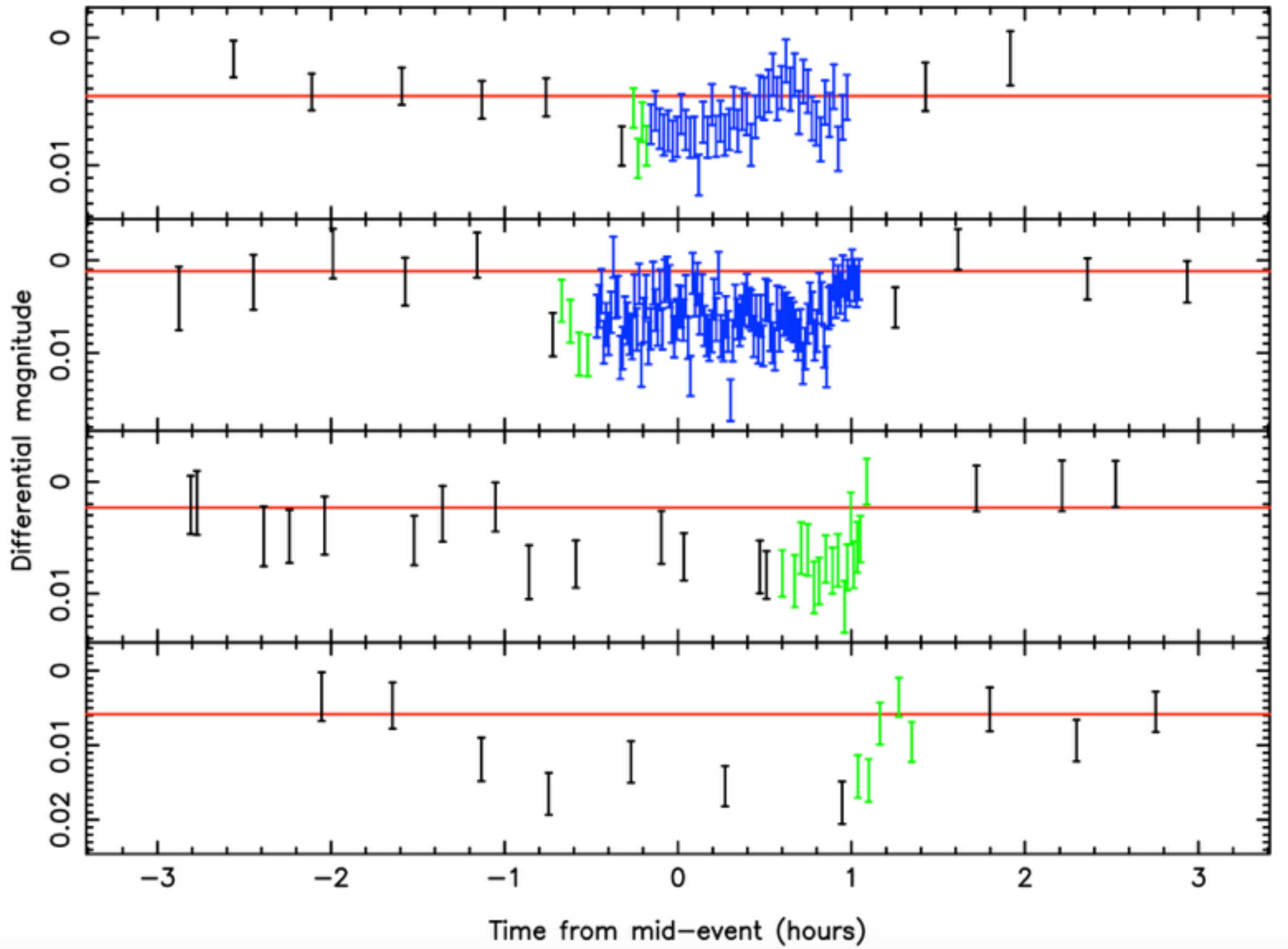


M4-M6 is optimal.
M3 and earlier: star is too big
M7 and later: too few optical photons

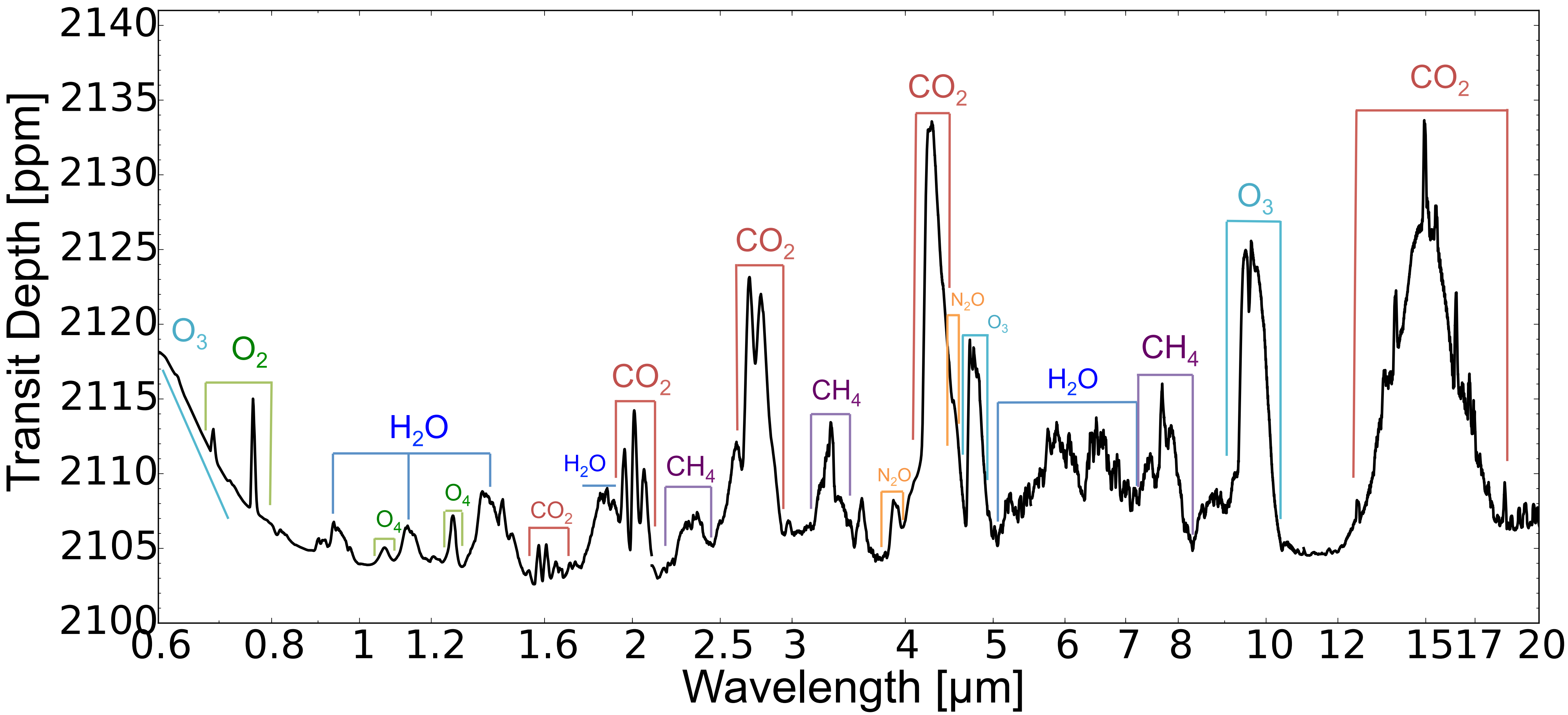


Slide: M. Lopez-Morales

Single-Event Candidates from MEarth: Need to Determine Period from RV Follow-Up



Modern Earth orbiting an M5V



Features at 2-30 ppm. Water vapor seen at the few ppm level.

Transmission model (includes refraction) from Misra et al., (2014)

Model is cloud-free, however continuum corresponds to 8km above the planetary surface, likely above any actual cloud deck.

Slide Courtesy of Prof. Victoria Meadows

R=1.4 R⊕ around M4.5V K=8.8
Earth-like atmosphere

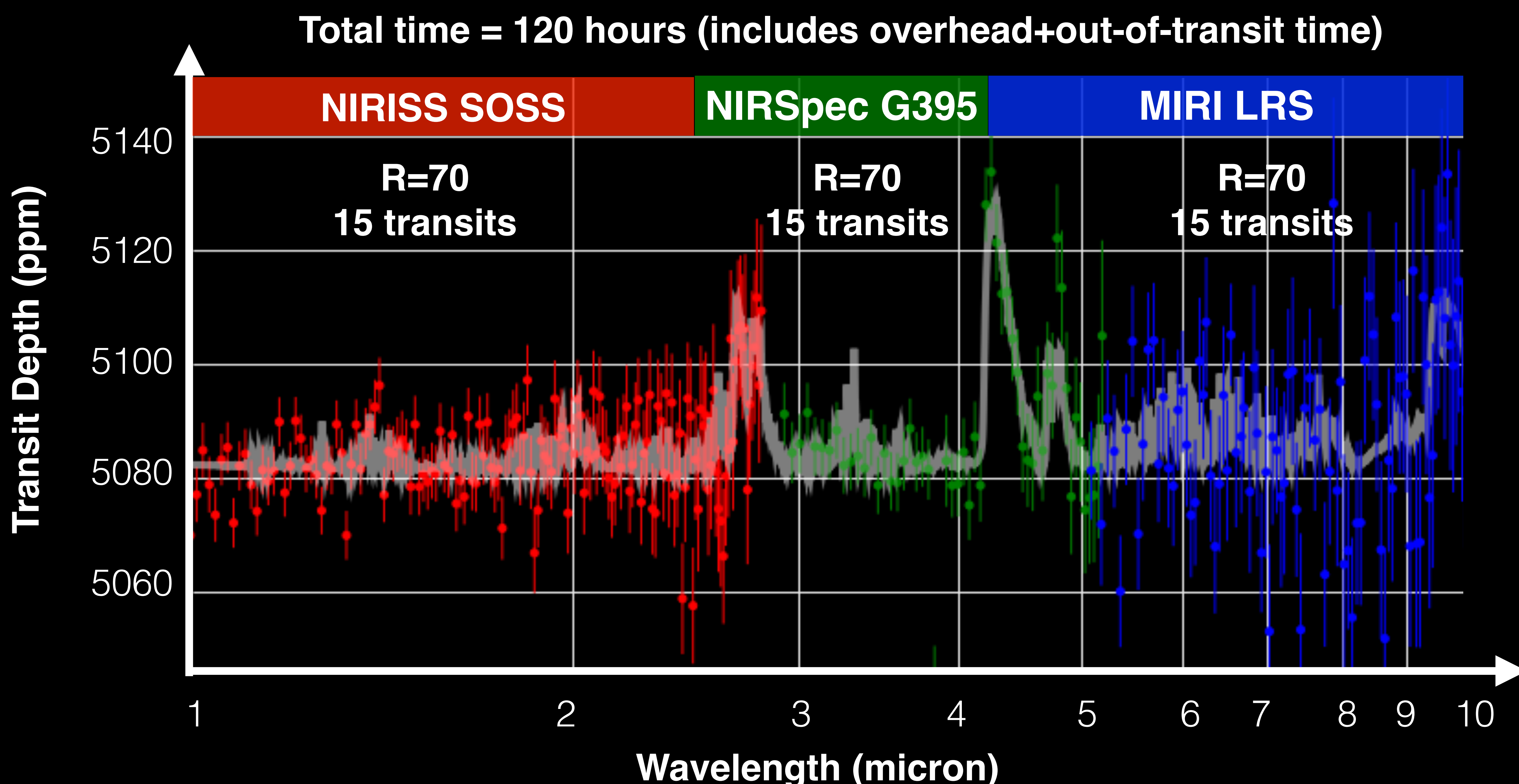
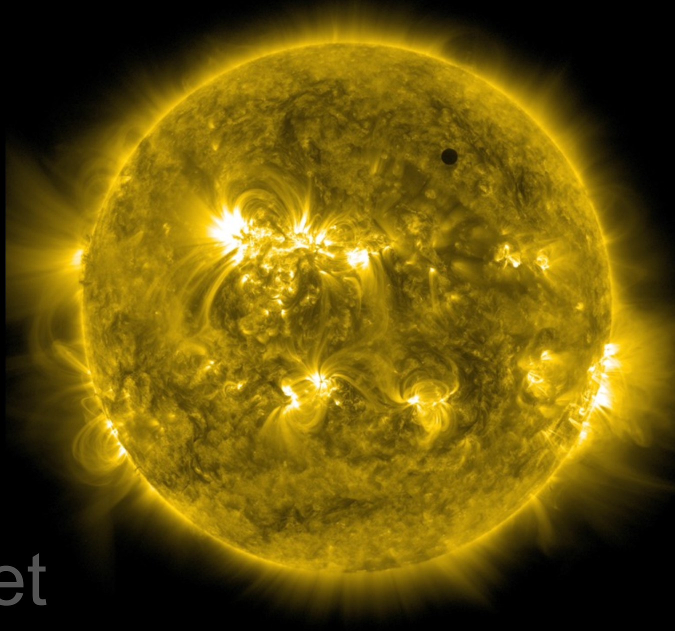


Figure Courtesy of Natasha Batalha & Nikole Lewis

Conclusions



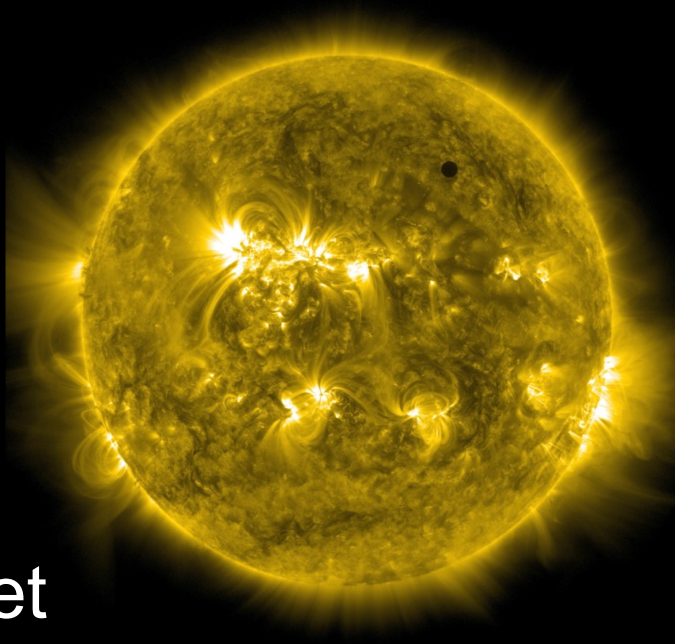
- Small planets are common:
  - At least 16% of Sun-like stars have an Earth-sized planet
  - Mean number of Earth-size planets per small star HZ is 0.24
  - Terrestrial planets are consistent with the Earth's ratio of Fe to $MgSiO_3$.

- JWST is a revolutionary opportunity to constrain the molecular constituents, temperature structures, and metallicities of exoplanet atmospheres.

- Only terrestrial exoplanets orbiting M-dwarfs are accessible to JWST.

- TESS will discover 300 Earths and super-Earths transiting nearby stars, and significant ground-based work is required for their follow-up.

- Dedicated M-dwarf exoplanet surveys may soon uncover some terrestrial, habitable-zone planets transiting nearby M-dwarfs.



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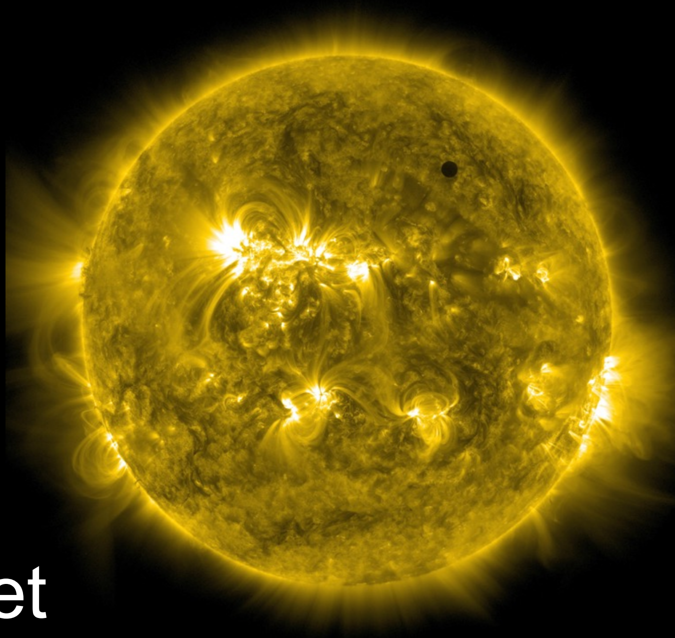

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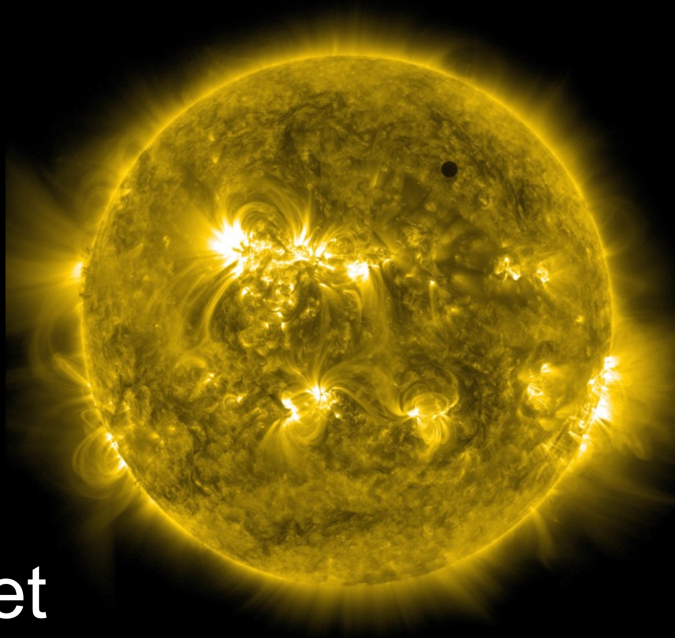

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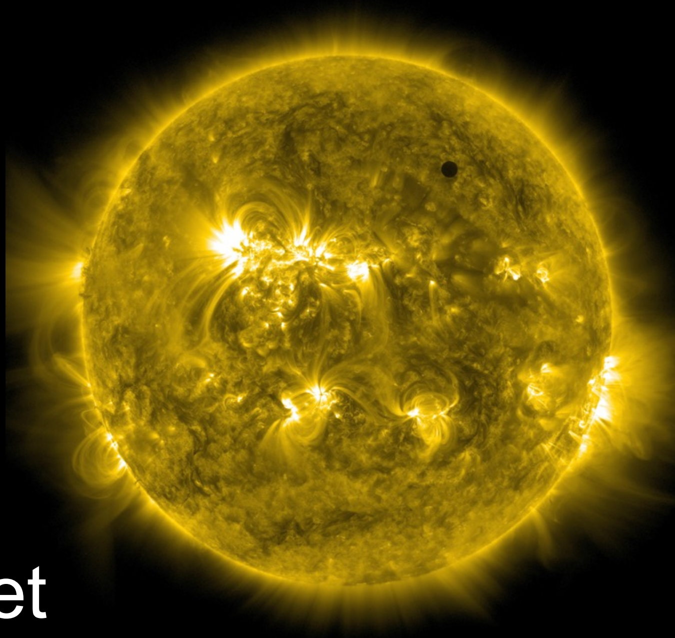

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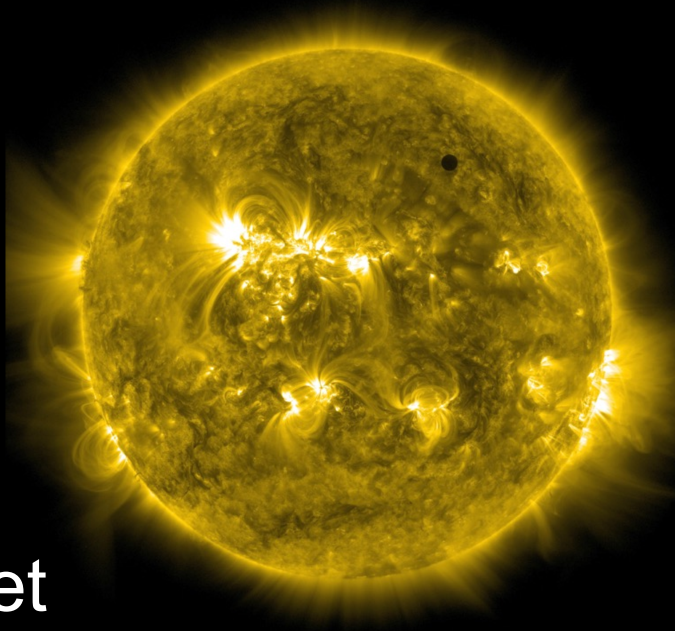

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