Exoplanets

Lecture 11
03.12.2021
MFF UK

Outline

- Frequency of exoplanets

- Composition of exoplanets

- Interesting exoplanetary systems

Motivation

- Drake's equation

  https://www.pbs.org/lifebeyondearth/listening/drake.html

And what do observations tell us?

Planet frequency

- We have now larger data set

- This is 2012, HARPS and CORALIE data

- Planets are quite frequent, at least every second star (FGK) has at least one planet

Table 1. Occurrence frequency of stars with at least one planet in the defined region. The results for various regions of the $m_2 \sin i - \log P$ plane are given.

Mass limits	Period limit	Planetary rate based on published planets	Planetary rate including candidates	Comments
$> 50\,M_\oplus$	< 10 years	13.9 ± 1.7 %	13.9 ± 1.7 %	Gaseous giant planets
$> 100\,M_\oplus$	< 10 years	9.7 ± 1.3 %	9.7 ± 1.3 %	Gaseous giant planets
$> 50\,M_\oplus$	< 11 days	0.89 ± 0.36 %	0.89 ± 0.36 %	Hot gaseous giant planets
Any masses	< 10 years	65.2 ± 6.6 %	75.1 ± 7.4 %	All "detectable" planets with $P < 10$ years
Any masses	< 100 days	50.6 ± 7.4 %	57.1 ± 8.0 %	At least 1 planet with $P < 100$ days
Any masses	< 100 days	68.0 ± 11.7 %	68.9 ± 11.6 %	F and G stars only
Any masses	< 100 days	41.1 ± 11.4 %	52.7 ± 13.2 %	K stars only
$< 30\,M_\oplus$	< 100 days	47.9 ± 8.5 %	54.1 ± 9.1 %	Super-Earths and Neptune-mass planets on tight orbits
$< 30\,M_\oplus$	< 50 days	38.8 ± 7.1 %	45.0 ± 7.8 %	As defined in Lovis et al. (2009)

Mayor et al 2012, A&A, https://arxiv.org/pdf/1109.2497.pdf

How frequent are gas giants?

- The rate of Jupiter-sized planets around GFK stars is estimated to be around 1%

  Wright et al. 2012, https://arxiv.org/pdf/1205.2273.pdf

- Are smaller planets more frequent?

- Jupiter-sized planets on long periodic orbits have a frequency of about 14% - see next slides.

- Recall the frequency of HJs in open clusters was about 6% (perhaps due to n-body interactions).

Small planets vs. large planets

- Left: low mass vs. High mass, right: same but only for short periodic planets less than 100 days

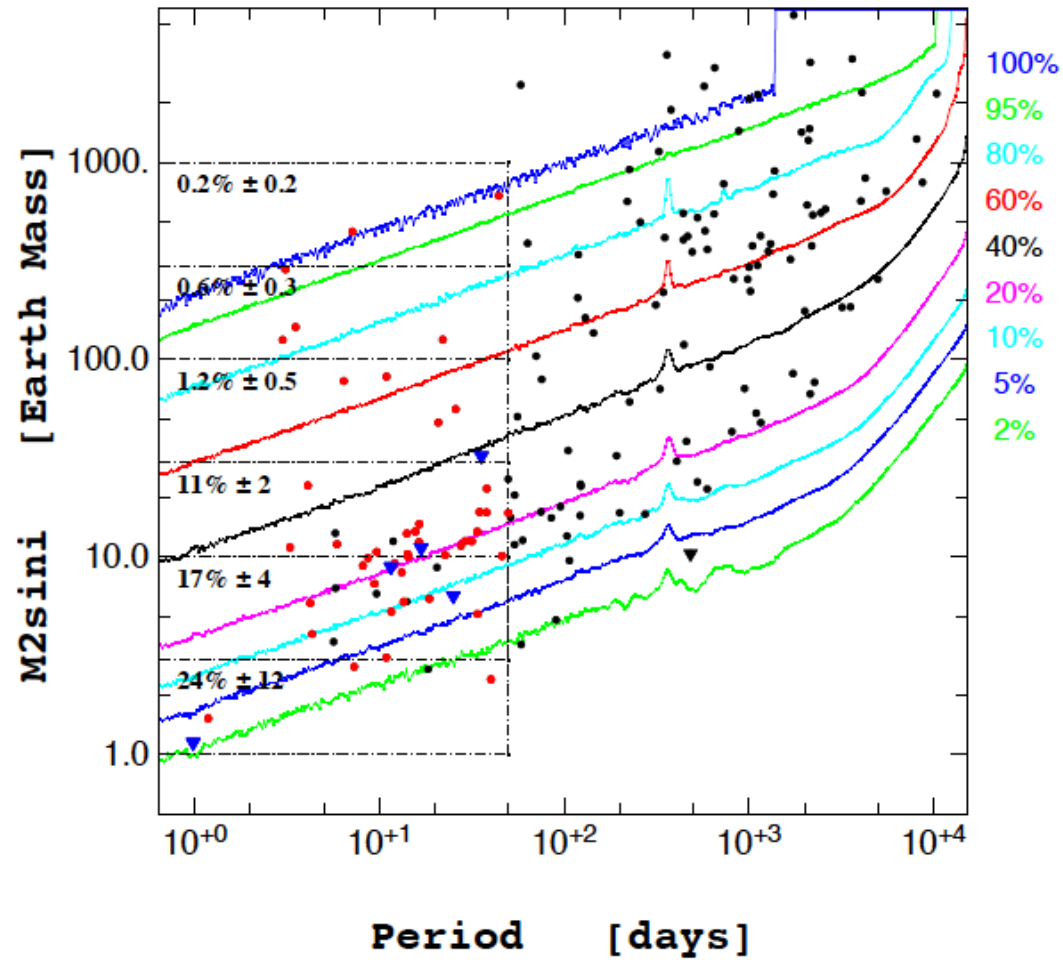Mayor et al 2012, A&A, https://arxiv.org/pdf/1109.2497.pdf
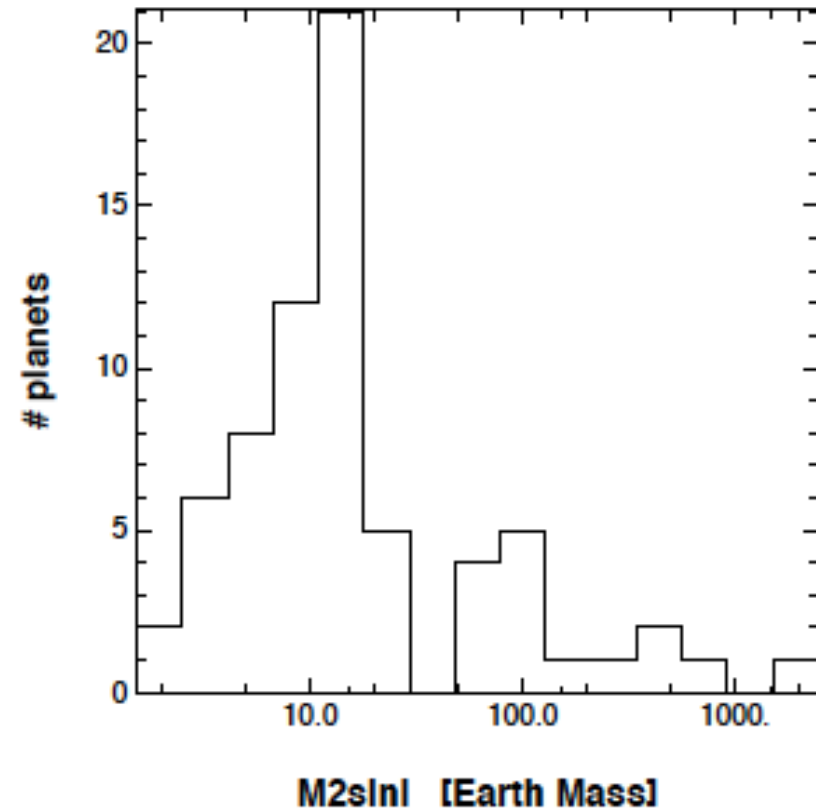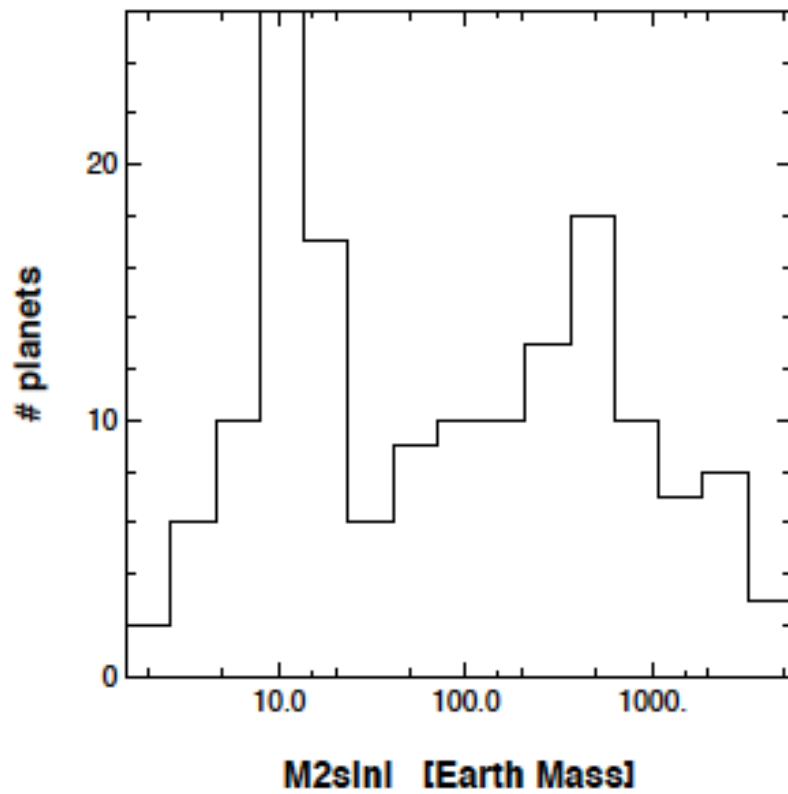
Small planets frequency

- Sample of 10 stars hosting 29 planets
- Sensitivity to detect 10 M Earth planet is close to 100%
- A 3 M Earth planet sensitivity is about 20%
- ESPRESSO is here now!

Mayor et al 2012, A&A, https://arxiv.org/pdf/1109.2497.pdf
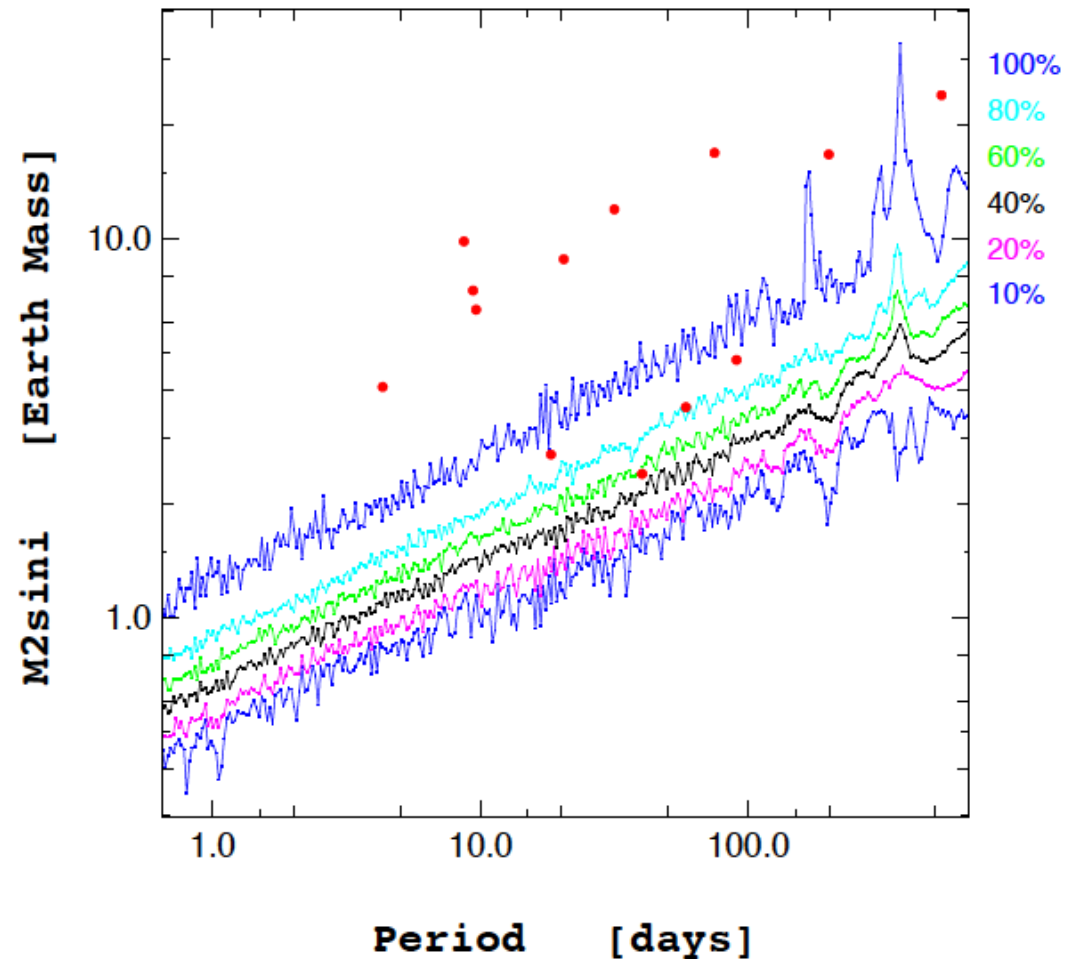
We have pretty good chances!

Mayor et al 2012, A&A, https://arxiv.org/pdf/1109.2497.pdf

Small vs. Large

- Metallicity of the system is a factor

- Large planets favor large metallicities

- Smaller planets are abundant also with lower metallicities

Mayor et al 2012, A&A, https://arxiv.org/pdf/1109.2497.pdf
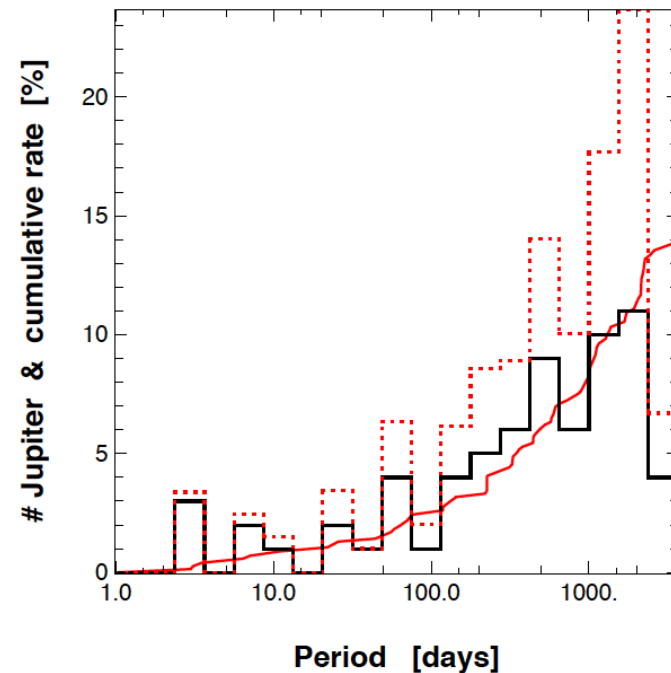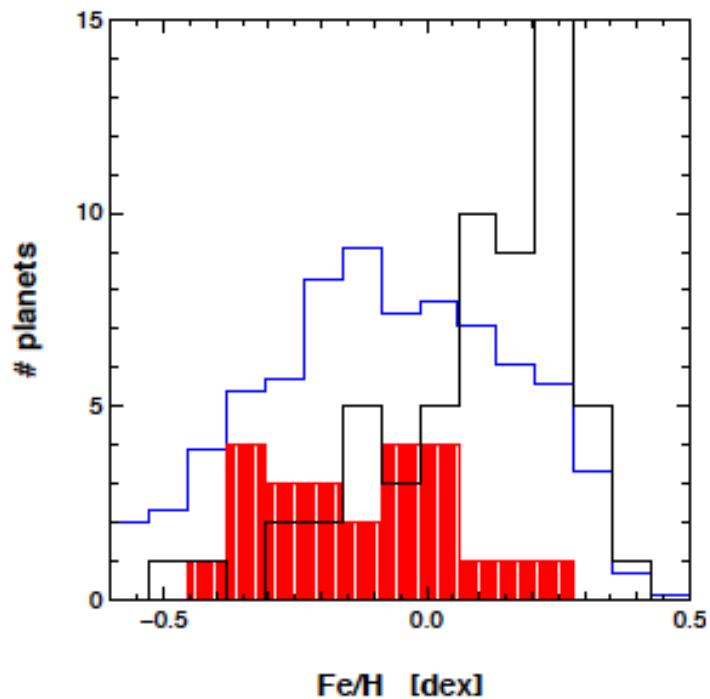
What the current data tell us?

What does TESS tell us?

- Forecasts before TESS launch
- Barclay et al. 2018
- Observing strategy permits multiple observations of similar sectors
- There is also a Continuous viewing zone

Barclay 2018 https://arxiv.org/abs/1804.05050
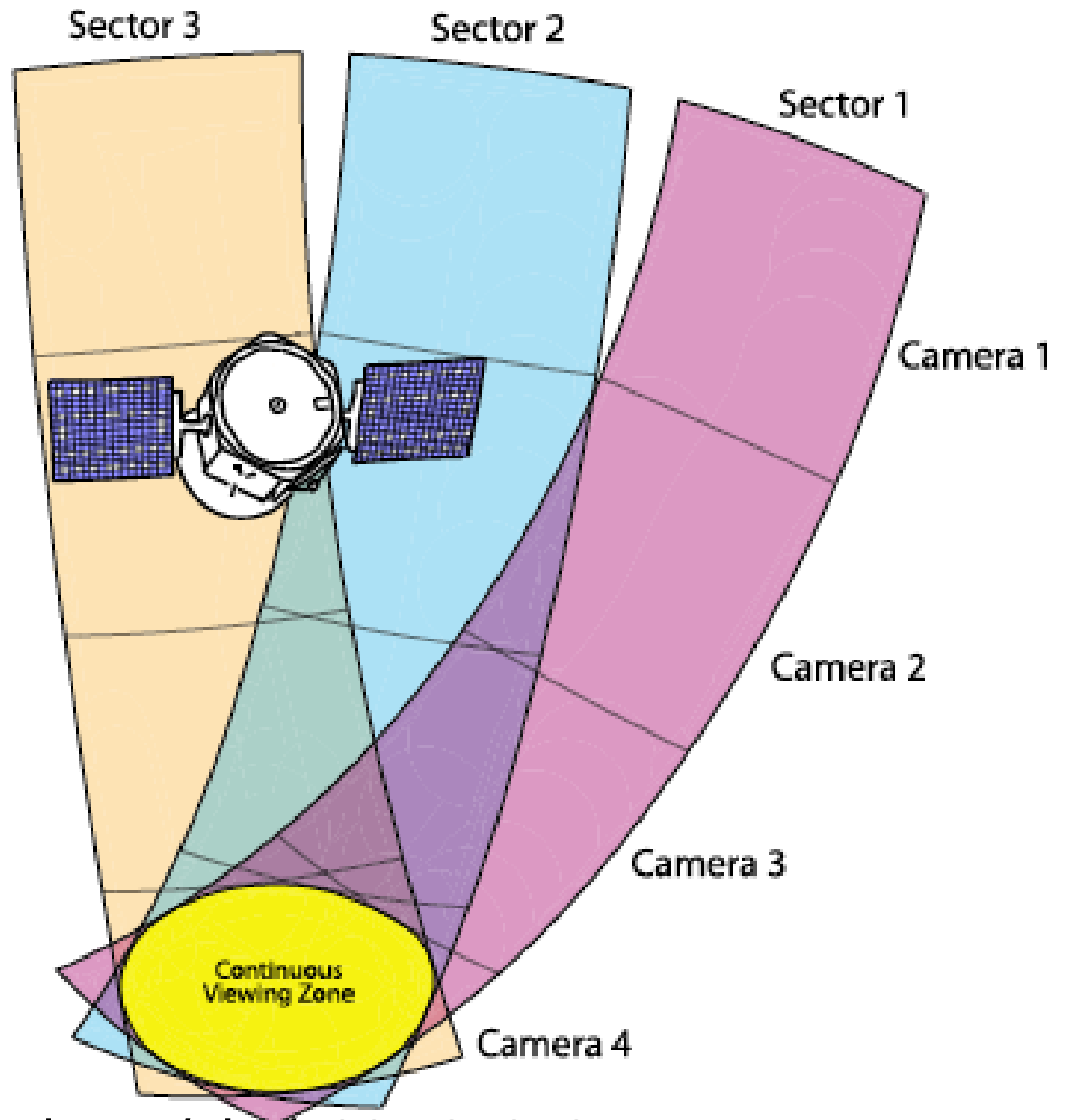
TESS targets

- In total 3.2 million of TESS Catalogue stars will be observed

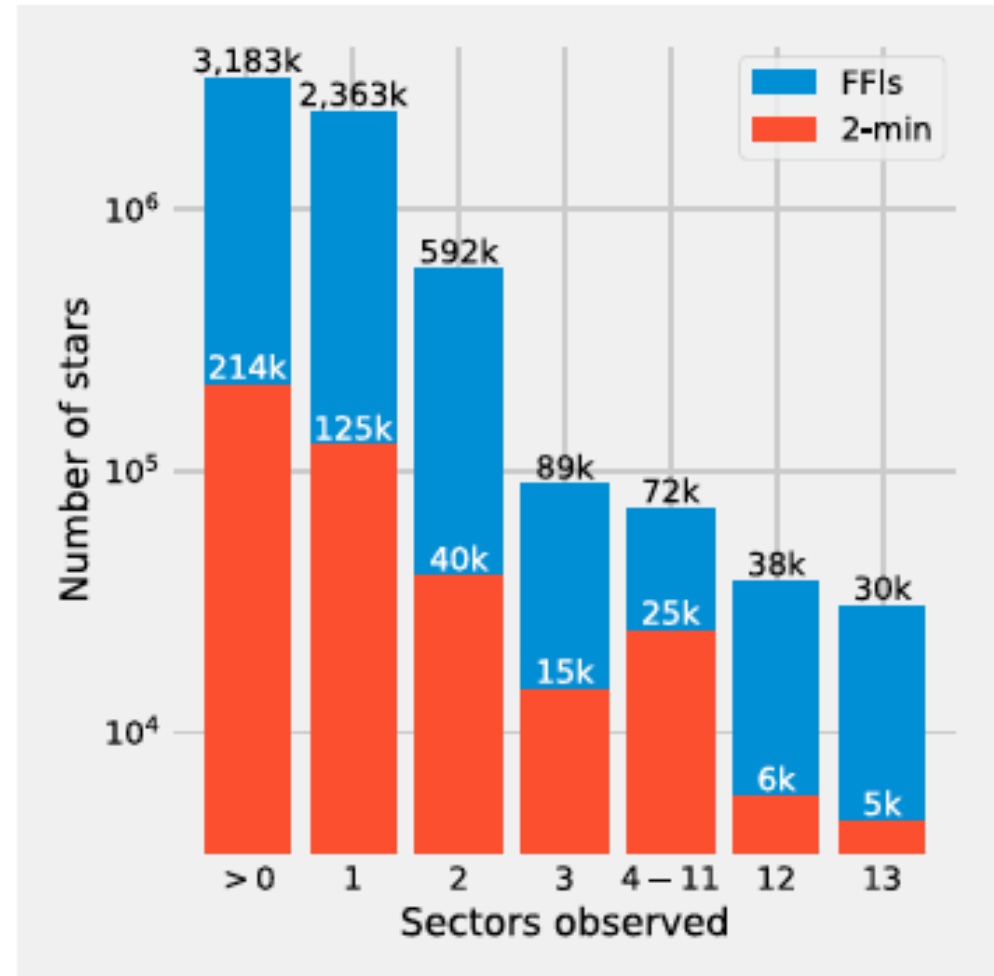- About 2% of stars will have 12-13 sectors coverage

Figure 2. Number of CTL targets observed for a given number of 27.4-day sectors. FFI targets are shown in blue, and 2-minute cadence targets in red. In total, 3.2 million CTL targets are observed, of which 214,000 are observed at 2-minute cadence. Roughly three-quarters of targets are only observed for a single sector, with just 2.1% having 12 or 13 sectors of coverage. The 2-minute cadence targets are disproportionately observed for more sectors, with 4.2% of the 2-minute cadence targets receiving 12 or 13 sectors of coverage.

Barclay 2018 https://arxiv.org/abs/1804.05050

TESS predictions

- TESS might find about 4400 planets orbiting TESS Catalogue stars
- 40 Earth-sized planets are expected to be detected
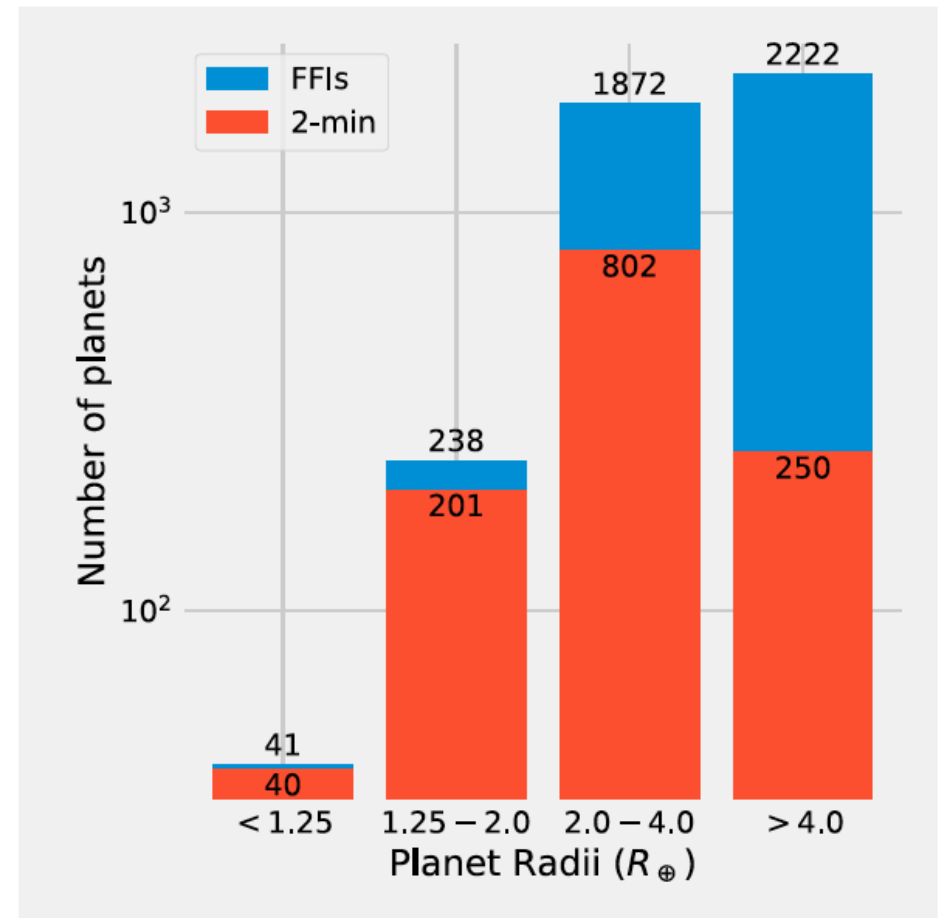- 1000 Super Earth and/or mini Neptunes expected

Figure 5. Our simulations predict that *TESS* will detect a total of about 4400 planets orbiting stars on the CTL, of which 1300 will be observed at 2-minute cadence. Roughly 40 Earth-sized planets will be found, almost all of which are on the 2-minute target list. A total of 1000 super-Earths and mini-Neptunes will also be found. Many new giant planets will be discovered, primarily through FFI data. The numbers shown above the FFI bars are total planets and include the planets found in 2-minute cadence data.

TESS hit rate

- The hit rate (planet found)

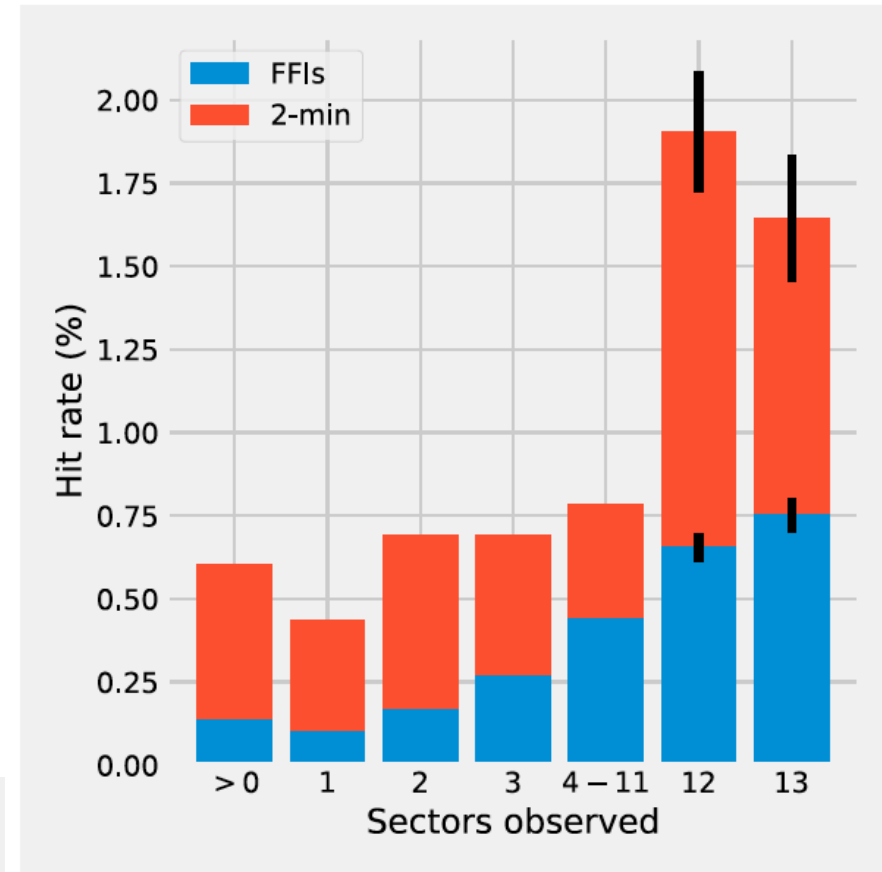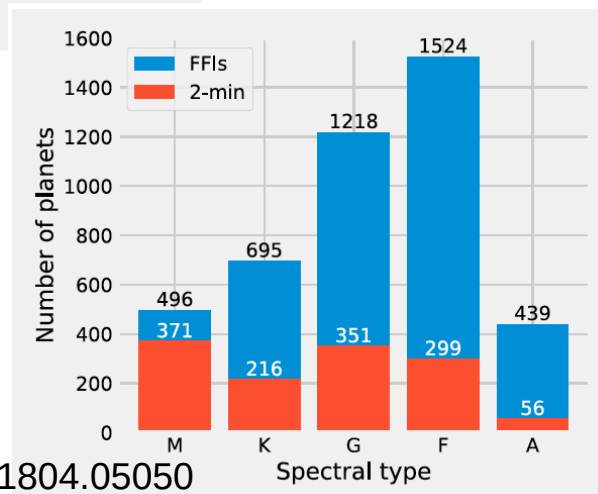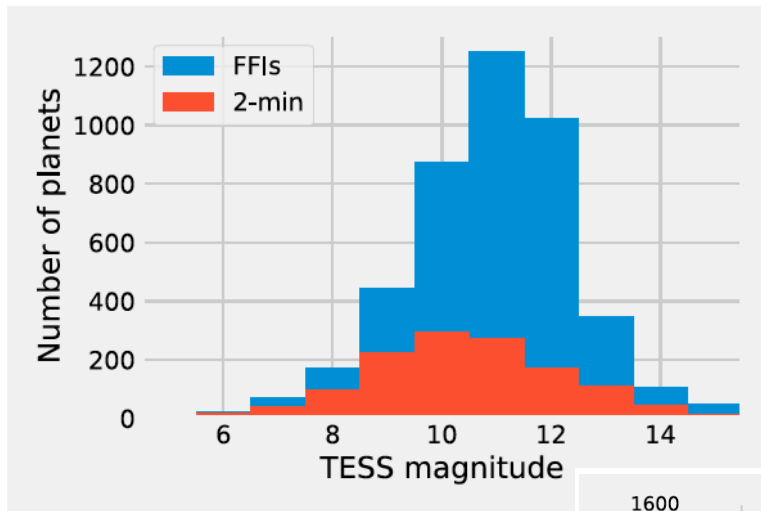 is varying between

  0.14% till a few %

Figure 7. Ratio of stars observed to planets detected as a function of the number of sectors a star is observed for. The longer a star was observed, the higher probability a planet would be detected. Targets observed at 2-minute cadence are shown in red, while blue are FFI targets. For 2-minute cadence stars the average hit rate was 0.60%, while including all stars on the CTL drops this to 0.14%. While observing for a longer baseline increased the number of planets, the increase is not linear. For 2-minute cadence targets, an increase of 12× in observing baseline increased the hit rate by a factor of just 4.4. There are comparatively few planets in the 12 and 13 sector bins, so we show Poisson uncertainties on these bars demonstrating that there is not a measurable difference between observing for 12 or 13 sectors. Red and blue bars are not stacked; both start at zero.

Barclay 2018 https://arxiv.org/abs/1804.05050

TESS actual

List of TESS Planets

Last updated: 11/30/2020

Total number of sectors: 30
Total number of TOIs: 2426

    Total number of TOIs with Radii < 4 Earth Radii: 748
    Total number of Confirmed Planets: 82
    Total number of False Positives: 624

Source: https://tess.mit.edu/publications/

2426 TOIs (so far!)

30 sectors

748 TOIs with TESS Rp < 4 Re

624 false positives

82 confirmed TESS Planets

Last updated: 11/30/2020

TESS and others

Summary Counts

All Exoplanets	4307
Confirmed Planets with Kepler Light Curves for Stellar Host	2414
Confirmed Planets Discovered by Kepler	2394
Kepler Project Candidates Yet To Be Confirmed	2366
Confirmed Planets with K2 Light Curves for Stellar Host	446
Confirmed Planets Discovered by K2	425
K2 Candidates Yet To Be Confirmed	889
Confirmed Planets Discovered by TESS [1]	82
TESS Project Candidates Integrated into Archive (2020-12-04 13:00:02) [2]	2428
Current date TESS Project Candidates at ExoFOP	2428
TESS Project Candidates Yet To Be Confirmed [3]	1458

[1] *Confirmed Planets Discovered by TESS* refers to the number planets that have been published in the refereed astronomical literature.

[2] *TESS Project Candidates* refers to the total number of transit-like events that appear to be astrophysical in origin, including false positives as identified by the TESS Project.

[3] *TESS Project Candidates Yet To Be Confirmed* refers to the number of TESS Project Candidates that have not yet been dispositioned as a Confirmed Planet or False Positive.

NASA Exoplanet archive https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html

TESS vs. other missions

Summary Counts

All Exoplanets	4307
Confirmed Planets with Kepler Light Curves for Stellar Host	2414
Confirmed Planets Discovered by Kepler	2394
Kepler Project Candidates Yet To Be Confirmed	2366
Confirmed Planets with K2 Light Curves for Stellar Host	446
Confirmed Planets Discovered by K2	425
K2 Candidates Yet To Be Confirmed	889
Confirmed Planets Discovered by TESS [1]	82
TESS Project Candidates Integrated into Archive (2020-12-04 13:00:02) [2]	2428
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NASA Exoplanet archive https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html

Different methods

Confirmed Exoplanet Statistics

Discovery Method	Number of Planets
Astrometry	1
Imaging	51
Radial Velocity	821
Transit	3275
Transit timing variations	21
Eclipse timing variations	16
Microlensing	106
Pulsar timing variations	7
Pulsation timing variations	2
Orbital brightness modulations	6
Disk Kinematics	1

Transiting Exoplanets	**3298**
All Exoplanets	**4307**

NASA Exoplanet archive https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html

Mass and radius

Exoplanet Mass and Radius

Confirmed Planets with mass	998
Confirmed Planets with m sin i	833
Confirmed Planets with radius	3300

Counts by Mass

M ≤ 3 M_Earth	41
3 < M ≤ 10 M_Earth	144
10 < M ≤ 30 M_Earth	103
30 < M ≤ 100 M_Earth	99
100 < M ≤ 300 M_Earth	227
300 M_Earth < M	384

Counts by Radius

R ≤ 1.25 R_Earth	417
1.25 < R ≤ 2 R_Earth	874
2 < R ≤ 6 R_Earth	1377
6 < R ≤ 15 R_Earth	467
15 R_Earth < R	165

NASA Exoplanet archive https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html

And how did Kepler perform?

Kepler Mission Counts

Confirmed Planets with Kepler Light Curves for Stellar Host [1]	2414
Confirmed Planets Discovered by Kepler [2]	2394
Candidates and Confirmed in Habitable Zone [1,3] (180 K < Equilibrium (T) < 310 K) or (0.25 < Insolation (Earth flux) < 2.2)	361
Kepler Project Candidates [3]	4717
Kepler Project Candidates Yet To Be Confirmed	2366
Total Candidates and Confirmed Planets [4]	**4780**

[1] This is the number of planets in the Kepler Field where the stellar host was observed by the Kepler Spacecraft. Not all of these planets were detected or discovered by Kepler.

[2] This is the number of planets that were discovered utilizing Kepler observations.

[3] Kepler Project Candidates are all KOIs marked by the Kepler Project as a CANDIDATE in the KOI Cumulative table. This includes planets that have been confirmed or validated.

[4] Total Candidates and Confirmed Planets is the union of the Confirmed Planets and KOI Cumulative data sets. Note that some confirmed planets were never designated as candidates.

Kepler Candidate Statistics

Radius Range	All Candidates	Insolation between 0.32 and 1.78
R ≤ 1.25 R_Earth	941	23
1.25 < R ≤ 2 R_Earth	1364	81
2 < R ≤ 6 R_Earth	1839	156
6 < R ≤ 15 R_Earth	314	18
15 R_Earth < R	154	10

NASA Exoplanet archive https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html

TOI-700 – TESS detection in the HZ

- Detection by TESS of an Earth-sized planet in the HZ

- Parent star is an M dwarf

- What are the prospects for further characterization?
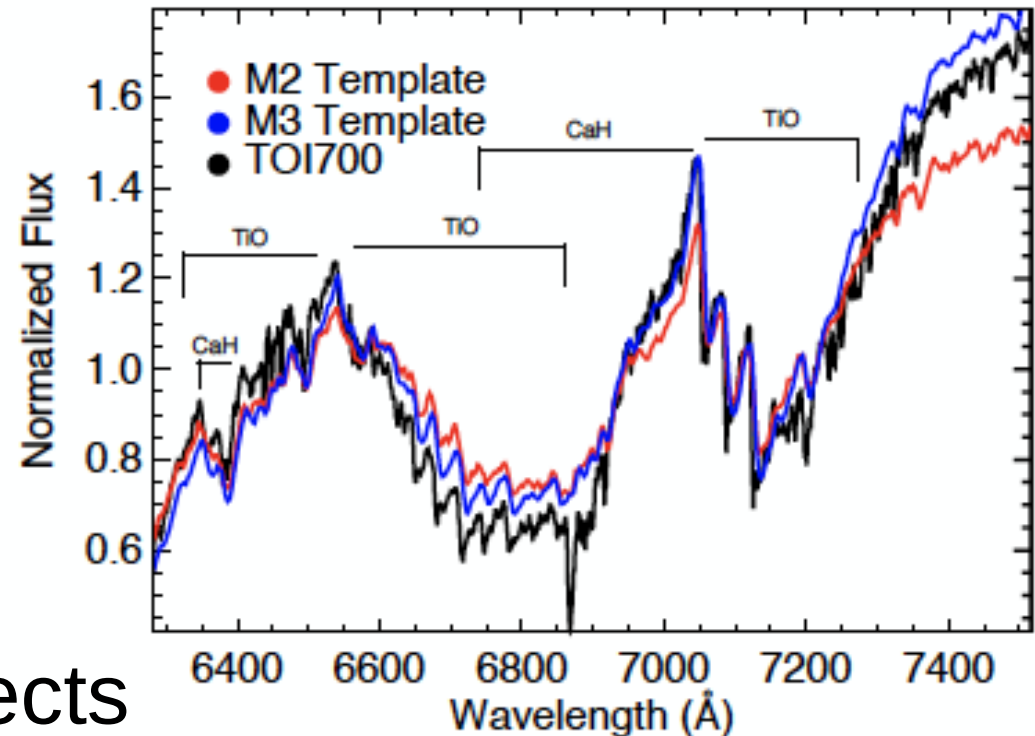
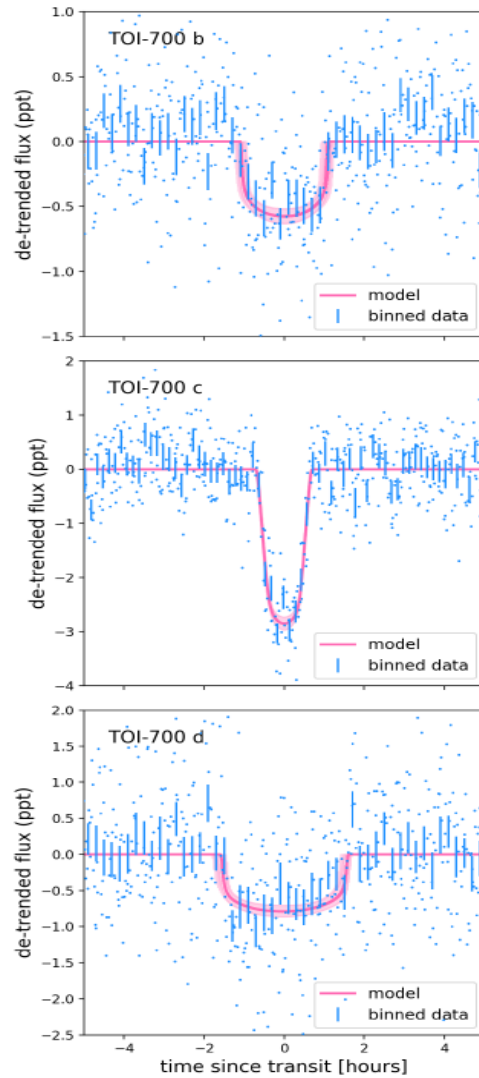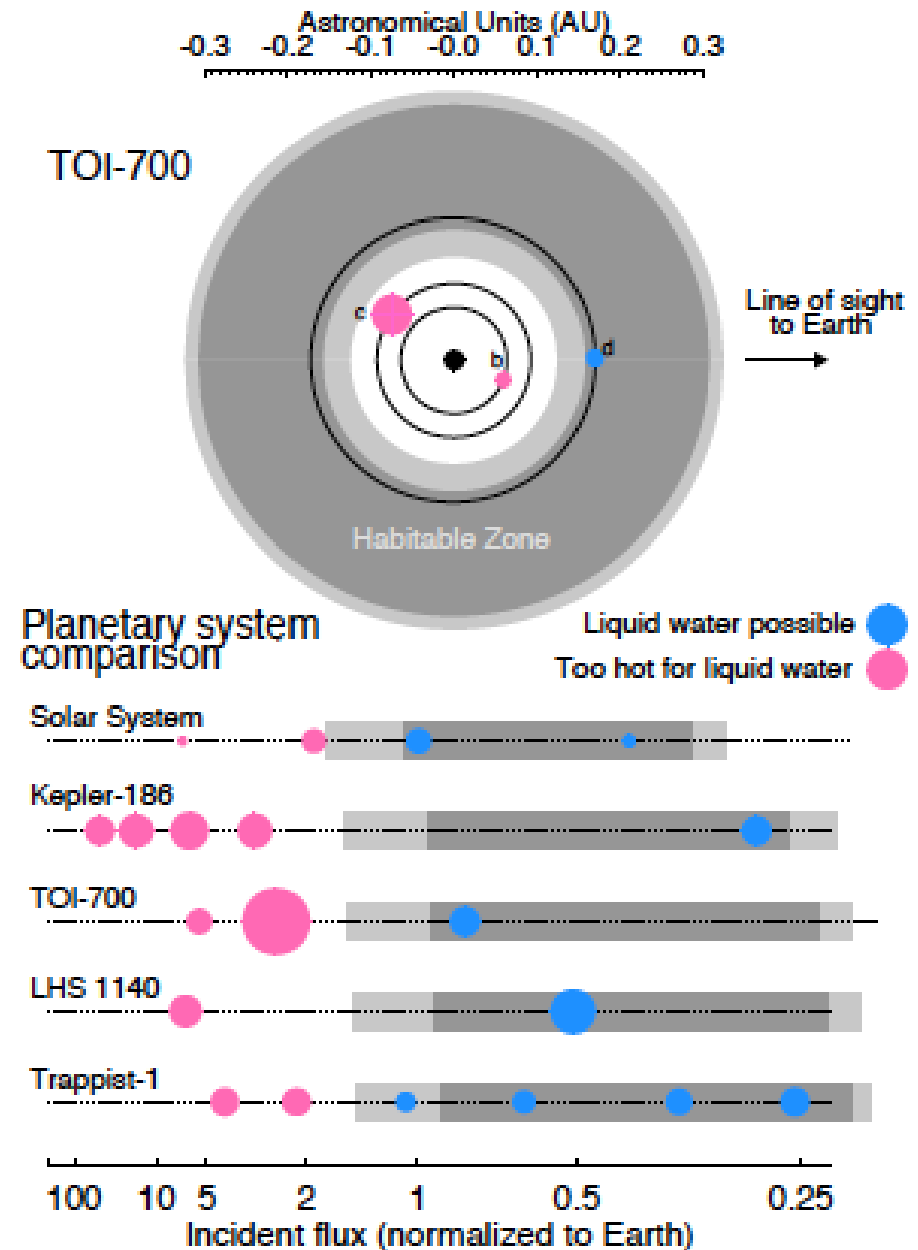# Planet from Continuous Viewing Zone
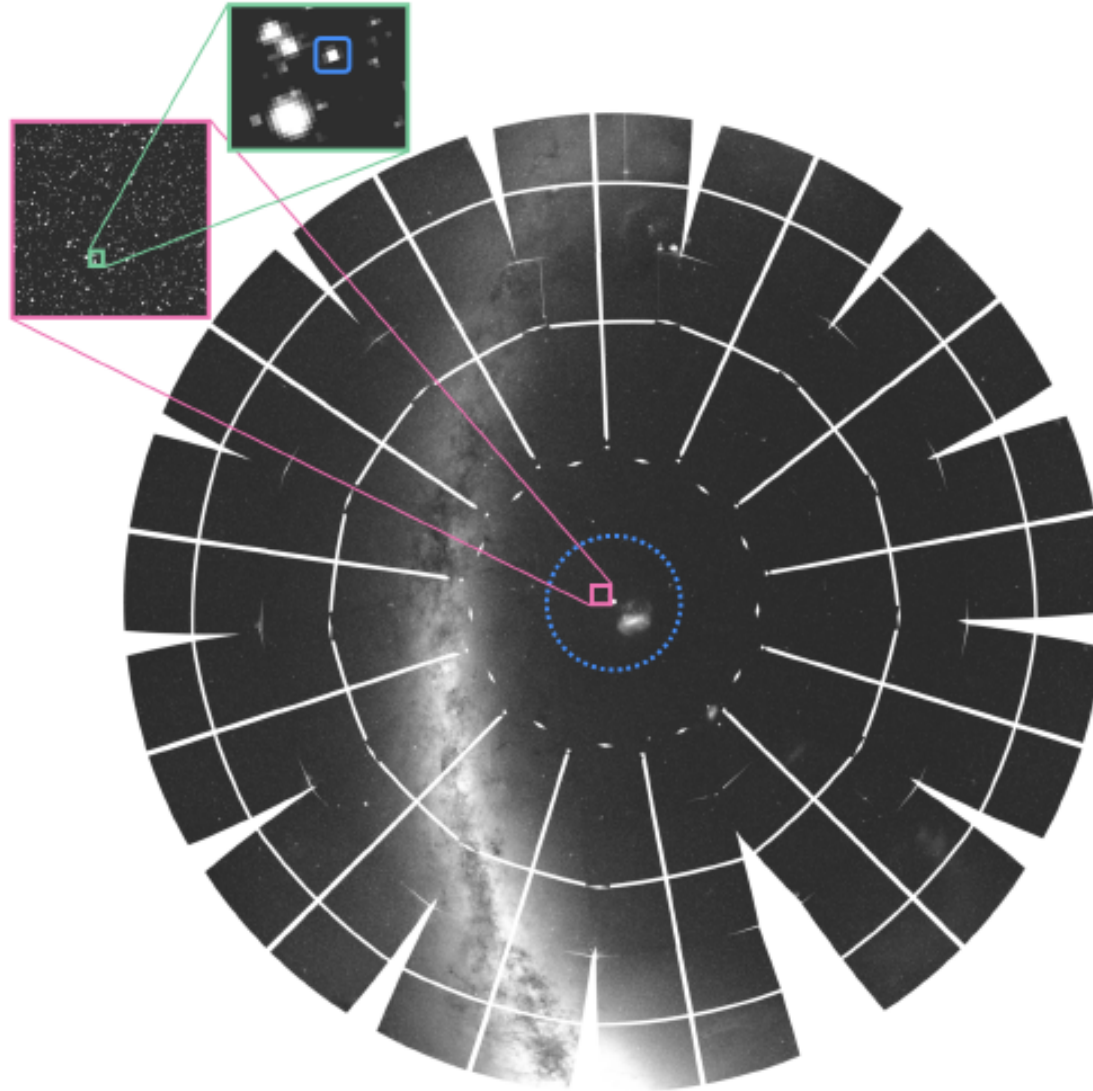
About TOI-700

Figure 4. Phase-folded, light curves from 11 sectors of TESS data for planets TOI-700 b (upper panel), TOI-700 c (middle panel), and TOI-700 d (lower panel), along with the respective transit model (pink) showing the 1-sigma range in models consistent with the observed data. The corresponding transit parameters are listed in Table 2.

Table 2. Planet Parameters

Parameter	Median	$+1\sigma$	-1σ
Model Parameters			
Star			
$\ln \rho$ [g cm^{-3}]	2.08	0.16	0.17
Limb darkening u_1	0.34	0.39	0.24
Limb darkening u_2	0.13	0.38	0.32
TOI-700 b			
T_0 (BJD - 2457000)	1331.3547	0.0048	0.0032
ln(Period[days])	2.300284	0.000024	0.000028
Impact parameter	0.20	0.19	0.14
$\ln R_p/R_*$	-3.809	0.049	0.55
eccentricity	0.032	0.050	0.024
ω [radians]	-0.6	2.5	1.8
TOI-700 c			
T_0 (BJD - 2457000)	1340.0887	0.0011	0.0010
ln *Period* [days]	2.7757773	0.0000055	0.0000058
Impact parameter	0.904	0.016	0.024
$\ln R_p/R_*$	-2.857	0.053	0.046
eccentricity	0.033	0.063	0.025
ω [radians]	0.4	1.8	2.4
TOI-700 d			
T_0 (BJD - 2457000)	1330.4737	0.0035	0.0040
ln *Period* [days]	3.622365	0.000020	0.000027
Impact parameter	0.40	0.15	0.22
$\ln R_p/R_*$	-3.641	0.053	0.060
eccentricity	0.032	0.054	0.023
ω [radians]	0.2	2.0	2.3
Derived Parameters			
TOI-700 b			
Period [days]	9.97701	0.00024	0.00028
R_p/R_*	0.0221	0.0011	0.0012
Radius [$R_\oplus$]	1.010	0.094	0.087
Insolation	5.0	1.1	0.9
a/R_*	34.8	1.9	1.9
a [AU]	0.0637	0.0064	0.0060
Inclination (deg)	89.67	0.23	0.32
Duration (hours)	2.15	0.15	0.7
TOI-700 c			
Period [days]	16.051098	0.000089	0.000092
R_p/R_*	0.0574	0.0032	0.0026
Radius [$R_\oplus$]	2.63	0.24	0.23
Insolation	2.66	0.58	0.46
a/R_*	47.8	2.7	2.6
a [AU]	0.0925	0.0088	0.0083
Inclination (deg)	88.90	0.08	0.11
Duration (hours)	1.41	0.14	0.09
TOI-700 d			
Period [days]	37.4260	0.0007	0.0010
R_p/R_*	0.0262	0.0014	0.0015
Radius [$R_\oplus$]	1.19	0.11	0.11
Insolation	0.86	0.19	0.15
a/R_*	84.0	4.7	4.6
a [AU]	0.163	0.015	0.015
Inclination (deg)	89.73	0.15	0.12
Duration (hours)	3.21	0.27	0.26

Gilbert 2020 - https://arxiv.org/abs/2001.00952

TOI-700d inhabitant if the HZ

- TESS TOI-700d is inhabiting the Habitable Zone around TOI-700

- How would the atmosphere look like?

Gilbert 2020 - https://arxiv.org/abs/2001.00952

Astronomical Units (AU)
-0.3   -0.2   -0.1   -0.0   0.1   0.2   0.3

TOI-700

Line of sight to Earth

Habitable Zone

Planetary system comparison

Liquid water possible
Too hot for liquid water

Solar System

Kepler-186

TOI-700

LHS 1140

Trappist-1

100   10 5   2   1   0.5   0.25
Incident flux (normalized to Earth)

Small planets in the HZs

- TOI-700d is populating the group of 11
- There are only 11 exoplanets with radii < 1,5REarth
- Which are the best targets for upcoming characterization?
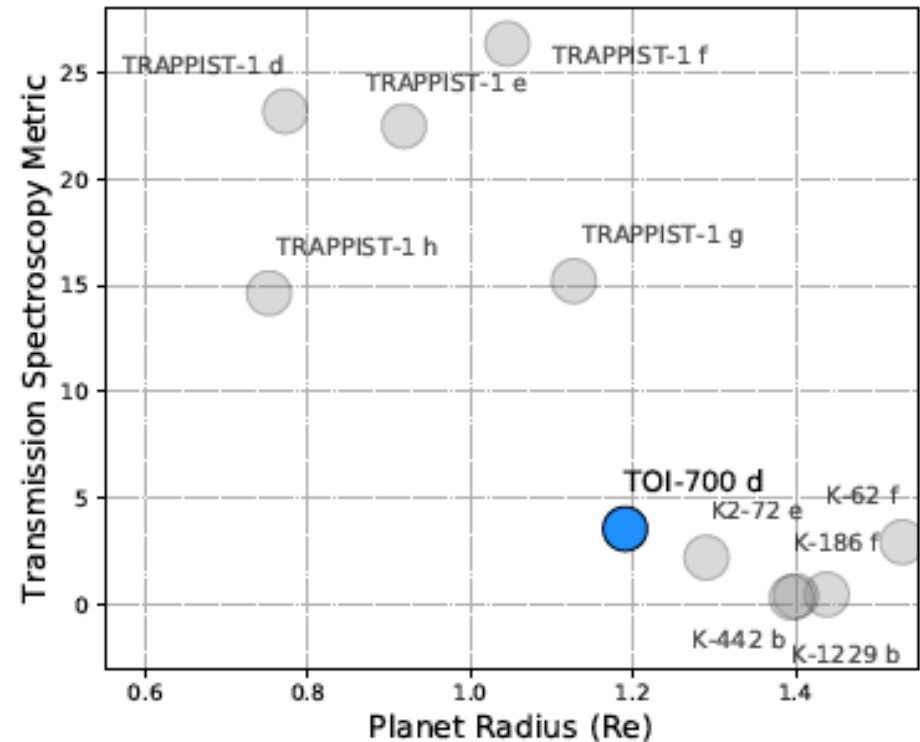
Figure 12. There are now 11 known exoplanets that have radii less than $1.5R_{\oplus}$ and orbit within their star's optimistic habitable zone (Kopparapu et al. 2013). Plotted are these planets' TSM values. The top candidates for atmospheric characterization orbit TRAPPIST-1. Beyond these, TOI-700 d has the highest TSM, although characterizing this planet will be challenging.

Bad news for now...

- TOI-700d characterization perhaps not feasible with JWST nor ELT

- The atmosphere is very thin and the detection for JWST is in 1 sigma regime, therefore not

  so promising

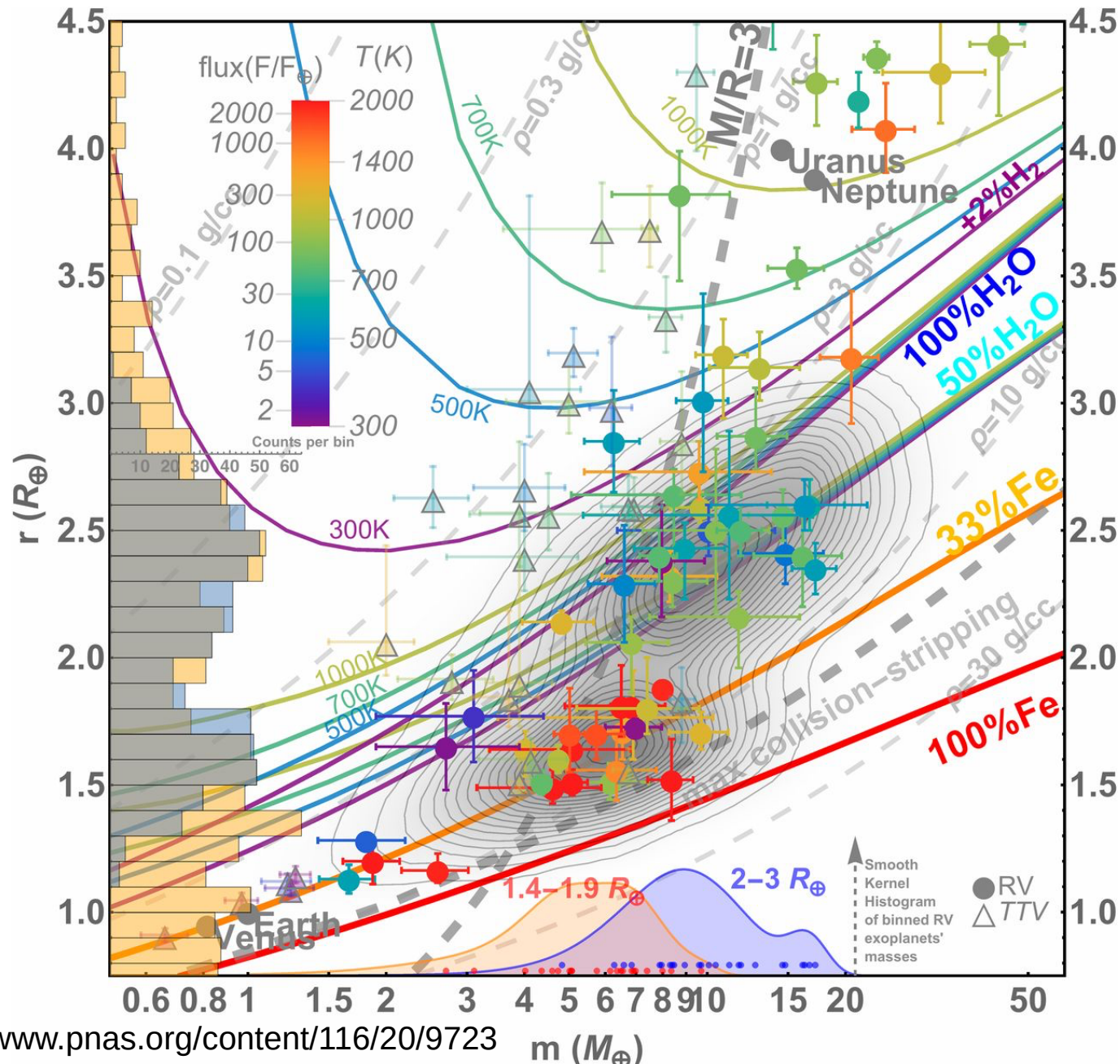- We have to wait for LUVOIR? Or other missions?

But what can we say more about exoplanetary structures?

- As discussed earlier, the main tool for characterization of exoplanets is the mass-radius diagram

- If we know the mass and the radius of an exoplanet, we can model the interiors, structure and the atmospheres

- Therefore, we need full characterization by RVs and transits ideally! We need also reasonable errors → challenging limits on accuracy

Mass-radius

Zeng et al. https://www.pnas.org/content/116/20/9723

Missing small planets?

Zeng et al. https://www.pnas.org/content/116/20/9723
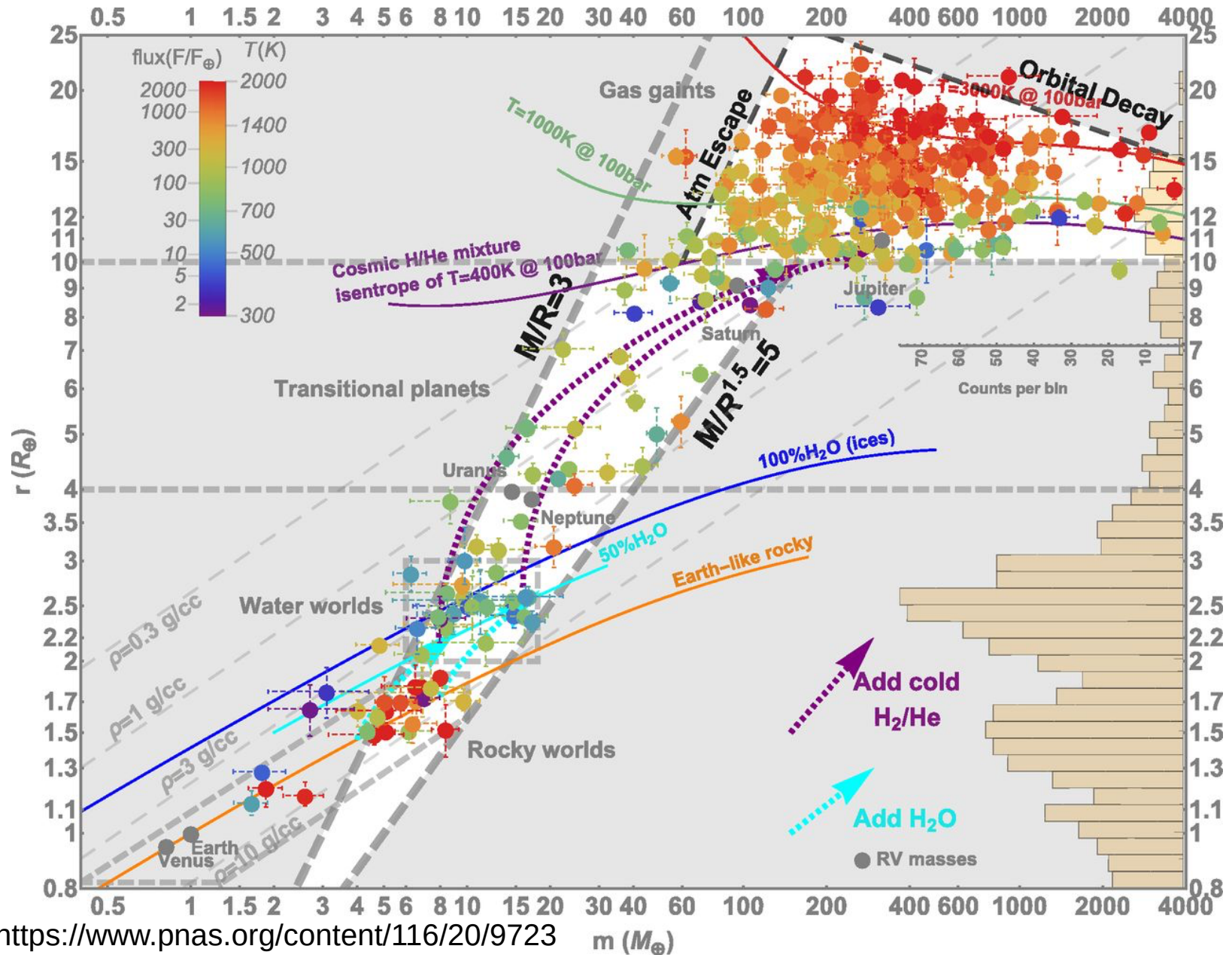
And how do planets look like inside?

- GJ-867b
- Super-Earth approx. 7MEarth
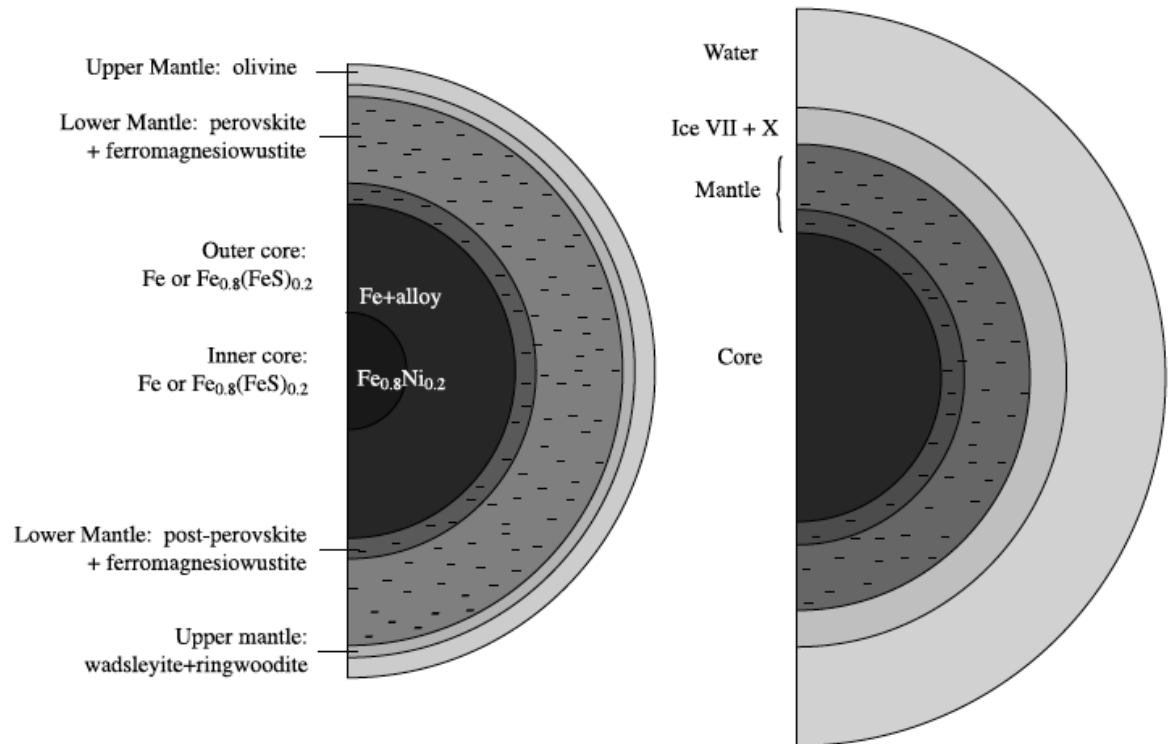- Orbiting an M4V star
- It was the first SuperEarth detected

FIG. 1.—Schematic representation of the model. To calculate the internal structure of a super-Earth, we assume a similar composition to that of Earth (*left*): a dense core of pure Fe or $Fe_{0.8}(FeS)_{0.2}$ as possible and likely cases (Earth has an outer core of Fe plus some unknown alloy, and the solid inner core has Fe and Ni); a lower mantle composed of two silicate shells (ppv+fmw, pv+fmw); and an upper mantle composed of two silicate shells (wd+rw, ol). The thickness of the shells will depend on the *P-T* profile for the planet and the amount of mass in the core. An ocean planet (*right*) will have an additional water/ice layer above the rocky core.

K-229b Earth which seems to be Mercury-like

Santerne et al. 2018- tps://www.nature.com/articles/s41550-018-0420-5
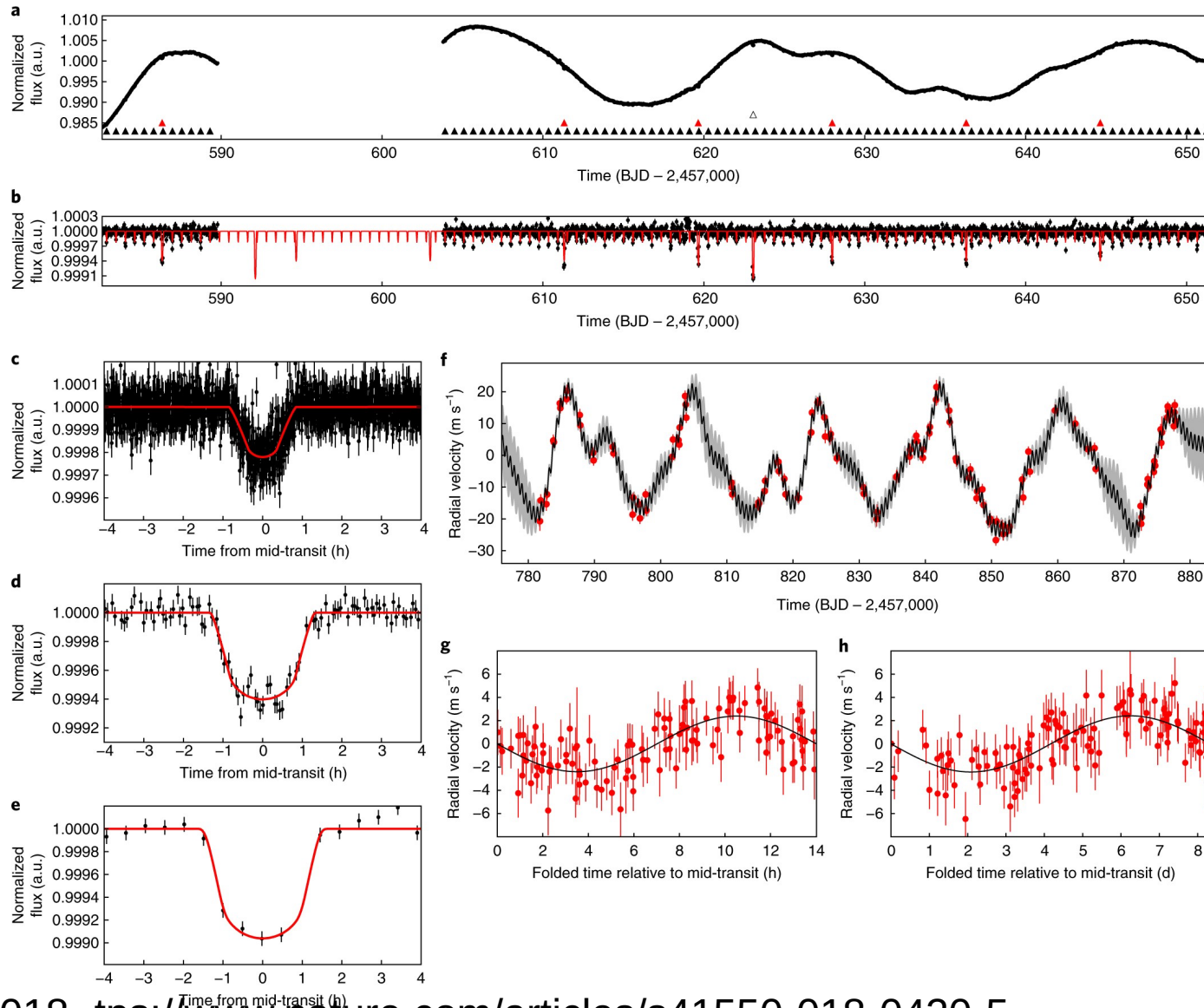
How close are we to 2nd Earth?
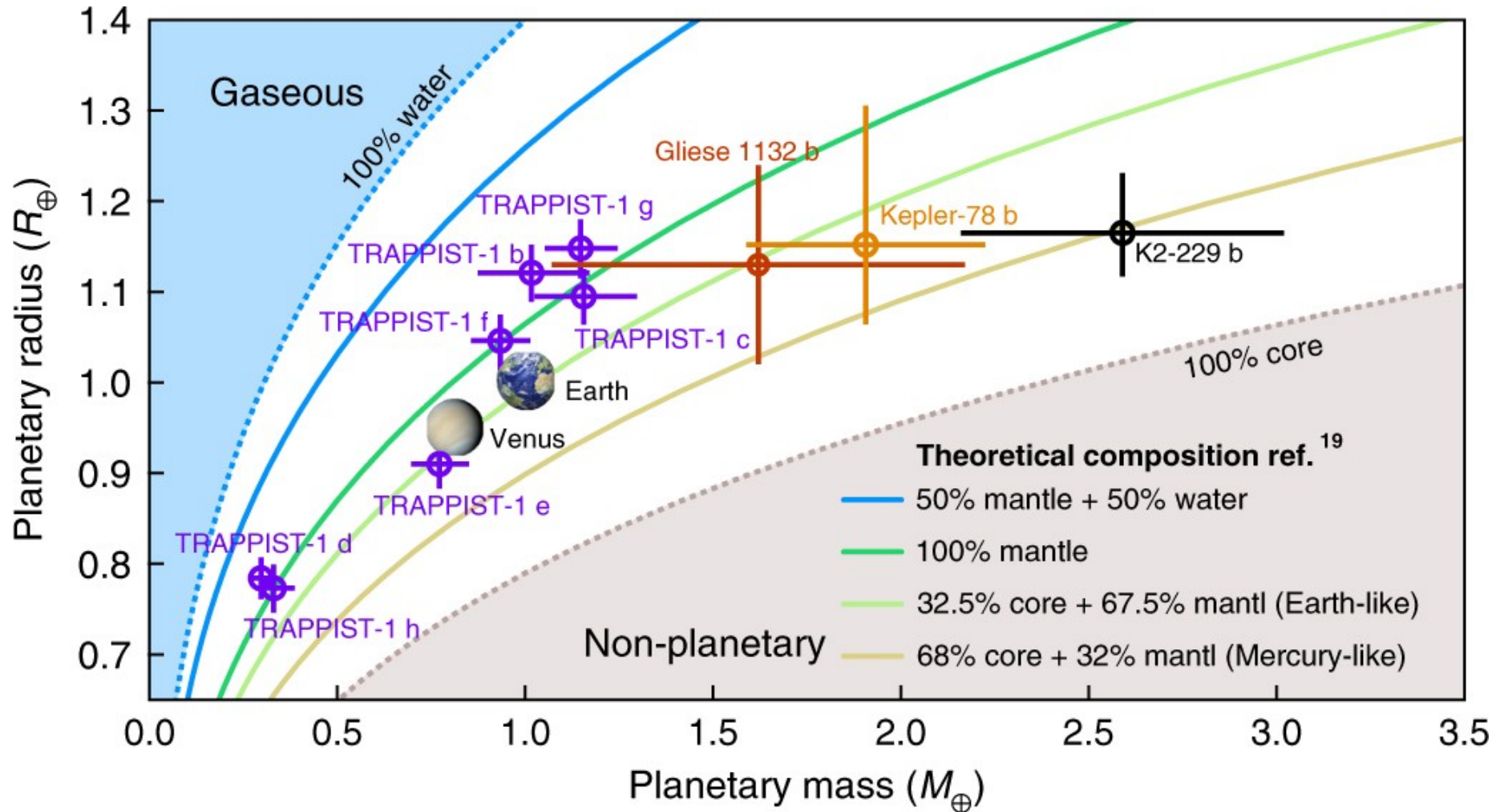
The 55 Cnc system

- This is now a very good Solar system analogue
- It hosts 5 planets, including Jupiter-sized

  and smaller

- The star 55 Cnc is similar age as our Sun and it is a G type star
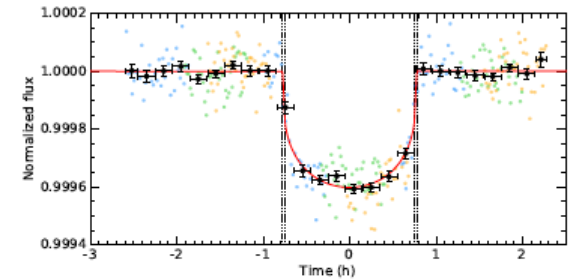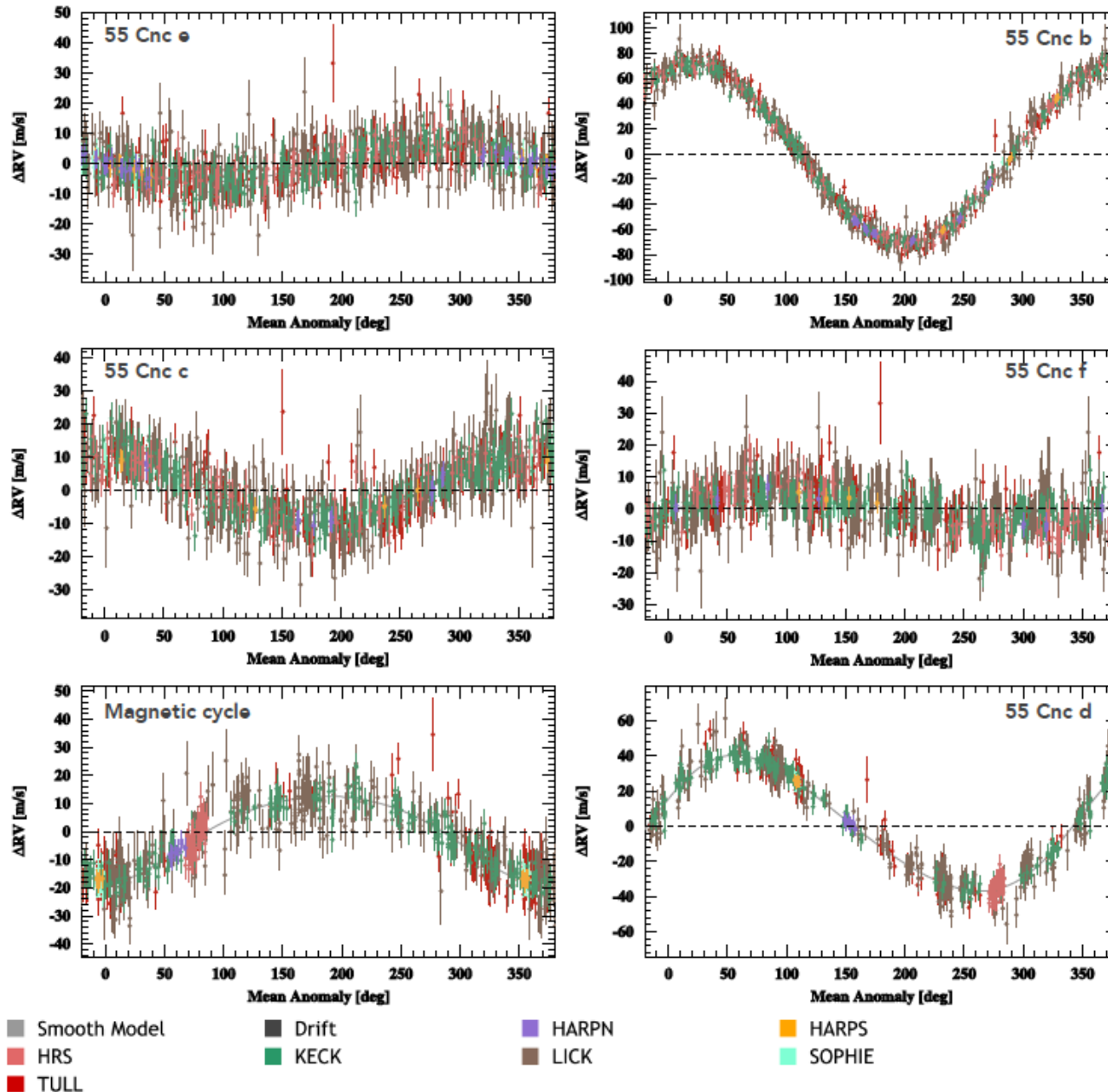- At least 55 Cnc e transits

The 55 Cnc system

Fig. 10 STIS transit light curve of 55 Cnc e in the visible band. Fluxes have been corrected for the breathing and long-term variations in Visit A$_{STIS}$ (blue), B$_{STIS}$ (green), and C$_{STIS}$ (orange). Black points show binned exposures. The red line is the best-fit transit light curve.

Dumusque et al. 2018 - https://arxiv.org/pdf/1807.04301.pdf

The 55 Cnc system

Param.	Units	55 Cnc e	55 Cnc b	55 Cnc c	55 Cnc f	magnetic cycle	55 Cnc d
P	[d]	$0.73654737^{+1.30\,10^{-6}}_{-1.44\,10^{-6}}$	$14.6516^{+0.0001}_{-0.0001}$	$44.3989^{+0.0042}_{-0.0043}$	$259.88^{+0.29}_{-0.29}$	$3822.4^{+76.4}_{-77.4}$	$5574.2^{+93.8}_{-88.6}$
K	[m s^{-1}]	$6.02^{+0.24}_{-0.23}$	$71.37^{+0.21}_{-0.21}$	$9.89^{+0.22}_{-0.22}$	$5.14^{+0.26}_{-0.25}$	$15.2^{+1.6}_{-1.8}$	$38.6^{+1.3}_{-1.4}$
e		$0.05^{+0.03}_{-0.03}$	$0.00^{+0.01}_{-0.01}$	$0.03^{+0.02}_{-0.02}$	$0.08^{+0.05}_{-0.04}$	$0.17^{+0.04}_{-0.04}$	$0.13^{+0.02}_{-0.02}$
ω	[deg]	$86.0^{+30.7}_{-33.4}$	$-21.5^{+56.9}_{-89.8}$	$2.4^{+43.1}_{-49.2}$	$-97.6^{+37.0}_{-51.3}$	$174.7^{+16.6}_{-14.1}$	$-69.1^{+9.1}_{-7.9}$
T_C	[d]	$55733.0060^{+0.0014}_{-0.0014}$	$55495.587^{+0.013}_{-0.016}$	$55492.02^{+0.34}_{-0.42}$	$55491.5^{+4.8}_{-4.8}$	$55336.9^{+45.5}_{-50.6}$	$56669.3^{+83.6}_{-76.5}$
a	[AU]	$0.0154^{+0.0001}_{-0.0001}$	$0.1134^{+0.0006}_{-0.0006}$	$0.2373^{+0.0013}_{-0.0013}$	$0.7708^{+0.0043}_{-0.0044}$	–	$5.957^{+0.074}_{-0.071}$
M	[M$_{Jup}$]	$0.0251^{+0.0010}_{-0.0010}$	–	–	–	–	–
M	[M$_{Earth}$]	$7.99^{+0.32}_{-0.33}$	–	–	–	–	–
M.sin i	[M$_{Jup}$]	–	$0.8036^{+0.0092}_{-0.0091}$	$0.1611^{+0.0040}_{-0.0040}$	$0.1503^{+0.0076}_{-0.0076}$	–	$3.12^{+0.10}_{-0.10}$
M.sin i	[M$_{Earth}$]	–	$255.4^{+2.9}_{-2.9}$	$51.2^{+1.3}_{-1.3}$	$47.8^{+2.4}_{-2.4}$	–	$991.6^{+30.7}_{-33.1}$

Dumusque et al. 2018 - https://arxiv.org/pdf/1807.04301.pdf

Scaling the Solar system

- Barbato et al. 2018 https://arxiv.org/abs/1804.08329

- Data from HARPS

- 20 Solar types stars sample

- The frequency of inner planets in the presence of giants is estimated to be about 10%
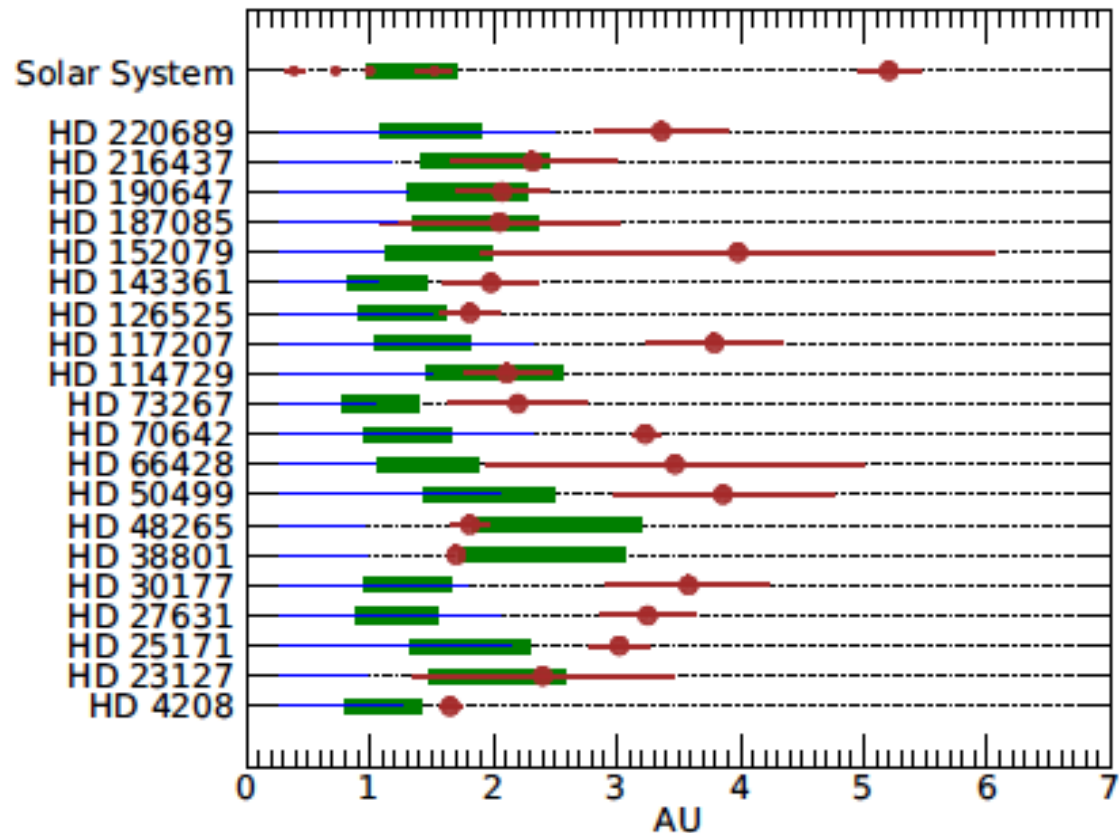
Scaling the Solar system

Fig. 1. Overview of the sample systems and a comparison with the inner Solar System's architecture. The sample's known giant planets are shown as brown circles, a thin brown line from periastron to apoastron showing their orbit's span. Each system's habitable zone, computed using the model detailed in Kopparapu et al. (2013), is shown as a thick green band, while the thin blue line indicates each system's region of dynamical stability for additional inner planets as computed through Hill's criterion detailed in Sect. 4.

Barbato et al. 2018 https://arxiv.org/abs/1804.08329
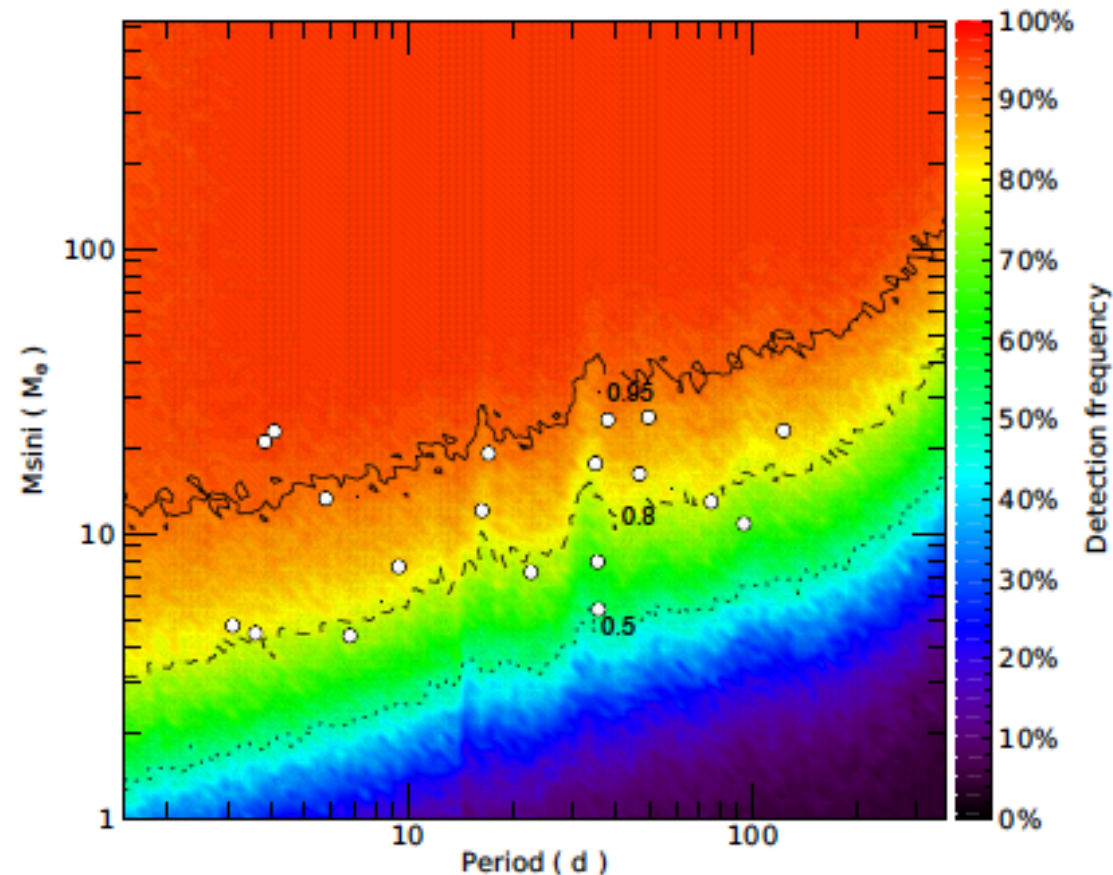
The exo-frequency from HARPS

Fig. 23. Color-coded HARPS precision detection frequency map for the whole 20-systems sample studied in this paper, period ranging from one day to one year and masses ranging from $1\,M_\oplus$ to $2\,M_J$. The detection frequency levels of 50%, 80% and 95% are respectively shown as dotted, dashed and solid curves. The low-mass inner planets of the 11 archival Solar System analogs discussed in Sect. 1 are shown as white circles.

The Trappist-1 system

- 7 planets orbiting an M dwarf
- All planets are within Mercury's orbit
- Planets might contain water
- Planets orbiting in resonances
- We are looking edge-on at the system
- System is relatively faint in optical but bright in IR
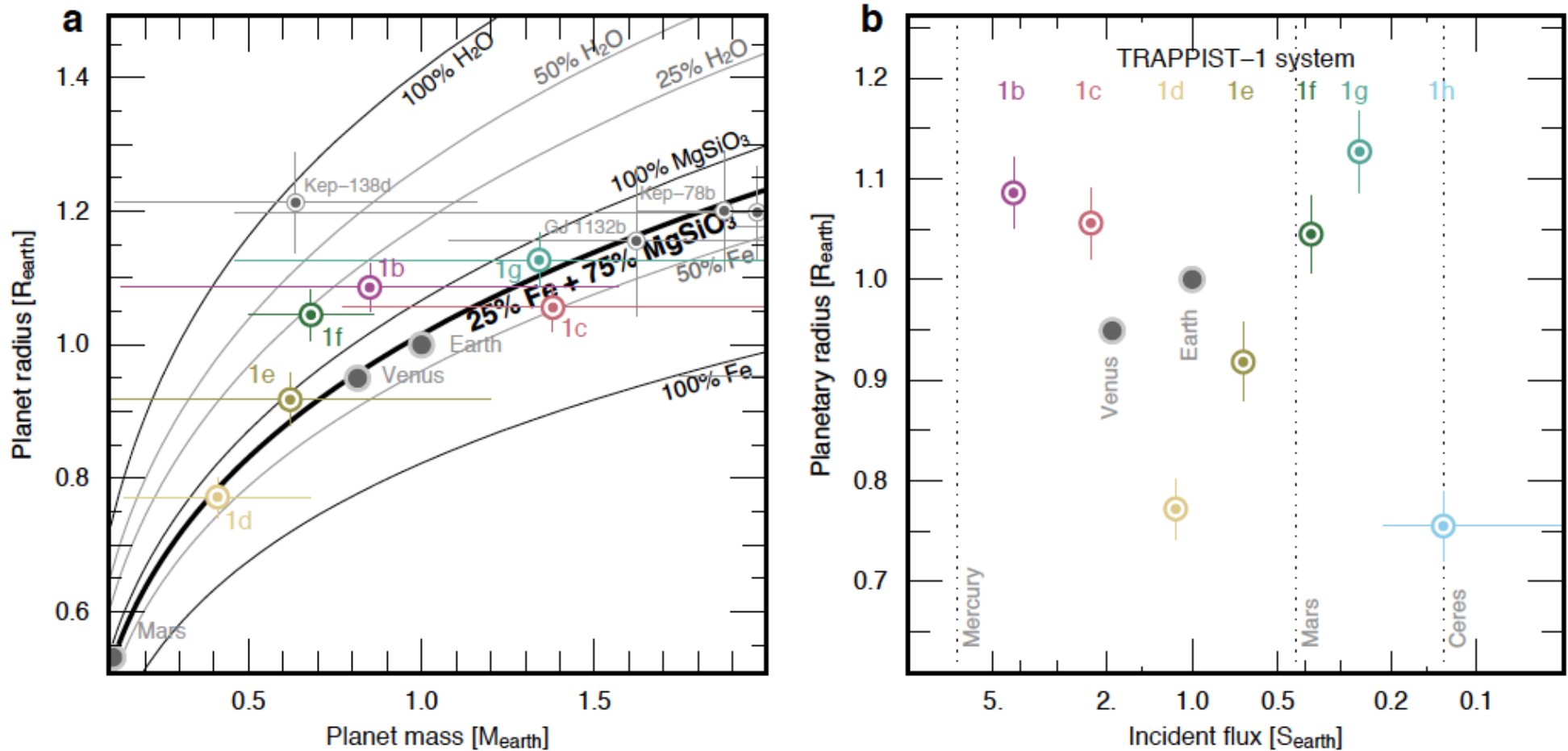- Gillon et al 2017 - https://arxiv.org/pdf/1703.01424.pdf

The Trappist-1

Table 1 | Updated properties of the TRAPPIST-1 planetary system

Parameter	Value						
Star	TRAPPIST-1 = 2MASS J23062928-0502285						
Magnitudes[1]	V=18.8, R=16.6, I=14.0, J=11.4, K=10.3						
Distance [pc][1]	12.1±0.4						
Mass $M_\star$ [$M_\odot$][a]	0.0802±0.0073						
Radius $R_\star$ [$R_\odot$][a]	0.117±0.0036						
Density $\rho_\star$ [$\rho_\odot$]	$50.7^{+1.2}_{-2.2}\,\rho_\odot$						
Luminosity $L_\star$ [$L_\odot$][a]	0.000524±0.000034						
Effective temperature T_{eff} [K][a]	2559±50						
Metallicity [Fe/H][a] [dex]	+0.04±0.08						
Planets	**b**	**c**	**d**	**e**	**f**	**g**	**h**
Number of unique transits observed	37	29	9	7	4	5	1
Period P [d]	1.51087081 ±0.60×10^{-6}	2.4218233 ±0.17×10^{-5}	4.049610 ±0.63×10^{-4}	6.099615 ±0.11×10^{-4}	9.206690 ±0.15×10^{-4}	12.35294 ±0.12×10^{-3}	20^{+15}_{-6}
Mid-transit time T_0 - 2,450,000 [BJD_{TDB}]	7322.51736 ±0.00010	7282.80728 ±0.00019	7670.14165 ±0.00035	7660.37859 ±0.00038	7671.39767 ±0.00023	7665.34937 ±0.00021	7662.55463 ±0.00056
Transit depth $(R_p/R_\star)^2$ [%]	0.7266 ±0.0088	0.687 ±0.010	0.367 ±0.017	0.519 ±0.026	0.673 ±0.023	0.782 ±0.027	0.352 ±0.0326
Transit impact parameter b [$R_\star$]	$0.126^{+0.092}_{-0.078}$	$0.161^{+0.076}_{-0.084}$	0.17±0.11	$0.12^{+0.11}_{-0.09}$	0.382 ±0.035	0.421 ±0.031	$0.45^{+0.22}_{-0.29}$
Transit duration W [min]	36.40±0.17	42.37±0.22	49.13±0.65	57.21±0.71	62.60±0.60	68.40±0.66	$76.7^{+2.7}_{-2.0}$
Inclination i [°]	$89.65^{+0.22}_{-0.27}$	89.67±0.17	89.75±0.16	$89.86^{+0.10}_{-0.12}$	89.680 ±0.034	89.710 ±0.025	$89.80^{+0.10}_{-0.05}$
Eccentricity e (2-σ upper limit from TTVs)	<0.081	<0.083	<0.070	<0.085	<0.063	<0.061	-
Semi-major axis a [10^{-3} au]	11.11±0.34	15.21±0.47	$21.44^{+0.66}_{-0.63}$	$28.17^{+0.83}_{-0.87}$	37.1±1.1	45.1±1.4	63^{+27}_{-13}
Scale parameter $a/R_\star$	$20.50^{+0.16}_{-0.31}$	$28.08^{+0.22}_{-0.42}$	$39.55^{+0.30}_{-0.59}$	$51.97^{+0.40}_{-0.77}$	$68.4^{+0.5}_{-1.0}$	$83.2^{+0.6}_{-1.2}$	117^{+50}_{-26}
Irradiation S_p [S_{Earth}]	4.25±0.33	2.27±0.18	1.143 ±0.088	0.662 ±0.051	0.382 ±0.030	0.258 ±0.020	$0.131^{+0.081}_{-0.067}$
Equilibrium temperature [K][b]	400.1 ±7.7	341.9 ±6.6	288.0 ±5.6	251.3 ±4.9	219.0 ±4.2	198.6 ±3.8	168^{+21}_{-28}
Radius R_p [R_{Earth}]	1.086 ±0.035	1.056 ±0.035	0.772 ±0.030	0.918 ±0.039	1.045 ±0.038	1.127 ±0.041	0.755 ±0.034
Mass M_p [M_{Earth}] (from TTVs)	0.85 ±0.72	1.38 ±0.61	0.41 ±0.27	0.62 ±0.58	0.68 ±0.18	1.34 ±0.88	-
Density ρ_p [ρ_{Earth}]	0.66 ±0.56	1.17 ±0.53	0.89 ±0.60	0.80 ±0.76	0.60 ±0.17	0.94 ±0.63	-

- Gillon et al 2017 - https://arxiv.org/pdf/1703.01424.pdf

The Trappist-1

- Gillon et al 2017 - https://arxiv.org/pdf/1703.01424.pdf

The Trappist-1

Gillon et al 2017 - https://arxiv.org/pdf/1703.01424.pdf

The Trappist-1

- Gillon et al 2017 - https://arxiv.org/pdf/1703.01424.pdf
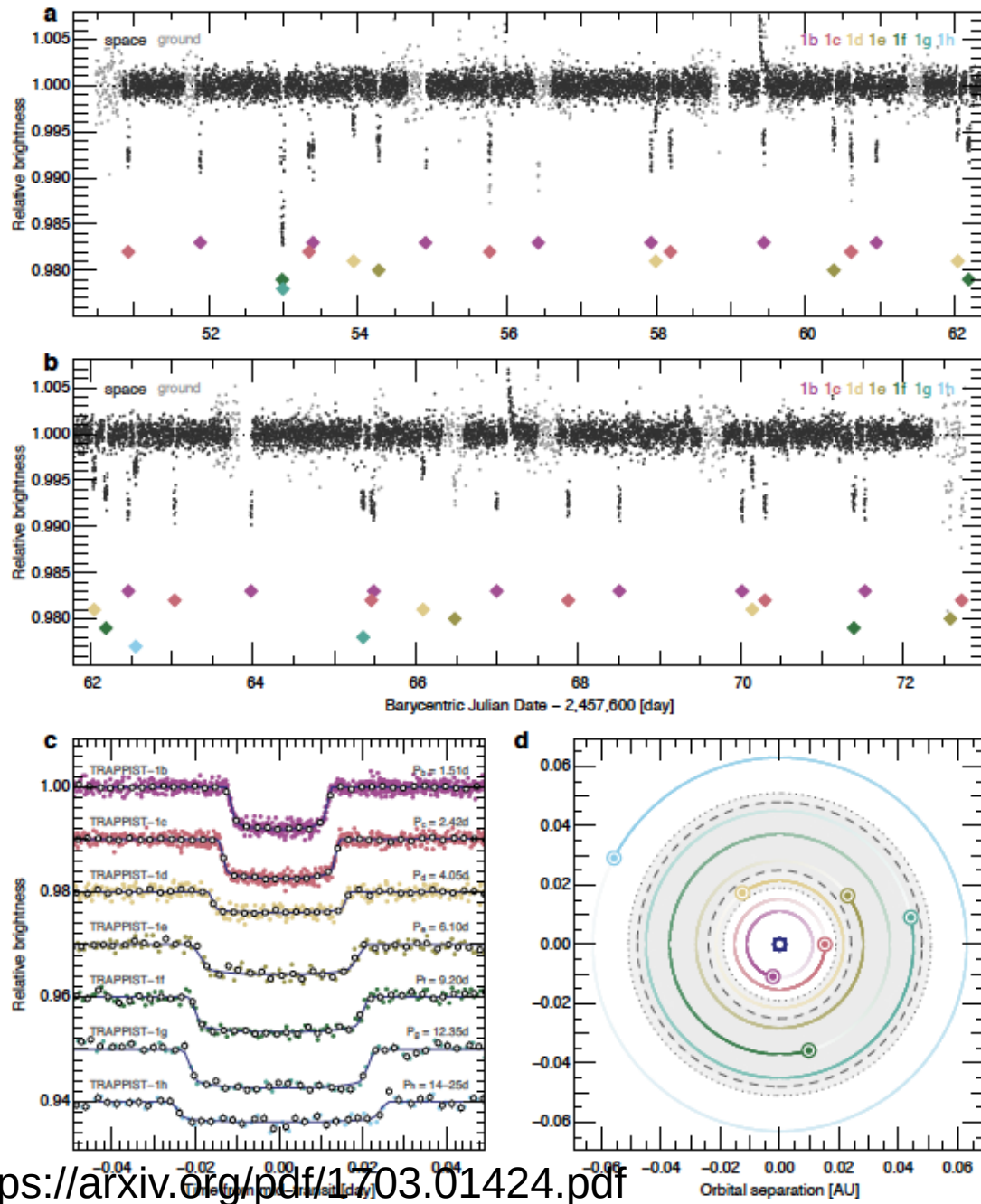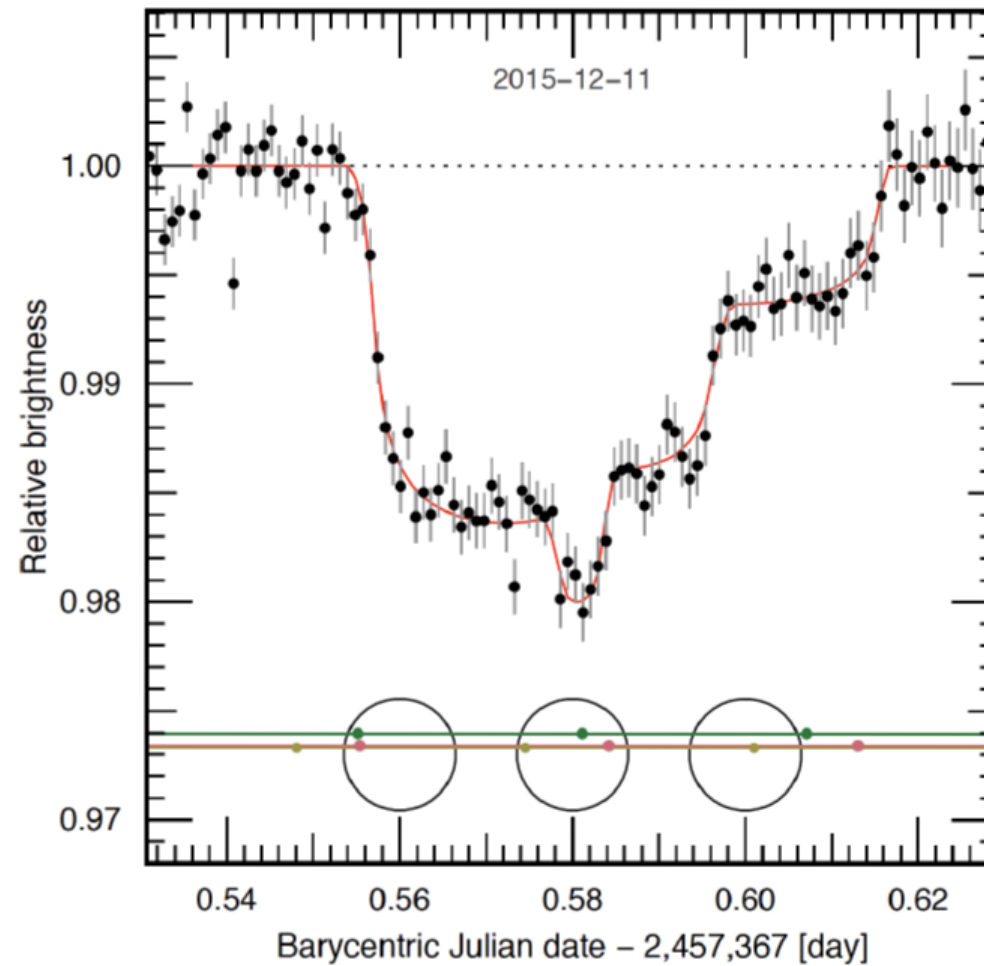
Composition of Trappist 1 planets

Trappist 1 HZ

Credit: NASA
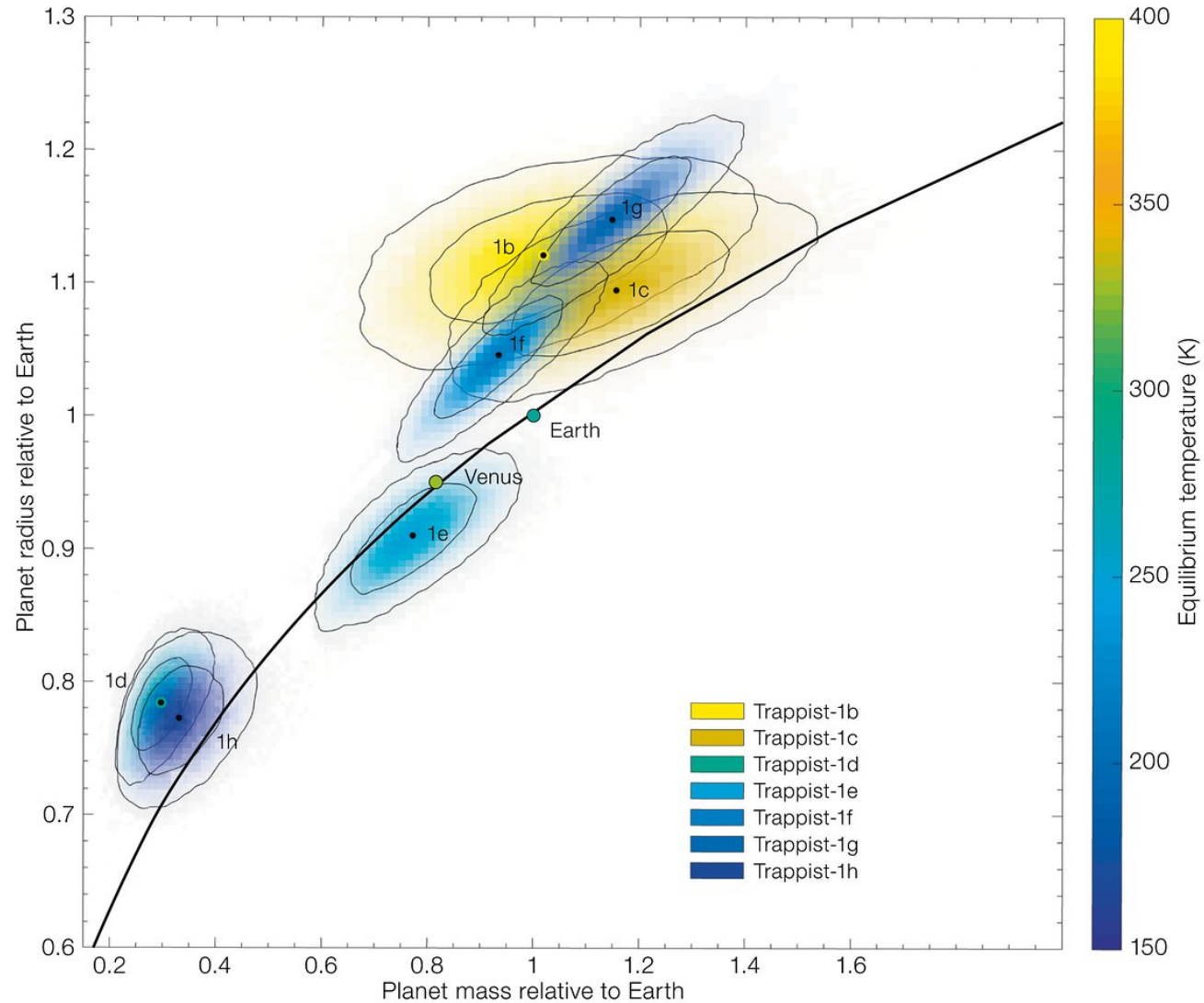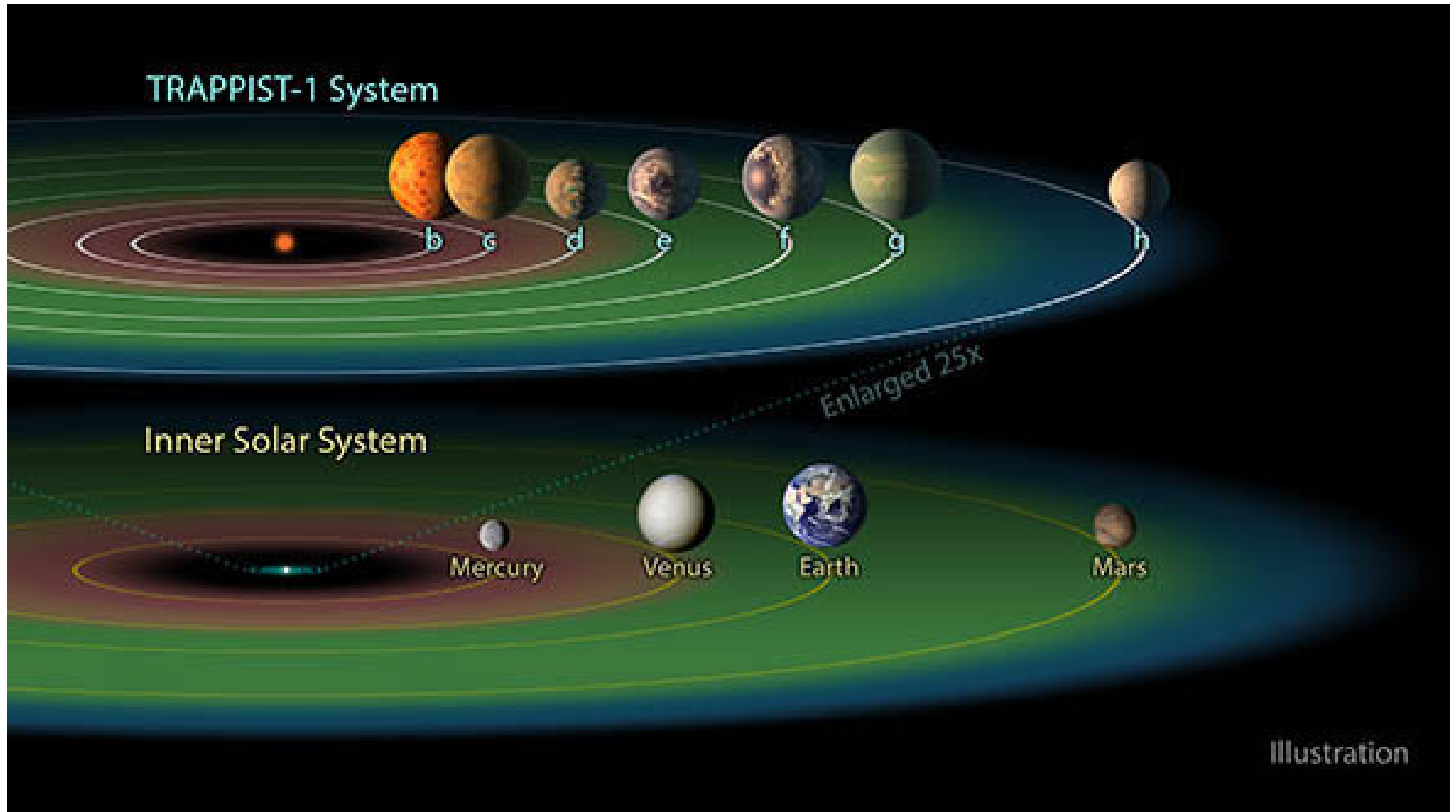
Let`s model your own exoplanet

- https://www.cfa.harvard.edu/~lzeng/planetmodels.html#matlabcode

- You need Mathematica or Free Mathematica player:

    https://www.wolfram.com/player/

Papers for Xmass session

- https://arxiv.org/abs/1505.07399

- https://www.nature.com/articles/s41550-020-1069-4#change-history

  http://articles.adsabs.harvard.edu/pdf/1976ApJS...32..737S