Exoplanets

Lecture 8
21.11.2025
MFF UK

Outlook

- Occurrence rates
- Radius valley, Neptune`s desert
- Statistics from available data sets
- Composition of planets

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.

Planet frequency

- We have now larger data set
- HARPS and CORALIE data
- Planets are quite frequent, at least every

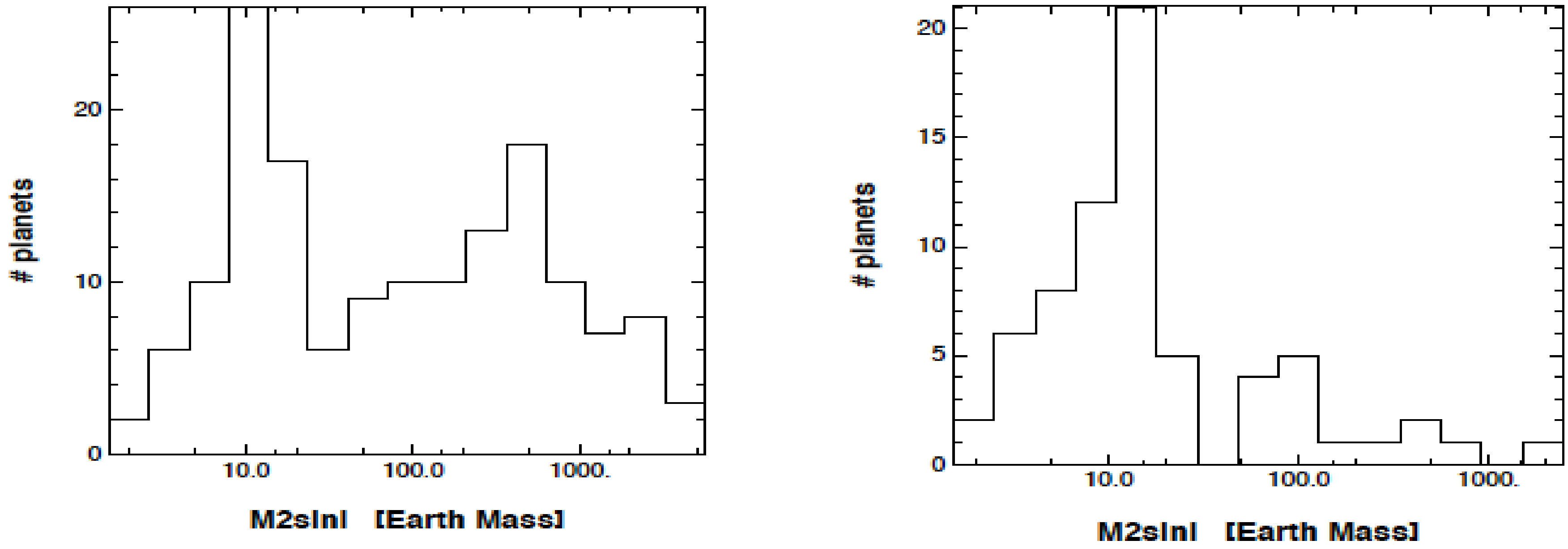
Table 1. Occurrence frequency of stars with at least one planet in the defined region. The results for various regions of the $m_2 \sin i$ – $\log P$ plane are given.

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

Small planets vs. large planets

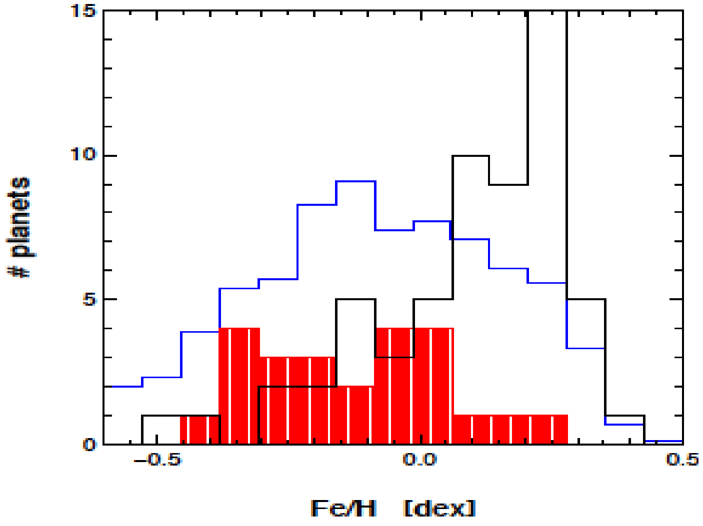
- Left: low mass vs. High mass, right: same but only for short periodic planets less than 100 days

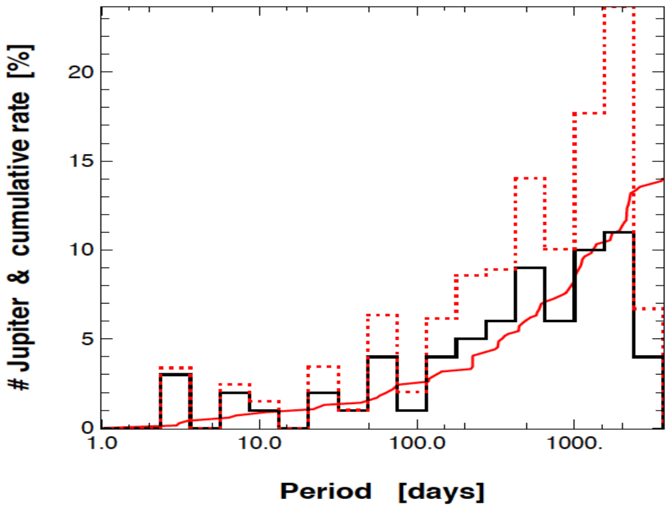


Mayor et al 2012, A&A, https://arxiv.org/pdf/1109.2497.pdf

Small vs. Large

- Metallicity of the system is a factor
- Large planets favor large metallicities
- Smaller planets are abundant also with lower metallicities





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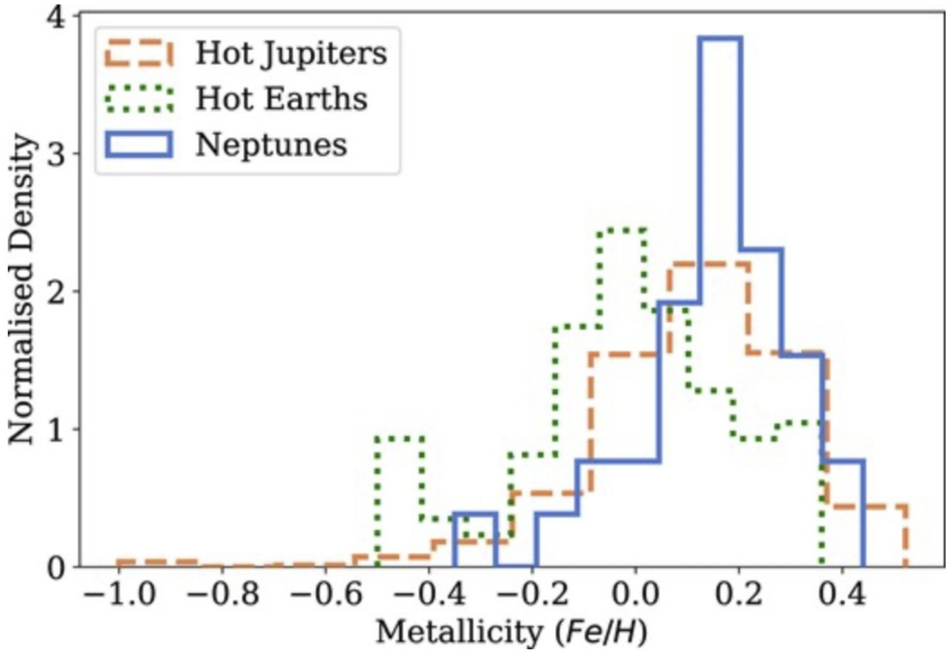
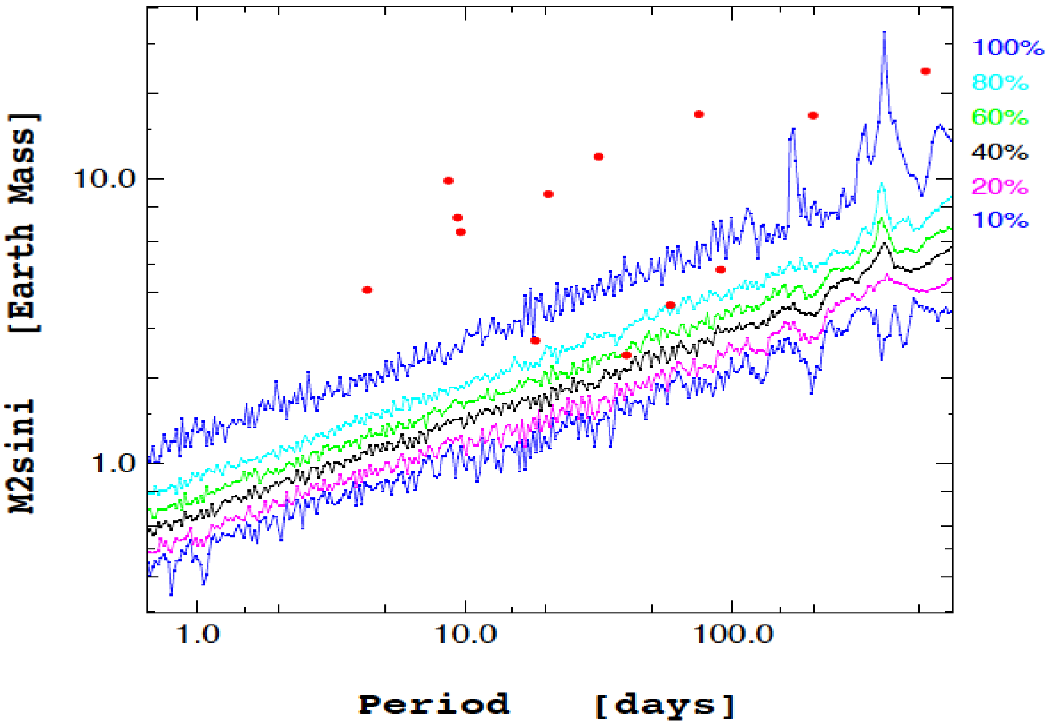


Figure 8. The metallicity distribution Fe/H for our 'gold' sample of Neptune desert targets (blue-solid) compared to the distribution of hot Jupiters (orange-dashed) and hot Earths (green-dotted). The hot Jupiter and hot Earth samples were taken from the TEPCat catalogue (https://www.astro.keele.ac.uk/jkt/tepcat/) both with $P_{orb} \leq 10$ d and M_p between 0.1–13 M_J and $M_p \leq 2\, M_{\oplus}$, respectively.

https://academic.oup.com/mnras/article/539/4/3138/8119410

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

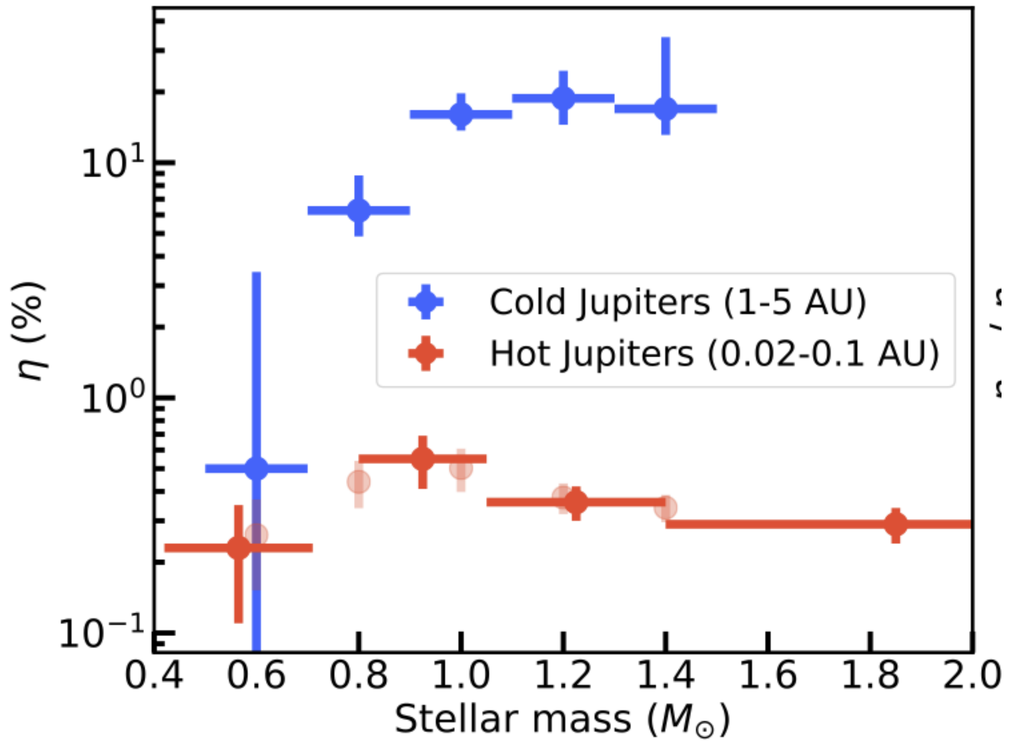
Different formation mechanisms?

- Different populations and occurrence rates

  suggest different populations and different formation mechanisms
- Neptune desert
- Radius valley
- WE NEED PRECISE MASSES!

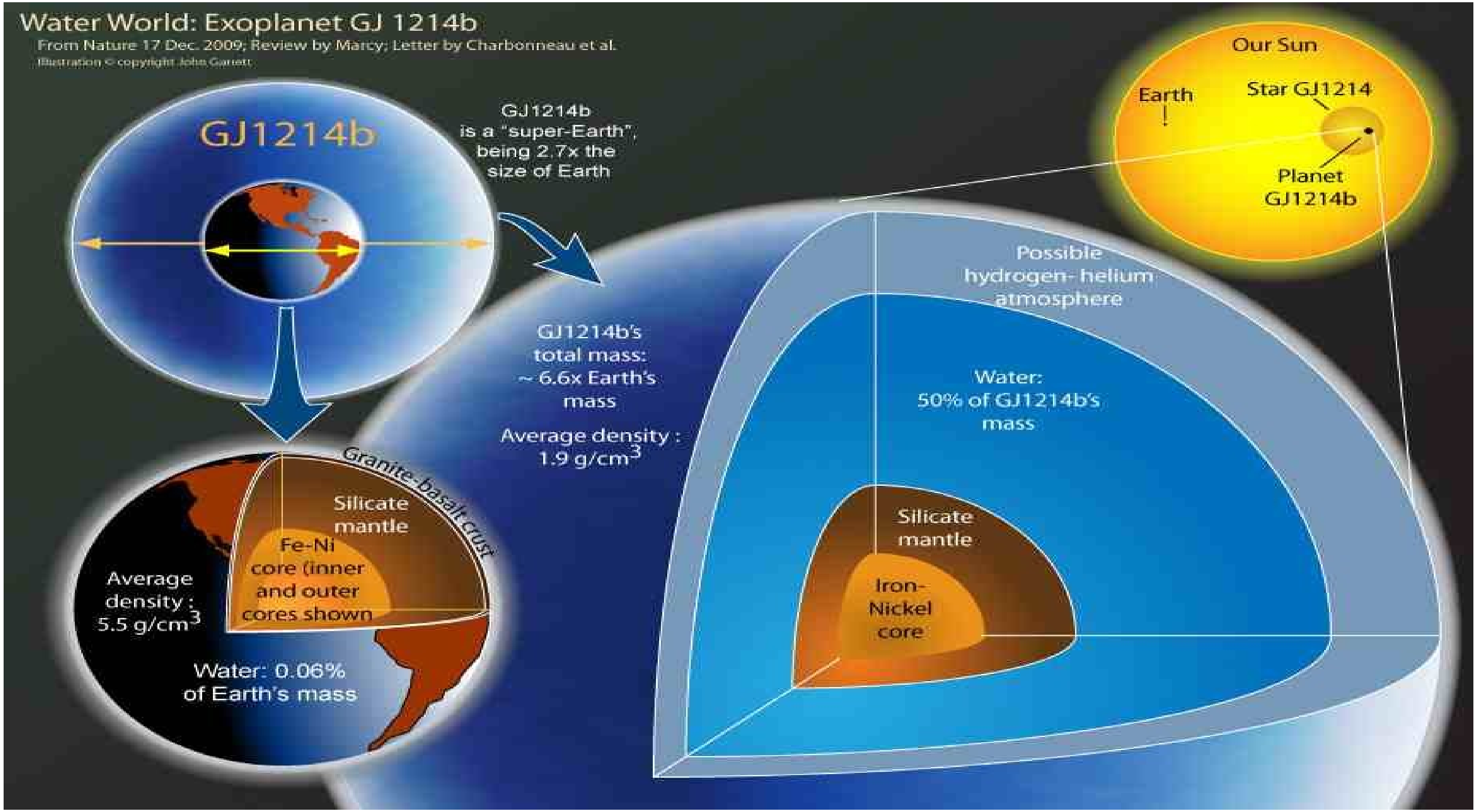
Hot Jupiters vs Cold Jupiters

- Rates higher for more massive stars
- Only part of the giants migrates
- Fraction of in-situ HJ unknown?



https://arxiv.org/pdf/2404.07033

Recap - (mini-)Neptune



Neptunes landscape

- Desert

  - planetary atmosphere likely evaporates

- Savanna

  high eccentricity migration

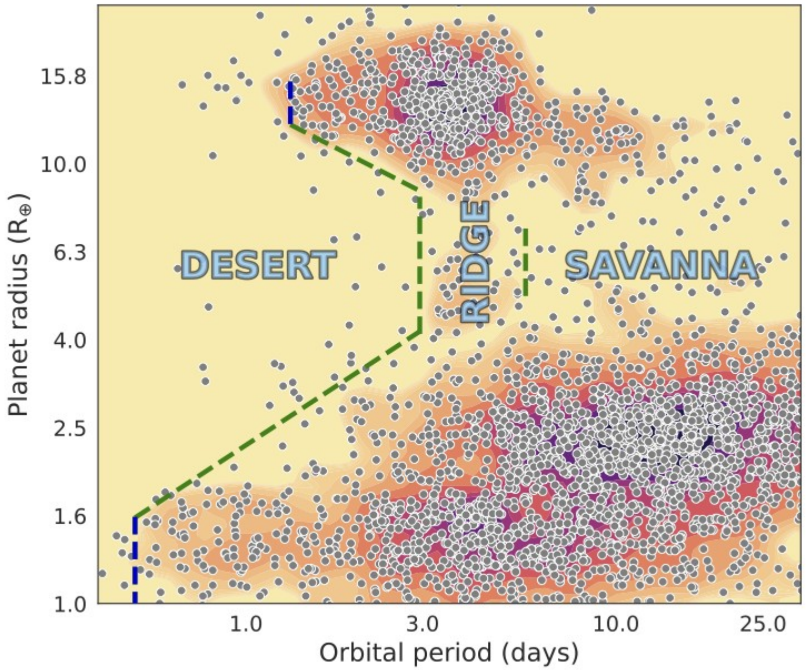


Fig. 4: Planet radius as a function of orbital period for all known exoplanets, where we highlight the location of the Neptunian desert, ridge, and savanna derived in this work (Eqs. (6) to (9)). The colour code represents the observed density of planets. This plot has been generated with nep-des (https://github.com/castro-gzlz/nep-des).

https://arxiv.org/pdf/2409.10517

Planet moving into a desert - TOI-5800b

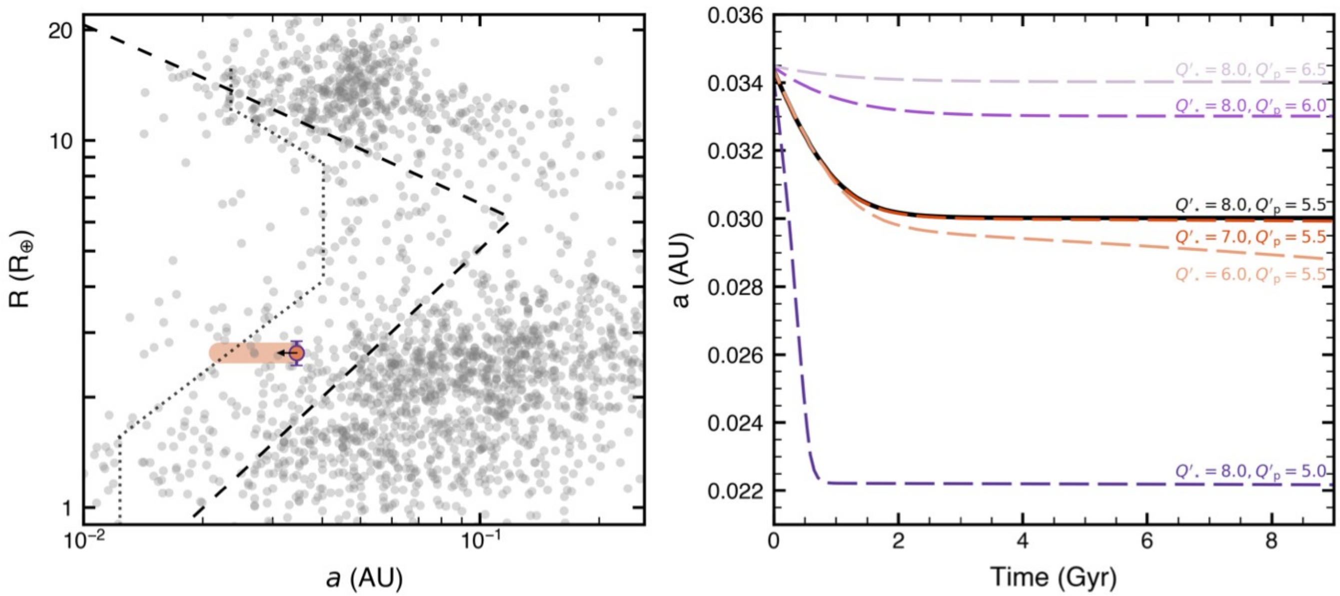


Figure 6. Left: Radius and semi-major axis of planets listed in the NASA Exoplanet Archive. The Neptune desert is demarked by the black dashed lines (Mazeh et al. 2016). We also include updated boundaries from Castro-González et al. (2024), denoted by the black dotted lines. TOI-5800 b is shown in orange. We expect the planet to circularize to a closer-in orbit, indicated by the black arrow. Right: Semi-major axis of TOI-5800 b as a function of time. Models for different values of $Q_\star$ and Q_p are shown in orange and purple, respectively. Assuming $Q_\star = 8.0$ and $Q_\mathrm{p} = 5.5$, we estimate a final semi-major axis of ~0.03 AU.

https://arxiv.org/pdf/2505.10324

TOI-3281b

- Surviving the desert
- Formed as a giant and was stripped by the photo-evaporation?

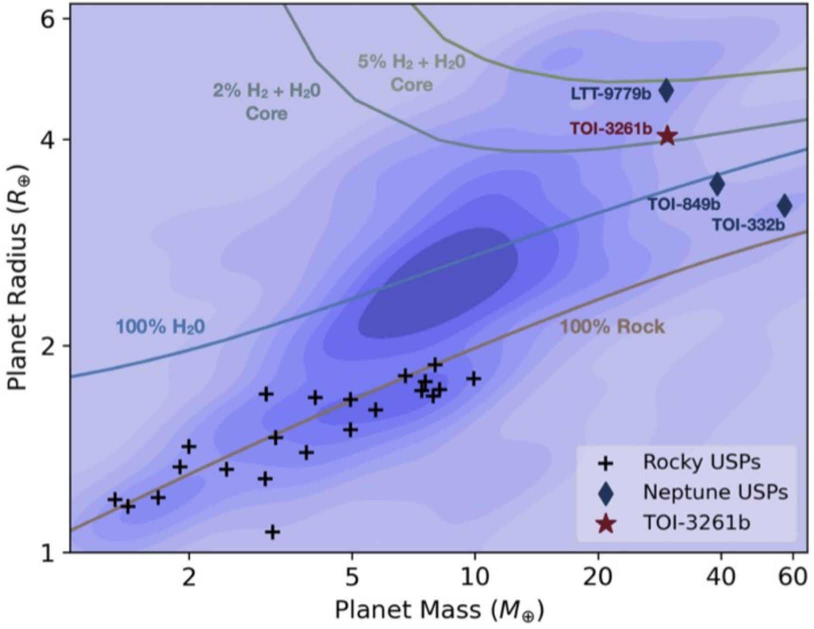
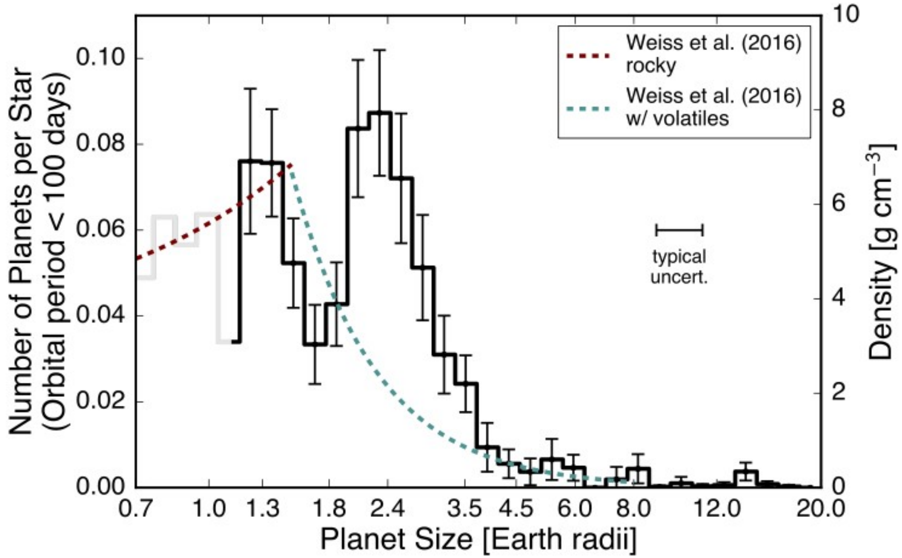


Figure 11. Mass-radius distributions of ultrahot Neptunes compared to those of traditional USPs. The contour plot depicts the density in mass-radius space of the population of confirmed, published exoplanets listed in the Exoplanet Archive as of 2024 February 4. While the latter population is composed of pure rock, Neptune-sized USPs instead are expected to have a non-negligible envelope atop a water-rich core. Overplotted are mass-radius relations for pure rock, pure water, and a combined rock/water core with various H_2 mass fractions. The mass-radius relations based on planet composition are taken from Zeng et al. (2016).

https://arxiv.org/pdf/2407.04225

The radius valley

- Gap between small planets Neptunes-Super-Earths
- 1.5-2.0 Earth radii
- Depends on spectral type of the host slightly
- Fulton 2017



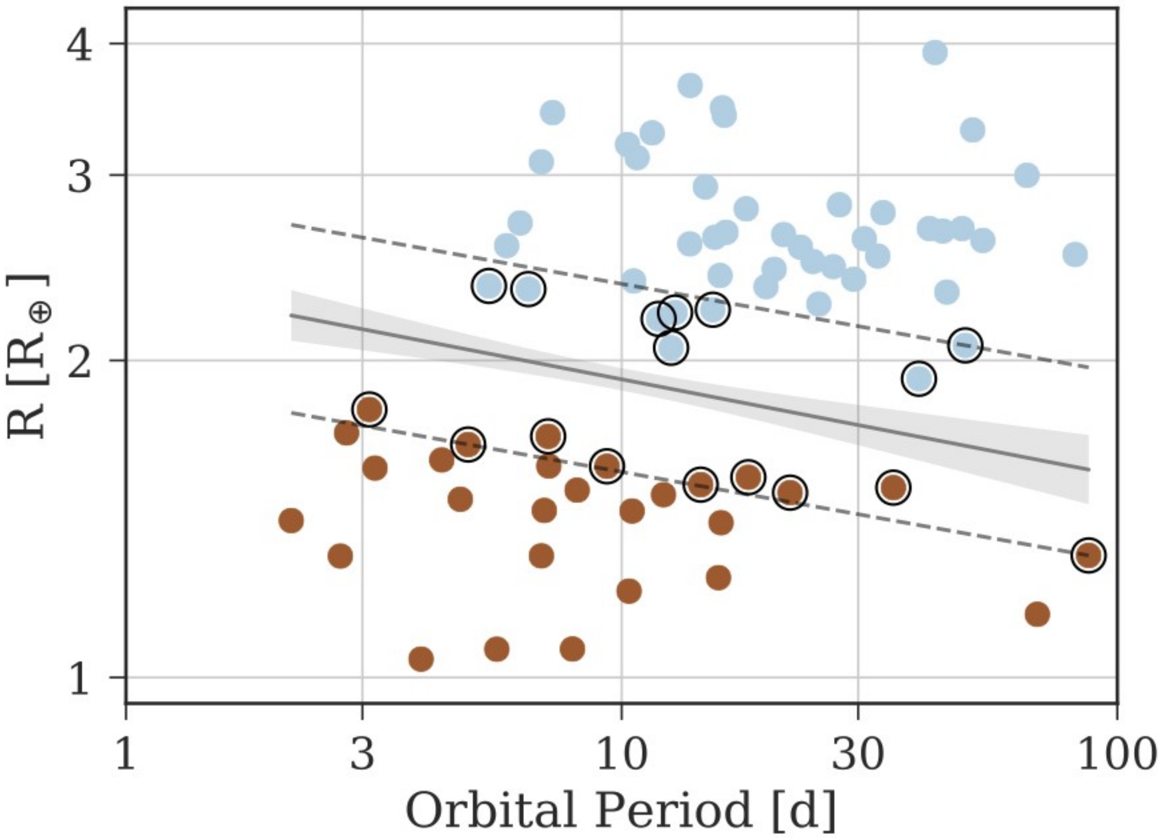
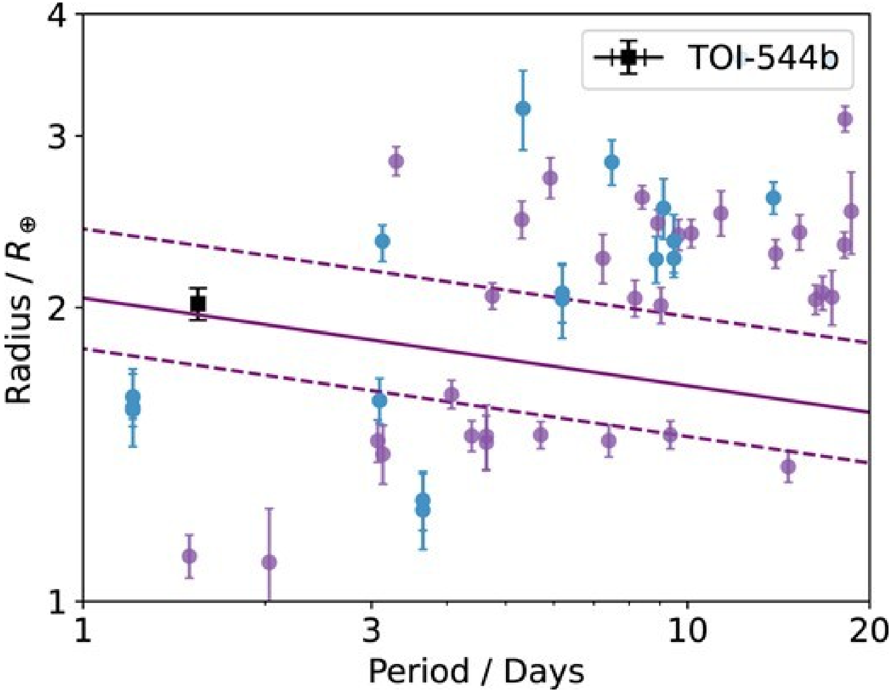


Figure 7. The slope of the radius valley as determined by support vector machines. The grey line represents the hyperplane of maximum separation, together with a 68% confidence interval derived from bootstrapping the original sample. The super-Earths below the radius valley are shown in red, while the sub-Neptunes above the valley are plotted in blue. The encircled data points are the support vectors, which determine the slope of the radius valley. The parallel dotted lines go through the support vectors, and are determined by offsets $a_{\rm low} = 0.29^{+0.04}_{-0.03}$ and $a_{\rm upp} = 0.44^{0.04}_{-0.03}$ respectively.

Populating the radius valley?

- TOI-544b – host K star
- Radius 2 Earth radii
- Orbital P=50 days
- Density consistent with a small fraction of H/He
- Sitting right at the valley!



https://academic.oup.com/mnras/article/527/4/11138/7472109

Obliquties statistics

- Exoplanets II – more detail
- The missalaginment/alignment of the spin axis can reveal the details about dynamical evolution

https://arxiv.org/pdf/2201.11768.pdf

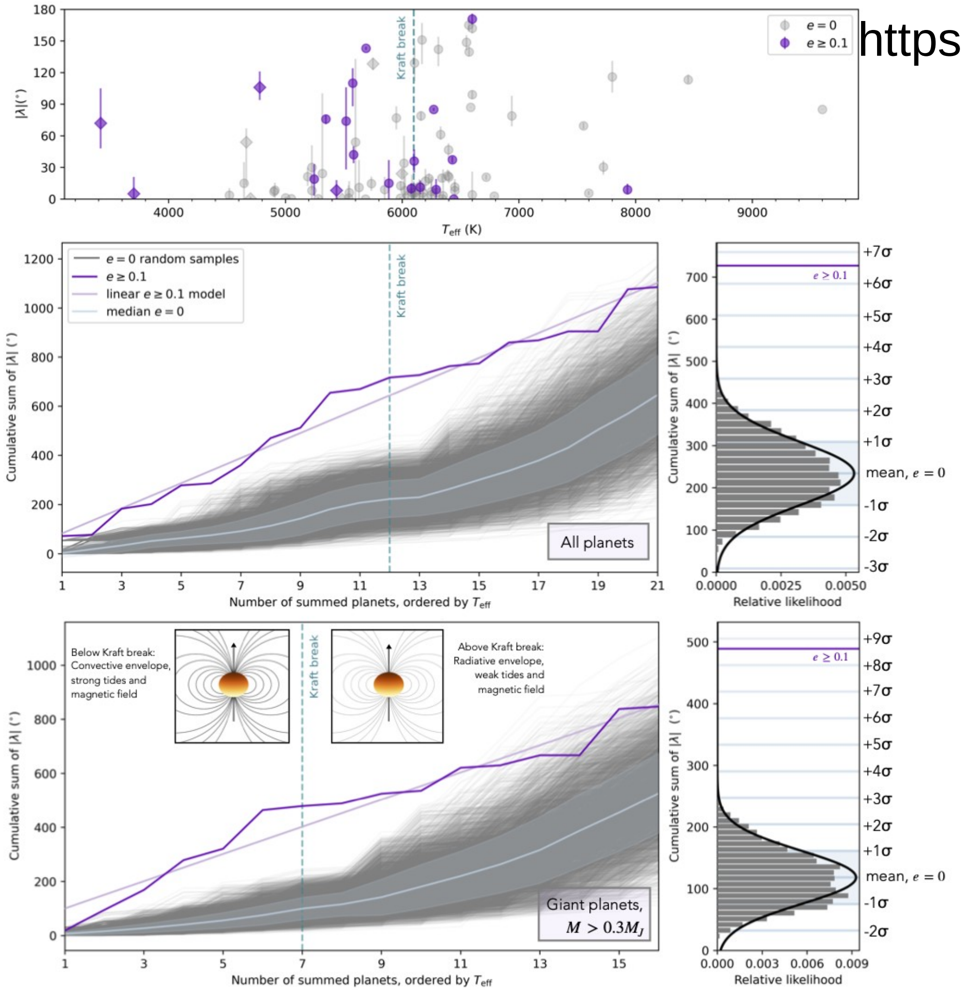
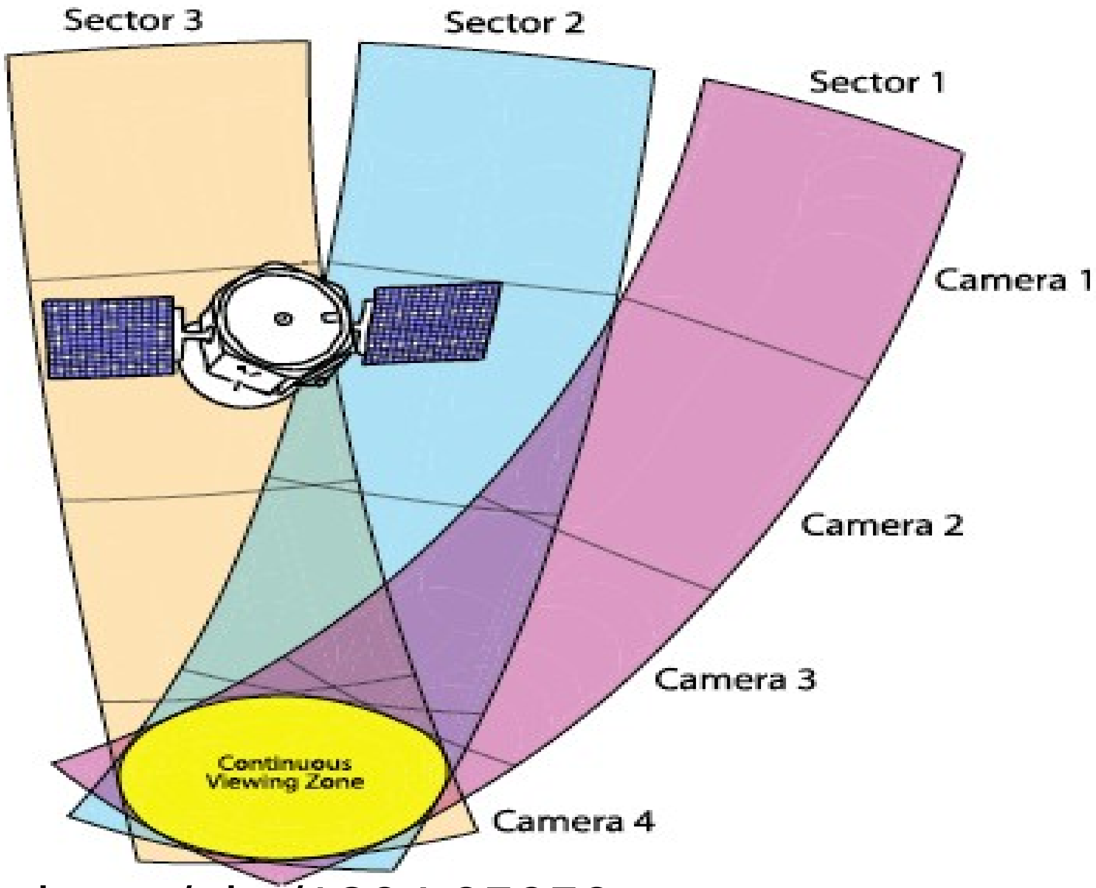


Figure 1. Comparison of the obliquity distributions for stars hosting exoplanets on circular vs. eccentric orbits. Top: Full sample of spin-orbit angles included in this study. Planets with $M < 0.3M_J$ are shown with diamond markers. The data behind this panel is available together with all other planet parameters used in this work, drawn from archival studies. Middle and bottom: Cumulative sums of $|\lambda|$ for eccentric exoplanets, compared with 5000 randomly sampled sets of circular exoplanets (sampled without replacement). Histograms on the right provide vertical cuts through the sums at the Kraft break. In each panel, a linear model fitting the $e \geq 0.1$ cumulative sum is shown in light purple, while the running median of the $e = 0$ population is provided in light blue together with the shaded region within 1σ of the median.

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

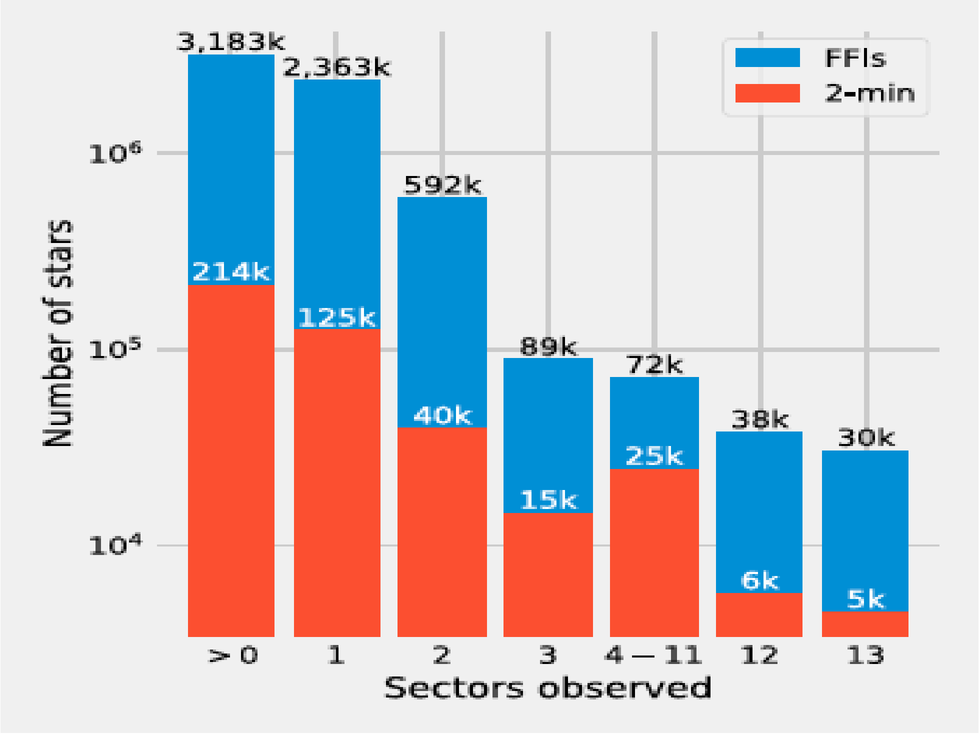


Figure 2. Number of CTL targets observed for a given number of 27.4-day sectors. FFI targets are shown in blue, and 2-minute cadence targets in red. In total, 3.2 million CTL targets are observed, of which 214,000 are observed at 2-minute cadence. Roughly three-quarters of targets are only observed for 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

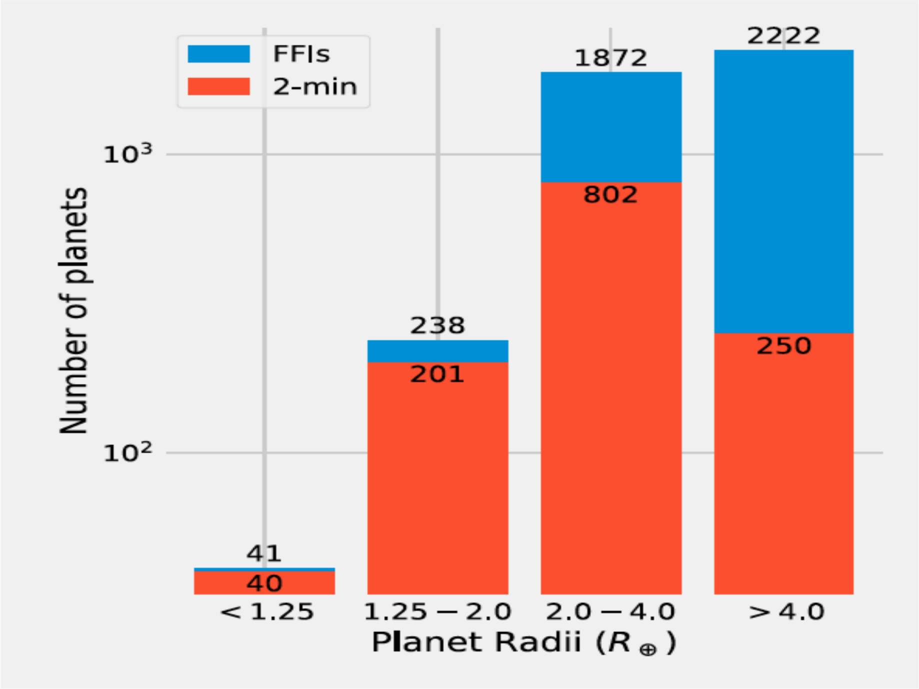
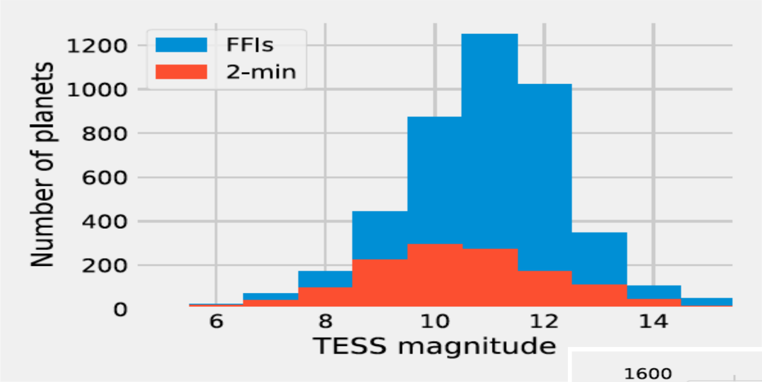


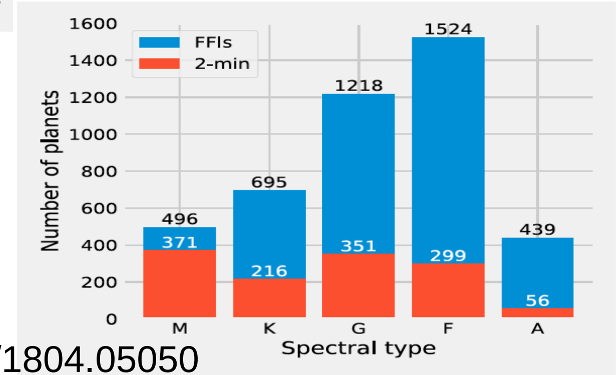
Figure 5. Our simulations predict that *TESS* will detect a total of about 4400 planets orbiting stars on the CTL, of which 1300 will be observed at 2-minute cadence. Roughly 40 Earth-sized planets will be found, almost all of which are on the 2-minute target list. A total of 1000 super-Earths and mini-Neptunes 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.

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

TESS hit rate

- The hit rate (planet found) is varying between





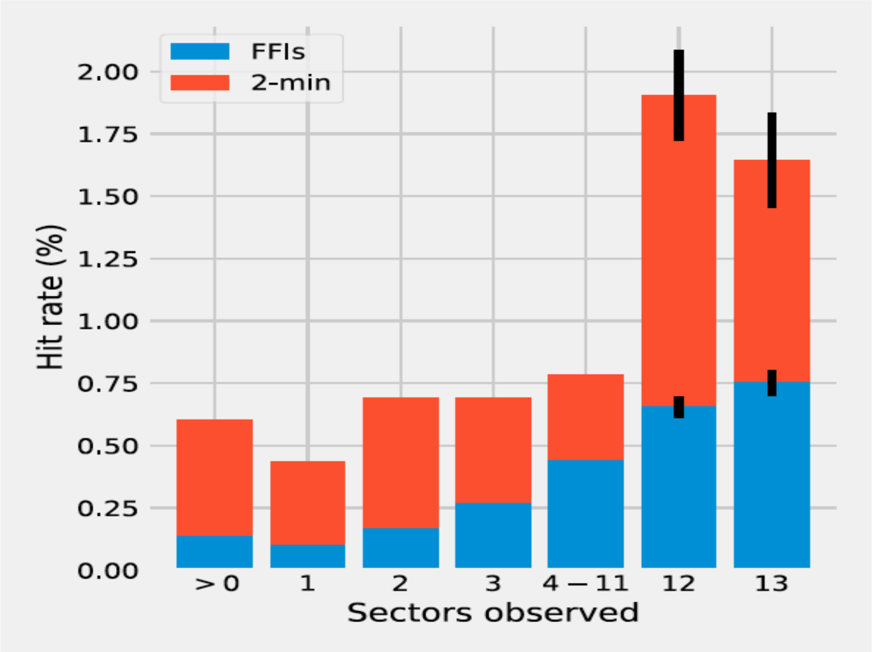


Figure 7. Ratio of stars observed to planets detected as a function of the number of sectors a star is observed for. The longer a star was observed, the higher probability a planet would be detected. Targets observed at 2-minute cadence are shown in red, while blue are FFI targets. For 2-minute cadence 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 2020

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

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 now

List of TESS Planets

Last updated: 4/13/2023

Total number of sectors: 62
Total number of TOIs: 6400

Total number of TOIs with Radii < 4 Earth Radii: 1367
Total number of Confirmed Planets: 329
Total number of False Positives: 1701

TESS Discovered Exoplanets

6400 TOIs (so far!)

62 sectors

1367 TOIs with TESS Rp < 4 Re

1701 false positives

329 confirmed TESS Planets

Last updated: 4/13/2023

TESS and others

All Exoplanets	**6052**
Confirmed Planets Discovered by Kepler	**2784**
Kepler Project Candidates Yet To Be Confirmed	**1979**
Confirmed Planets Discovered by K2	**549**
K2 Candidates Yet To Be Confirmed	**976**
Confirmed Planets Discovered by TESS [1]	**710**
TESS Project Candidates Integrated into Archive [2]	**7771**
Current date TESS Project Candidates at ExoFOP	**7821**
TESS Project Candidates Yet To Be Confirmed [3]	**4694**

[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 (2020)

All Exoplanets	4575
Confirmed Planets Discovered by Kepler	2402
Kepler Project Candidates Yet To Be Confirmed	2361
Confirmed Planets Discovered by K2	477
K2 Candidates Yet To Be Confirmed	1022
Confirmed Planets Discovered by TESS [1]	172
TESS Project Candidates Integrated into Archive (2021-11-19 12:04:01) [2]	4704
Current date TESS Project Candidates at ExoFOP	4704
TESS Project Candidates Yet To Be Confirmed [3]	3124

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

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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	5
Imaging	87
Radial Velocity	1158
Transit	4464
Transit timing variations	39
Eclipse timing variations	17
Microlensing	262
Pulsar timing variations	8
Pulsation timing variations	2
Orbital brightness modulations	9
Disk Kinematics	1

Transiting Exoplanets	**4504**
All Exoplanets	**6052**

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

Mass and radius

Counts by Radius

R ≤ 1.25 R_Earth	544
1.25 < R ≤ 2 R_Earth	1109
2 < R ≤ 6 R_Earth	1918
6 < R ≤ 15 R_Earth	715
15 R_Earth < R	224

Counts by Mass

M ≤ 3 M_Earth	103
3 < M ≤ 10 M_Earth	340
10 < M ≤ 30 M_Earth	235
30 < M ≤ 100 M_Earth	208
100 < M ≤ 300 M_Earth	355
300 M_Earth < M	764

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

And how did Kepler perform 2021?

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

Kepler today

Kepler Mission Counts

Confirmed Planets Discovered by Kepler [2]	2778
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	1984
Total Candidates and Confirmed Planets [4]	**4781**

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Kepler Candidate Statistics

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6 < R ≤ 15 R_Earth	314	18
15 R_Earth < R	154	10

K2 Mission Counts

Confirmed Planets Discovered by K2 [1]	548
K2 Candidates Yet To Be Confirmed	977
K2 Campaign 9 Microlensing Events	

[1] This is the number of planets that were discovered utilizing Kepler/K2 observations.

How does TESS really do?

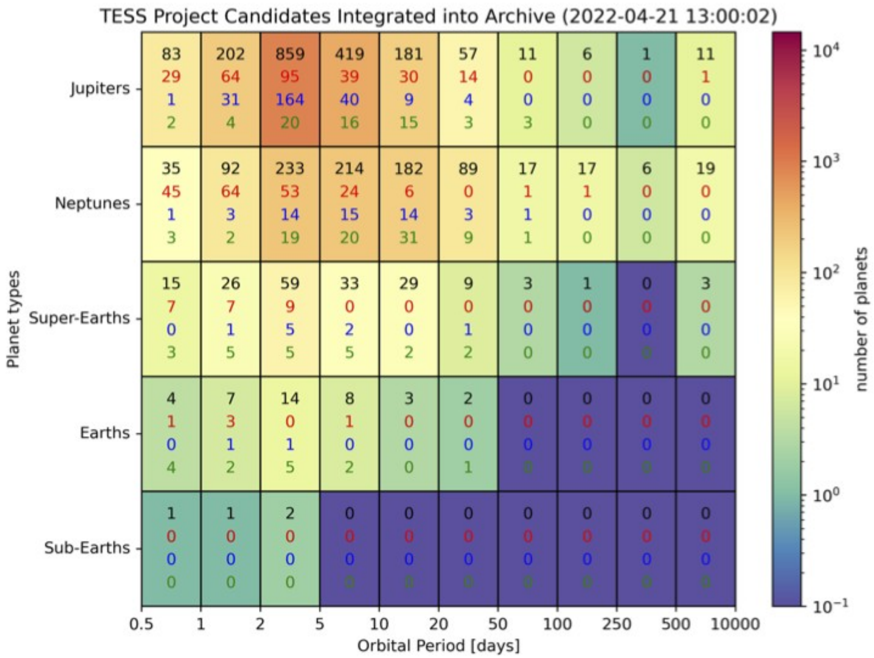


Fig. 11. TESS exoplanets as a function of planet type and orbital period, separated into planet candidates (black), false positives (red), previously known planets discovered by other missions than TESS (blue), and confirmed planets verified through additional observations using other telescopes (green).

https://www.aanda.org/articles/aa/pdf/2023/09/aa45287-22.pdf

Expectations from PLATO

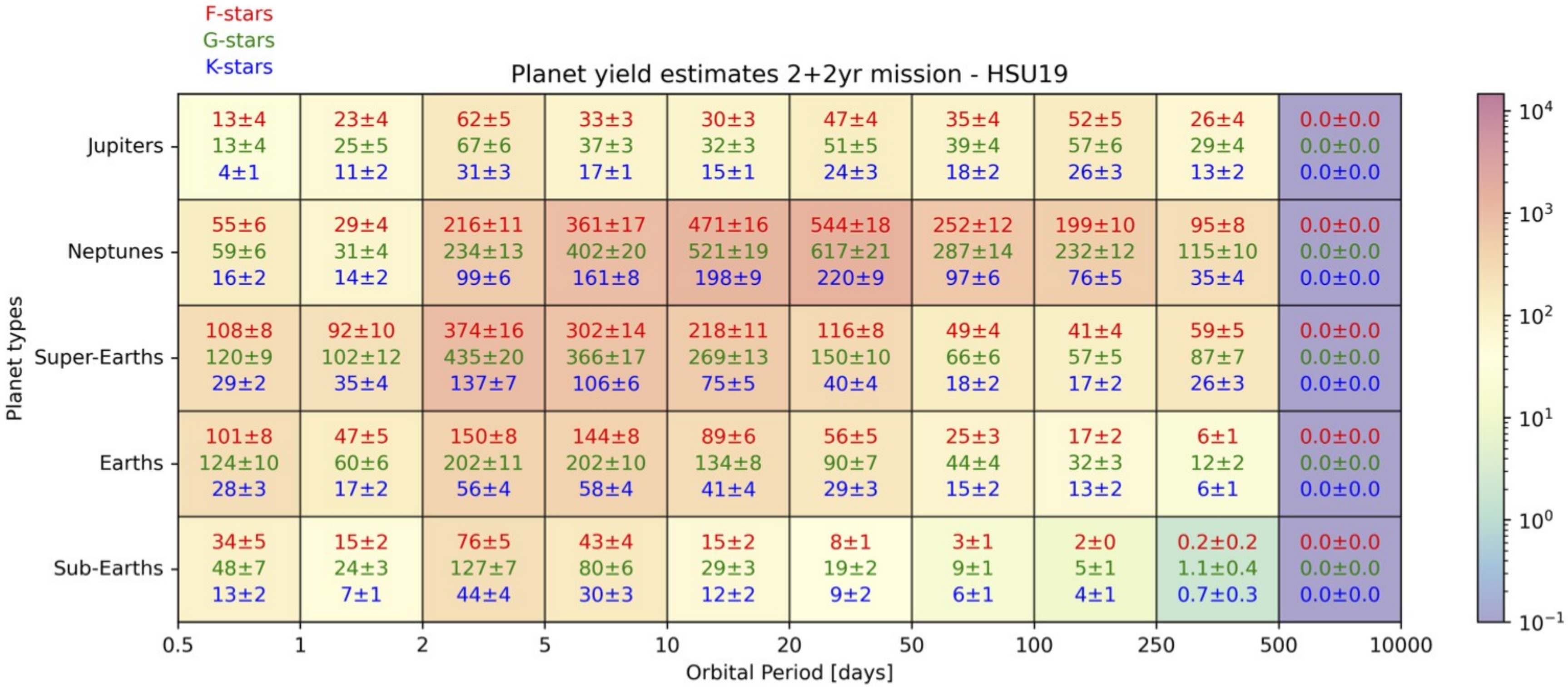


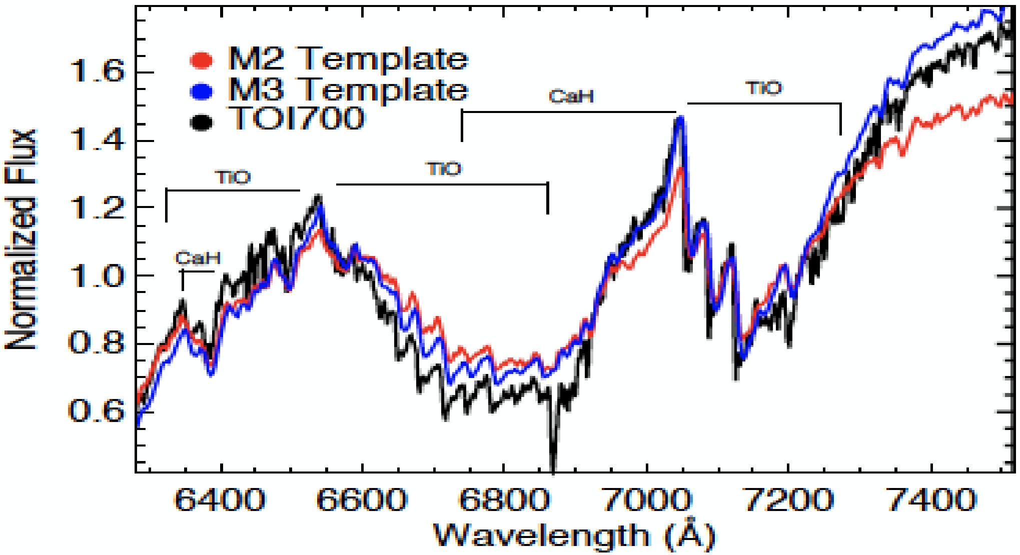
Fig. 8. PPY as a function of binned planet size and binned orbital period for the 2+2 yr mission scenario and the HSU19 population around F (red), G (green), and K stars (blue).

https://www.aanda.org/articles/aa/pdf/2023/09/aa45287-22.pdf

Some interesting planets

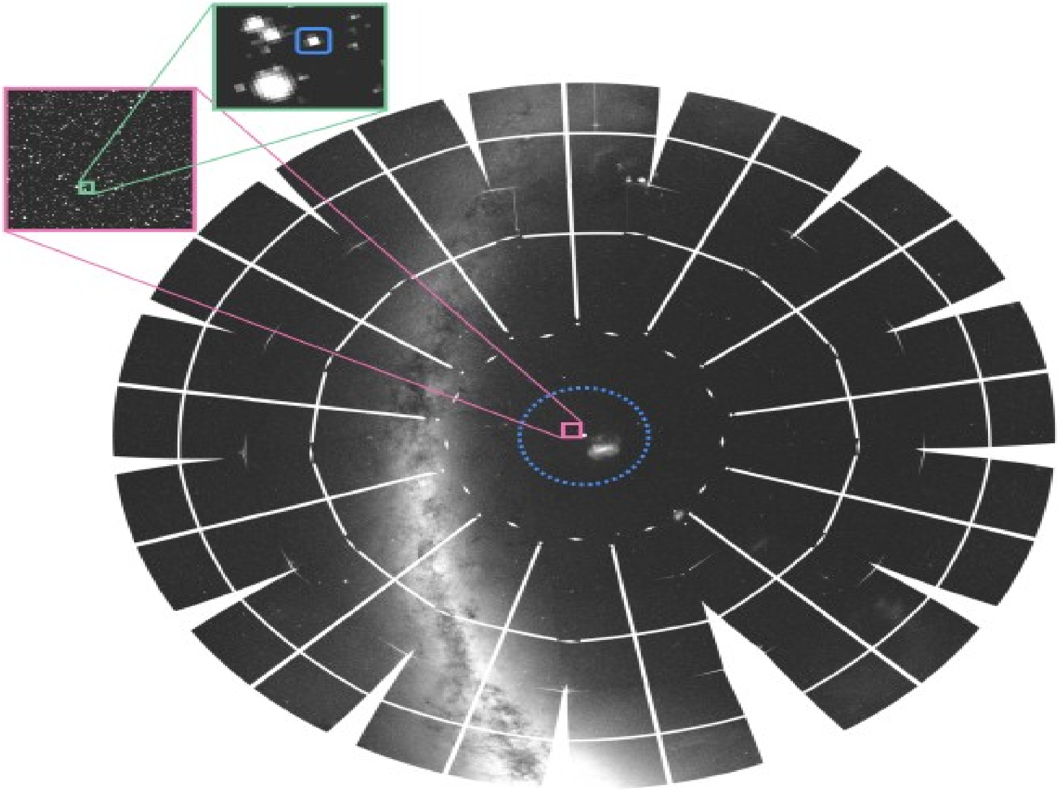
TOI-700 – TESS detection in the HZ

- Detection by TESS of an Earth-sized planet in the HZ
- Parent star is an M dwarf
- What are the prospects for further characterization?



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

Planet from Continuous Viewing Zone



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

About TOI-700

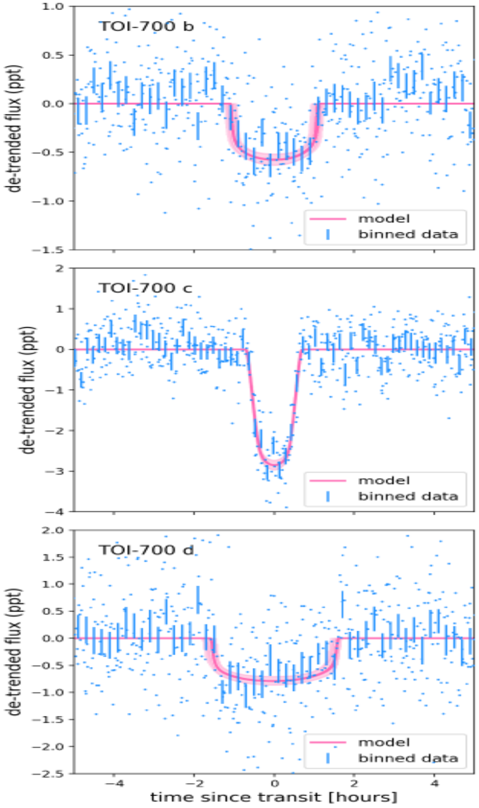


Figure 4. Phase-folded, light curves from 11 sectors of TESS data for planets TOI-700 b (upper panel), TOI-700 c (middle panel), and TOI-700 d (lower panel), along with the respective transit model (pink) showing the 1-sigma range in models consistent with the observed data. The corresponding transit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

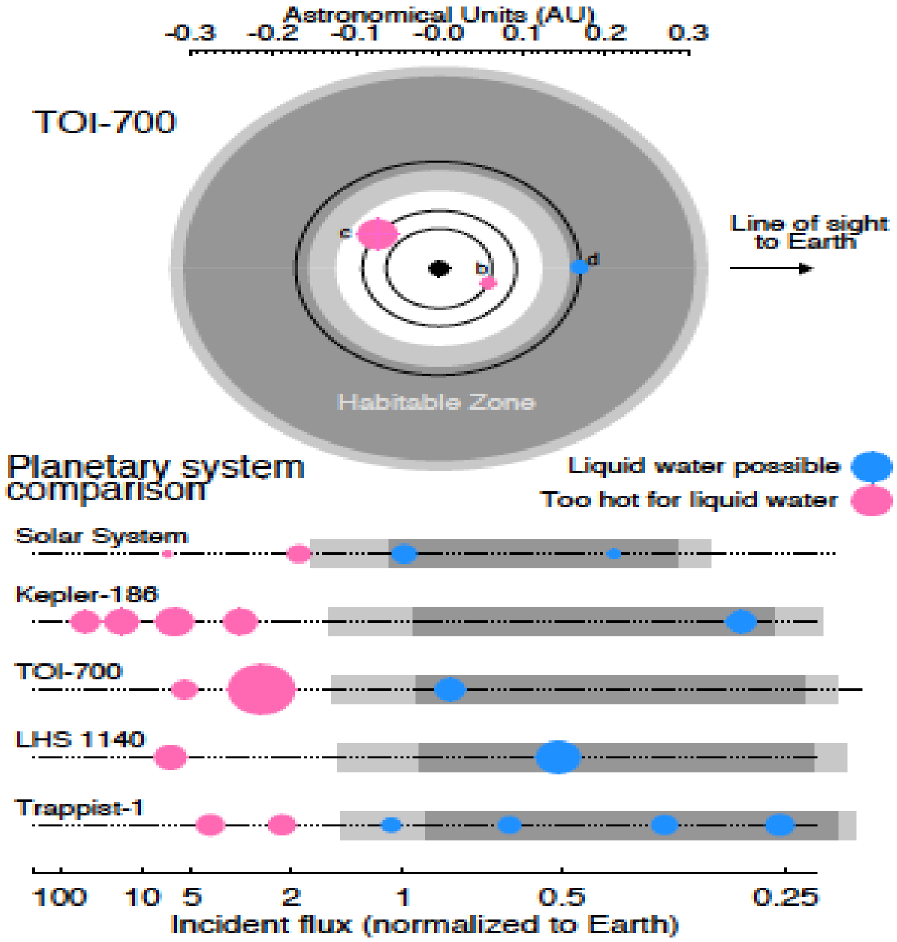
Table 2. Planet Parameters

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 atmosph look like?



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

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?

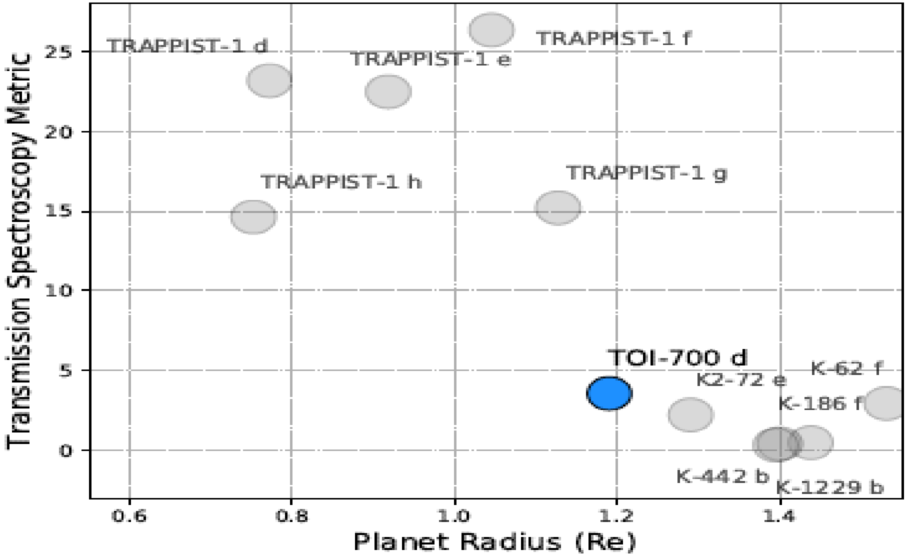


Figure 12. There are now 11 known exoplanets that have radii less than $1.5R_{\oplus}$ and orbit within their star's optimistic habitable zone (Kopparapu et al. 2013). Plotted are these planets' TSM values. The top candidates for atmospheric characterization orbit TRAPPIST-1. Beyond these, TOI-700 d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

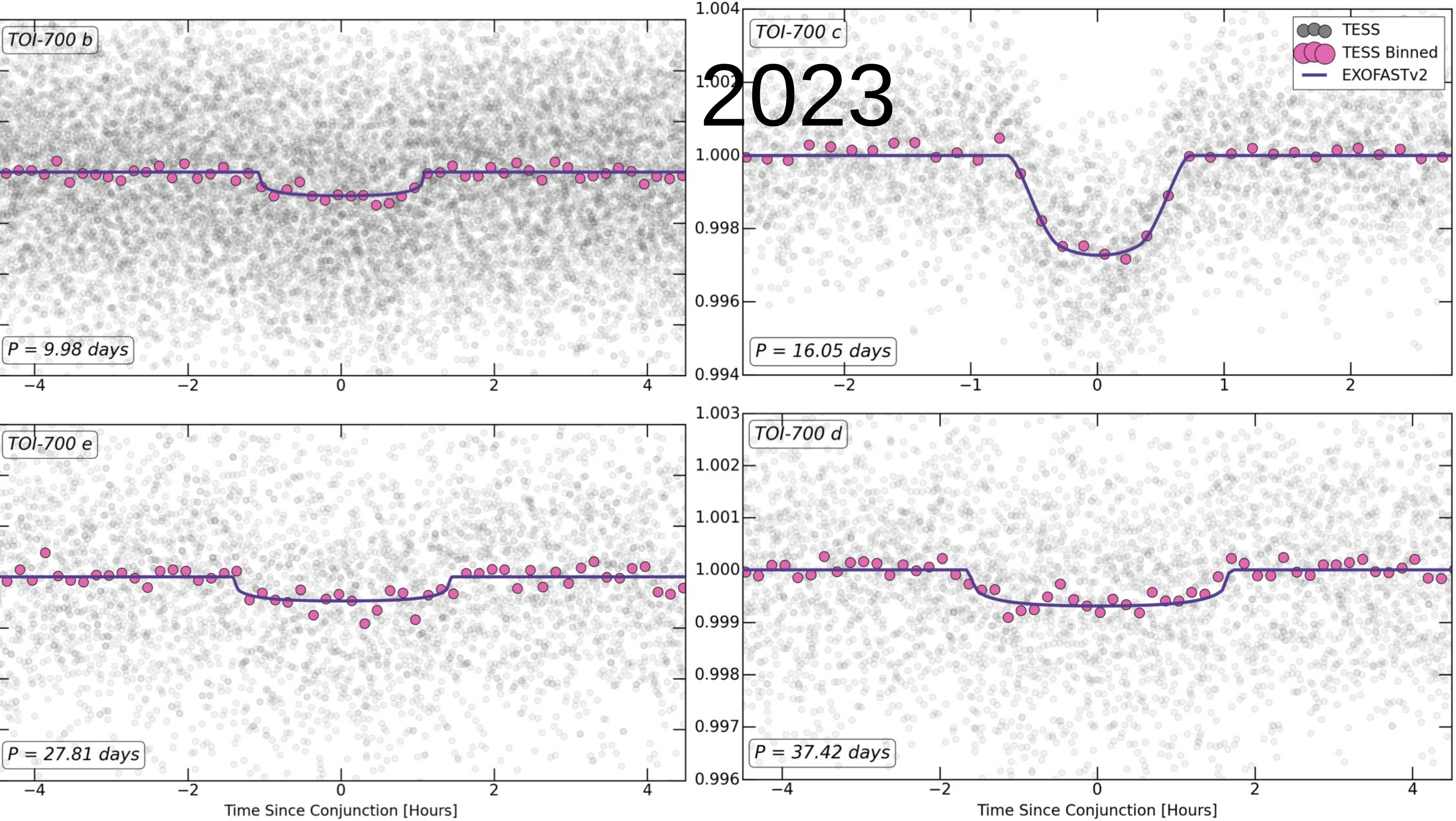
Gilbert 2020 - https://arxiv.org/abs/2001.00952

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
- However, the star is quiet in the UV!!!
- We have to wait for LUVOIR? Or other missions?

2023



2023 - https://arxiv.org/pdf/2301.03617.pdf

HZs in 2023

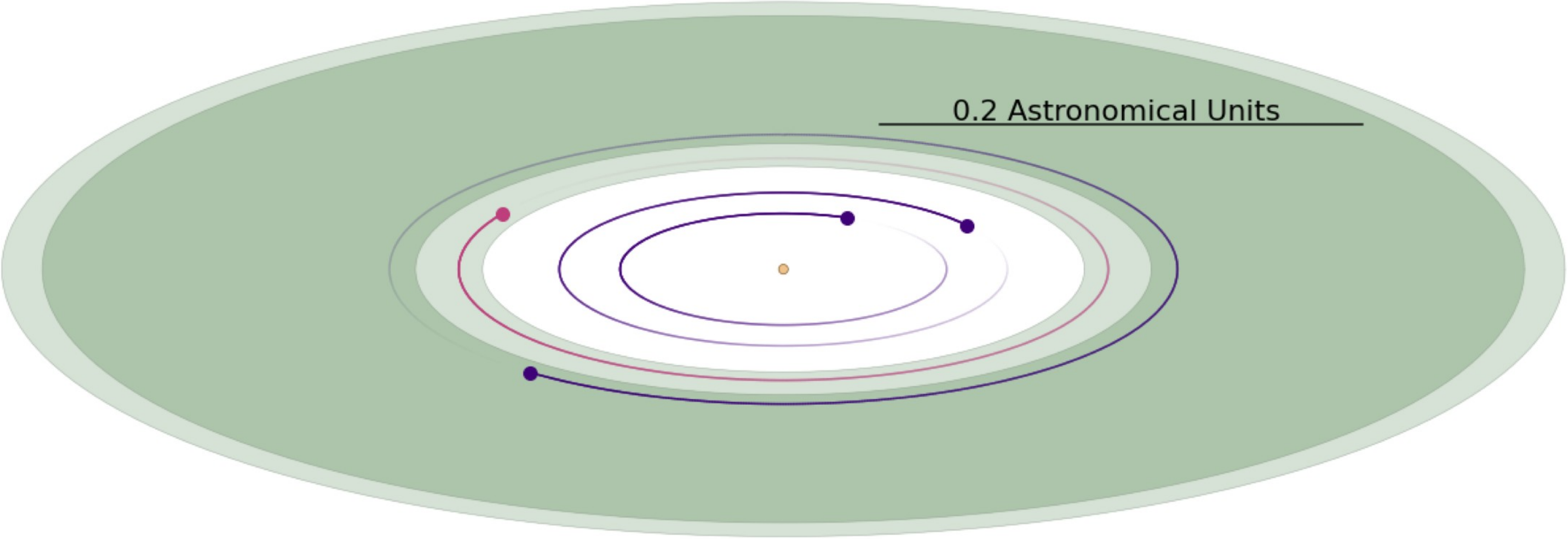


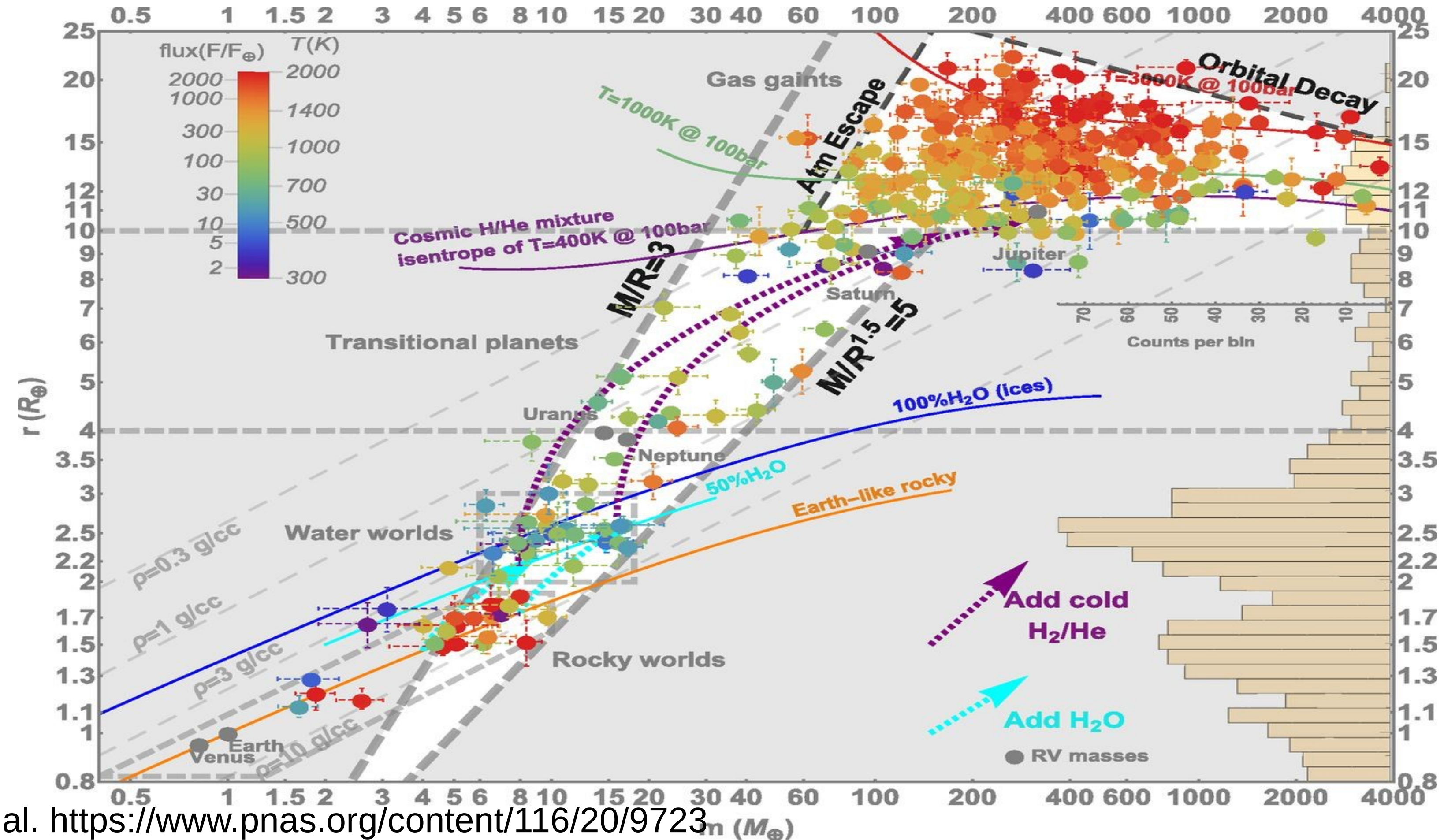
Figure 4. TOI-700 e (pink) resides in the Optimistic Habitable Zone (light green) around its host star in between the orbits of TOI-700 c and d. The Conservative Habitable Zone is shown in dark green, and planets b, c, and d (from inner to outer) are shown in indigo.

2023 - https://arxiv.org/pdf/2301.03617.pdf

But what can we say more about exoplanetary structures?

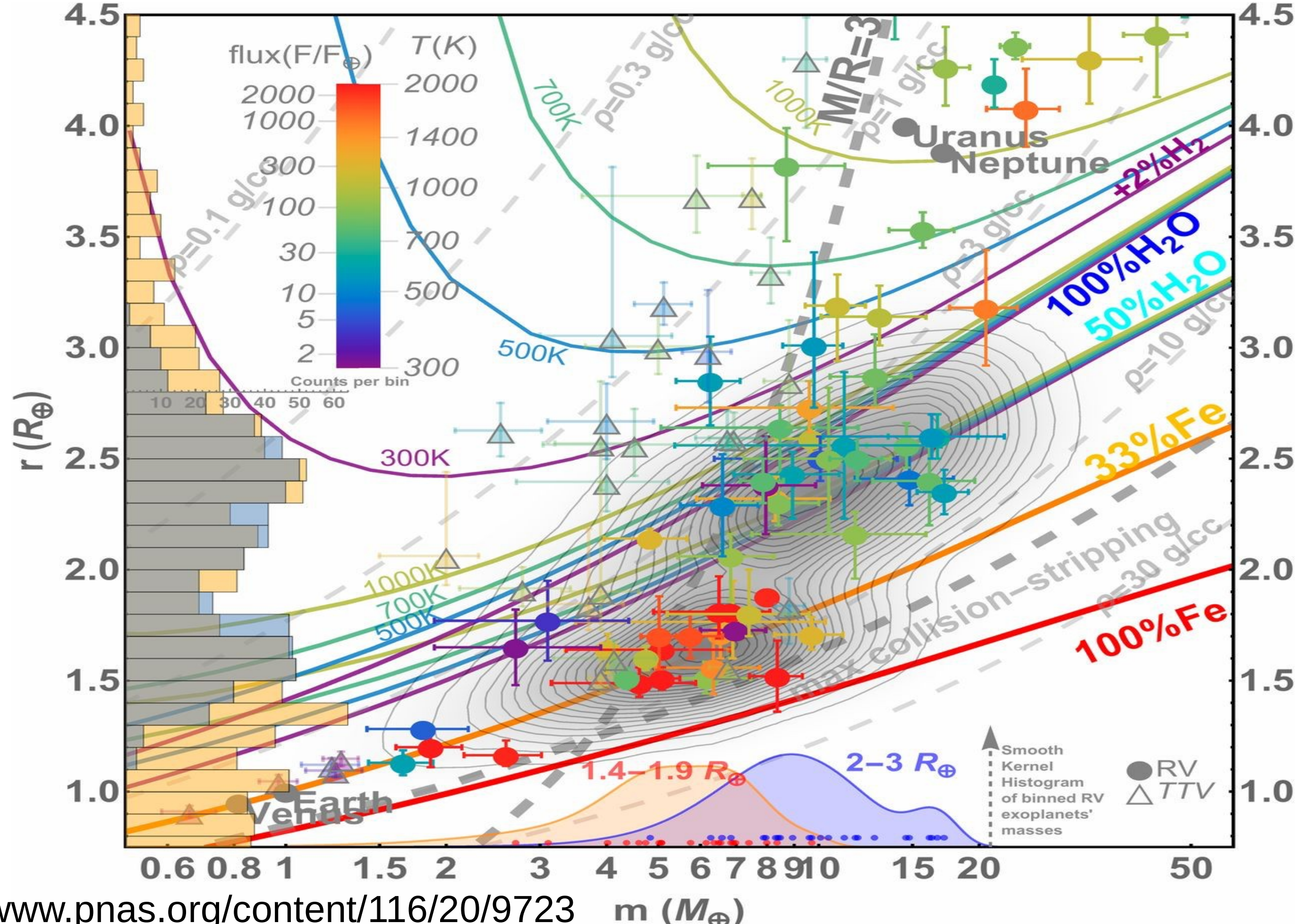
- As discussed earlier, the main tool for characterization of exoplanets is the mass-radius diagram
- If we know the mass and the radius of an exoplanet, we can model the interiors, structure and the atmospheres
- Therefore, we need full characterization by RVs and transits ideally! We need also reasonable 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

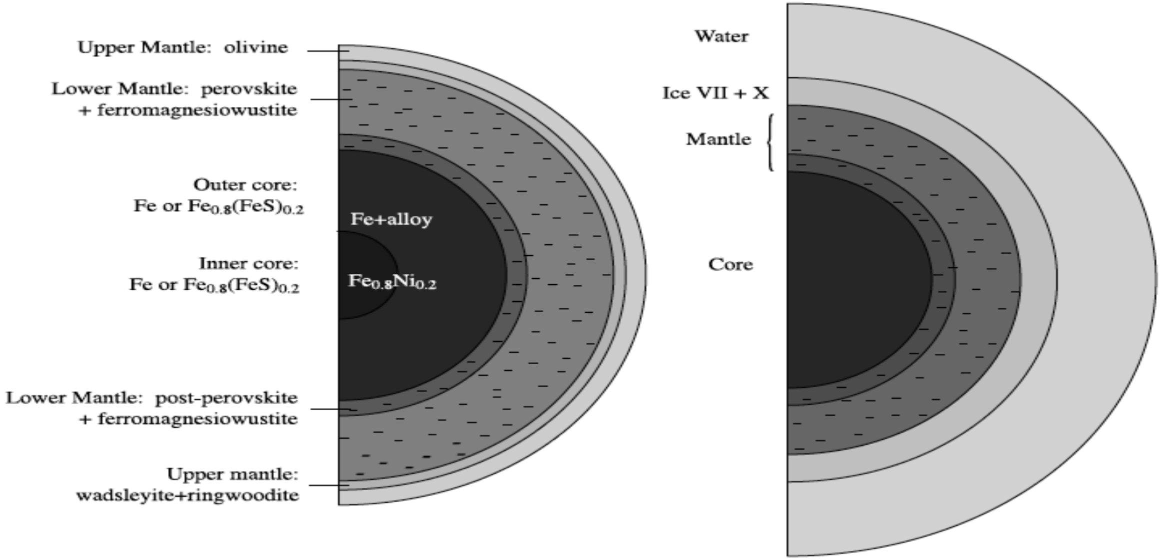
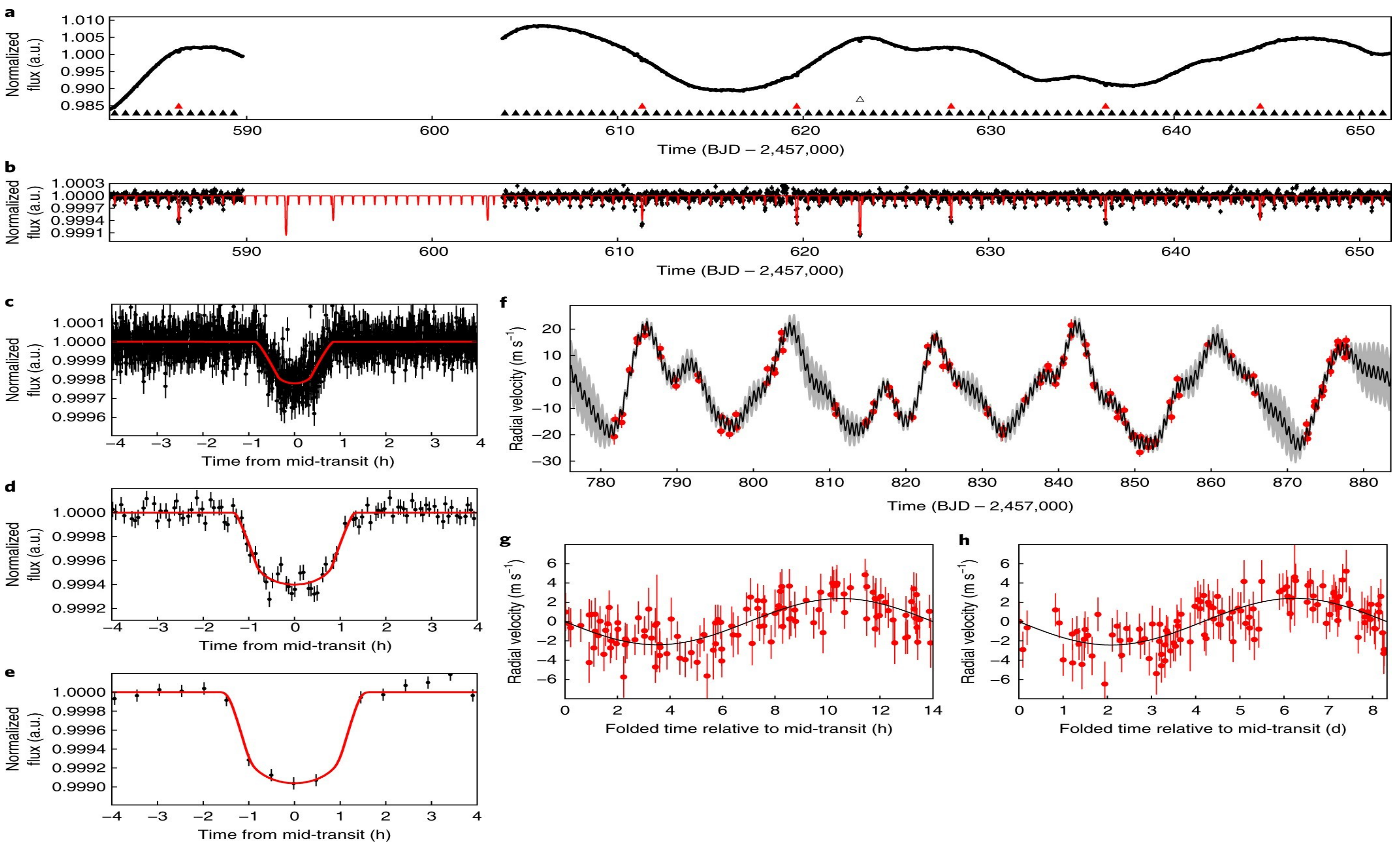


FIG. 1.—Schematic representation of the model. To calculate the internal structure of a super-Earth, we assume a similar composition to that of Earth (*left*): a dense core of pure Fe or $Fe_{0.8}(FeS)_{0.2}$ as possible and likely cases (Earth has an outer core of Fe plus some unknown alloy, and the 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.

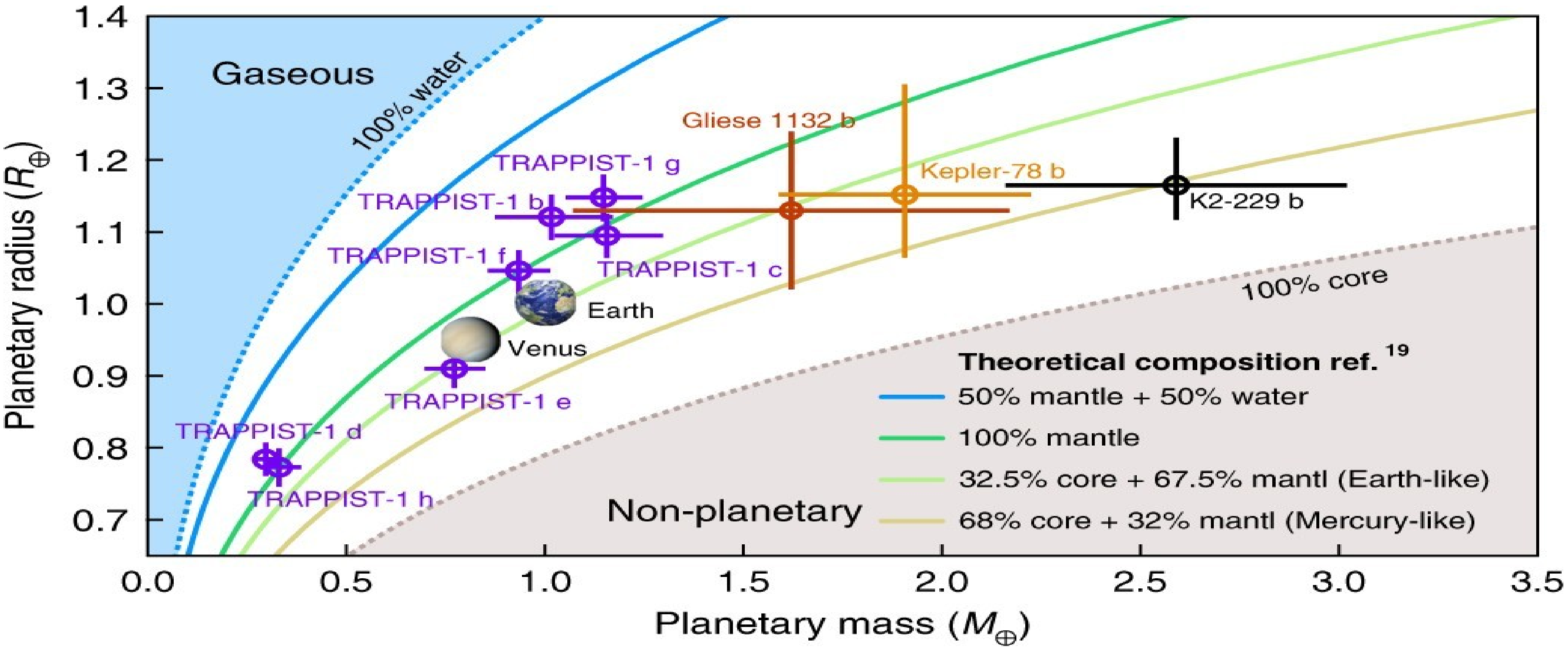
Valencia et al. 2007 https://iopscience.iop.org/article/10.1086/509800

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?

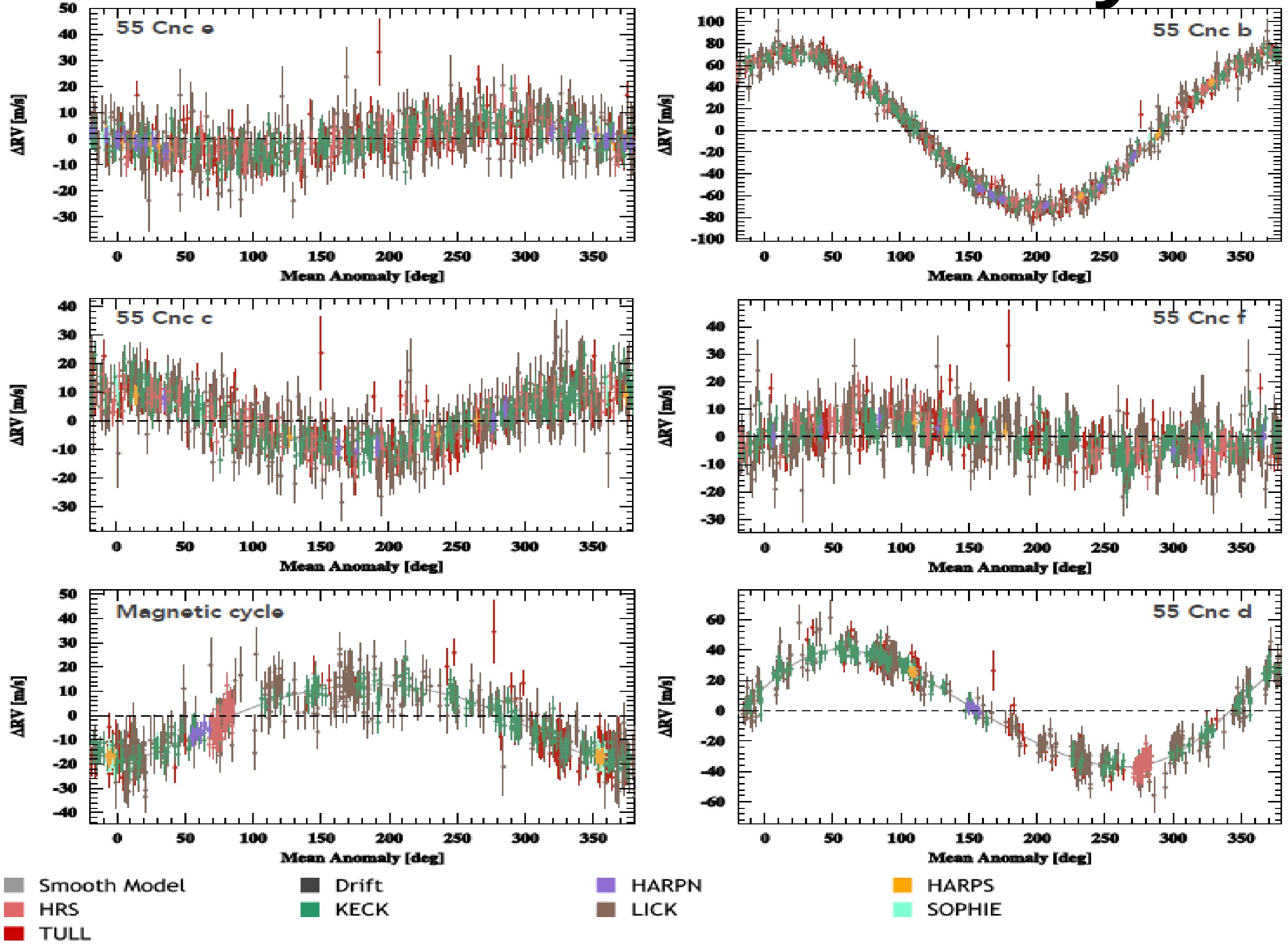


The 55 Cnc system

- 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



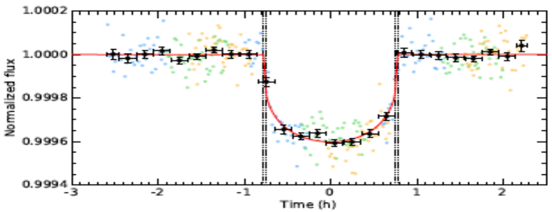


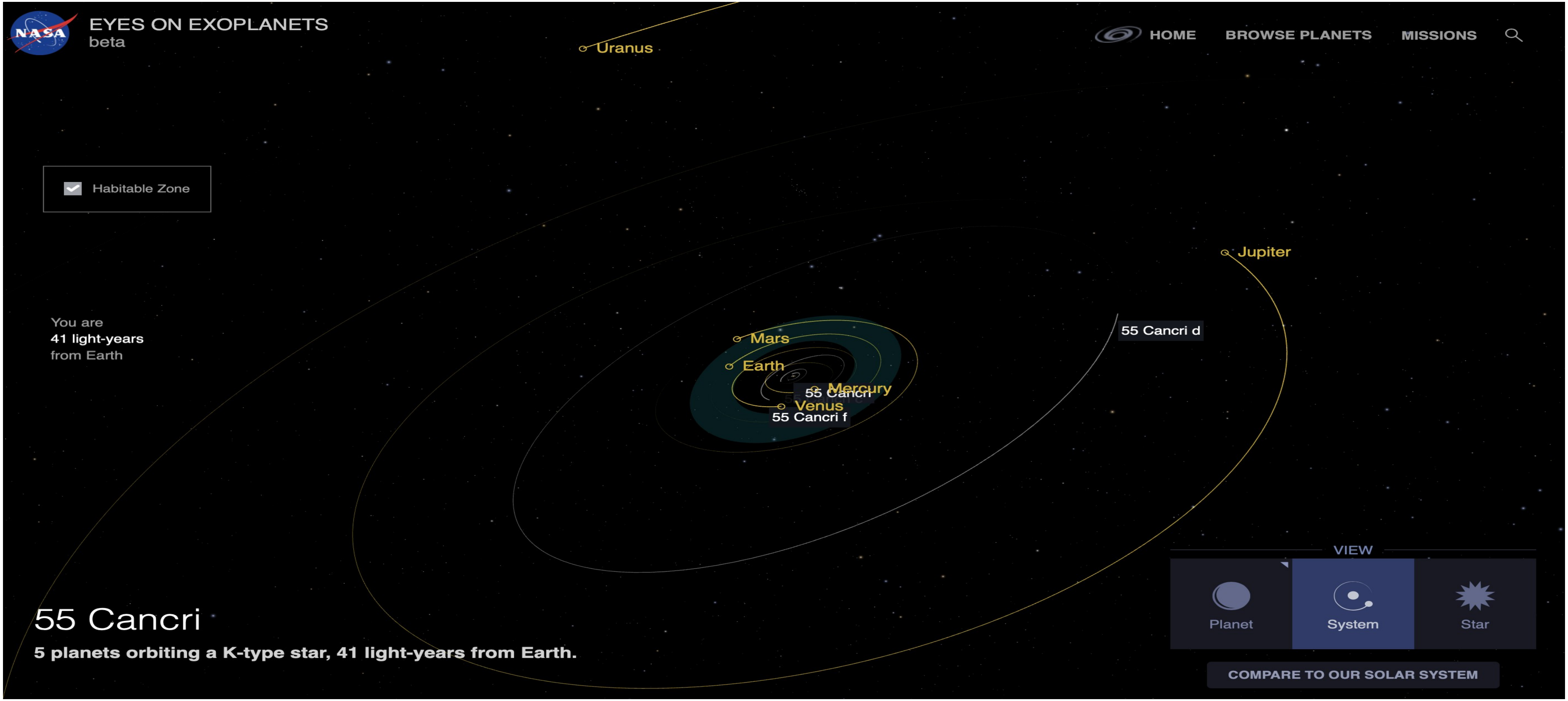
Fig. 10 STIS transit light curve of 55 Cnc e in the visible band. Fluxes have been corrected for the breathing and long-term variations in Visit A_{STIS} (blue), B_{STIS} (green), and C_{STIS} (orange). Black points show binned exposures. The red line is the best-fit transit light curve.

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

The 55 Cnc system

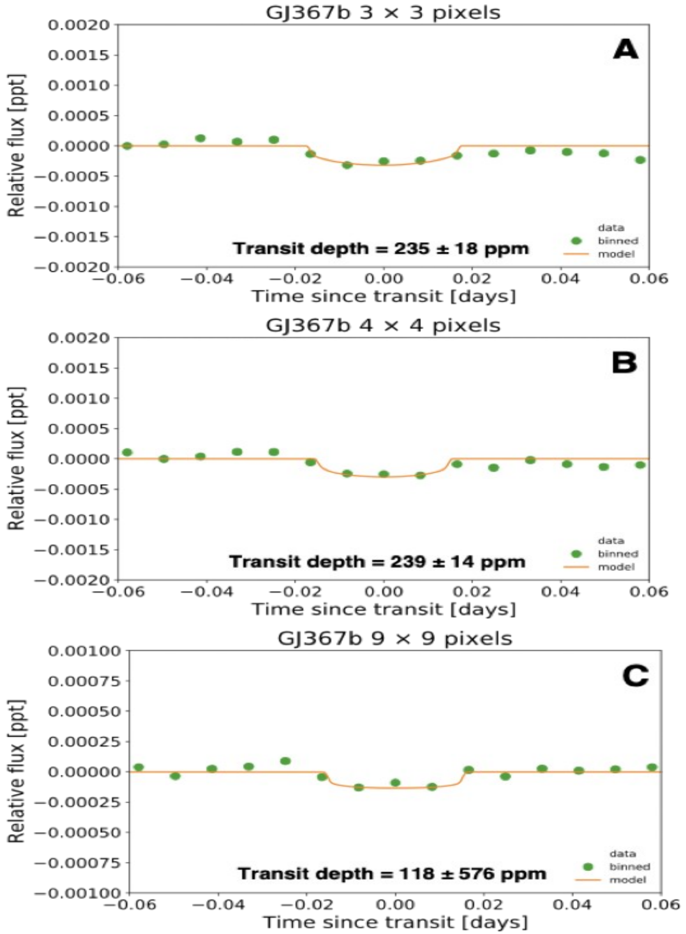
Param.	Units	55 Cnc e	55 Cnc b	55 Cnc c	55 Cnc f	magnetic cycle	55 Cnc d
P	[d]	$0.73654737^{+1.30\,10^{-6}}_{-1.44\,10^{-6}}$	$14.6516^{+0.0001}_{-0.0001}$	$44.3989^{+0.0042}_{-0.0043}$	$259.88^{+0.29}_{-0.29}$	$3822.4^{+76.4}_{-77.4}$	$5574.2^{+93.8}_{-88.6}$
K	[m s^{-1}]	$6.02^{+0.24}_{-0.23}$	$71.37^{+0.21}_{-0.21}$	$9.89^{+0.22}_{-0.22}$	$5.14^{+0.26}_{-0.25}$	$15.2^{+1.6}_{-1.8}$	$38.6^{+1.3}_{-1.4}$
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



EYES ON EXOPLANETS
beta
HOME
BROWSE PLANETS
MISSIONS
Uranus
Habitable Zone
Jupiter
You are
41 light-years
from Earth
Mars
Earth
55 Cancri d
55 Cancri
Mercury
Venus
55 Cancri f
VIEW
Planet
System
Star
55 Cancri
5 planets orbiting a K-type star, 41 light-years from Earth.
COMPARE TO OUR SOLAR SYSTEM

Exo-Mars



Lam et al. 2021, Science, VOL. 374, NO. 6572

Planet GJ 367b	
Epoch, T_0 [barycentric Julian date, BJD_{TDB}]	2458544.1348 ± 0.0004
Orbital Period, P (days)	
Planet-to-star radius ratio, R_p/R_s	
Scaled orbital semi-major axis, a/R_s	
Impact parameter, b	
Radial velocity semi-amplitude†, K (cm s^{-1})	79.8 ± 11.0
Systemic radial velocity‡, v_γ (km s^{-1})	47.9258 ± 0.0003
Eccentricity, e	0
Transit duration, T_{14} (min)	
Orbital semi-major axis, a (au)	0.0071 ± 0.0002
Orbital inclination, i (º)	80.75 ± 0.64
Planet mass, M_p ($M_\oplus$)	0.546 ± 0.078
Planet radius, R_p ($R_\oplus$)	0.718 ± 0.054
Planet bulk density, ρ_p (g cm^{-3})	8.106 ± 2.165
Equilibrium Dayside Temperature§, T_{eq} (K)	
—Earth-like bond albedo (A_b = 0.3)	1597 ± 39

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

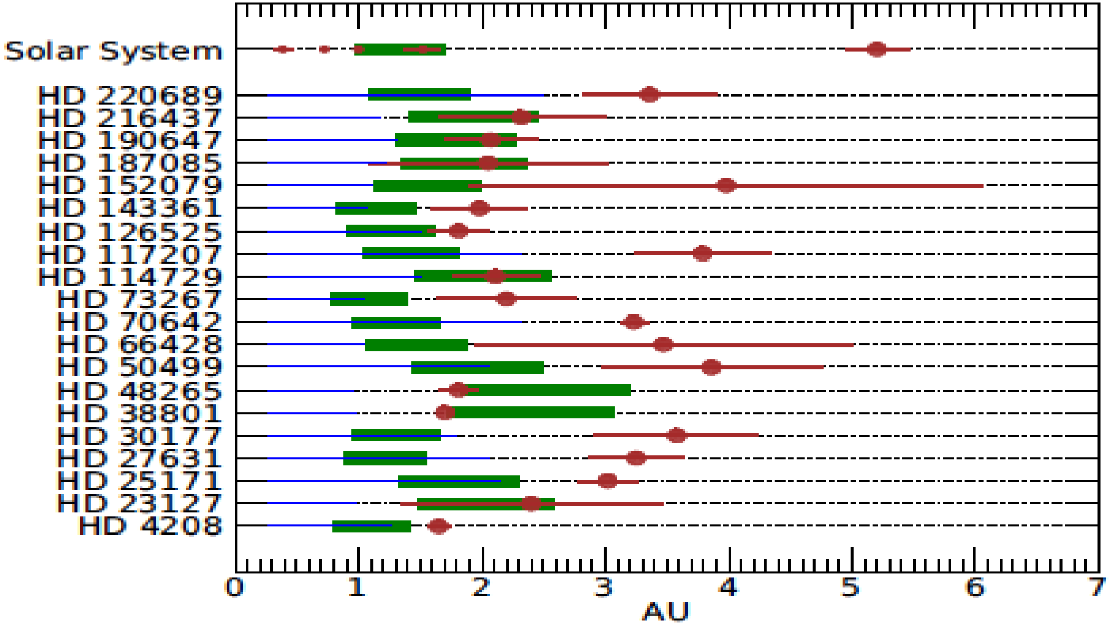


Fig. 1. Overview of the sample systems and a comparison with the inner Solar System's architecture. The sample's known giant planets are shown as brown circles, a thin brown line from periastron to apoastron showing their orbit's span. Each system's habitable zone, computed using the model detailed in 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 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

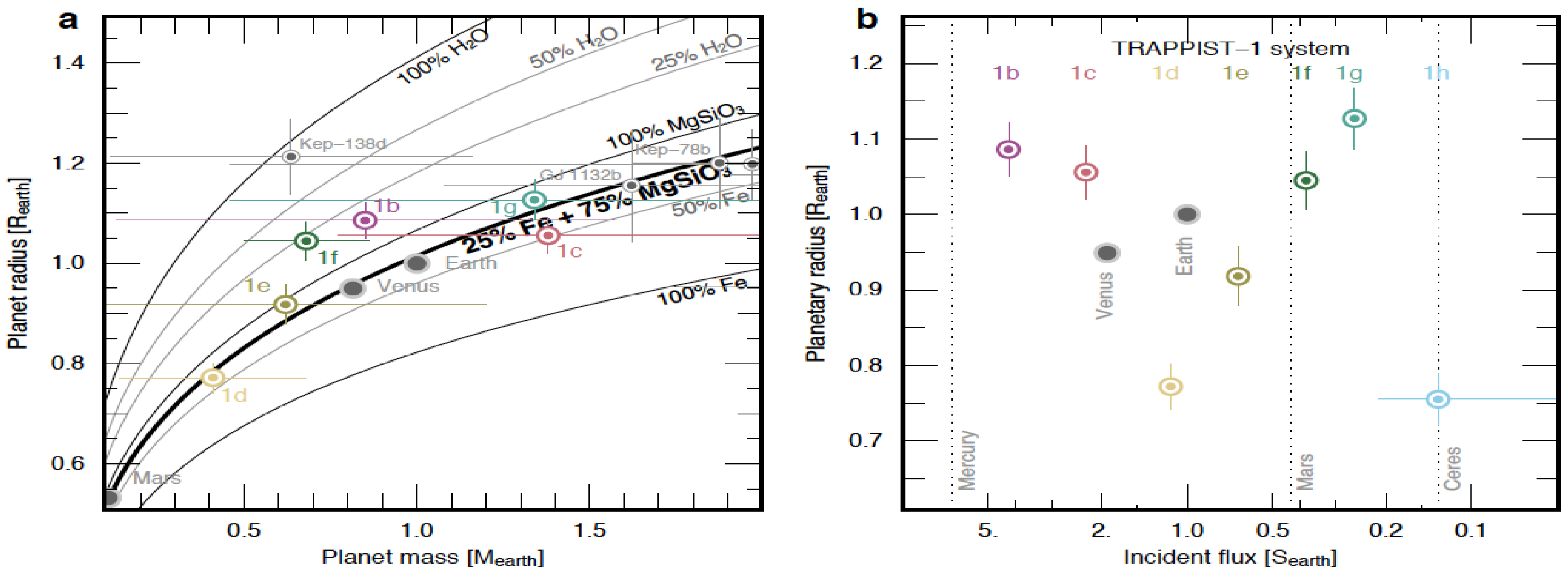
The Trappist-1

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 $\pm 0.60\times10^{-6}$	2.4218233 $\pm 0.17\times10^{-5}$	4.049610 $\pm 0.63\times10^{-4}$	6.099615 $\pm 0.11\times10^{-4}$	9.206690 $\pm 0.15\times10^{-4}$	12.35294 $\pm 0.12\times10^{-3}$	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	-

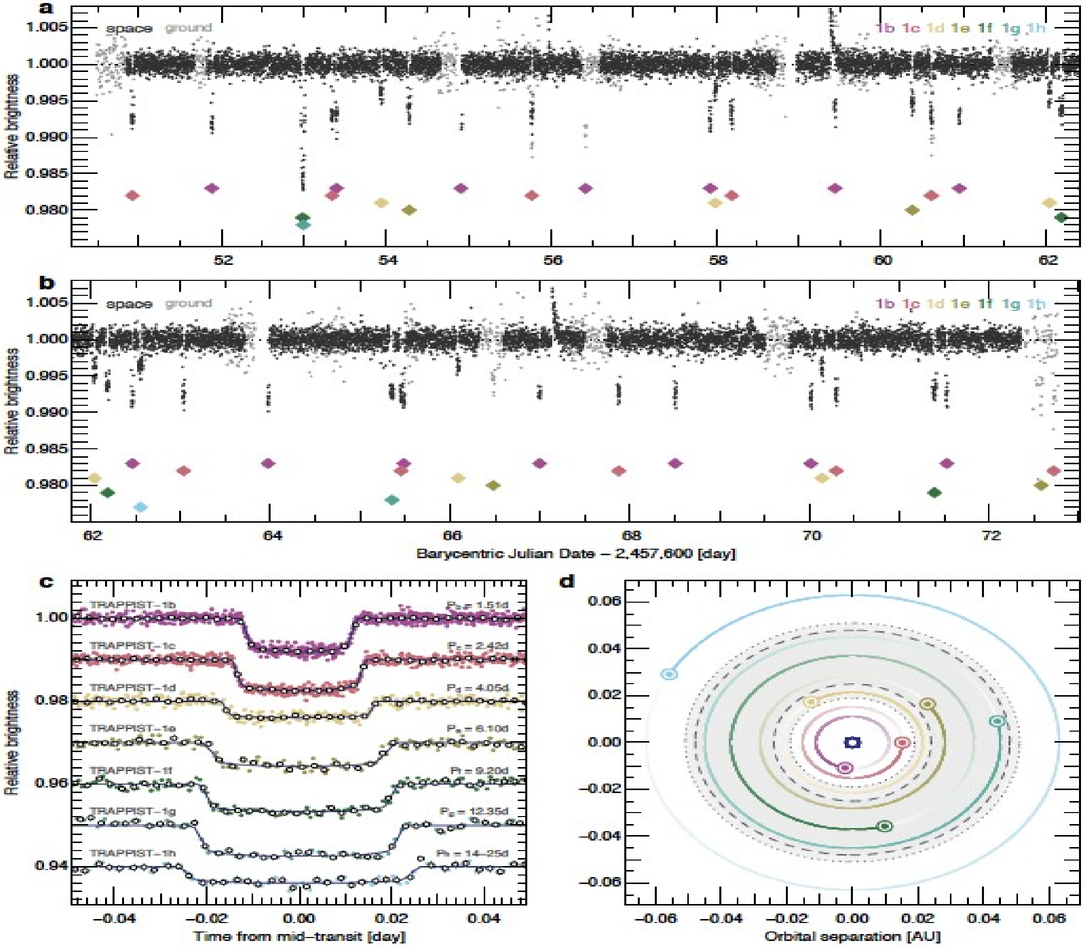
- Gillon et al 2017 - https://arxiv.org/pdf/1703.01424.pdf

The Trappist-1



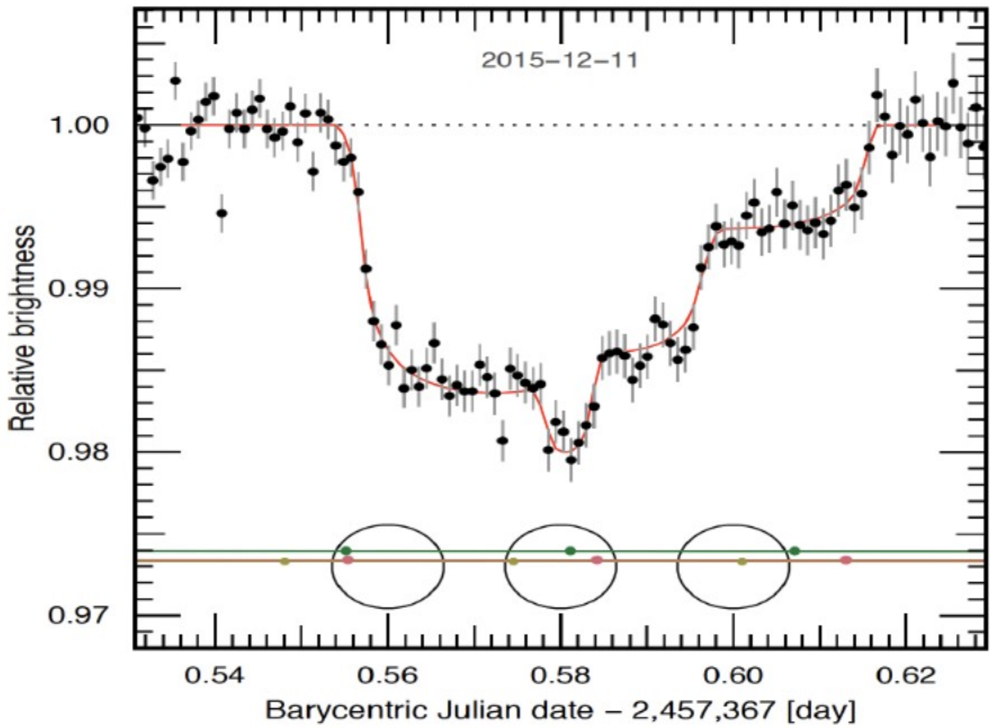
- Gillon et al 2017 - https://arxiv.org/pdf/1703.01424.pdf

The Trappist-1



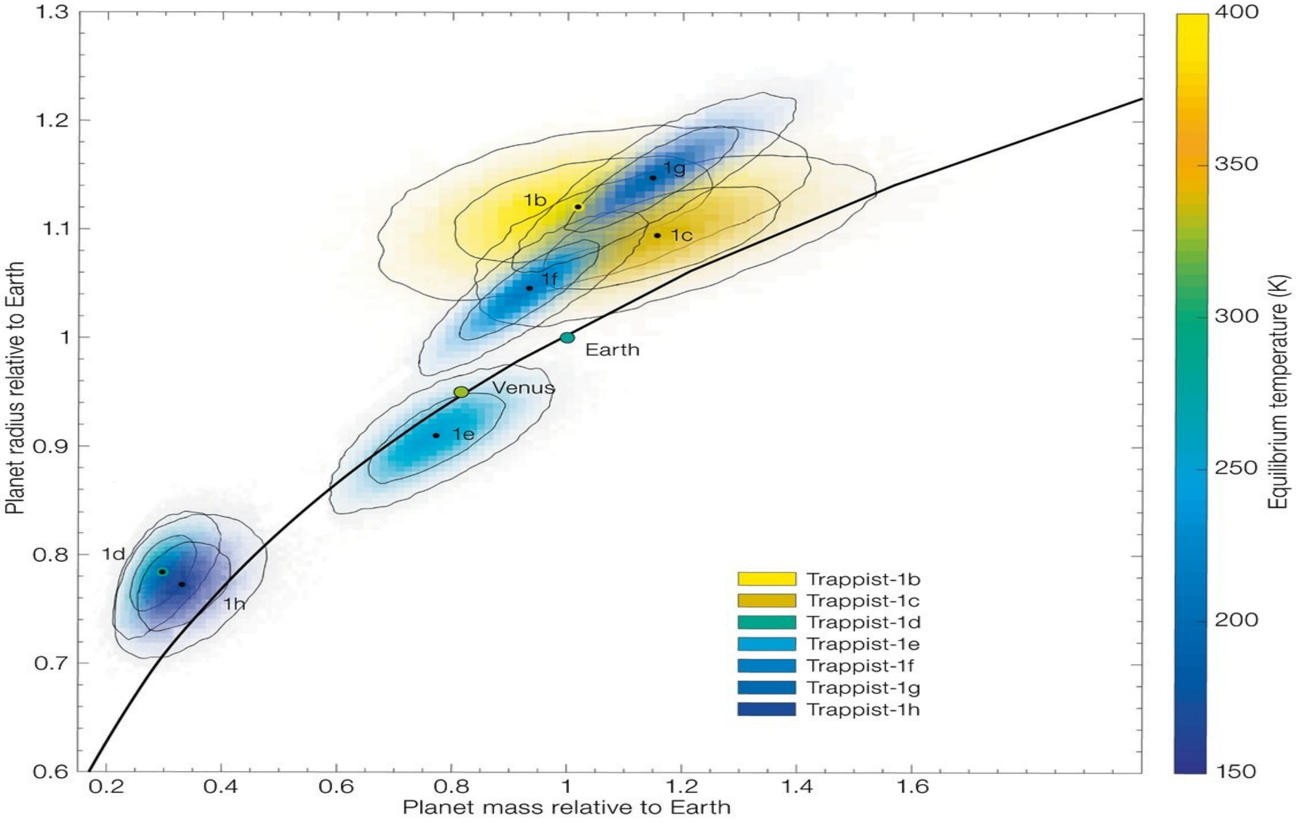
- Gillon et al 2017 - https://arxiv.org/pdf/1703.01424.pdf

The Trappist-1



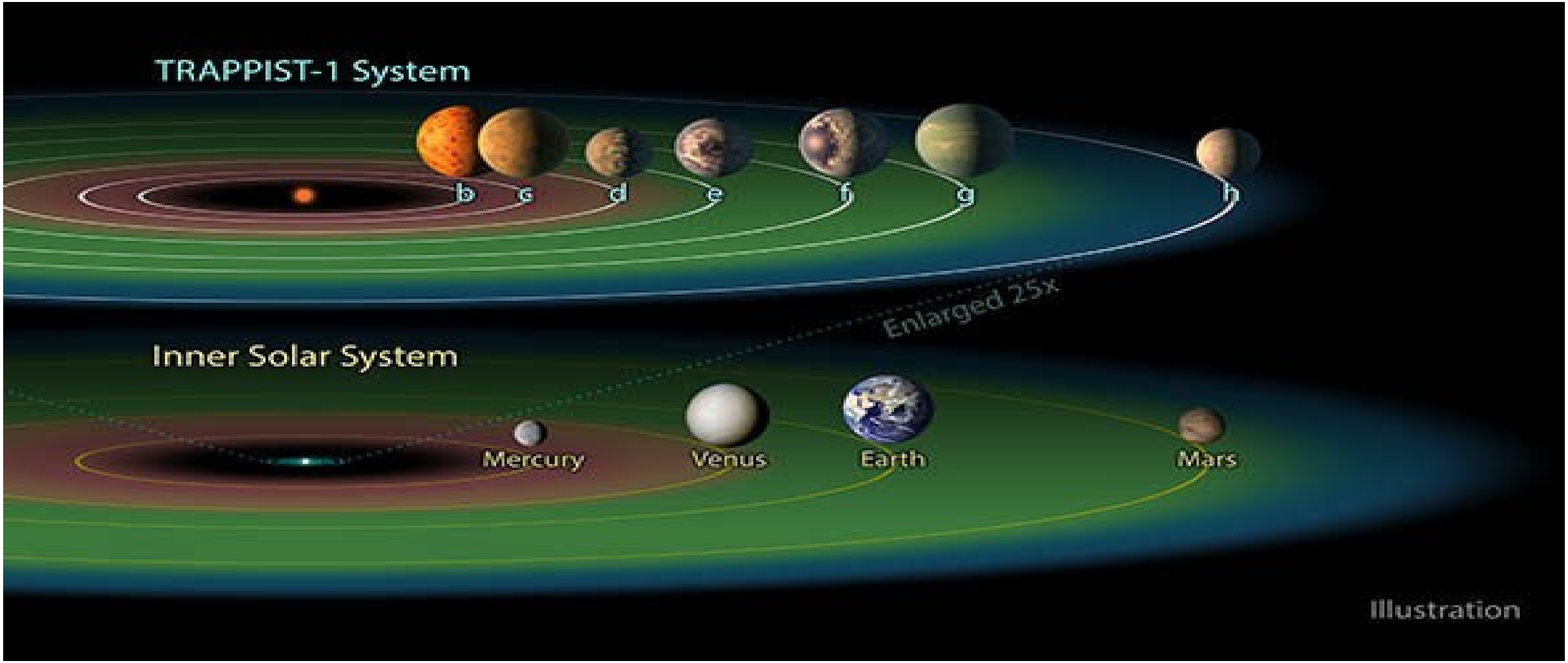
- Gillon et al 2017 - https://arxiv.org/pdf/1703.01424.pdf

Composition of Trappist 1 planets



https://www.eso.org/public/czechrepublic/images/eso1805e/

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/

Thank you