

Exoplanets

Lecture 8
29.11.2023
MFF UK

And what do observations tell us?
(finishing the last lecture)

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

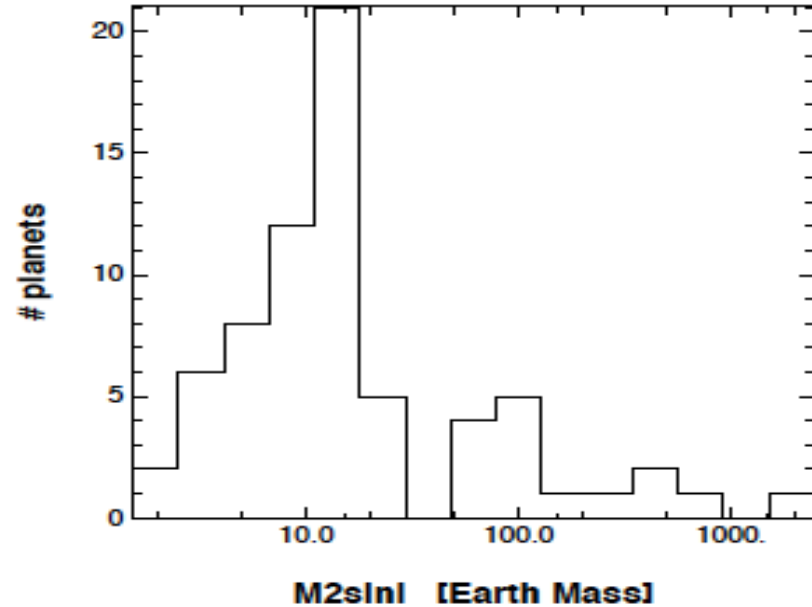
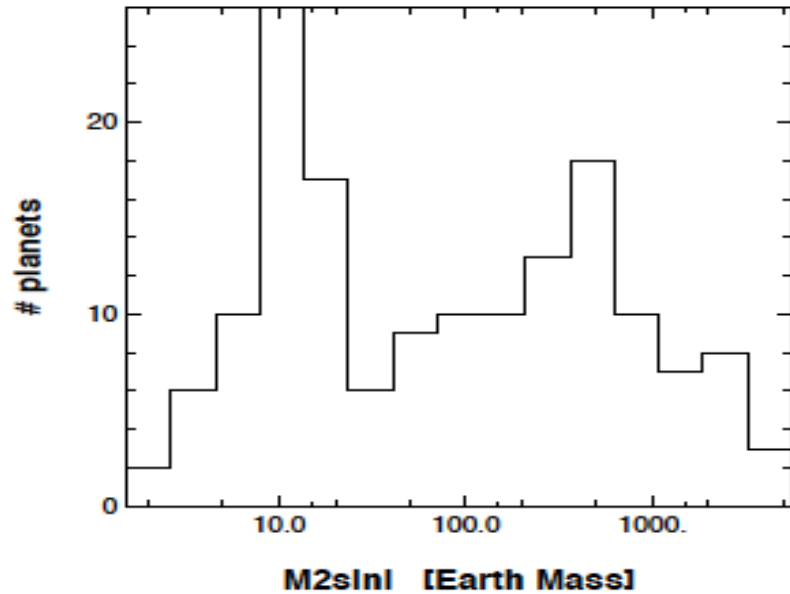
- We have now larger data set
- HARPS and CORALIE data
- Planets are quite frequent, at least every

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

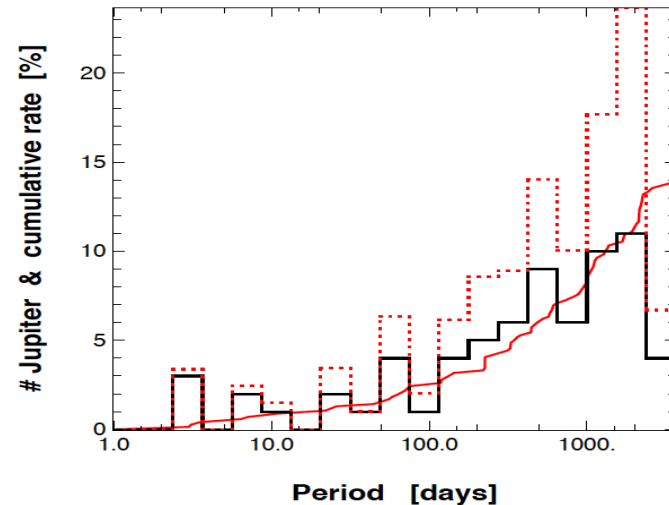
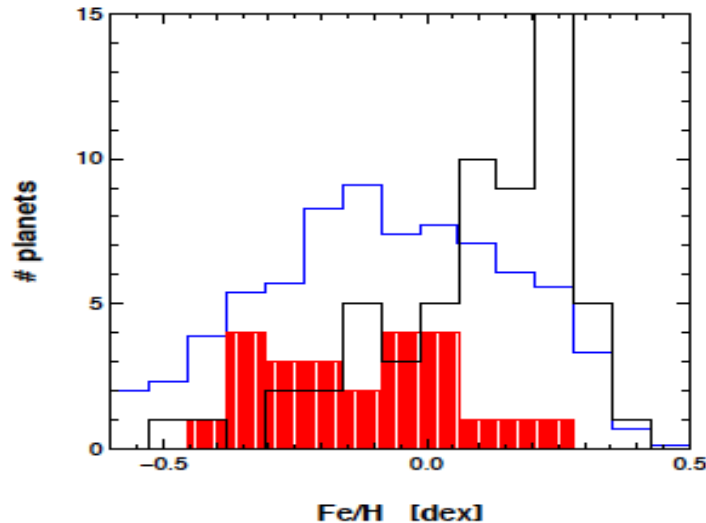
Small planets vs. large planets

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



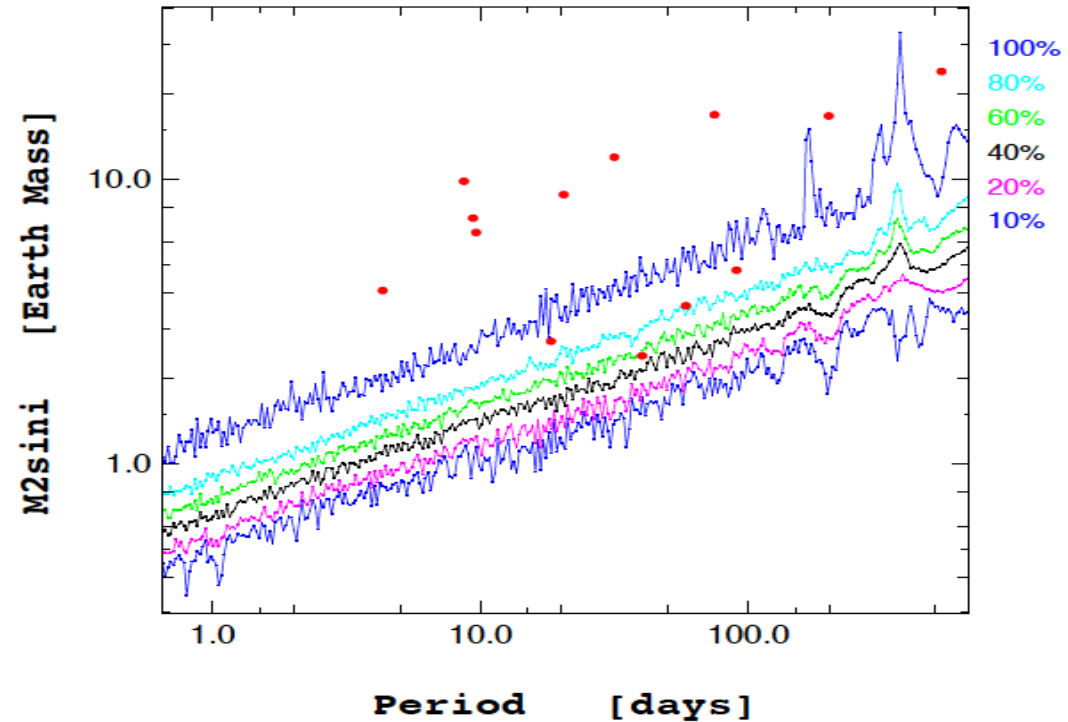
Small vs. Large

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

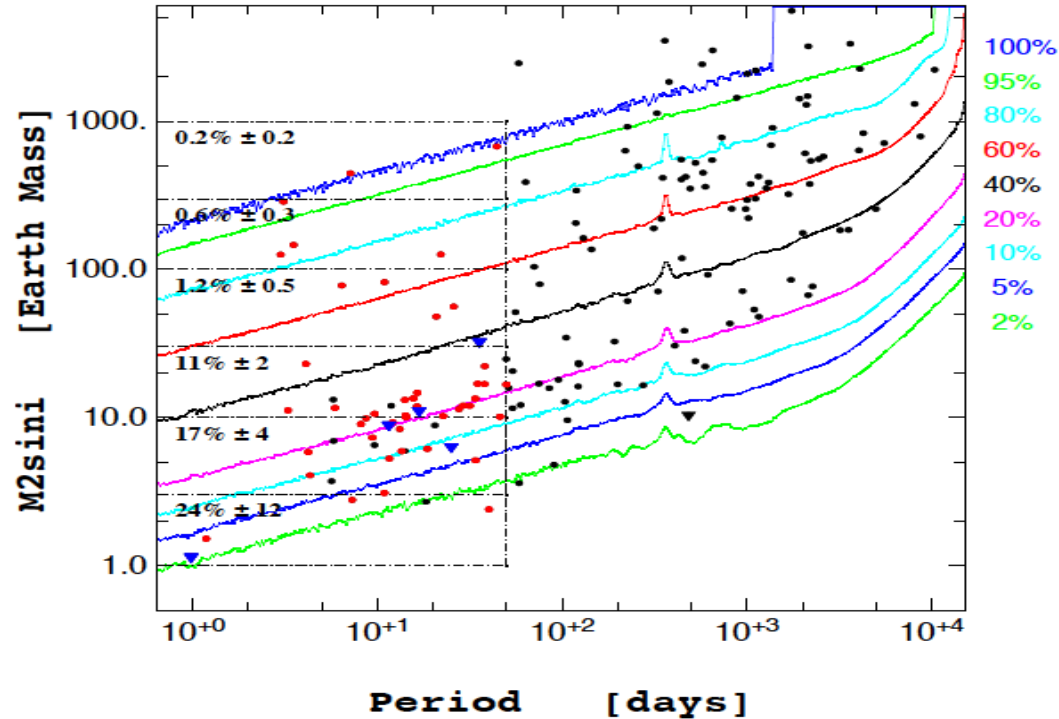


Small planets frequency

- 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!



We have pretty good chances!



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

Occurance rates papers

- https://exoplanetarchive.ipac.caltech.edu/docs/occurrence_rate_papers.html

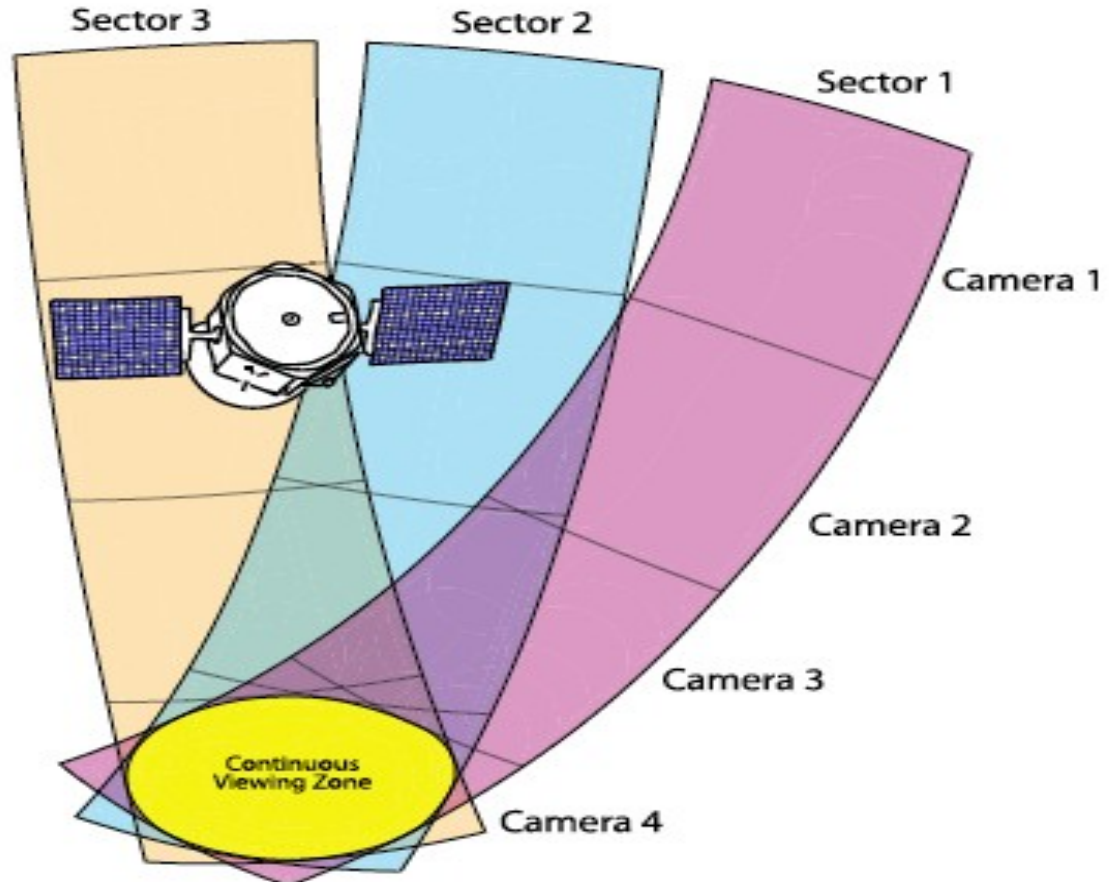
Outline

- Frequency of exoplanets
- Composition of exoplanets
- Interesting exoplanetary systems

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



TESS targets

- In total 3.2 million of TESS Catalogue stars will be observed
- About 2% of stars will have 12-13 sectors coverage

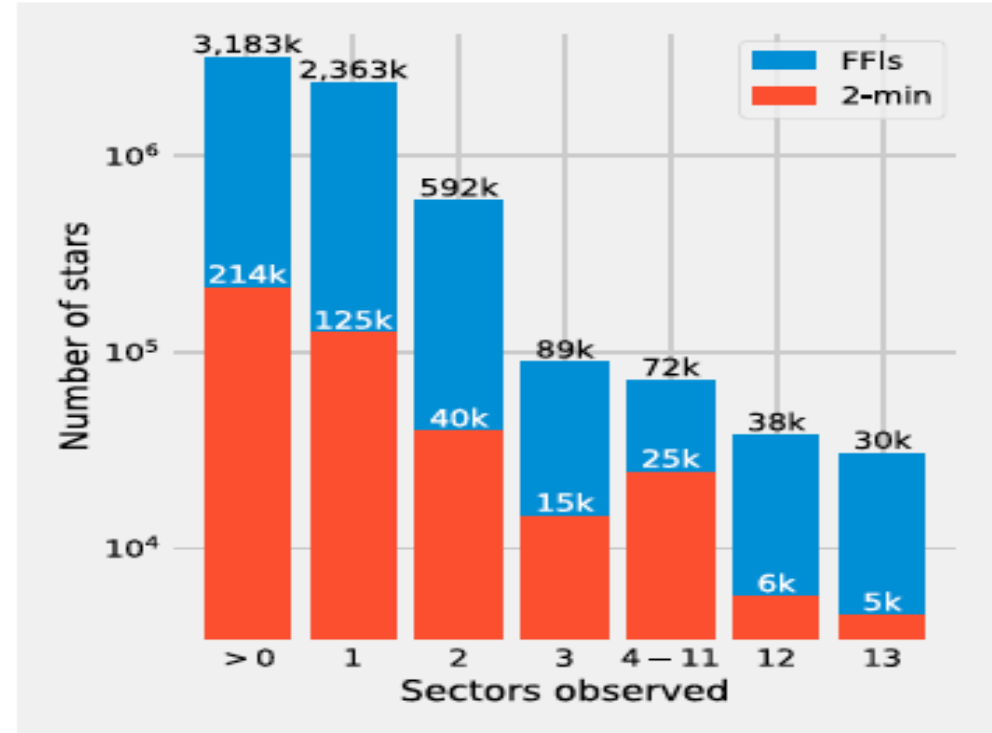


Figure 2. Number of CTL targets observed for a given number of 27.4-day sectors. FFI targets are shown in blue, and 2-minute cadence targets in red. In total, 3.2 million CTL targets are observed, of which 214,000 are observed at 2-minute cadence. Roughly three-quarters of targets are only observed for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

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

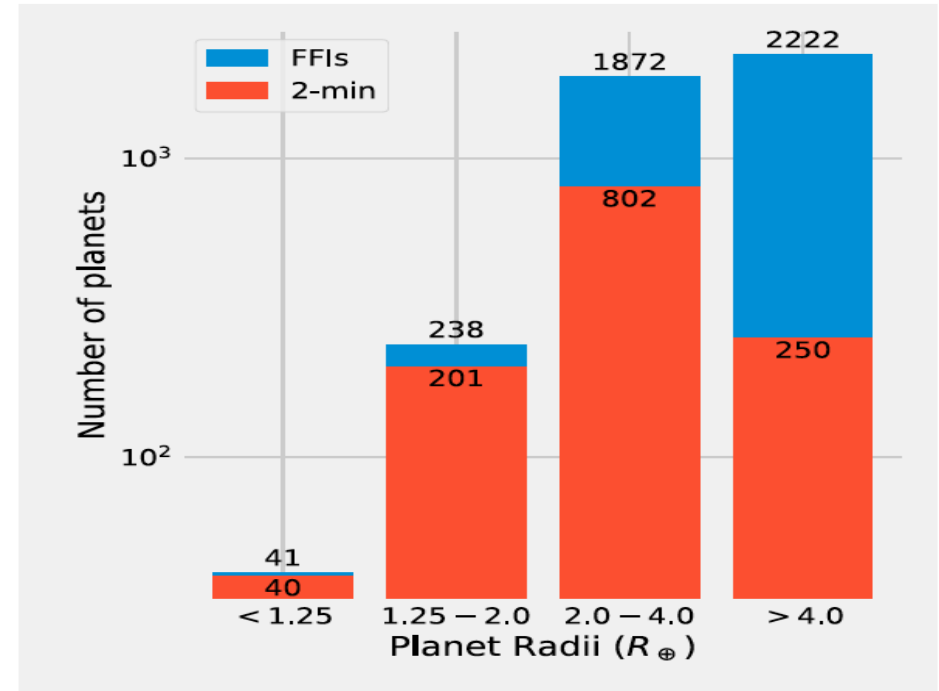


Figure 5. Our simulations predict that *TESS* will detect a total of about 4400 planets orbiting stars on the CTL, of which 1300 will be observed at 2-minute cadence. Roughly 40 Earth-sized planets will be found, almost all of which are on the 2-minute target list. A total of 1000 super-Earths and mini-Neptunes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

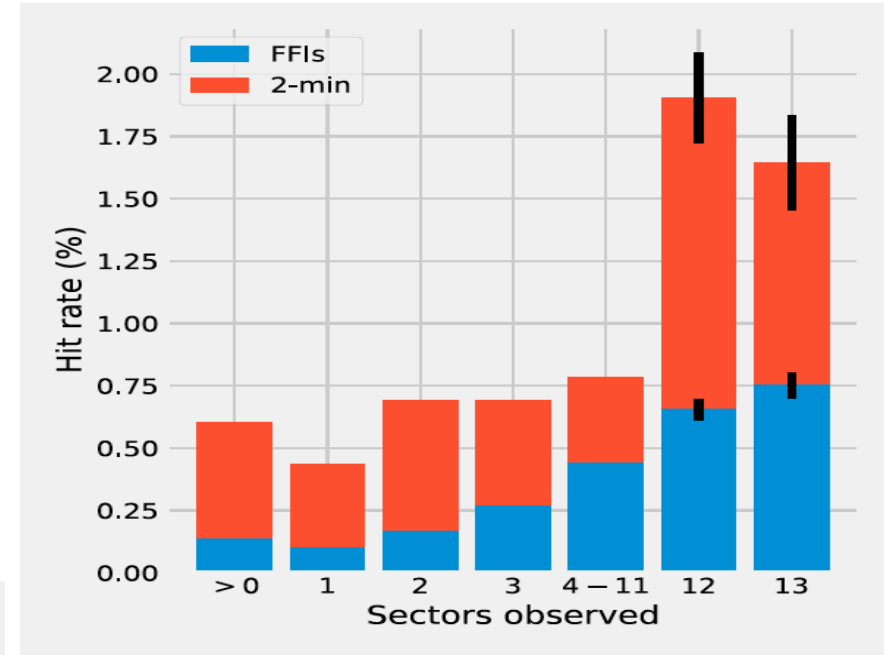
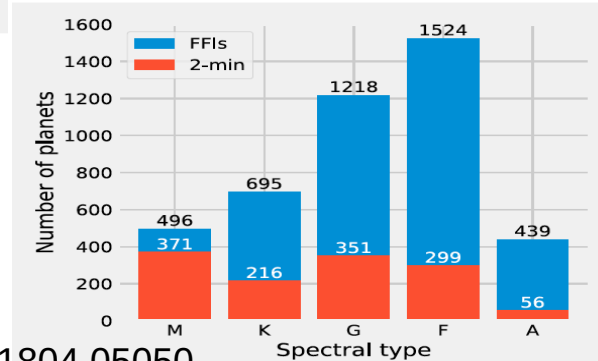
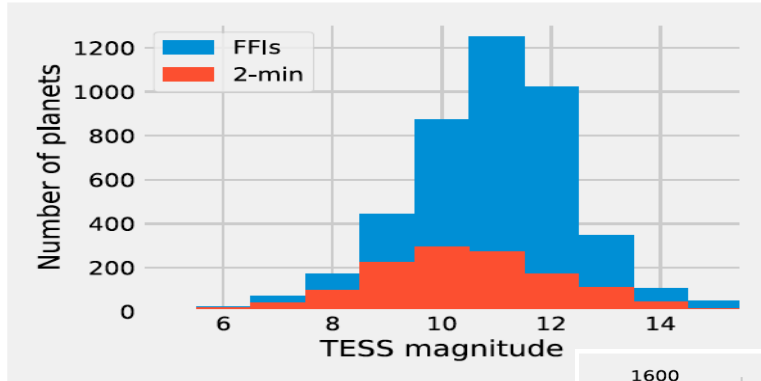


Figure 7. Ratio of stars observed to planets detected as a function of the number of sectors a star is observed for. The longer a star was observed, the higher probability a planet would be detected. Targets observed at 2-minute cadence are shown in red, while blue are FFI targets. For 2-minute cadence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

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 $R_p < 4 R_e$

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 $R_p < 4 R_e$

1701 false positives

329 confirmed TESS Planets

Last updated: 4/13/2023

TESS and others

Summary Counts

All Exoplanets	5539
Confirmed Planets Discovered by Kepler	2778
Kepler Project Candidates Yet To Be Confirmed	1984
Confirmed Planets Discovered by K2	548
K2 Candidates Yet To Be Confirmed	277
Confirmed Planets Discovered by TESS ¹	402
TESS Project Candidates Integrated into Archive ²	6977
Current date TESS Project Candidates at ExoFOP	6977
TESS Project Candidates Yet To Be Confirmed ³	4639

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.

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

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Different methods

Confirmed Exoplanet Statistics

Discovery Method	Number of Planets
Astrometry	3
Imaging	69
Radial Velocity	1068
Transit	4132
Transit timing variations	27
Eclipse timing variations	17
Microlensing	204
Pulsar timing variations	7
Pulsation timing variations	2
Orbital brightness modulations	9
Disk Kinematics	1

Transiting Exoplanets	4168
All Exoplanets	5539

Mass and radius

Counts by Radius

$R \leq 1.25 R_{\text{Earth}}$	520
$1.25 < R \leq 2 R_{\text{Earth}}$	1061
$2 < R \leq 6 R_{\text{Earth}}$	1794
$6 < R \leq 15 R_{\text{Earth}}$	603
$15 R_{\text{Earth}} < R$	199

Counts by Mass

$M \leq 3 M_{\text{Earth}}$	80
$3 < M \leq 10 M_{\text{Earth}}$	244
$10 < M \leq 30 M_{\text{Earth}}$	175
$30 < M \leq 100 M_{\text{Earth}}$	156
$100 < M \leq 300 M_{\text{Earth}}$	301
$300 M_{\text{Earth}} < M$	633

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
$R \leq 1.25 R_{\text{Earth}}$	941	23
$1.25 < R \leq 2 R_{\text{Earth}}$	1364	81
$2 < R \leq 6 R_{\text{Earth}}$	1839	156
$6 < R \leq 15 R_{\text{Earth}}$	314	18
$15 R_{\text{Earth}} < R$	154	10

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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K2 Mission Counts

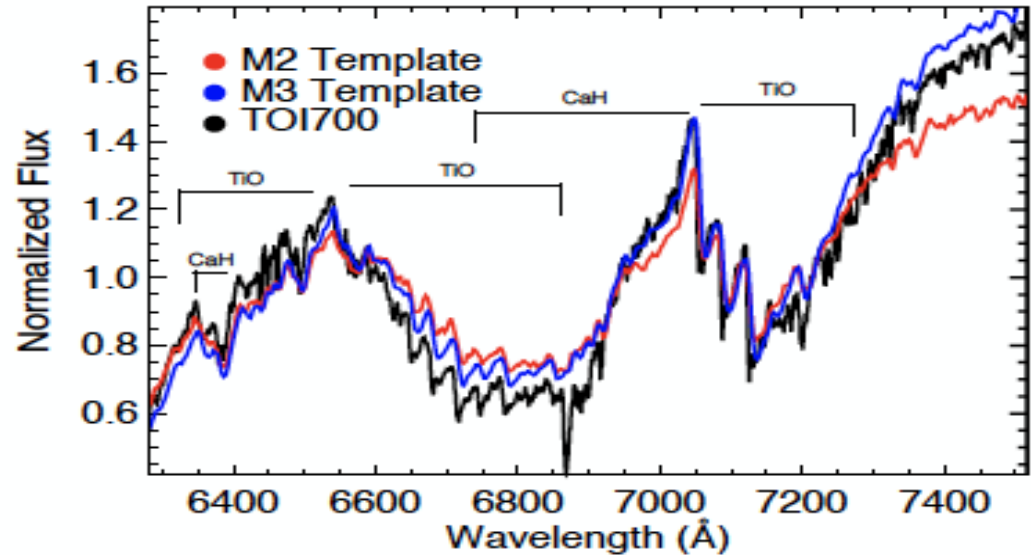
Confirmed Planets Discovered by K2 ¹	548
K2 Candidates Yet To Be Confirmed	977
K2 Campaign 9 Microlensing Events	

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

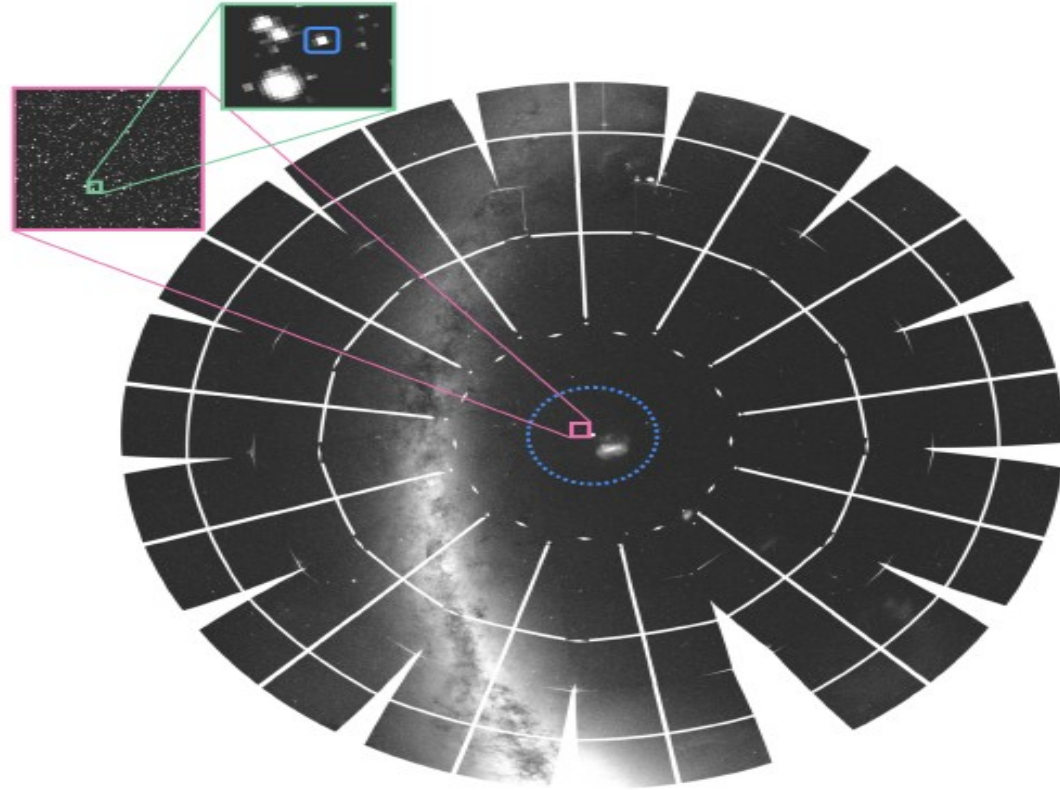
Some interesting examples

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

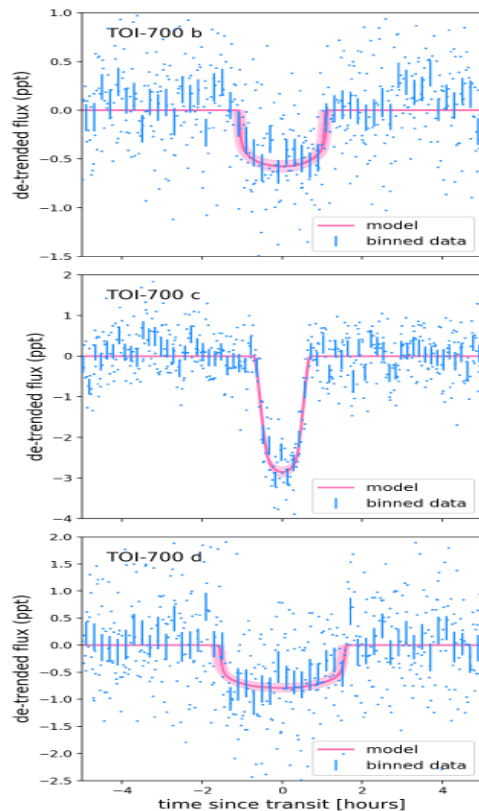


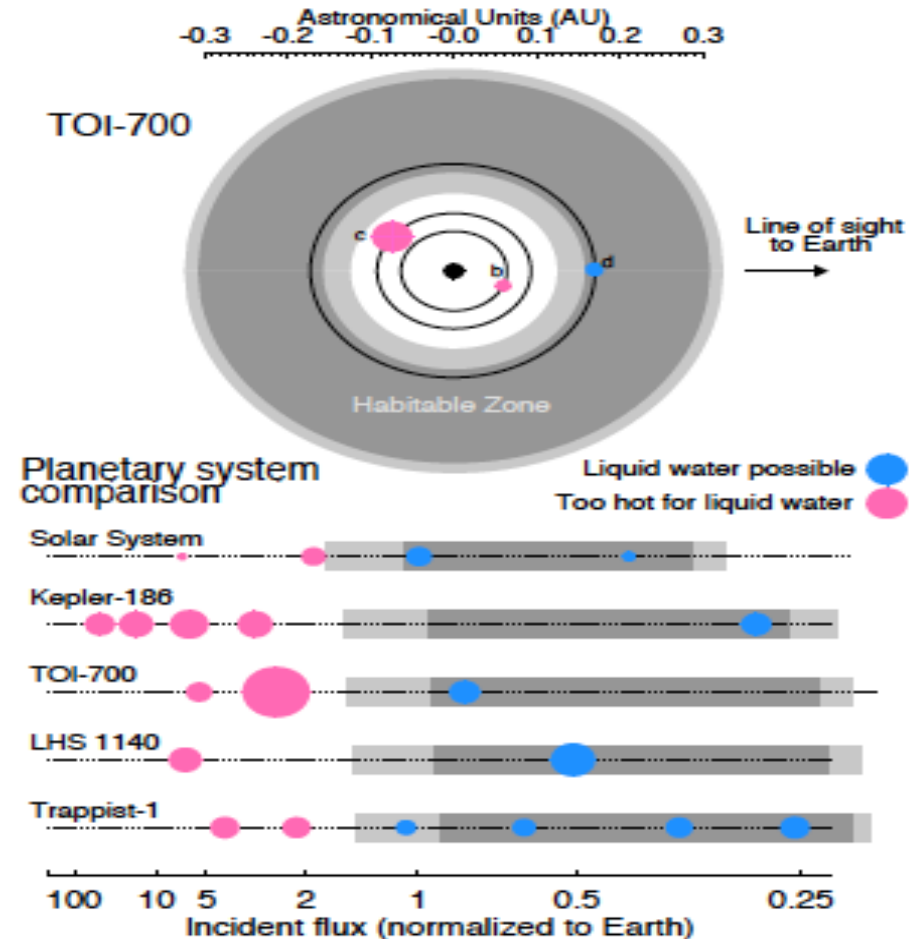
Figure 4. Phase-folded, light curves from 11 sectors of TESS data for planets TOI-700 b (upper panel), TOI-700 c (middle panel), and TOI-700 d (lower panel), along with the respective transit model (pink) showing the 1-sigma range in models consistent with the observed data. The corresponding transit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

Table 2. Planet Parameters

Parameter	Median	+1 σ	-1 σ
<i>Model Parameters</i>			
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
$\ln(\text{Period}[\text{days}])$	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
$\ln \text{Period} [\text{days}]$	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
$\ln \text{Period} [\text{days}]$	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
<i>Derived Parameters</i>			
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

TOI-700d inhabitant if the HZ

- TESS TOI-700d is inhabiting the Habitable Zone around TOI-700
- How would the atmosphere look like?



Small planets in the HZs

- TOI-700d is populating the group of 11
- There are only 11 exoplanets with radii $< 1.5R_{\text{Earth}}$
- Which are the best targets for upcoming characterization?

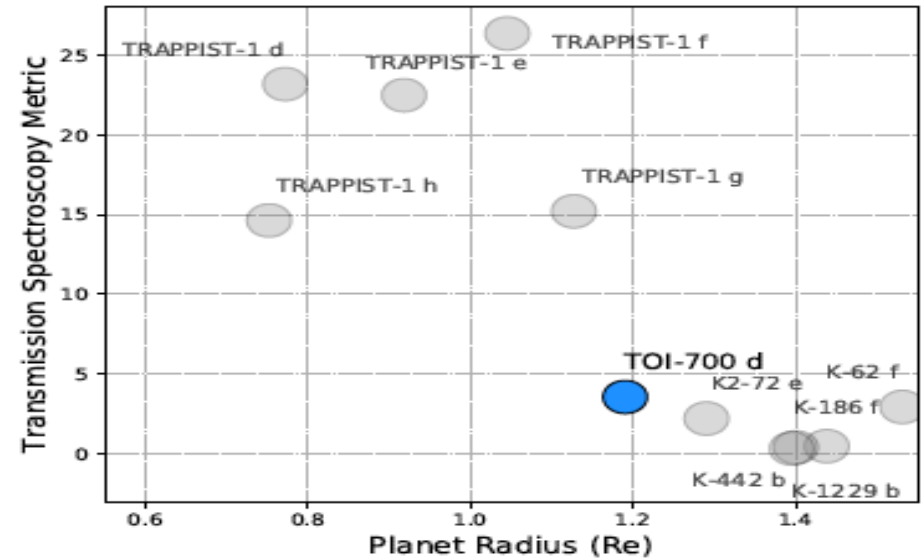
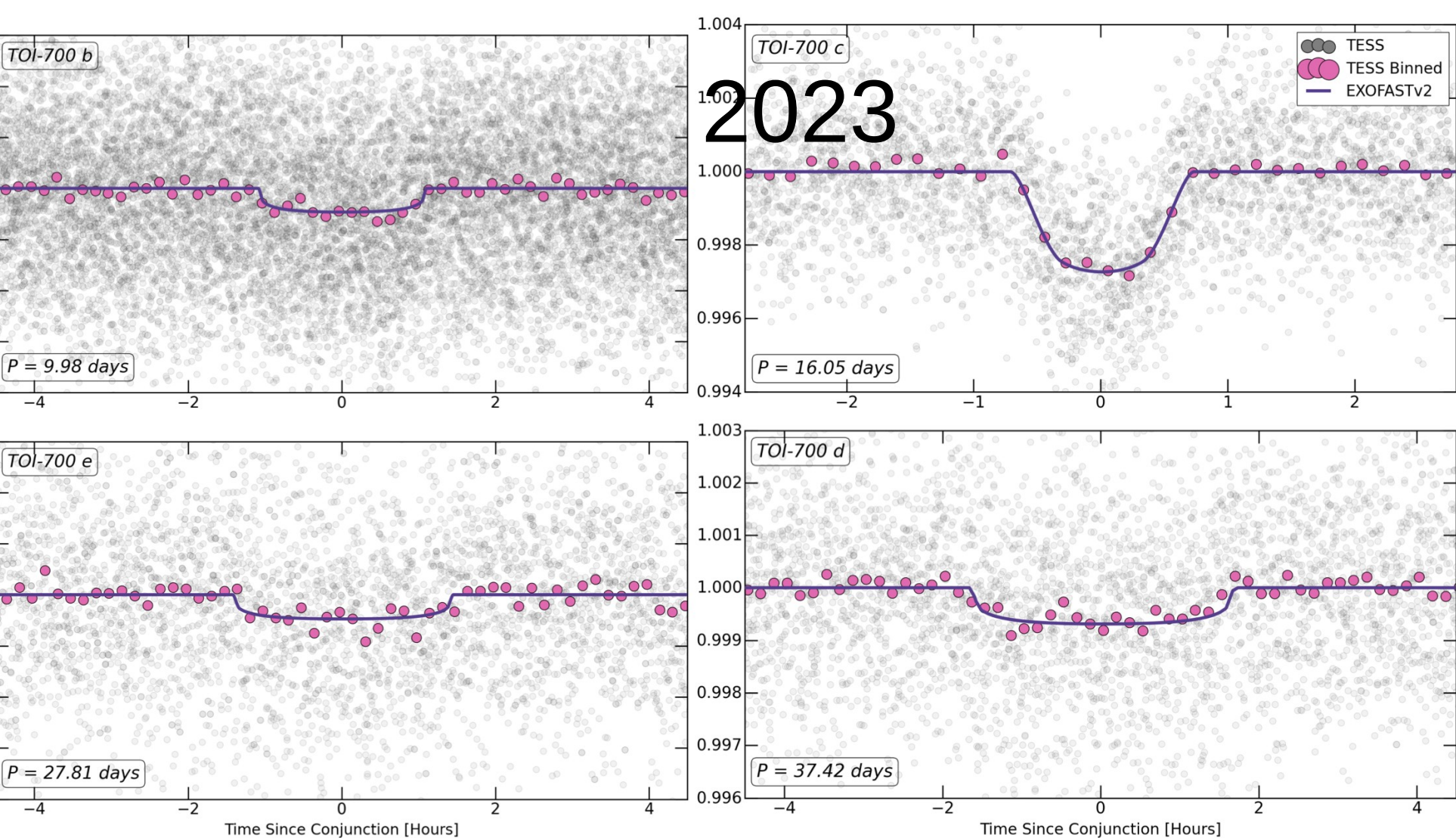


Figure 12. There are now 11 known exoplanets that have radii less than $1.5R_{\oplus}$ and orbit within their star's optimistic habitable zone (Kopparapu et al. 2013). Plotted are these planets' TSM values. The top candidates for atmospheric characterization orbit TRAPPIST-1. Beyond these, TOI-700 d 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
- However, the star is quiet in the UV!!!
- We have to wait for LUVVOIR? Or other missions?



HZs in 2023

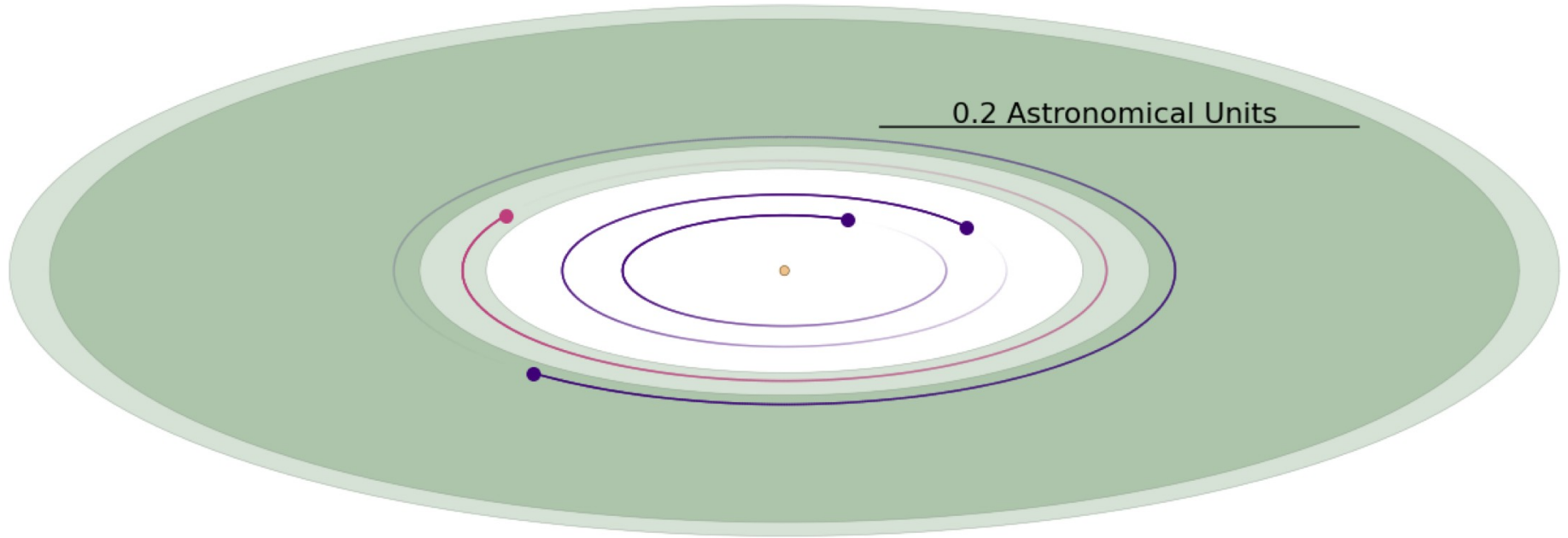
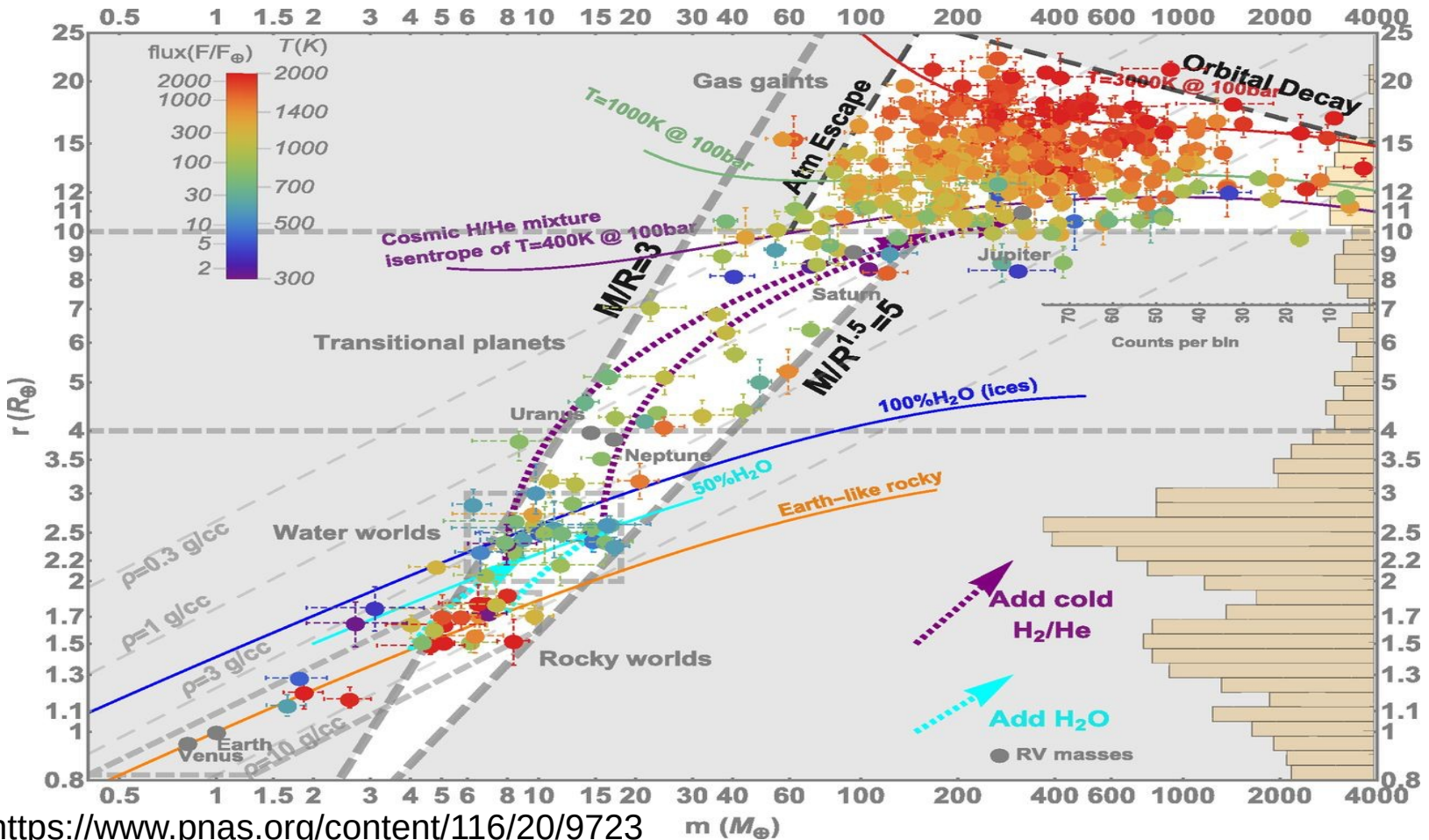


Figure 4. TOI-700 e (pink) resides in the Optimistic Habitable Zone (light green) around its host star in between the orbits of TOI-700 c and d. The Conservative Habitable Zone is shown in dark green, and planets b, c, and d (from inner to outer) are shown in indigo.

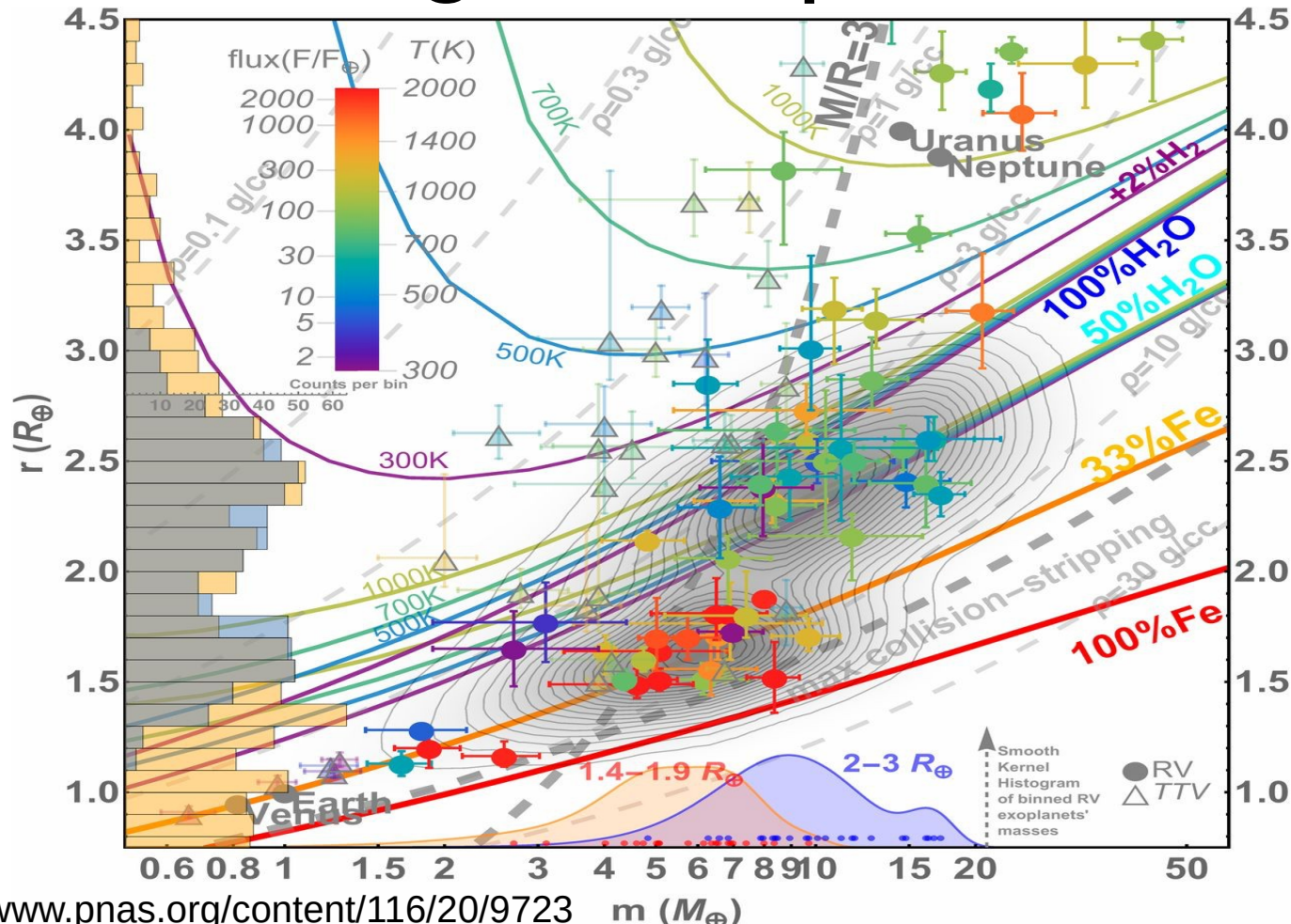
But what can we say more about exoplanetary structures?

- 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



Missing small planets?



And how do planets look like inside?

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

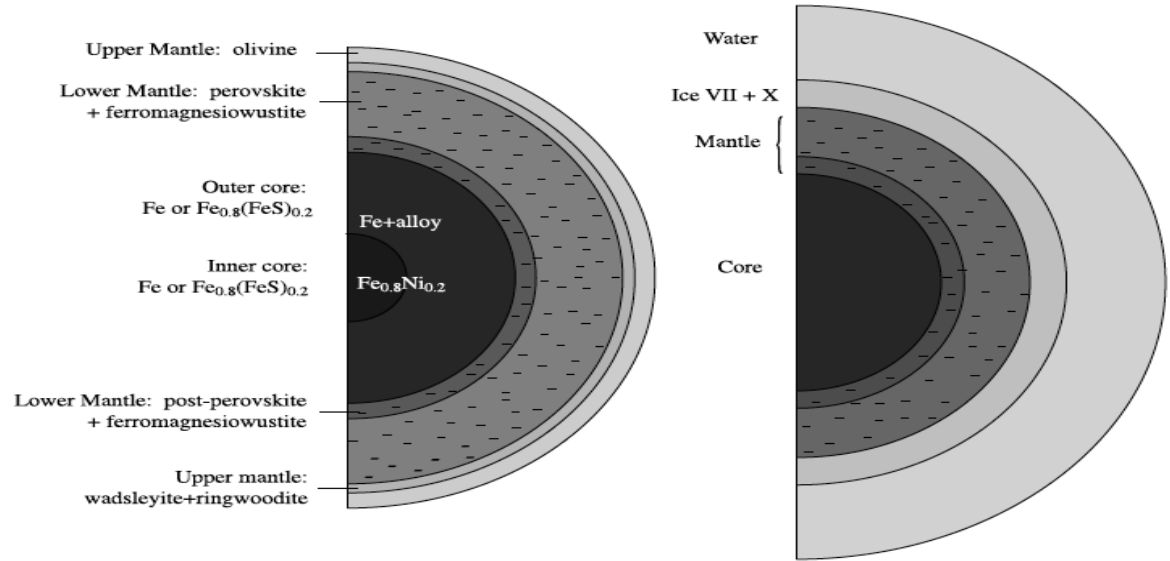
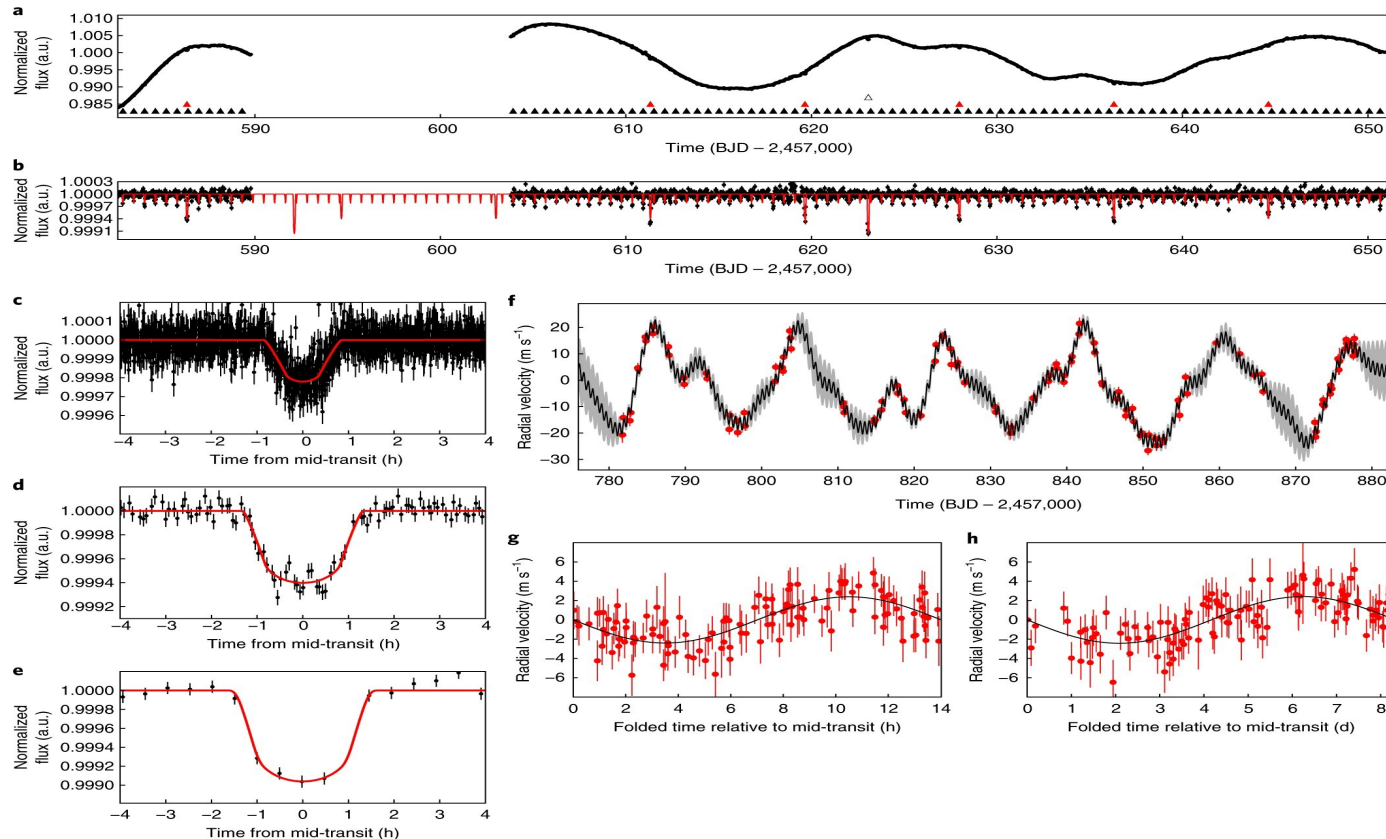
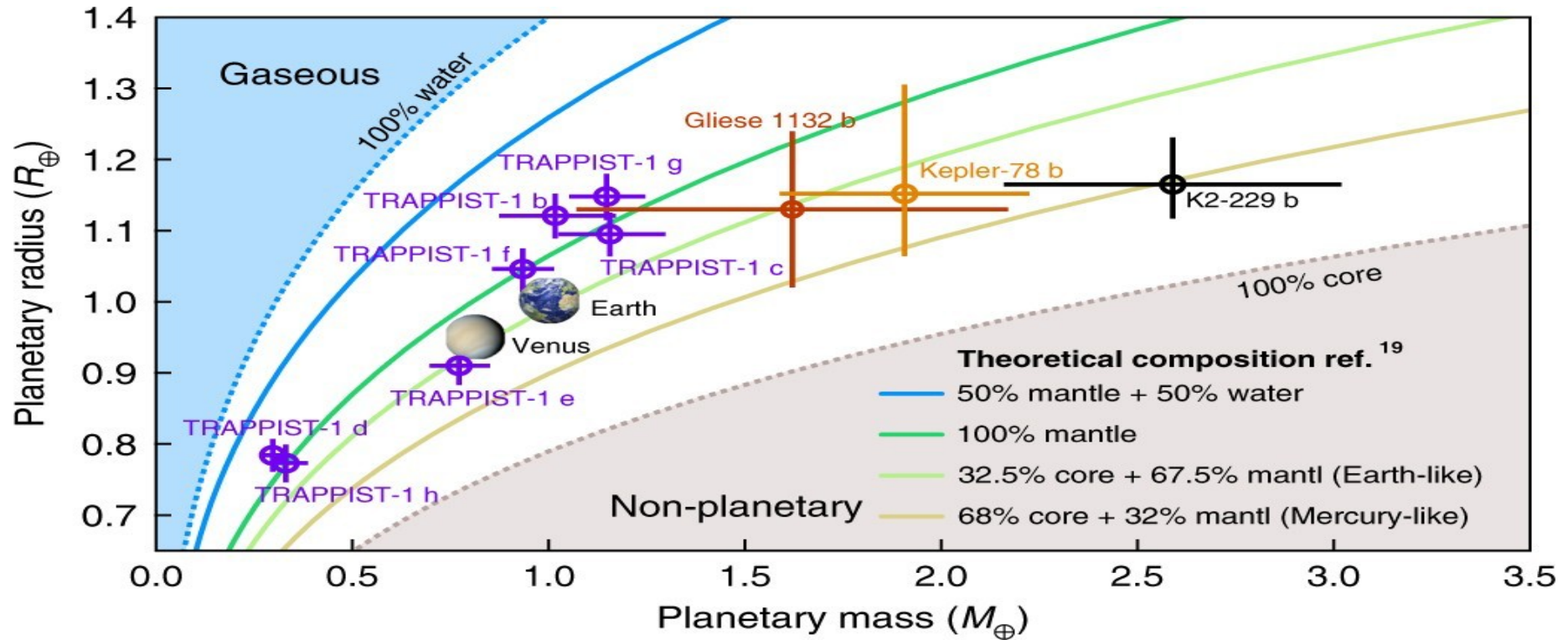


FIG. 1.—Schematic representation of the model. To calculate the internal structure of a super-Earth, we assume a similar composition to that of Earth (*left*): a dense core of pure Fe or Fe_{0.8}(FeS)_{0.2} as possible and likely cases (Earth has an outer core of Fe plus some unknown alloy, and the solid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



How close are we to 2nd Earth?



Solar system analogue

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

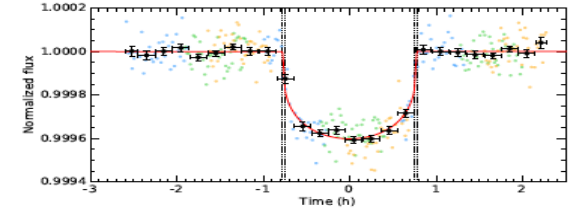
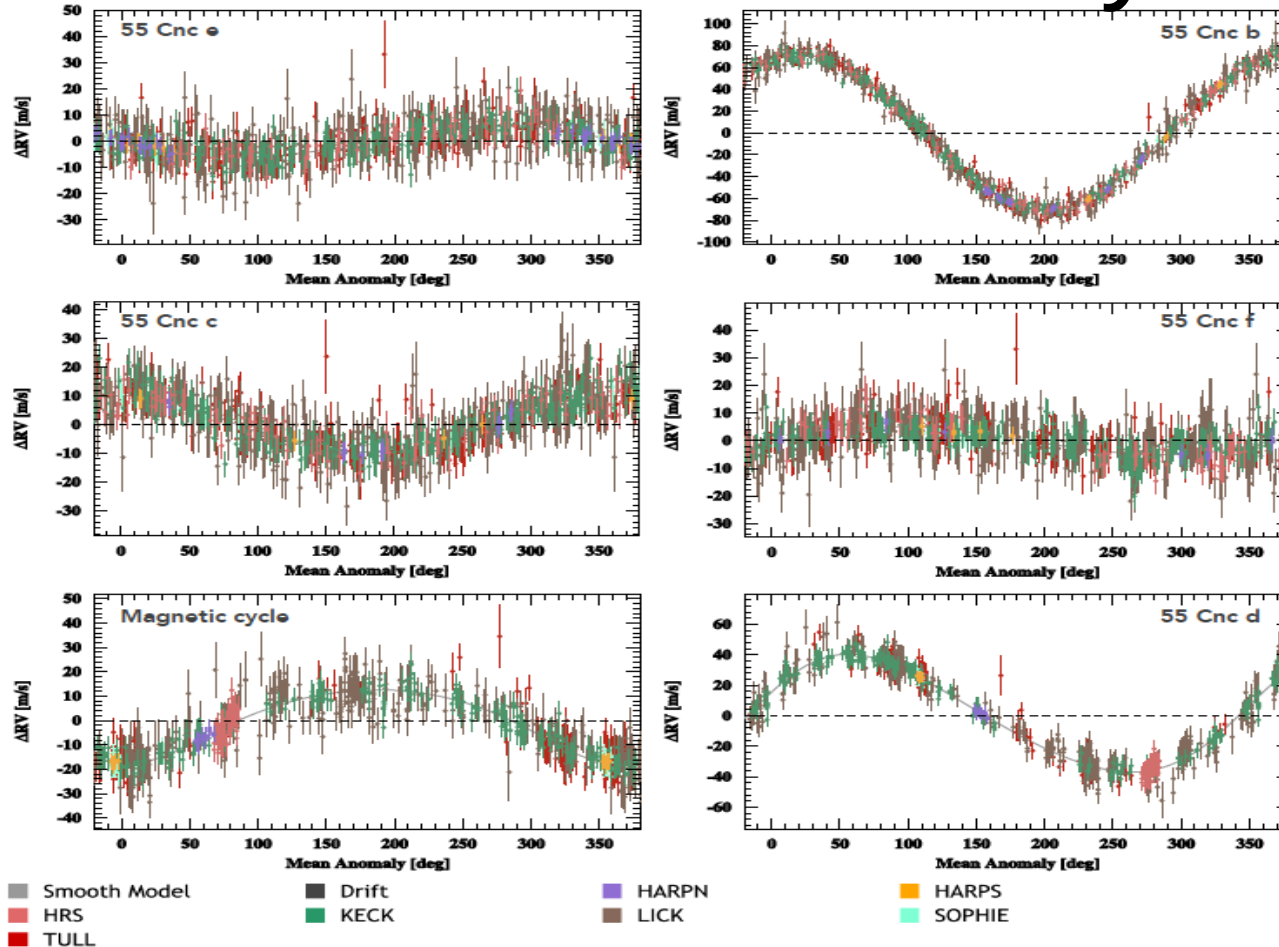


Fig. 10 STIS transit light curve of 55 Cnc e in the visible band. Fluxes have been corrected for the breathing and long-term variations in Visit A_{STIS} (blue), B_{STIS} (green), and C_{STIS} (orange). Black points show binned exposures. The red line is the best-fit transit light curve.

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]	$0.73654737^{+1.30 \cdot 10^{-6}}_{-1.44 \cdot 10^{-6}}$	$14.6516^{+0.0001}_{-0.0001}$	$44.3989^{+0.0042}_{-0.0043}$	$259.88^{+0.29}_{-0.29}$	$3822.4^{+76.4}_{-77.4}$	$5574.2^{+93.8}_{-88.6}$
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}]	$7.99^{+0.32}_{-0.33}$	—	—	—	—	—
$M \cdot \sin i$	[M _{Jup}]	—	$0.8036^{+0.0092}_{-0.0091}$	$0.1611^{+0.0040}_{-0.0040}$	$0.1503^{+0.0076}_{-0.0076}$	—	$3.12^{+0.10}_{-0.10}$
$M \cdot \sin i$	[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>



Habitable Zone

You are
41 light-years
from Earth

55 Cancri

5 planets orbiting a K-type star, 41 light-years from Earth.

Uranus

Mars

Earth

Mercury

Venus

55 Cancri f

Jupiter

55 Cancri d

VIEW



Planet



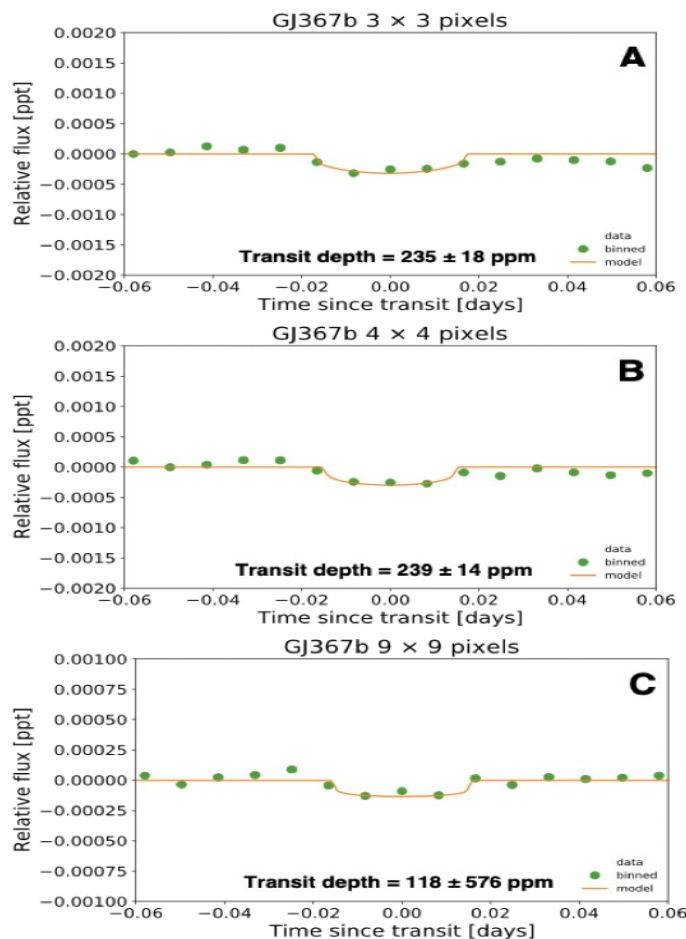
System



Star

COMPARE TO OUR SOLAR SYSTEM

Exo-Mars



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_r (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 ($^\circ$)	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

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

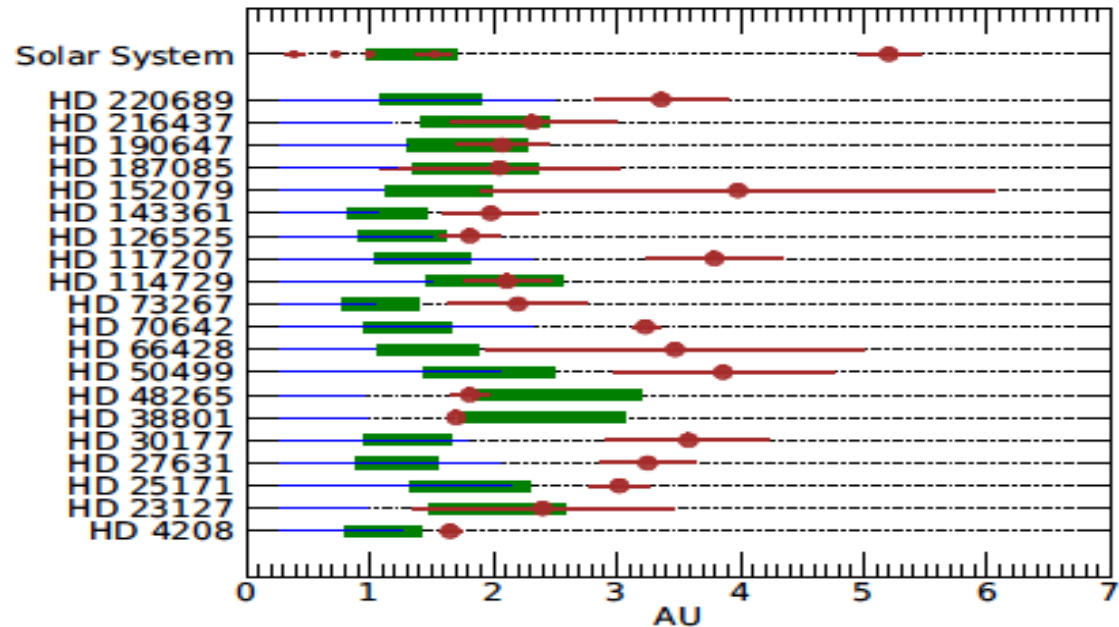


Fig. 1. Overview of the sample systems and a comparison with the inner Solar System's architecture. The sample's known giant planets are shown as brown circles, a thin brown line from periastron to apoastron showing their orbit's span. Each system's habitable zone, computed using the model detailed in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

The exo-frequency from HARPS

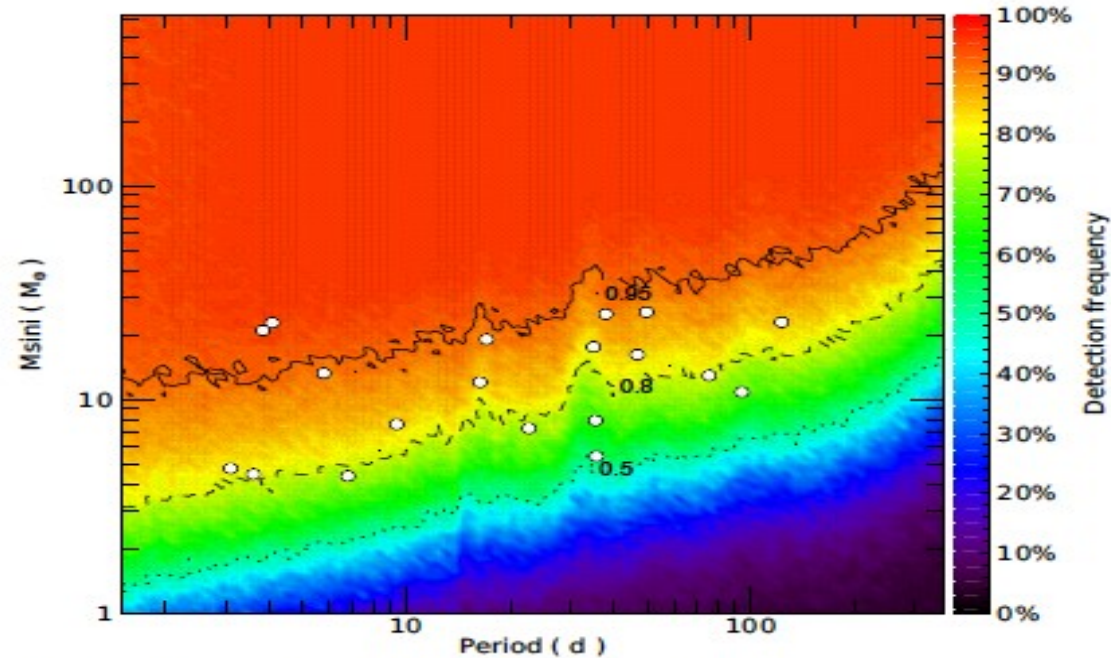


Fig. 23. Color-coded HARPS precision detection frequency map for the whole 20-systems sample studied in this paper, period ranging from one day to one year and masses ranging from $1 M_{\oplus}$ to $2 M_J$. The detection frequency levels of 50%, 80% and 95% are respectively shown as dotted, dashed and 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>

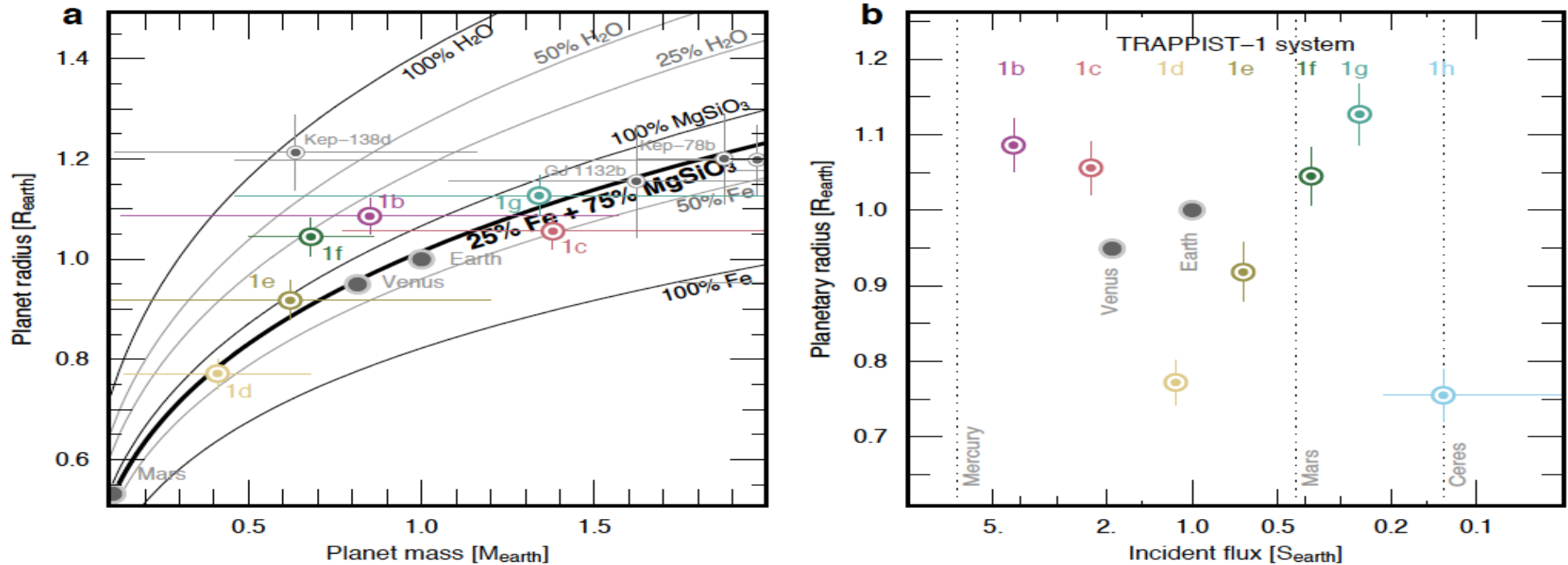
The Trappist-1

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_* [M_\odot] ^a	0.0802±0.0073						
Radius R_* [R_\odot] ^a	0.117±0.0036						
Density ρ_* [ρ_\odot]	50.7 ^{+1.2} _{-2.2} ρ_\odot						
Luminosity L_* [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 $(R_p/R_*)^2$ [%]	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_*]	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} _{-0.62}	28.17 ^{+0.83} _{-0.87}	37.1±1.1	45.1±1.4	63 ⁺²⁷ ₋₁₂
Scale parameter a/R_*	20.50 ^{+0.16} _{-0.31}	28.08 ^{+0.22} _{-0.42}	39.55 ^{+0.20} _{-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 ^{+0.091} _{-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	-

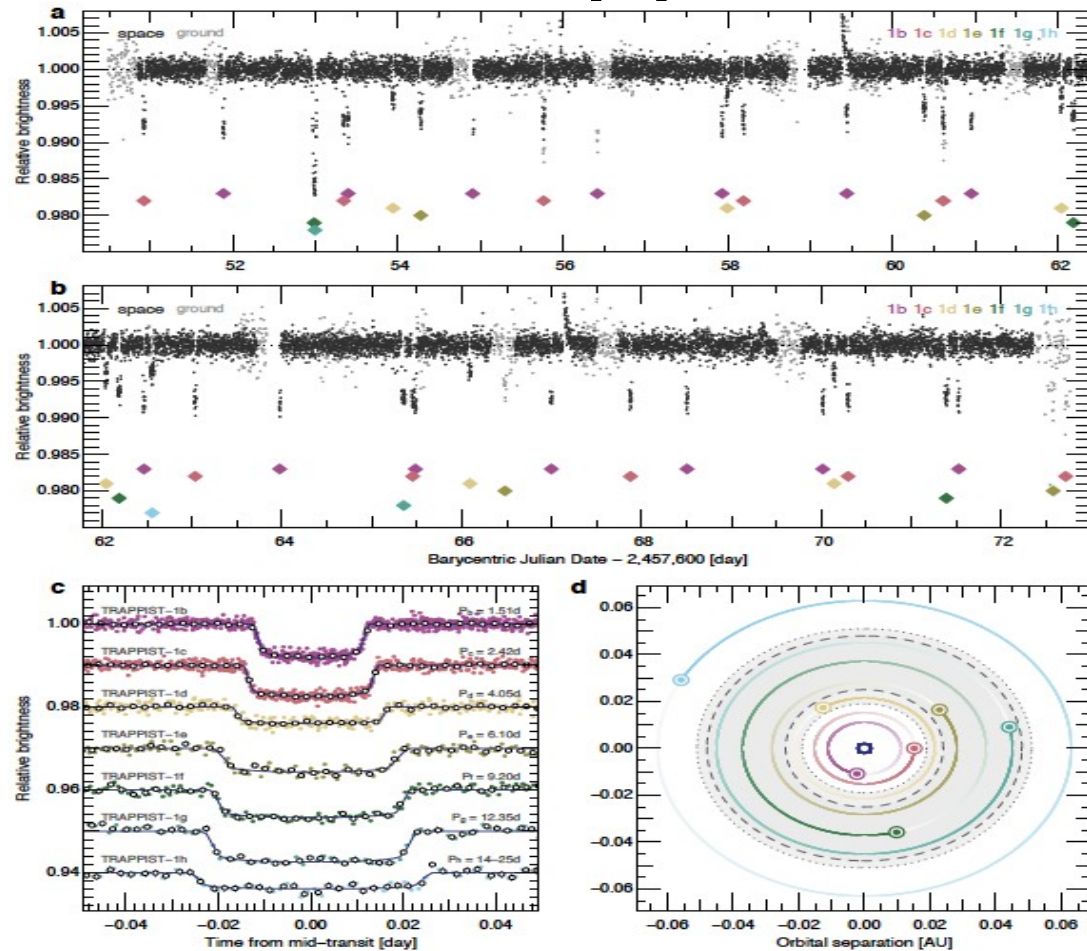
- Gillon et al 2017 - <https://arxiv.org/pdf/1703.01424.pdf>

The Trappist-1

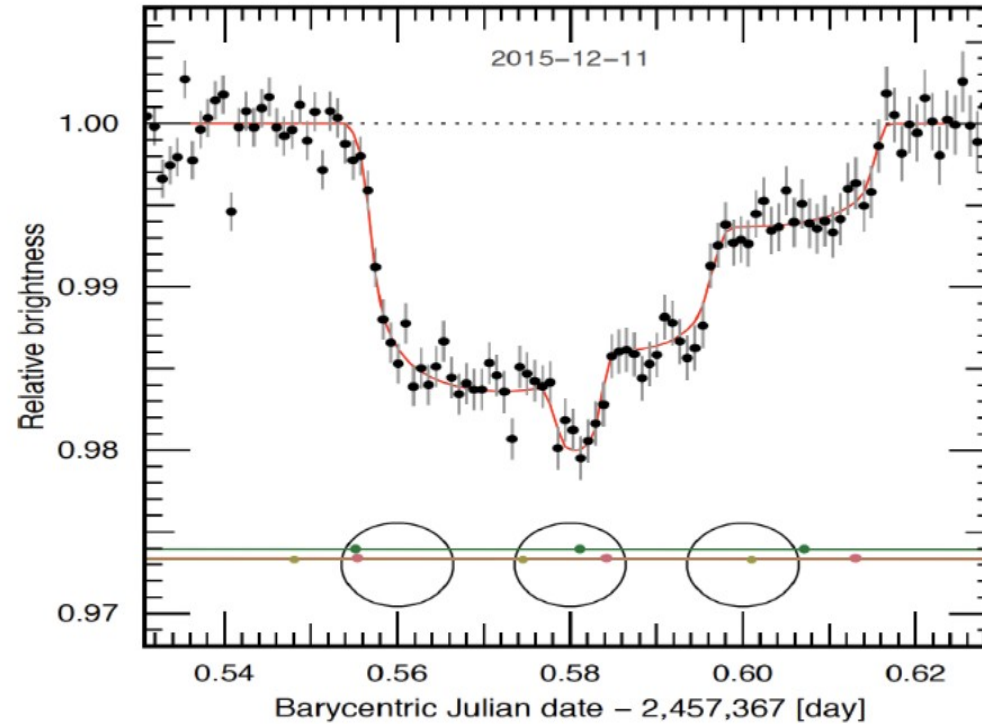


- Gillon et al 2017 - <https://arxiv.org/pdf/1703.01424.pdf>

The Trappist-1

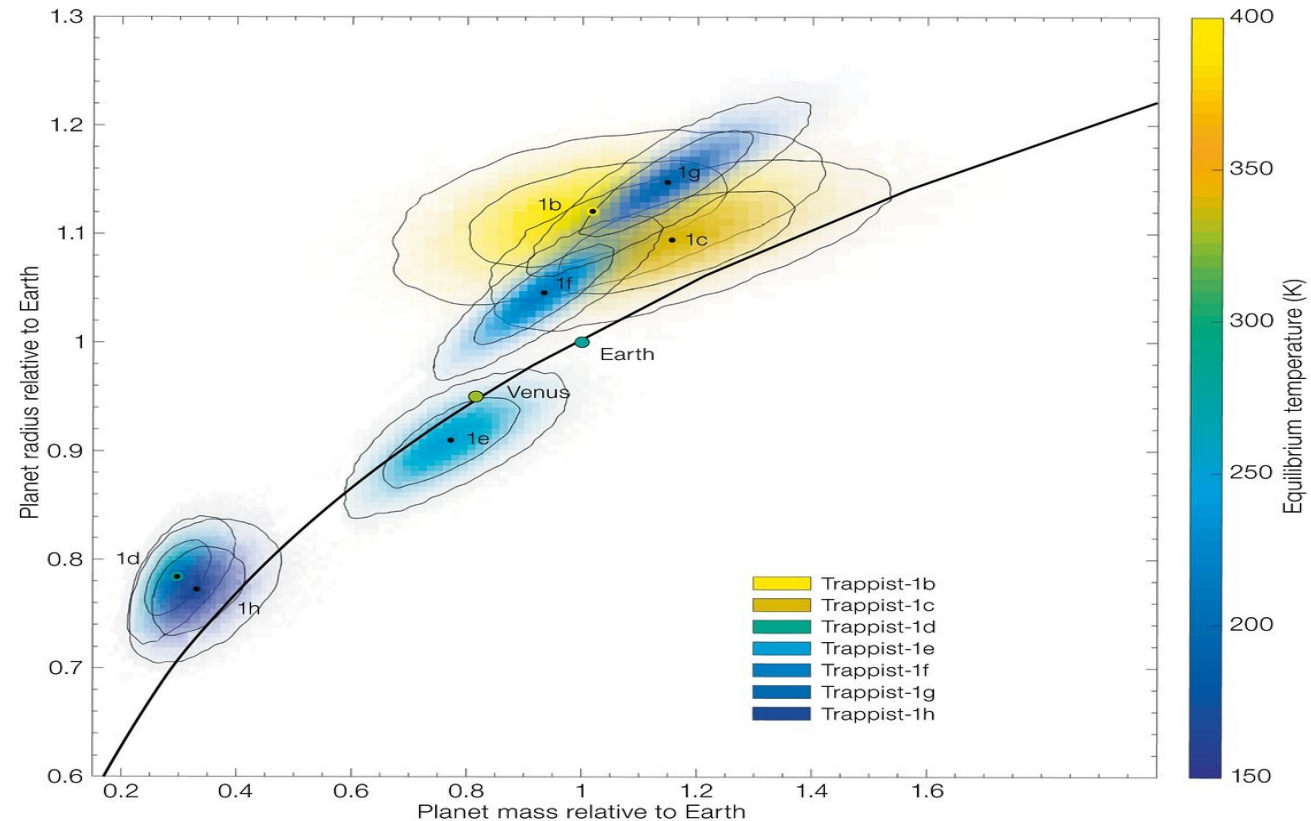


The Trappist-1

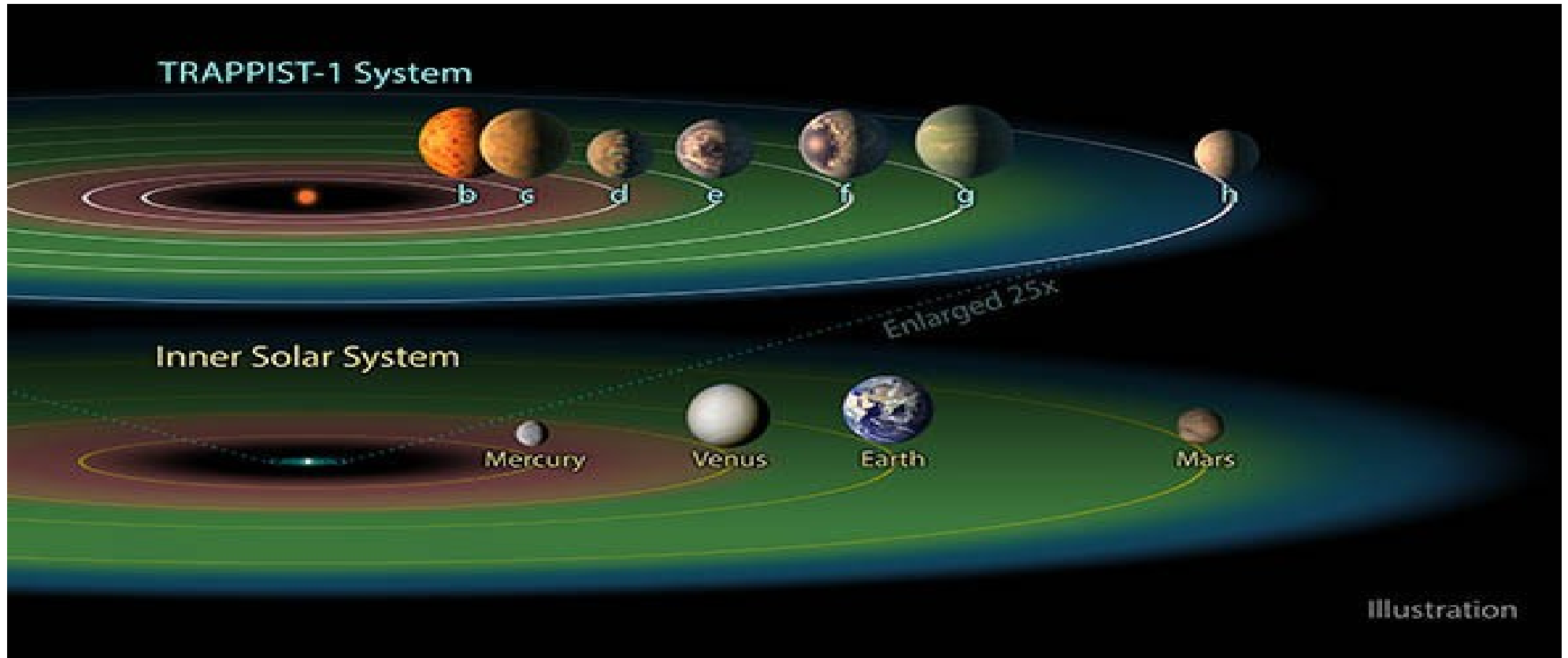


- Gillon et al 2017 - <https://arxiv.org/pdf/1703.01424.pdf>

Composition of Trappist 1 planets



Trappist 1 HZ



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

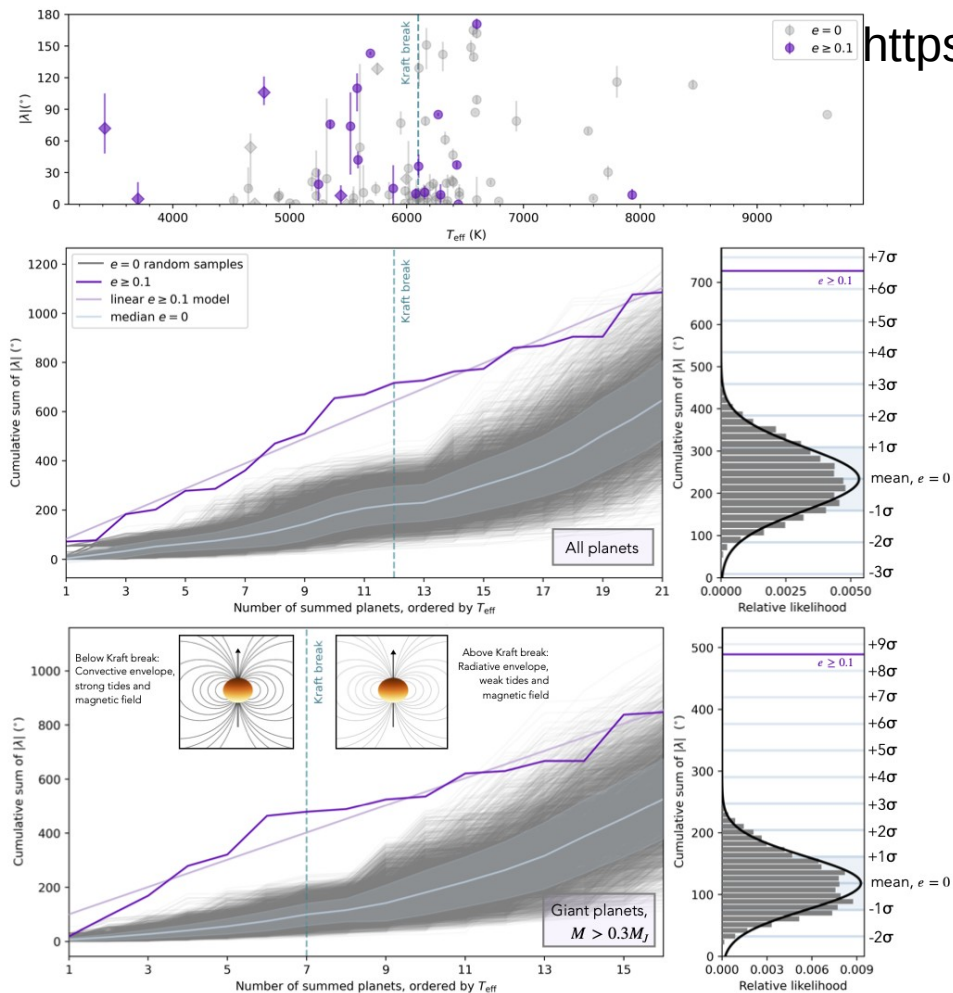


Figure 1. Comparison of the obliquity distributions for stars hosting exoplanets on circular vs. eccentric orbits. Top: Full sample of spin-orbit angles included in this study. Planets with $M < 0.3M_J$ are shown with diamond markers. The data behind this panel is available together with all other planet 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.

A slide from the last lecture

- Rossiter - McLaughlin effect

$$A_{\text{RM}} \simeq \frac{2}{3} D v \sin i_{\star} \sqrt{1 - b^2}$$

$$D = (R_p/R_{\star})^2$$

- b – impact param., $v \sin i_{\star}$ stellar rotational velocity
- <https://arxiv.org/pdf/1709.06376.pdf>