TESS Update

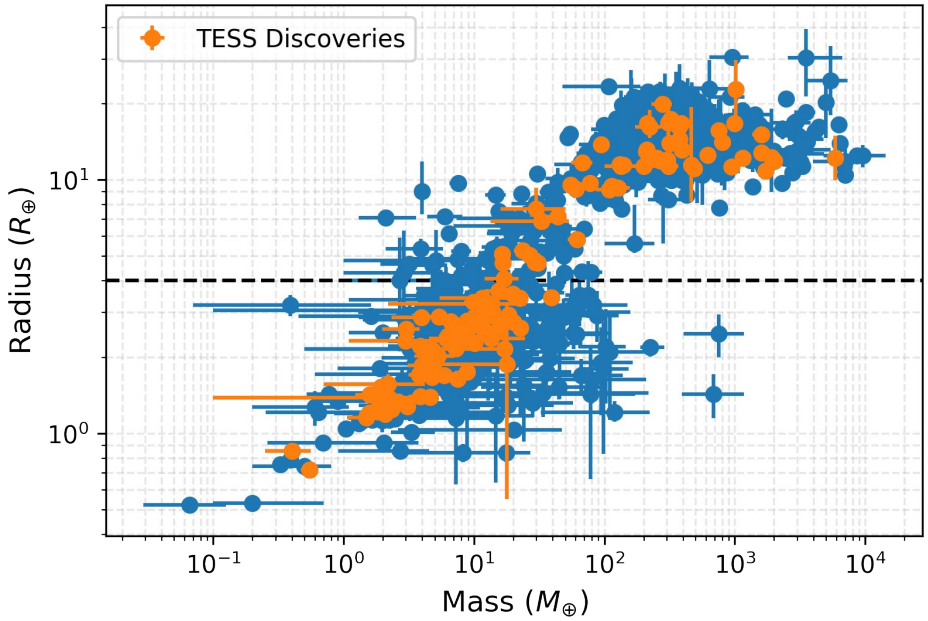
Michelle Kunimoto
TESS Postdoctoral Associate,
MIT Kavli Institute

ExoPAG 25
January 12, 2022

NASA.gov

Mission Highlights

- TESS achieved the main goal of its Primary Mission: ***to detect 50 planets smaller than Neptune and measure their masses***

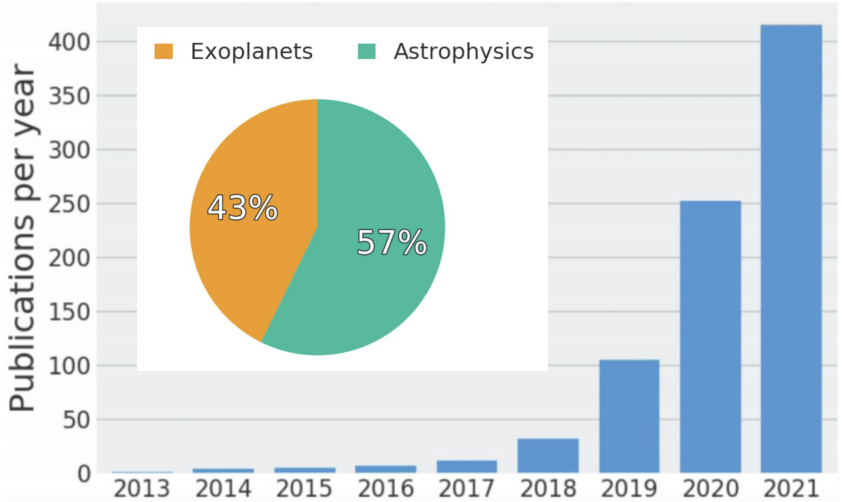


Parameters from Planetary Systems Composite Data Table (NASA Exoplanet Archive)

Mission Highlights

- TESS achieved the main goal of its Primary Mission: ***to detect 50 planets smaller than Neptune and measure their masses***

- ~1 publication pertaining to TESS per day

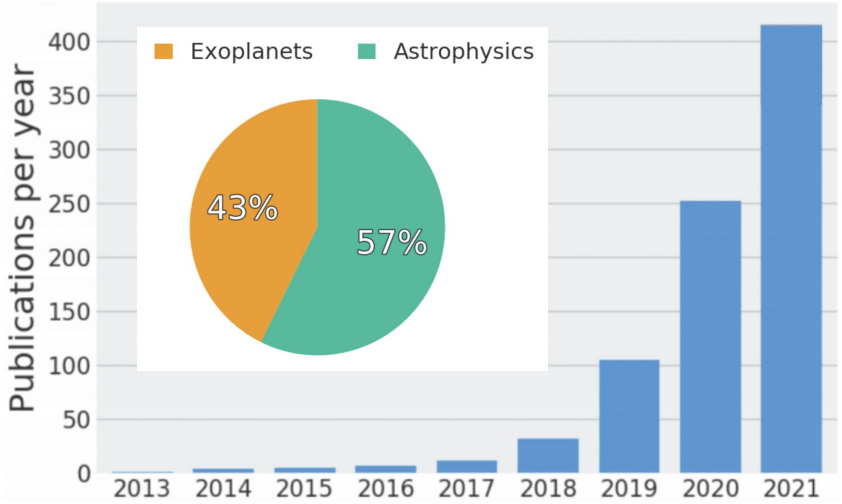


https://heasarc.gsfc.nasa.gov/docs/tess/publications.html

Mission Highlights

- TESS achieved the main goal of its Primary Mission: ***to detect 50 planets smaller than Neptune and measure their masses***
- ~1 publication pertaining to TESS per day

~1000 publications in 2022?



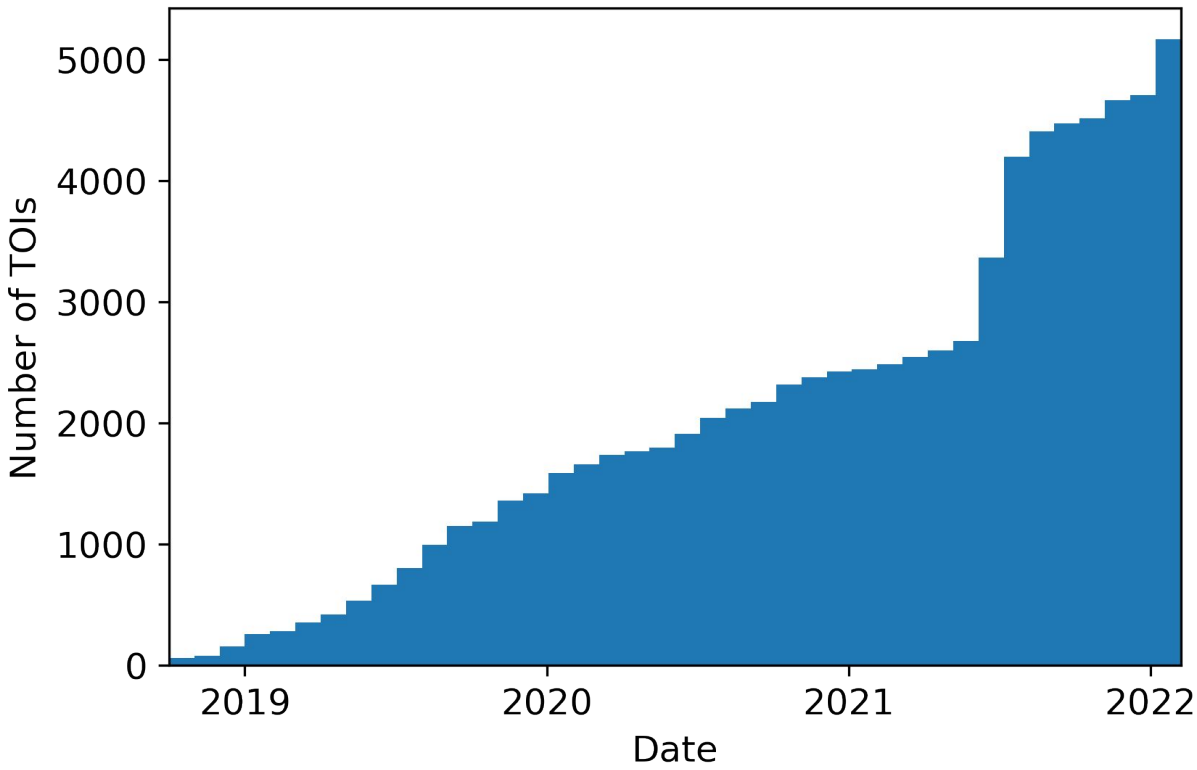
https://heasarc.gsfc.nasa.gov/docs/tess/publications.html

Mission Highlights

- TESS achieved the main goal of its Primary Mission: ***to detect 50 planets smaller than Neptune and measure their masses***
- ~1 publication pertaining to TESS per day
- TESS Science Conference II (August 2021): 900 registered participants!

tsc.mit.edu/2021

5000+ TESS Objects of Interest!

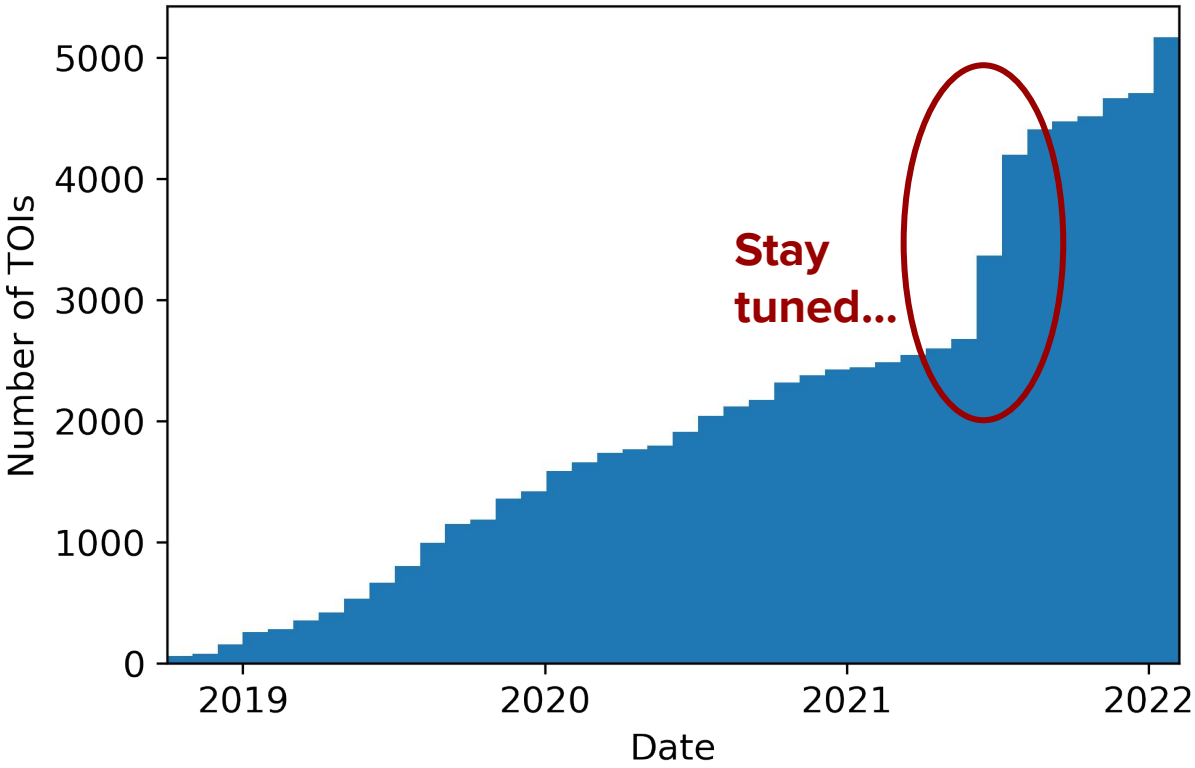


5164 TOIs

4371 TOIs (false positives removed)

- ❏ 1313 TOIs with Rp < 4 $R_\oplus$
- ❏ 161 Confirmed Planets

5000+ TESS Objects of Interest!



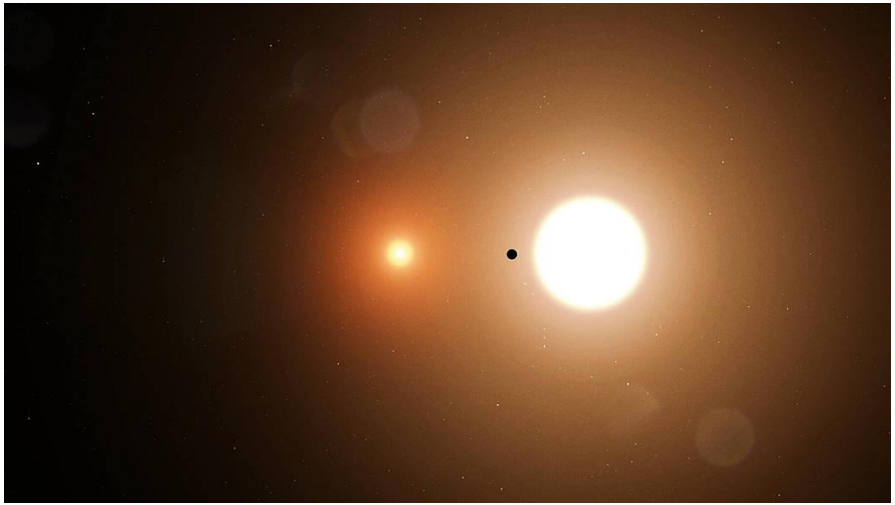
5164 TOIs

4371 TOIs (false positives removed)

- ❏ 1313 TOIs with Rp < 4 $R_\oplus$
- ❏ 161 Confirmed Planets

Exoplanet Highlights

- 125 planets and planet candidates in multi-planet systems
- Exotic exoplanets
  - circumbinary planets
  - hot Jupiters with companions
  - planets in the Neptune desert
  - planets around young stars



NASA

Exoplanet Highlights

- ❏ 125 planets and planet candidates in multi-planet systems
- ❏ Exotic exoplanets
  - ❏ circumbinary planets
  - ❏ hot Jupiters with companions
  - ❏ planets in the Neptune desert
  - ❏ planets around young stars
- ❏ Prime Mission TESS Objects of Interest Catalog released (Guerrero et al. 2021)

THE ASTROPHYSICAL JOURNAL
SUPPLEMENT SERIES

The TESS Objects of Interest Catalog from the TESS Prime Mission

Natalia M. Guerrero[1], S. Seager[1,2,3], Chelsea X. Huang[53,1], Andrew Vanderburg[54,4,5], Aylin Garcia Soto[6], Ismael Mireles[1], Katharine Hesse[1], William Fong[1], Ana Glidden[1,2], Avi Shporer[1]
+ Show full author list

The Astrophysical Journal Supplement Series, Volume 254, Number 2
Citation Natalia M. Guerrero *et al* 2021 *ApJS* **254** 39

Other Astrophysics

Solar System Objects

Thousands in 3.5 years

- ❑ occultation events
- ❑ comets
- ❑ asteroids
- ❑ trans-neptunian objects
- ❑ SDOs/Centaurs

Explosive & Variable Extragalactic Sources

Thousands in 3.5 years

- ❑ supernovae
- ❑ AGNs
- ❑ blazars
- ❑ quasars
- ❑ tidal-disruption events
- ❑ gamma-ray bursts
- ❑ kilonovae
- ❑ hypernovae

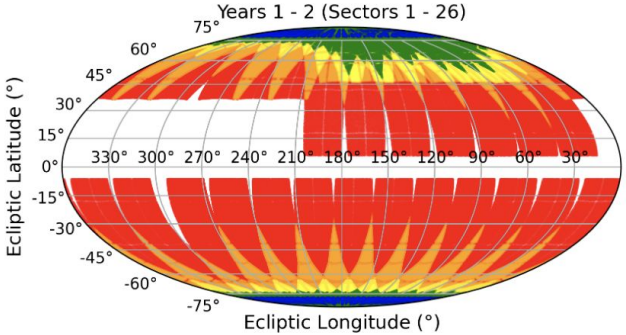
Variable Stars

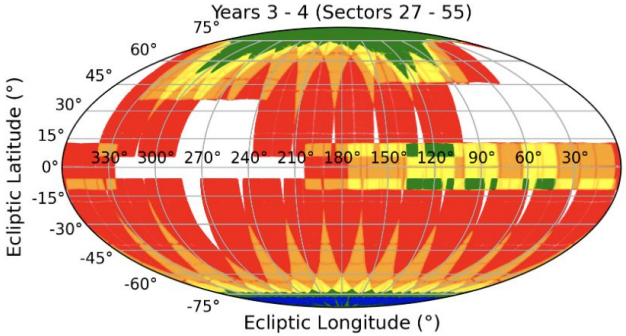
Millions in 3.5 years

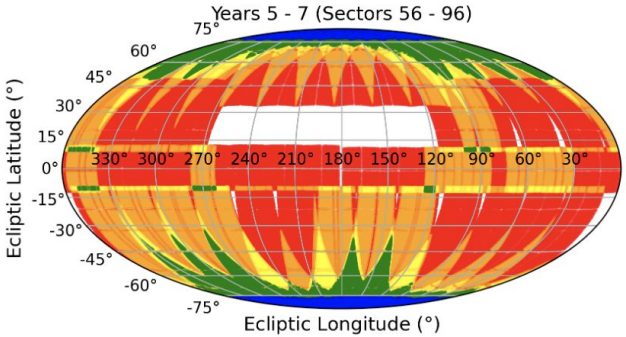
- ❑ asteroseismology
- ❑ brown dwarfs
- ❑ eclipsing binaries
- ❑ flare stars
- ❑ cepheids
- ❑ emission line stars
- ❑ RR Lyrae stars
- ❑ T Tauri stars
- ❑ neutron stars
- ❑ white dwarfs
- ❑ WD oscillations
- ❑ young stellar objects

Proposal for Extended Mission 2

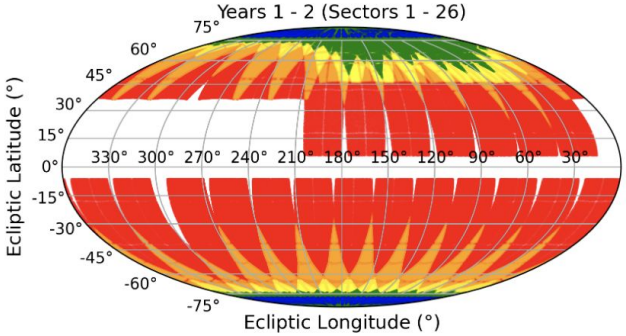
- Three years: Sectors 56 - 96
- FFI cadence improved from 600s to 200s
- calibrated FFIs available as soon as 4-5 days after downlink
- revisit the North/South, finish the Ecliptic

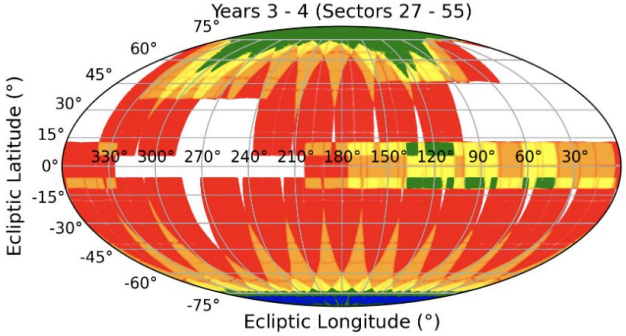


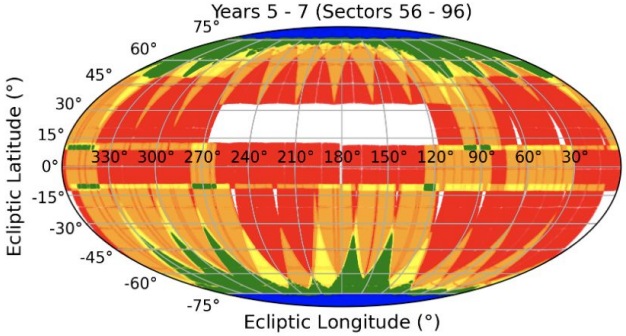




What can we expect from EM2?



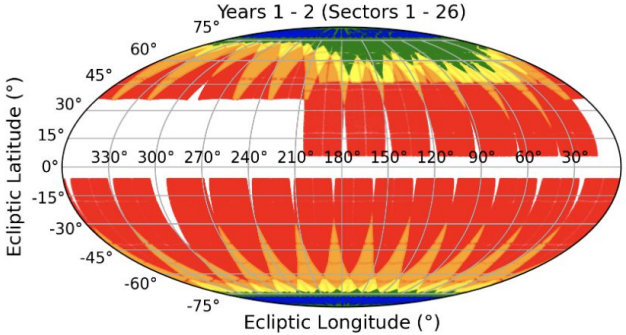


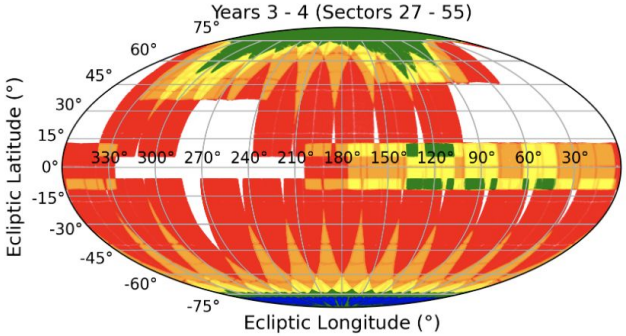


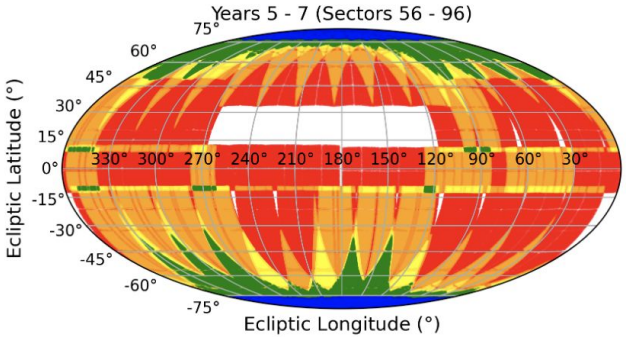
What can we expect from EM2?

1. How many planets should be detectable?
2. How many planets will be in the Habitable Zone?
3. How many planets will be promising follow-up targets?
4. How well do these predictions reflect the actual TESS exoplanet yield?

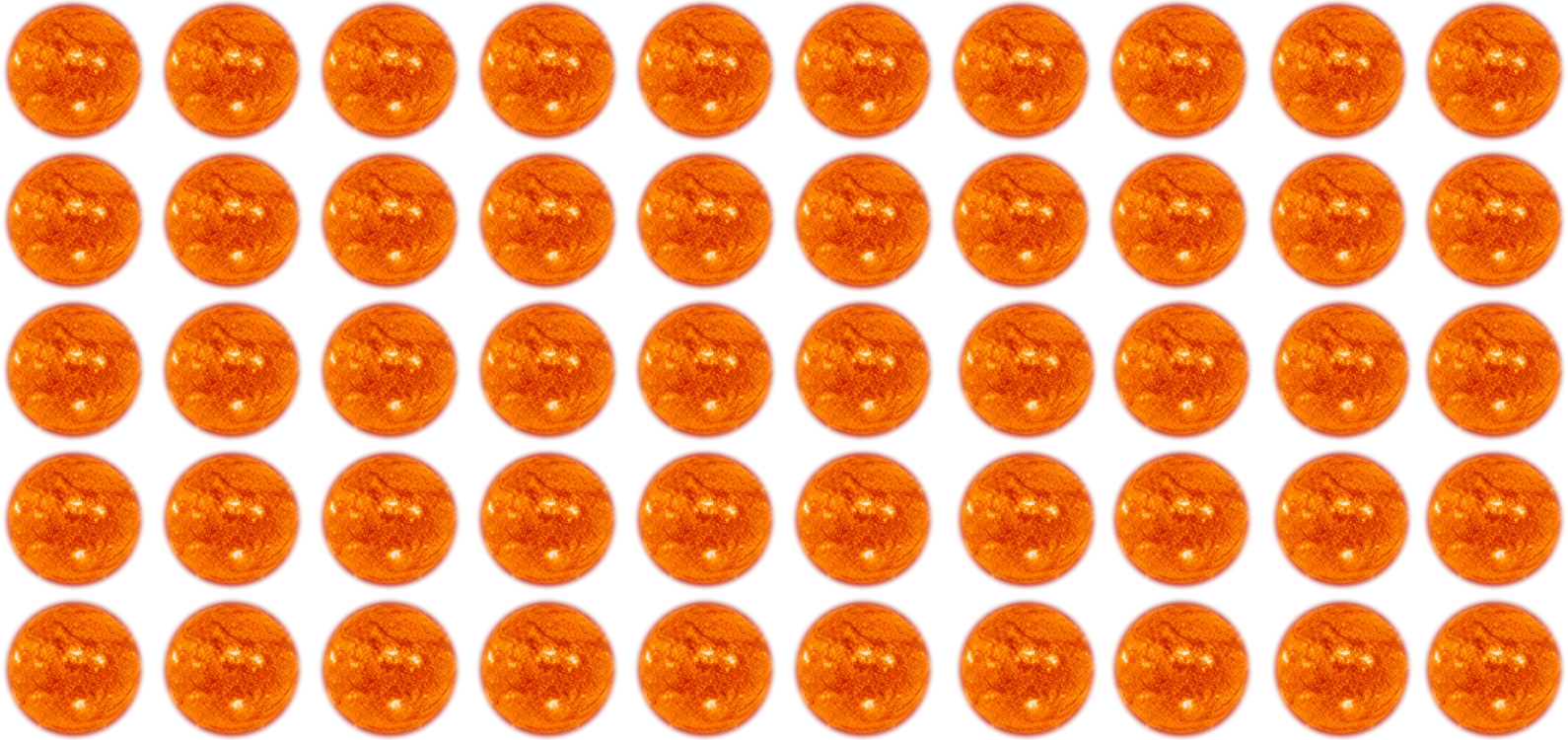
See: simulations from Sullivan et al. (2015), Bouma et al. (2017), Barclay et al. (2018), etc





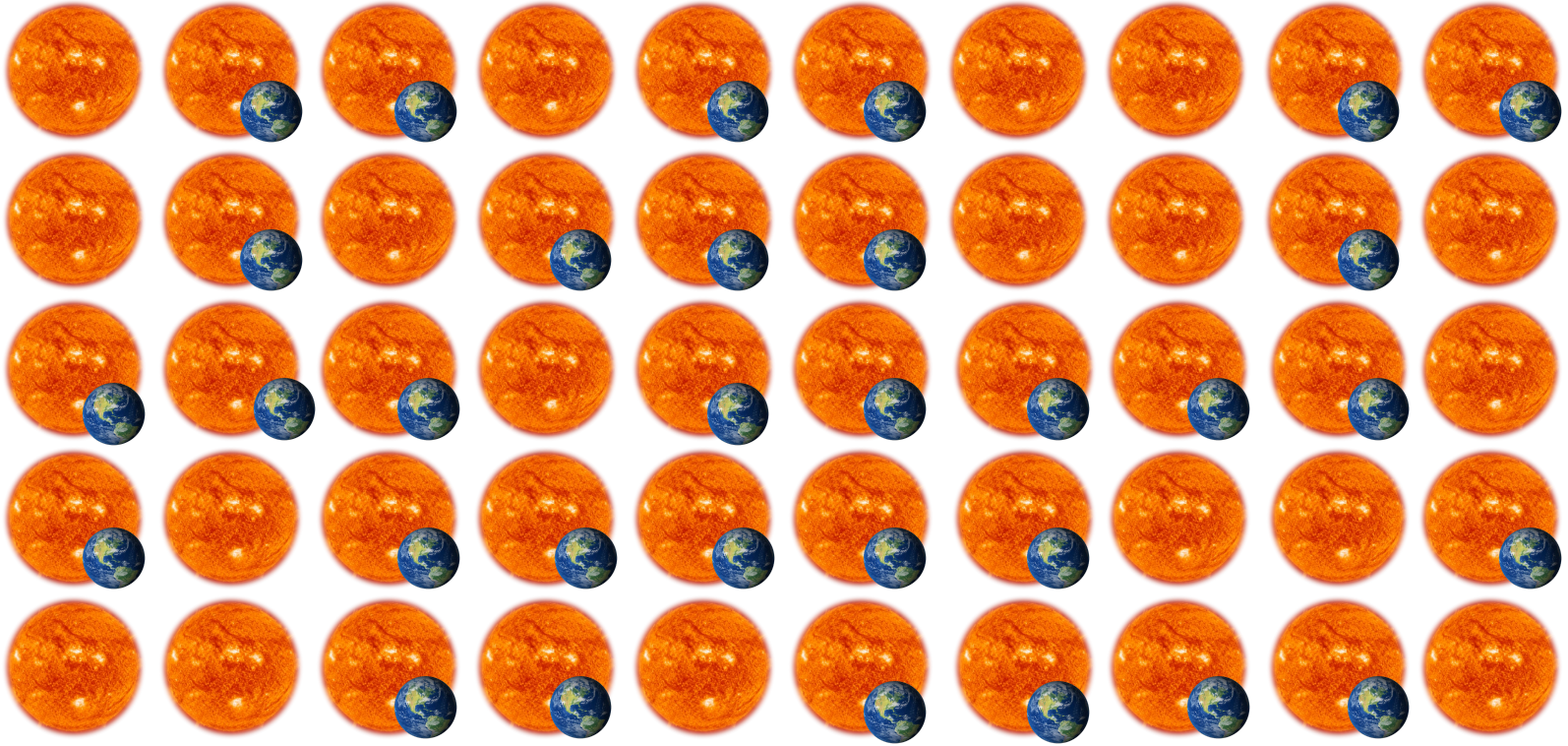


~ 9.4 million AFGKM stars in the Candidate Target List (CTL) v8

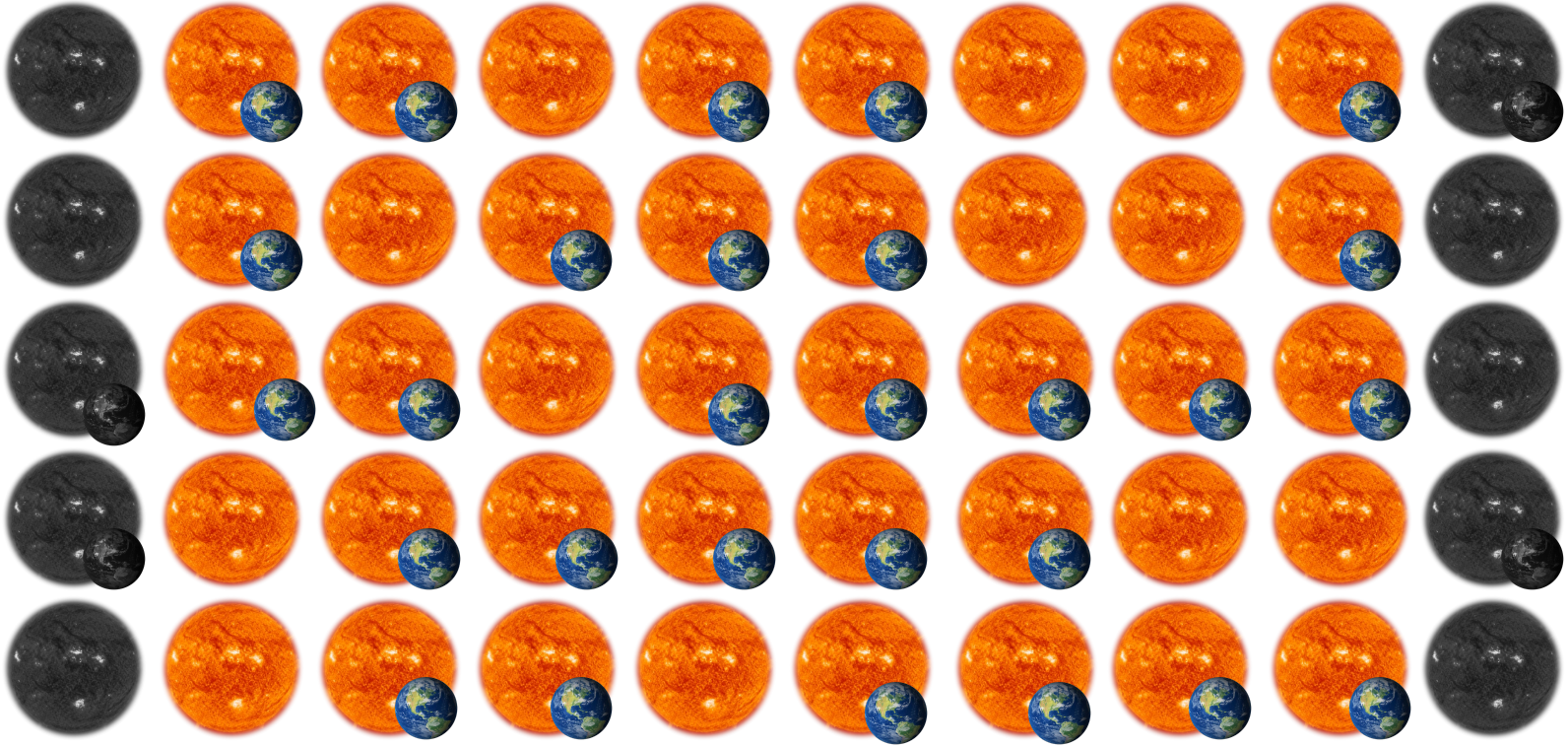


AFGK stars: Kunimoto & Matthews (2020)
M stars: Dressing & Charbonneau (2015)

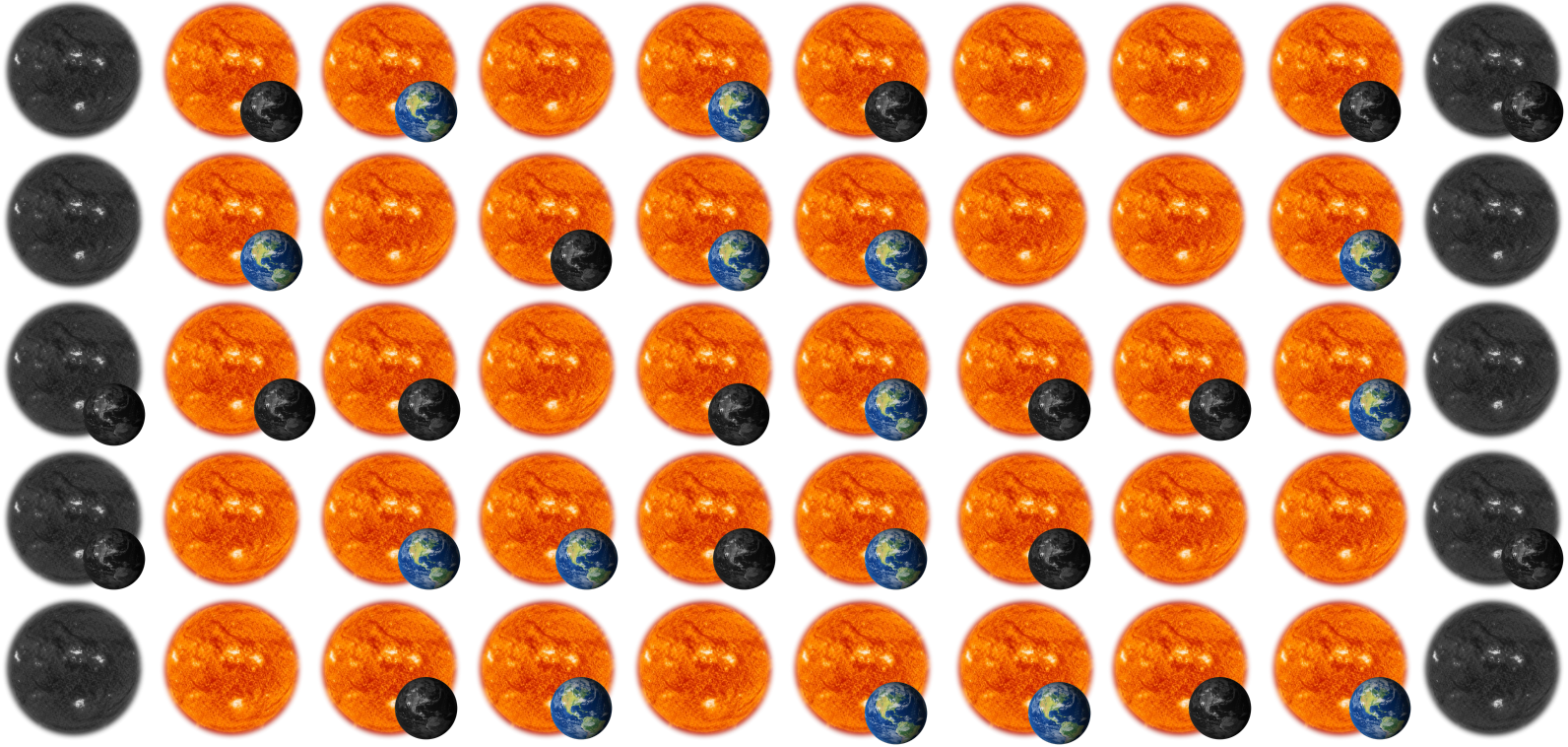
Simulate planets around each star



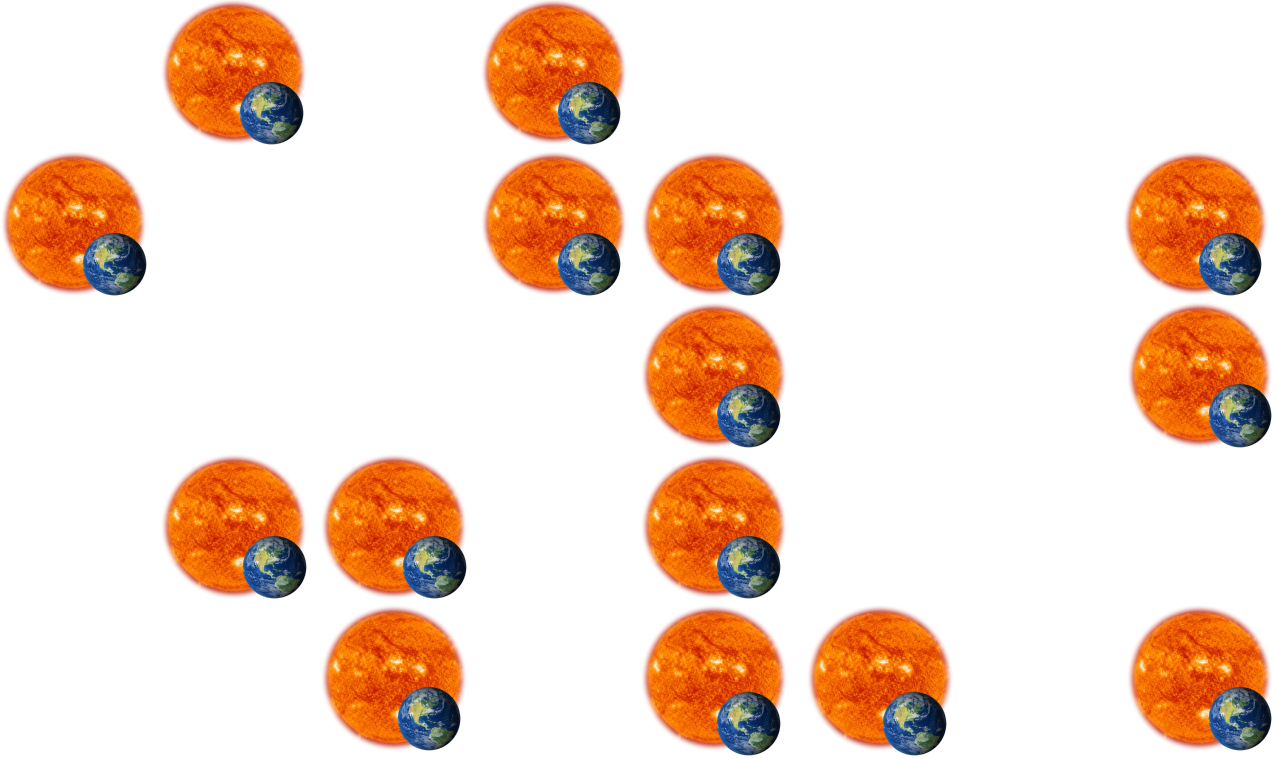
Check with stars are observed by TESS



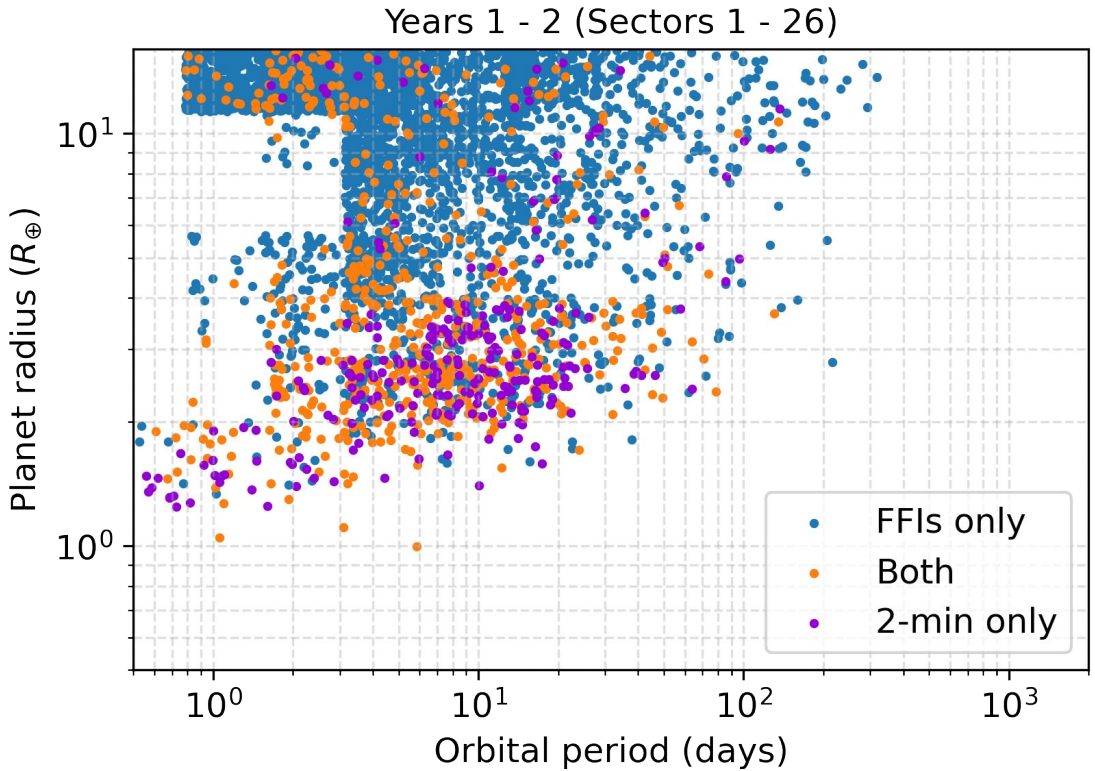
Predict which planets will be detectable in TESS lightcurves



Assess the final list of simulated TESS detections



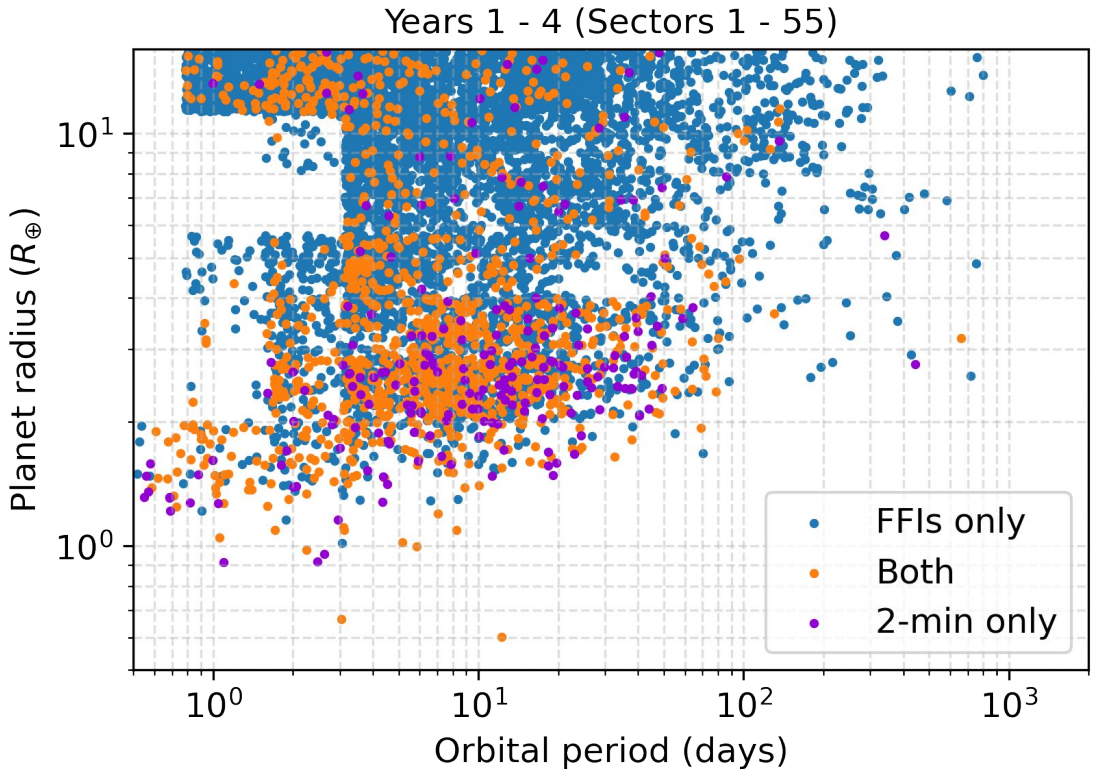
1. How many planets should be detectable?



Primary Mission:

4721 ± 330 planets

1. How many planets should be detectable?

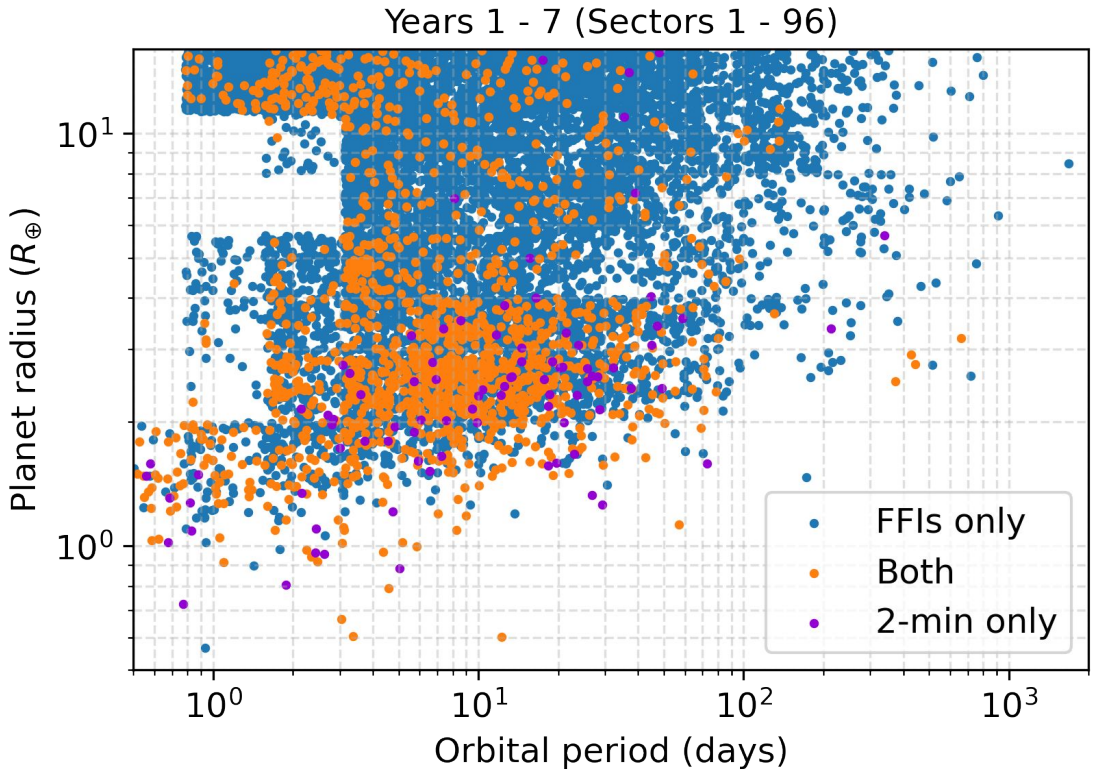


Extended Mission 1:

3703 ± 217 planets

(8424 ± 518 planets in total)

1. How many planets should be detectable?

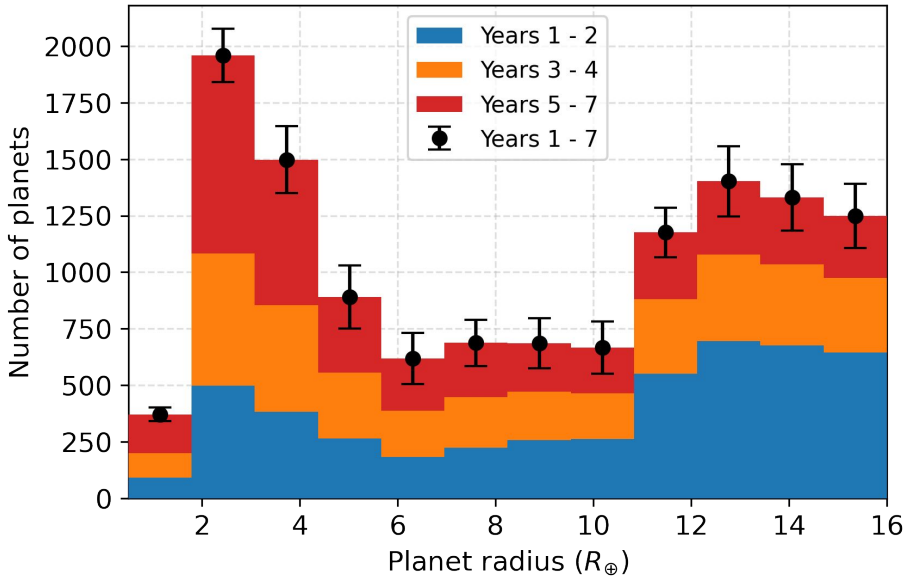


Extended Mission 2:

4100 ± 205 planets

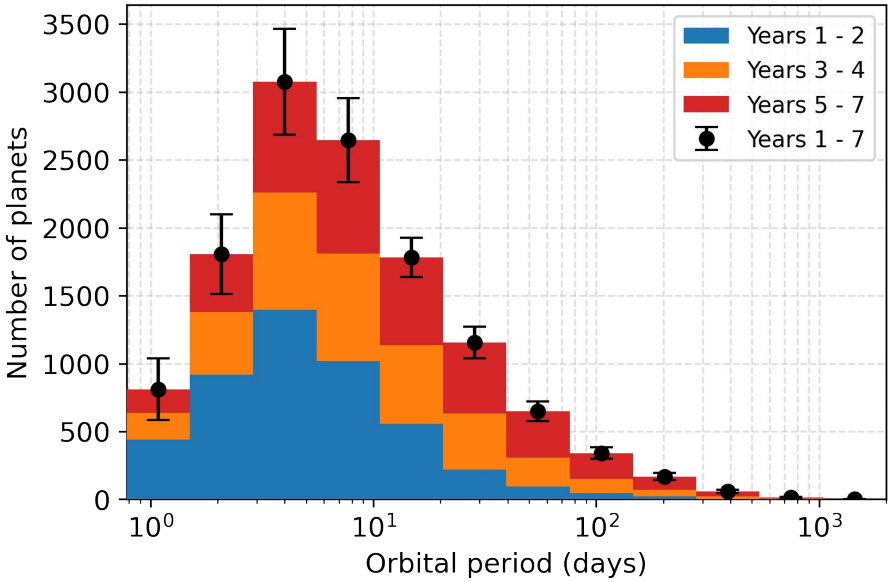
(12524 ± 676 planets in total)

1. How many planets should be detectable?



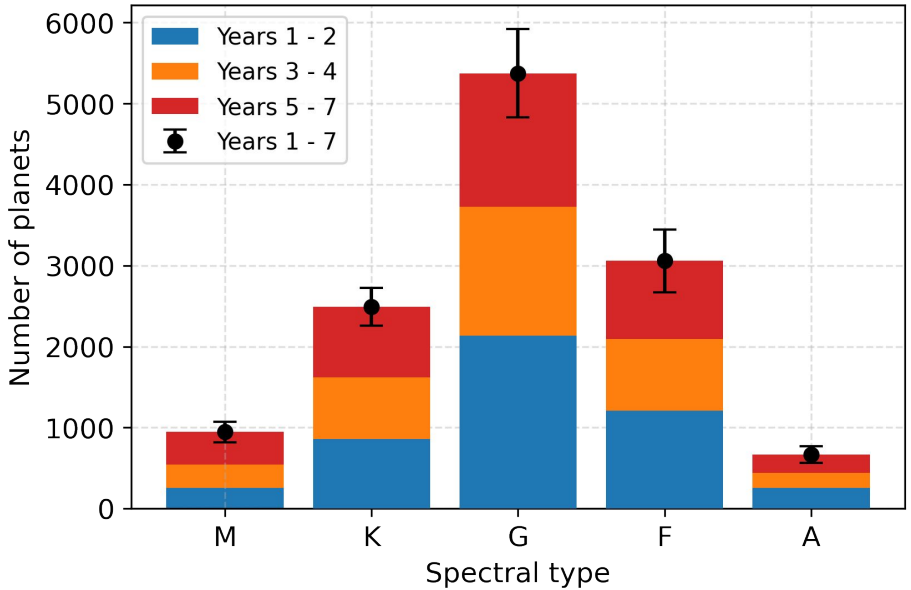
The small planet (Rp < 4 R⊕) yield could double in EM2

1. How many planets should be detectable?



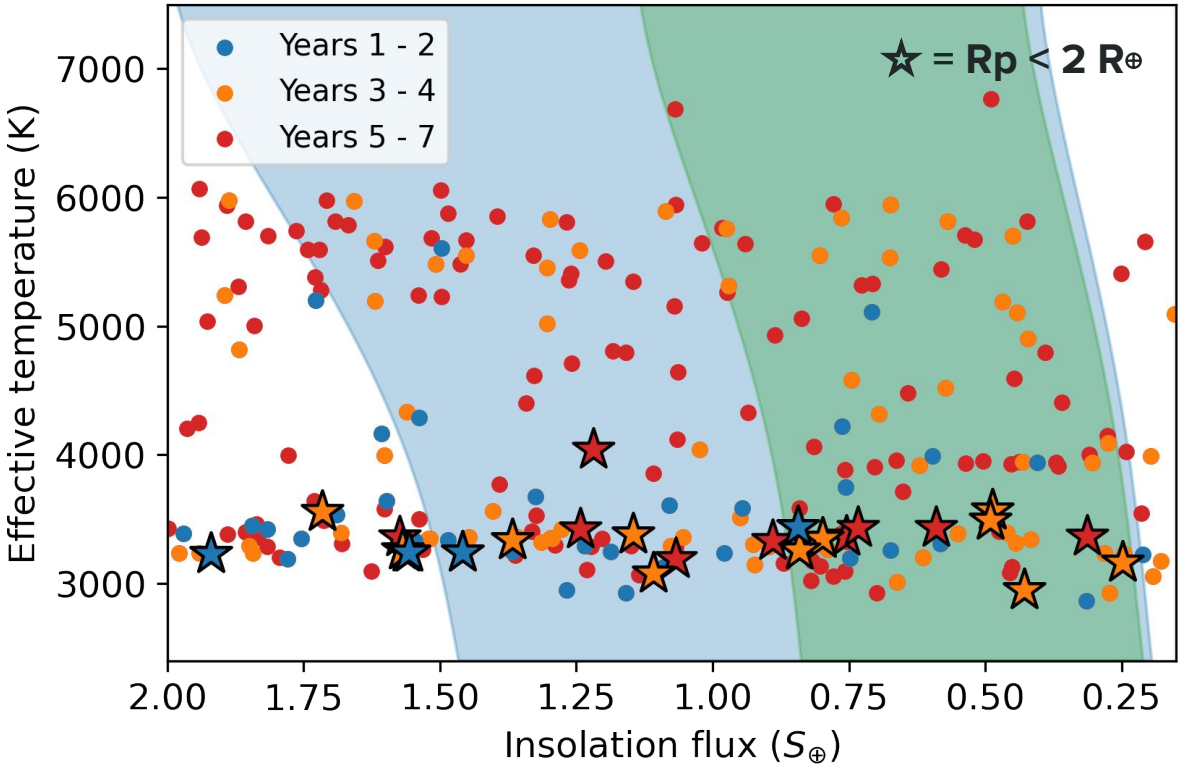
Typical planets will have progressively longer periods

1. How many planets should be detectable?



G dwarf stars are the most common TESS planet hosts

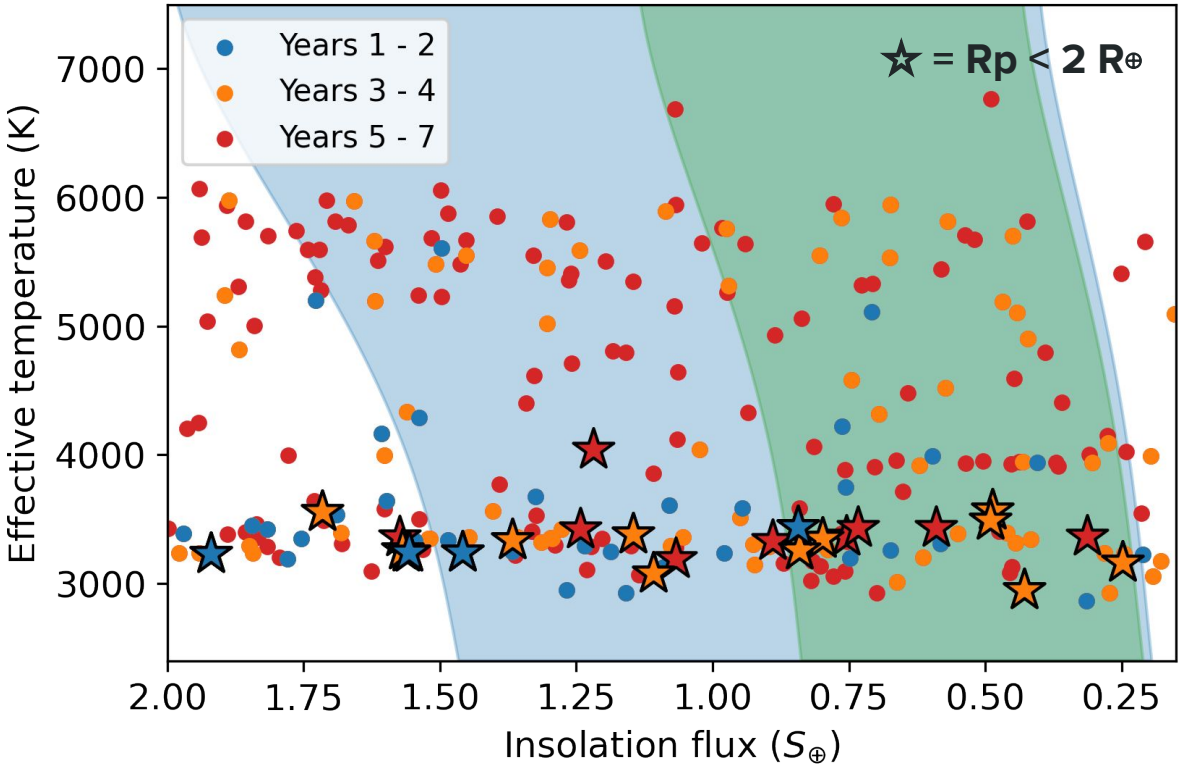
2. How many planets will be in the Habitable Zone?



Sectors 1 - 45 ($R_p < 2\ R_\oplus$):

Optimistic Habitable Zone	
Prediction	6 ± 2
Actual	5 TOIs
Conservative Habitable Zone	
Prediction	3 ± 1
Actual	2 TOIs

2. How many planets will be in the Habitable Zone?



Sectors 1 - 96:

Optimistic Habitable Zone	
Rp < 2 R⊕	18 ± 5
All planets	198 ± 24
Conservative Habitable Zone	
Rp < 2 R⊕	9 ± 3
All planets	97 ± 14

3. How many will be promising follow-up targets?

Radial Velocity (RV) Observations ($R_p < 4\ R_\oplus$):

Mission Duration	K > 3 m/s V < 11 mag	K > 5 m/s V < 11 mag
Years 1 - 2	117 ± 17	24 ± 7
Years 1 - 4	196 ± 28	36 ± 10
Years 1 - 7	268 ± 36	44 ± 12

3. How many will be promising follow-up targets?

Radial Velocity (RV) Observations ($R_p < 4\ R_\oplus$):

Mission Duration	K > 3 m/s V < 11 mag	K > 5 m/s V < 11 mag
Years 1 - 2	117 ± 17	24 ± 7
Years 1 - 4	196 ± 28	36 ± 10
Years 1 - 7	268 ± 36	44 ± 12

Atmospheric Characterization (using Transmission Spectroscopy Metric (TSM) from Kempton et al. 2018):

Mission Duration	$R_p < 1.5\ R_\oplus$ TSM > 10	$1.5 < R_p < 10\ R_\oplus$ TSM > 90
Years 1 - 2	21 ± 6	366 ± 35
Years 1 - 4	41 ± 9	529 ± 48
Years 1 - 7	58 ± 11	632 ± 55

4. How well do the predictions reflect actual yields?

4. How well do the predictions reflect actual yields?

Important notes:

- ❏ I'm only comparing to TOIs orbiting CTLv8 AFGKM stars within simulated range ($R_p < 16\ R_\oplus$)

4. How well do the predictions reflect actual yields?

Important notes:

- ❏ I'm only comparing to TOIs orbiting CTLv8 AFGKM stars within simulated range ($R_p < 16\ R_\oplus$)
- ❏ I'm only comparing to Primary Mission TOIs (Guerrero et al. 2021)

4. How well do the predictions reflect actual yields?

Important notes:

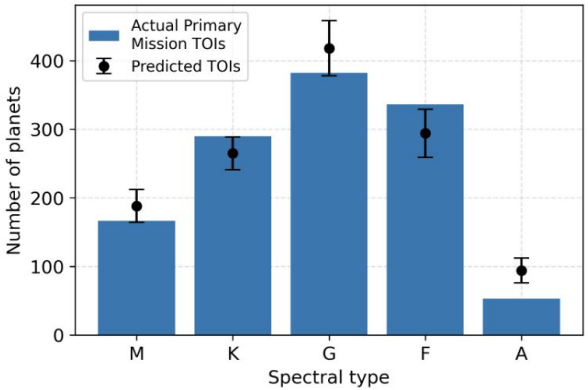
- ❏ I'm only comparing to TOIs orbiting CTLv8 AFGKM stars within simulated range ($R_p < 16\ R_\oplus$)
- ❏ I'm only comparing to Primary Mission TOIs (Guerrero et al. 2021)
- ❏ the TOI identification process is not complete or straightforward to simulate

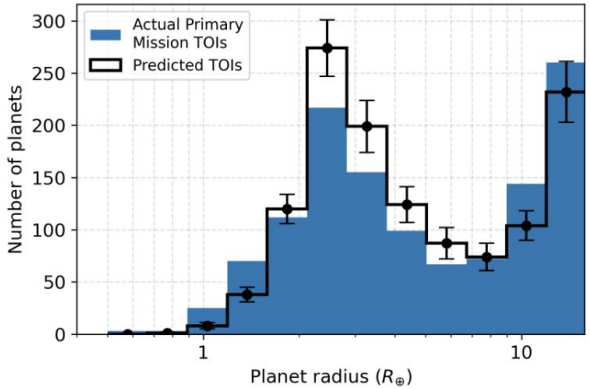
4. How well do the predictions reflect actual yields?

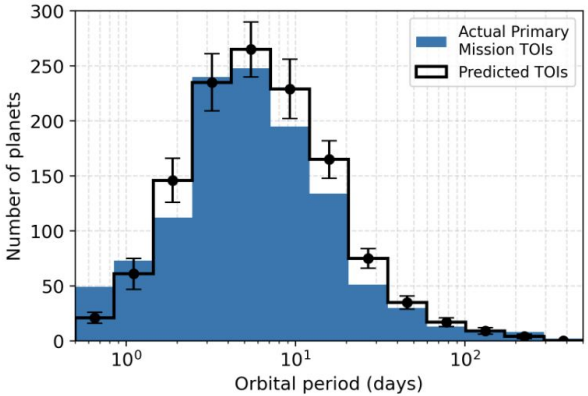
Important notes:

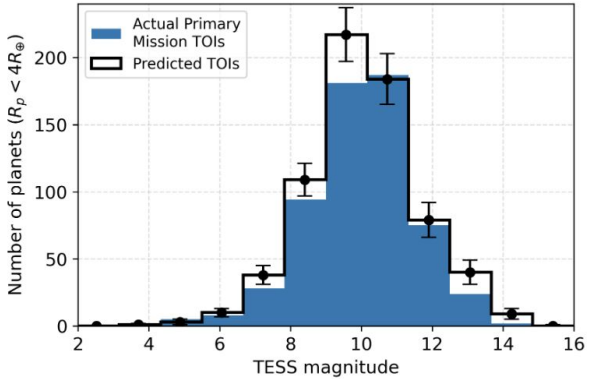
- ❏ I'm only comparing to TOIs orbiting CTLv8 AFGKM stars within simulated range ($R_p < 16\ R_\oplus$)
- ❏ I'm only comparing to Primary Mission TOIs (Guerrero et al. 2021)
- ❏ the TOI identification process is not complete or straightforward to simulate
  - ❏ Assume simulated 2min detections reflect NASA's SPOC pipeline
  - ❏ Assume simulated FFI detections with $T < 10.5$ mag reflect the Quick Look Pipeline (QLP)

4. How well do the predictions reflect actual yields?









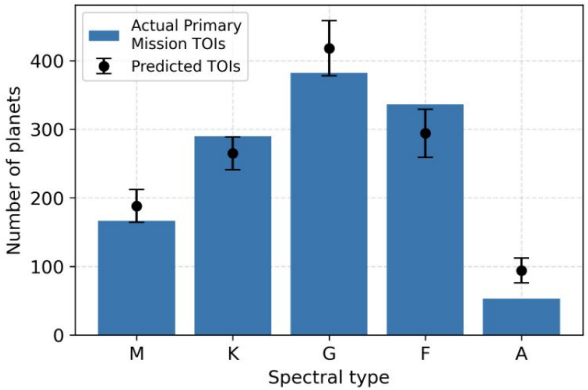
Predictions for the TESS Primary Mission TOI yield:

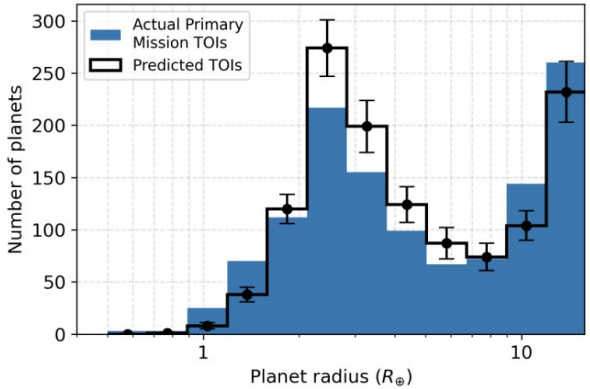
1259 ± 58 planets

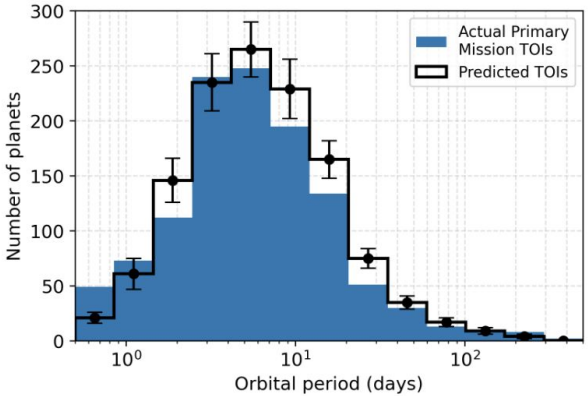
Actual TESS TOIs (Guerrero et al. 2021):

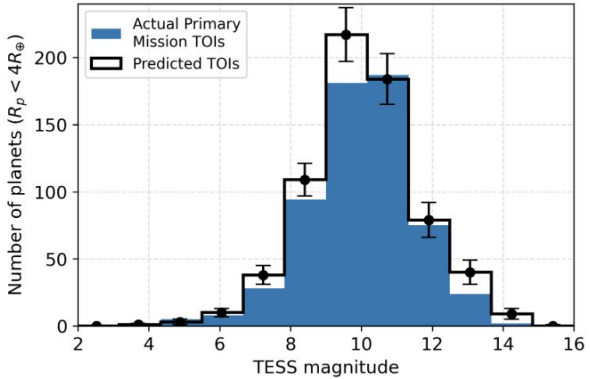
1227 TOIs

4. How well do the predictions reflect actual yields?









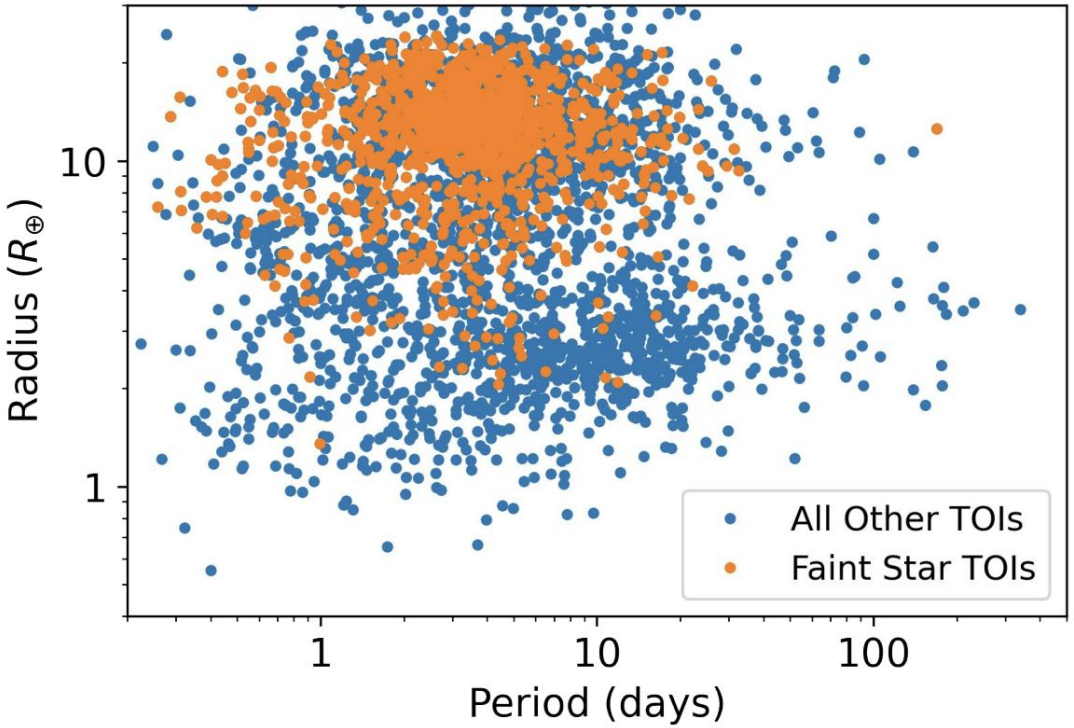
Predictions for the TESS Primary Mission TOI yield:

1259 ± 58 planets

Recall my predictions for the full Primary Mission yield:

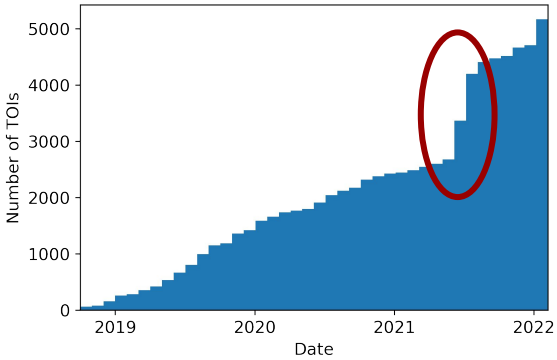
4721 ± 330 planets

TESS Faint Star Search



1617 new TOIs from the Primary Mission

412 new TOIs from Extended Mission 1 (ongoing)



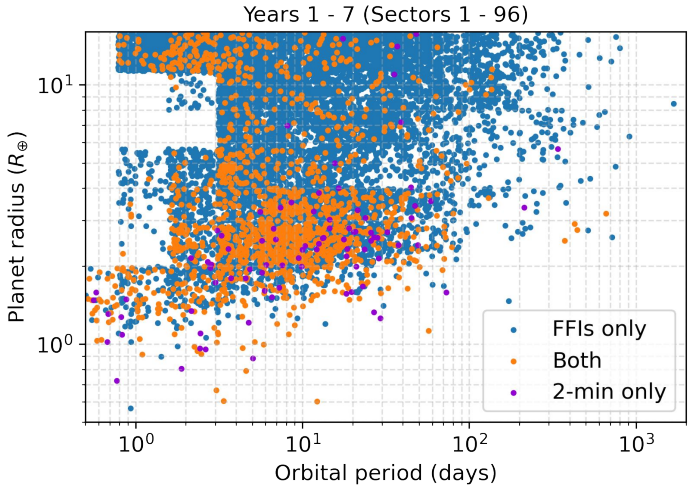
Takeaways

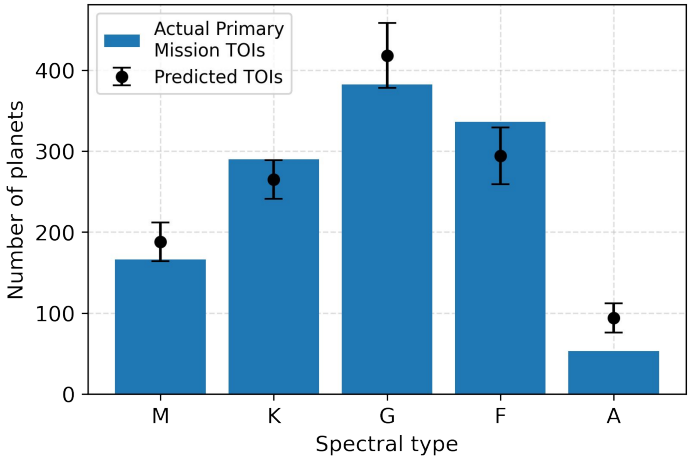
1. ***More than 12000 planets should be detectable*** by the end of EM2

2. New planets will be smaller, with longer orbital periods, orbiting fainter stars

3. The ***Rp < 4 R⊕ yield should double*** between EM1 and EM2

4. Thousands more TESS planets can be detected ***even with the data at hand***





Supplemental Slides

Comparisons to previous works

Sullivan et al. 2013
Bouma et al. 2017
Barclay et al. 2018
Huang et al. 2018
Cooke et al. 2018, 2019
Villanueva et al. 2019

Component	This work	Previous works
Stellar sample	CTLv8 (9.5 million stars)*	TRILEGAL galaxy simulations/ CTLv6 (3.8 million stars)
Planet distribution	AFGK: Kunimoto & Matthews (2020) M: Dressing & Charbonneau (2015)	AFGK: Fressin et al. (2013) M: Dressing & Charbonneau (2015)
Lightcurve characteristics	Empirical*	Predicted
Detection criteria	Kepler detection probability, S/N > 7.3	S/N > 7.3

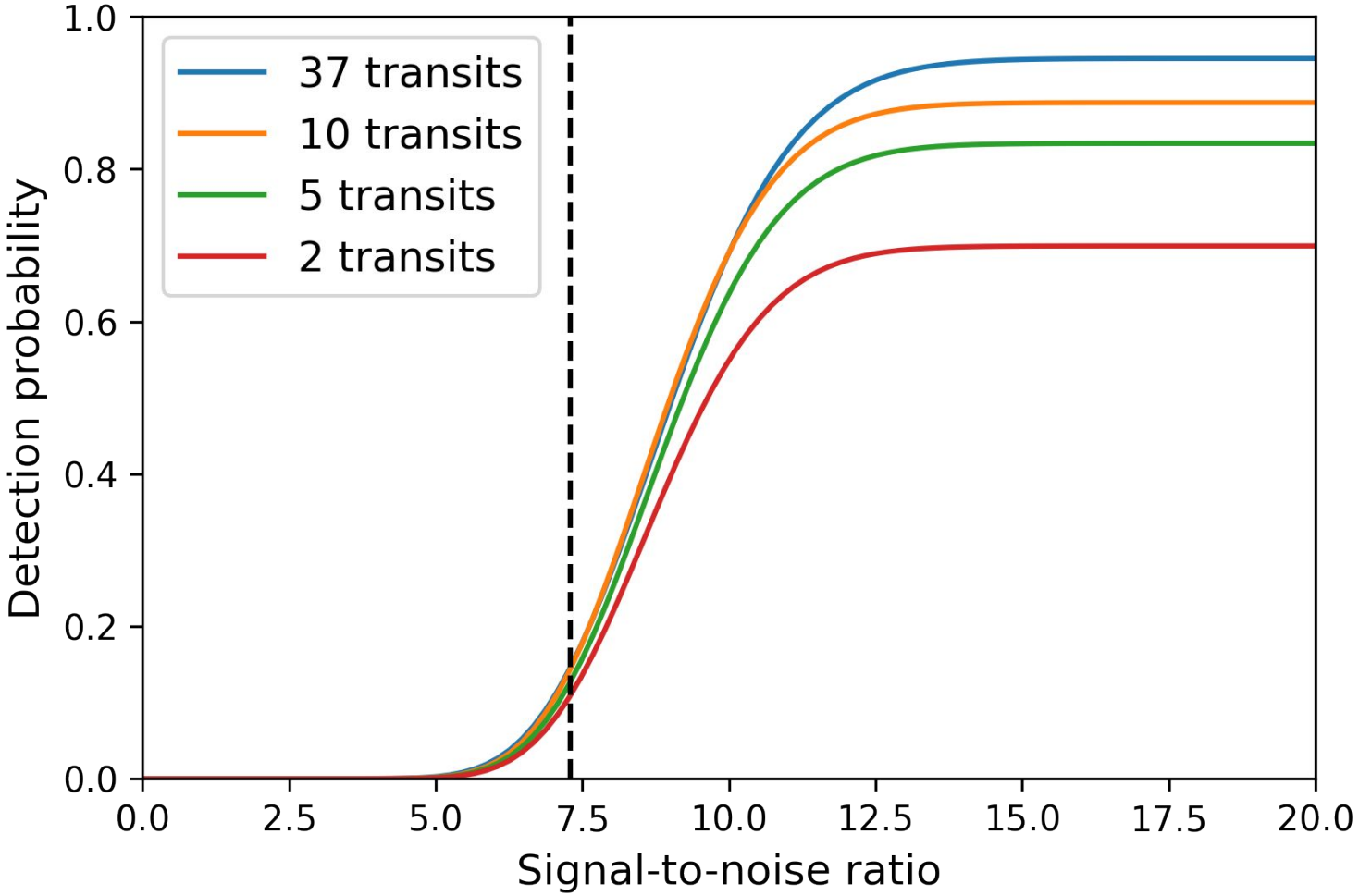
* also featured in Cooke et al. (2019)

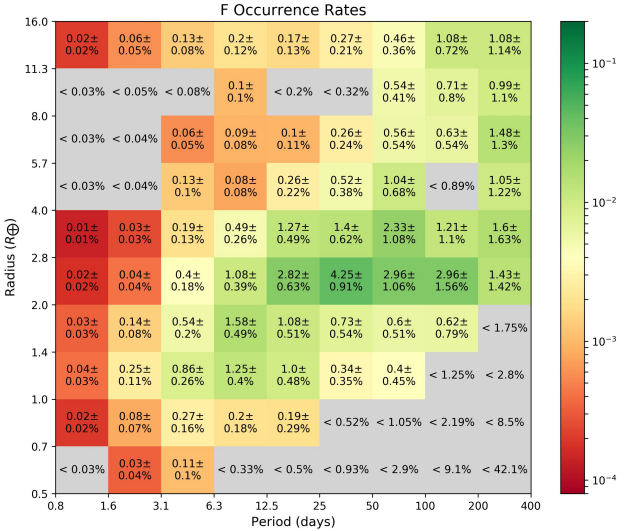
Comparisons to previous works

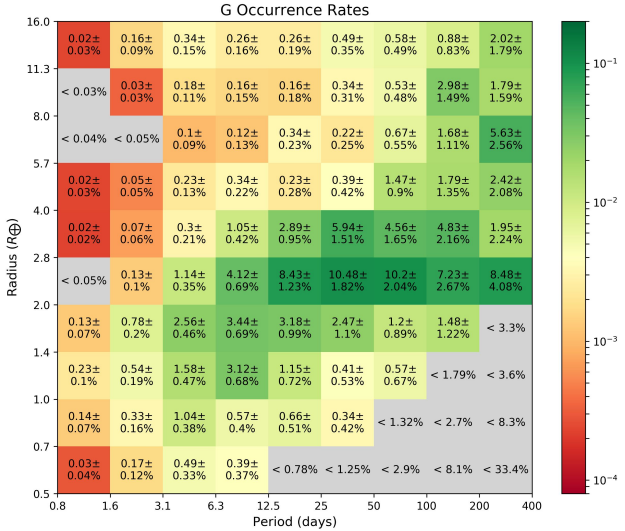
Sullivan et al. 2013
Bouma et al. 2017
Barclay et al. 2018
Huang et al. 2018
Cooke et al. 2018, 2019
Villanueva et al. 2019

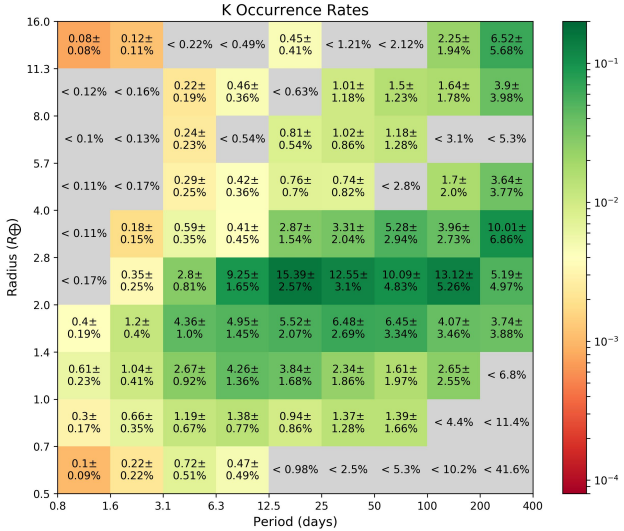
Component	This work	Previous works
Stellar sample	CTLv8 (9.5 million stars)*	TRILEGAL galaxy simulations/ CTLv6 (3.8 million stars)
Planet distribution	AFGK: Kunimoto & Matthews (2020) M: Dressing & Charbonneau (2015)	AFGK: Fressin et al. (2013) M: Dressing & Charbonneau (2015)
Lightcurve characteristics	Empirical*	Predicted
Detection criteria	Kepler detection probability, S/N > 7.3	S/N > 7.3

* also featured in Cooke et al. (2019)


37 transits
10 transits
5 transits
2 transits
Detection probability
Signal-to-noise ratio
0.0
0.2
0.4
0.6
0.8
1.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0


F Occurrence Rates
Radius (R⊕)
Period (days)
16.0
11.3
8.0
5.7
4.0
2.8
2.0
1.4
1.0
0.7
0.5
0.8
1.6
3.1
6.3
12.5
25
50
100
200
400
0.02± 0.02%
0.06± 0.05%
0.13± 0.08%
0.2± 0.12%
0.17± 0.13%
0.27± 0.21%
0.46± 0.36%
1.08± 0.72%
1.08± 1.14%
< 0.03%
< 0.05%
< 0.08%
0.1± 0.1%
< 0.2%
< 0.32%
0.54± 0.41%
0.71± 0.8%
0.99± 1.1%
< 0.03%
< 0.04%
0.06± 0.05%
0.09± 0.08%
0.1± 0.11%
0.26± 0.24%
0.56± 0.54%
0.63± 0.54%
1.48± 1.3%
< 0.03%
< 0.04%
0.13± 0.1%
0.08± 0.08%
0.26± 0.22%
0.52± 0.38%
1.04± 0.68%
< 0.89%
1.05± 1.22%
0.01± 0.01%
0.03± 0.03%
0.19± 0.13%
0.49± 0.26%
1.27± 0.49%
1.4± 0.62%
2.33± 1.08%
1.21± 1.1%
1.6± 1.63%
0.02± 0.02%
0.04± 0.04%
0.4± 0.18%
1.08± 0.39%
2.82± 0.63%
4.25± 0.91%
2.96± 1.06%
2.96± 1.56%
1.43± 1.42%
0.03± 0.03%
0.14± 0.08%
0.54± 0.2%
1.58± 0.49%
1.08± 0.51%
0.73± 0.54%
0.6± 0.51%
0.62± 0.79%
< 1.75%
0.04± 0.03%
0.25± 0.11%
0.86± 0.26%
1.25± 0.4%
1.0± 0.48%
0.34± 0.35%
0.4± 0.45%
< 1.25%
< 2.8%
0.02± 0.02%
0.08± 0.07%
0.27± 0.16%
0.2± 0.18%
0.19± 0.29%
< 0.52%
< 1.05%
< 2.19%
< 8.5%
< 0.03%
0.03± 0.04%
0.11± 0.1%
< 0.33%
< 0.5%
< 0.93%
< 2.9%
< 9.1%
< 42.1%
10^{-1}
10^{-2}
10^{-3}
10^{-4}


G Occurrence Rates
Radius (R⊕)
Period (days)
16.0
11.3
8.0
5.7
4.0
2.8
2.0
1.4
1.0
0.7
0.5
0.8
1.6
3.1
6.3
12.5
25
50
100
200
400
0.02± 0.03%
0.16± 0.09%
0.34± 0.15%
0.26± 0.16%
0.26± 0.19%
0.49± 0.35%
0.58± 0.49%
0.88± 0.83%
2.02± 1.79%
< 0.03%
0.03± 0.03%
0.18± 0.11%
0.16± 0.15%
0.16± 0.18%
0.34± 0.31%
0.53± 0.48%
2.98± 1.49%
1.79± 1.59%
< 0.04%
< 0.05%
0.1± 0.09%
0.12± 0.13%
0.34± 0.23%
0.22± 0.25%
0.67± 0.55%
1.68± 1.11%
5.63± 2.56%
0.02± 0.03%
0.05± 0.05%
0.23± 0.13%
0.34± 0.22%
0.23± 0.28%
0.39± 0.42%
1.47± 0.9%
1.79± 1.35%
2.42± 2.08%
0.02± 0.02%
0.07± 0.06%
0.3± 0.21%
1.05± 0.42%
2.89± 0.95%
5.94± 1.51%
4.56± 1.65%
4.83± 2.16%
1.95± 2.24%
< 0.05%
0.13± 0.1%
1.14± 0.35%
4.12± 0.69%
8.43± 1.23%
10.48± 1.82%
10.2± 2.04%
7.23± 2.67%
8.48± 4.08%
0.13± 0.07%
0.78± 0.2%
2.56± 0.46%
3.44± 0.69%
3.18± 0.99%
2.47± 1.1%
1.2± 0.89%
1.48± 1.22%
< 3.3%
0.23± 0.1%
0.54± 0.19%
1.58± 0.47%
3.12± 0.68%
1.15± 0.72%
0.41± 0.53%
0.57± 0.67%
< 1.79%
< 3.6%
0.14± 0.07%
0.33± 0.16%
1.04± 0.38%
0.57± 0.4%
0.66± 0.51%
0.34± 0.42%
< 1.32%
< 2.7%
< 8.3%
0.03± 0.04%
0.17± 0.12%
0.49± 0.33%
0.39± 0.37%
< 0.78%
< 1.25%
< 2.9%
< 8.1%
< 33.4%
10^{-1}
10^{-2}
10^{-3}
10^{-4}


K Occurrence Rates
Radius (R⊕)
Period (days)
16.0
11.3
8.0
5.7
4.0
2.8
2.0
1.4
1.0
0.7
0.5
0.8
1.6
3.1
6.3
12.5
25
50
100
200
400
0.08± 0.08%
0.12± 0.11%
< 0.22%
< 0.49%
0.45± 0.41%
< 1.21%
< 2.12%
2.25± 1.94%
6.52± 5.68%
< 0.12%
< 0.16%
0.22± 0.19%
0.46± 0.36%
< 0.63%
1.01± 1.18%
1.5± 1.23%
1.64± 1.78%
3.9± 3.98%
< 0.1%
< 0.13%
0.24± 0.23%
< 0.54%
0.81± 0.54%
1.02± 0.86%
1.18± 1.28%
< 3.1%
< 5.3%
< 0.11%
< 0.17%
0.29± 0.25%
0.42± 0.36%
0.76± 0.7%
0.74± 0.82%
< 2.8%
1.7± 2.0%
3.64± 3.77%
< 0.11%
0.18± 0.15%
0.59± 0.35%
0.41± 0.45%
2.87± 1.54%
3.31± 2.04%
5.28± 2.94%
3.96± 2.73%
10.01± 6.86%
< 0.17%
0.35± 0.25%
2.8± 0.81%
9.25± 1.65%
15.39± 2.57%
12.55± 3.1%
10.09± 4.83%
13.12± 5.26%
5.19± 4.97%
0.4± 0.19%
1.2± 0.4%
4.36± 1.0%
4.95± 1.45%
5.52± 2.07%
6.48± 2.69%
6.45± 3.34%
4.07± 3.46%
3.74± 3.88%
0.61± 0.23%
1.04± 0.41%
2.67± 0.92%
4.26± 1.36%
3.84± 1.68%
2.34± 1.86%
1.61± 1.97%
2.65± 2.55%
< 6.8%
0.3± 0.17%
0.66± 0.35%
1.19± 0.67%
1.38± 0.77%
0.94± 0.86%
1.37± 1.28%
1.39± 1.66%
< 4.4%
< 11.4%
0.1± 0.09%
0.22± 0.22%
0.72± 0.51%
0.47± 0.49%
< 0.98%
< 2.5%
< 5.3%
< 10.2%
< 41.6%
10^{-1}
10^{-2}
10^{-3}
10^{-4}

Simulation results using Fressin et al. (2013) occurrence rates, S/N > 7