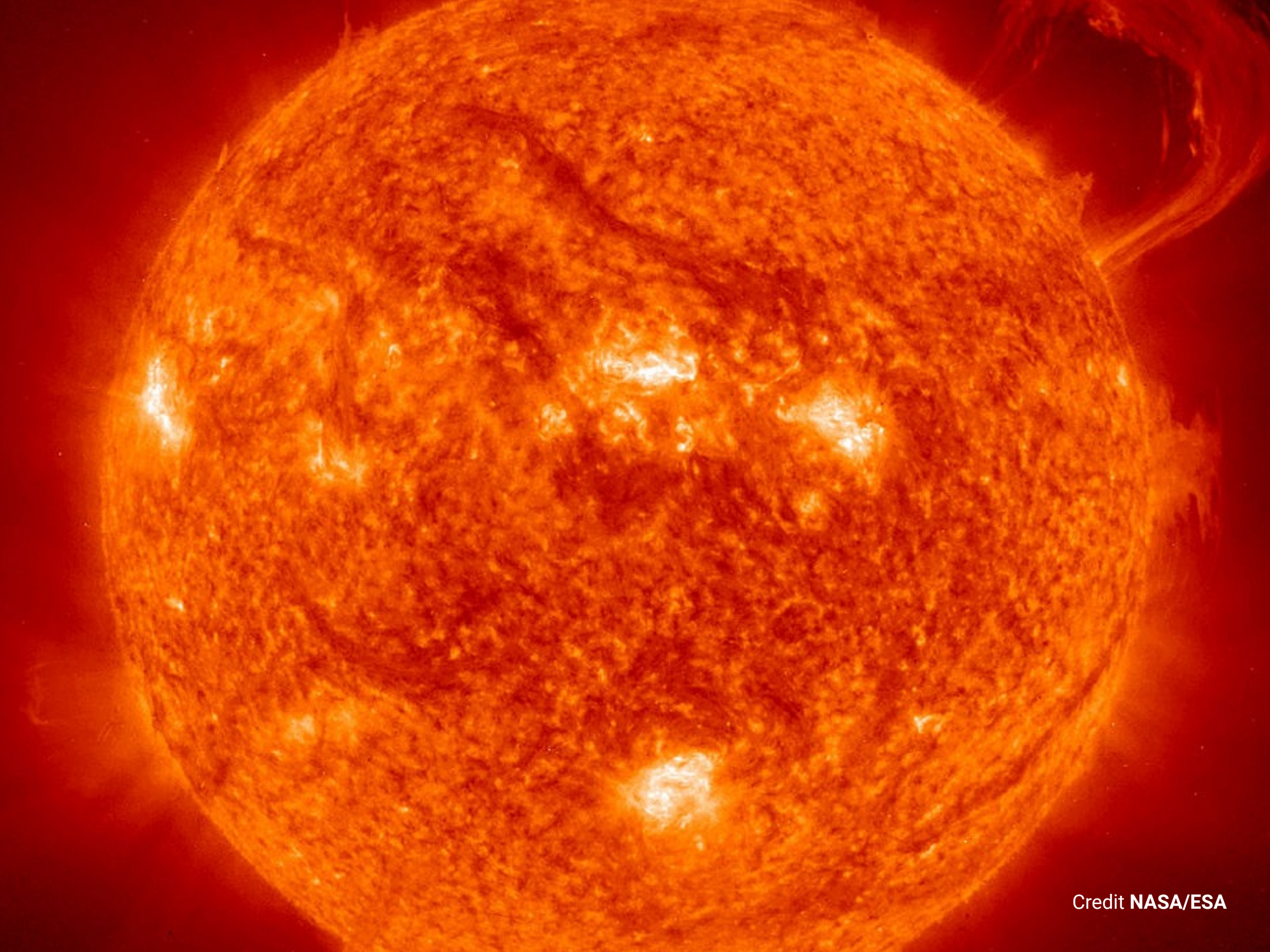
LONG-PERIOD TRANSITING EXOPLANETS

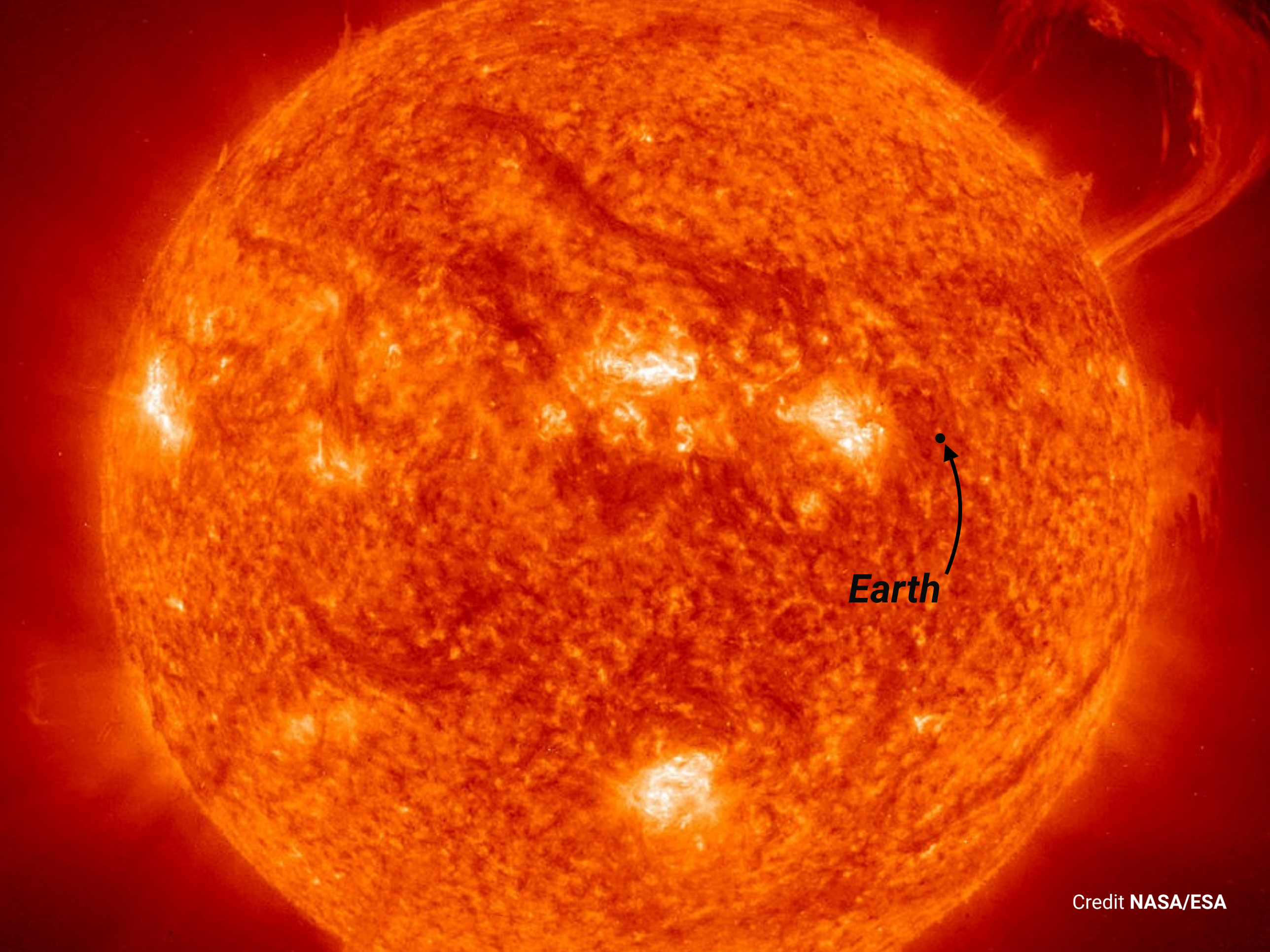
Dan Foreman-Mackey
Sagan Fellow @ University of Washington
github.com/dfm // dfm.io // @exoplaneteer

The "population" of exoplanets

Transiting exoplanets



Credit **NASA/ESA**



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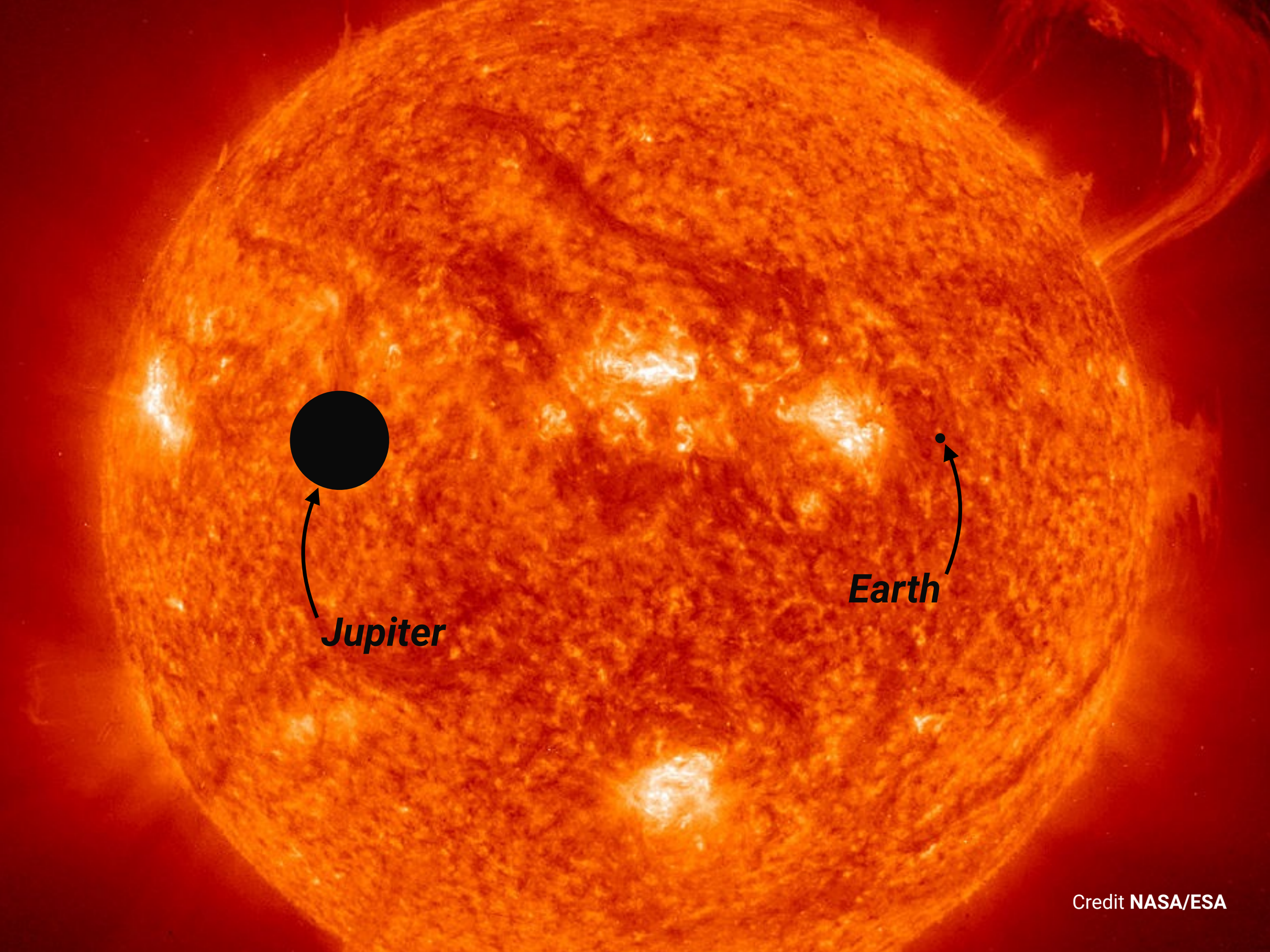
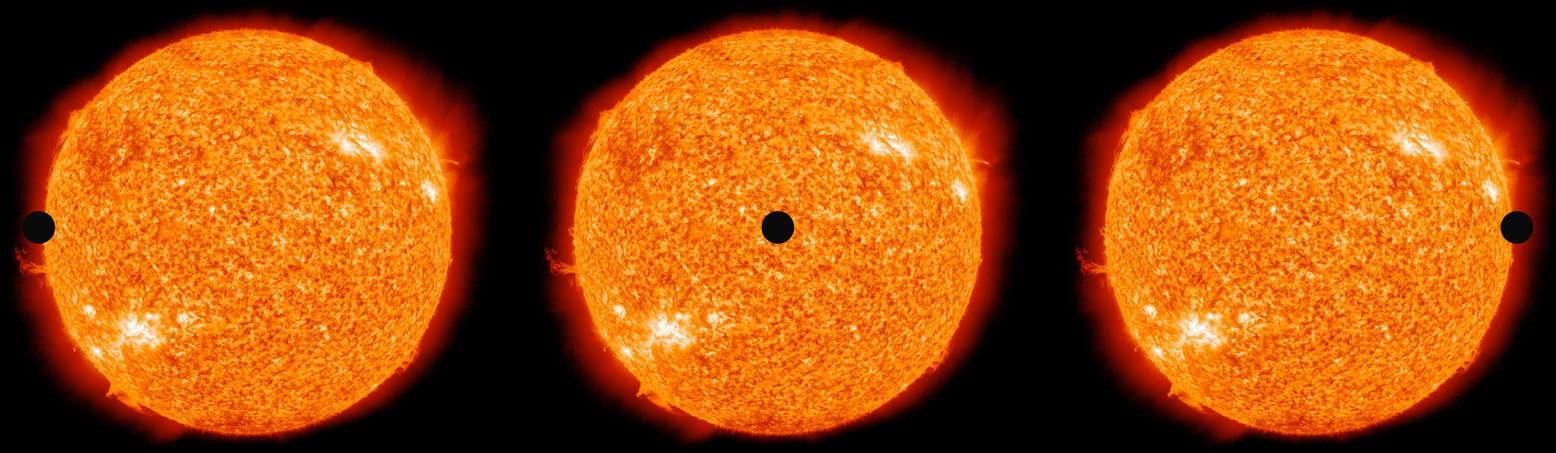
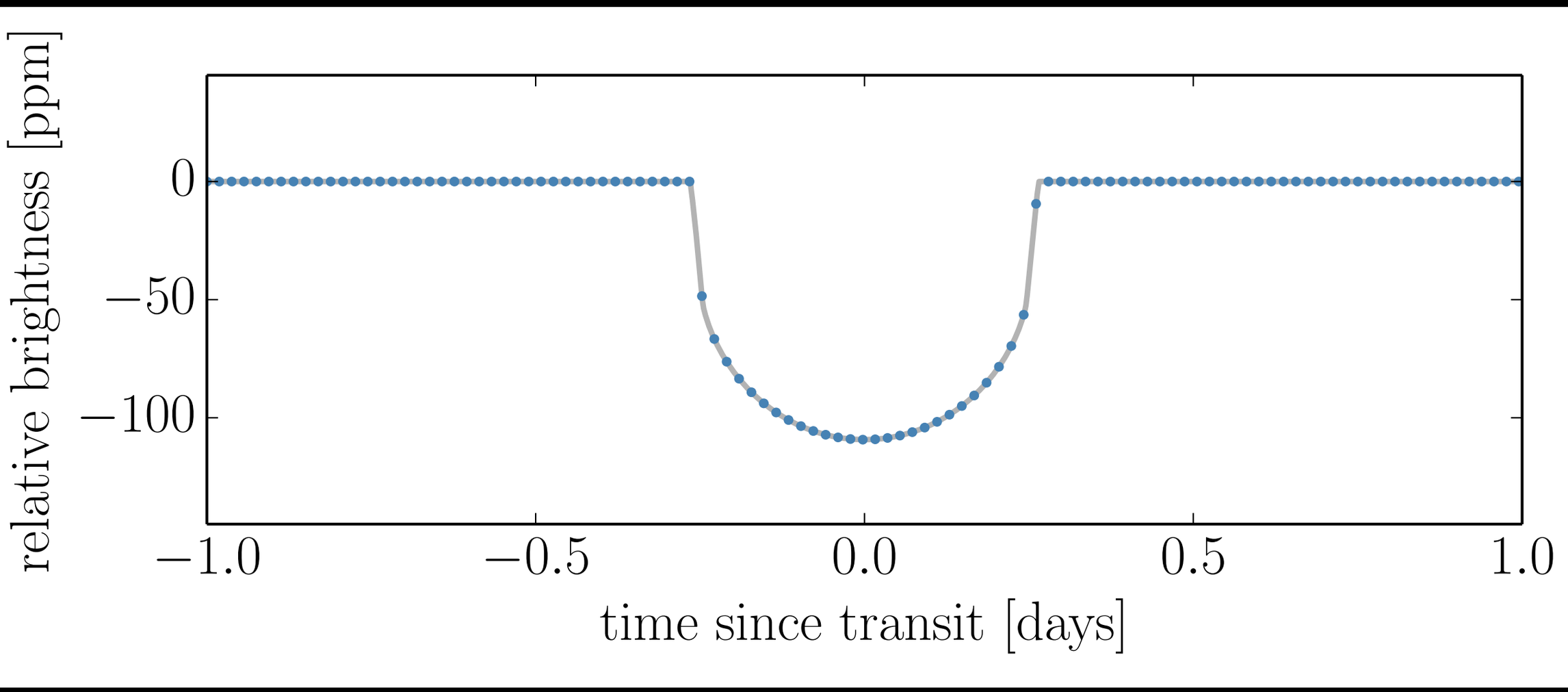

Jupiter
Earth
Credit NASA/ESA

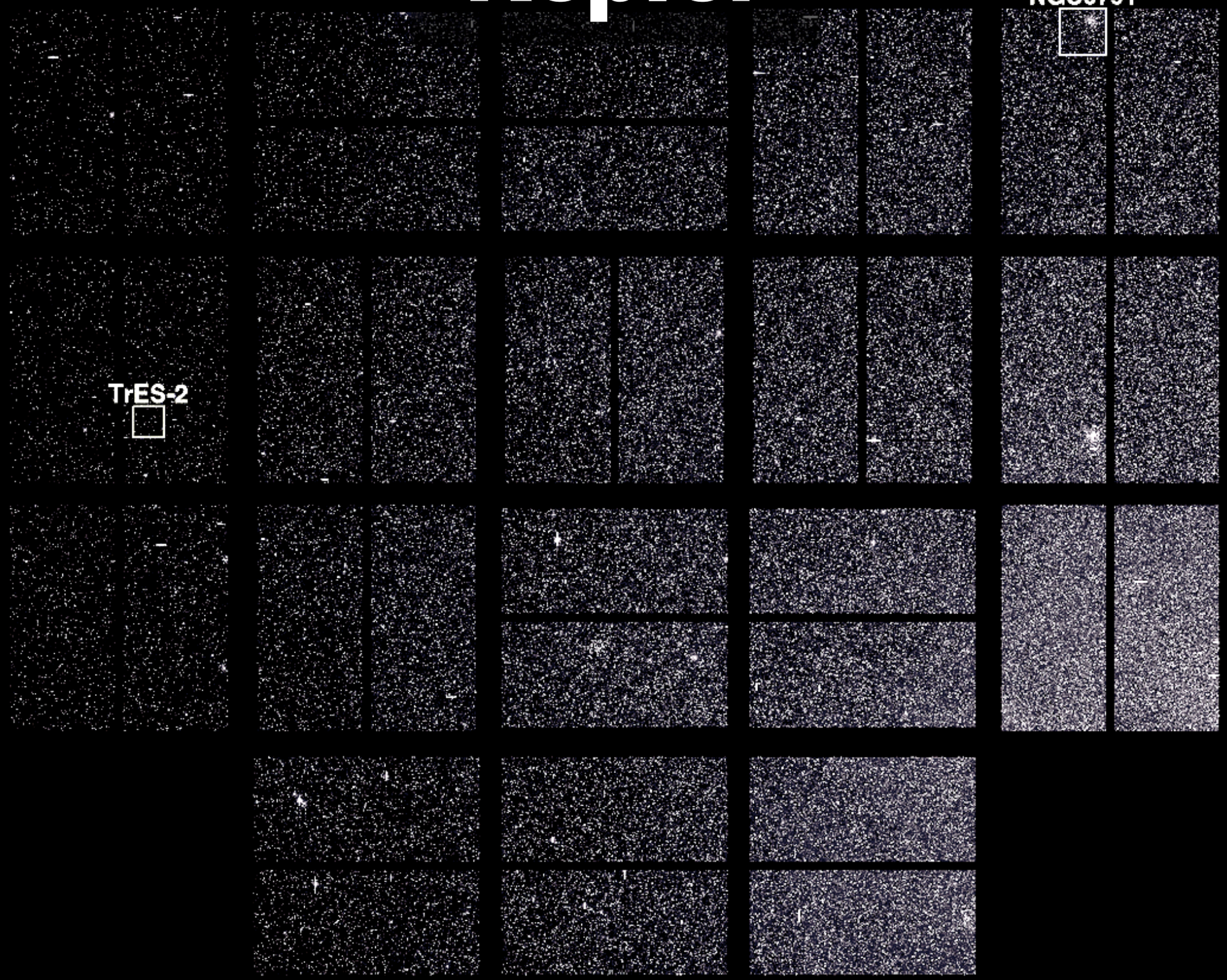



relative brightness [ppm]
0
−50
−100
−1.0
−0.5
0.0
0.5
1.0
time since transit [days]

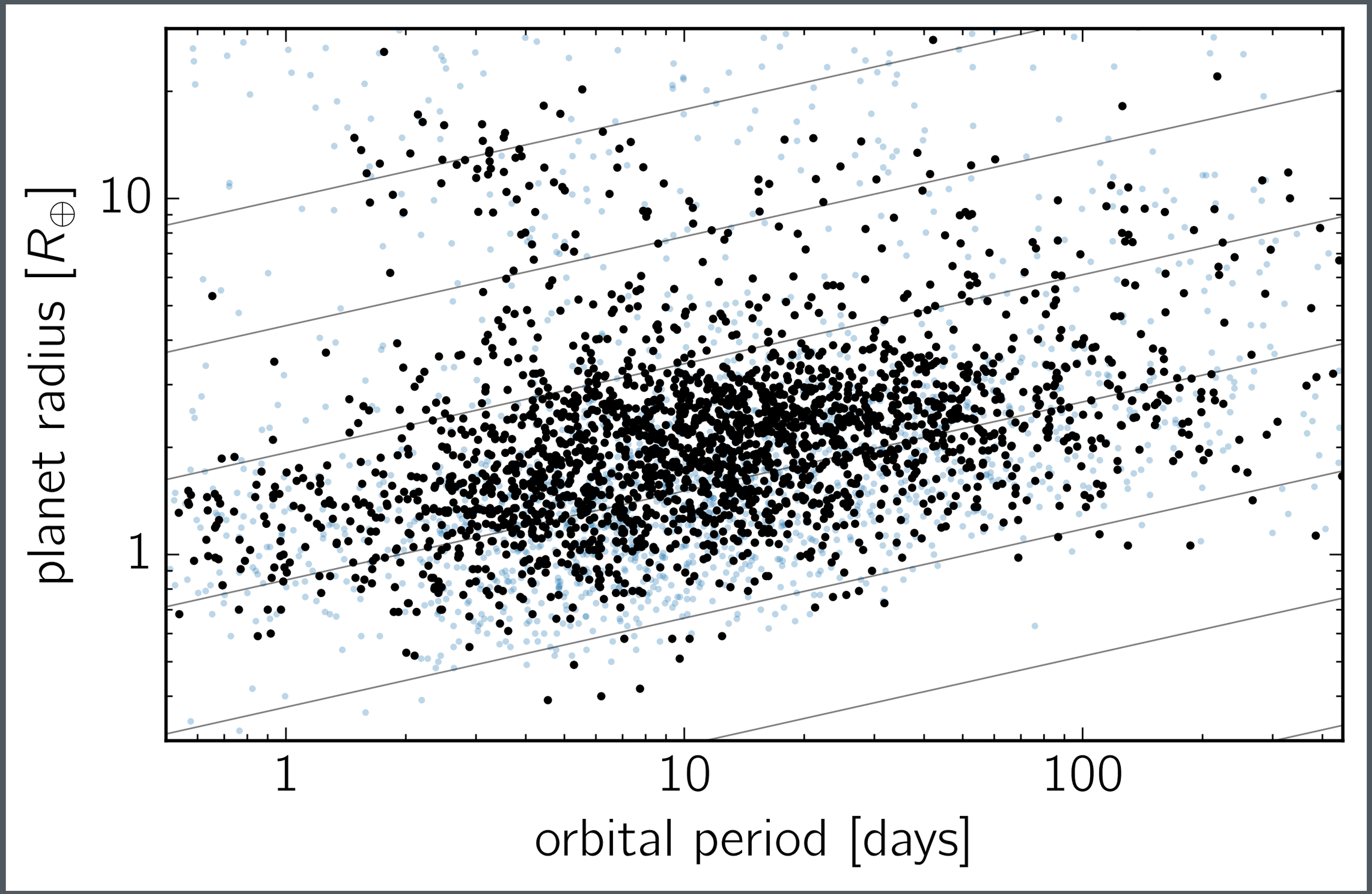
Kepler

Credit **NASA**

Kepler



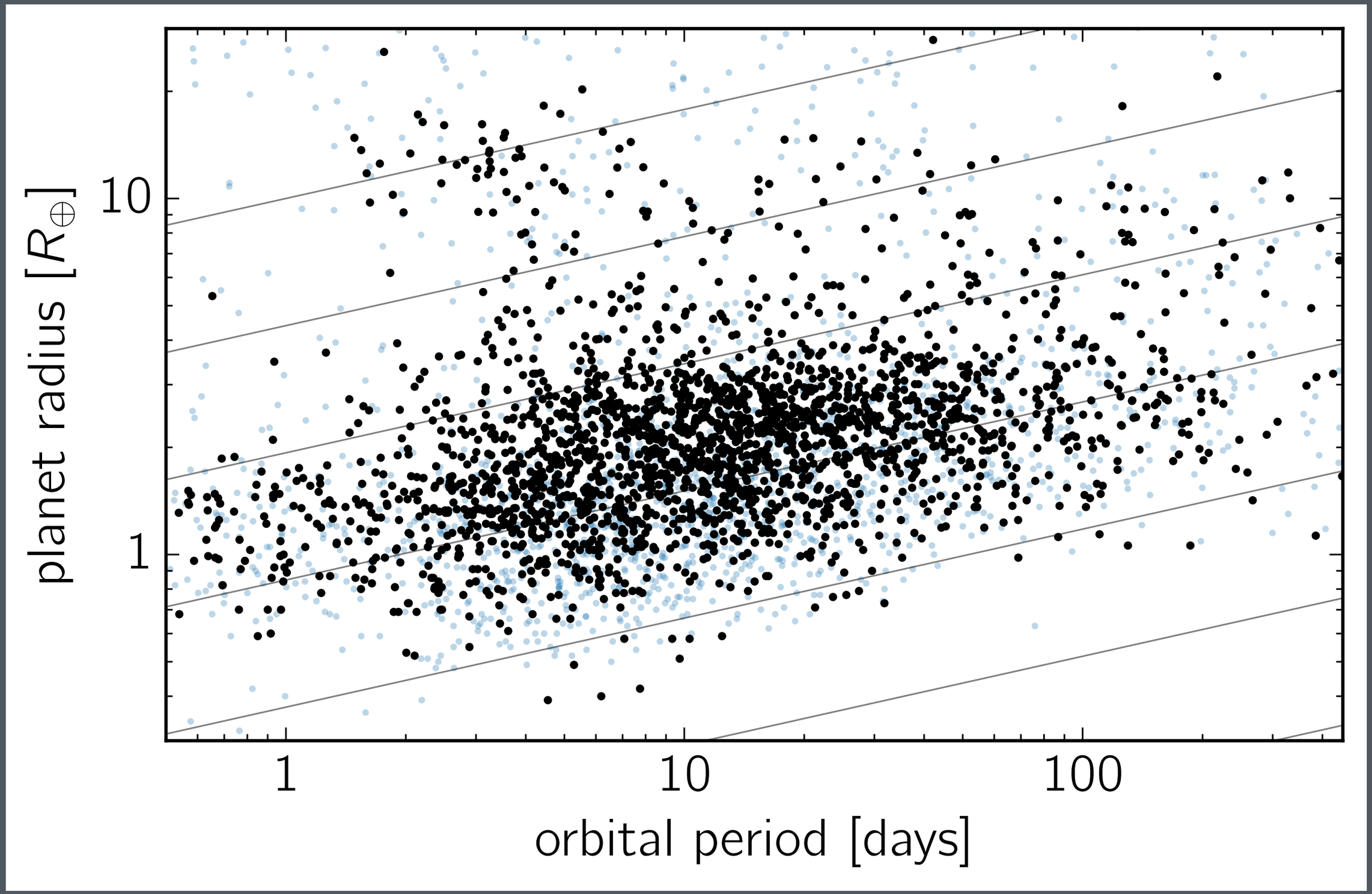
Credit **NASA**



Data from **NASA Exoplanet Archive**

Who cares?

The population of exoplanets



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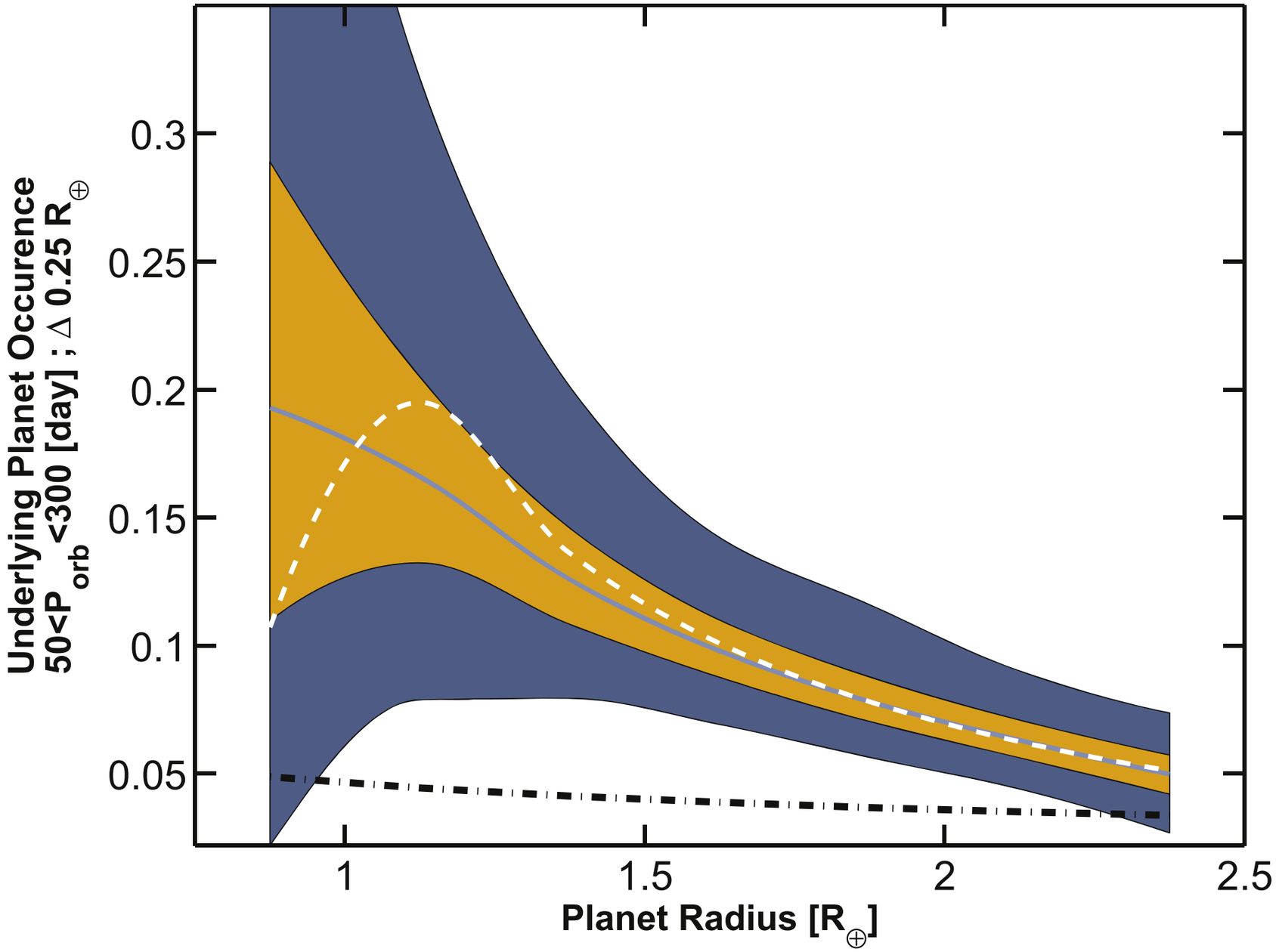
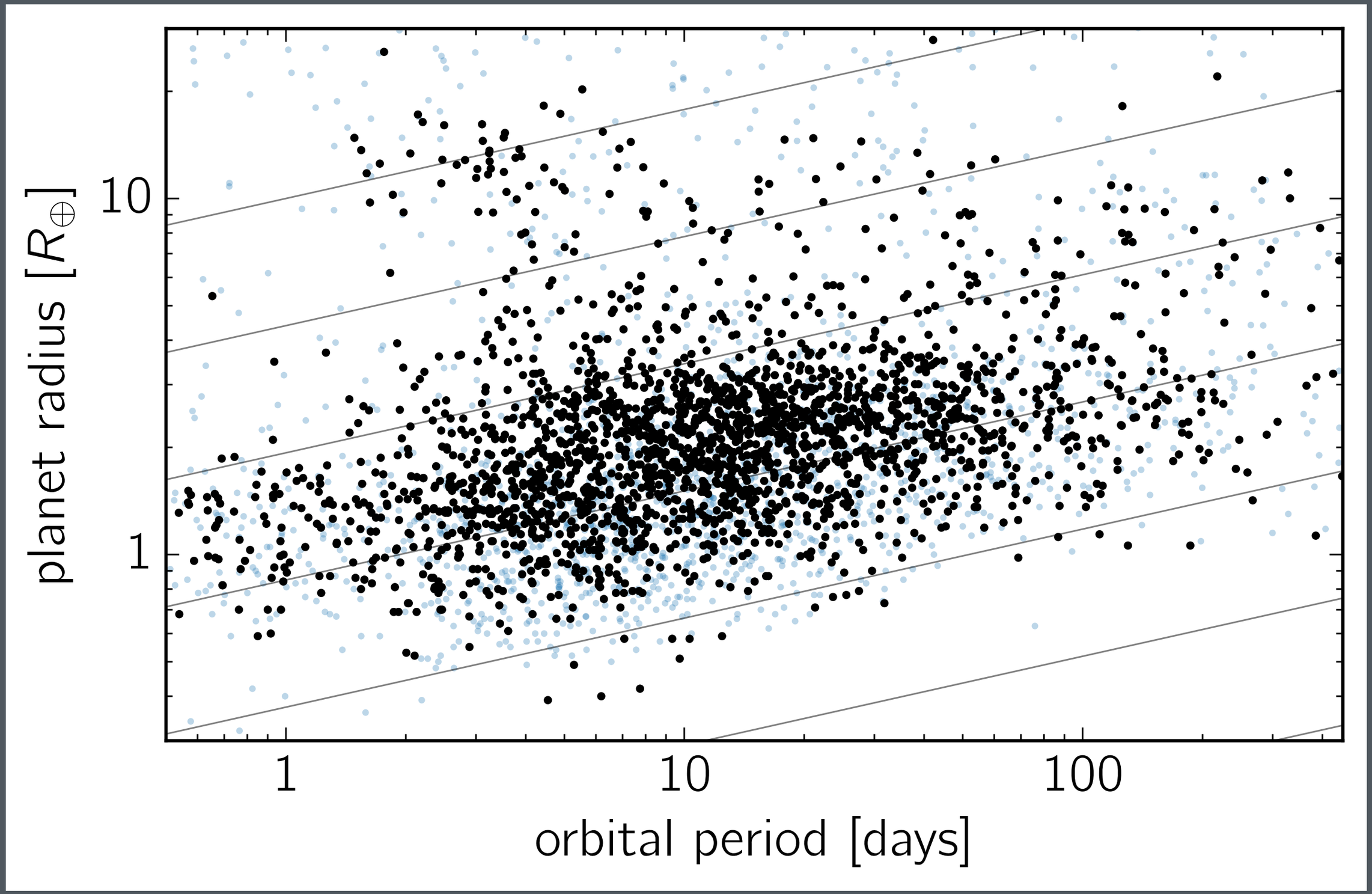


Burke *et al.* (2015)



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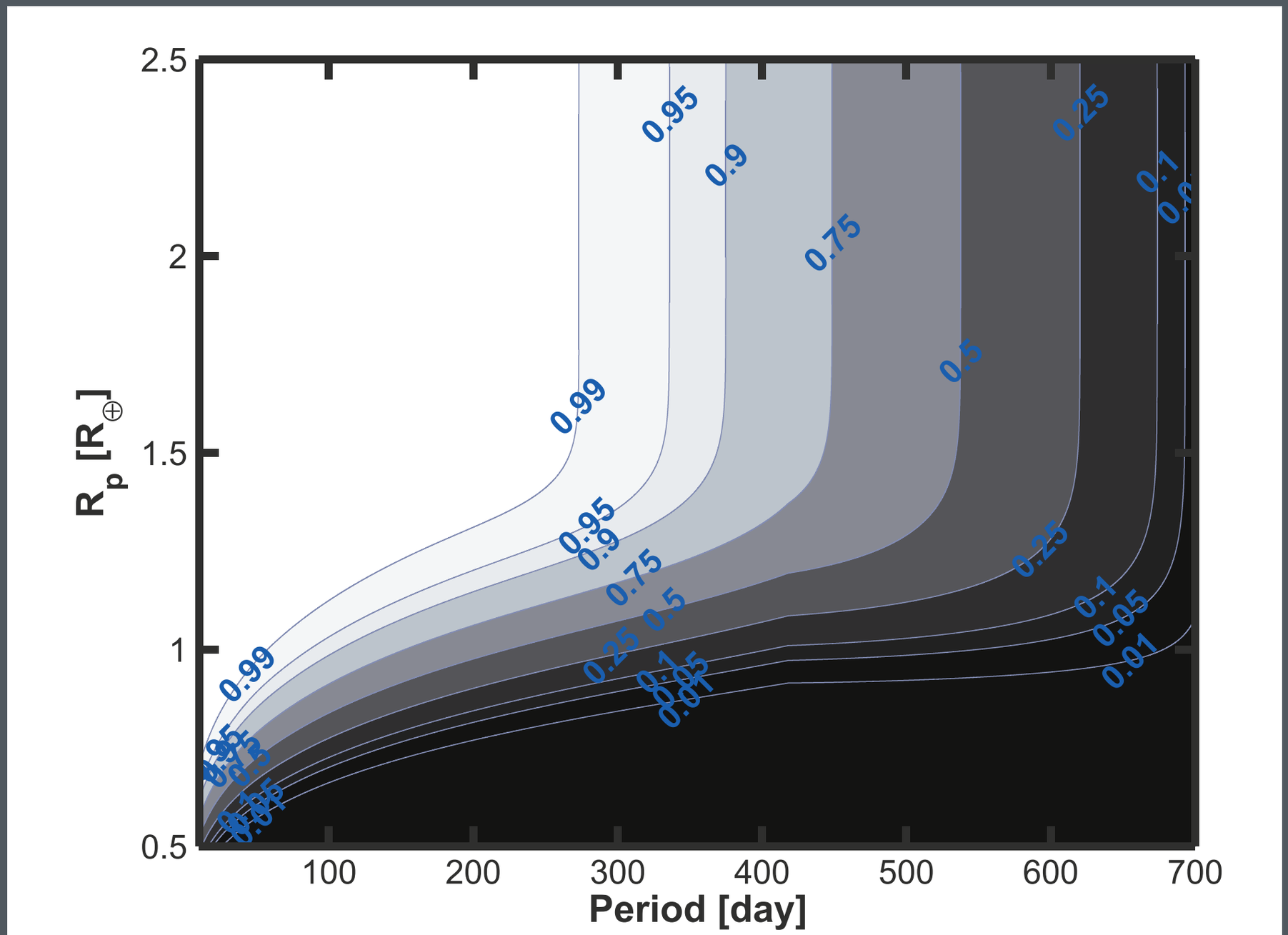
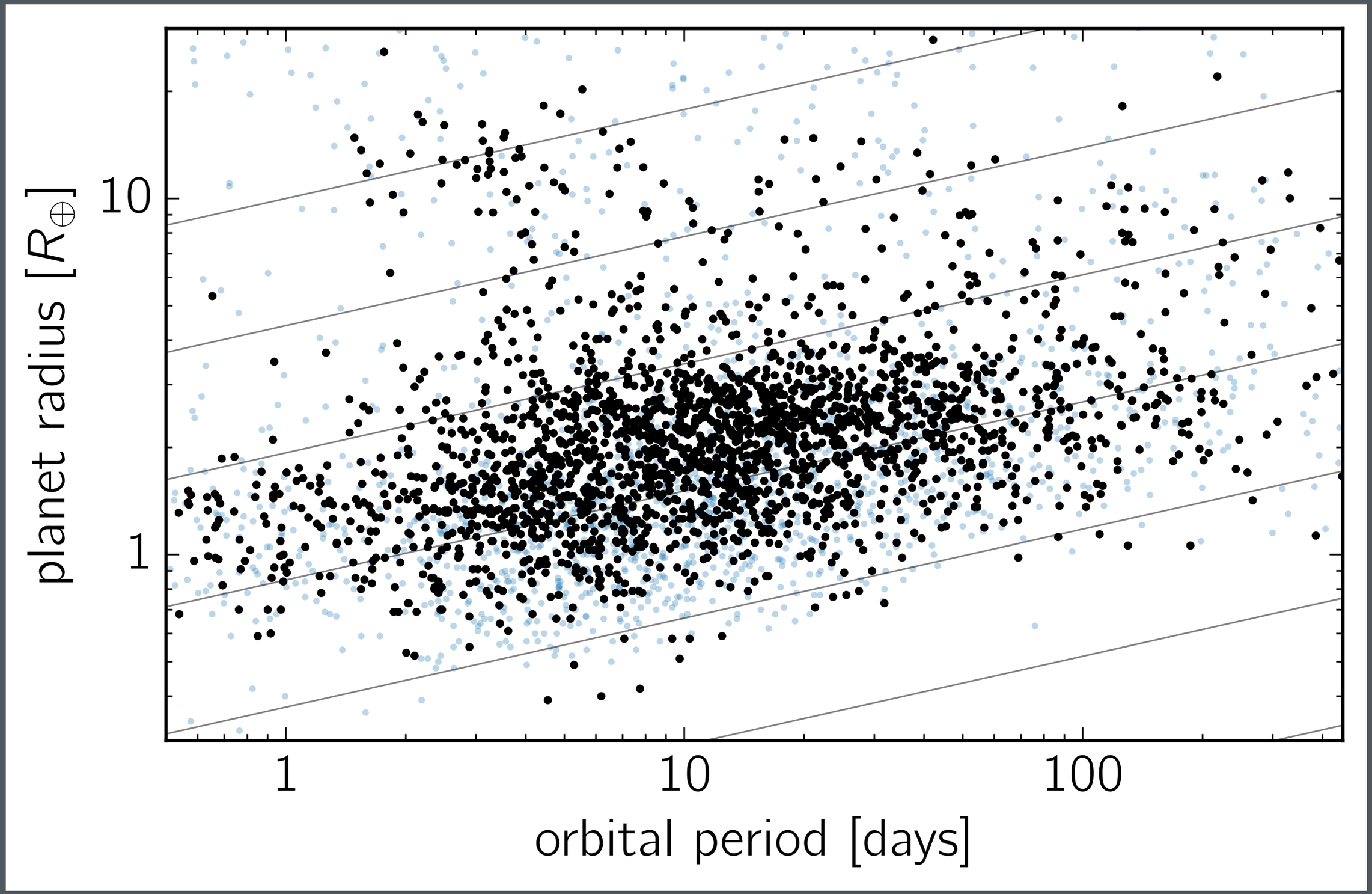
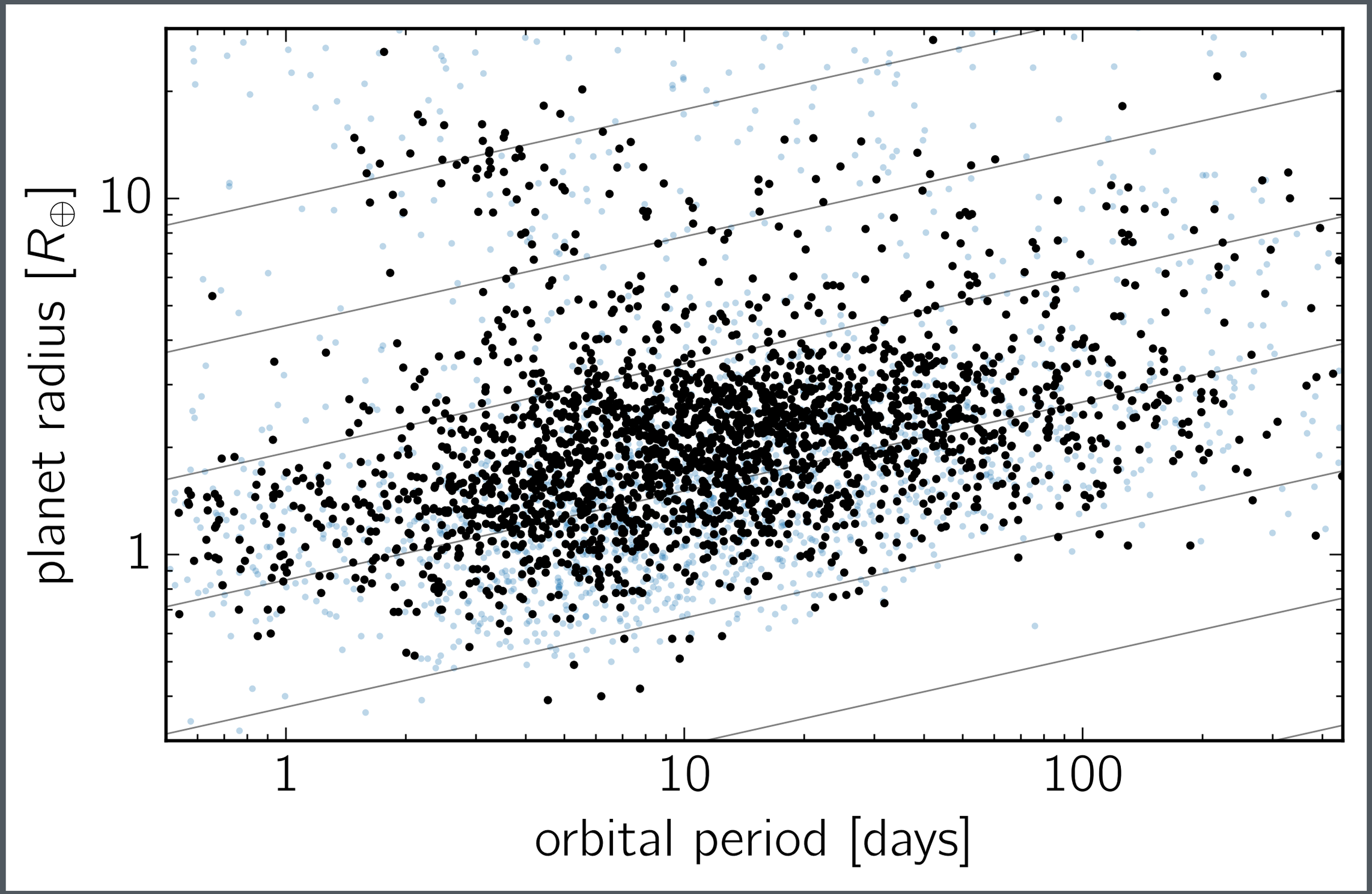


Burke *et al.* (2015)



Data from **NASA Exoplanet Archive**

The frequency of Solar System analogs



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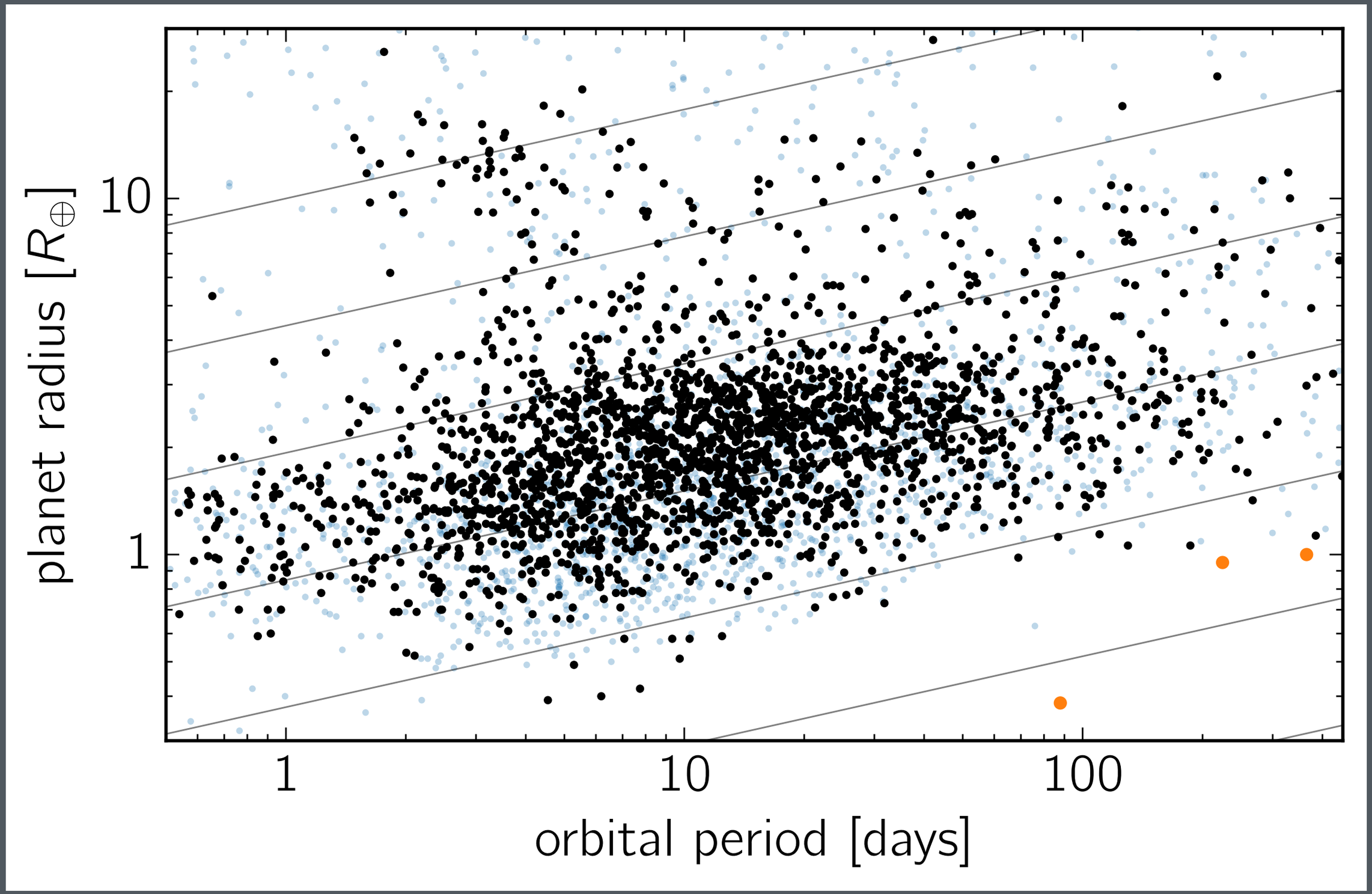

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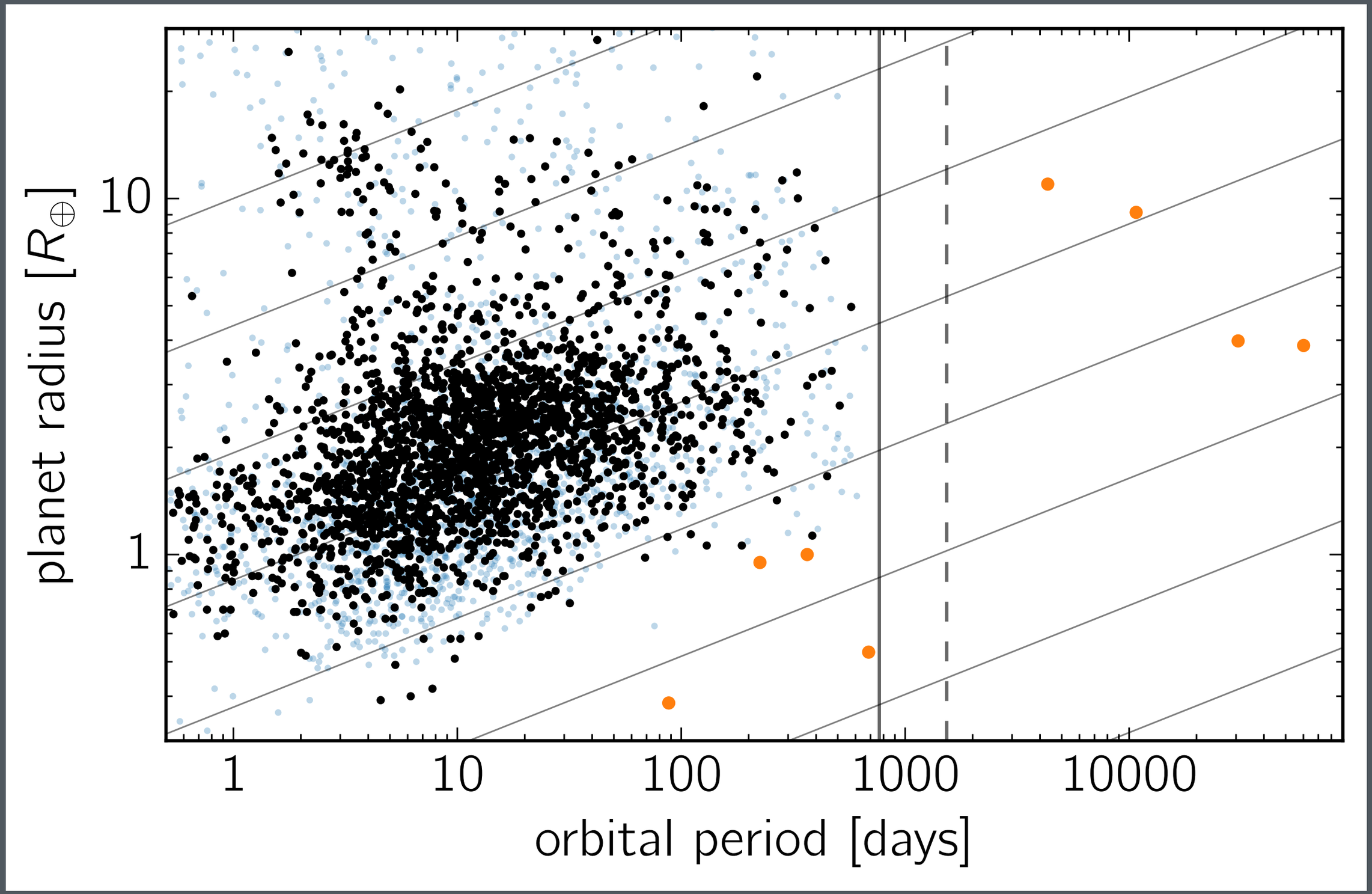

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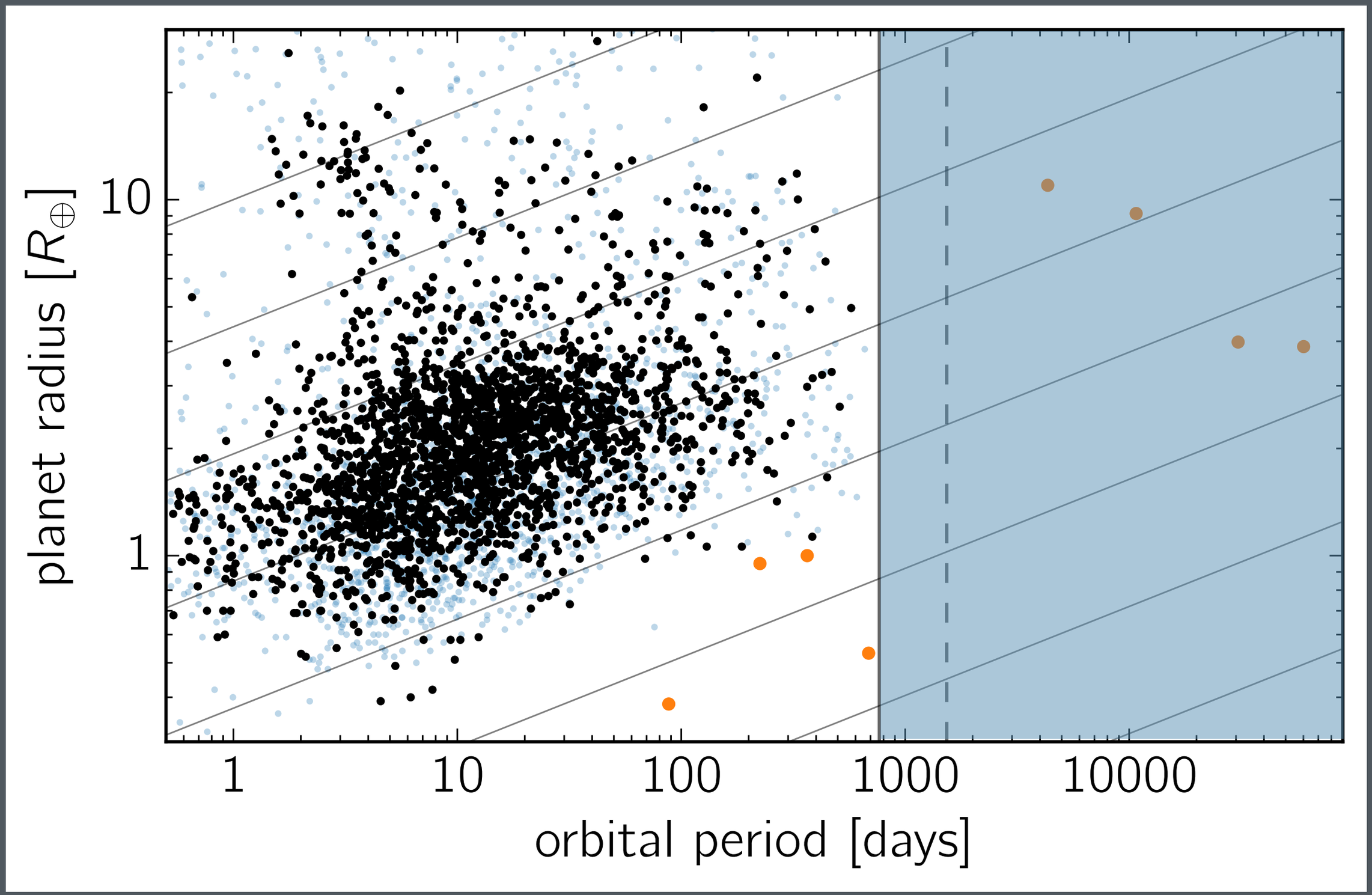


Data from **NASA Exoplanet Archive**

Why Kepler?

Why Kepler?

1. *Systematic target selection*
2. *Homogeneous stellar properties*
3. *Sensitivity to small planets*

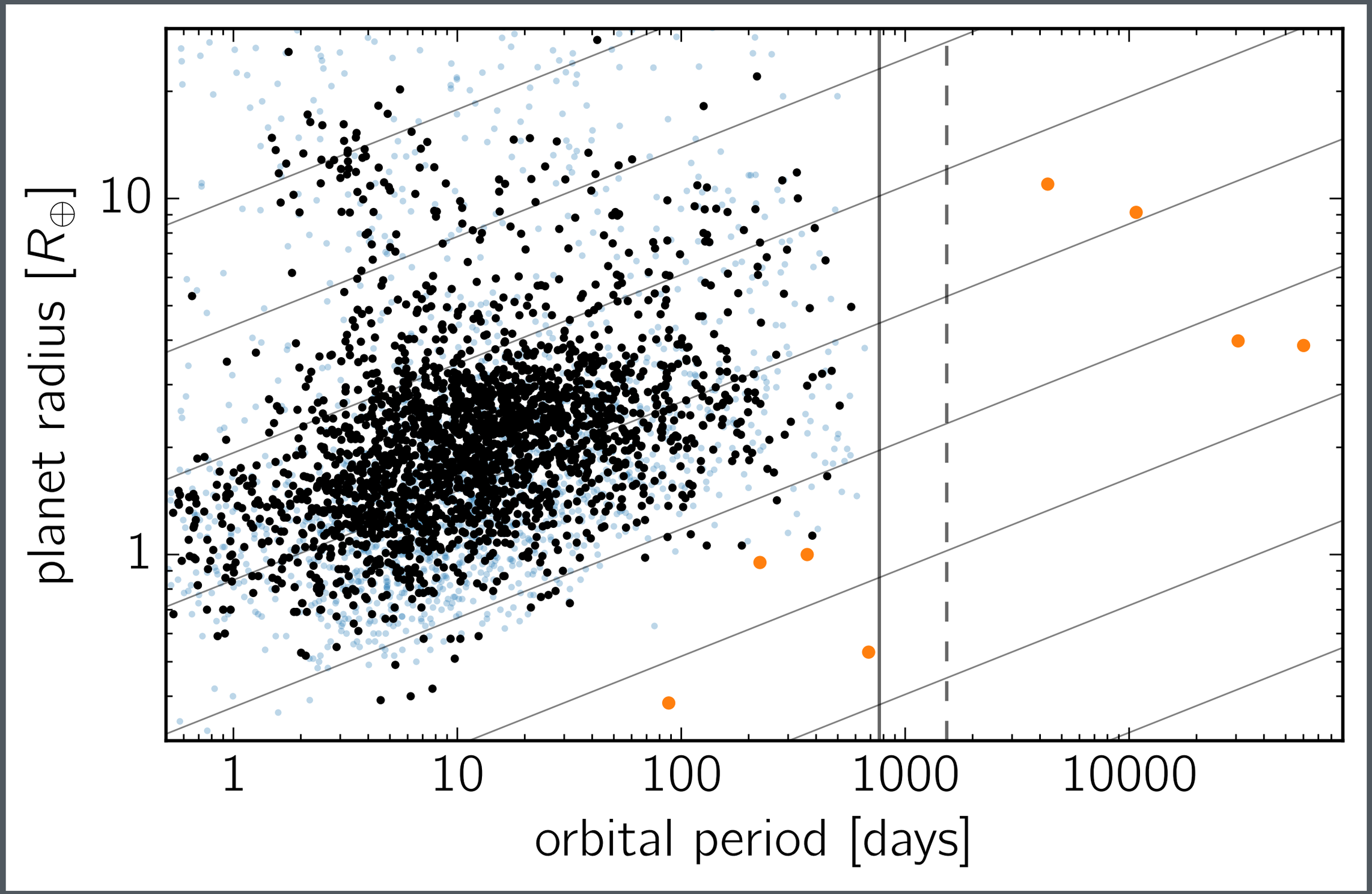
Why Kepler?

1. *Systematic target selection*
2. *Homogeneous stellar properties*
3. *Sensitivity to small planets*
4. *The data exist*

Ingredients for population inference

1. *Systematic planet candidate catalog*
2. *Measured completeness & reliability*
3. *Quantification of false positive rates*

Today's punch line



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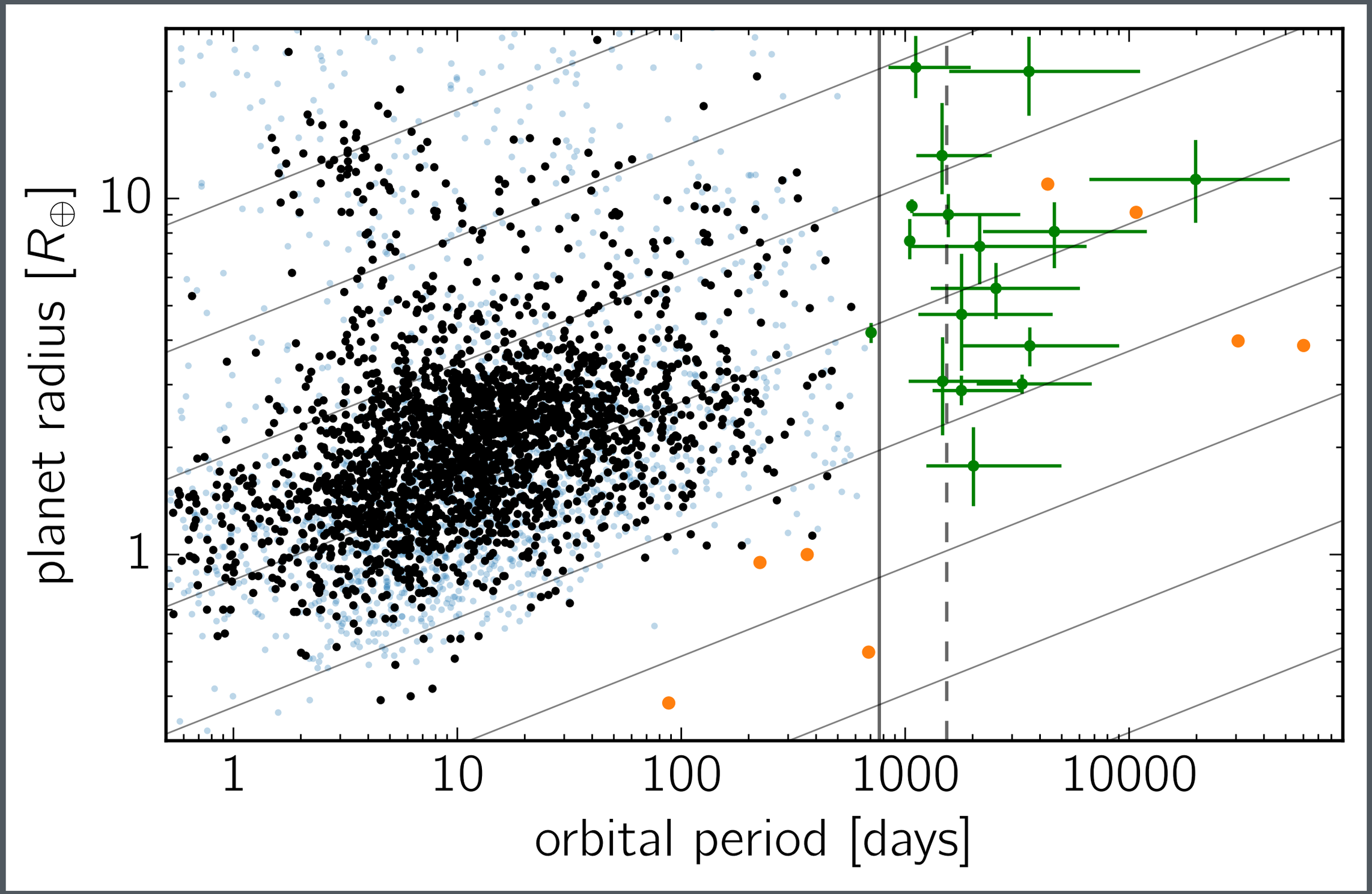
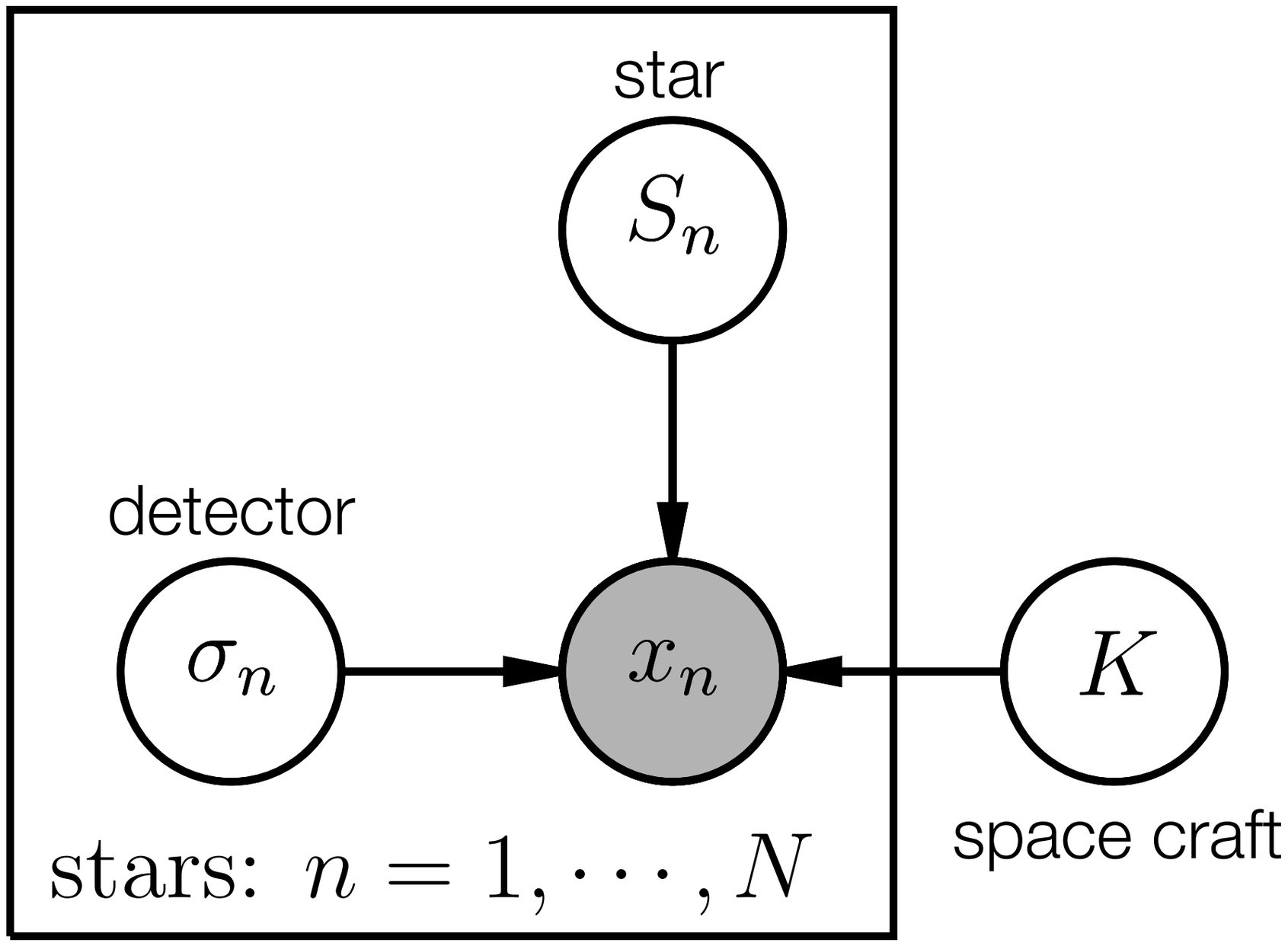


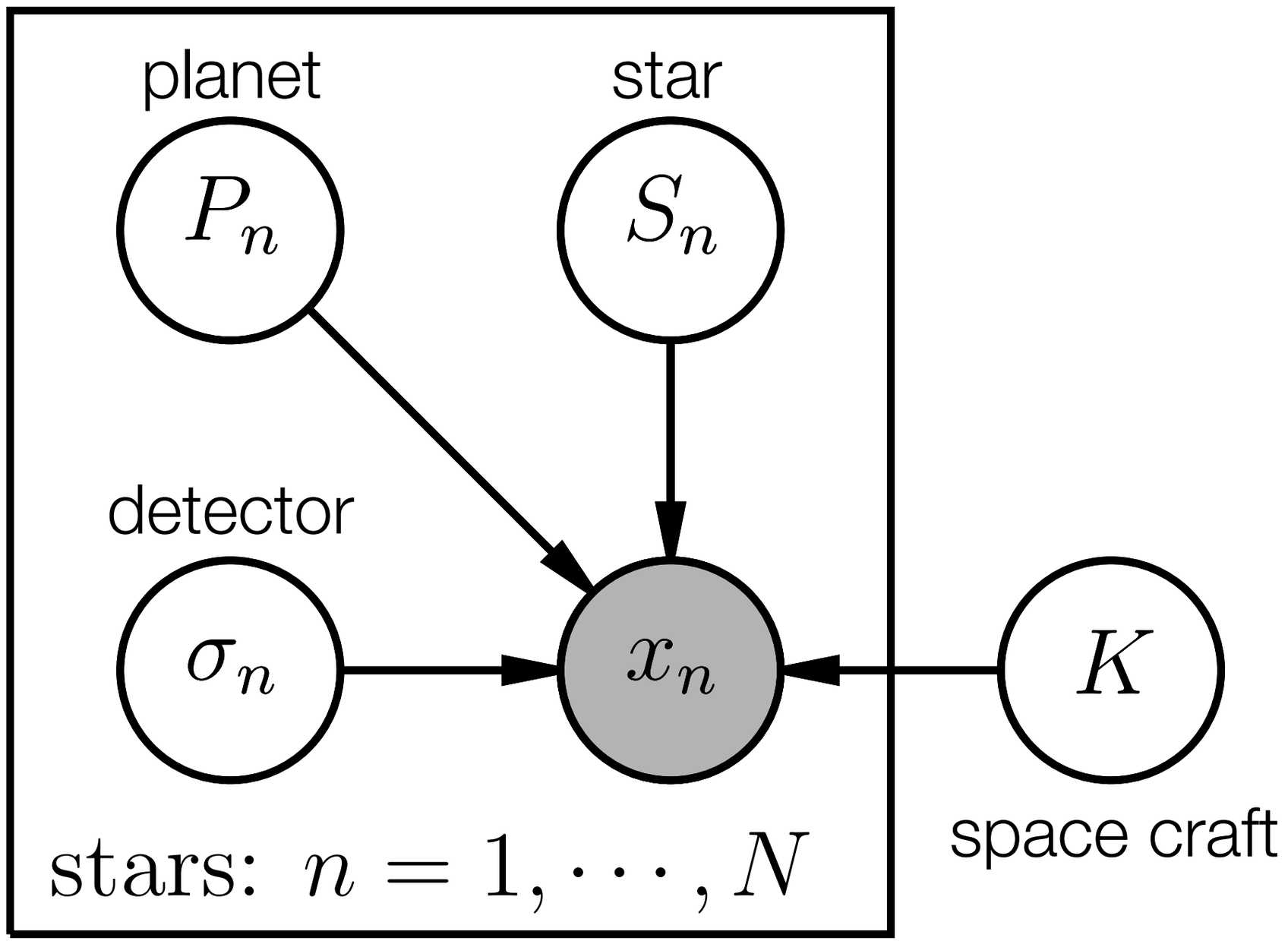
Candidates (green) from **DFM *et al.* (in prep)**; Data from **NASA Exoplanet Archive**

How to find a transiting planet…

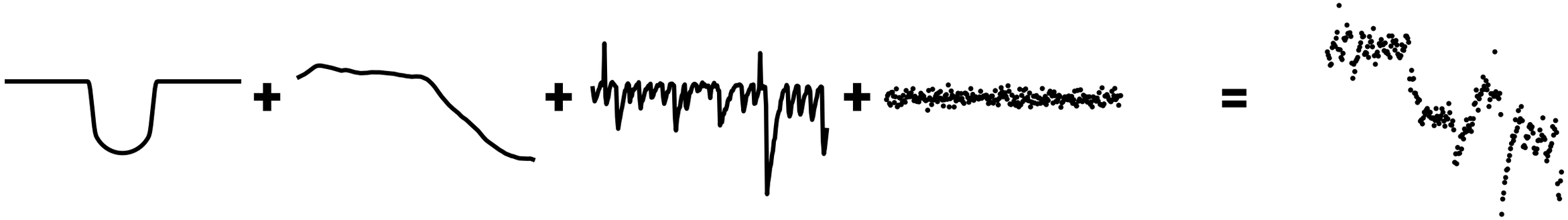
short-period

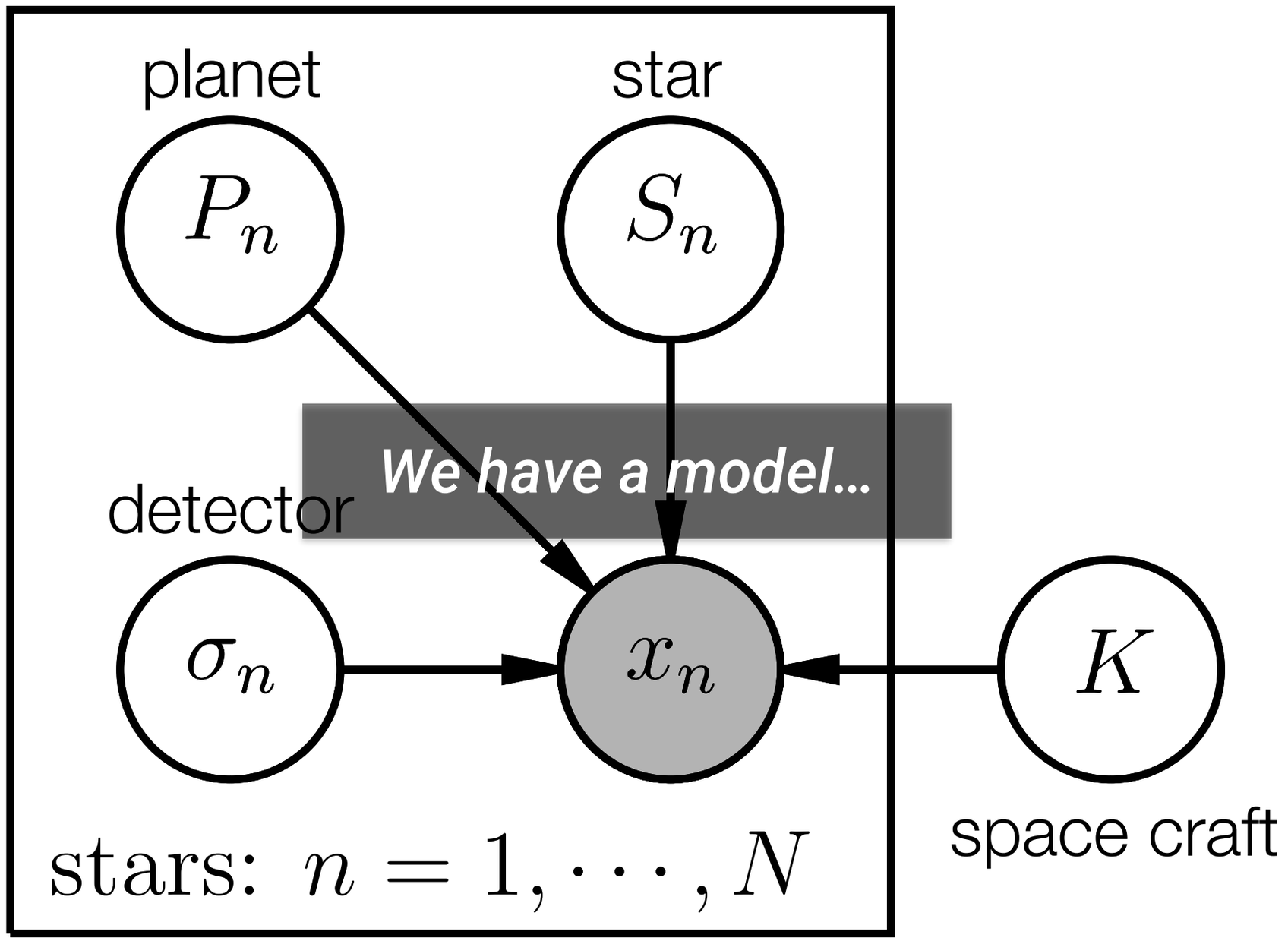
How to find a transiting planet…


star
S_n
detector
σ_n
x_n
K
space craft
stars: $n = 1, \cdots, N$


planet
star
P_n
S_n
detector
σ_n
x_n
K
space craft
stars: $n = 1, \cdots, N$

The anatomy of a transit




planet
star
P_n
S_n
We have a model...
detector
σ_n
x_n
K
space craft
stars: $n = 1, \cdots, N$

… just do the inference?

no.

How to find "short-period" transiting exoplanets

1 *Filter the data to "remove" systematics*

2 *Template-based grid of likelihoods*
(restricted to systems with >2 transits)

3 *Remove false alarms by "visual inspection"*

How to find "short-period" transiting exoplanets

1 *Filter the data to "remove" systematics*

2 *Template-based grid of likelihoods*
(restricted to systems with >2 transits)

3 *Remove false alarms using magic*

How to find "short-period" transiting exoplanets

1 *~190,000 target stars*

2 *Template-based grid of likelihoods*
(restricted to systems with >2 transits)

3 *Remove false alarms using magic*

How to find "short-period" transiting exoplanets

1 *~190,000 target stars*

2 *~35,000 candidates*

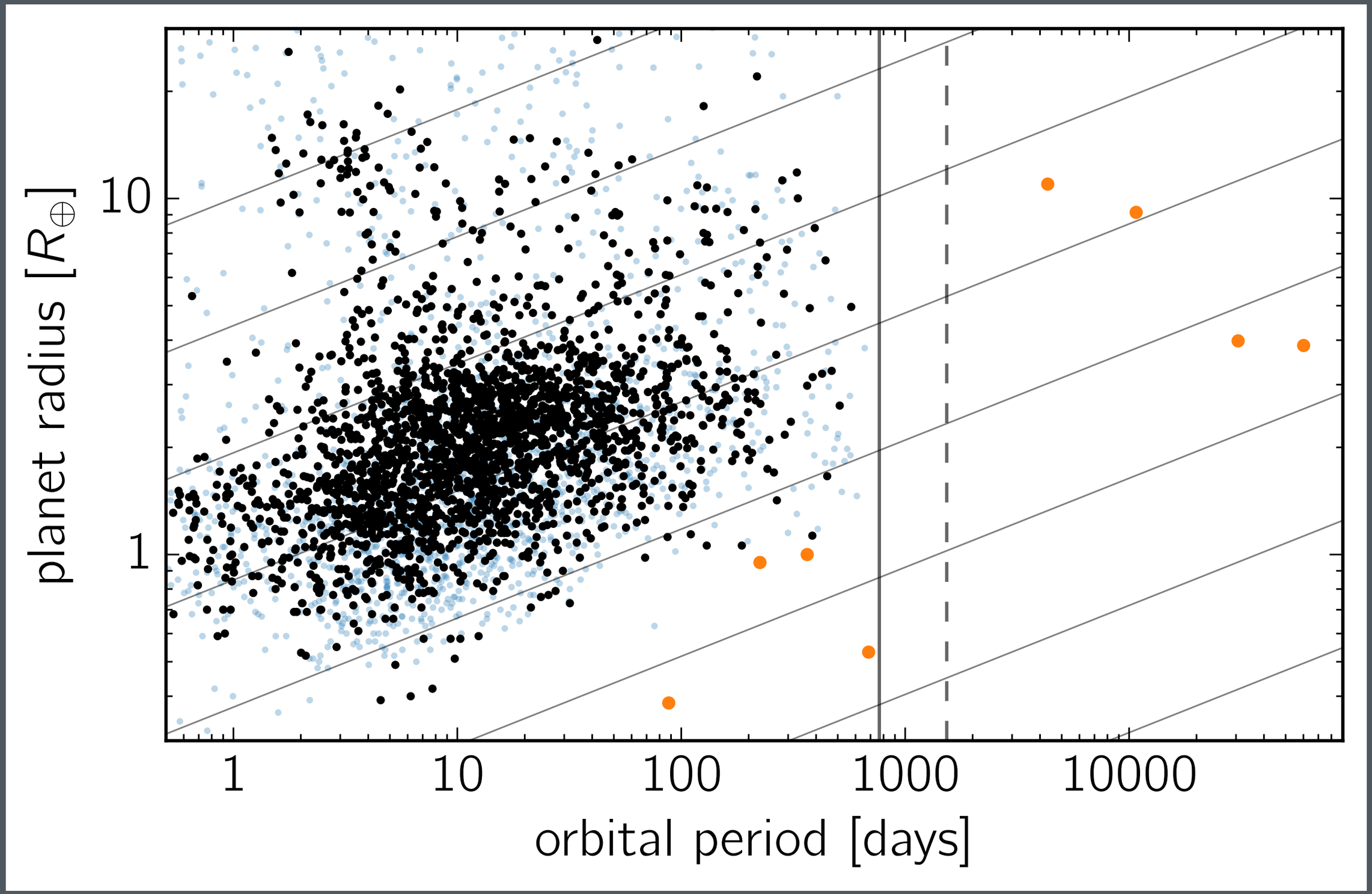
3 *Remove false alarms using magic*

How to find "short-period" transiting exoplanets

1 *~190,000 target stars*

2 *~35,000 candidates*

3 *~5,000 exoplanets*



Data from **NASA Exoplanet Archive**

How to find "long-period" transiting exoplanets

e.g. **Wang *et al.* (2015); Uehara *et al.* (2016); Kipping *et al.* (2016)**

How to find "long-period" transiting exoplanets

1

Visual inspection

e.g. **Wang *et al.* (2015); Uehara *et al.* (2016); Kipping *et al.* (2016)**

Ingredients for population inference

1. *Systematic planet candidate catalog*
2. *Measured completeness & reliability*
3. *Quantification of false positive rates*

Ingredients for population inference

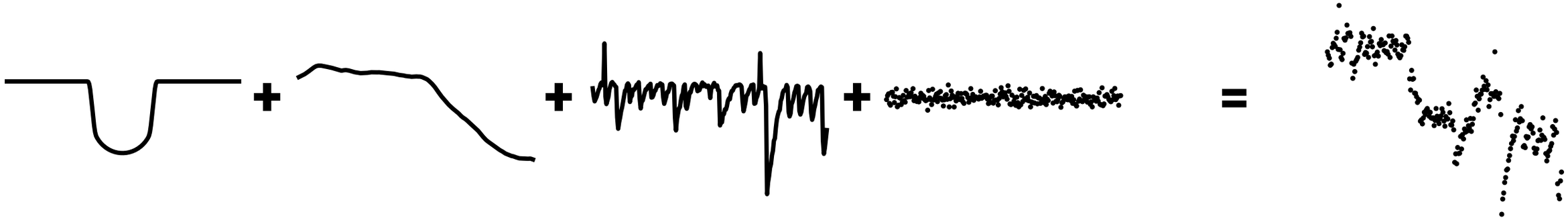
1 *A fully-automated detection method*

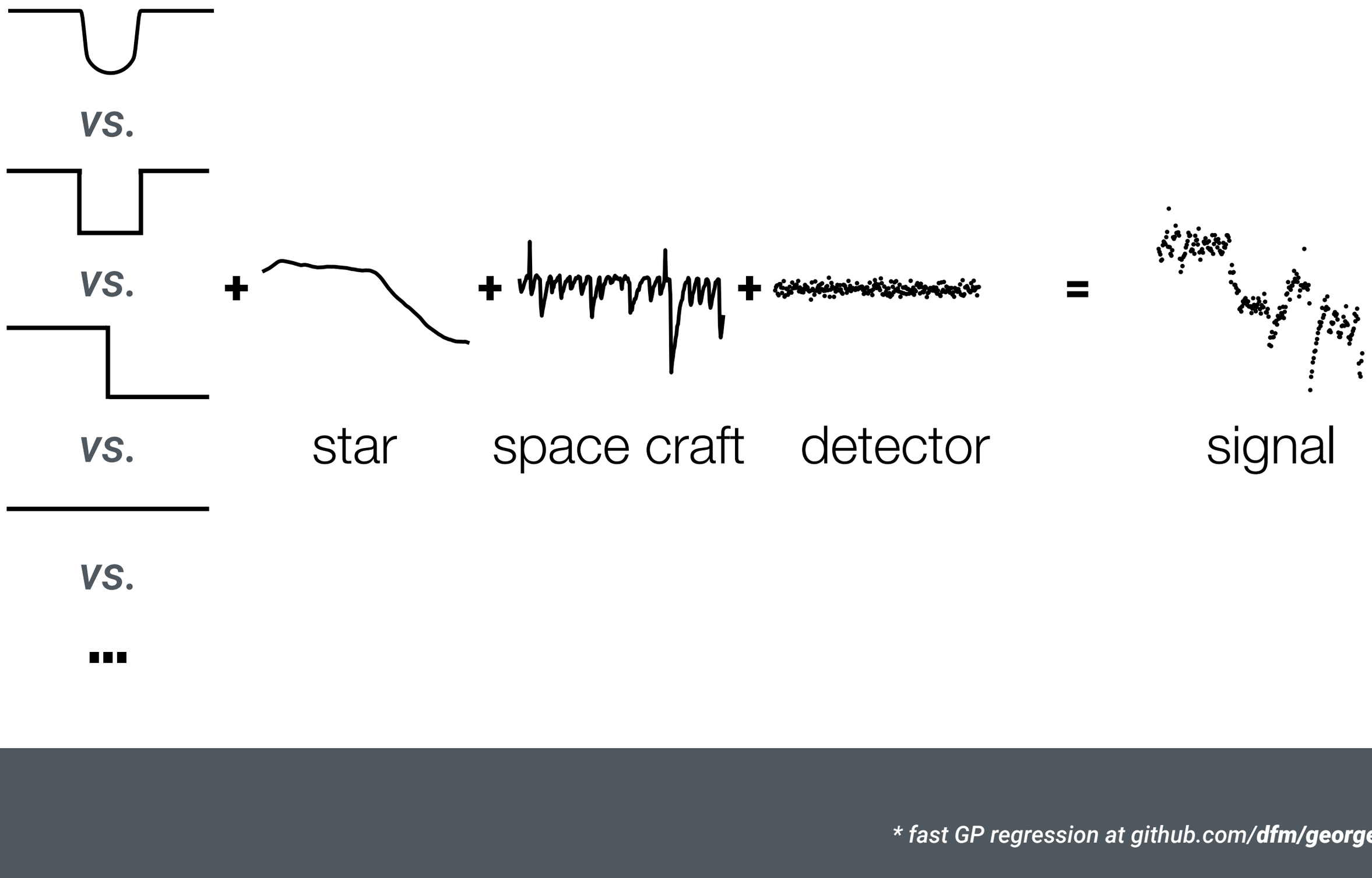
My method for finding long-period transiting planets

1 *Filter the data to "remove" systematics*

2 *Template-based grid of likelihoods*
(restricted to high signal-to-noise candidates)

3 *Remove false alarms using model comparison*


+
+
+
=
planet
star
space craft
detector
signal

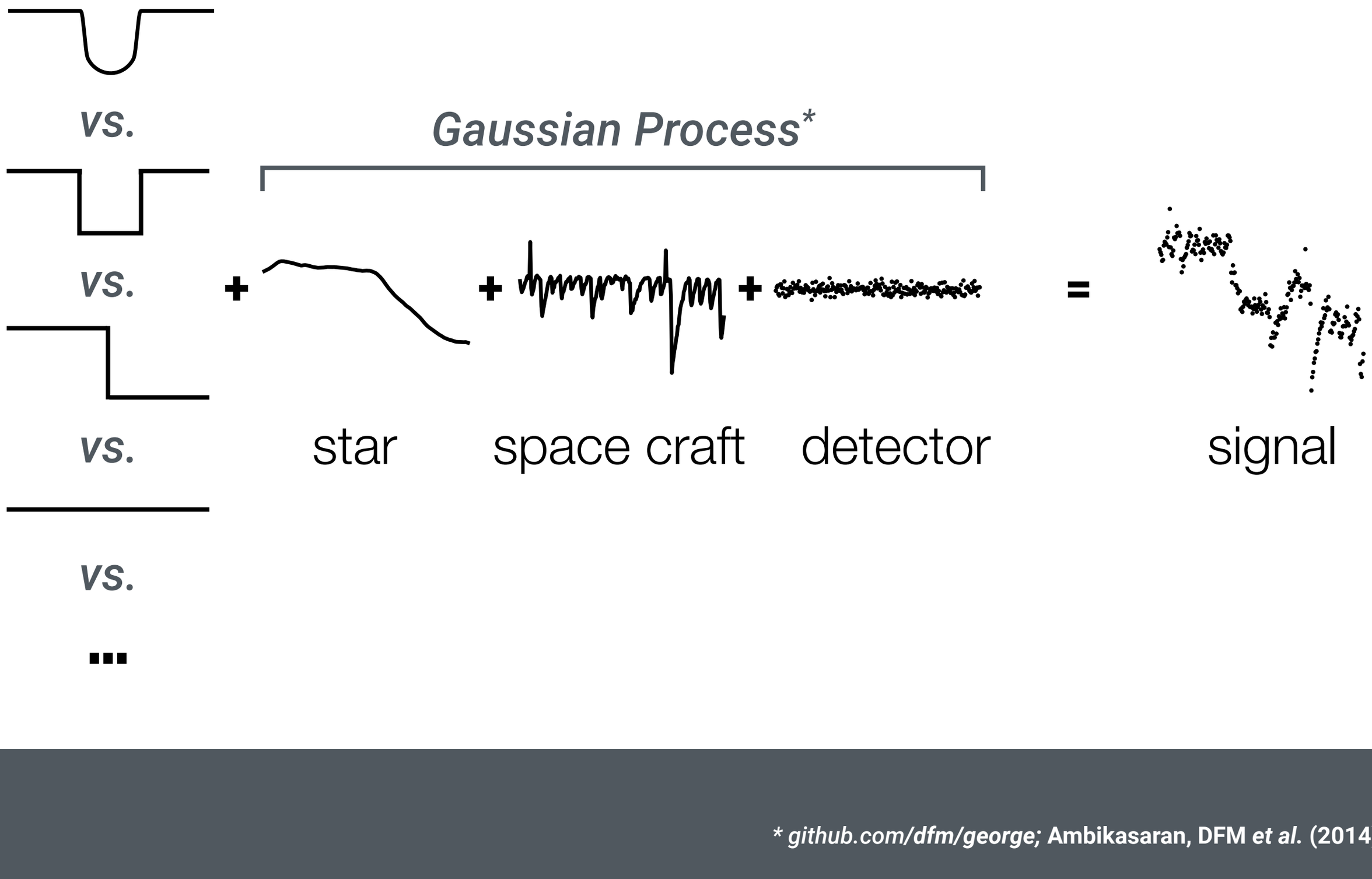


** fast GP regression at github.com/**dfm/george***

Still too expensive…

*...use BIC**

* don't take this slide out of context



* *github.com/dfm/george;* **Ambikasaran, DFM *et al.* (2014)**

Autodiff

vs.

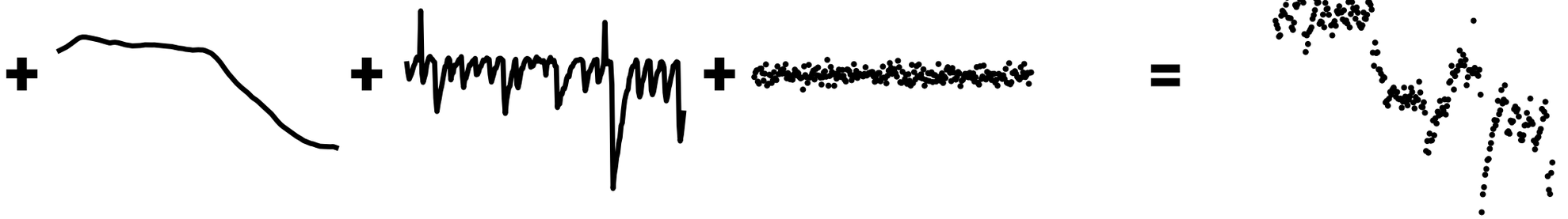
vs.

vs.

vs.

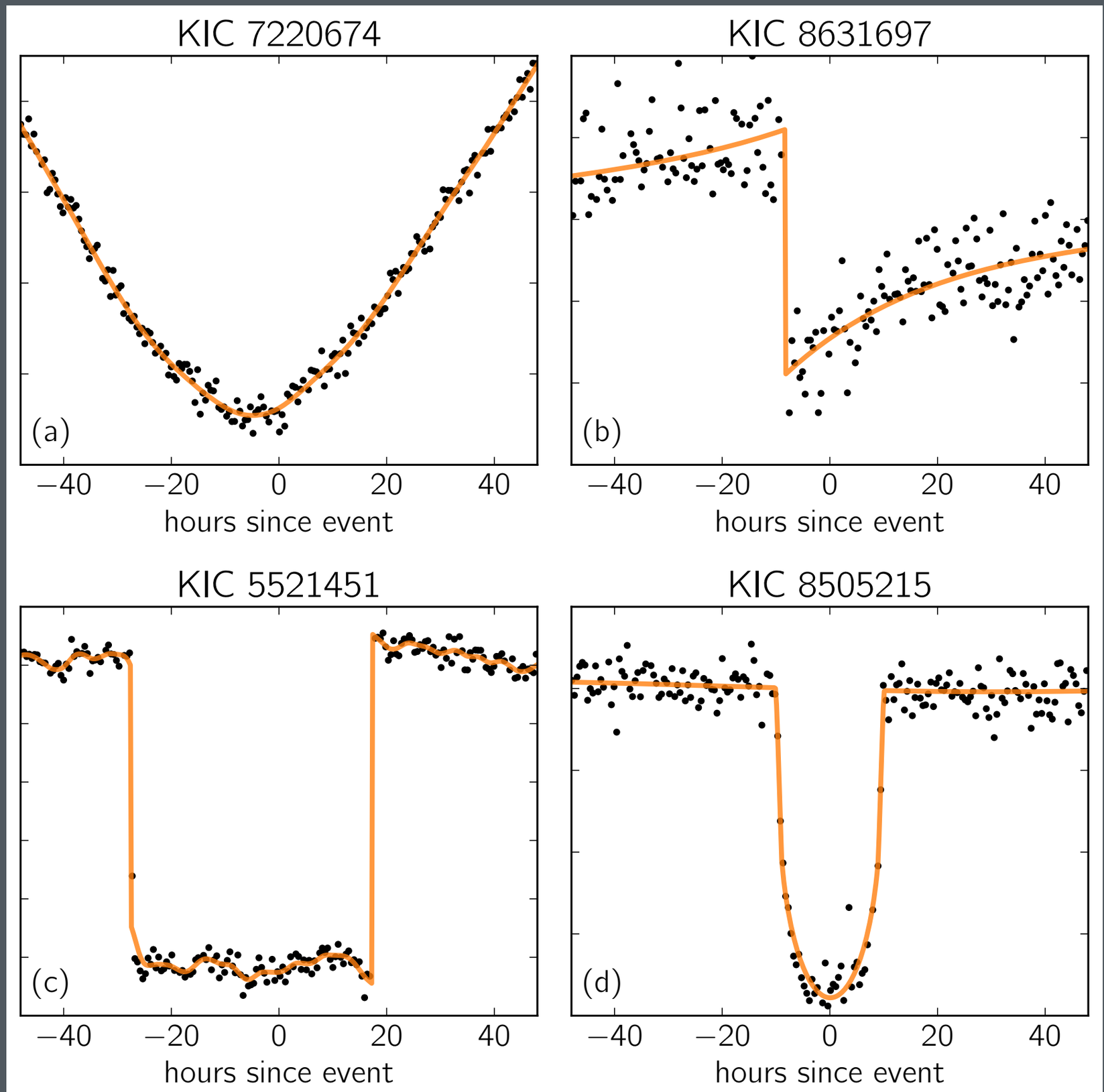
...

*Gaussian Process**



star space craft detector signal

* *github.com/dfm/george;* **Ambikasaran, DFM *et al.* (2014)**



DFM *et al.* (in prep)

Why not Machine Learning?

(e.g. supervised classification)

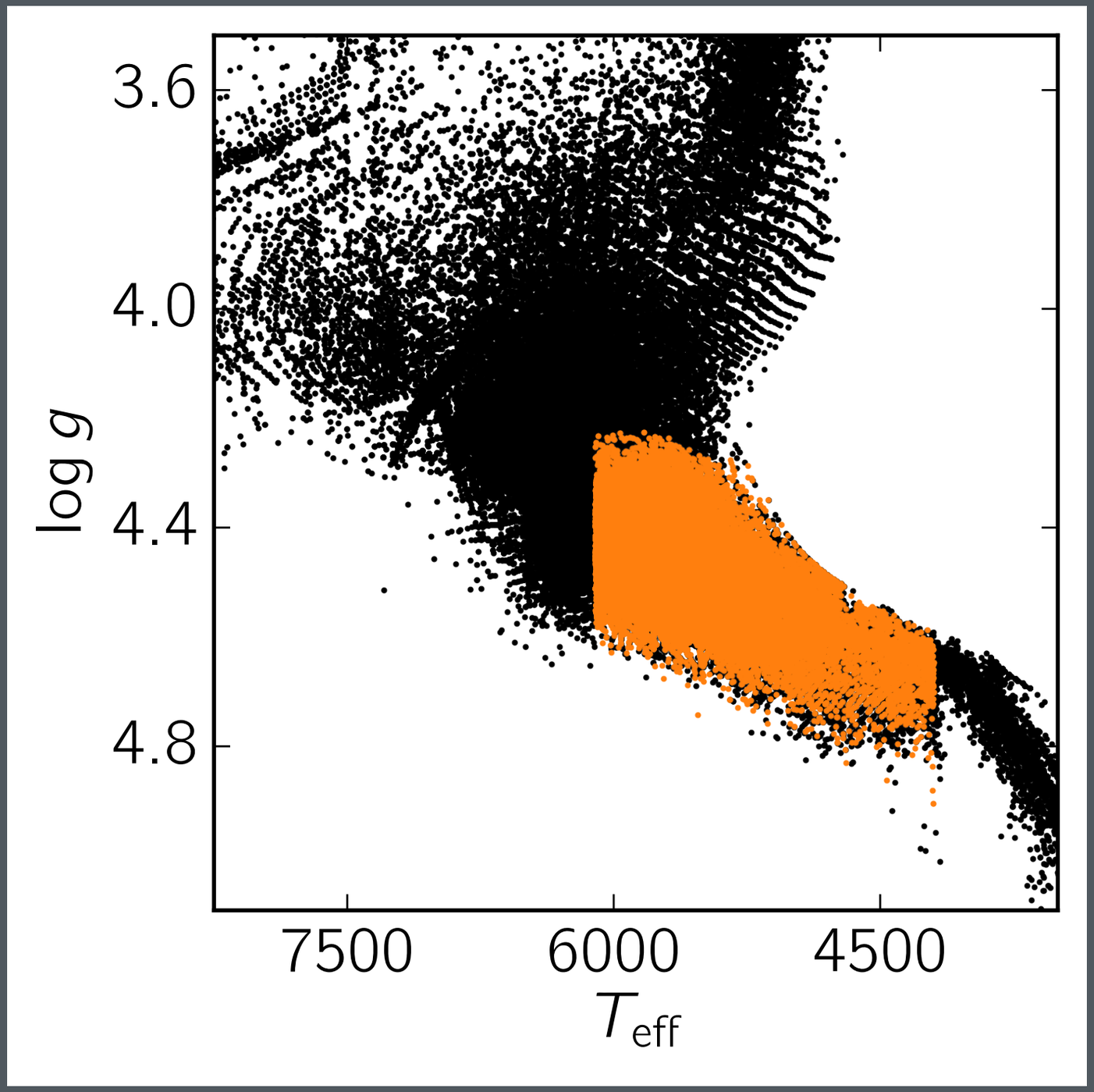
The Kepler data are not Big™.

all but ~0.02% of

*The Kepler data are Boring™.**

** don't quote me*

Results



DFM *et al.* (in prep)

My method for finding long-period transiting planets

1 *Filter the data to "remove" systematics*

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(restricted to high signal-to-noise candidates)

3 *Remove false alarms using model comparison*

My method for finding long-period transiting planets

1 *~40,000 target stars*

2 *Template-based grid of likelihoods*
(restricted to high signal-to-noise candidates)

3 *Remove false alarms using model comparison*

My method for finding long-period transiting planets

1 *~40,000 target stars*

2 *~4,000 candidates*

3 *Remove false alarms using model comparison*

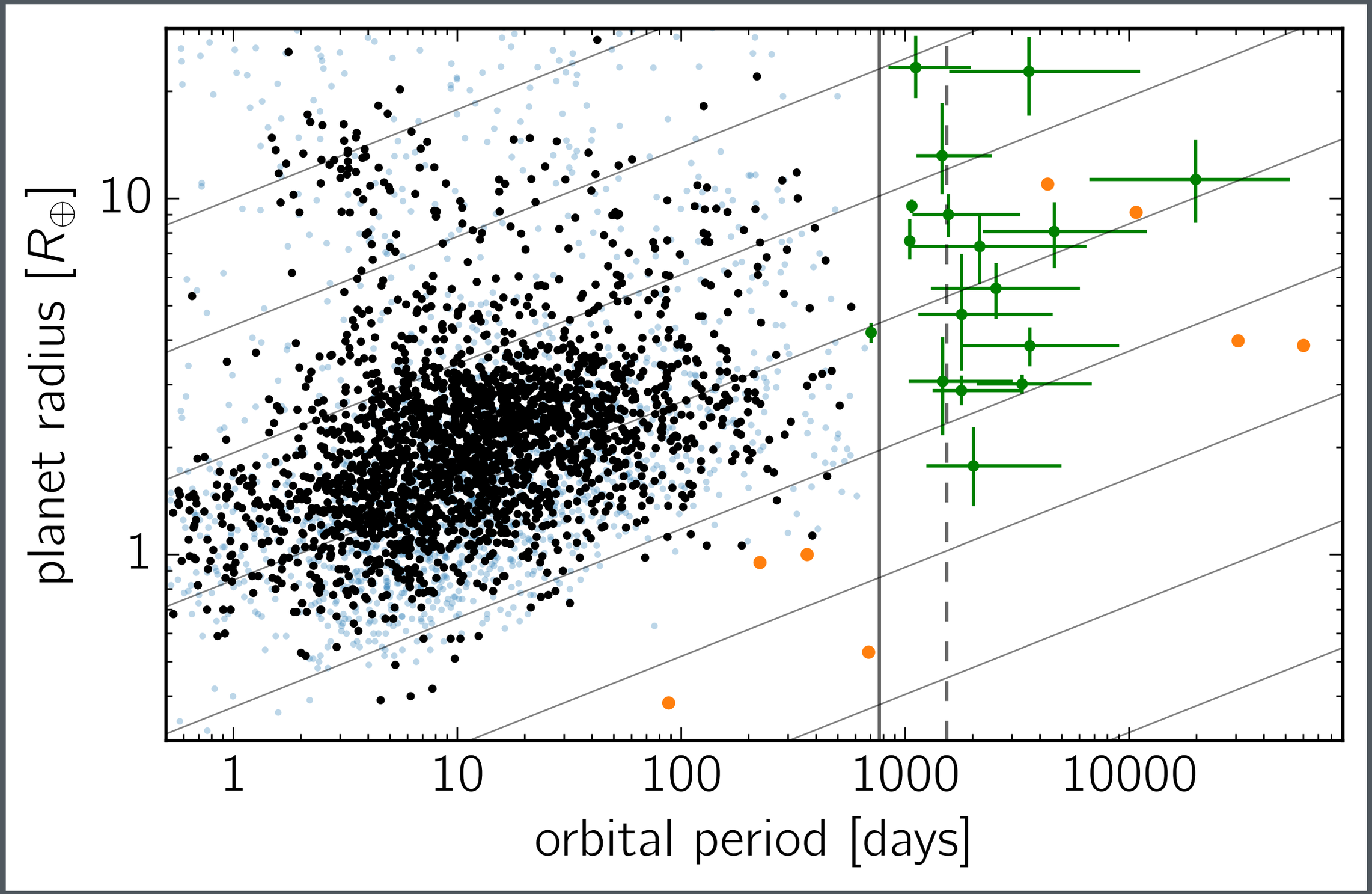
My method for finding long-period transiting planets

1 *~40,000 target stars*

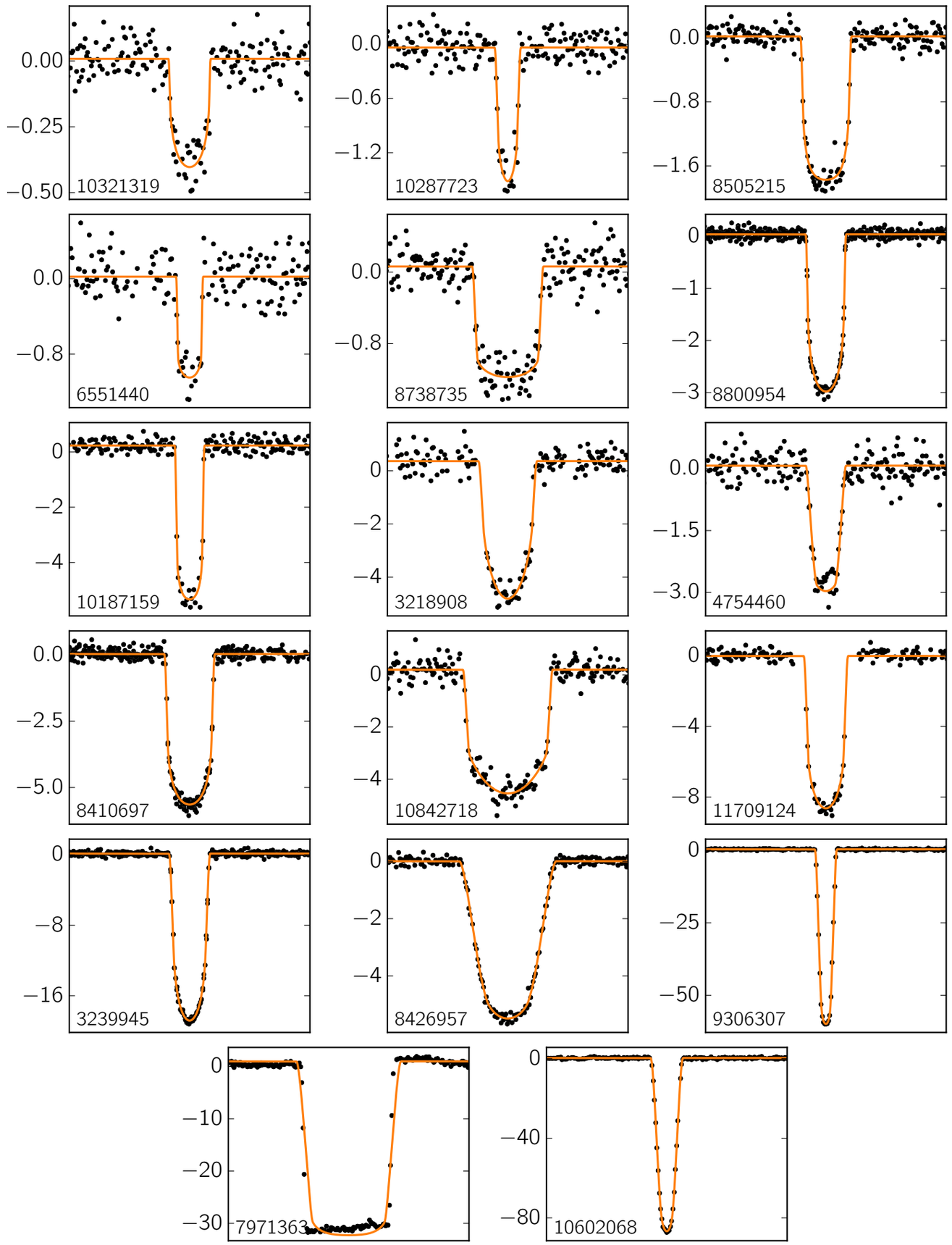
2 *~4,000 candidates*

3 *17 exoplanets**

** some contamination from EB secondary eclipses*



Candidates (green) from **DFM *et al.* (in prep)**; Data from **NASA Exoplanet Archive**



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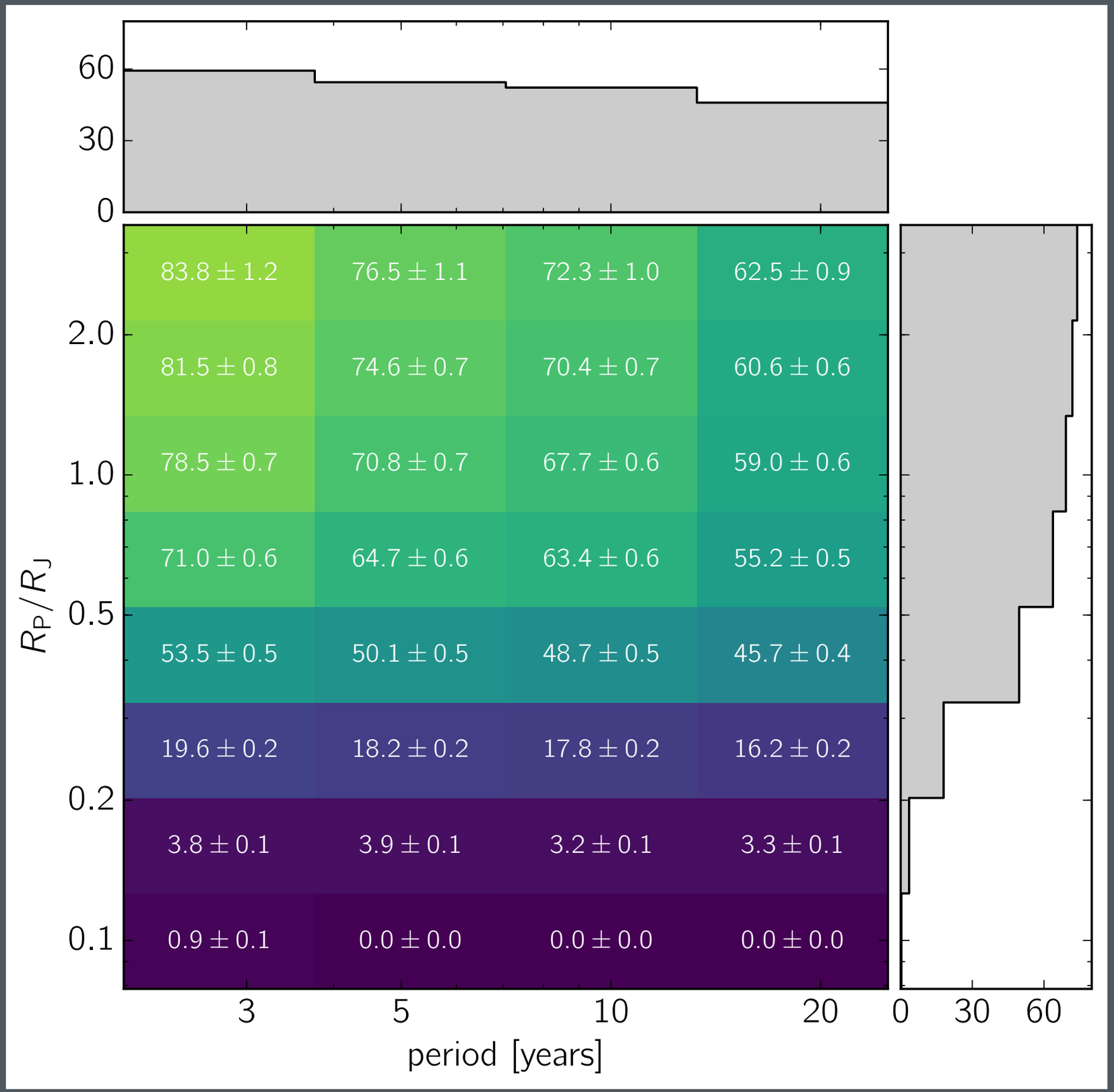

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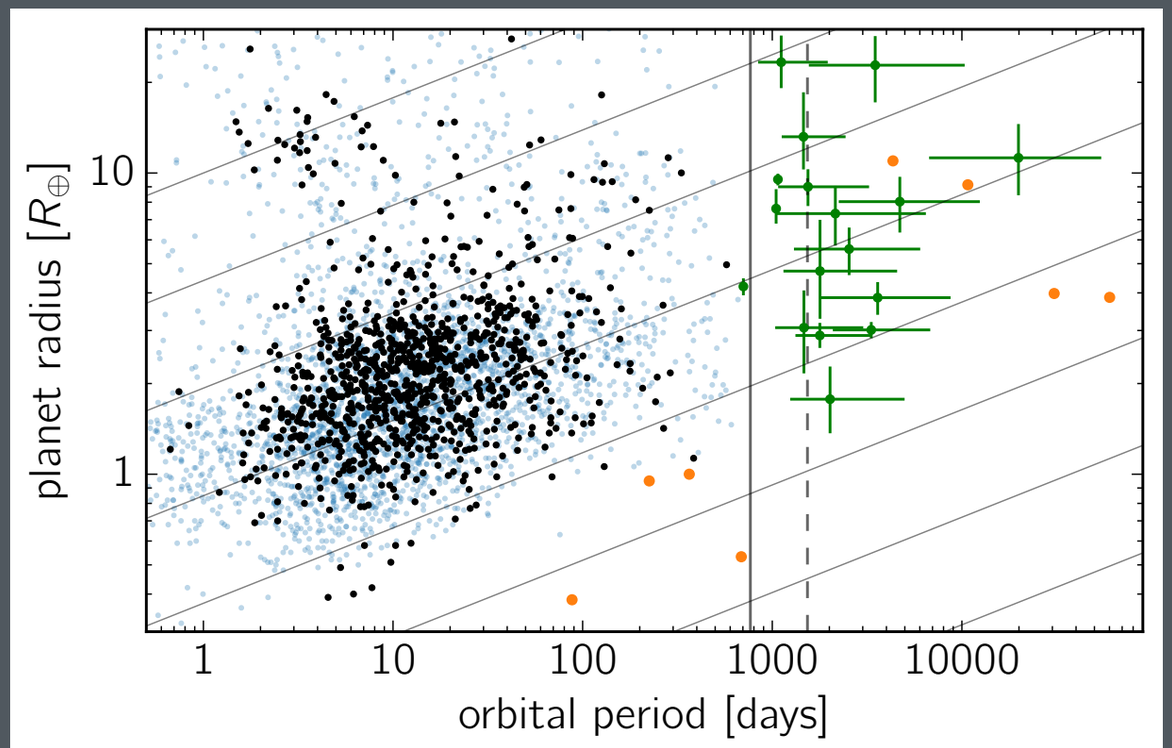
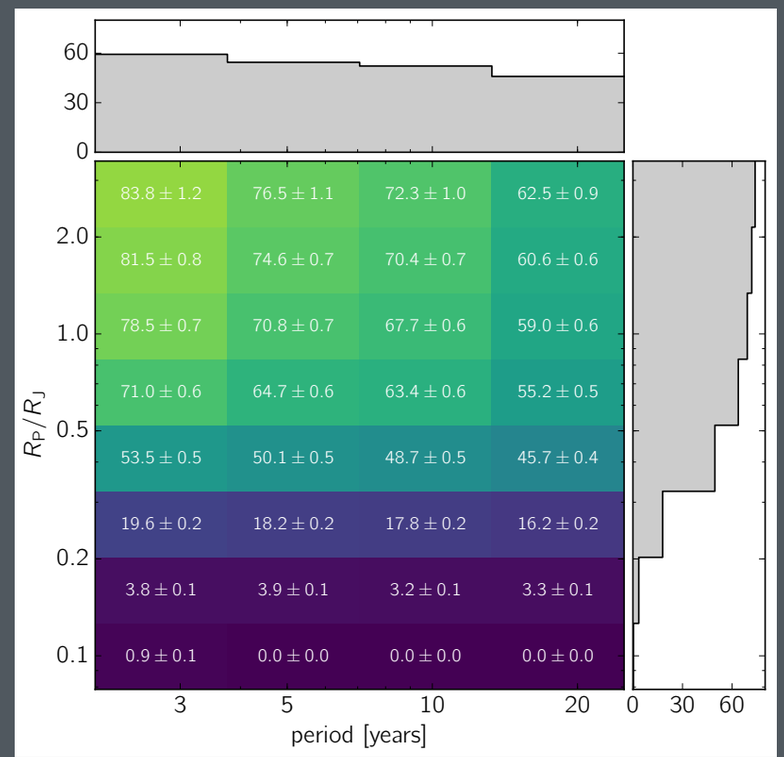


+



Candidates (green) from **DFM *et al.* (in prep)**; Data from **NASA Exoplanet Archive**

occurrence rate in period range 2 – 25 years

$R_E - R_N$	$R_N - R_J$
~0.40	~0.17

per G/K- dwarf, per ln-radius, per ln-period

DFM *et al.* (in prep)
compare with **Bryan *et al.* (2016); Shvartzvald *et al.* (2016)**

Summary

1. *Fully automated discovery of long-period transiting exoplanets in Kepler archival data*

2. *Empirical measurement of search completeness*

3. *Estimate of the occurrence rate of long-period exoplanets*

Dan Foreman-Mackey
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