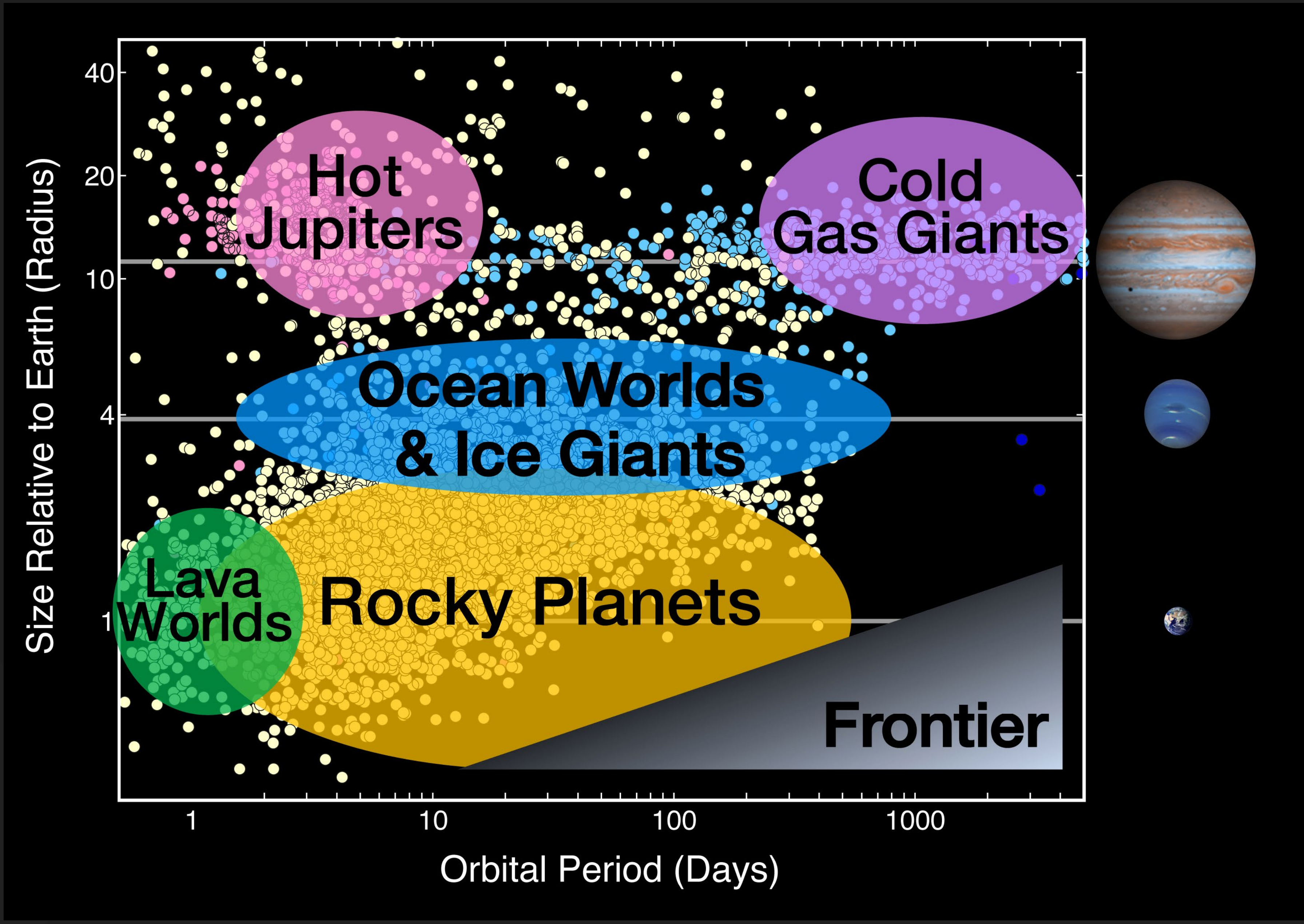
Exoplanet Research

Empirical Predictions for the Period Distribution of Planets to be Discovered by TESS

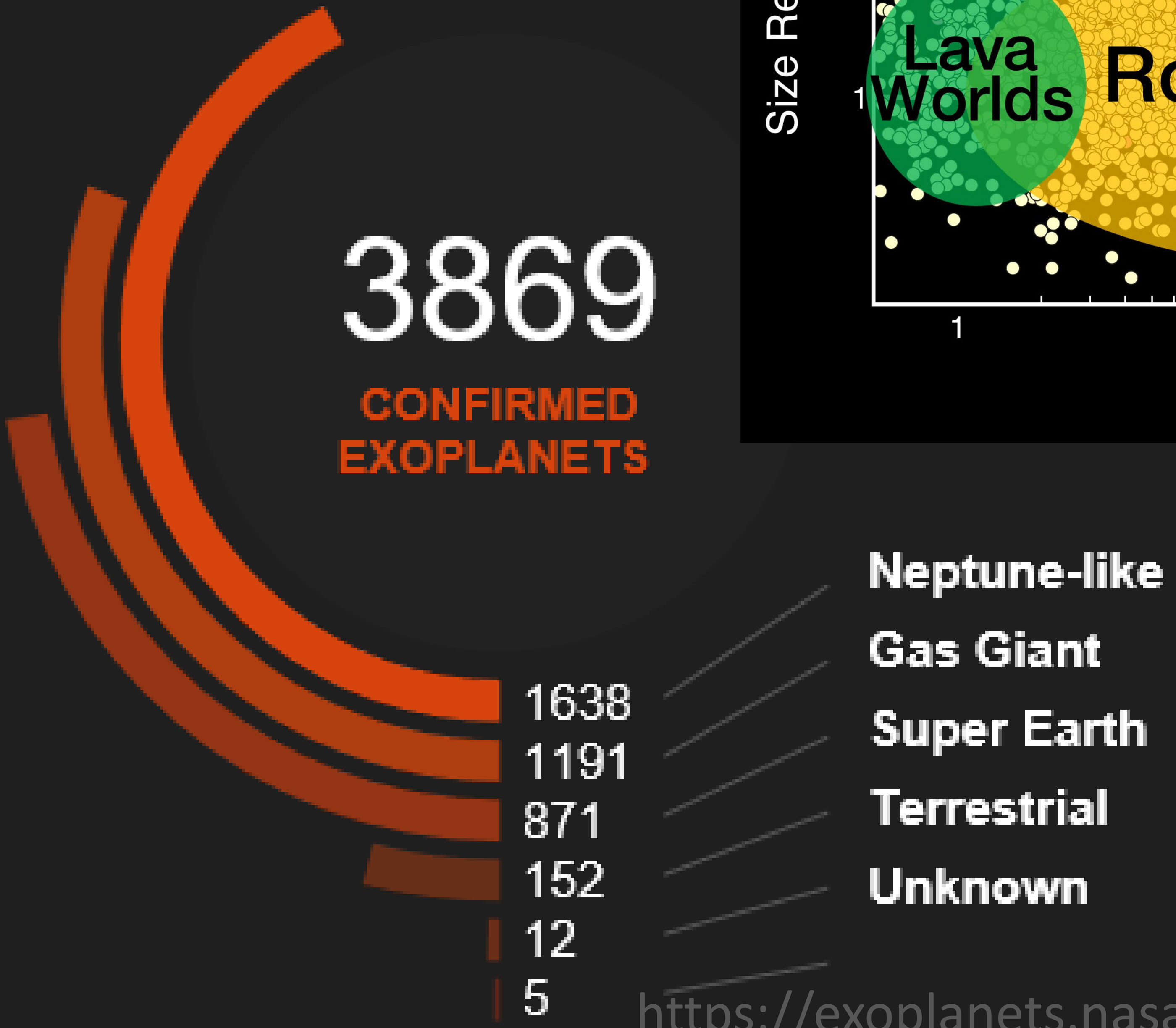
Speaker: Xuan Ji

- *Introduction to exoplanets*
- *Methods of detecting exoplanets*
- *My project*
    - ✓ *Abstract*
    - ✓ *Methodology*
    - ✓ *Results and Summary*

Exoplanets Demography



NASA/Ames Research Center/Natalie Batalha/Wendy Stenzel

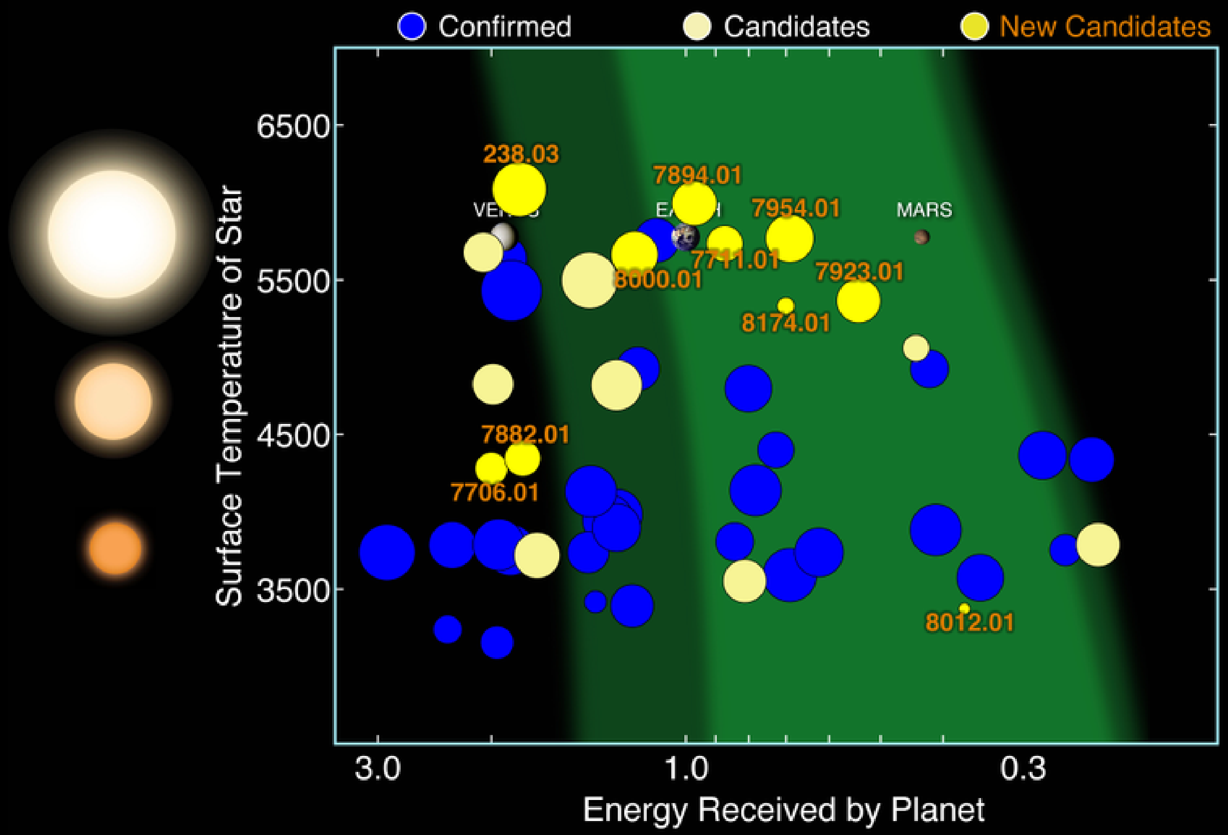


https://exoplanets.nasa.gov/

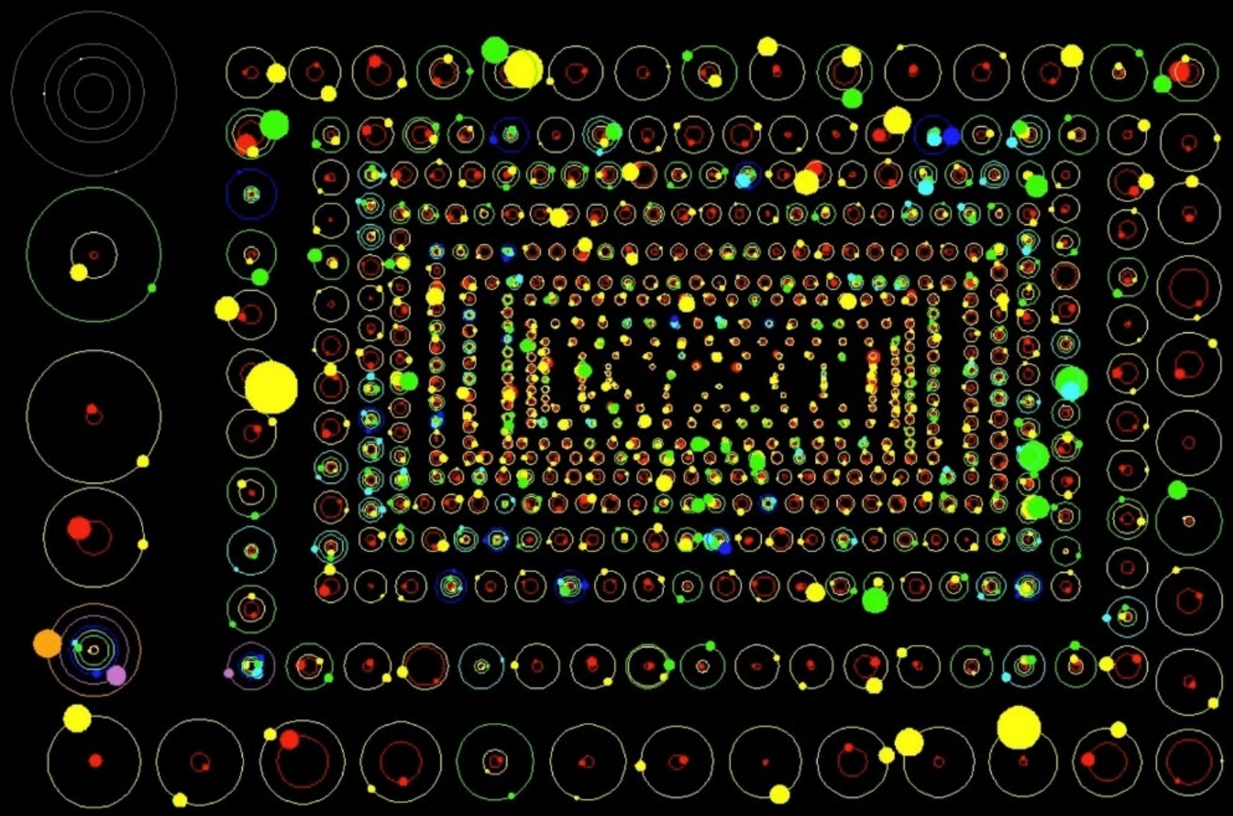
What can we learn from exoplanets?

- *1）Life outside the Solar System*

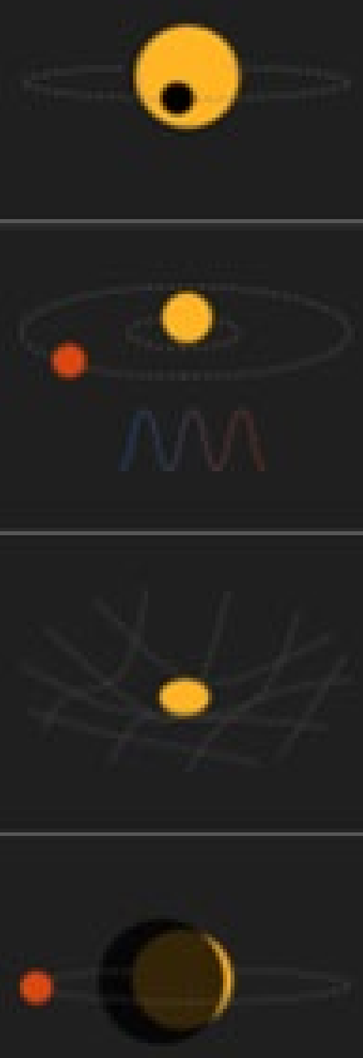
2）planetary formation and evolution



NASA/Ames Research Center/Wendy Stenzel



NASA/Kepler/Dan Fabricky



77.8% Transit

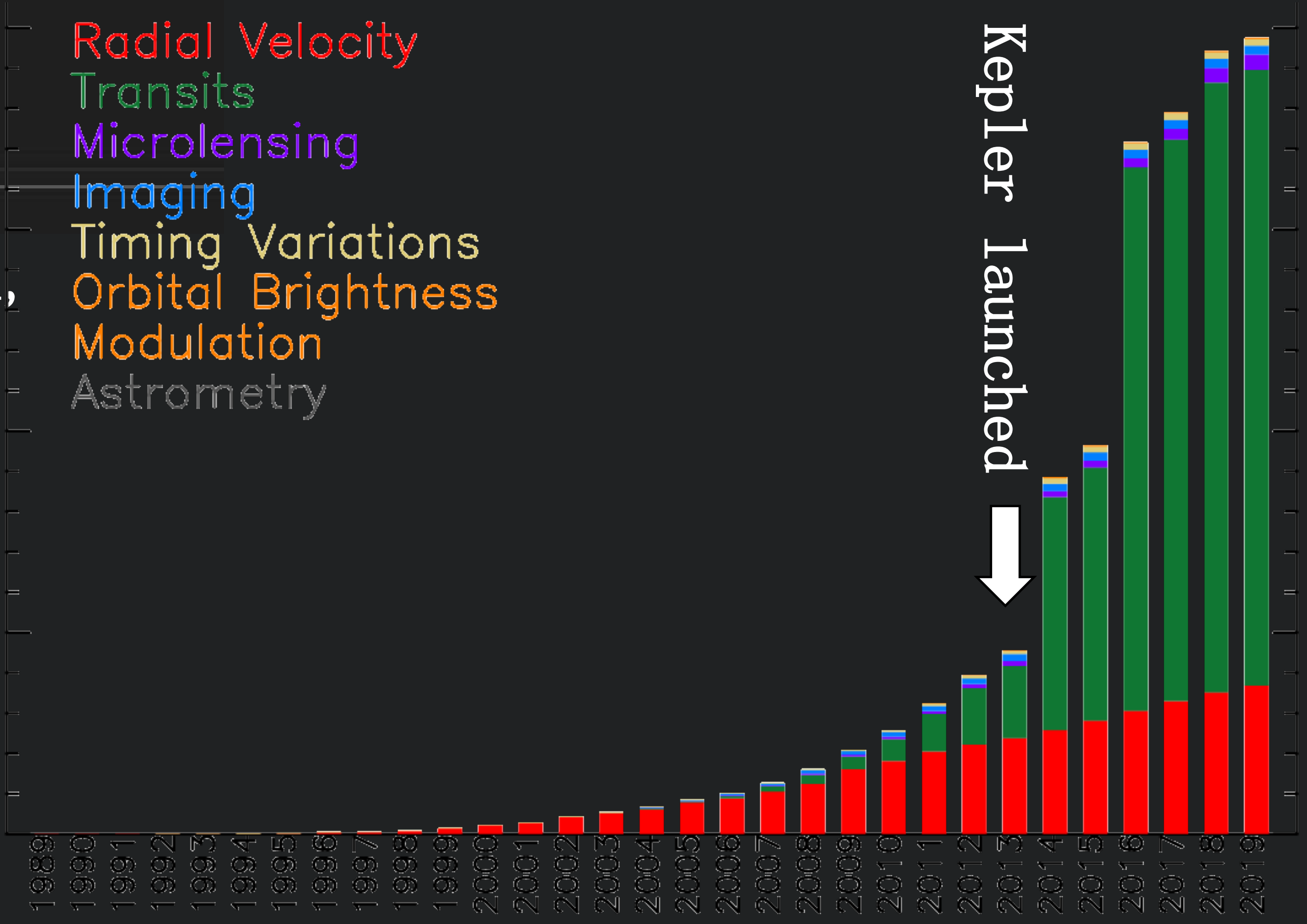
18.2% Radial Velocity →

1.9% Microlensing

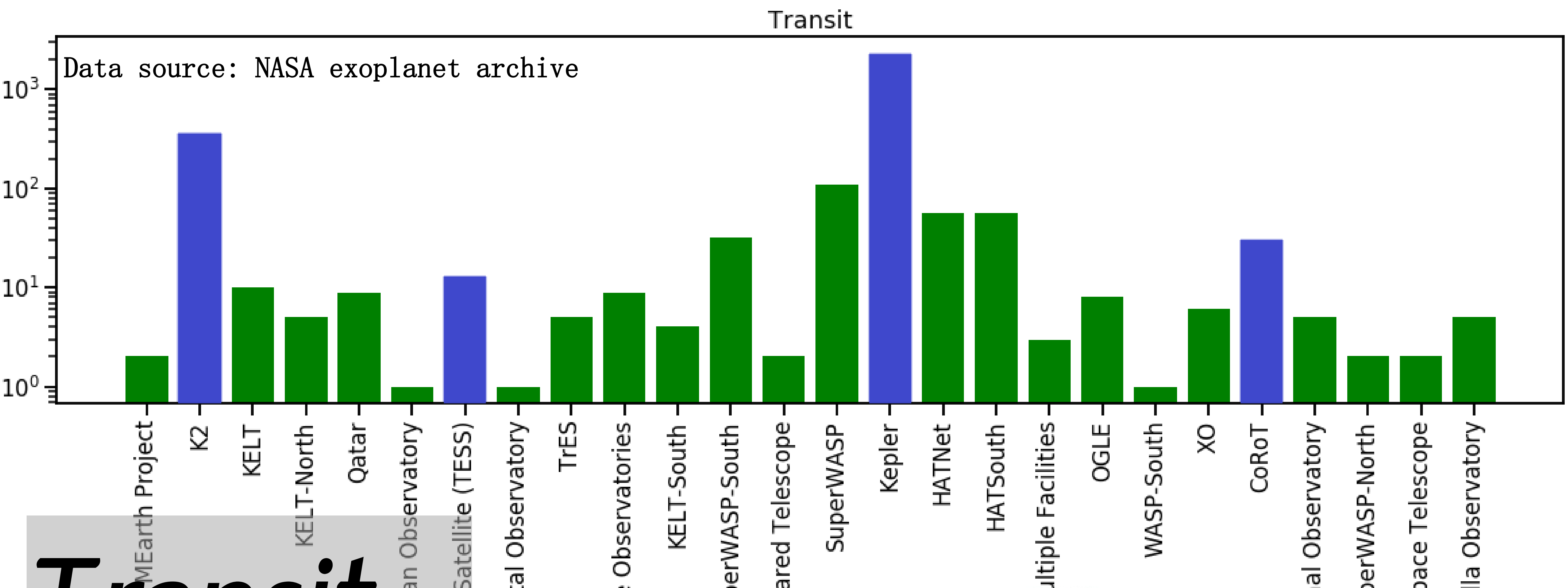
1.1% Imaging

In 1995, Mayor and Queloz discovered the 1st exoplanet orbiting a sun-like star. Haute-Provence Observatory, France

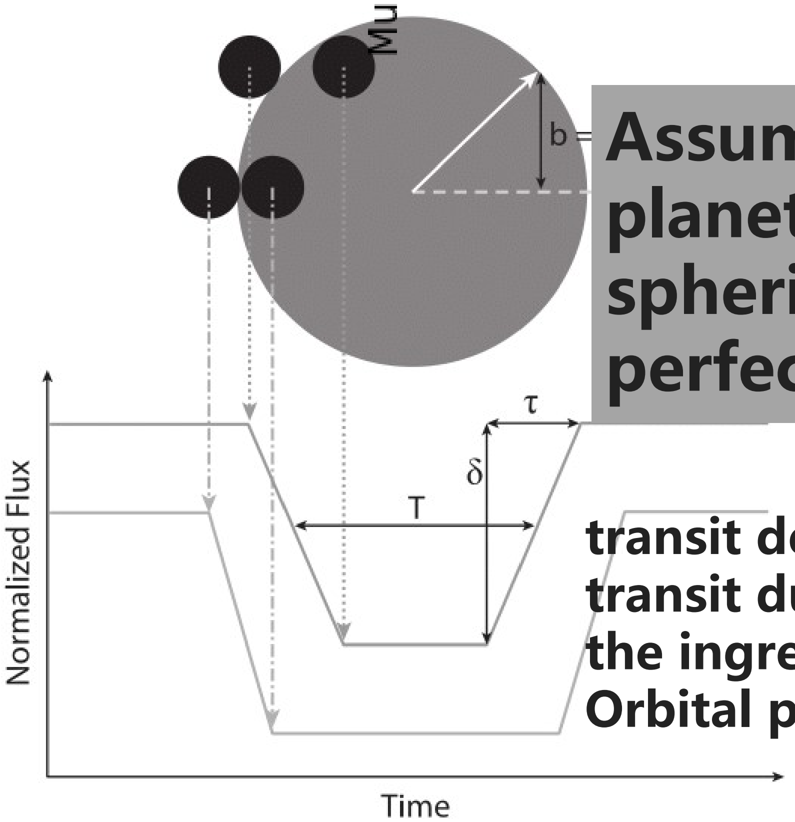
- 0.16% Orbital Brightness Modulation,
- 0.03% Astrometry
- 0.39% Transit Timing Variations,
- 0.23% Eclipse Timing Variations,
- 0.16% Pulsar Timing,
- 0.05% Pulsation Timing Variations,



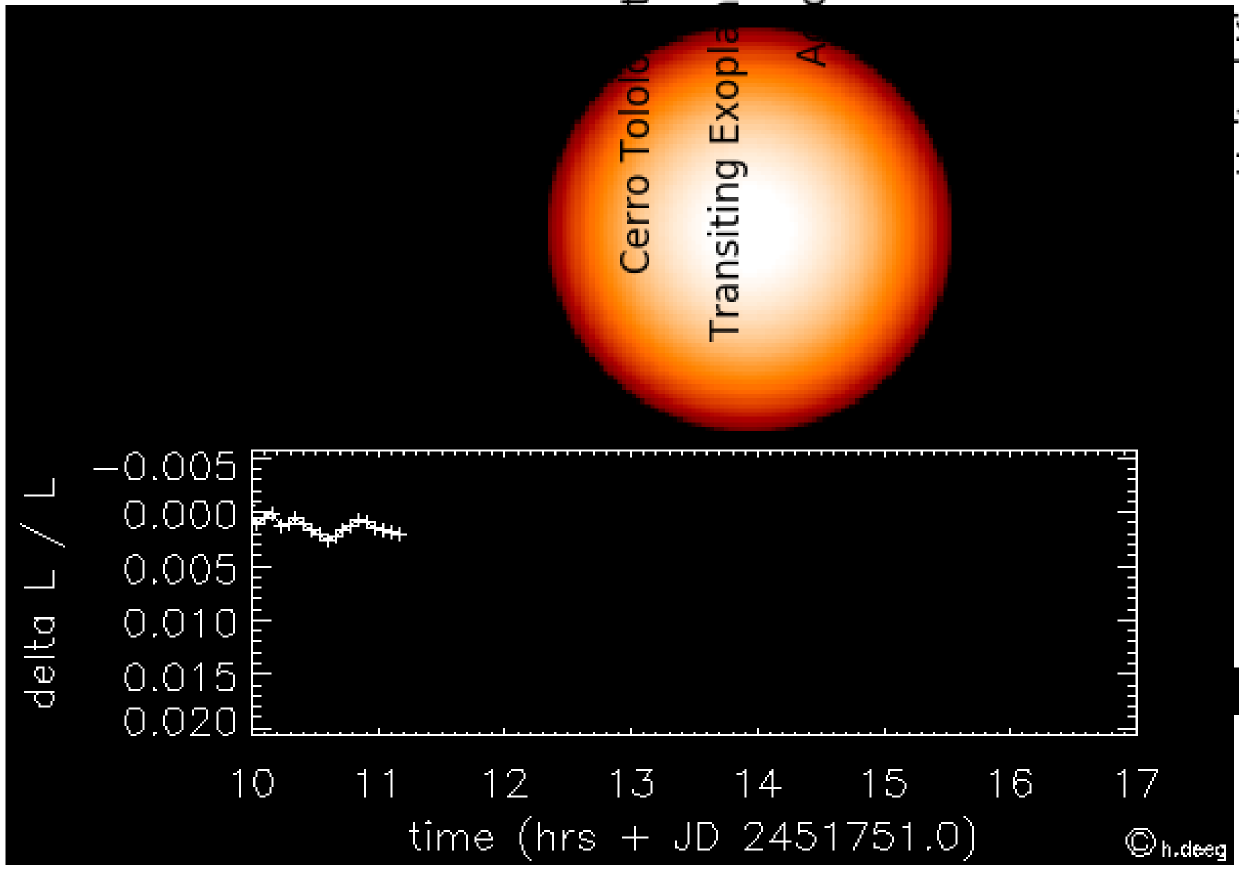
Transit



Assumption: The planets and stars are spherical; The orbit is perfect circle



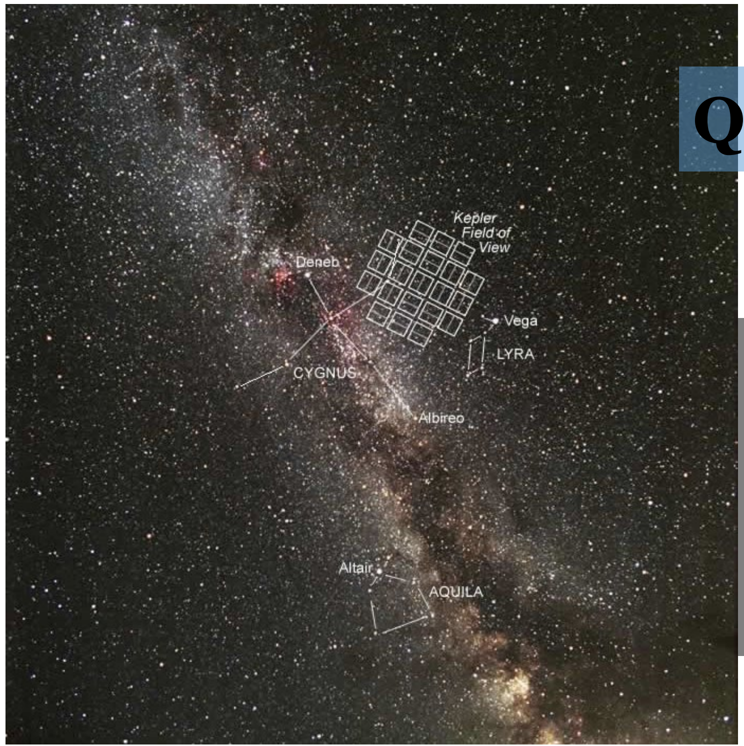
transit depth (δ)
transit duration (T),
the ingress/egress duration (τ),
Orbital period(P)



Semi-major axis, stellar mass, stellar radius, planetary radius, eccentricity, inclination ~~, planetary mass~~

Transit——Kepler

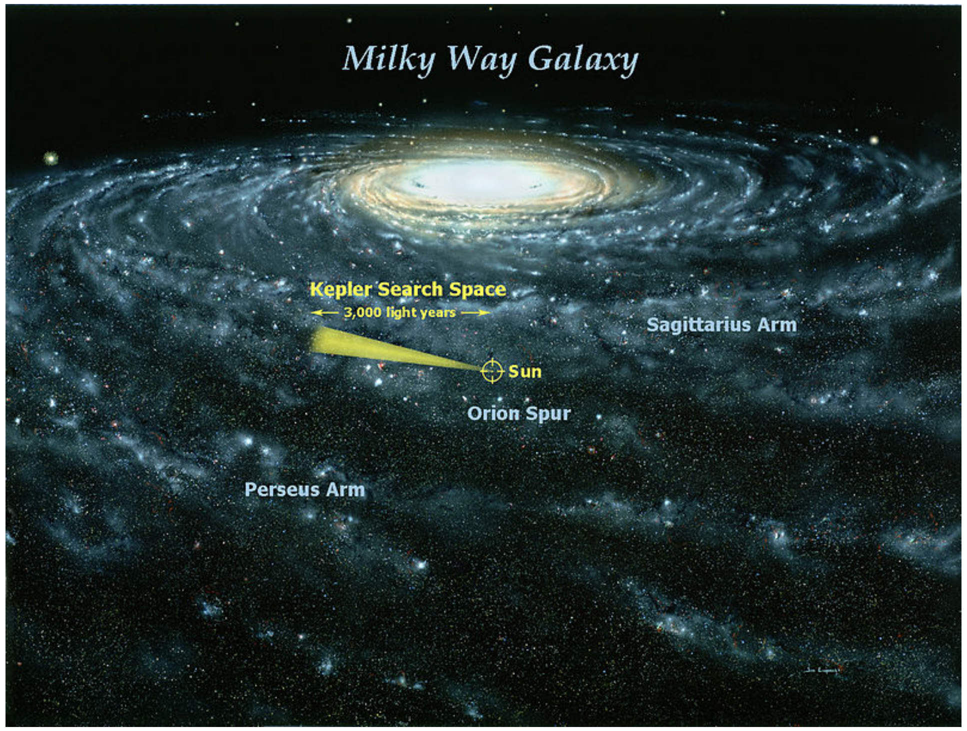
Observing strategy:



Quarterly rolls

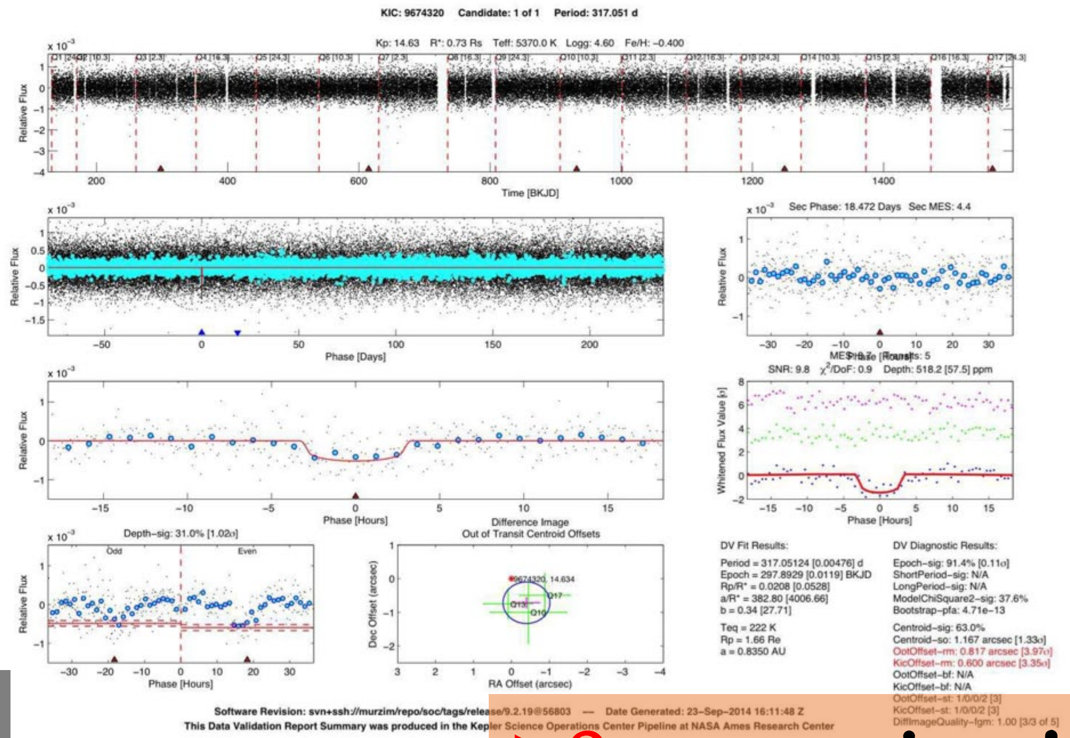
- 115 square degree
- 0.25% full sky
- 400 Kepler can cover the whole sky

https://www.jpl.nasa.gov/news/press_kits/Kepler-presskit-2-19-smfile.pdf



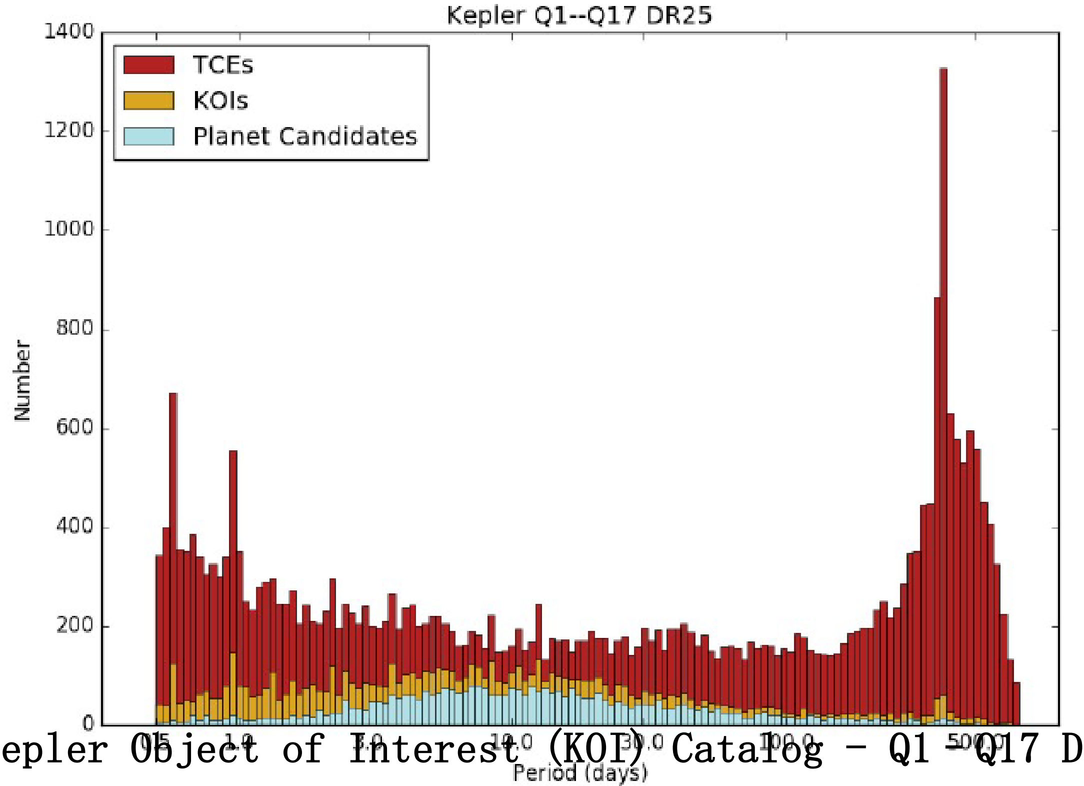
http://kepler.nasa.gov/images/LombergA1600-full.jpeg

Pipeline:



≥3 transits!

Pixels → TCEs → KOIs
→planet candidates
→confirmed planets

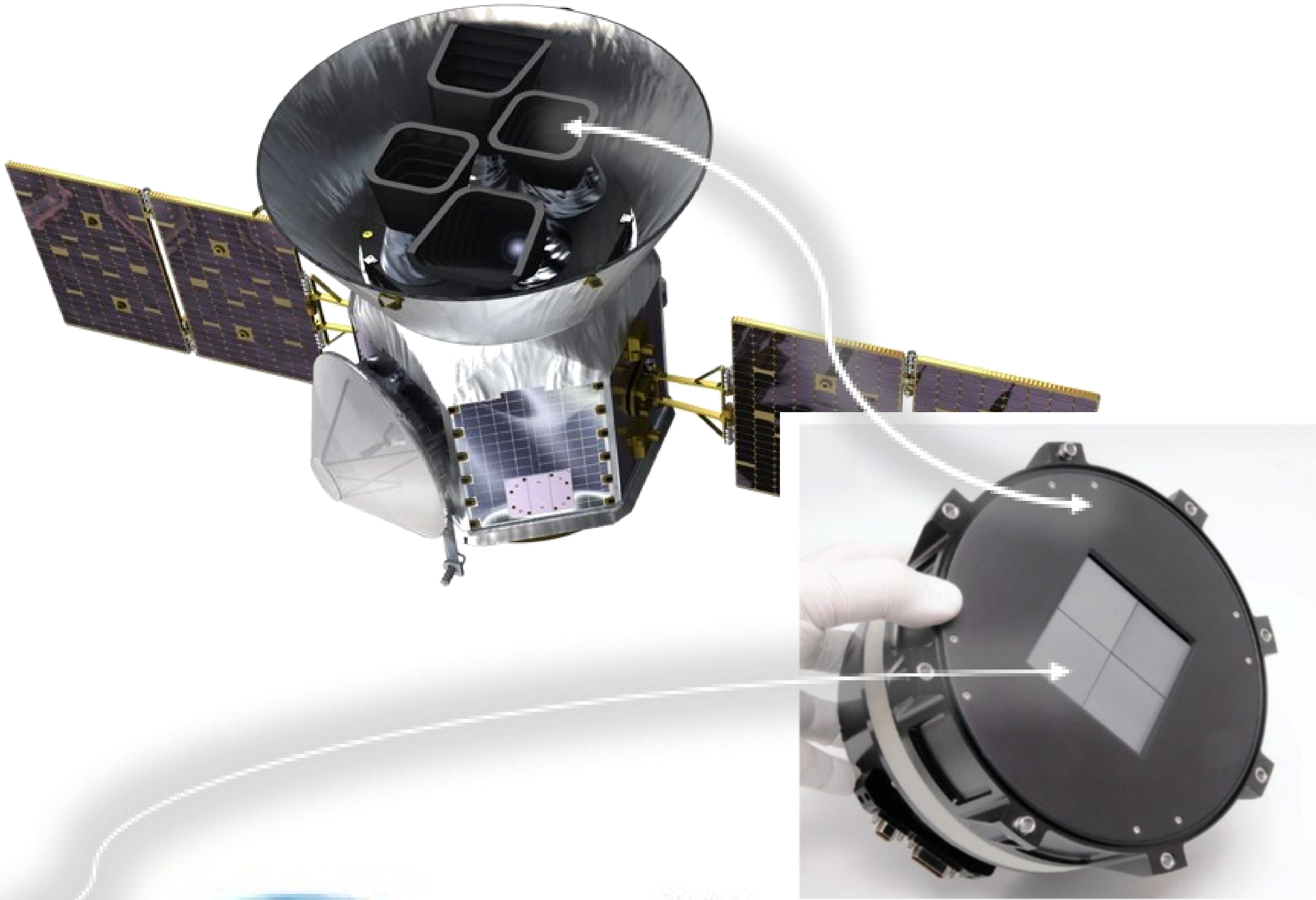


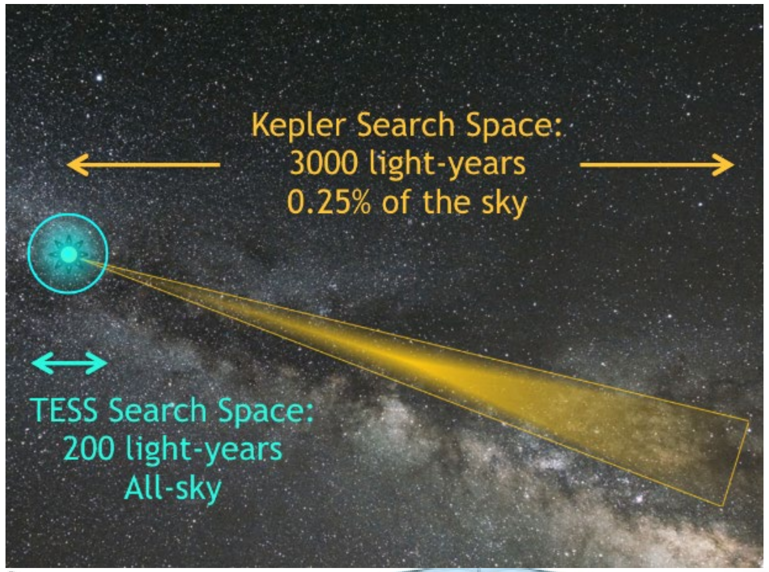
Kepler Object of Interest (KOI) Catalog - Q1 -Q17 DR 25

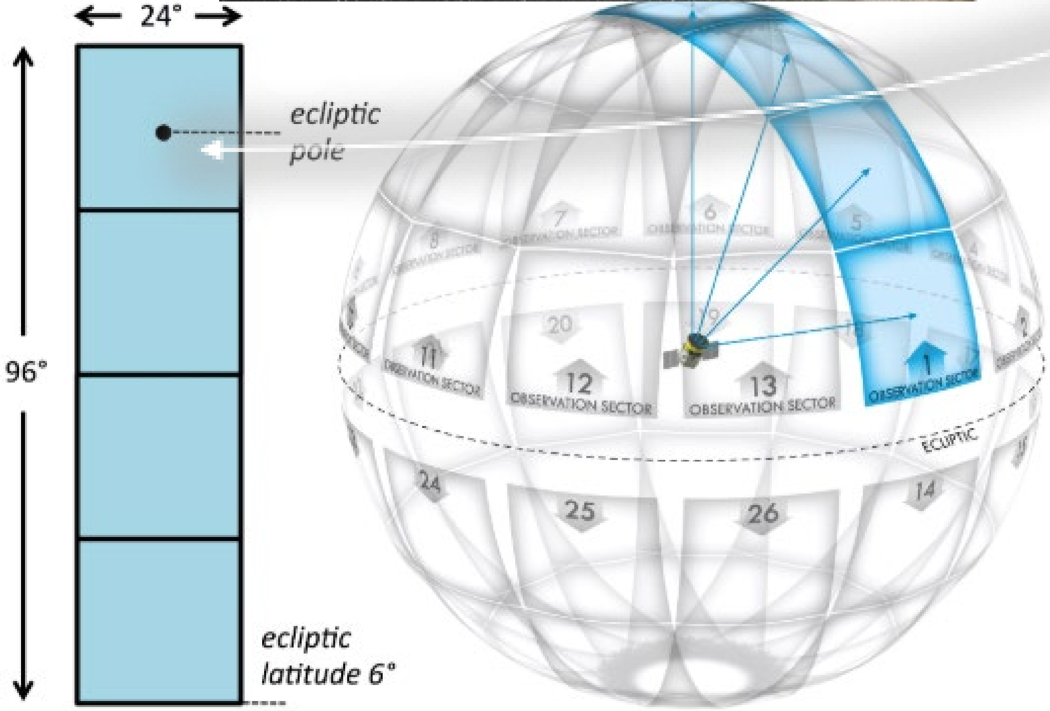
Transit——TESS

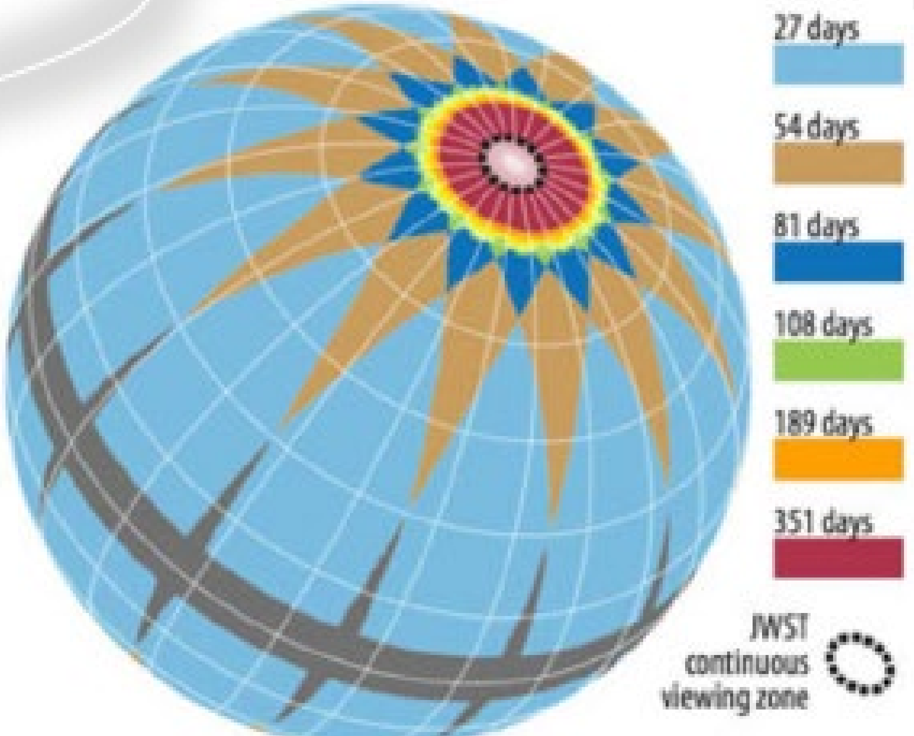
Launched April 18, 2018
Started science operations July 25, 2018

- 10 cm aperture
- Bandpass: 600 – 1100 nm
- 13.7-day elliptical orbit









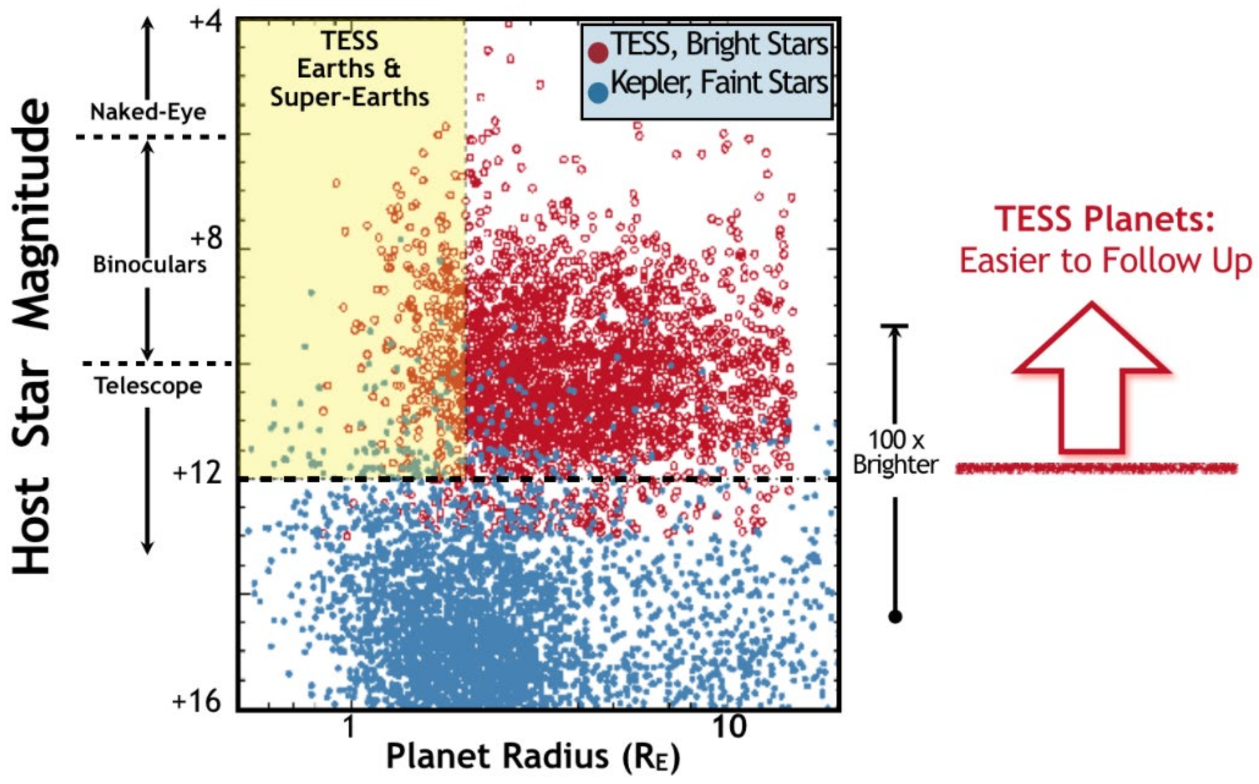
短周期、
近轨道行星

https://heasarc.gsfc.nasa.gov/docs/tess/primary-science.htm

Transit——TESS

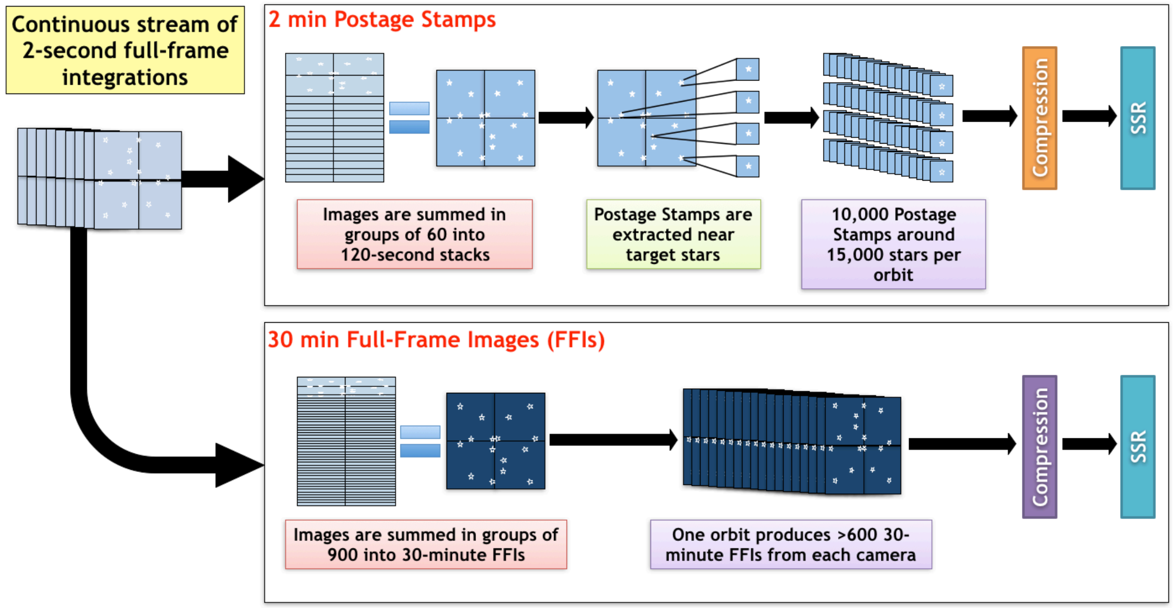
Science Goal: Bright!

- *Improve statistics for studies of the mass–radius relation of small planets as a function of distance from host stars.*
- *More temperate planets among which to select the best for atmospheric characterization with the JWST/ELTs*
- ……



TESS Will Discover Earths & Super-Earths Orbiting Bright Stars

Image Credit: MIT



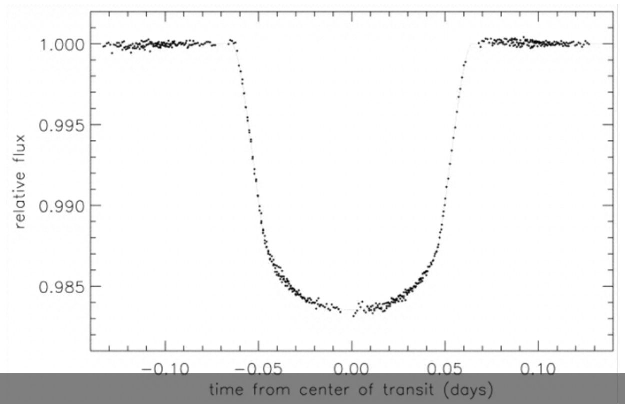
Villanueva, Dragomir & Gaudi (2019)

Transit——TESS

Single Transit

Stellar density
Eccentric

+



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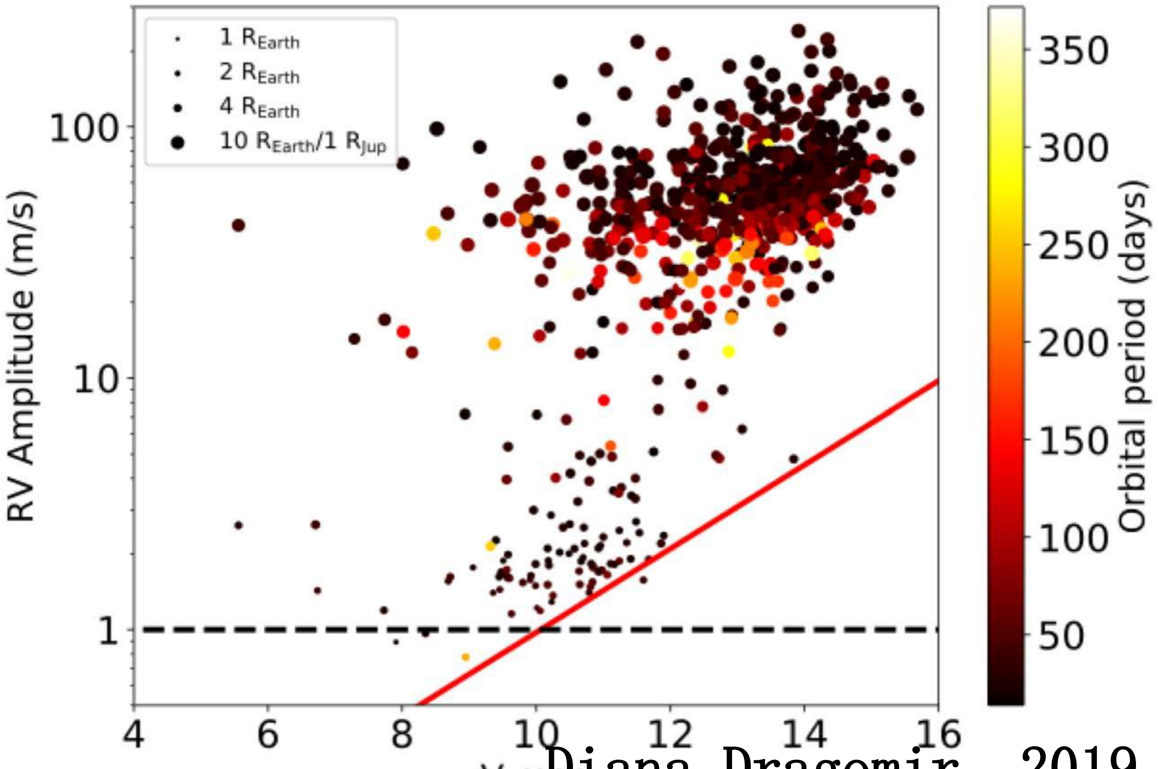
Orbital Period

Seager & Mallén-Ornelas (2003)
Yee & Gaudi (2008)

Density: Gaia (Raidus) and spectroscopy/ asteroseismology (spectroscopy). *Eccentricity*: prior from known distribution).

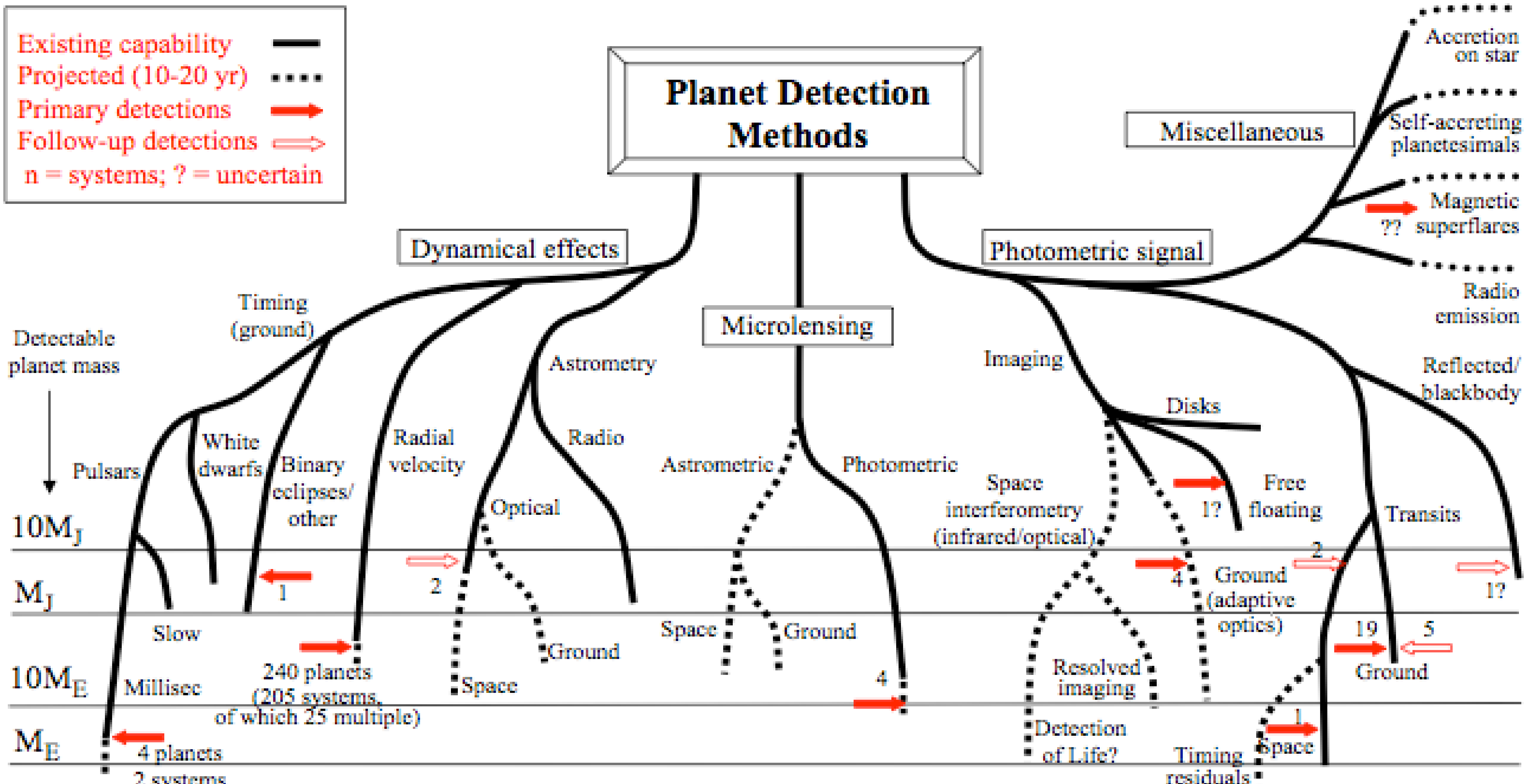
Radial Velocity Prospects for Single-Transit Planets

- **If period constrained well enough**
  → get photometry to catch next transit
- **Not well enough**
  → use RV measurements to improve constraint



Diana Dragomir, 2019

Detection Methods and Statistic

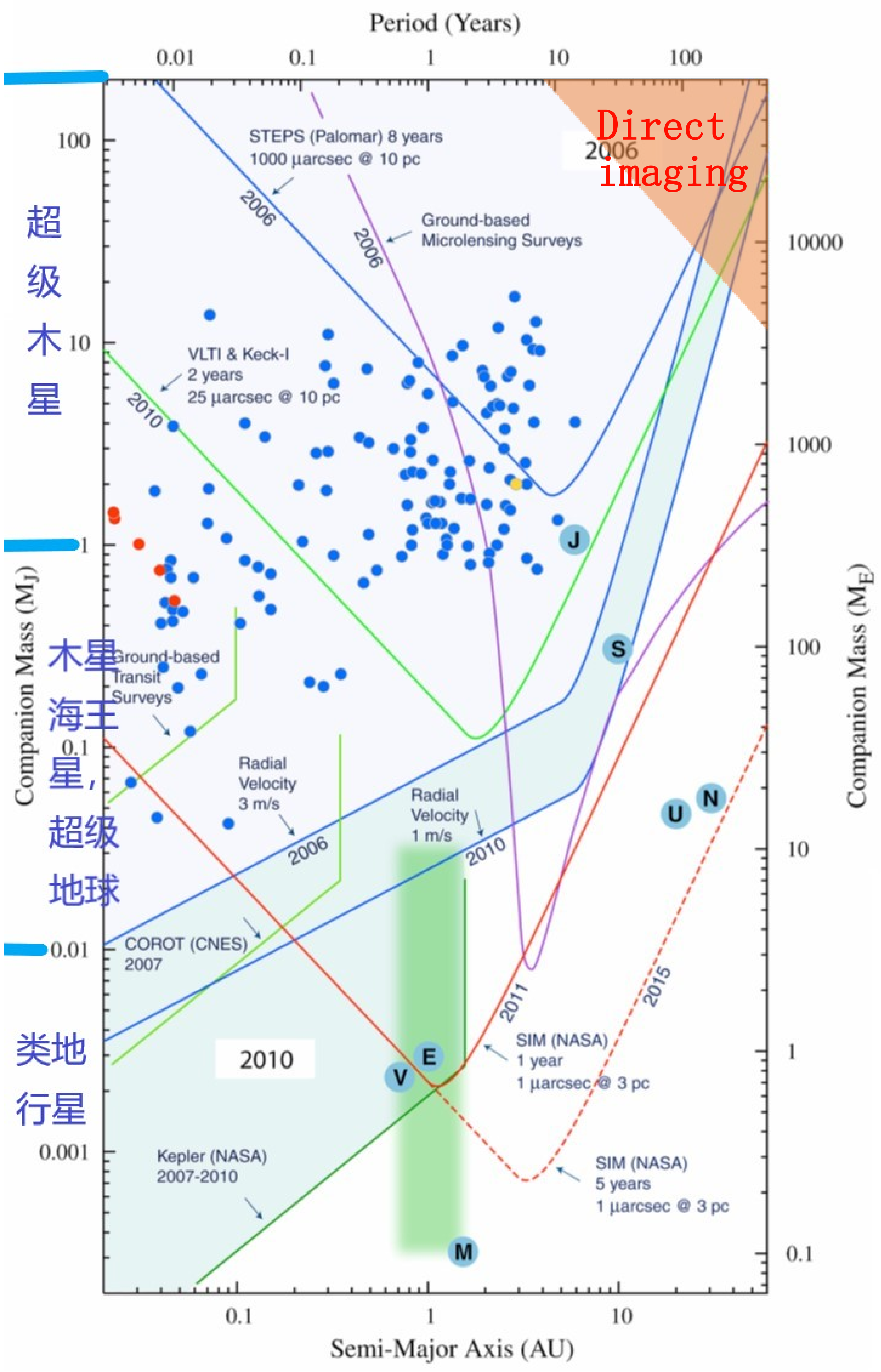


Planet Detection Methods

Michael Perryman, Rep. Prog. Phys., 2000, 63, 1209 (updated 3 October 2007)

Detection Method and Statistic

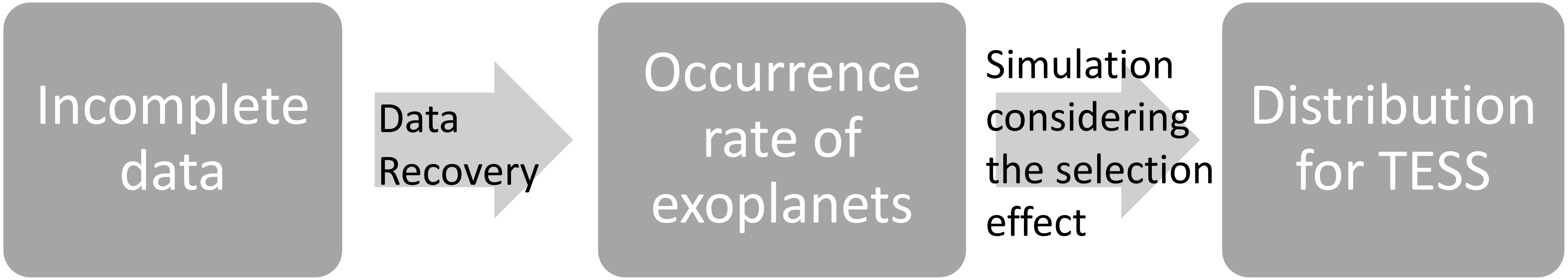
- habitable zone(green area)
- ~150 exoplanets detected in 2004
- – r.v. (blue)
  - – transits (red)
  - – microlensing (yellow)
  - – pulsar timing (purple)
  - – Imaging(magenta)



My Project

- ***Empirical Predictions for the Period Distribution of Planets to be Discovered by TESS***

Previous work ：



Incomplete data

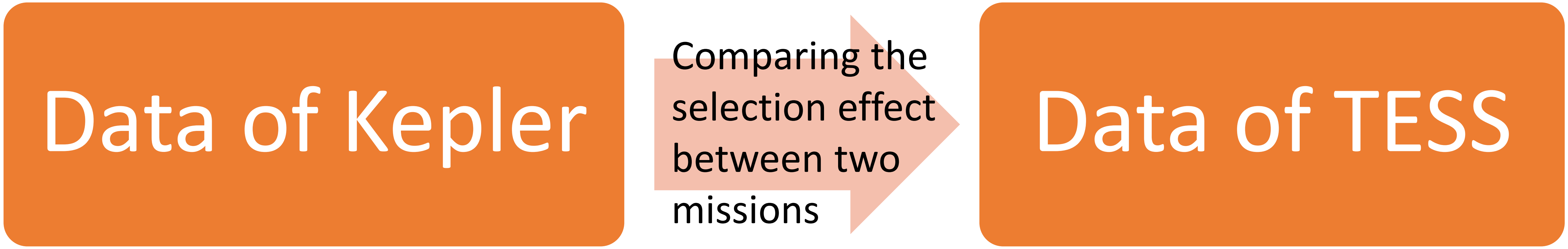
Data Recovery

Occurrence rate of exoplanets

Simulation considering the selection effect

Distribution for TESS

My work：



Data of Kepler

Comparing the selection effect between two missions

Data of TESS

Methodology

The probability that an exoplanet of which orbital period is P days is detected by TESS

The occurrence rate of an exoplanet of which orbital period is P days

The probability that the orbital period of a detected exoplanet is P days :

$$\Pr ob(P|TESS) = \frac{\Pr ob(TESS|P)\times \Pr ob(P)}{\Pr ob(TESS)}$$

constant

$$\Pr \mathrm{ob}(TESS|P) = \Pr \mathrm{ob}(Tr|P)\times \Pr \mathrm{ob}(NTr(\tau_1)|Tr,P)\times \Pr \mathrm{ob}(SNR\_T|NTr(\tau_1),Tr,P)$$

geometric probability of detecting a transit around a star for a fixed period

the probability of observing the transit(s) more than N times during the finite observing baseline of observations for TESS for a fixed period, given that the transit is detected

the probability that the signal–to–noise ratio (SNR) of the exoplanet is higher than the threshold given that it transits at least N times over the course of the observations.

Methodology

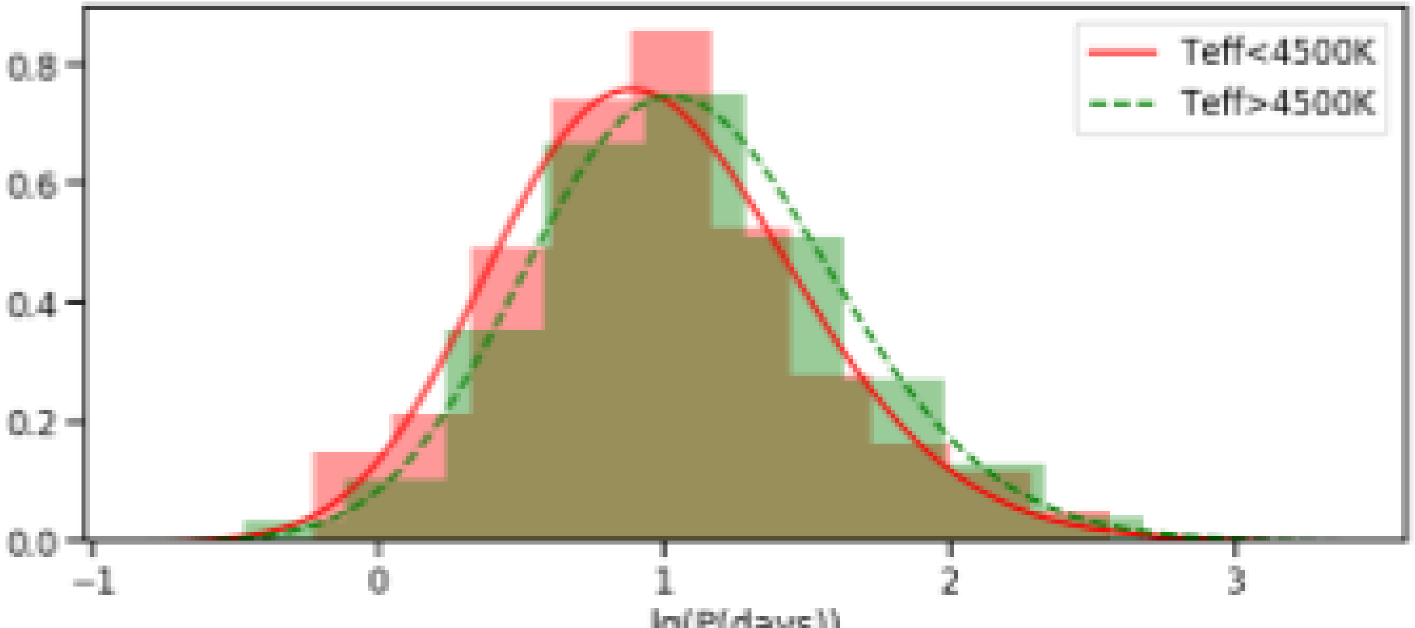
TESS : CTL
(dwarfs and subgiants)

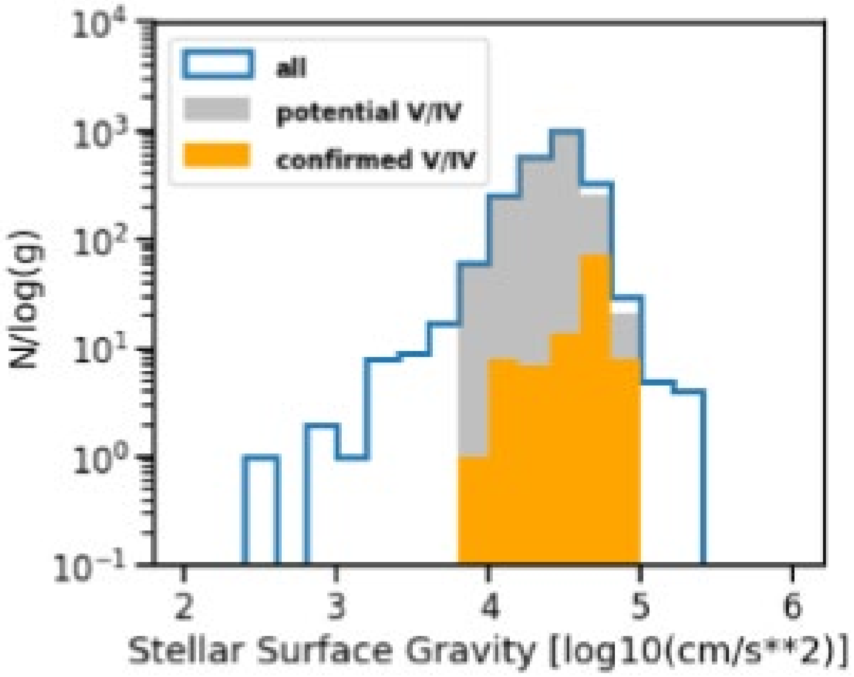
Input Catalogue

$$\mathrm{Prob}(P|TESS) = \frac{\mathrm{Prob}(tr|P)\cdot\mathrm{Prob}(Ntrs_T|P,tr)\cdot\mathrm{Prob}(\mathrm{SNR}_T > \mathrm{SNRT}_{min}|P,tr,Ntrs_T)\cdot\mathrm{Prob}(P)}{\mathrm{Prob}(TESS)}$$

Likewise, repeat the above analysis but for Kepler:

$$\mathrm{Prob}(P|Kepler) = \frac{\mathrm{Prob}(tr|P)\cdot\mathrm{Prob}(Ntrs_K|P,tr)\cdot\mathrm{Prob}(\mathrm{SNR}_K > \mathrm{SNR}K_{min}|P,tr,Ntrs_K)\cdot\mathrm{Prob}(P)}{\mathrm{Prob}(Kepler)}$$





Methodology

1. Prob (tr|P)

$$\text{Prob}\,(tr|P) = \int \frac{R_*}{a} f_{R_*,a|P}(R_*,a)\,dR_*\,da = \int \left(\frac{4\pi^2}{G}\right)^{\frac{1}{3}} R_* M_*^{-\frac{1}{3}} P^{-\frac{2}{3}} f_{R_*,M_*|P}(R_*,M_*)\,dR_*\,dM_*$$

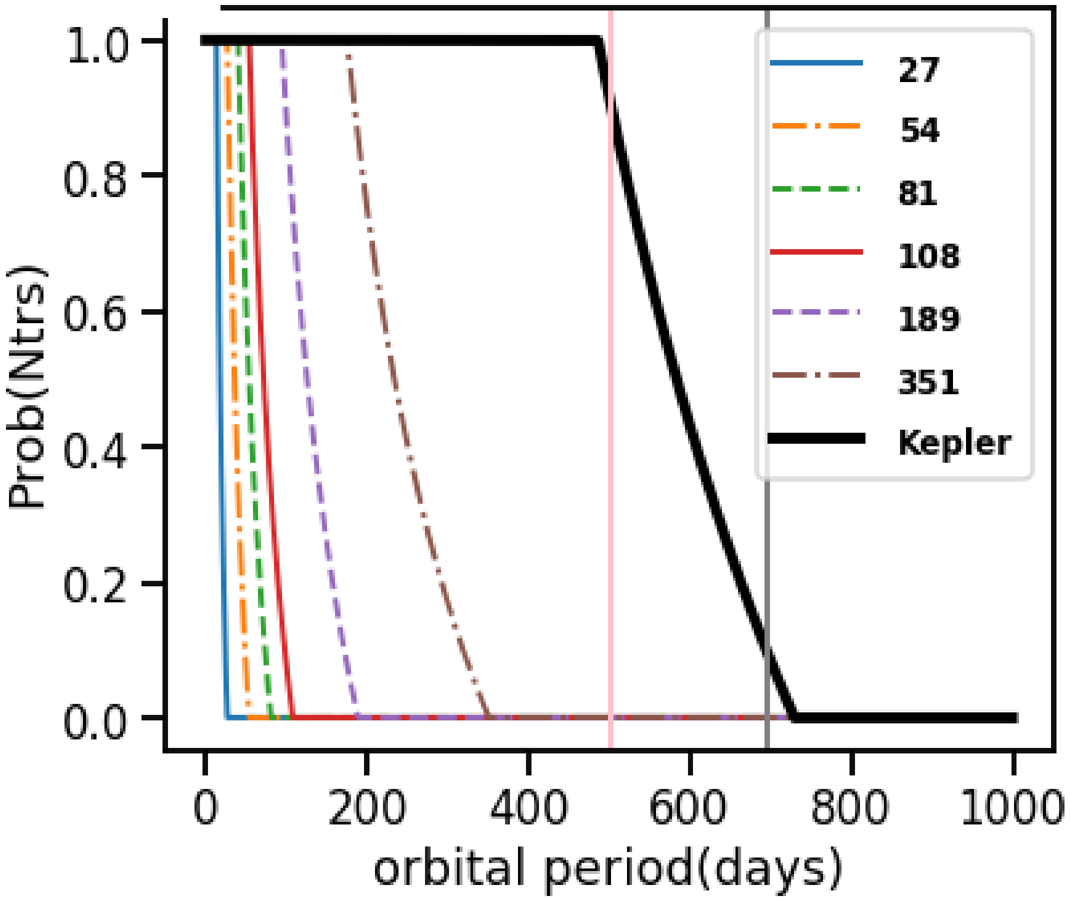
$2.\ \ Prob(2Tr(\tau_1)|Tr,P)$

$$\text{Prob}\,(Ntrs_T|P,tr) = \begin{cases} 0, & t \le (N-1)P \\ \frac{t-(N-1)\cdot P}{P}, & (N-1)P < t < NP \\ 1, & t \ge N\cdot P \end{cases}$$

↓

$$\mathbf{Prob}_i(P|TESS) = c_i\mathbf{Prob}_i(P|Kepler)\,\frac{\mathbf{Prob}_i(Ntrs_T|P,tr)\cdot\mathbf{Prob}_i\left(\mathbf{SNR}_T > \mathbf{SNRT}_{min}|P,tr,Ntrs_T\right)}{\mathbf{Prob}_i(Ntrs_K|P,tr)\cdot\mathbf{Prob}_i\left(\mathbf{SNR}_K > \mathbf{SNRK}_{min}|P,tr,Ntrs_K\right)}$$

The gray vertical line is 694.76 days beyond which the probability that it can be detected by Kepler is less than 10% and the pink vertical line is 503.10 days within which the probability is higher than 90%



Methodology

3. $\mathbf{Pr}\boldsymbol{ob}(\boldsymbol{SNR\_T}|\boldsymbol{2Tr}(\boldsymbol{\tau_1}),\boldsymbol{Tr},\boldsymbol{P})$

$$\mathrm{SNR} = R_p^2 P^{-\frac{1}{3}} \left(\frac{4\pi^2}{GM_*}\right)^{\frac{1}{6}} \sqrt{\frac{At_m}{4R_* r^2} \int_{\lambda_1}^{\lambda_2} \tau\pi B(\lambda, T_*) \left(\frac{\lambda}{hc}\right) d\lambda}\,,$$

$$\mathrm{SNR} = \mathrm{f}(\mathbb{P})\mathrm{g}(\mathbb{S})\mathrm{h}(\mathbb{M}, \mathbf{T}_*)$$

$$\mathrm{f}(\mathbb{P}) = R_p^2 P^{-\frac{1}{3}}$$

$$\mathrm{g}(\mathbb{S}) = \left(\frac{4\pi^2}{GM_*}\right)^{\frac{1}{6}} \sqrt{\frac{1}{4R_*}}$$

$$\mathrm{h}(\mathbb{M}, \mathbf{T}_*) = \sqrt{\frac{At_m}{r^2} \int_{\lambda_1}^{\lambda_2} \tau\pi B(\lambda, T_*) \left(\frac{\lambda}{hc}\right) d\lambda}$$

$$\mathrm{SNR}_K = \mathrm{f}(\mathbb{P})\mathrm{g}(\mathbb{S})\mathrm{h}(\mathbb{M}_K, T_*);$$

$$\mathrm{SNR}_T = \mathrm{f}(\mathbb{P})\mathrm{g}(\mathbb{S})\mathrm{h}(\mathbb{M}_T, T_*)$$

↓

$$\mathrm{SNR}_T = \mathrm{SNR}_K \frac{\mathrm{h}(\mathbb{M}_\mathrm{T}, T_*)}{\mathrm{h}(\mathbb{M}_\mathrm{K}, T_*)}$$

$$= k(\mathbb{M}_T, \mathbb{M}_K, T_*) \cdot \mathrm{SNR}_K$$

	T_*	k (27 days)	k (54 days)	k (81 days)	k (108 days)	k (189 days)	k (351 days)
< 4500K	3974.41	0.0327	0.0463	0.0567	0.0655	0.0866	0.1180
> 4500K	5653.53	0.0621	0.0878	0.1075	0.1242	0.1643	0.2239

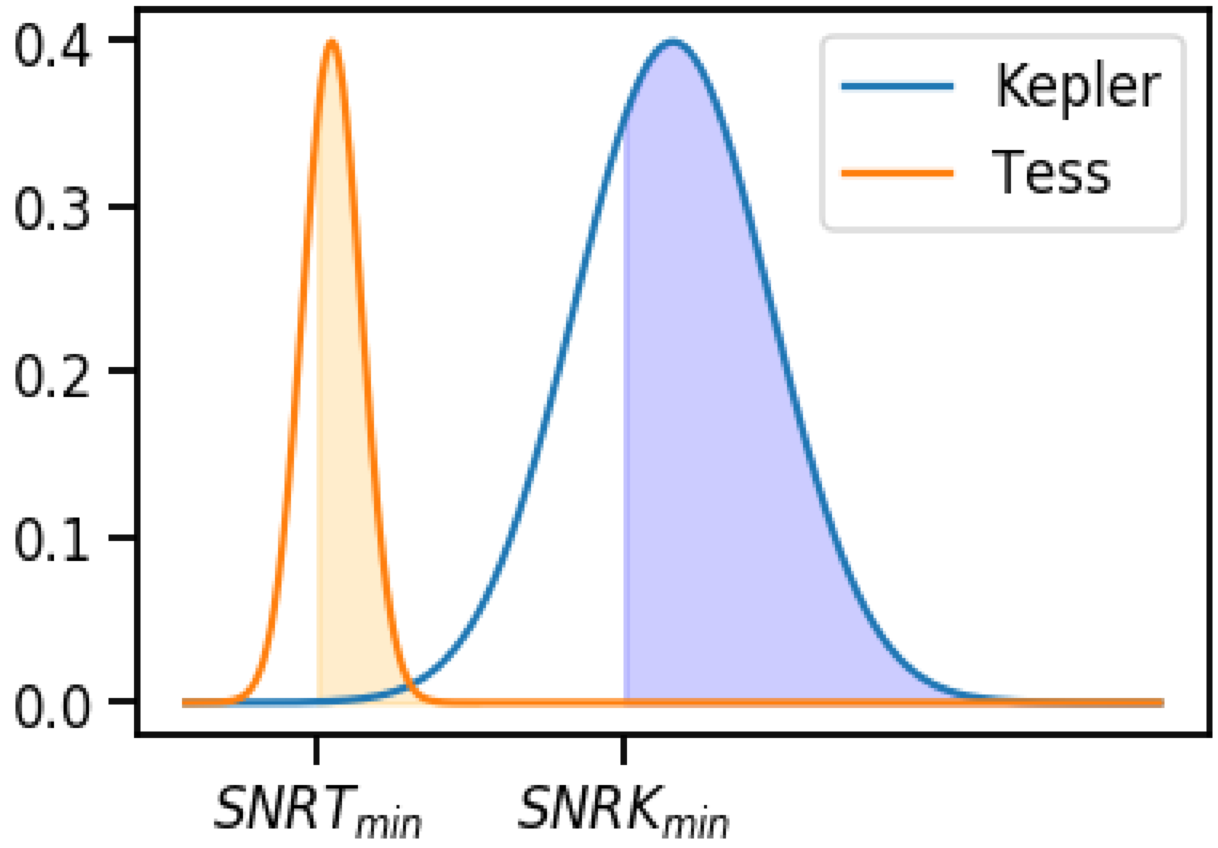
Methodology

3. $\mathbf{Pr}\boldsymbol{ob}(\boldsymbol{SNR\_T}|\mathbf{2}\boldsymbol{Tr}(\boldsymbol{\tau_1}),\boldsymbol{Tr},\boldsymbol{P})$

$$f_{\mathrm{SNRT}i}(\mathrm{SNR}_T|P,tr)=f_{SNRTi}(k\cdot\mathrm{SNR}_K|P,tr)=f_{SNRKi}(\mathrm{SNR}_K|P,tr)$$

$$f_{\mathrm{SNRT}i}(\mathrm{SNR}|P,tr)=f_{\mathrm{SNRK}i}(\mathrm{SNR}/k|P,tr)$$

$$\begin{aligned}
&\mathrm{Prob}_i(\mathrm{SNR}_T>\mathrm{SNRT}_{min}\,|P,tr)\\
&=\int_{\mathrm{SNRT}_{min}}^{\infty} f_{\mathrm{SNRT}i}\,(SNR'|P,tr)dSNR'\\
&=\int_{\mathrm{SNRT}_{min}}^{\infty} f_{\mathrm{SNRK}i}\left(\frac{SNR'}{k}|P,tr\right)dSNR'\\
&=\int_{\frac{\mathrm{SNRT}_{\mathrm{min}}}{k}}^{\infty} k\cdot f_{\mathrm{SNRK}i}\,(SNR''|P,tr)dSNR''\\
&=k\cdot\mathrm{Prob}_i\left(\mathrm{SNR}_K>\frac{\mathrm{SNRT}_{min}}{k}\middle|P,tr\right)
\end{aligned}$$



↓

$$\frac{\mathrm{Prob}_i(\mathrm{SNR}_T>\mathrm{SNRT}_{min}\,|P,tr)}{\mathrm{Prob}_i(\mathrm{SNR}_K>\mathrm{SNRK}_{min}\,|P,tr)}=k\cdot\frac{\mathrm{Prob}_i\left(\mathrm{SNR}_K>\frac{\mathrm{SNRT}_{min}}{k}\middle|P,tr\right)}{\mathrm{Prob}_i(\mathrm{SNR}_K>\mathrm{SNRK}_{min}\,|P,tr)}$$

?

Methodology

$\mathbf{3.\ Prob(SNR\_T|2Tr(\tau_1),Tr,P)}$

$$\mathrm{Prob}(TESS\,|\,P)=\mathrm{Prob}(Tr\,|\,P)\times\mathrm{Prob}(NTr(\tau_1)\,|\,Tr,P)\times\mathrm{Prob}(SNR\_T\,|\,NTr(\tau_1)\,|\,Tr,P)$$

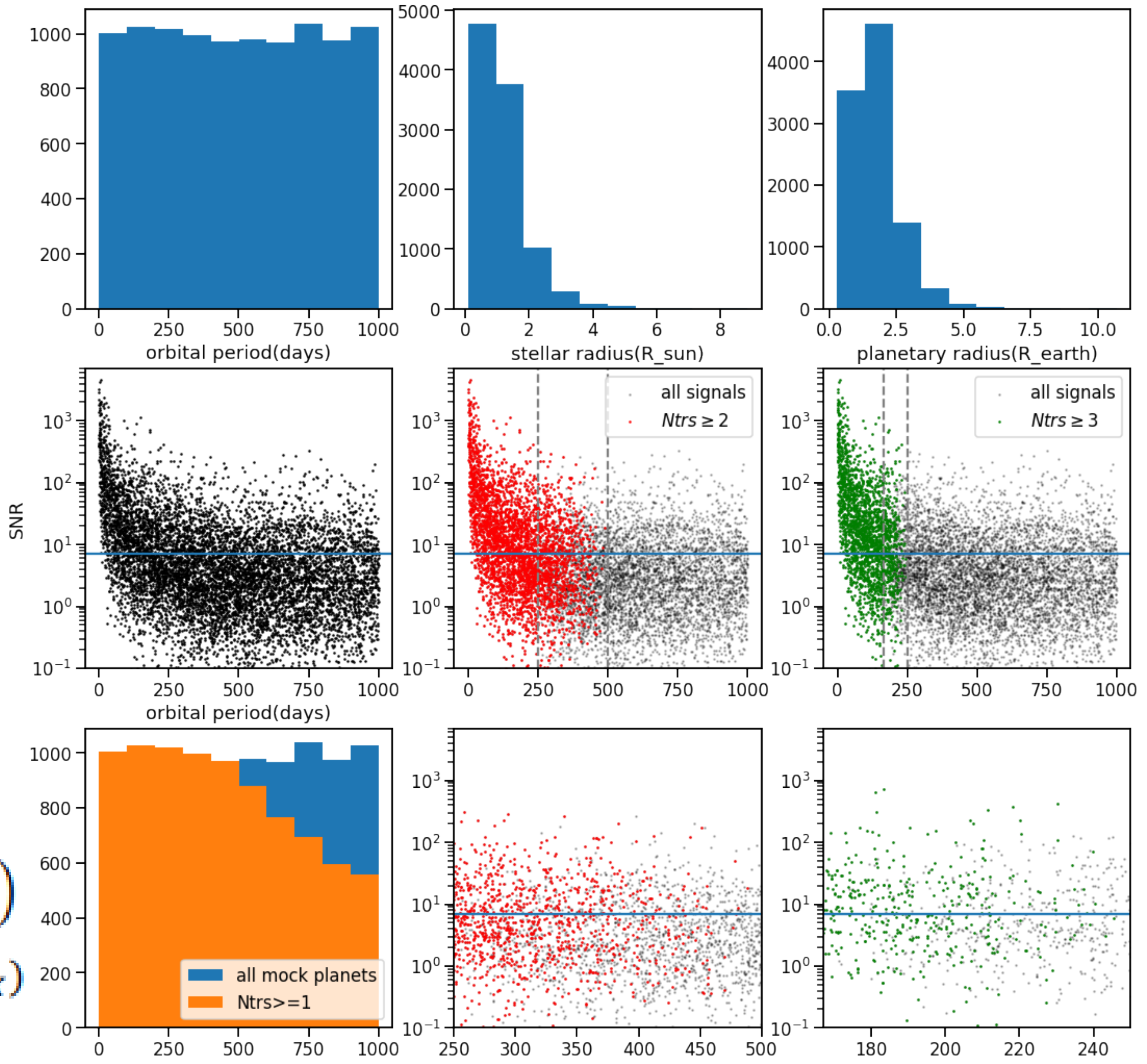
3 scenarios:

$$\mathrm{Prob}\ (Ntrs_T|P,tr) = \begin{cases} 0, & t \le (N-1)P \\ \dfrac{t-N\cdot P}{P}, & (N-1)P < t < NP \\ 1, & t \ge N\cdot P \end{cases}$$

⬇

$$\mathrm{Prob}_i\left(\mathrm{SNR}_K > \frac{\mathrm{SNRT}_{min}}{k}\middle|P,tr\right) \rightarrow \mathrm{Prob}_i\left(\mathrm{SNR}_K > \frac{\mathrm{SNRT}_{min}}{k}\middle|P,tr,3trs_K\right)$$

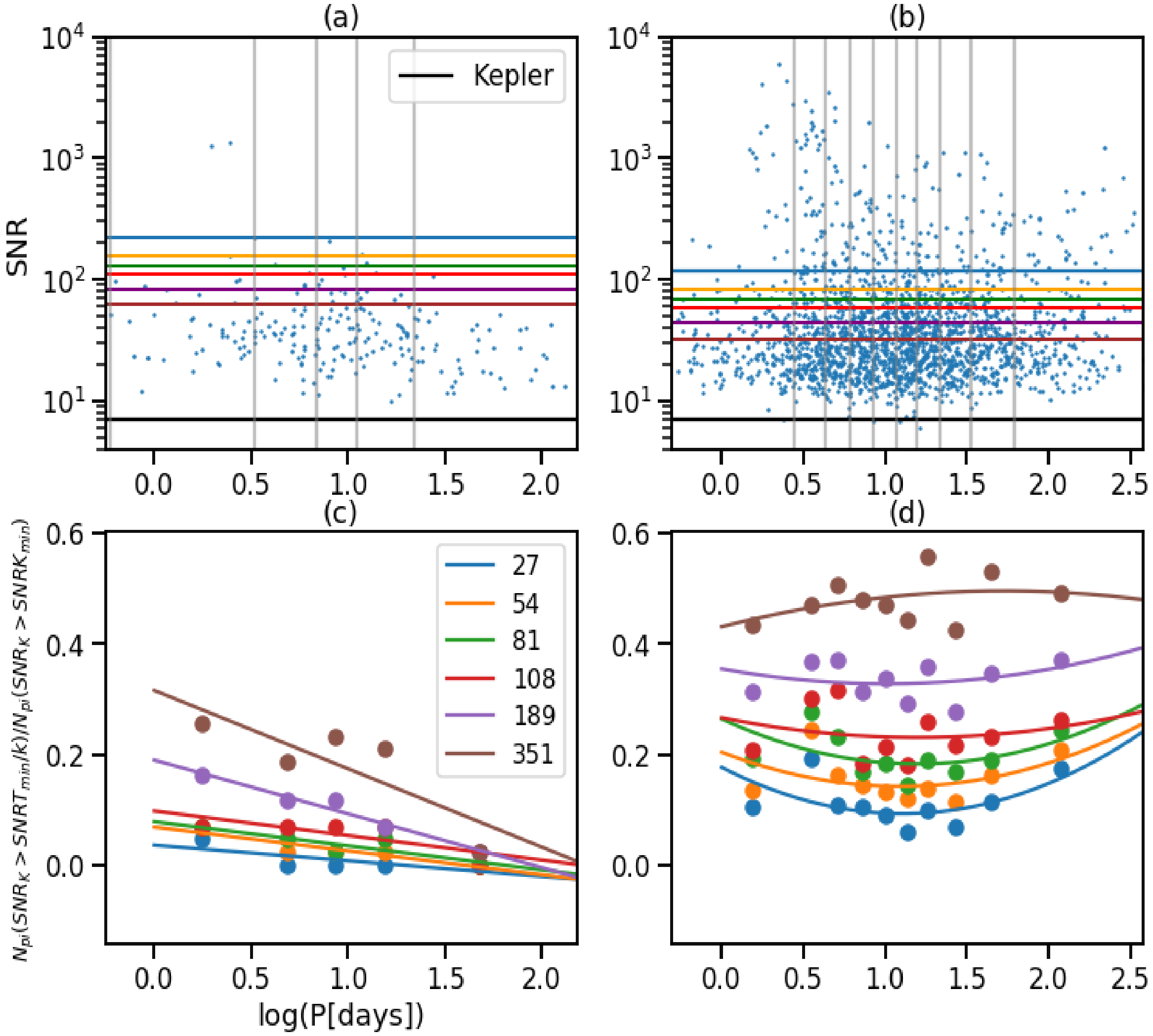
$$\mathrm{Prob}_i\ (\mathrm{SNR}_K > \mathrm{SNRK}_{min}\ |P,tr) \rightarrow \mathrm{Prob}_i\ (\mathrm{SNR}_K > \mathrm{SNRK}_{min}\ |P,tr,3trs_K)$$



Methodology

$$\frac{\text{Prob}_i\left(\text{SNR}_K > \frac{\text{SNRT}_{min}}{k} \middle| P, tr, 3trs_K\right)}{\text{Prob}_i(\text{SNR}_K > \text{SNRK}_{min} \,|P, tr, 3trs_K)} = \frac{N_{Pi}\left(\text{SNR}_K > \frac{\text{SNRT}_{min}}{k}\right)/N_{Pi}}{N_{Pi}(\text{SNR}_K > \text{SNRK}_{min})/N_{Pi}}$$

$$= \frac{N_{Pi}\left(\text{SNR}_K > \frac{\text{SNRT}_{min}}{k}\right)}{N_{Pi}(\text{SNR}_K > \text{SNRK}_{min})}$$

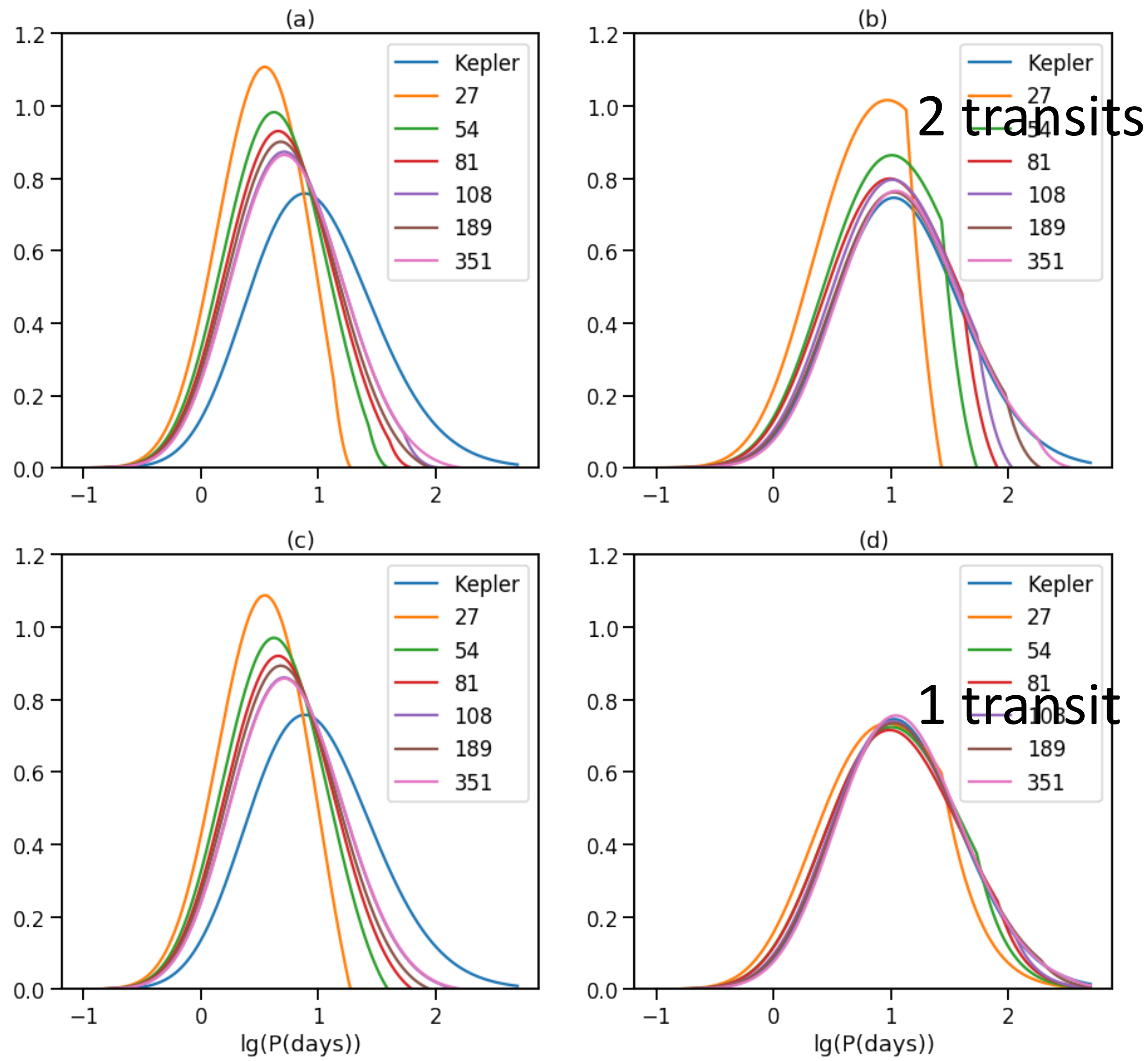


$$\textbf{Prob}_i(P|TESS)$$

$$= c_i\textbf{Prob}_i(P|Kepler)\,\frac{\textbf{Prob}_i(Ntrs_T|P,tr)\cdot\textbf{Prob}_i\left(\textbf{SNR}_T > \textbf{SNRT}_{min}\middle|P,tr,Ntrs_T\right)}{\textbf{Prob}_i(Ntrs_K|P,tr)\cdot\textbf{Prob}_i\left(\textbf{SNR}_K > \textbf{SNRK}_{min}\middle|P,tr,Ntrs_K\right)}$$

Results

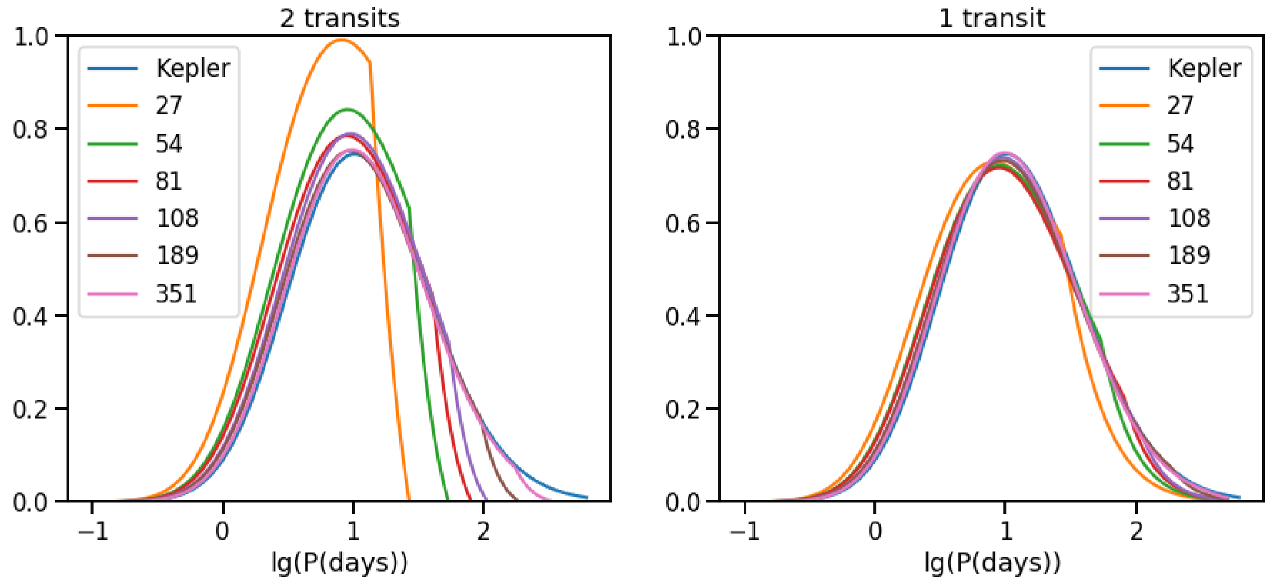
1. Results of two subsamples for different observation baseline

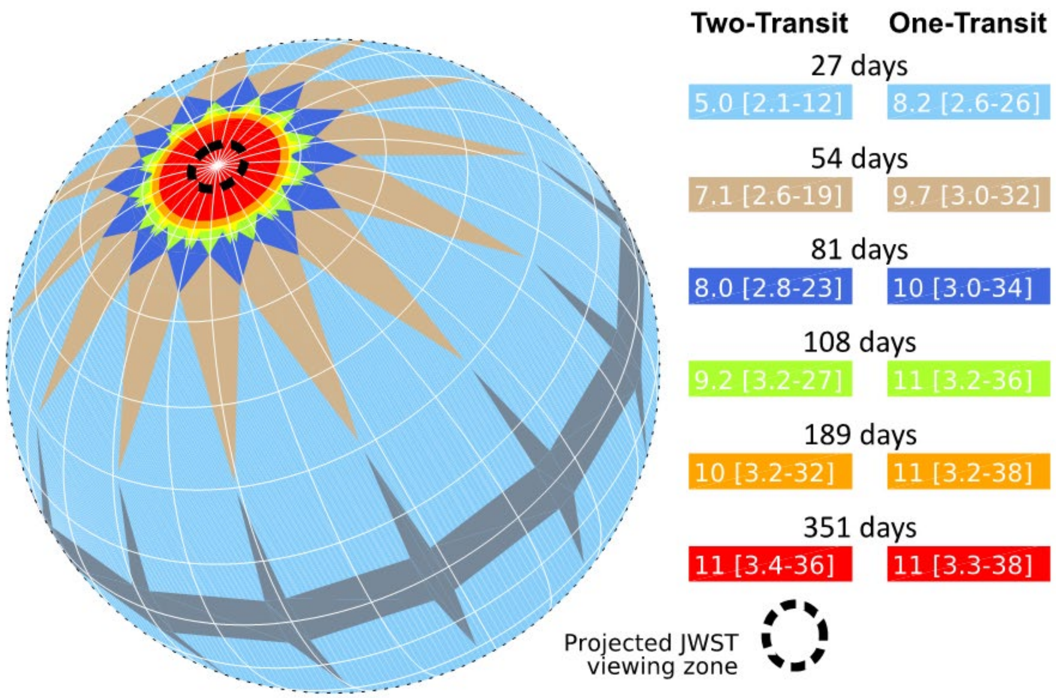


2 transits

1 transit

2. Results of different observation baseline

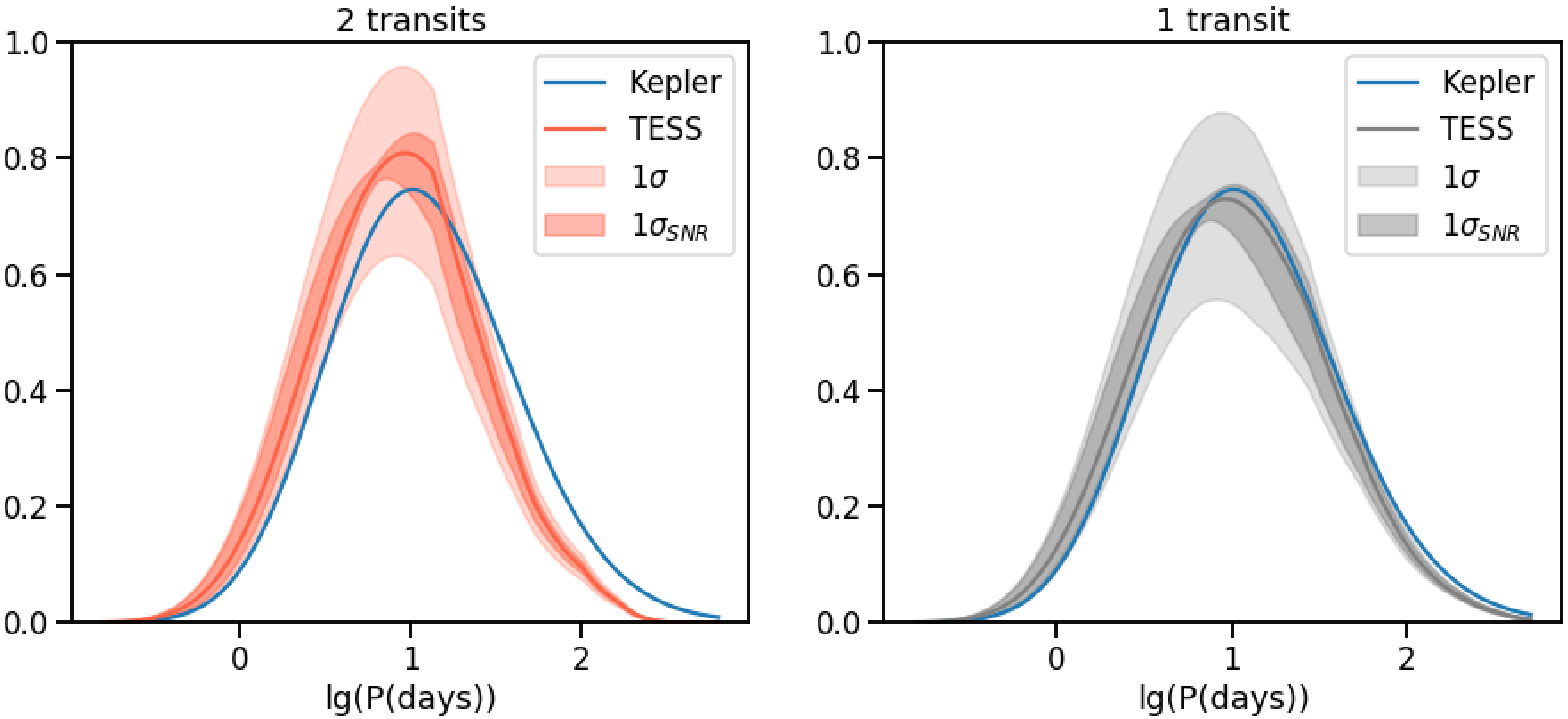




	Two-Transit	One-Transit
27 days	5.0 [2.1-12]	8.2 [2.6-26]
54 days	7.1 [2.6-19]	9.7 [3.0-32]
81 days	8.0 [2.8-23]	10 [3.0-34]
108 days	9.2 [3.2-27]	11 [3.2-36]
189 days	10 [3.2-32]	11 [3.2-38]
351 days	11 [3.4-36]	11 [3.3-38]

Projected JWST viewing zone

Results

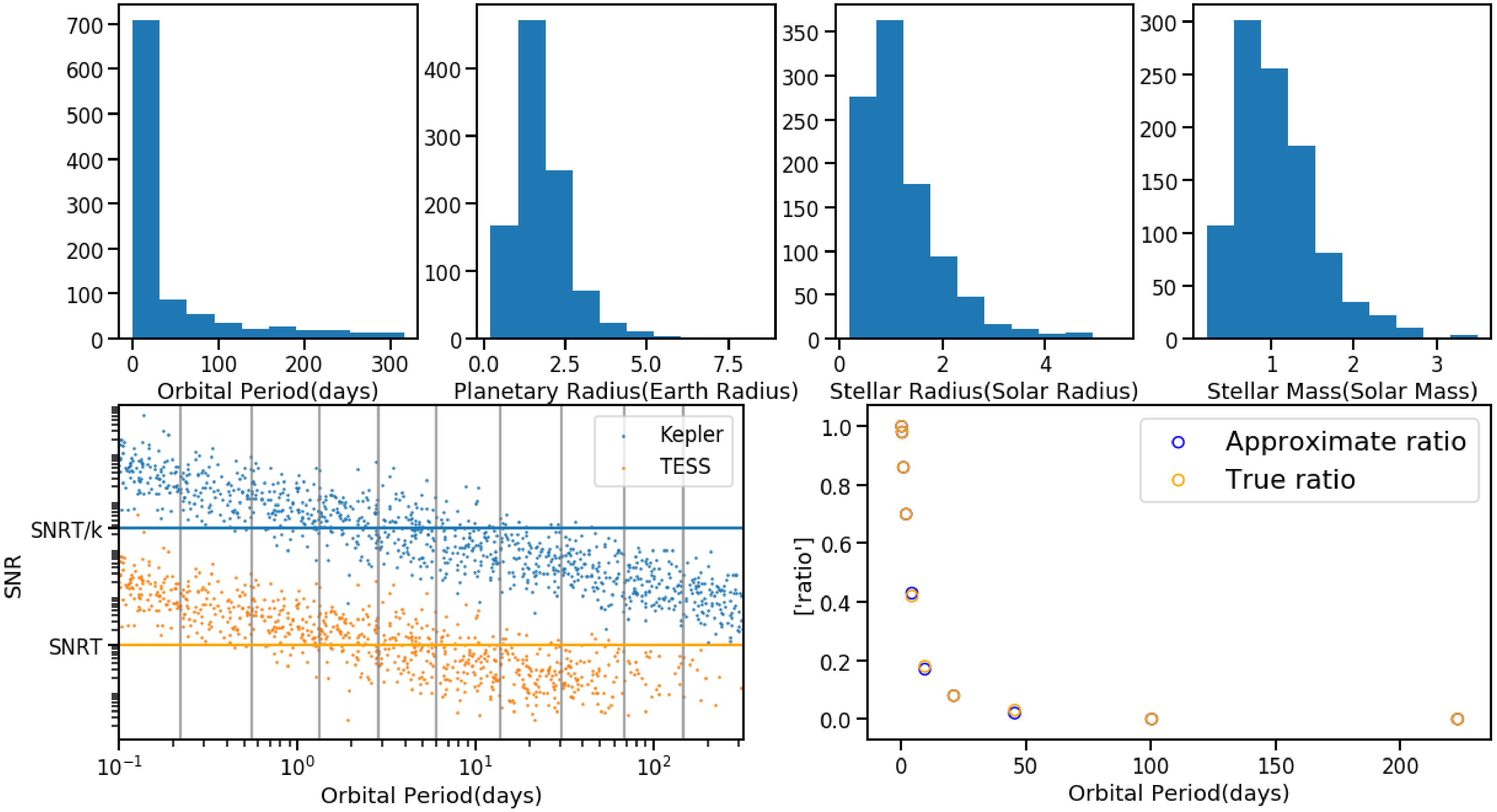


Duration of Observation (days)	TESS	Kepler
MP(days) -2 transits	8.47	11.89
1σ (days) -2 transits	2.75-26.12	3.45-41.04
MP(days) -1 transit	10.09	-
1σ (days) -1 transit	2.99-34.08	-

Uncertainty

- Uncertainty of approximating $\boldsymbol{Ntrs}$

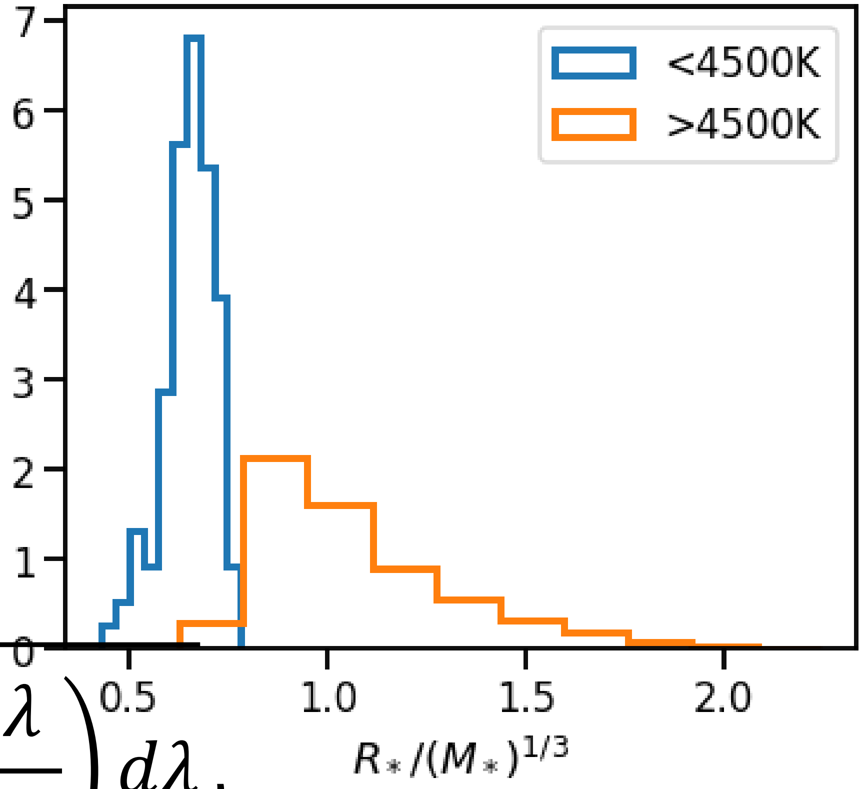
$$\mathbf{SNR} = \boldsymbol{R_p^2}\left(\frac{4\boldsymbol{\pi}^2\boldsymbol{P}}{\boldsymbol{GM_*}}\right)^{\frac{1}{6}}\sqrt{\frac{\boldsymbol{N_{trs}A}}{4\boldsymbol{R_*r^2}}\int_{\lambda_1}^{\lambda_2}\boldsymbol{\tau\pi B(\lambda,T_*)}\left(\frac{\boldsymbol{\lambda}}{\boldsymbol{hc}}\right)\boldsymbol{d\lambda}}$$



Uncertainty

- Uncertainty of Stellar Parameters

$$\mathrm{Prob}_i(P|TESS) = c_i\mathrm{Prob}_i(P|Kepler)\cdot\frac{\mathrm{Prob}(\boldsymbol{tr}|\boldsymbol{P})}{\mathrm{Prob}(\boldsymbol{tr}|\boldsymbol{P})}\cdot\frac{\mathrm{Prob}_i(Ntrs_T|P,tr)}{\mathrm{Prob}_i(Ntrs_K|P,tr)}\cdot\frac{\mathrm{Prob}_i(\mathrm{SNR}_T>\mathrm{SNRT}_{min}|P,tr)}{\mathrm{Prob}_i(\mathrm{SNR}_K>\mathrm{SNRK}_{min}|P,tr)}$$



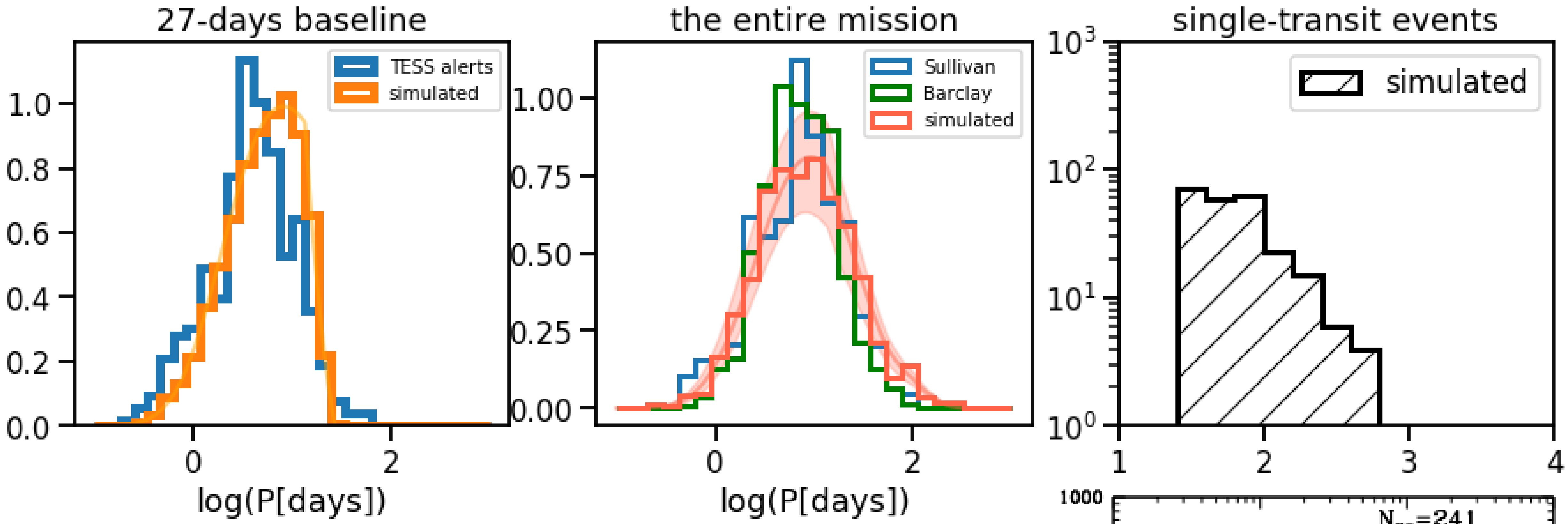
- Uncertainty of SNR model

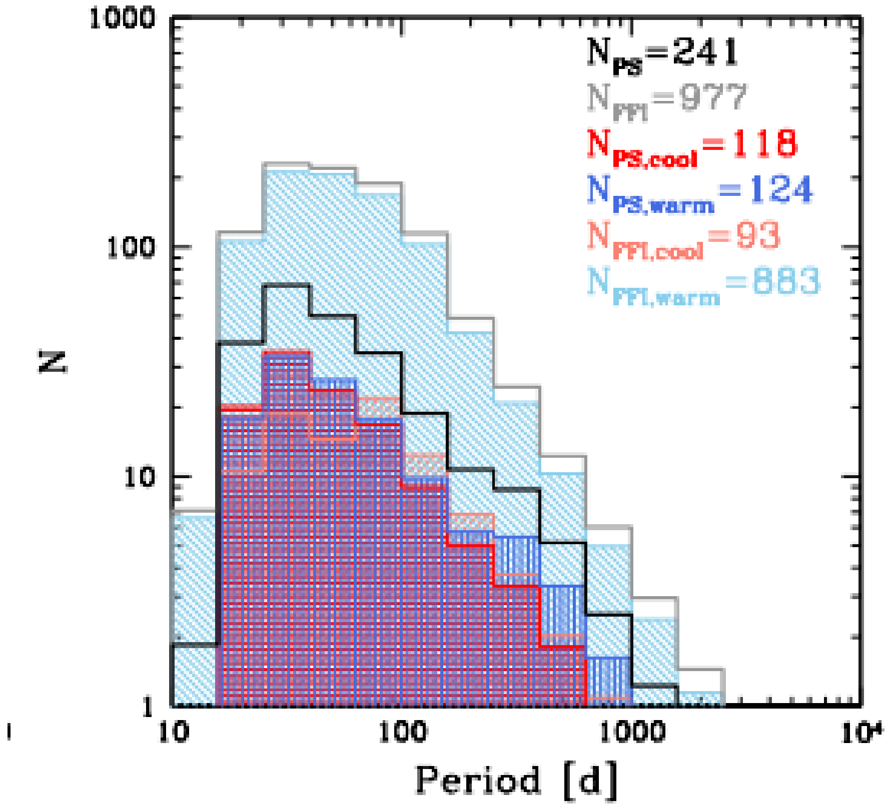
$$\mathrm{SNR} = R_p^2P^{-\frac{1}{3}}\left(\frac{4\pi^2}{GM_*}\right)^{\frac{1}{6}}\sqrt{\frac{At_m}{4R_*r^2}\int_{\lambda_1}^{\lambda_2}\tau\pi B(\lambda,T_*)\left(\frac{\lambda}{hc}\right)d\lambda},$$

$$\mathrm{h}(\mathbb{M},\mathbf{T}_*) = \sqrt{\frac{At_m}{r^2}\int_{\lambda_1}^{\lambda_2}\tau\pi B(\lambda,T_*)\left(\frac{\lambda}{hc}\right)d\lambda}$$

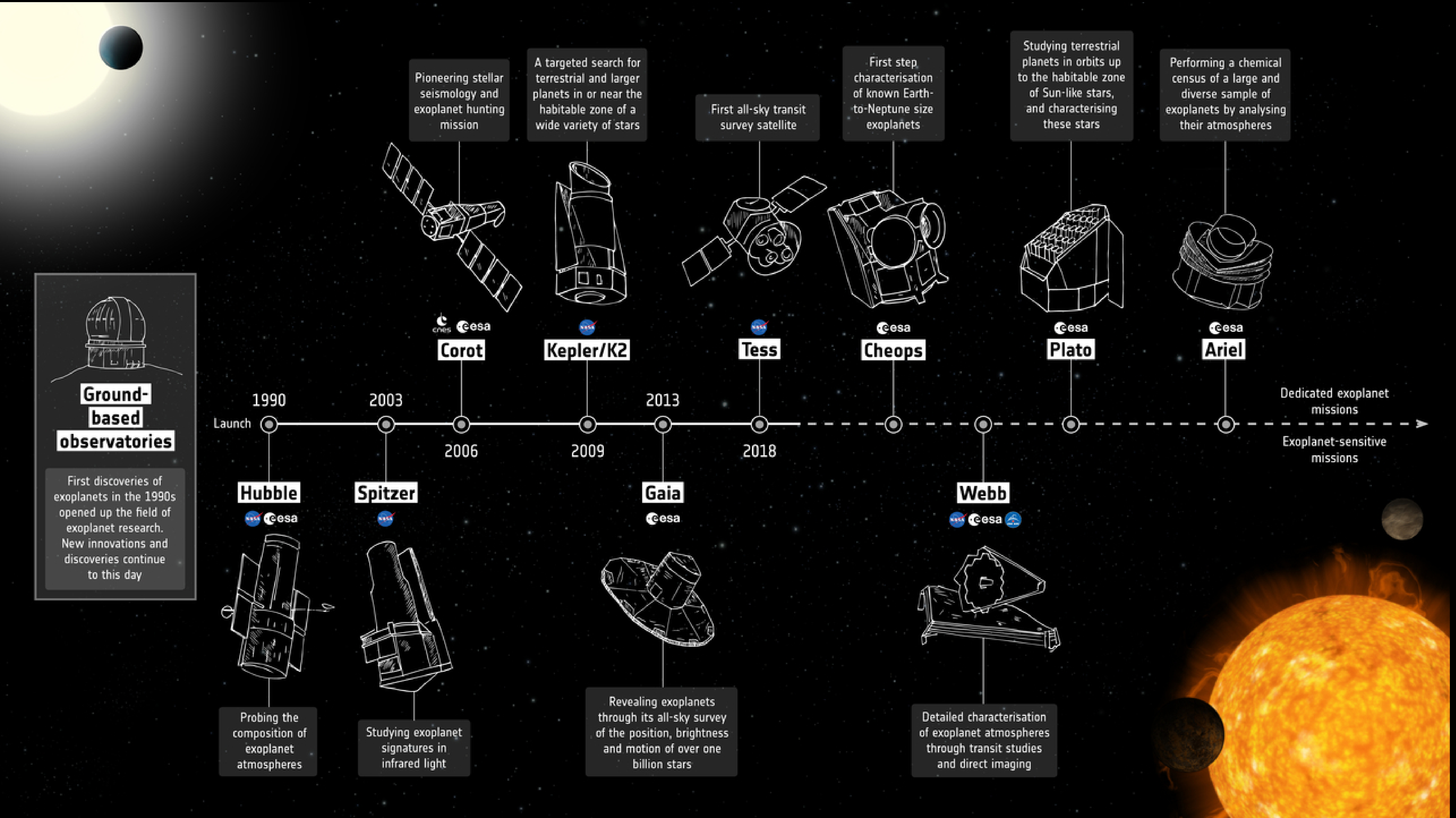
1000 times

Comparison


27-days baseline
TESS alerts
simulated
1.0
0.8
0.6
0.4
0.2
0.0
0
2
log(P[days])
the entire mission
Sullivan
Barclay
simulated
1.00
0.75
0.50
0.25
0.00
0
2
log(P[days])
single-transit events
simulated
10^3
10^2
10^1
10^0
1
2
3
4


$N_{PS}=241$
$N_{FPI}=977$
$N_{PS,cool}=118$
$N_{PS,warm}=124$
$N_{FPI,cool}=93$
$N_{FPI,warm}=883$
1000
100
10
1
N
10
100
1000
10^4
Period [d]

BRIGHT FUTURE!



Ground-based observatories

First discoveries of exoplanets in the 1990s opened up the field of exoplanet research. New innovations and discoveries continue to this day

Launch

1990 **Hubble** esa: Probing the composition of exoplanet atmospheres

2003 **Spitzer**: Studying exoplanet signatures in infrared light

2006 **Corot** cnes esa: Pioneering stellar seismology and exoplanet hunting mission

2009 **Kepler/K2**: A targeted search for terrestrial and larger planets in or near the habitable zone of a wide variety of stars

2013 **Gaia** esa: Revealing exoplanets through its all-sky survey of the position, brightness and motion of over one billion stars

2018 **Tess**: First all-sky transit survey satellite

Cheops esa: First step characterisation of known Earth-to-Neptune size exoplanets

Webb esa: Detailed characterisation of exoplanet atmospheres through transit studies and direct imaging

Plato esa: Studying terrestrial planets in orbits up to the habitable zone of Sun-like stars, and characterising these stars

Ariel esa: Performing a chemical census of a large and diverse sample of exoplanets by analysing their atmospheres

Dedicated exoplanet missions

Exoplanet-sensitive missions