Twenty-five years of transiting planets

Josh Winn PRINCETON UNIVERSITY

NASA/SDO

A wealth of information from transits

Planet properties

Radius
Mass
Atmospheric spectrum
Oblateness, obliquity
Moons, rings

Host star properties

Rotational obliquity
Starspot sizes, latitudes
Limb darkening
Gravity darkening
Companion stars

Orbital properties

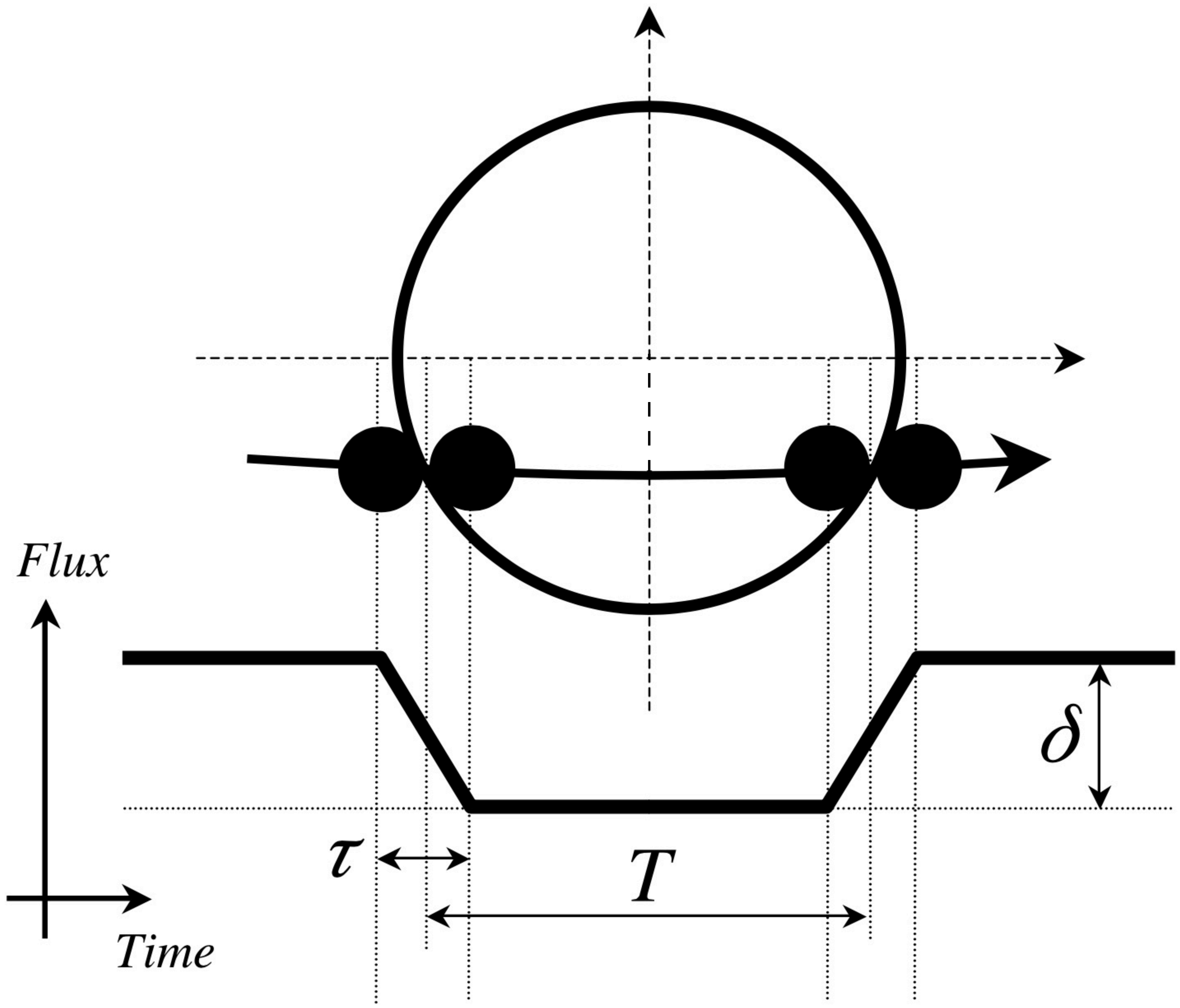
Period
Eccentricity
Resonances
Secular effects

Population properties

Overall occurrence
Period/radius distribution
Multiplicity distribution
Mutual inclinations

NASA/SDO

The key transit observables



Winn (2010)

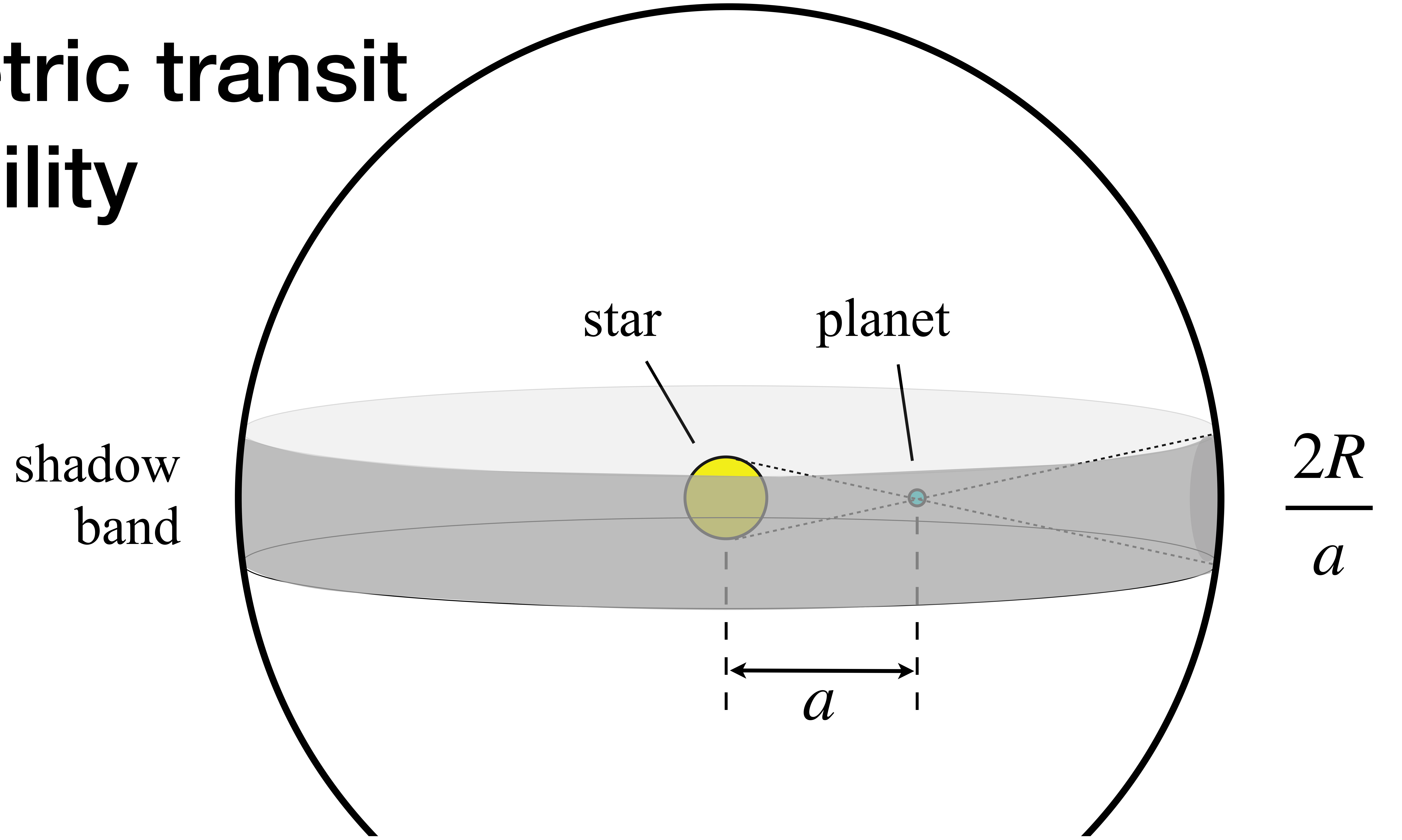
Depth

$$\delta \approx \left(\frac{r}{R}\right)^2 \quad \begin{cases} 10^{-2}, \text{ Jupiter} \\ 10^{-4}, \text{ Earth} \end{cases}$$

Duration

$$T \lesssim P\,\frac{R}{\pi a} \quad \begin{cases} 2\,\text{hr}, \text{ hot Jupiter} \\ 13\,\text{hr}, \text{ Earth} \end{cases}$$

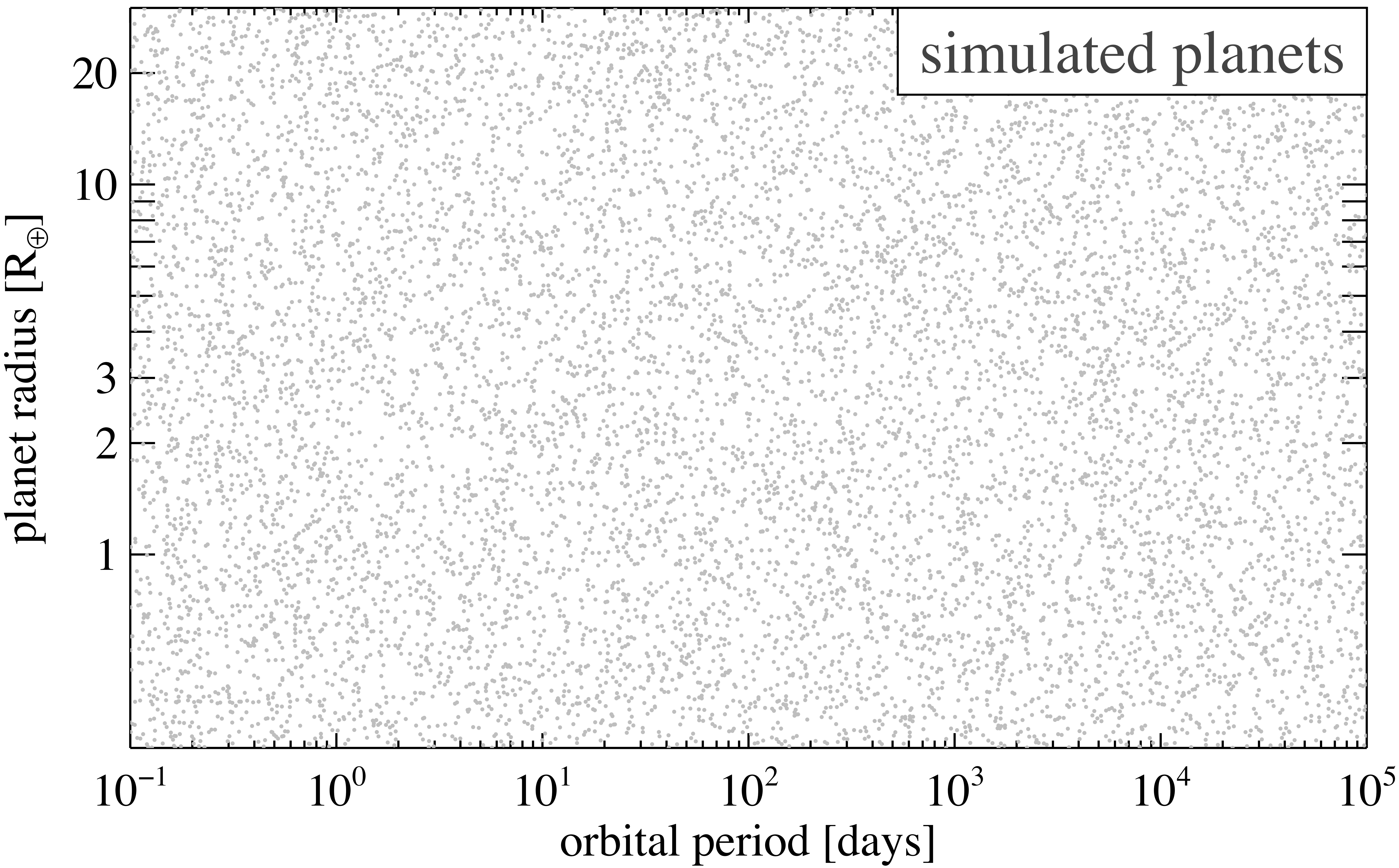
Geometric transit probability



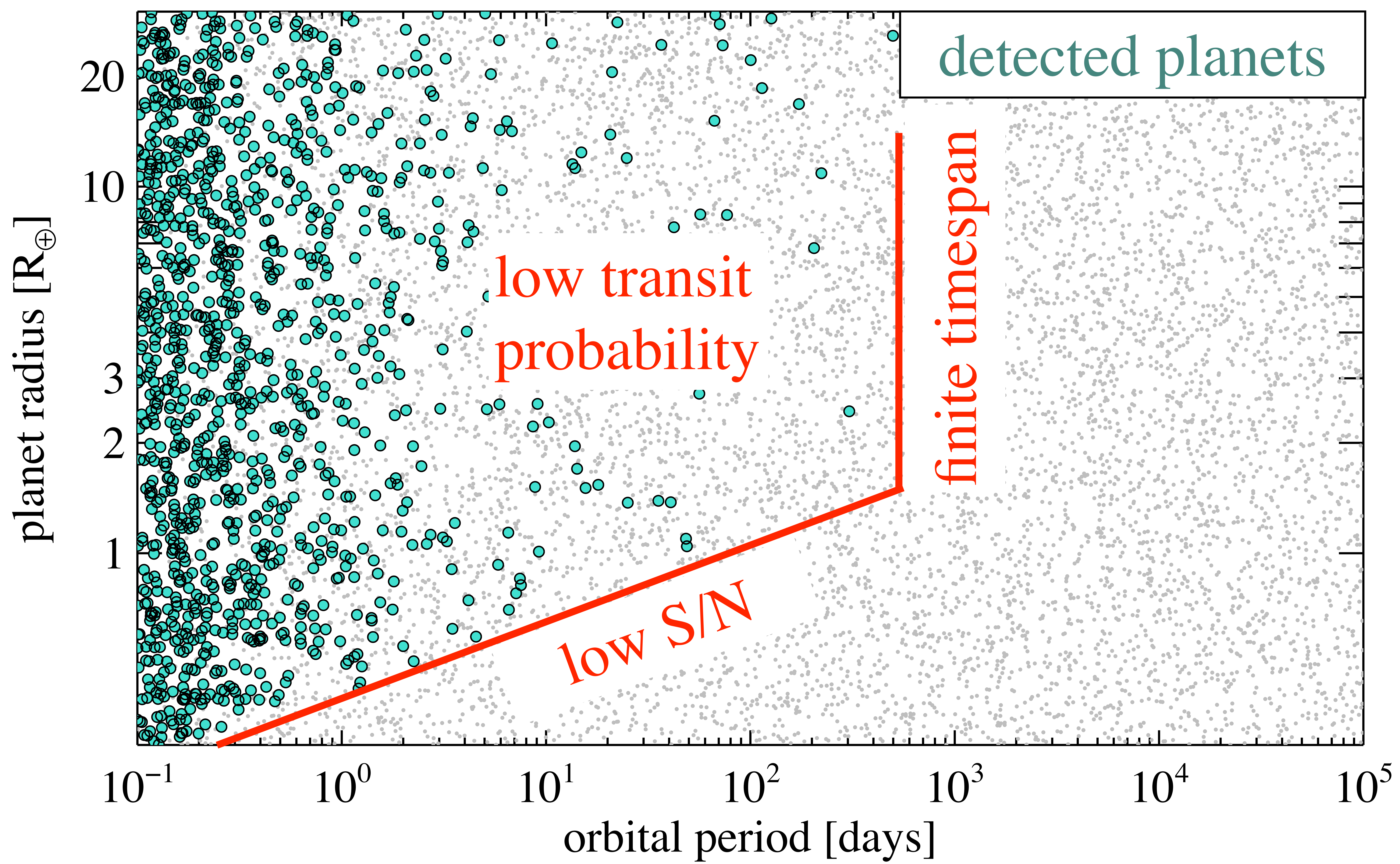
$$\text{transit probability} = \frac{2\pi \times \frac{2R}{a}}{4\pi} = \frac{R}{a} = \frac{1}{215}\left(\frac{R}{R_\odot}\right)\left(\frac{a}{1\ \text{AU}}\right)^{-1}$$

Winn (2010)

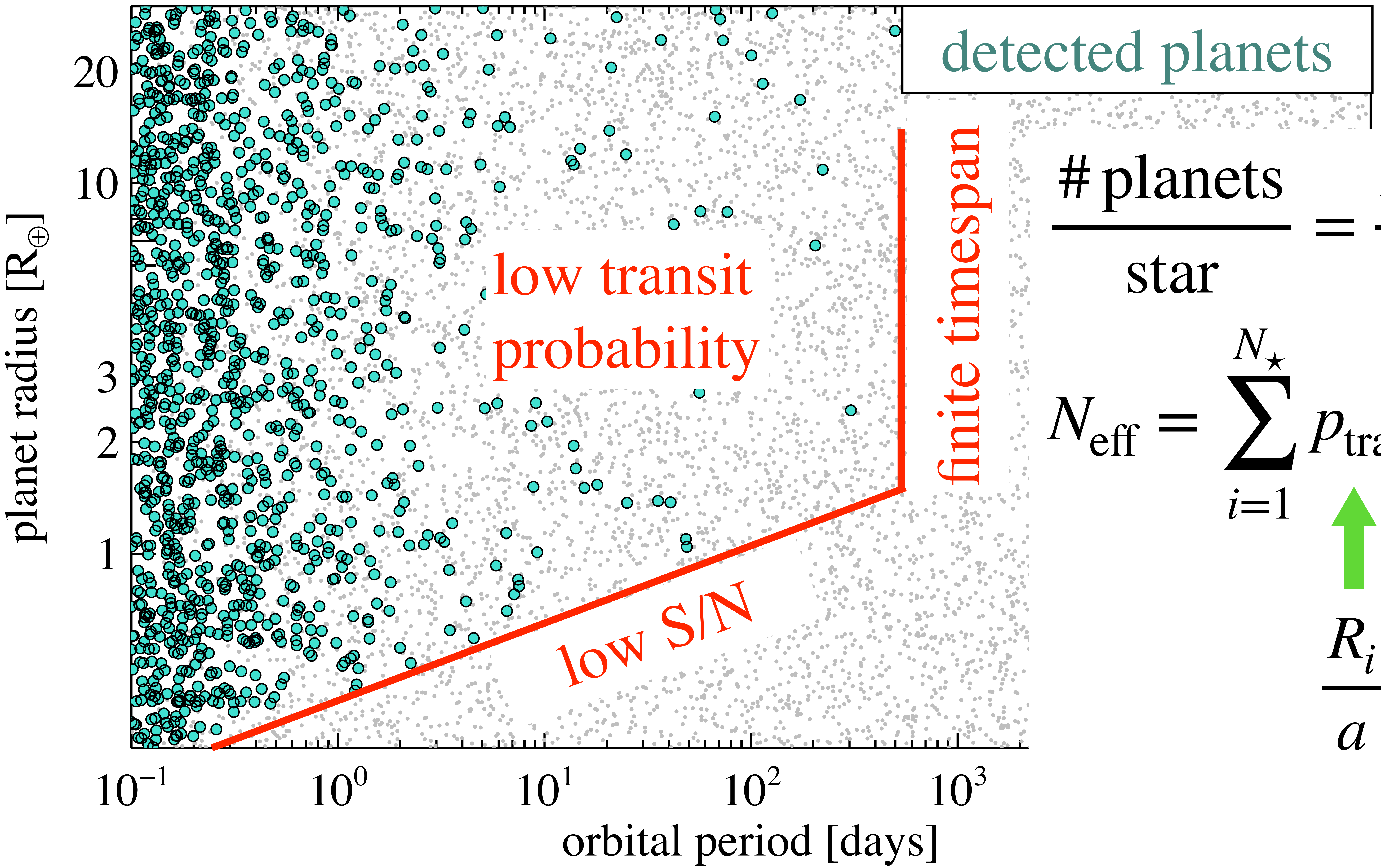
Selection bias in transit surveys



Selection bias in transit surveys



Selection bias in transit surveys



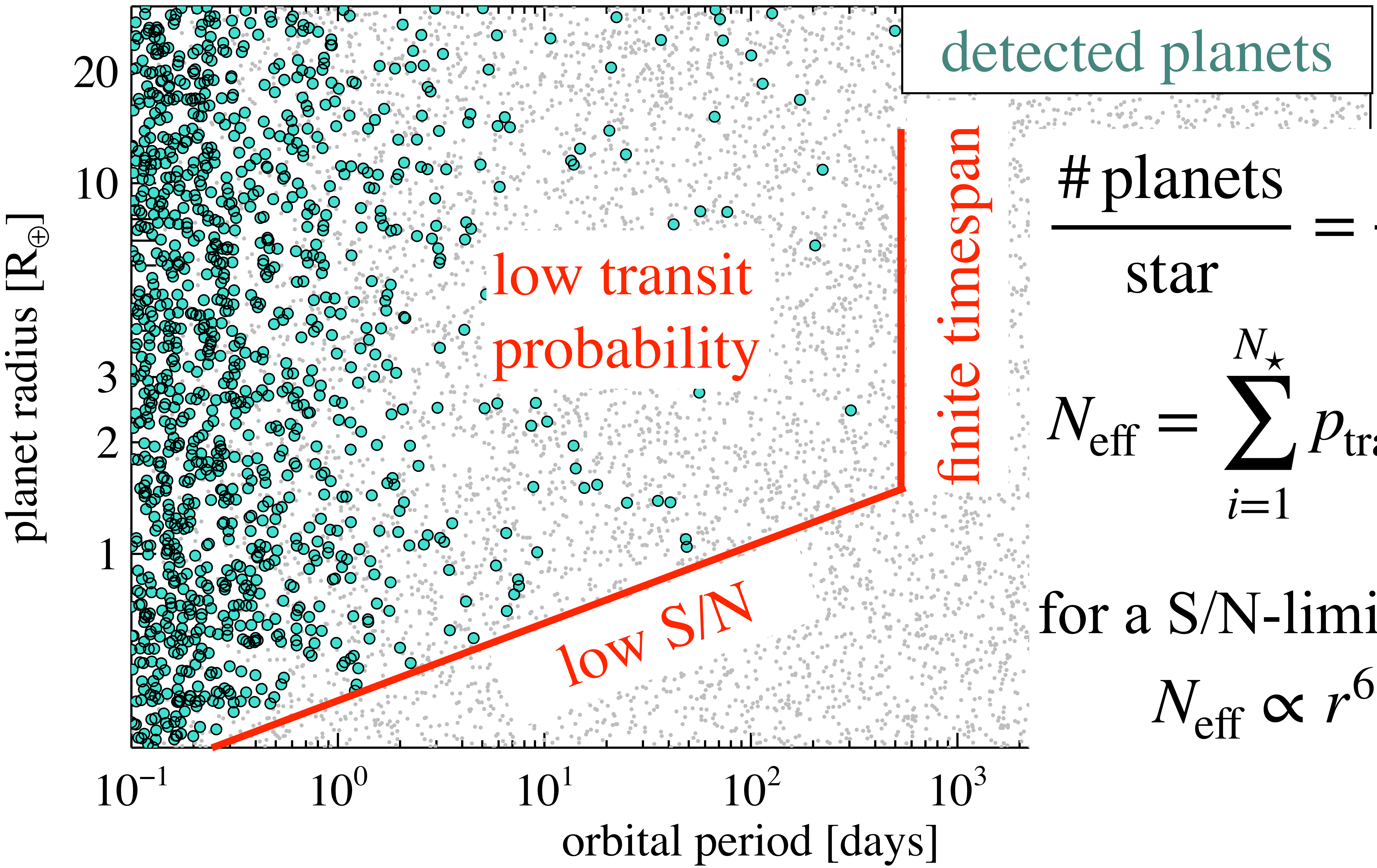
$$\frac{\#\,\text{planets}}{\text{star}} = \frac{N_{\text{det}}}{N_{\text{eff}}}$$

$$N_{\text{eff}} = \sum_{i=1}^{N_\star} p_{\text{tra},i}\, p_{\text{det},i}$$

$p_{\text{tra},i}$: $\frac{R_i}{a}$

$p_{\text{det},i}$: depends on brightness, R_i, P, and detection algorithm

Selection bias in transit surveys



$$\frac{\#\,\text{planets}}{\text{star}} = \frac{N_{\rm det}}{N_{\rm eff}}$$

$$N_{\rm eff} = \sum_{i=1}^{N_\star} p_{{\rm tra},i}\, p_{{\rm det},i}$$

for a S/N-limited survey,

$$N_{\rm eff} \propto r^6\, P^{-5/3}$$

Pepper et al. (2003)

Demographics with transit surveys

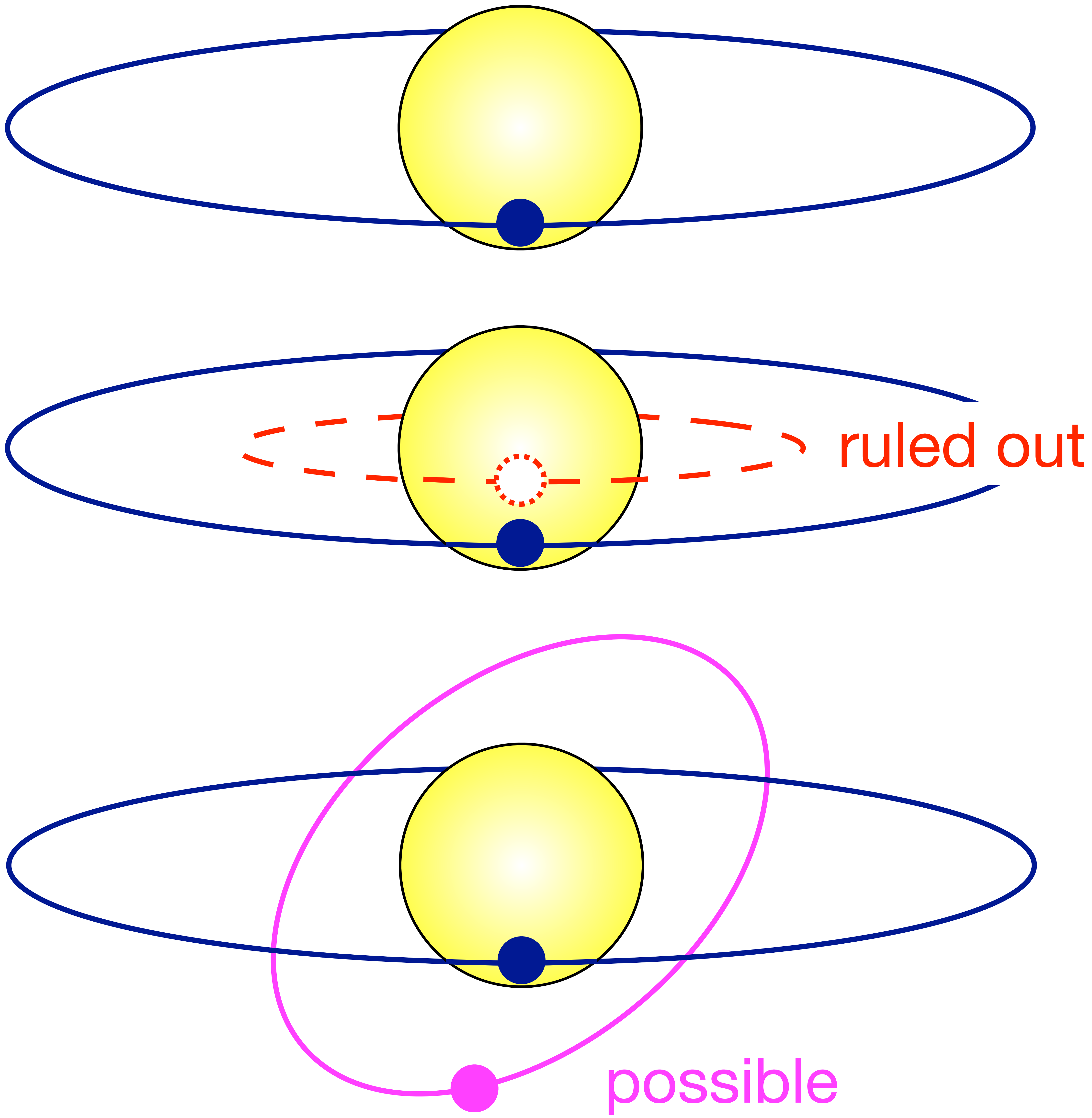
- **Inefficient** because of low transit probability
- **Strongly biased** in favor of large and short-period planets, making corrections sensitive to details
- **Degeneracy** between multiplicity and mutual inclination dispersion

Multiplicity and mutual inclinations

Suppose we detect only
one transiting planet.

If mutual inclinations are low, the non-detection of other transits suggests other planets do not exist.

If mutual inclinations are high, the non-detection of other transits has little bearing on the existence of other planets.



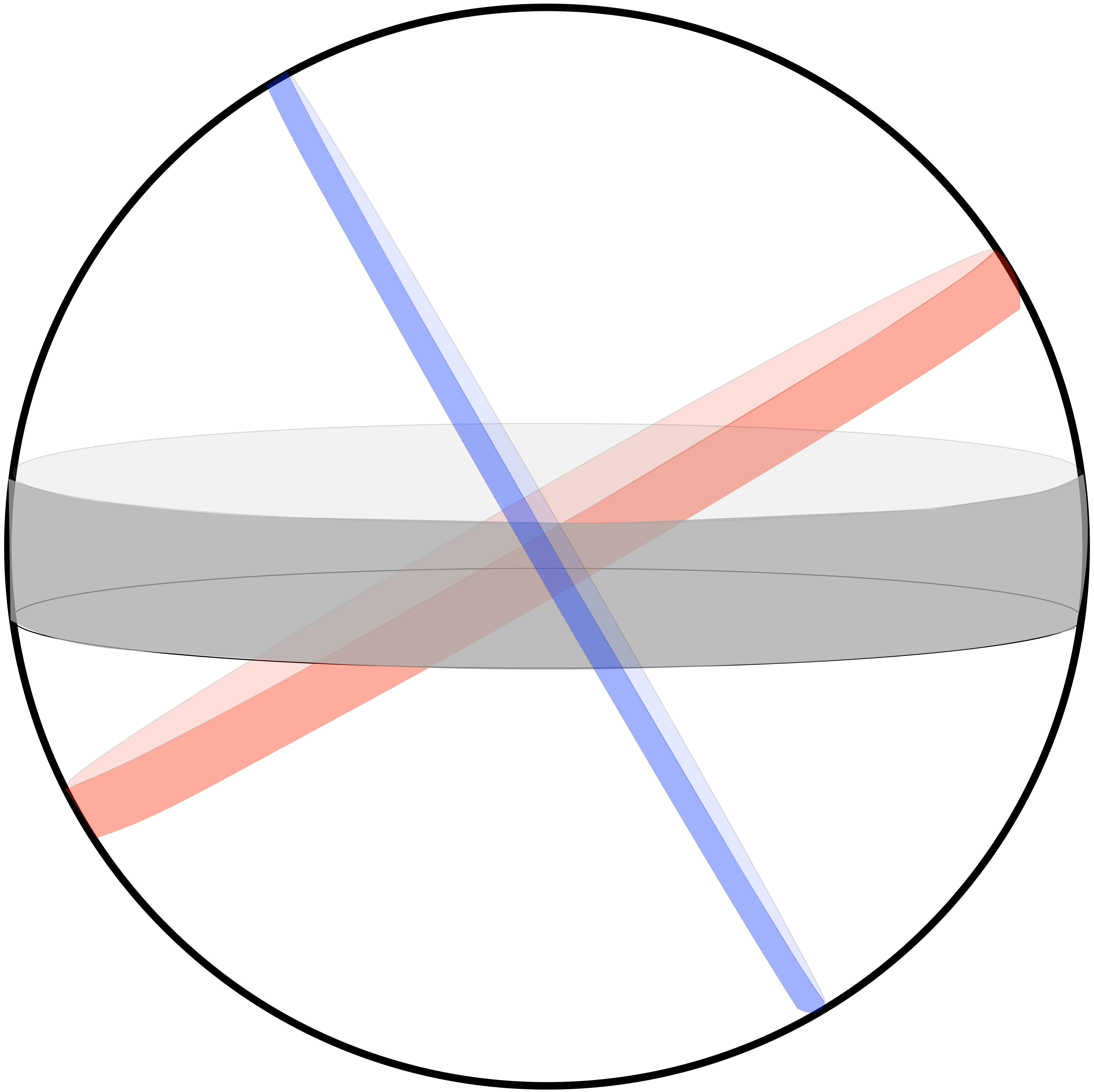
Geometric transit probabilities for multiple planets

Complicated, because the orientations of orbital planes are correlated

$$p(\mathrm{tra}_1 \,\&\, \mathrm{tra}_2) = p(\mathrm{tra}_1) \cdot p(\mathrm{tra}_2 \,|\, \mathrm{tra}_1)$$

$p(\mathrm{tra}_1)$: $\dfrac{R}{a_1}$

$p(\mathrm{tra}_2 \,|\, \mathrm{tra}_1)$: depends on mutual inclination

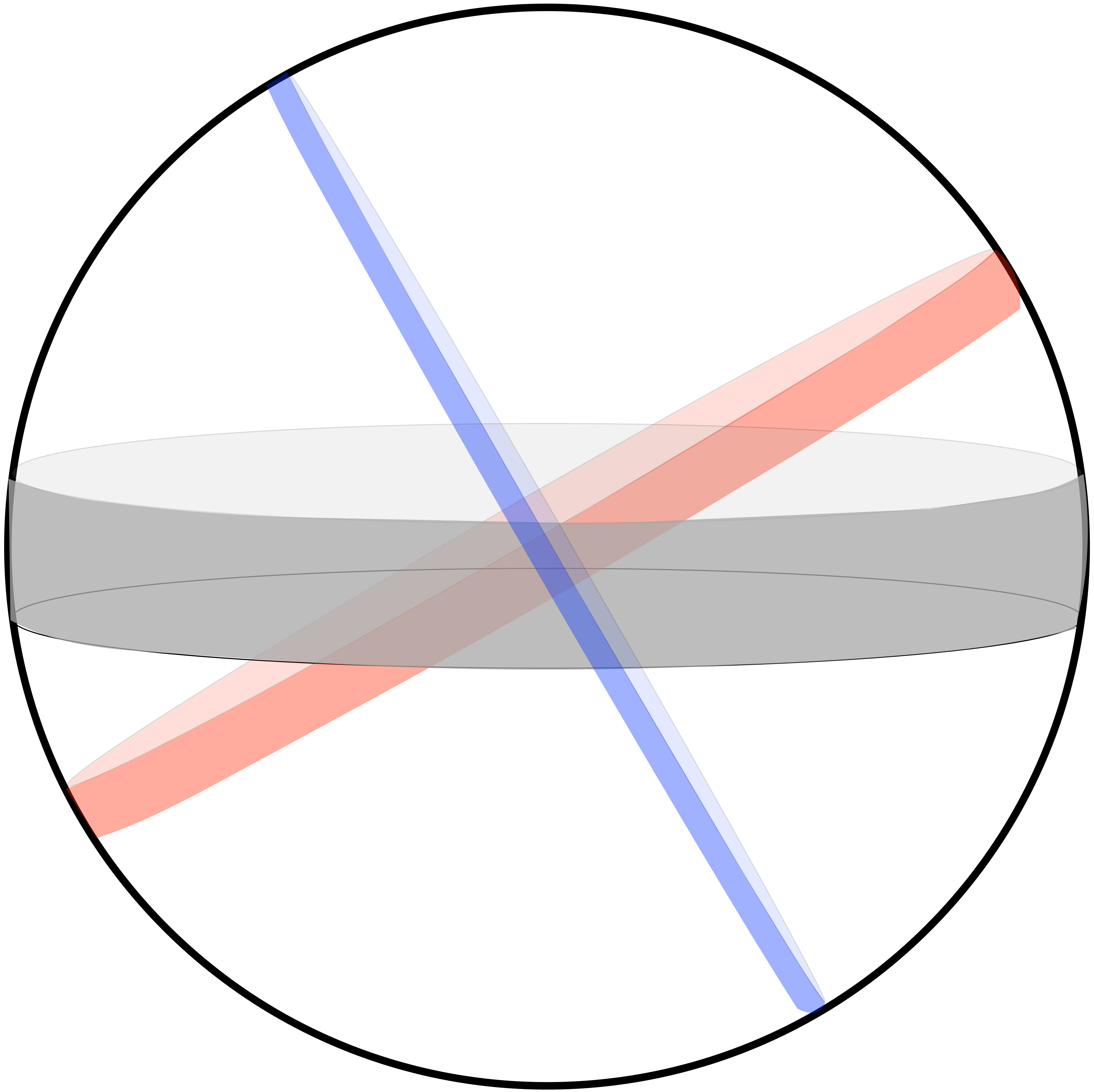


Brakensiek & Ragozzine (2016)

Geometric transit probabilities for multiple planets

Solar System Transit Probabilities

Planets	Probability
Mercury–Venus	6.84×10^{-4}
Earth–Venus	3.22×10^{-4}
Earth–Mars	2.84×10^{-4}
Mercury–Earth–Mars	2.10×10^{-4}
Mercury–Venus–Saturn	3.53×10^{-5}
Mercury–Earth–Uranus	6.15×10^{-8}
Venus–Earth–Uranus	2.17×10^{-5}
Mercury–Mars–Uranus	4.95×10^{-6}
Jupiter–Saturn–Uranus	2.22×10^{-6}
Mercury–Venus–Neptune	1.77×10^{-6}
Mars–Jupiter–Neptune	2.56×10^{-6}



Brakensiek & Ragozzine (2016)

Demographics with transit surveys

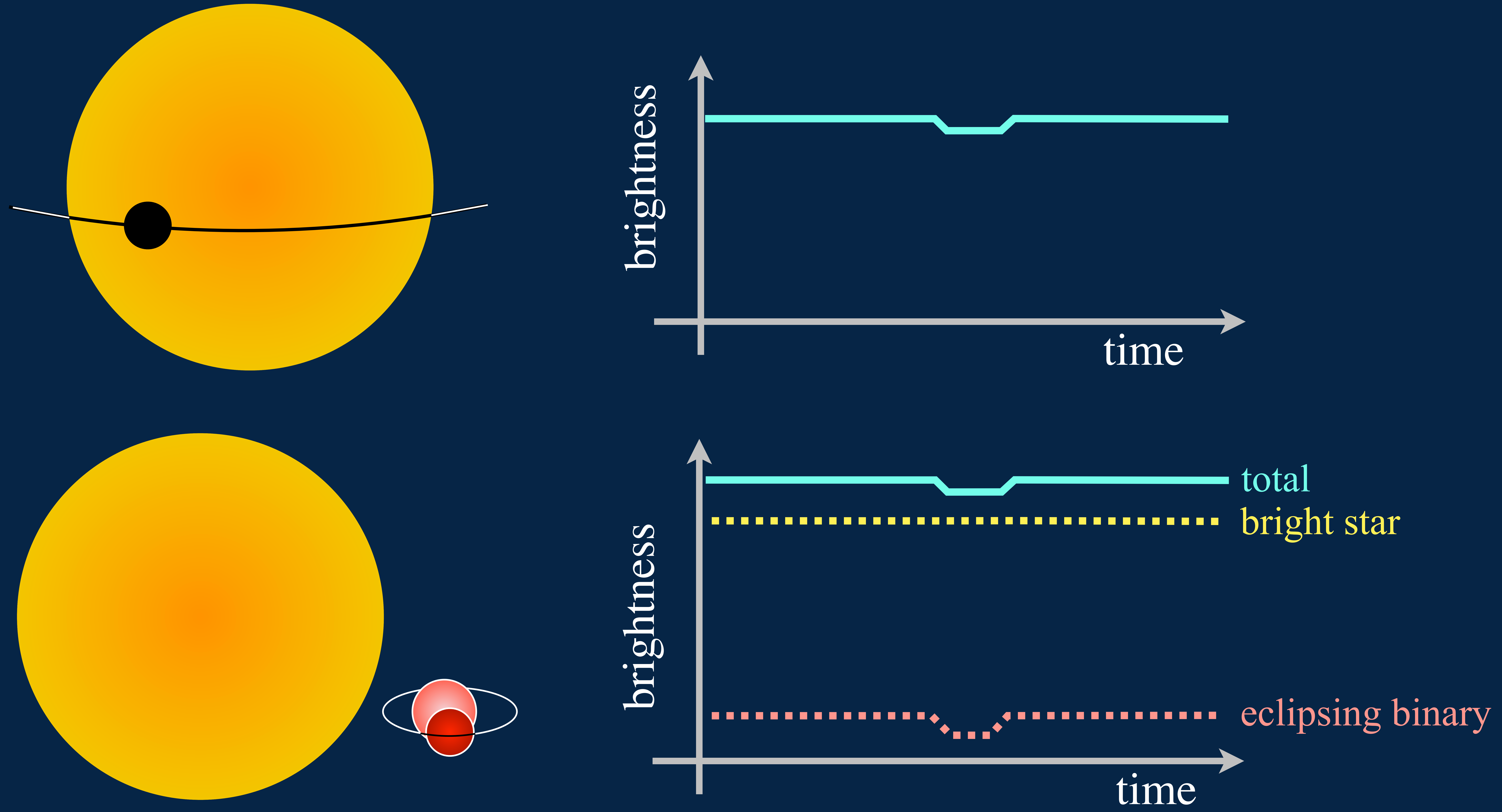
- **Inefficient** because of low transit probability
- **Strongly biased** in favor of large and short-period planets, making corrections sensitive to details
- **Degeneracy** between multiplicity and mutual inclination dispersion

- We are lucky that **short period planets** turned out to be **abundant**
- Hundreds of thousands of stars can be **searched simultaneously**
- Surveys with space telescopes provide **precise** and **homogeneous** datasets
- Degeneracy can be **broken** with Doppler and TTV measurements

A brief history of transit surveys

Transiting Planets in 2001

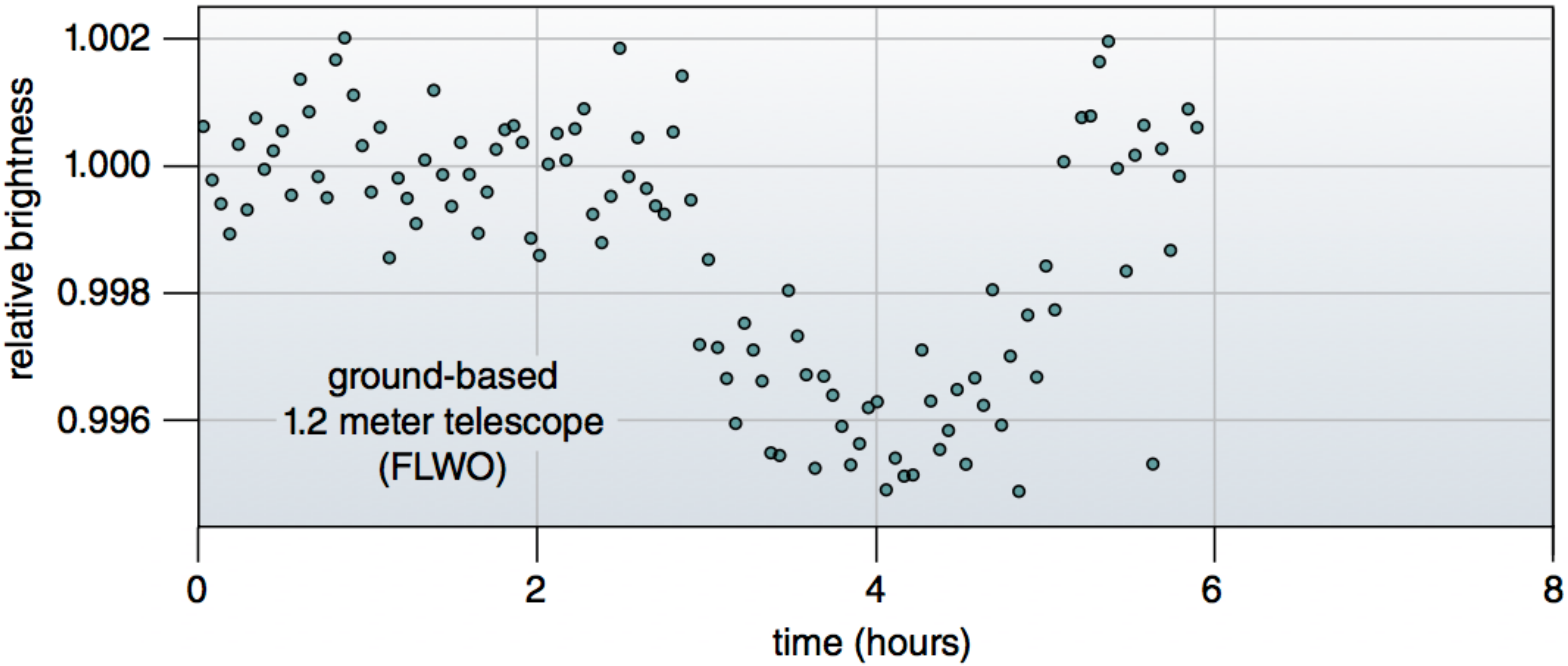
Transiting Planets in 2007


brightness
time
total
bright star
eclipsing binary
brightness
time

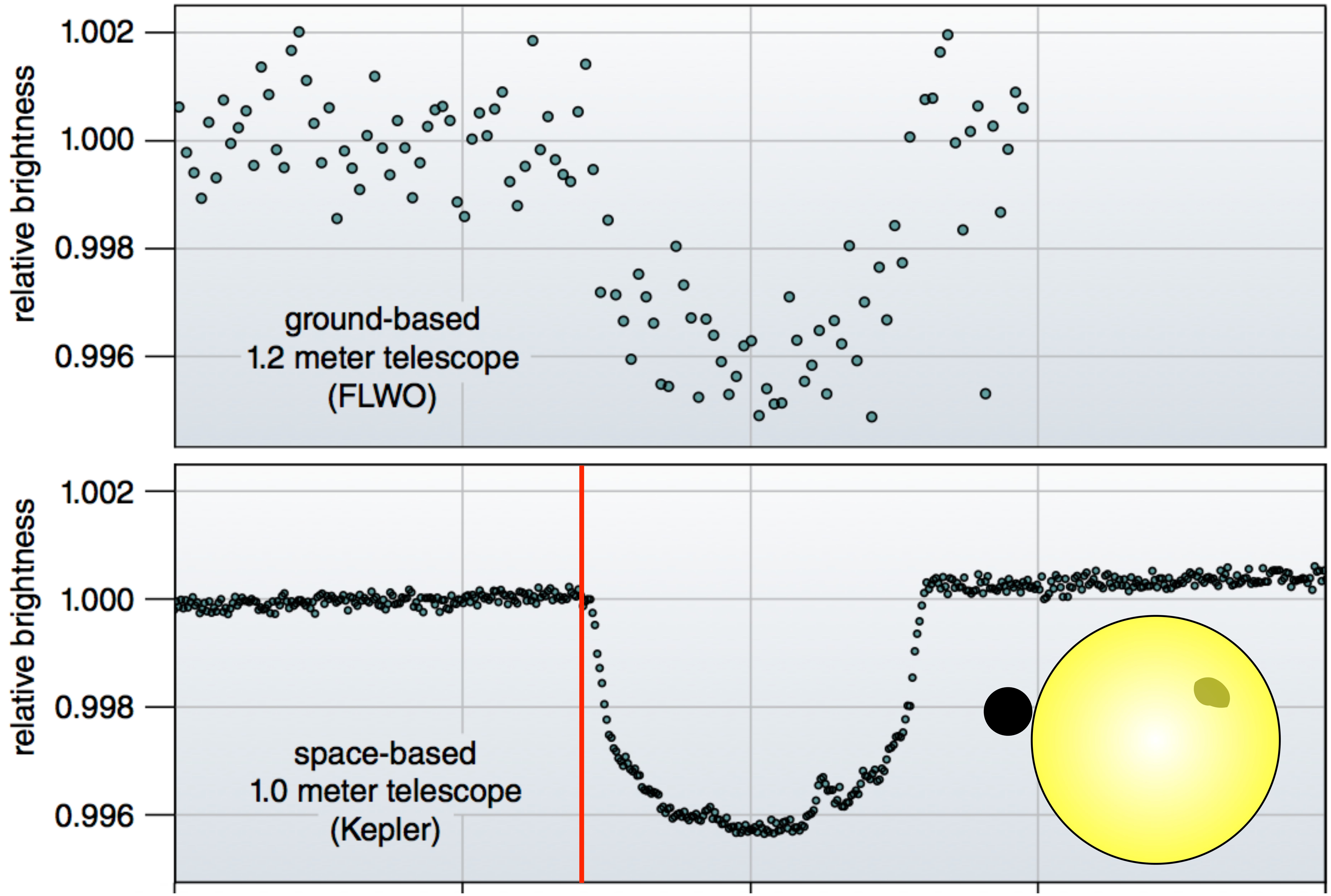

Transiting Planets in 2007
Doppler-first
Ground-based
6th mag
10th mag
16th mag

Transiting Planets in 2007

Brighter Stars are Better



Heng & Winn (2016)



Space Telescopes are Better

Heng & Winn (2016)

CoRoT

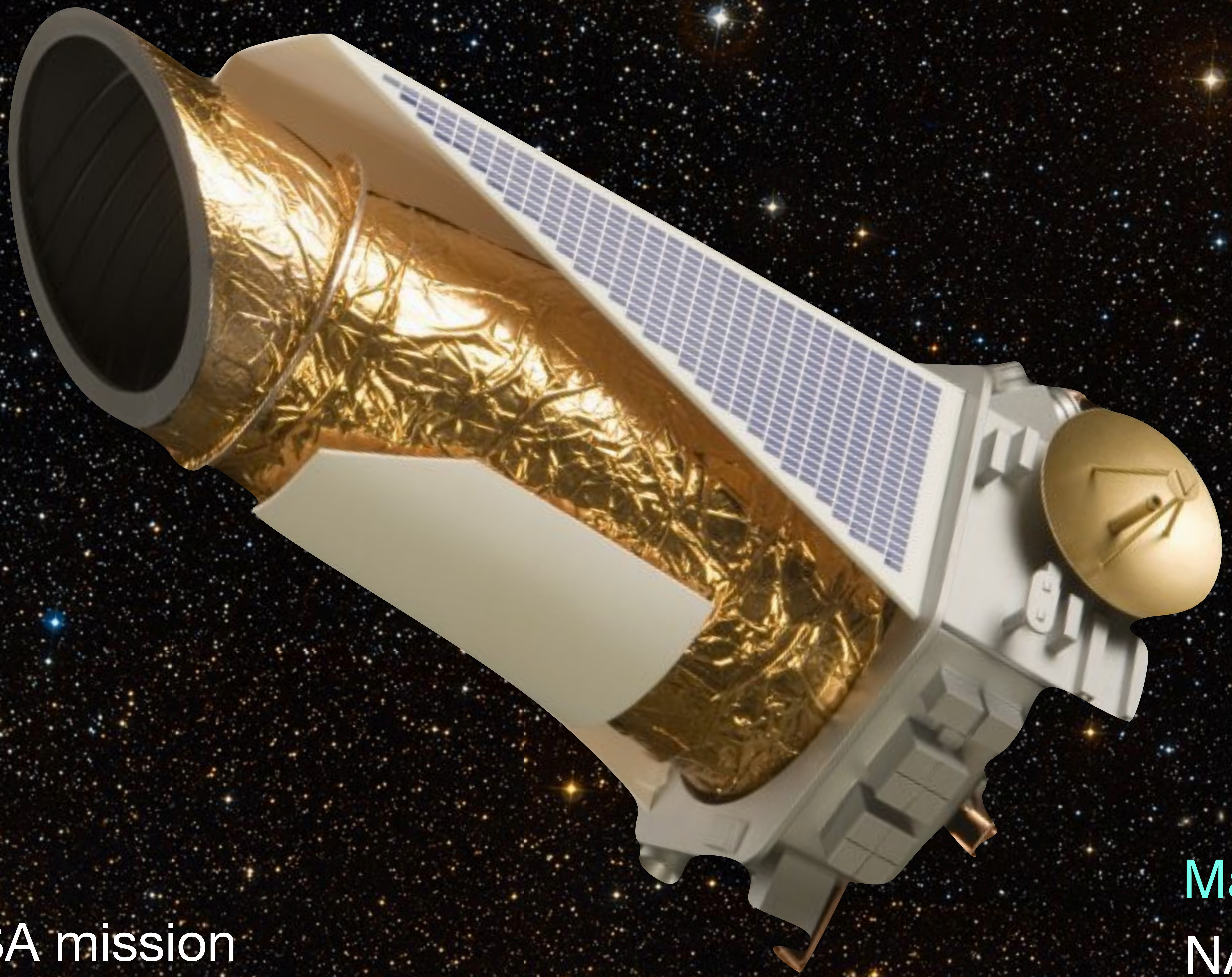
€170 million CNES mission
Principal Investigator: Annie Baglin (Paris Observatory)
First proposed 1993, launched 2006, ended 2013

Major partners:

CNES, ESA, France, Austria, Belgium, Brazil, Germany, Spain

Transiting Planets in 2009

Transiting Planets *Smaller than Neptune* in 2009



Kepler

$600 million NASA mission
Principal Investigator: William Borucki (NASA Ames)
First proposed 1992, launched 2009, ended 2013 (and 2018)

Major partners:
NASA Ames, JPL,
Ball Aerospace,
SETI Institute

Transiting Planets *Smaller than Neptune* in 2010

Transiting Planets *Smaller than Neptune* in 2011

Transiting Planets *Smaller than Neptune* in 2012

Transiting Planets *Smaller than Neptune* in 2013

Transiting Planets *Smaller than Neptune* in 2014


Kepler Search Space
3,000 light years
Sagittarius Arm
Sun
Orion Spur
Perseus Arm
Kepler Mission How common are Earth-like planets?
TESS Mission Where are the nearest transiting planets?
short-period
Jon Lomberg

TESS

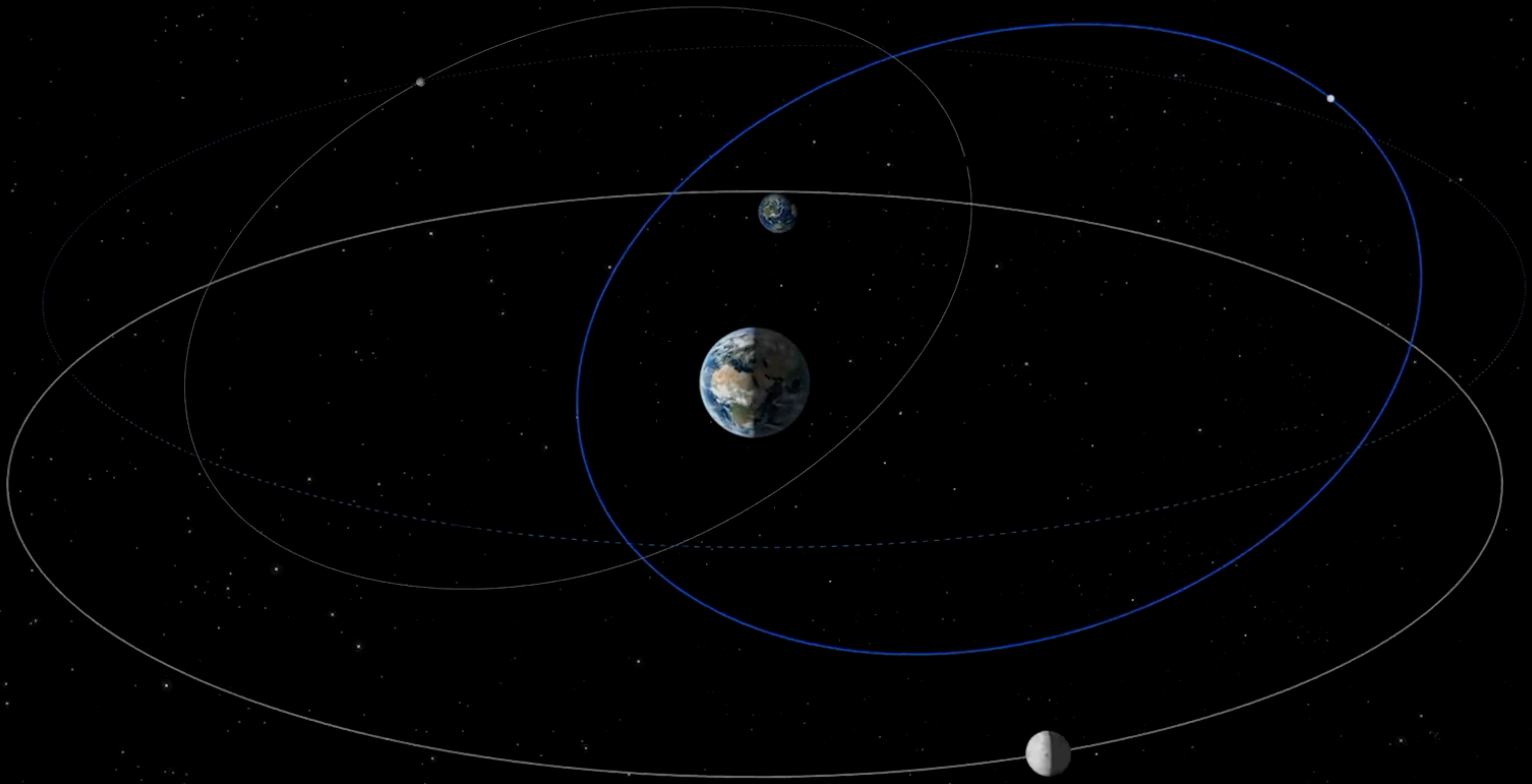
$230 million NASA Explorer Mission
Principal Investigator: George Ricker (MIT)
Director of Science: David Latham (CfA)
Proposed 2011, launched 2018

Major partners:
MIT (MKI and Lincoln Labs), CfA, NASA GSFC, NASA Ames, STScI, Northrup Grumman

D=10.5 cm, f/1.4
24° field of view
600 – 1050 nm

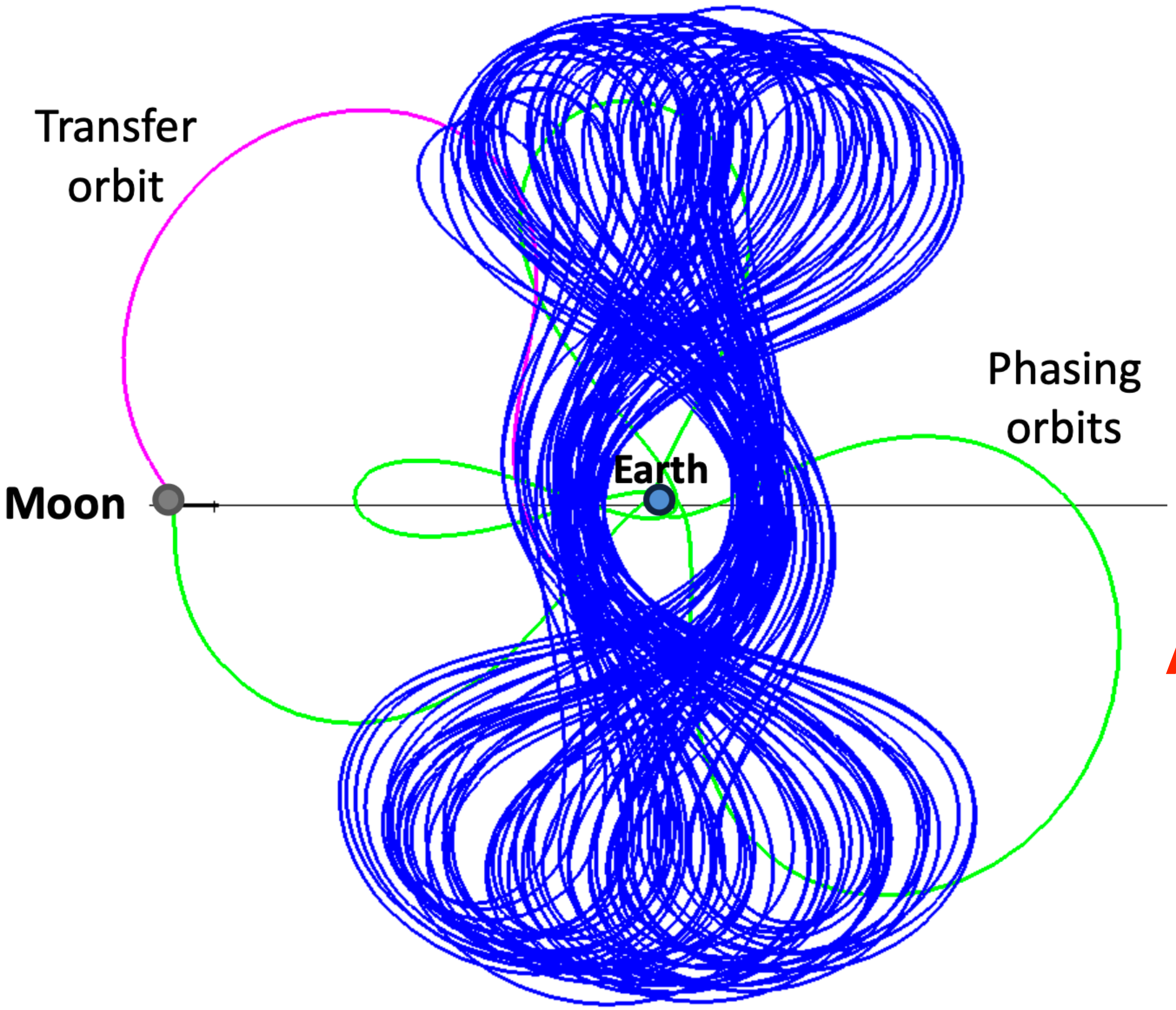

Sara
Seager
George Ricker
David
Charbonneau

TESS's *P*/2 High Earth Orbit



Gangestad et al. (2013)

TESS's *P*/2 High Earth Orbit



(a) P/2-HEO in Earth-Moon rotating frame.

Gangestad et al. (2013)

April 2013 TESS is selected by NASA

May 2013 Kepler mission ends after a reaction wheel failure

The K2 mission

2015 – 2018

Karen Teramura (UHIfA)/Miloslav Druckmüller and Shadia Habbal/NASA

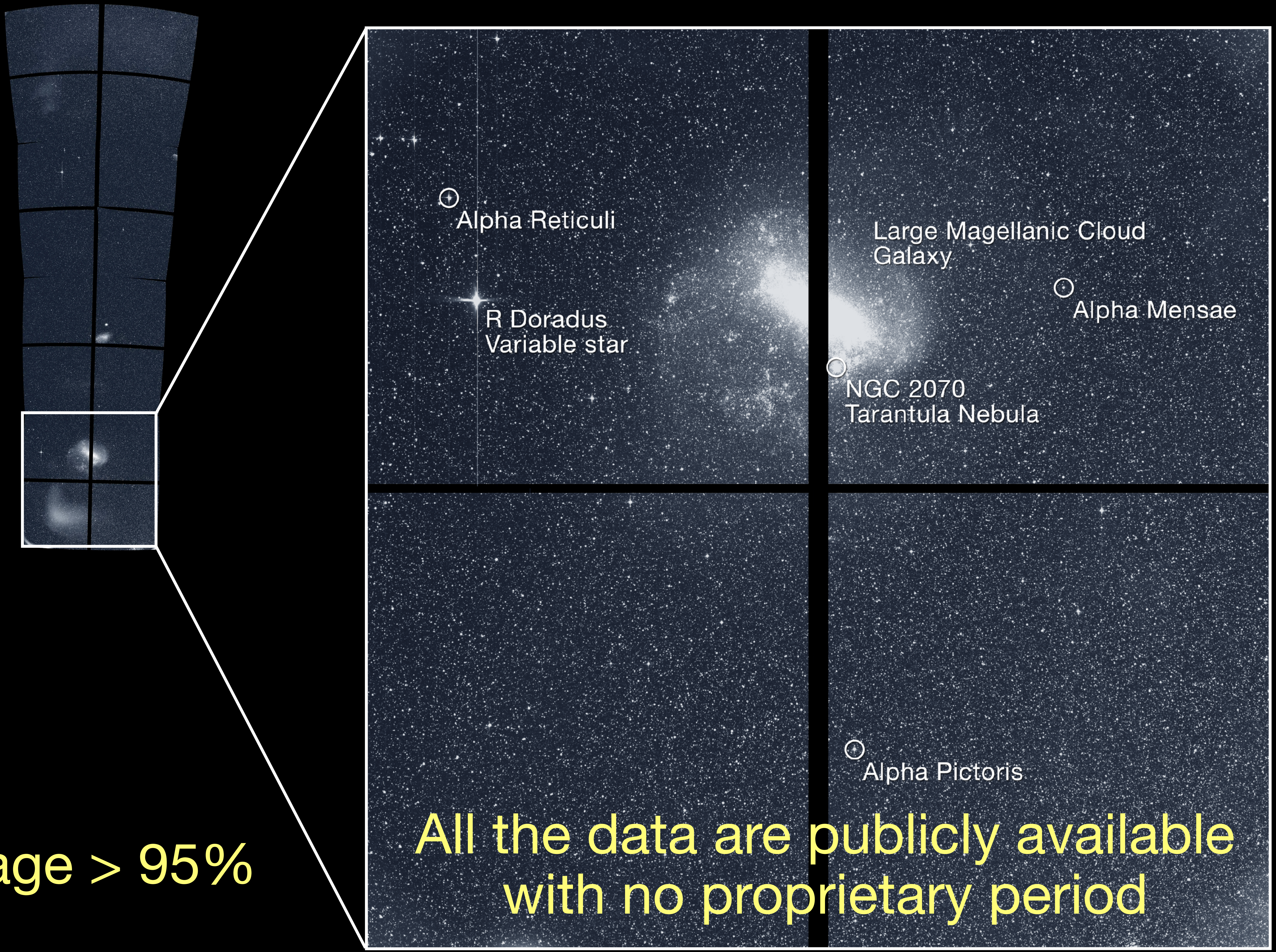
Transiting Planets *Smaller than Neptune* in 2014

Transiting Planets *Smaller than Neptune* in 2015

Transiting Planets *Smaller than Neptune* in 2016

Transiting Planets *Smaller than Neptune* in 2017

Transiting Planets *Smaller than Neptune* in 2018



All the data are publicly available with no proprietary period

Total sky coverage > 95%

E. Kruse

Transiting Planets *Smaller than Neptune* in 2018

Transiting Planets *Smaller than Neptune* in 2019


Transiting Planets Smaller than Neptune in 2020
Doppler-first
Ground-based
CoRoT
Kepler / K2
TESS
6th mag
10th mag
16th mag

Transiting Planets *Smaller than Neptune* in 2021

Transiting Planets *Smaller than Neptune* in 2022

Transiting Planets *Smaller than Neptune* in 2023

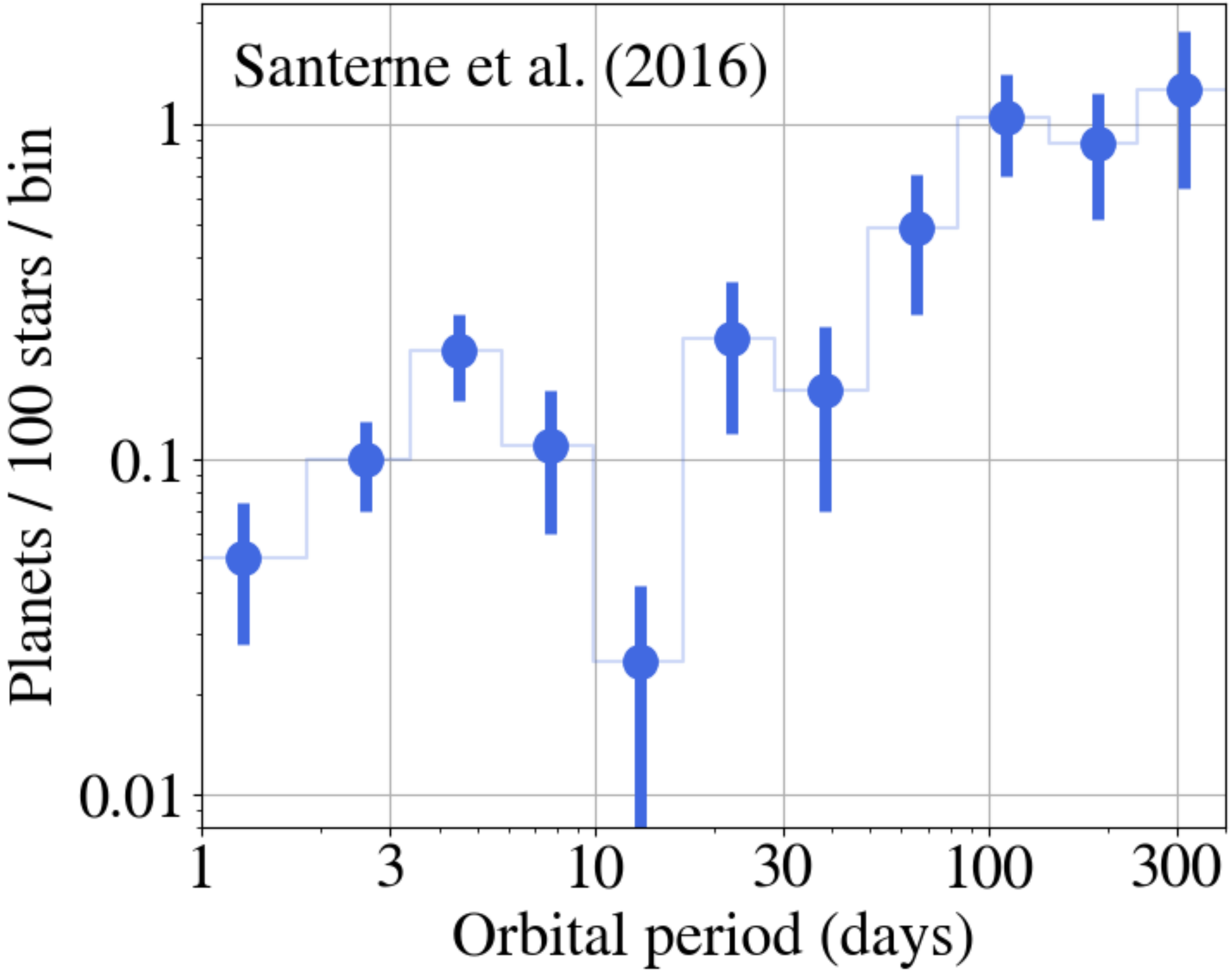
Transiting Planets *Smaller than Neptune* in 2024

Transiting Planets *and Planet Candidates* *Smaller than Neptune* in 2024

Transiting Planets *and Planet Candidates* in 2024

A brief review of demographics from transit surveys

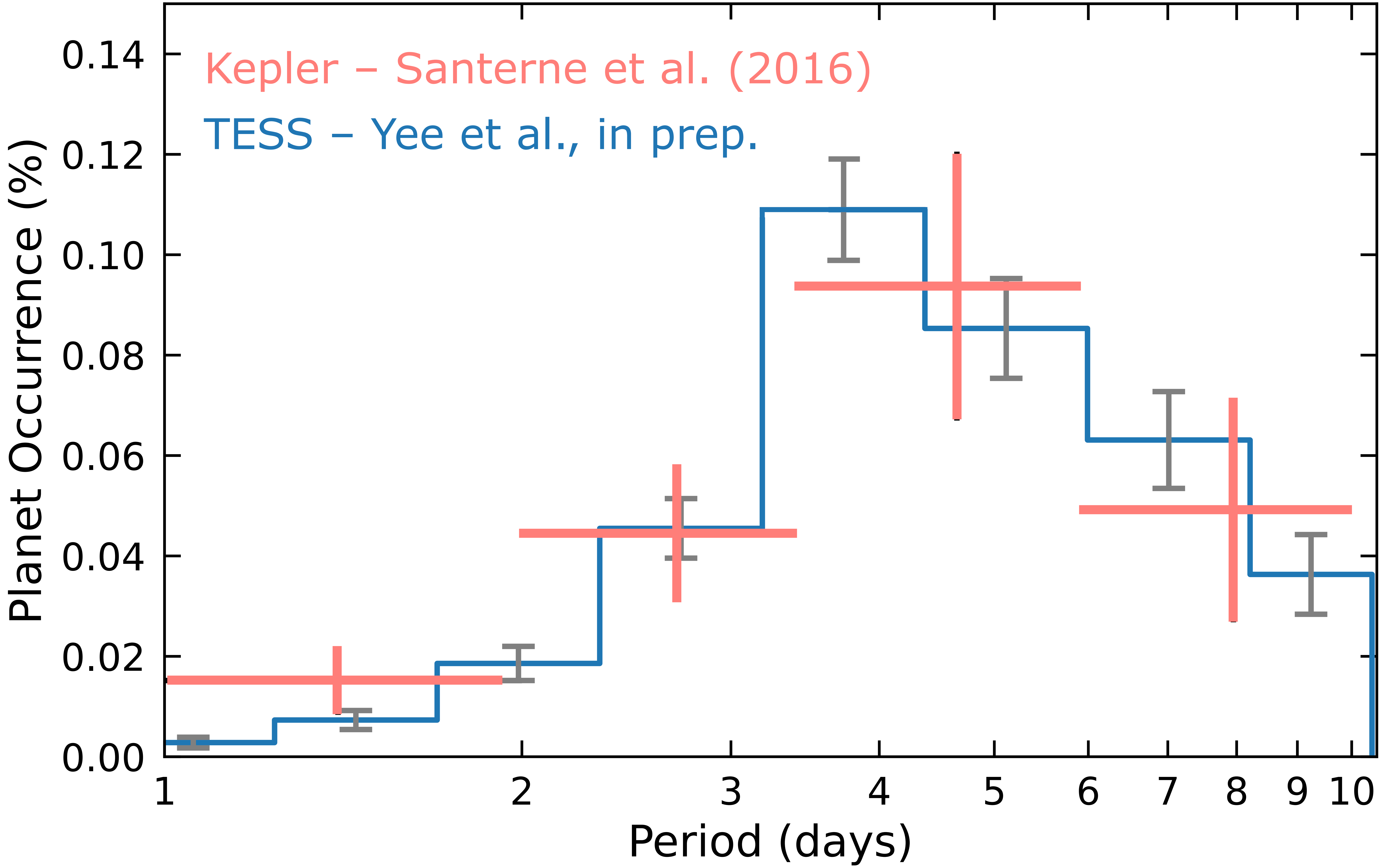
Occurrence of giant planets



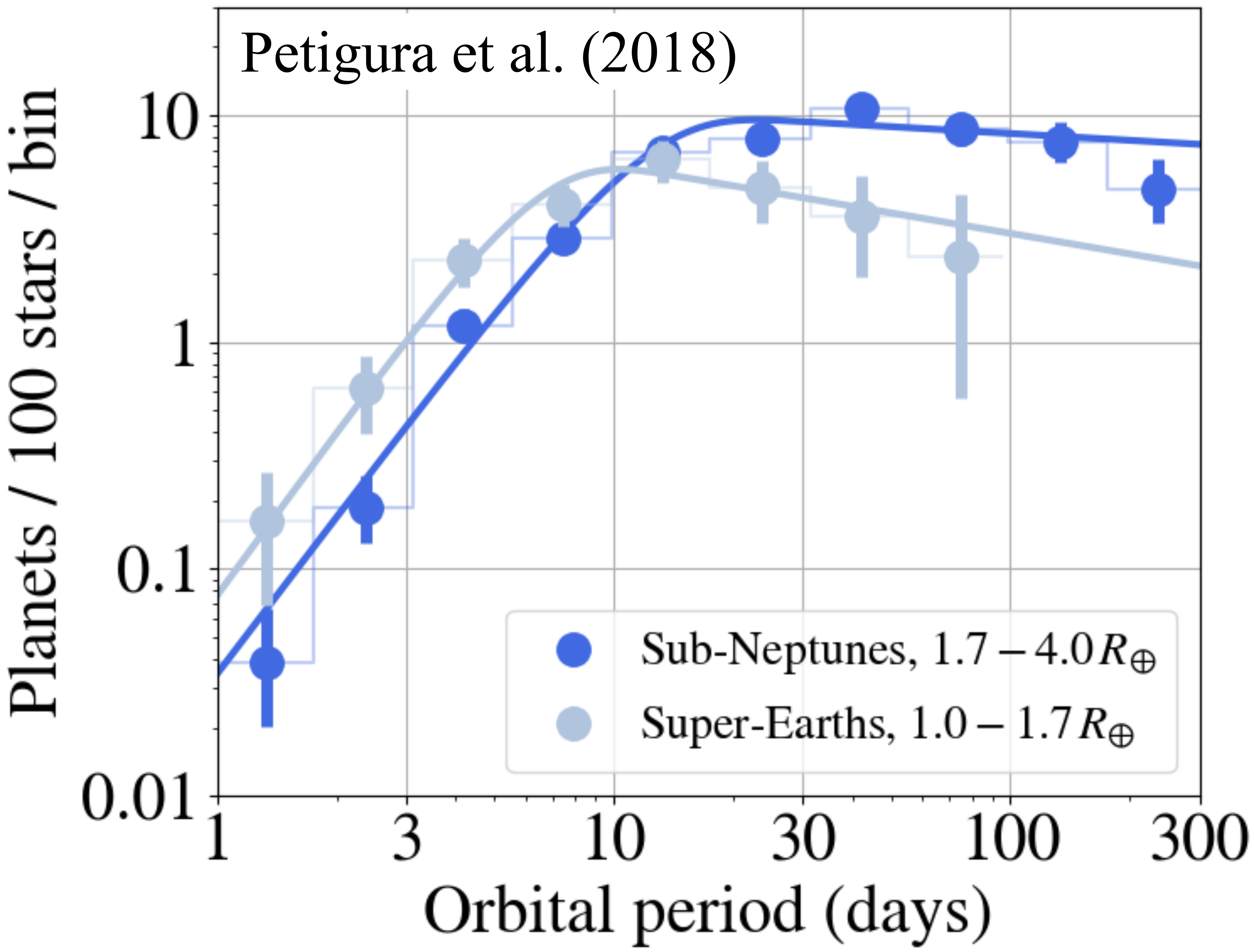
An example of a **non-parametric** occurrence function

Winn & Petigura (2024)

The Grand Unified Hot Jupiter Survey



Occurrence of dwarf planets

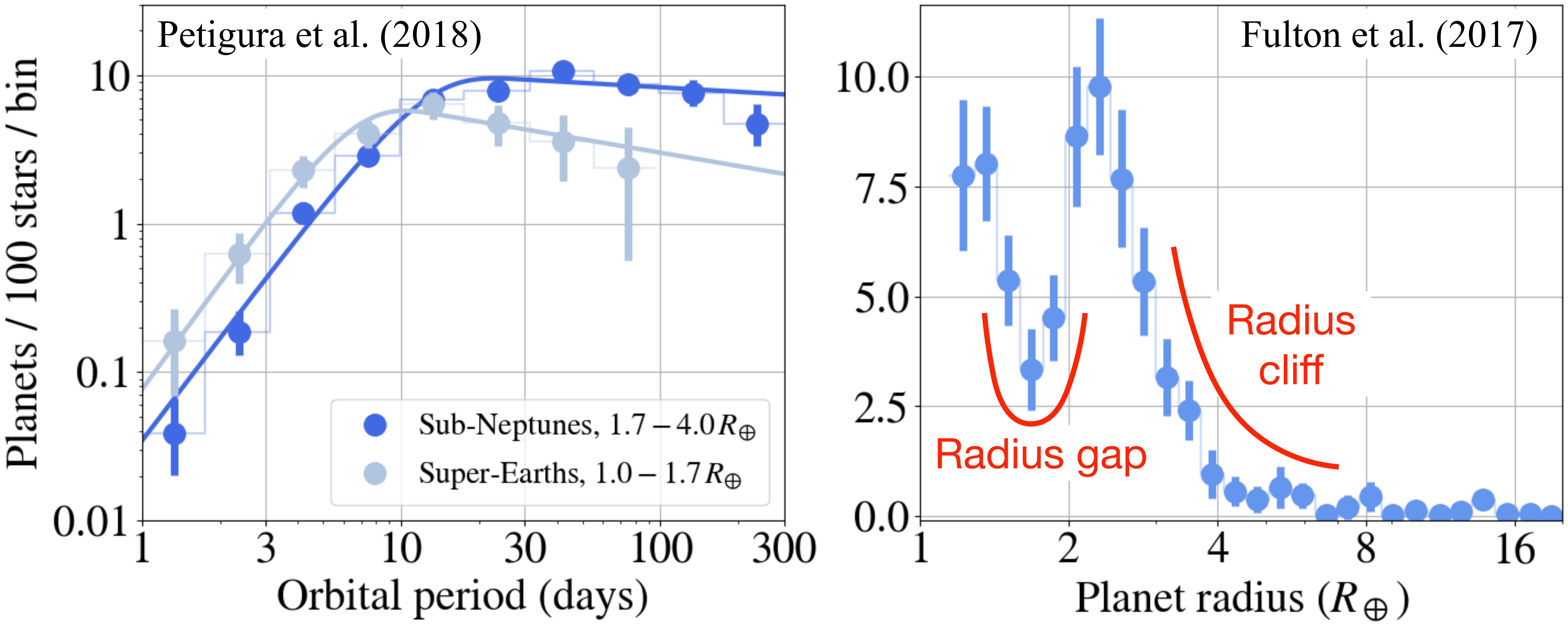


An example of a **parametric** occurrence function

$$\frac{dN_\mathrm{p}}{dN_\star \, d\log P} = C\,P^\beta \left[1 - e^{-\left(\frac{P}{P_0}\right)^\gamma}\right]$$

Winn & Petigura (2024)

Occurrence of dwarf planets

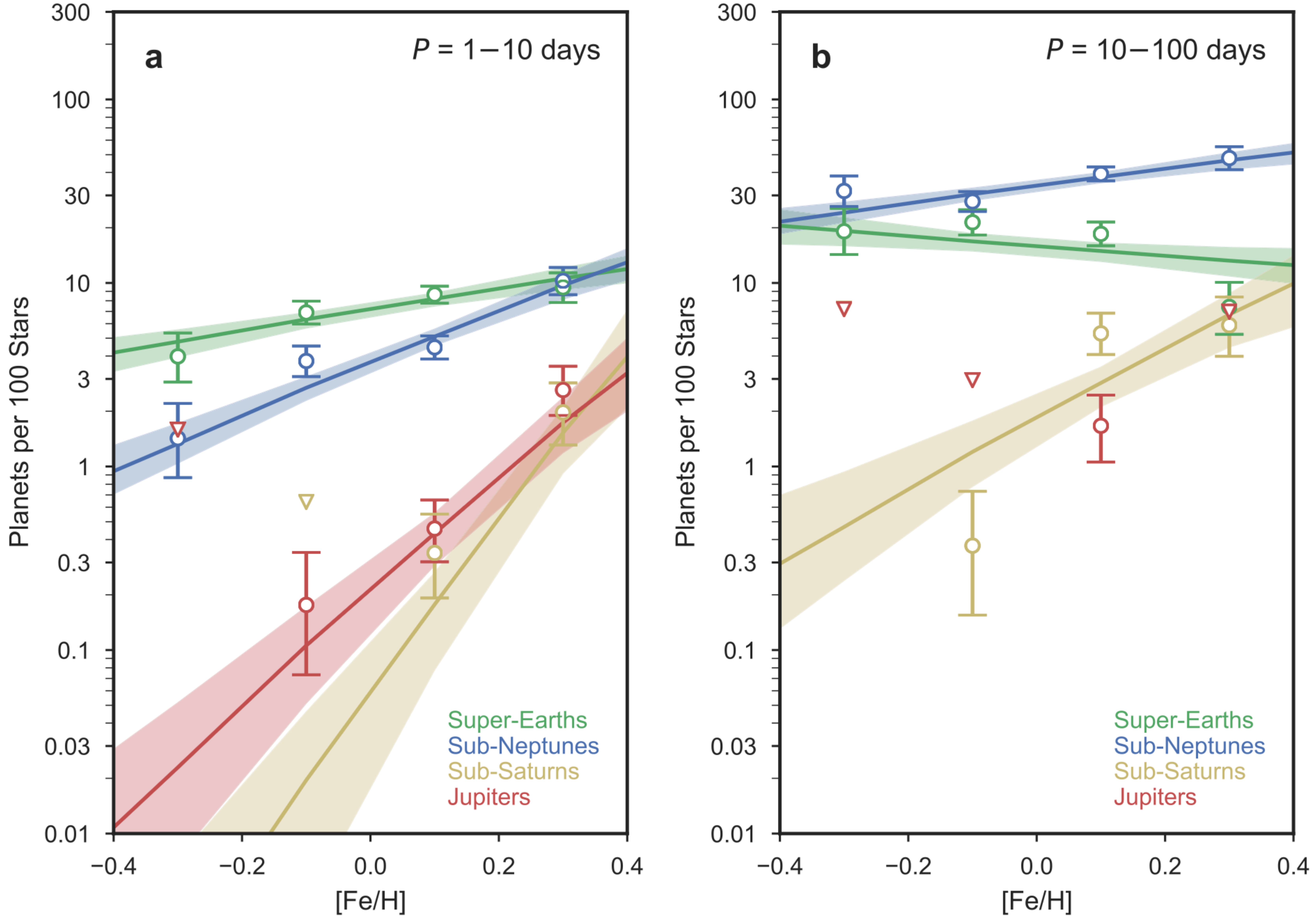


Winn & Petigura (2024)

Occurrence vs. radius and period

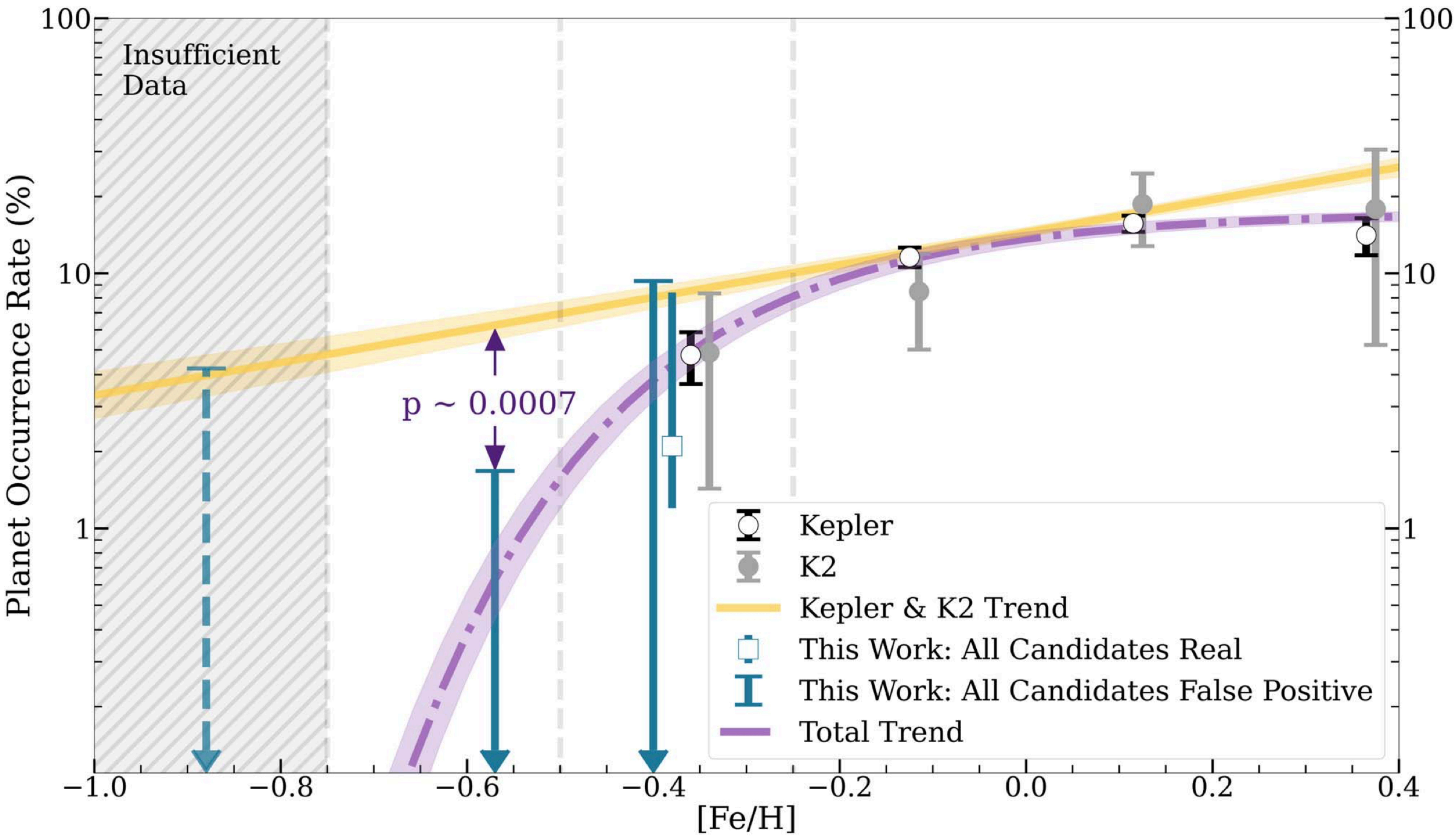
Petigura et al. (2018)

Occurrence vs. stellar metallicity



Petigura et al. (2018)

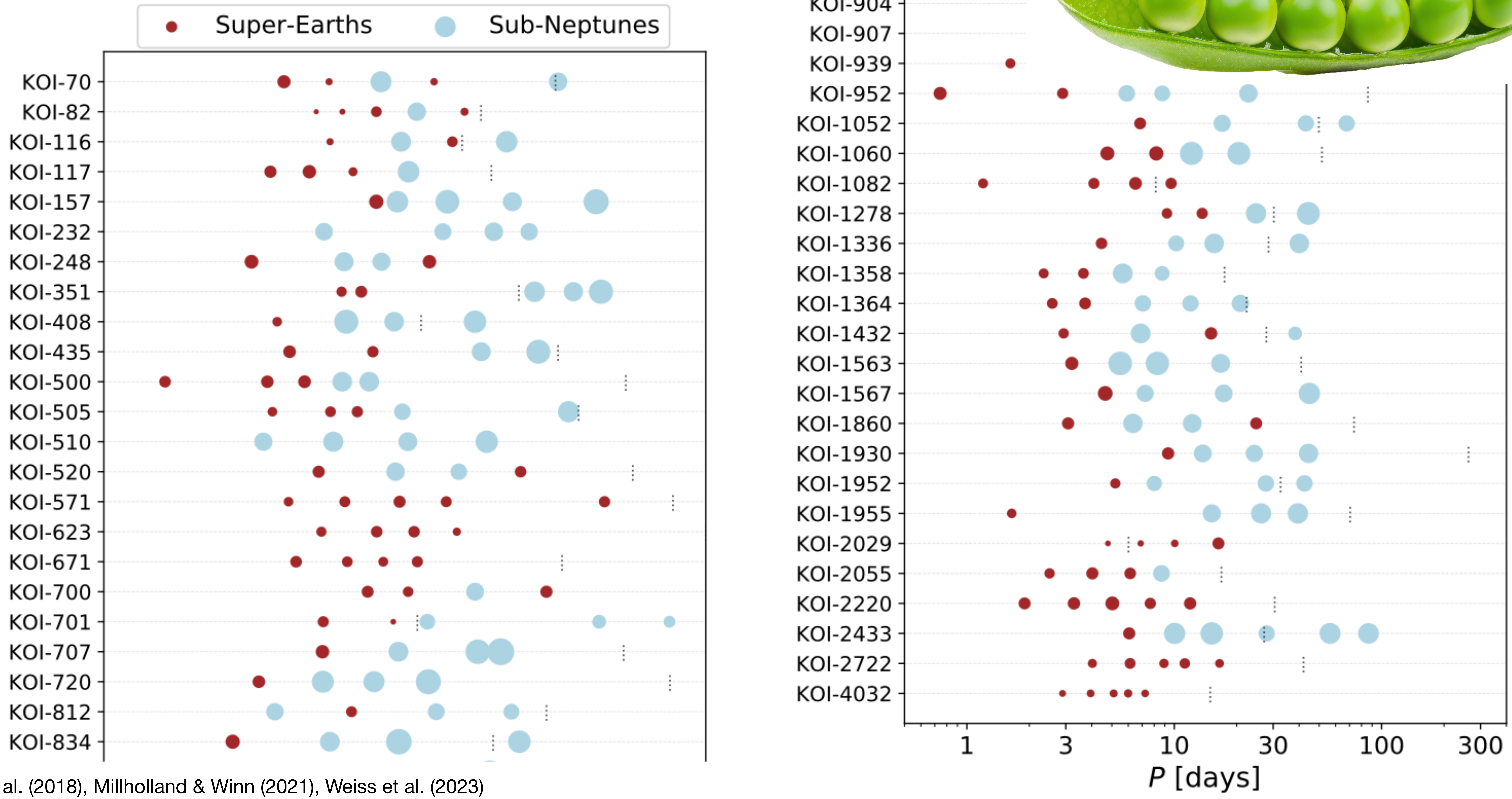
Occurrence vs. stellar metallicity



Boley et al. (2024)

Intra-system regularity

Peas in a Pod



Weiss et al. (2018), Millholland & Winn (2021), Weiss et al. (2023)

Intra-system regularity

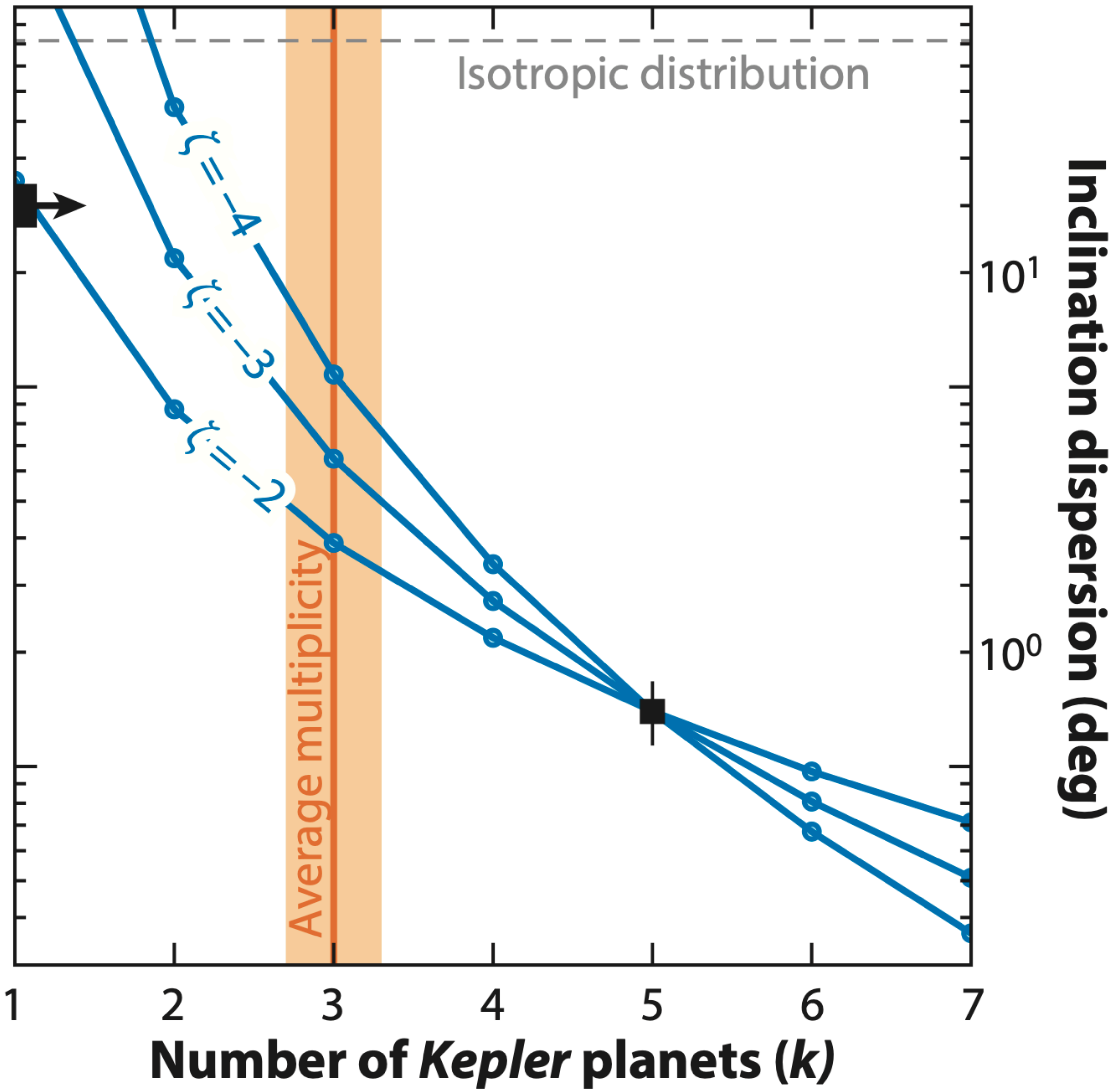
Peas in a Pod

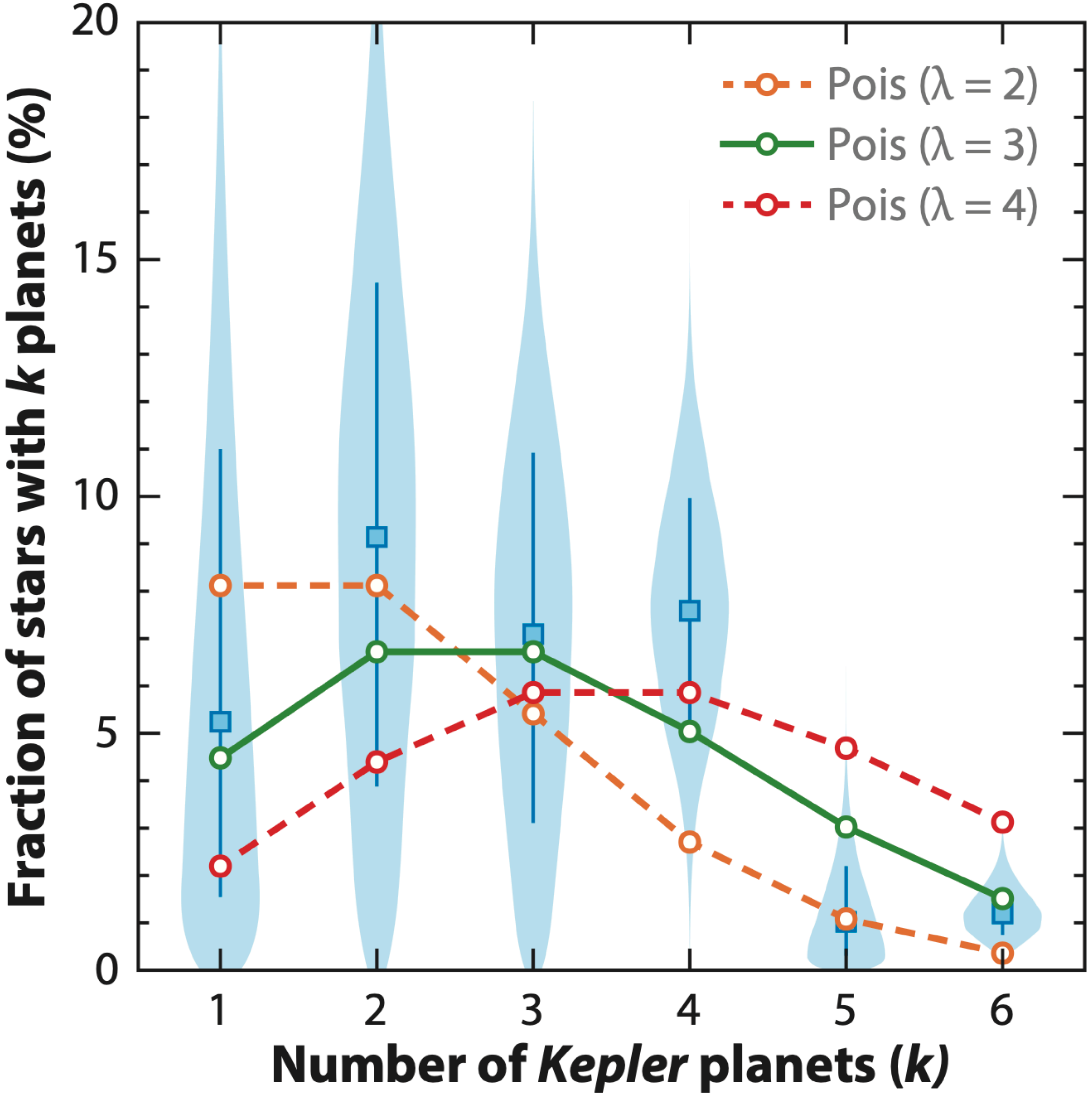
Weiss et al. (2018), Millholland & Winn (2021), Weiss et al. (2023)

Compact multiple-planet systems

Luque et al. (2023)

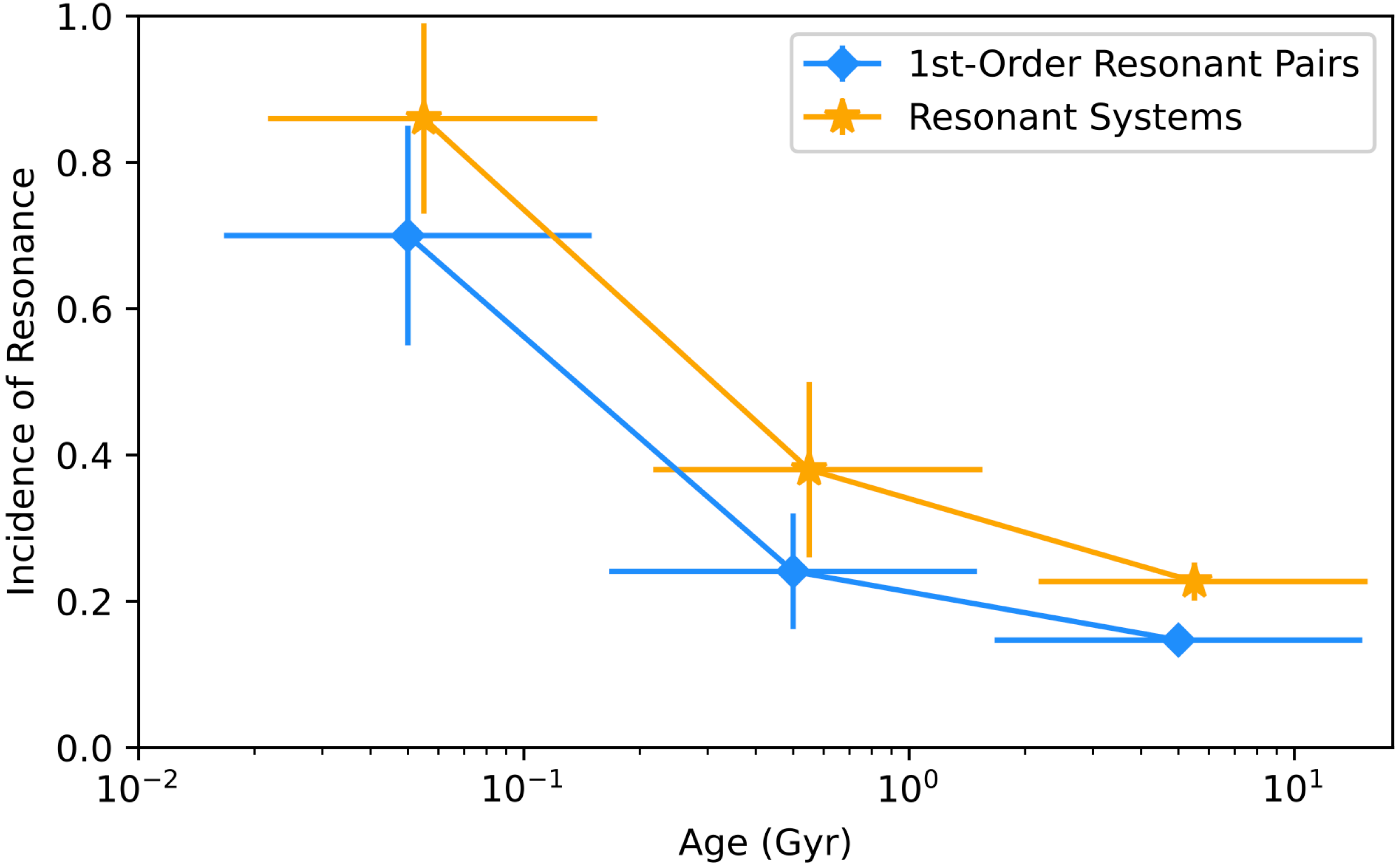
Compact multiple-planet systems





Zhu et al. (2018), Zhu & Dong (2021)

Compact multiple-planet systems



Near-resonances are more common around ***young*** stars than ***old*** stars

Seems to imply that planetary systems form in resonant chains, which break over ~10^8 yr

Dai et al. (2024)

Other occurrence results

- ***Occurrence versus age*** (Yang et al. 2023, Vach et al. 2024, Sayeed et al. 2025, Zink et al. 2023)
- ***Occurrence versus stellar mass*** (Dressing et al. 2015, Mulders, Pascucci, & Apai 2015, Hardegree-Ullman et al. 2019, Kunimoto & Matthews 2020, He, Ford, & Ragozzine 2021, Giacalone & Dressing 2025, Kristo & Charbonneau 2023)
- ***Conditional occurrence*** of outer giants and compact multi-planet systems (Zhu & Wu 2018, Bryan et al. 2019, Mulders et al. 2021, Bonomo et al. 2023, Lefevre-Forjan & Mulders 2025, Van Zandt et al. 2025, Weiss+...
- ***Potentially rocky planets in the habitable zone*** (Hsu et al. 2020, Bryson et al. 2021, Bergsten et al. 2022)
- ***Review articles:*** Zhu & Wu (2021), Winn & Petigura (2024)

Future transit surveys


figure: L. Bouma
Declination
60°
30°
0°
-30°
-60°
8h
4h
0h
20h
16h
GC
13+
3-12
2
1
0
months of data
HETE-2 MOO
TESS named
SMEX proposal
TESS rejected
Kepler results
High Orbit
Explorer proposal
TESS selected
SpaceX contract
Launch
Primary Mission
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023

figure: L. Bouma
60°
30°
0°
-30°
-60°
Declination
8h
4h
0h
20h
16h
GC
13+
3-12
2
1
0
months of data
HETE-2 MOO
TESS named
SMEX proposal
TESS rejected
Kepler results
High Orbit
Explorer proposal
TESS selected
SpaceX contract
Launch
Primary Mission
Extended Mission I
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023

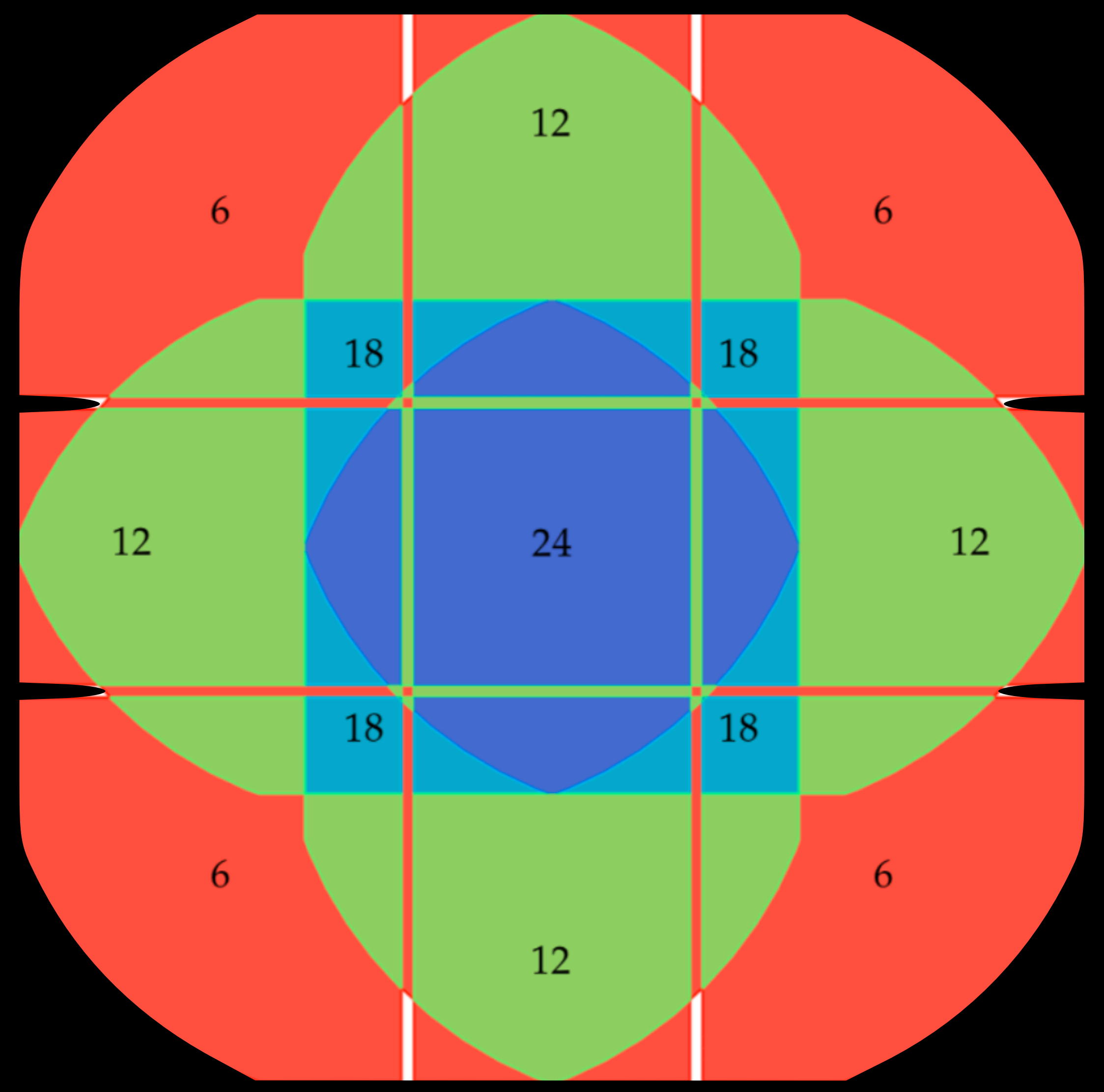
figure: L. Bouma

PLATO

ESA mission – medium-class Cosmic Vision
Principal Investigator: Heike Rauer
Selected in 2014, to be launched in late 2026

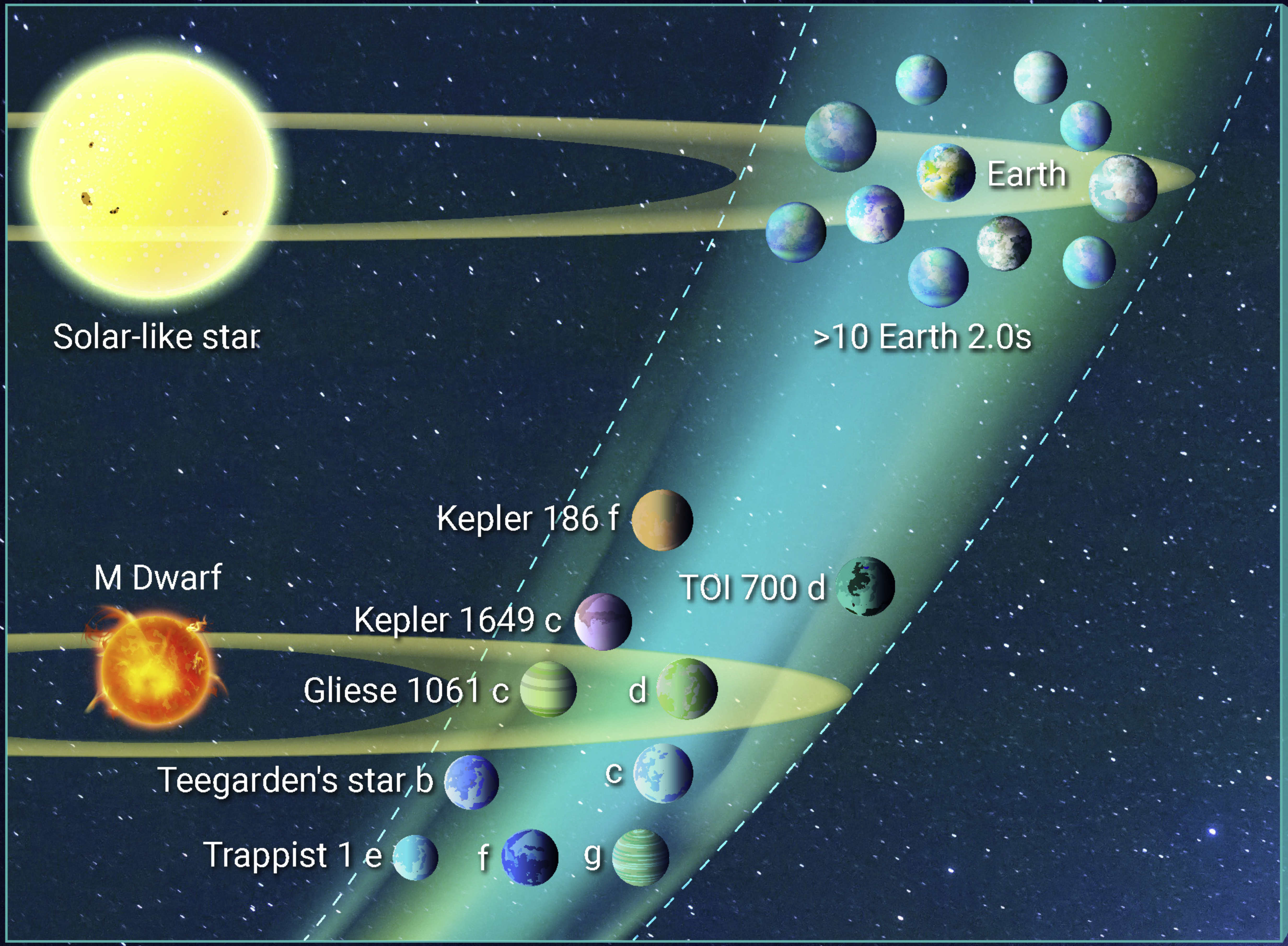
26 x 12 cm optical telescopes

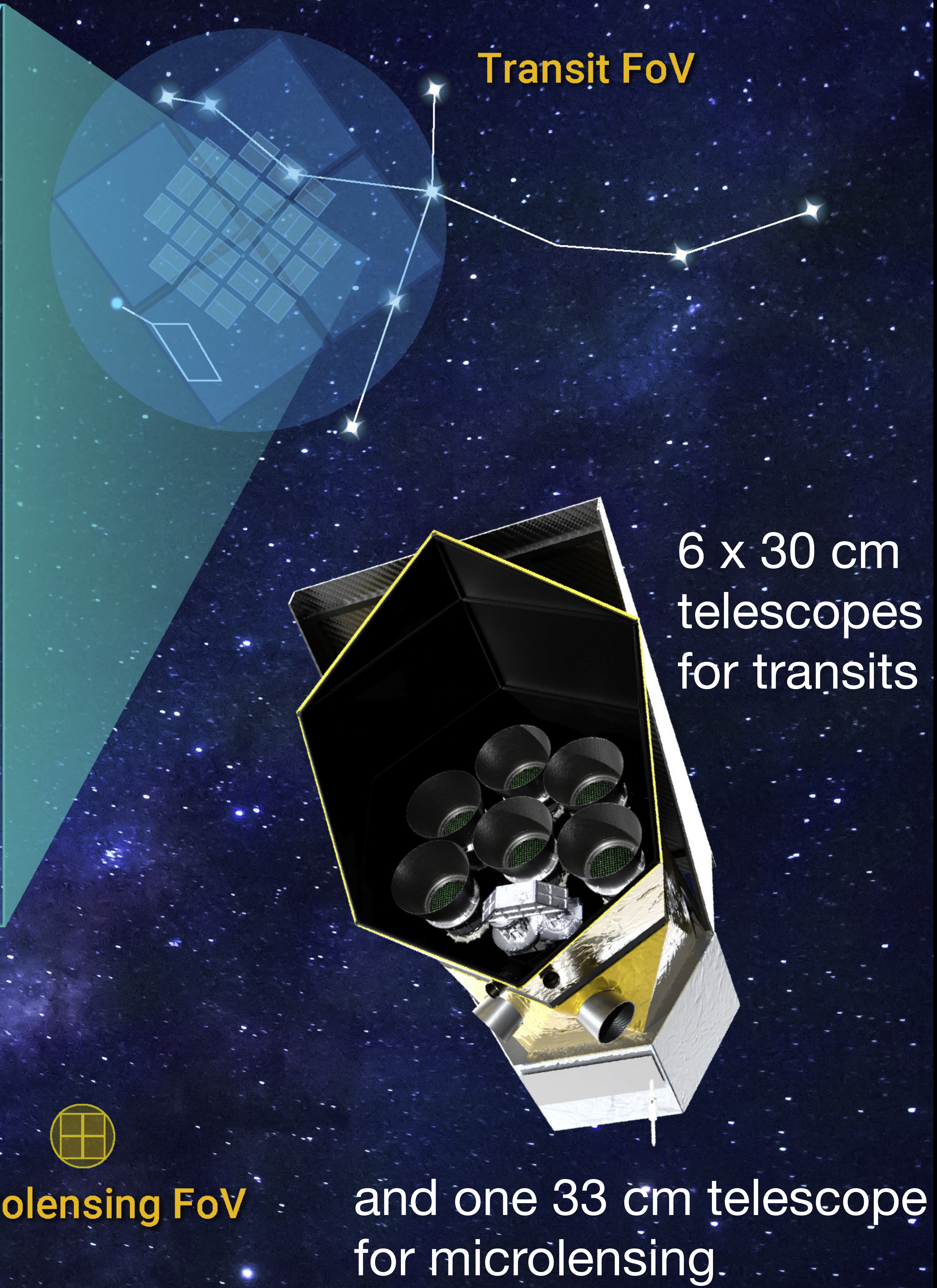
Partially overlapping fields of view



Combined field is 2,132 square degrees (5% of the sky)

PLAnetary Transits and Oscillations of stars





Earth Two

Chinese Academy of Sciences
Principal Investigator: Jian Ge
Anticipated launch in late 2028