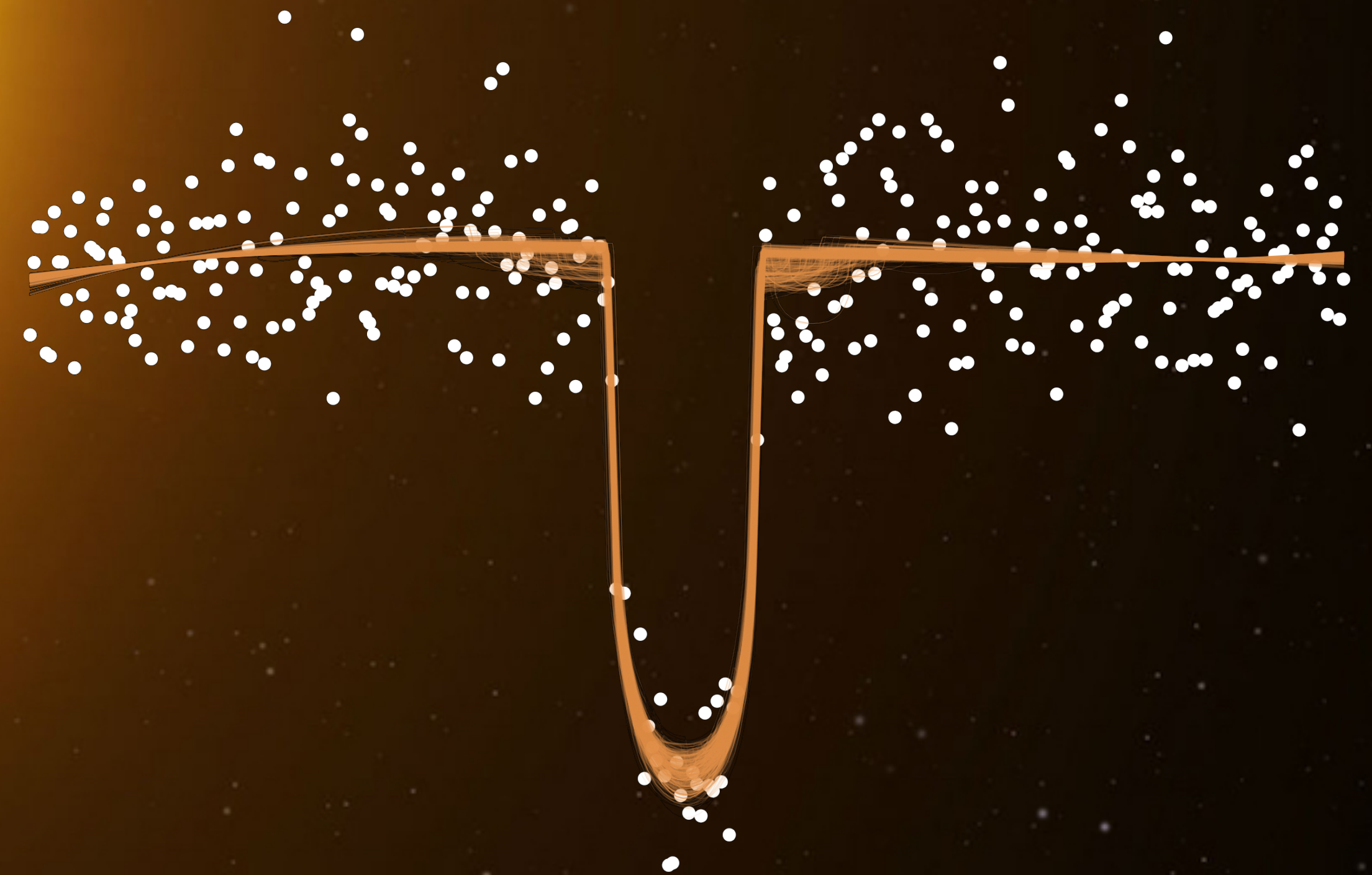


Detection of Extrasolar Moons in the Presence of Stellar Variability

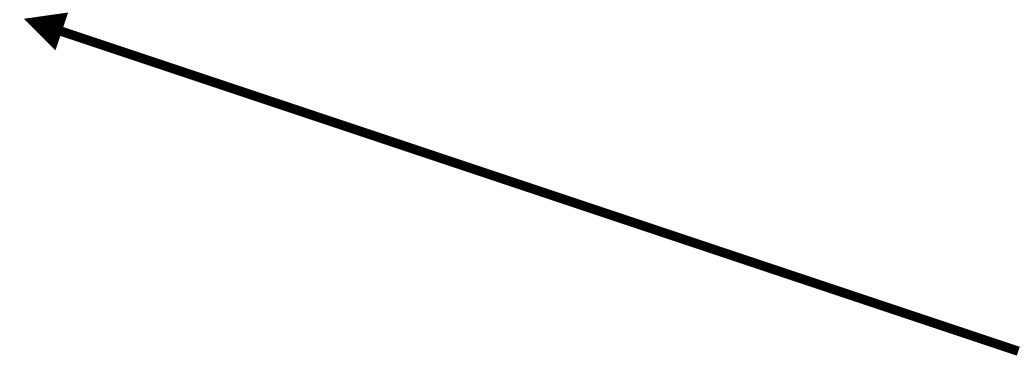
The Exomoon Candidate Around Kepler-1625 b

René Heller

Max Planck Institute for Solar
System Research, Göttingen



1806.04672

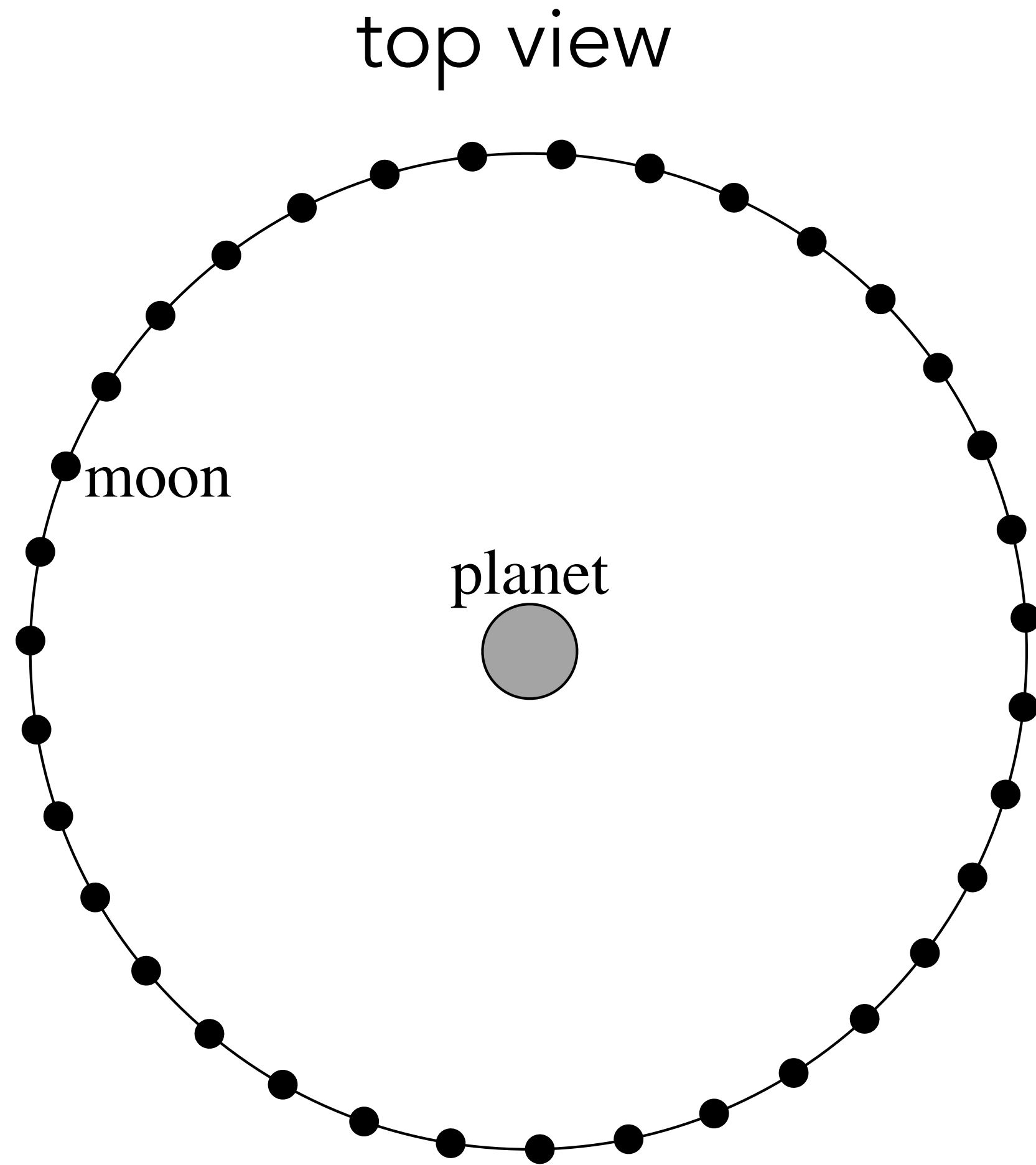


Rodenbeck, Heller, Hippke, Gizon

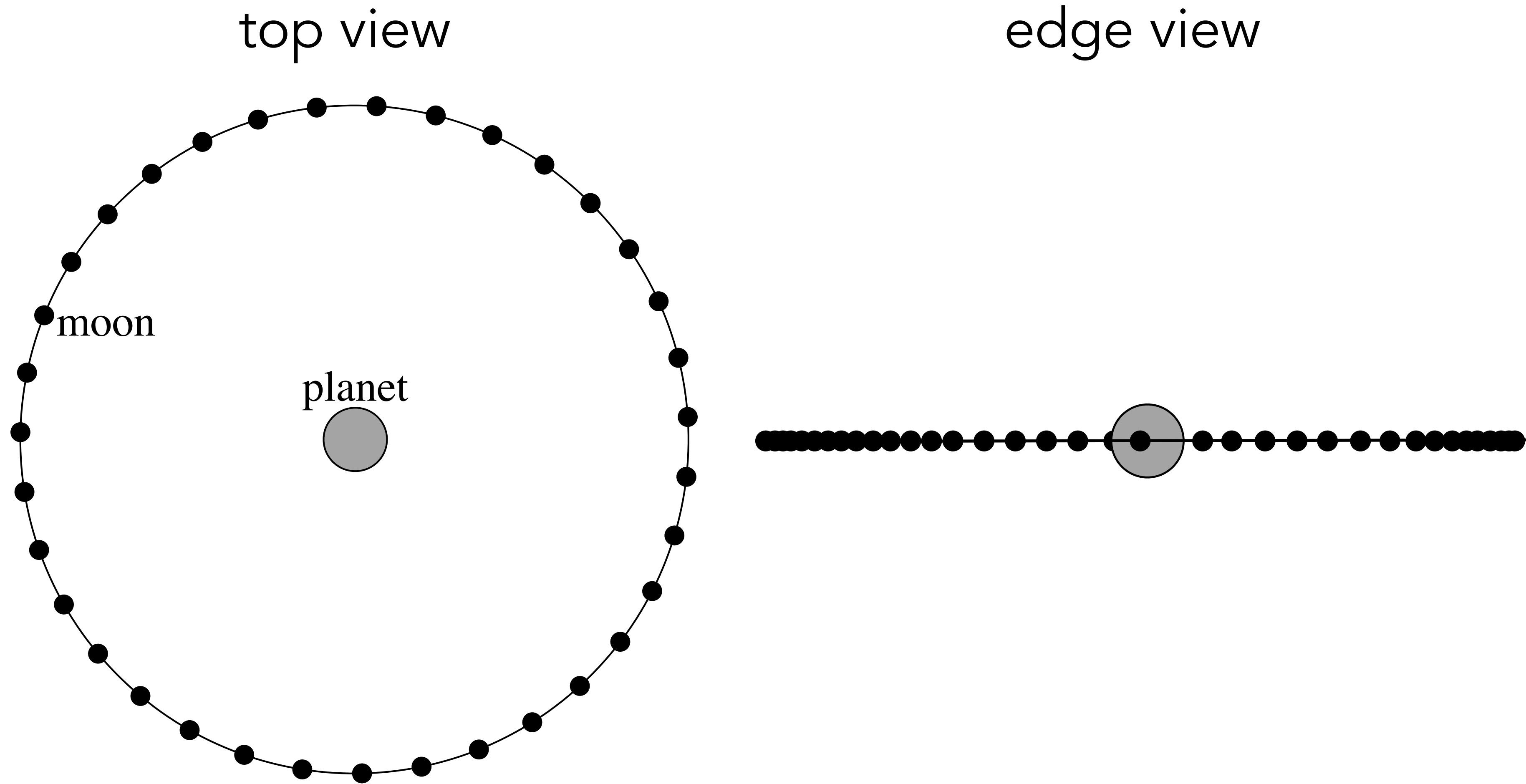
"Revisiting the exomoon candidate signal around Kepler-1625b"

A&A, Vol. 617, id A49

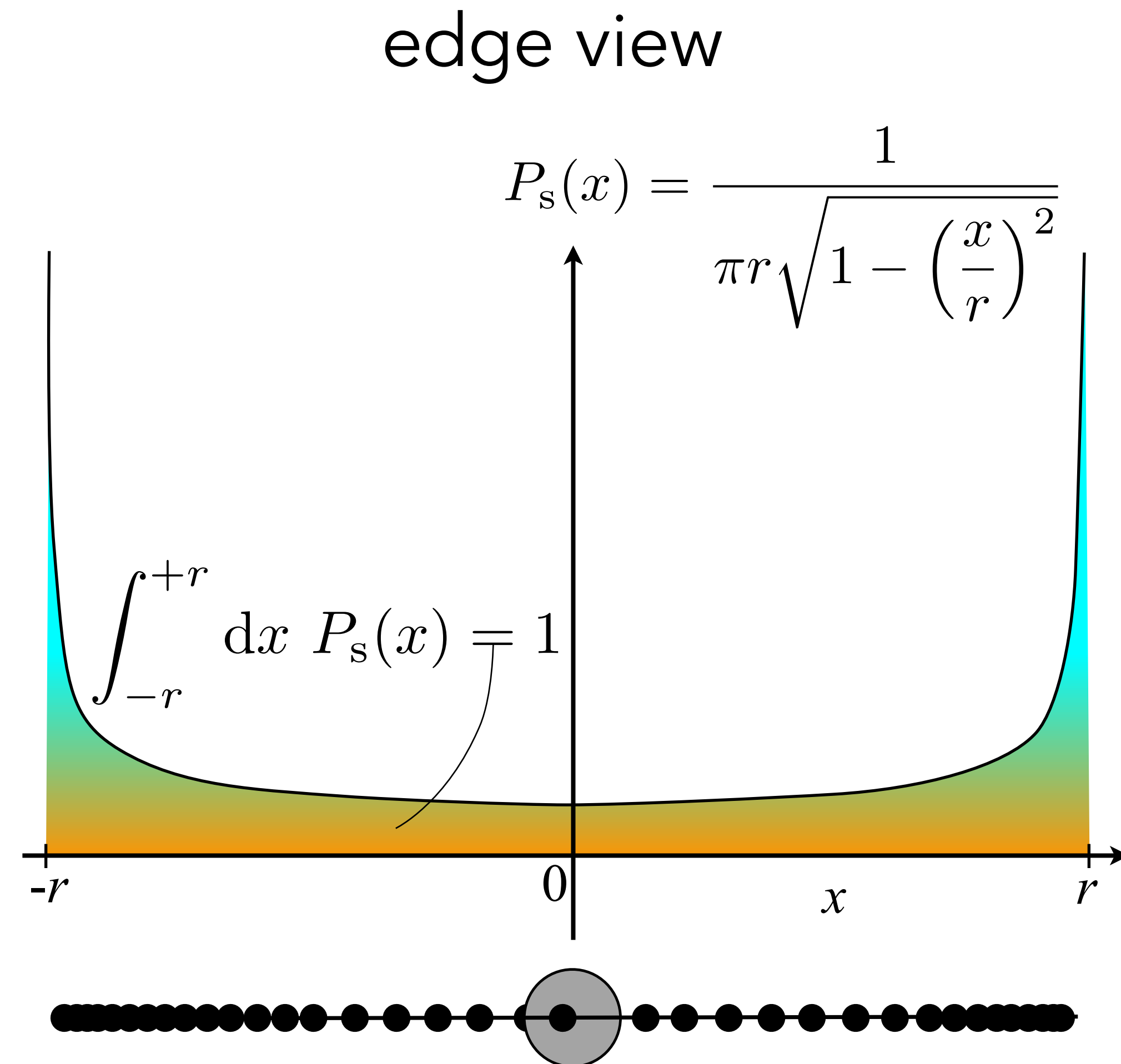
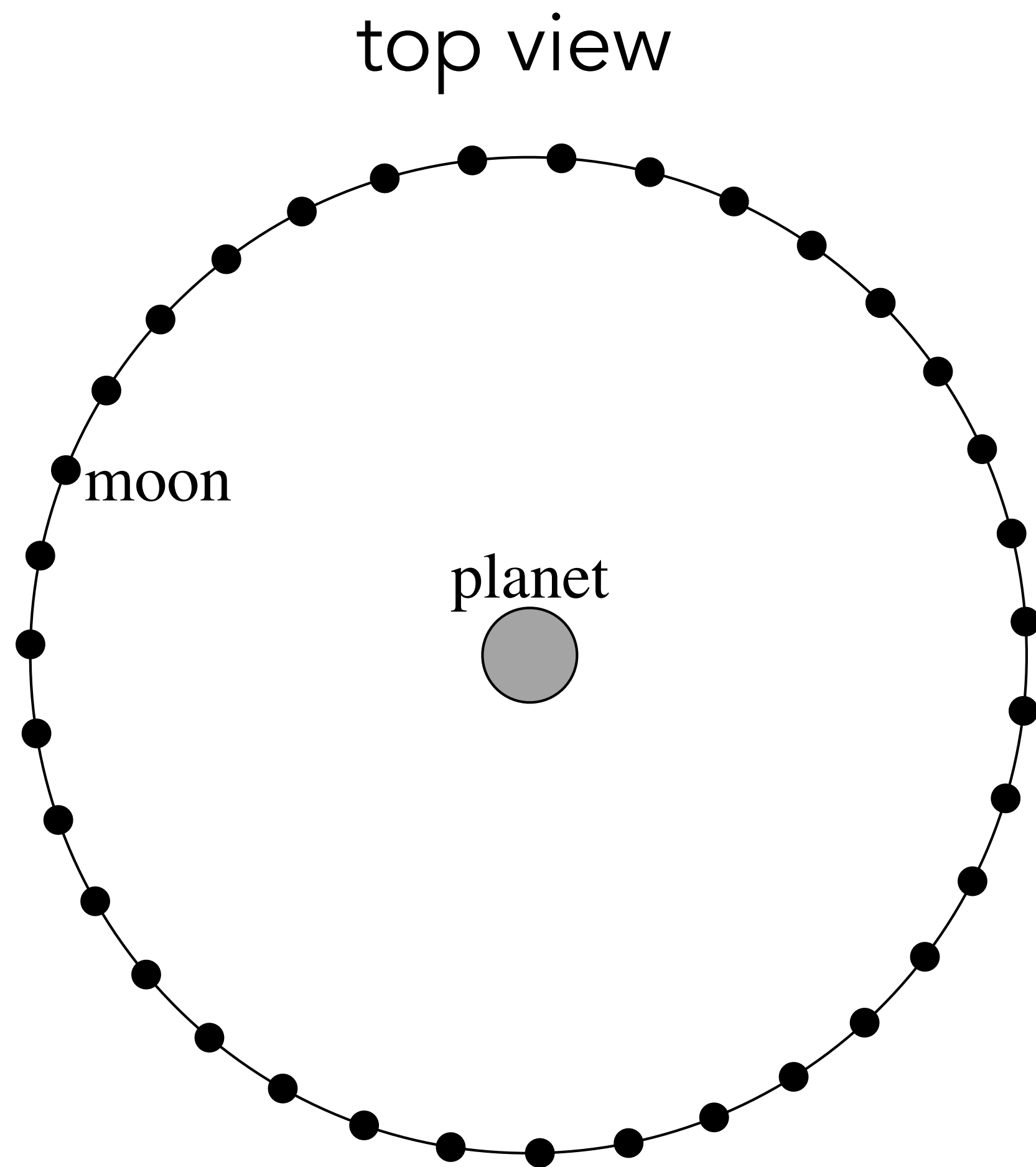
An Efficient Way to Find Exomoons – The Orbital Sampling Effect



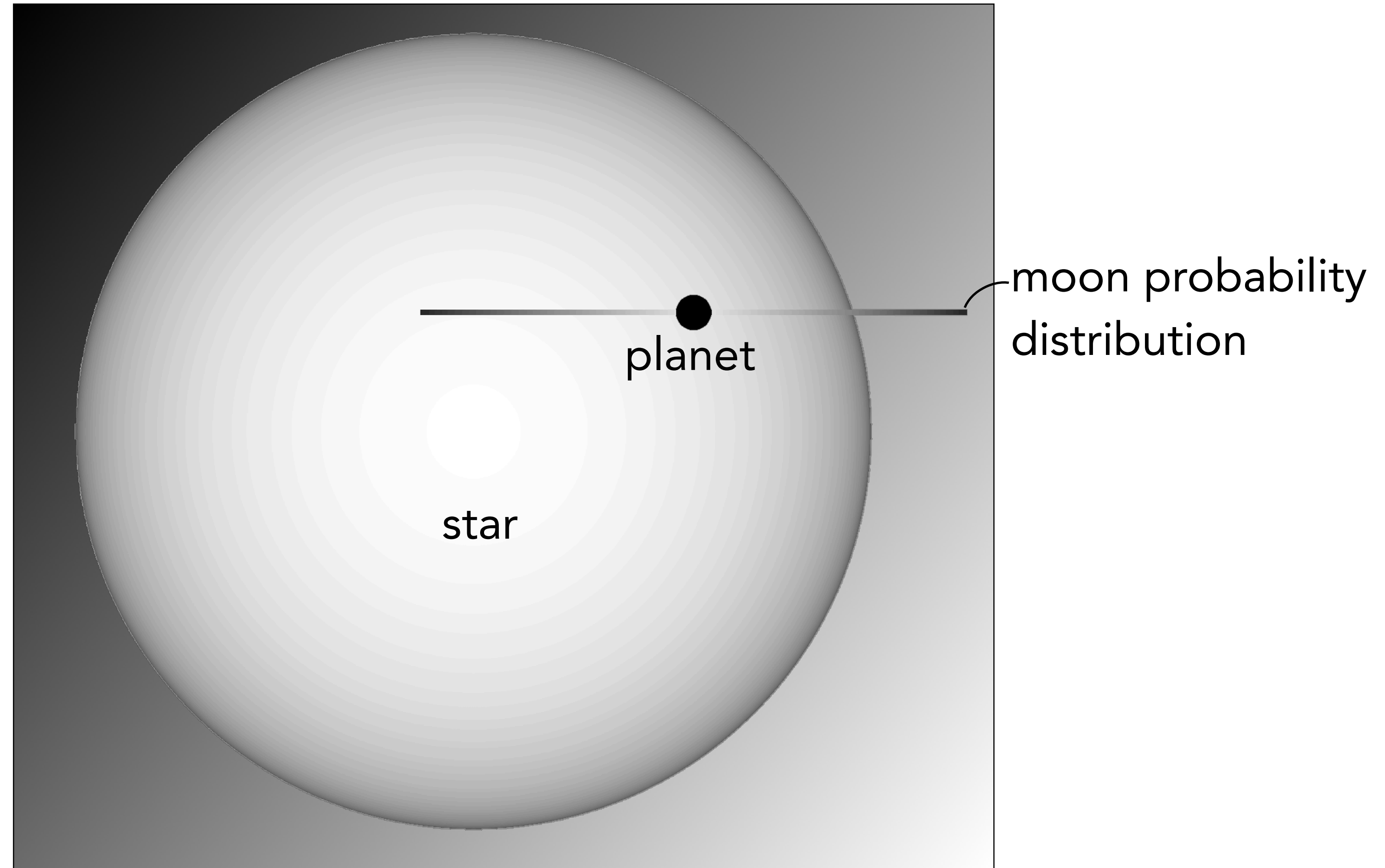
An Efficient Way to Find Exomoons – The Orbital Sampling Effect



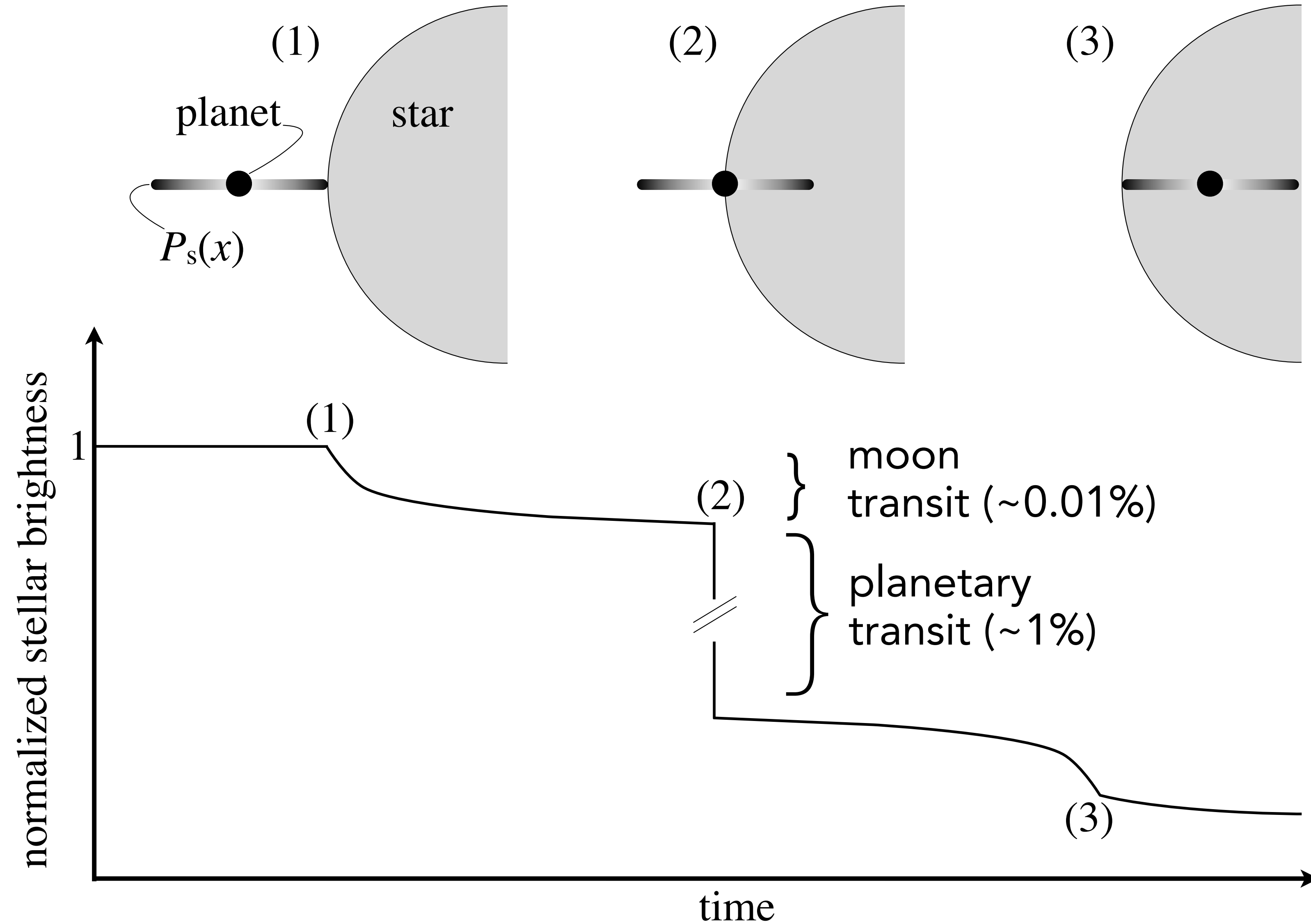
An Efficient Way to Find Exomoons – The Orbital Sampling Effect



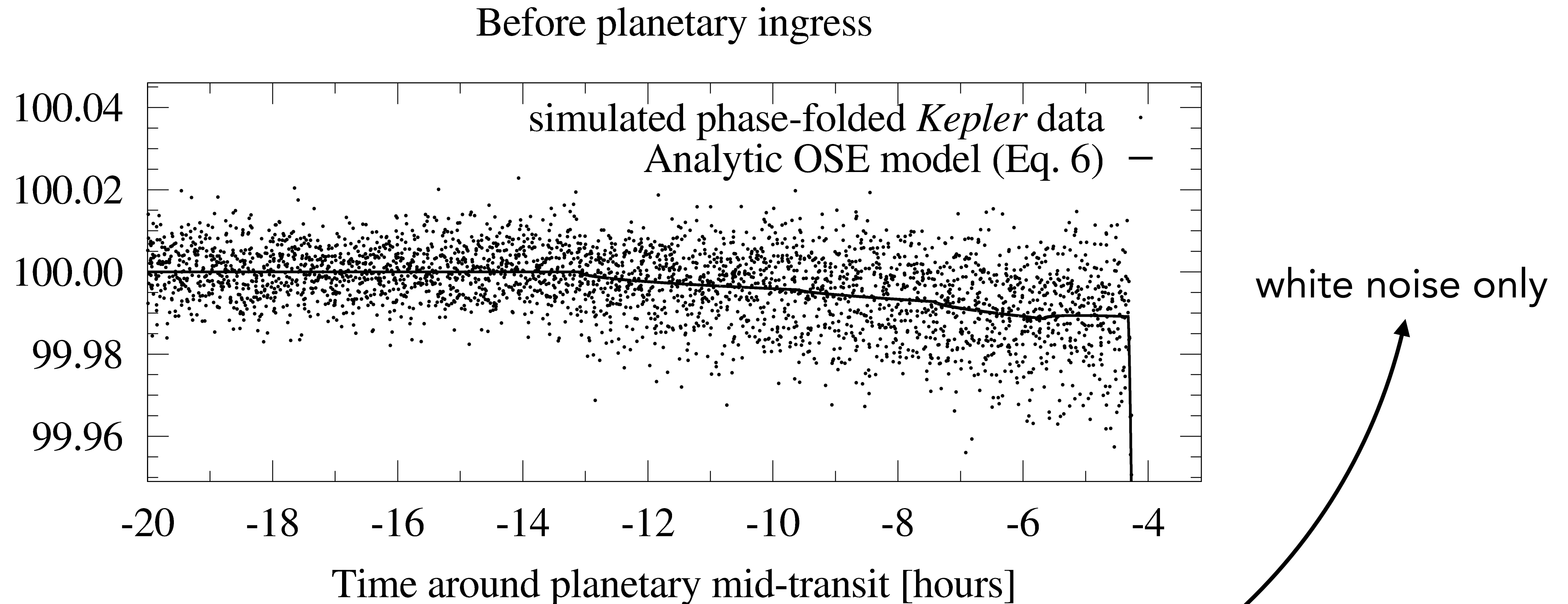
An Efficient Way to Find Exomoons – The Orbital Sampling Effect



An Efficient Way to Find Exomoons – The Orbital Sampling Effect



An Efficient Way to Find Exomoons – The Orbital Sampling Effect



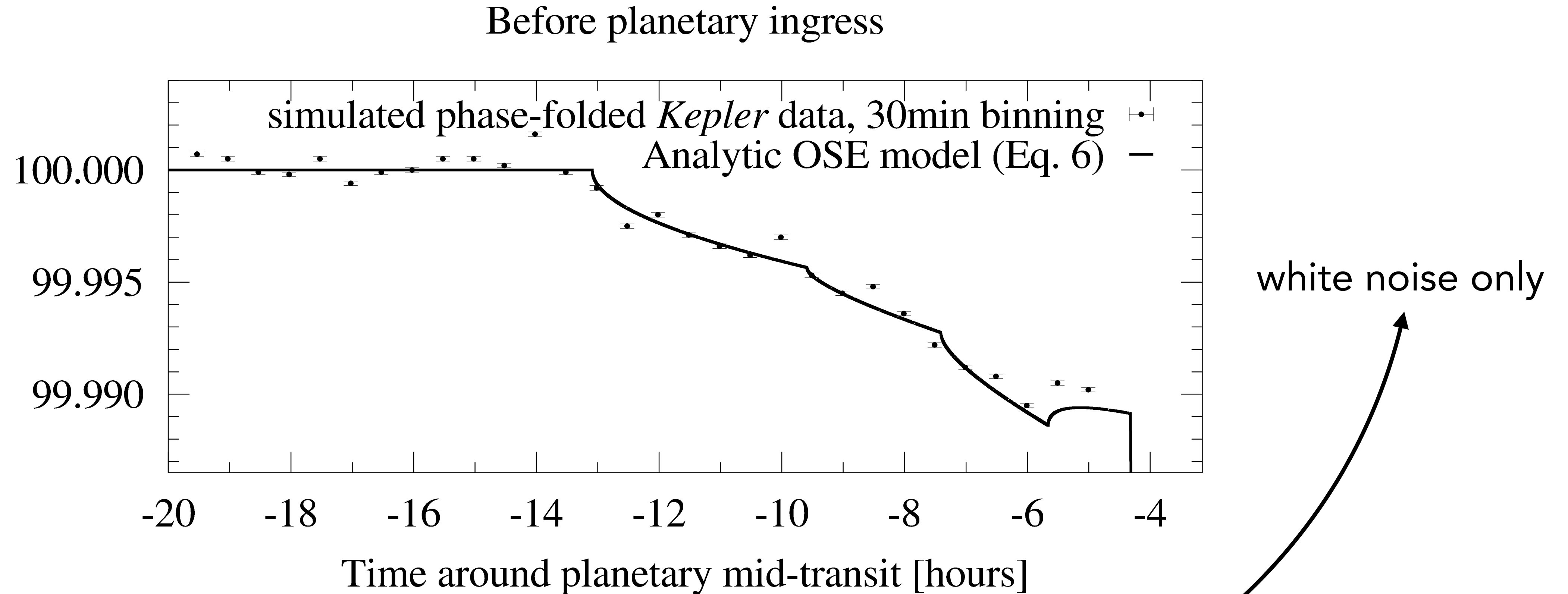
100 simulated Kepler transits (long cadence)

star: K dwarf, $m_K = 12$

planet: Jupiter-sized

3 moons: super-Io, super-Europa, super-Ganymede

An Efficient Way to Find Exomoons – The Orbital Sampling Effect



100 simulated Kepler transits (long cadence)

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An Efficient Way to Find Exomoons – The Orbital Sampling Effect

THE ASTRONOMICAL JOURNAL, 155:36 (20pp), 2018 January

Teachey, Kipping, & Schmitt

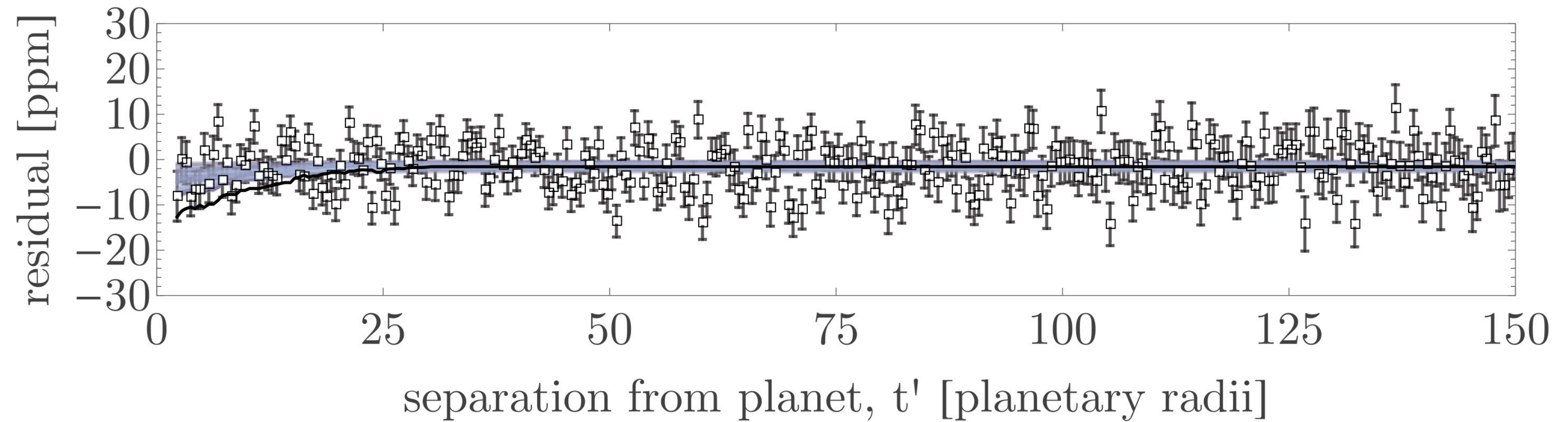


Figure 7. Phase-folded planet-stacked light curve of all 284 KOIs deemed to be of acceptable quality. Temporal axis has been re-scaled and binned, with uncertainties shown given by the standard deviations within each bin. Black solid line represents the expected signature if $\eta = 100\%$ of the KOIs had a Galilean analog moon system. Blue lines show 100 posterior samples from our fits, giving $\eta = 0.16^{+0.13}_{-0.10}$.

284 KOIs used for a Kepler superstack

blue lines: 100 posterior samples

black line: signature if all KOIs had Galilean-like moon system

The Exomoon Candidate Around Kepler-1625b

figure from [Rodenbeck et al. \(2018a\)](#)

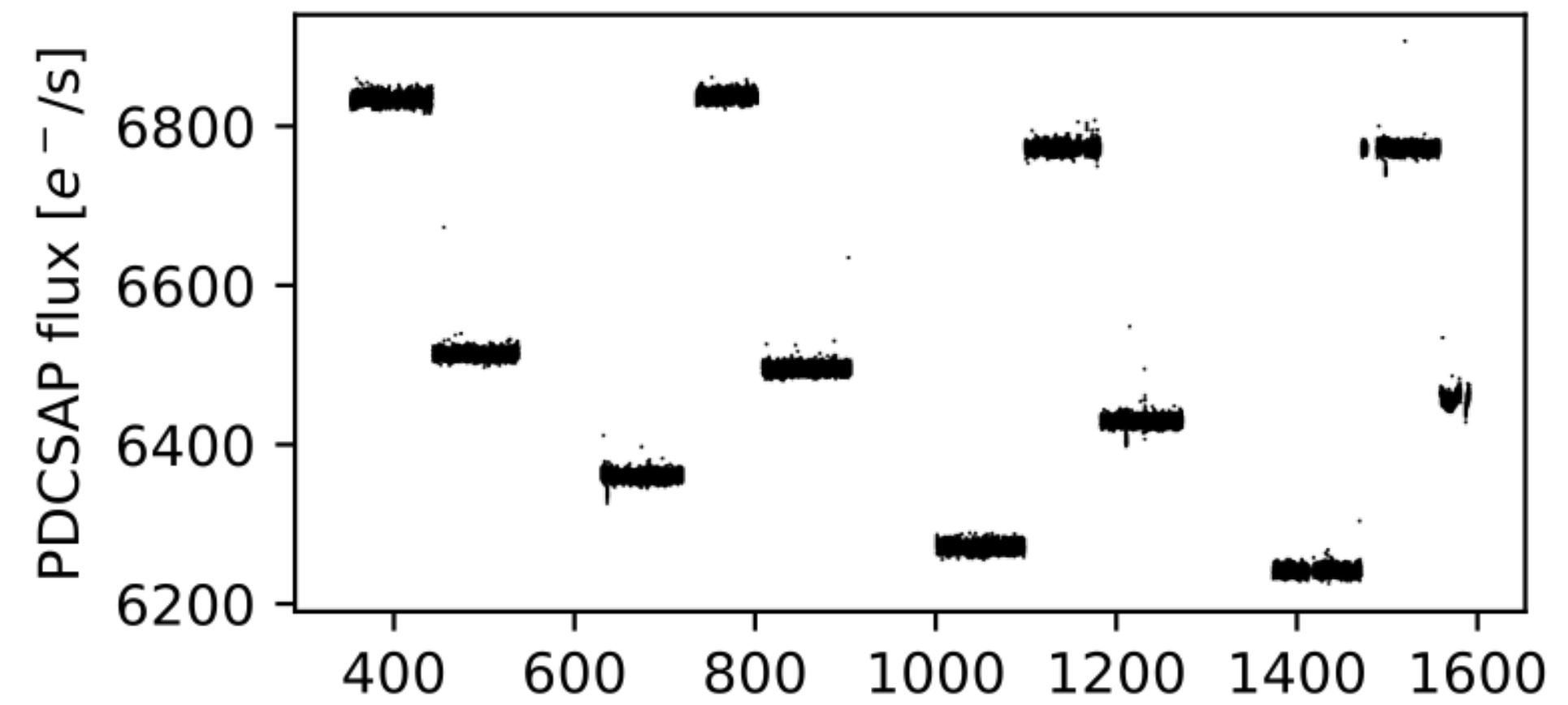
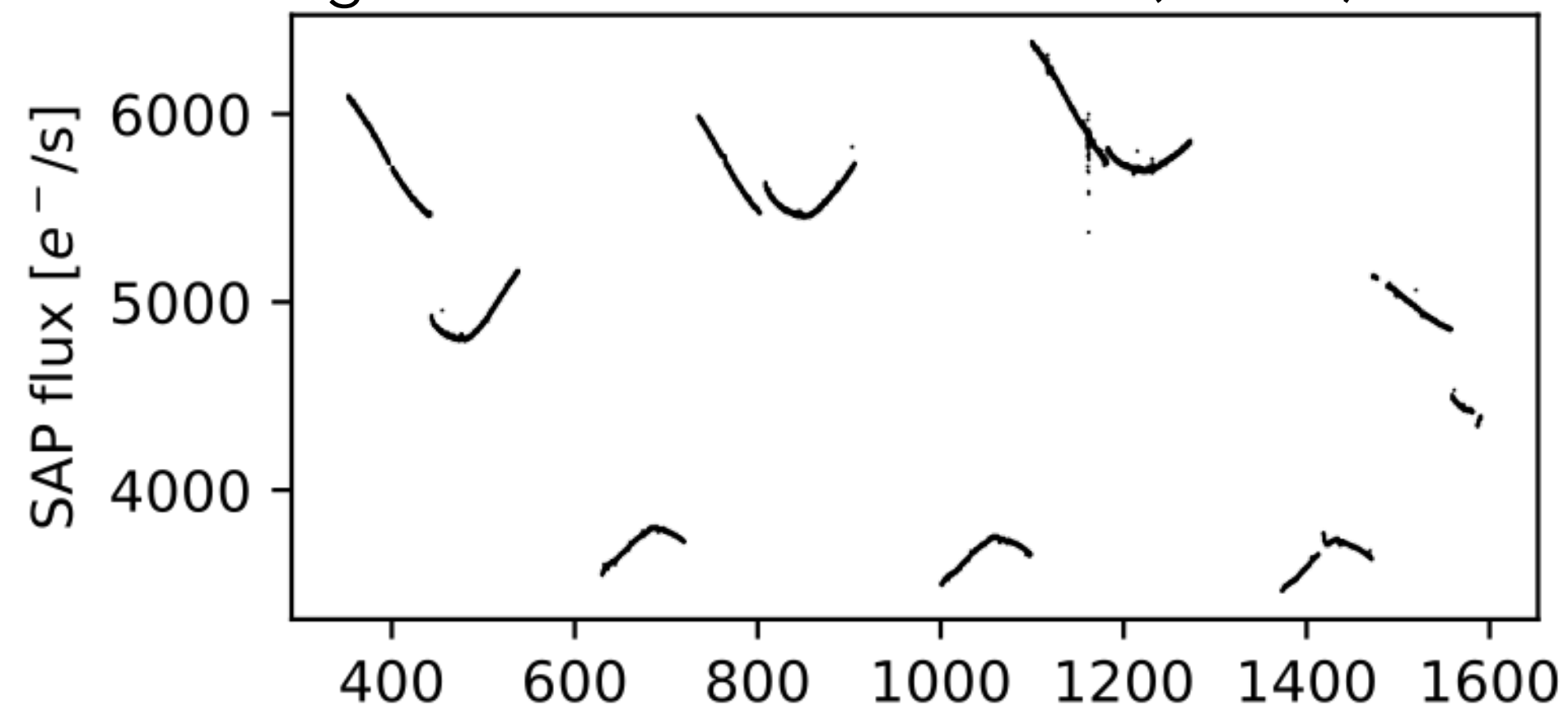
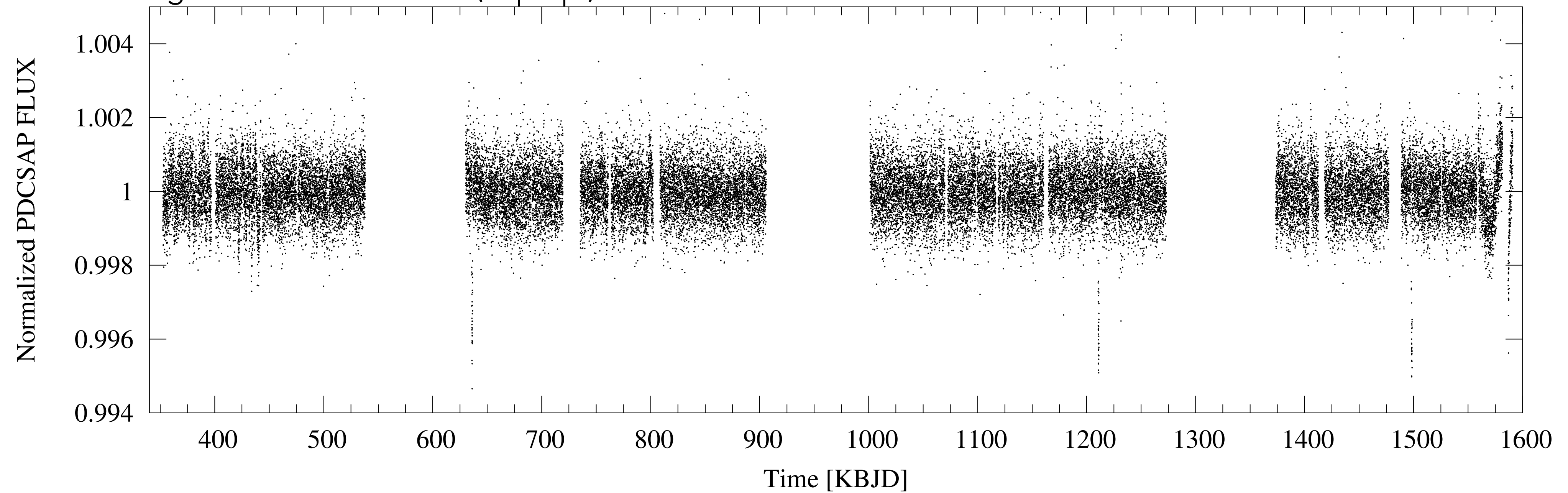
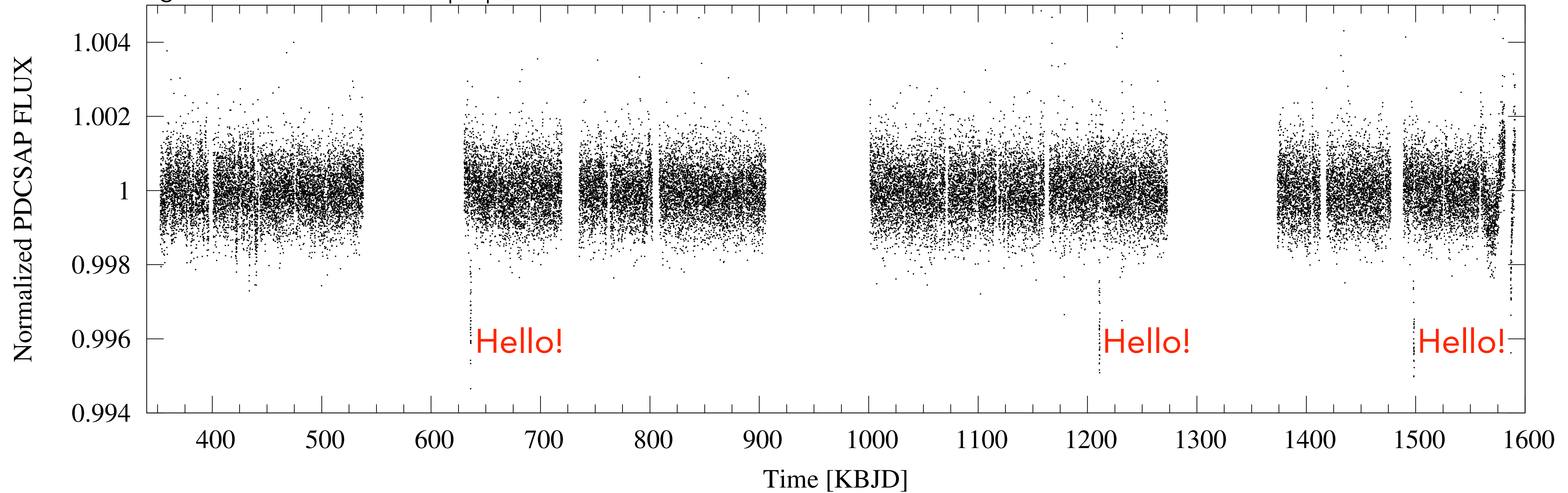


figure from Heller et al. (in prep.)

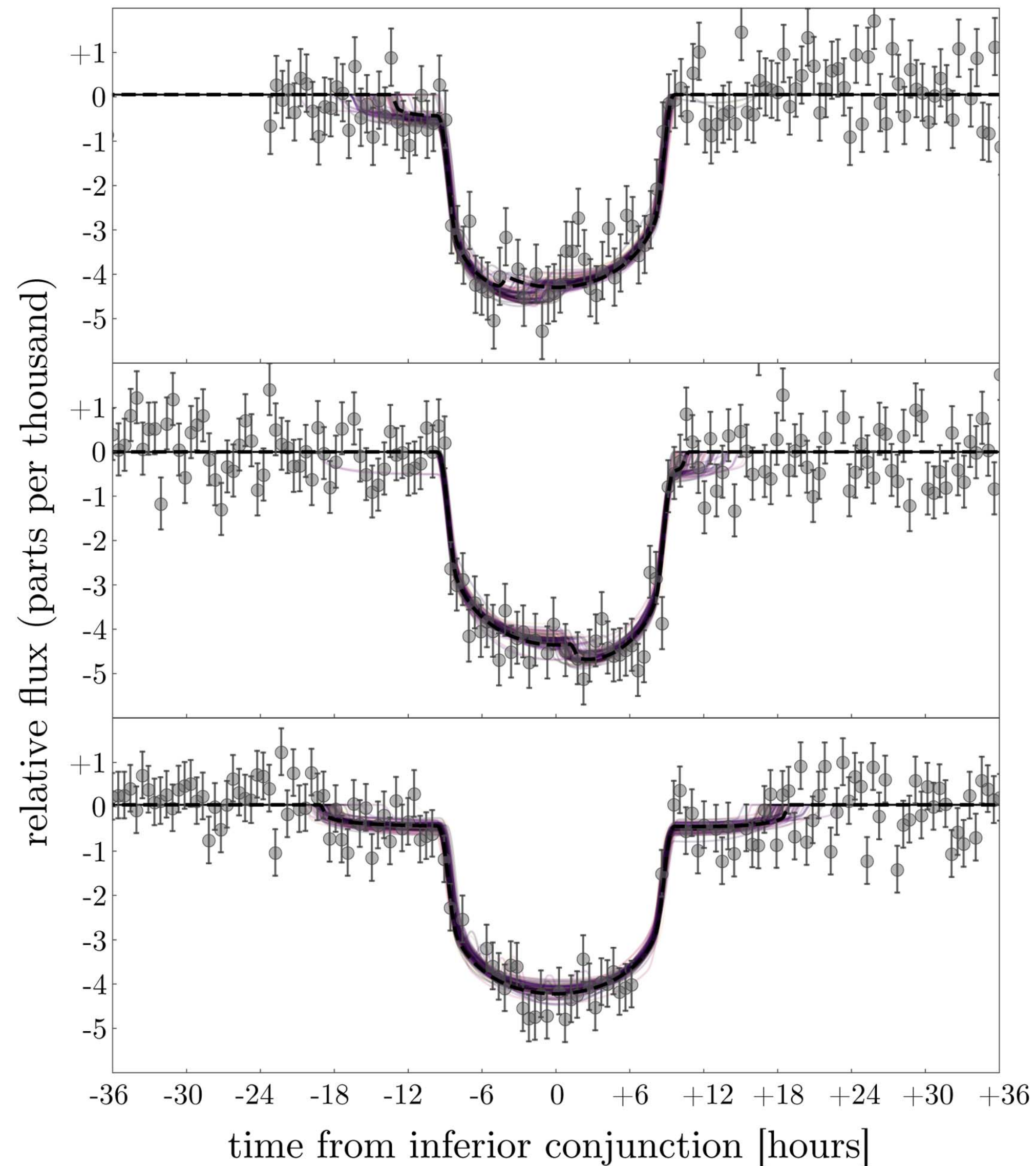


The Exomoon Candidate Around Kepler-1625b

figure from Heller et al. (in prep.)

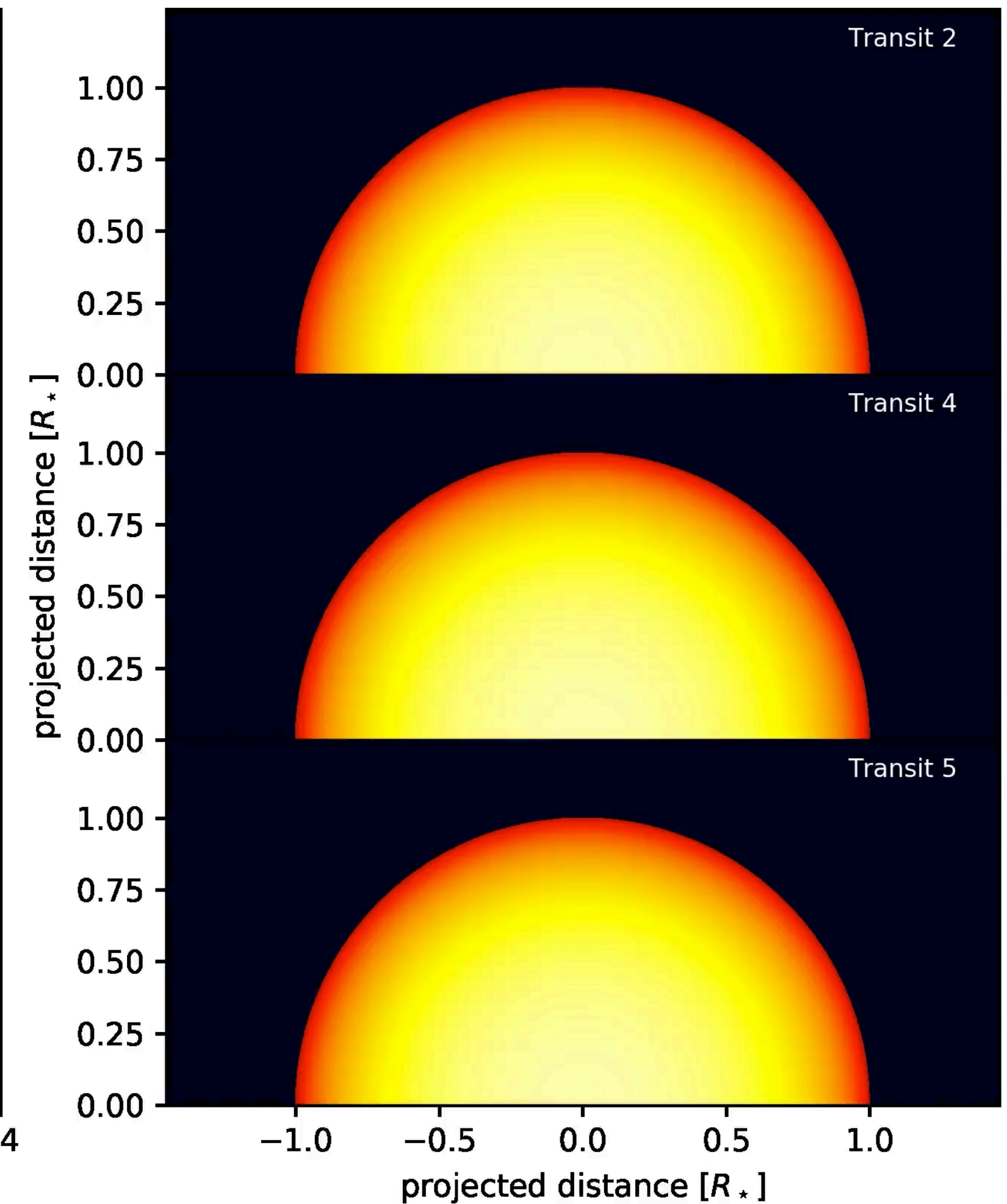
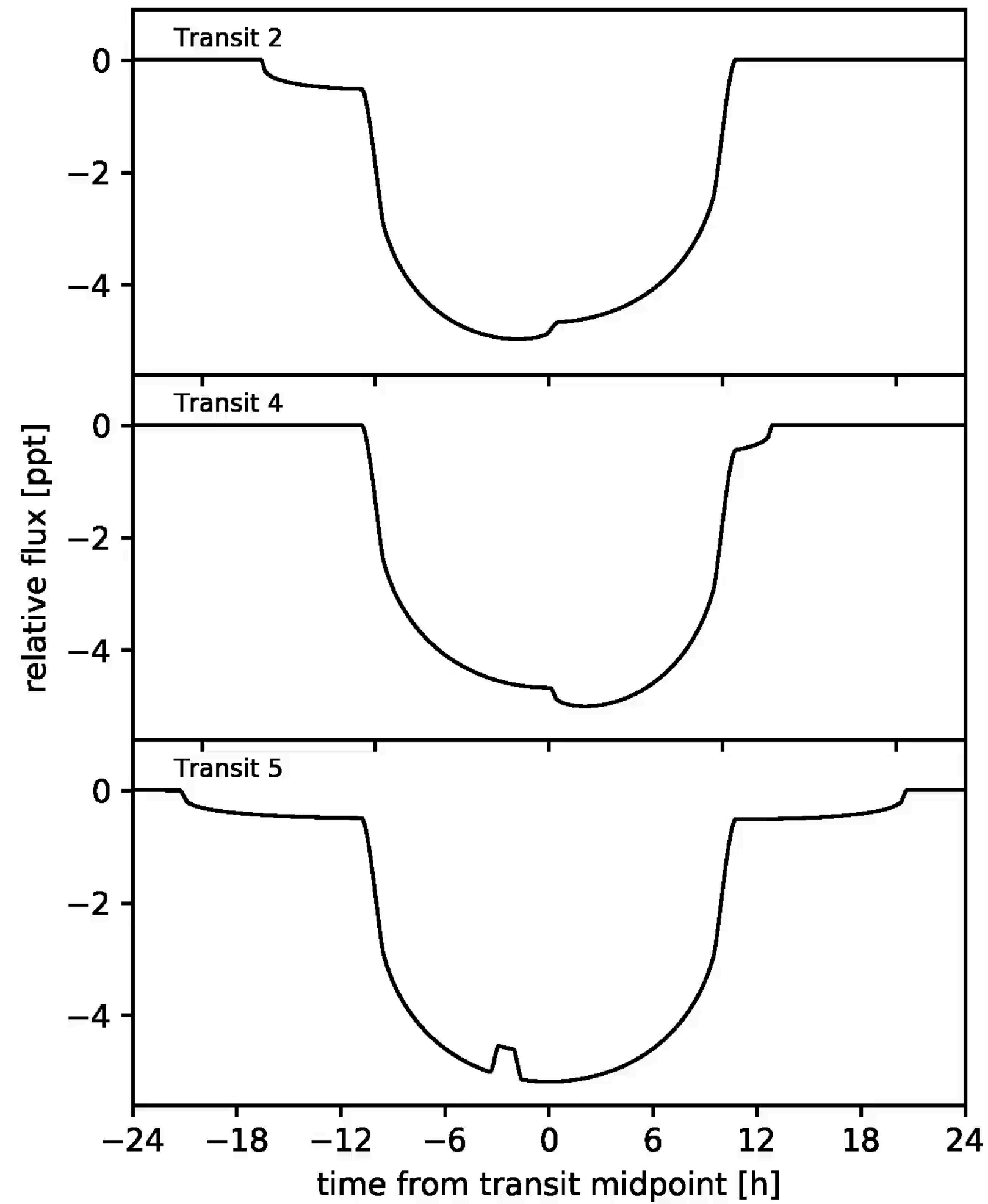
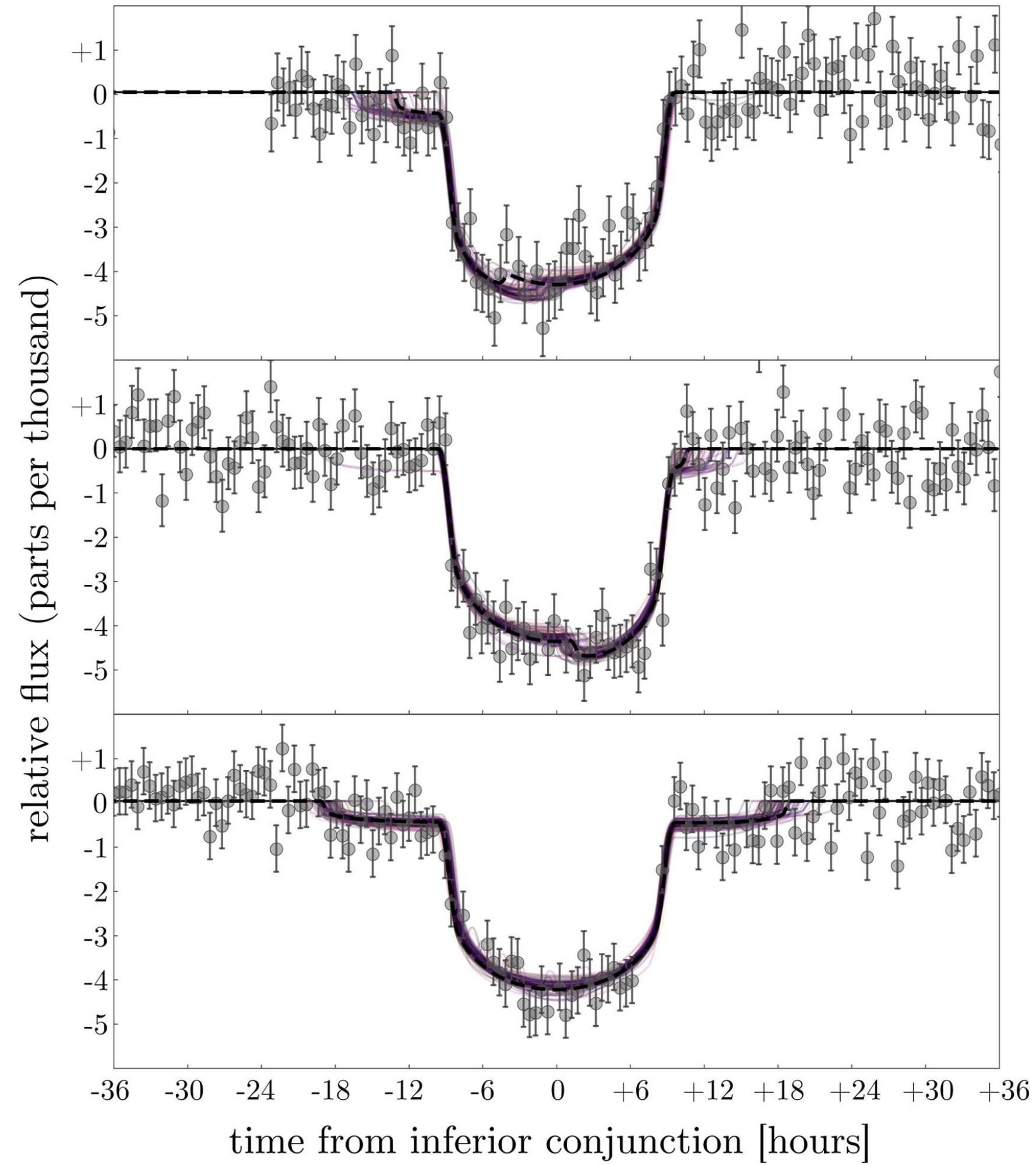


The Exomoon Candidate Around Kepler-1625b



- star: solar mass, slightly evolved:
1.793 (+0.263, -0.488) R_{\odot} ([Mathur et al. 2017](#))
- planet: Jupiter-sized, super-massive ($10 M_{\text{Jup}}$)
- moon: Neptune-sized, orbit 19.1 (+2.1, -1.9) R_{p}
(comparison: Galilean moons between 6 and 27 R_{Jup})

The Exomoon Candidate Around Kepler-1625b



The Exomoon Candidate Around Kepler-1625b

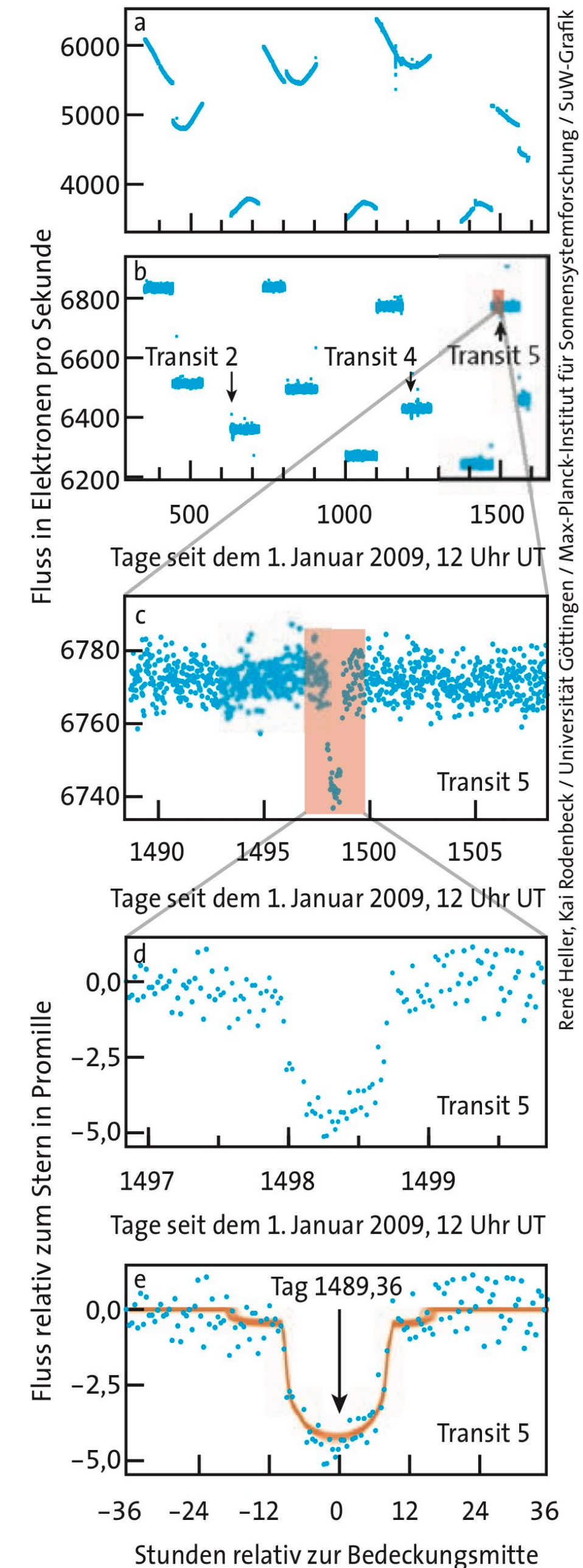
"Simple Aperture Photometry" (SAP), 4 years of almost continuous observations
pixel summation time series of calibrated flux in optimal aperture

"Pre-search Data Conditioning Simple Aperture Photometry" (PDCSAP), 4 years
SAP corrected for systematic trends found by correlating times series of quiet stars

zoom into PDCSAP flux of transit 5
note the stellar (and systematic?) variability!

zoom into detrended ("pre-whitened") PDCSAP flux of transit 5
stellar variability removed to some (not fully known) extent with a sum of cosines

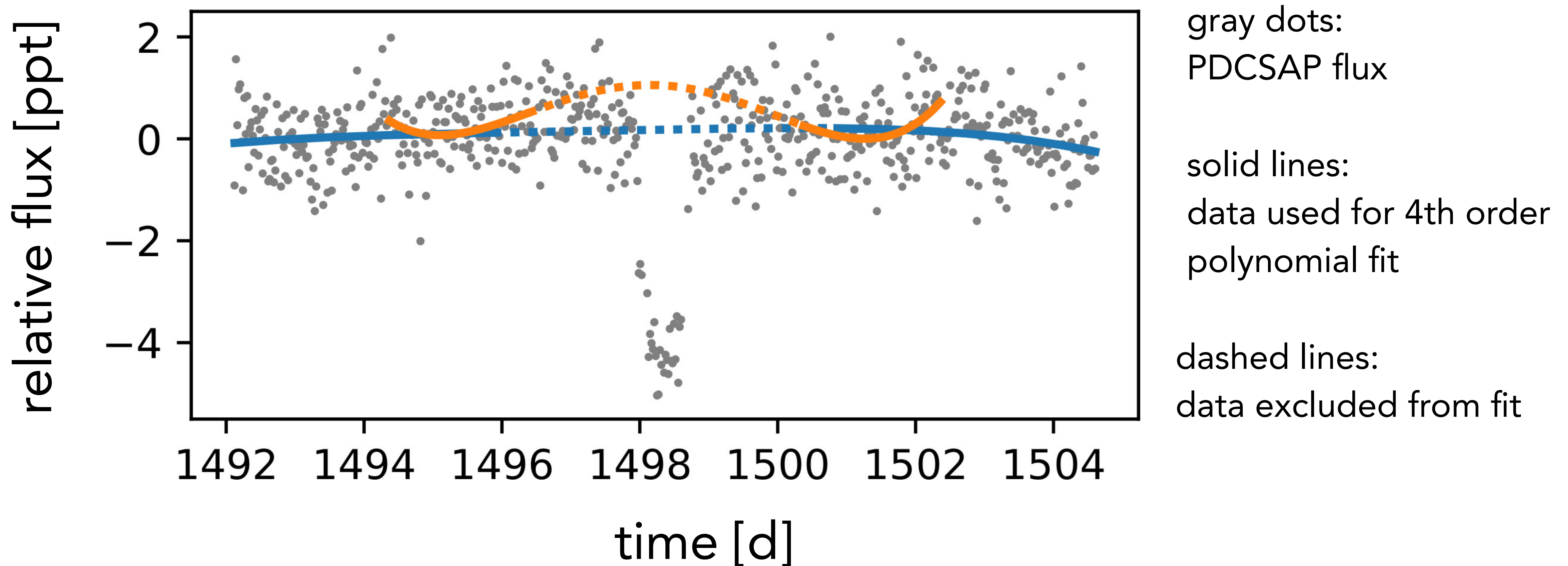
"pre-whitened" PDCSAP flux of transit 5
with 100 MCMC realizations



The Exomoon Candidate Around Kepler-1625b

Detrending / "Pre-whitening"

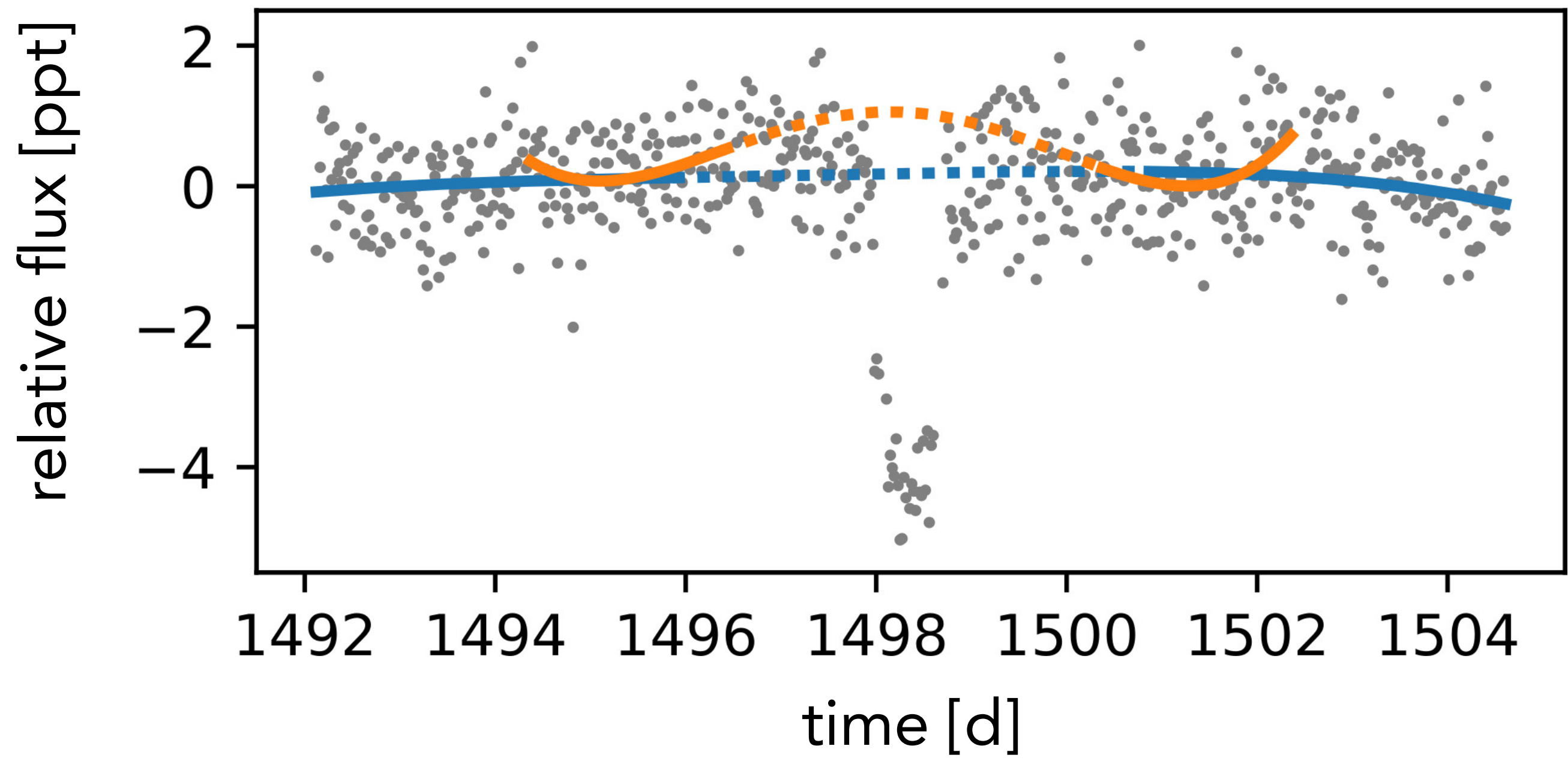
3rd Kepler transit of Kepler-1625 b



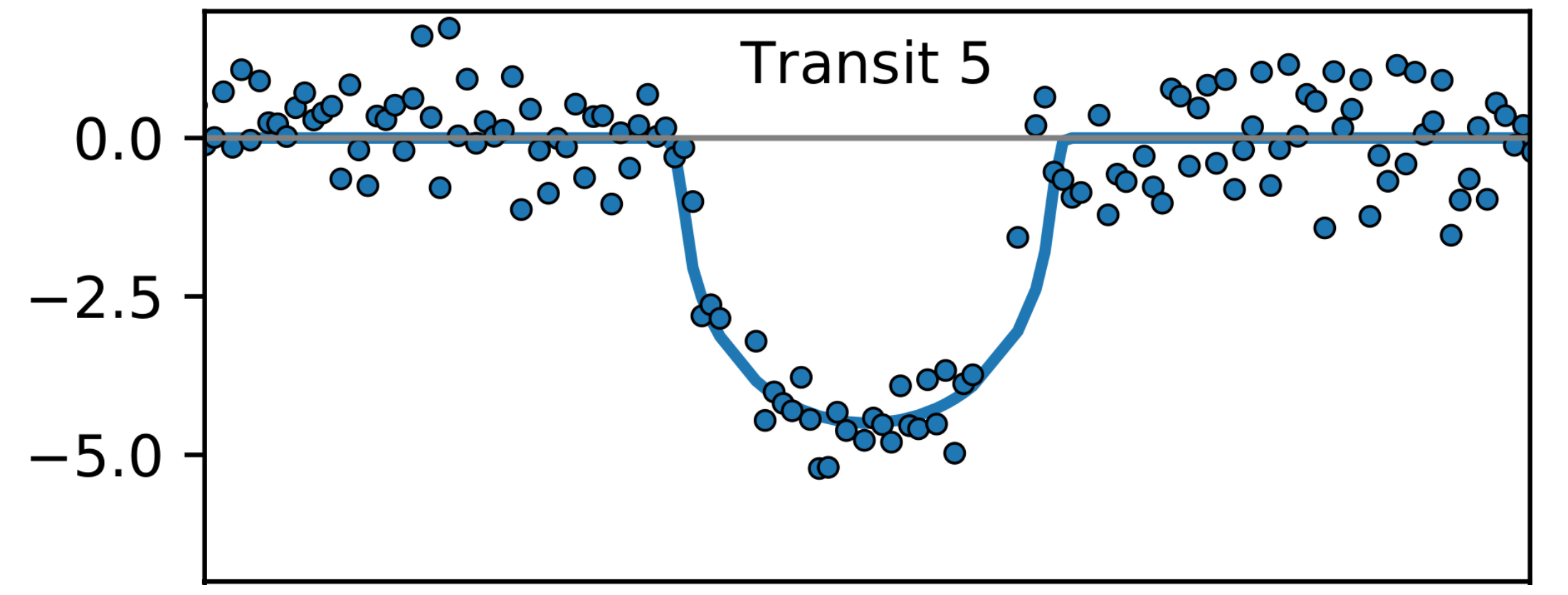
The Exomoon Candidate Around Kepler-1625b

Detrending / "Pre-whitening"

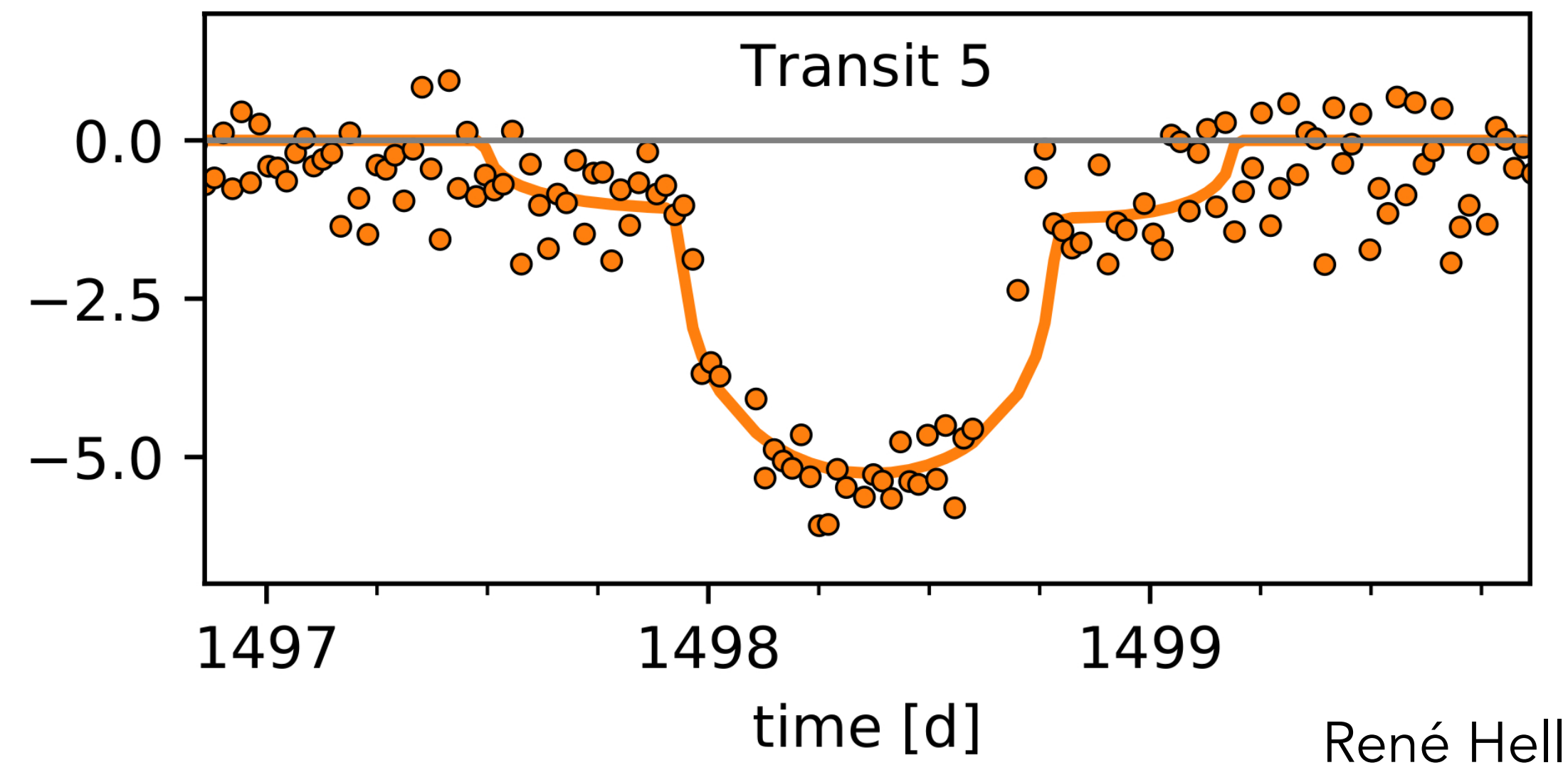
3rd Kepler transit of Kepler-1625 b, PDCSAP flux



detrended light curve looks like planet only



detrended light curve looks like a planet with a moon

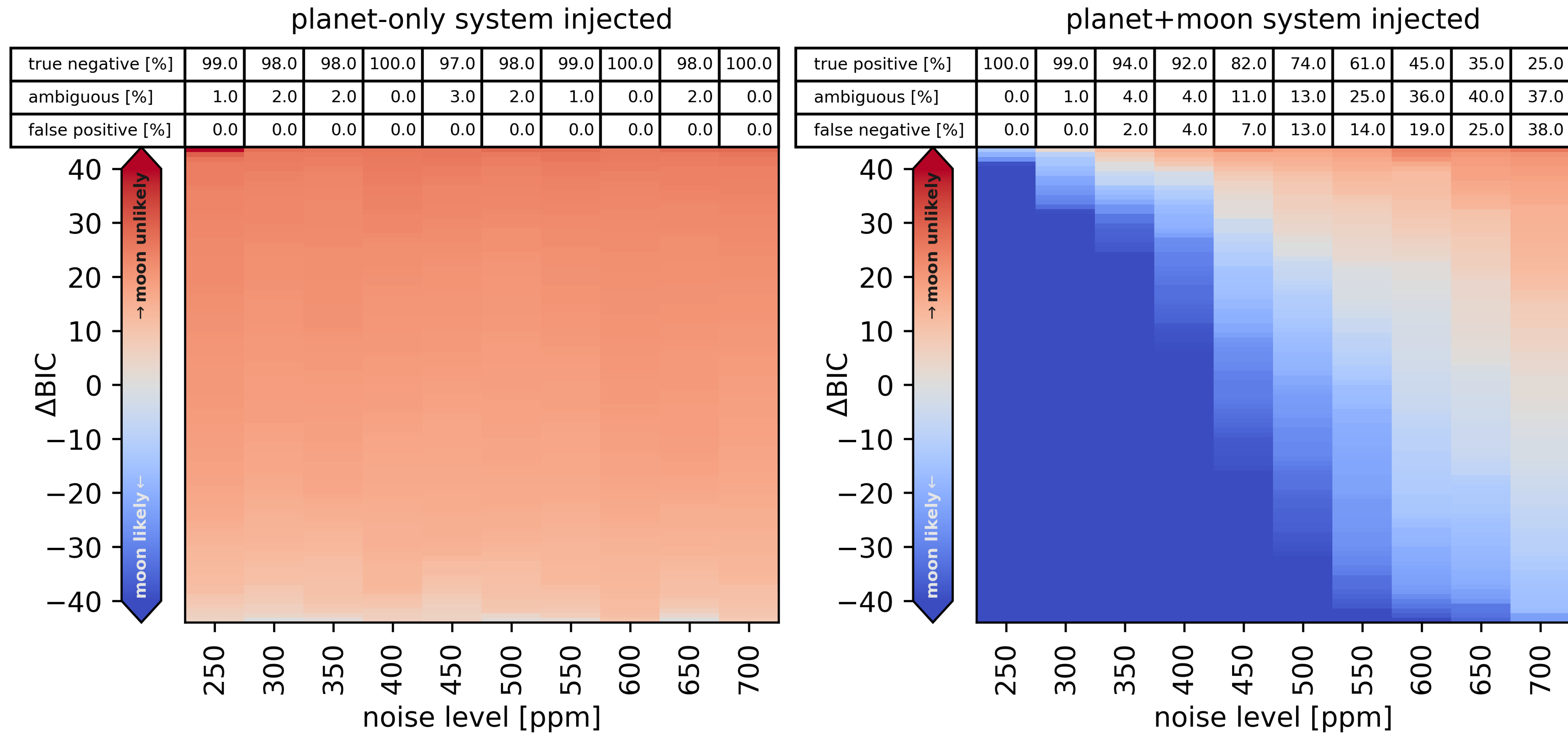


figures from Rodenbeck et al. (2018a)

The Exomoon Candidate Around Kepler-1625b

Injection-Retrieval Experiments

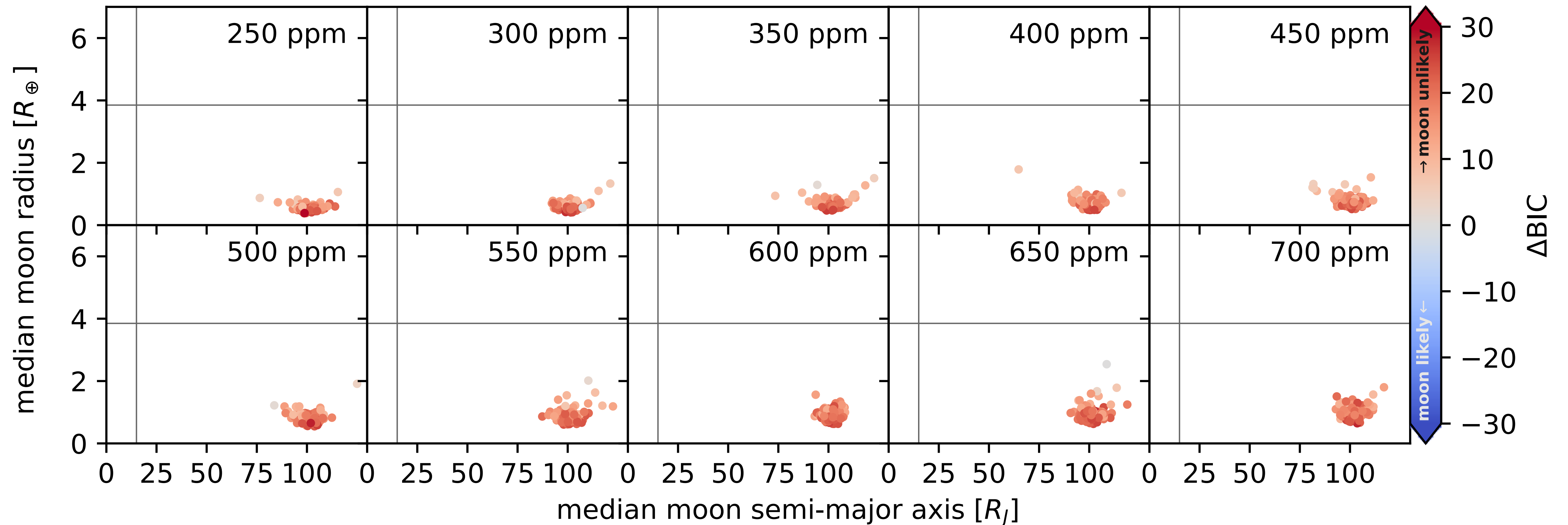
Each panel 10 × 100 sequences of three transits with white noise only fitted with a planet-moon model



The Exomoon Candidate Around Kepler-1625b

Injection-Retrieval Experiments

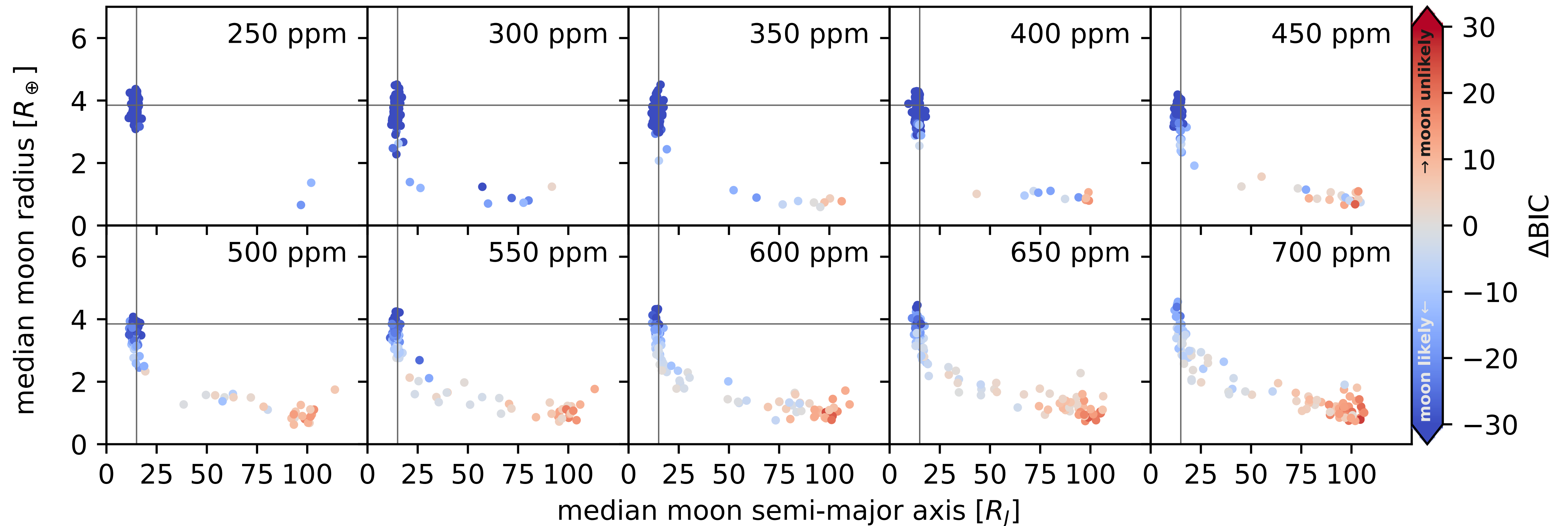
planet-only system injected



The Exomoon Candidate Around Kepler-1625b

Injection-Retrieval Experiments

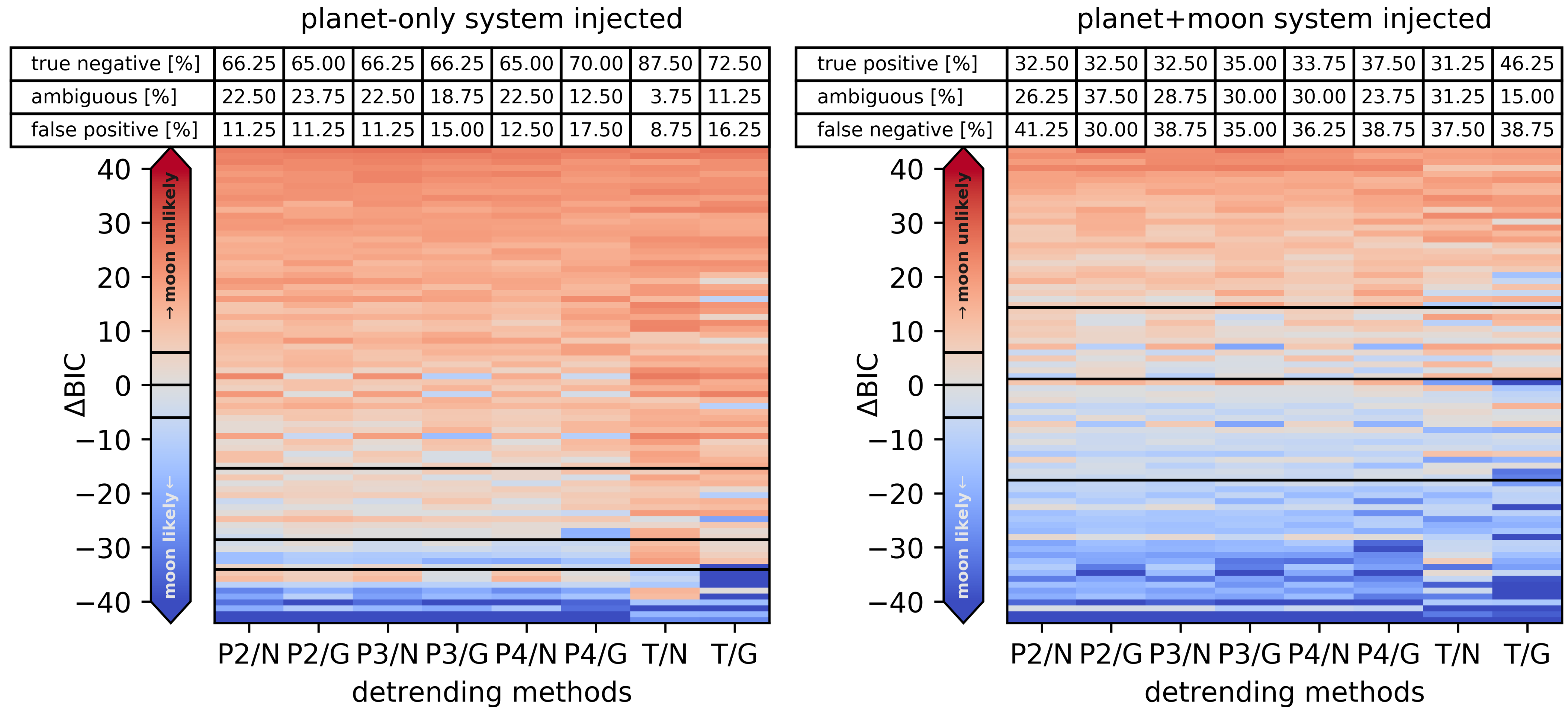
planet+moon system injected



The Exomoon Candidate Around Kepler-1625b

Injection-Retrieval Experiments

Each panel 10 × 100 sequences of three transits with white noise only fitted with a planet-moon model

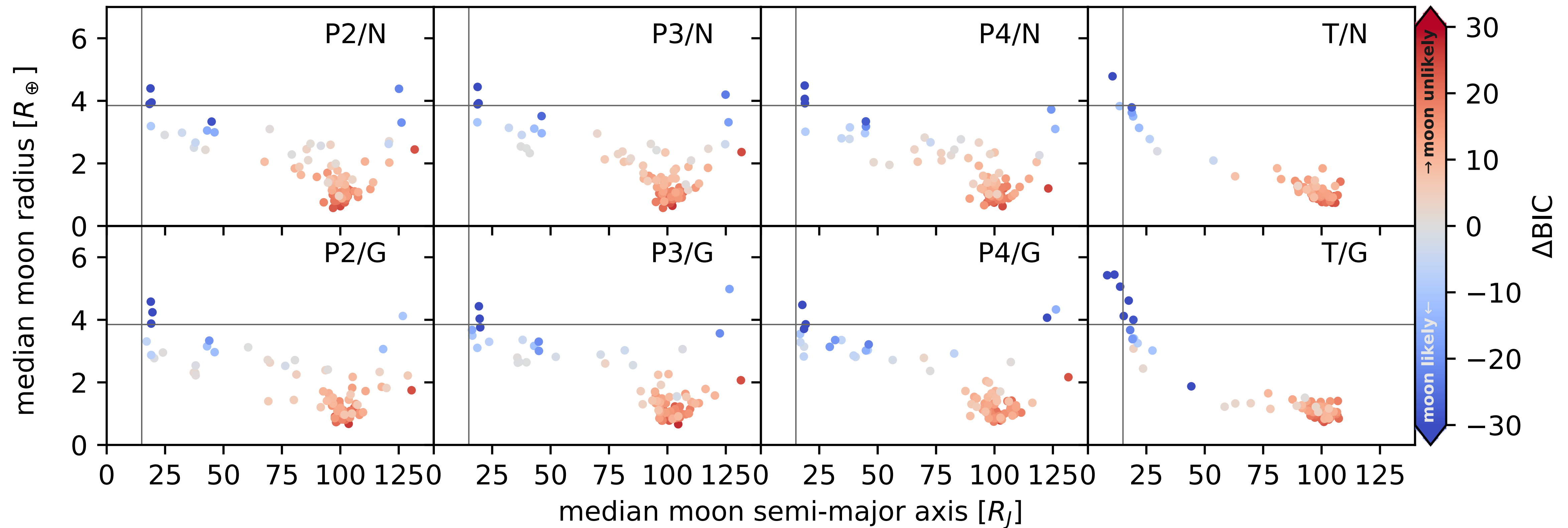


The Exomoon Candidate Around Kepler-1625b

Injection-Retrieval Experiments

10 × 100 sequences of three transits with white noise only fitted with a planet-moon model

planet-only system injected

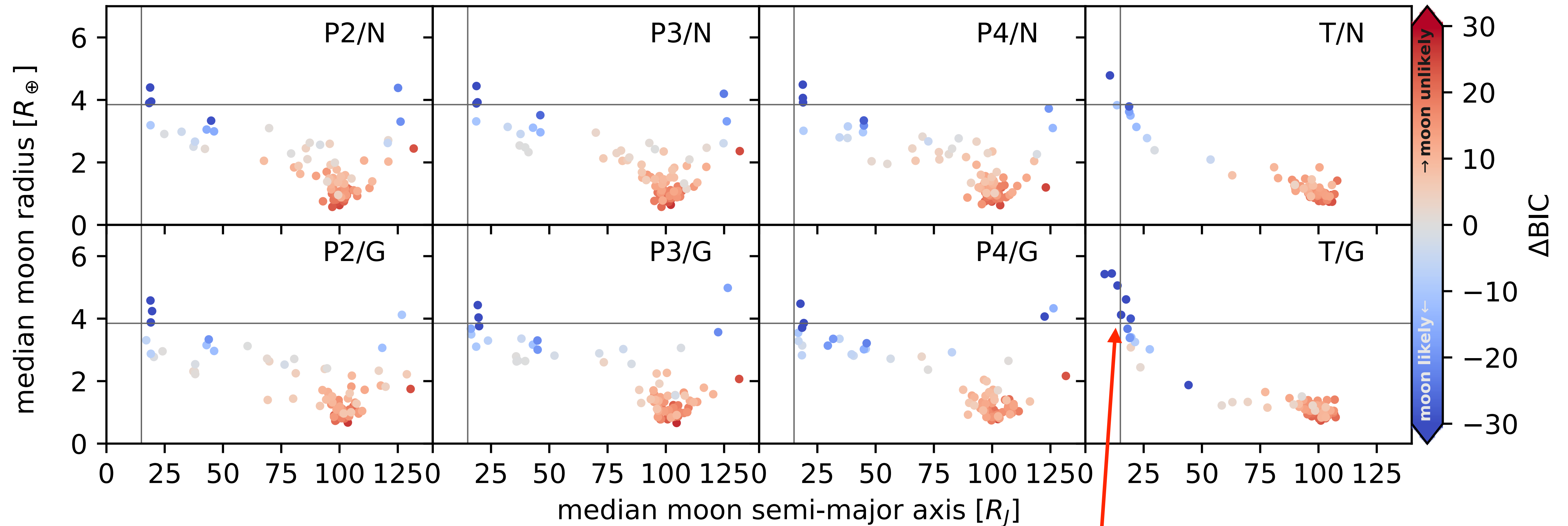


The Exomoon Candidate Around Kepler-1625b

Injection-Retrieval Experiments

10 × 100 sequences of three transits with white noise only fitted with a planet-moon model

planet-only system injected



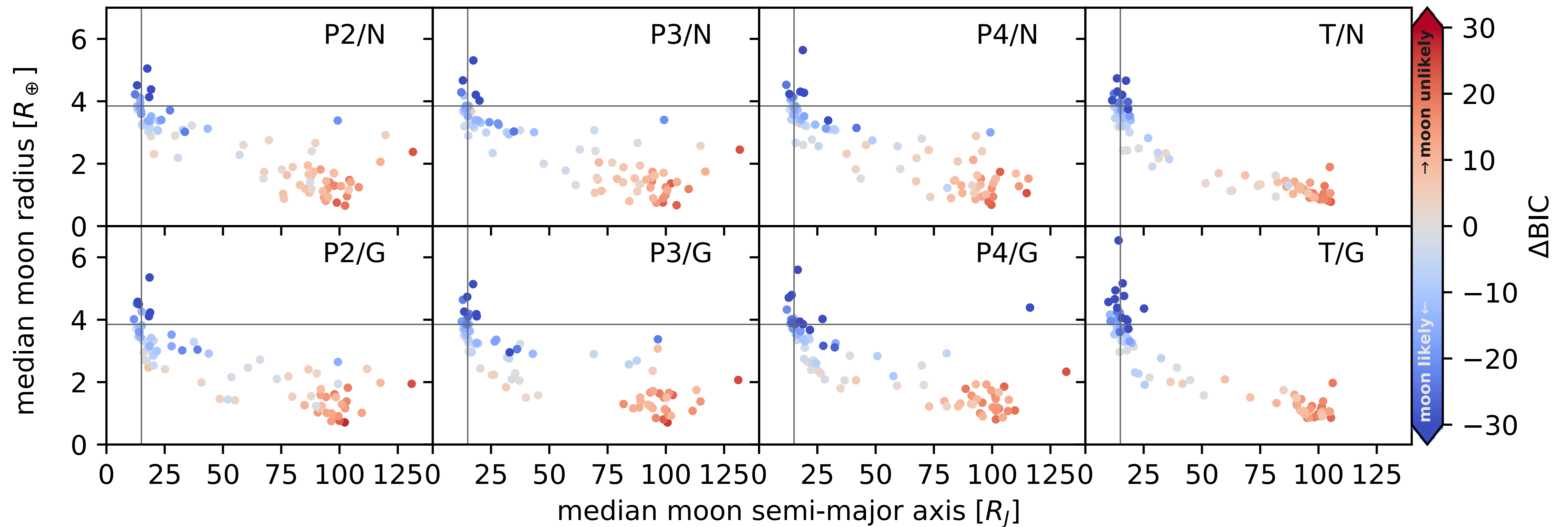
False positive moons have radii and orbits similar to the proposed exomoon candidate Kepler-1625b-i

The Exomoon Candidate Around Kepler-1625b

Injection-Retrieval Experiments

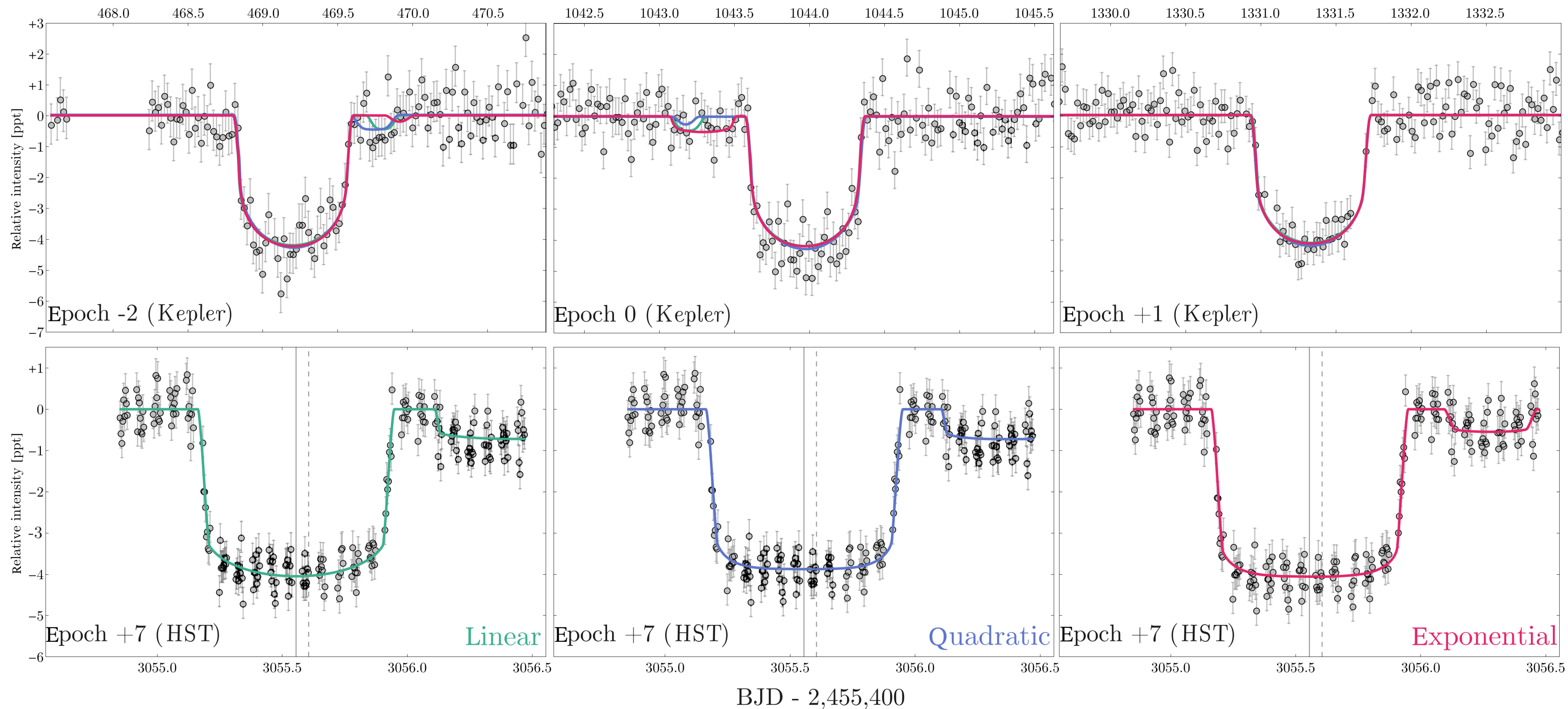
10 × 100 sequences of three transits with white noise only fitted with a planet-moon model

planet+moon system injected



The Exomoon Candidate Around Kepler-1625b

Kepler (2009-2013) and Hubble (Oct 2017) observations



Simple Aperture Photometry (SAP)
Kepler Science Operations Center pipeline version 9.0

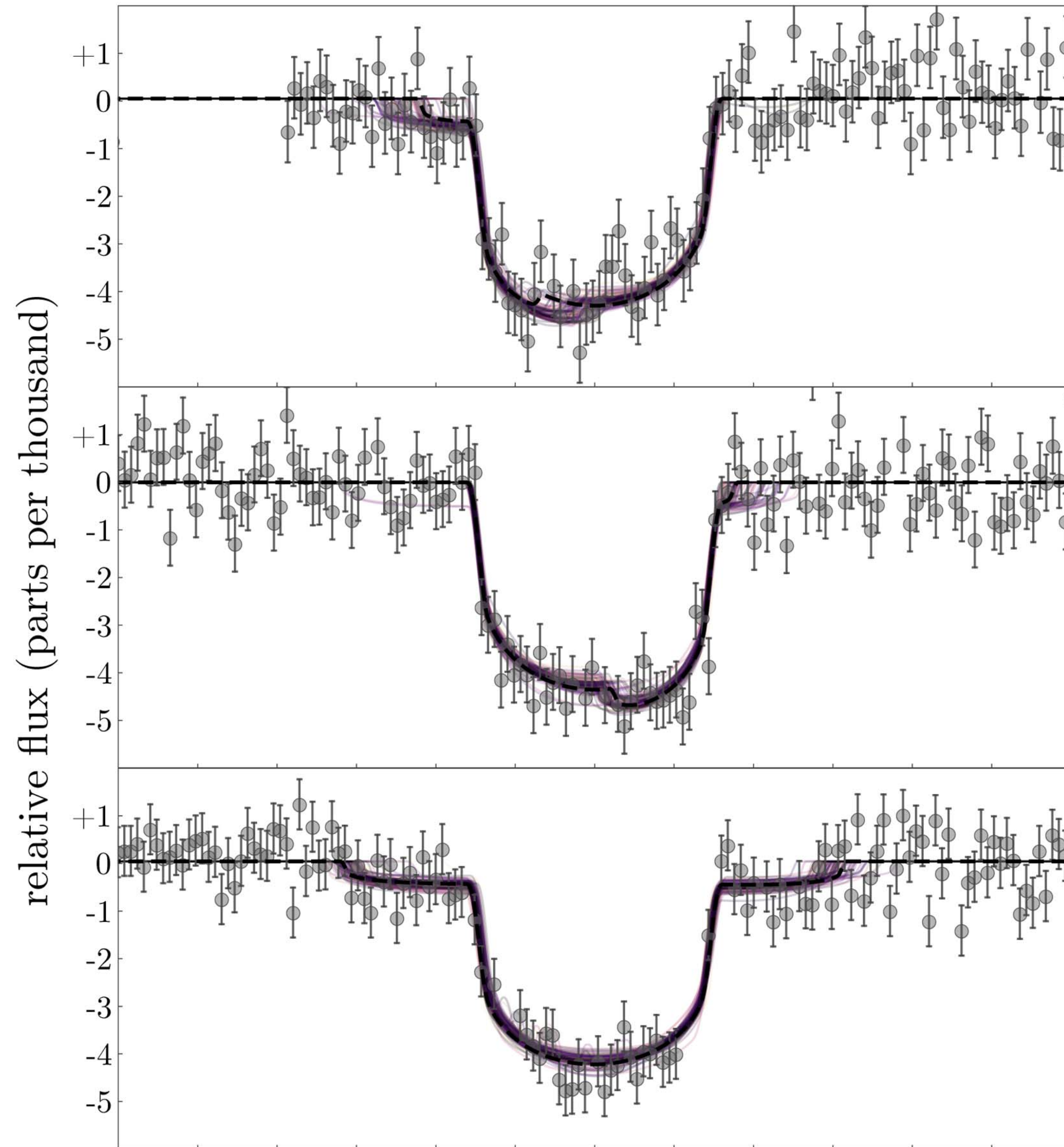


figure from [Teachey et al. \(2018\)](#)

Simple Aperture Photometry (SAP)
Kepler Science Operations Center pipeline version 9.3

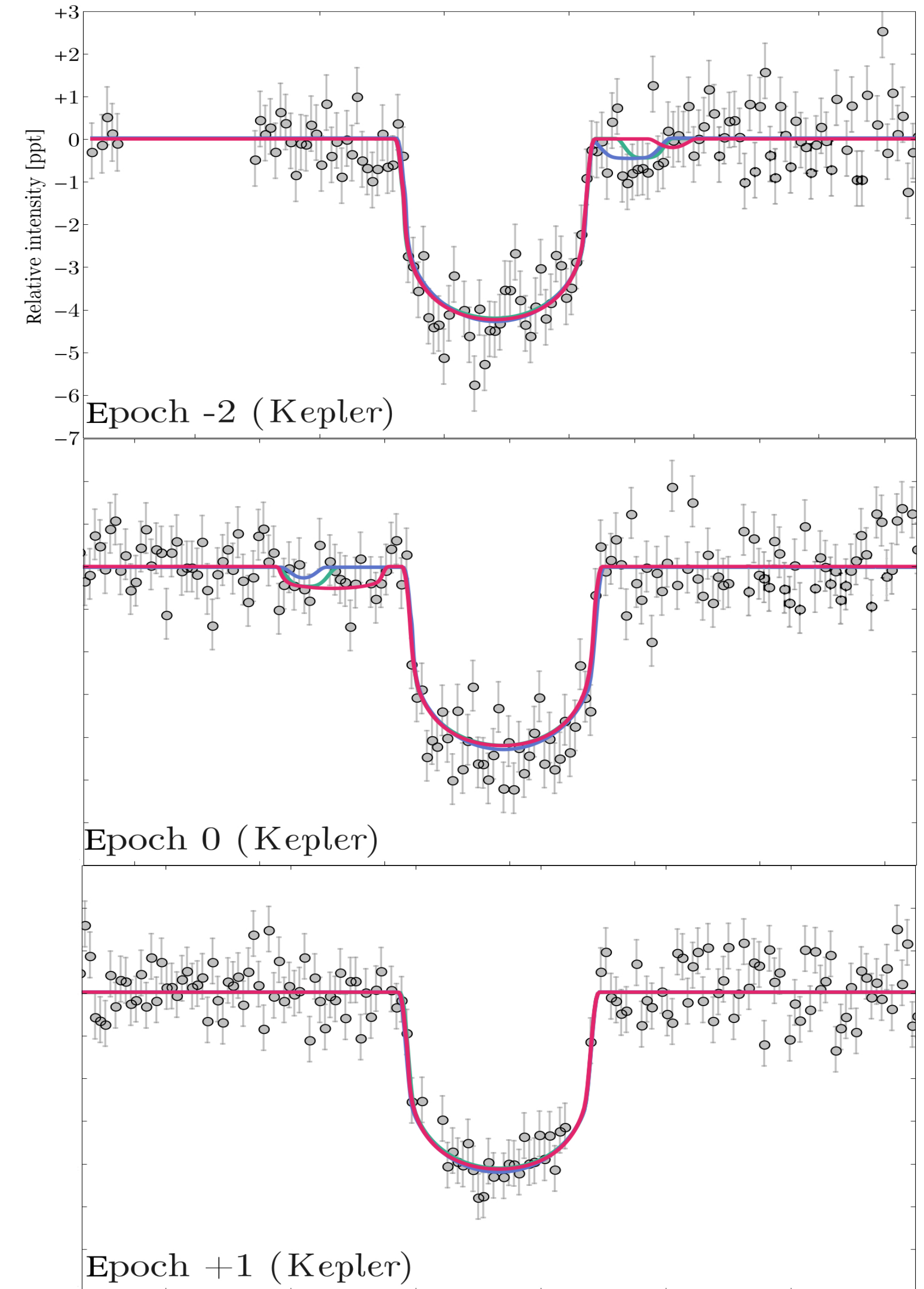


figure from [Teachey & Kipping \(2018\)](#)

following slides with work from
Heller, Rodenbeck et al. (in prep.) embargoed



**The Exomoon Candidate
Around Kepler-1625 b**

special thanks to

Kai Rodenbeck

University of Göttingen

&

Max Planck Institute
for Solar System Research

