TRANSITING EXOMOONS

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THANK-YOU SAGAN!

"A Search for Exomoons", David M. Kipping

1. INTRODUCTION

The detection of a moon around an extrasolar planet represents an outstanding challenge in modern astronomy. The announcement of an "exomoon" would usher in a new age of discovery with the promise of solving many unanswered questions about the nature, origin and evolution of planetary systems. Perhaps most interestingly, moons could be common habitable environments in the Galactic neighborhood and may even outnumber planets as temperate abodes for life. I propose here a program of observations and theoretical development to search for an exomoon. This search will provide many opportunities for parallel science, which will be exploited, as done with my previous publications. The principal science goals may be summarized as:

I. A search for exomoons in transiting systems, with primarily (but not exclusively) *Kepler*
II. A search for perturbing planets and Trojan bodies in transiting systems
III. Characterization of transiting exoplanets using secondary eclipse measurements

2. EXTRASOLAR MOONS

In the last two decades we have witnessed the discovery of hundreds of extrasolar planets, ranging from super-hot Jupiters to frozen super-Earths (see http://exoplanet.eu). As the catalogue of known planets continues to swell, one of the great last questions in exoplanetary science is - do exoplanets have moons? Based on a Copernican view of the Universe and the observations of our own Solar System, it seems very probable that exomoons are common throughout the Galaxy. Indeed, it has been postulated that exomoons could be frequent habitable environments - maybe even outnumbering habitable planets [1,2]. In light of this, the search for an exomoon is of paramount importance to furthering our understanding of not just planetary formation and evolution, but more profoundly, our place in the Universe.

I have spent a substantial portion of my PhD researching methods to detect extrasolar moons and this work constitutes the core of my thesis. My research so far on this subject can be split into two principal components: (1) theoretical development (2) observational searches. In 2009, I published a series of three theoretical papers which:

- Devised a new technique for detecting exomoons [3]
- Explored second-order effects [4]
- Showed that habitable-zone exomoons down to $0.2M_{\oplus}$ are detectable with *Kepler* [5]

Although detecting an exomoon is feasible [5], it requires a detailed understanding of the effects at play, which are much more subtle than the techniques used in exoplanet detection. I believe I am uniquely placed to lead an observational search as a result of the years of research I have already invested towards this challenging goal.

3. OBSERVATIONAL METHOD & STRATEGY

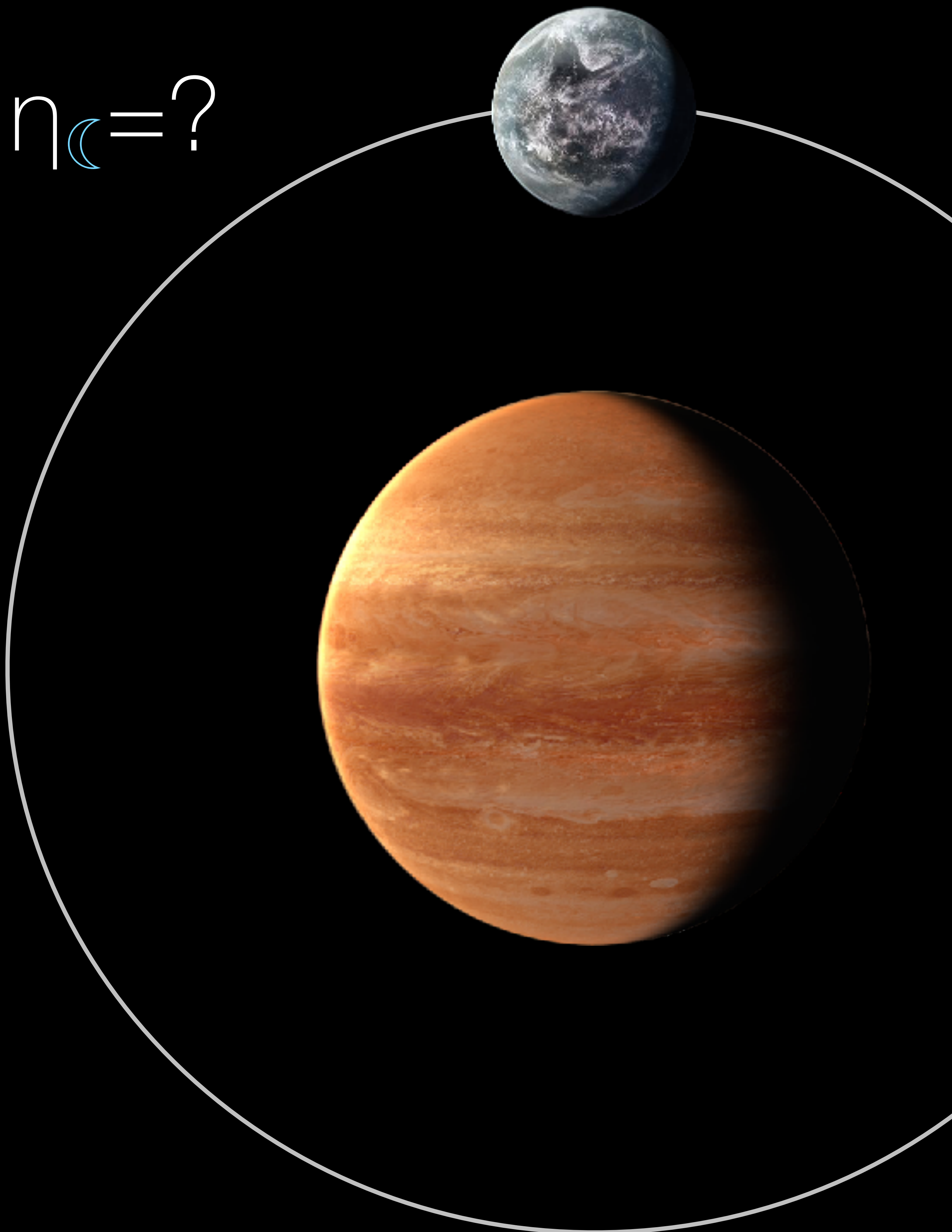
If a planet has a moon, the pair of bodies orbit a common center-of-mass, which is usually located very close to the planet's center. As a result, the planet appears to wobble about during the course of its motion around the host star. More precisely, both the position and velocity of the planet oscillate around some local mean value and these changes manifest as transit time and duration variations (TTV & TDV). With TTV being a positional-effect and TDV a velocity-effect, the two will always be $\pi/2$ out-of-phase, providing a unique exomoon signature that may be searched for (see Fig. 1 left panel, and [3,4] for more technical details). TTV and TDV are conceptually analogous to the astrometry and radial velocity methods, respectively, of finding exoplanets. *Kepler* is estimated to be capable of detecting habitable-zone exomoons down to $0.2M_{\oplus}$ with TTV/TDV [5], demonstrating the feasibility of the search we propose here.

HOW OFTEN DO PLANETS HAVE (LARGE) MOONS?

$\eta_{☾}=?$

- Habitable moons
- Habitable planets with large moons
- Satellite formation

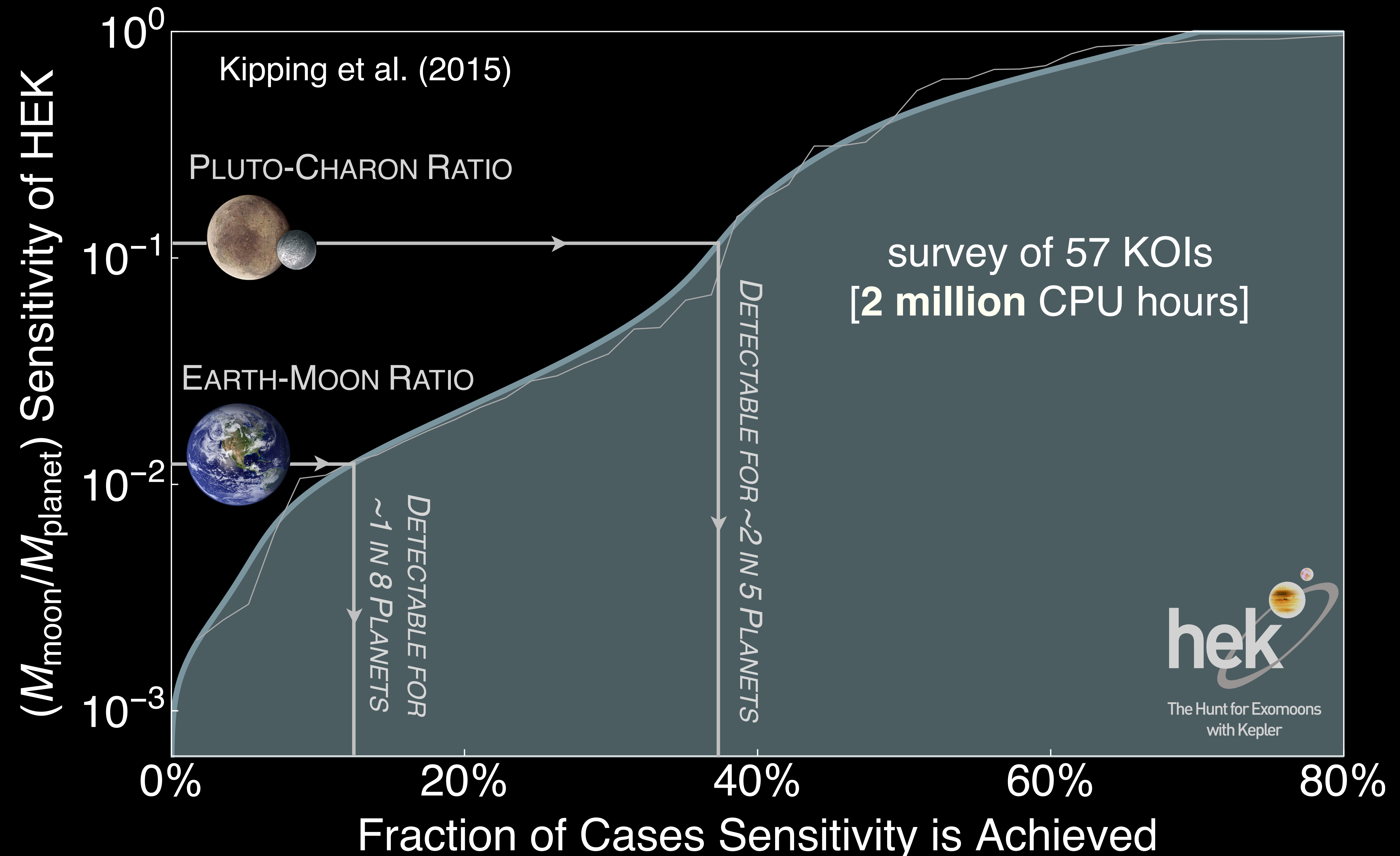
The Hunt for Exomoons with Kepler



The Hunt for Exomoons with Kepler

Edge-on system view: Giant planet with a highly-inclined moon

Simulated transit lightcurve of both planet and moon



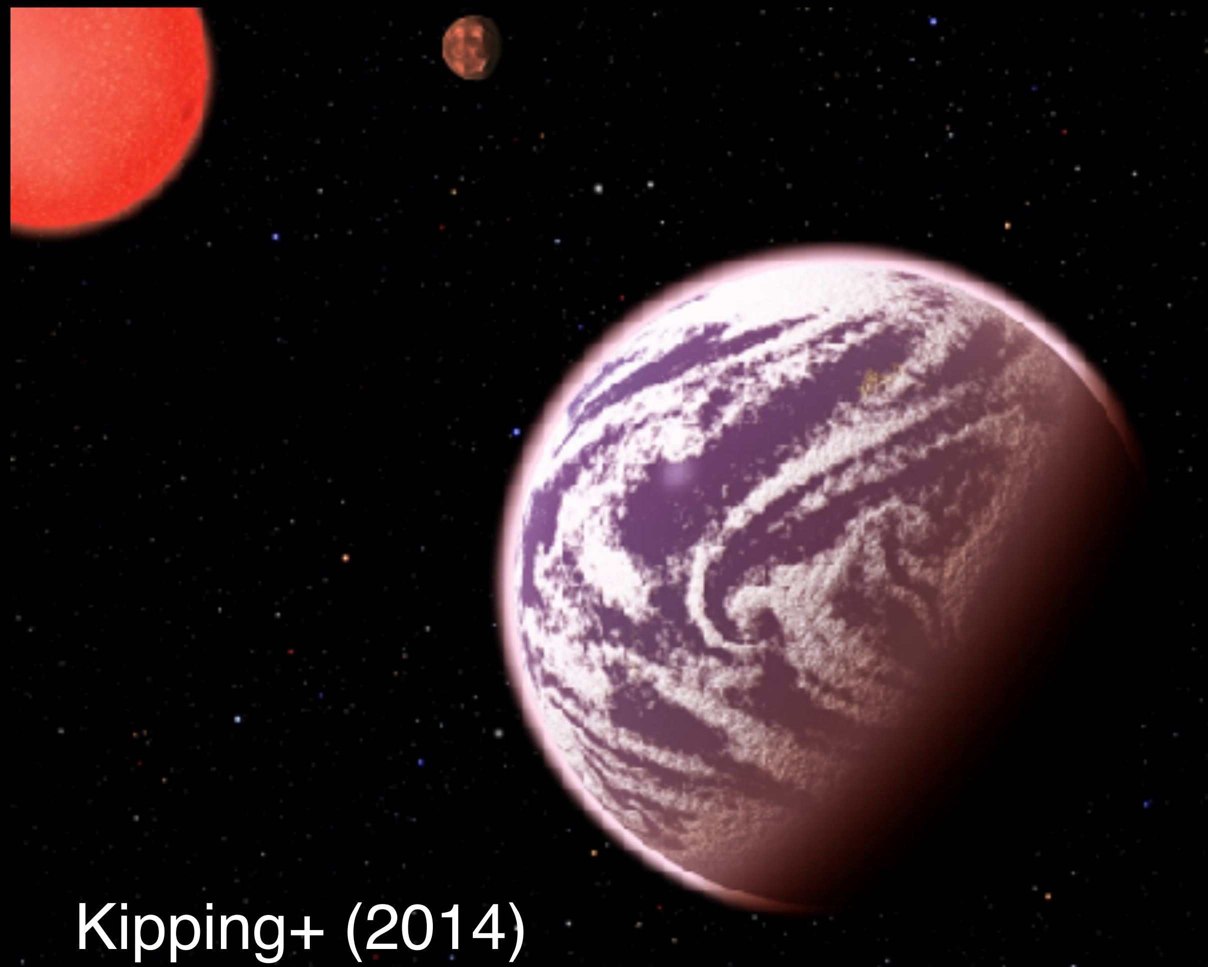
10^0
10^{-1}
10^{-2}
10^{-3}
(M_{moon}/M_{planet}) Sensitivity of HEK
Kipping et al. (2015)
PLUTO-CHARON RATIO
EARTH-MOON RATIO
DETECTABLE FOR ~1 IN 8 PLANETS
DETECTABLE FOR ~2 IN 5 PLANETS
survey of 57 KOIs
[2 million CPU hours]
hek
The Hunt for Exomoons with Kepler
0%
20%
40%
60%
80%
Fraction of Cases Sensitivity is Achieved

y science

(TTVs) due to perturbing

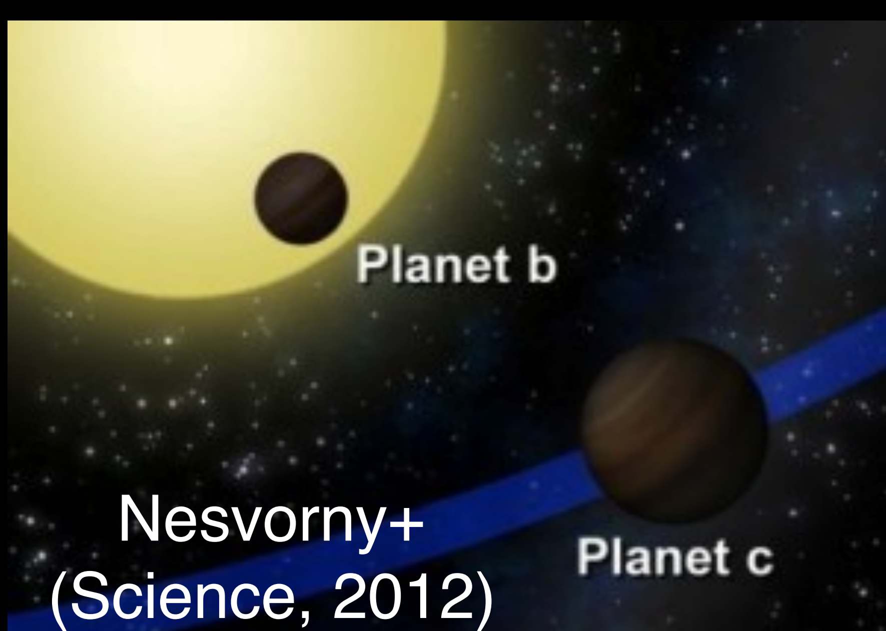
ve for

several secondary science

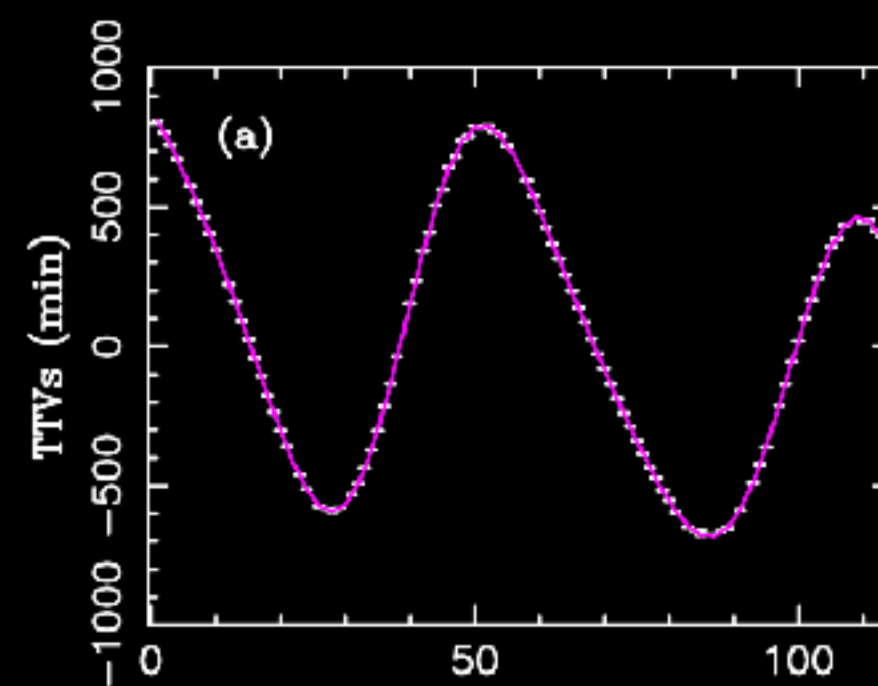


KOI-314c: Lowest mass transiting planet found to date at 1.0 Earth masses. Composition likely a mini-Neptune and not rocky!

KOI-872c, first non-transiting planet with a unique orbit found using TTVs



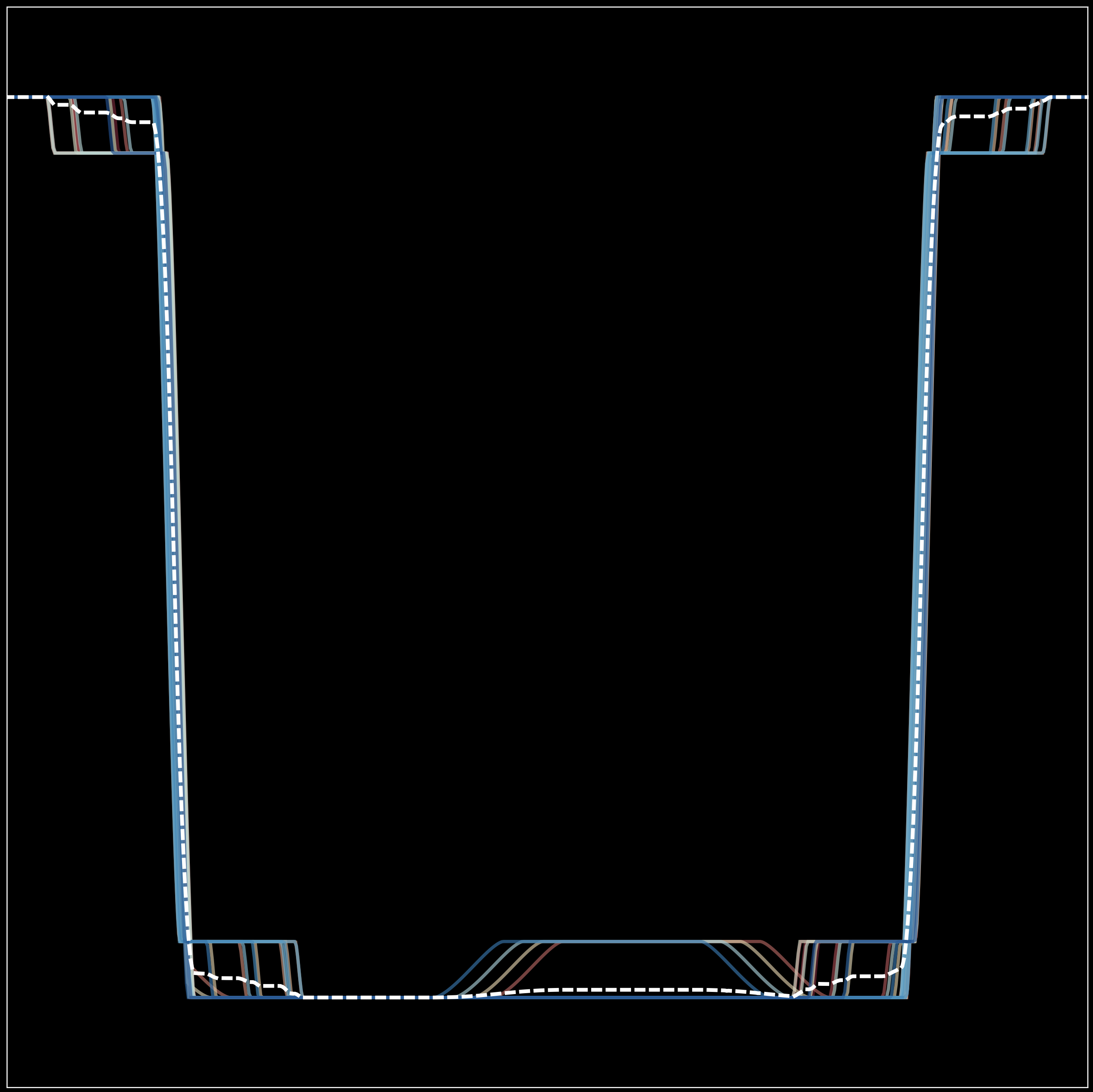
Nesvorny+ (2013)



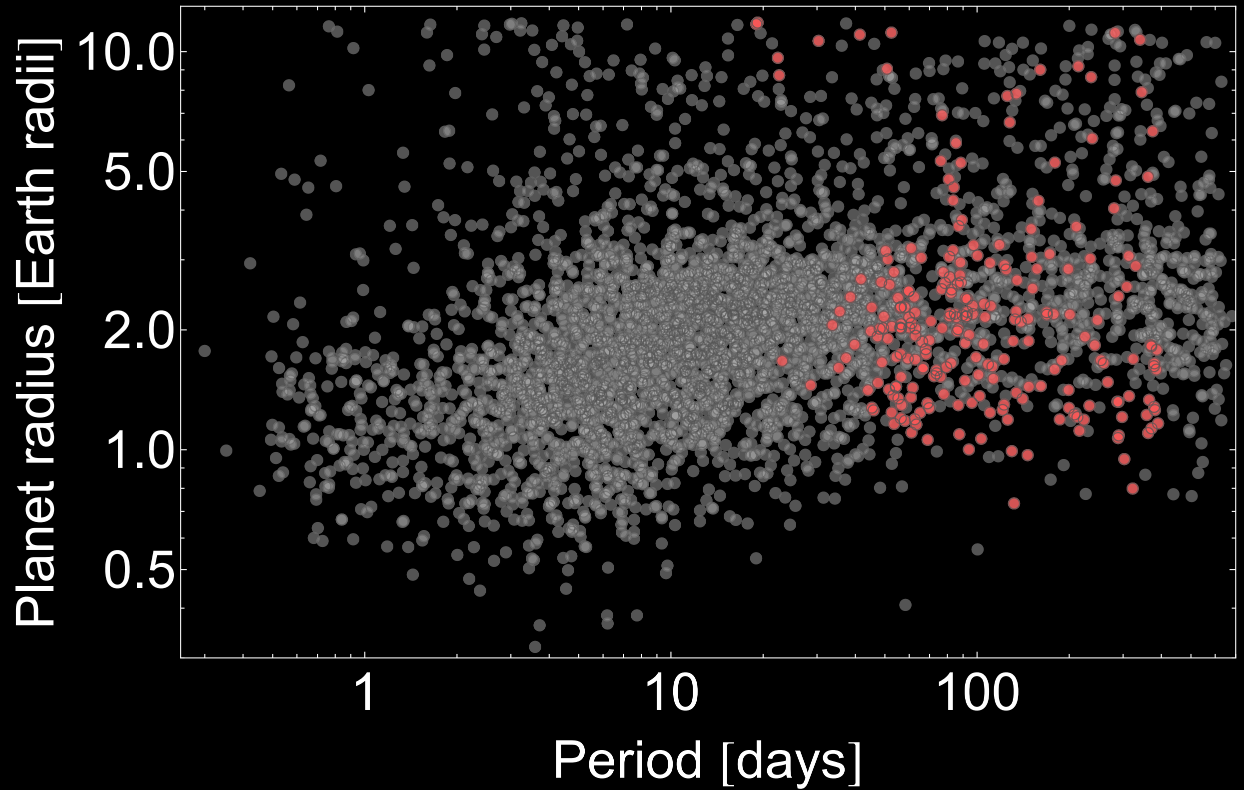
KOI-142b: The King of TTVs

stack it

statistical inference of moon populations

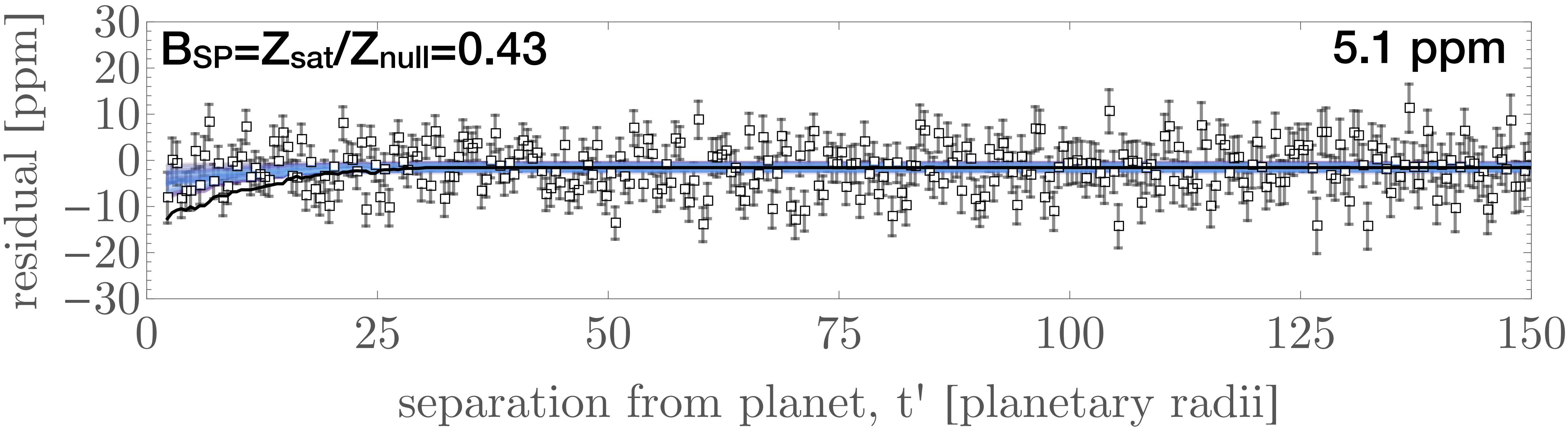


requires N»1 transits, so we have to stack different planets together

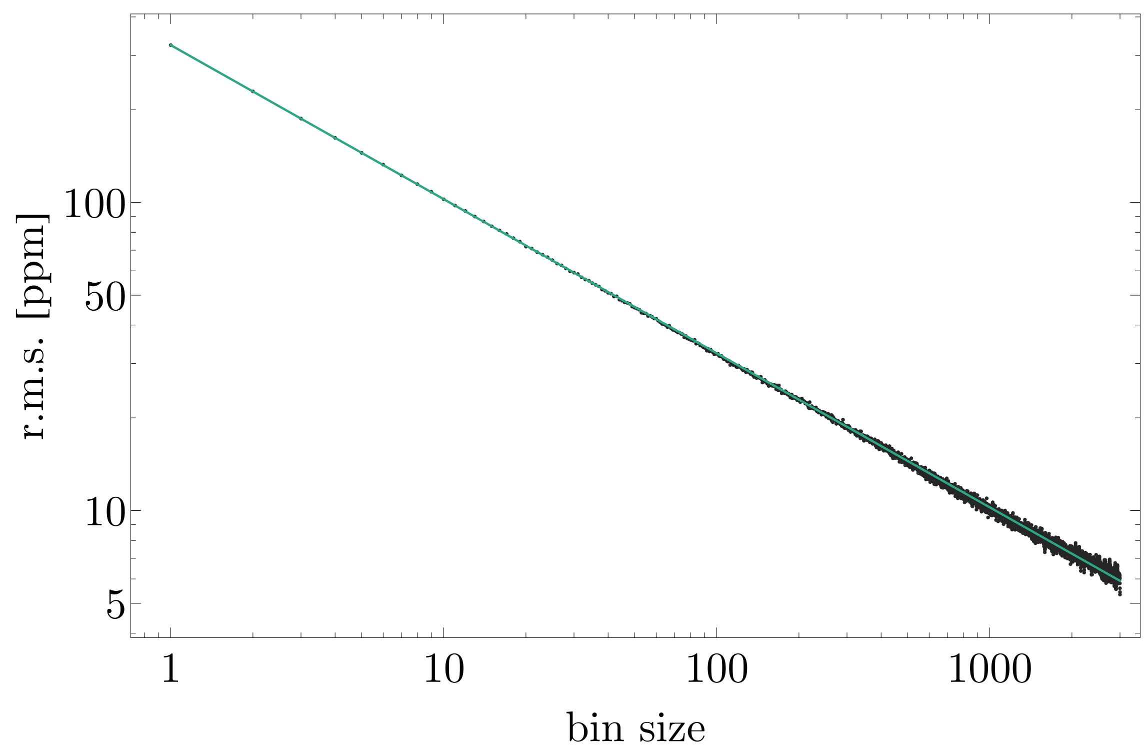


Simon et al. (2011) and later Heller (2014) proposed stacking many transits of a planet may reveal an averaged signal of exomoons

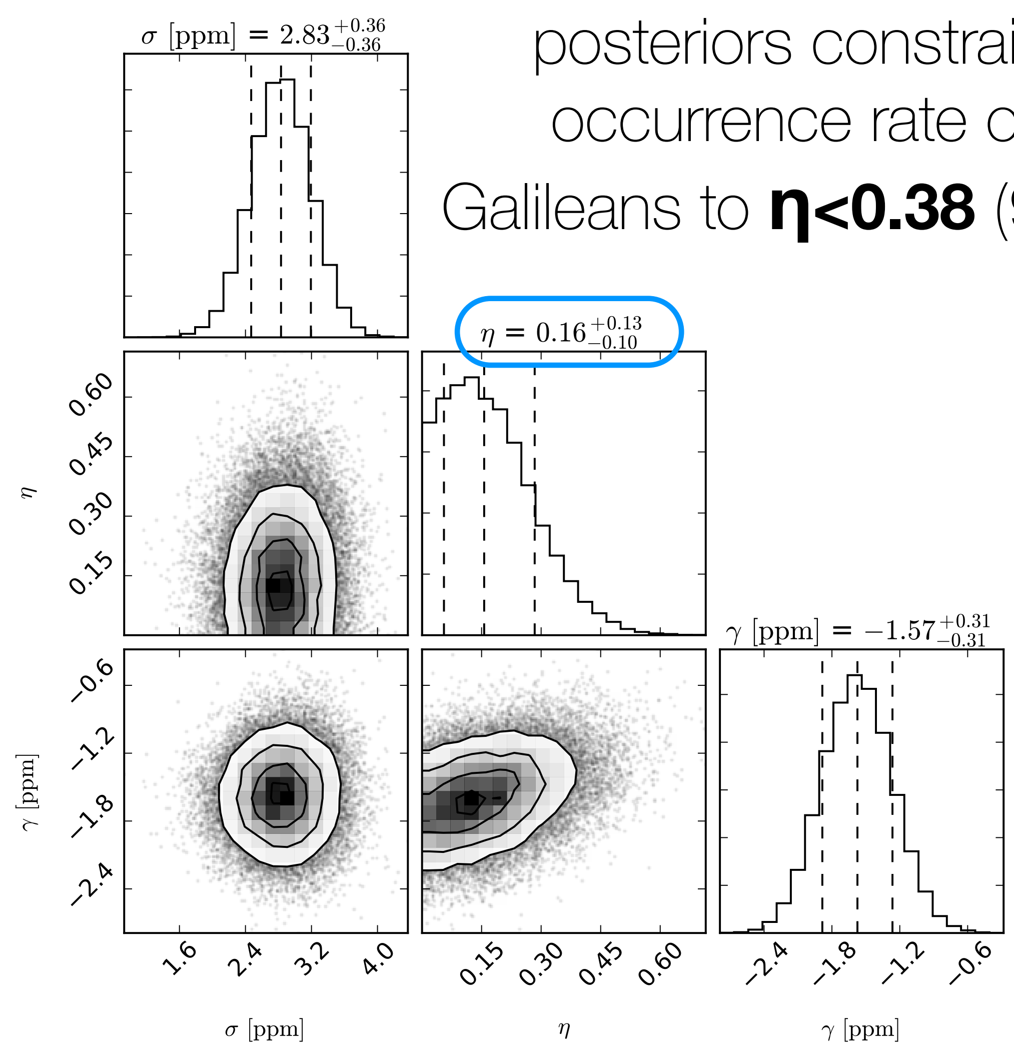
Galilean clones are uncommon...

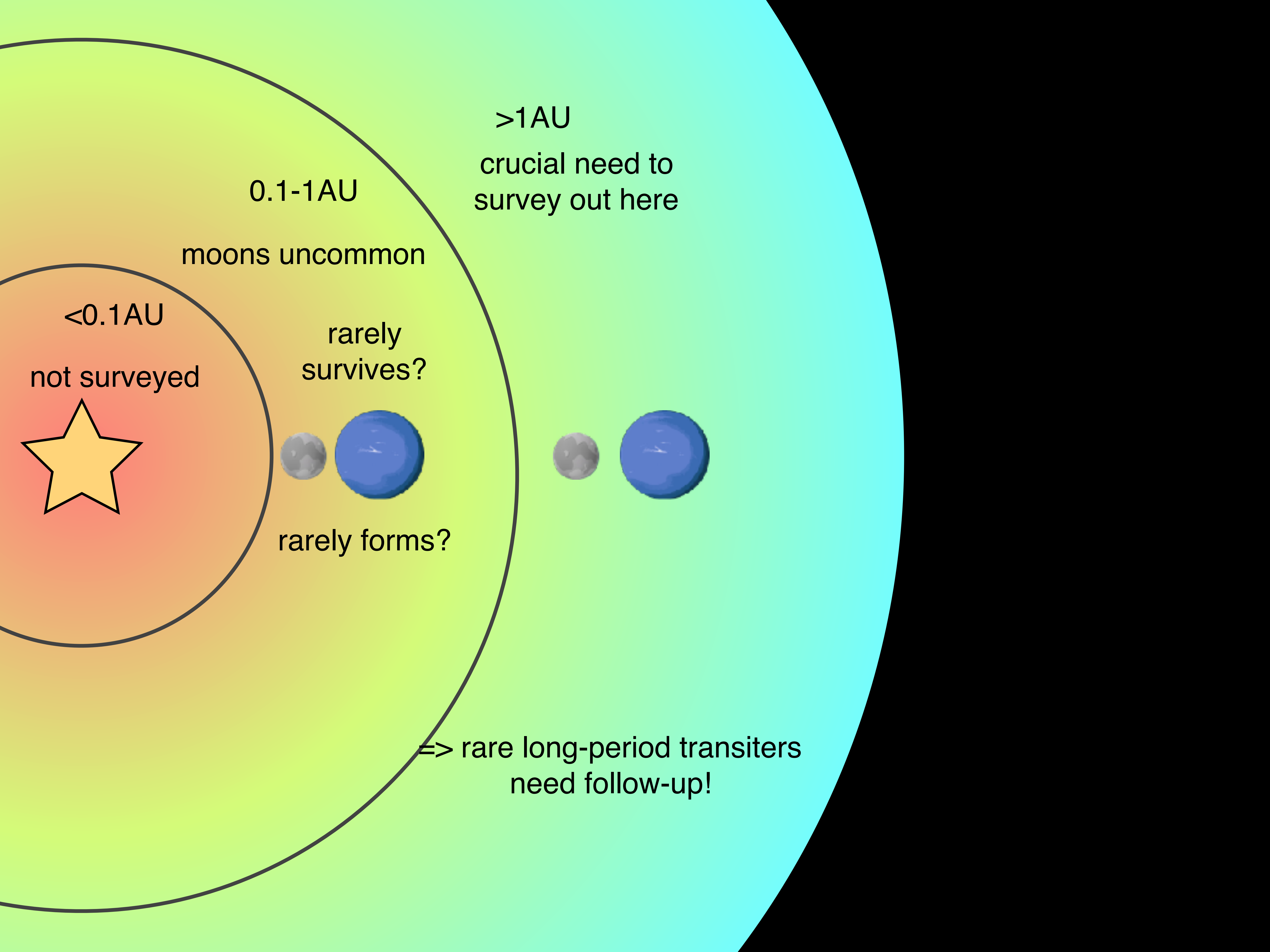


noise looks well-behaved...



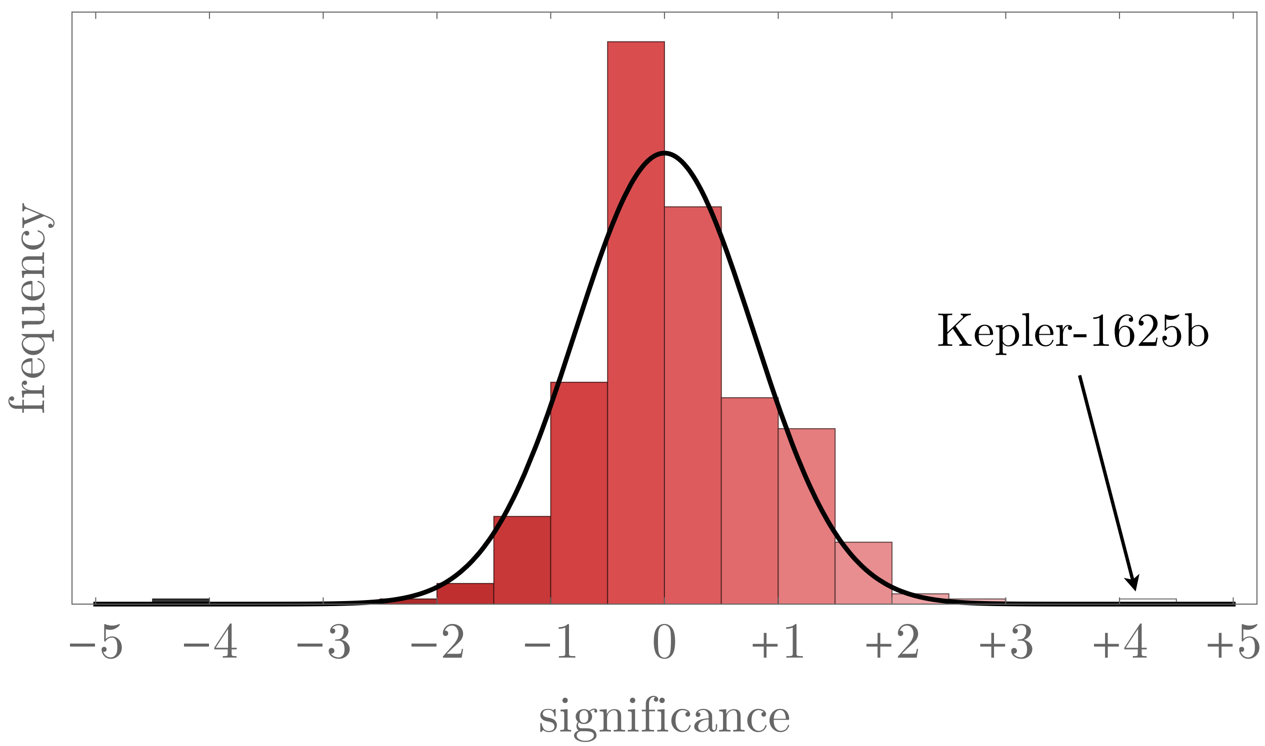
posteriors constrain occurrence rate of Galileans to **η<0.38** (95%)




>1AU
crucial need to
survey out here
0.1-1AU
moons uncommon
<0.1AU
not surveyed
rarely
survives?
rarely forms?
=> rare long-period transiters
need follow-up!

wait... but I just saw this...!

but one object did stand out...

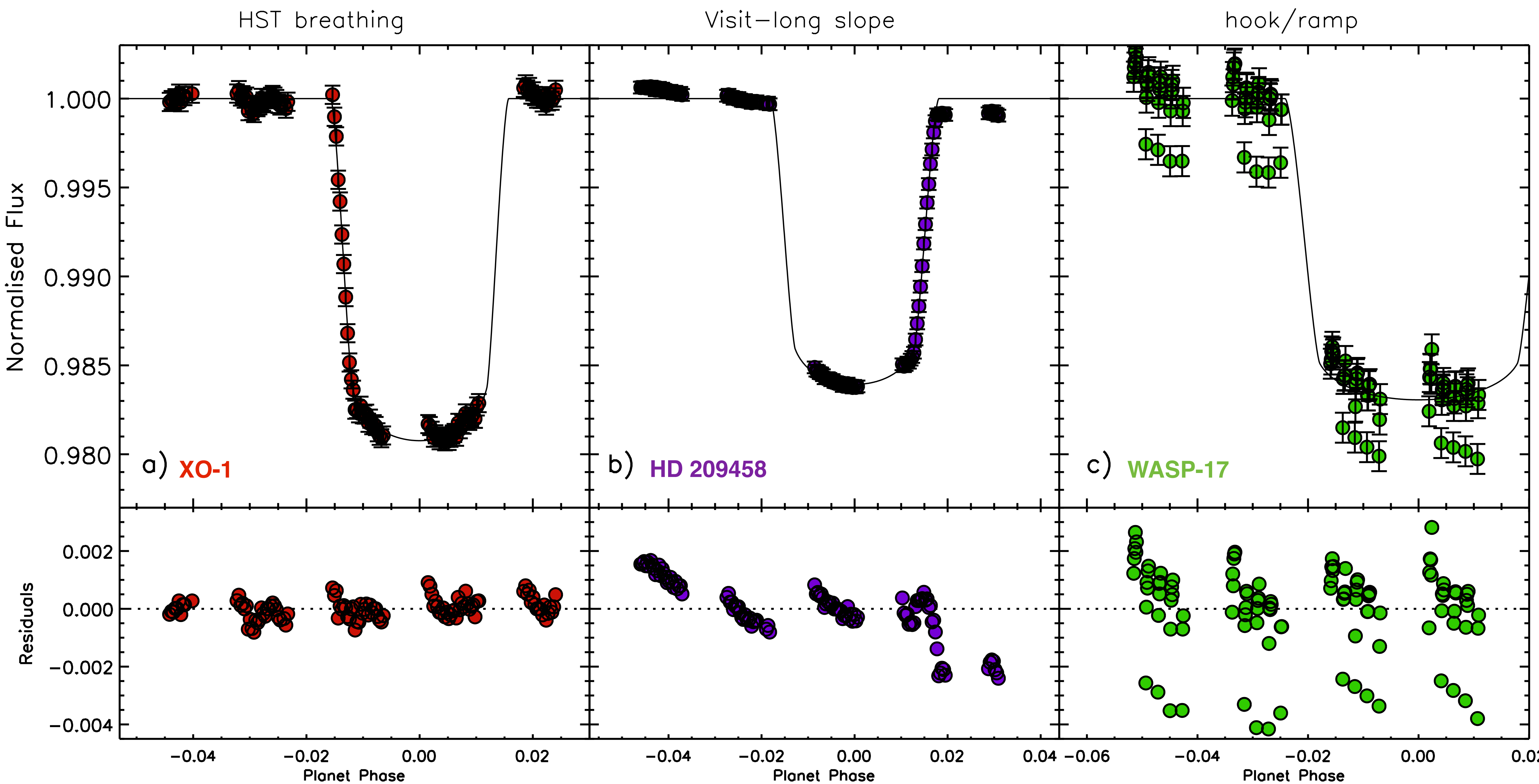


Teachey, Kipping & Schmitt
2017, AJ, 155, 36
(arXiv:1707.08563)

287d 11 M_J, **1R_J** super-Jupiter with 4 R_E, 30 M_E "Neptmoon", 20 R_P sep @ 3 days

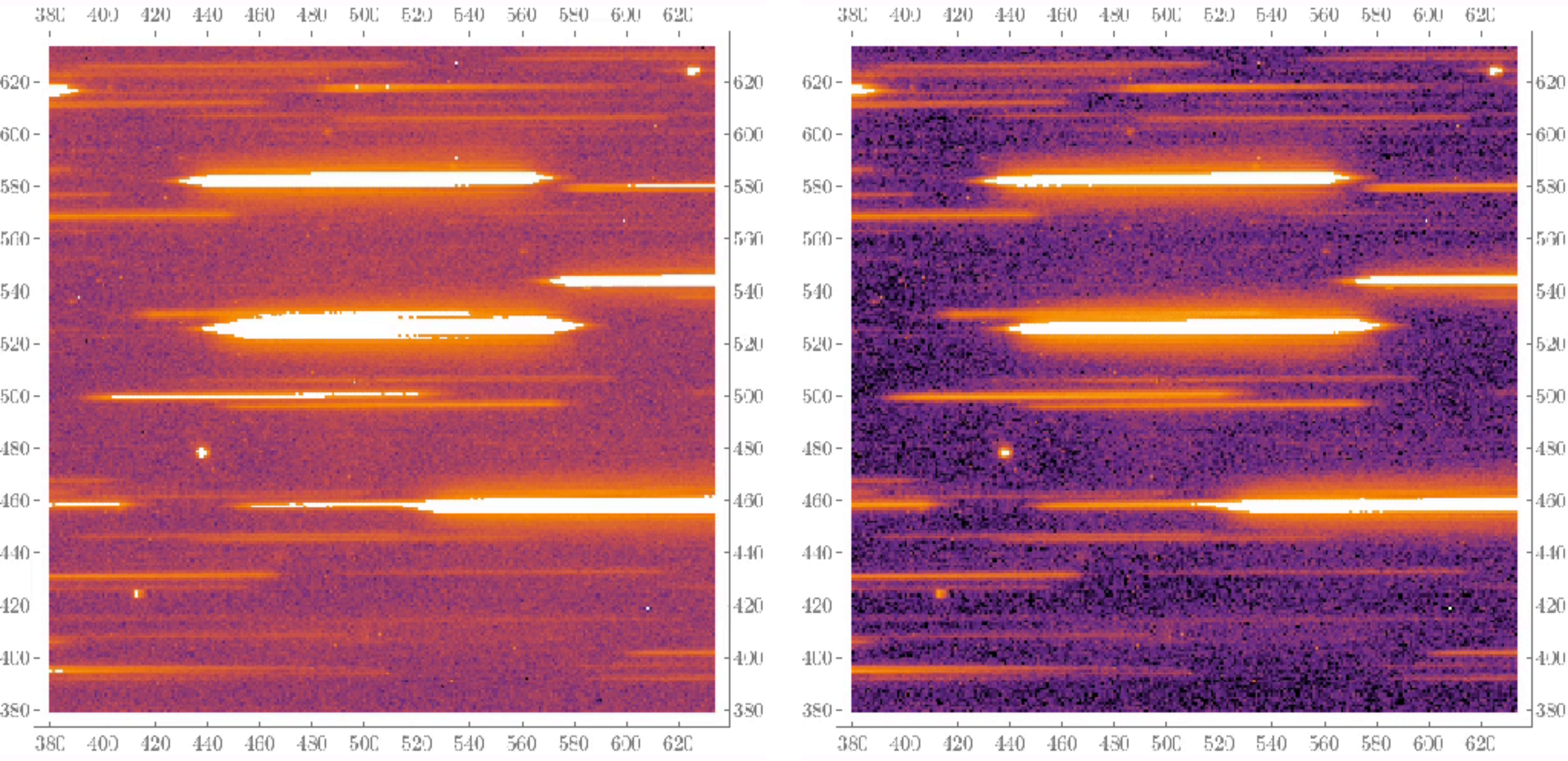
we didn't feel convinced by this (!) and so
we asked for HST time

WFC3 has 3 important systematics to deal with

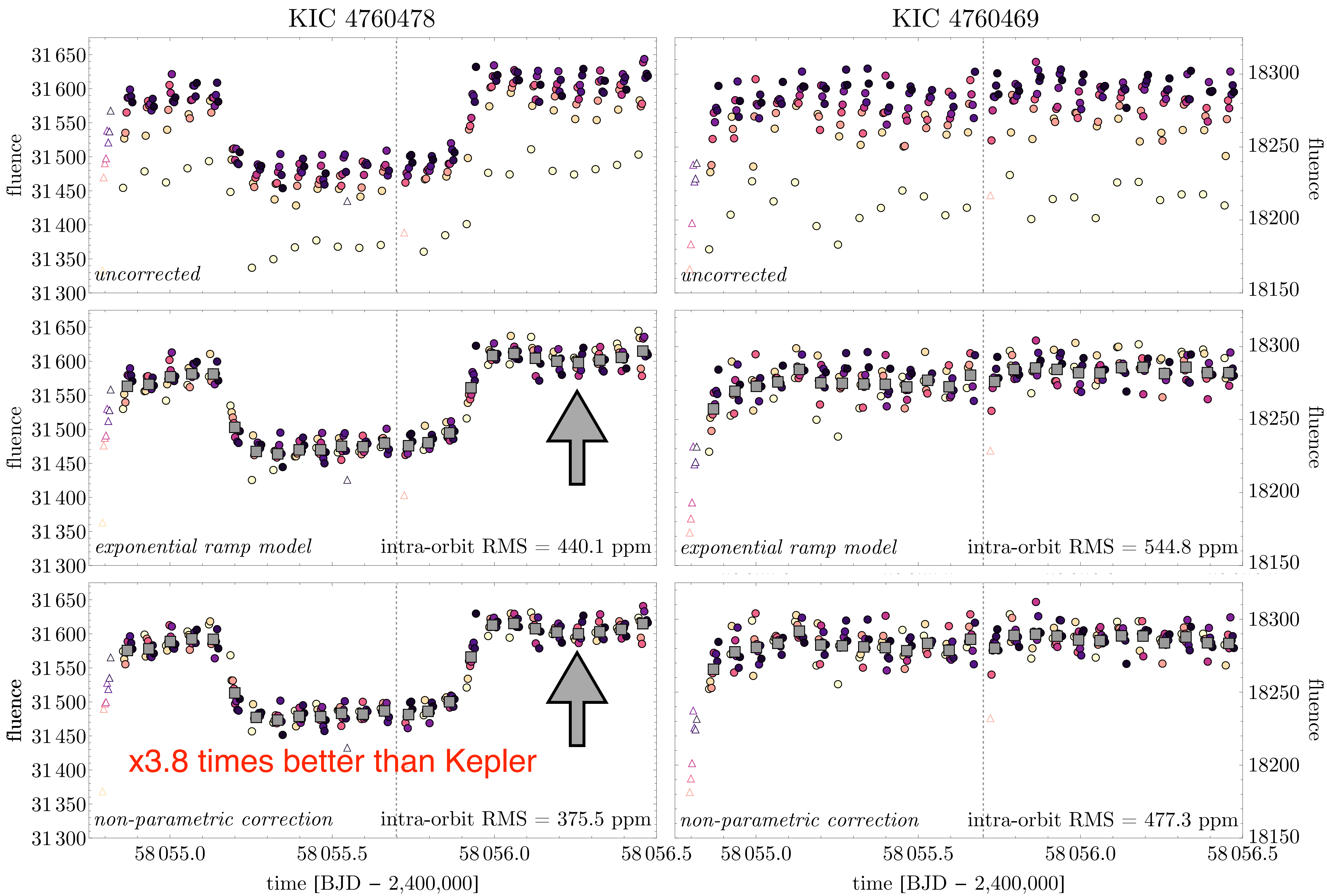


Wakeford et al. (2016)

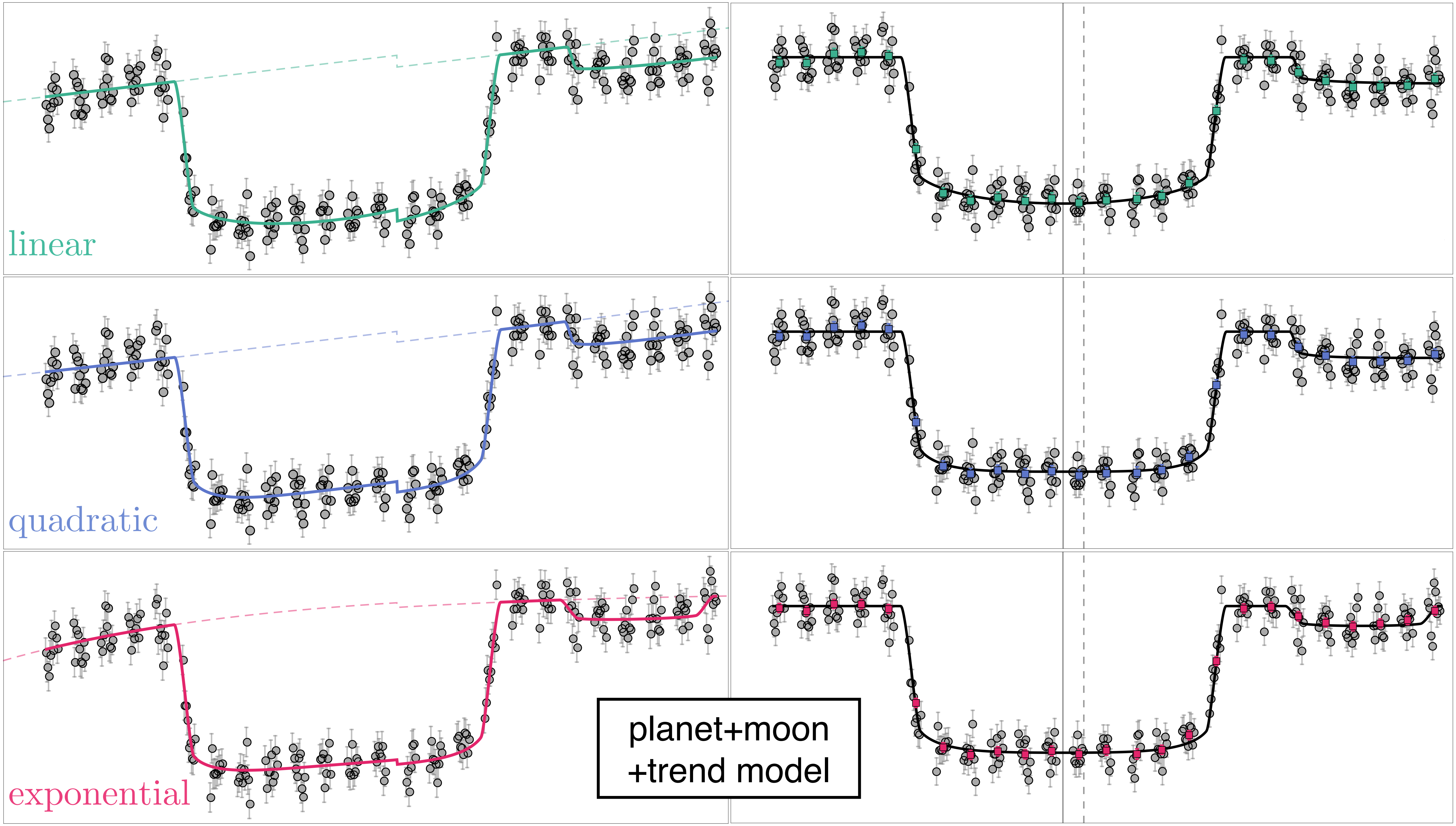
step 1: remove breathing



step 2: remove hooks



step 3: fit long-term trend with transit model



typical WFC3 approach is linear trend (Huitson+ 2013, Ranjan+ 2014, Knutson+ 2014), some have used quadratic (Stevenson+ 2014a,b) step 3: fit long-term trend with transit model

compute Bayesian evidences of 3x trend models and 4x transit models

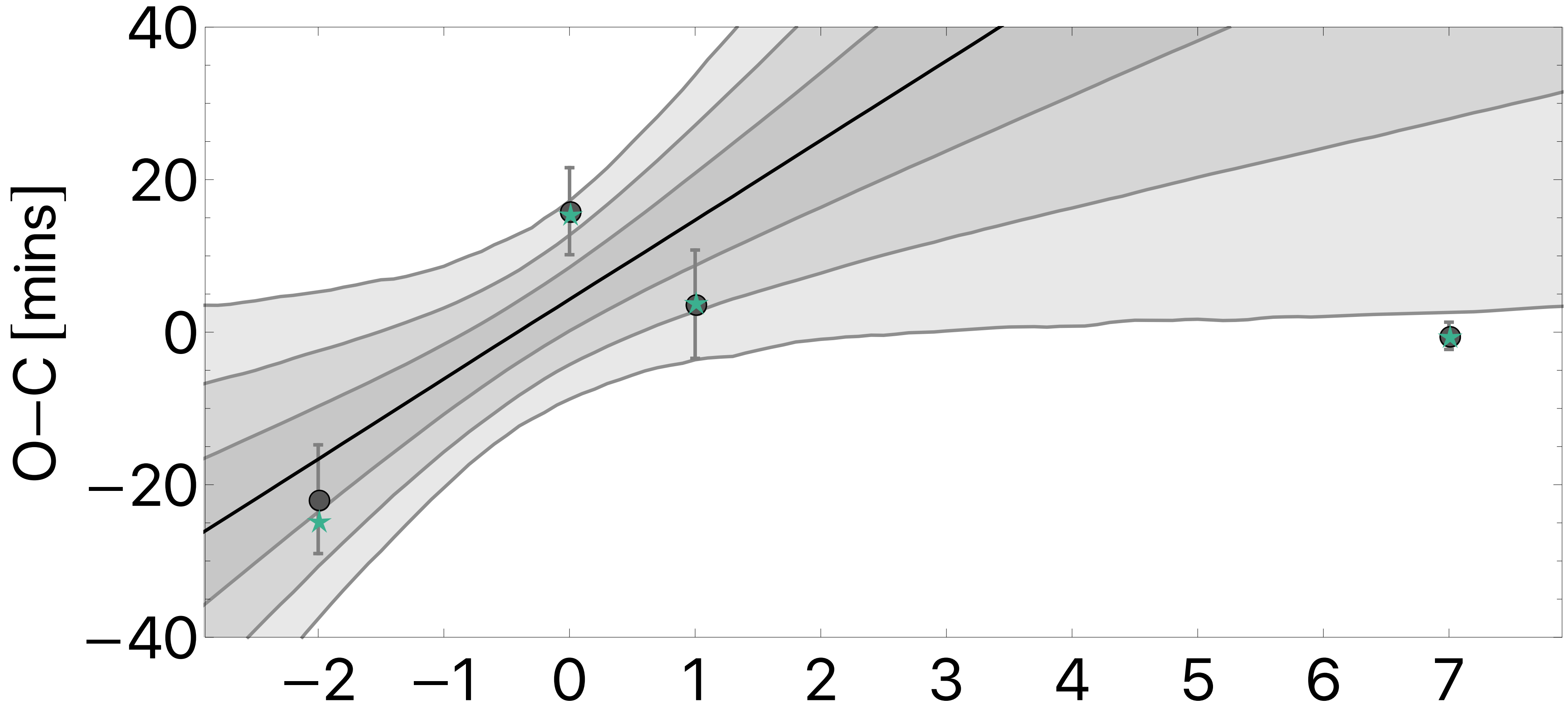
	linear	quadratic	exponential
$\log \mathcal{Z}_{\rm P}$	6302.79 ± 0.11	6306.68 ± 0.11	6308.41 ± 0.11
$\log \mathcal{Z}_{\rm T}$	6304.86 ± 0.11	6308.81 ± 0.12	6305.11 ± 0.11
$\log \mathcal{Z}_{\rm Z}$	6306.84 ± 0.11	6311.12 ± 0.12	6310.82 ± 0.12
$\log \mathcal{Z}_{\rm M}$	6315.73 ± 0.12	6312.92 ± 0.12	6314.01 ± 0.12
$2 \log K(\mathcal{Z}'_{\rm M}/\mathcal{Z}'_{\rm P})$	1.00 ± 0.22		
$2\log(\mathcal{Z}_{\rm M}/\mathcal{Z}_{\rm P})$	25.88 ± 0.32	12.47 ± 0.33	11.19 ± 0.32
$2\log(\mathcal{Z}_{\rm M}/\mathcal{Z}_{\rm T})$	21.72 ± 0.33	8.21 ± 0.34	17.81 ± 0.33
$2\log(\mathcal{Z}_{\rm M}/\mathcal{Z}_{\rm Z})$	17.77 ± 0.33	3.61 ± 0.33	6.38 ± 0.34
$\Delta\chi'^2_{\rm PM} = 2\log(\hat{\mathcal{L}}'_{\rm M}/\hat{\mathcal{L}}'_{\rm P})$	18.66		
$\Delta\chi^2_{\rm PM} = 2\log(\hat{\mathcal{L}}_{\rm M}/\hat{\mathcal{L}}_{\rm P})$	54.93	41.04	41.57
$\Delta\chi^2_{\rm TM} = 2\log(\hat{\mathcal{L}}_{\rm M}/\hat{\mathcal{L}}_{\rm T})$	35.69	23.97	38.71
$\Delta\chi^2_{\rm ZM} = 2\log(\hat{\mathcal{L}}_{\rm M}/\hat{\mathcal{L}}_{\rm Z})$	33.68	19.59	19.22

planet+moon strongly favored over planet-only

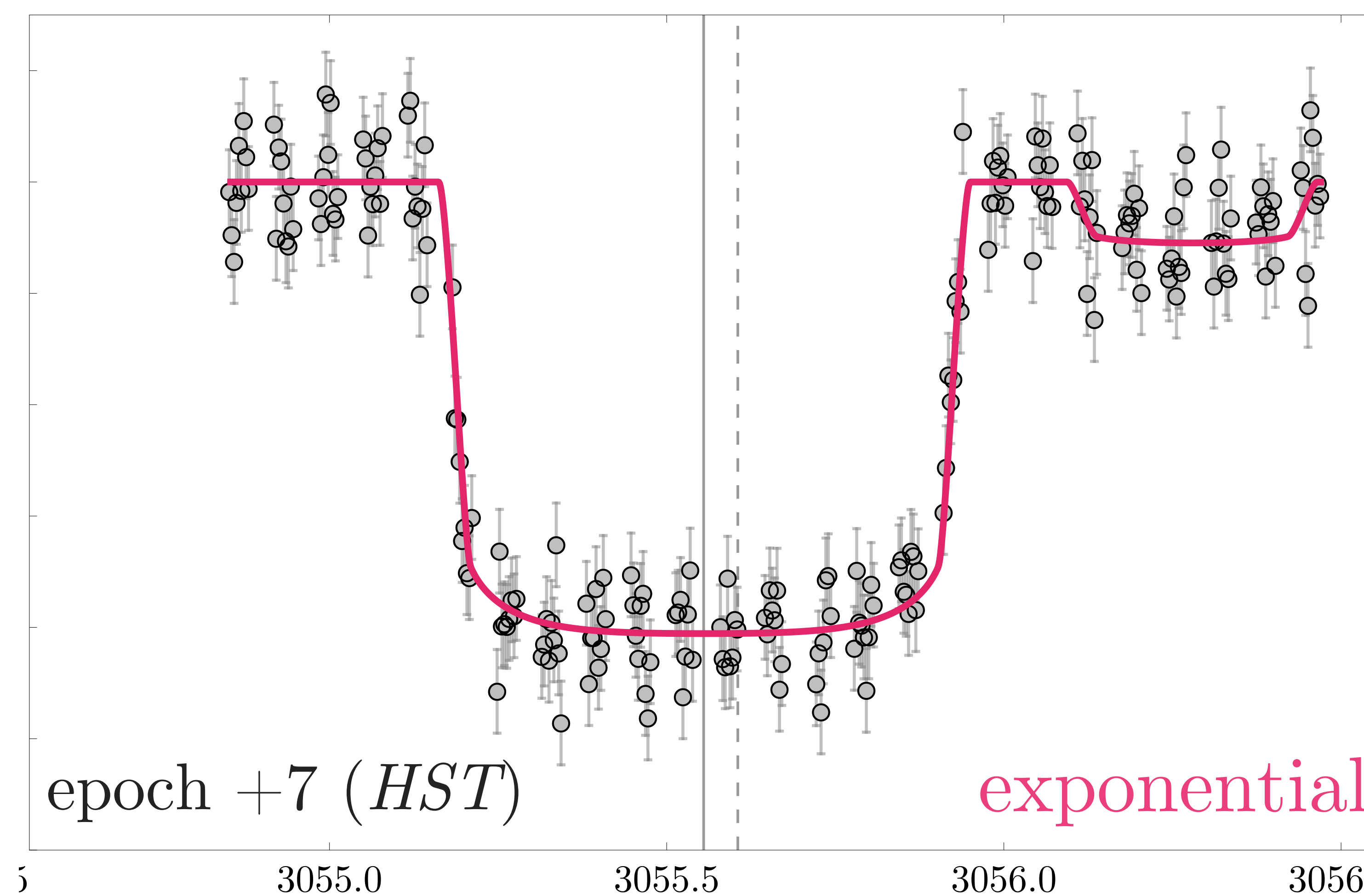
what drives this?

P = planet-only model (linear ephemeris)
T = planet with TTVs
M = planet + moon model
Z = planet + zero-radius moon

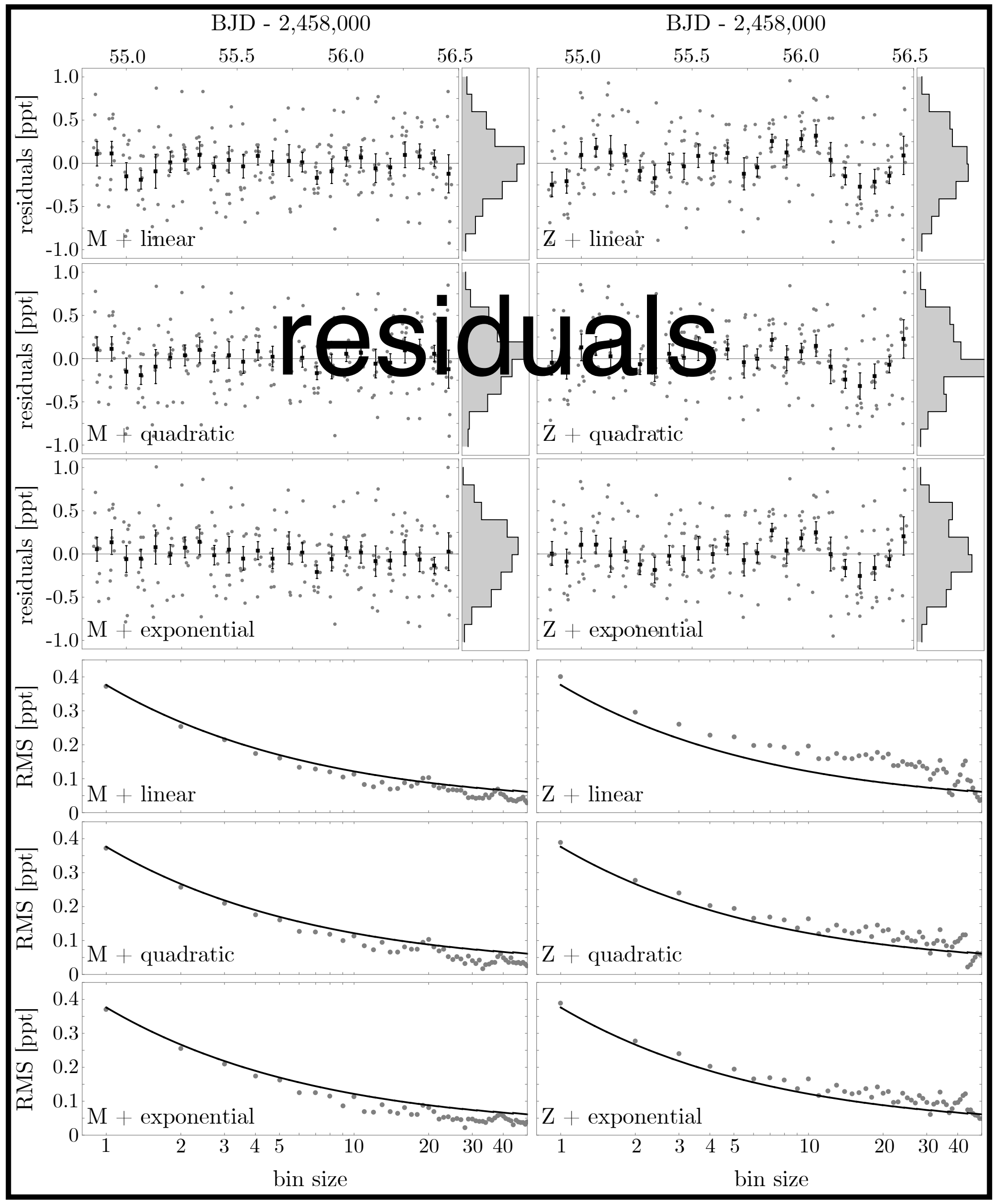
anomaly 1: HST transit comes in 78±25 mins early [SNR_{ttv} = 4.3]

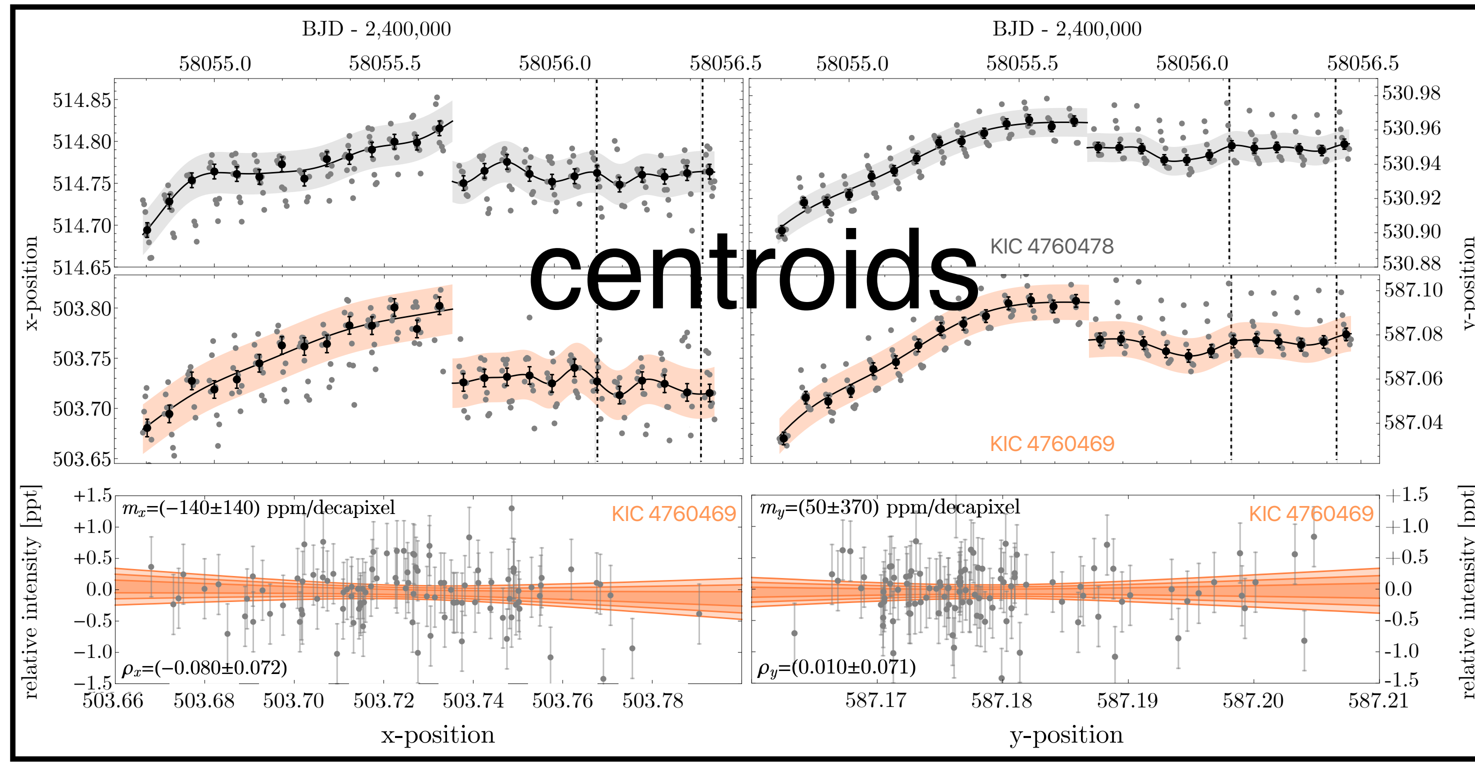


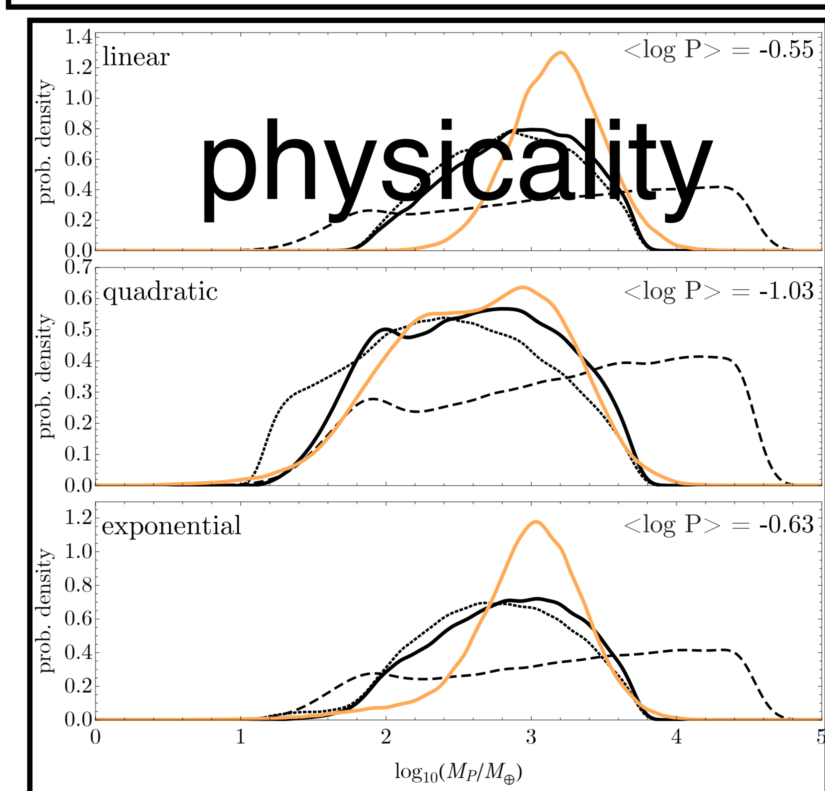
anomaly 2: a second decrease in brightness 3.5 hours after the planetary transit [SNR_{dip} = 5.1]



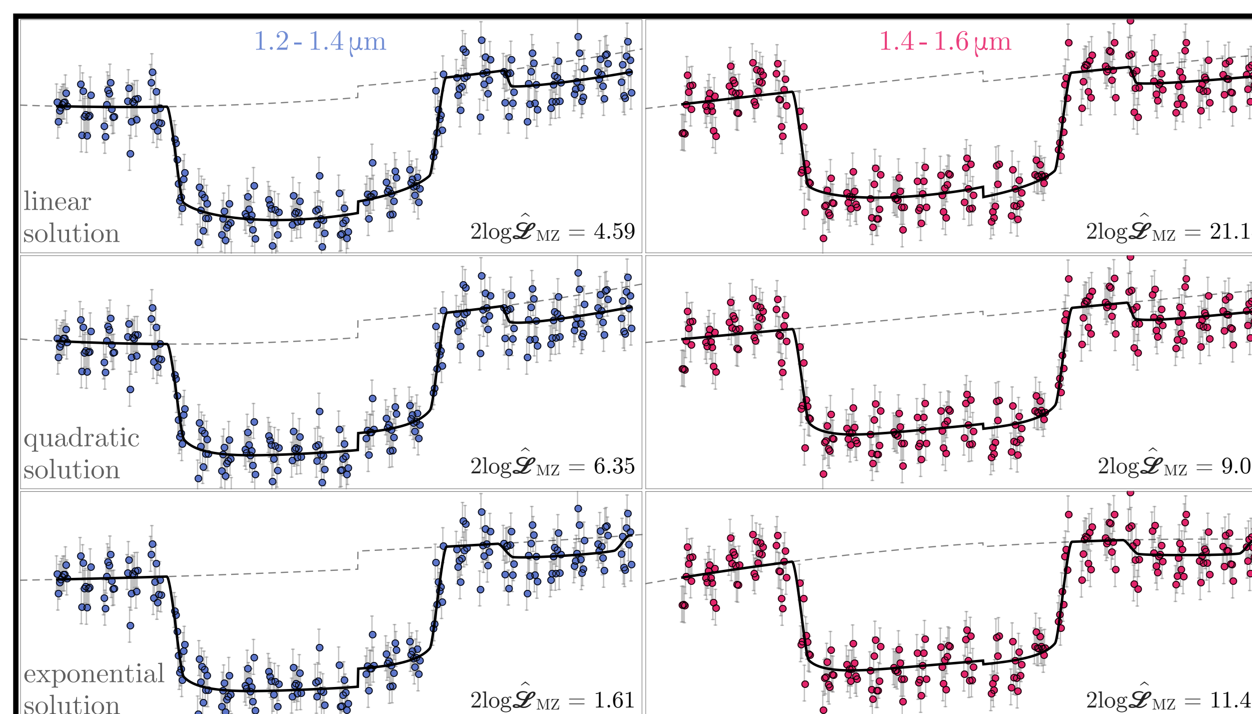
dip does not appear to be instrumental







achromatic



is it real? we advocate for more data!

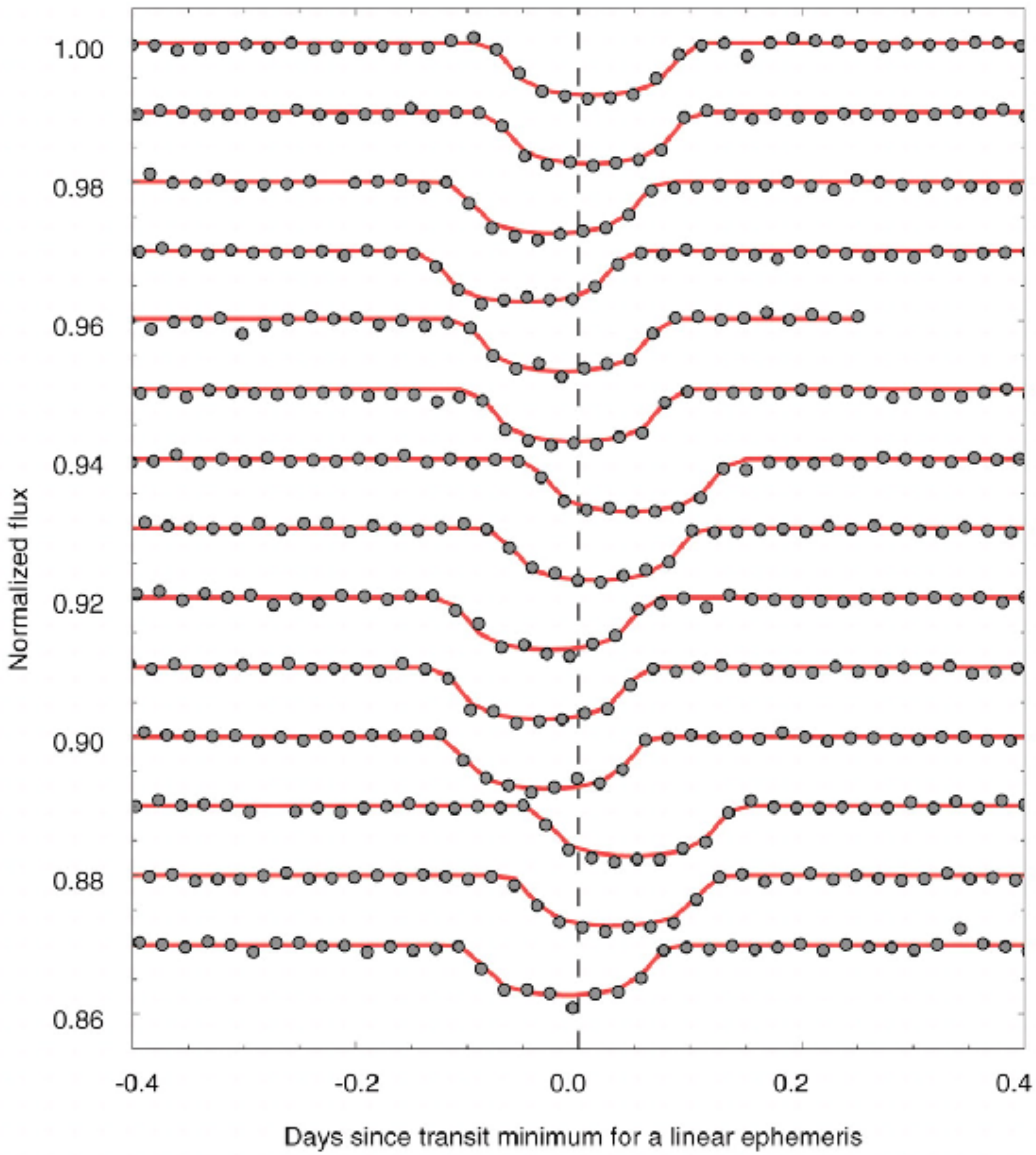
pros	cons
- we detect a TTV anomaly (SNR~4) and a second dip (SNR~5) with HST around a long-period Jupiter	- because HST data is so much more precise than Kepler, HST dominates the regression and so we only really have one event
- moon hypothesis is the simplest explanation for both anomalies	- in revised Kepler data, the moon is less apparent and we probably may not have applied for time if we'd used DR25!
- dip does not appear to be instrumental after residual inspection, centroid analysis, SAA consideration, chromatic testing, comparison star check and hook correction method	- we have no post-moon transit data
- moon is a Neptune sized body, seemingly stable with self-consistent masses and radii for system	- not anticipated from formation theory

SCIENCE ADVANCES | RESEARCH ARTICLE

ASTRONOMY

Evidence for a large exomoon orbiting Kepler-1625b

Alex Teachey* and David M. Kipping



Nesvorny, Kipping et al. (2014)

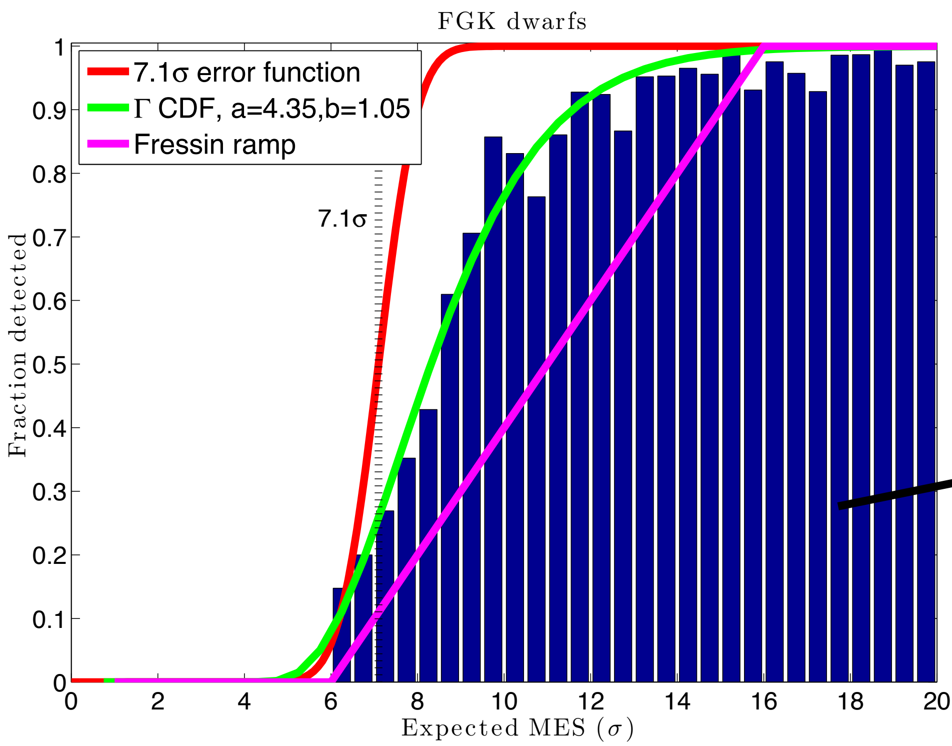
TTVs could easily be caused by an unseen perturbing planet

but this doesn't explain the dip…

unless - could the second dip, corresponding to a Neptune-sized body, be a previously undetected transiting planet?

could the second dip, corresponding to a Neptune-sized body, be a previously undetected transiting planet?

duration is at least 7.8 hours, means P>24.3 days



Christiansen et al. (2015)

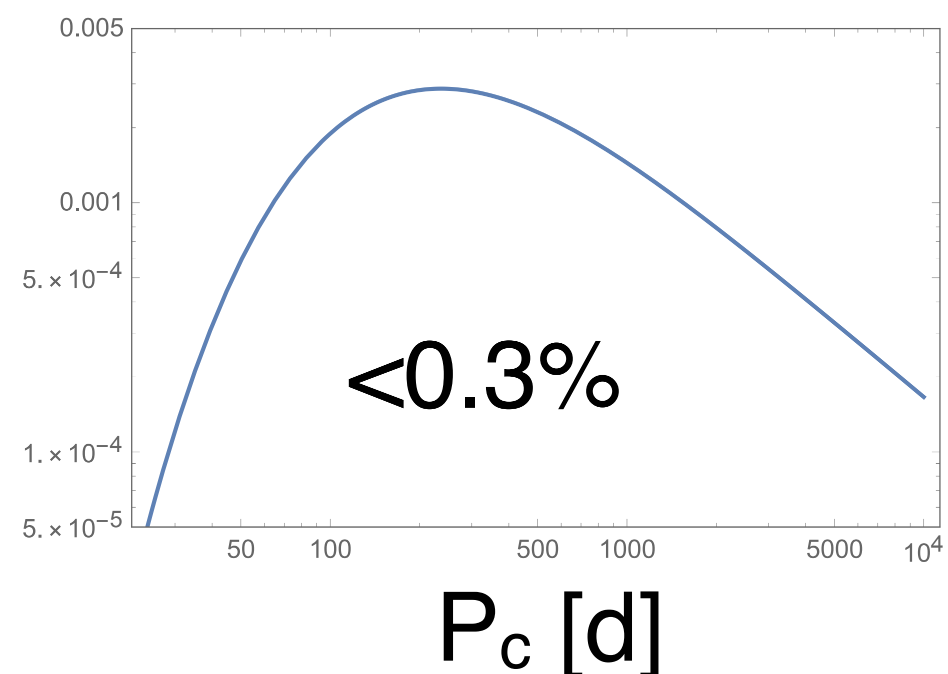
$$SNR_c = \frac{SNR_b}{(11.4/4)^2} \frac{\sqrt{P_b}}{\sqrt{P_c}}$$

Pr(detecting clcoplanar)

+

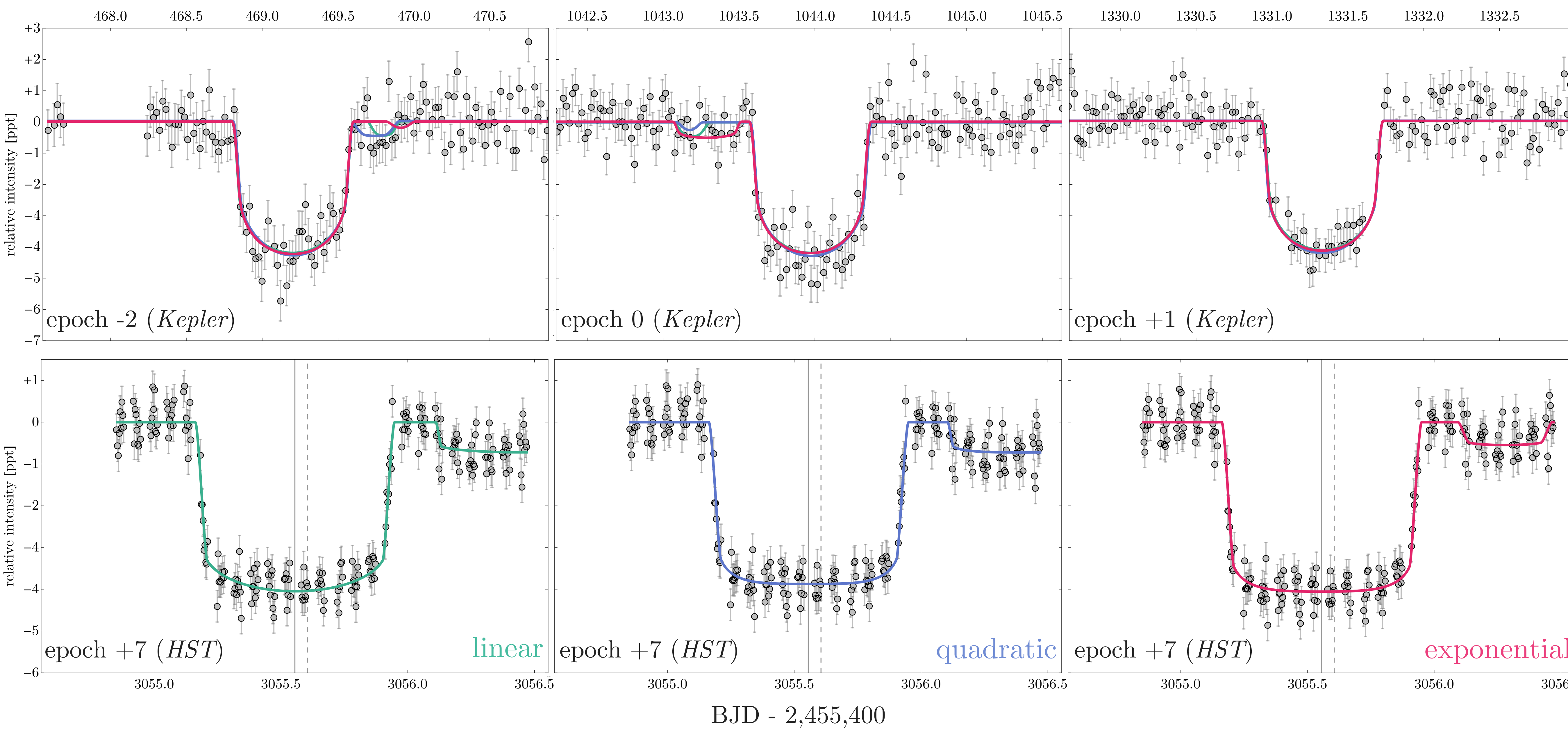
Pr(appears in 40hr window) $= 40\text{hrs}/P_c$

Pr(c not detected by Kepler AND appears in 40 hr HST window)

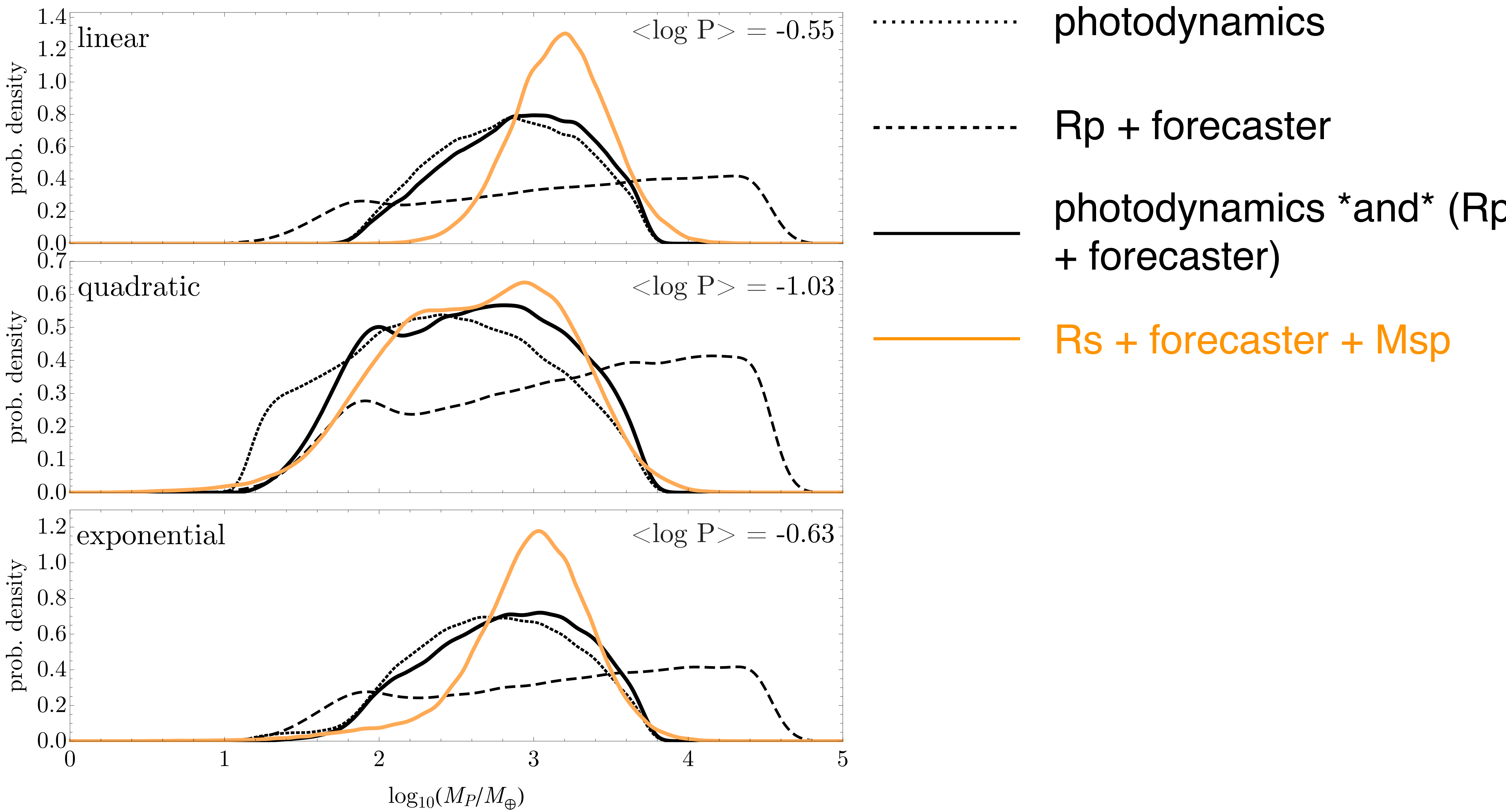


highly improbable

can the TTVs and the second dip be explained by a self-consistent moon model?



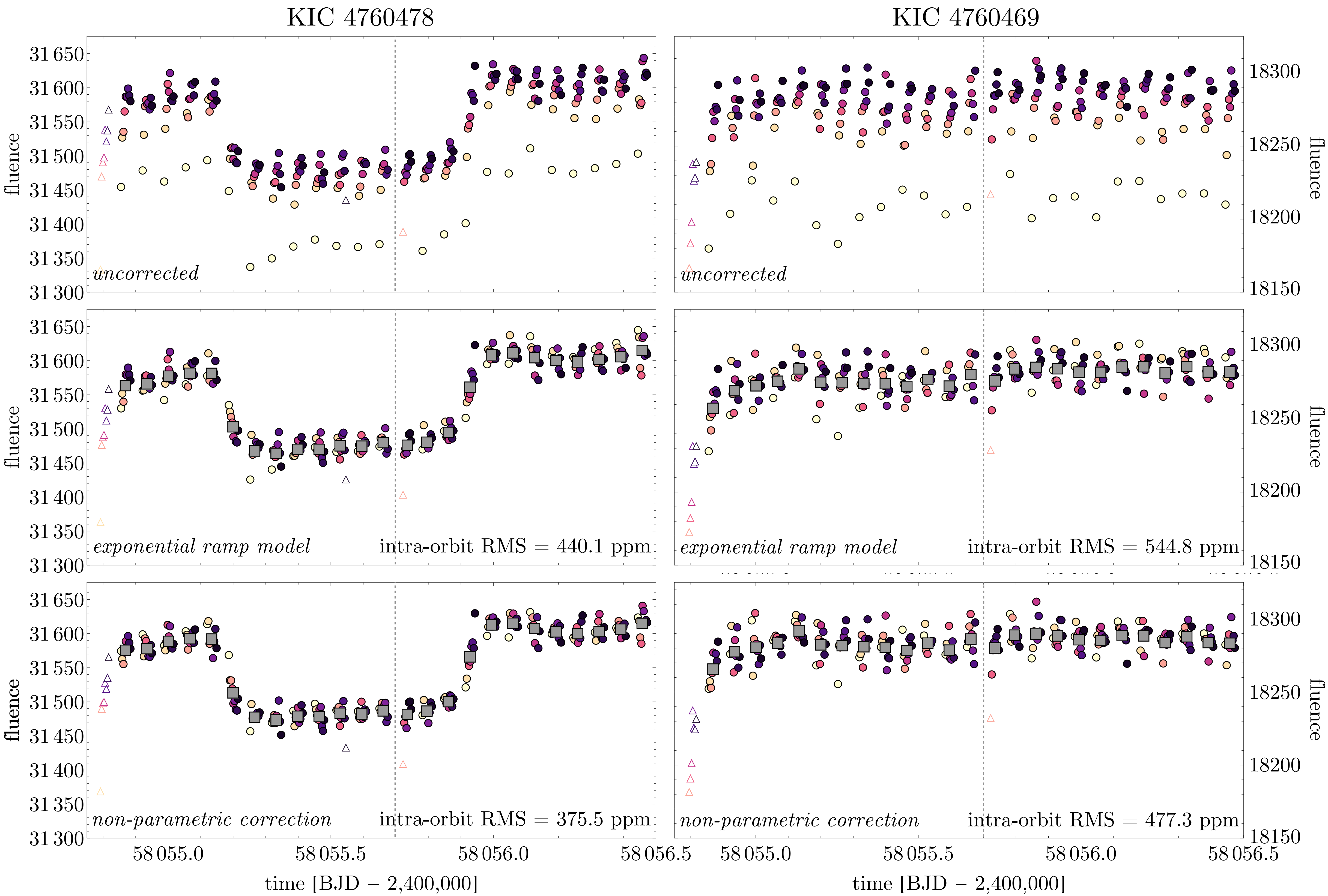
- Neptune size moon at ~40 planetary radii explains all data can the TTVs and the second dip be explained by a self-consistent moon model?



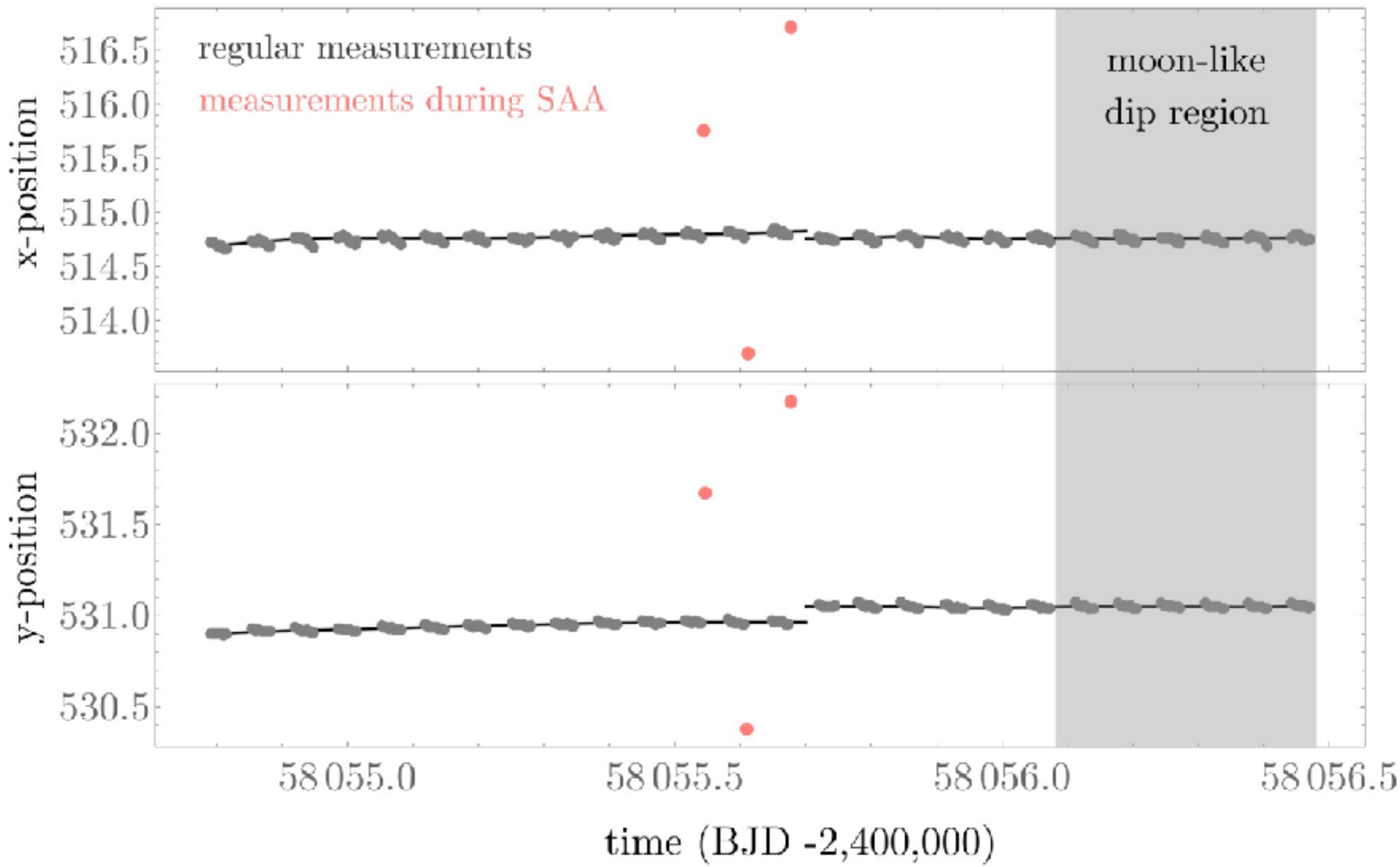
- Neptune size moon at ~40 planetary radii explains all data
- planet & moon mass/radius are self-consistent => physically sound
- asp = 20% of the Hill sphere, stable in 78% of posterior samples

the case for a moon really rests on that second dip,
could it be due to an **instrumental effect**?

comparison star is stable at this time



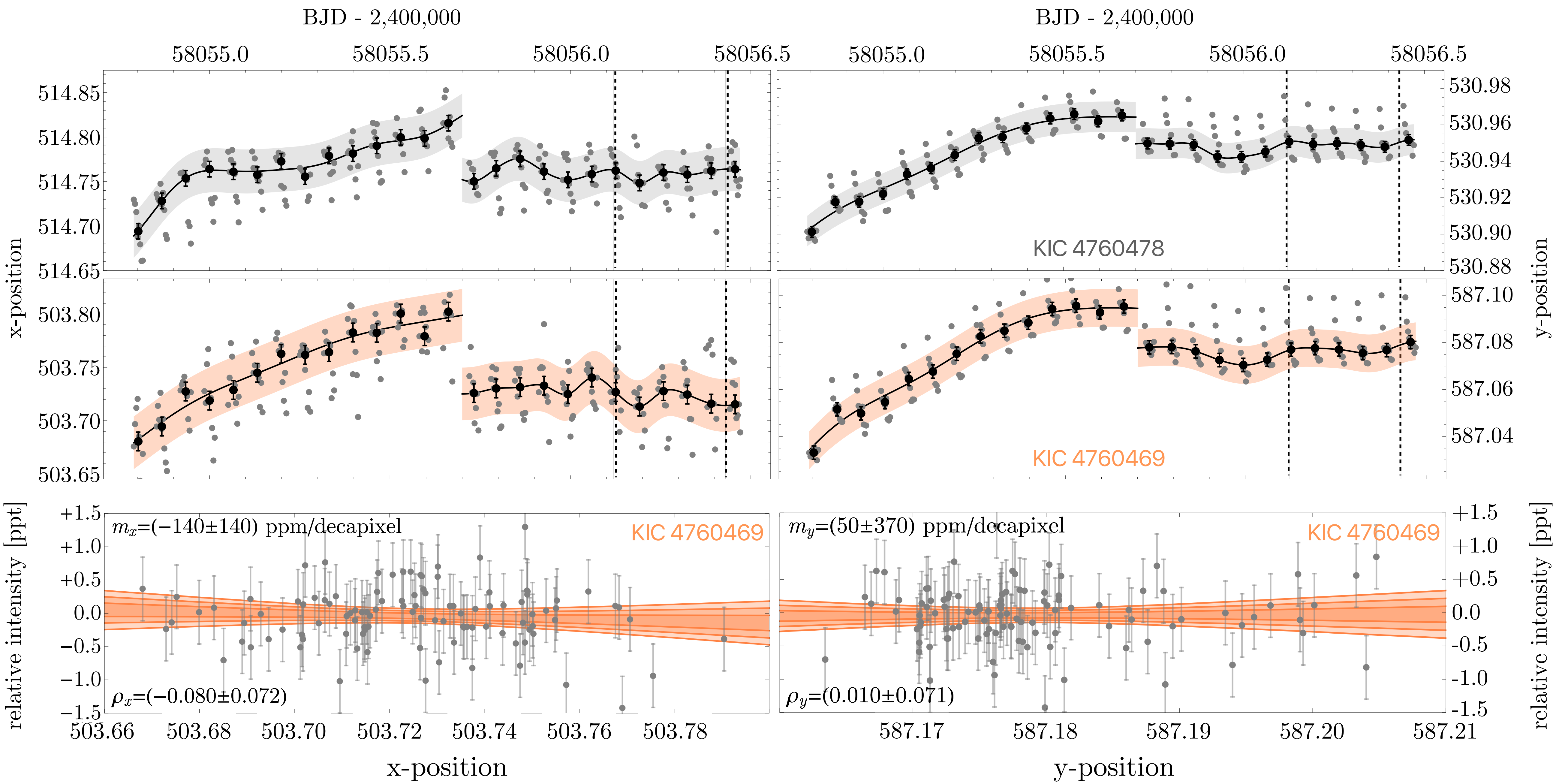
moon-like dip is nowhere near an SAA crossing



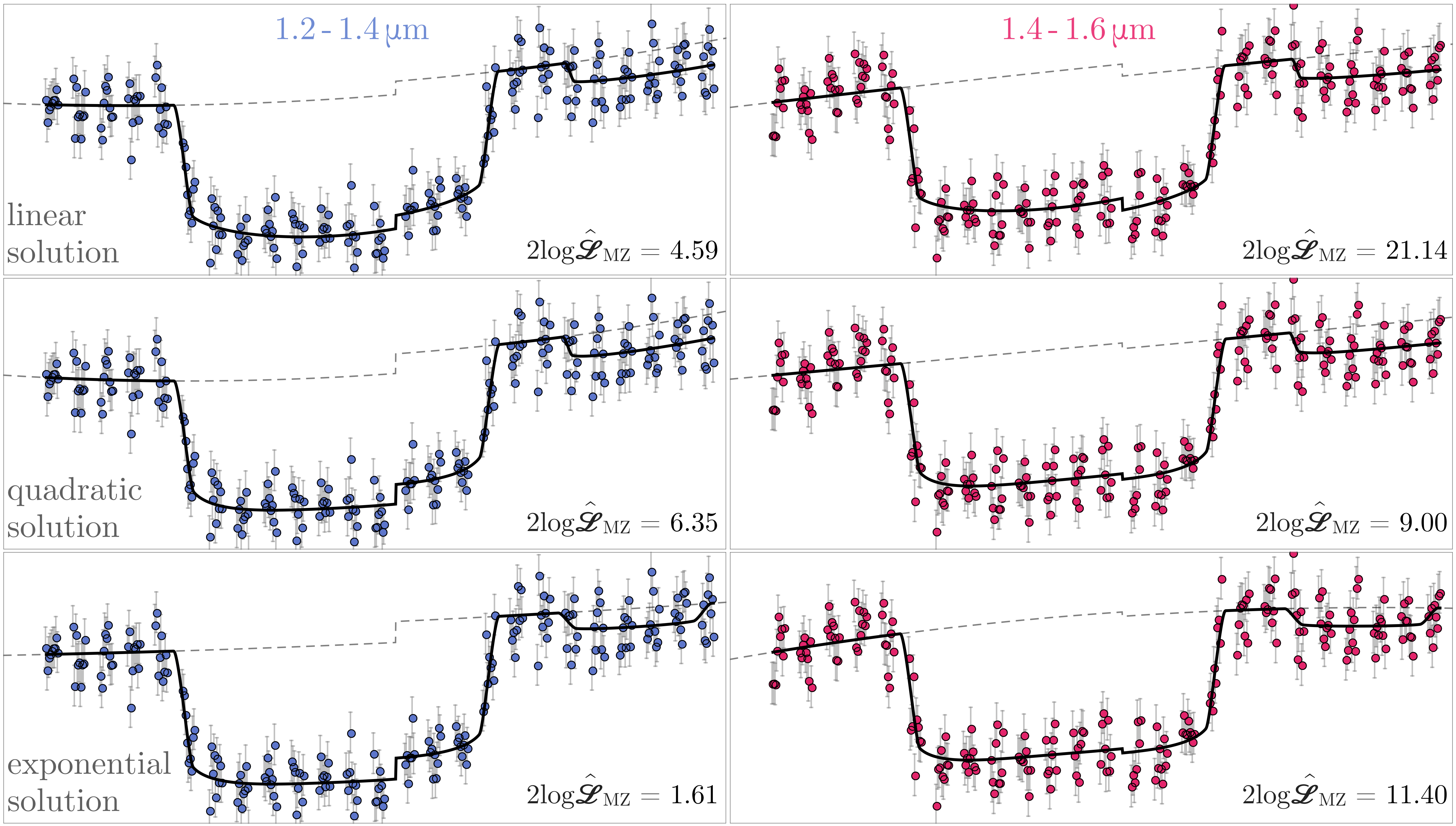
Phase II primary support contact, Bill Januszewski

The other incredible thing is right now it looks like only 3 exposures will actually be done when HST is physically in the SAA. To say that you lucked out with how well this interacts with the SAA is an understatement. Most of the SAA passages take place when the target is in occultation and for the ones that do impact you it is only for a few minutes at the end of three orbits. I'm still shaking my head on how well this worked out.

centroids look very stable around this time

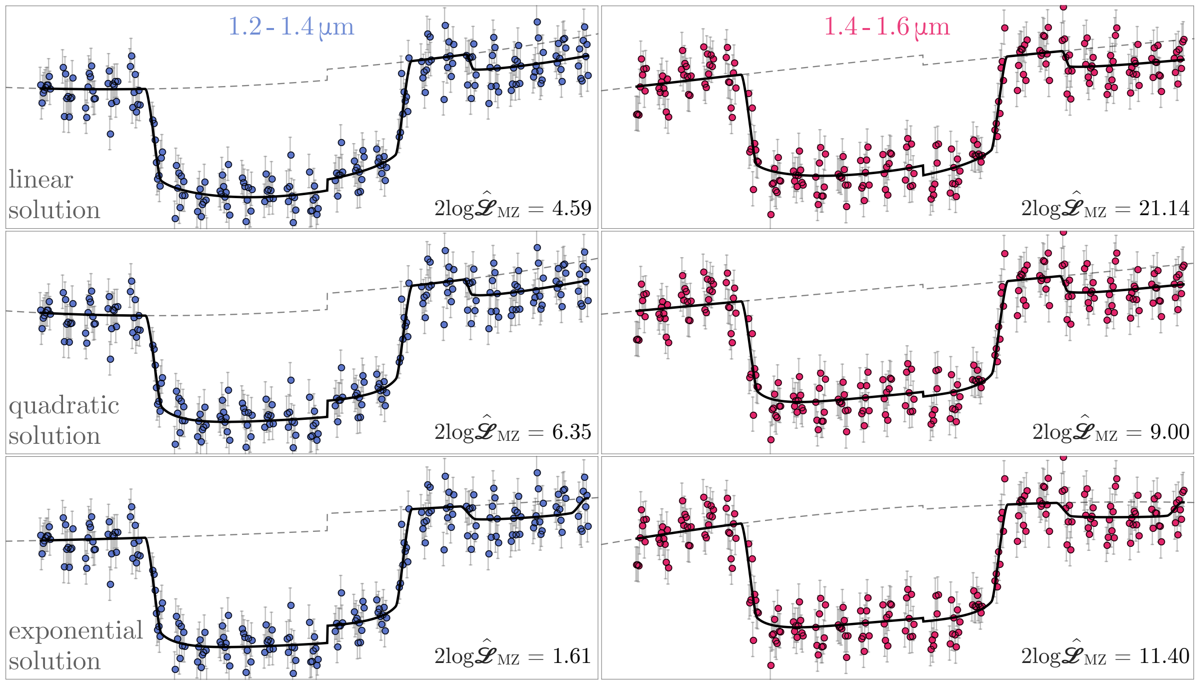


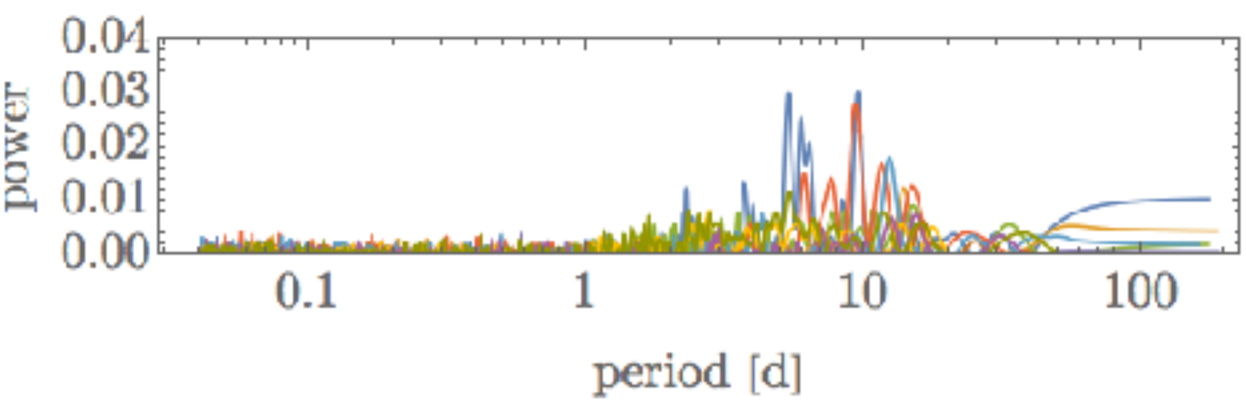
+ no noticeable correlation between centroid and flux signal also appears to be achromatic

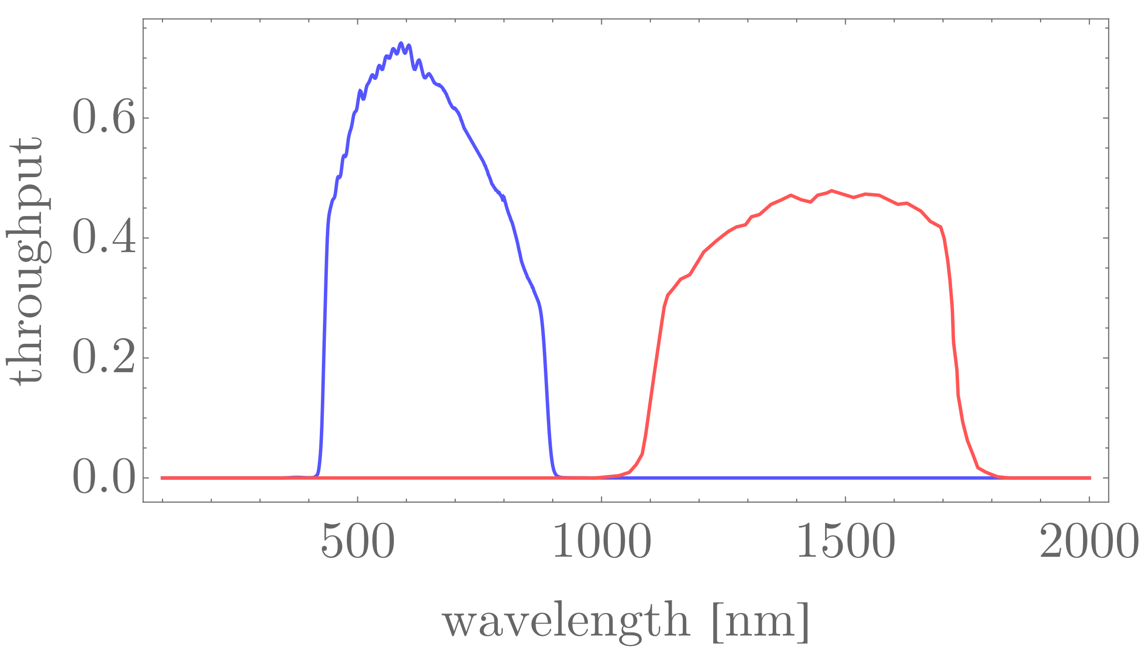


chromatic residual interpixel sensitivity variations unlikely are
thus unlikely to explain the dip

signal also appears to be achromatic





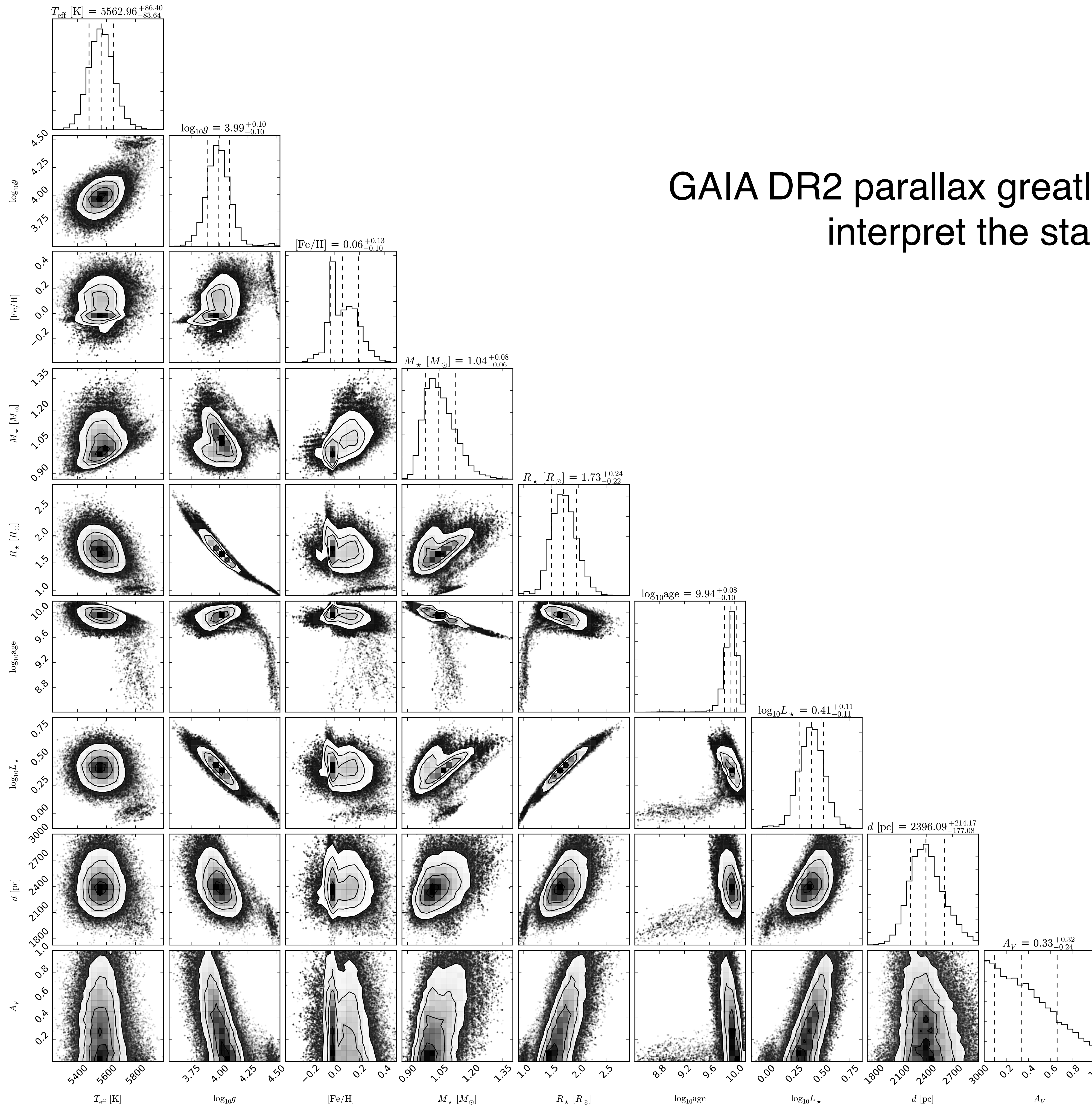


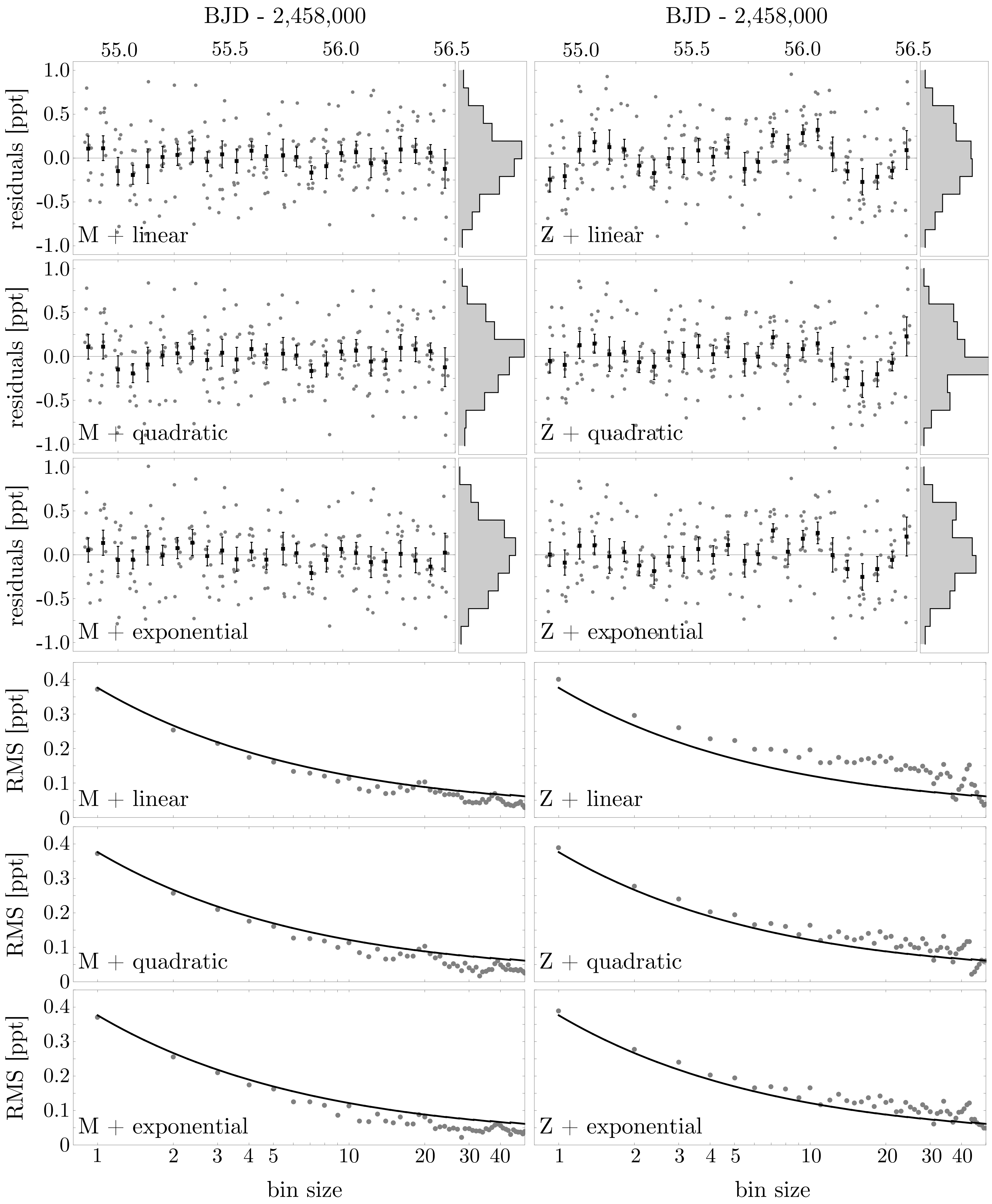
stellar activity?

- HST achromaticity suggests no
- sharp dips away from main transit difficult to conjure using spots
- star is old (9Gyr) and somewhat evolved (1->1.7 RSun) suggesting a slow rotation period
- indeed no rotation period is detectable in Kepler data (McQuillan+ 2015)
- global LS periodogram finds best fitting peak of 66ppm, quarter-by-quarter median is 136 ppm (c.f. 500ppm dip)
- WFC3 suppresses spots by 30% (assuming ΔT=2000K spots)

v unlikely to be the product of stellar activity

GAIA DR2 parallax greatly helps us interpret the star





+ big artifact sticks out

residuals bin as Gaussian noise, but without a moon the binning looks worse