Does WASP-47 e have friends?

Occurrence Rate of Inner Companions to Hot Jupiters with *TESS* FFI Data

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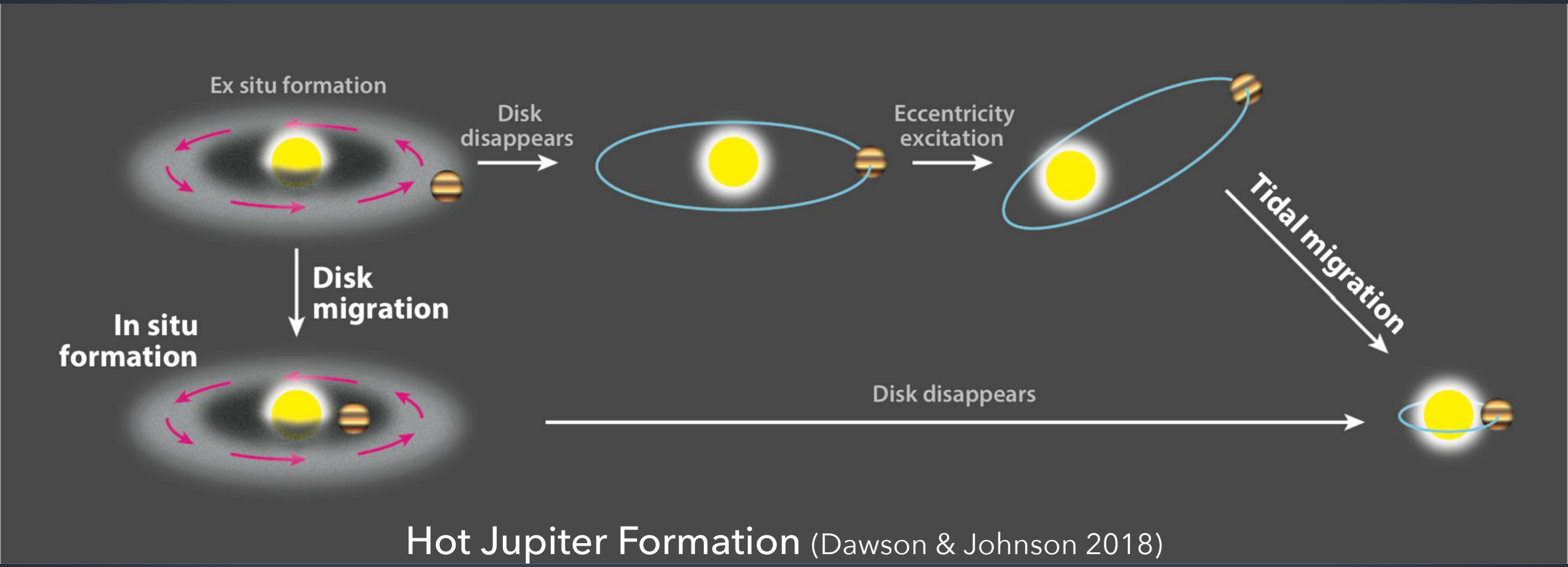
31 July 2019
TESS Science Conference I

In this talk. . .

- Uniform BLS Search for Hot Jupiter inner companions in *TESS*, *Kepler*, and *K2* data

- A new upper limit on their **occurrence rate**

Why study hot Jupiter inner companions?

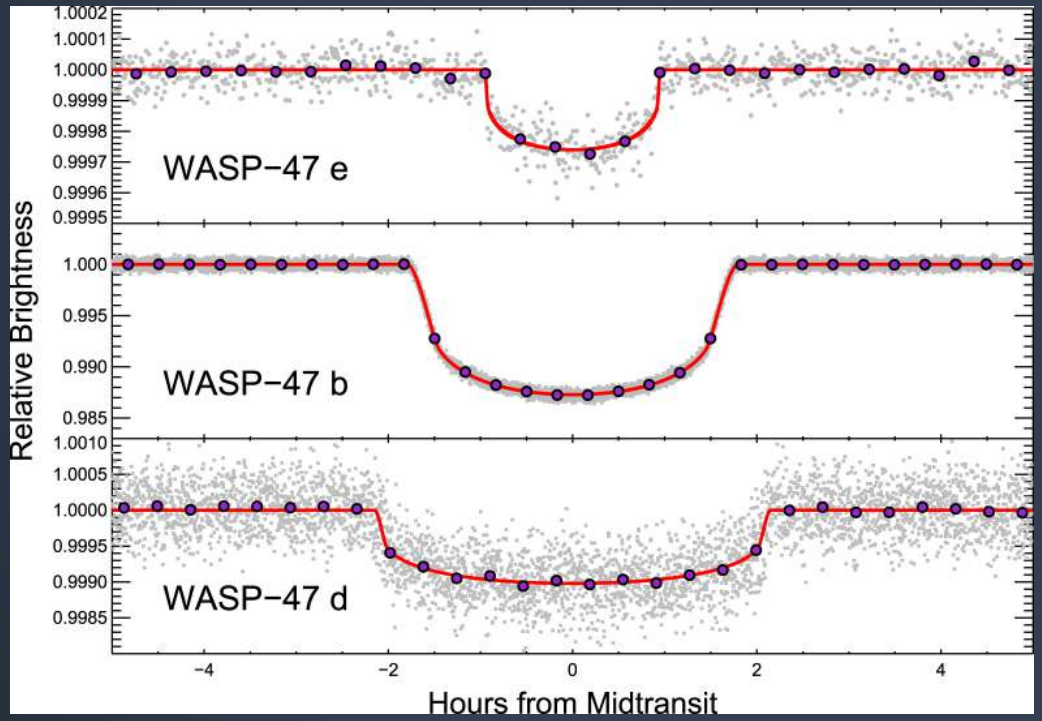


Hot Jupiter Formation (Dawson & Johnson 2018)

Only hot Jupiters formed *in situ* can have inner companions.

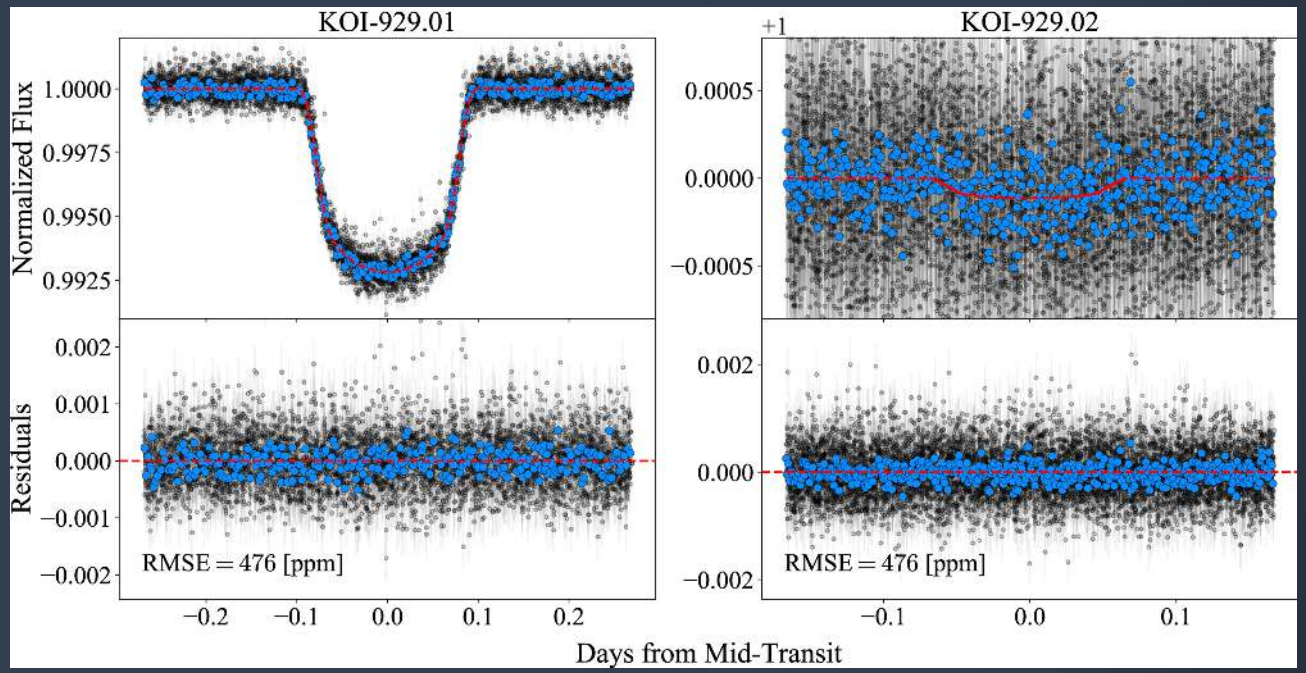
Two known hot Jupiter companions

WASP-47 e



Becker et al. 2015

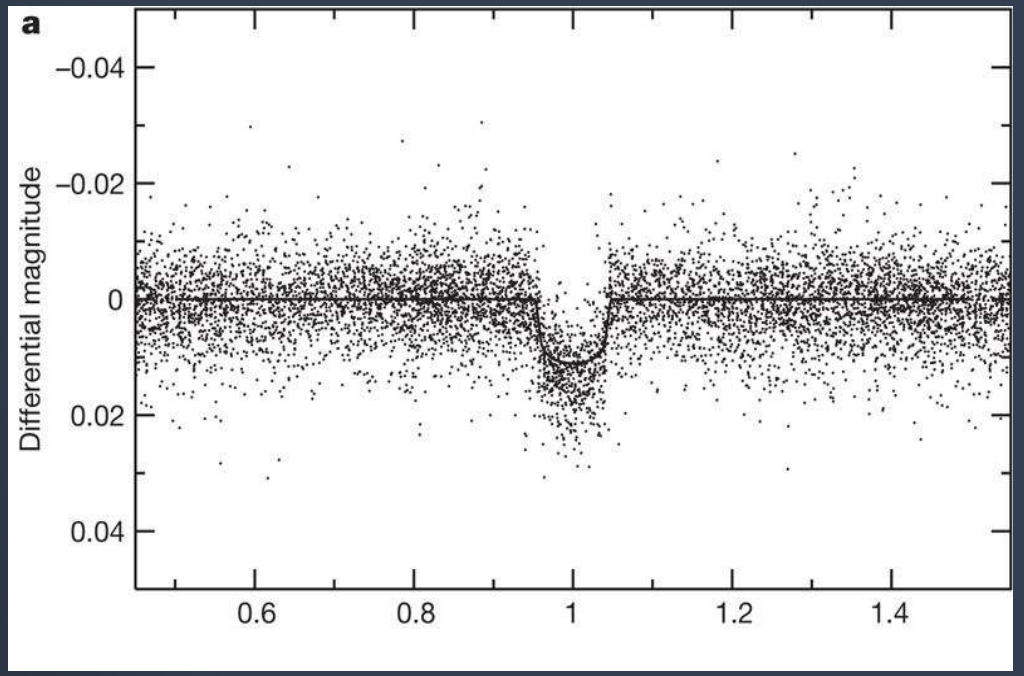
KOI-909.02 (Kepler-370)



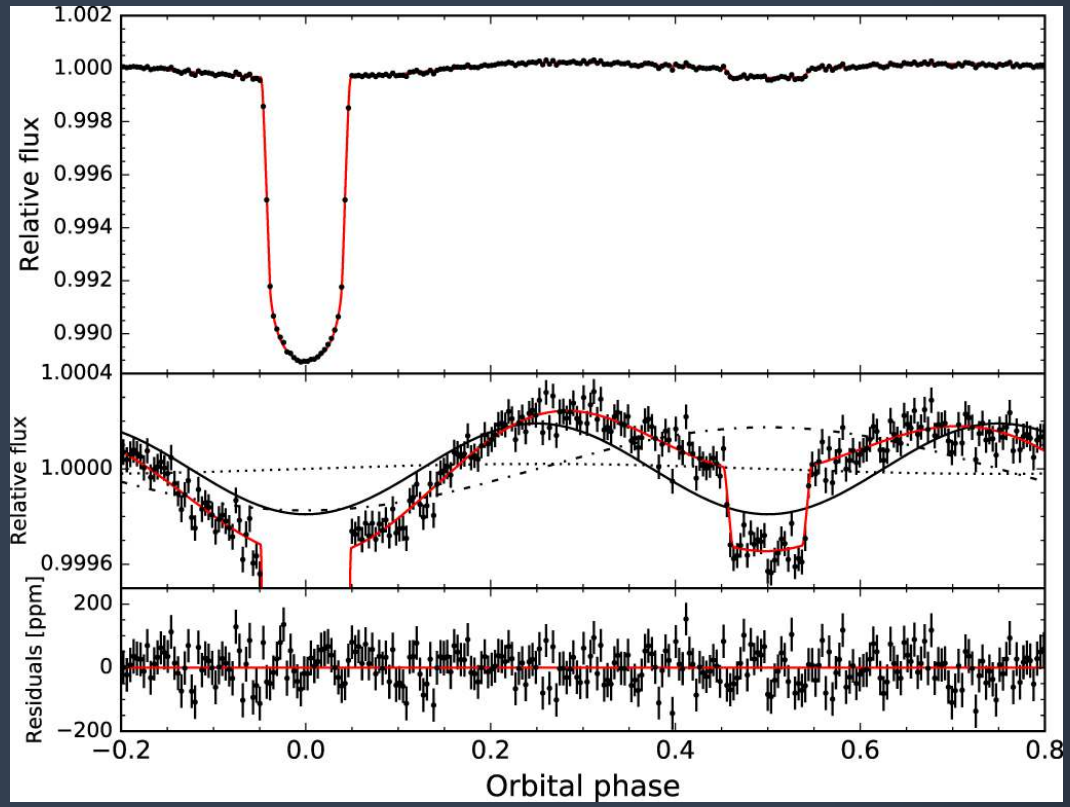
Zhu et al. 2018, figure: Cañas et al. 2019

Why study HJs with *TESS*?

Ground-based observations do not have the precision to detect companions.



WASP-18b observed by WASP
(Hellier et al. 2009)



WASP-18b observed by *TESS*
(Shporer et al. 2019)

Only *TESS* can detect small planets near HJs

Ground observations

- Insufficient precision
- Gaps due to daytime, weather

Kepler

- Low HJ yield
  - 60 confirmed
  - 37 candidates

TESS

- High precision photometry
- Observes “continuously”
- > 85% sky coverage
- In Sectors 1–8:
  - 61 newly confirmed or known
  - 137 candidates

In this work. . .

Select a list of *TESS*, *Kepler*, and *K2* hot Jupiters

Uniform BLS search for inner companion

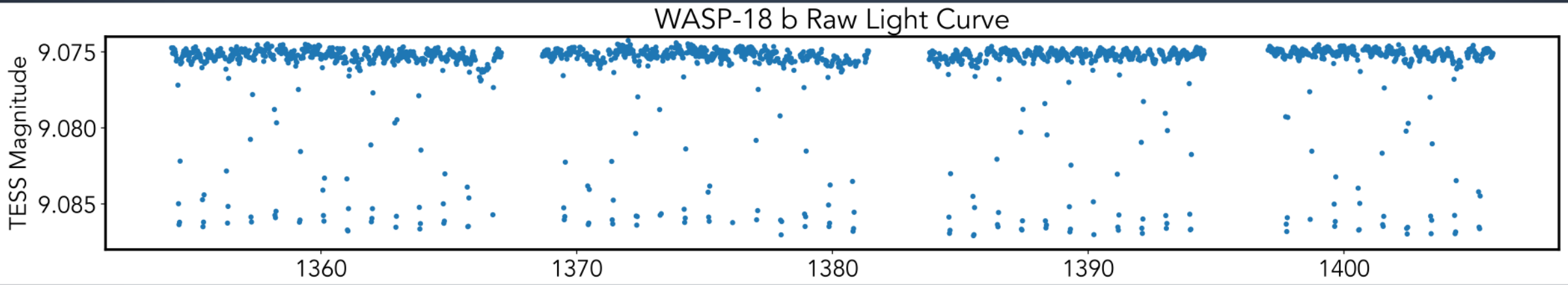
Vet TCEs manually

Calculate refined occurrence rate upper limit

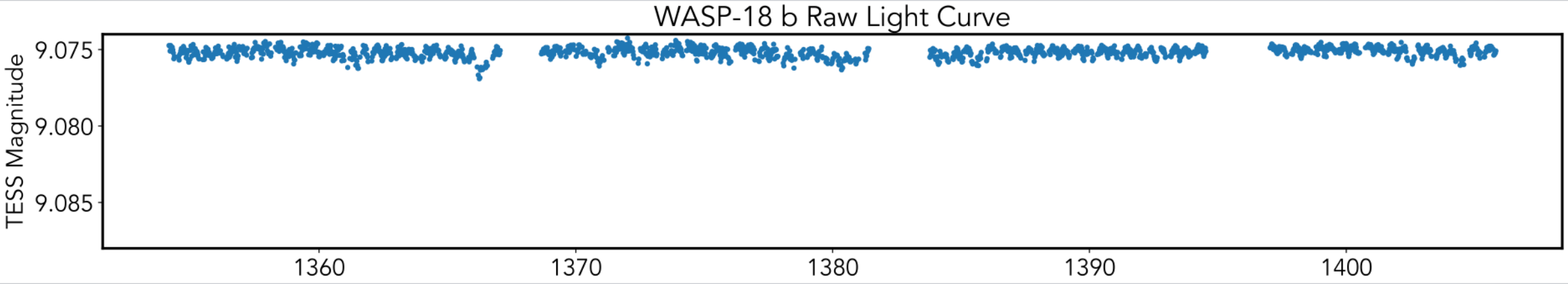
How we select hot Jupiters

Parameter	Criterion
Period	< 10 days
Planet radius	$\in [6, 25]\ R_\oplus$
Impact parameter	< 0.9
Star brightness (*TESS* HJs only)	< 11th *TESS* magnitude

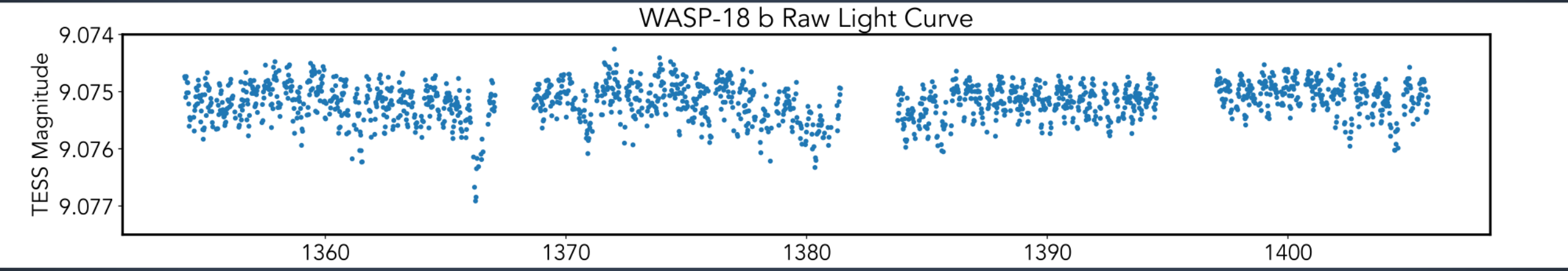
MIT Quick Look Pipeline FFI light curve



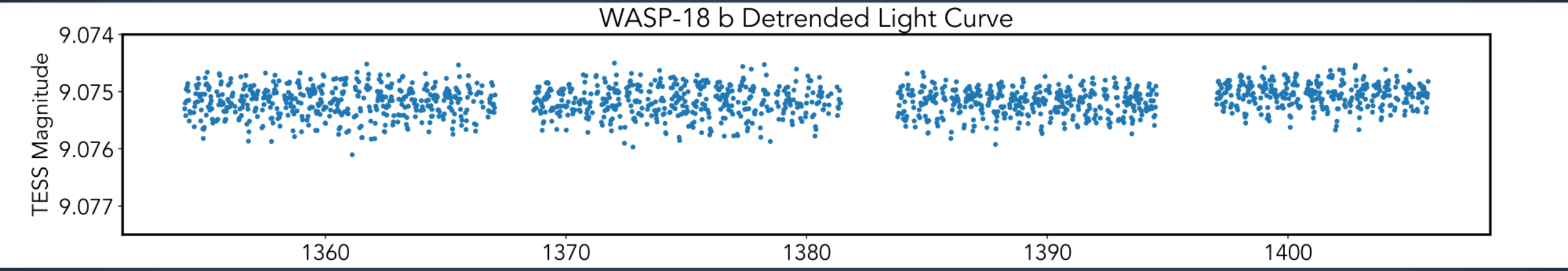
Mask planet signal with ephemeris



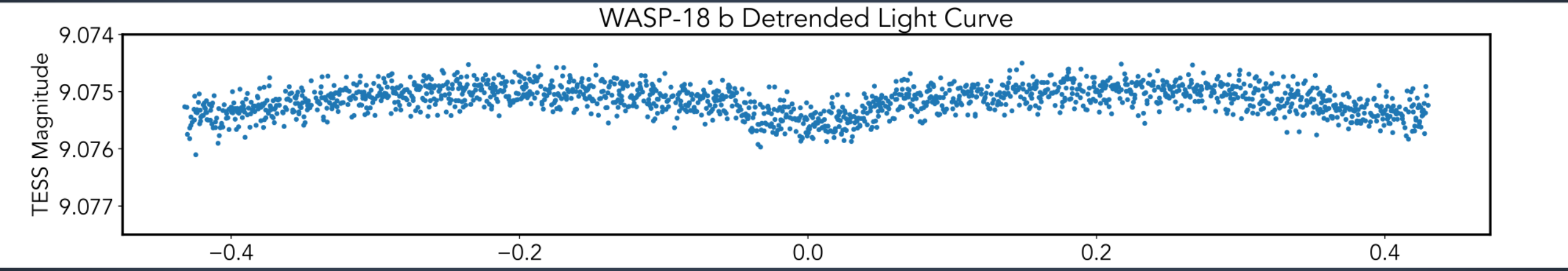
Mask planet signal with ephemeris



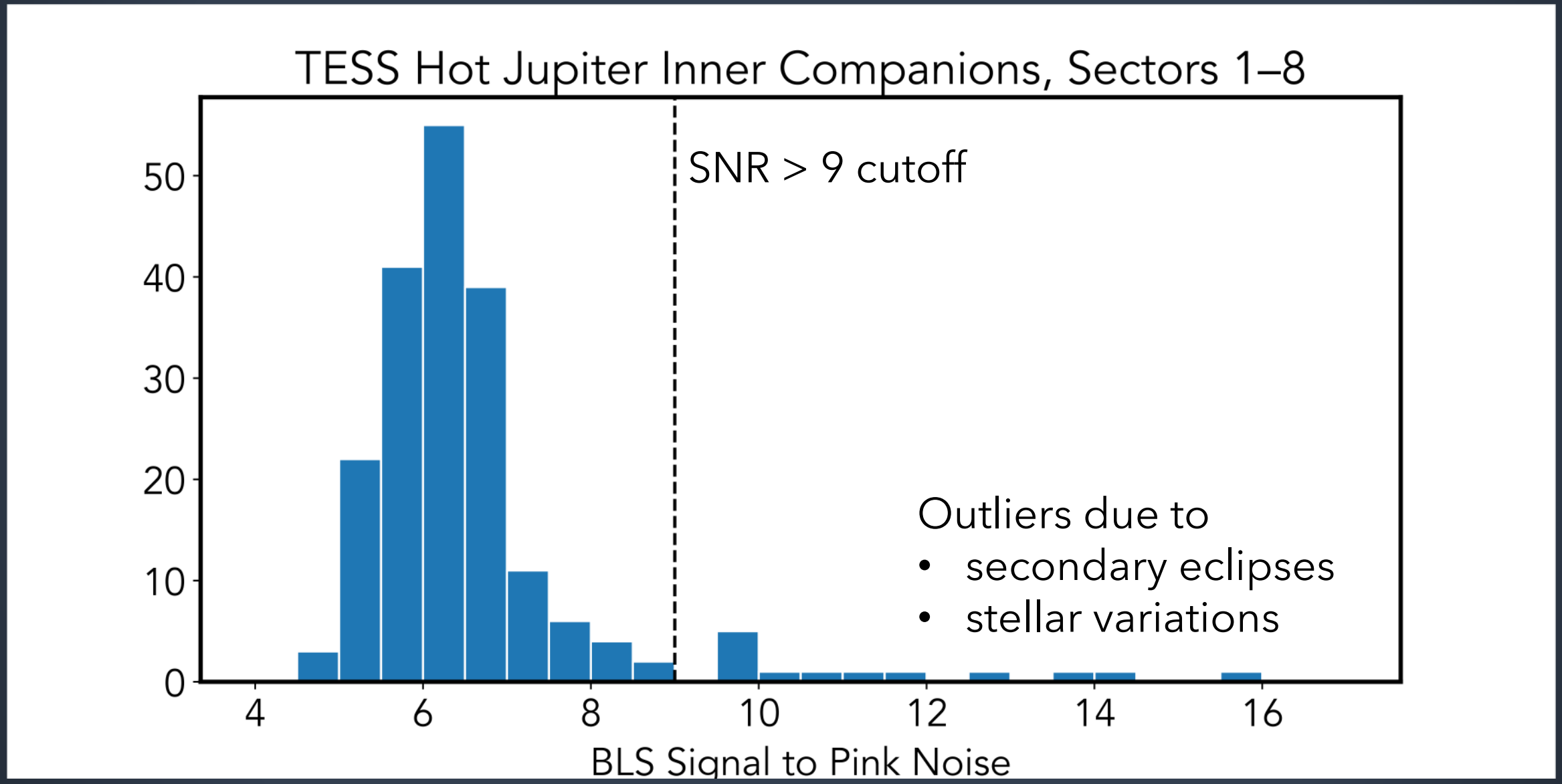
Detrend using *K2* Spline (Vanderburg & Johnson 2014)



BLS using VARTOOLS (Hartman & Barkos 2016)



No new HJ inner companions found (. . . yet)


TESS Hot Jupiter Inner Companions, Sectors 1–8
SNR > 9 cutoff
Outliers due to
• secondary eclipses
• stellar variations
50
40
30
20
10
0
4
6
8
10
12
14
16
BLS Signal to Pink Noise

Calculating occurrence rate is equivalent to the unfair coin toss problem.

An unfair coin is tossed N times
and lands on heads m times.
What is the true probability p of
the coin landing on heads?

Completeness: finding the number of trials

For each HJ star, randomly generate inner companions of various radii and periods

Transit? ($b < 0.9$)

Detection? (SNR > 9)

The proportion of “successful” planets contribute to the total number of trials

Completeness tally

	TESS	*Kepler*	*K2*	Total
Confirmed or Known Planet	61	60	35	156
Planet Candidates*	137	37‡	N/A	174‡
Total stars	198	95	35	328
Adjusted total†	40.82	70.23	27.82	138.87

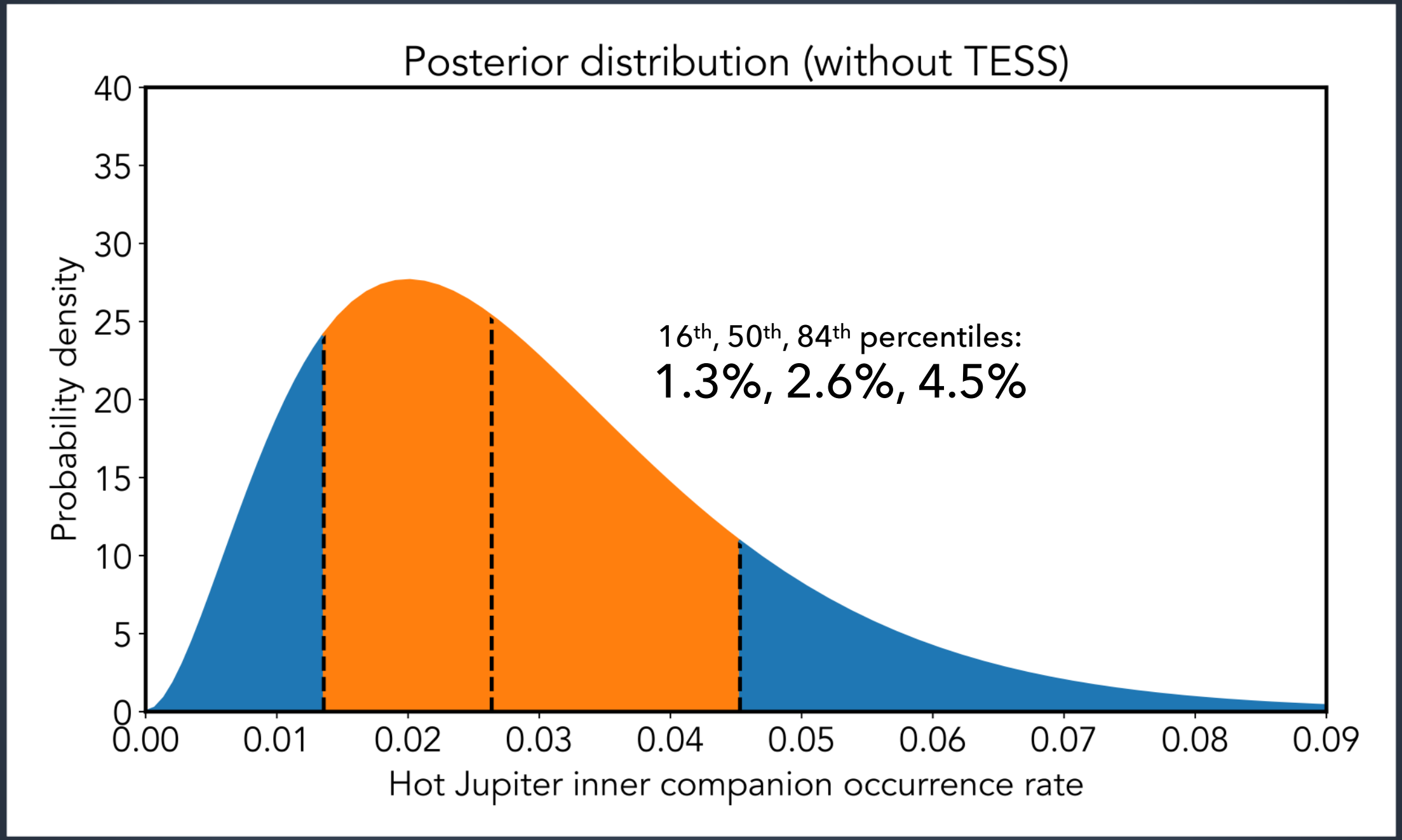
* Assumes false positive rate of 30%
† Excludes targets with no known Gaia stellar mass or radius
‡ Includes KOI-2093, a system with 3 hot Jupiter candidates

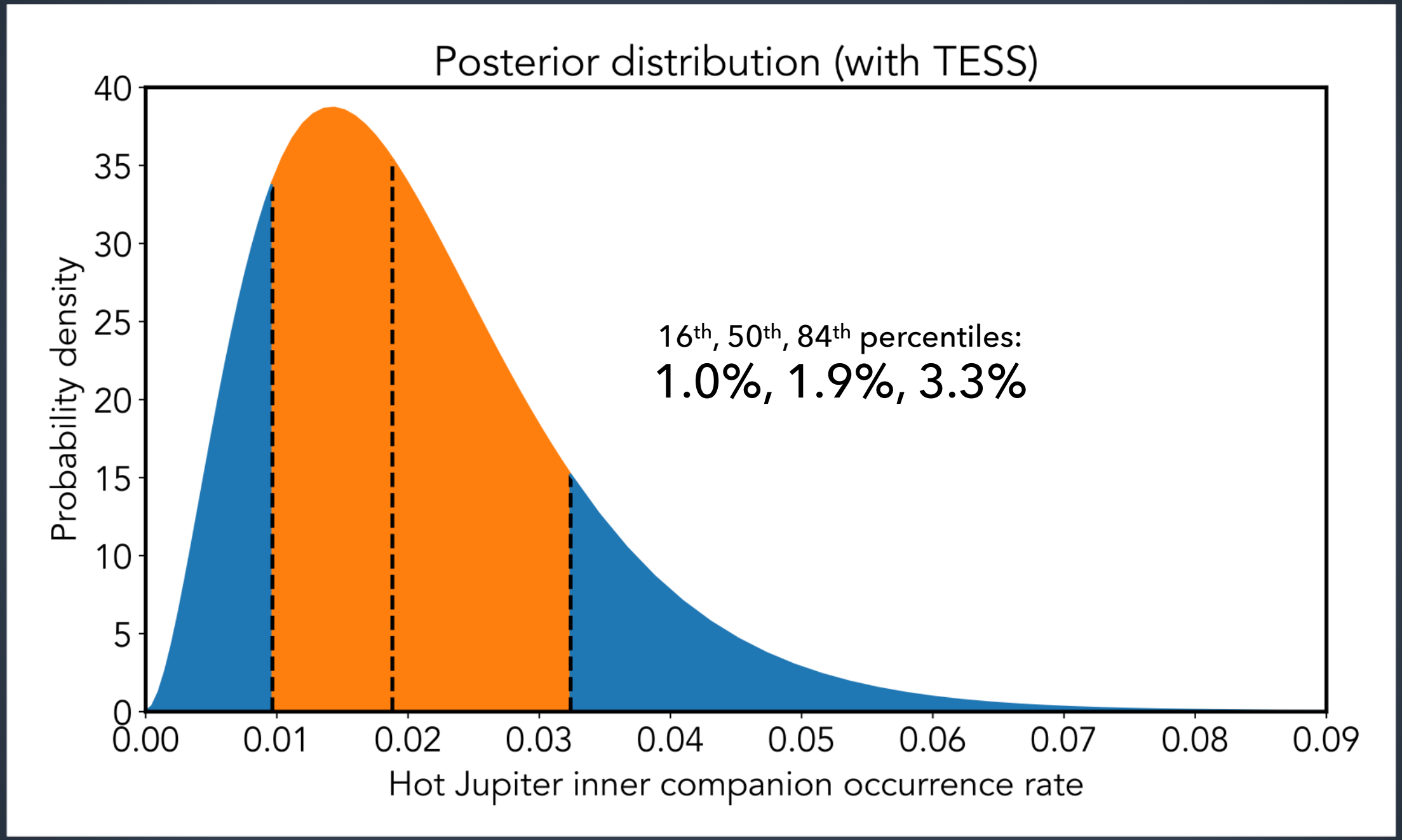
Hot Jupiter inner companions are uncommon

	# found	# of trials	Occurrence rate
TESS	0	40.82	$< 6.9\%$ *
Kepler	1	70.23	$2.3^{+2.2}_{-1.3}\%$ †
K2	1	27.82	$5.6^{+5.1}_{-3.2}\%$ †
Total	2	138.87	$1.9^{+1.4}_{-0.9}\%$ †

* 95% credible interval

† 16th, 50th, 84th percentiles


Posterior distribution (without TESS)
Probability density
0
5
10
15
20
25
30
35
40
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
Hot Jupiter inner companion occurrence rate
16th, 50th, 84th percentiles:
1.3%, 2.6%, 4.5%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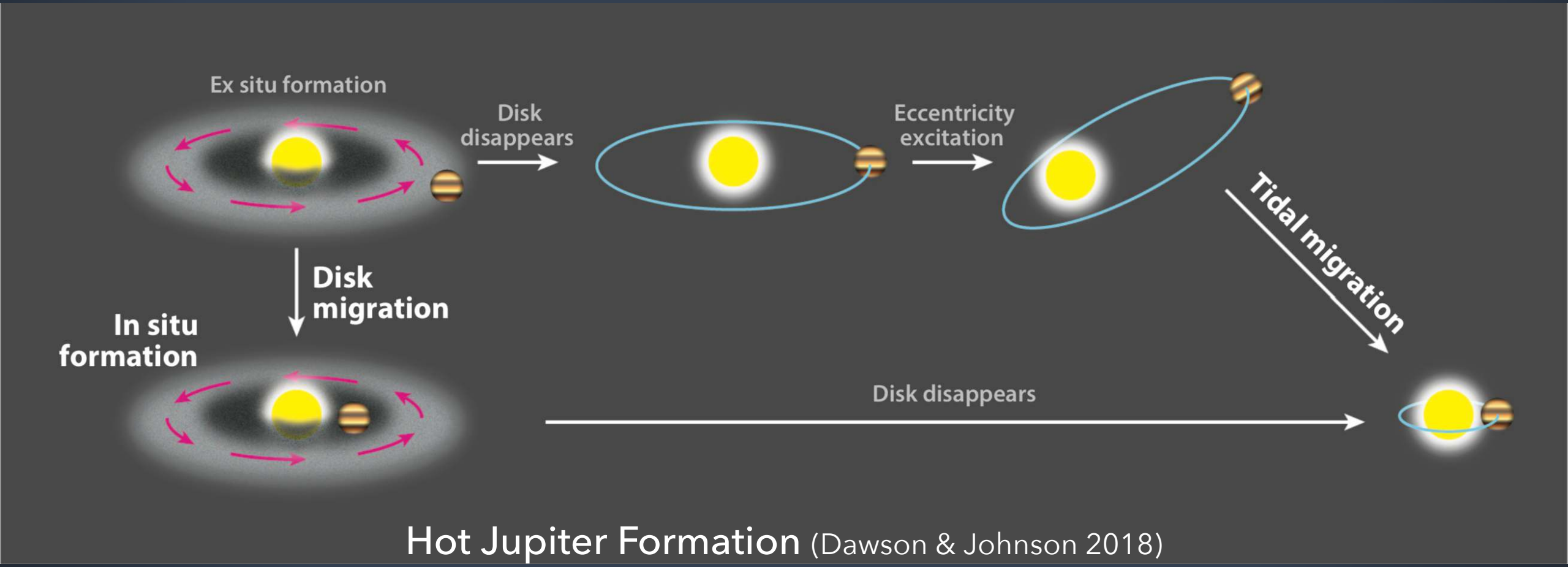
0.05
0.06
0.07
0.08
0.09
Hot Jupiter inner companion occurrence rate
16th, 50th, 84th percentiles:
1.0%, 1.9%, 3.3%

Low occurrence rate of inner companions tells us that the vast majority of HJs are formed *ex situ*.



Hot Jupiter Formation (Dawson & Johnson 2018)

Thank you!

Questions?

Occurrence rate: the math

An unfair coin is tossed *N* times and lands on heads *m* times. What is the probability that the true probability of the coin landing on heads is *p*?

$$\mathcal{P}(m, N|\, p) = \binom{N}{m} p^m (1-p)^{N-m}$$

$$\mathcal{P}(p|\, m, N) = \frac{\mathcal{P}(p)\, \mathcal{P}(m, N|\, p)}{\int_0^1 \mathcal{P}(t)\, \mathcal{P}(m, N|\, t)\, \mathrm{d}t}$$

$$\mathcal{P}(p|\, m, N) = \frac{p^m (1-p)^{N-m}}{\mathcal{B}(m+1, N-m+1)} = \frac{p^m (1-p)^{N-m}}{\int_0^1 t^m (1-t)^{N-m}\, \mathrm{d}t}$$

Completeness: SNR calculation

$$\mathrm{SNR} = \frac{1}{\sigma}\left(\frac{R_\mathrm{p}}{R_\star}\right)^2 \sqrt{\frac{\text{baseline}}{\text{period}}} \sqrt{\frac{\text{transit duration}}{\text{exposure time}}}$$

σ = light curve white noise

baseline = exposure time × num of frames

References

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Hartman, J. D., & Bakos, G. Á. 2016, Astronomy and Computing, 17, 1

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Shporer, A., Wong, I., Huang, C. X., et al. 2019, AJ, 157, 178

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