Drawing Insights on Past Planetary Migration from Current System States

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with

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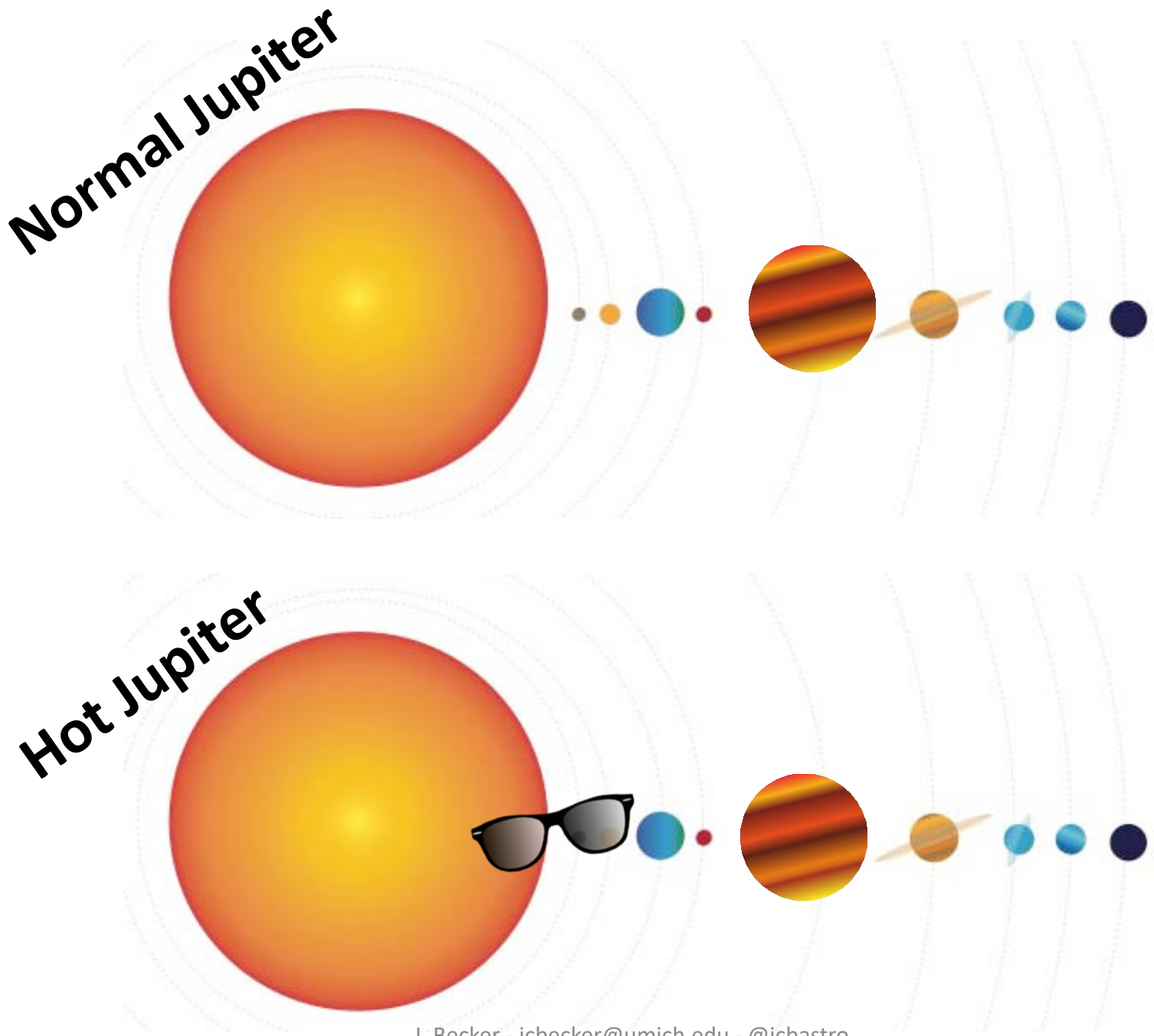
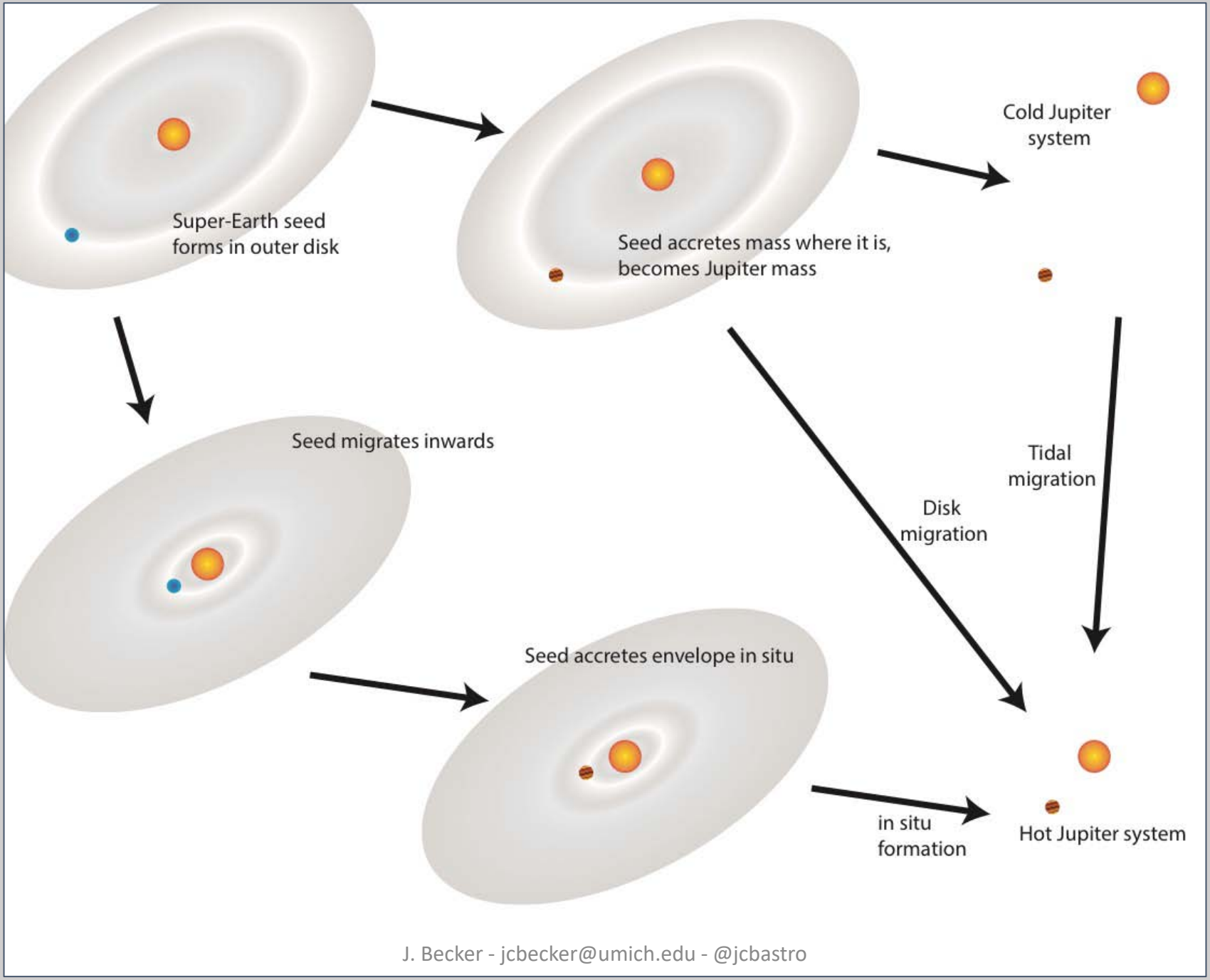

Normal Jupiter
Hot Jupiter



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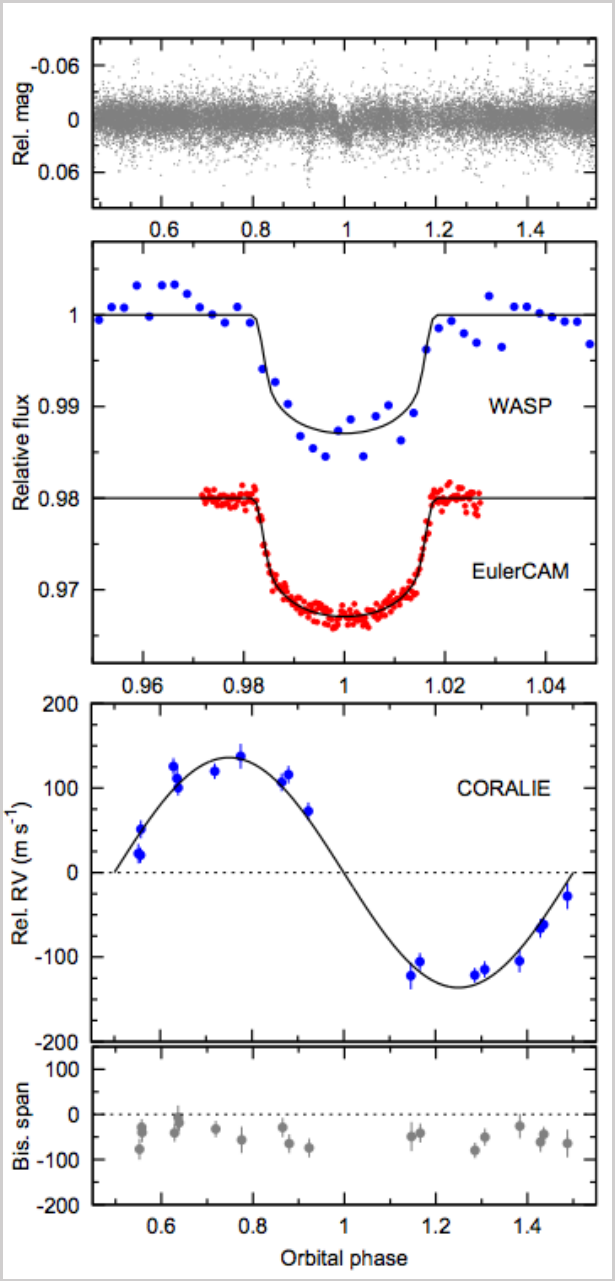
WASP-47 discovery

Hellier et al (2012)

"With an orbital period of 4.16 d, a mass of 1.14 M_{Jup} and a radius of 1.15 R_{Jup} WASP-47b is an entirely typical hot Jupiter."

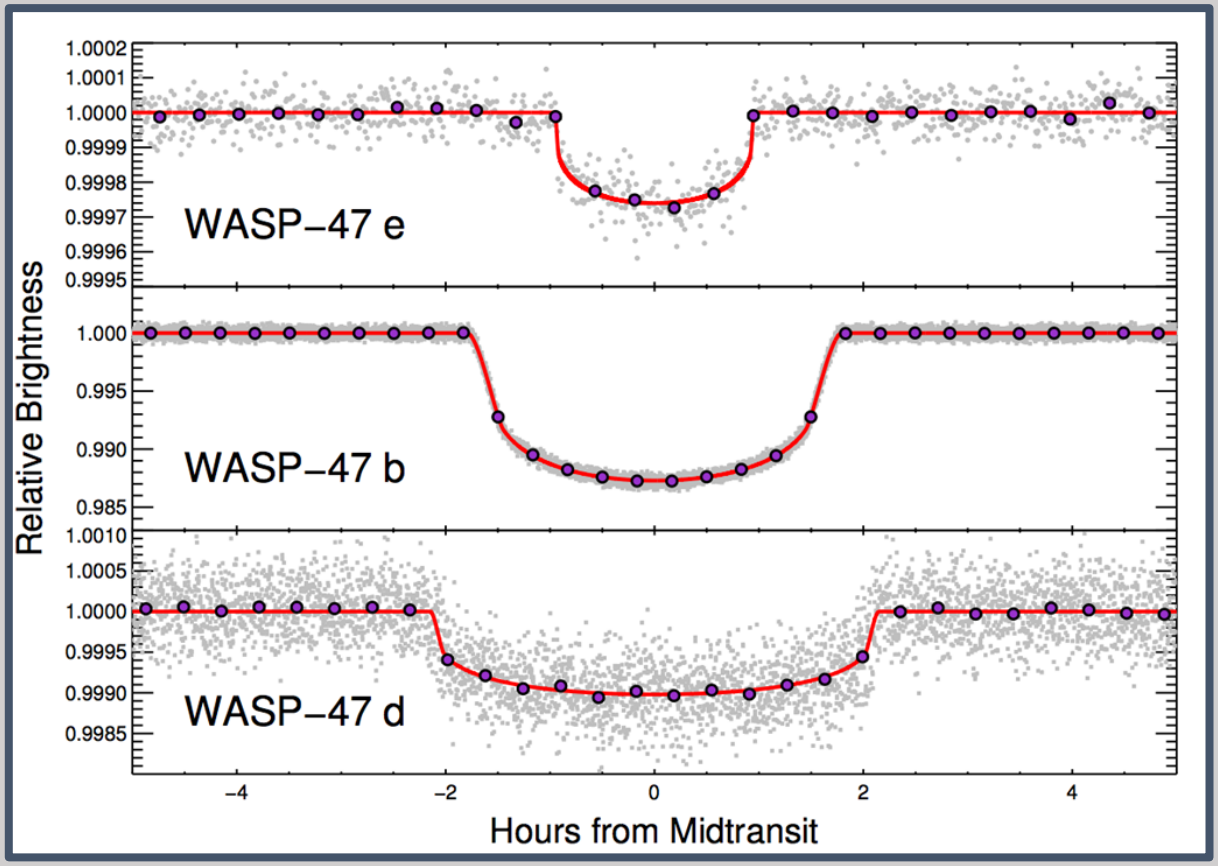


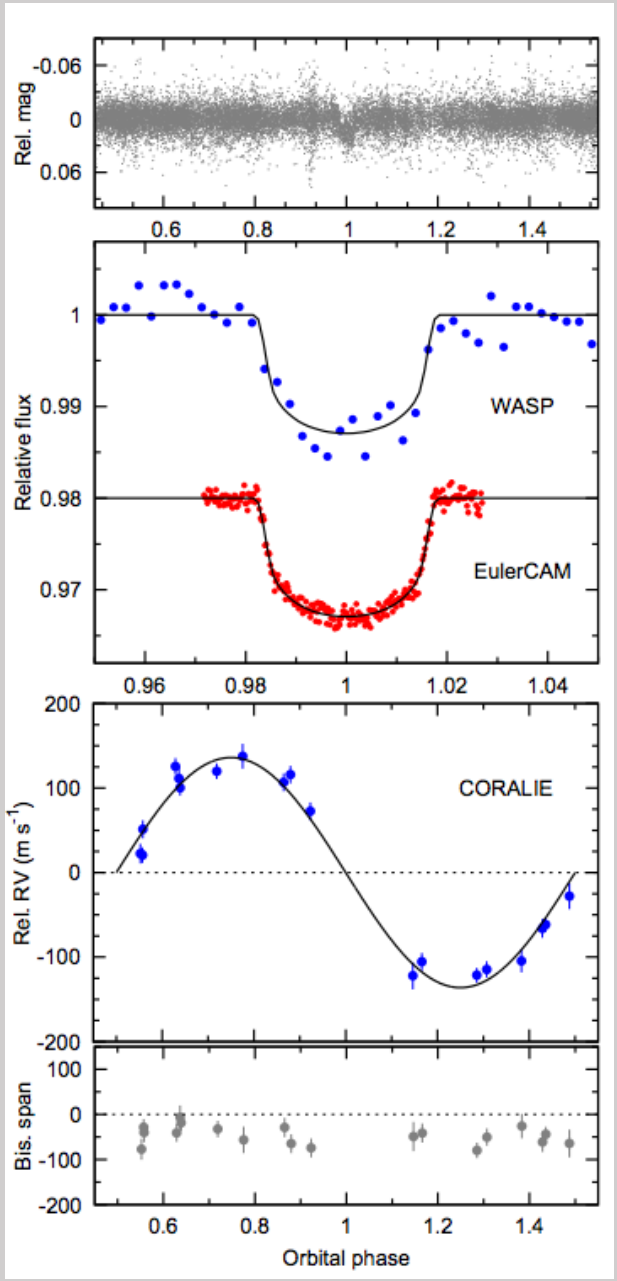
WASP-47 b discovery

Hellier et al (2012)

WASP-47 d, e discovery

Becker et al (2015)





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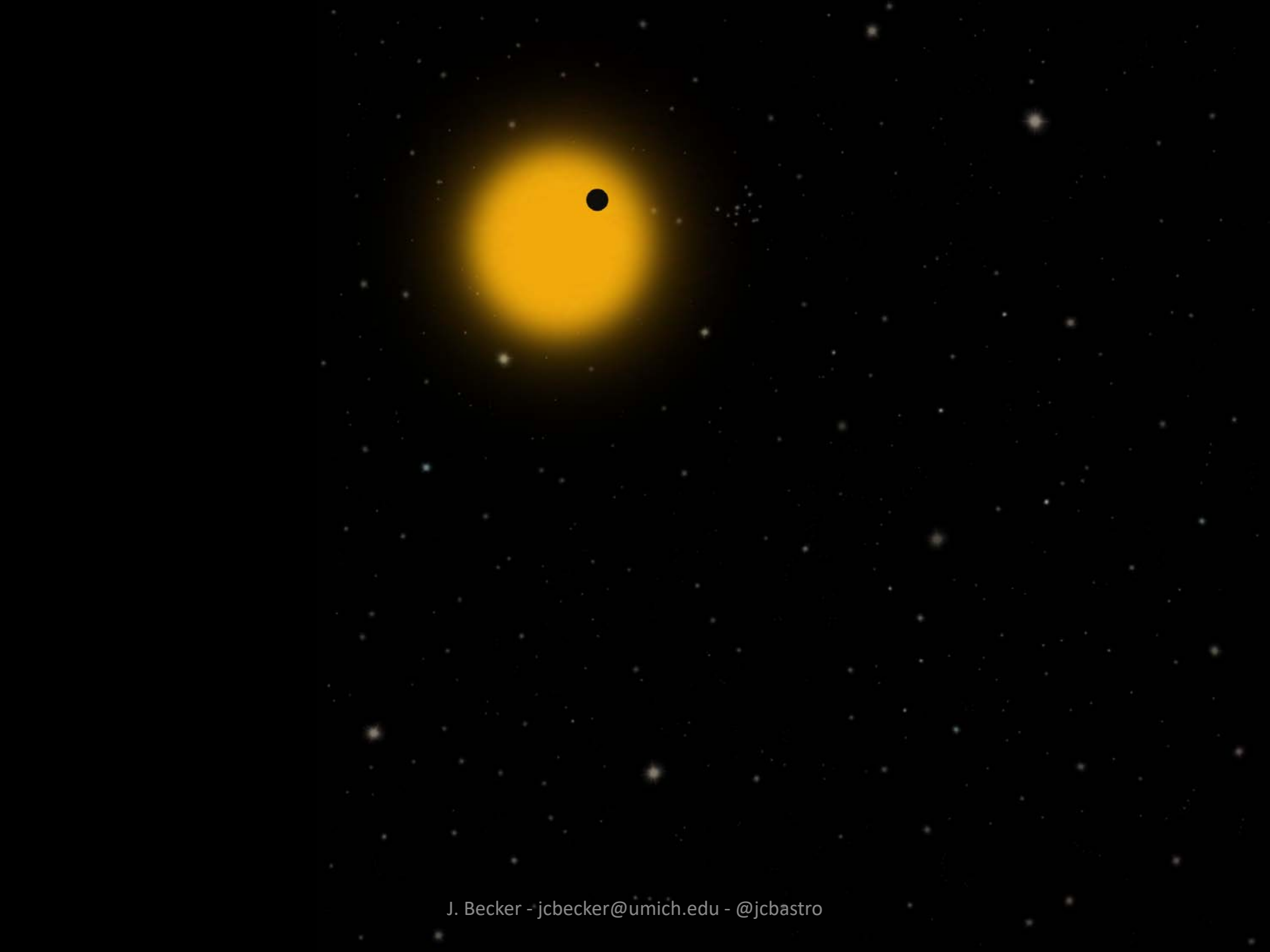

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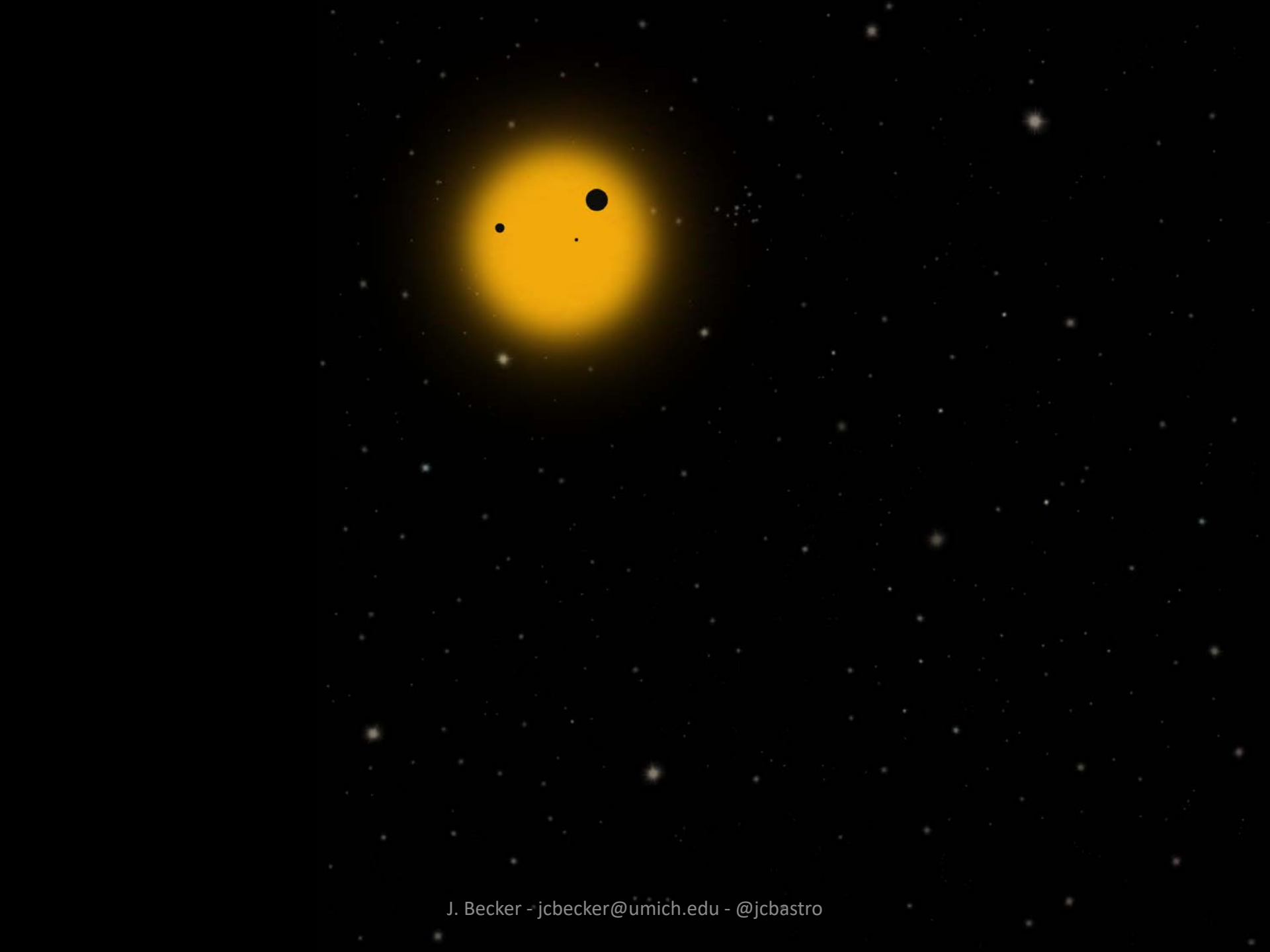

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An extra, long-period companion

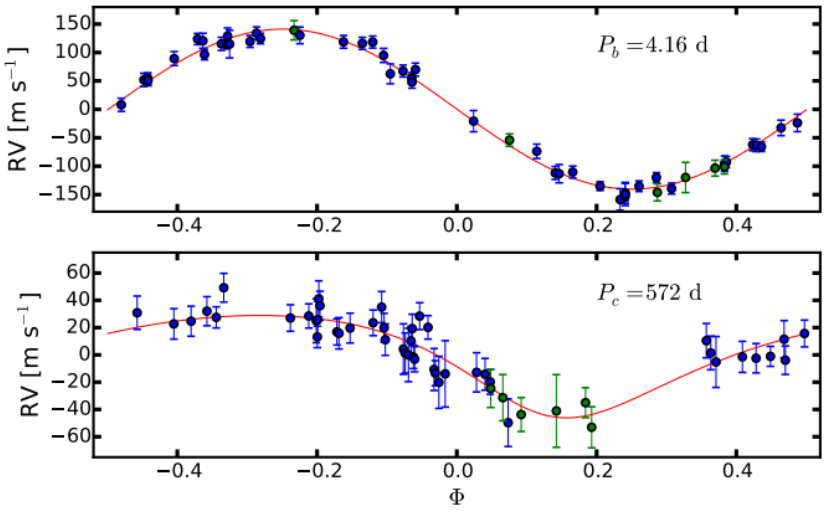
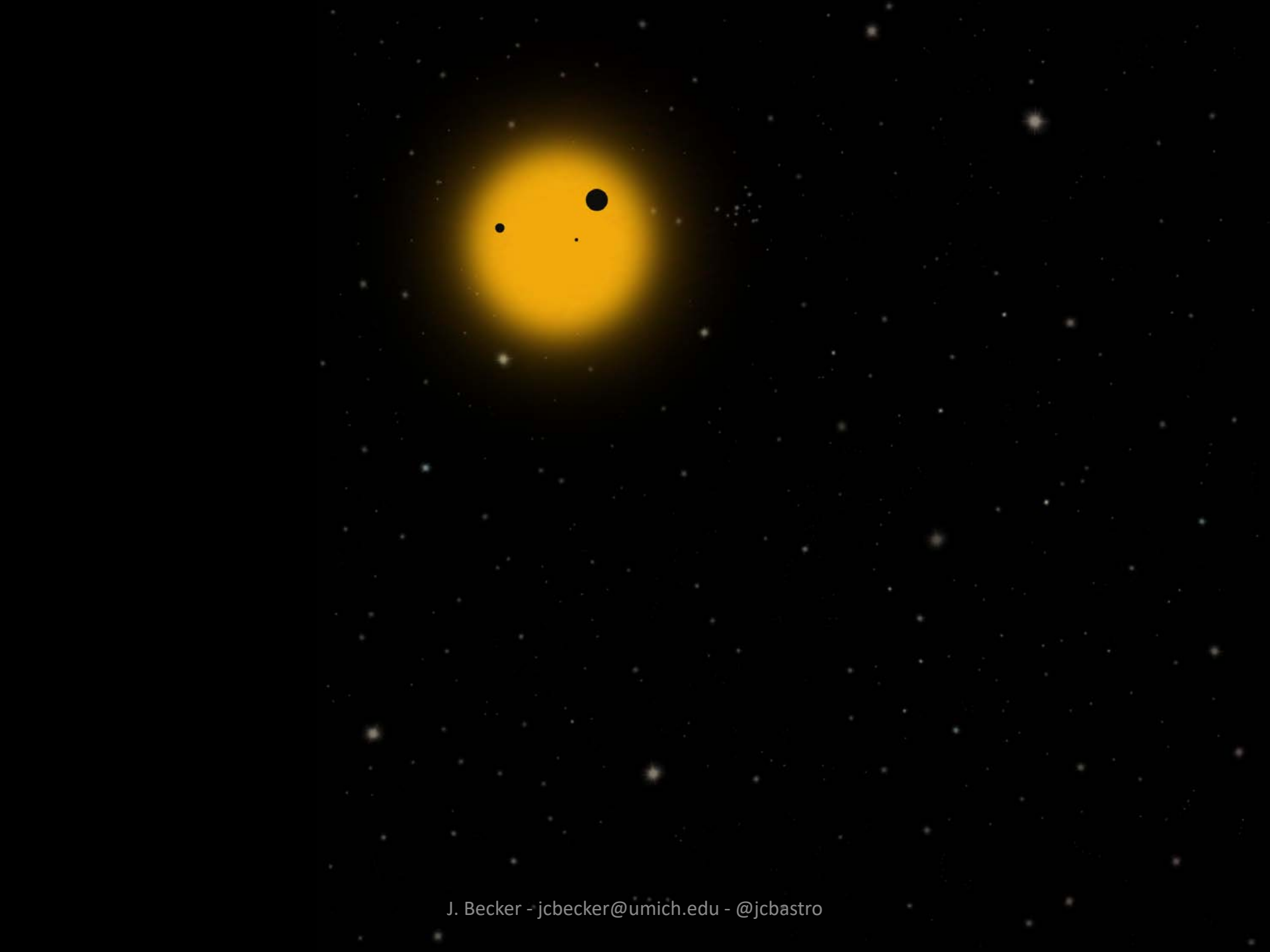


Fig. 2. WASP-47 CORALIE radial velocity data (Blue/Green dots: before/after the upgrade) and best fit model (Red line). Top: phase-folded on the period of the inner planet (outer planet subtracted). Bottom: phase-folded on the period of the outer planet (inner planet subtracted).

Neveu-VanMalle et al. (2016) reported the discovery of a 1.24 Jupiter mass gas giant at a period of 572 days, for a total of four planets in the system.



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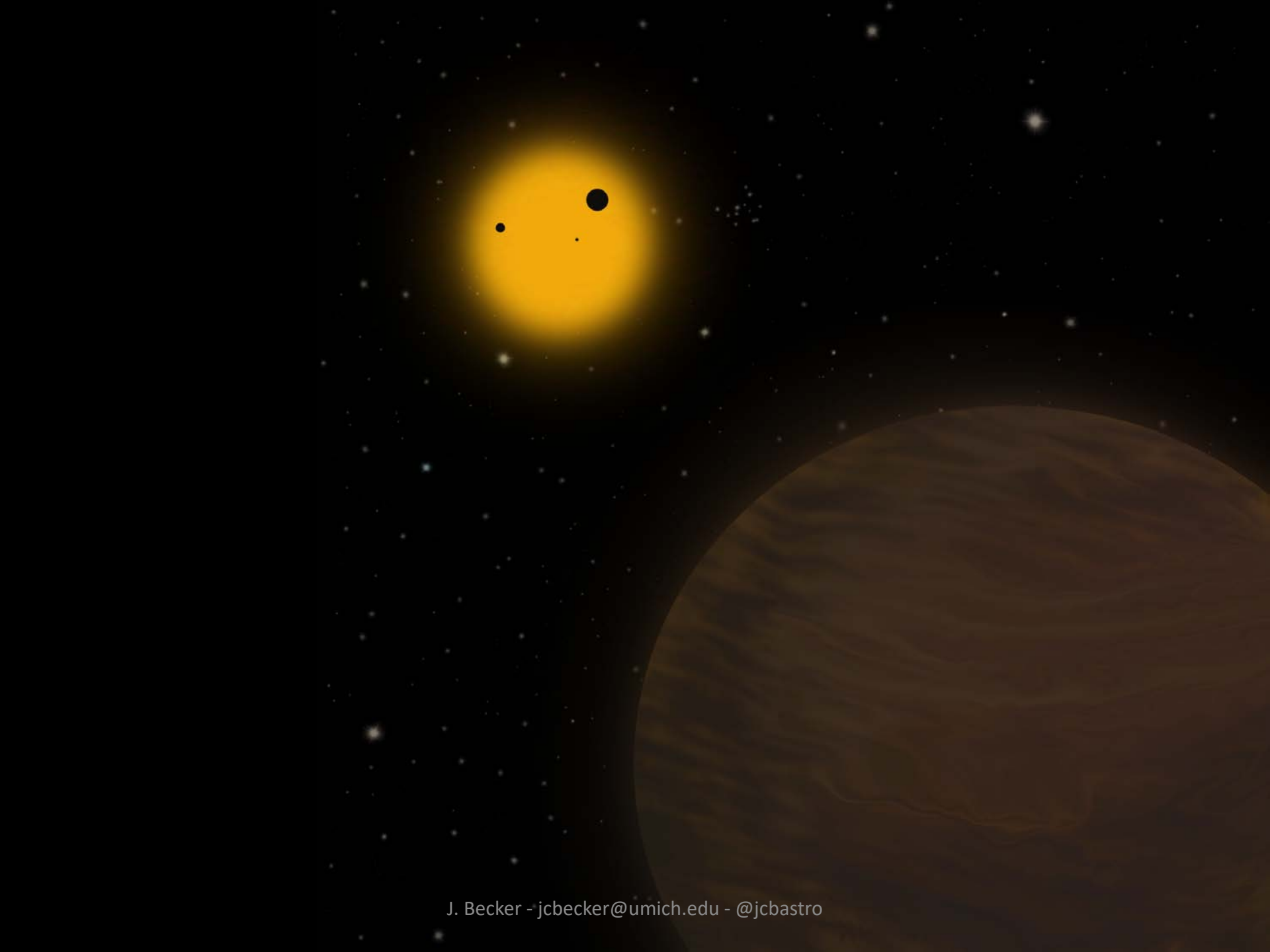

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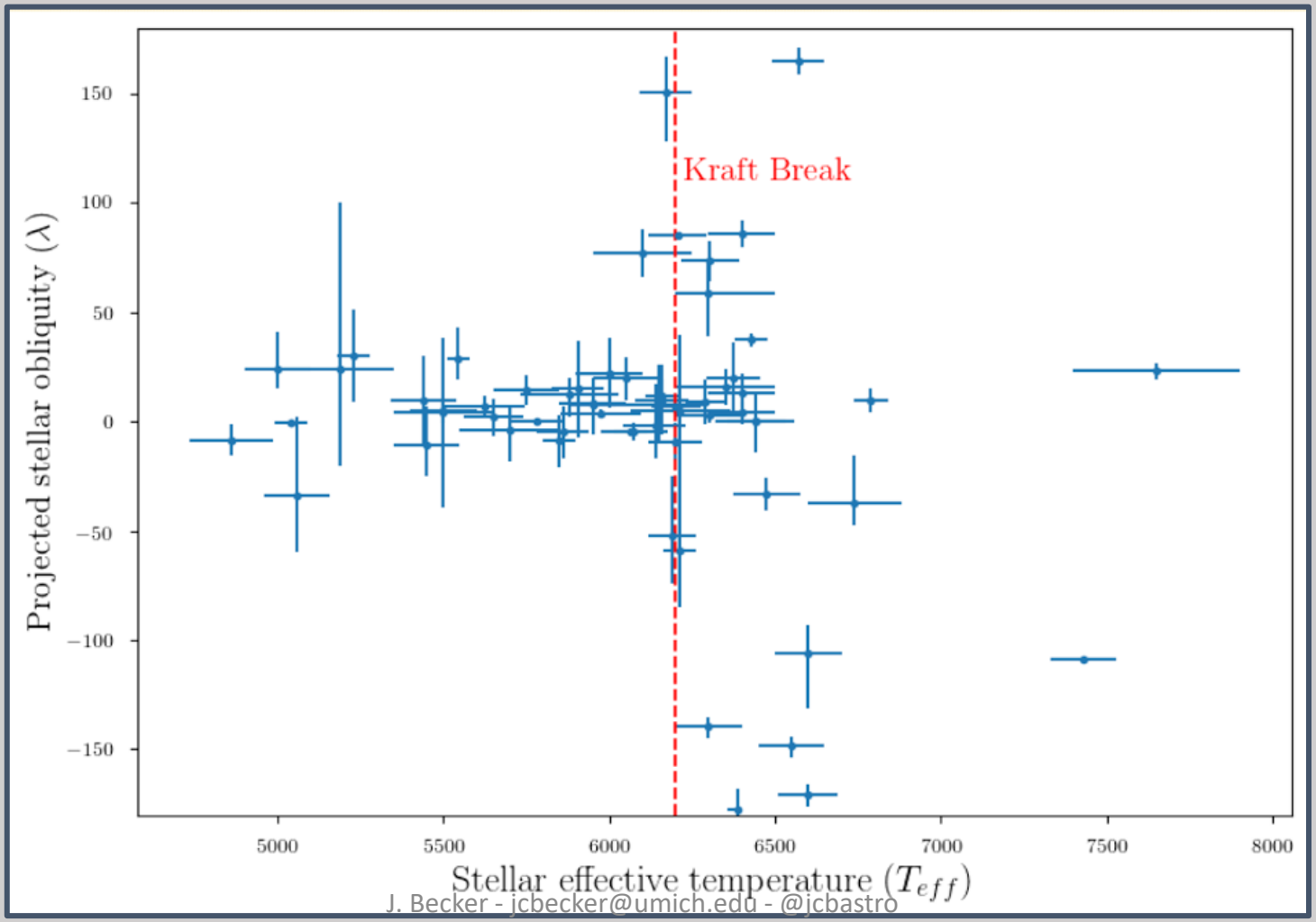
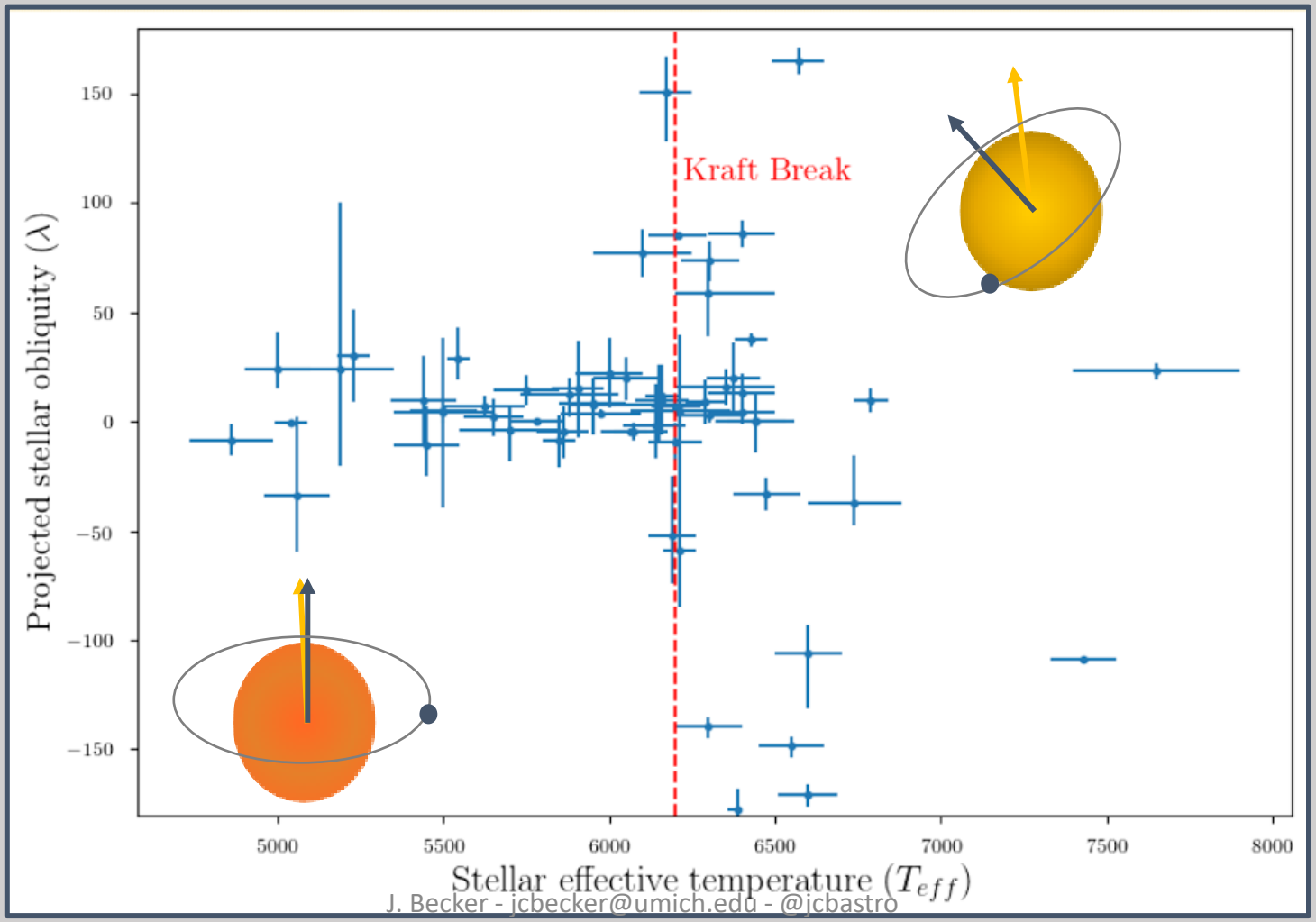
General Correlation

cool stars have low obliquities



General Correlation

cool stars hosting hot Jupiters have low obliquities



WASP-47b has a low obliquity

Sanchis-Ojeda et al. (2015)

Implies dynamically quiet history and (maybe) low inclination of WASP-47c

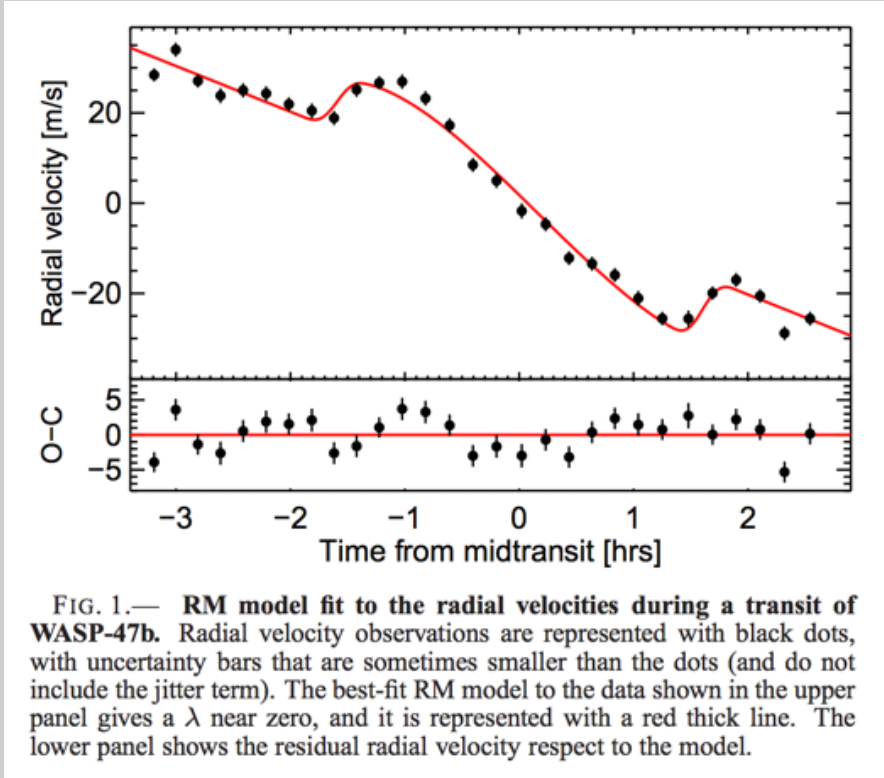
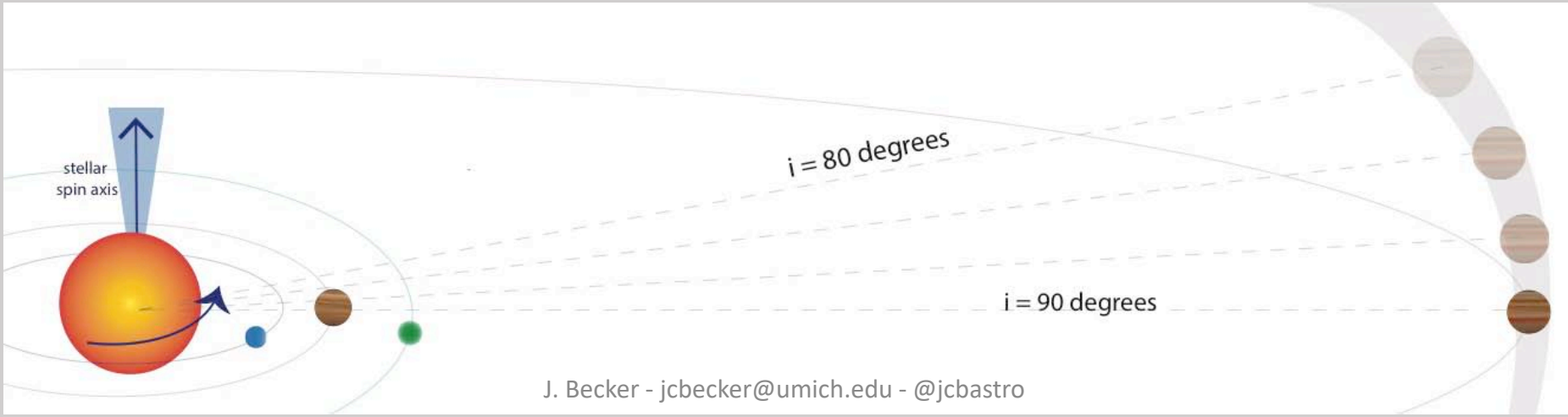


FIG. 1.— **RM model fit to the radial velocities during a transit of WASP-47b.** Radial velocity observations are represented with black dots, with uncertainty bars that are sometimes smaller than the dots (and do not include the jitter term). The best-fit RM model to the data shown in the upper panel gives a λ near zero, and it is represented with a red thick line. The lower panel shows the residual radial velocity respect to the model.



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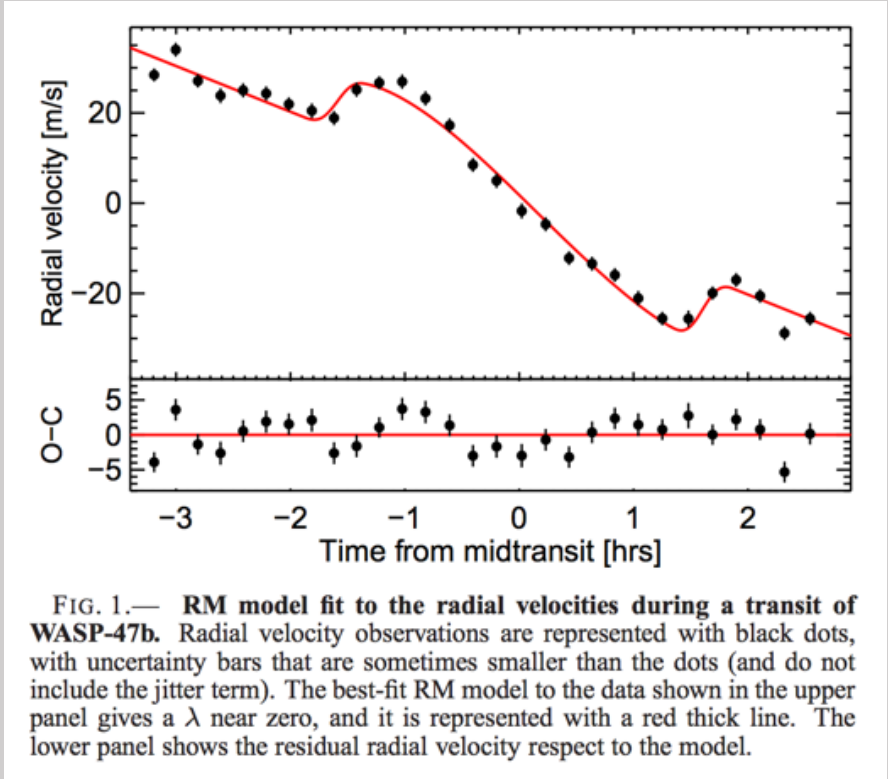

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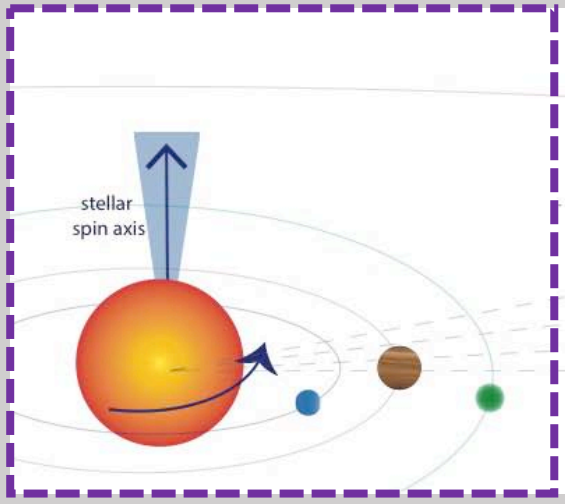
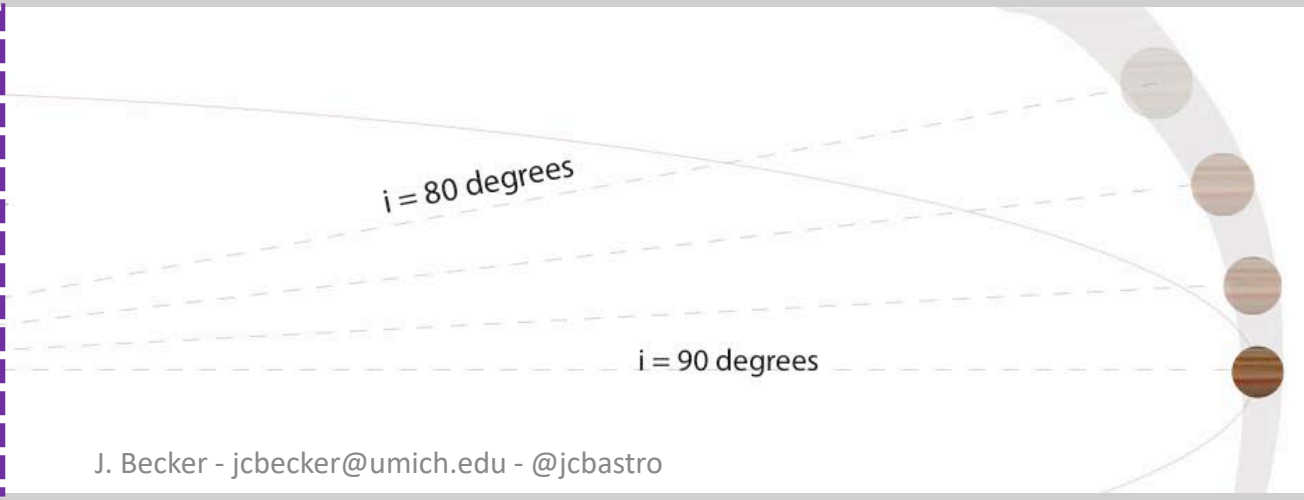
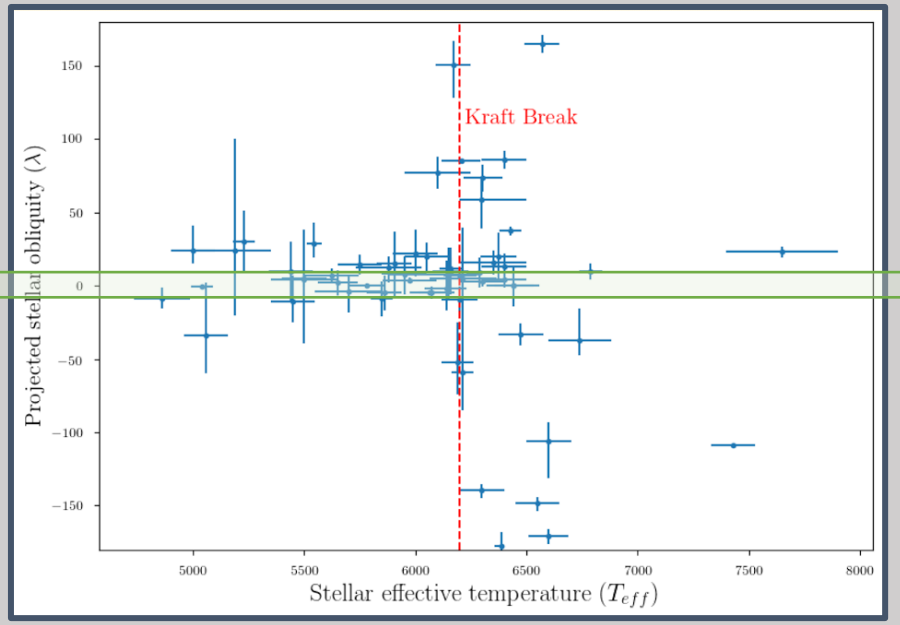
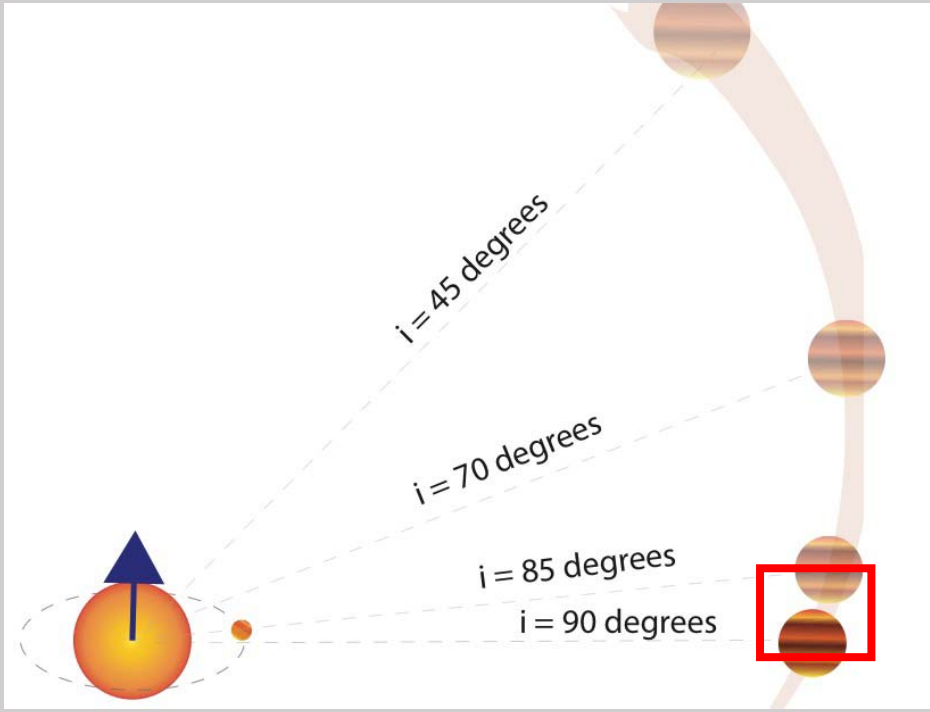
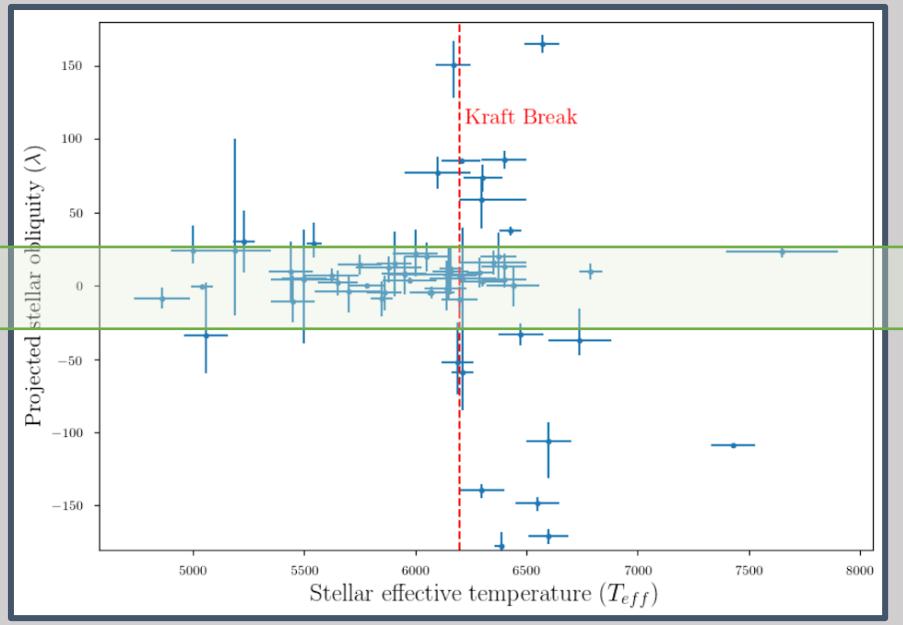





Kraft Break
Projected stellar obliquity (λ)
150
100
50
0
−50
−100
−150
5000
5500
6000
6500
7000
7500
8000
Stellar effective temperature (T_{eff})


i = 45 degrees
i = 70 degrees
i = 85 degrees
i = 90 degrees


Kraft Break
Projected stellar obliquity (λ)
150
100
50
0
−50
−100
−150
5000
5500
6000
6500
7000
7500
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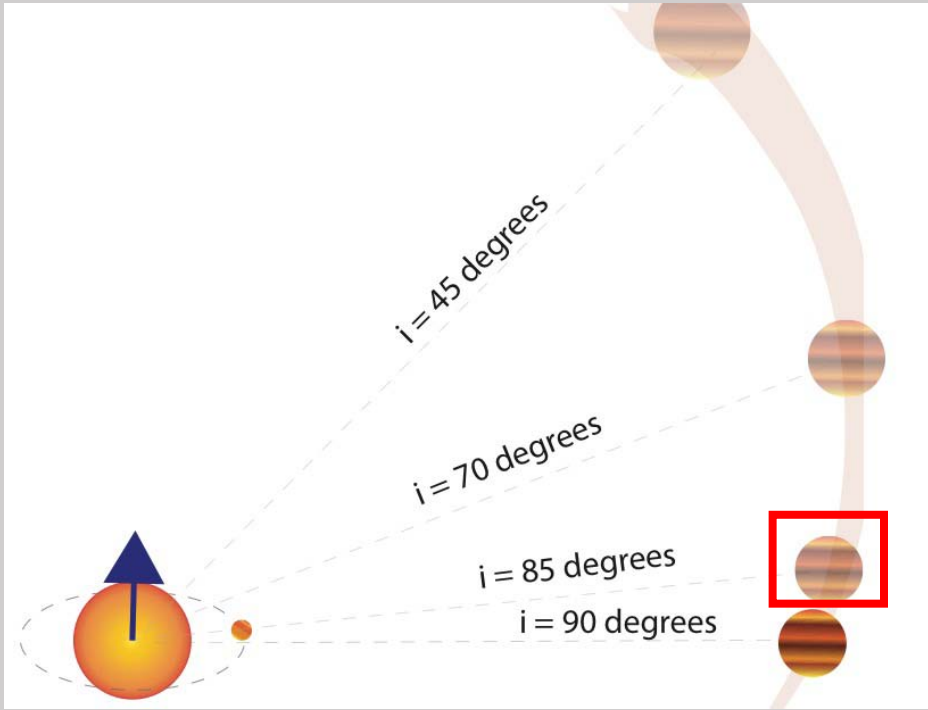
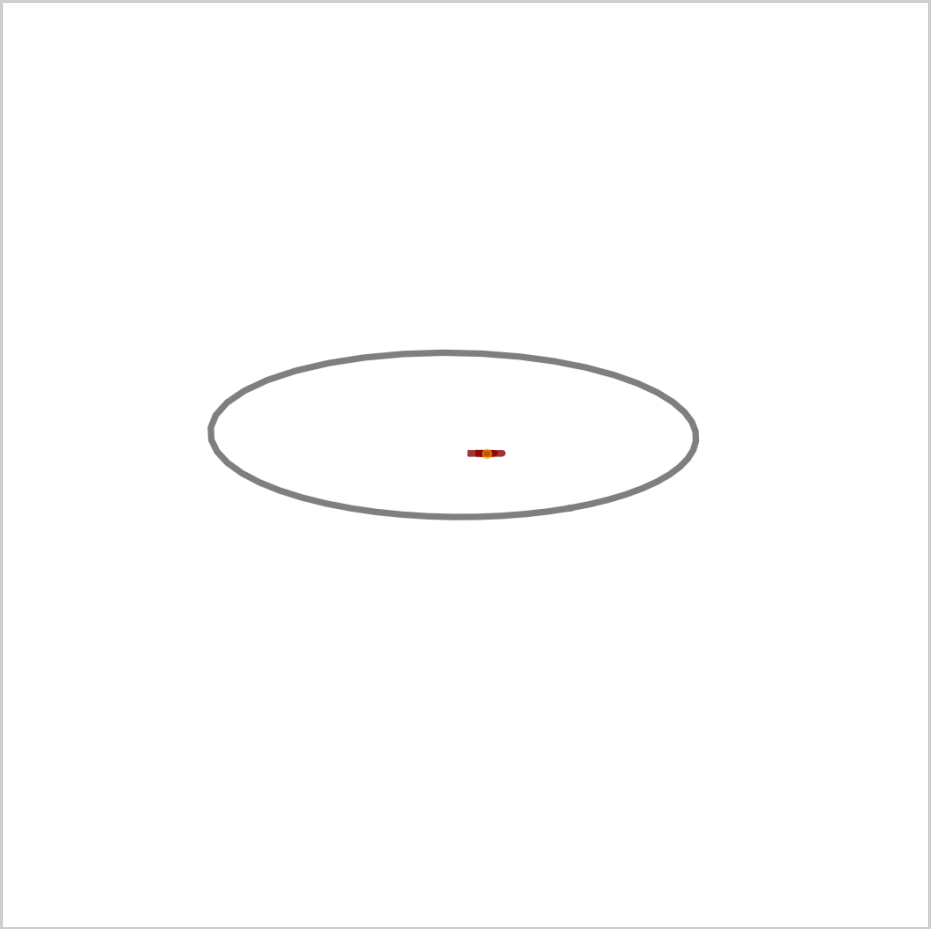
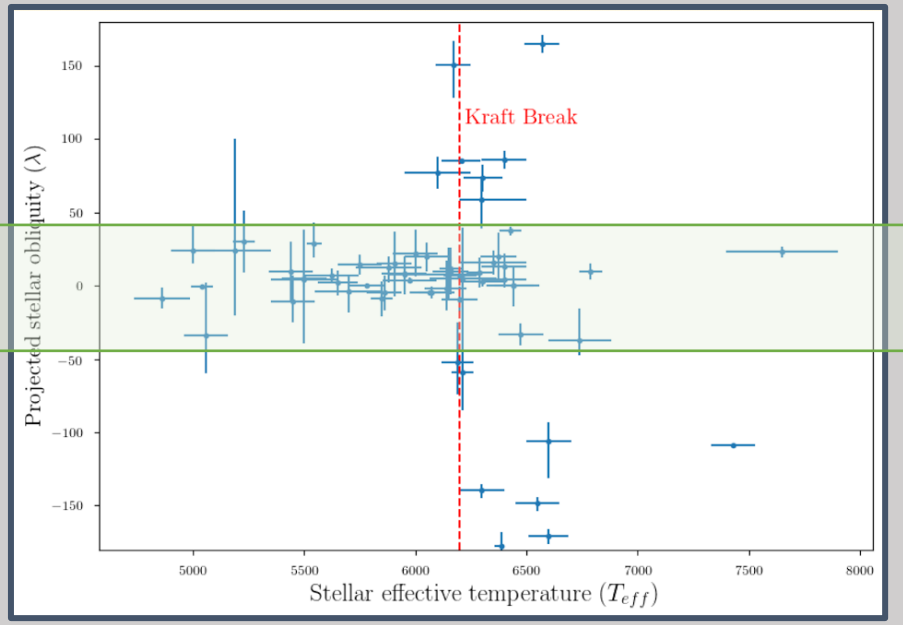
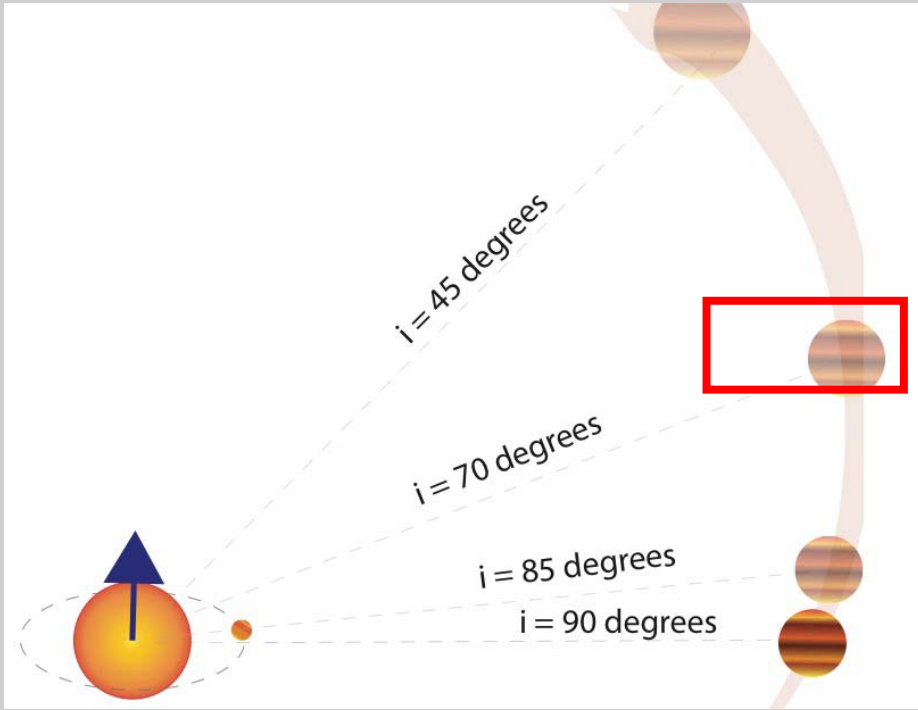
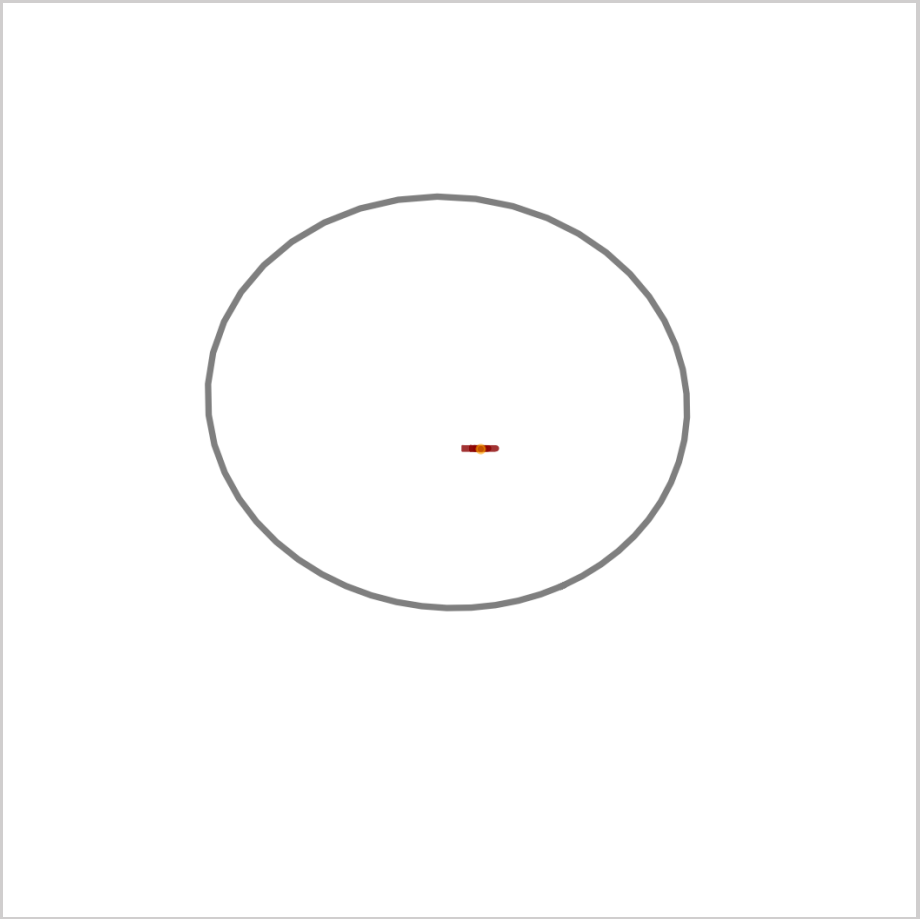
Stellar effective temperature (T_{eff})

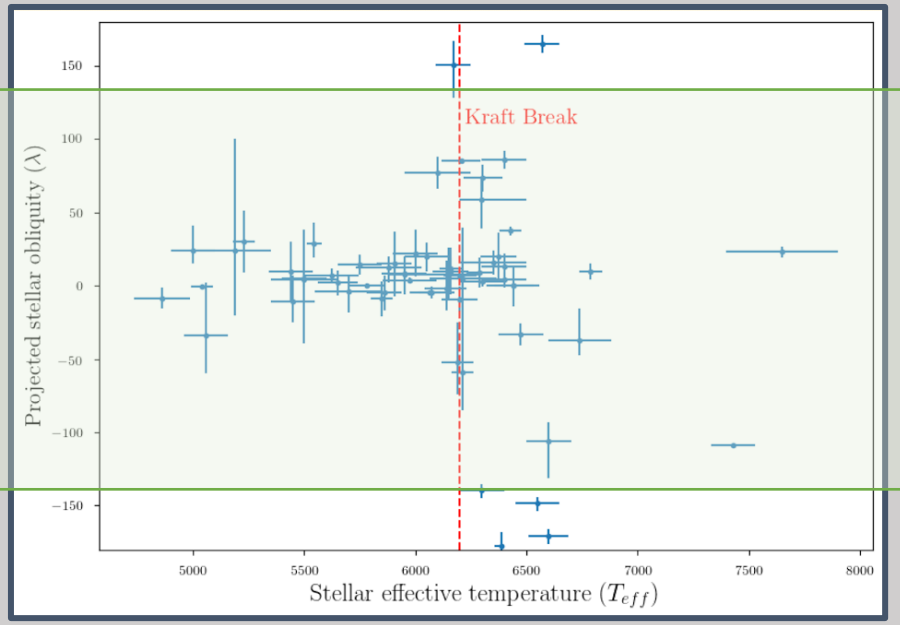

i = 45 degrees
i = 70 degrees
i = 85 degrees
i = 90 degrees

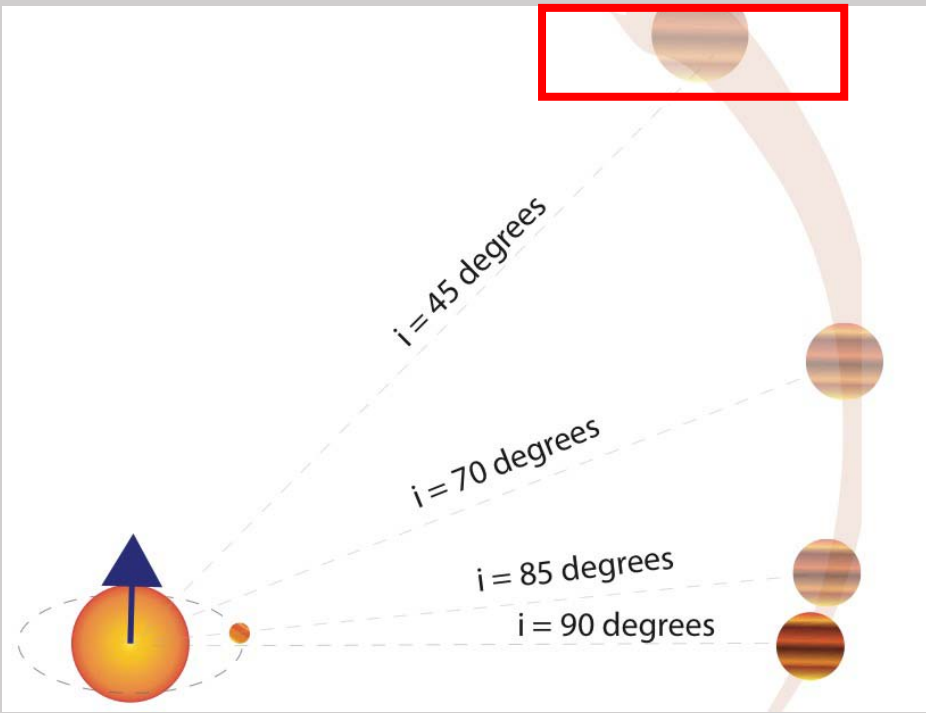



Kraft Break
Projected stellar obliquity (λ)
150
100
50
0
−50
−100
−150
5000
5500
6000
6500
7000
7500
8000
Stellar effective temperature (T_{eff})

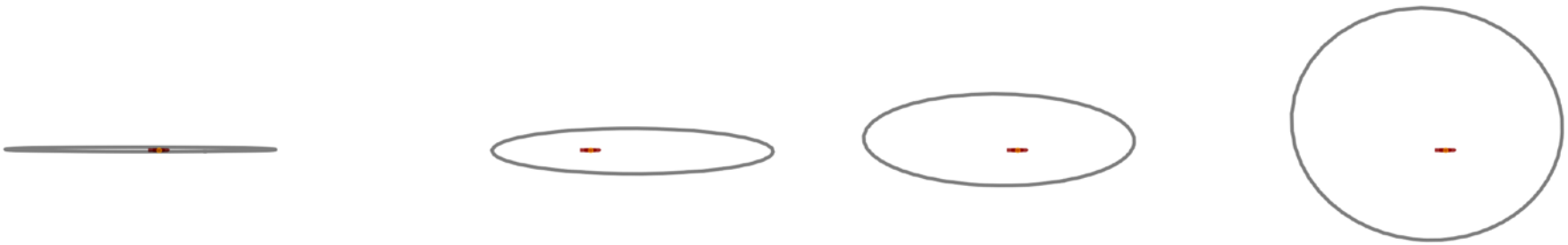

i = 45 degrees
i = 70 degrees
i = 85 degrees
i = 90 degrees




Kraft Break
Projected stellar obliquity (λ)
Stellar effective temperature (T_{eff})
150
100
50
0
−50
−100
−150
5000
5500
6000
6500
7000
7500
8000


i = 45 degrees
i = 70 degrees
i = 85 degrees
i = 90 degrees

Increasing mutual inclination of companion



More variability in stellar obliquity with respect to hot Jupiter

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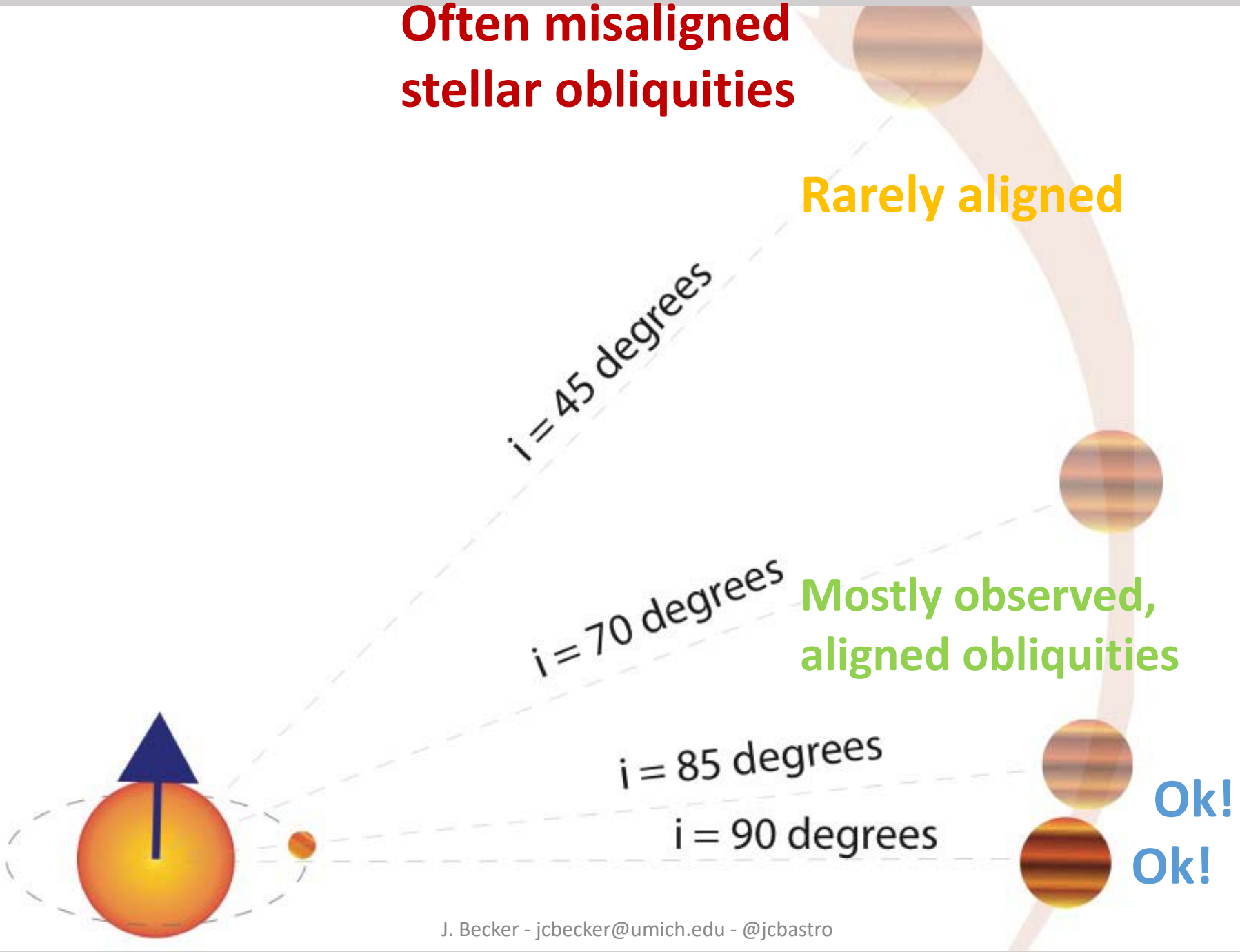
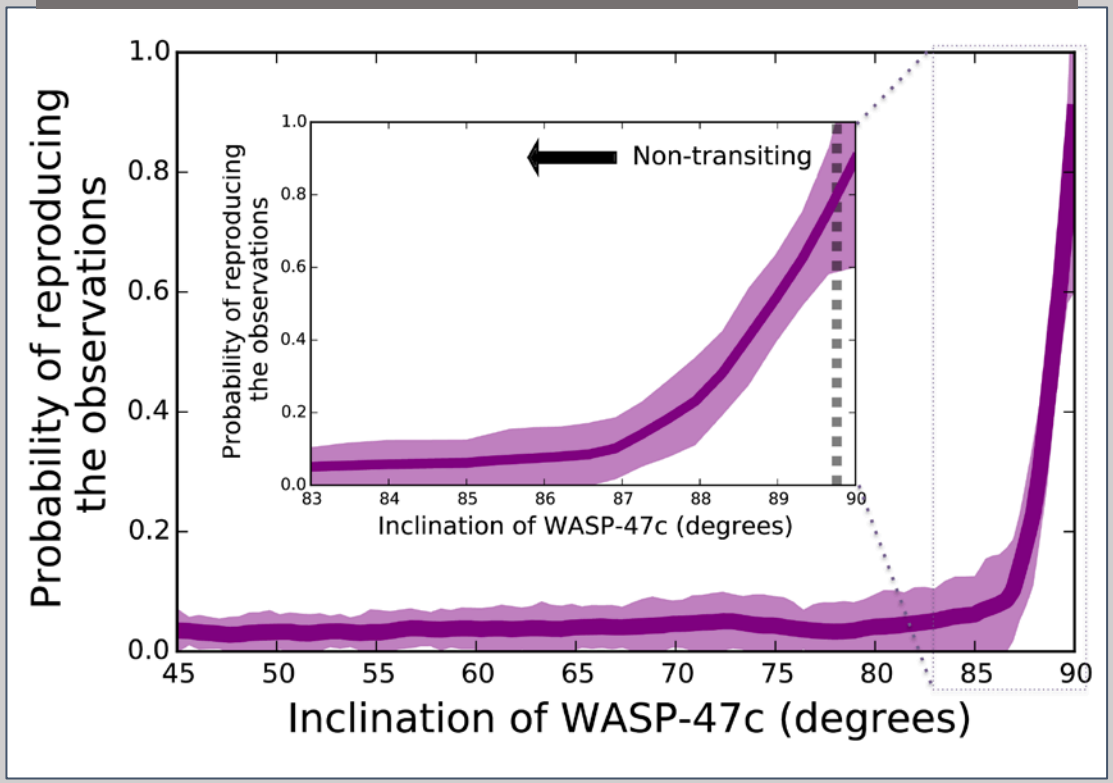
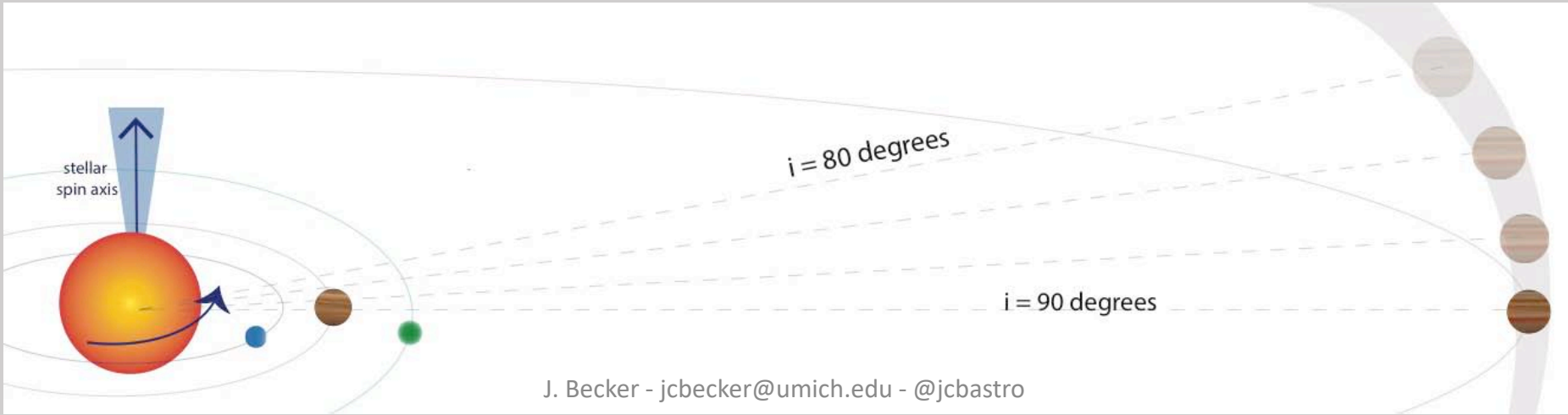
Often misaligned stellar obliquities



Results on this slide published in: Vanderburg, Becker, et al. 2017

Constraints on the inclination of WASP-47c come from obliquity, transit, and dynamical stability limits





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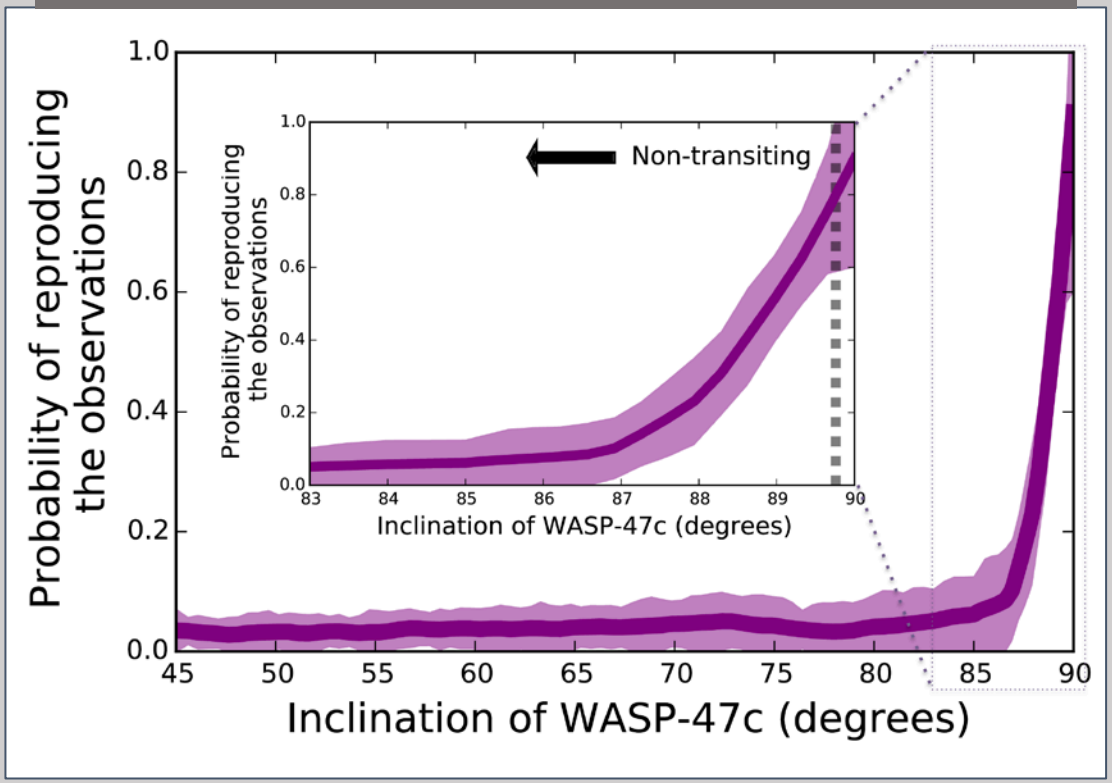
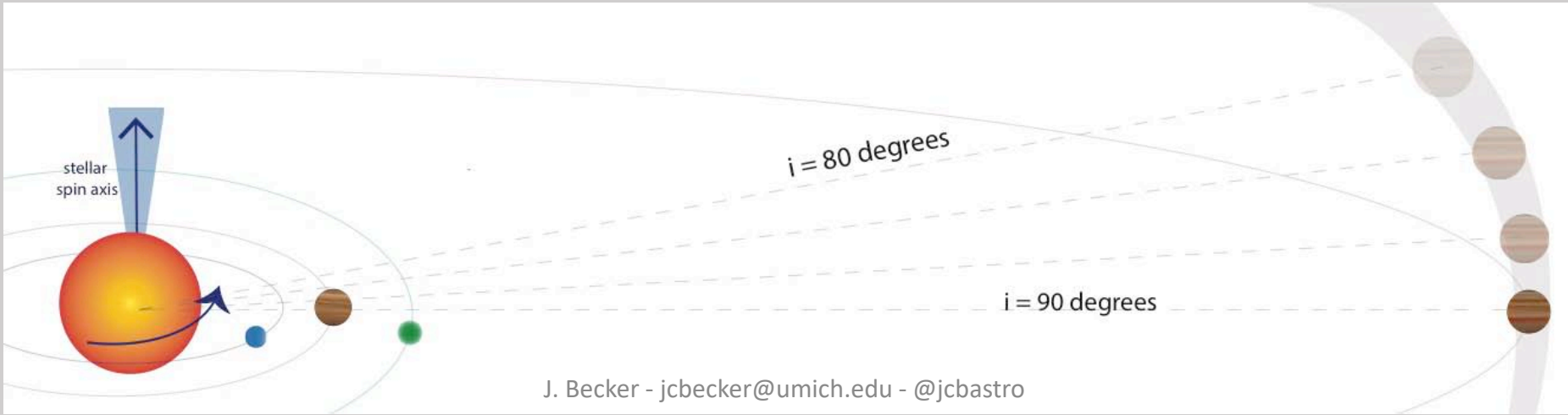
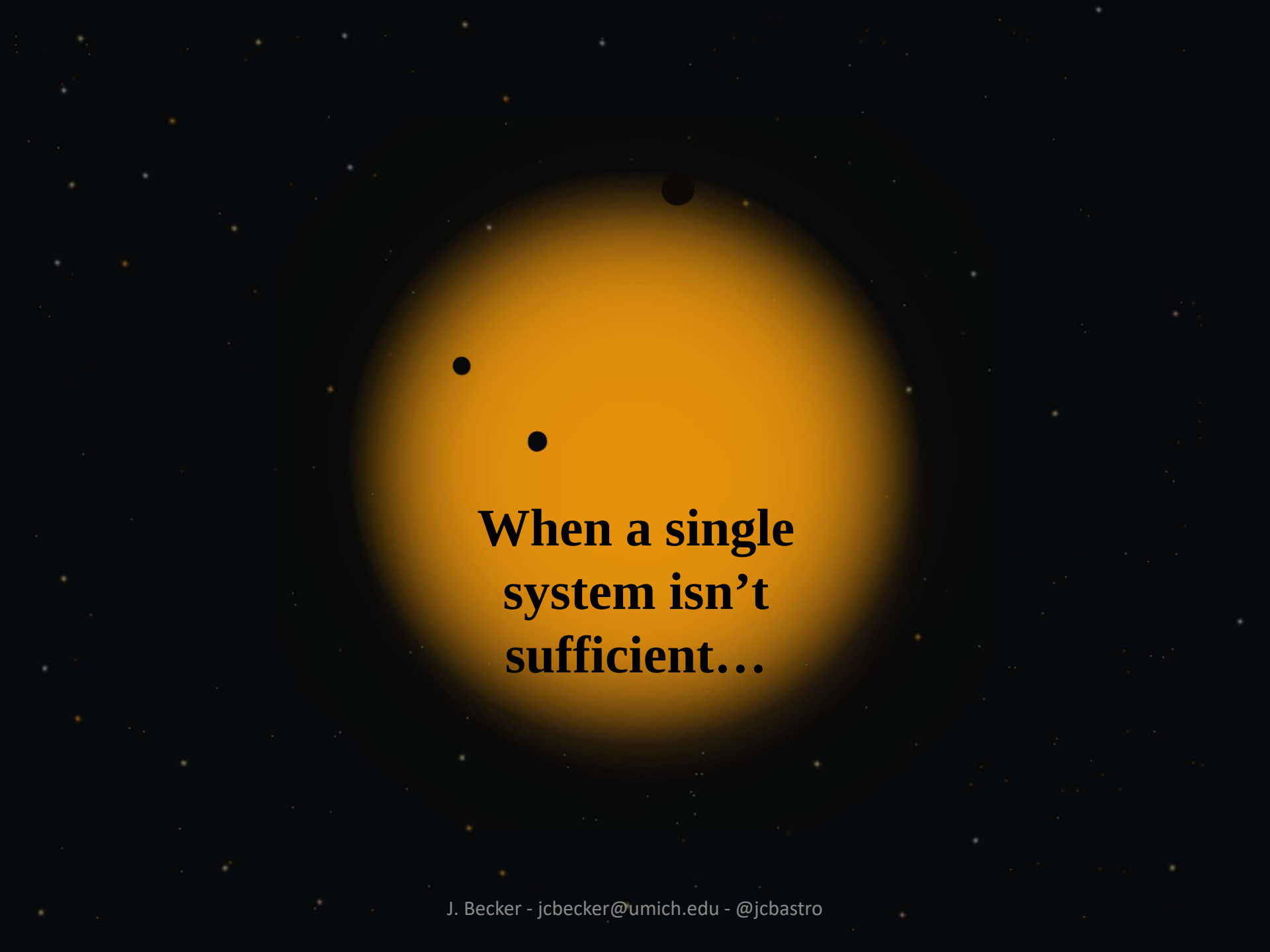
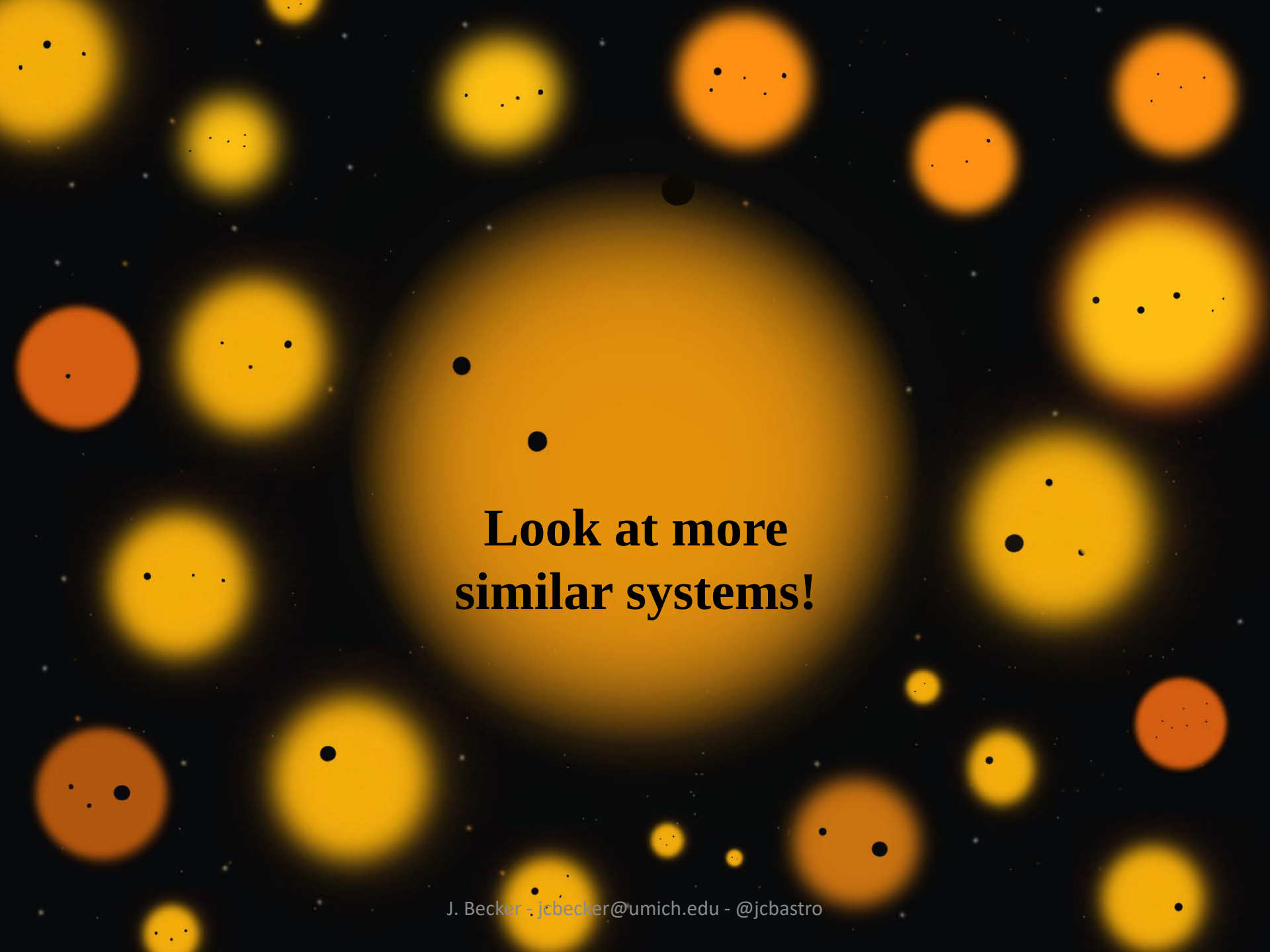
WARNING: This diagram does not actually tell you the inclination of the companion.

Results on this slide published in: Vanderburg, Becker, et al. 2017

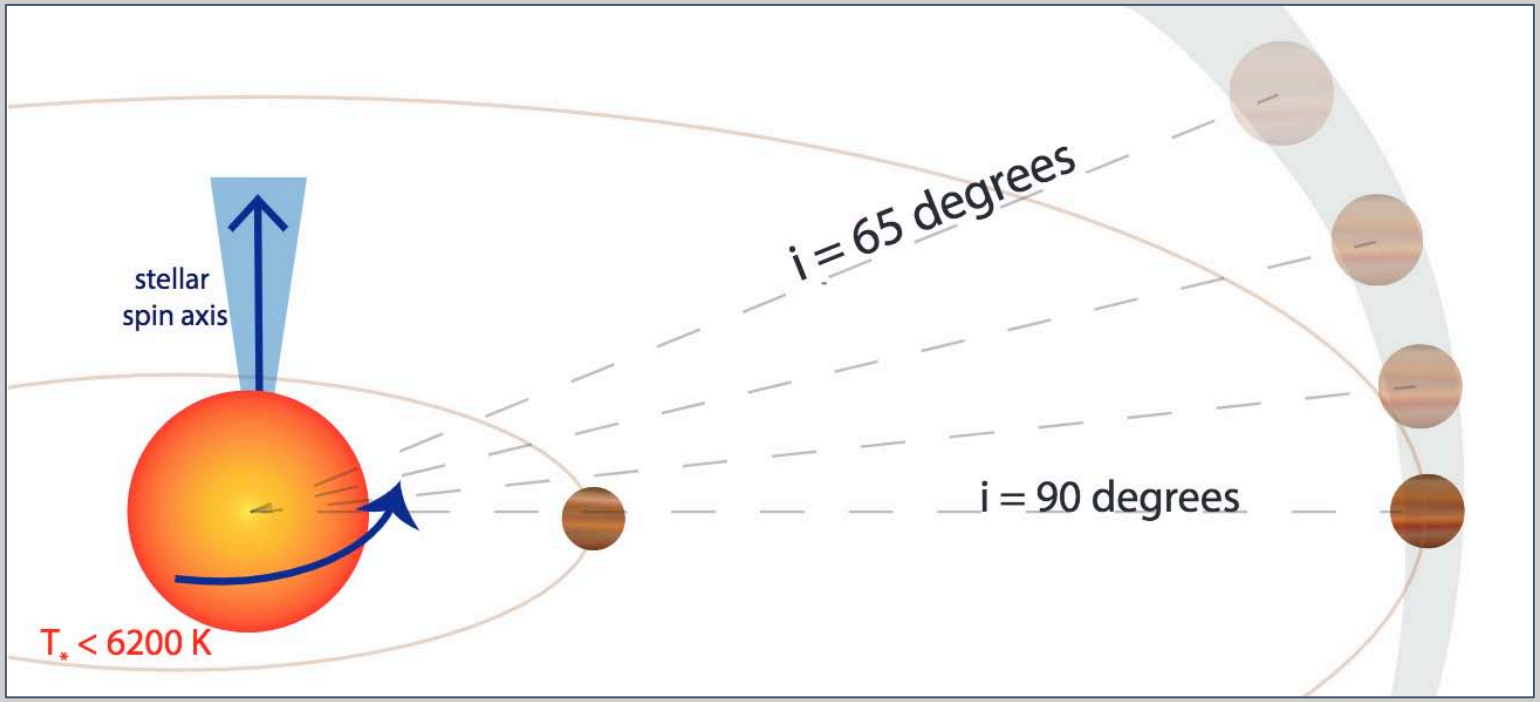





When a single system isn’t sufficient…


Look at more
similar systems!

Constraining the population of companions to cool stars hosting hot Jupiters



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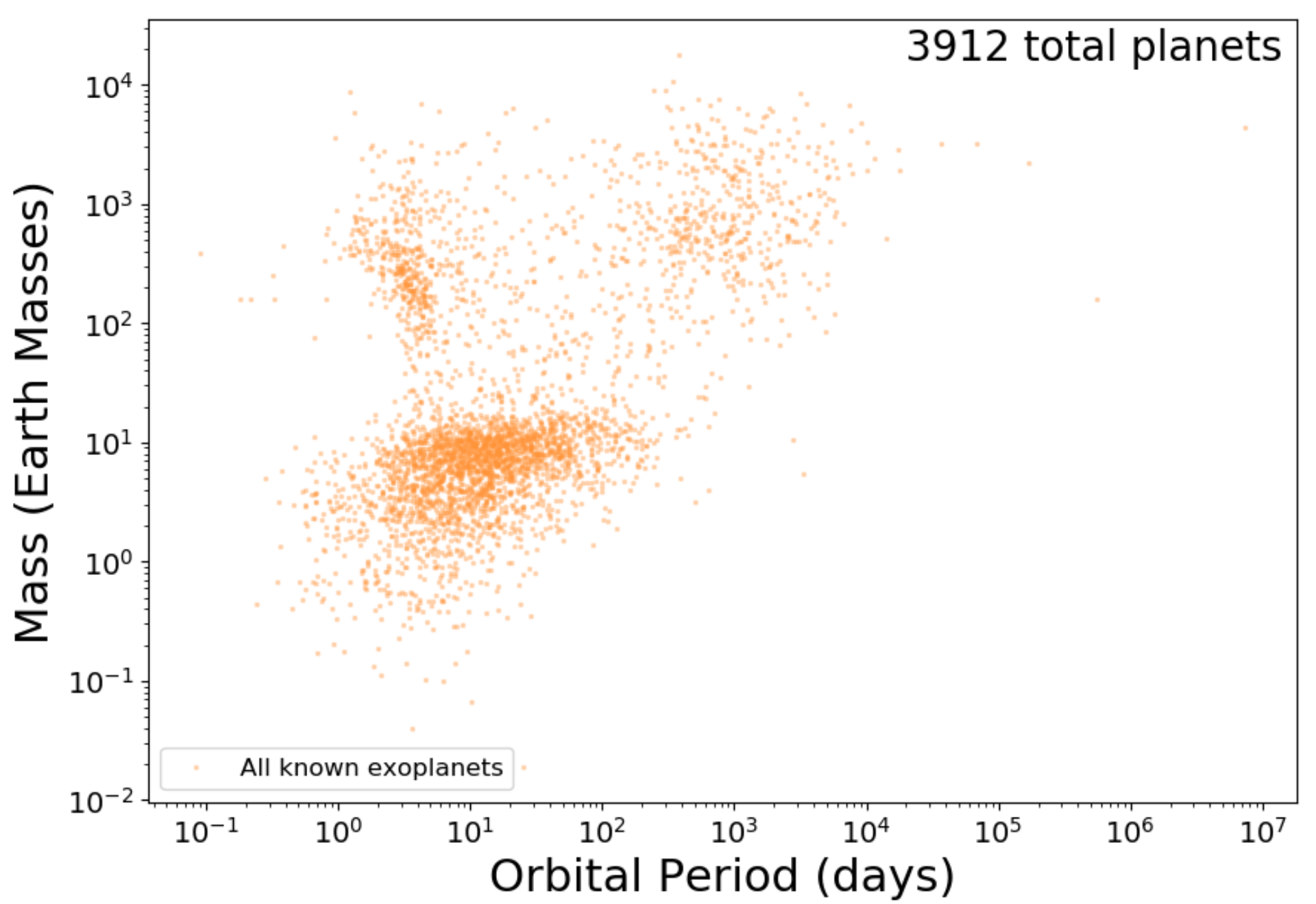
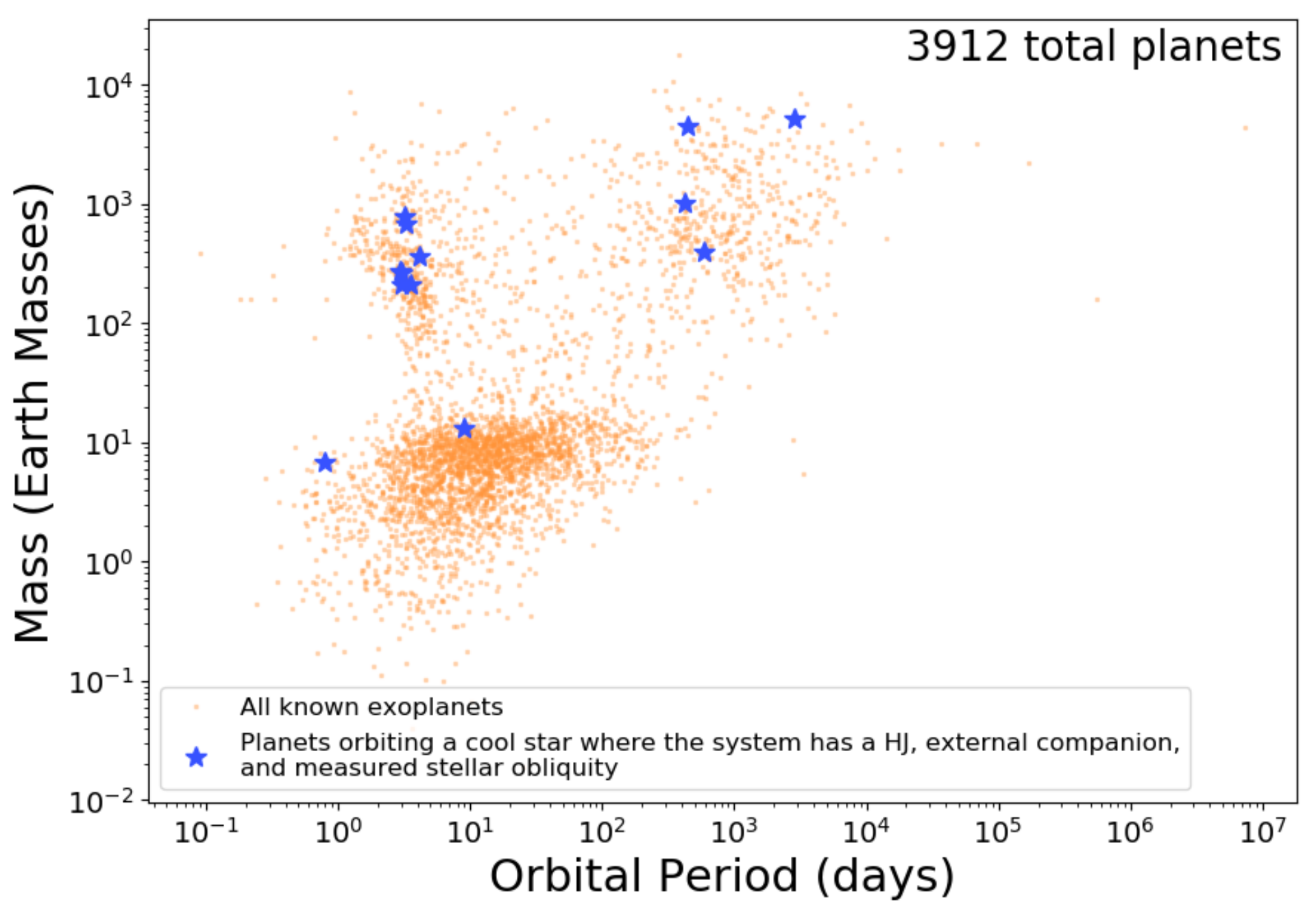
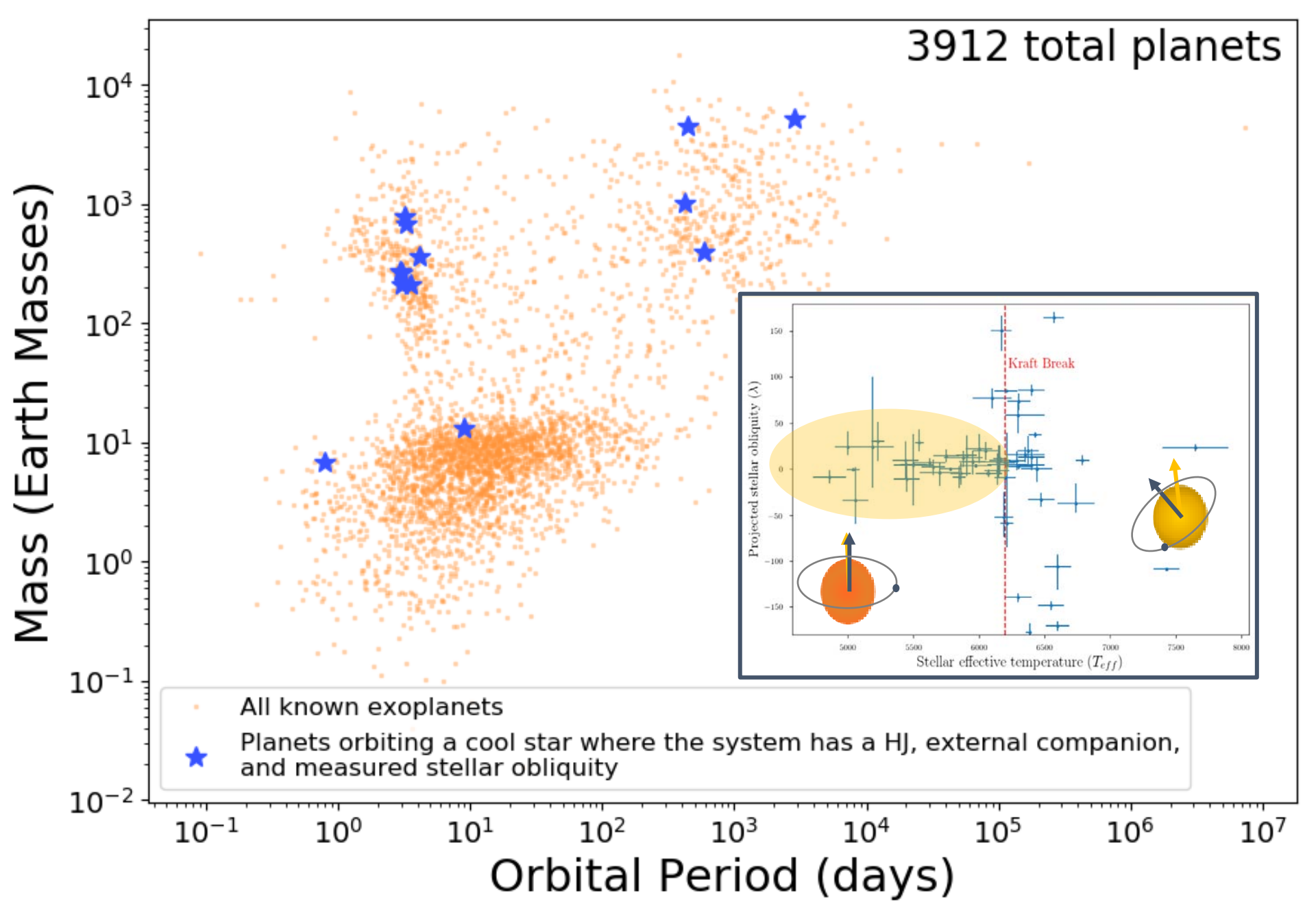
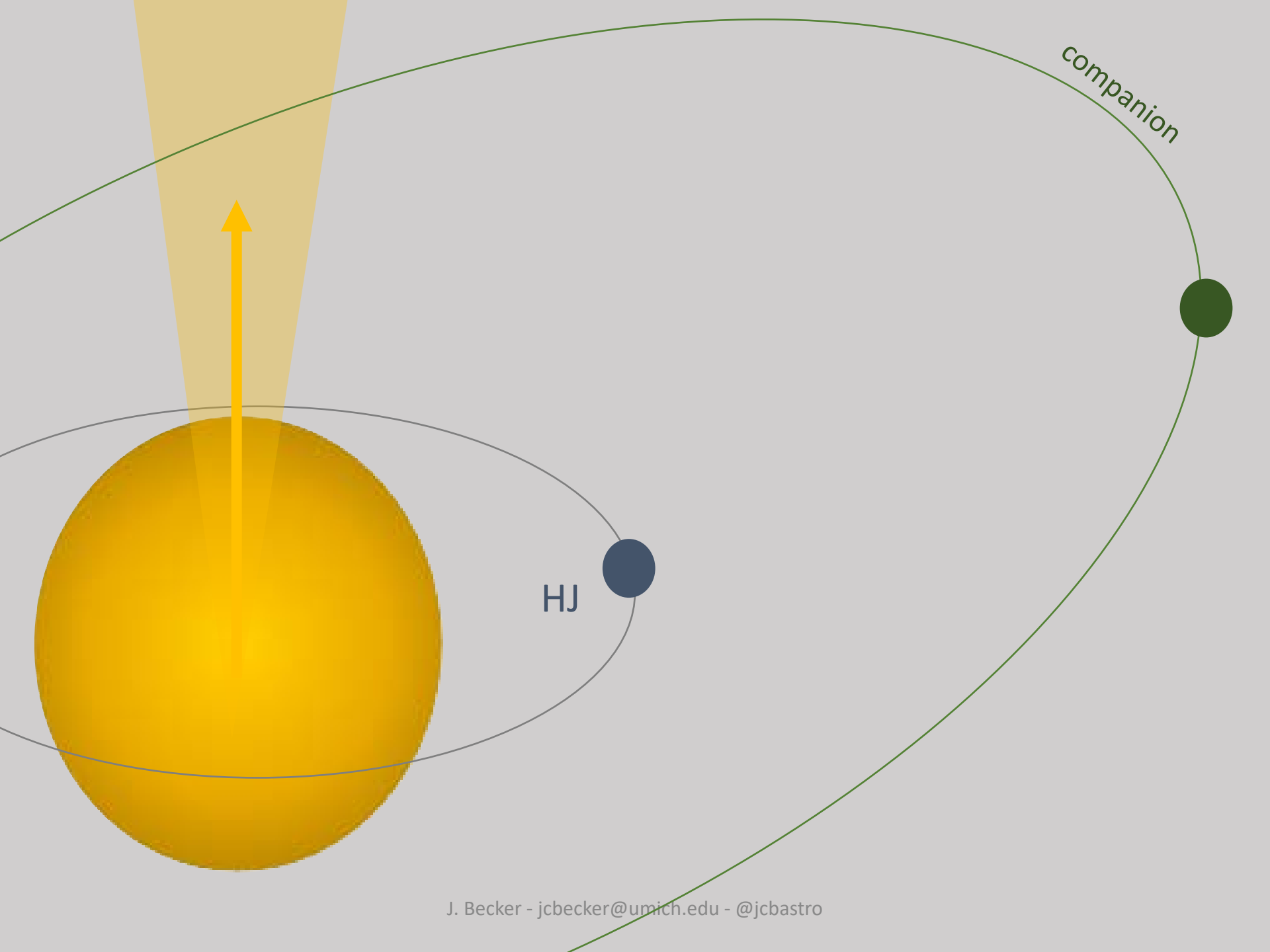
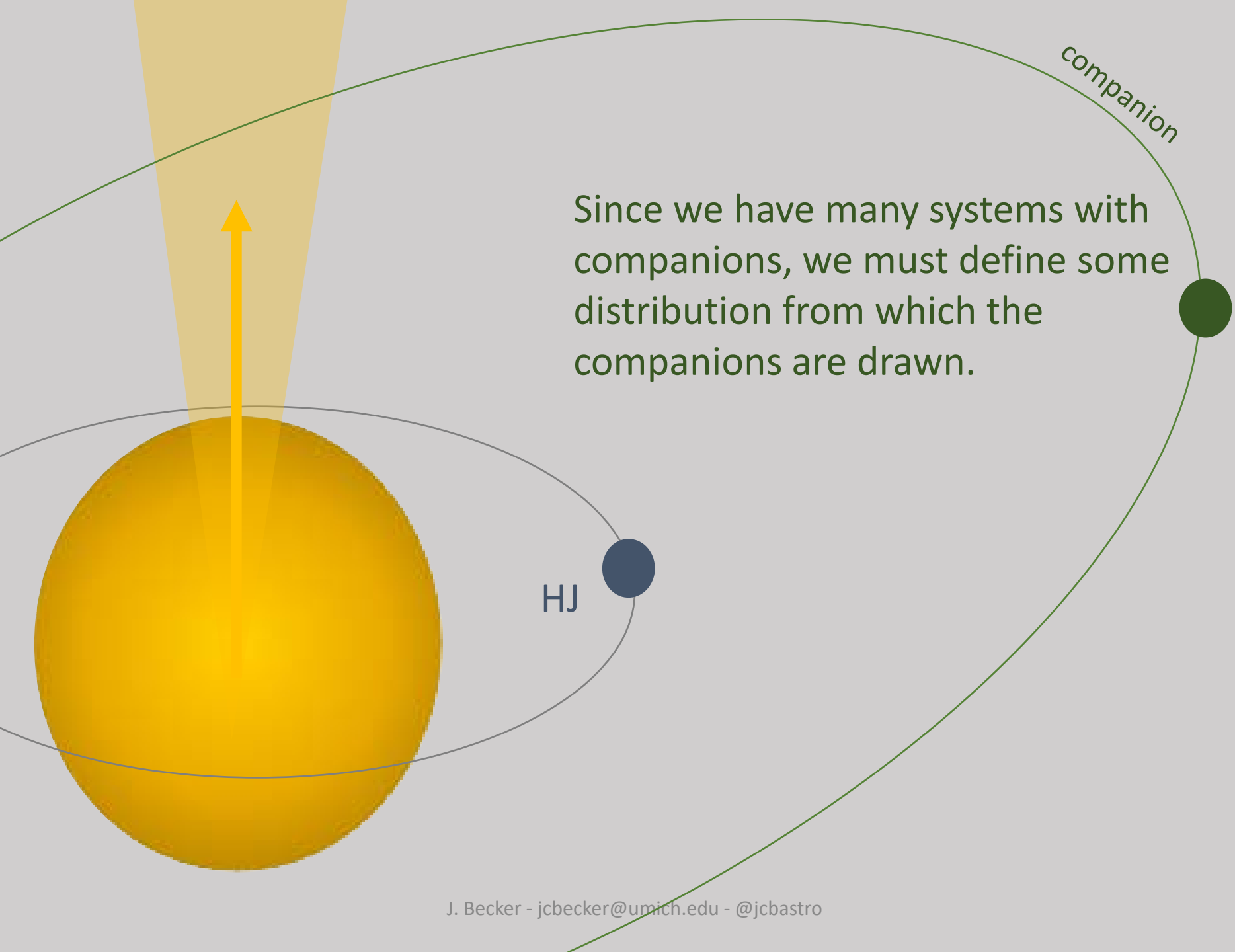

3912 total planets
Mass (Earth Masses)
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
All known exoplanets
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
Orbital Period (days)


3912 total planets
Mass (Earth Masses)
Orbital Period (days)
All known exoplanets
Planets orbiting a cool star where the system has a HJ, external companion, and measured stellar obliquity


3912 total planets
Mass (Earth Masses)
Orbital Period (days)
All known exoplanets
Planets orbiting a cool star where the system has a HJ, external companion, and measured stellar obliquity
Kraft Break
Projected stellar obliquity (λ)
Stellar effective temperature (T_{eff})


companion
HJ



Since we have many systems with companions, we must define some distribution from which the companions are drawn.

companion

HJ

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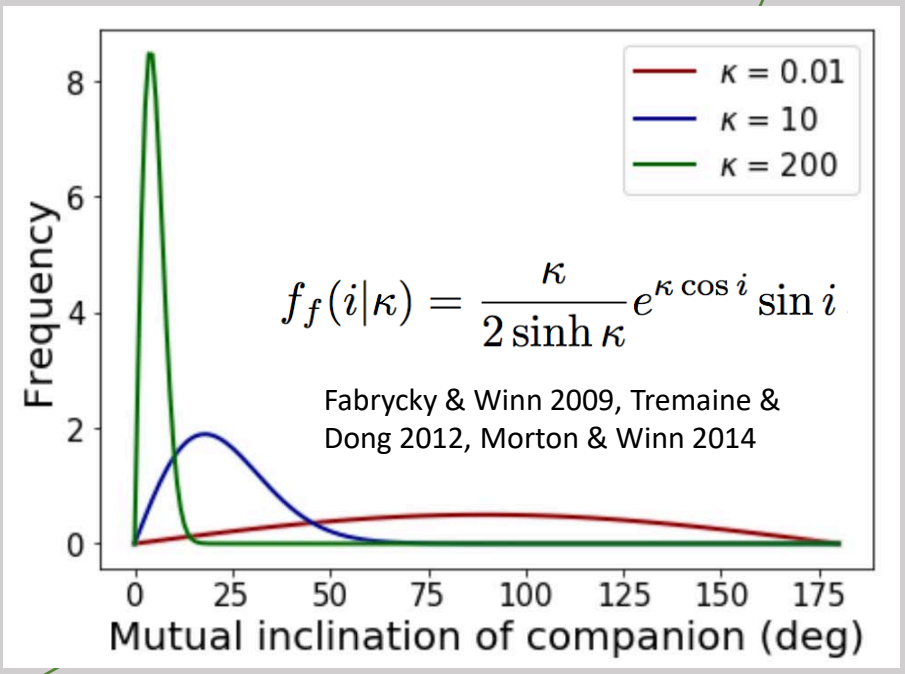
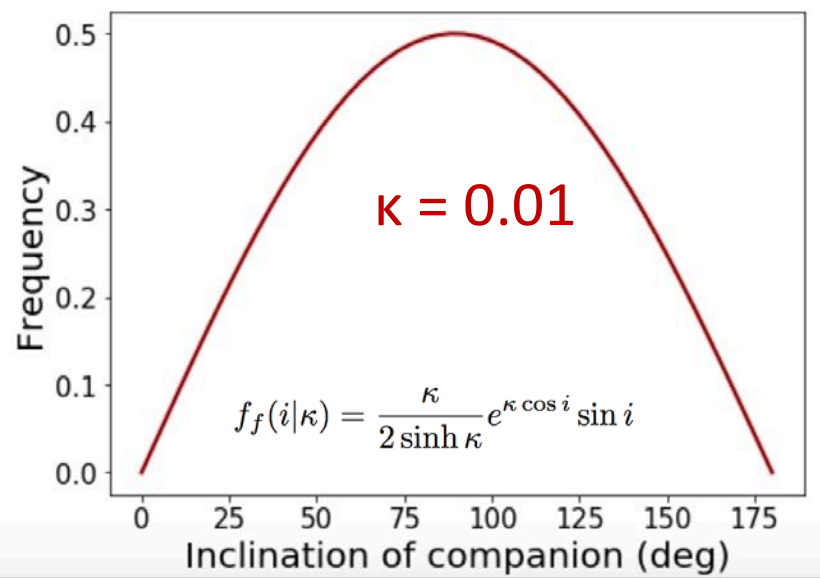
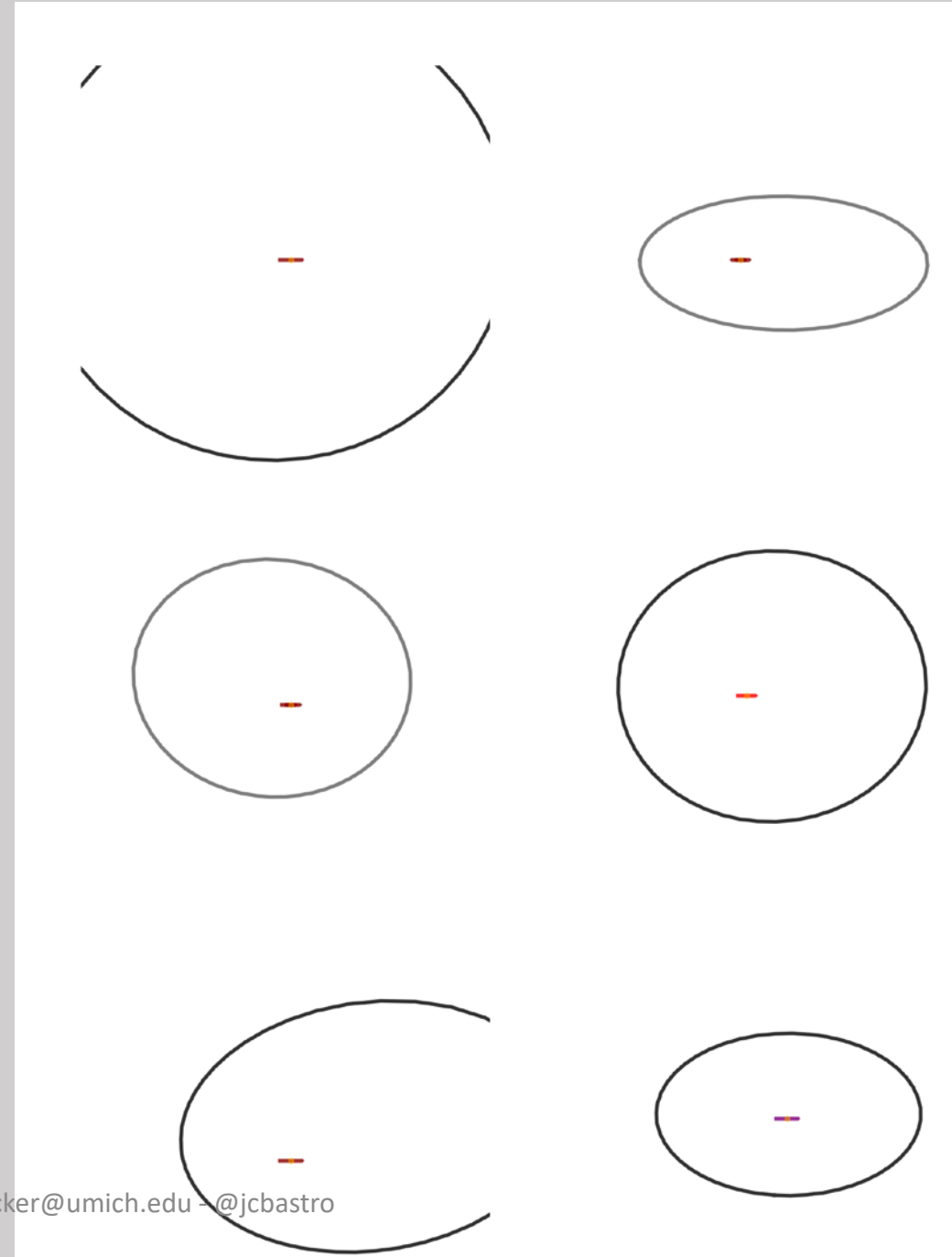
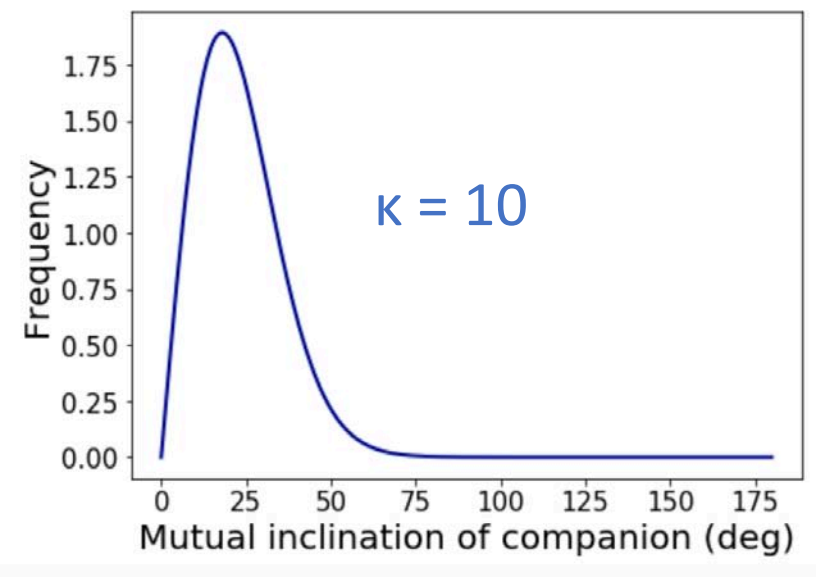




Probability of reproducing observation:

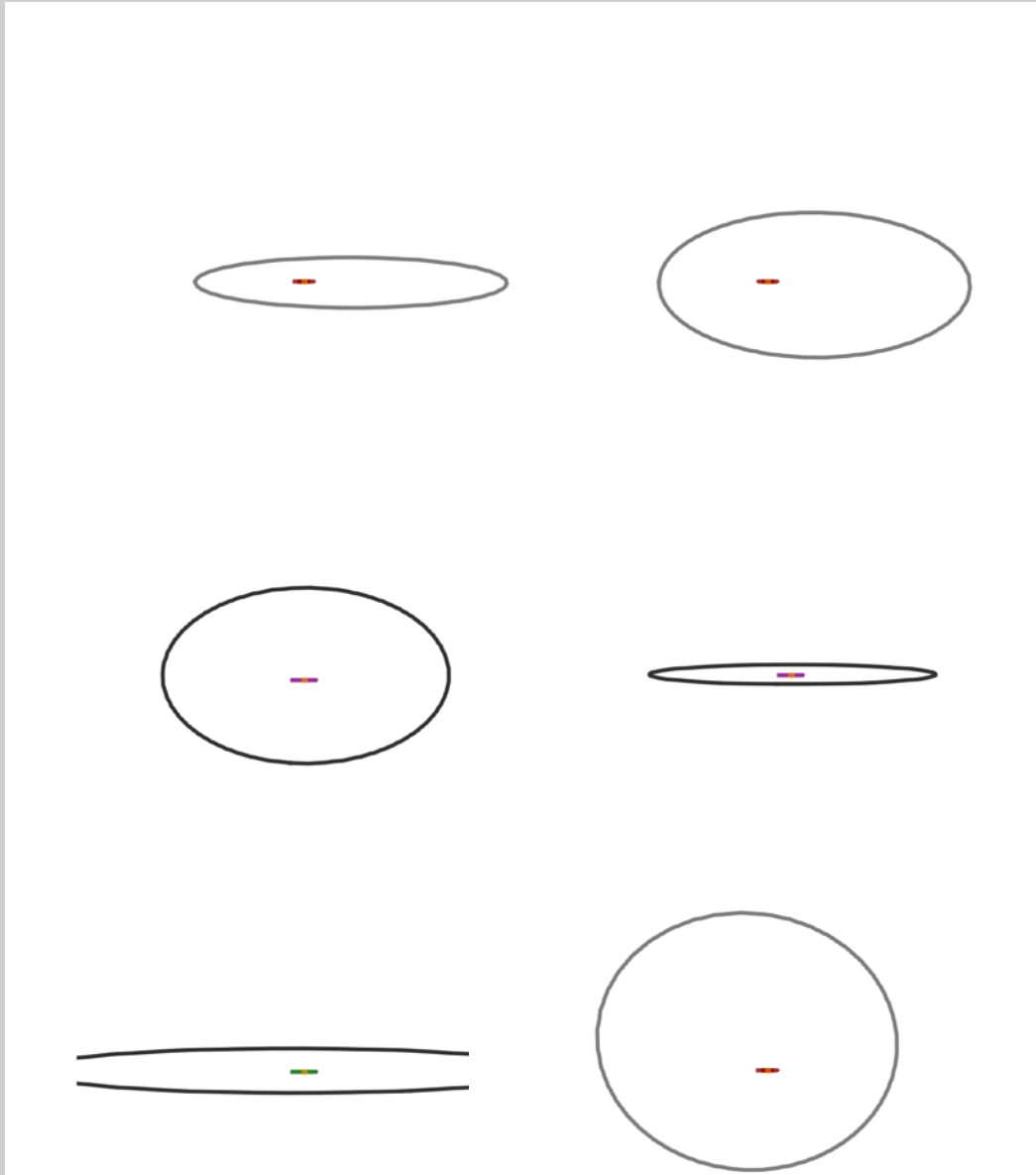
0.2%

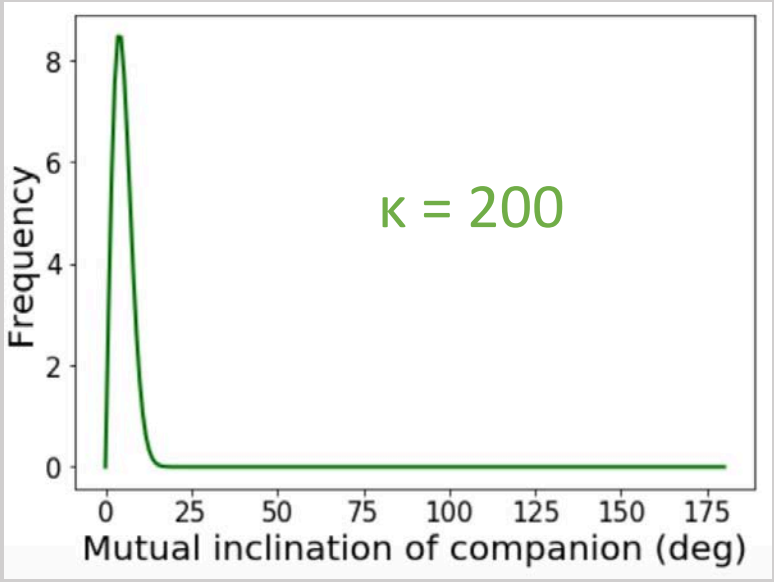




Probability of reproducing observation:

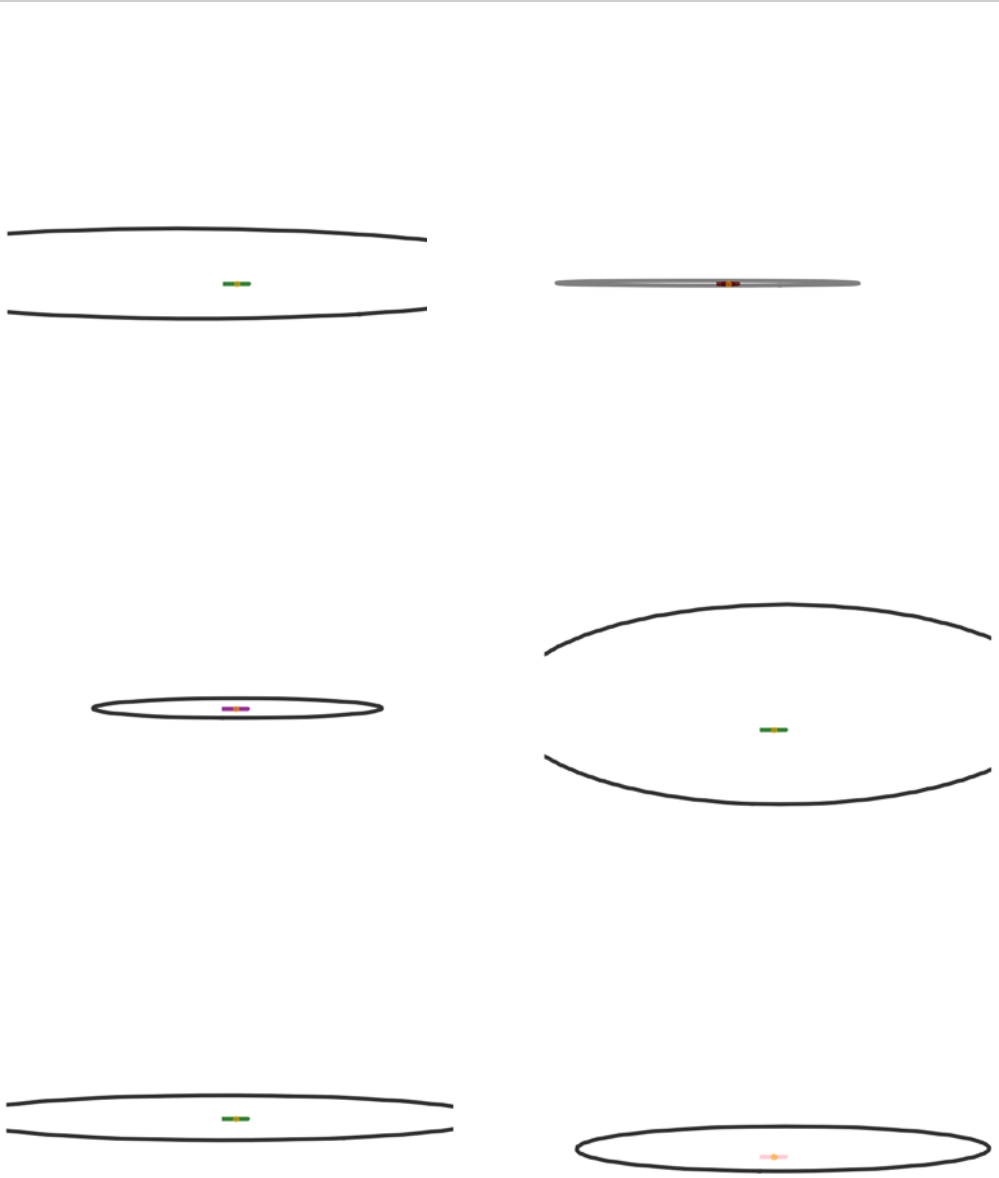
3%

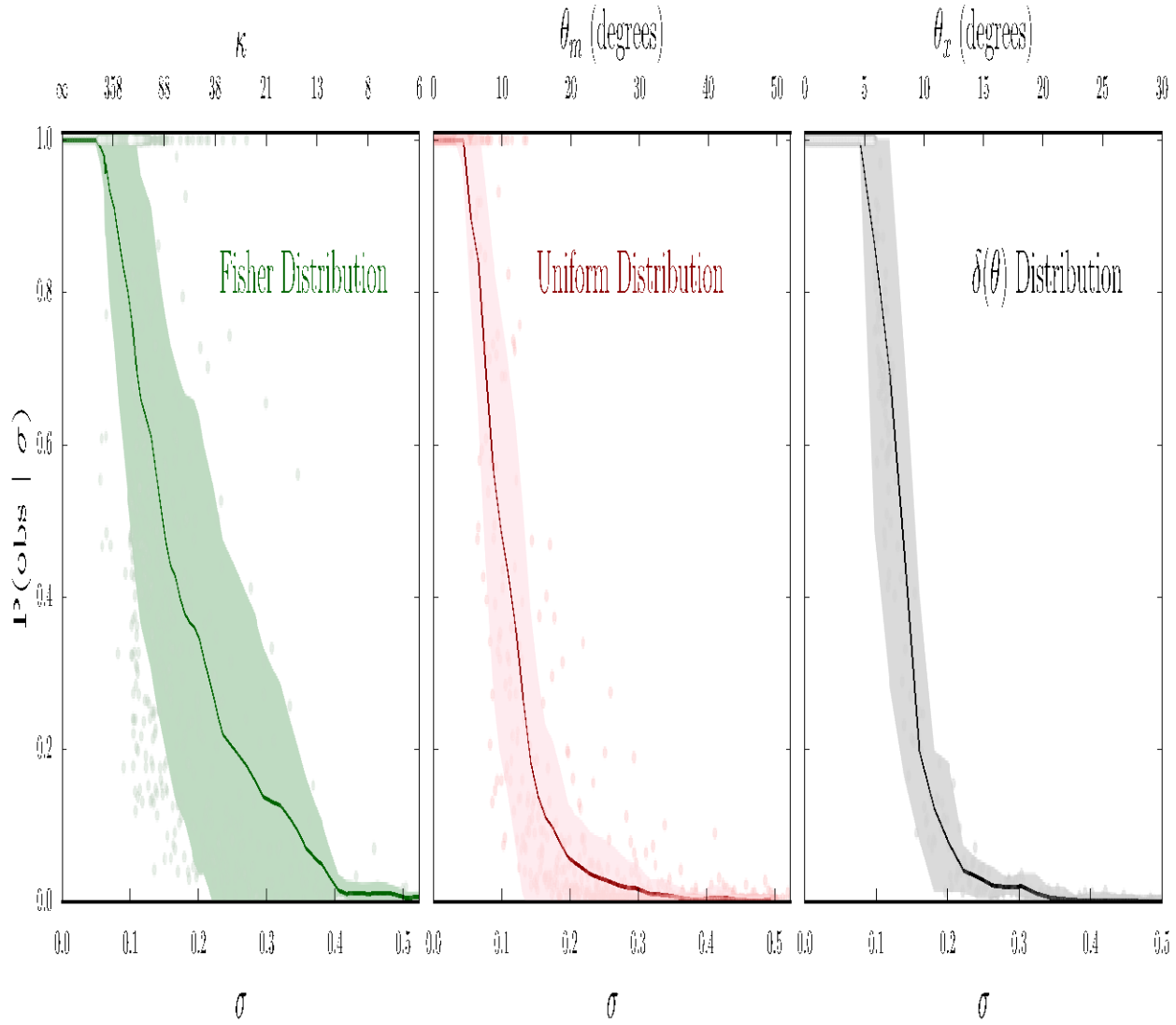


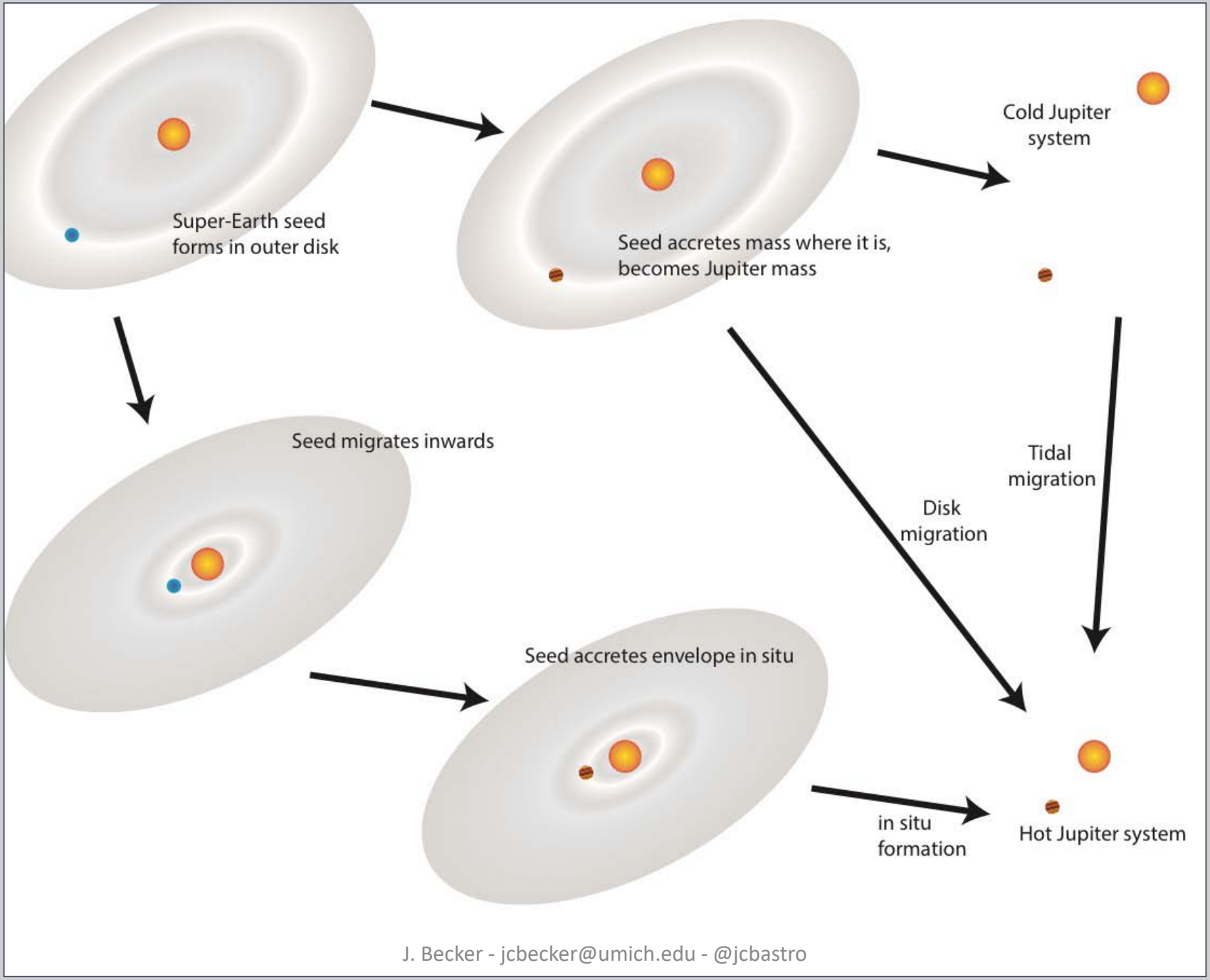


Probability of reproducing observation:

93%




κ
θ_m (degrees)
θ_z (degrees)
Fisher Distribution
Uniform Distribution
$\delta(\theta)$ Distribution
$P(\text{obs} \mid \sigma)$
σ



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What does the evidence support so far?

	Origin hypothesis		
Evidence	**In situ**	**Disk migration**	**Tidal migration**
Elliptical hot Jupiters (HJ)	x	x	
Inflated HJ radii			
HJ semi-major axis distribution			
T Tauri HJ			x
Host star ages	?	?	?
Atmospheres	?	?	?
Nearby planetary companions (*population*)			x
Occurrence rates	?		x
Elliptical warm Jupiters (WJ)	x	x	
Obliquity of cool stars (*population*)			x (high-i)

unknown	consistent	inconsistent

Table inspired by
Dawson & Johnson 2018

Drawing Insights on Past Planetary Migration from Current System States

Single systems are great inspiration / test cases, but **cannot** be used to make population-wide inferences

Populations containing systems similar in some significant way **can** be used to make inferences – large amounts of creativity required to do this!

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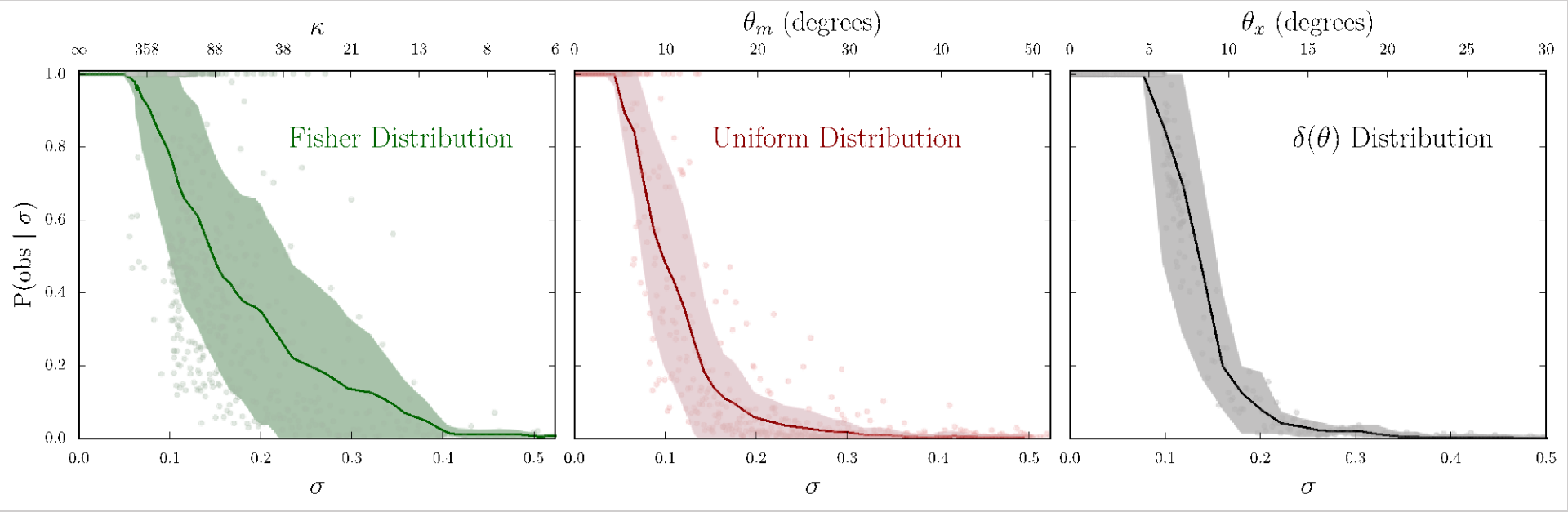
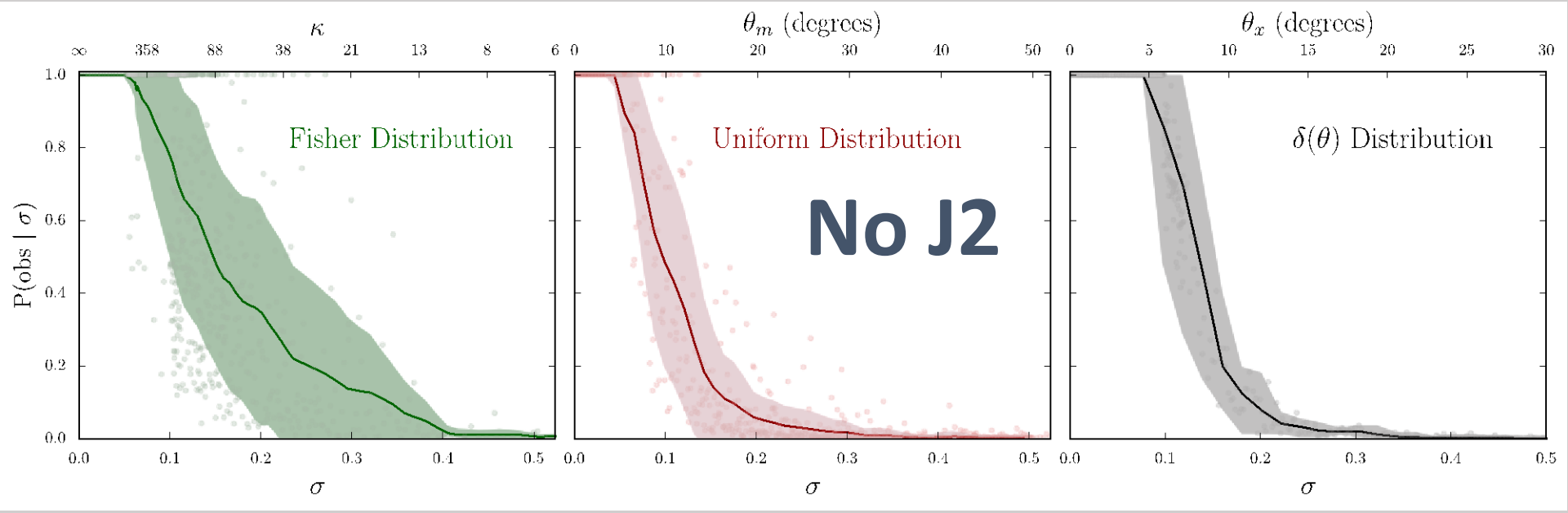
extra slides

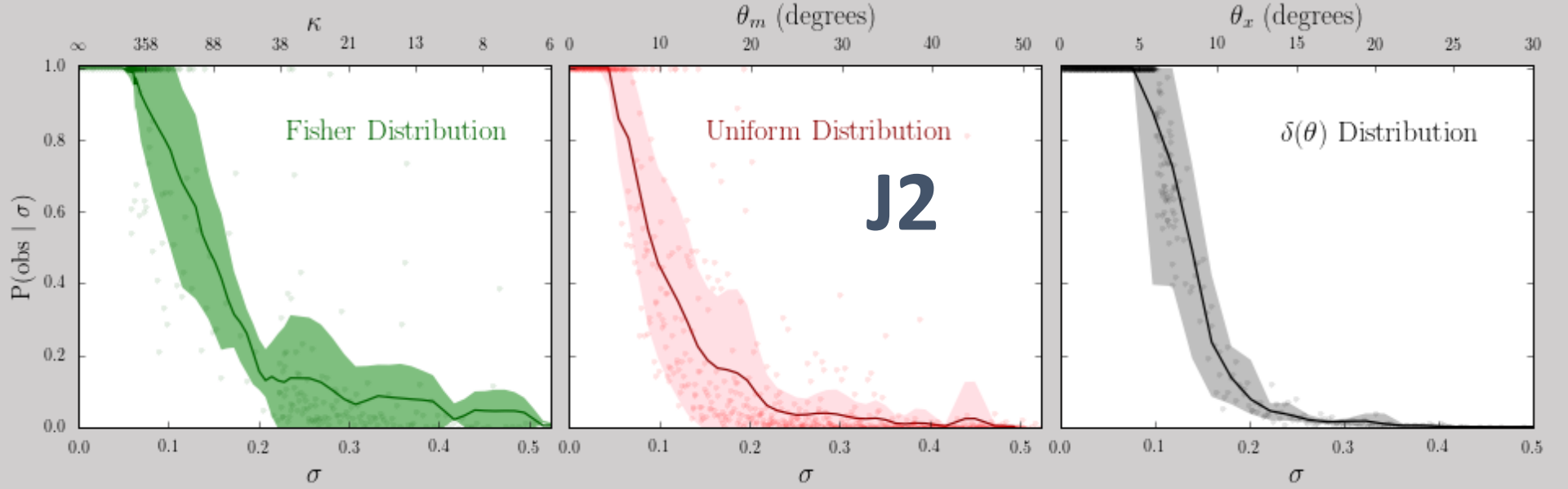
Final result:



The resultant probability distribution for the underlying population of companions

Results on this slide published in: Becker, Vanderburg, Adams et al. 2017


κ
∞ 358 88 38 21 13 8 6
θm (degrees)
0 10 20 30 40 50
θx (degrees)
0 5 10 15 20 25 30
Fisher Distribution
Uniform Distribution
δ(θ) Distribution
No J2
P(obs | σ)
σ


κ
∞ 358 88 38 21 13 8 6
θm (degrees)
0 10 20 30 40 50
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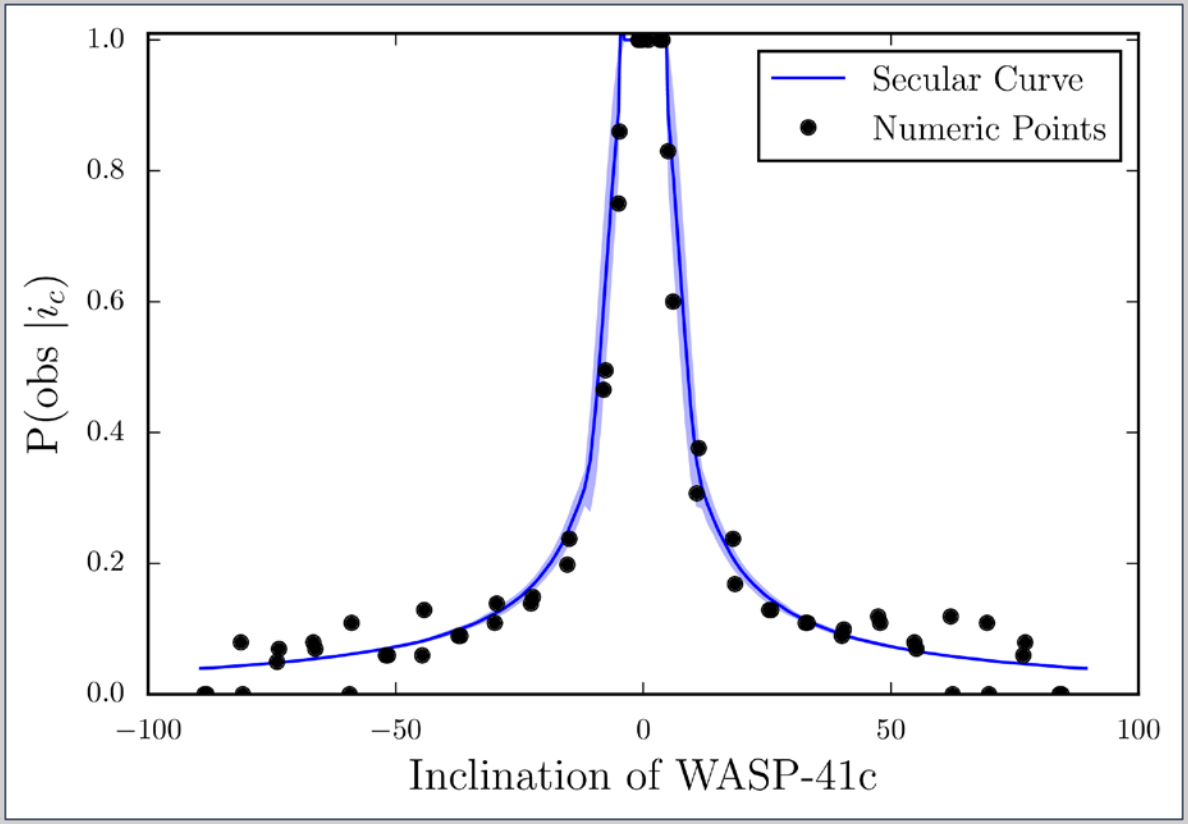
0 5 10 15 20 25 30
Fisher Distribution
Uniform Distribution
δ(θ) Distribution
J2
P(obs | σ)
σ

Results on this slide published in: Becker, Vanderburg, Adams et al. 2017

So, using simulations, check the probability of recreating observations with various inclinations for the outer companions



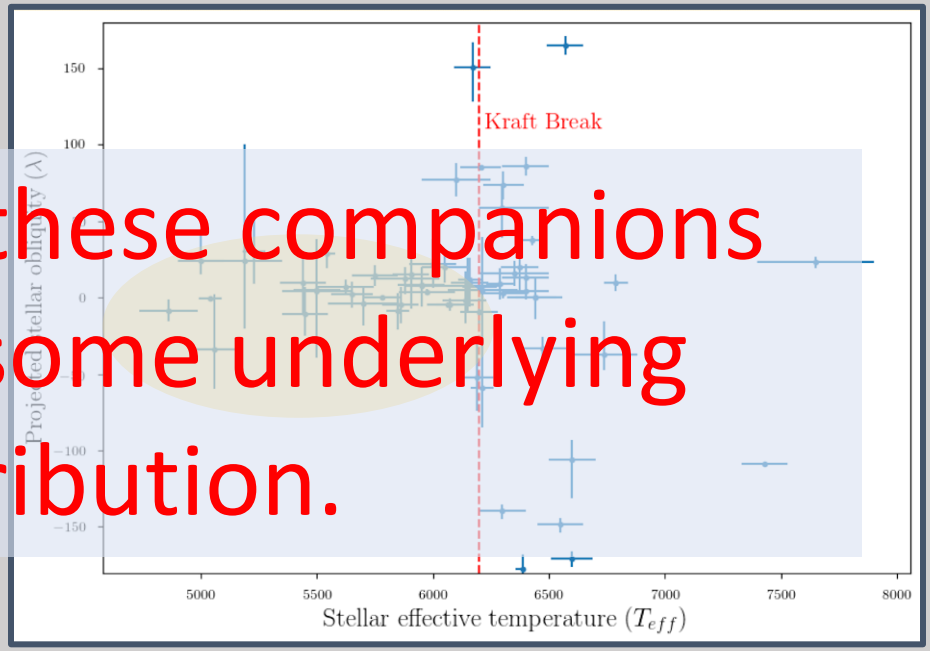
Constraining the population of companions to cool stars hosting hot Jupiters

Systems included in our analysis

HAT-P-4
HAT-P-13
WASP-22
WASP-41
WASP-47
WASP-53

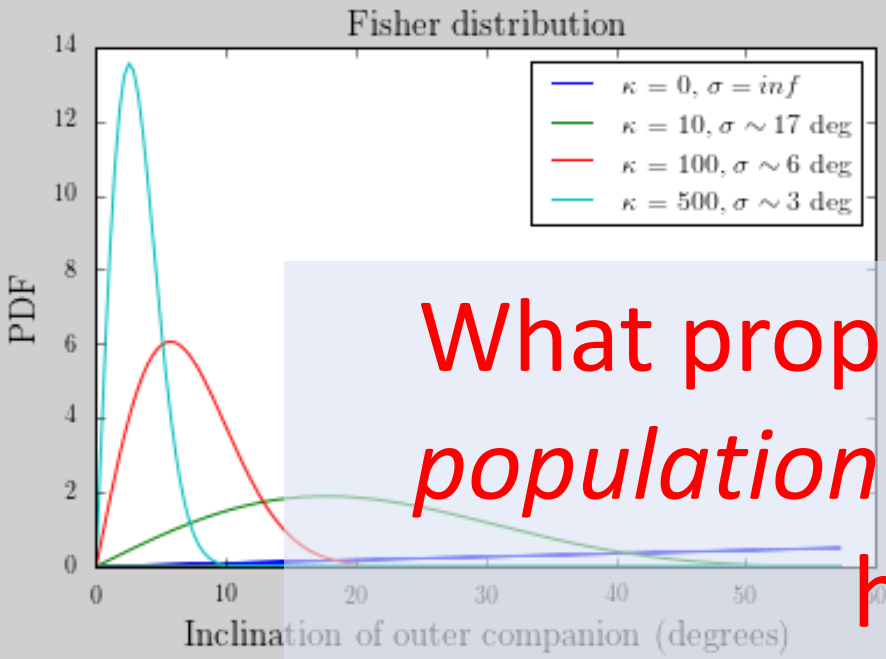
Systems since found to also fit trend (but not included)

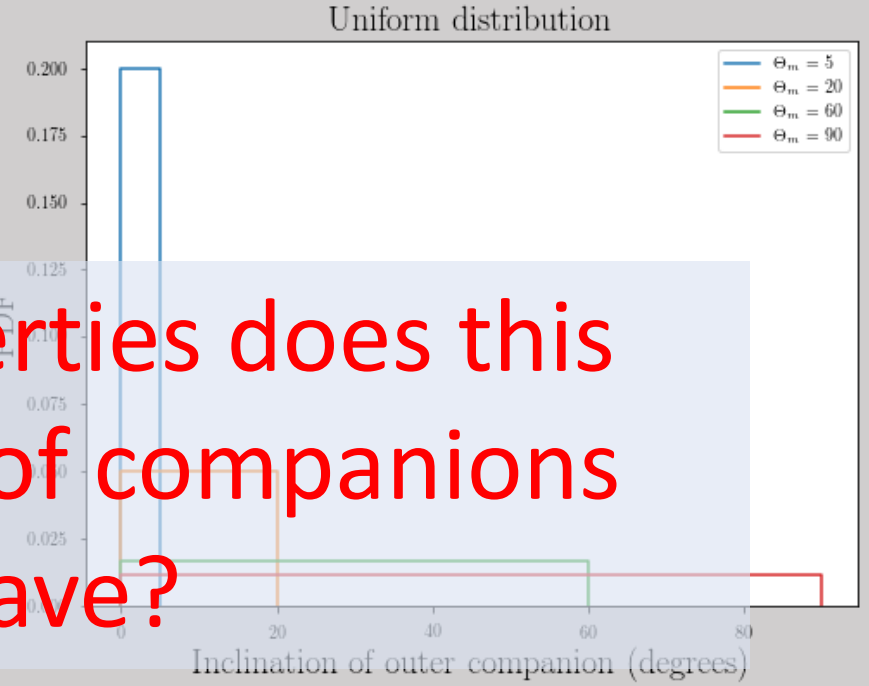
HAT-P-22



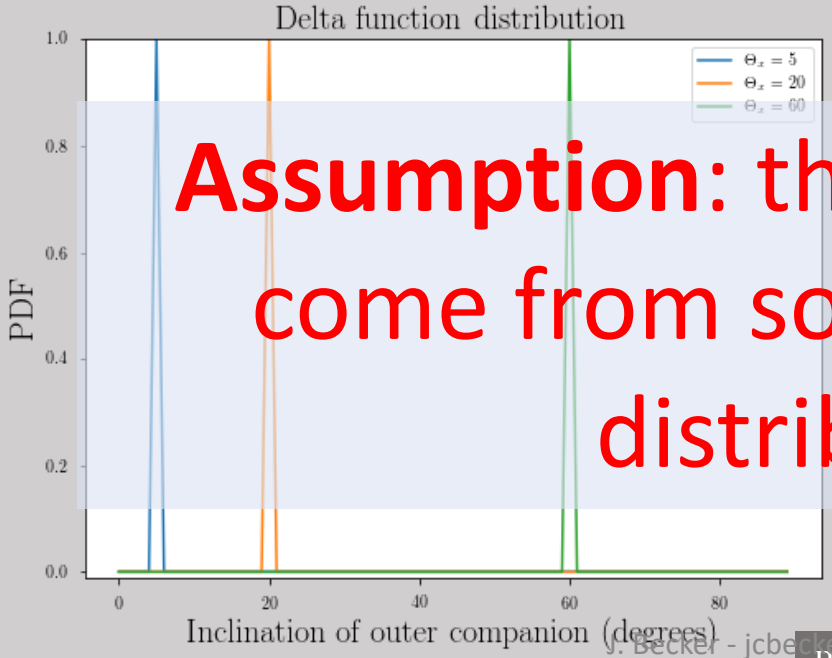
Assumption: these companions come from some underlying distribution.

Results on this slide published in: Becker, Vanderburg, Adams et al. 2017





What properties does this *population* of companions have?



Assumption: these companions come from some underlying distribution.

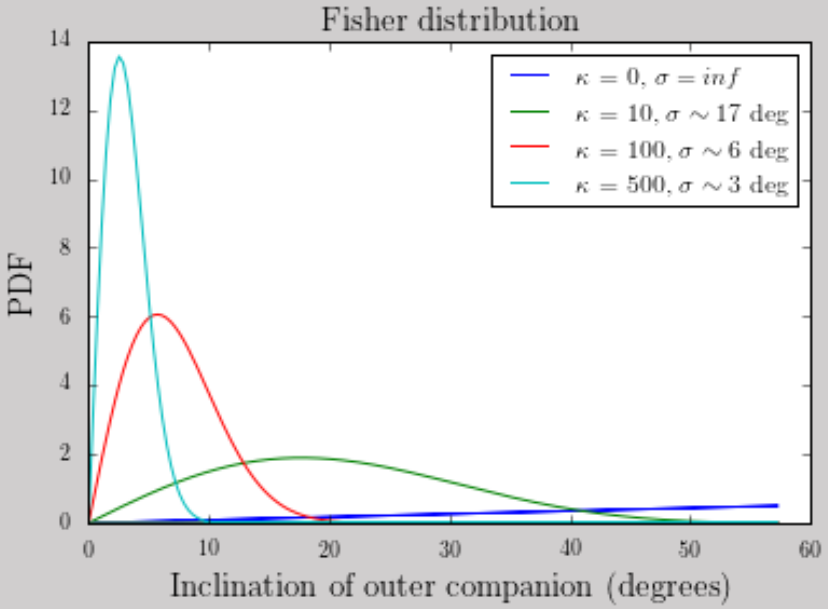
Results on this slide published in: Becker, Vanderburg, Adams et al. 2017

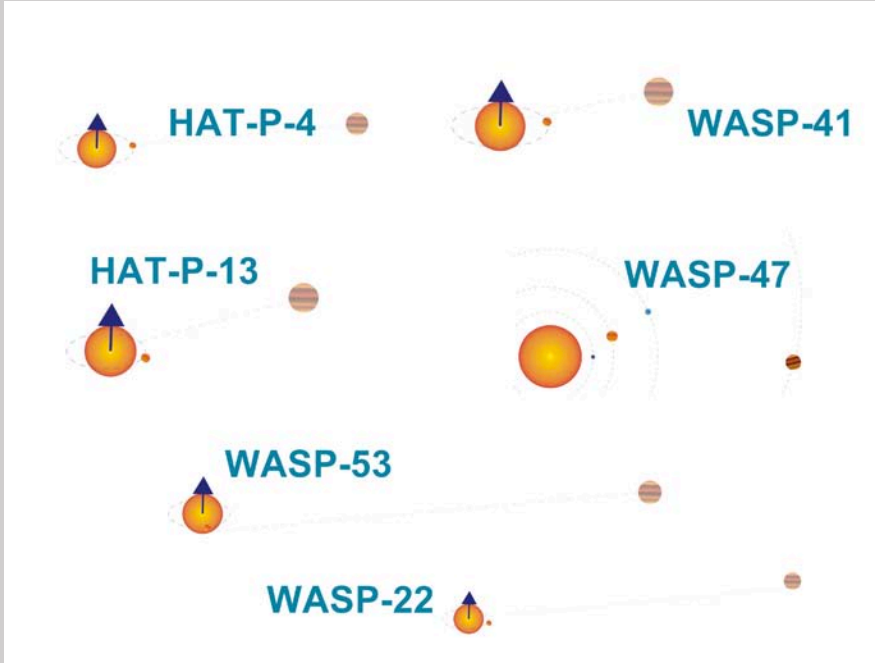
Per each companion distribution type:

1) Choose a width from which to draw companion inclinations

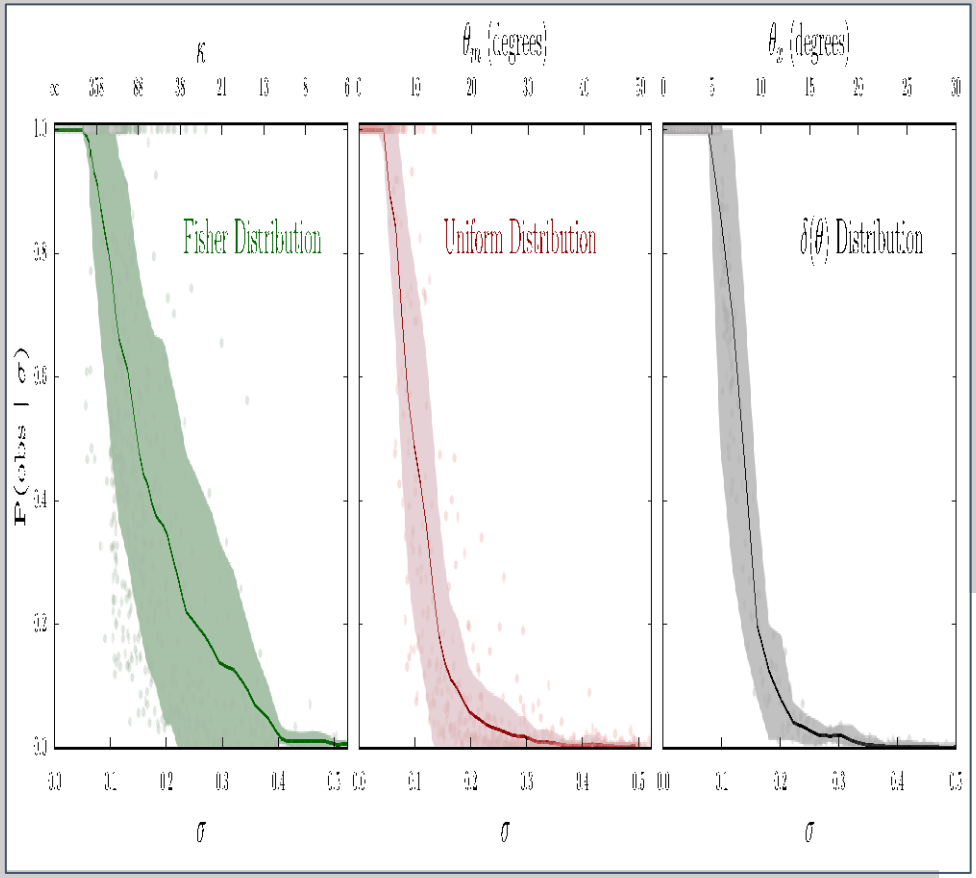
2) Generate the "observations" by generating all systems, choosing inclinations from the distribution chosen

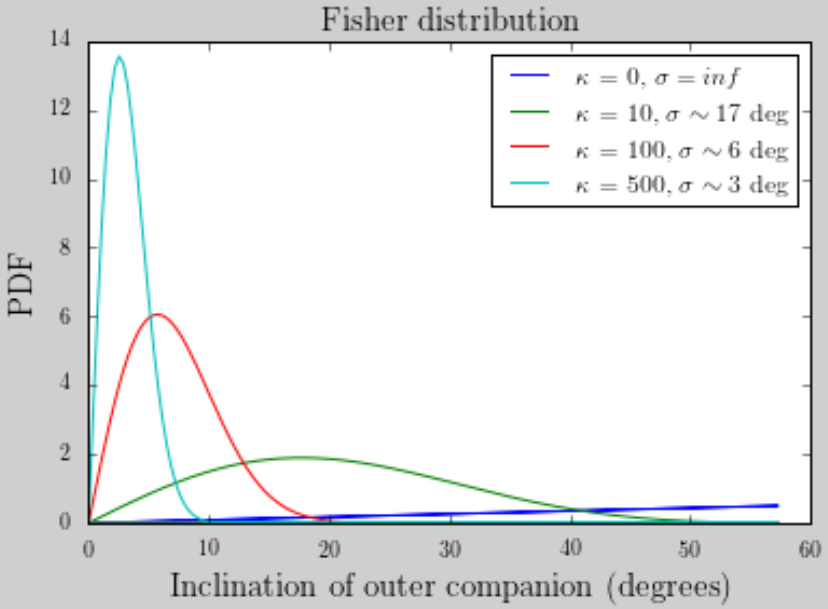
3) Test if our simulated observations recreate **true observation**

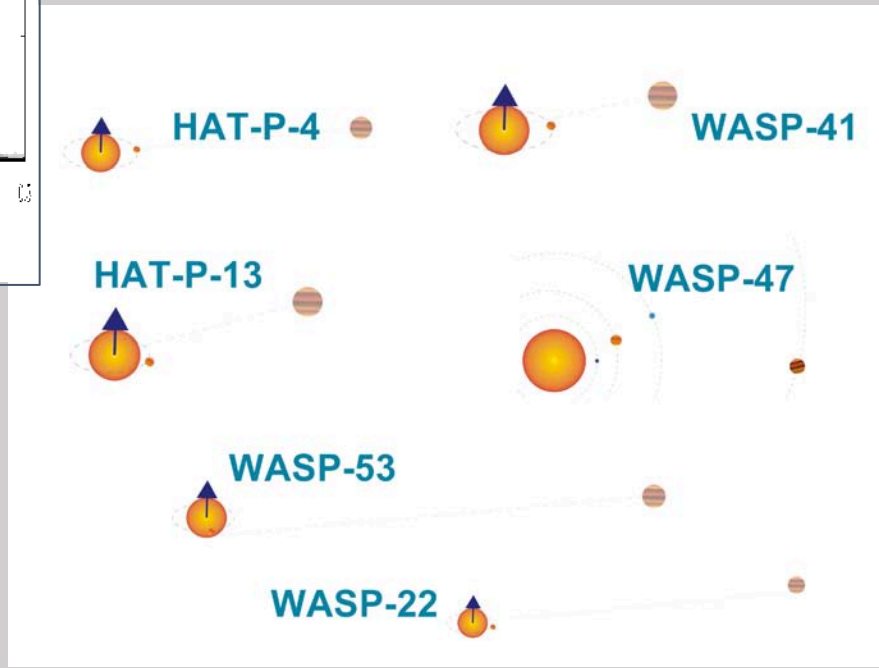




Results on this slide published in: Becker, Vanderburg, Adams et al. 2017







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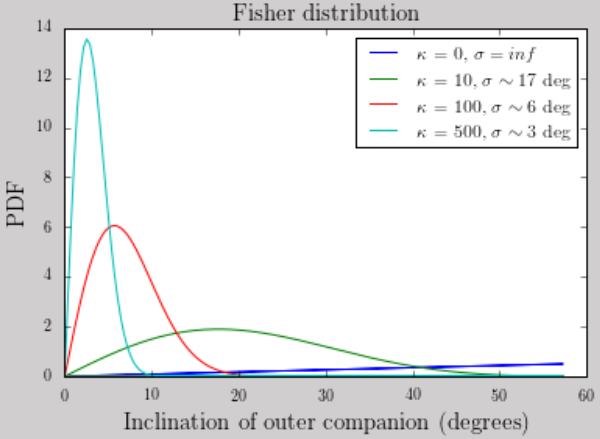

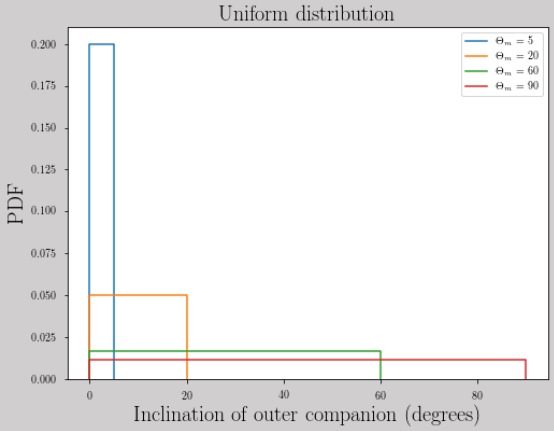

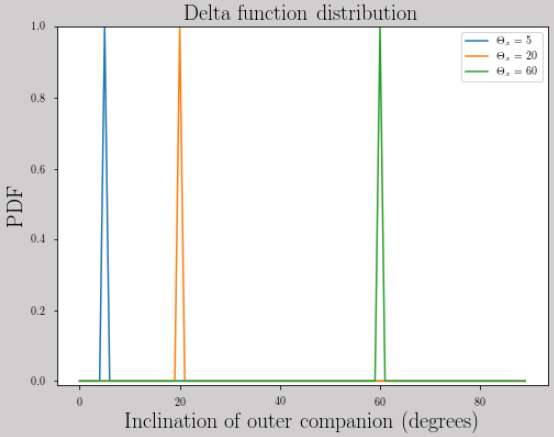

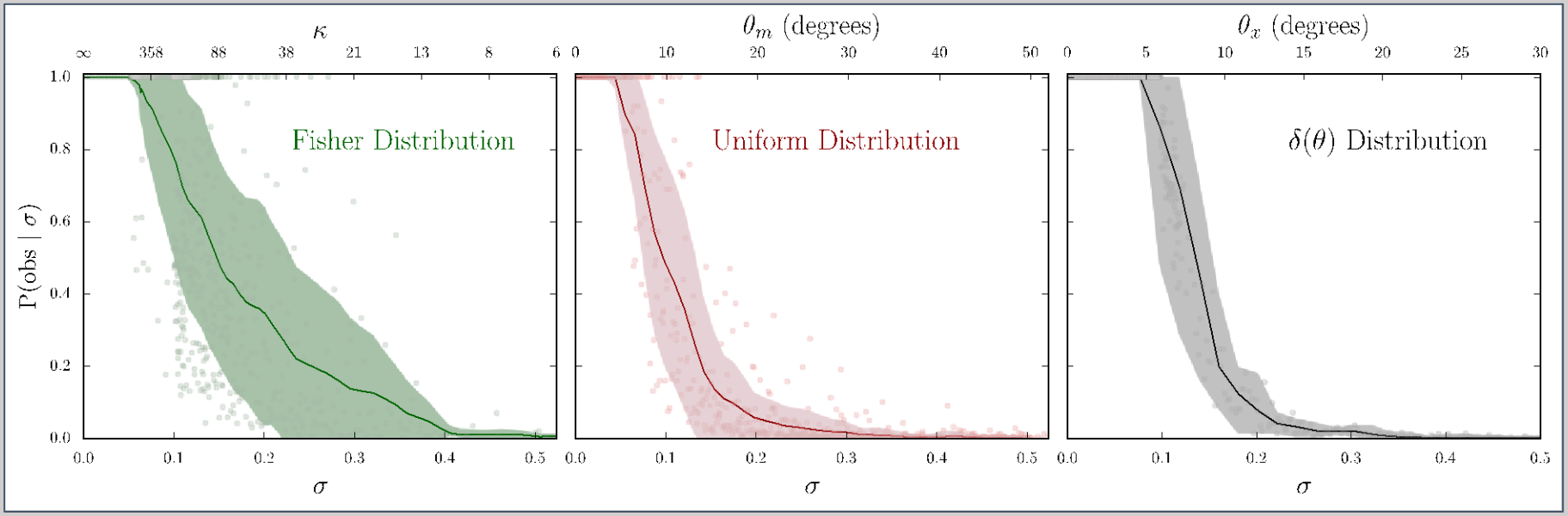

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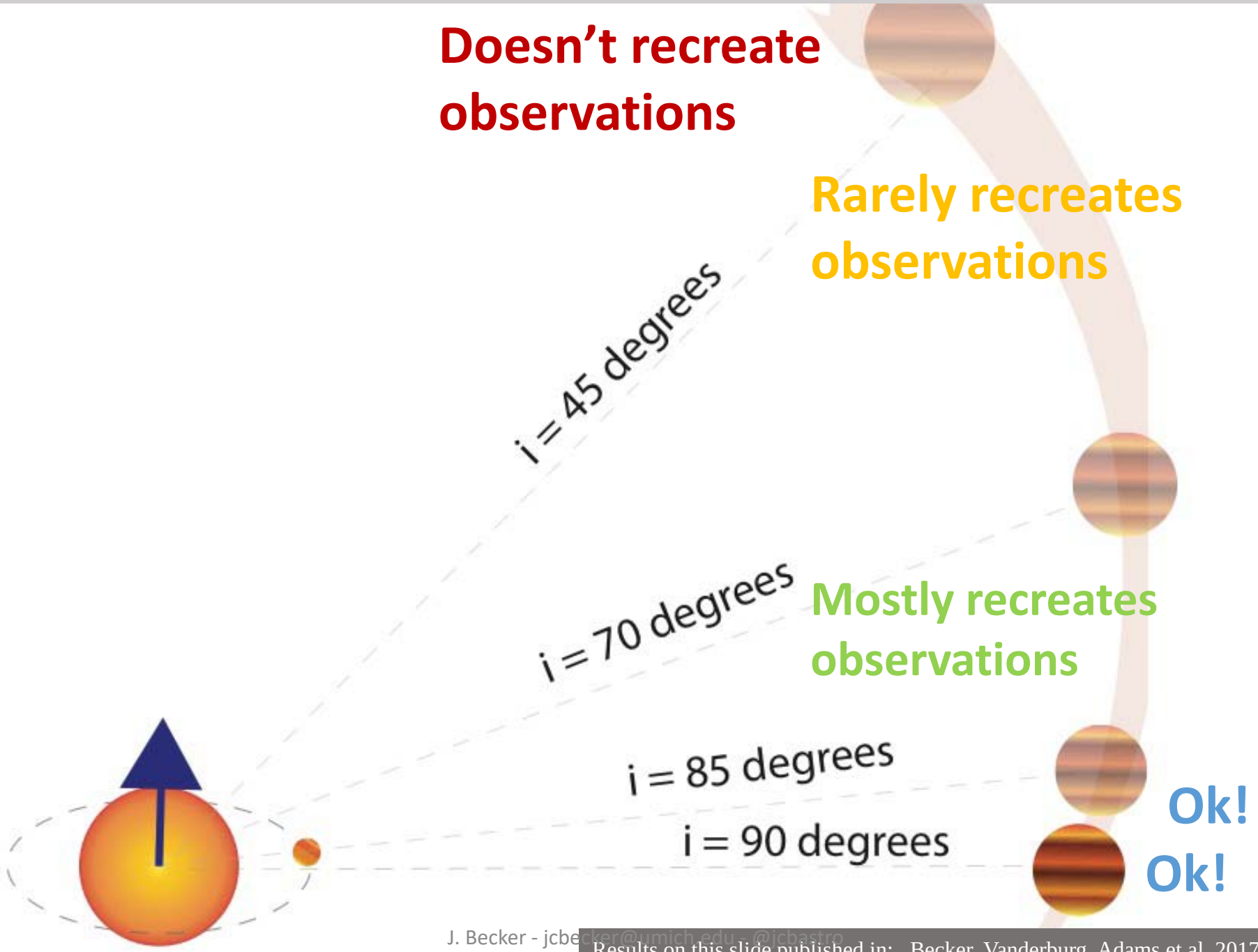
Doesn't recreate observations

Rarely recreates observations



Mostly recreates observations

Ok!

Ok!

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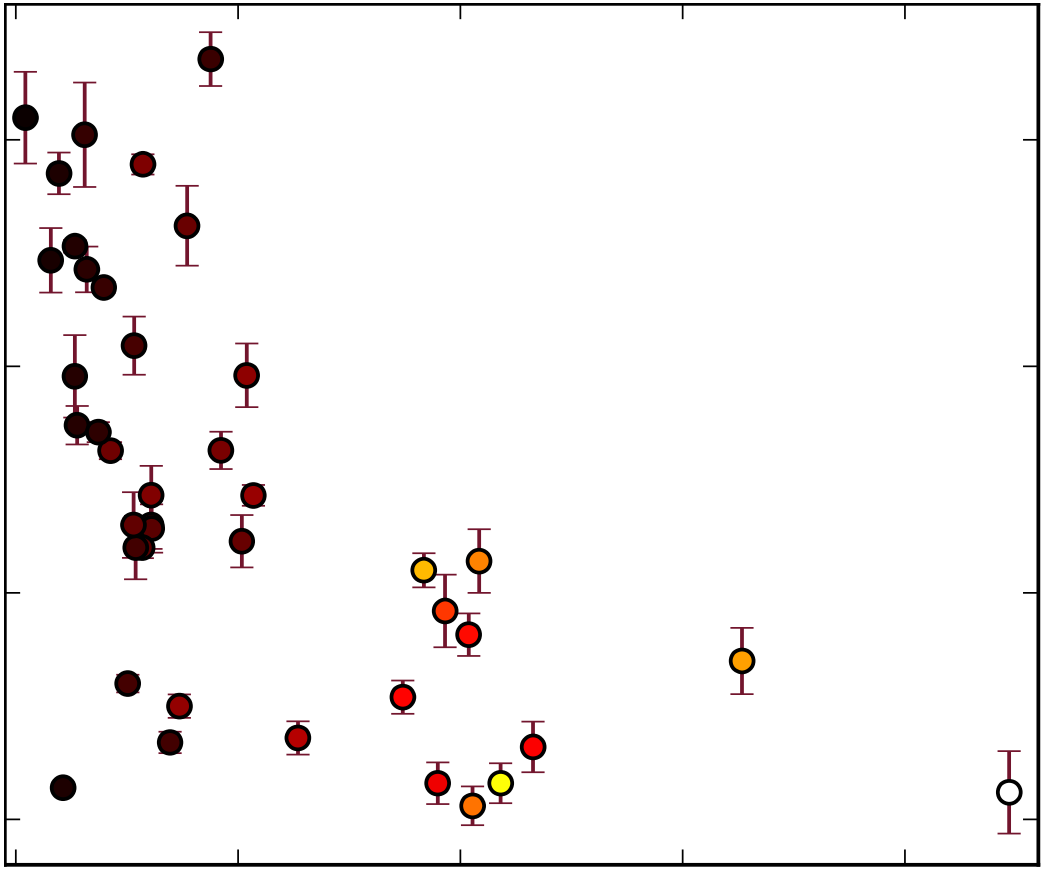

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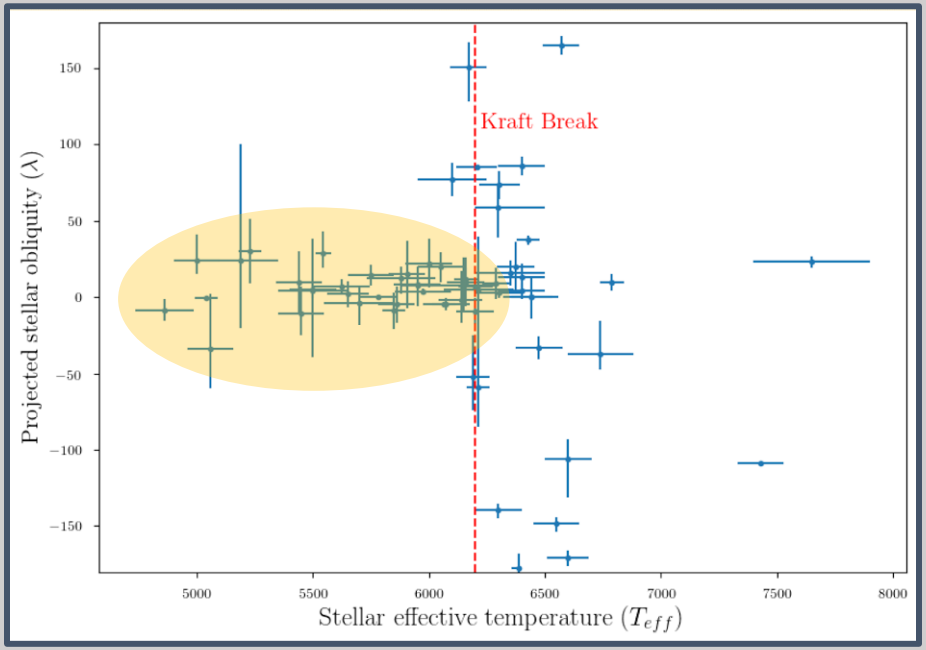

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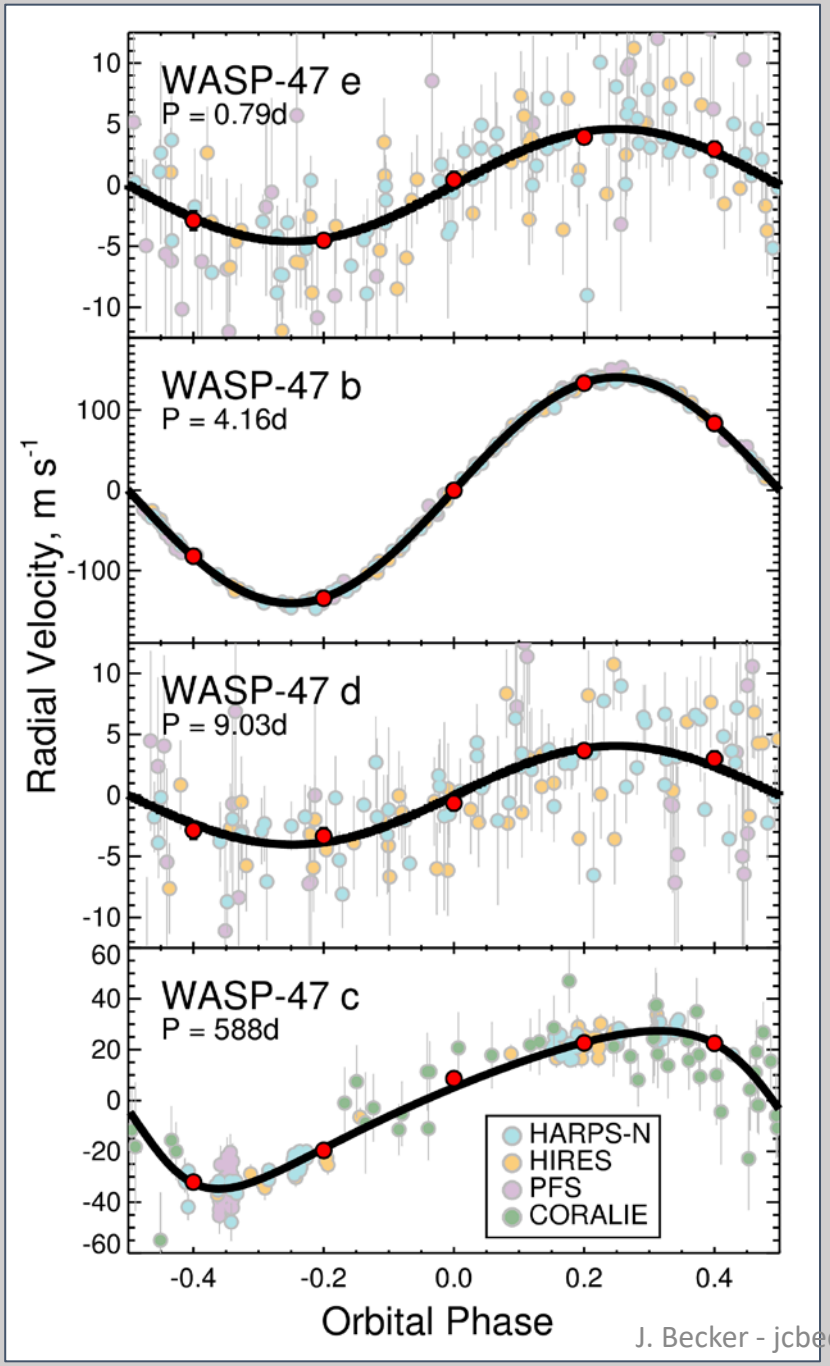

HARPS-N radial velocities of WASP-47 allow **much** improved measurements of the planetary mases, including the outer planet

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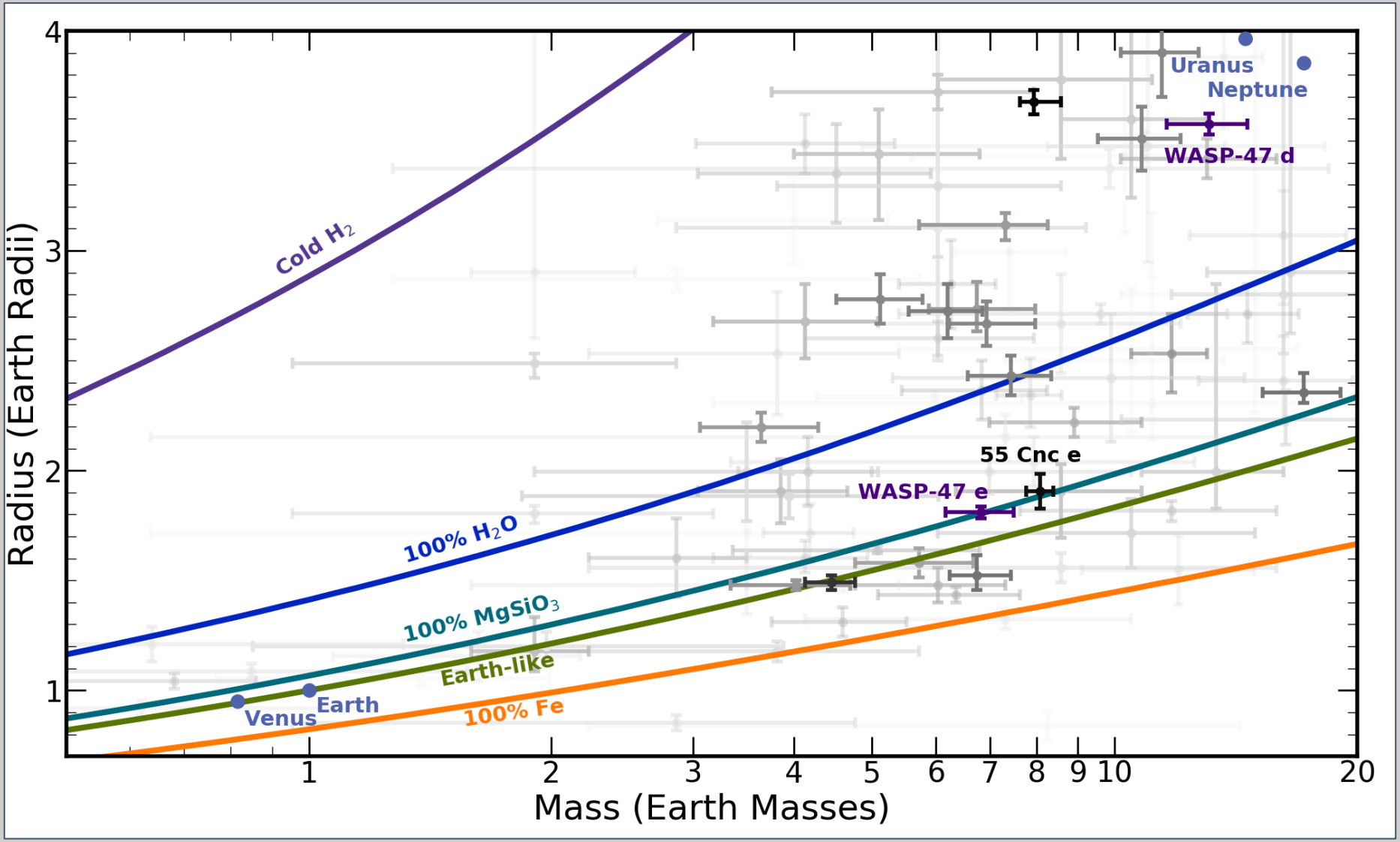
(Updated) mass-radius measurements



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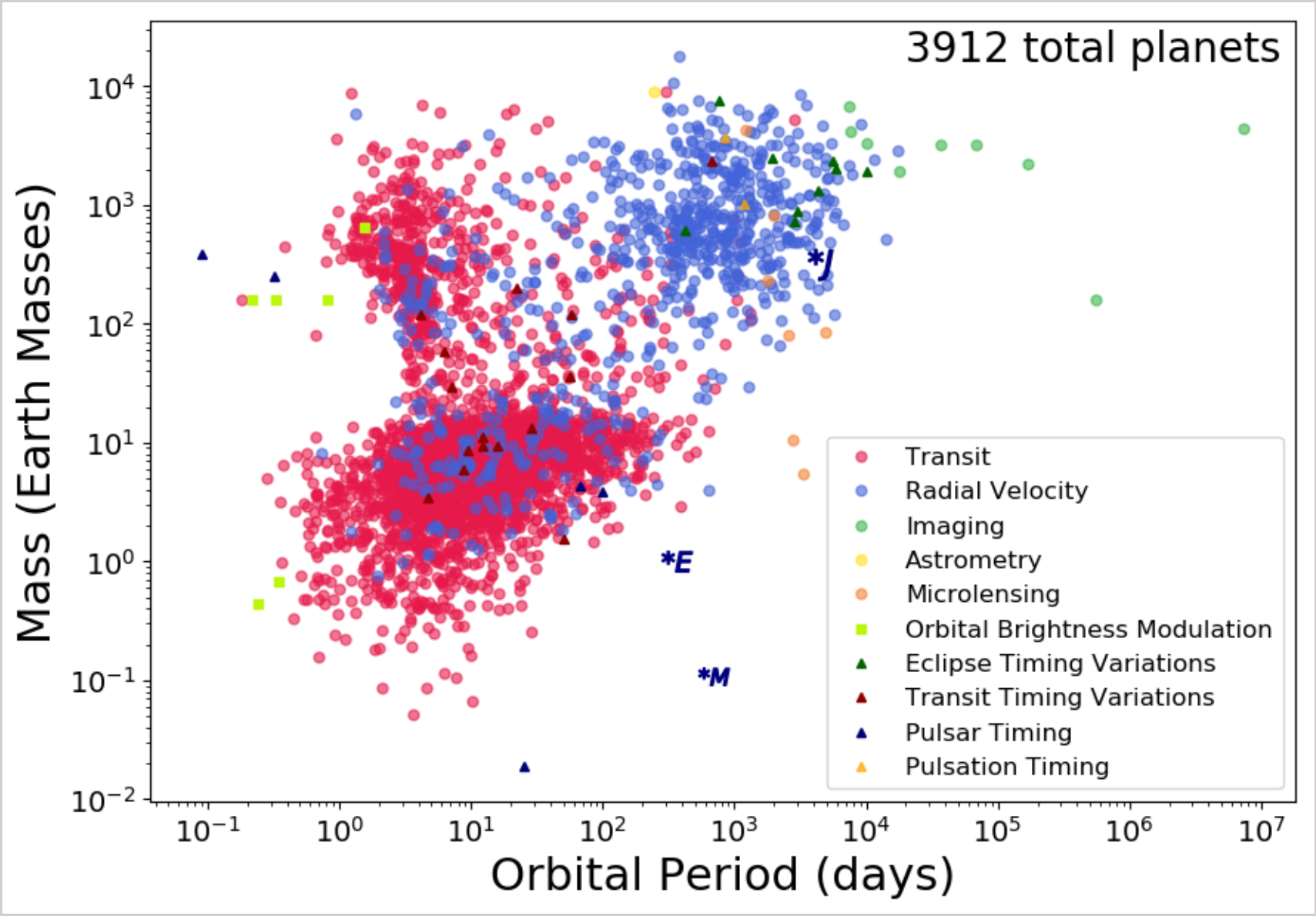

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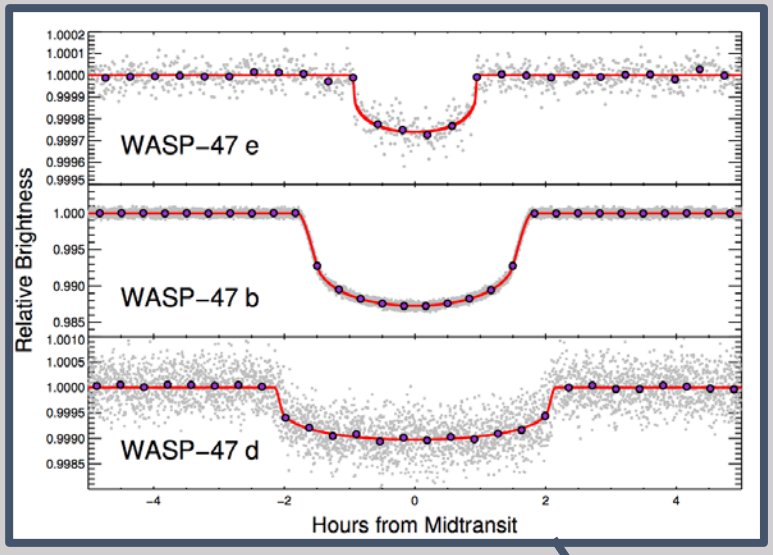
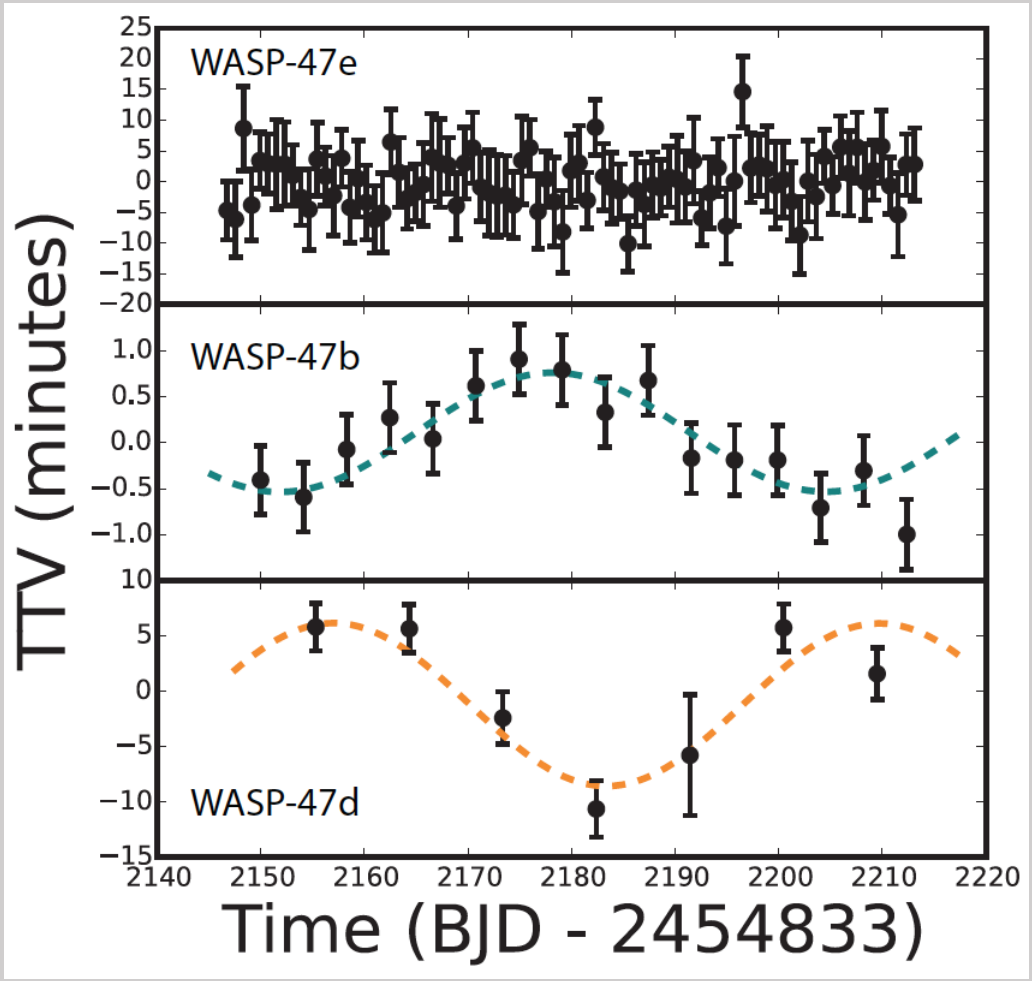
From transits, we can get TTVs





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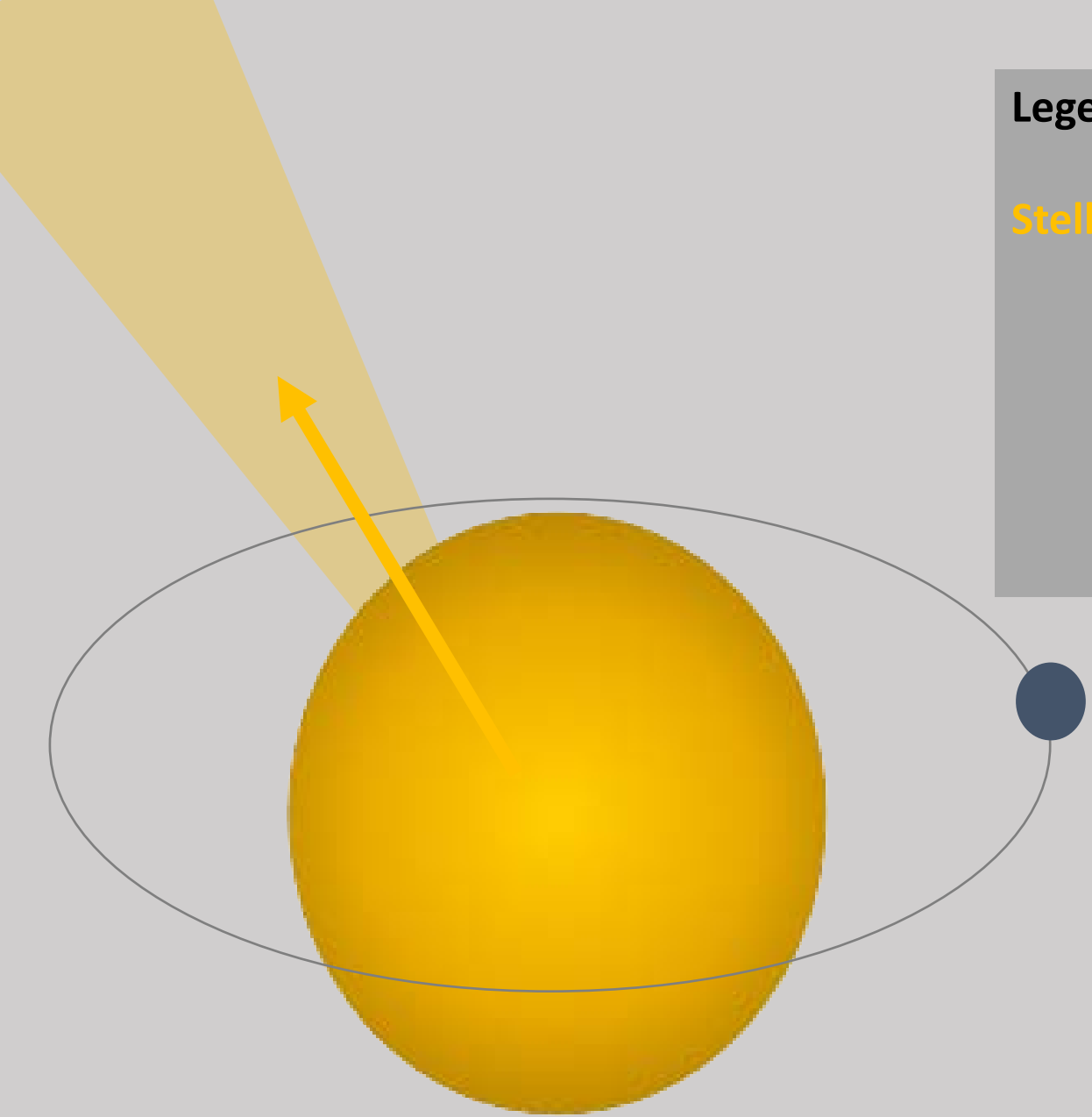

Legend:

Stellar spin axis

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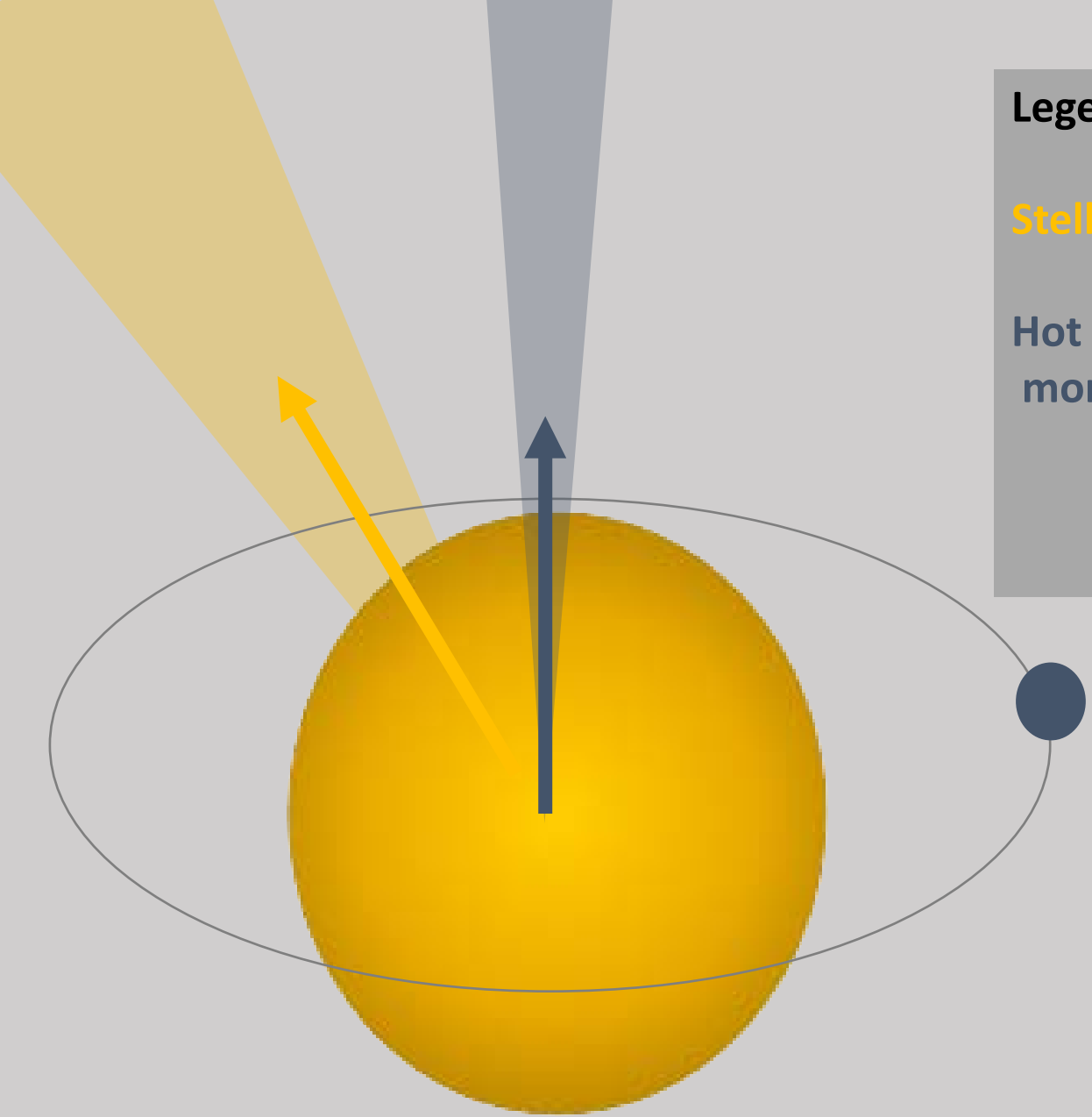

Legend:

Stellar spin axis

Hot Jupiter orbital angular momentum direction

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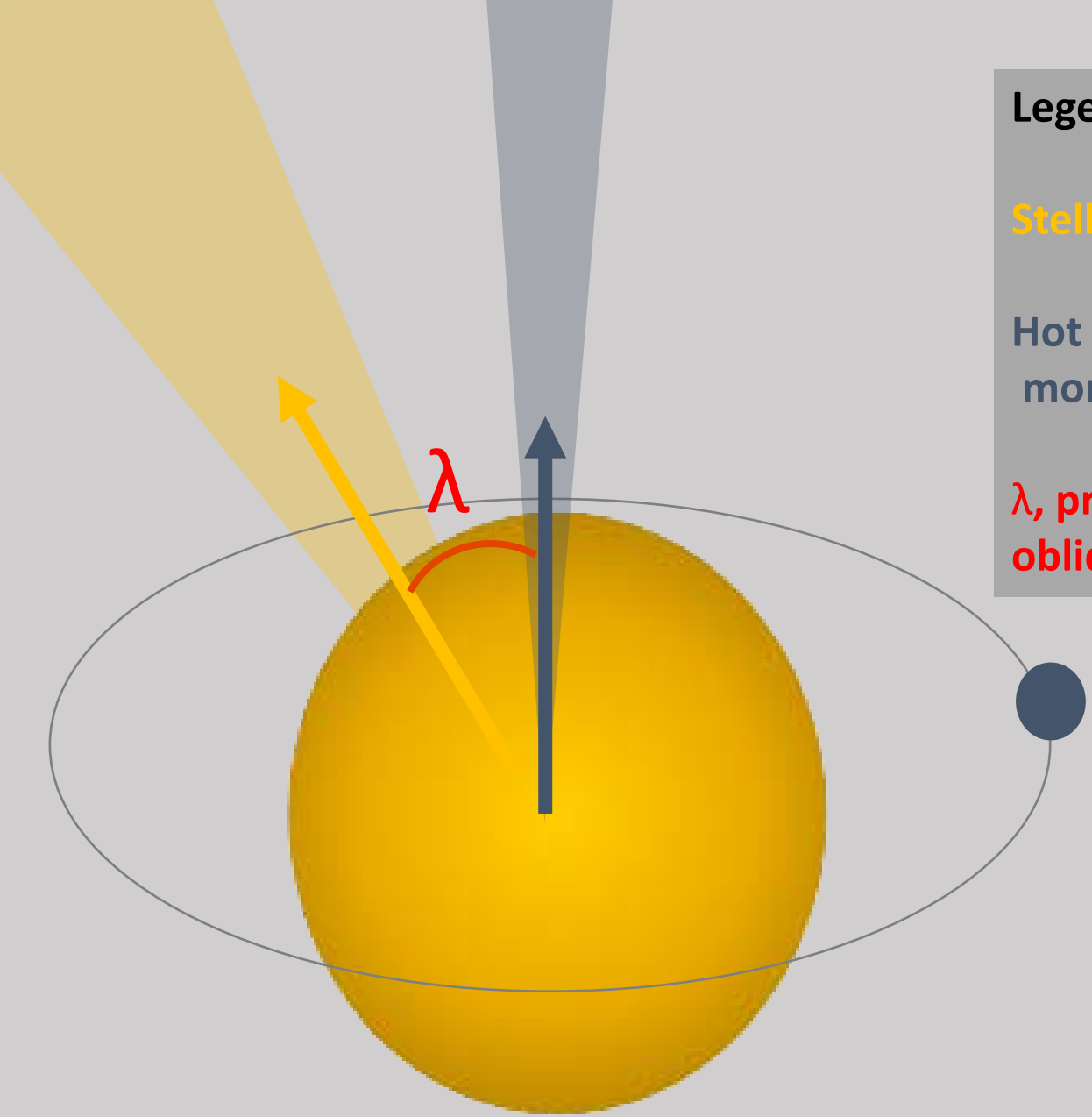

Legend:

Stellar spin axis

Hot Jupiter orbital angular momentum direction

λ, projected stellar obliquity

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