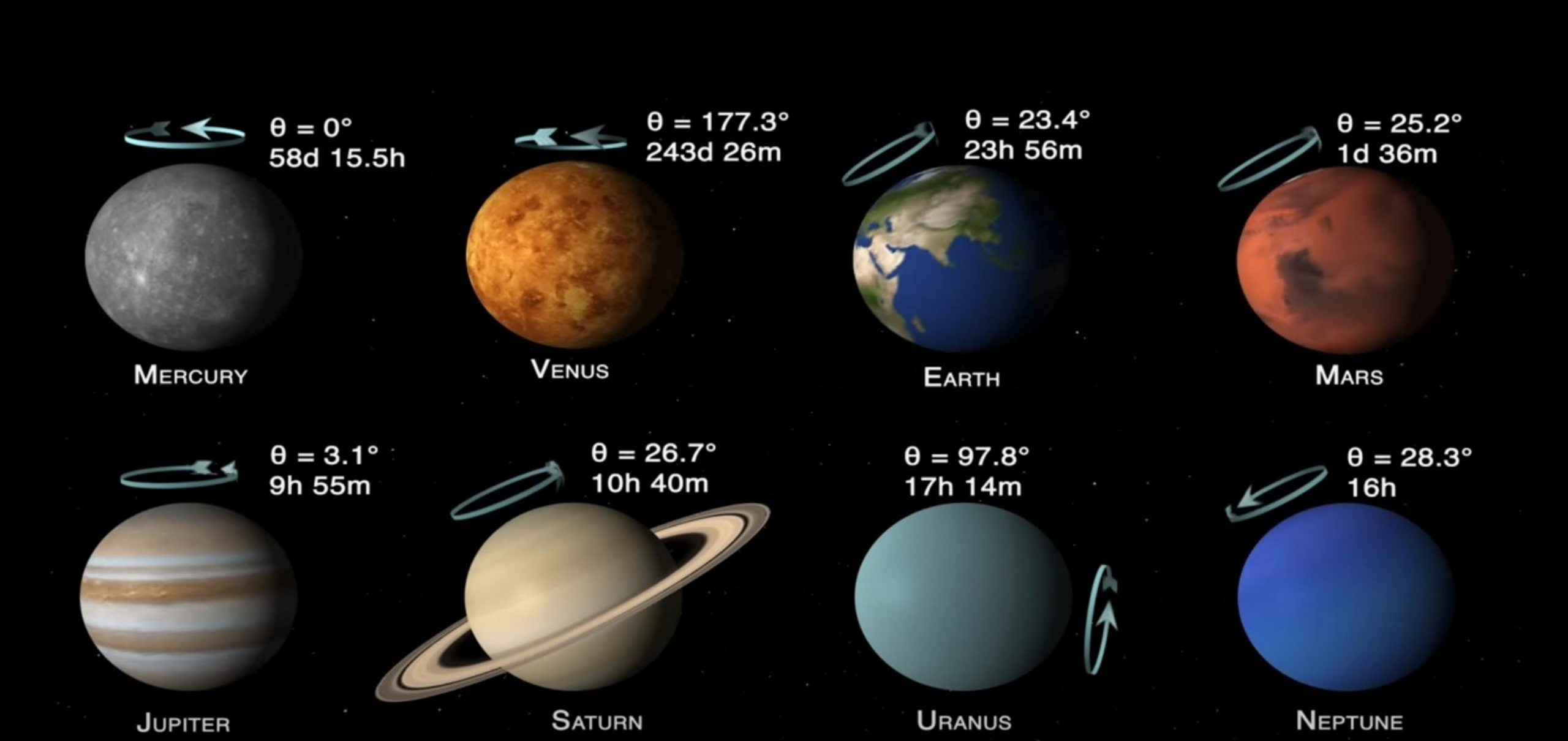
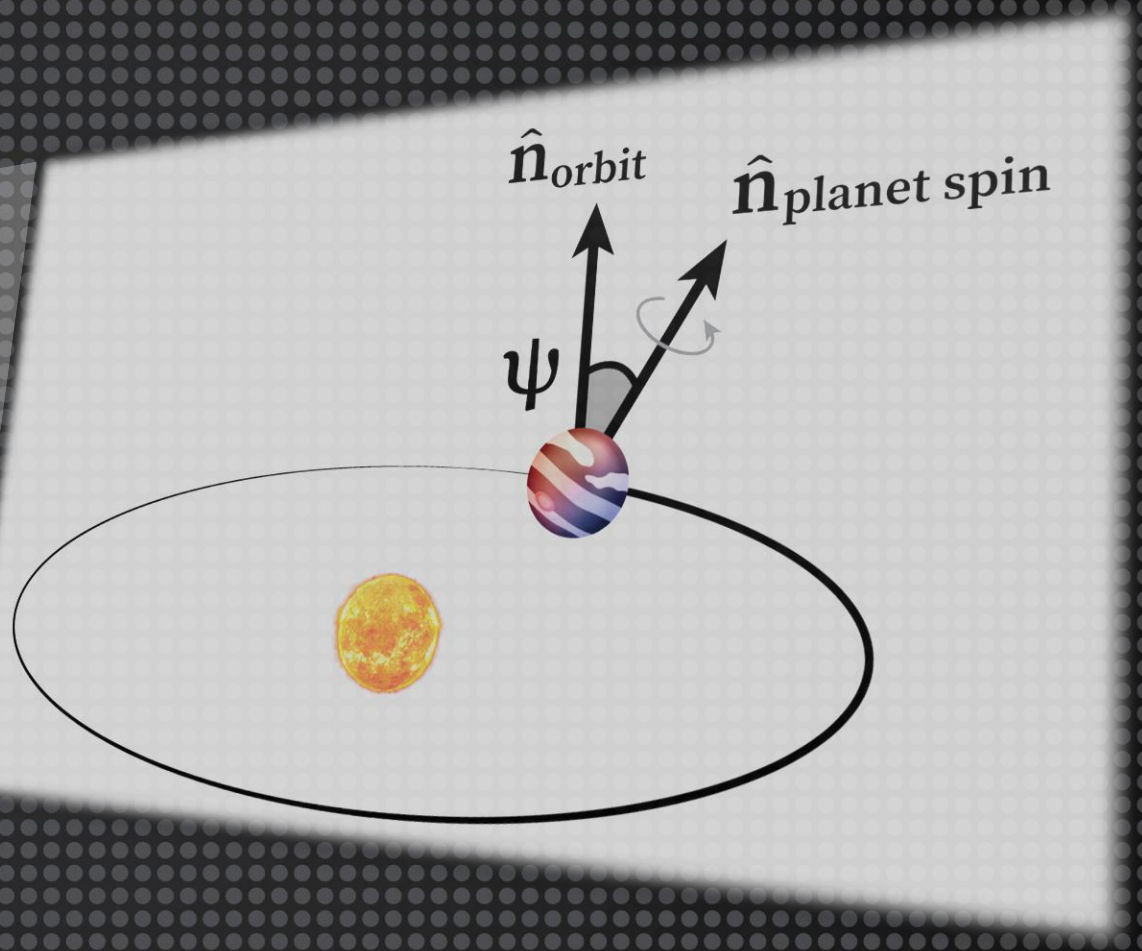


Credit: James O'Donoghue / NASA

Early evidence for ? planetary obliquities in young super-Jupiter systems

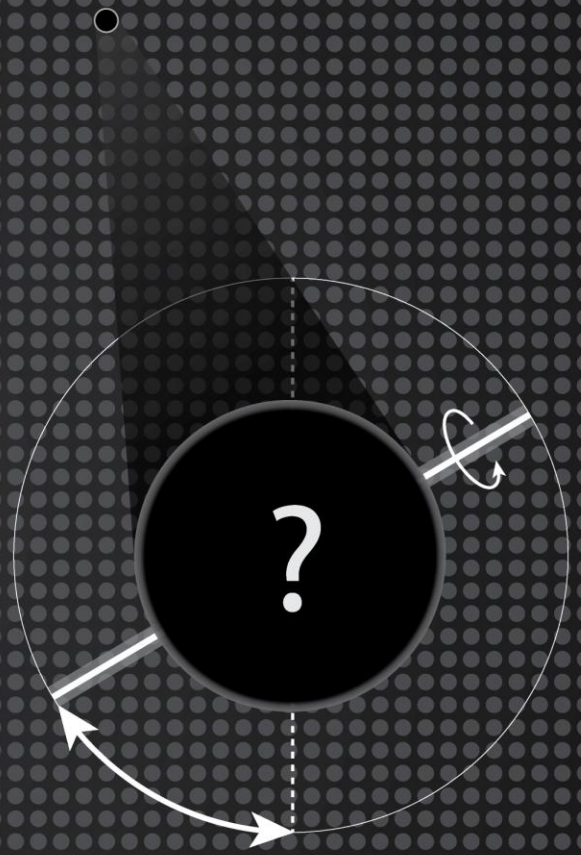


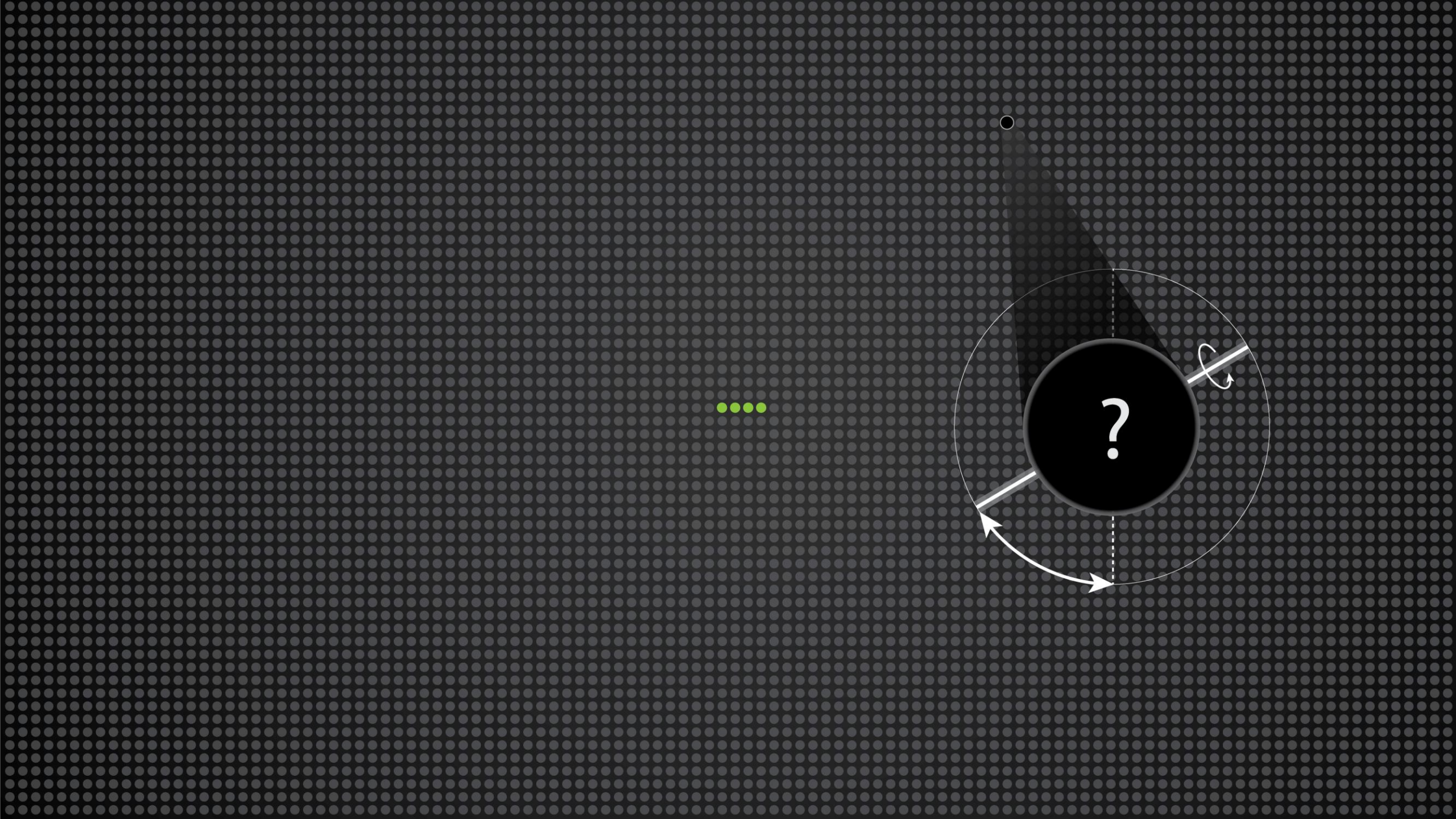
Michael Poon

Final Year PhD Candidate

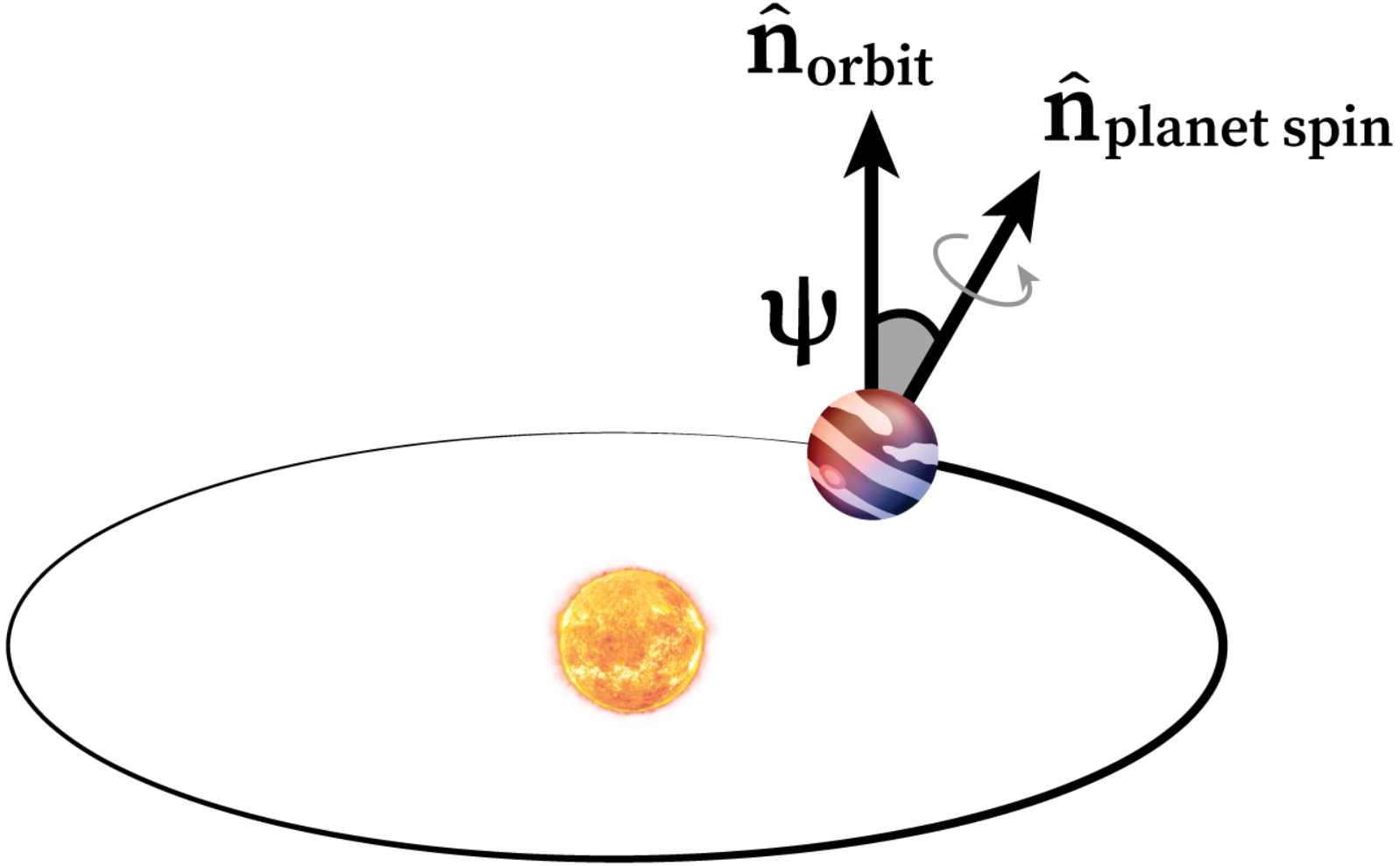
University of Toronto

51 Peg b 30th Anniversary – Oct. 9, 2025

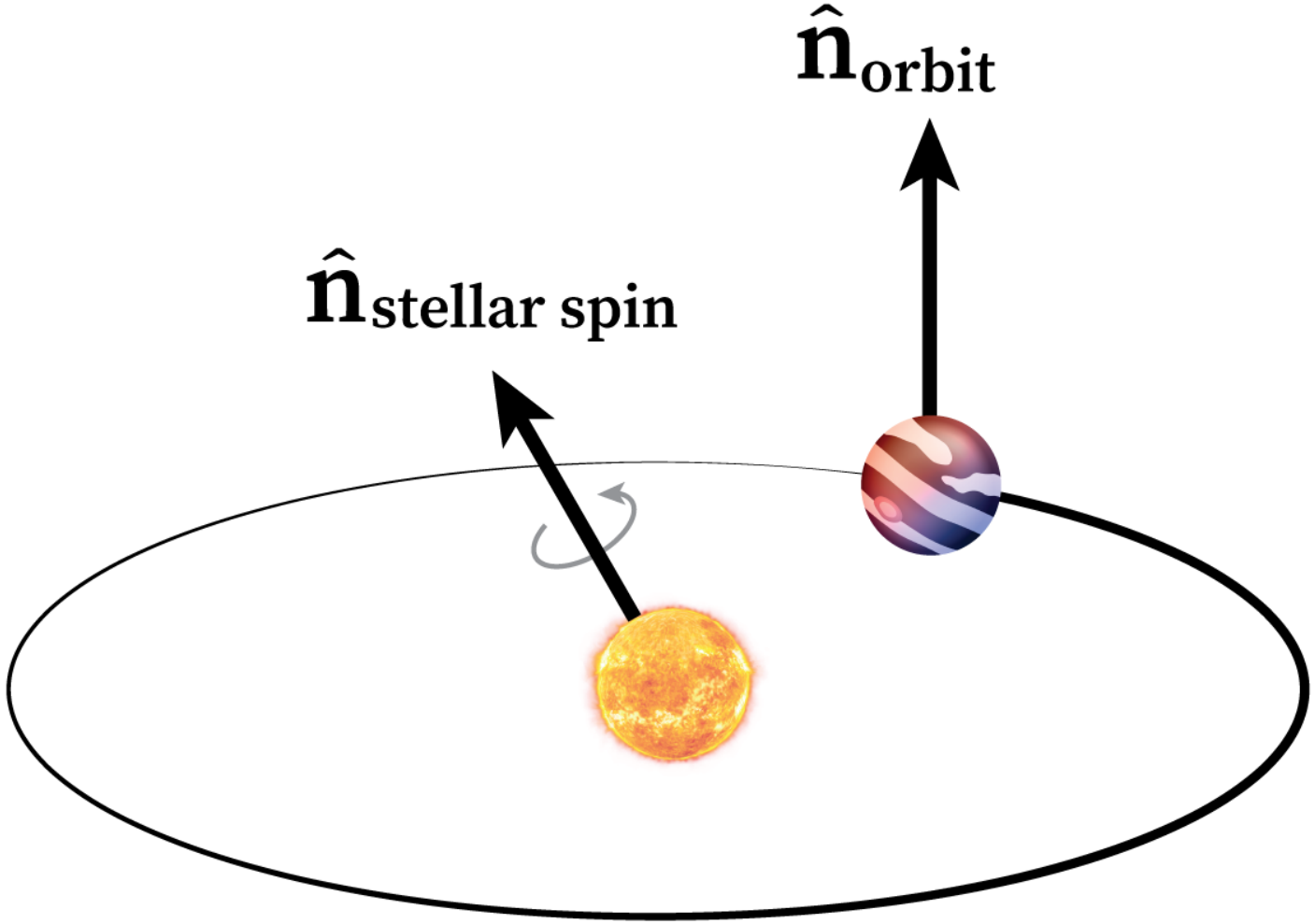




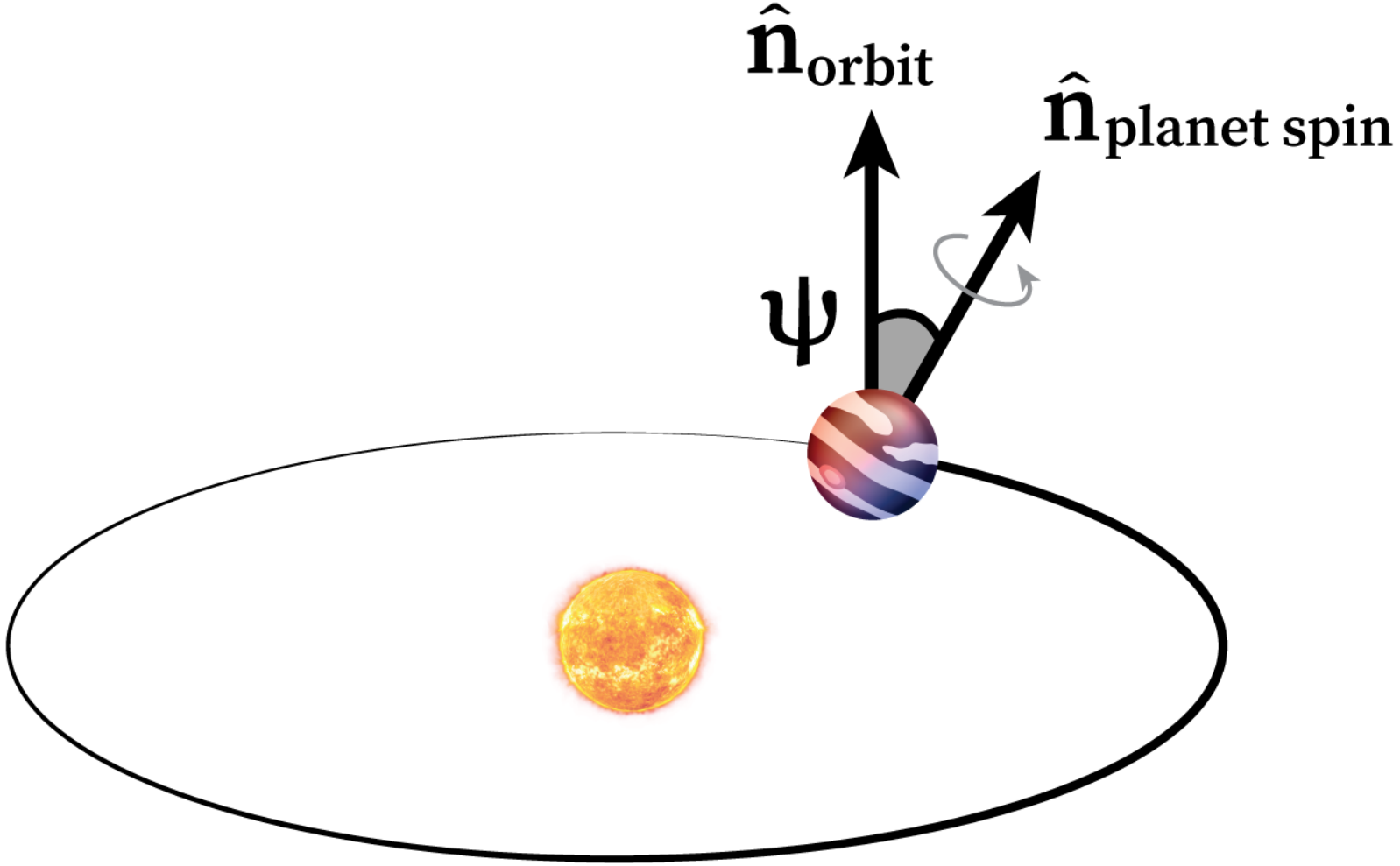
*To clarify, this is a ***planetary*** obliquity



*NOT a ***stellar*** obliquity

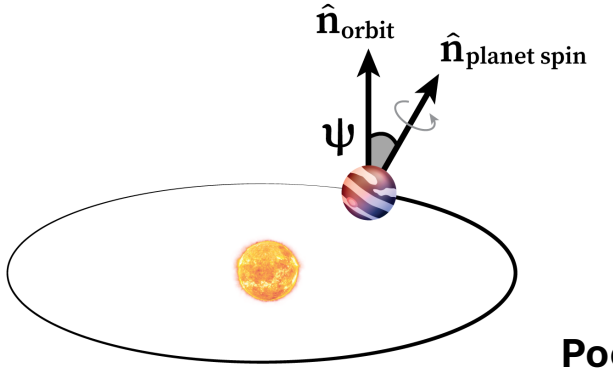


*To clarify, this is a ***planetary*** obliquity



Measuring a planet obliquity requires **3 observables**

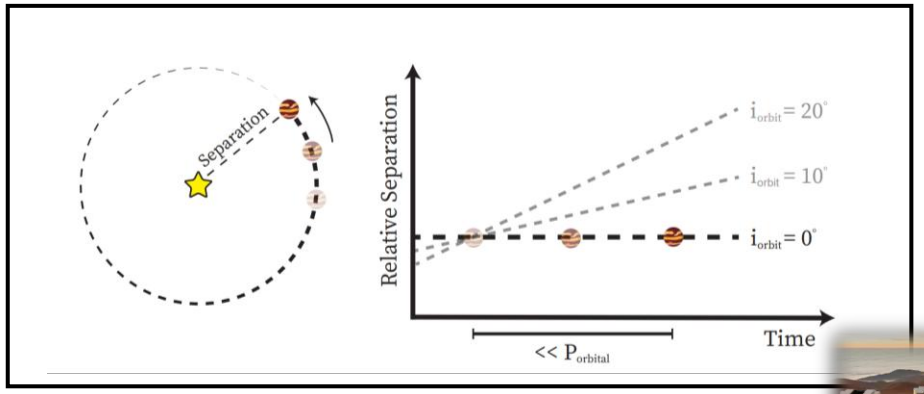
Measuring a planet obliquity requires **3 observables**



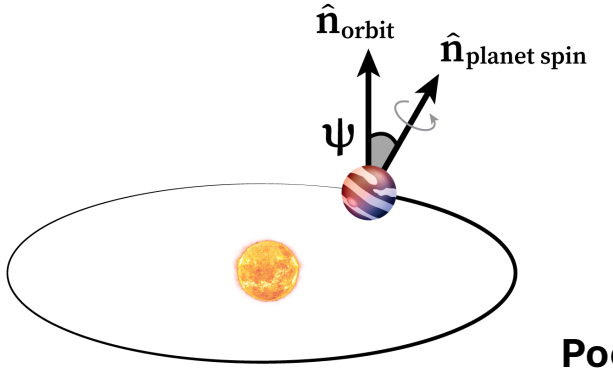
Poon et al. 2024

Measuring a planet obliquity requires **3 observables**

(1) Orbital inclination



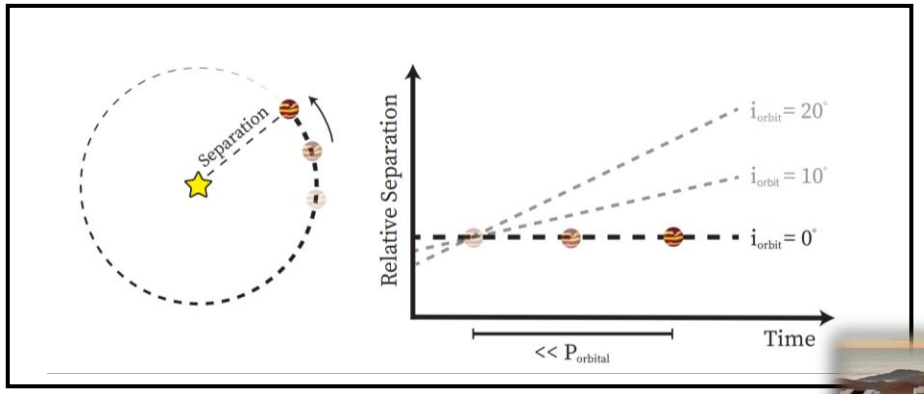
~10 yr baseline on 8m-class (e.g. VLT/ELT)



Poon et al. 2024

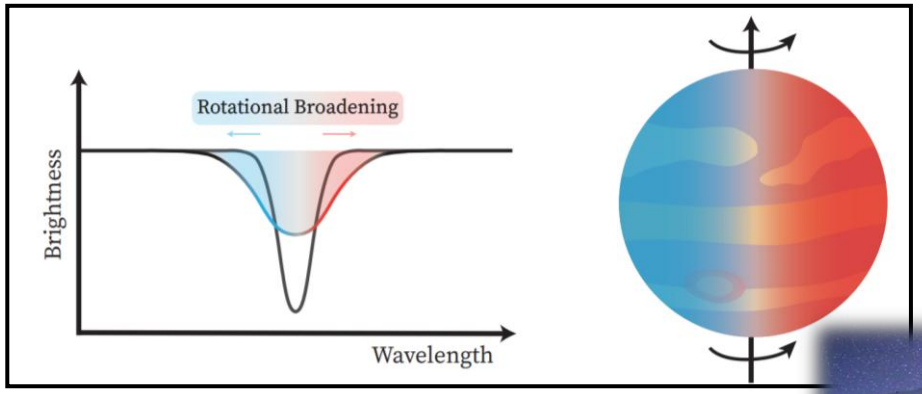
Measuring a planet obliquity requires **3 observables**

(1) Orbital inclination

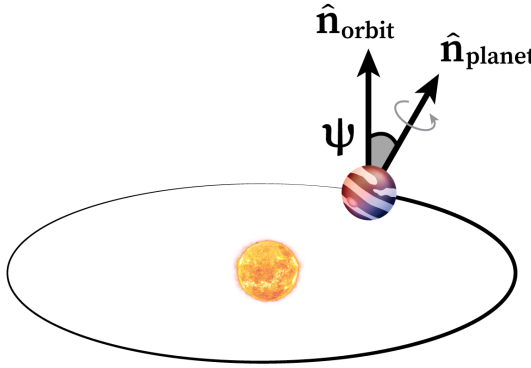


~10 yr baseline on 8m-class (e.g. VLT/ELT)

(2) Rotational broadening



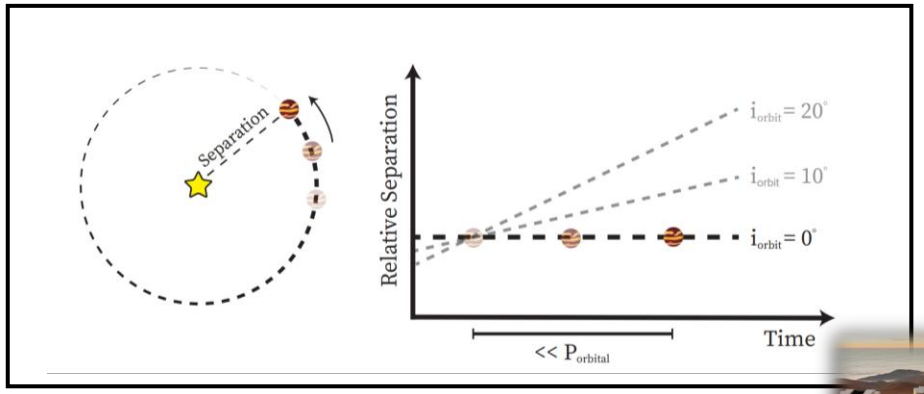
~4-8 hours on 8m-class (e.g. Keck/Gemini)



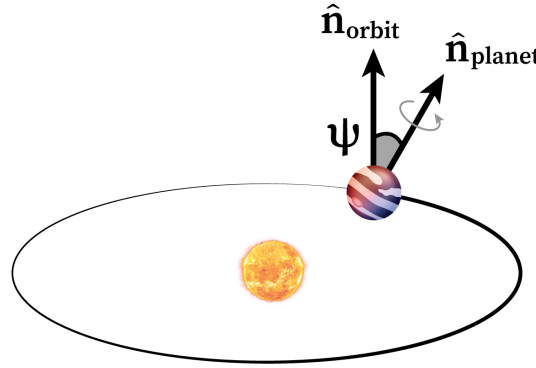
Poon et al. 2024

Measuring a planet obliquity requires **3 observables**

(1) Orbital inclination

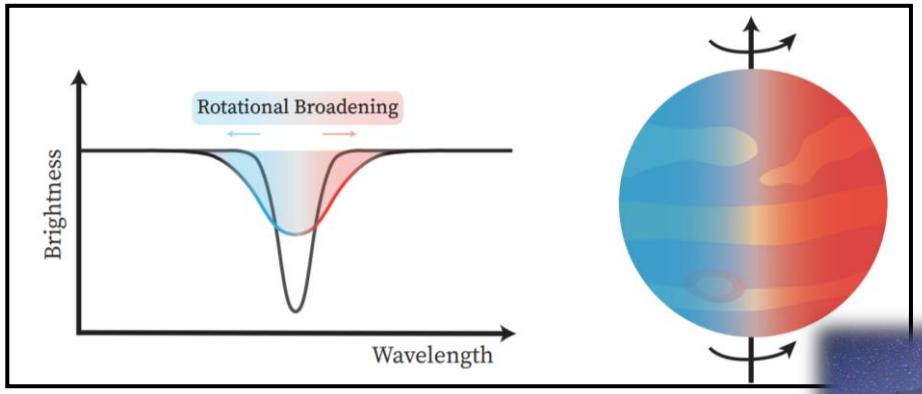


~10 yr baseline on 8m-class (e.g. VLT/ELT)



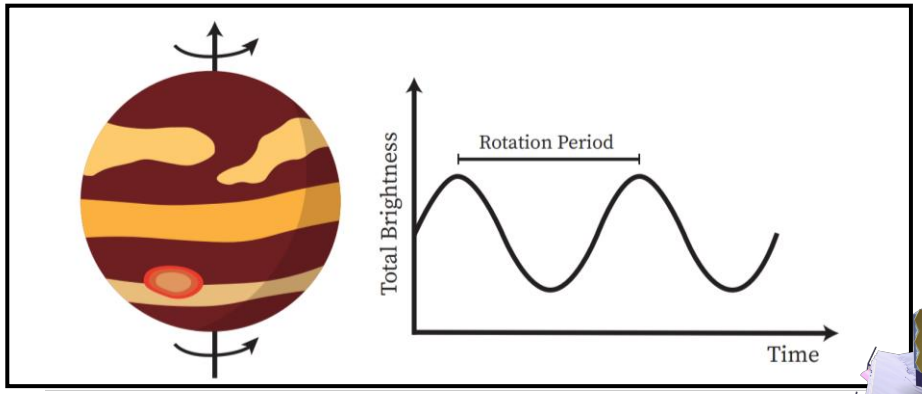
Poon et al. 2024

(2) Rotational broadening

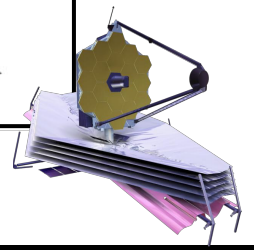


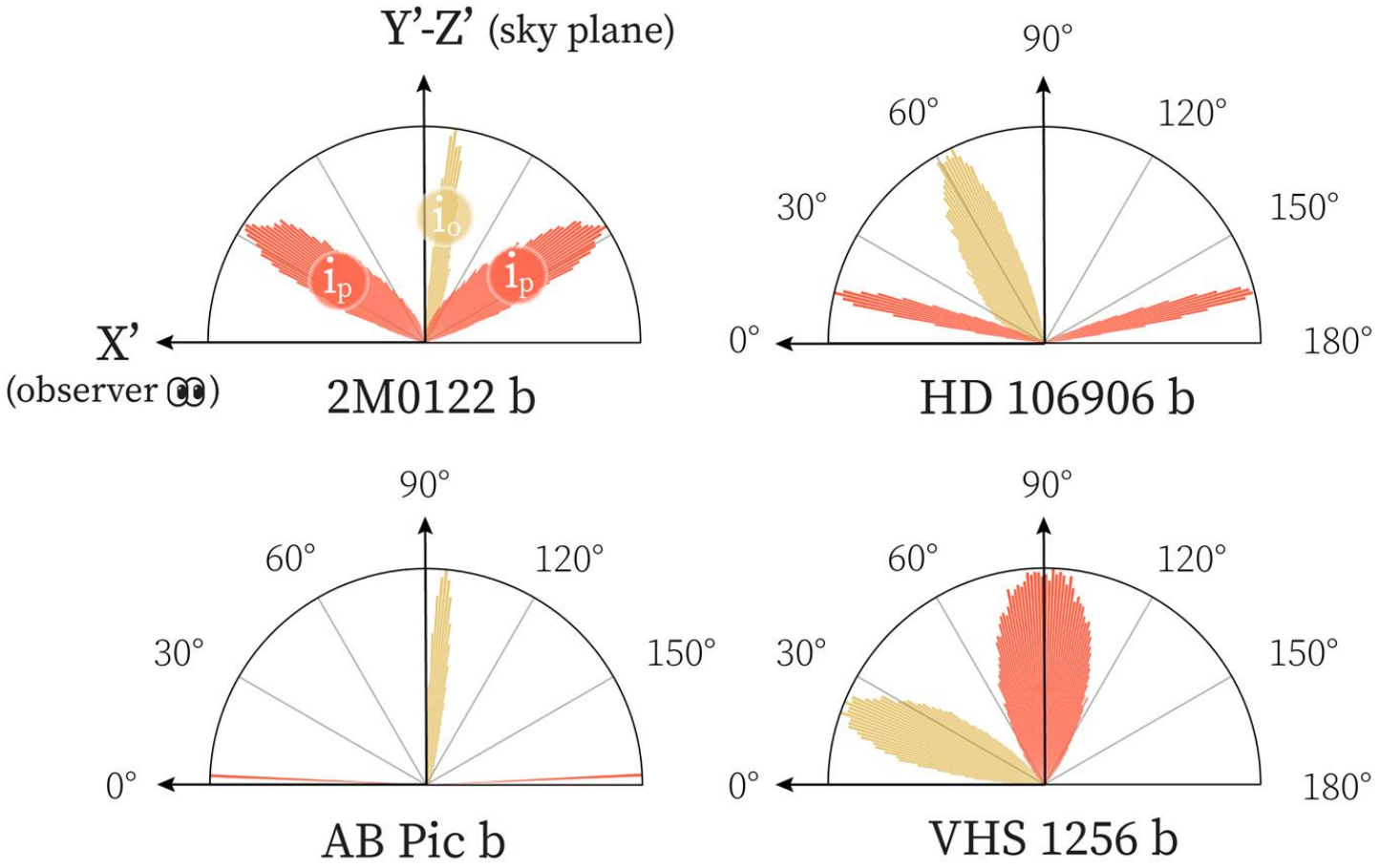
~4-8 hours on 8m-class (e.g. Keck/Gemini)

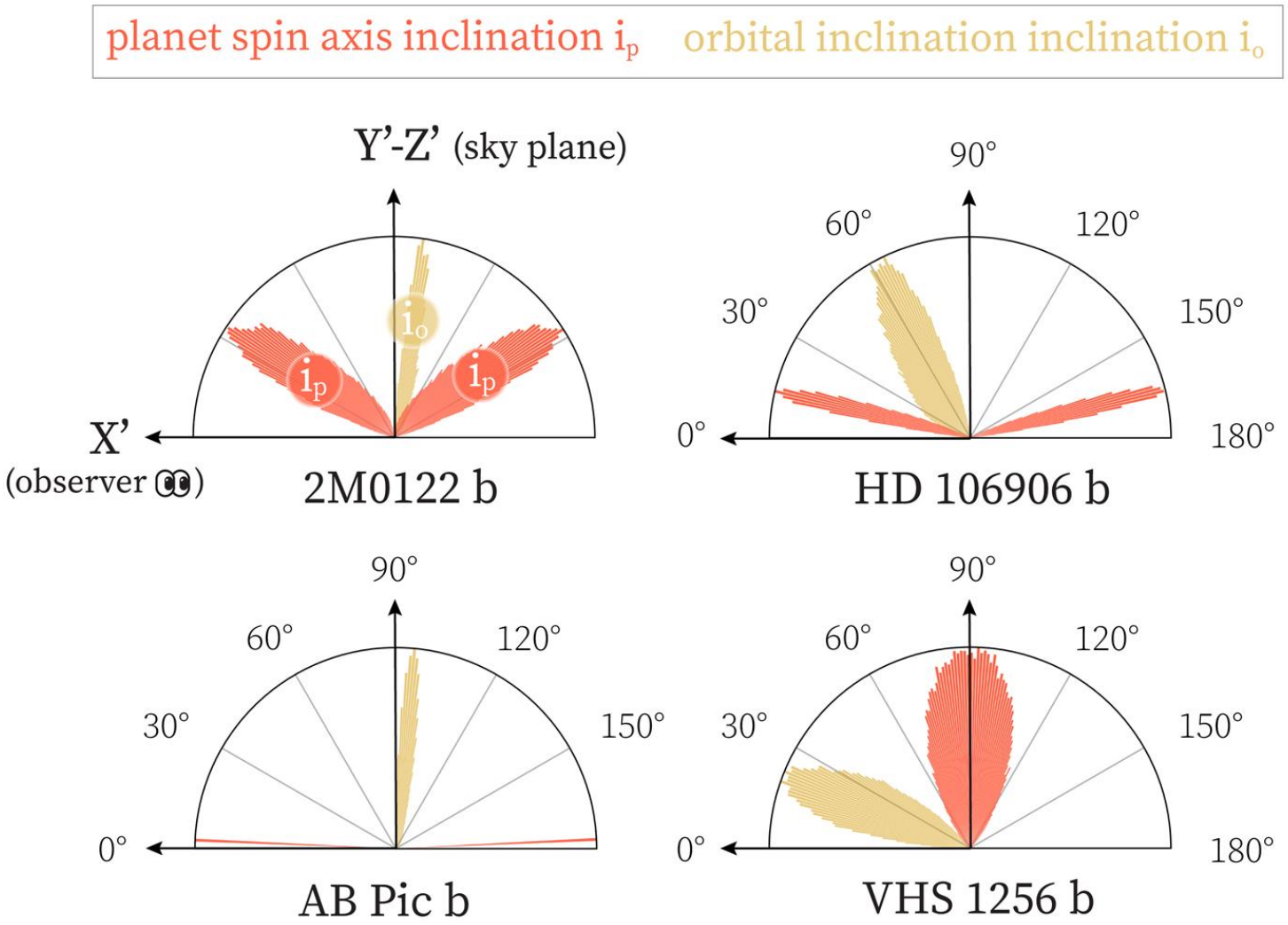
(3) Rotation period



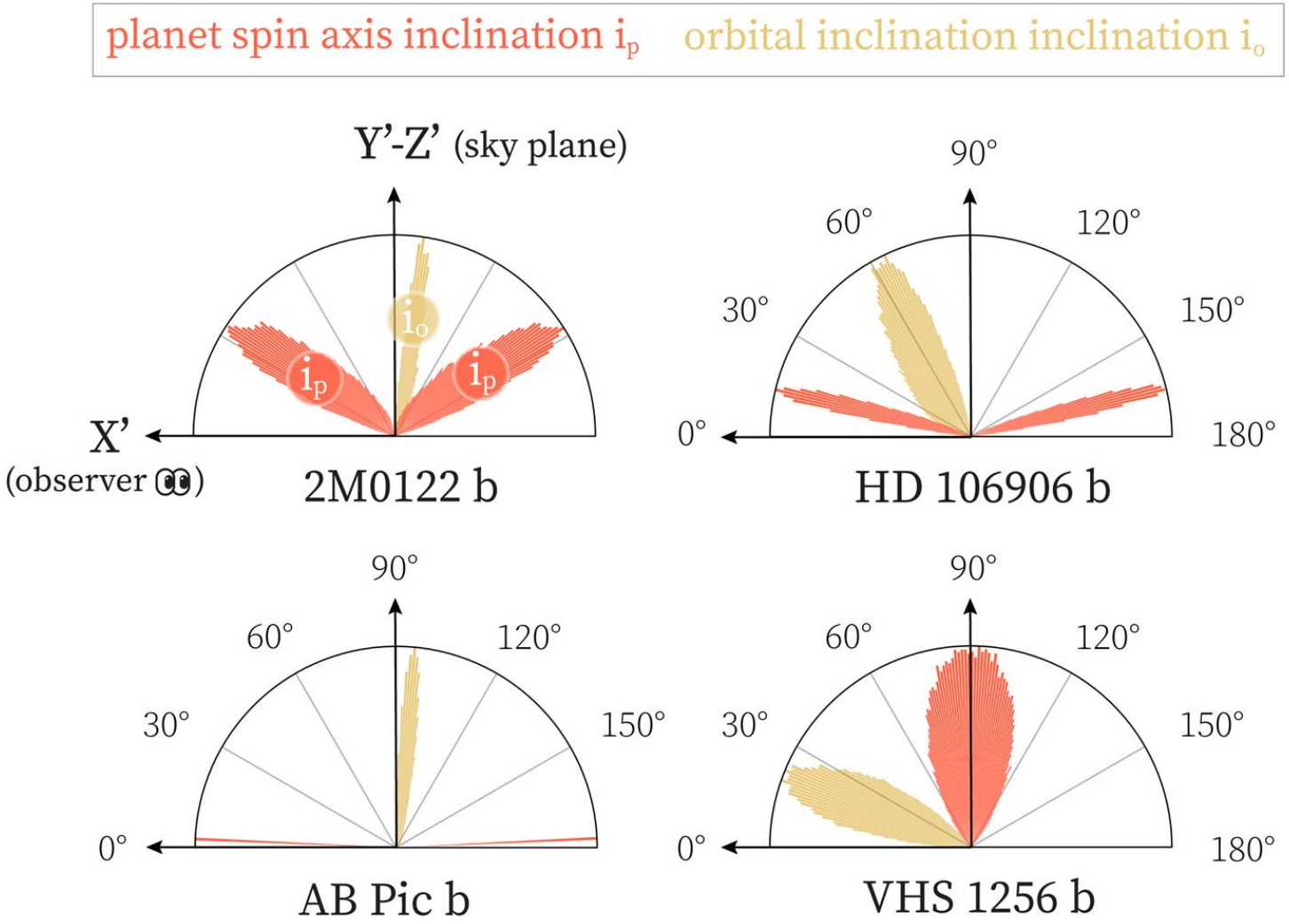
~10-20 hours from space-based telescope
(e.g. Hubble/JWST)




Y'-Z' (sky plane)
X'
(observer)
i_o
i_p
i_p
2M0122 b
90°
60°
120°
30°
150°
0°
180°
HD 106906 b
90°
60°
120°
30°
150°
0°
AB Pic b
90°
60°
120°
30°
150°
0°
VHS 1256 b



Bryan et al. 2020a
Bryan et al. 2021
Poon et al. 2024
Gandhi et al. 2025
Poon et al. (in review)



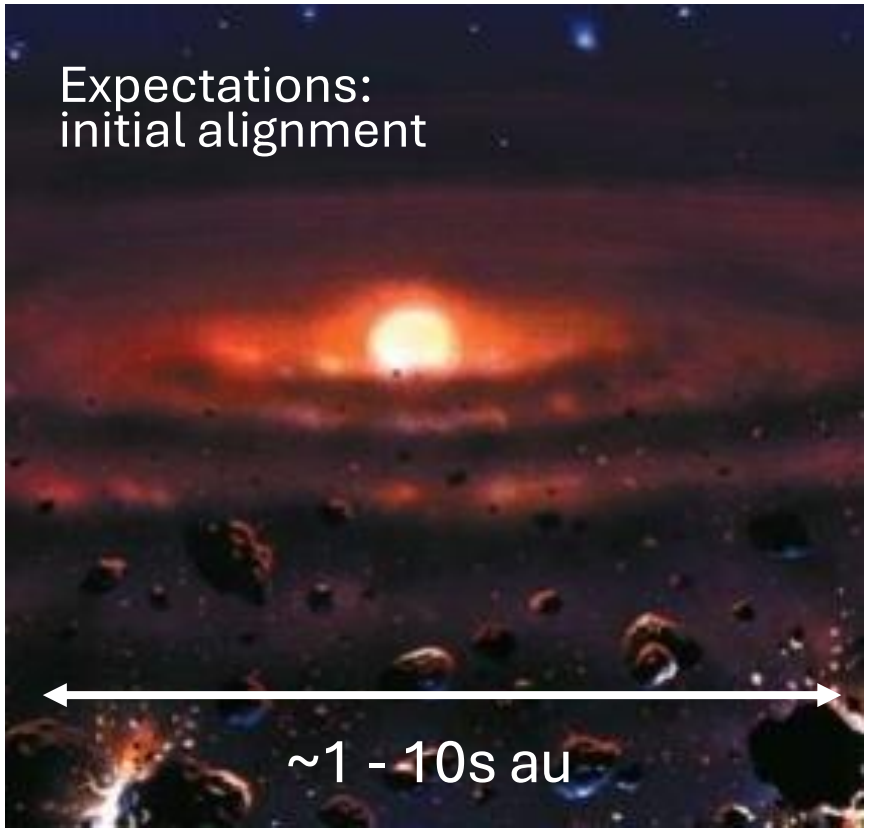
Bryan et al. 2020a
Bryan et al. 2021
Poon et al. 2024
Gandhi et al. 2025
Poon et al. (in review)

Did these super-Jupiters form like *scaled-up planets* or *scaled-down stars?*

Did these super-Jupiters form like *scaled-up planets* or *scaled-down stars?*

Did these super-Jupiters form like *scaled-up planets* or *scaled-down stars?*

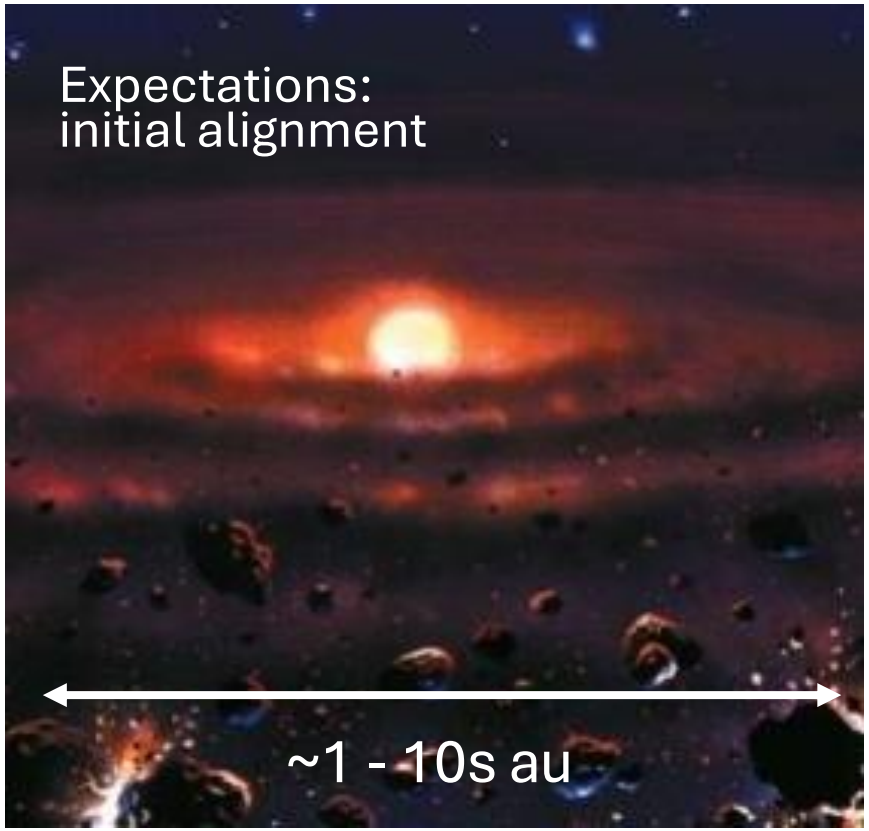
bottom-up like a **planet**?



scienceclarified.com

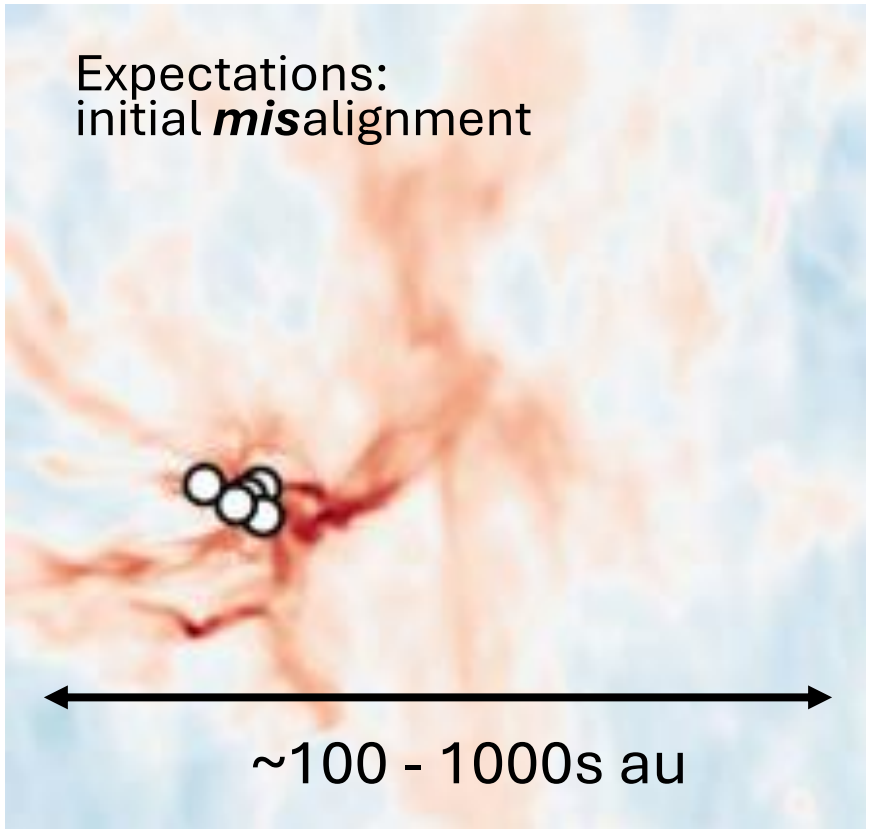
Did these super-Jupiters form like *scaled-up planets* or *scaled-down stars?*

bottom-up like a **planet**?



scienceclarified.com

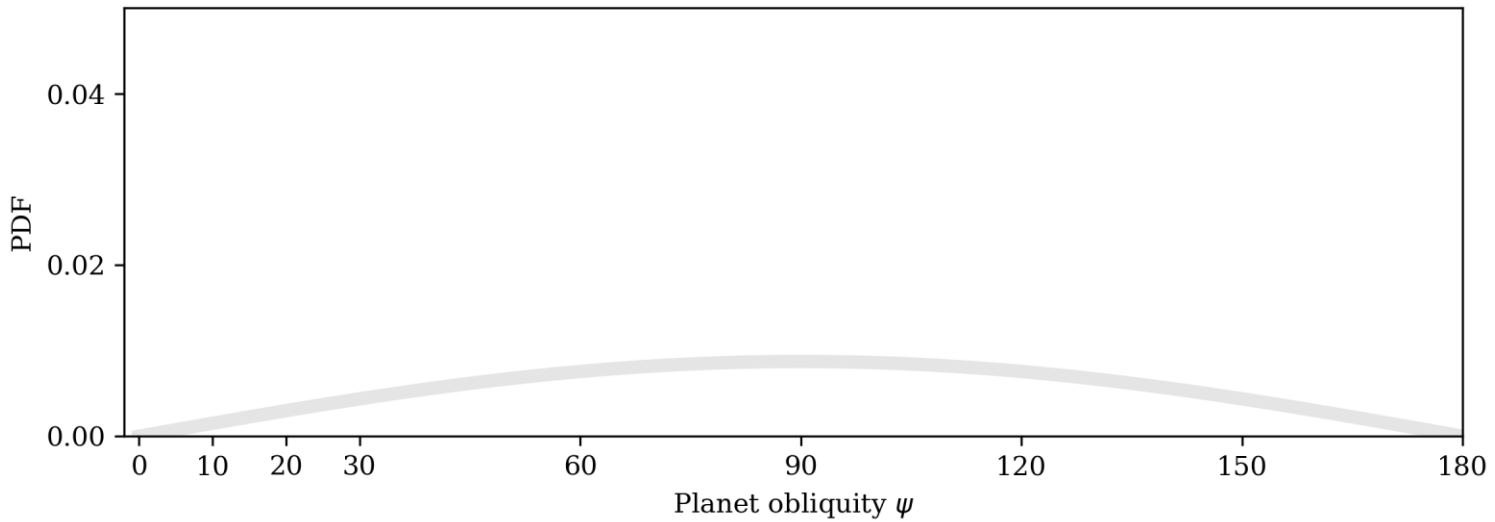
top-down like a **star**?



Adapted from Lee+2019

We use a Fisher distribution to infer overall formation

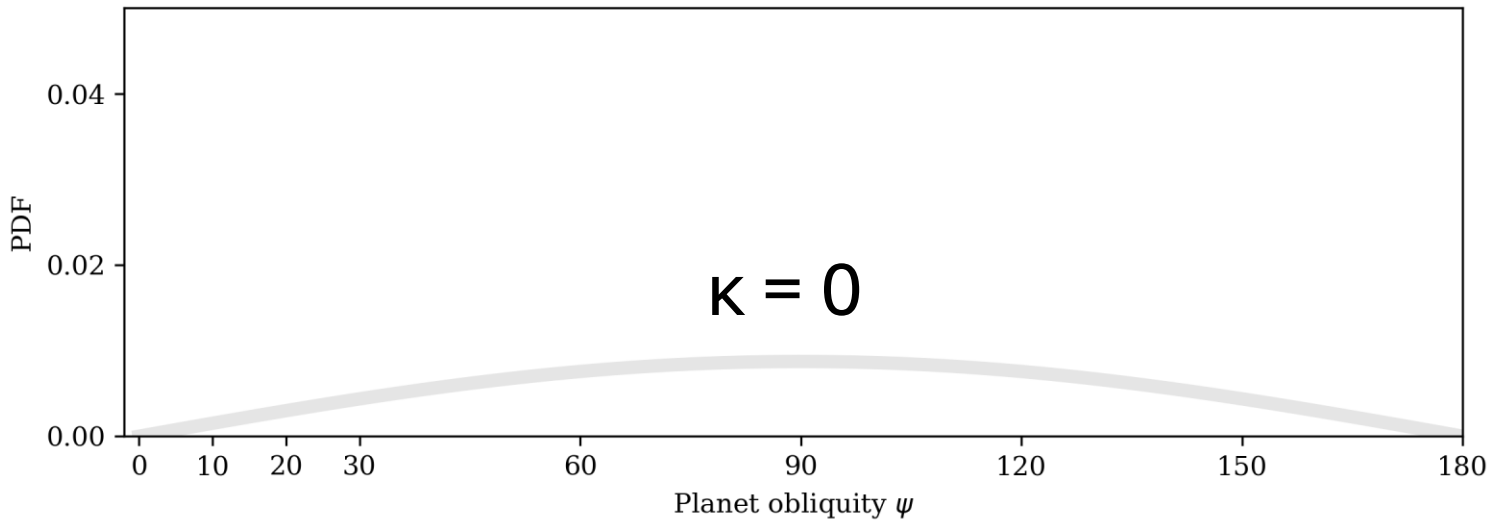
Mercury, Jupiter, *Earth, Mars, Saturn, Neptune,* *Uranus,* *Venus*



Poon et al. (in review)

We use a Fisher distribution to infer overall formation

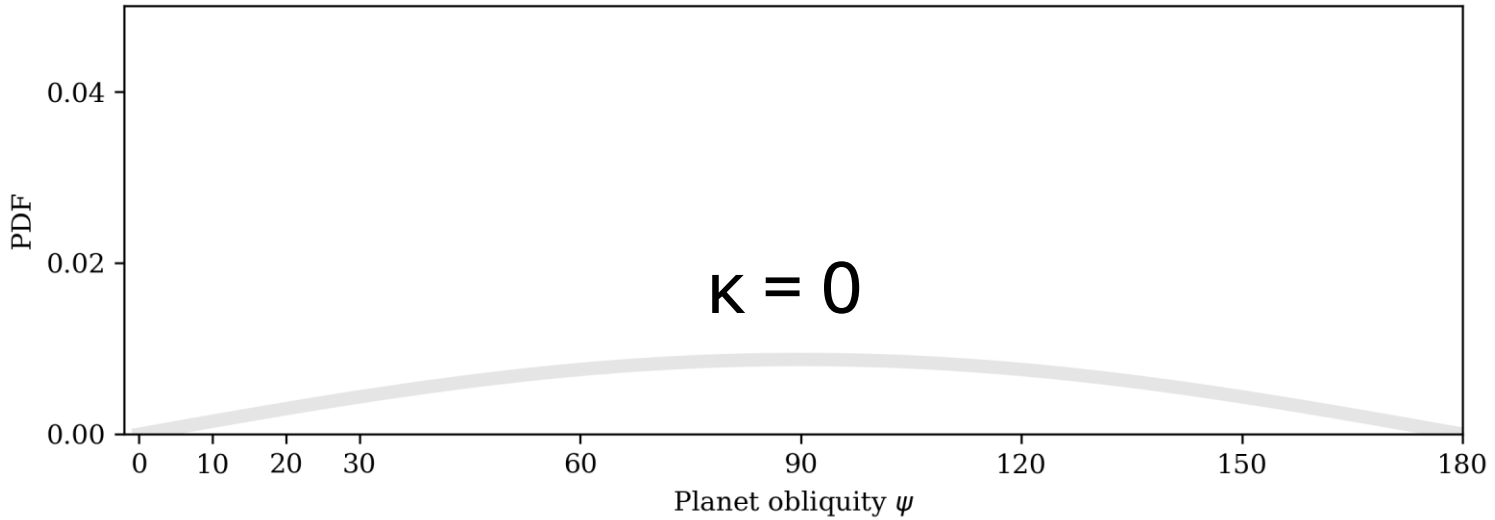
Mercury, Jupiter, *Earth, Mars, Saturn, Neptune,* *Uranus,* *Venus*

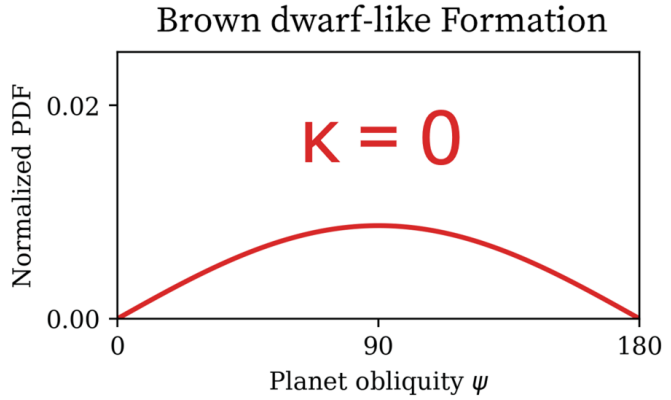


Poon et al. (in review)

We use a Fisher distribution to infer overall formation

Mercury, Jupiter, *Earth, Mars, Saturn, Neptune,* *Uranus,* *Venus*

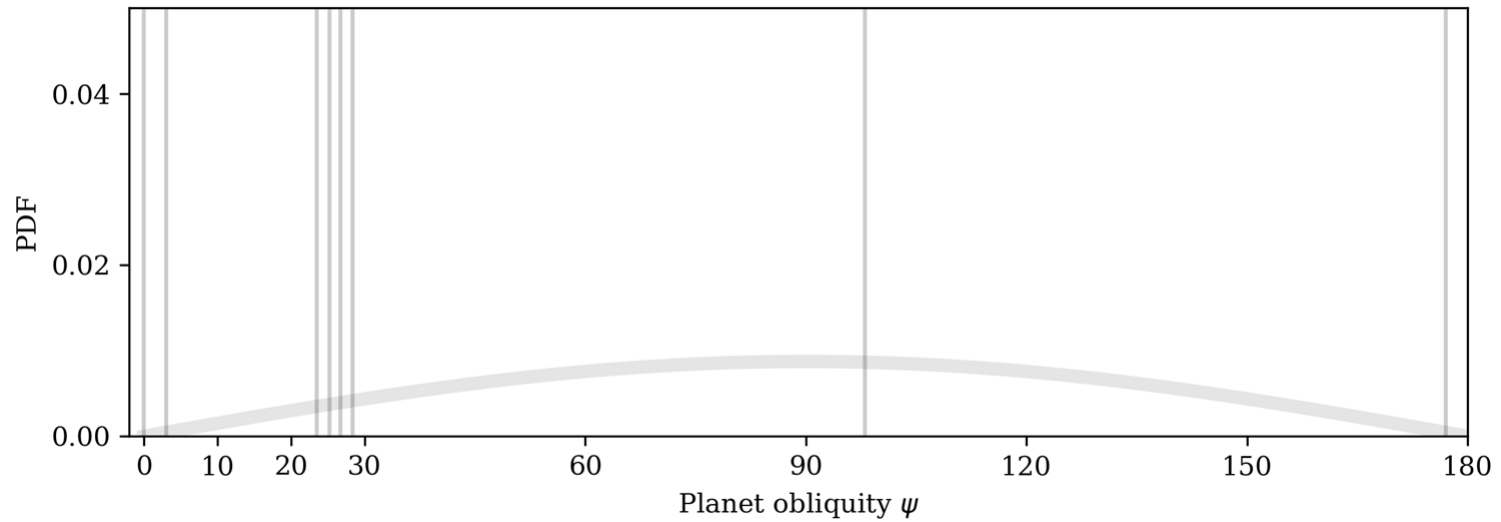


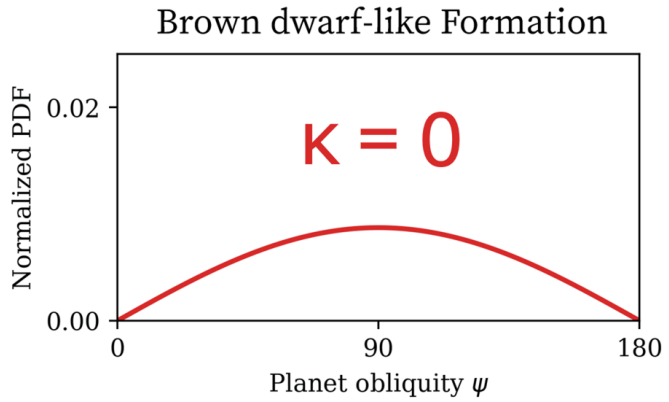


Poon et al. (in review)

We use a Fisher distribution to infer overall formation

Mercury, Jupiter, *Earth, Mars, Saturn, Neptune,* *Uranus,* *Venus*

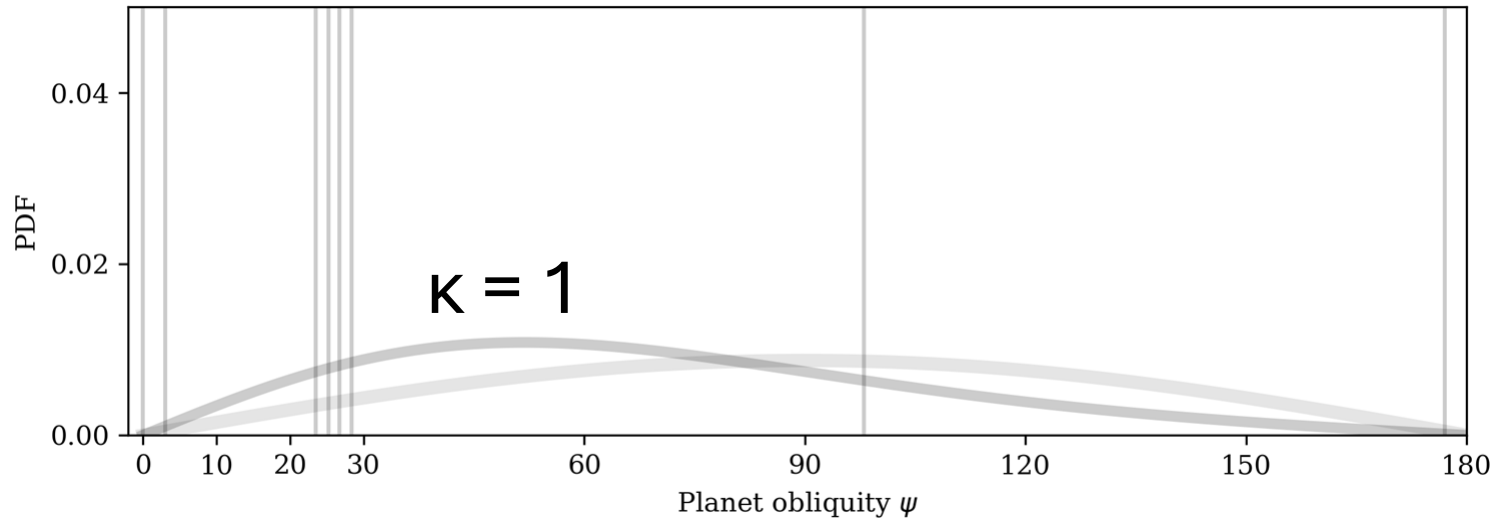


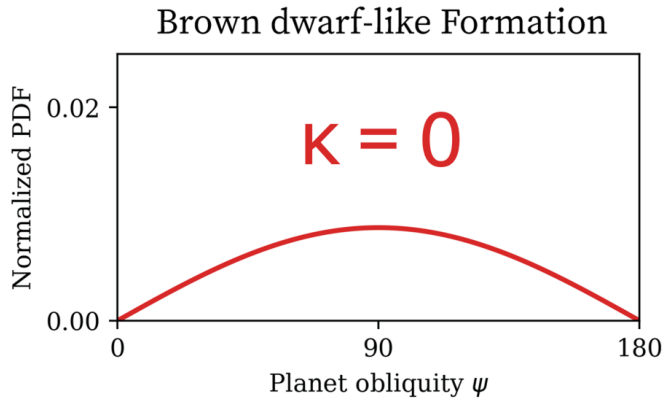


Poon et al. (in review)

We use a Fisher distribution to infer overall formation

Mercury, Jupiter, *Earth, Mars, Saturn, Neptune,* *Uranus,* *Venus*

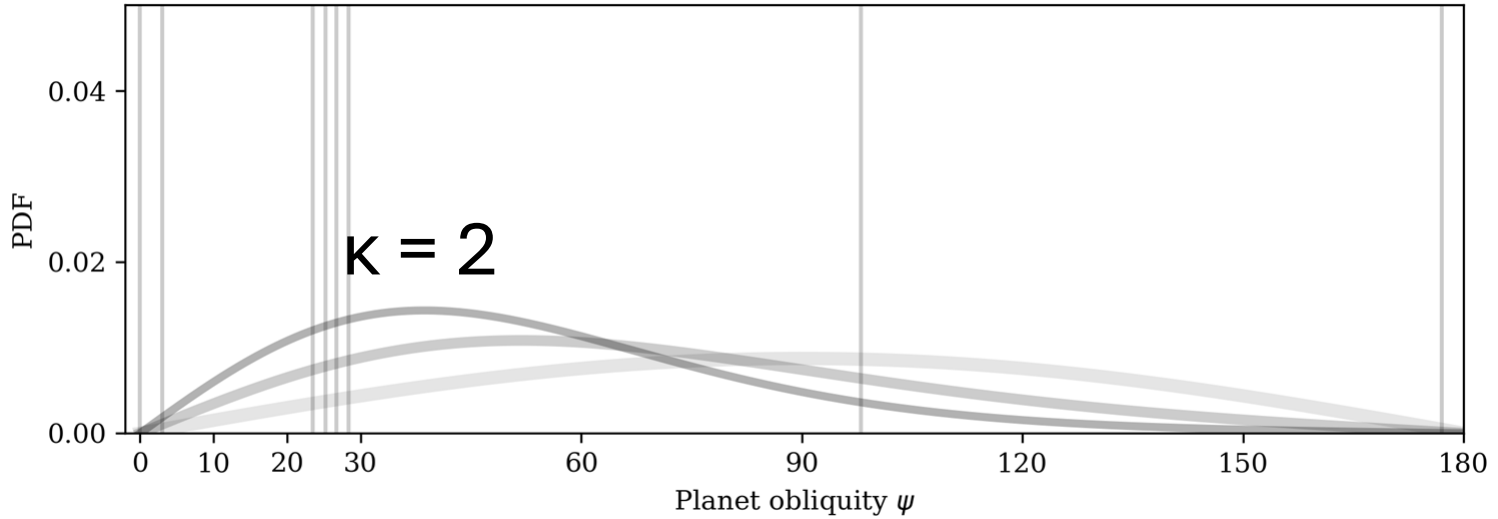


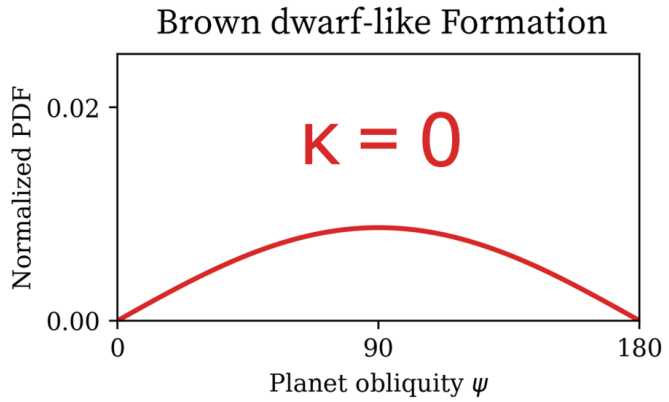


Poon et al. (in review)

We use a Fisher distribution to infer overall formation

Mercury, Jupiter, *Earth, Mars, Saturn, Neptune,* *Uranus,* *Venus*

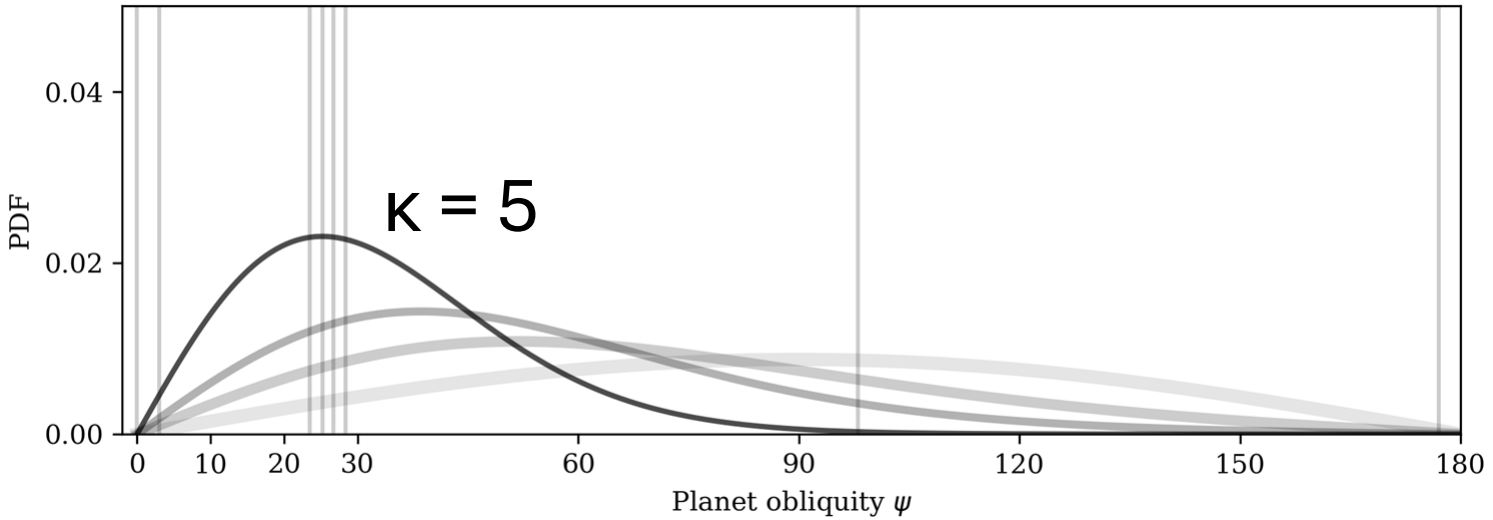


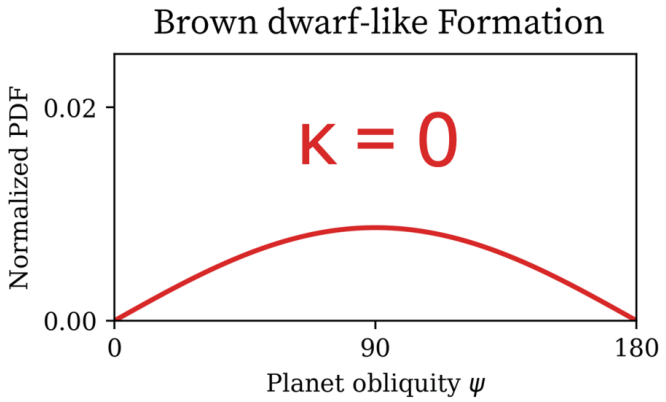


Poon et al. (in review)

We use a Fisher distribution to infer overall formation

Mercury, Jupiter, *Earth, Mars, Saturn, Neptune,* *Uranus,* *Venus*

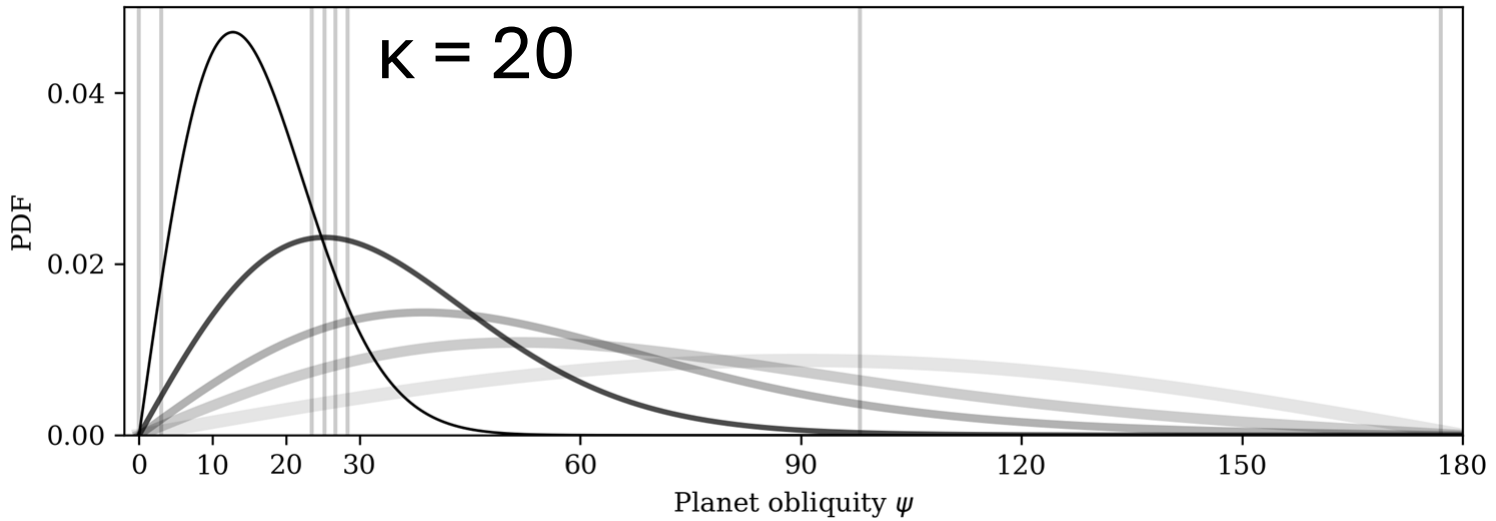


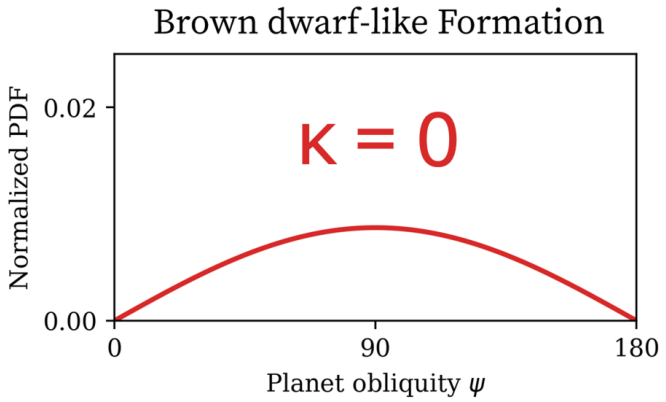


Poon et al. (in review)

We use a Fisher distribution to infer overall formation

Mercury, Jupiter, *Earth, Mars, Saturn, Neptune,* *Uranus,* *Venus*

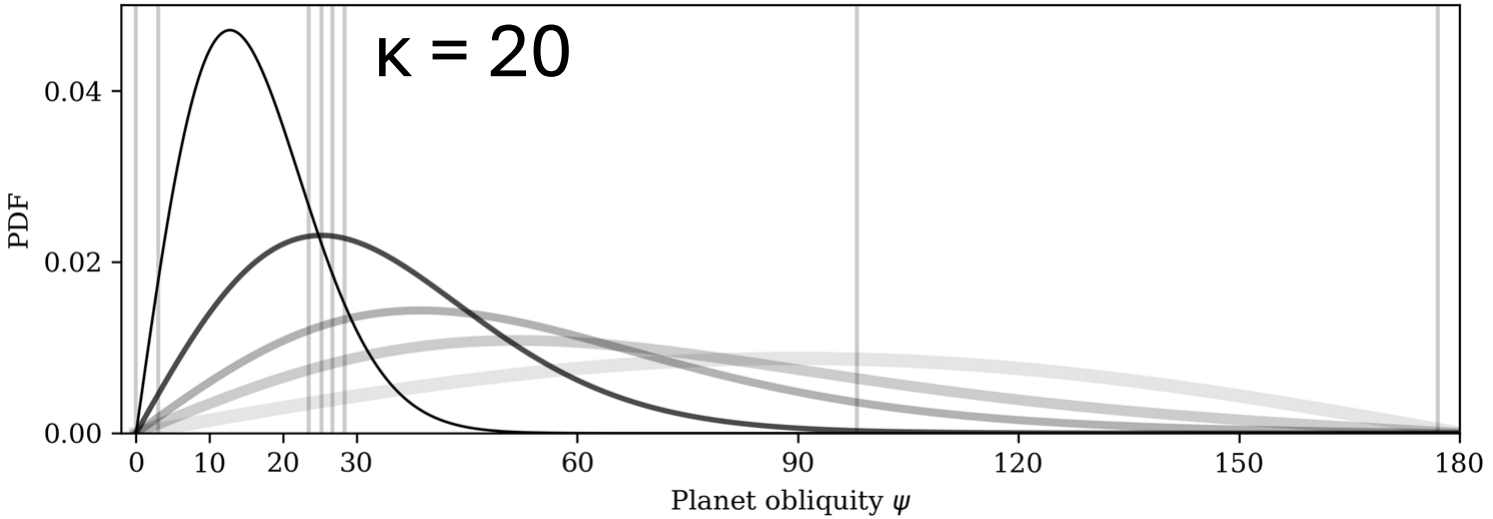


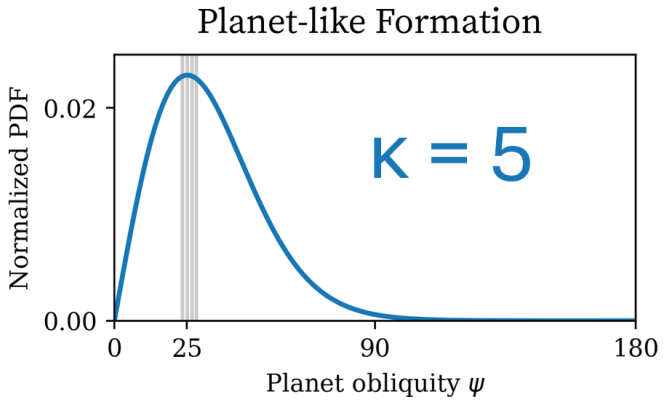


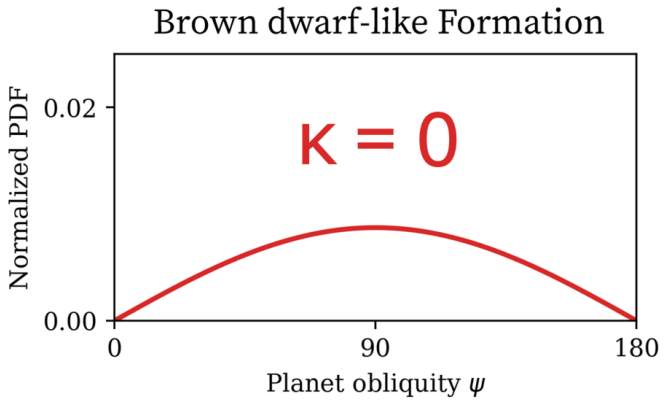
Poon et al. (in review)

We use a Fisher distribution to infer overall formation

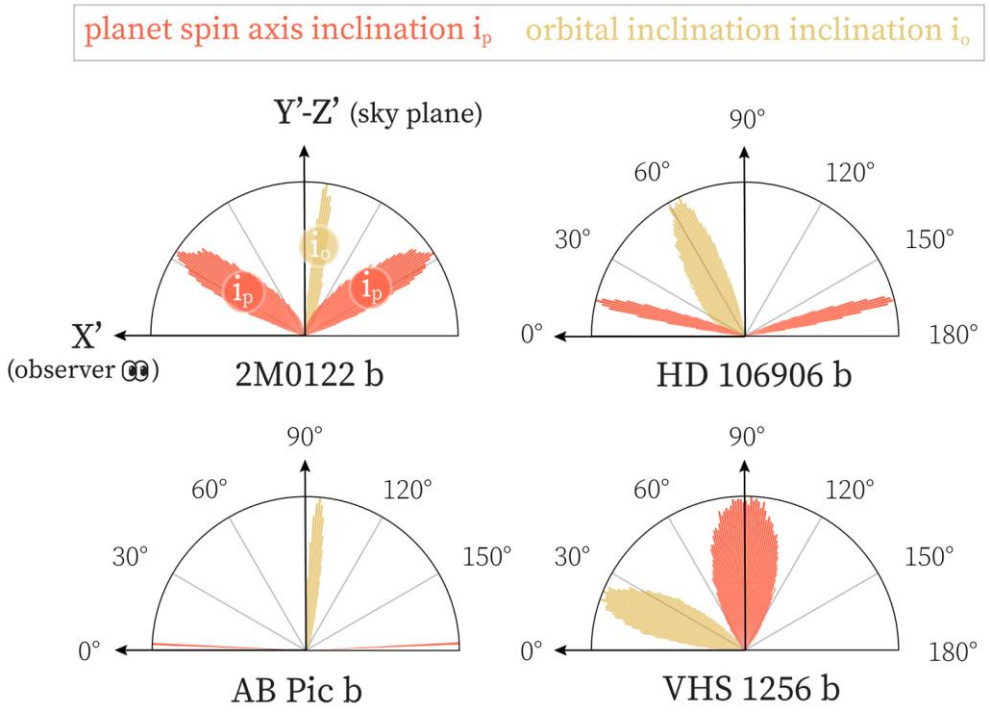
Mercury, Jupiter, *Earth, Mars, Saturn, Neptune,* *Uranus,* *Venus*

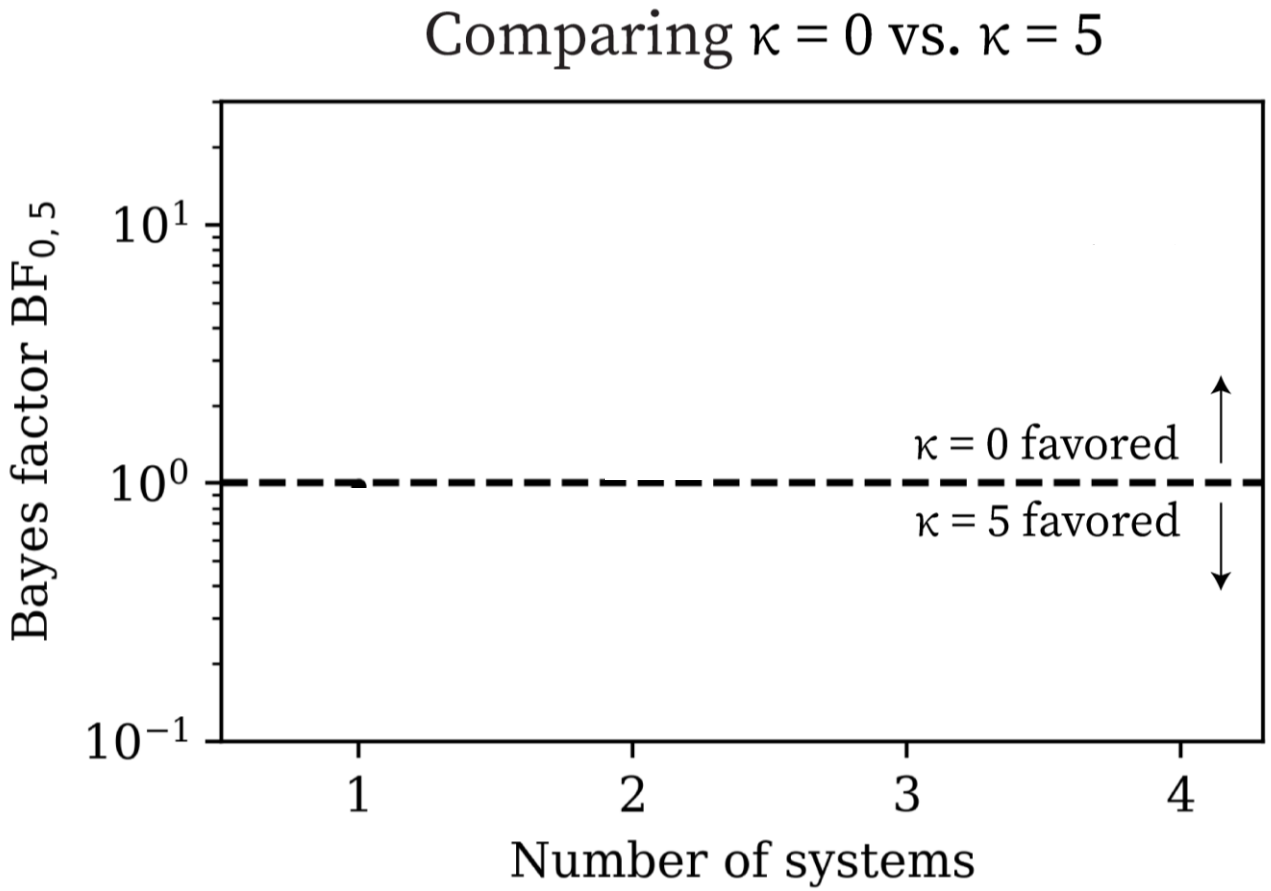


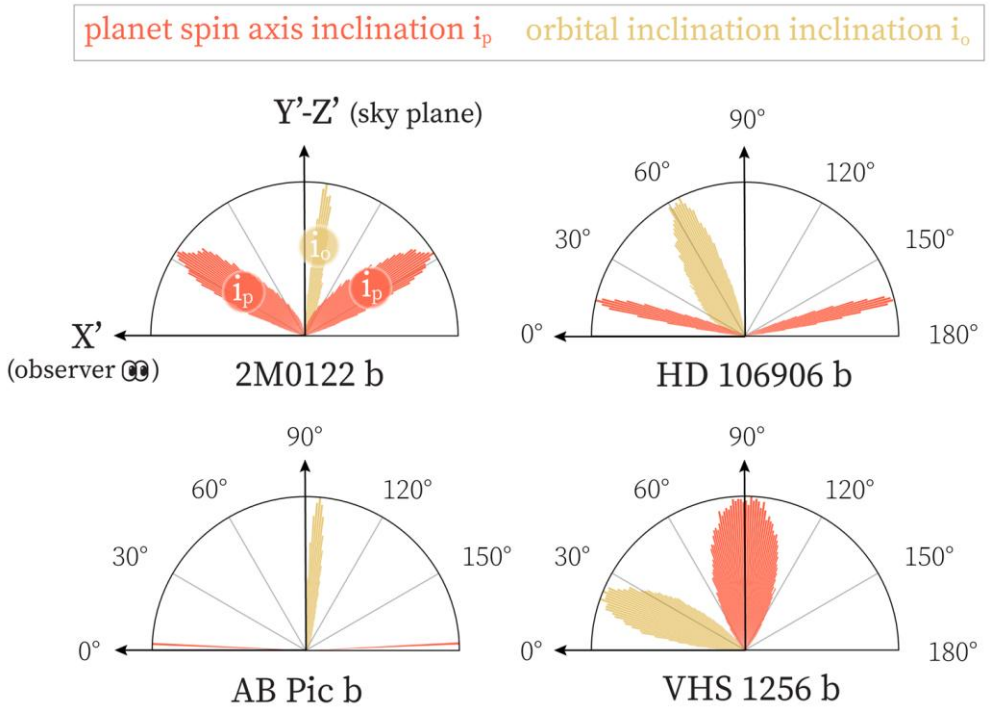


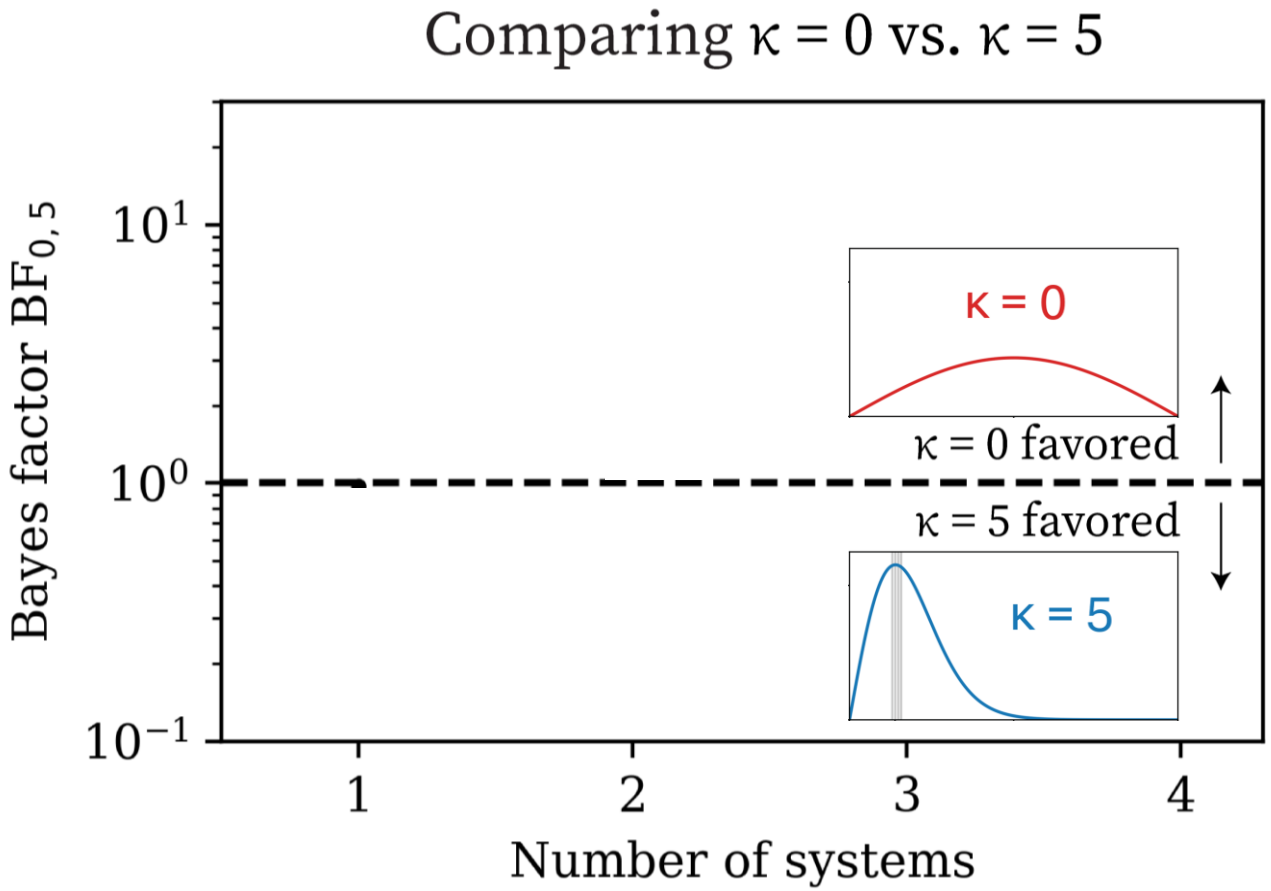


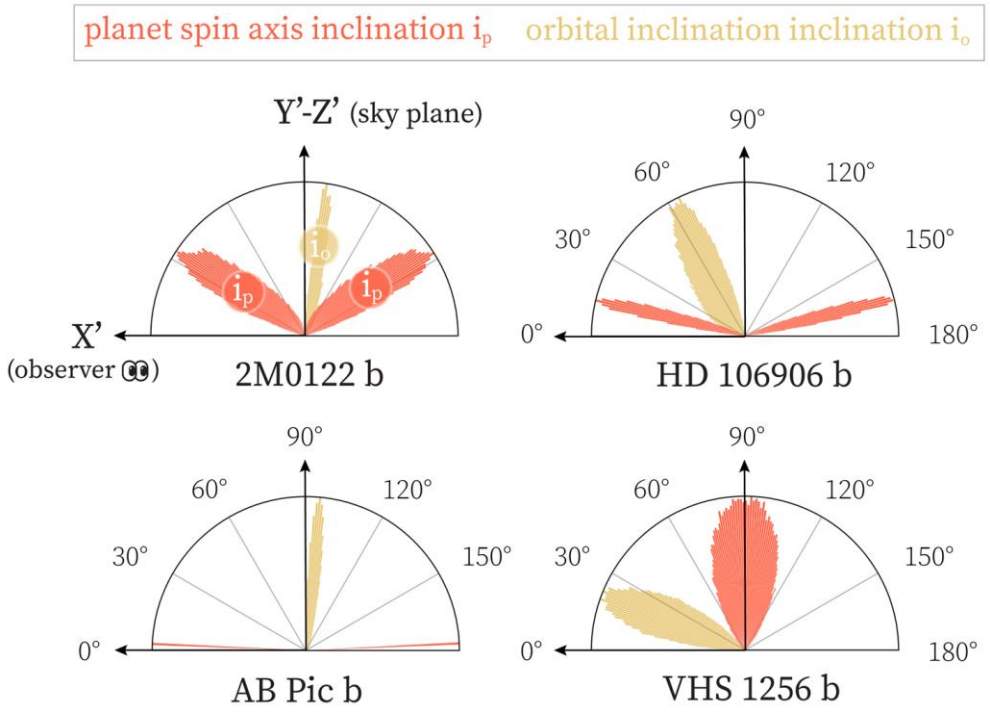
Poon et al. (in review)

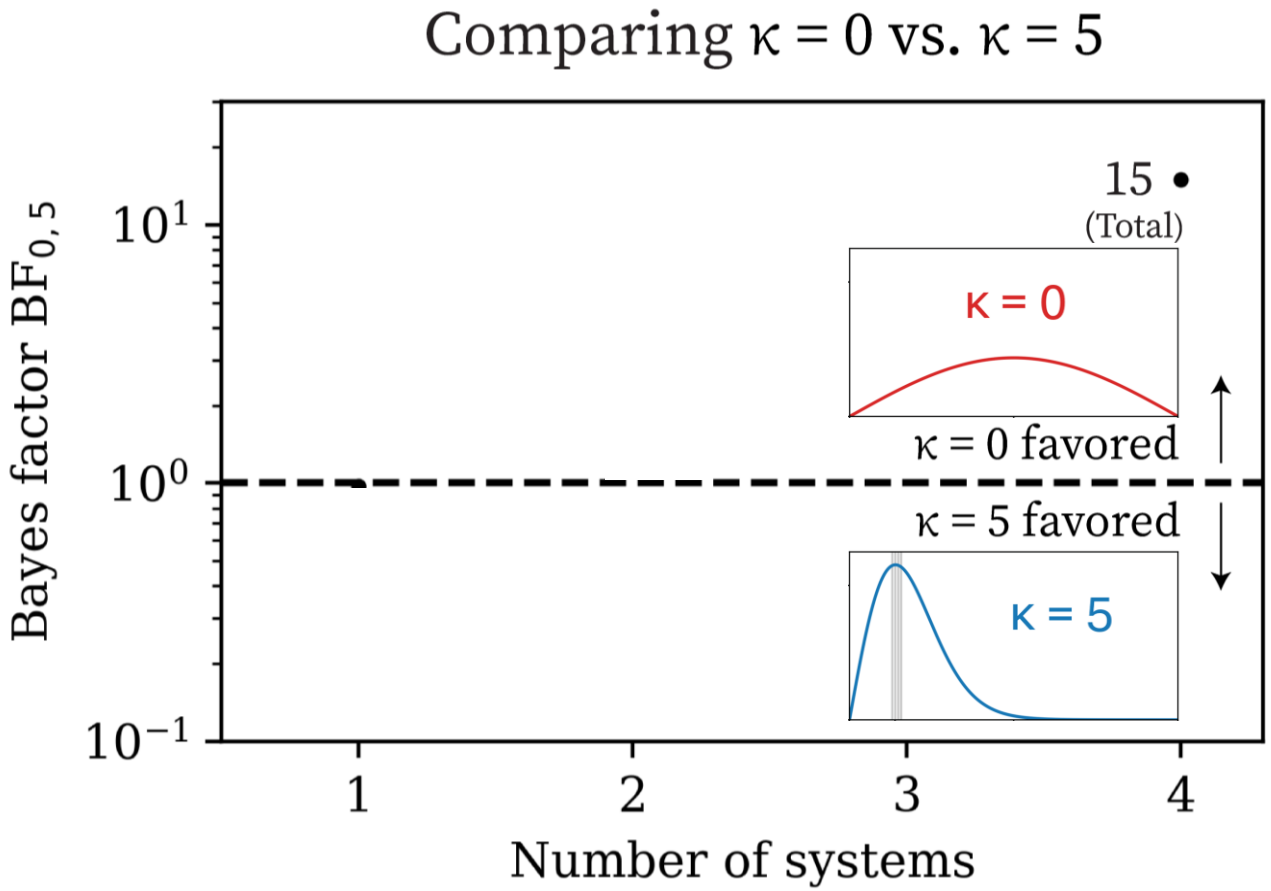

planet spin axis inclination i_p
orbital inclination inclination i_o
Y'-Z' (sky plane)
X'
(observer)
i_o
i_p
i_p
2M0122 b
90°
60°
120°
30°
150°
0°
180°
HD 106906 b
AB Pic b
VHS 1256 b

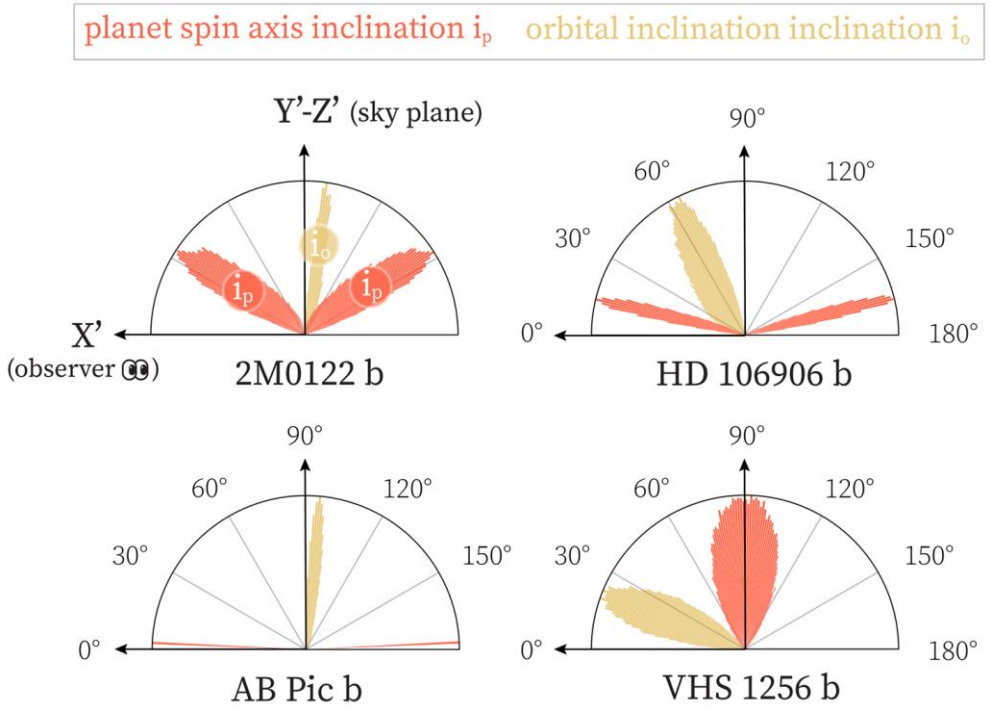

Comparing κ = 0 vs. κ = 5
Bayes factor $BF_{0,5}$
10^1
10^0
10^{-1}
κ = 0 favored
κ = 5 favored
1
2
3
4
Number of systems

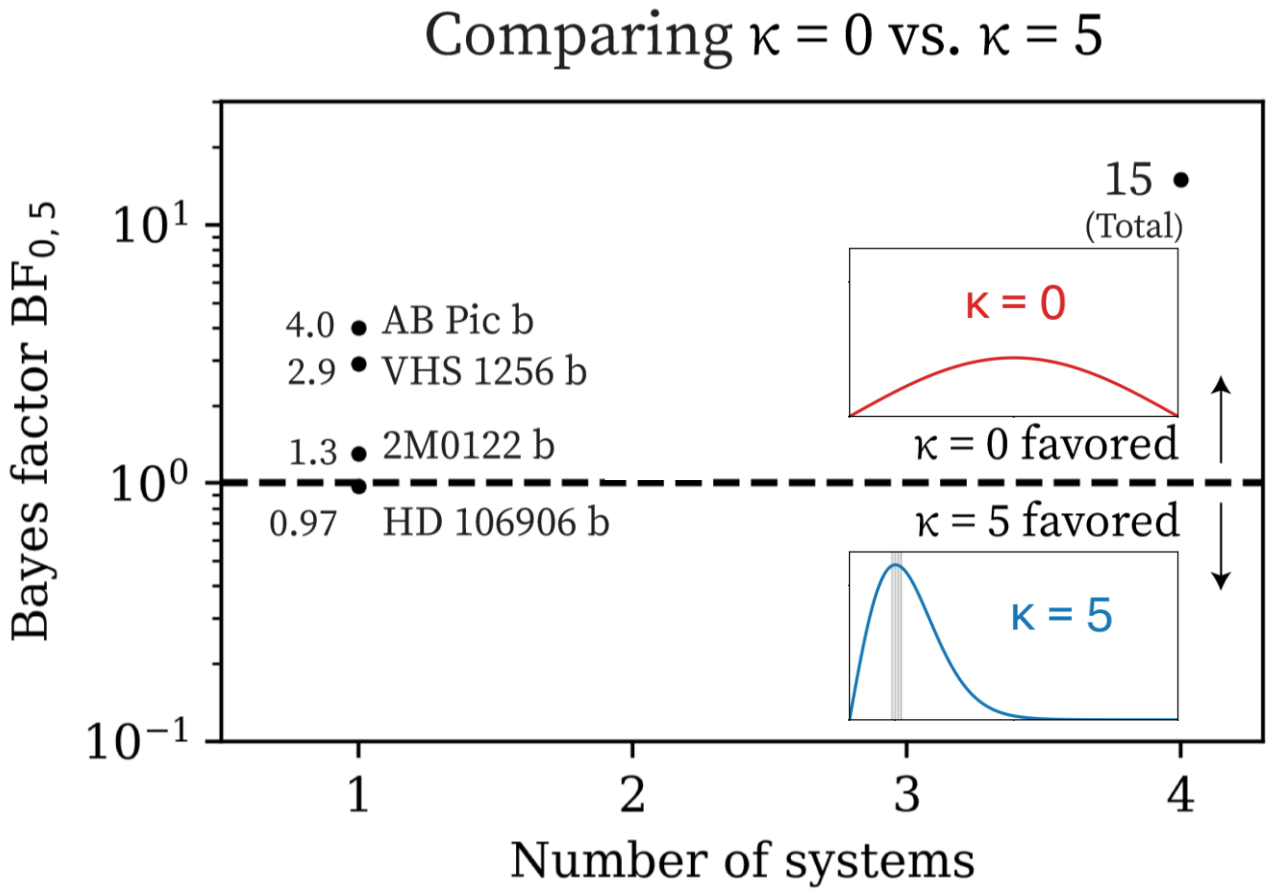

planet spin axis inclination i_p
orbital inclination inclination i_o
Y'-Z' (sky plane)
X'
(observer)
i_o
i_p
i_p
2M0122 b
90°
60°
120°
30°
150°
0°
180°
HD 106906 b
AB Pic b
VHS 1256 b

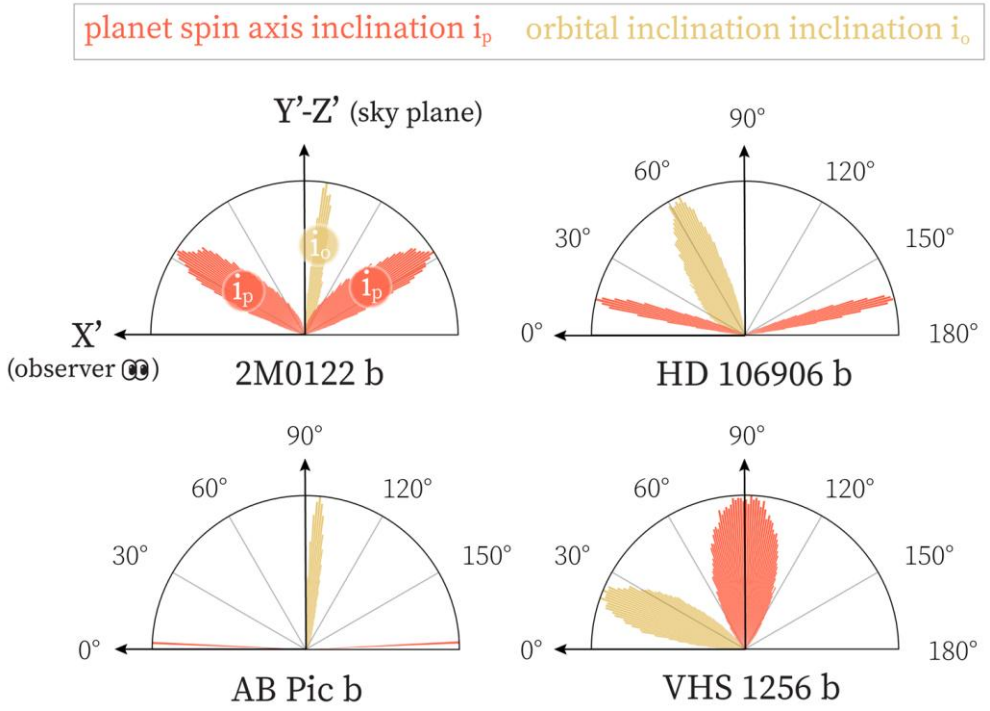

Comparing κ = 0 vs. κ = 5
Bayes factor $BF_{0,5}$
10^1
10^0
10^{-1}
κ = 0
κ = 0 favored
κ = 5 favored
κ = 5
1
2
3
4
Number of systems


planet spin axis inclination i_p
orbital inclination inclination i_o
Y'-Z' (sky plane)
X'
(observer ⊙)
2M0122 b
HD 106906 b
AB Pic b
VHS 1256 b
90°
60°
120°
30°
150°
0°
180°

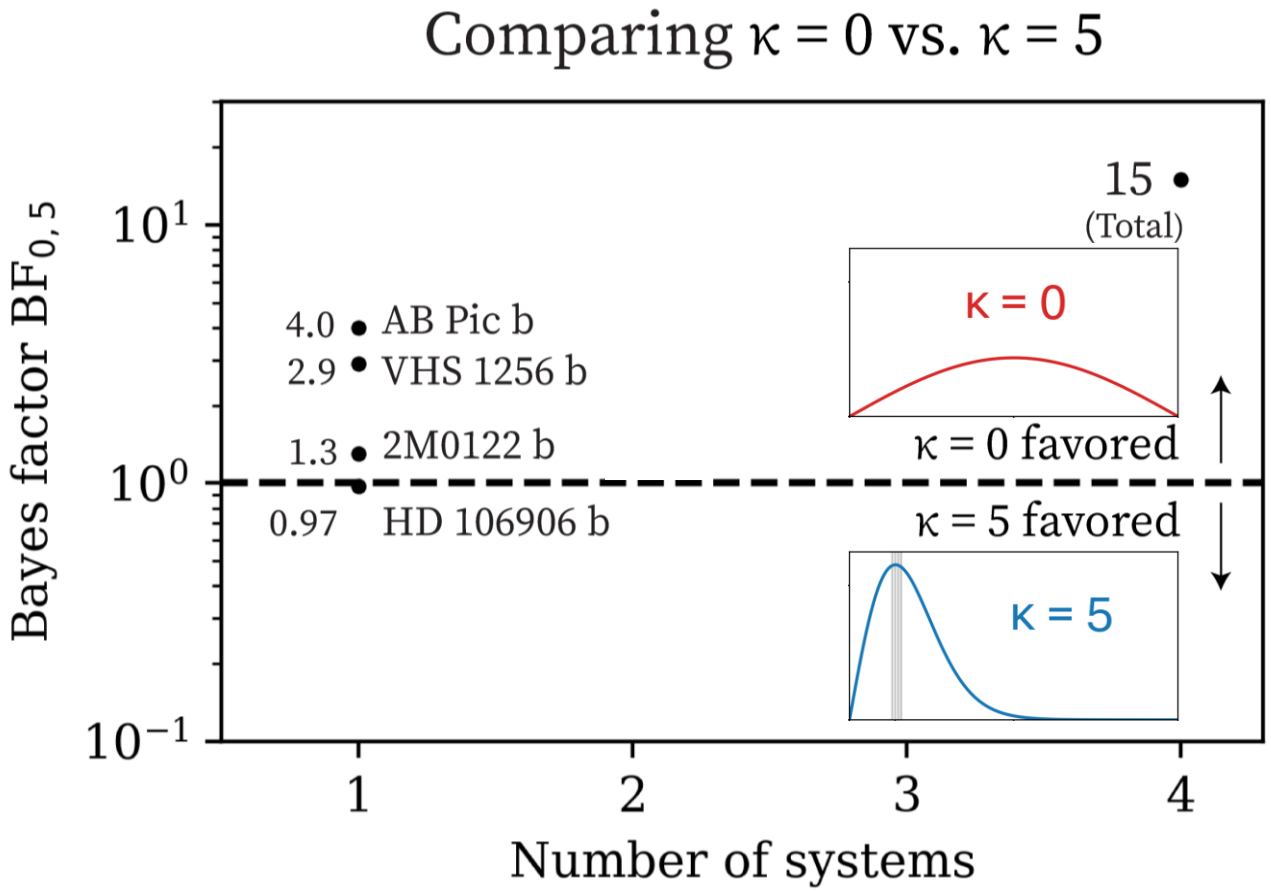

Comparing κ = 0 vs. κ = 5
Bayes factor $BF_{0,5}$
10^1
10^0
10^{-1}
15 •
(Total)
κ = 0
κ = 0 favored
κ = 5 favored
κ = 5
1
2
3
4
Number of systems

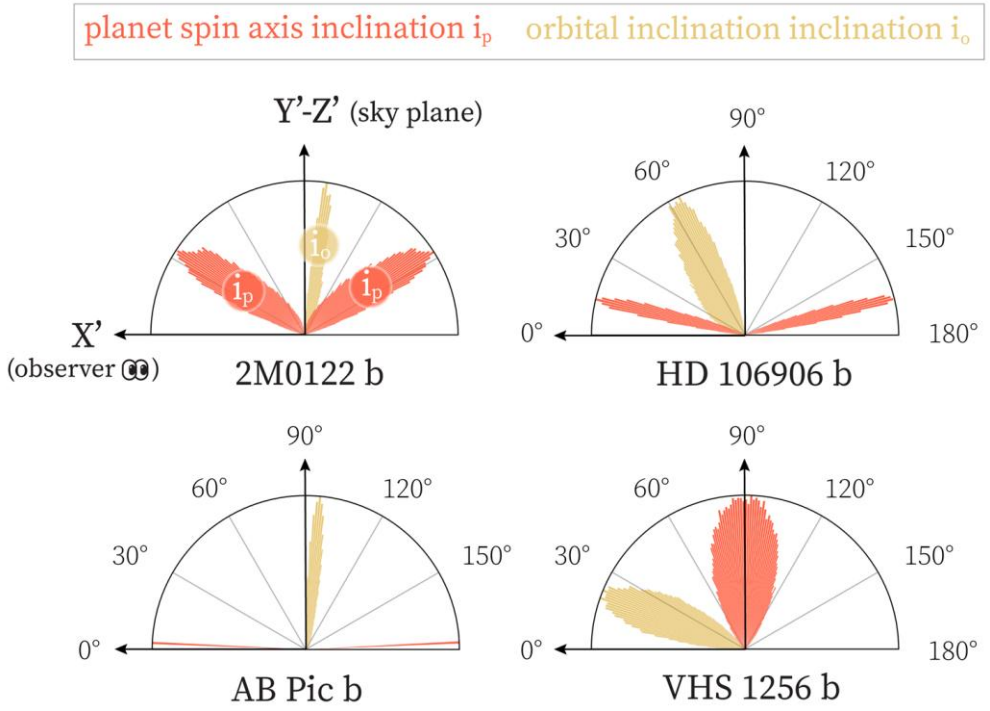

planet spin axis inclination i_p
orbital inclination inclination i_o
Y'-Z' (sky plane)
X'
(observer ∞)
2M0122 b
HD 106906 b
AB Pic b
VHS 1256 b
90°
60°
120°
30°
150°
0°
180°


Comparing κ = 0 vs. κ = 5
Bayes factor $BF_{0,5}$
10^1
10^0
10^{-1}
15 •
(Total)
κ = 0
4.0 • AB Pic b
2.9 • VHS 1256 b
1.3 • 2M0122 b
κ = 0 favored
0.97 HD 106906 b
κ = 5 favored
κ = 5
1
2
3
4
Number of systems

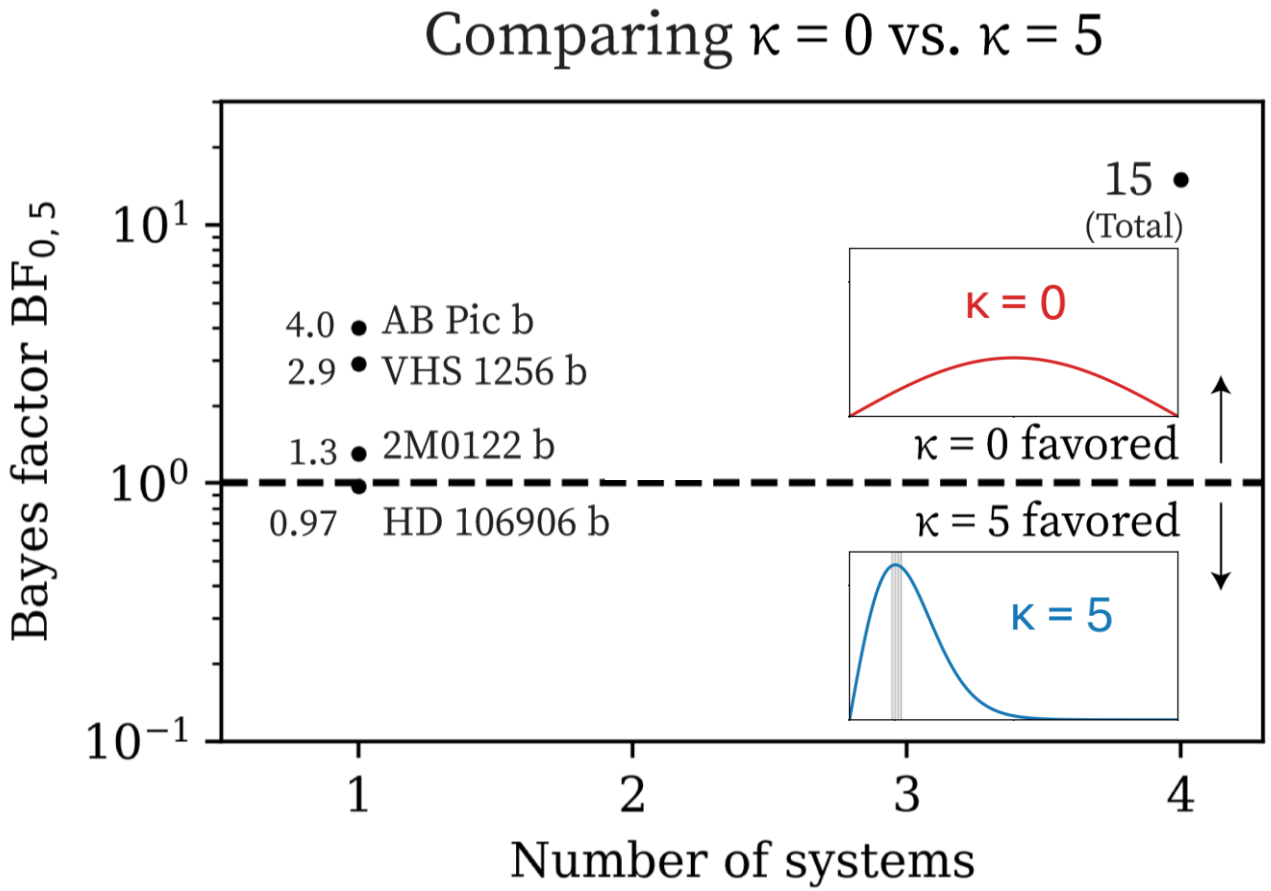

planet spin axis inclination i_p
orbital inclination inclination i_o
Y'-Z' (sky plane)
X'
(observer ⊙)
2M0122 b
HD 106906 b
AB Pic b
VHS 1256 b
90°
60°
120°
30°
150°
0°
180°

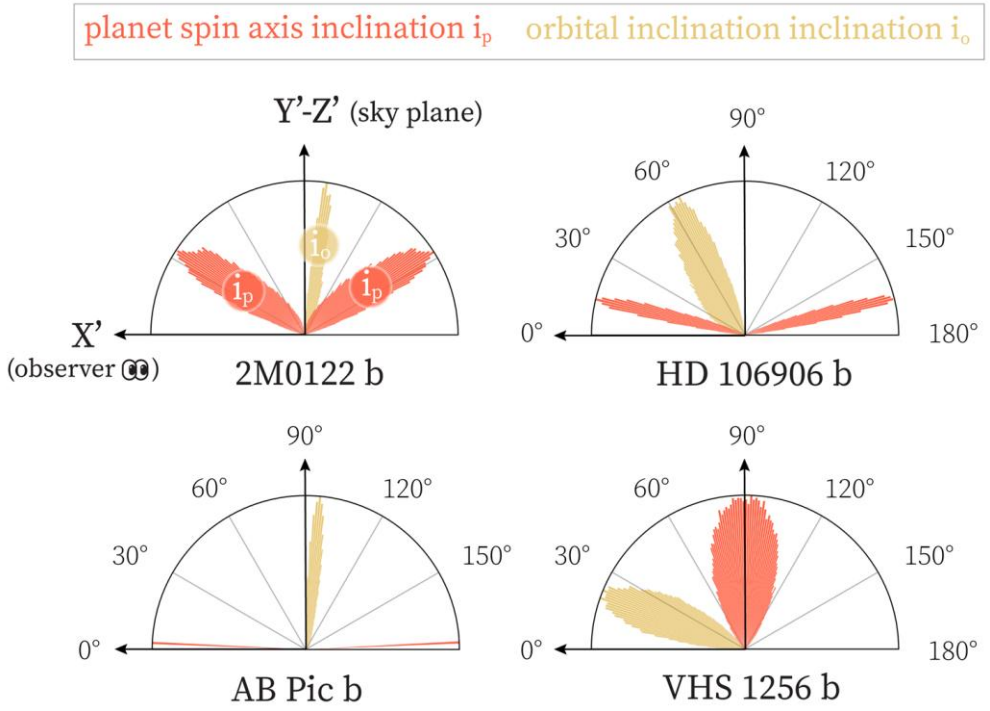
Brown dwarf-like formation is favored with a Bayes factor of 15





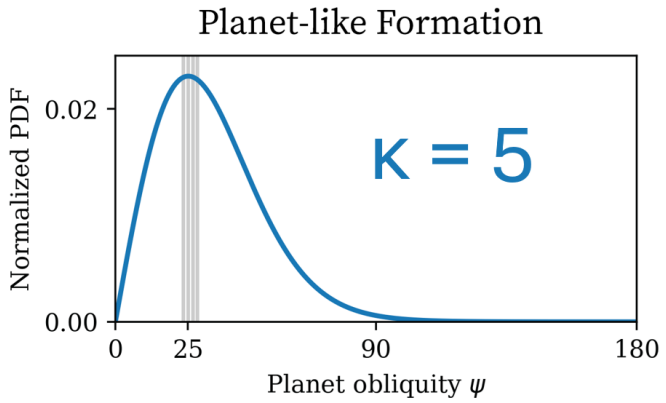
Brown dwarf-like formation is favored with a Bayes factor of 15

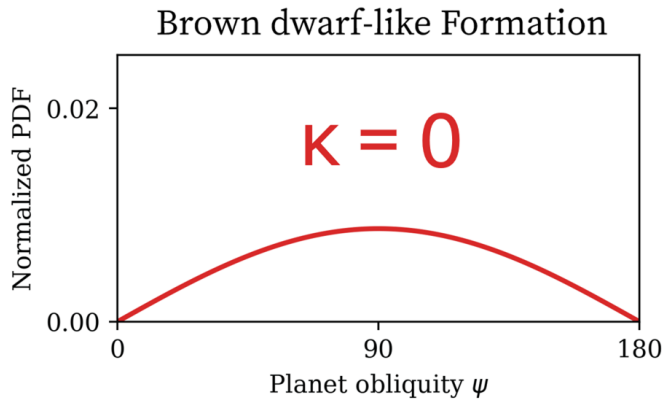




Early evidence for *isotropic* planetary obliquities in young super-Jupiter systems (Poon et al. in review)

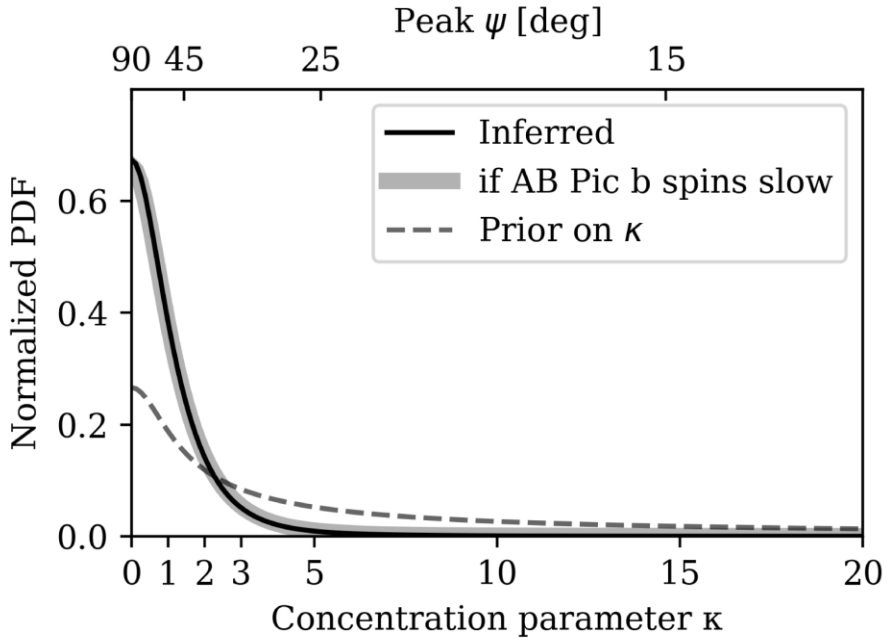
We develop a hierarchical Bayesian model to infer overall formation

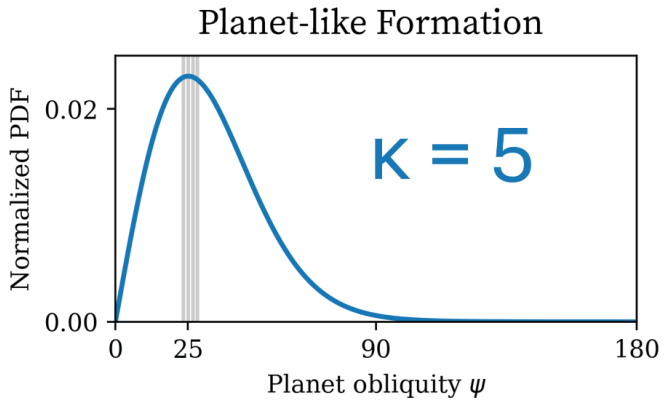


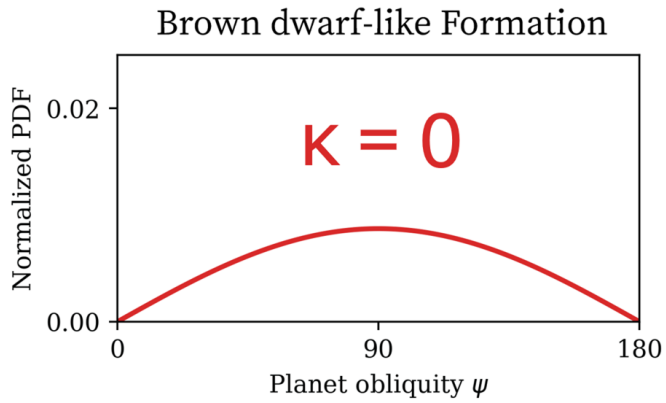


Poon et al. (in review)

We develop a hierarchical Bayesian model to infer overall formation

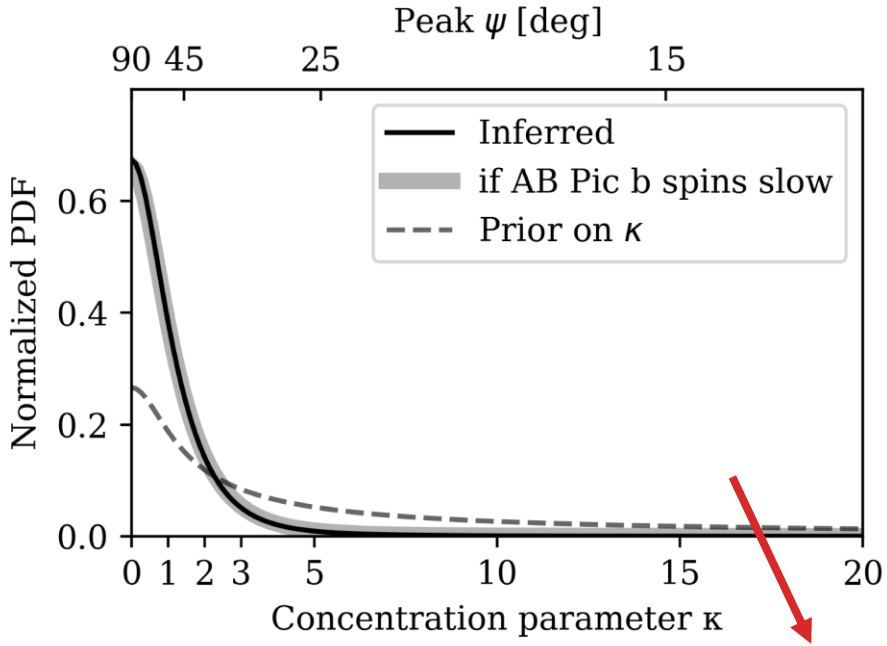




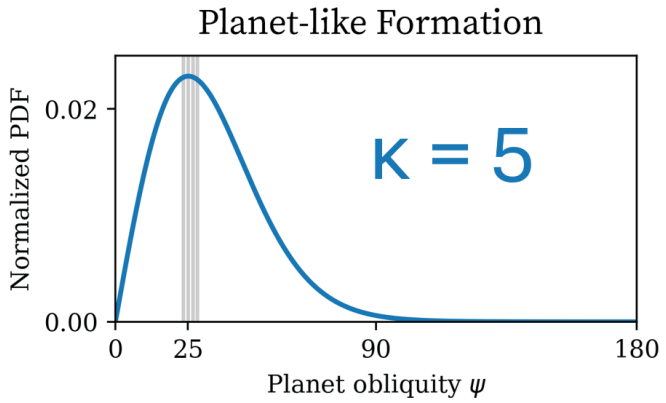


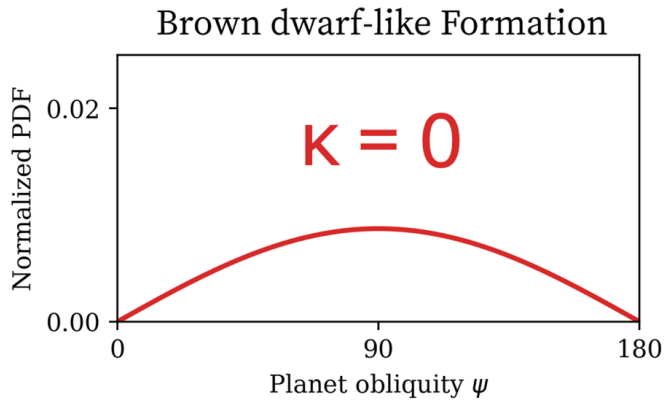
Poon et al. (in review)

We develop a hierarchical Bayesian model to infer overall formation



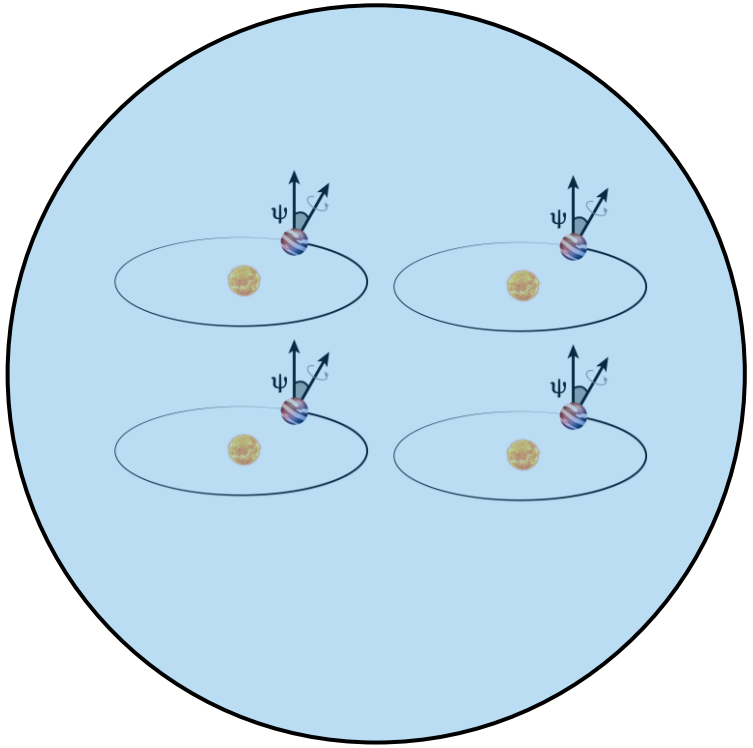
favored





Poon et al. (in review)

Early evidence for *isotropic* planetary obliquities in young super-Jupiter systems (Poon et al. in review)



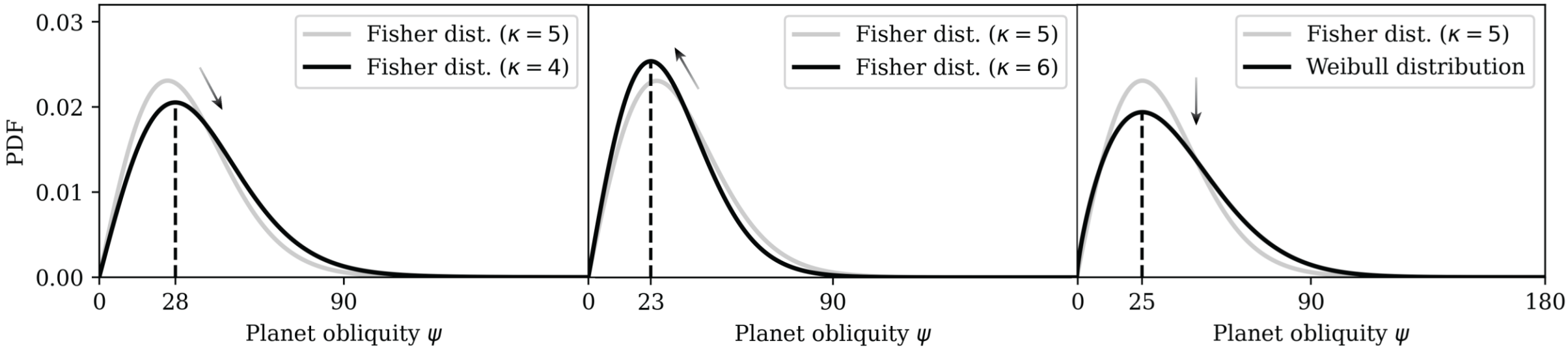
1. We find evidence **favoring a brown-dwarf formation** pathway for young super-Jupiters

2. Sample size motivates **further observations** to strengthen inference

**Ping Pong Announcement after this!!*

extra slides

What about different κ for planet-like formation? (1/2)

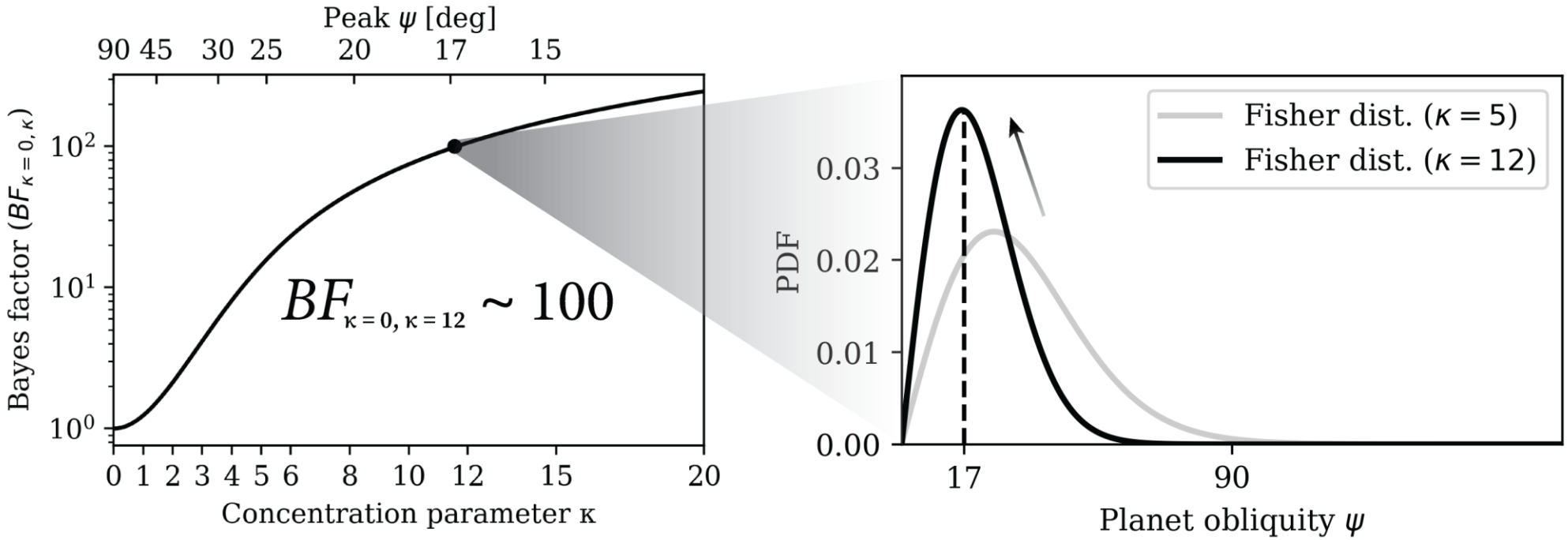


Bayes factor = 8

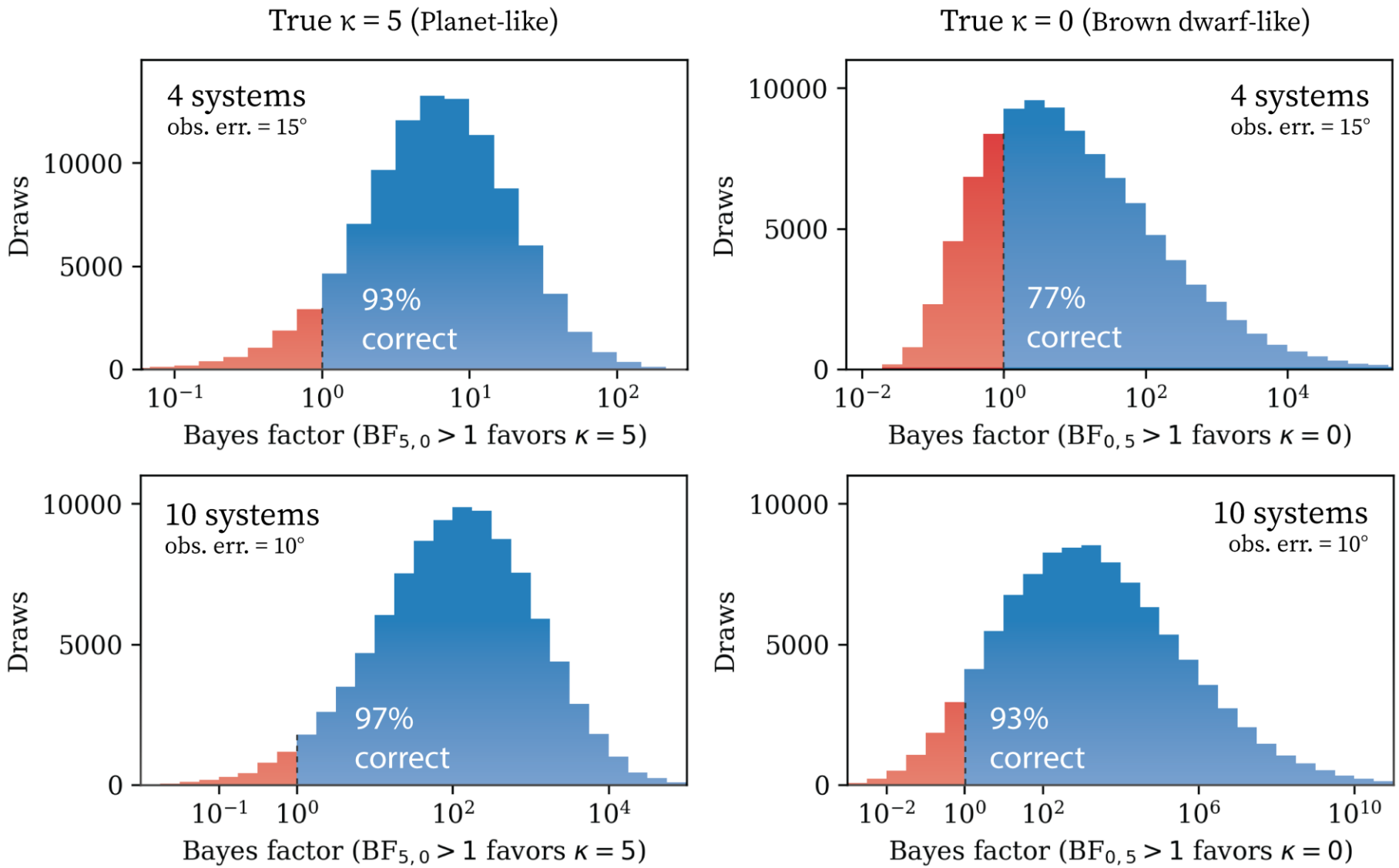
Bayes factor = 24

Bayes factor = 9

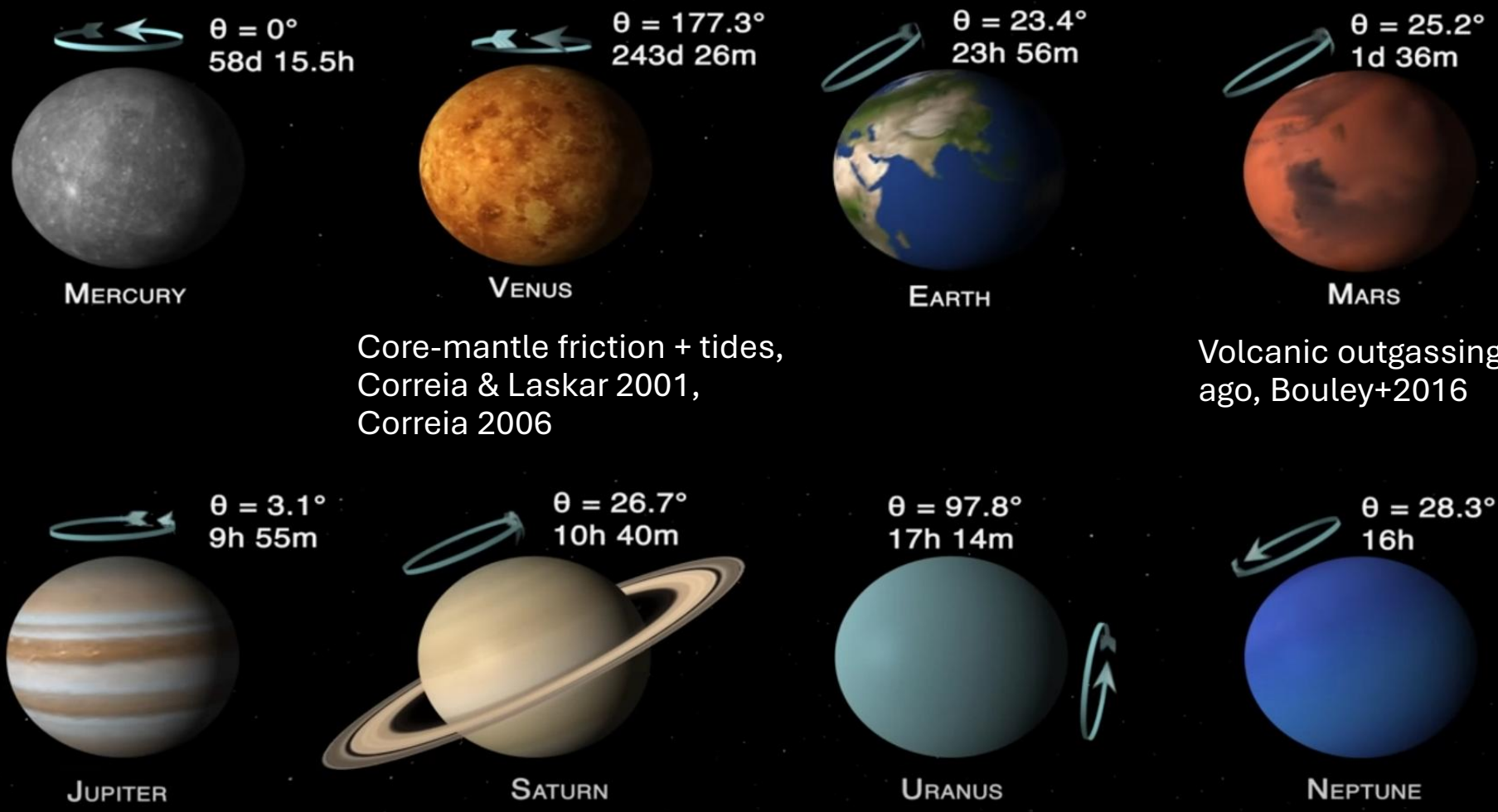
What about different κ for planet-like formation? (2/2)



Can a Bayes factor identify the correct formation scenario?



What causes obliquities in our Solar System?



Core-mantle friction + tides, Correia & Laskar 2001, Correia 2006

Volcanic outgassing 3 Gyr ago, Bouley+2016

Spin-orbit resonance, Ward & Hamilton 2004, Saillenfest+2021

Grazing collision, Reinhardt+2020

Head-on collision, Reinhardt+2020

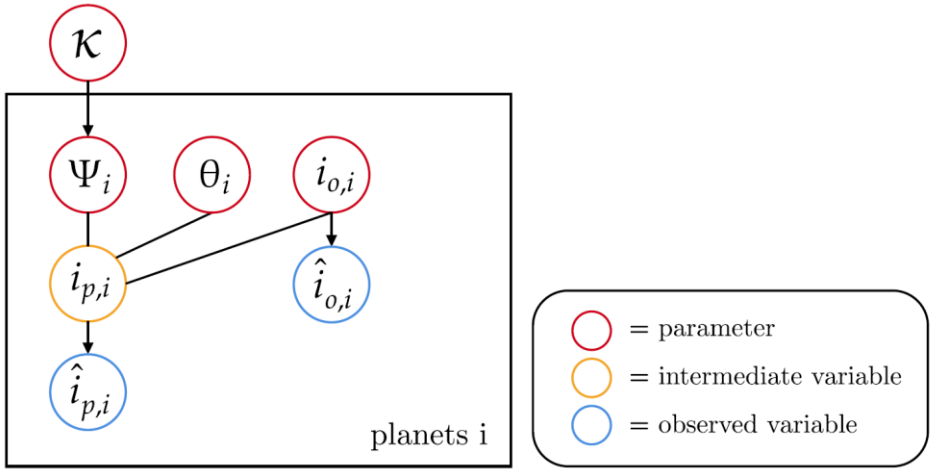
Credit: James O'Donoghue / NASA

The juicy details

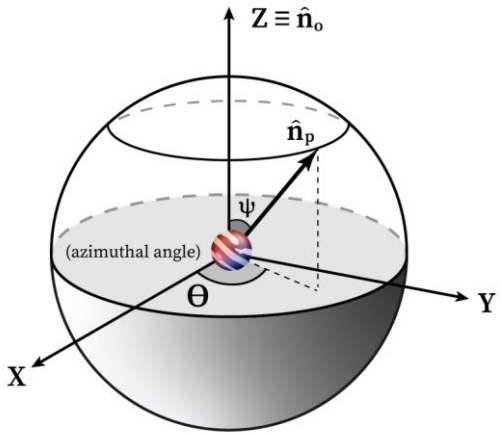
1. We use a Fisher distribution to model the overall distribution of planetary obliquities

$$P(\psi|\kappa) = \frac{\kappa}{2\sinh\kappa}\exp\left(\kappa\cos\psi\right)\sin\psi$$

2. Diagram of hierarchical model



3. Coordinate system for data generation

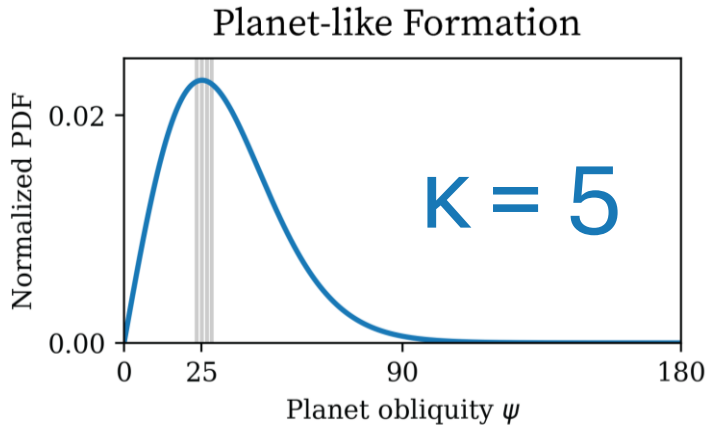


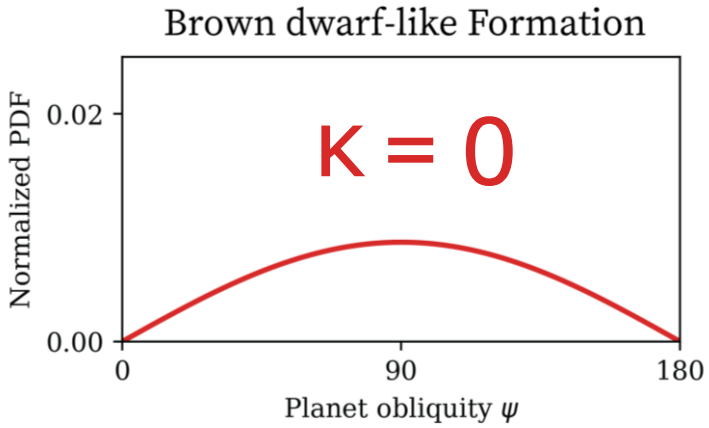
4. Posterior of hierarchical model

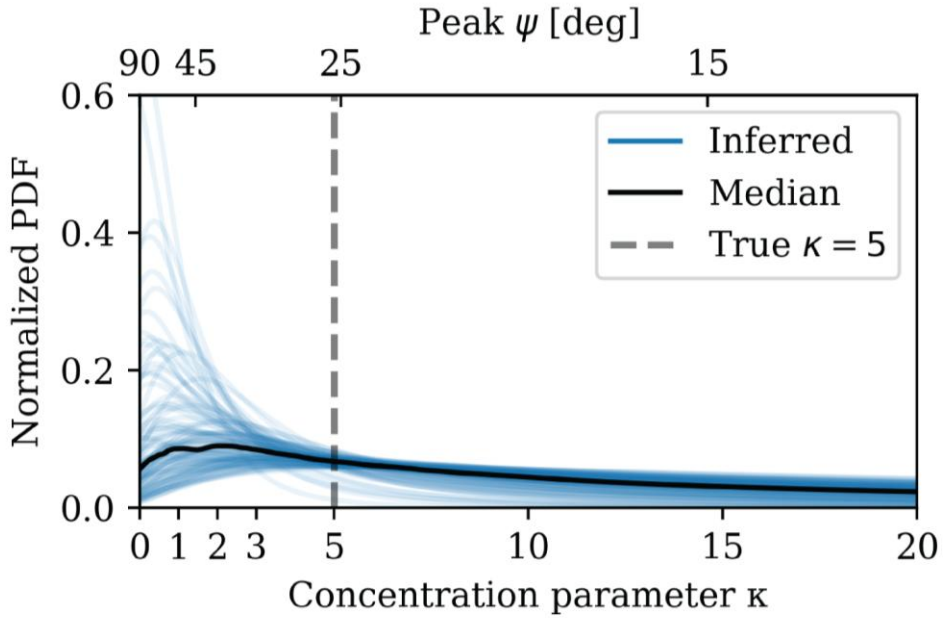
$$P\left(\kappa, \{\psi_i, \theta_i, i_{o,i}\}\middle|\{\hat{i}_{p,i}, \hat{i}_{o,i}\}\right) \propto \overbrace{P(\kappa)}^{\text{hyperprior}} \times \underbrace{\prod_{i=1}^{n}}_{\text{iid}} \underbrace{P(\{\psi_i\}|\kappa)P(\{\theta_i\})P(\{i_{o,i}\})}_{\text{prior}} \times \underbrace{P(\{\hat{i}_{p,i}\}|\{\psi_i, \theta_i, i_{o,i}\})P(\{\hat{i}_{o,i}\}|\{i_{o,i}\})}_{\text{likelihood}},$$

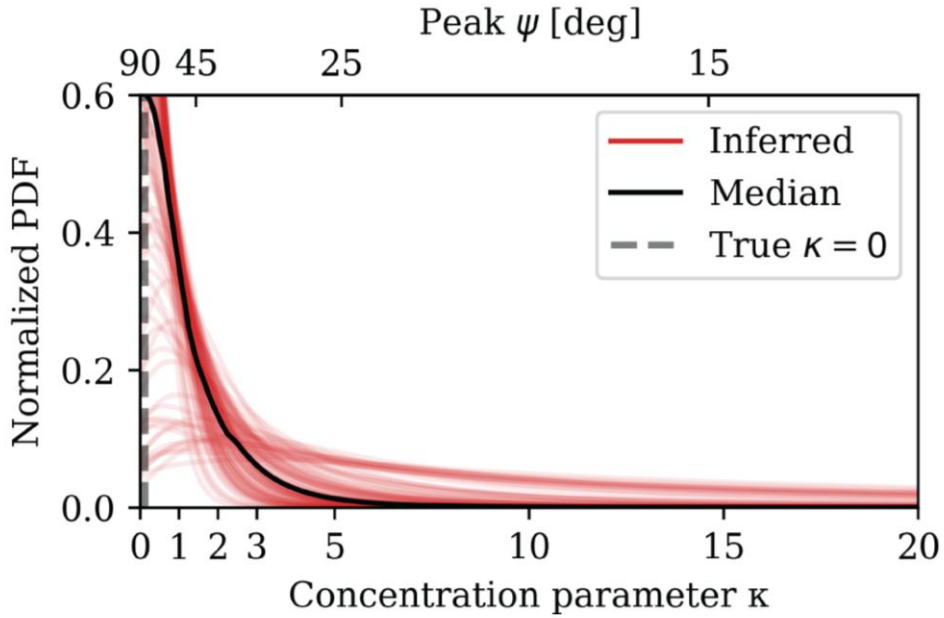
Poon et al. (in prep)

We test the performance of our hierarchical model on simulated data









Poon et al. (in prep)

51 Peg. 30th Anniversary OHP 2v2 Ping Pong championship

51 Peg. 30th Anniversary OHP 2v2 Ping Pong championship

ALDUKE (Aldo+ Luca)

CFL Violators (Alex + Emmanuel)

Ping Pong Planets (Jesse + Jorge)

Notre Dame de Paris (Florian + David)

Team Canada (Caleb + Michael)

Team Luigi & Marc

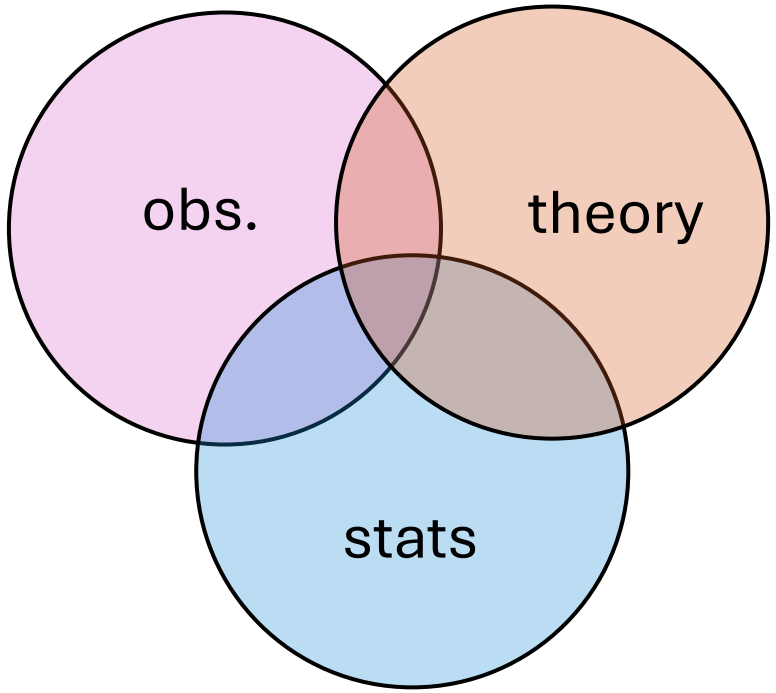
51 Peg. 30th Anniversary OHP 2v2 Ping Pong championship

1st ALDUKE (Aldo Bonomo + Luca Naponiello)

2nd Ping Pong Planets (Jesse Weder + Jorge Lillo-box)

3rd Team Canada (Caleb Lammers + Michael Poon)

Exoplanetary obliquity through three lenses:



Main takeaways:

Observational constraints on the first Uranus-like tilt of an exoplanet

Poon, Bryan, Rein et al. 2024

Exomoons can tilt planets, applied to β Pic b

Poon, Rein & Pham 2024

Widely-separated super-Jupiters form like brown dwarfs

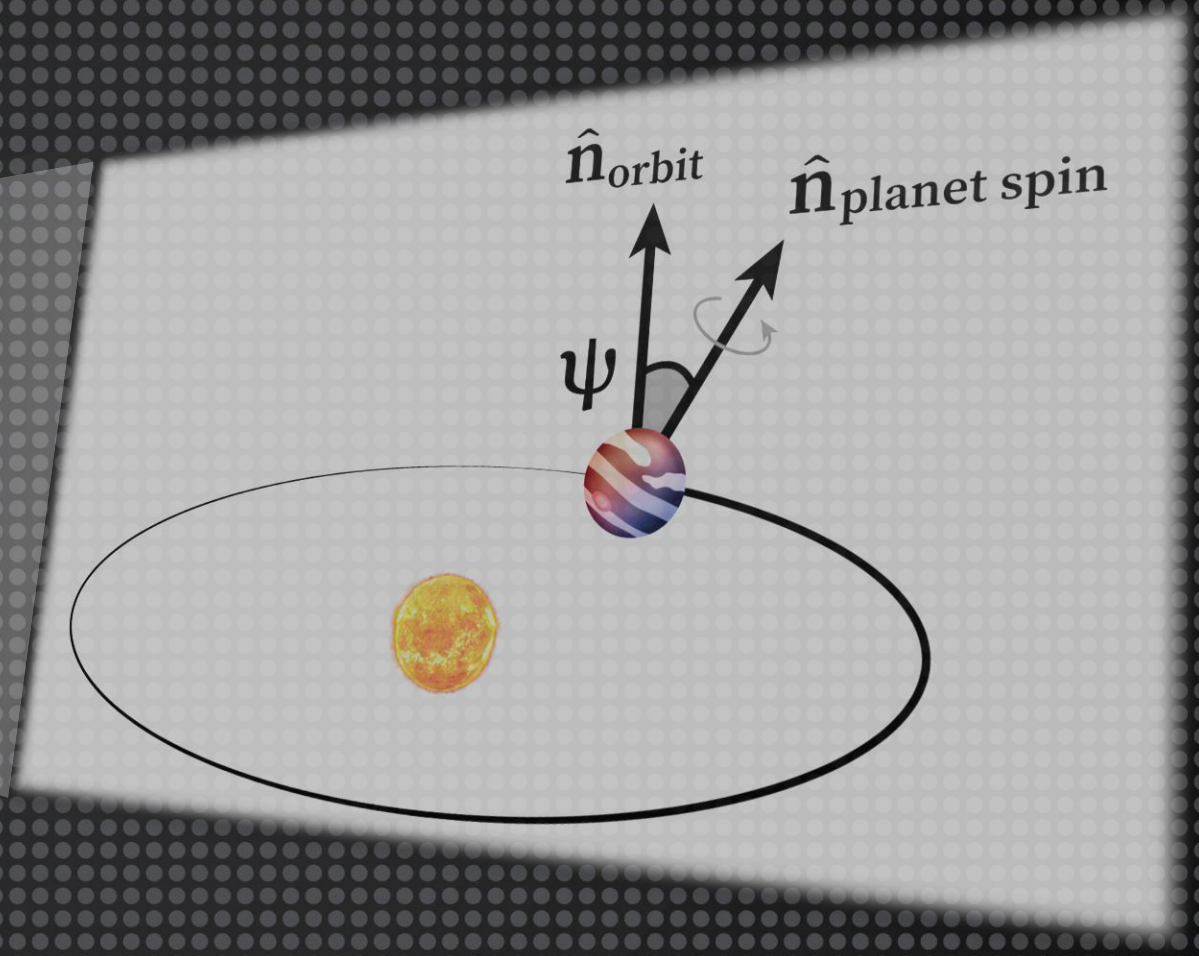
Poon, Bryan, Rein & Dong (in review)

What about planet obliquities from JWST transits?

EARLY EVIDENCE FOR ? PLANETARY OBLIQUITIES IN YOUNG SUPER-JUPITER SYSTEMS

plar

Early evidence for ? planetary obliquities in young super-Jupiter systems



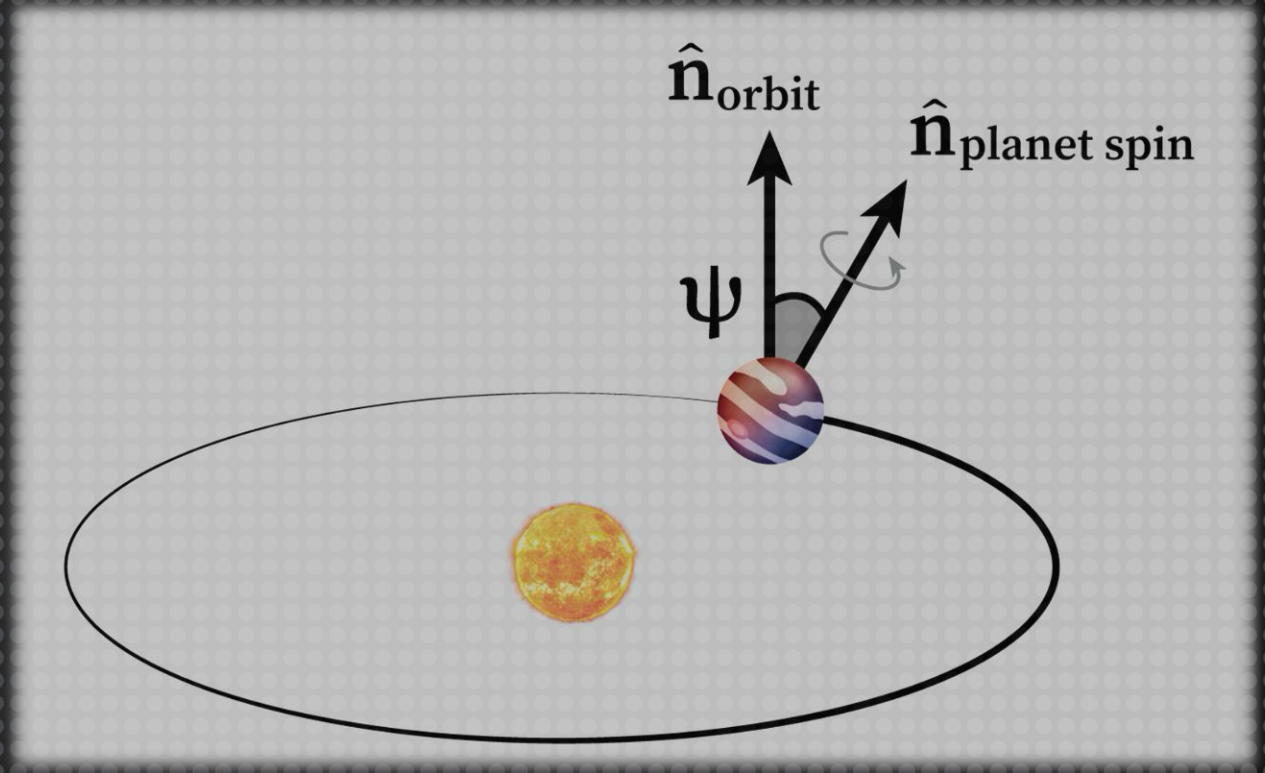
Michael Poon

Final Year PhD Candidate

University of Toronto

51 Peg b 30th Anniversary – Oct. 9, 2025

Early evidence for ? planetary obliquities in young super-Jupiter systems



Michael Poon

Final Year PhD Candidate

University of Toronto

51 Peg b 30th Anniversary – Oct. 9, 2025