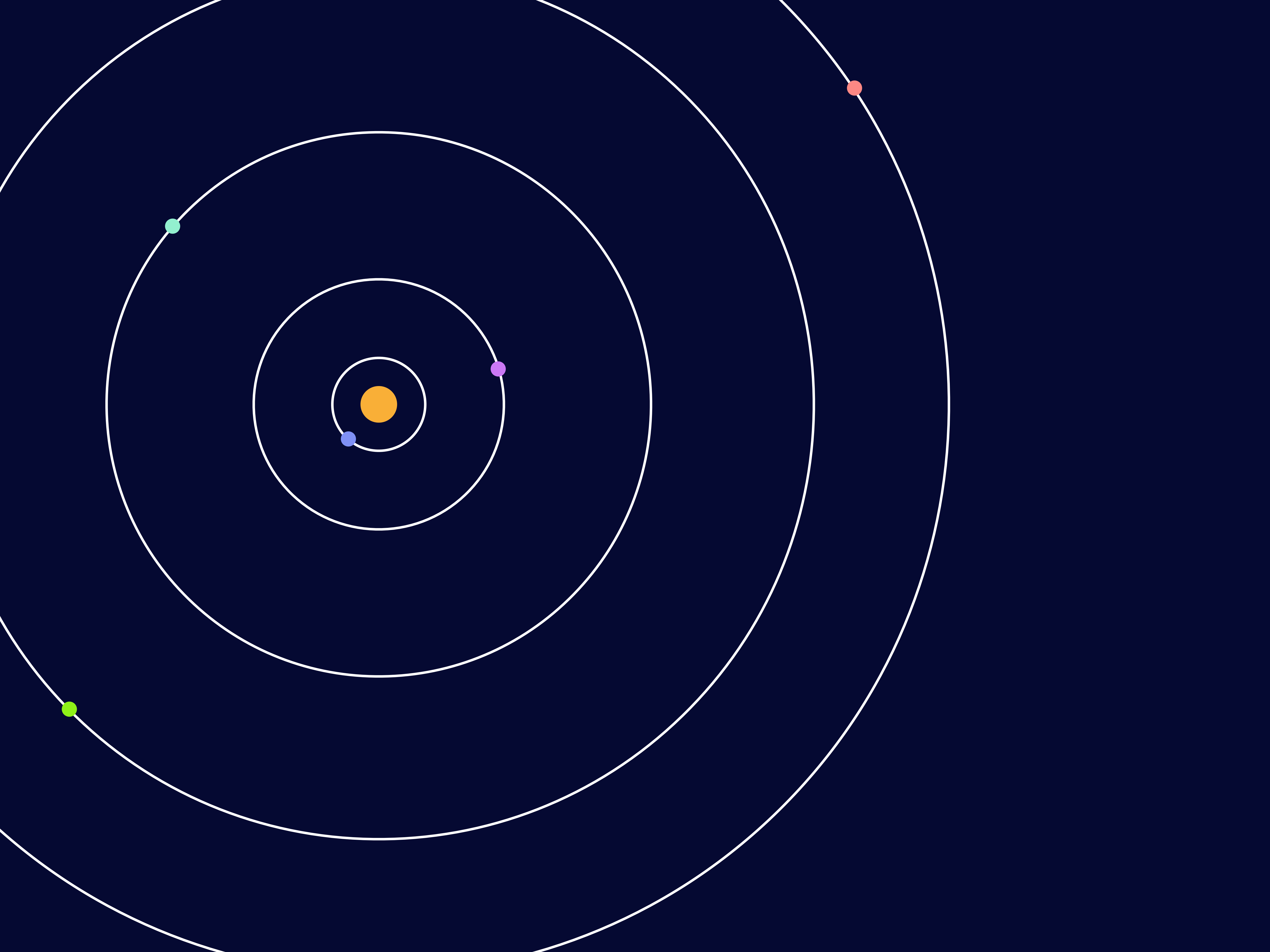
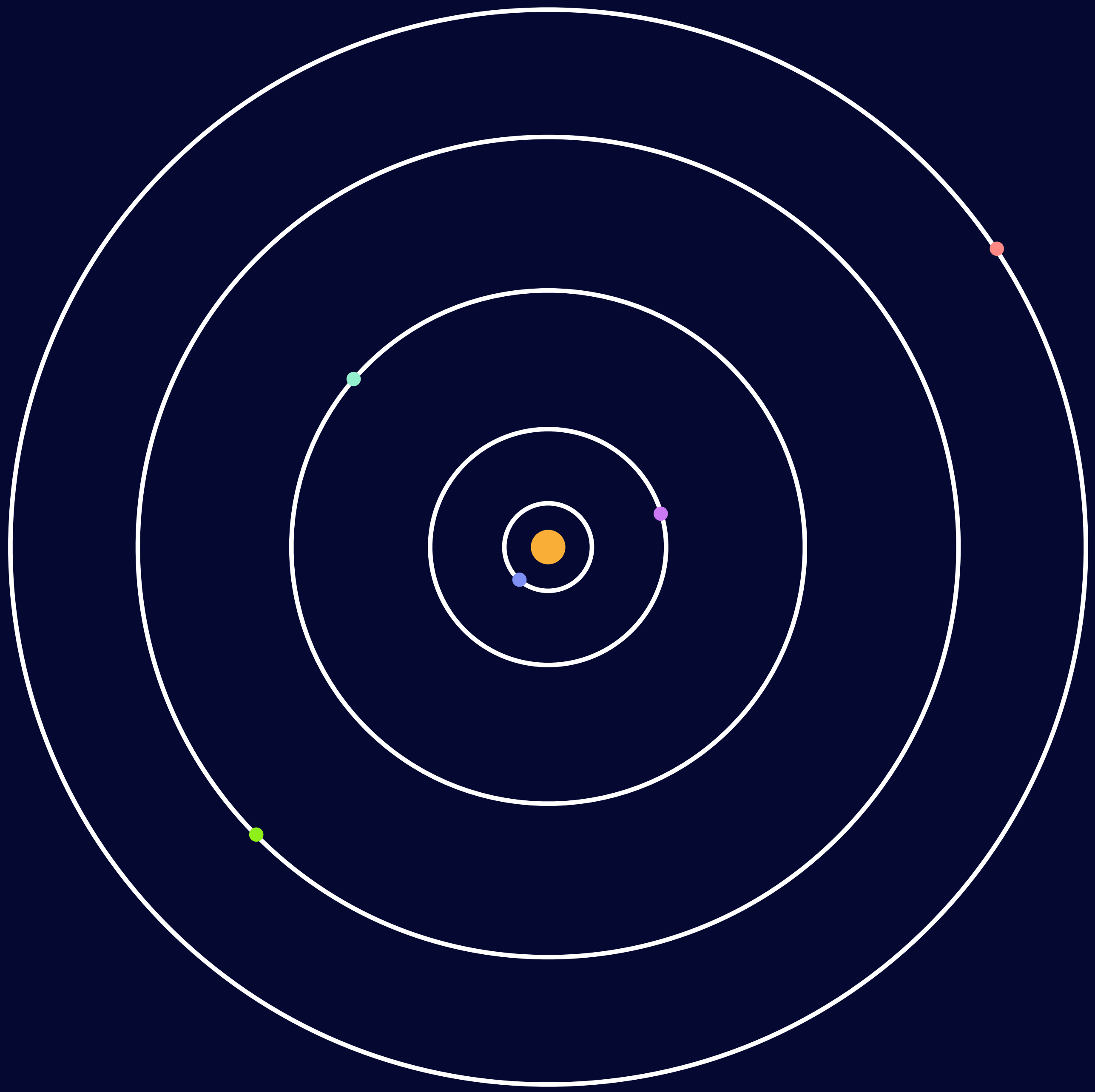
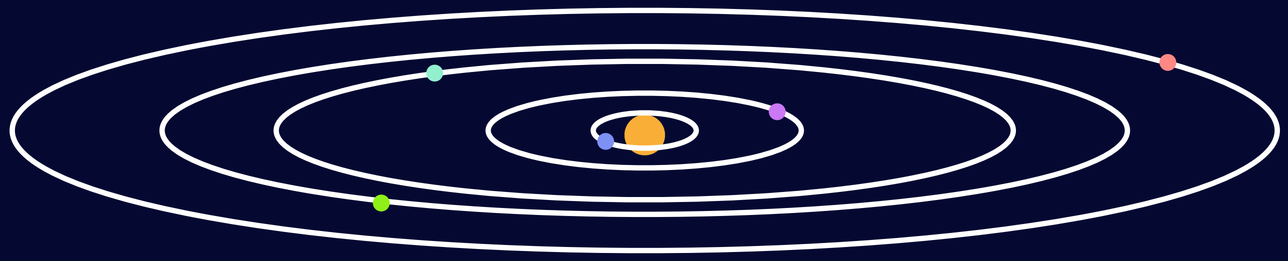
Demographics of Star-Planet Orbital Orientations

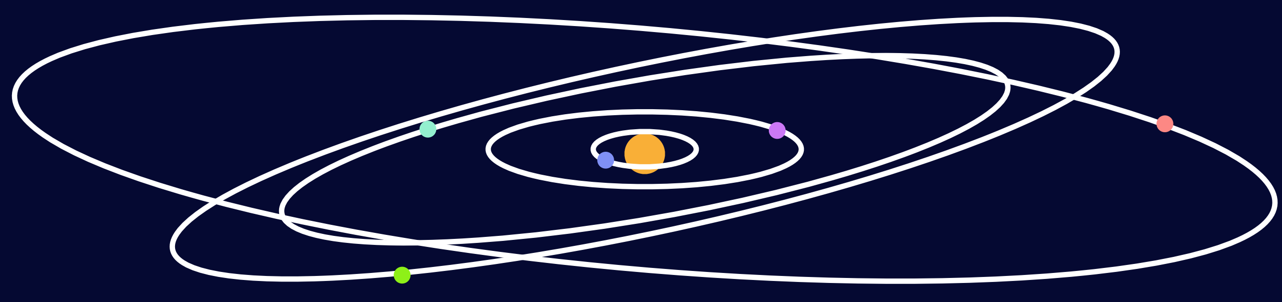
Know Thy Star, Know Thy Planet II
February 6, 2025

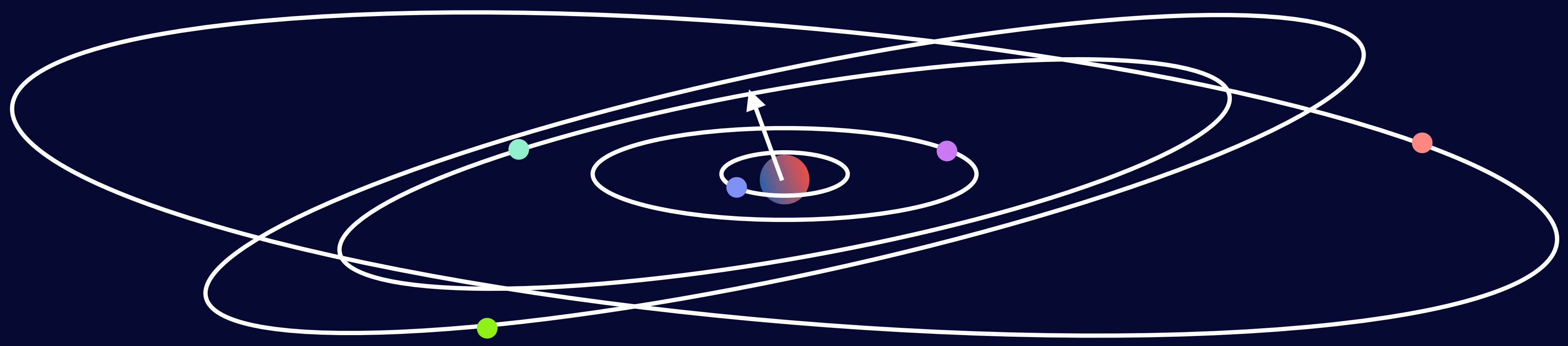
Malena Rice
Yale University

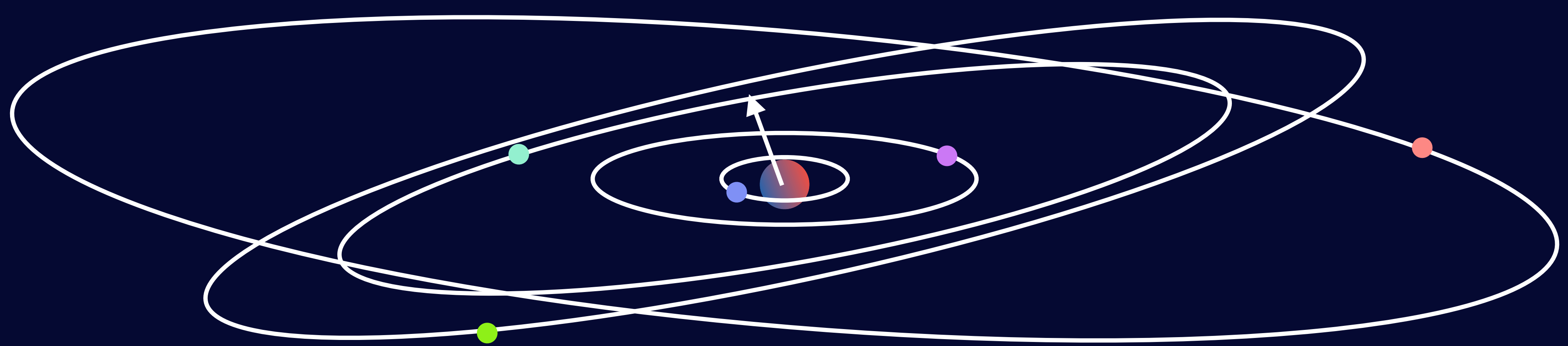




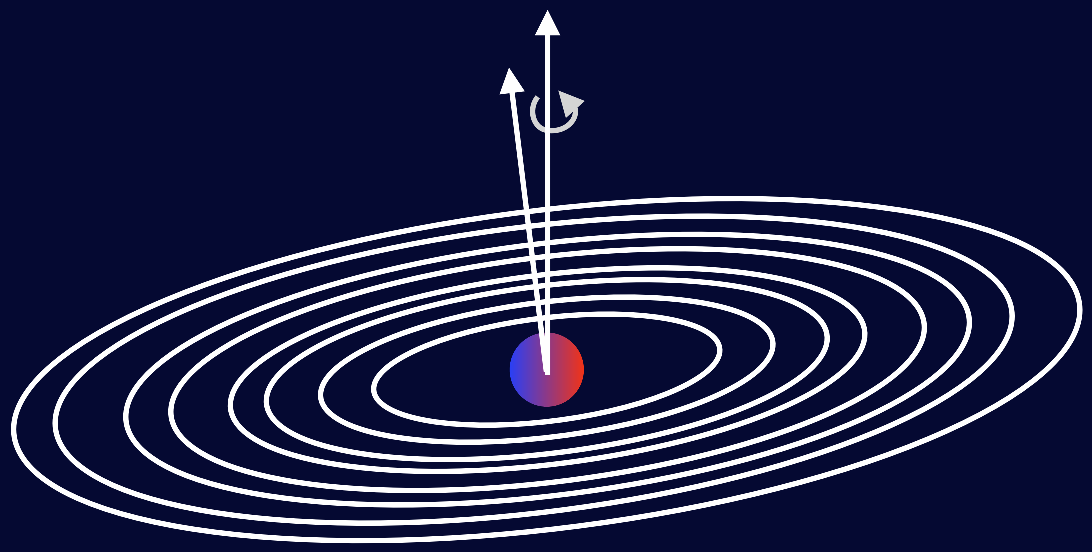




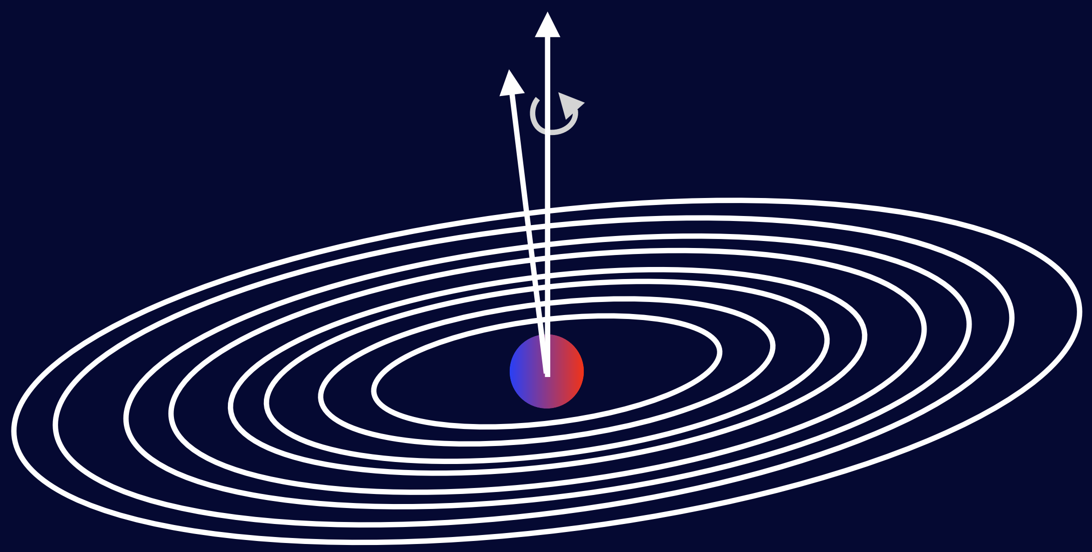




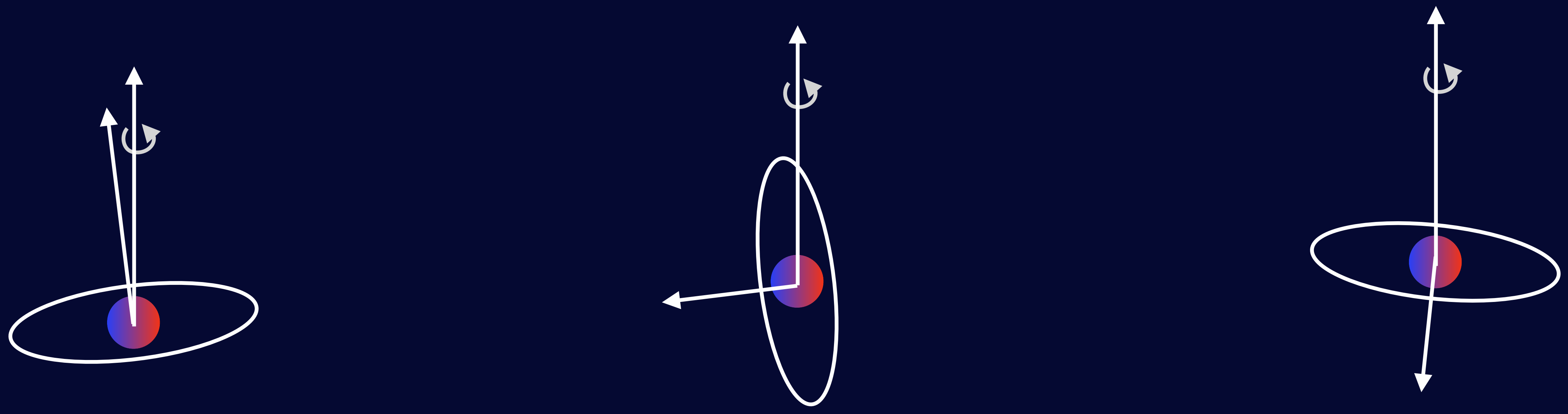
“stellar obliquity”: the angle between the stellar spin axis and the net orbital angular momentum vector solar system



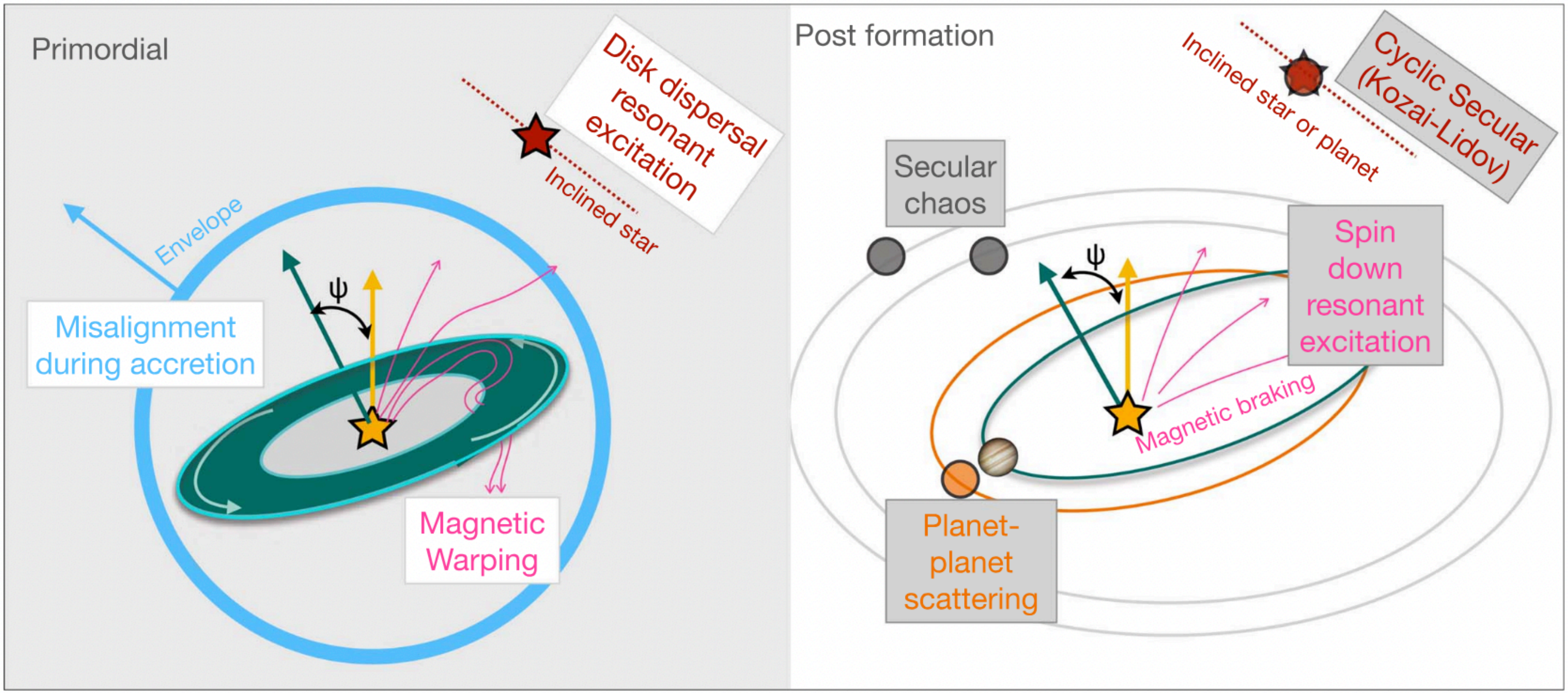
solar system



gas giant exoplanets

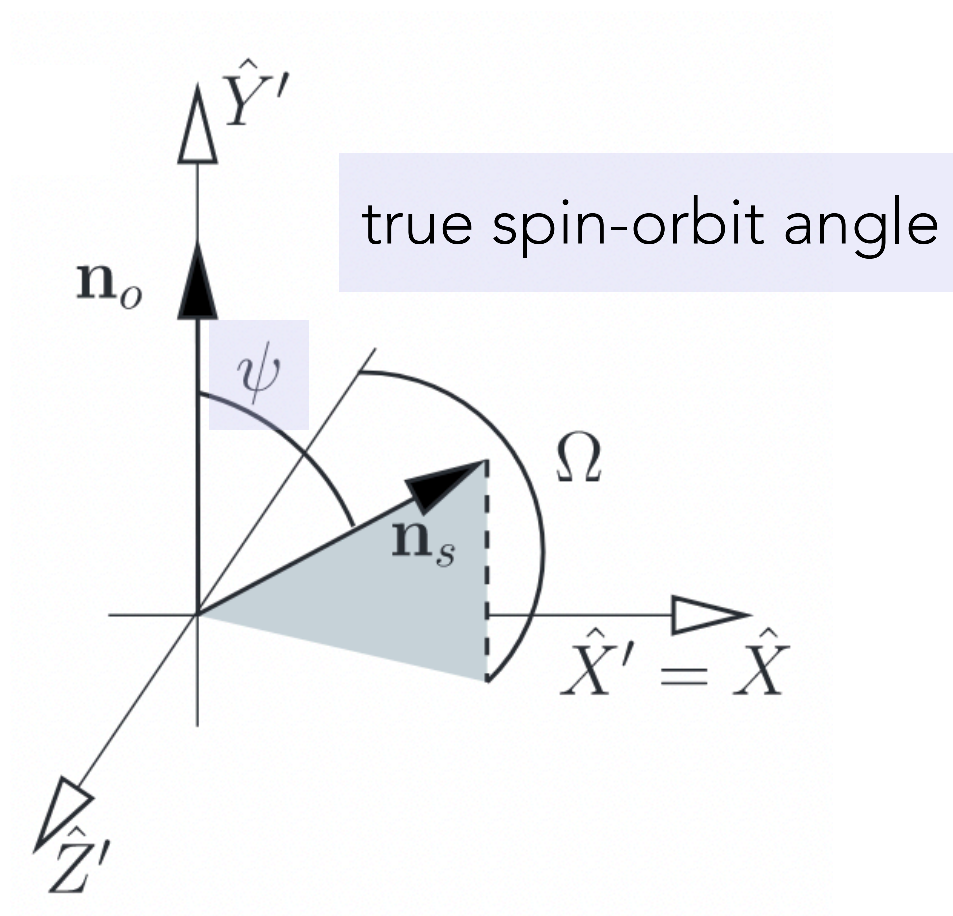


Ways to misalign a planetary system

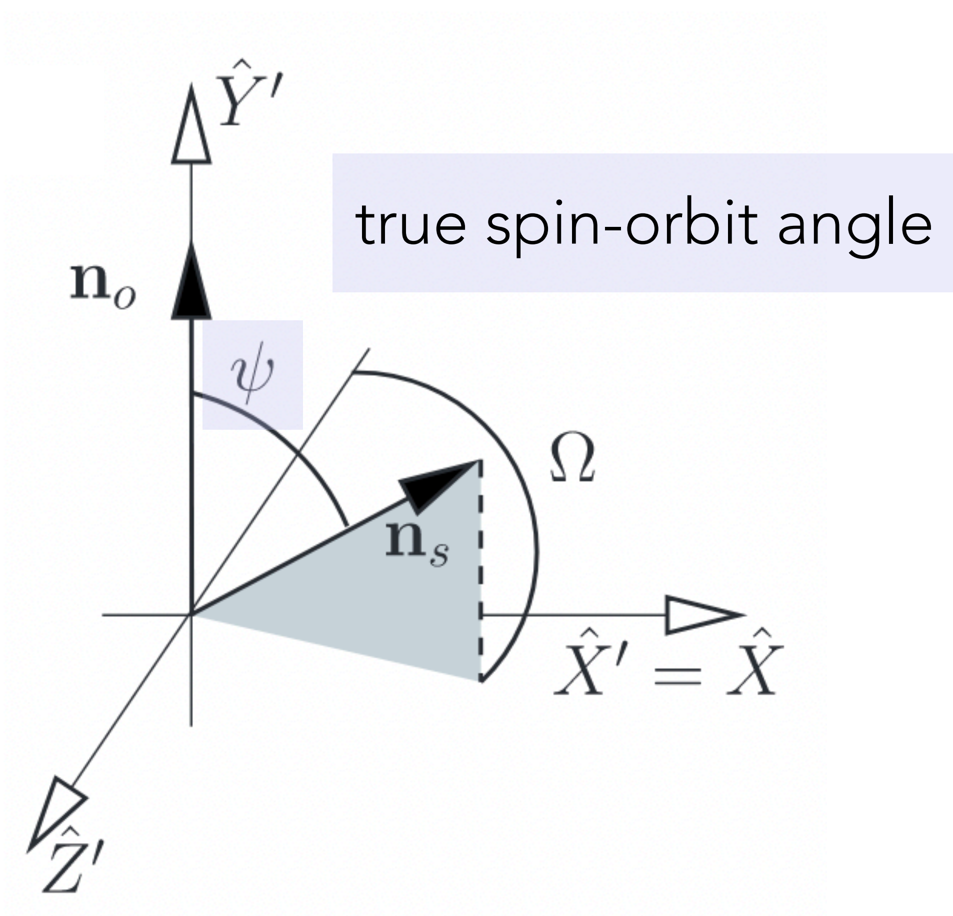


Winn, Fabrycky, Albrecht, & Johnson 2010; see also Schlaufman 2010

Albrecht, Dawson, & Winn 2022



what we want to know



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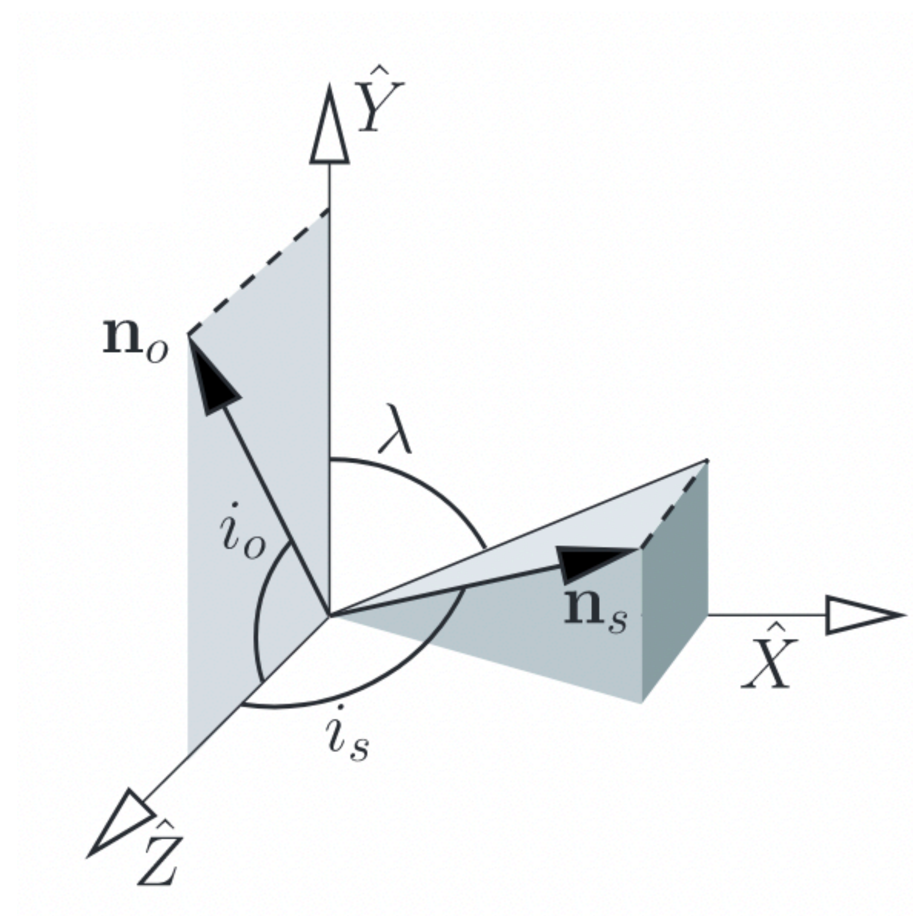
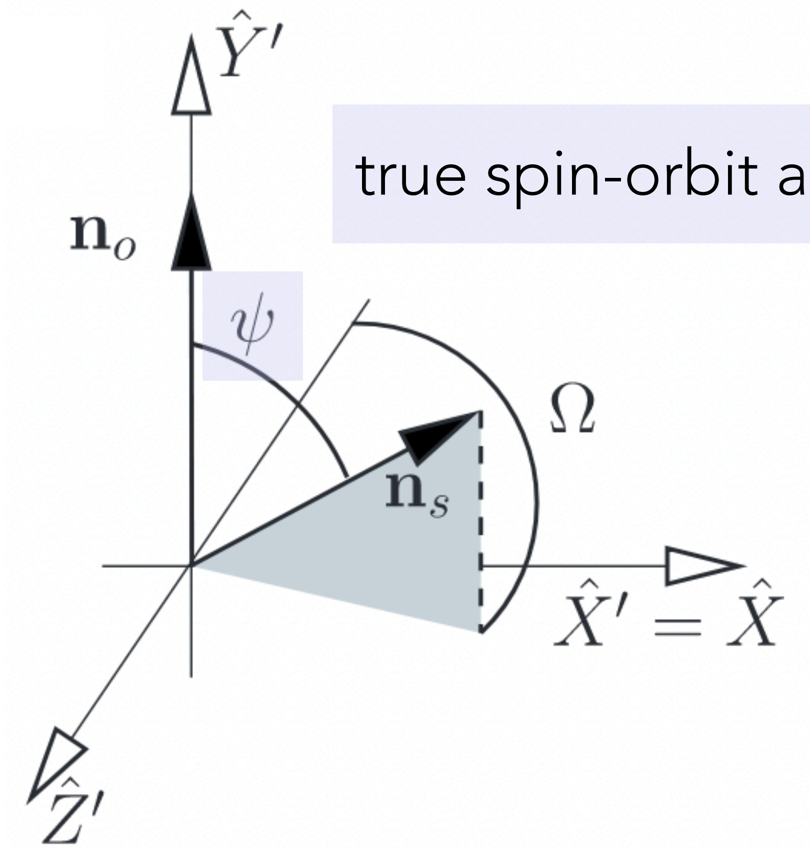


what we measure

$$\cos\psi = \cos i_s \cos i_0 + \sin i_s \sin i_0 \cos\lambda$$

adapted from Fabrycky & Winn 2009



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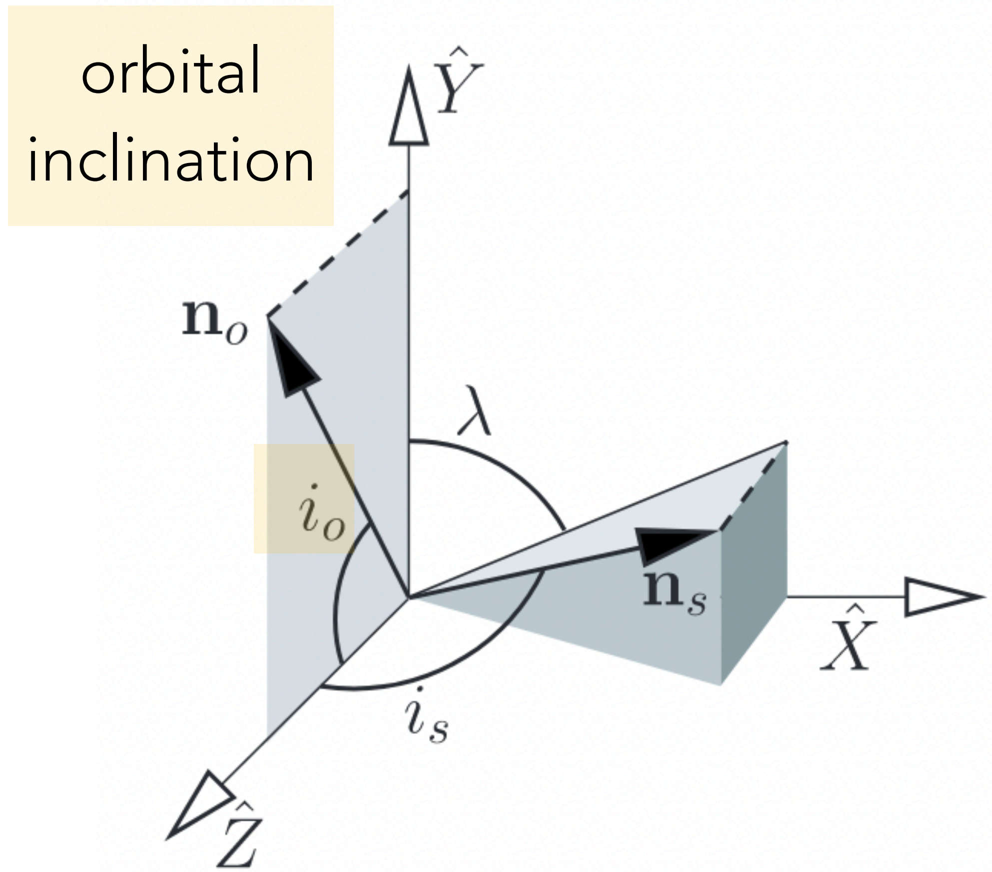

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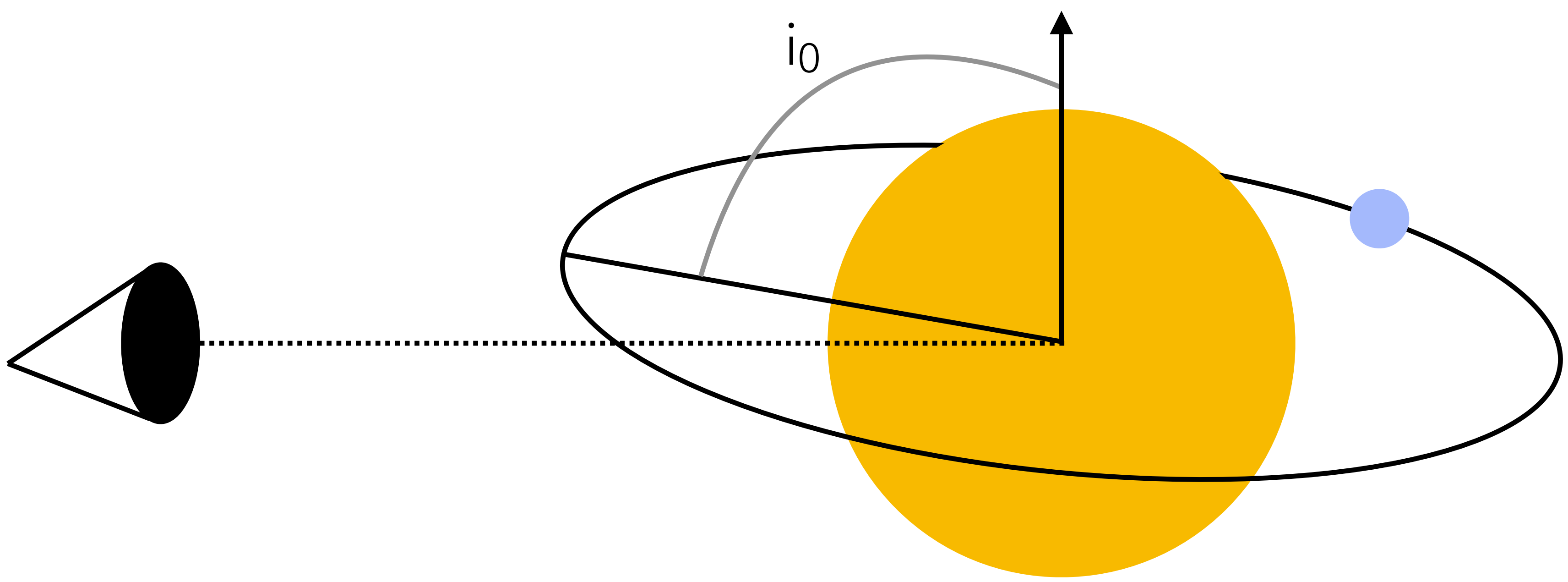
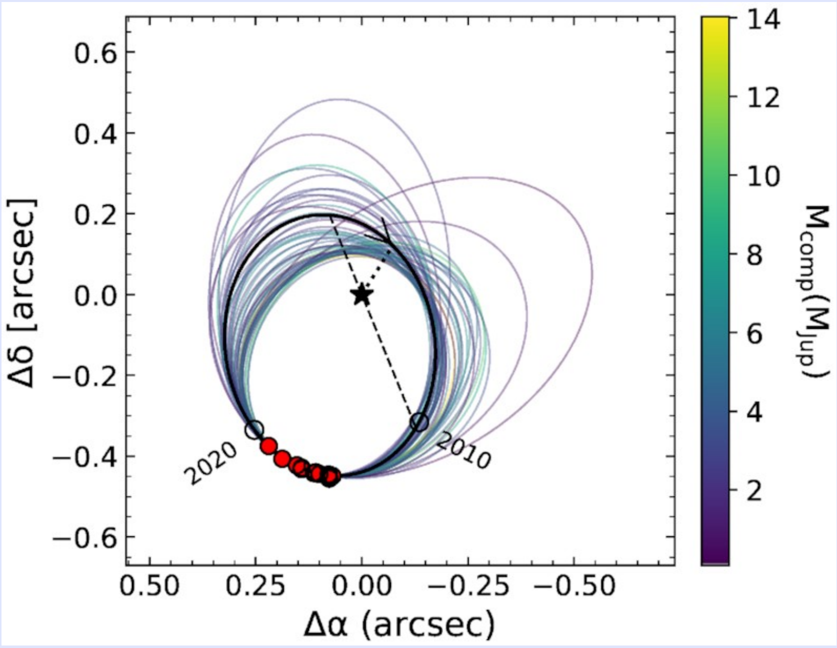
Transiting exoplanets: by definition, close to $i_0 = 90^{\circ}$



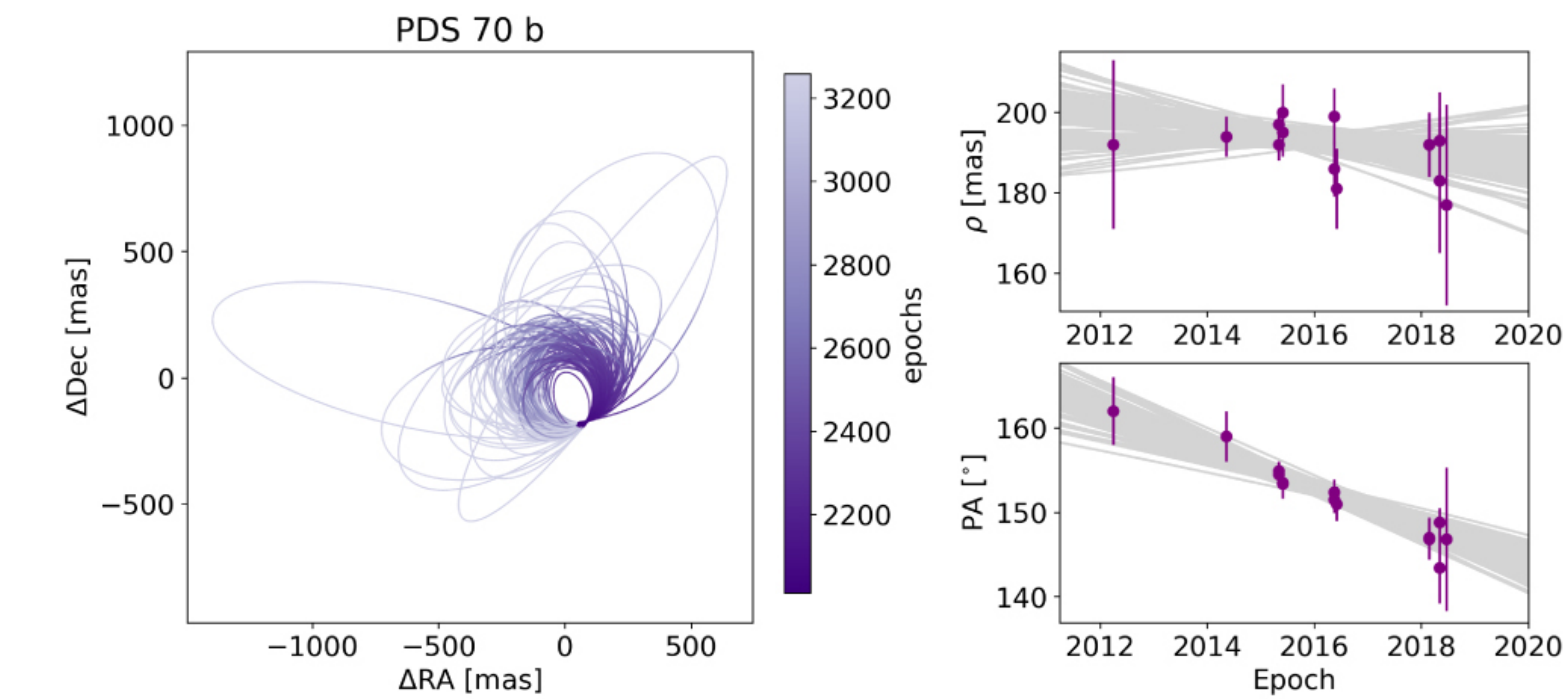
Dupuy, Brandt, Brandt, et al. 2022
orvara: Brandt, Dupuy, Li, et al. 2021

Astrometric orbital inclinations: fitting to epoch observations

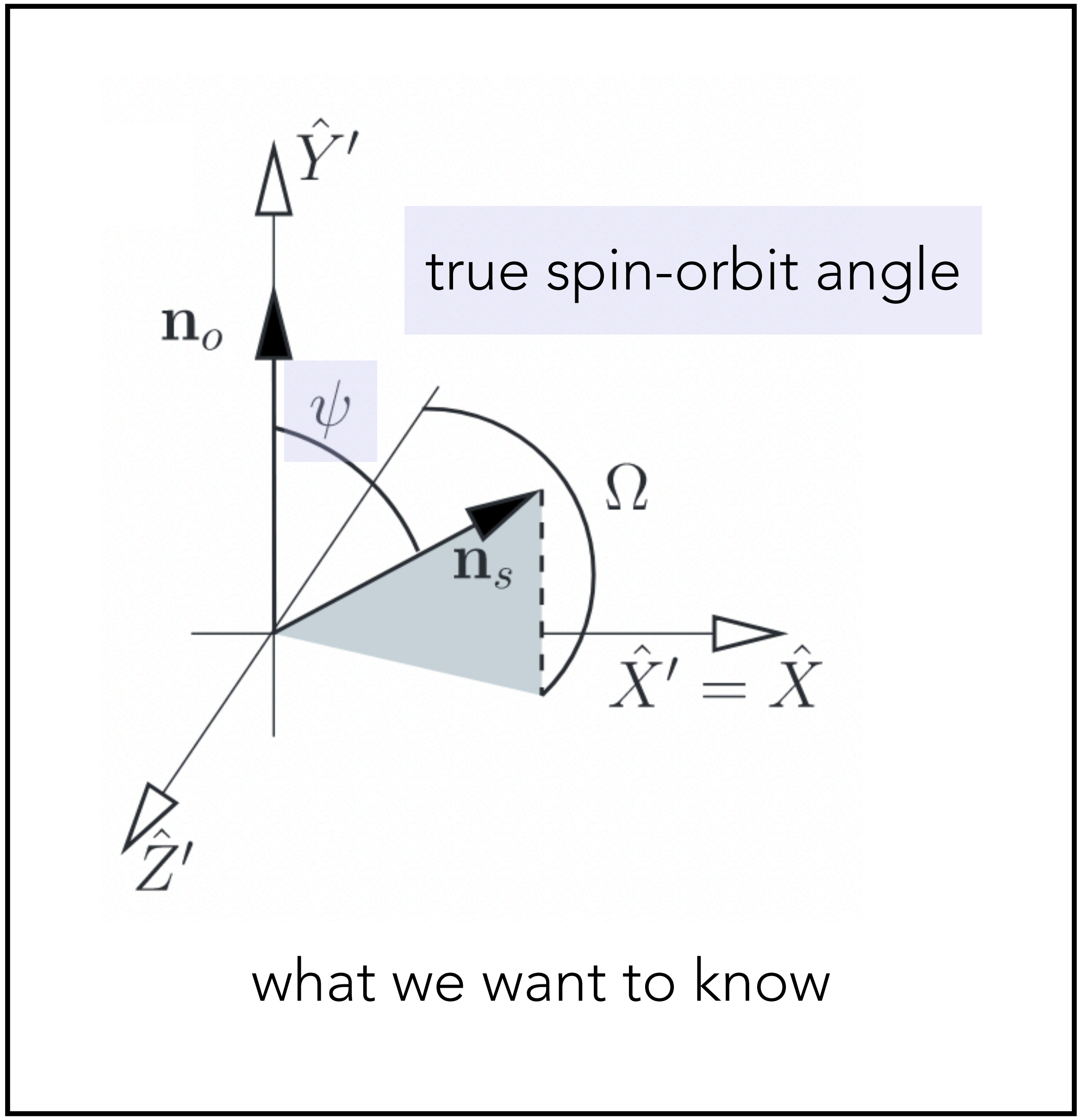
51 Eri b astrometric fit with orvara

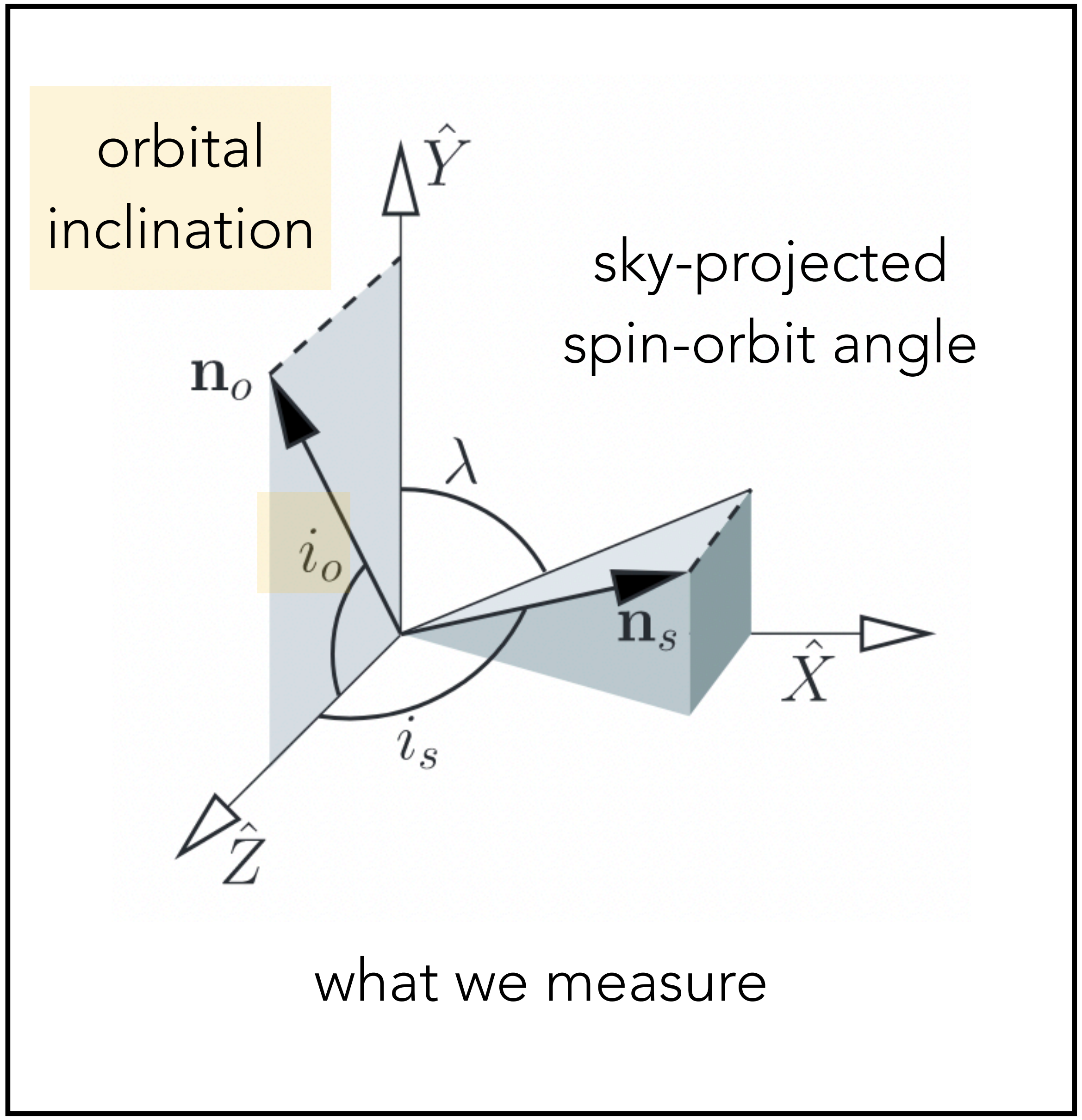


PDS 70 b astrometric fit with *orbitize!*



Bowler, Blunt, & Nielsen 2020
orbitize!: Blunt, Wang, Angelo, et al. 2020





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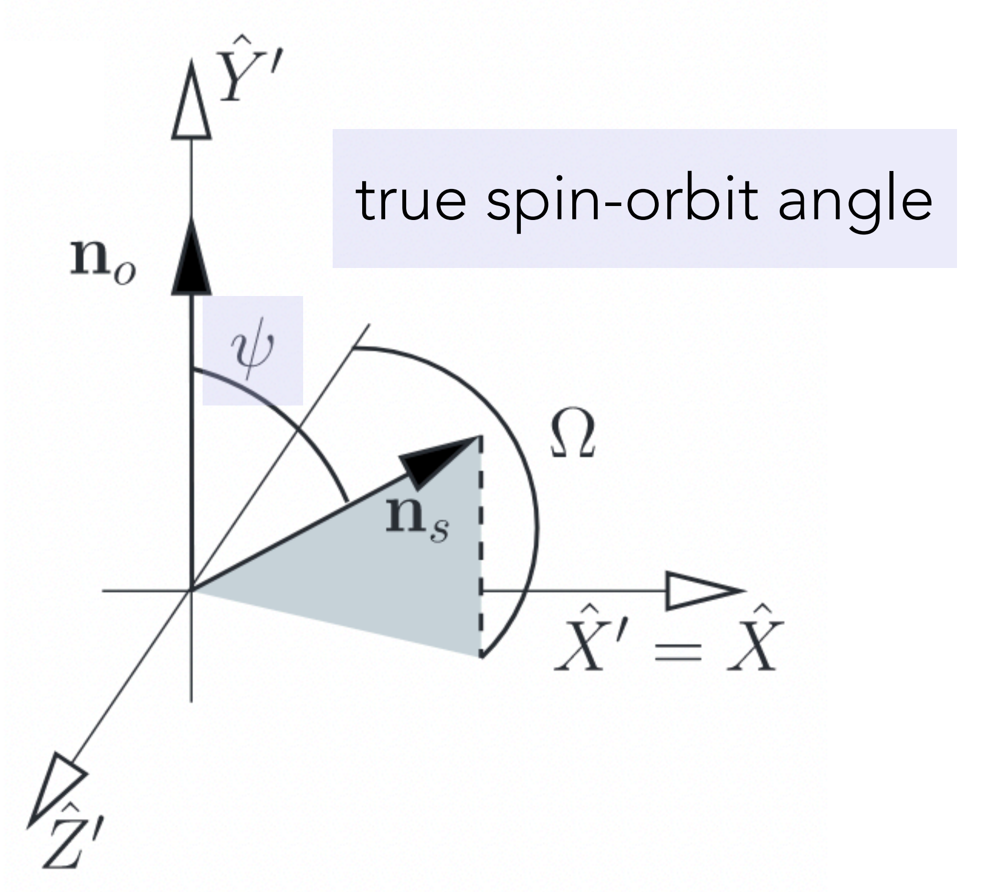

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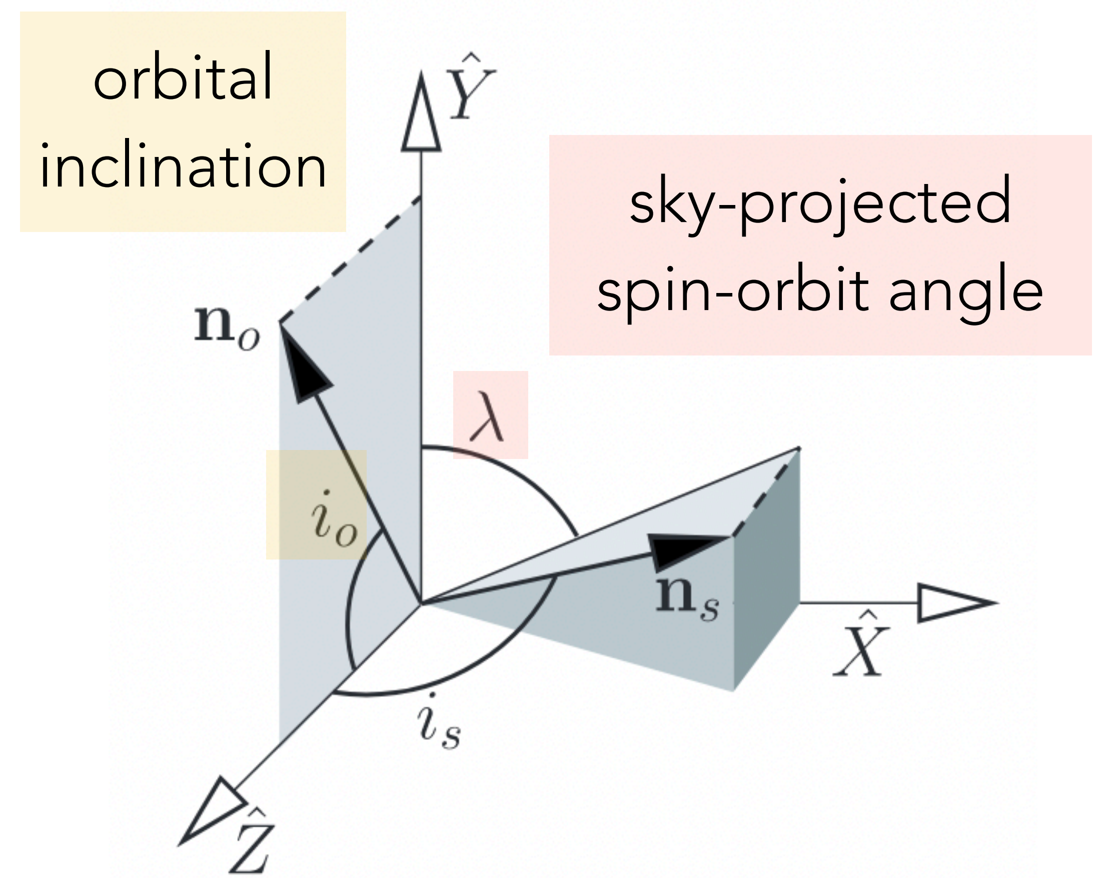

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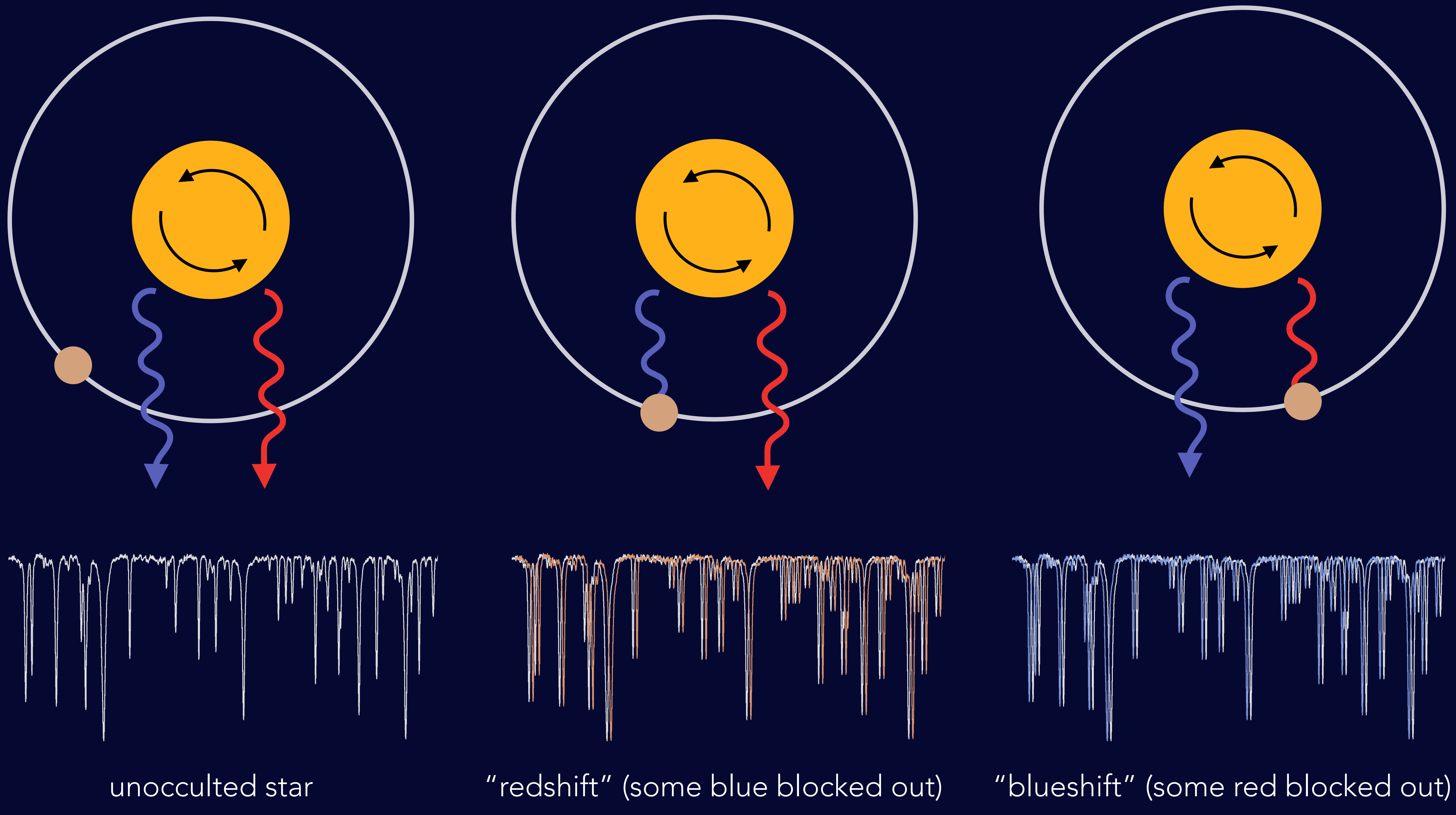
Holt 1893, Schlesinger 1910, Rossiter 1924, McLaughlin 1924, Queloz et al. 2000

The Rossiter-McLaughlin Effect



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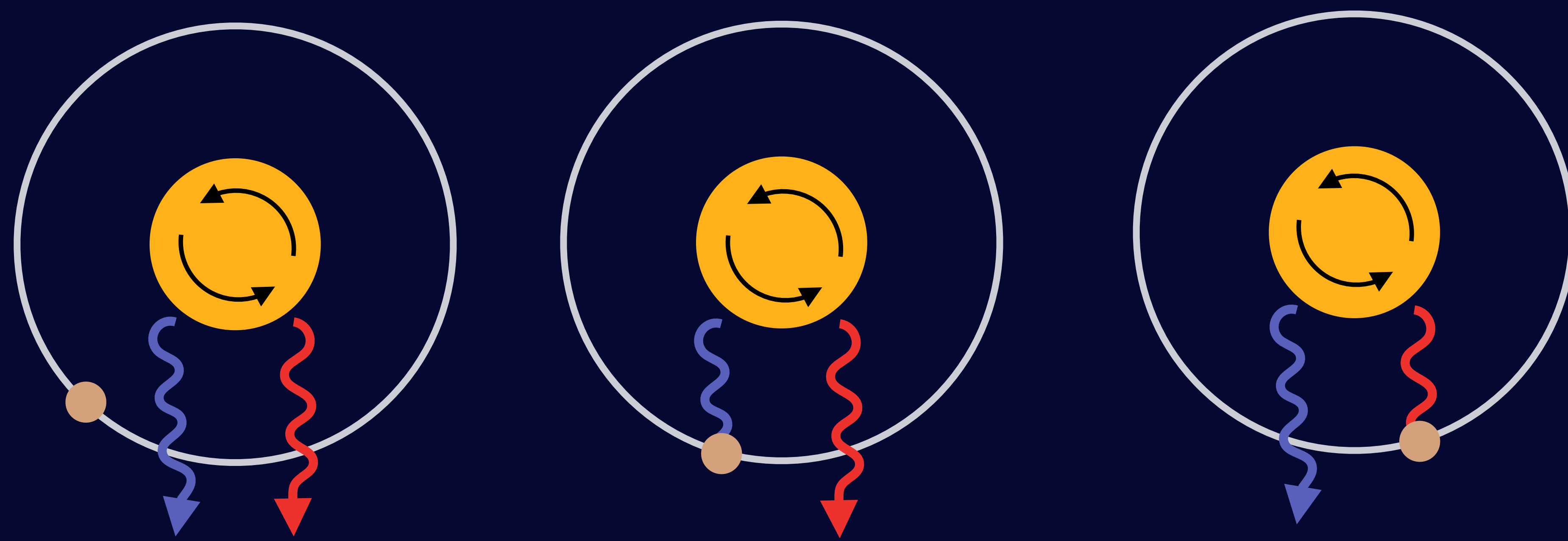
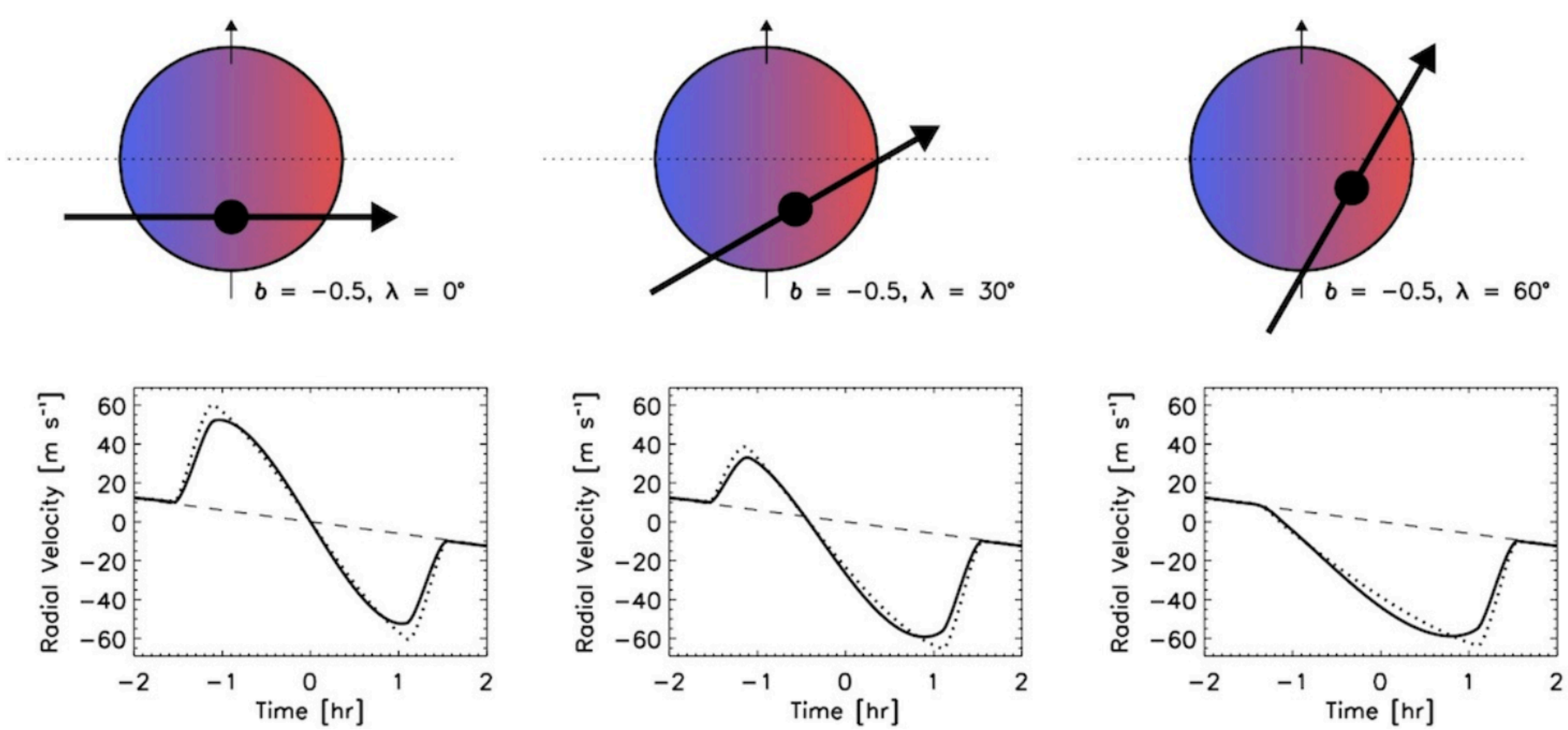




Gaudi & Winn 2007, WASP team

$$A_{RM} \simeq \frac{2}{3} D v \sin i_* \sqrt{(1 - b^2)}$$

A_{RM} = semi-amplitude

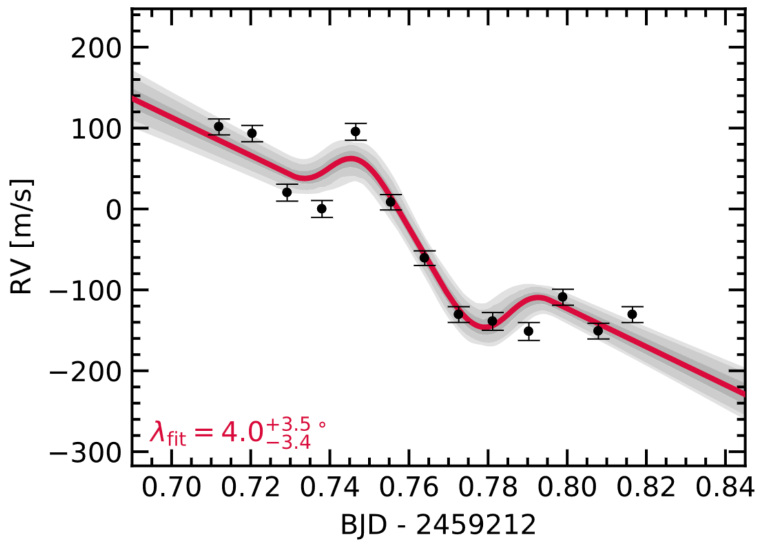
D = transit depth $(R_p/R_*)^2$

vsini = projected stellar rotational velocity

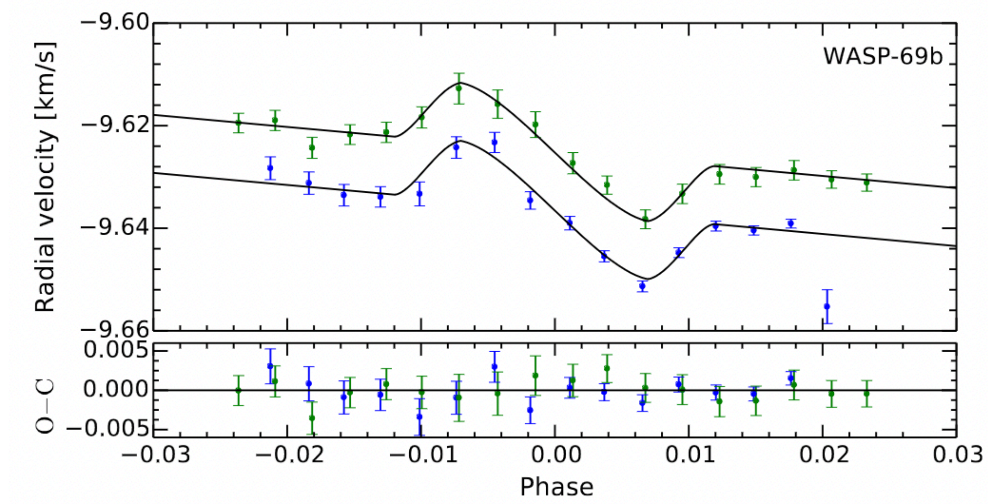
b = impact parameter

Triaud 2018

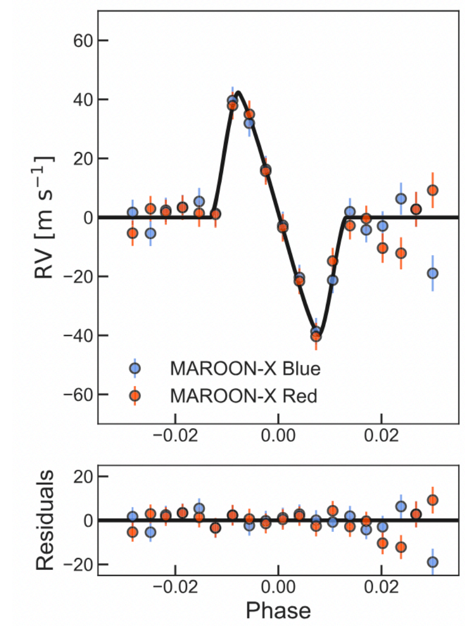
TOI-1937 A b
Yee, Winn, Hartman, et al. 2023



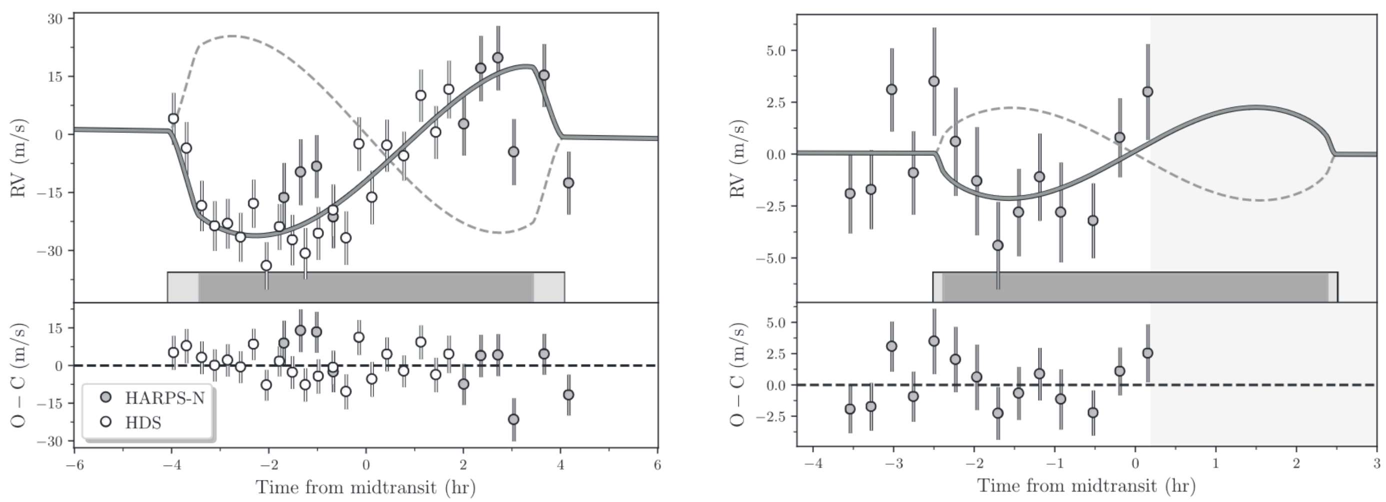
WASP-69 b
Casasayas-Barris, Palle, Nowak, et al. 2017



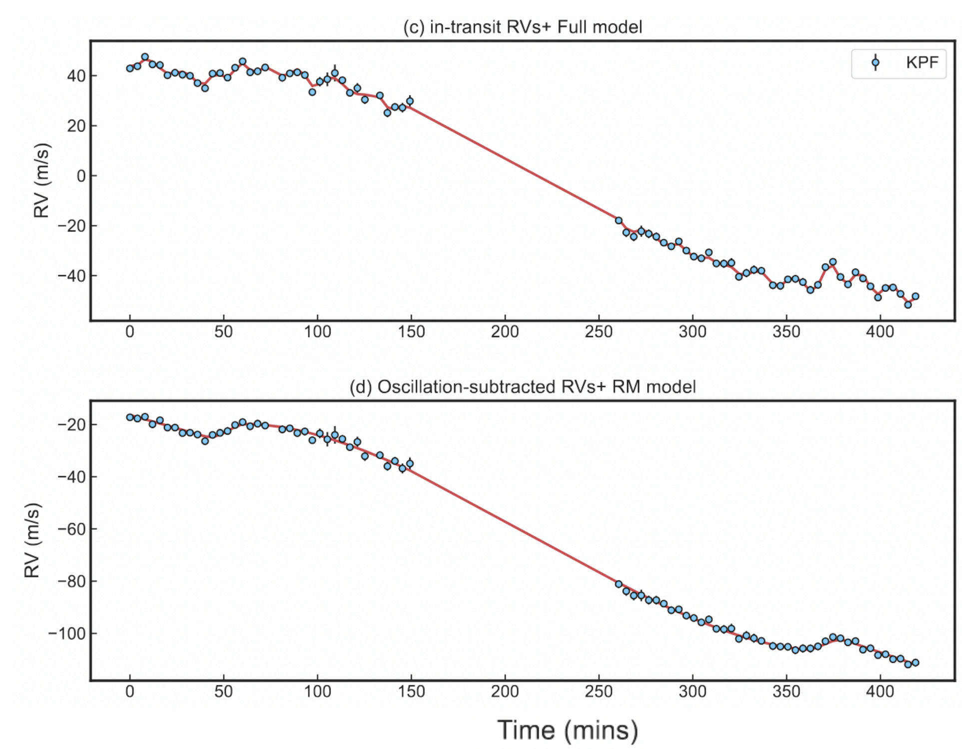
TOI-4201 b
Gan, Wang, Dai, et al. 2024



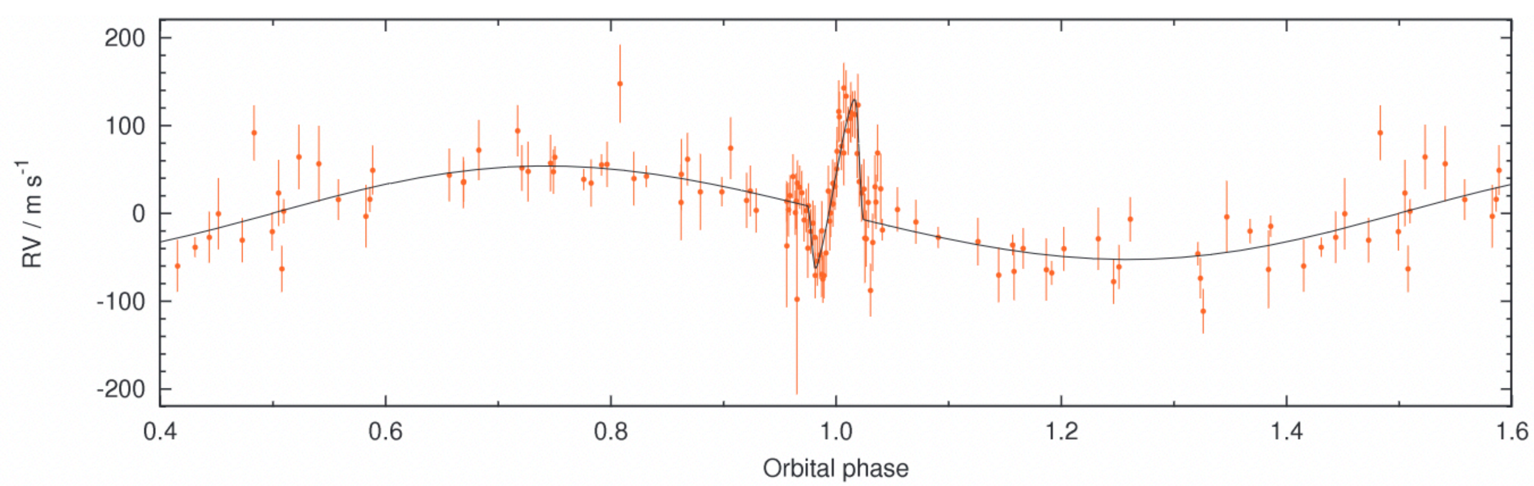
K2-290 A b and c
Hjorth, Albrecht, Hirano, et al. 2021



HD 118203 d
Zhang, Huber, Weiss, et al. 2024

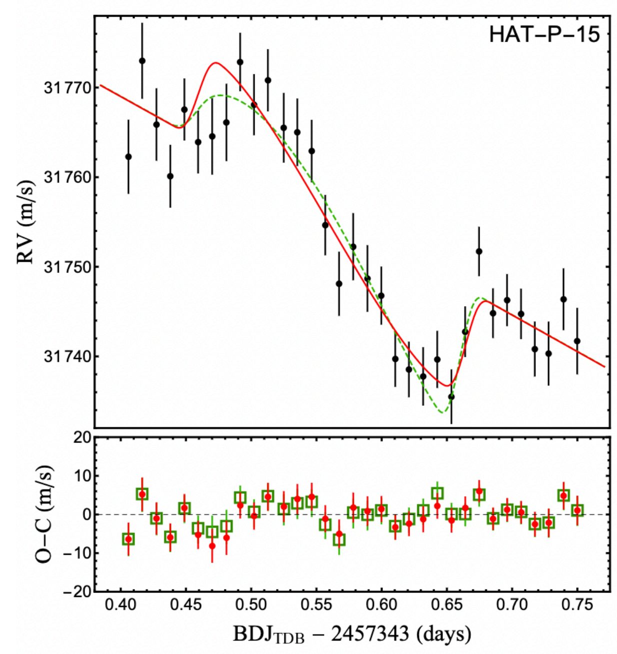


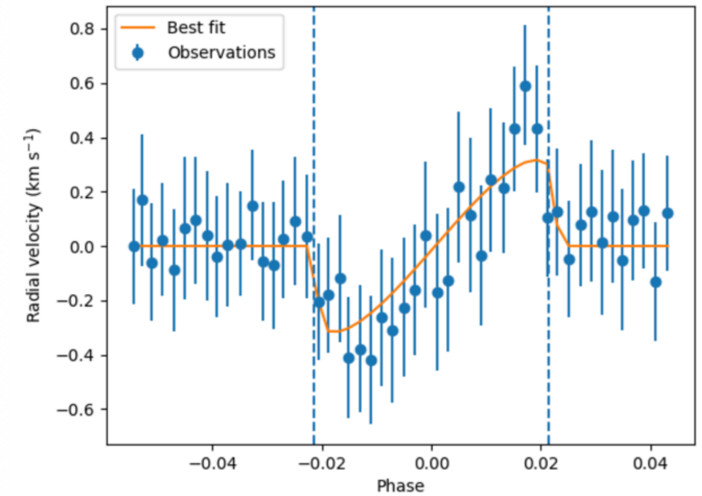
WASP-17 b
Anderson, Smith, Lanotte, et al. 2011

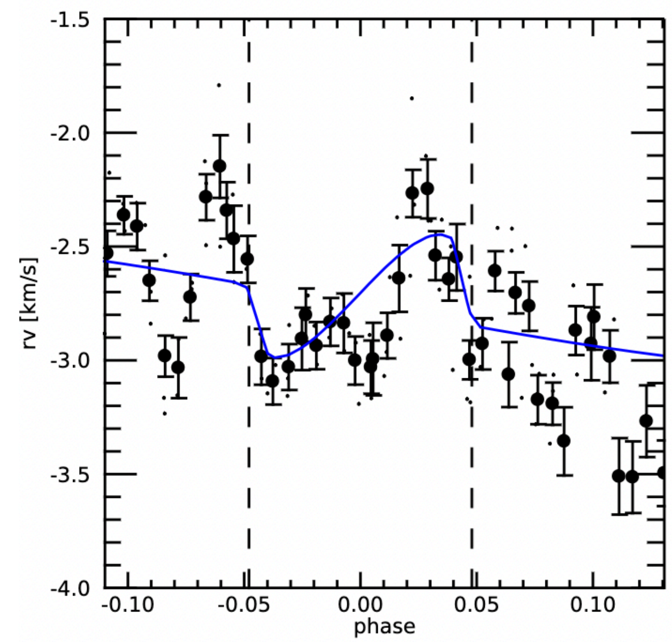


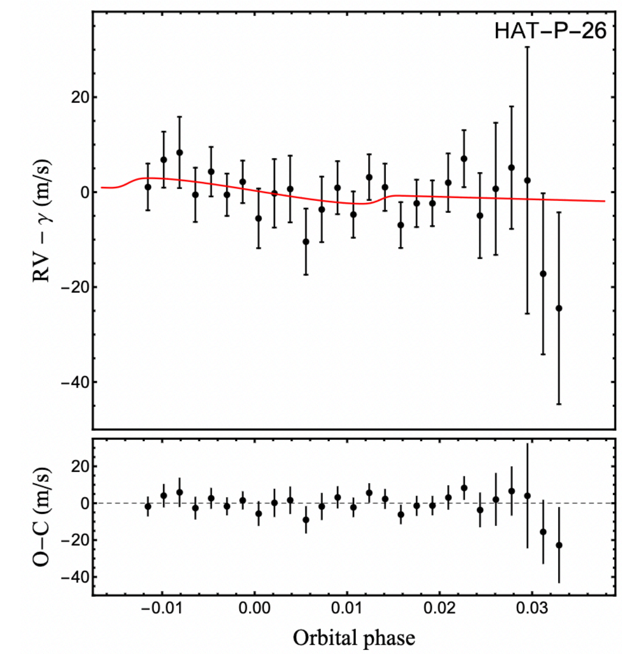
The Global Architecture of Planetary Systems (GAPS) Programme at Telescopio Nazionale Galileo (TNG)

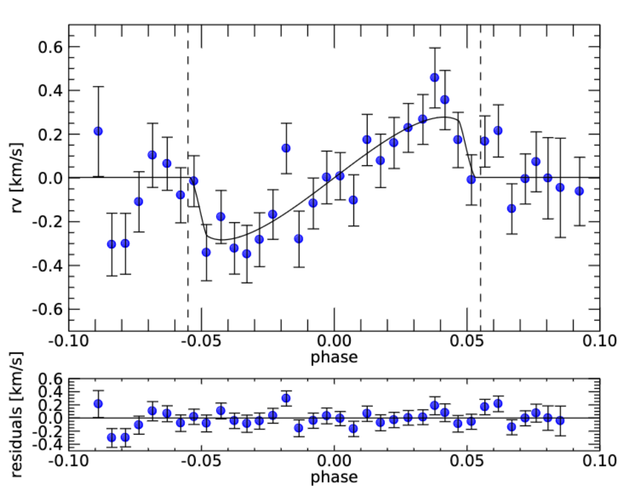
Damasso, Esposito, Nascimbeni, et al. 2015
Damasso, Biazzo, Bonomo, et al. 2015
Borsa, Rainer, Bonomo, et al. 2019
Borsa, Lanza, Raspantini, et al. 2021
Rainer, Borsa, Pino, et al. 2021
Mancini, Esposito, Covino, et al. 2022

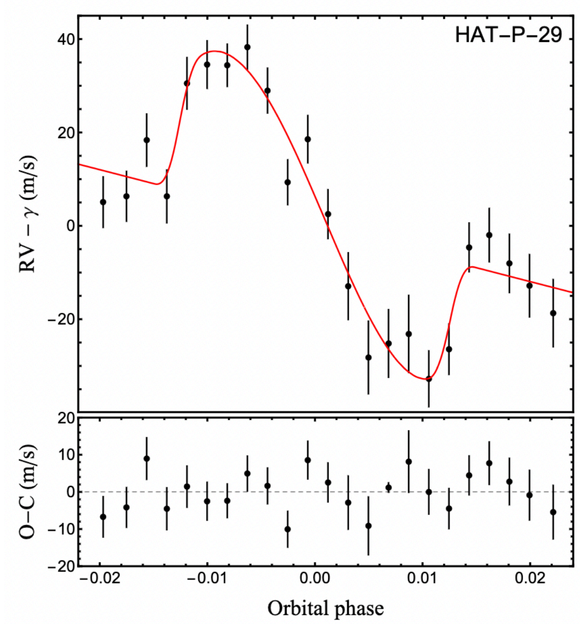


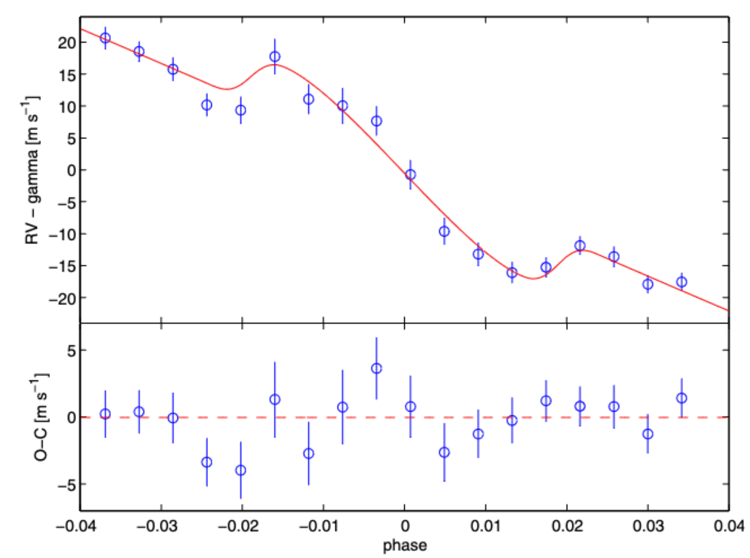


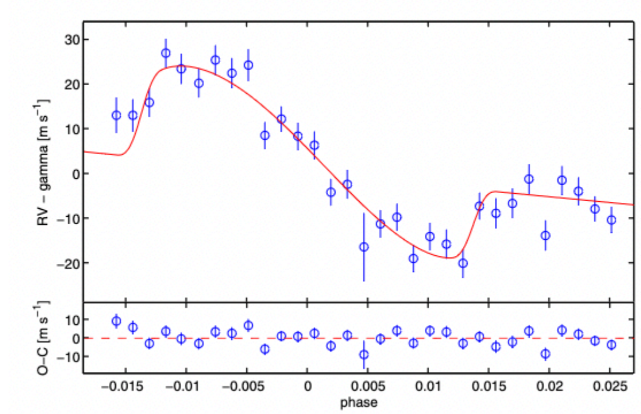




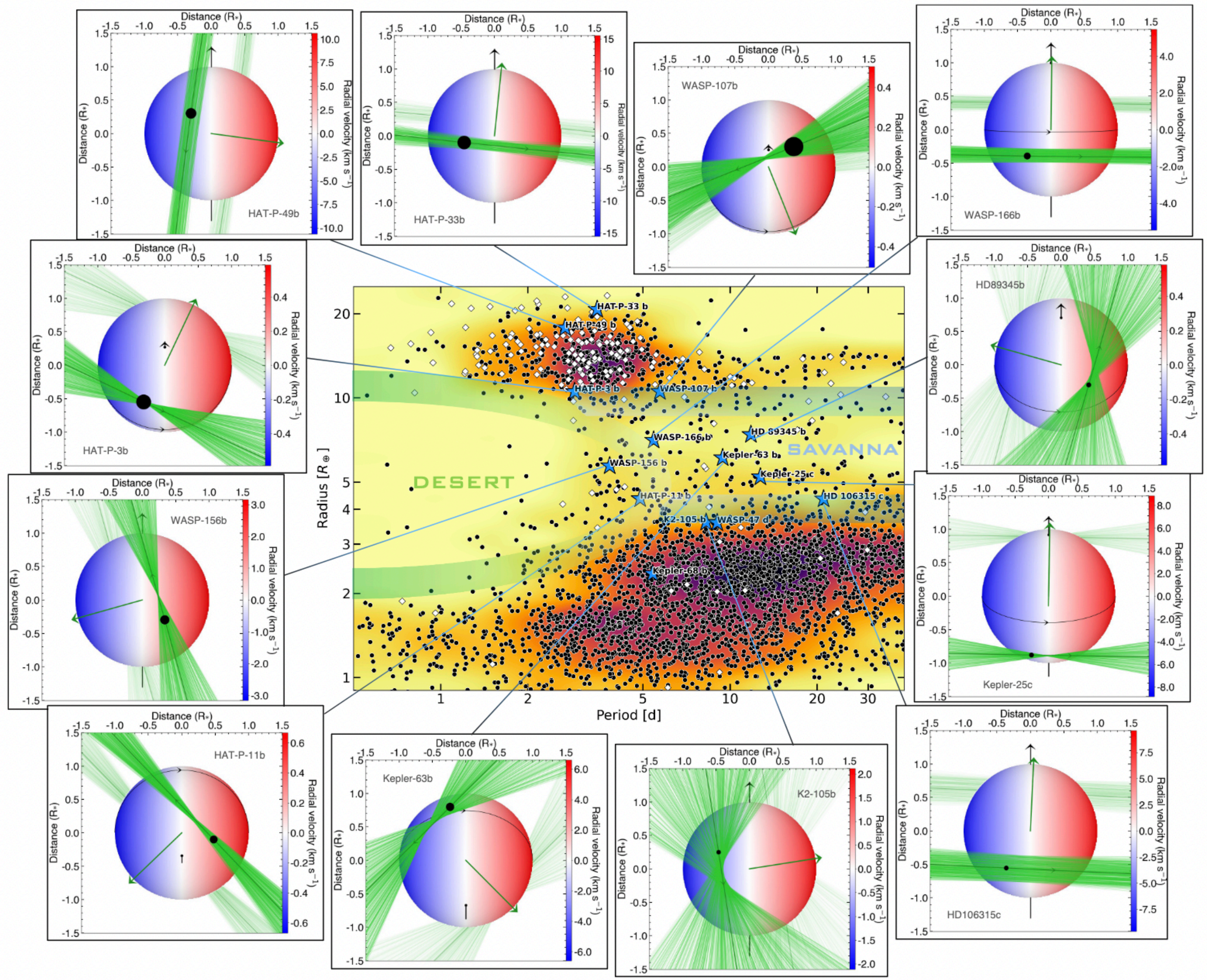








The Desert-Rim Exoplanets Atmosphere and Migration (DREAM) program



Bourrier, Attia, Mallonn, et al. 2023
Attia, Bourrier, Delisle, Eggenberger, et al. 2023

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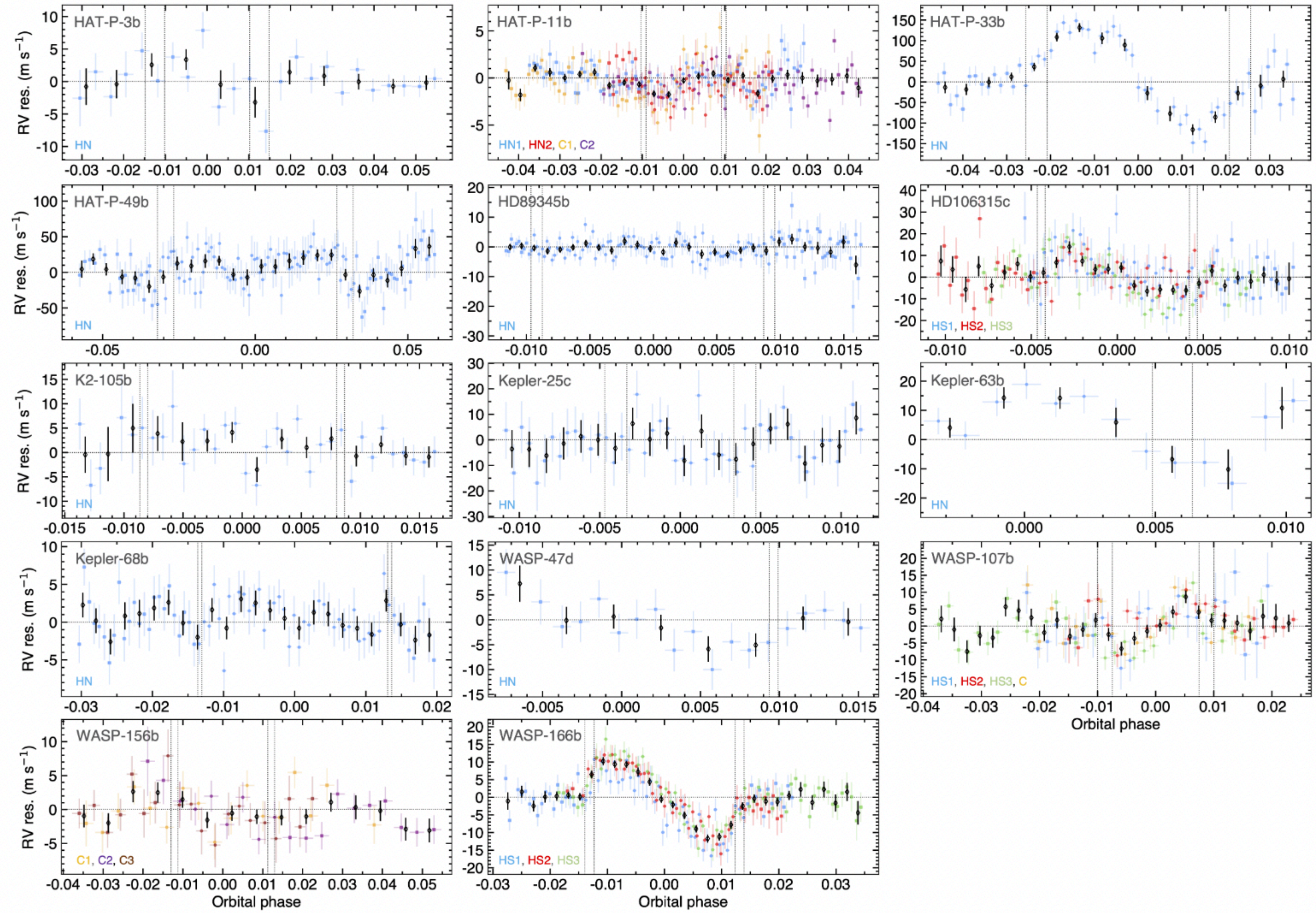
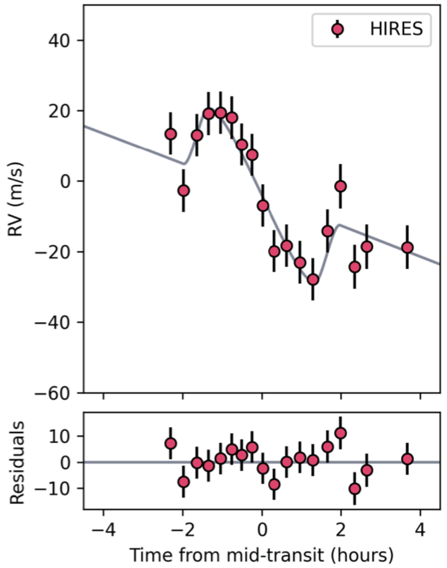
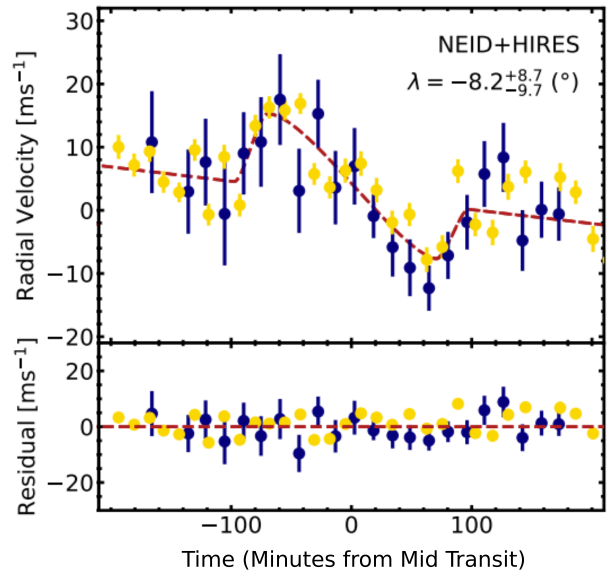


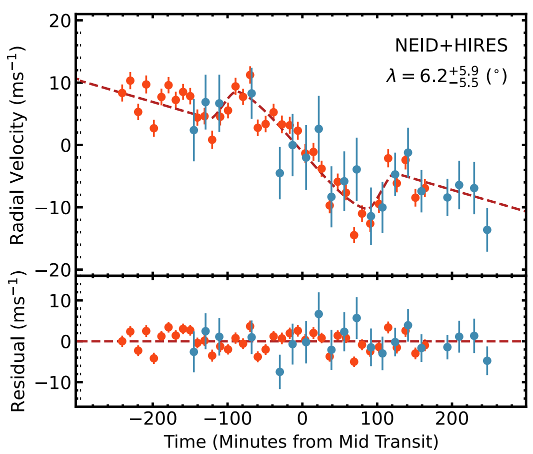
Bourrier, Attia, Mallonn, et al. 2023
Attia, Bourrier, Delisle, Eggenberger, et al. 2023

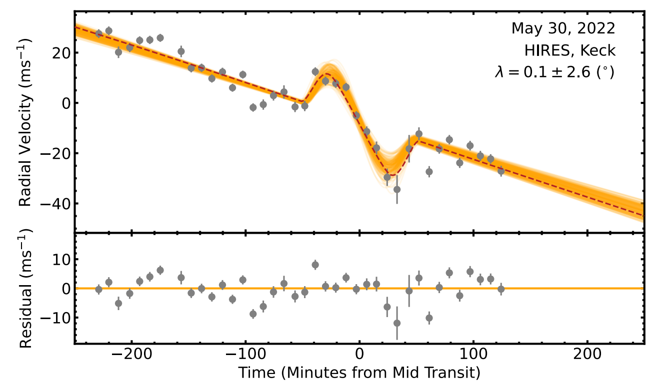
The Stellar Obliquities in Long-period Exoplanet Systems (SOLES) Survey

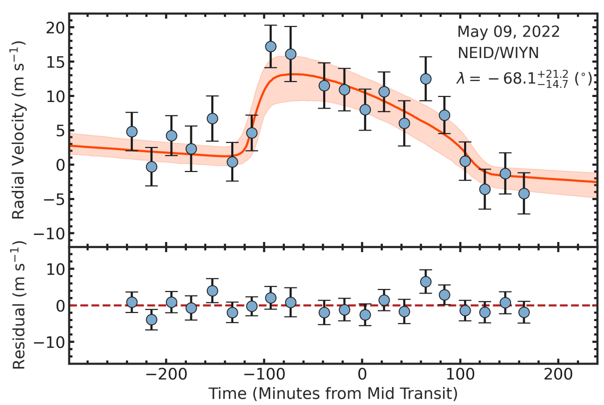
Rice, Wang, et al. 2021
Wang, Rice, et al. 2022
Rice, Wang, et al. 2022b
Rice, Wang, et al. 2023a
Hixenbaugh, Wang, Rice, et al. 2023
Dong, Wang, Rice et al. 2023
Wright, Rice, Wang, et al. 2023
Rice, Wang, et al. 2023b
Lubin, Wang, Rice, et al. 2023
Hu, Rice, et al. 2024
Radzom, Dong, Rice, et al. 2024
Ferreira, Rice, et al. 2024
Wang, Rice, et al. 2024
Radzom, Dong, Rice, et al. 2025 (in press)
Rusznak, Wang, Rice, & Wang 2025 (in review)

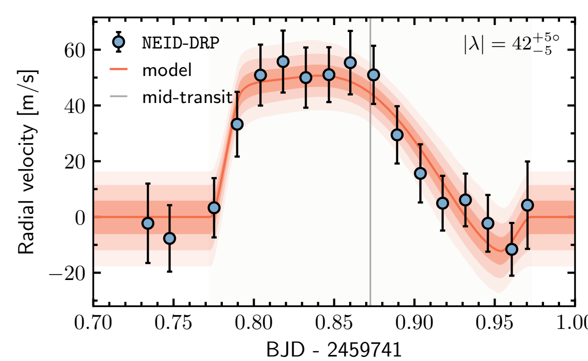


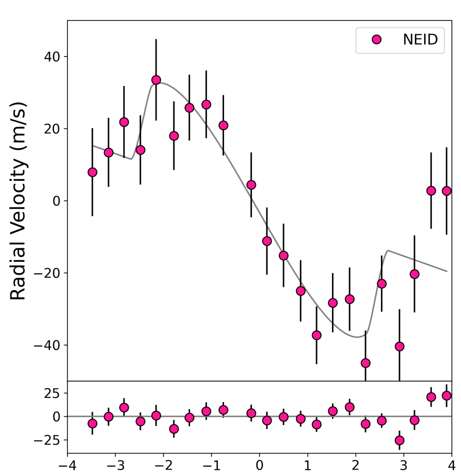


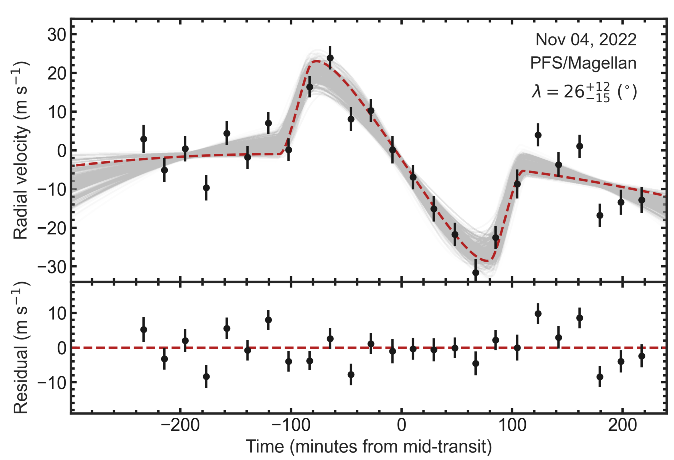


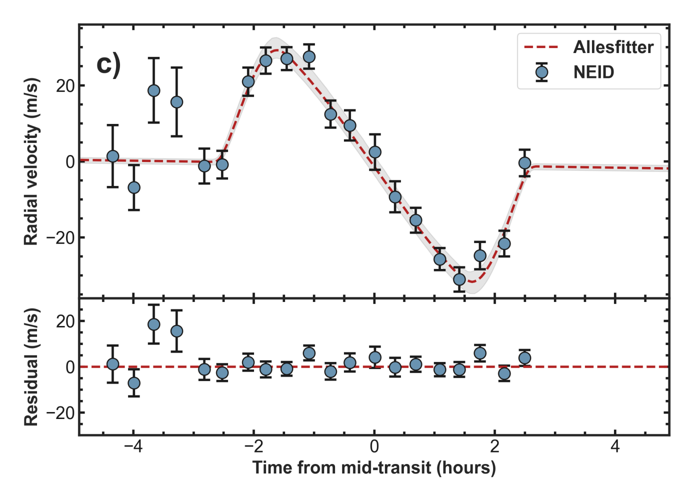


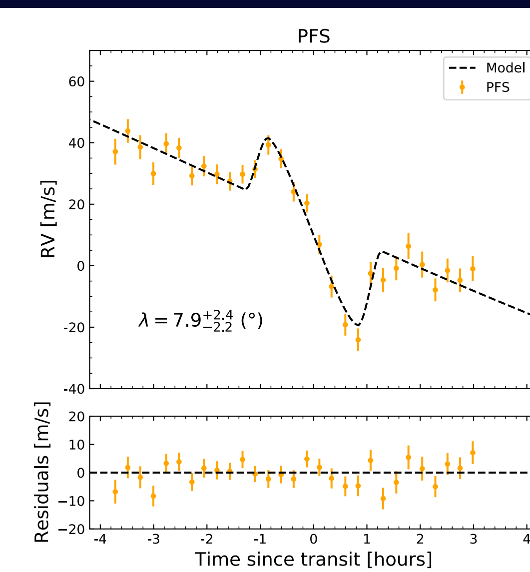




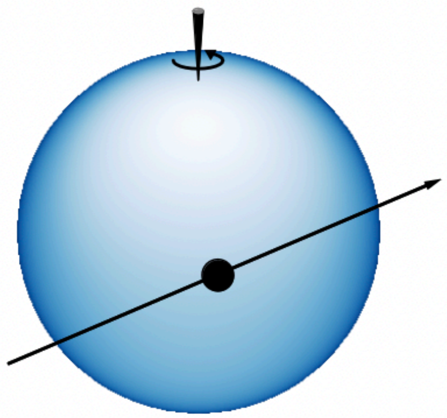


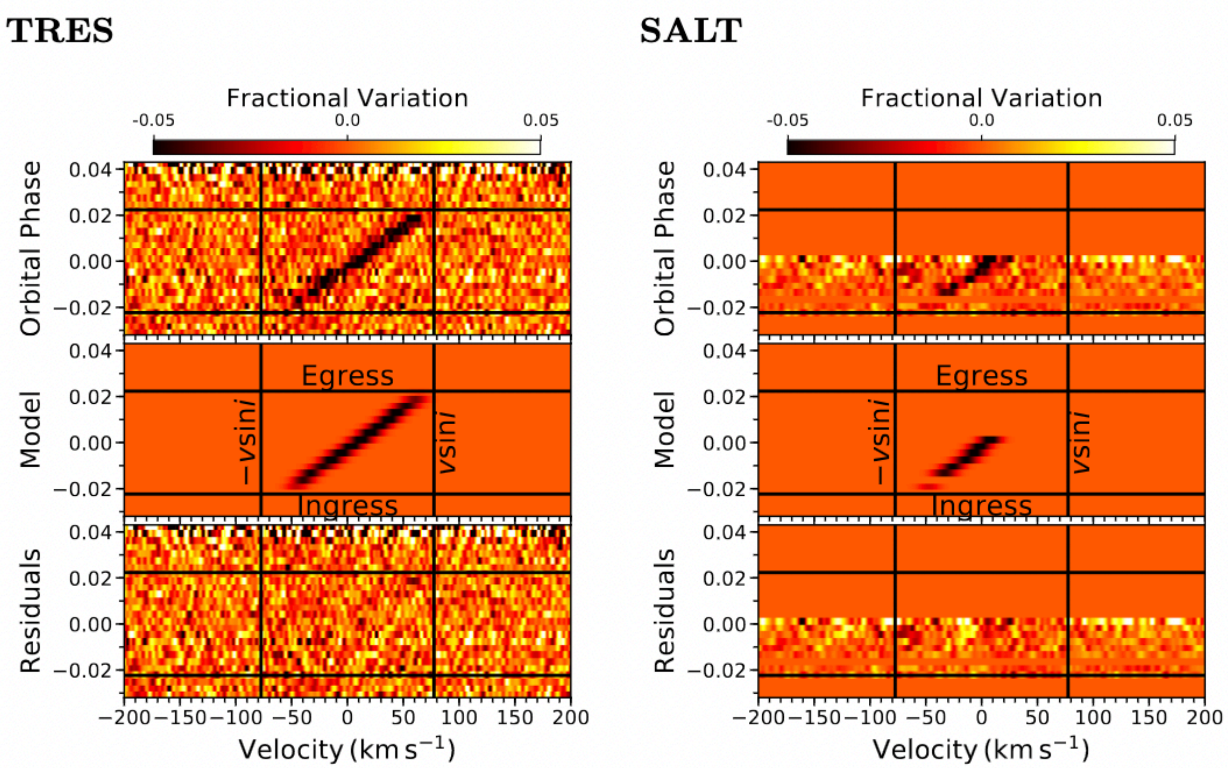




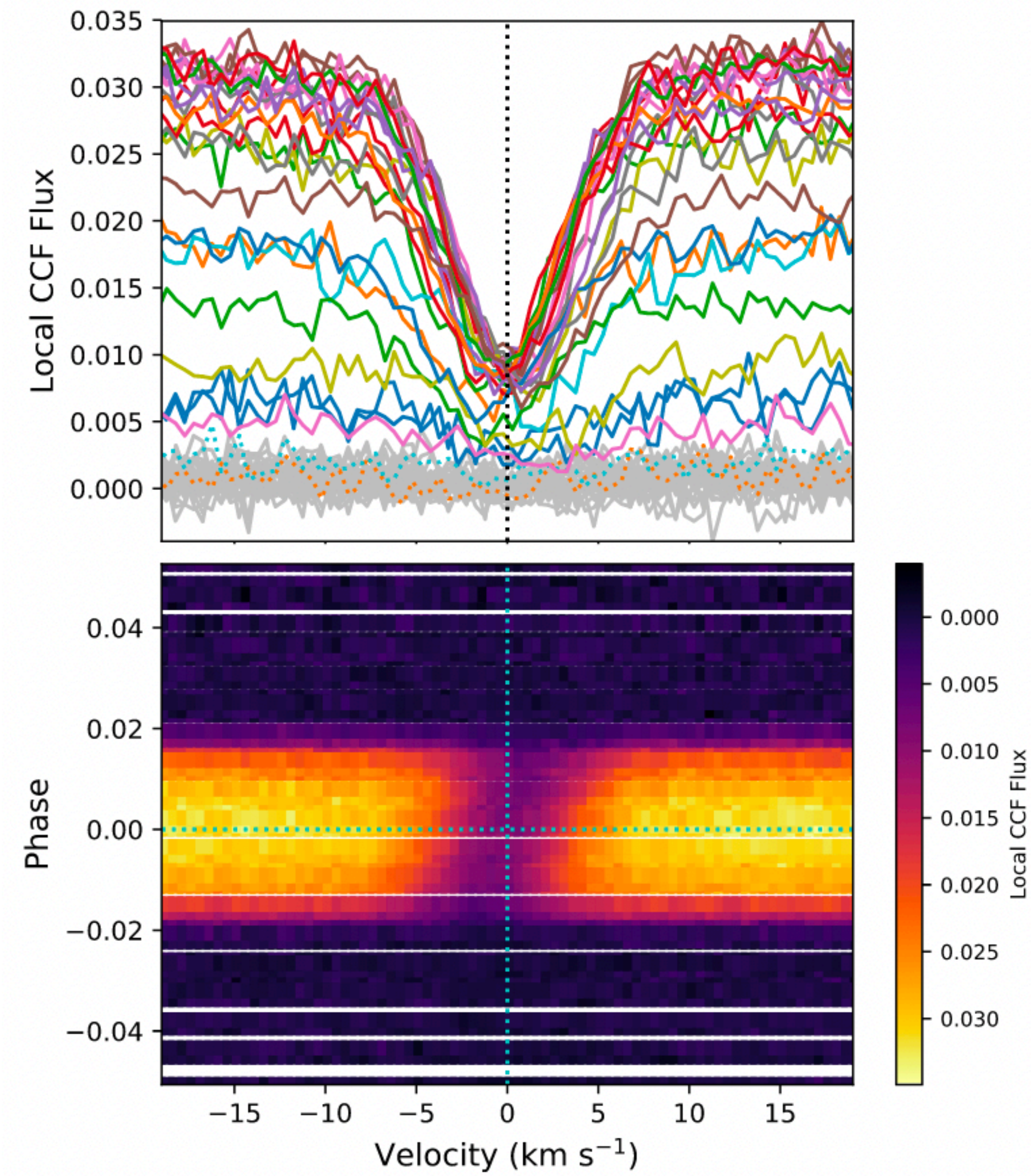


HAT-P-69 b
Doppler shadow/transit/tomography



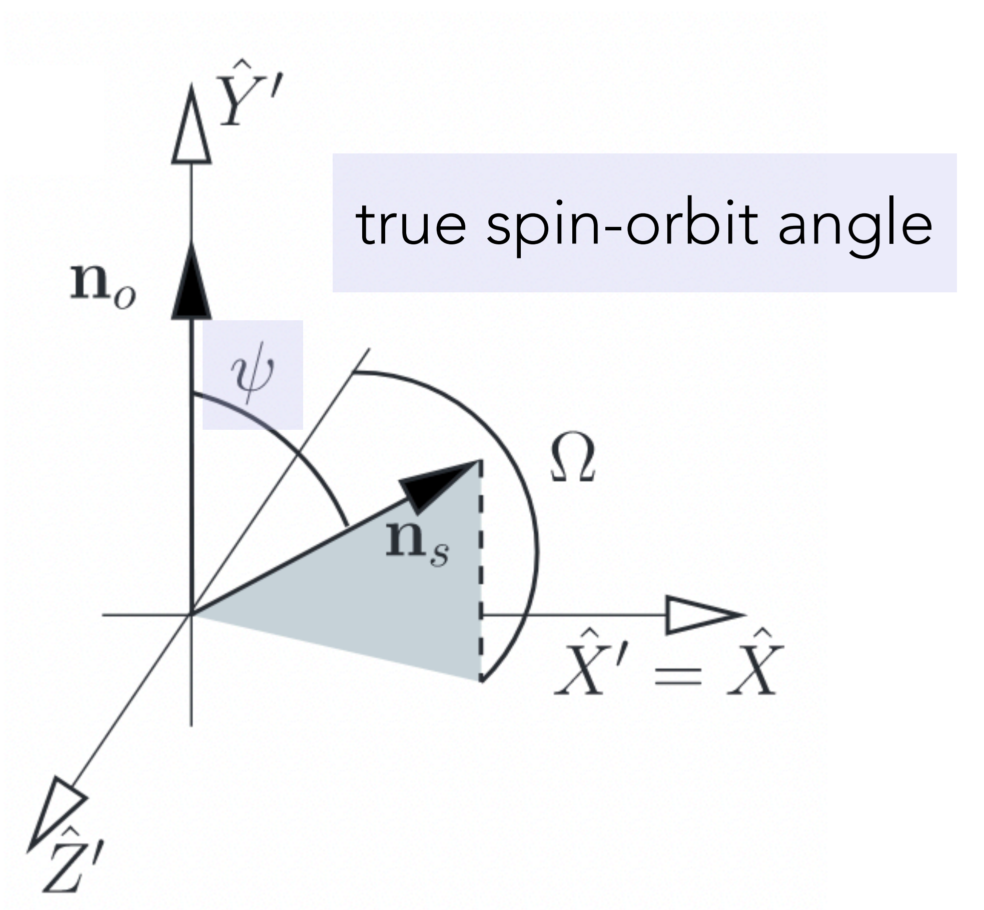


WASP-52 b
Rossiter-McLaughlin Reloaded



Zhou, Huang, Bakos, et al. 2019

Cegla, Roguet-Kern, Lendl, et al. 2023



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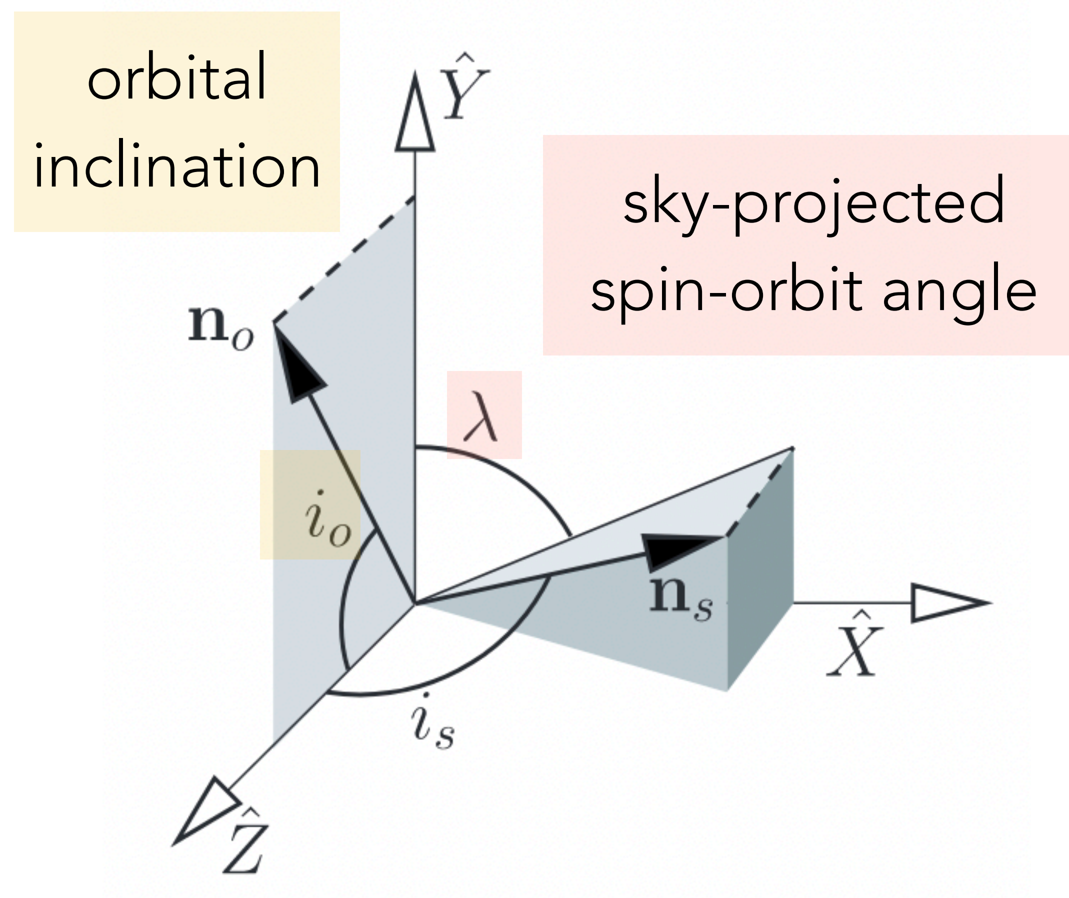

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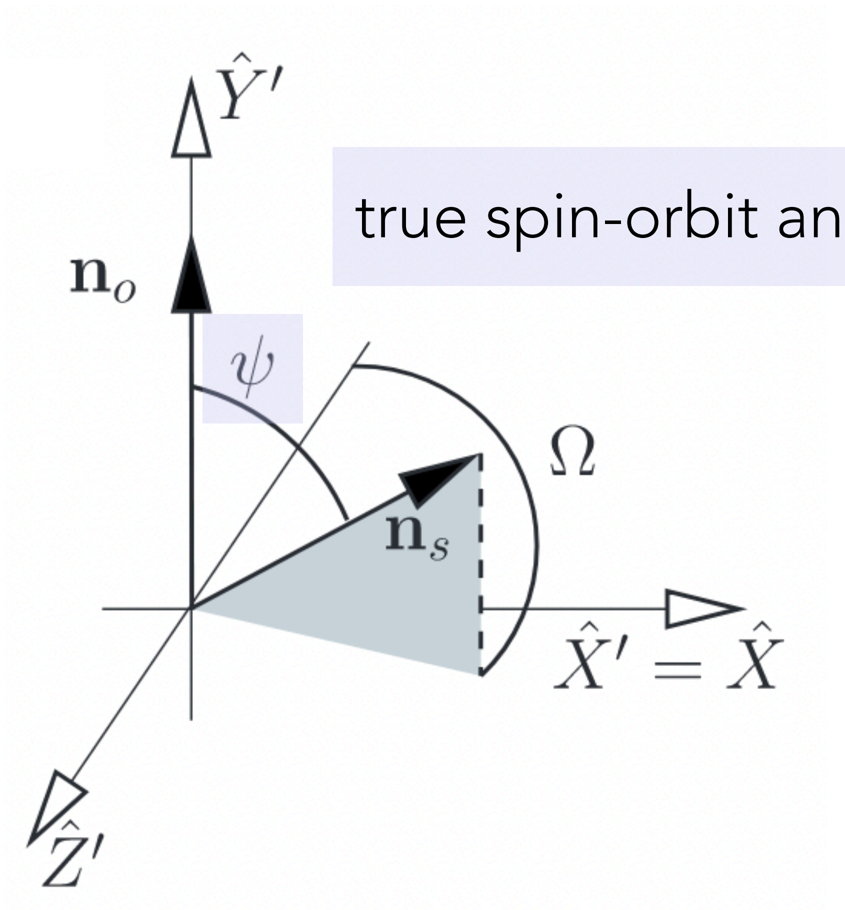
adapted from Fabrycky & Winn 2009



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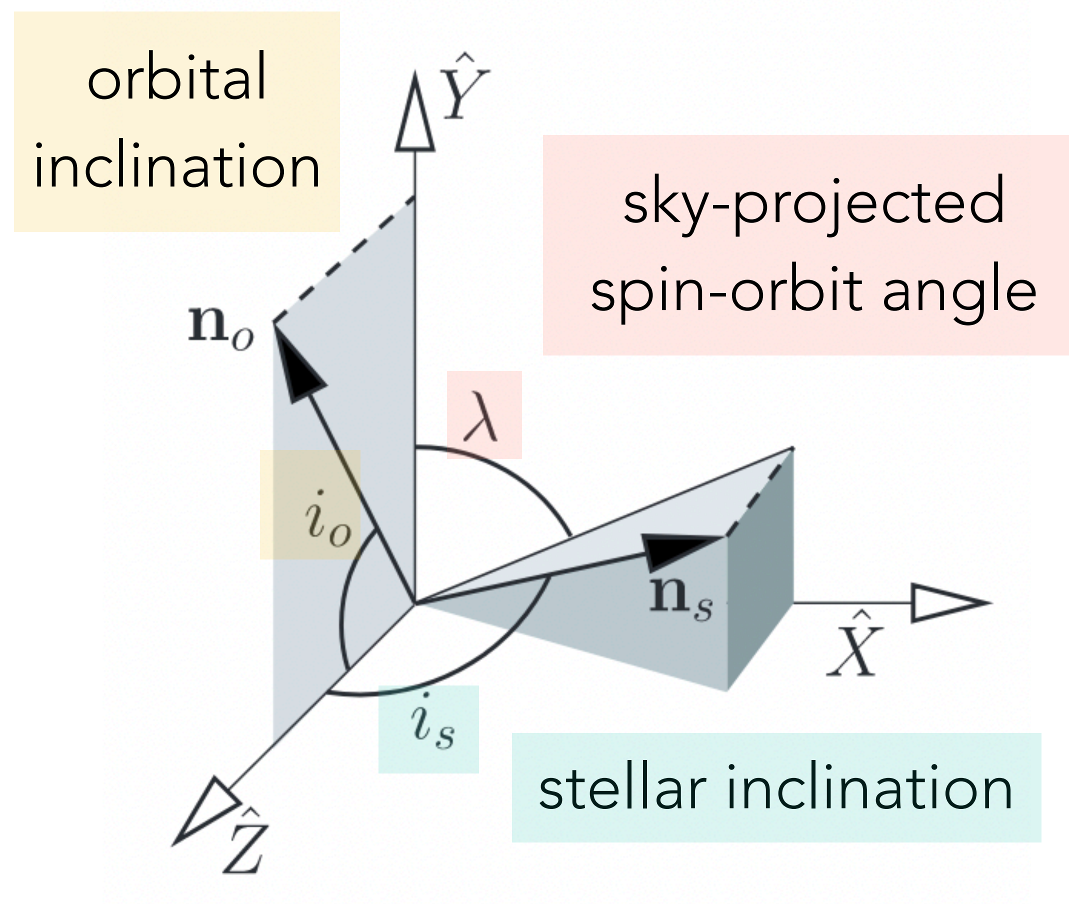

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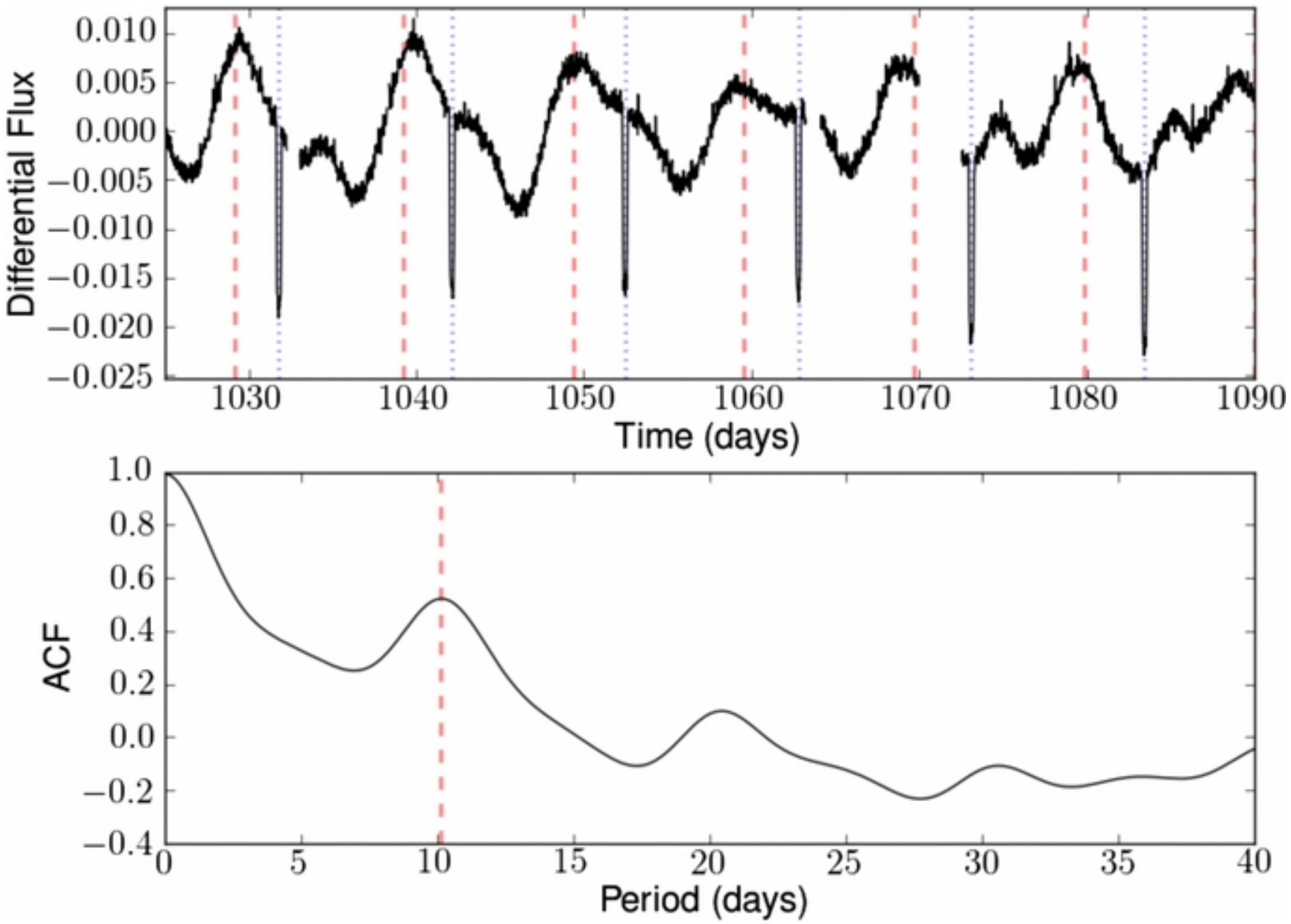


Stellar rotation periods (P): typically inferred from photometry to derive stellar inclinations in combination with $v\sin i_s$ measurements.

$$i_s = \arcsin\left(\frac{v\sin i_s}{v}\right) = \arcsin\left(\frac{v\sin i_s}{2\pi R/P}\right)$$

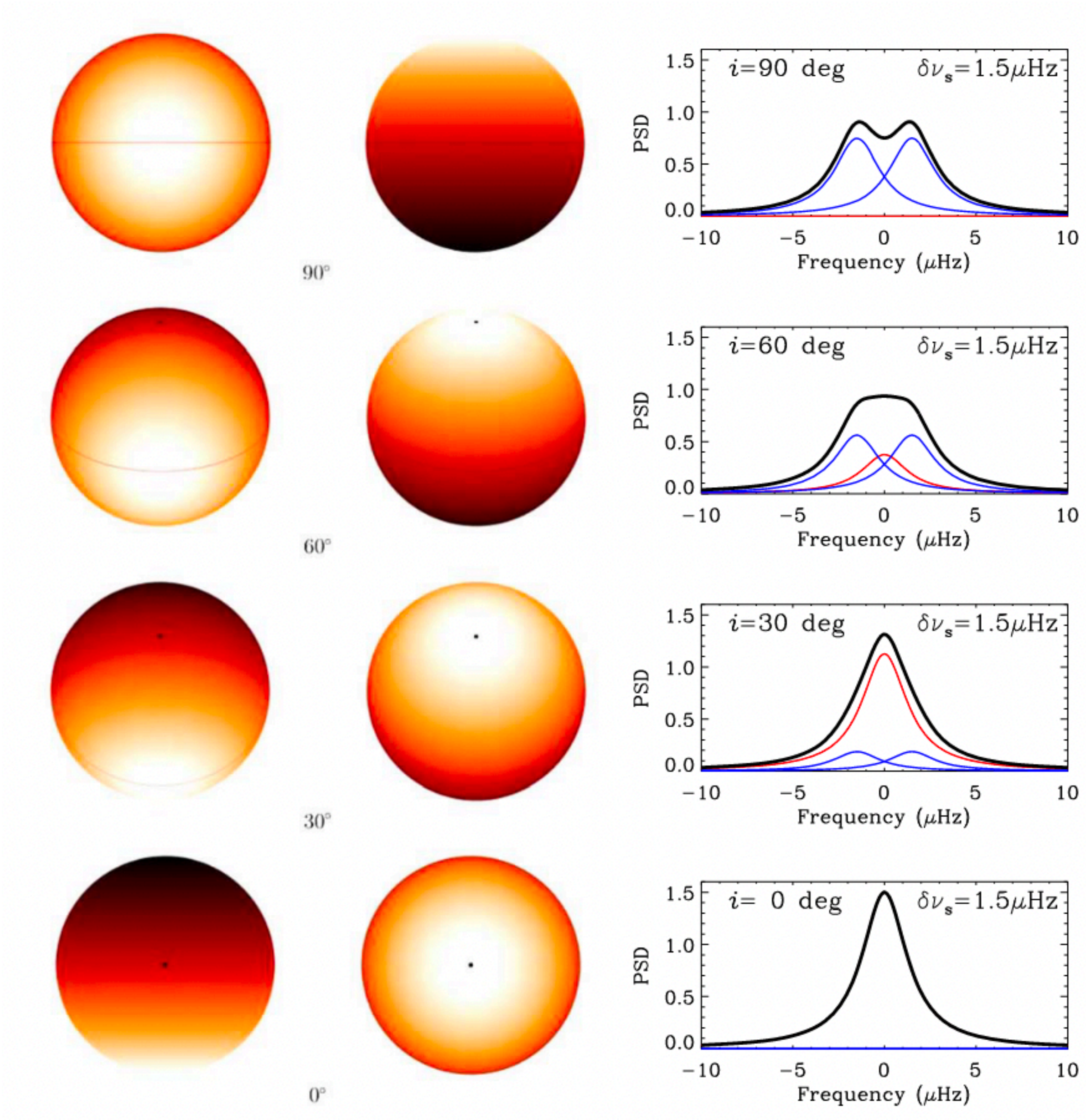
Note that care must be taken when applying this equation, especially for large or asymmetric uncertainties! See Masuda & Winn 2020 for more details.

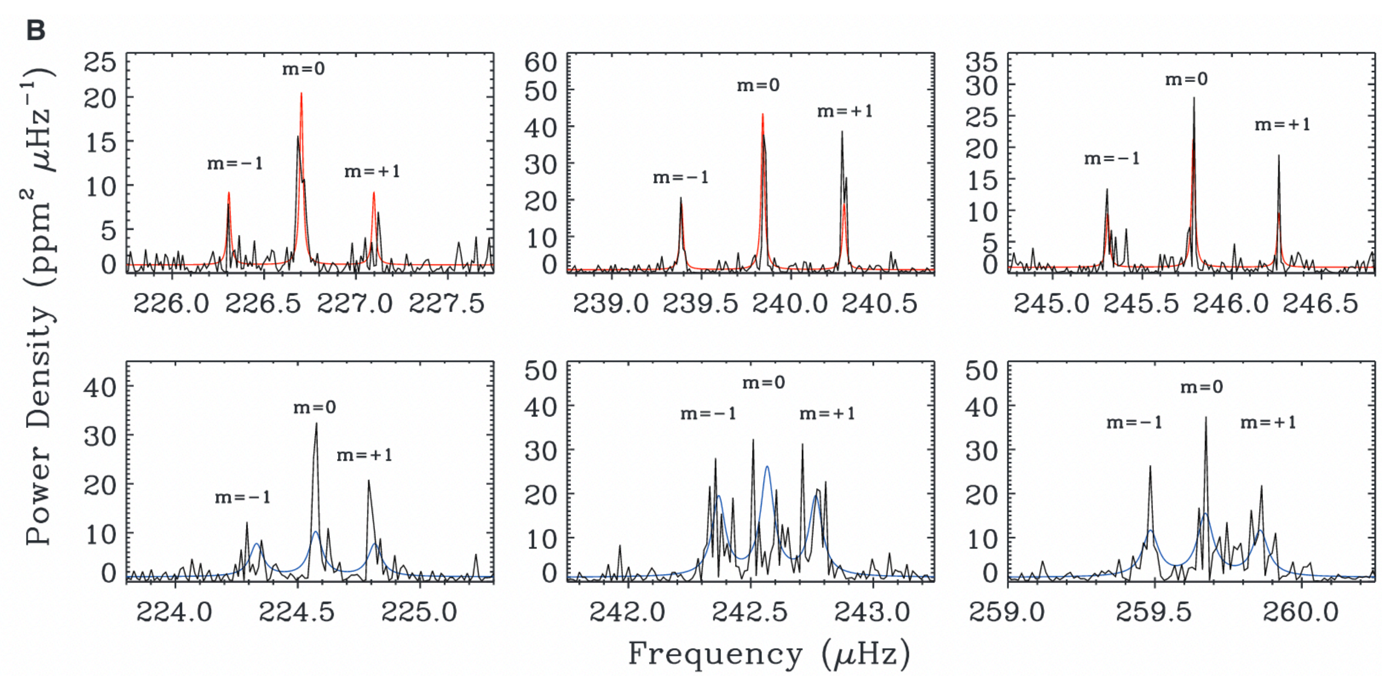
McQuillen, Mazeh, & Aigrain 2013

Kepler-56 mixed dipole modes, split into triplets by rotation

$i_s = 47 \pm 6^{\circ}$; two confirmed transiting planets

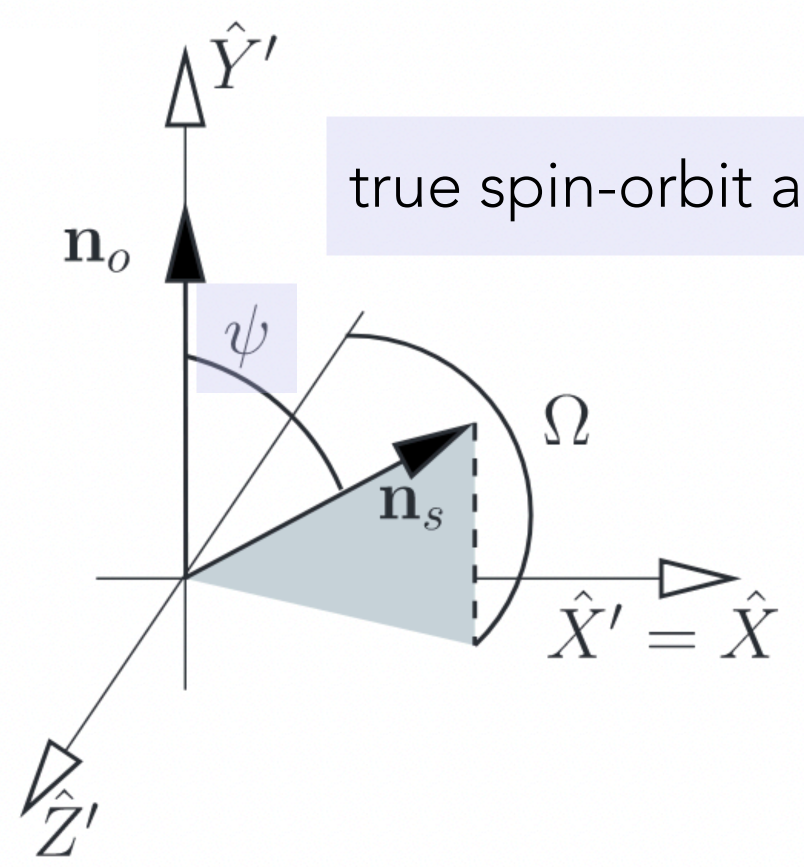
Core is misaligned, but outer layer may be aligned (Ong 2025)





Albrecht, Dawson, & Winn 2022

Huber, Carter, Barbieri, et al. 2013



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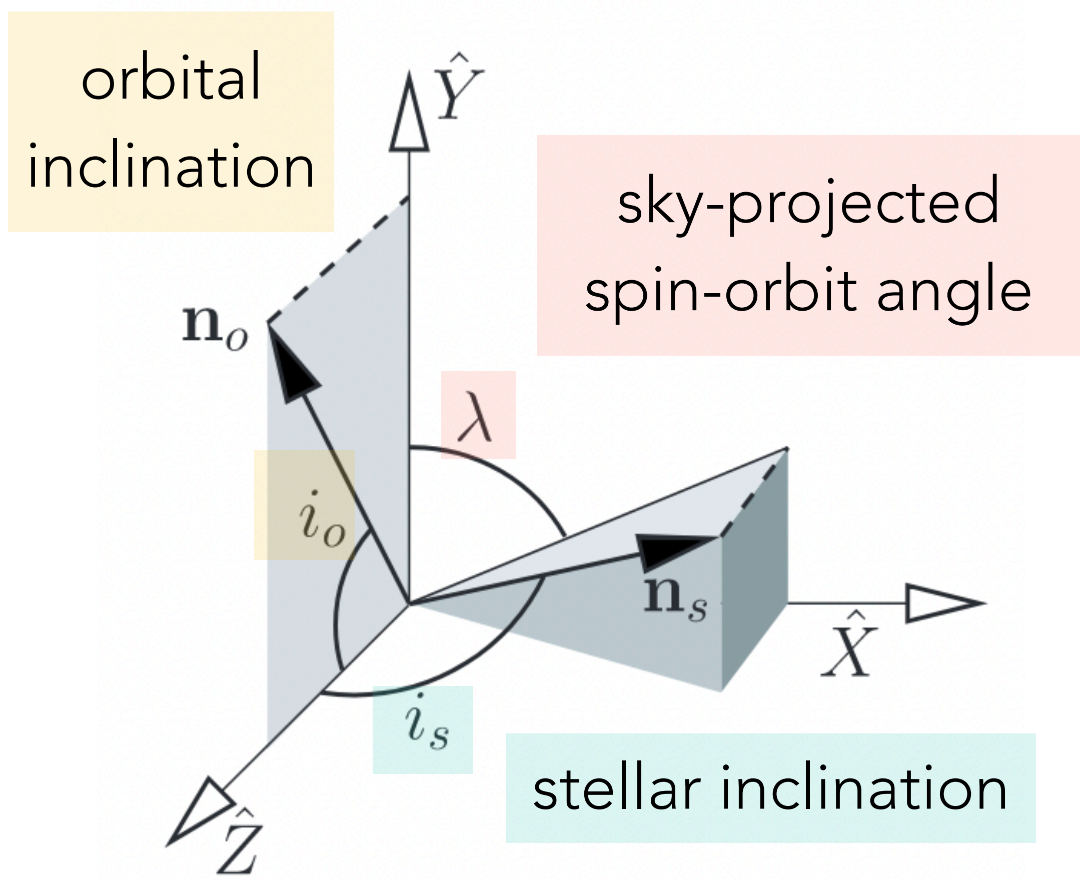
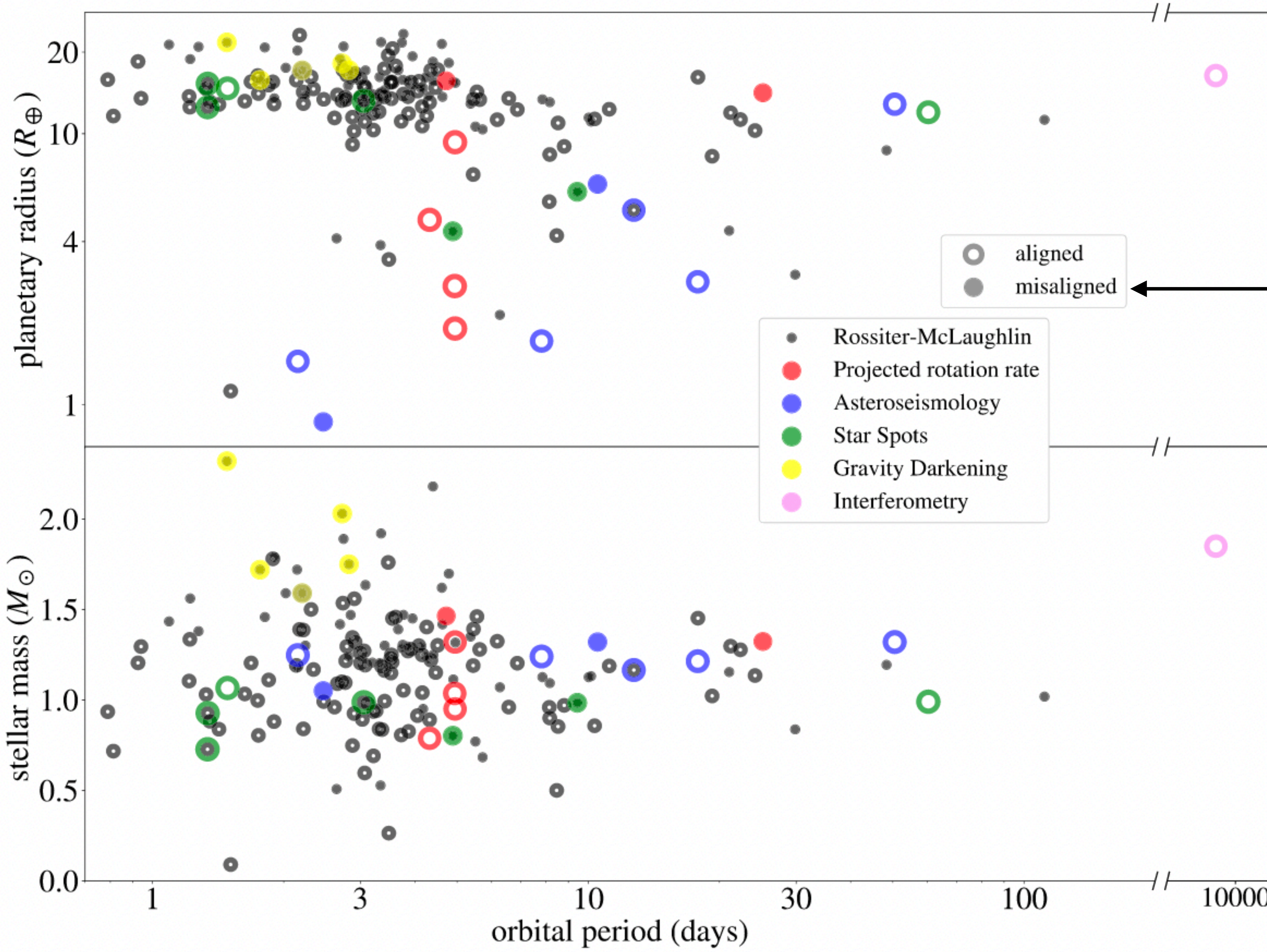


what we measure

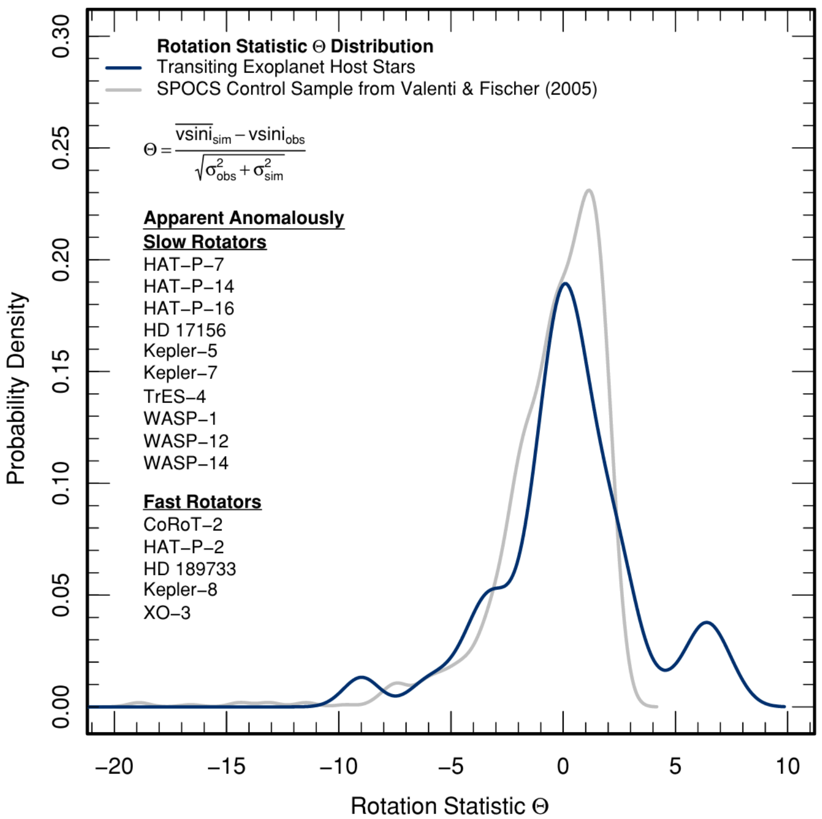
$$\cos\psi = \cos i_s \cos i_0 + \sin i_s \sin i_0 \cos\lambda$$



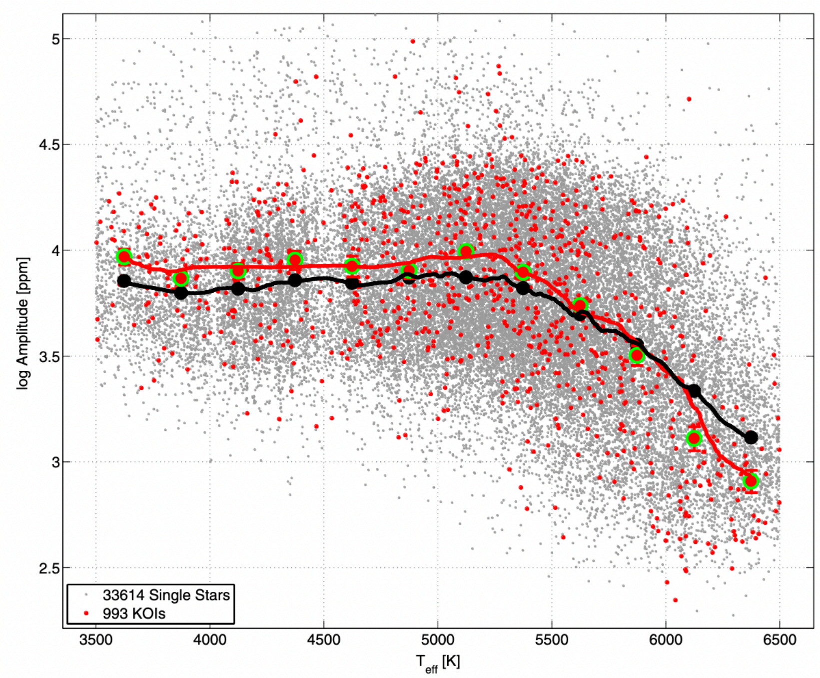
By more than 10°
and >3σ from 0°

Albrecht, Dawson, & Winn 2022

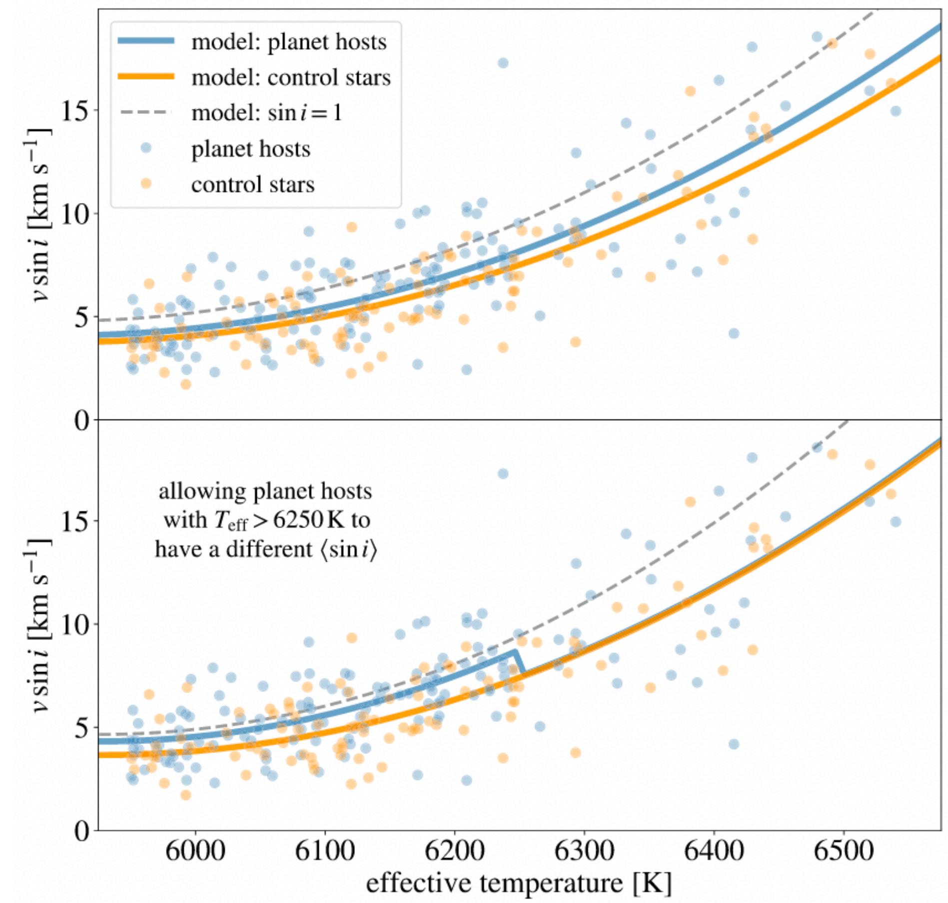
Schlaufman 2010



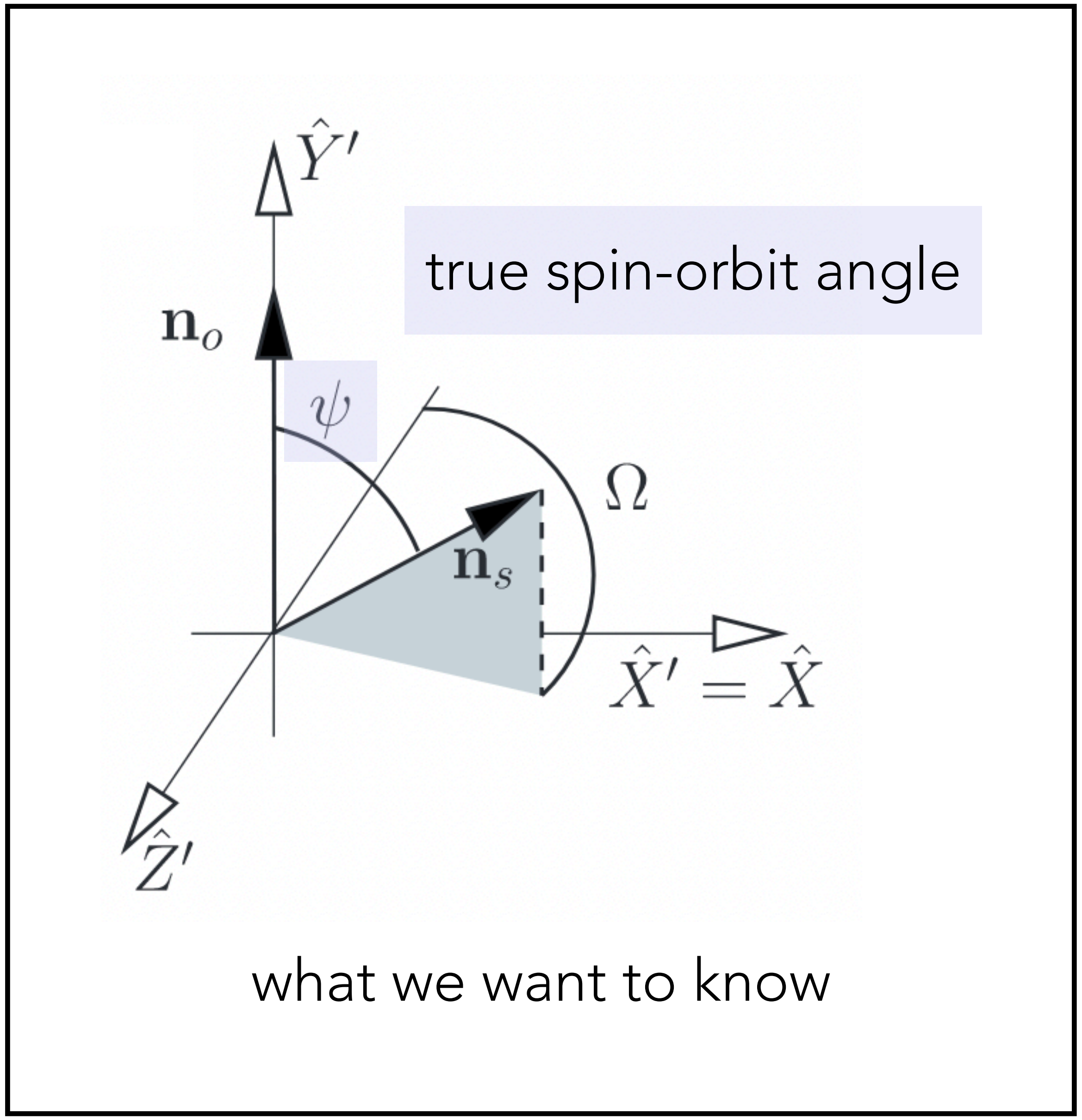
Mazeh, Perets, McQuillan, & Goldstein 2015

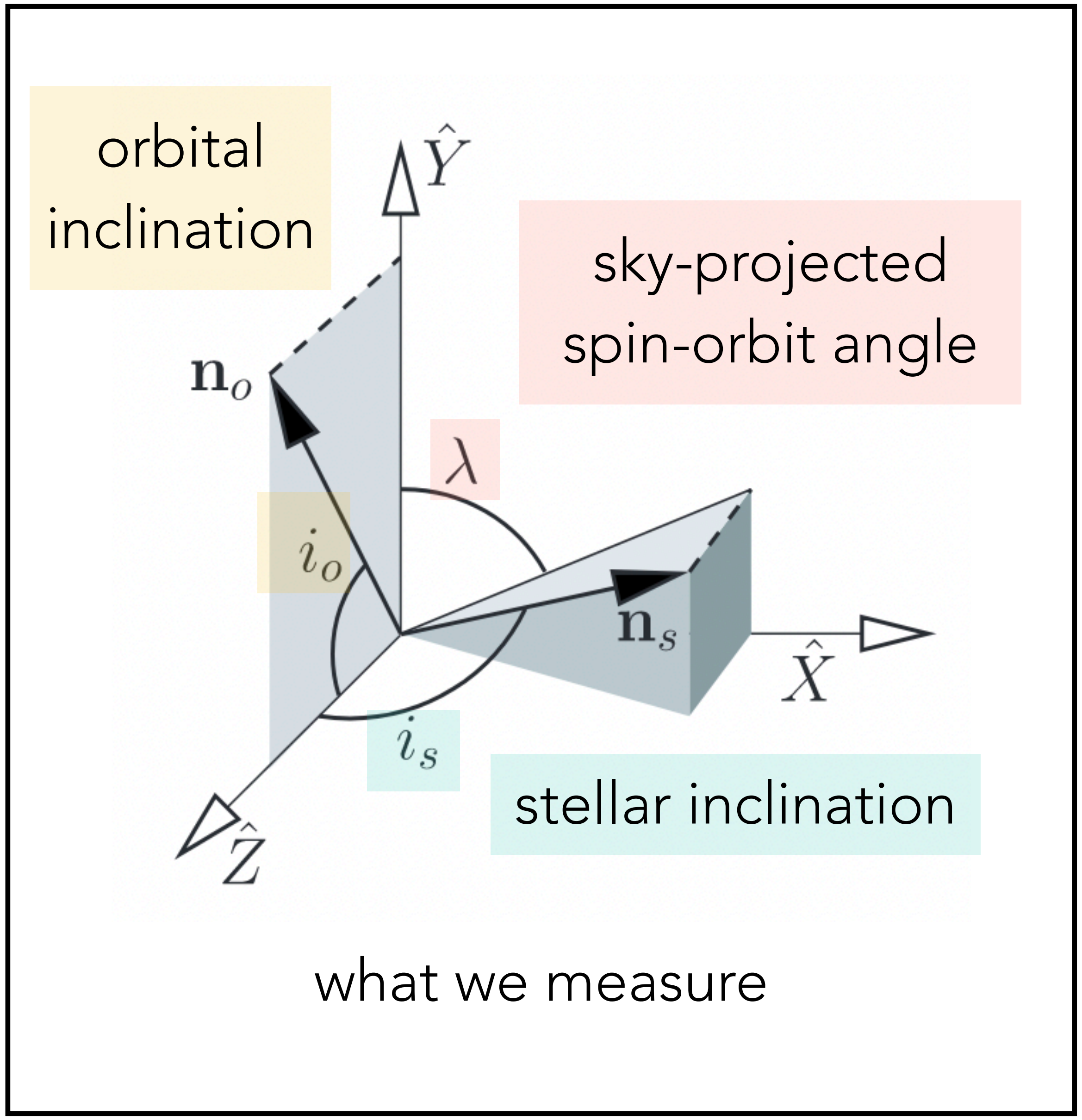


Louden, Winn, Petigura, et al. 2021



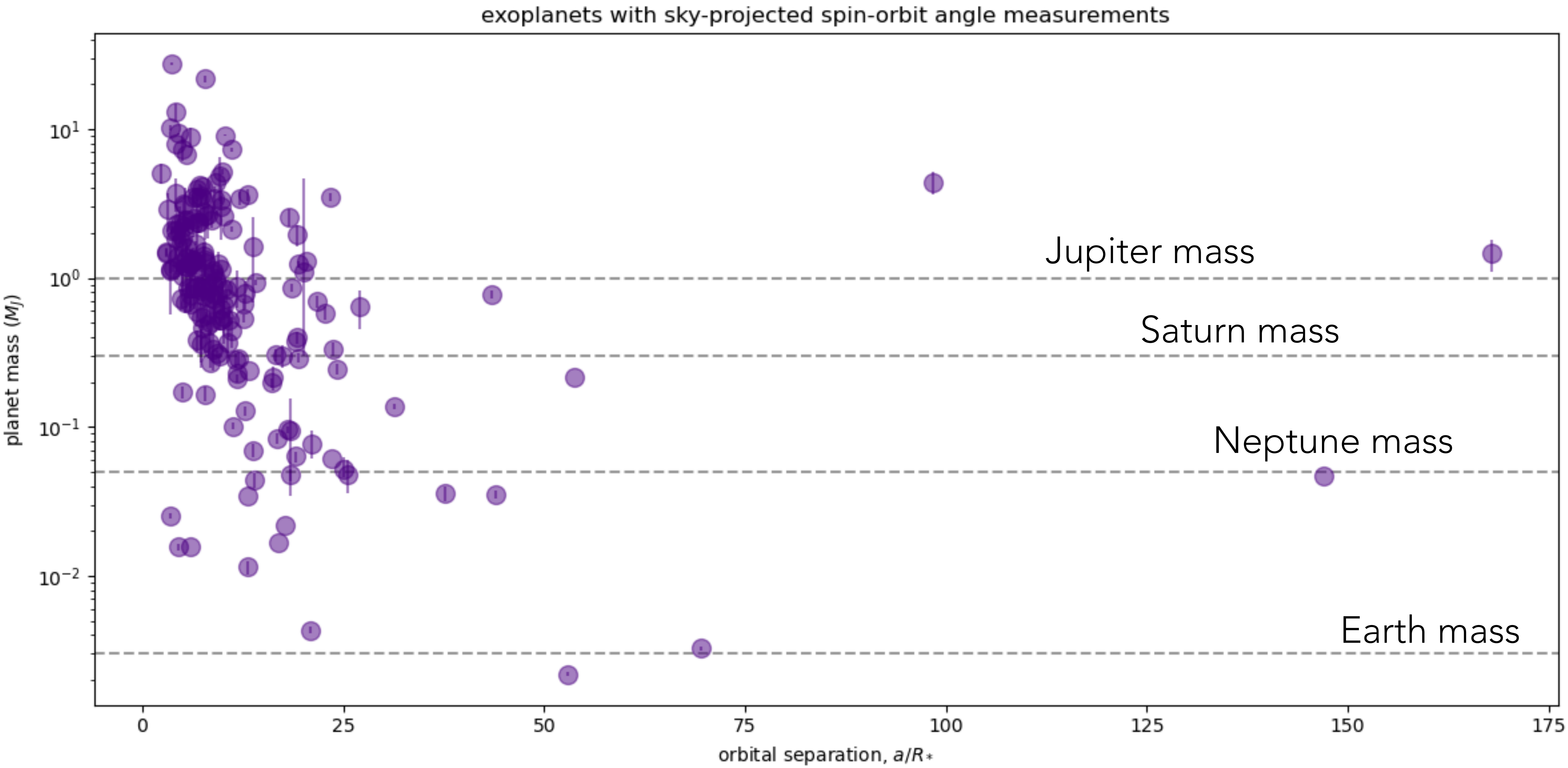
The stellar inclination distribution may also be examined in population studies without inferring v and i_s separately.

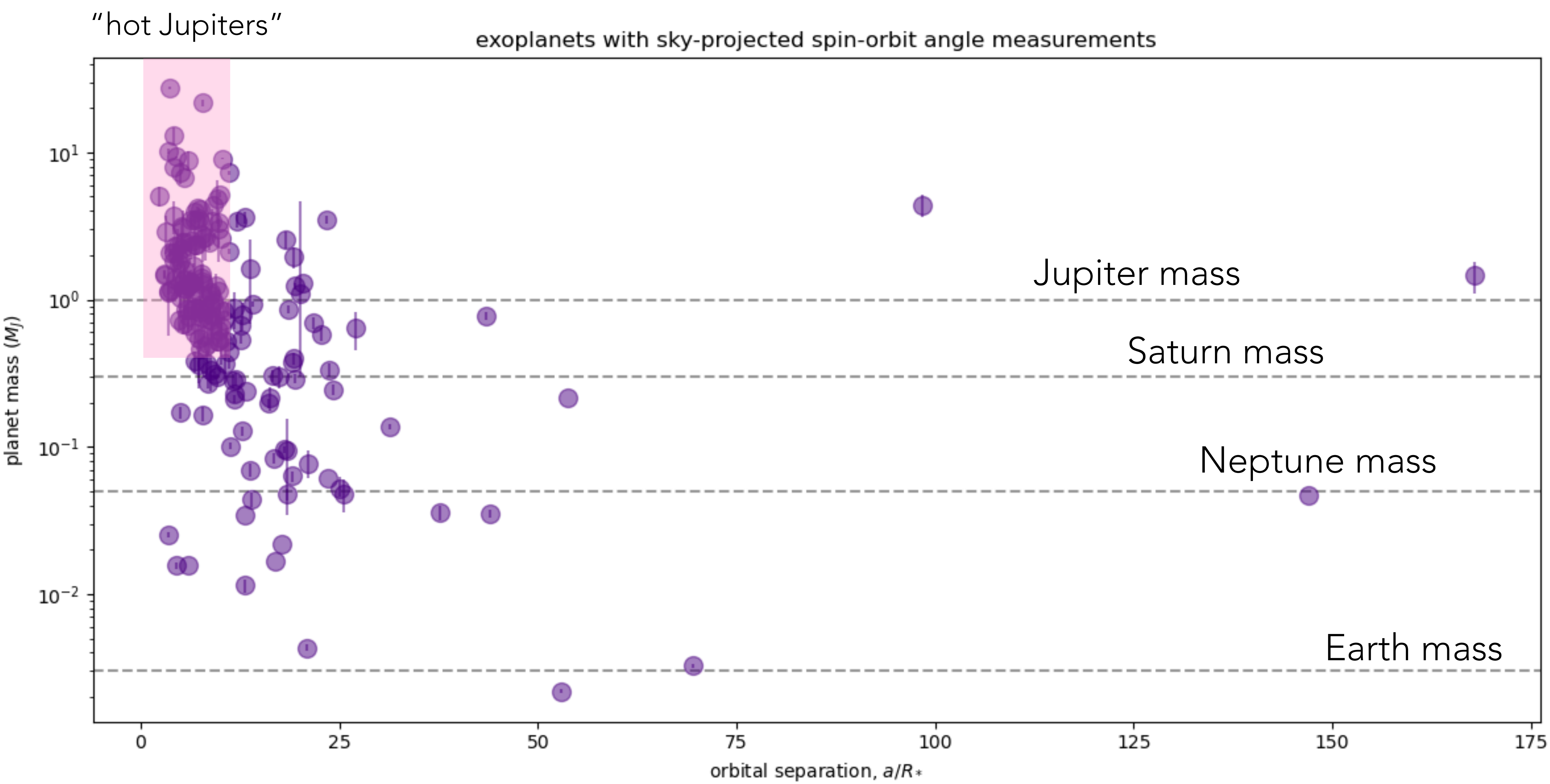




$$\cos\psi = \cos i_s \cos i_0 + \sin i_s \sin i_0 \cos\lambda$$

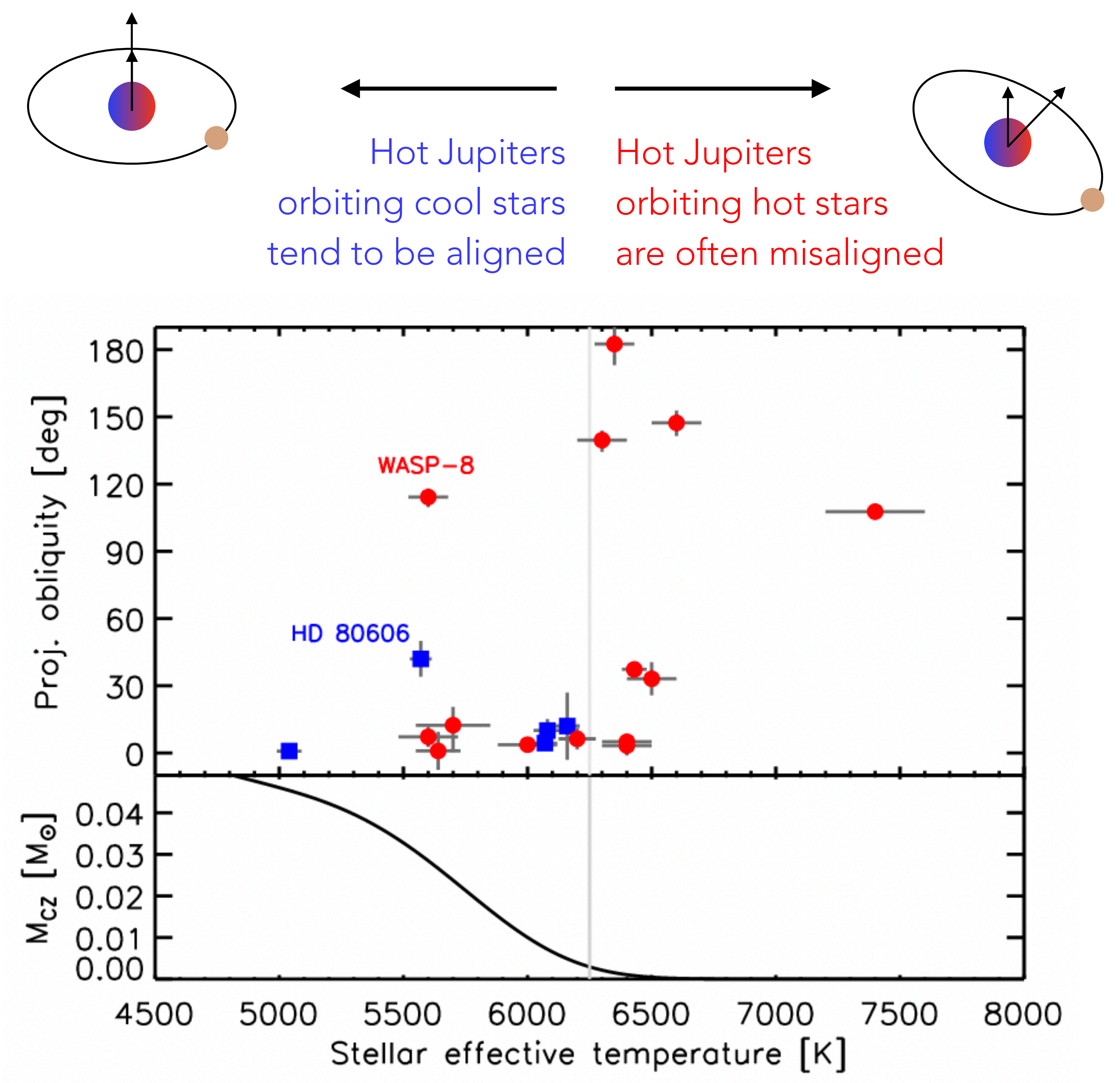
adapted from Fabrycky & Winn 2009


exoplanets with sky-projected spin-orbit angle measurements
planet mass (M_J)
orbital separation, a/R_*
10^1
10^0
10^{-1}
10^{-2}
0
25
50
75
100
125
150
175
Jupiter mass
Saturn mass
Neptune mass
Earth mass


"hot Jupiters"
exoplanets with sky-projected spin-orbit angle measurements
planet mass (M_J)
orbital separation, a/R_*
Jupiter mass
Saturn mass
Neptune mass
Earth mass
10^1
10^0
10^{-1}
10^{-2}
0
25
50
75
100
125
150
175

Observed trends: hot Jupiters

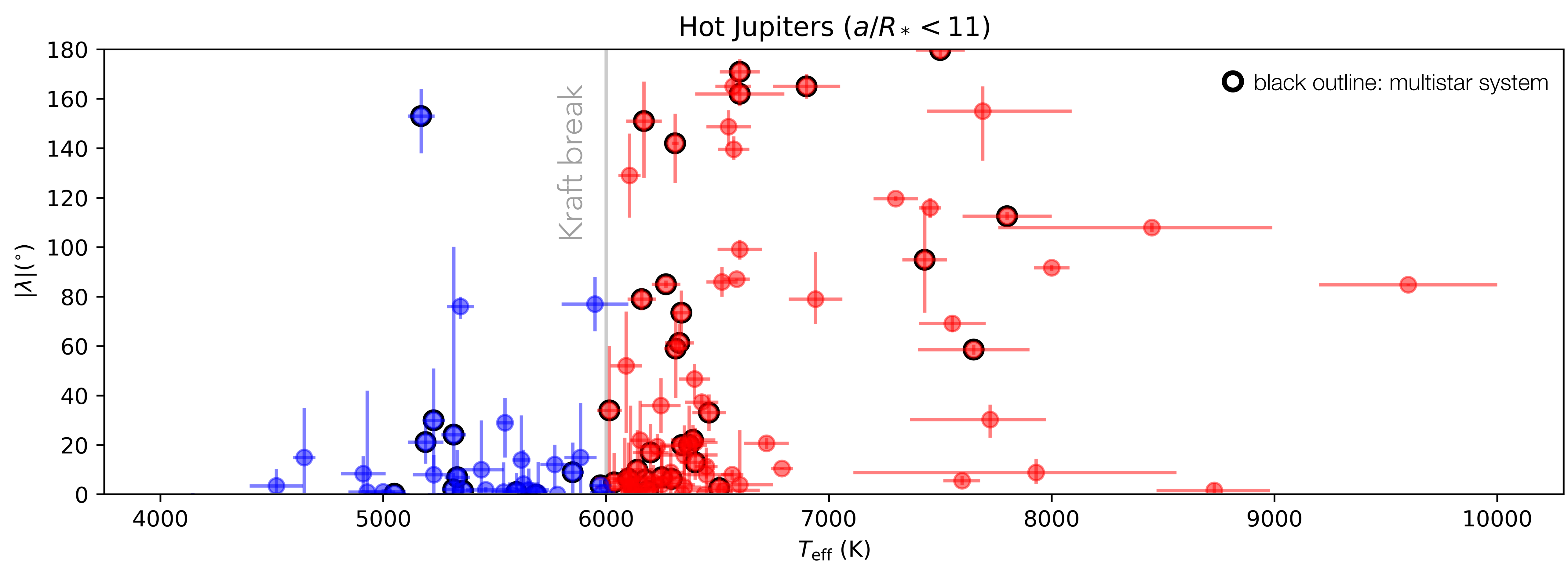
Hot Jupiters around hot stars are more often misaligned than hot Jupiters around cool stars



Winn, Fabrycky, Albrecht, & Johnson 2010; see also Schlaufman 2010

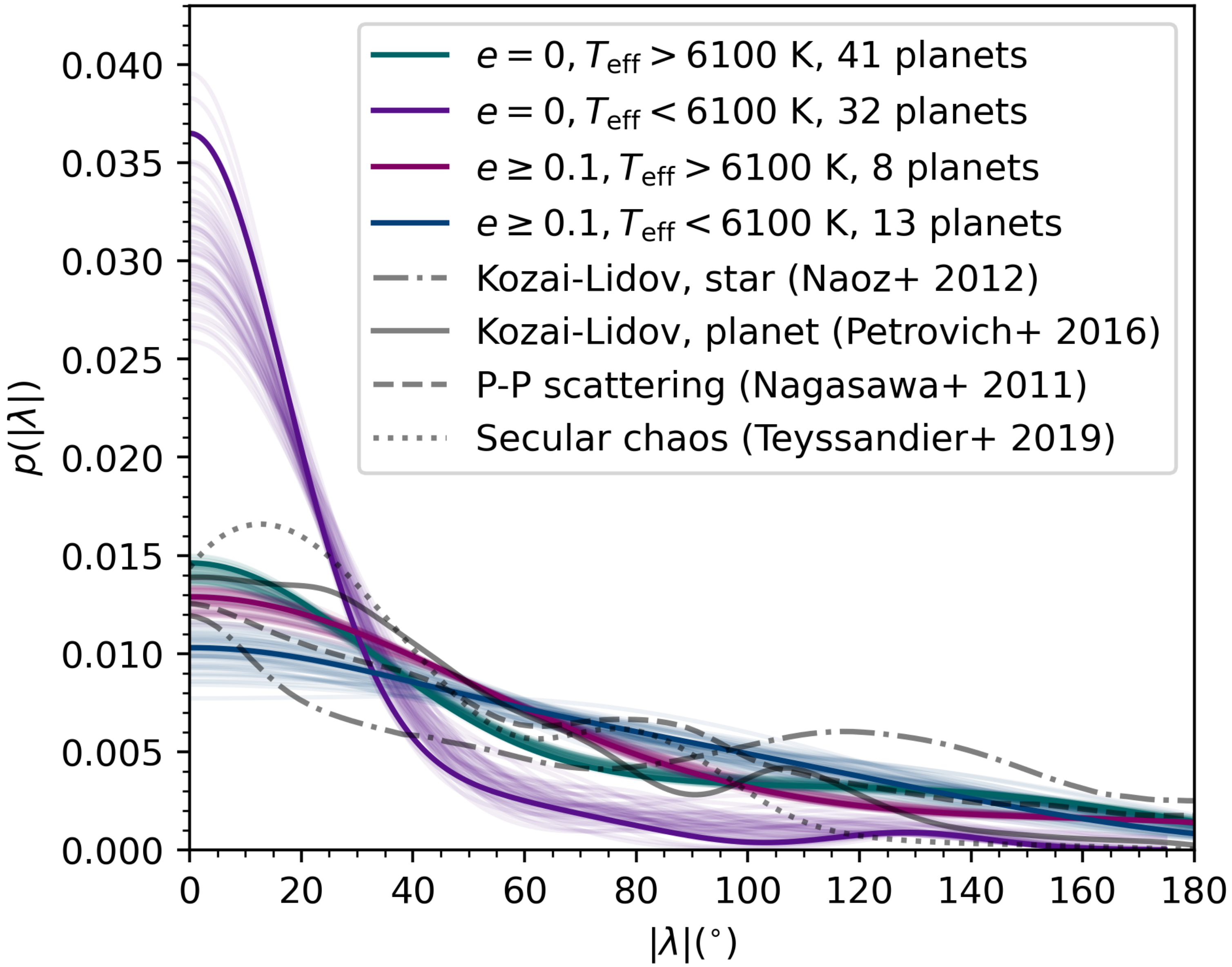
Observed trends: hot Jupiters

Hot Jupiters around hot stars are more often misaligned than hot Jupiters around cool stars → Trend still holds in 2025, 15 years after initial discovery.*



Signature of tidal realignment for cool stars? (see talk by J. J. Zanazzi)

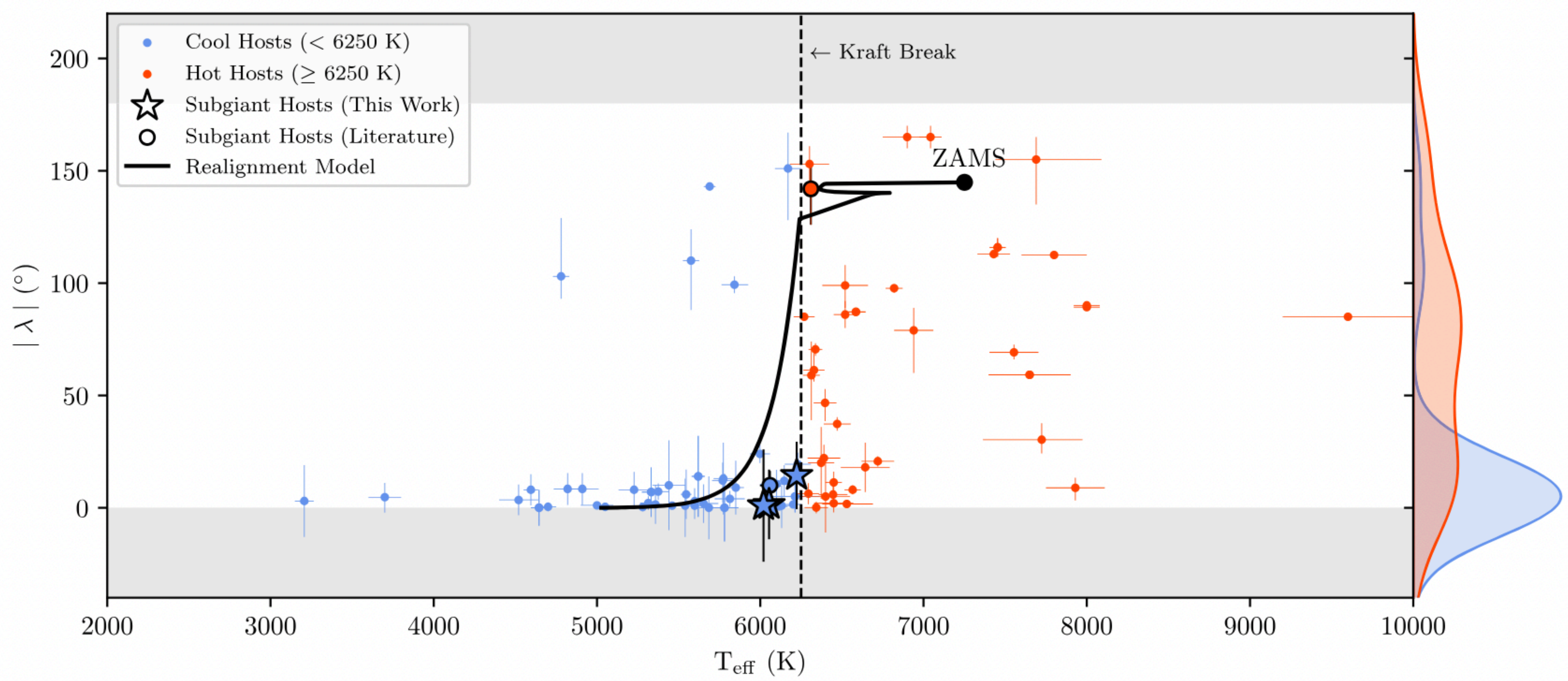
Observed trends: hot Jupiters



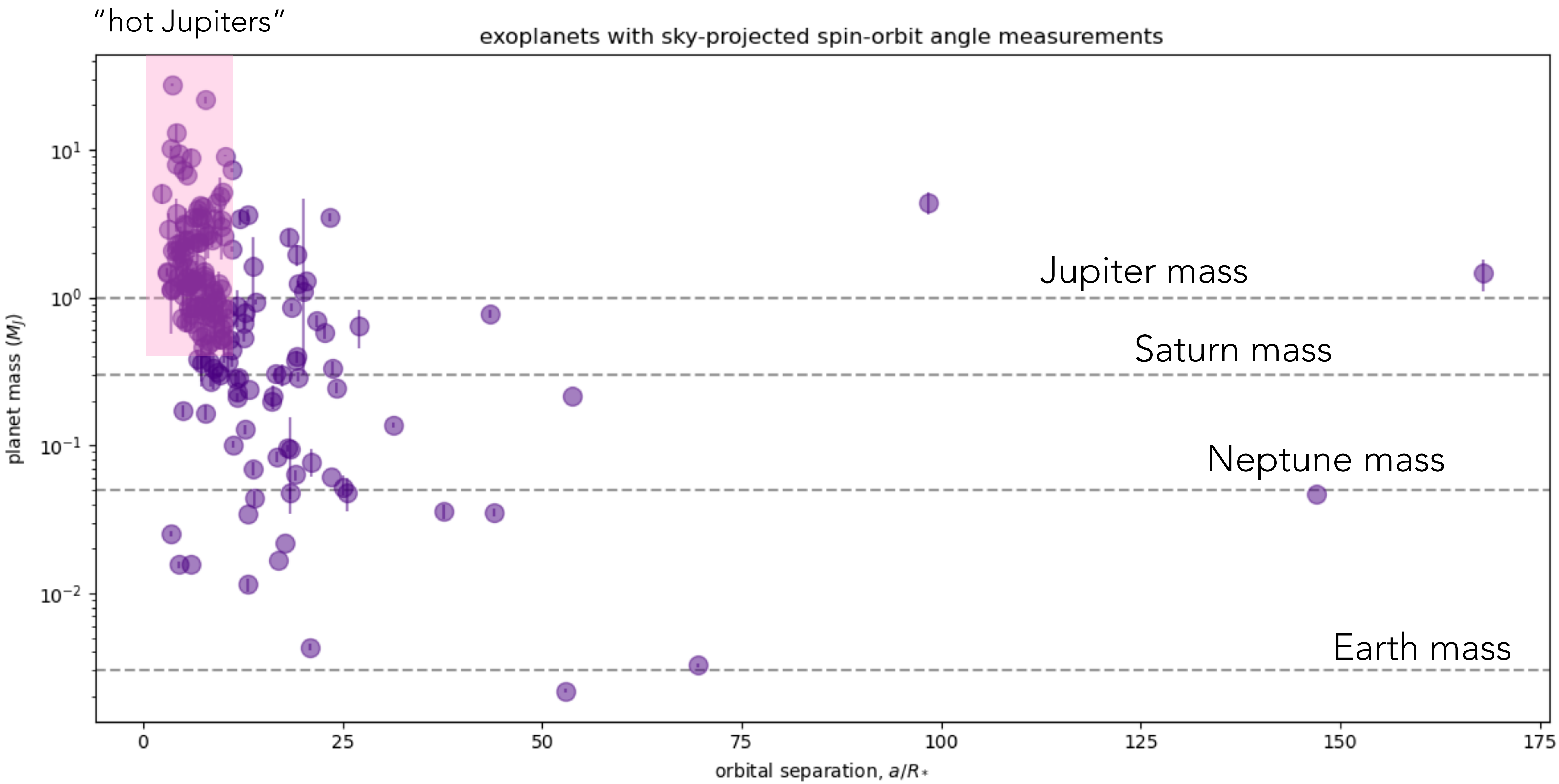
*The difference in stellar obliquities at the Kraft break is significant *only for circular orbits*

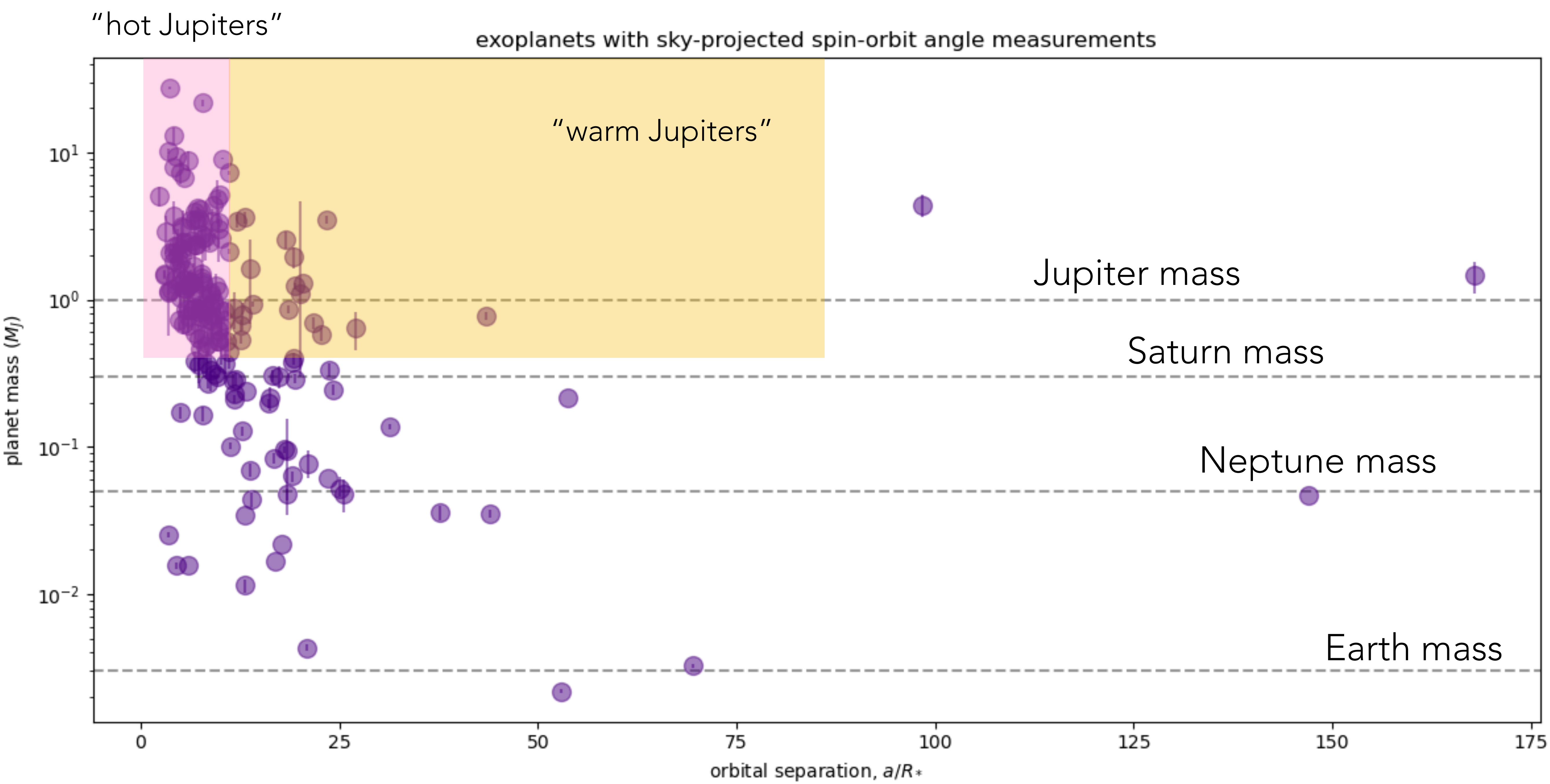
Rice, Wang, & Laughlin 2022

Evolved systems with stars once above the Kraft break, that have since developed deep convective envelopes — so far all near aligned. Signature of efficient tidal realignment?



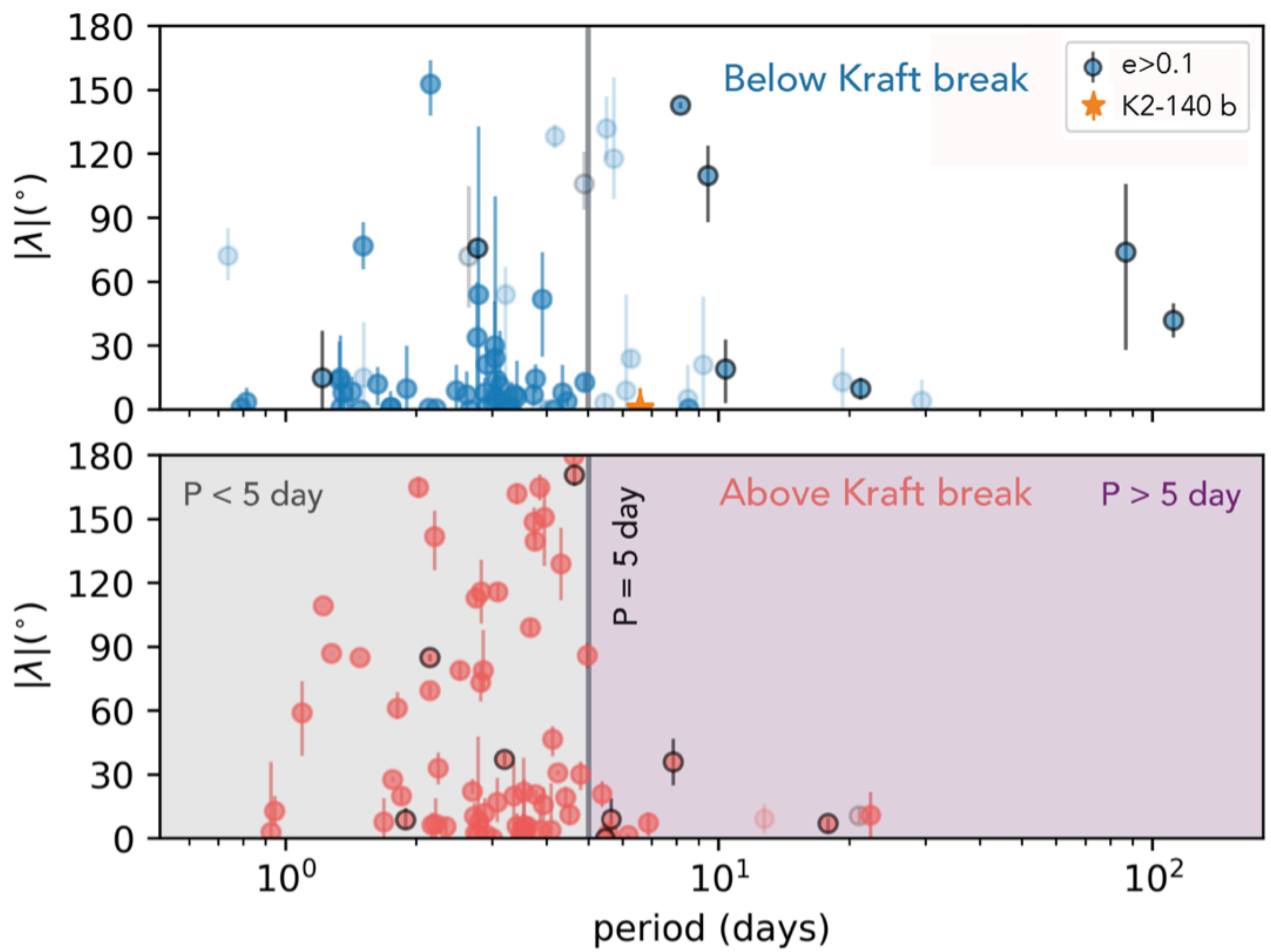
Saunders, Grunblatt, Chontos et al. 2024


"hot Jupiters"
exoplanets with sky-projected spin-orbit angle measurements
Jupiter mass
Saturn mass
Neptune mass
Earth mass
planet mass (M_J)
10^1
10^0
10^{-1}
10^{-2}
0
25
50
75
100
125
150
175
orbital separation, a/R_*


"hot Jupiters"
exoplanets with sky-projected spin-orbit angle measurements
"warm Jupiters"
Jupiter mass
Saturn mass
Neptune mass
Earth mass
planet mass (M_J)
10^1
10^0
10^{-1}
10^{-2}
0
25
50
75
100
125
150
175
orbital separation, a/R_*

Observed trends: warm Jupiters

Warm Jupiters do not appear to follow the same temperature break trend as hot Jupiters.

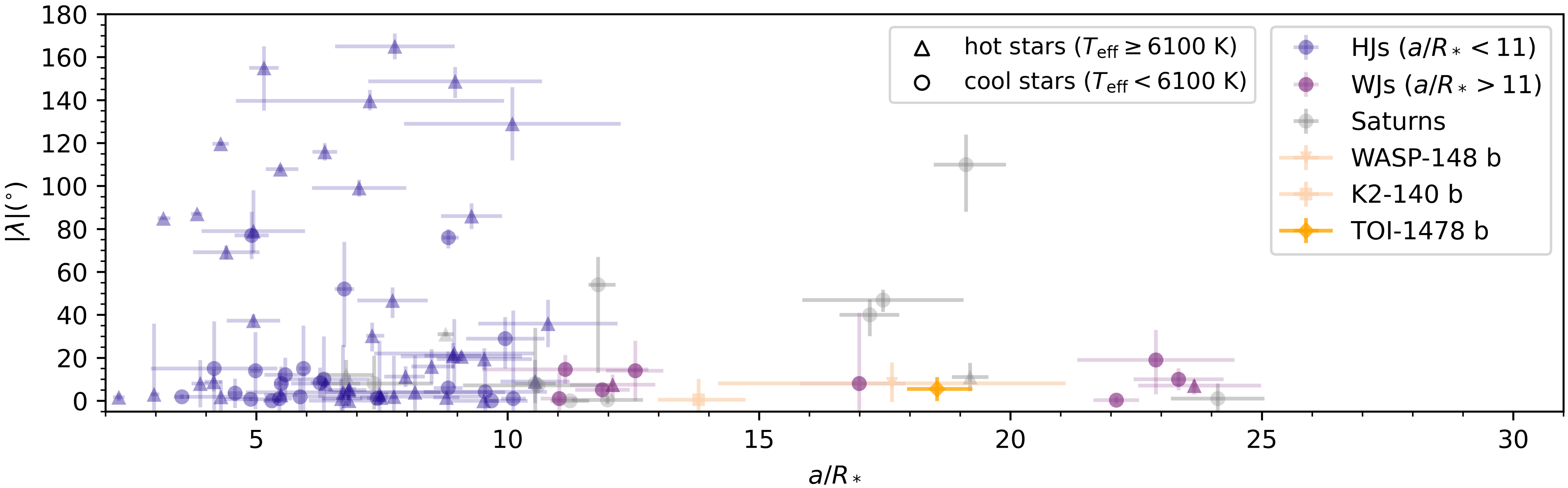


Rice, Wang, Howard, et al. 2021

In single-star systems, warm Jupiters tend to be aligned

single-star systems:

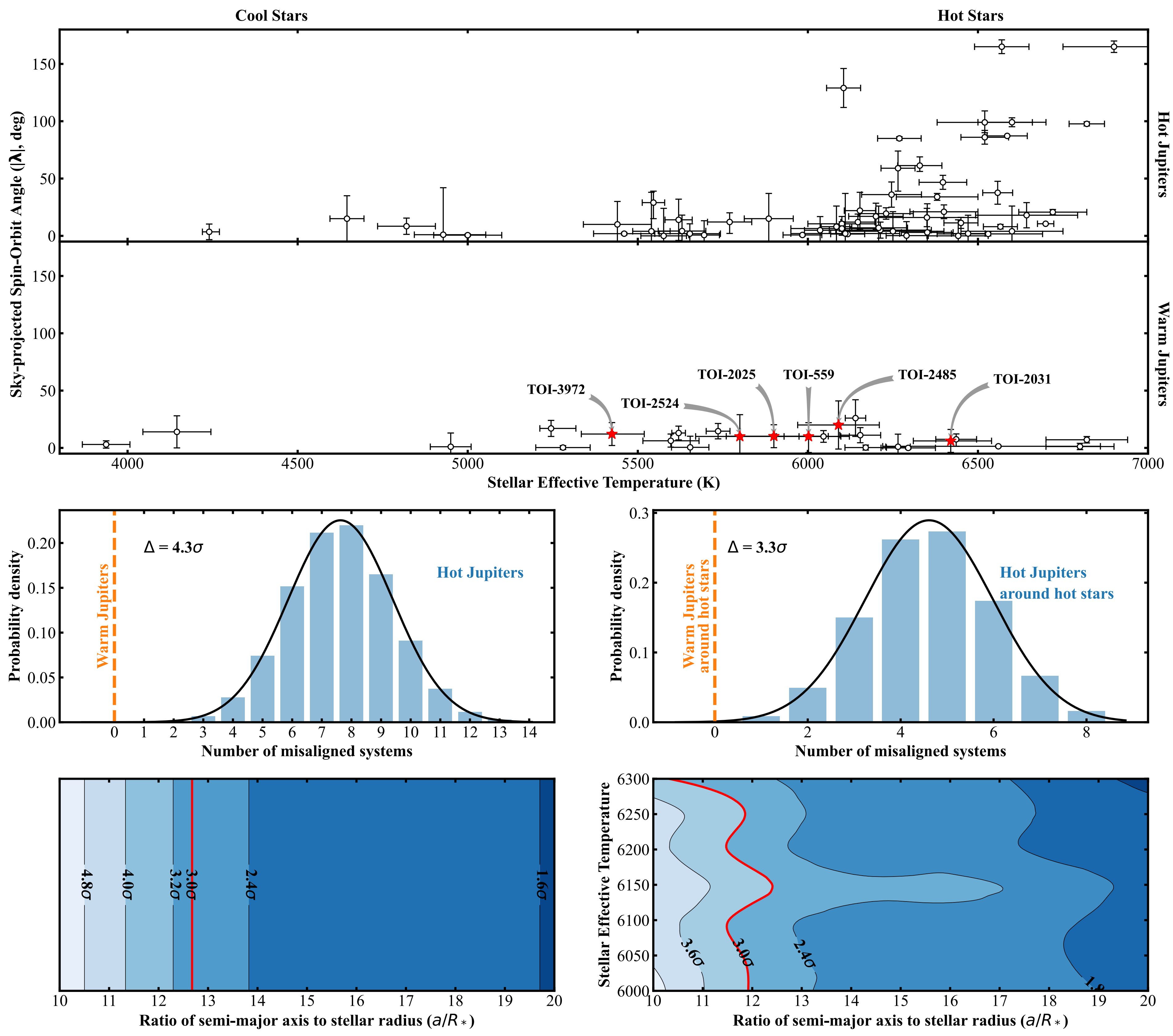
Saturns defined here as $0.2M_J \leq M_{pl} \leq 0.4M_J$



In single-star systems, warm Jupiters tend to be aligned.

Rice, Wang, Wang, et al. 2022

In single-star systems, warm Jupiters tend to be aligned



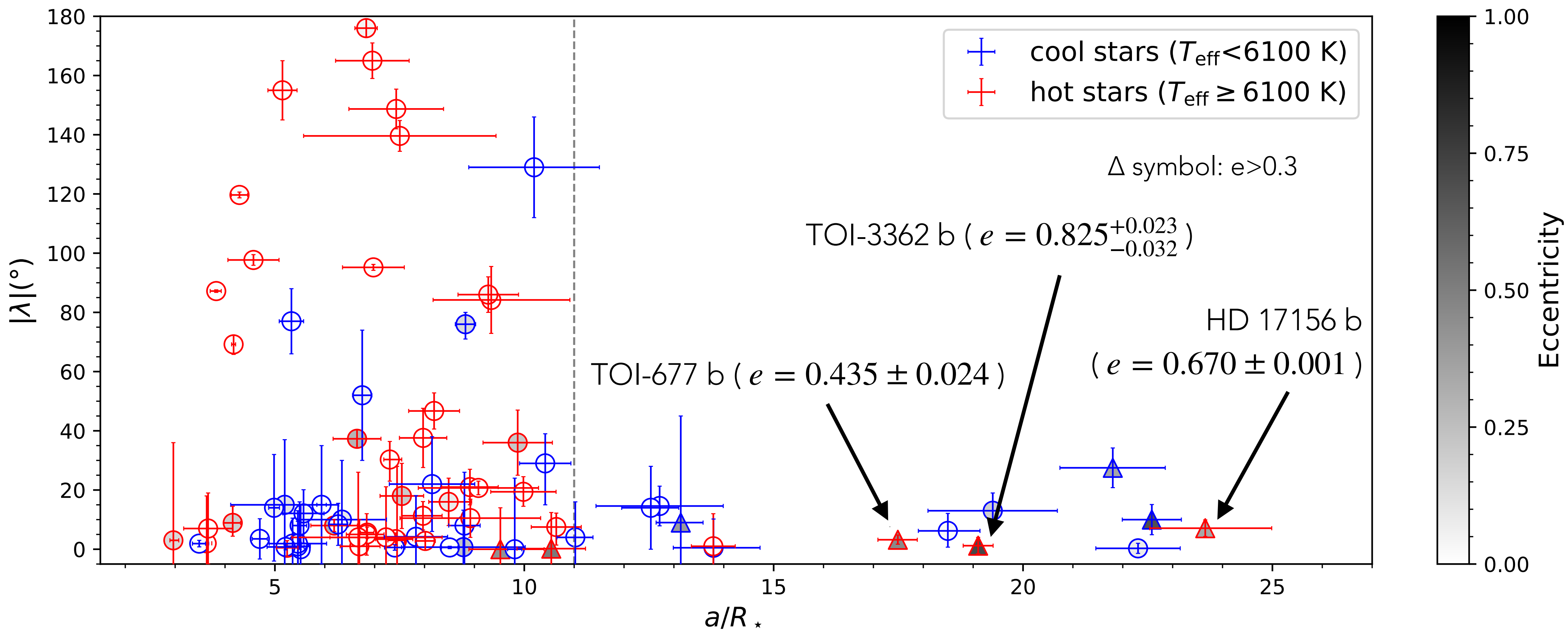
… even when accounting for stellar host biases (see talk by X.-Y. Wang)

Wang, Rice, Wang, et al. 2024

In single-star systems, warm Jupiters tend to be aligned

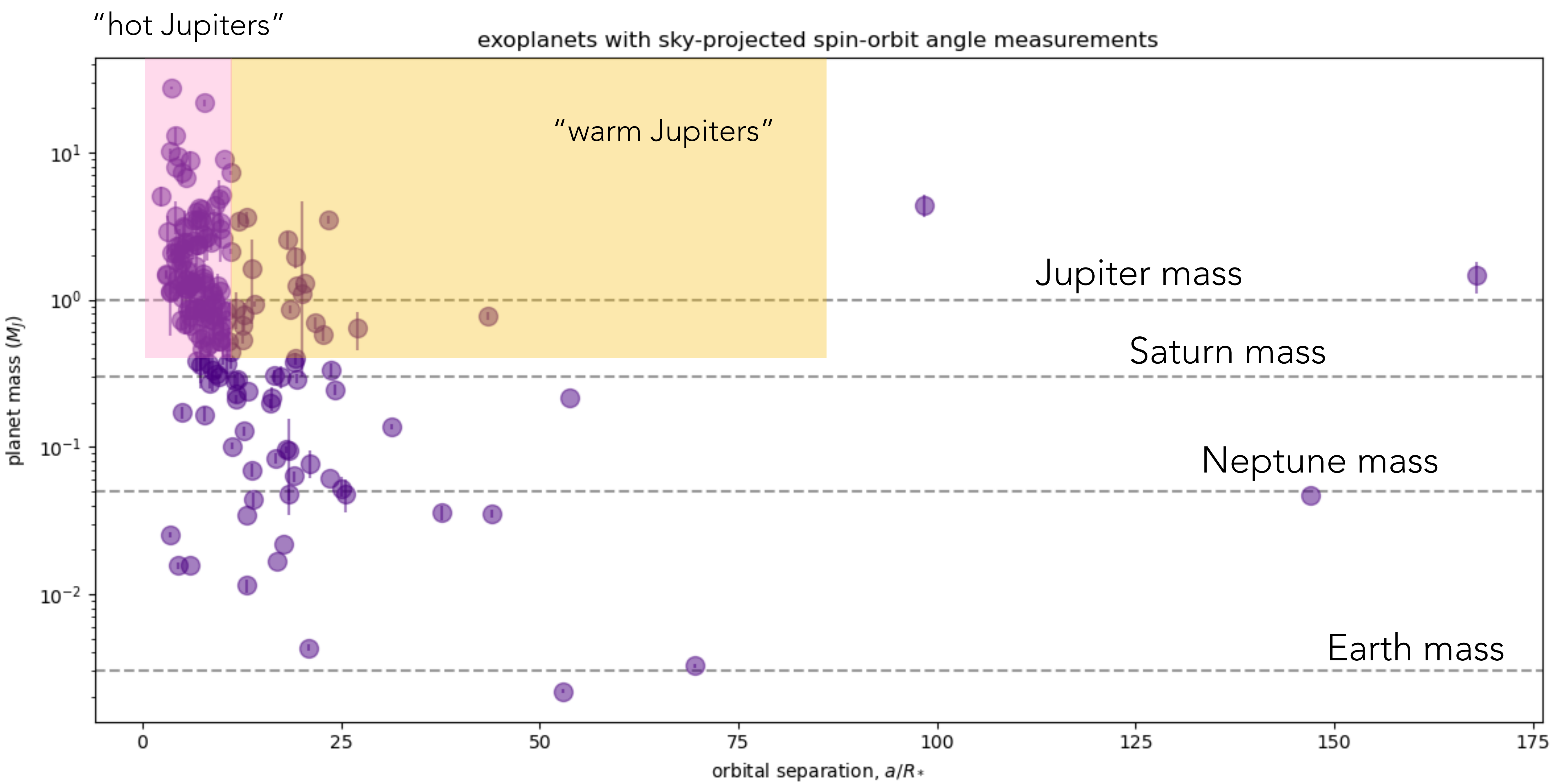
… even when on highly eccentric orbits

single-star systems, updated sample (as of December 2023):



Narita et al. 2009; Espinoza-Retamal et al. 2023; Sedaghati et al. 2023

Hu, Rice, Wang, et al. 2024



"hot Jupiters"
exoplanets with sky-projected spin-orbit angle measurements
"warm Jupiters"
Jupiter mass
Saturn mass
Neptune mass
Earth mass
planet mass (M_J)
10^1
10^0
10^{-1}
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0
25
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75
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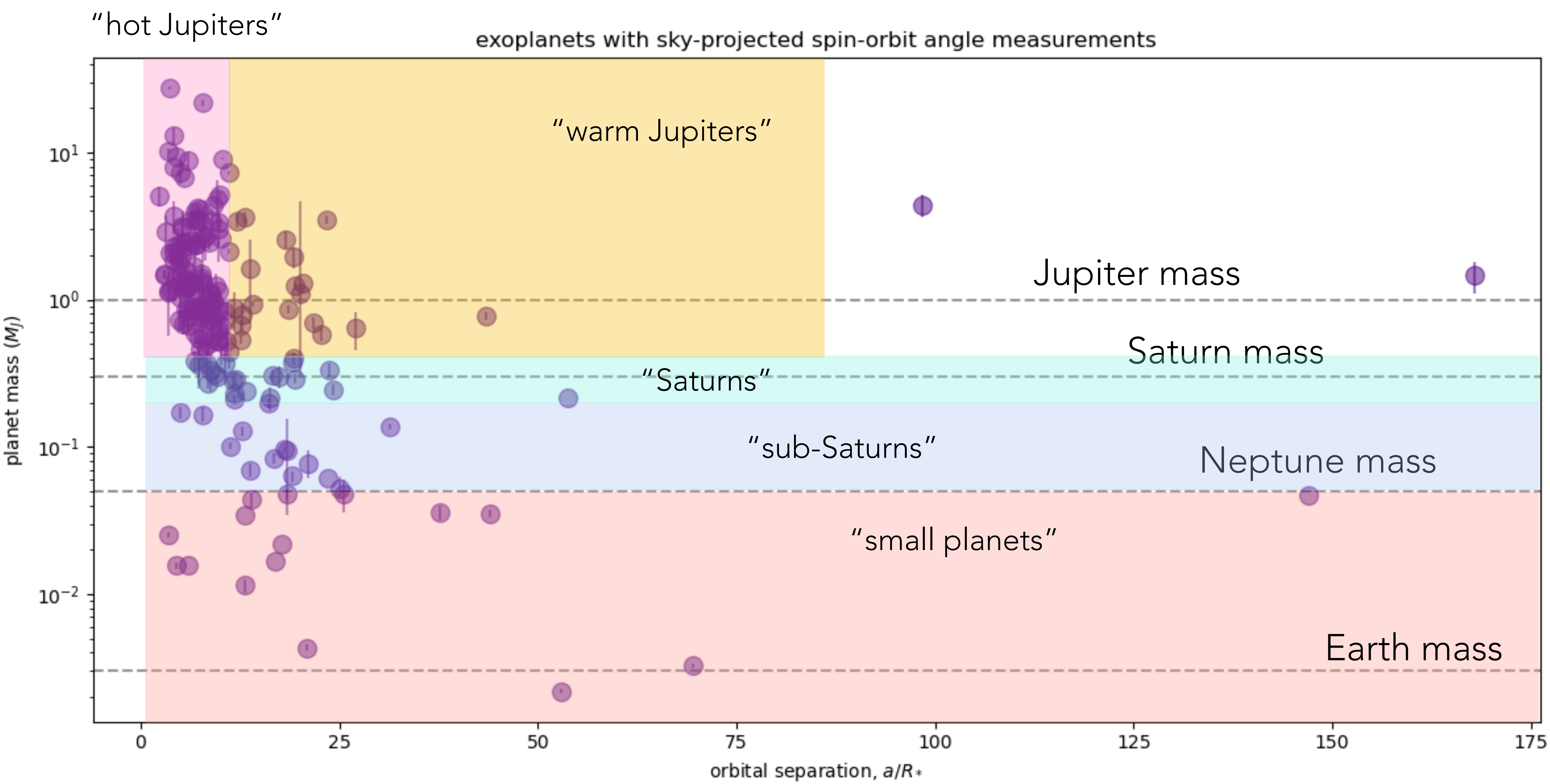
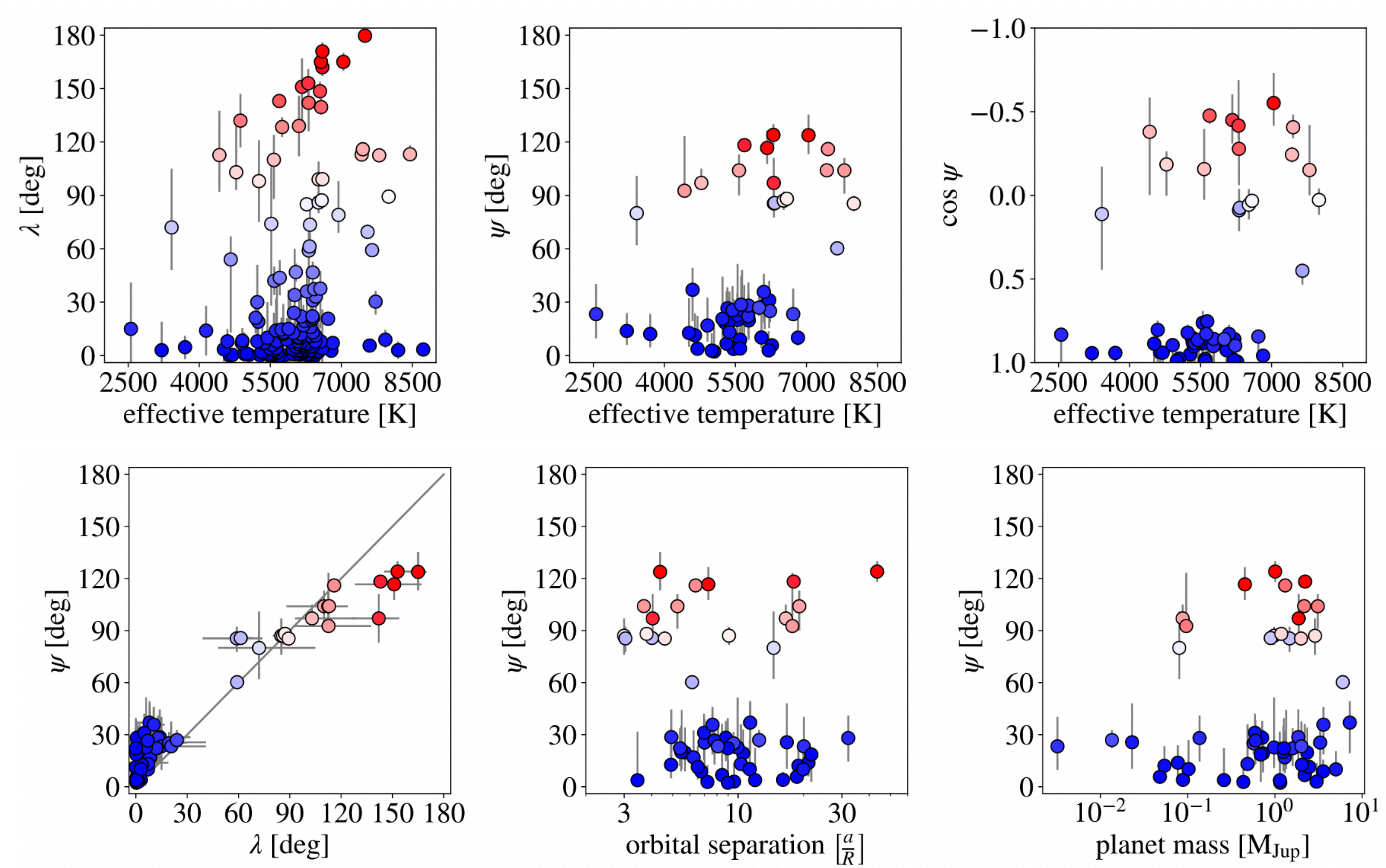
175
orbital separation, a/R_*

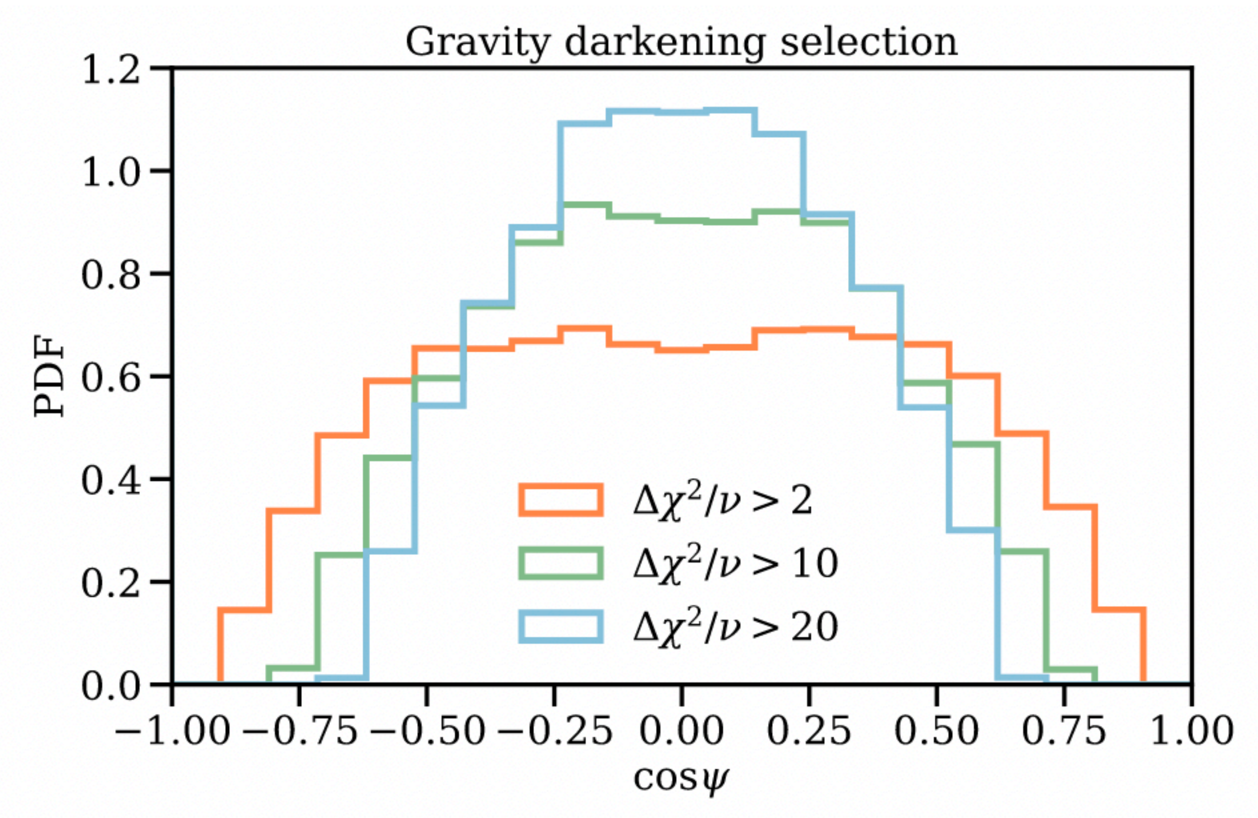

"hot Jupiters"
exoplanets with sky-projected spin-orbit angle measurements
"warm Jupiters"
Jupiter mass
Saturn mass
"Saturns"
"sub-Saturns"
Neptune mass
"small planets"
Earth mass
planet mass (M_J)
orbital separation, a/R*
10^1
10^0
10^-1
10^-2
0
25
50
75
100
125
150
175

A pile-up of polar-orbiting exoplanets?

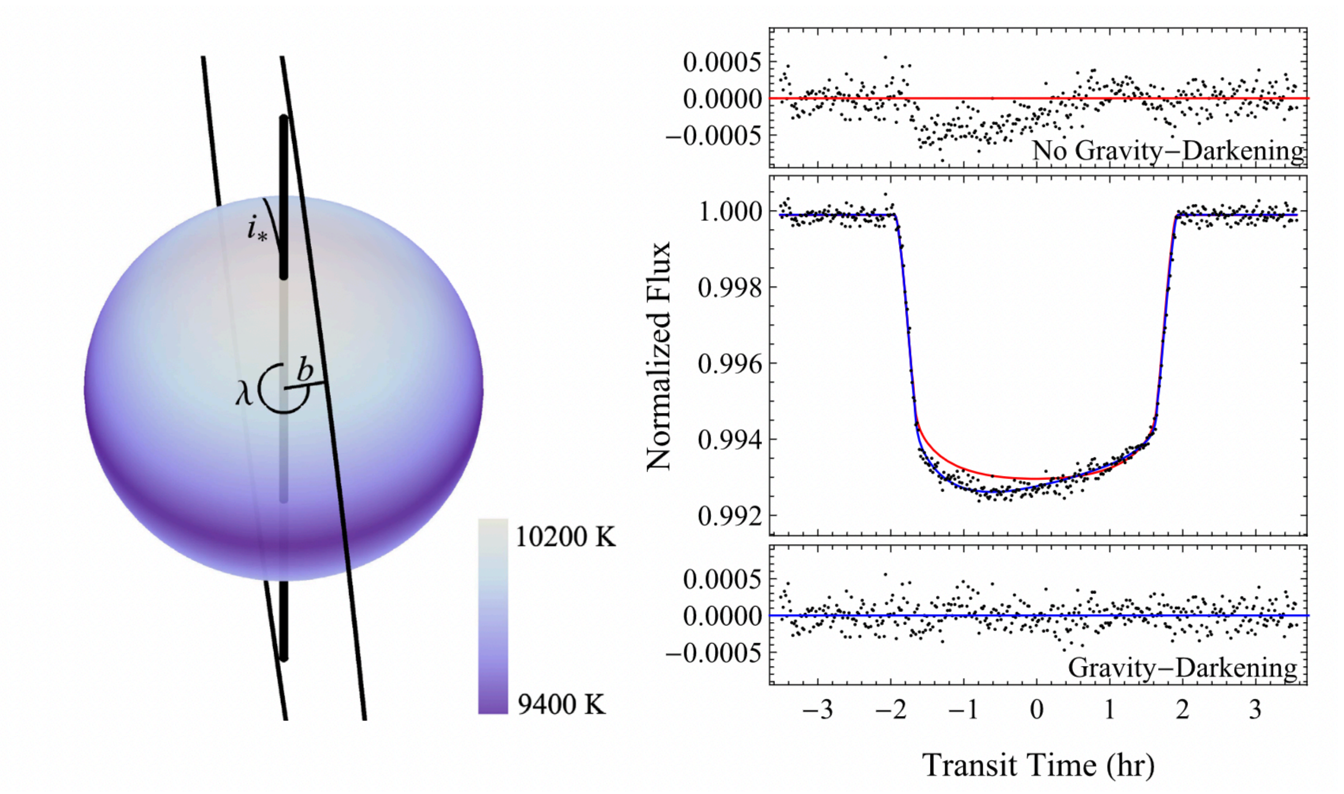


Albrecht, Marcussen, Winn, Dawson, & Knudstrup 2021

A pile-up of polar-orbiting exoplanets?



A gravity darkening profile can be most significantly distinguished from a standard transit profile when a planet is closer to a polar orbit.

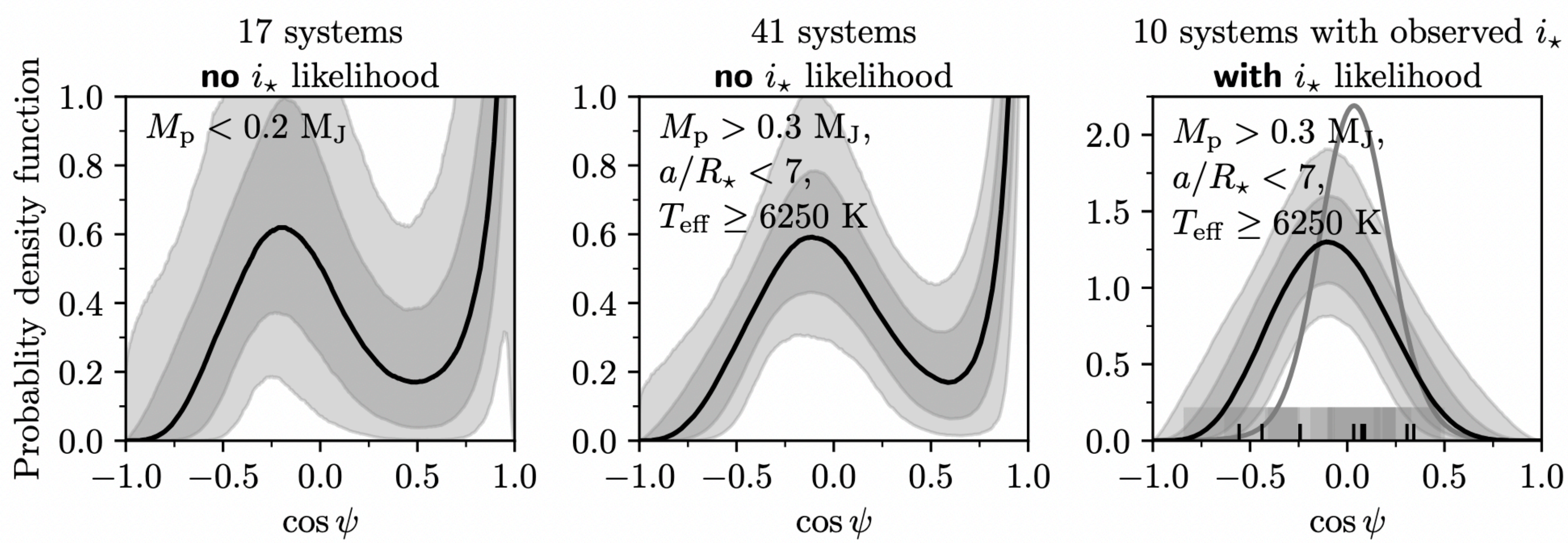


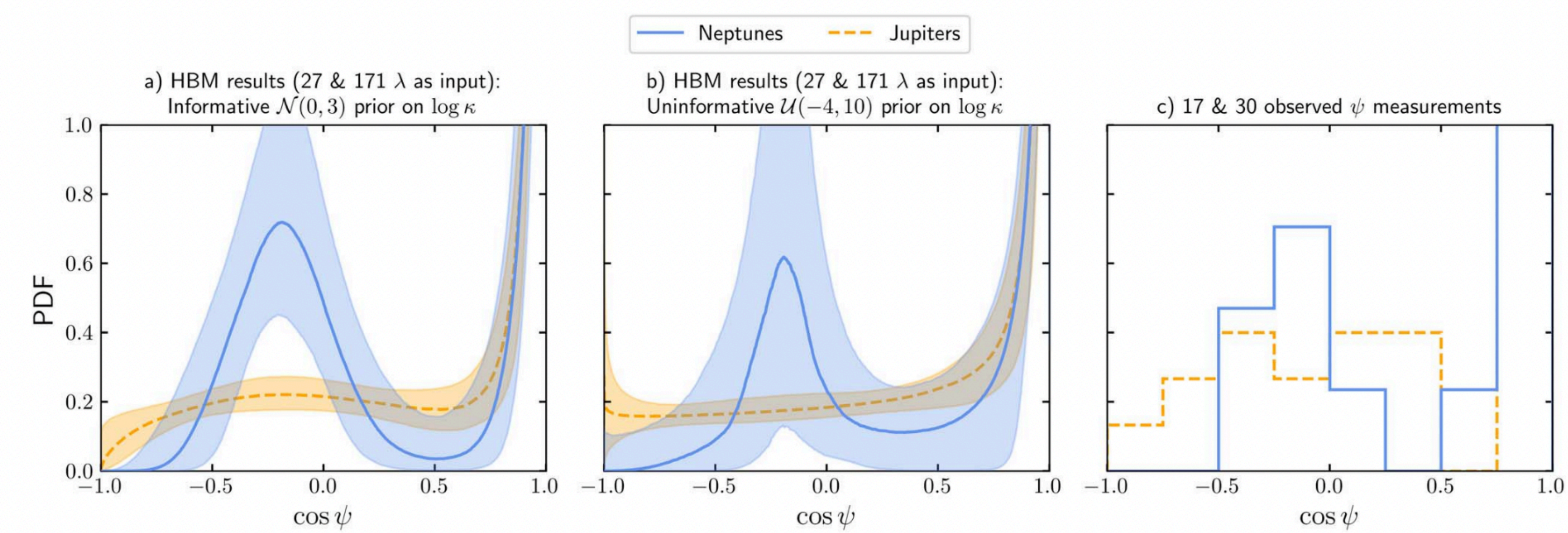
KELT-9 b; Ahlers, Johnson, Stassen, et al. 2020

Siegel, Winn, & Albrecht 2023
See also Section 5, Dong & Foreman-Mackey 2023

A pile-up of polar-orbiting exoplanets?

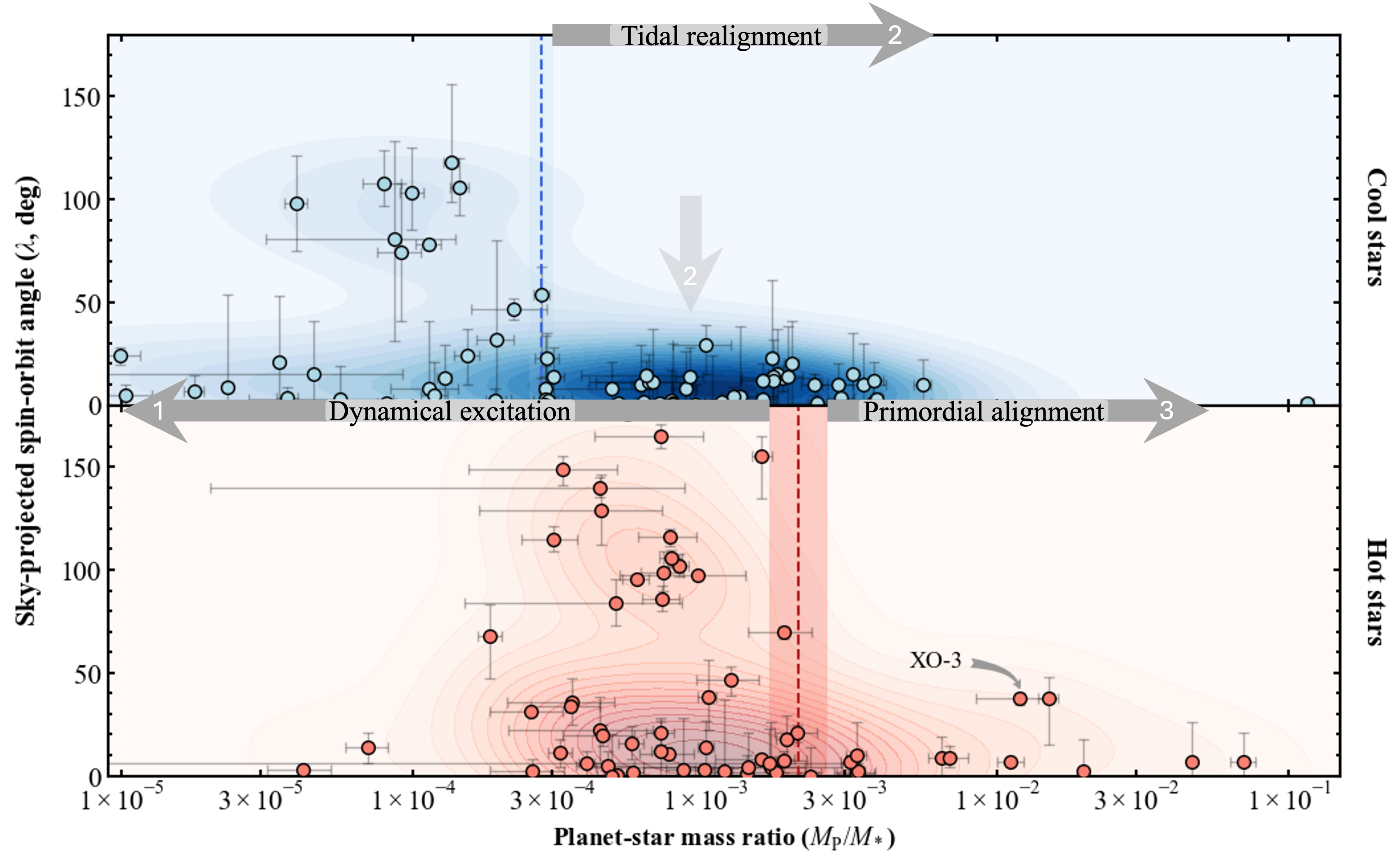
Knudstrup, Albrecht, Winn, et al. 2024





Espinoza-Retamal, Stefánsson, Petrovich, et al. 2024

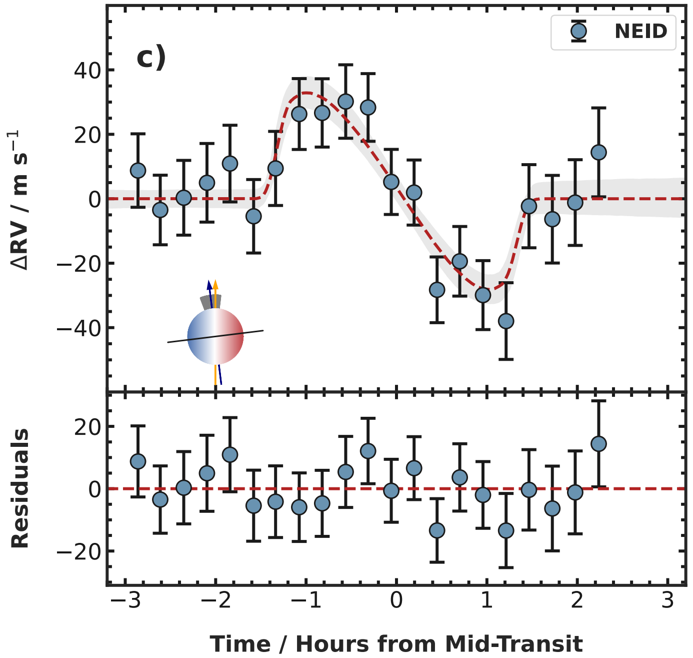
Single-star systems above mass ratio 2×10^{-3}: so far, aligned



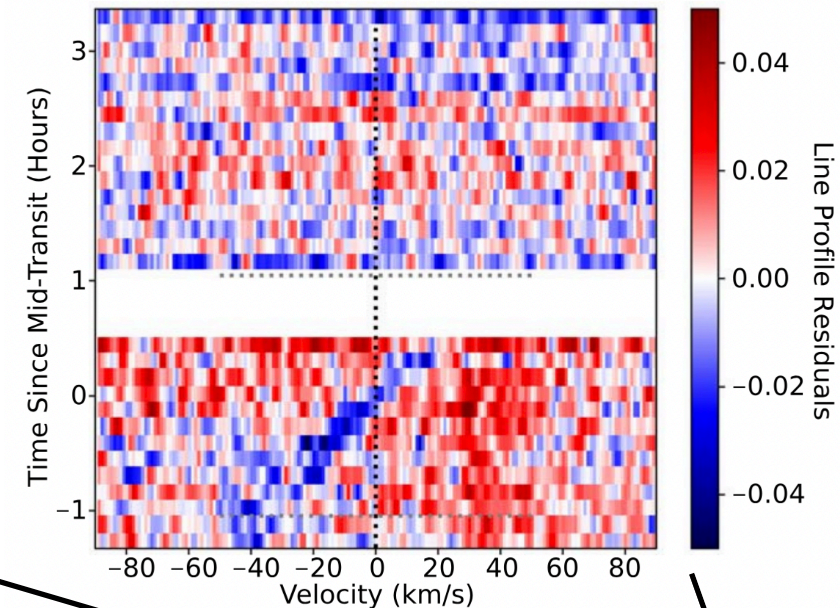
Rusznak, Wang, Rice, & Wang 2025 (in review)

A growing census of spin-orbit measurements for transiting brown dwarfs

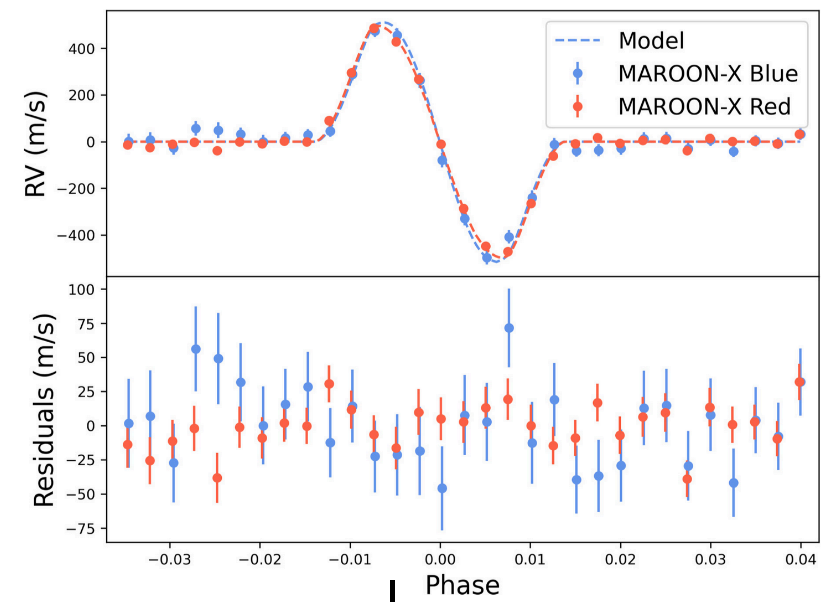
TOI-2533 b
Ferreira, Rice, Wang, & Wang 2024



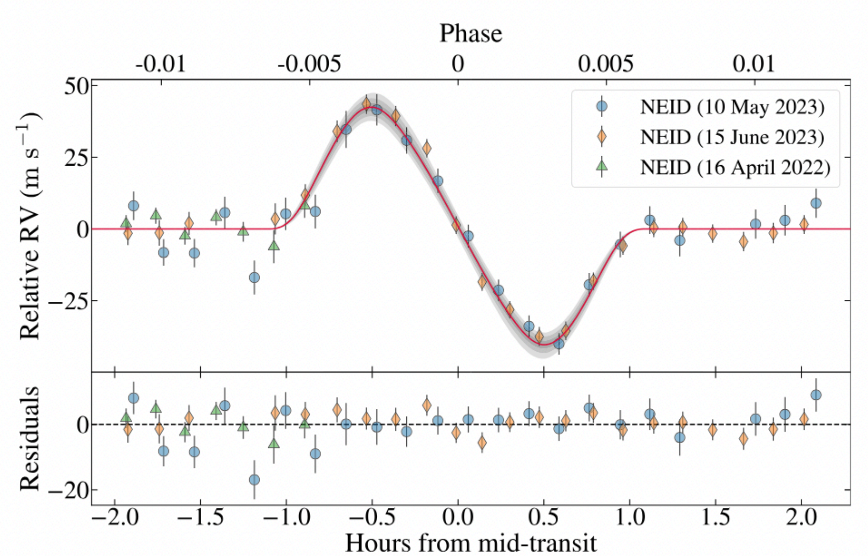
GPX-1 b
Giacalone, Dai, Zanazzi, et al. 2024

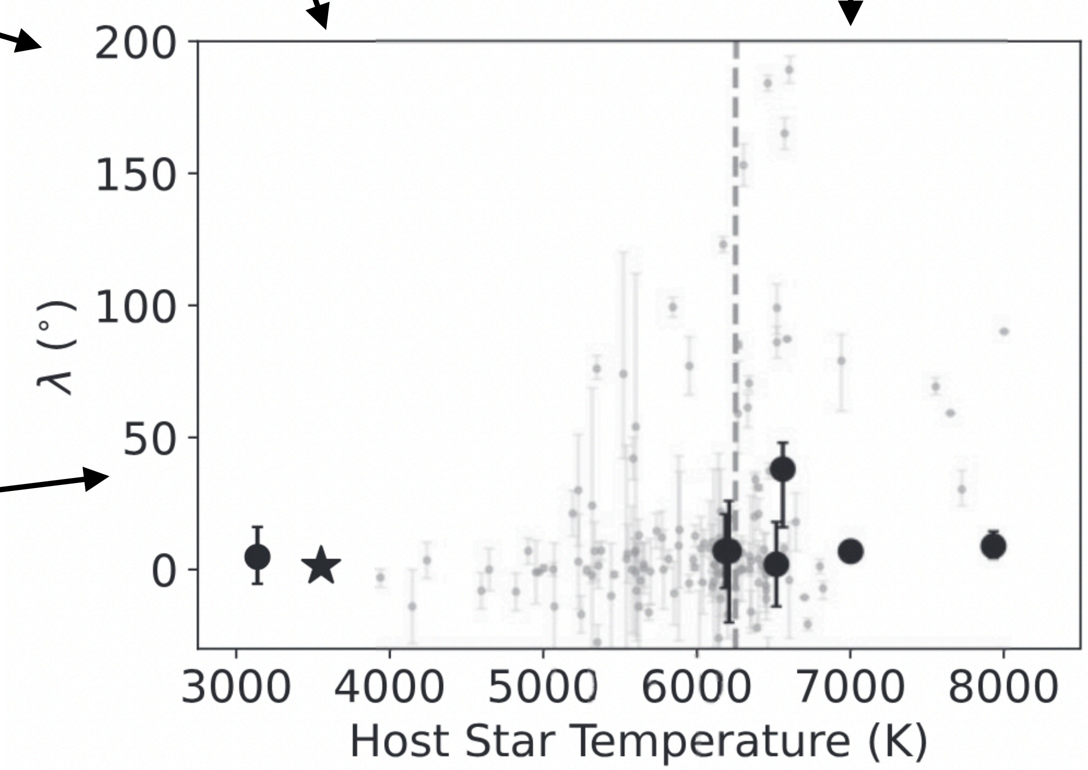


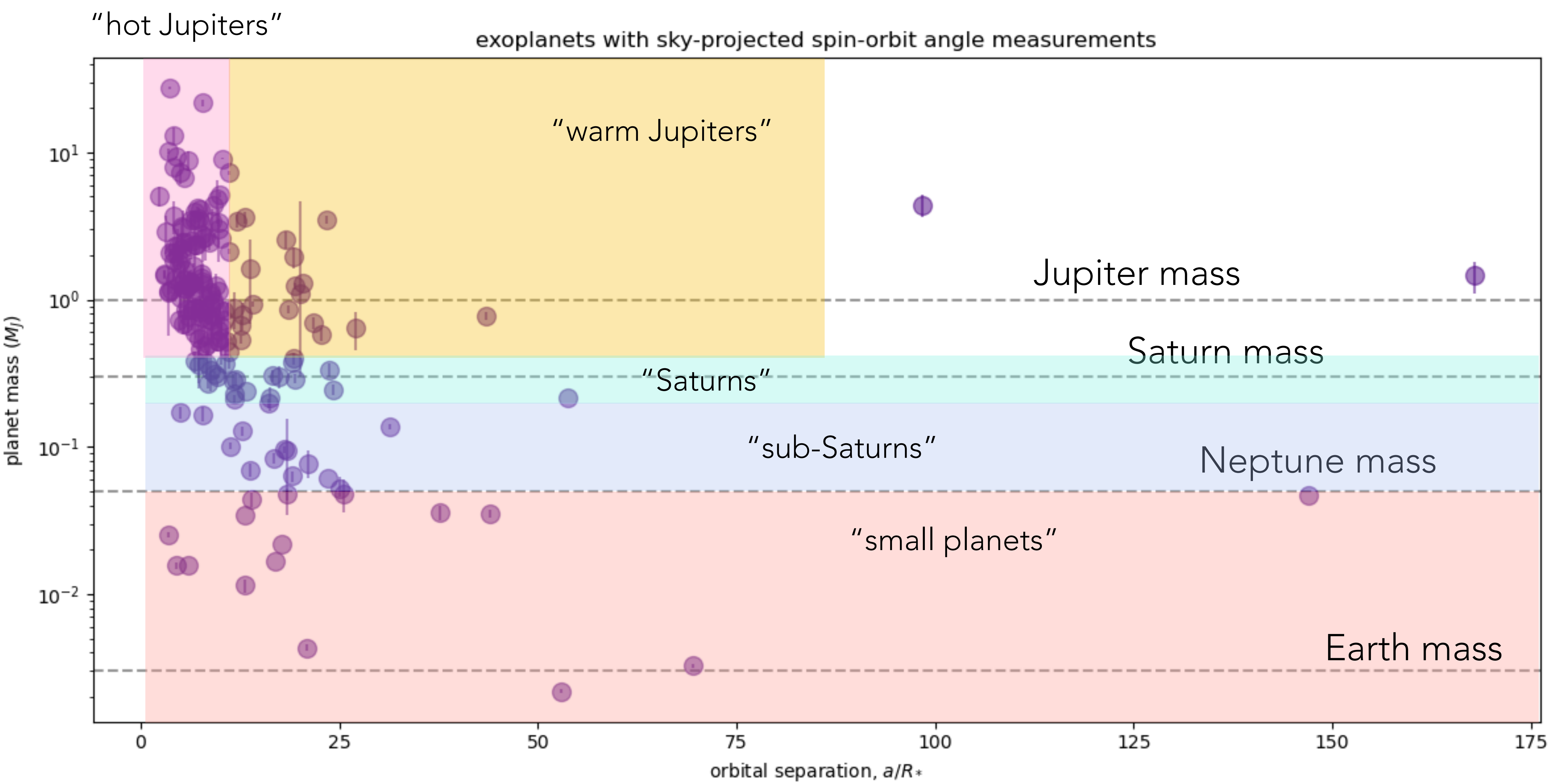
TOI-1779 b
Brady, Bean, Stefánsson, et al. 2025



TOI-2119 b
Doyle, Cañas, Libby-Roberts et al. 2025







"hot Jupiters"
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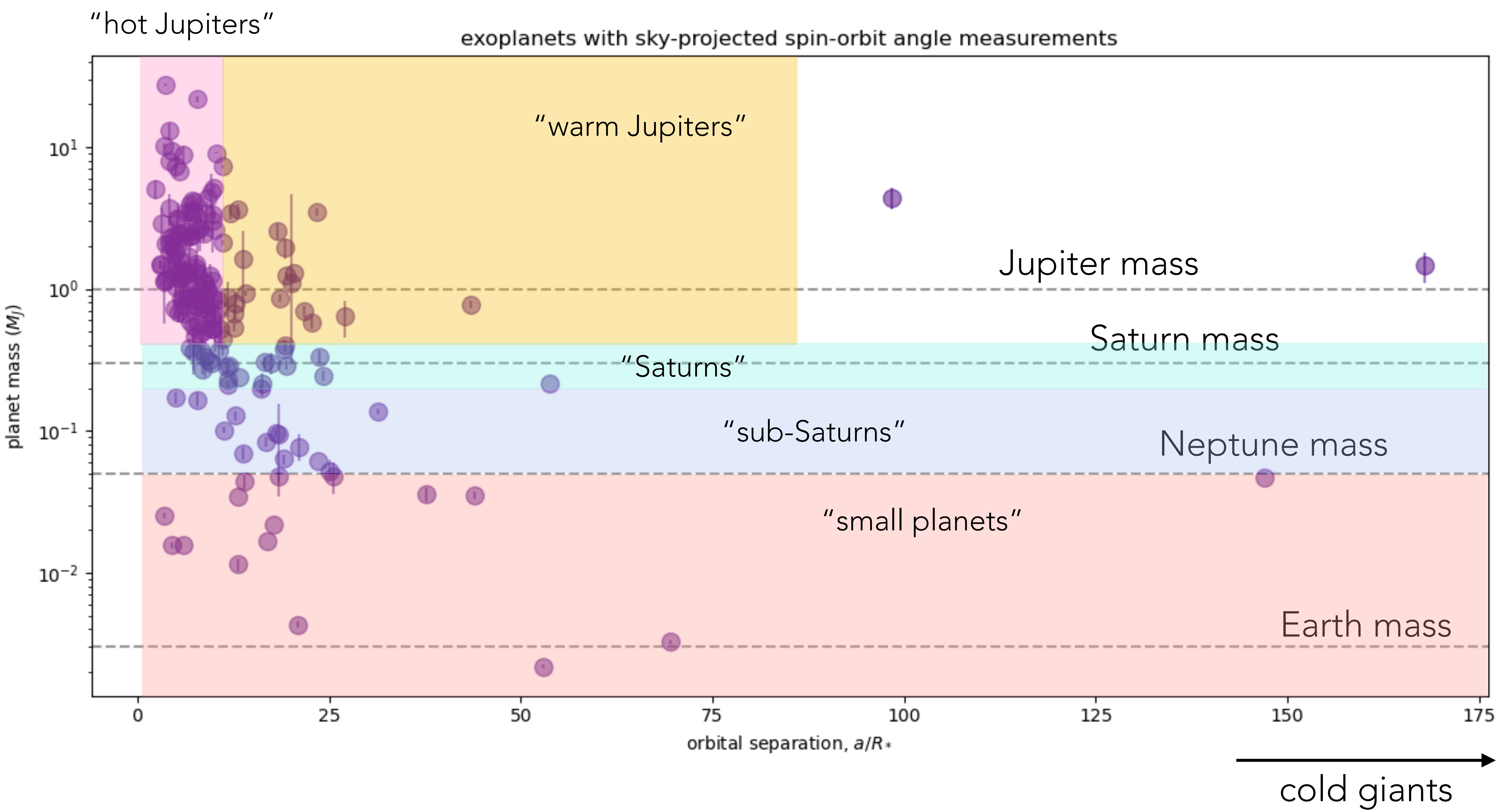
"warm Jupiters"
Jupiter mass
Saturn mass
"Saturns"
"sub-Saturns"
Neptune mass
"small planets"
Earth mass
planet mass (M_J)
orbital separation, a/R_*



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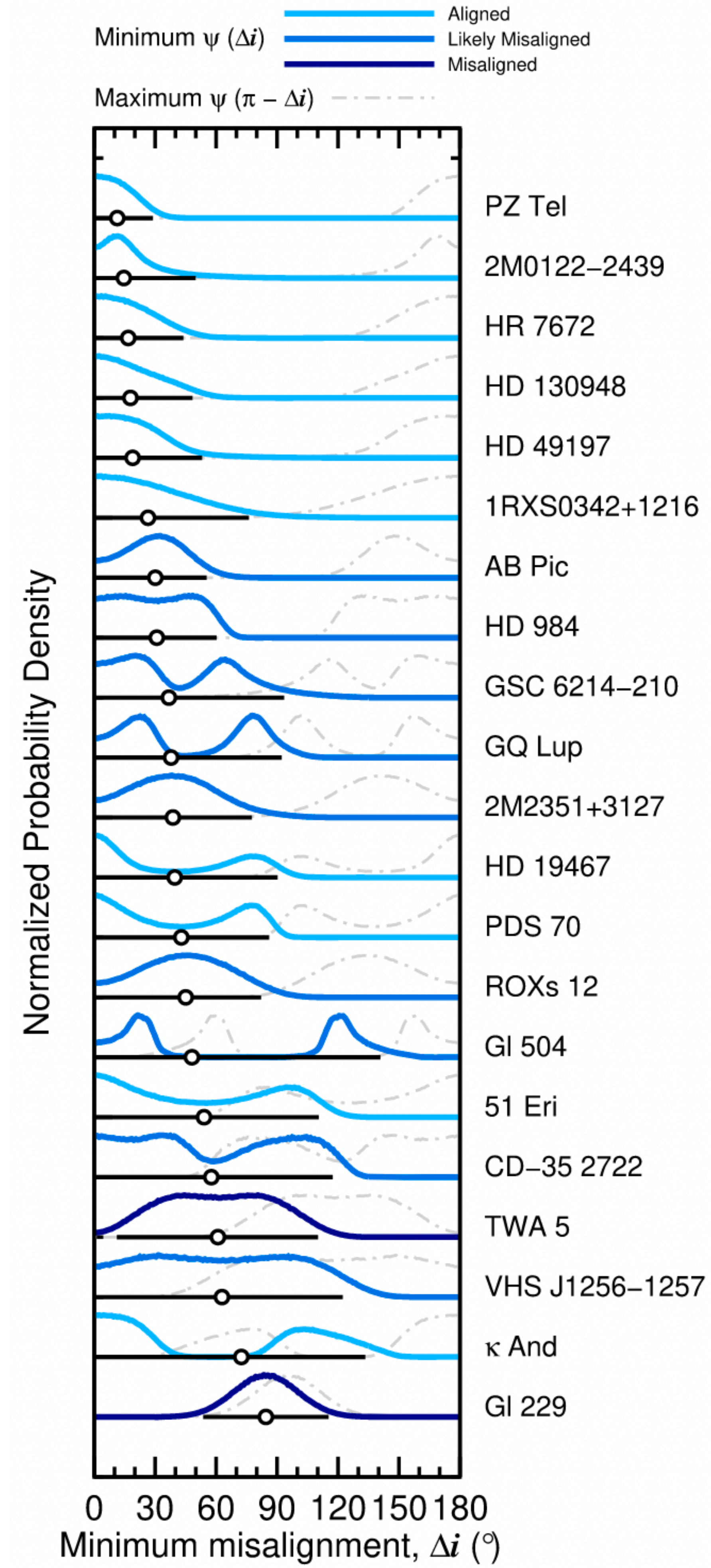
10^1
10^0
10^{-1}
10^{-2}
0
25
50
75
100
125
150
175
orbital separation, a/R_*
cold giants

Observed trends: cold Jupiters (+)

Spin-orbit constraints for directly imaged substellar companions (brown dwarfs and giant planets), combining:

- orbit fitting from astrometry and/or radial velocity data
- spectroscopic vsini constraints
- photometric starspot constraints



Bowler, Tran, Zhang, et al. 2023

Observed trends: cold Jupiters (+)

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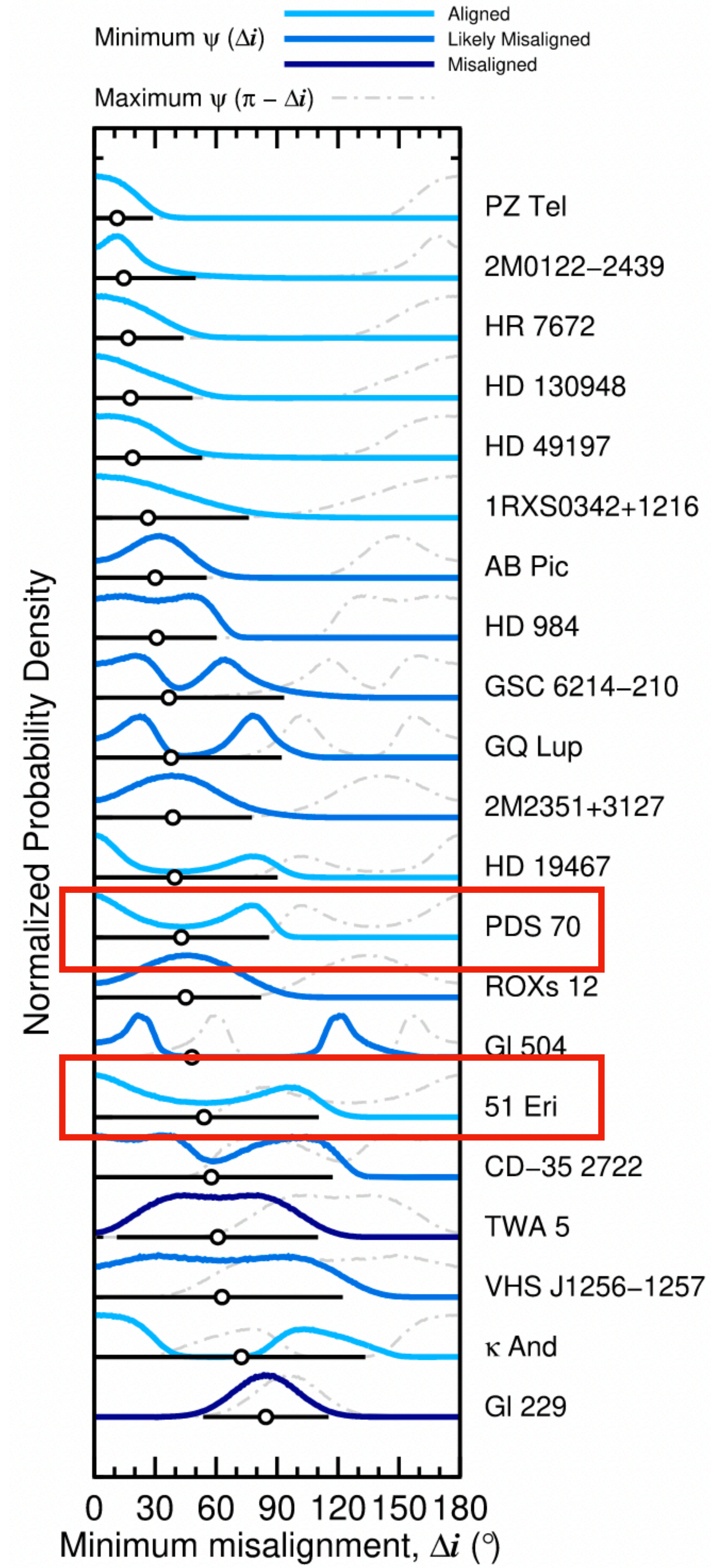
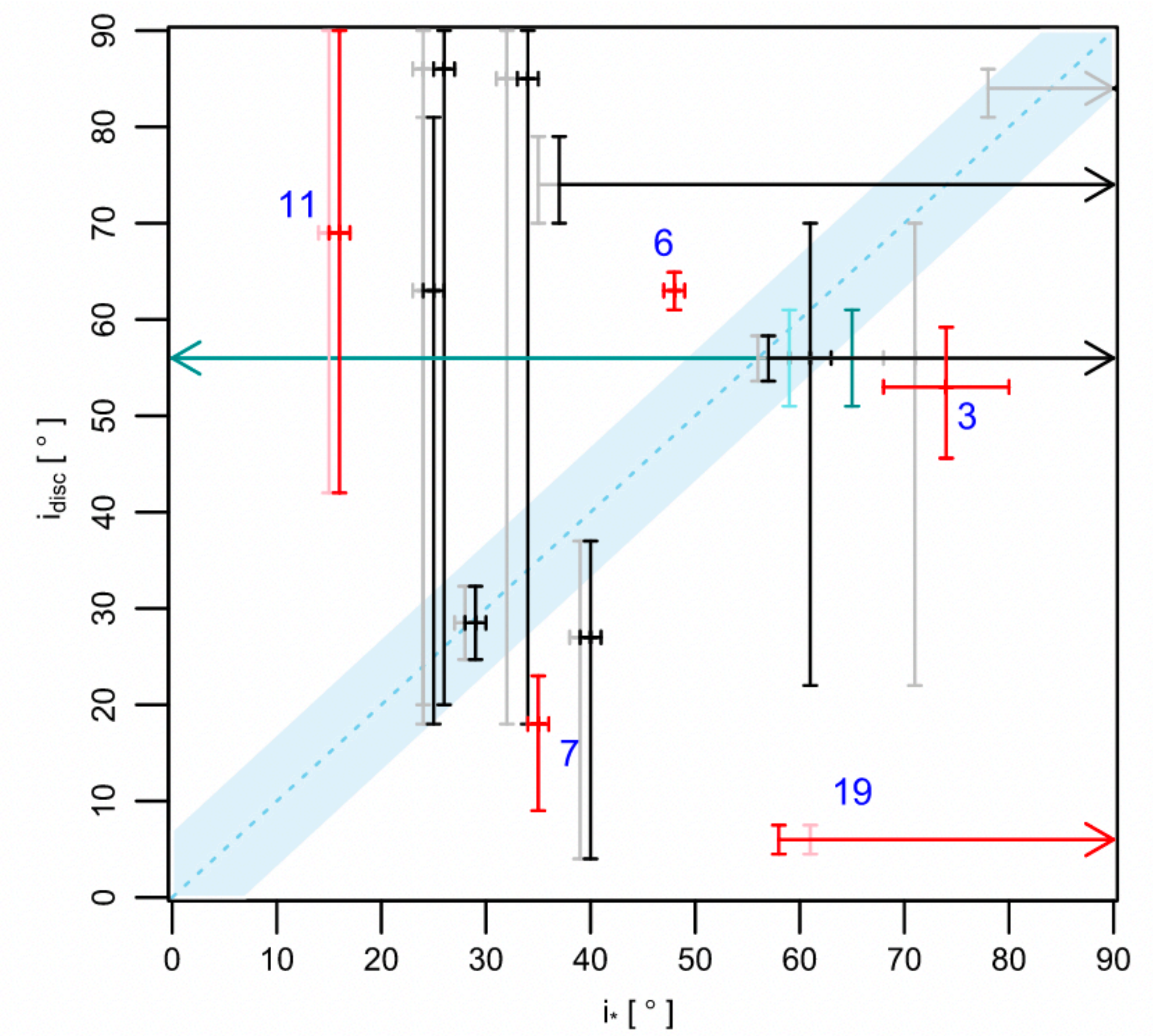


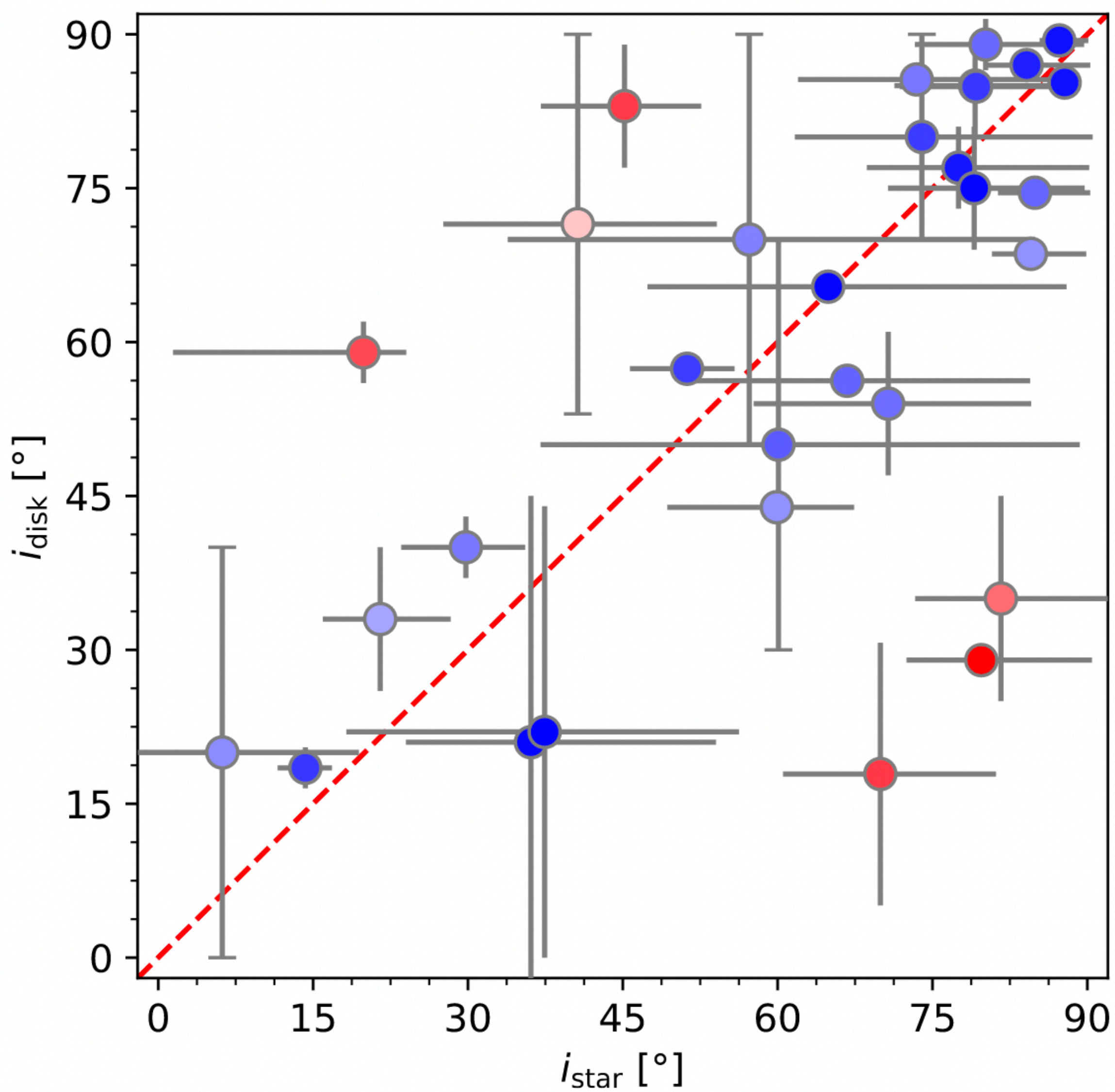
Bowler, Tran, Zhang, et al. 2023

Insights from disk inclinations

protoplanetary disks



debris disks

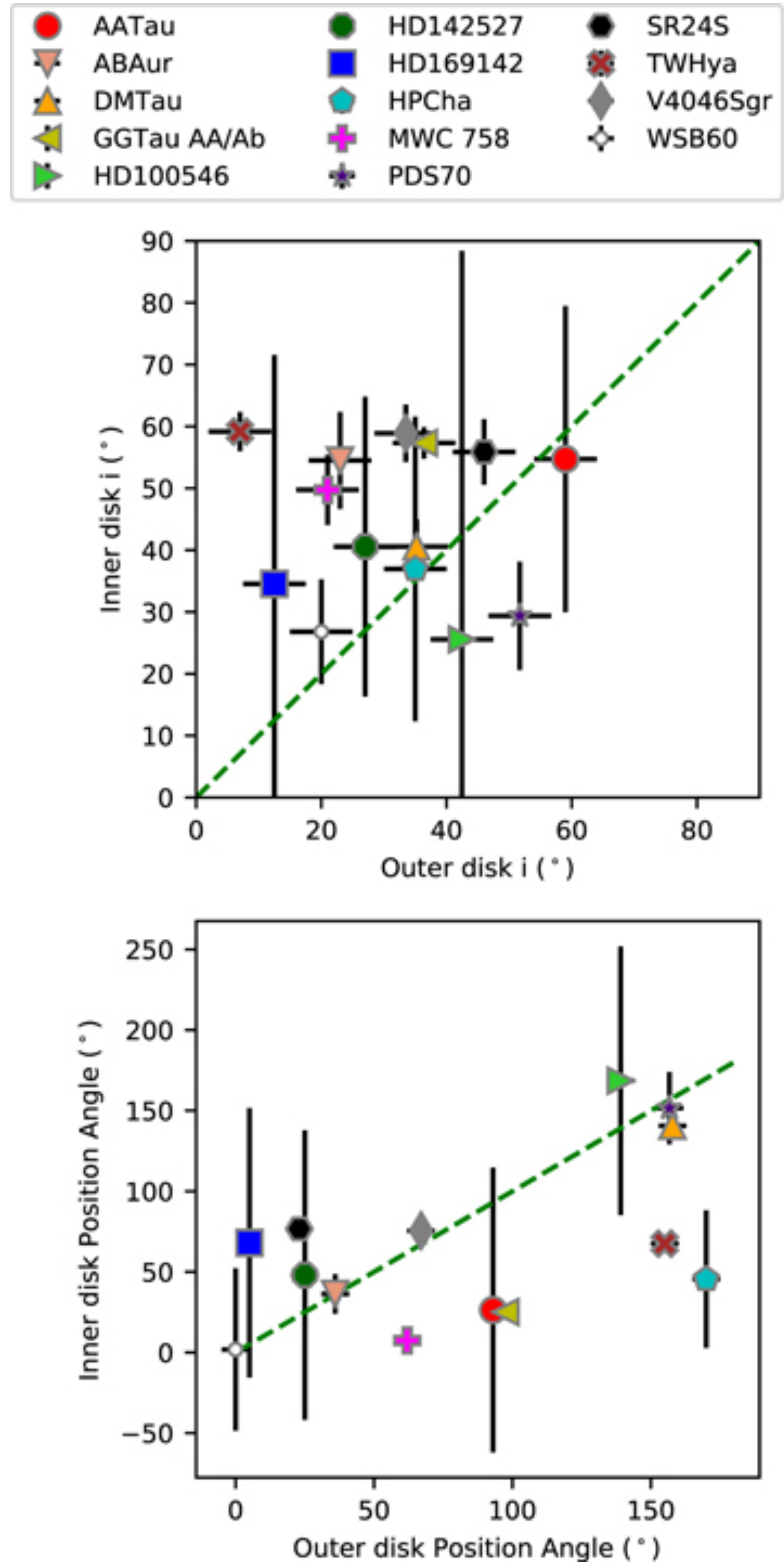


Davies 2019

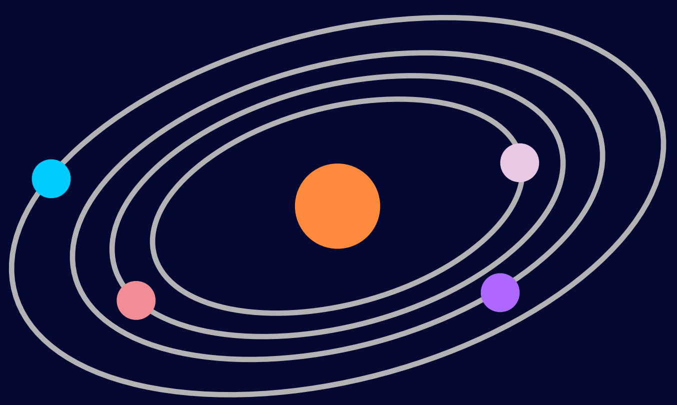
Hurt & MacGregor 2023

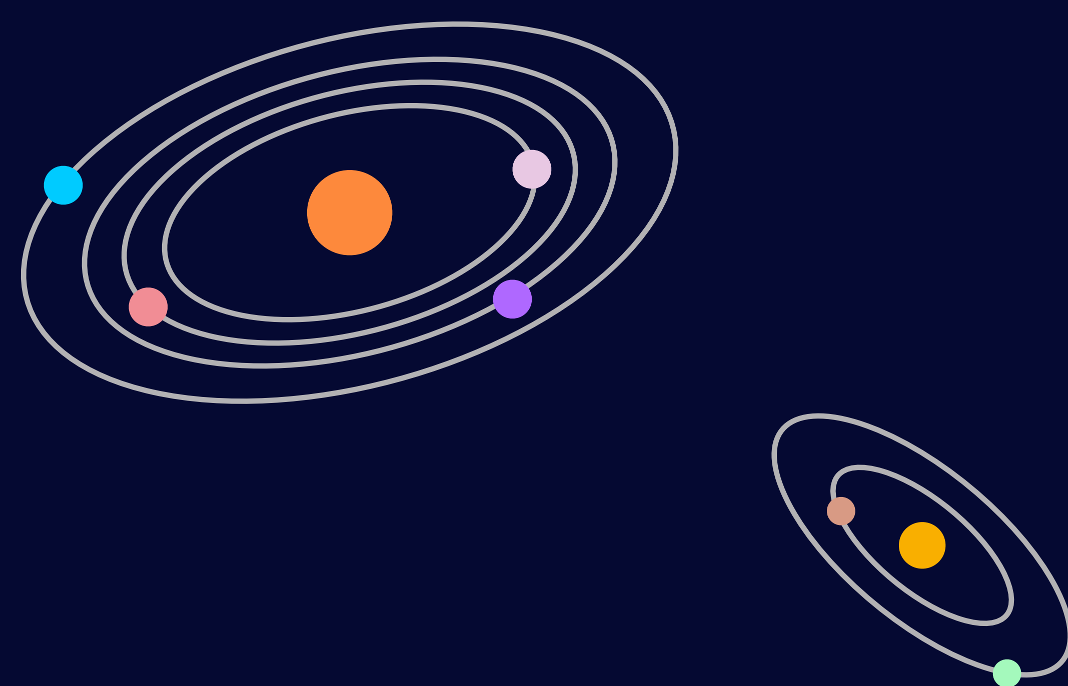
Insights from disk inclinations

Protoplanetary disks with multiple components: indications that inner and outer disk are sometimes misaligned

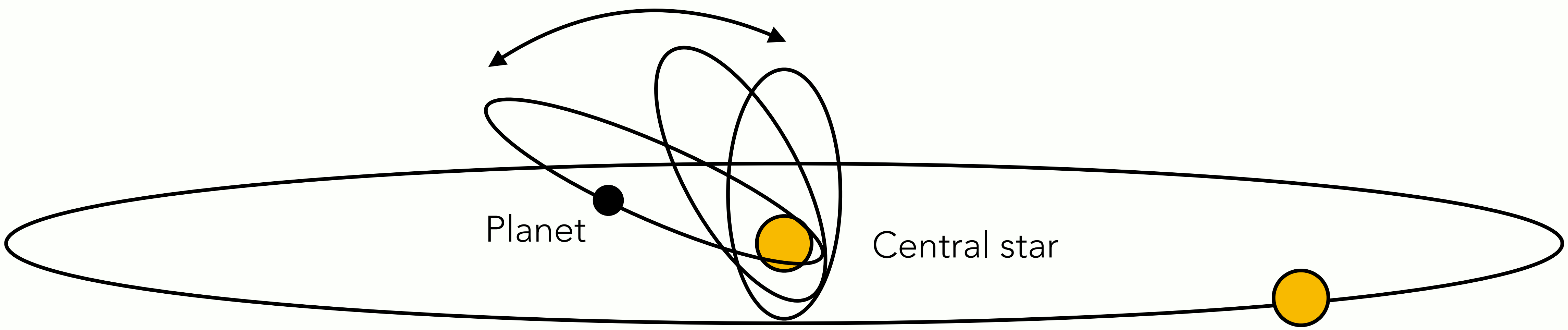


Francis & van der Marel 2020



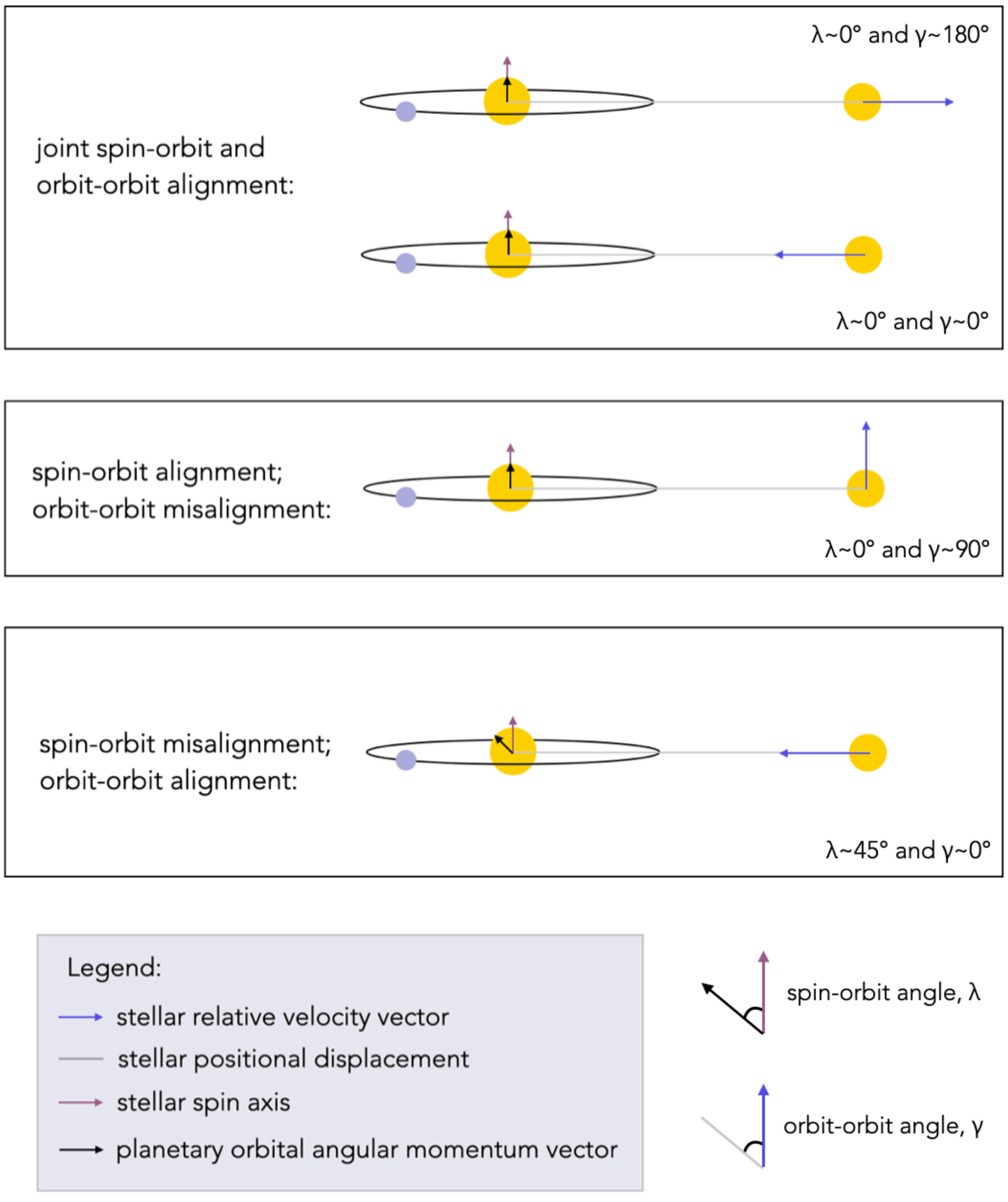


The von Zeipel-Lidov-Kozai (ZLK) mechanism: secular dynamics as an avenue to misalign planetary systems



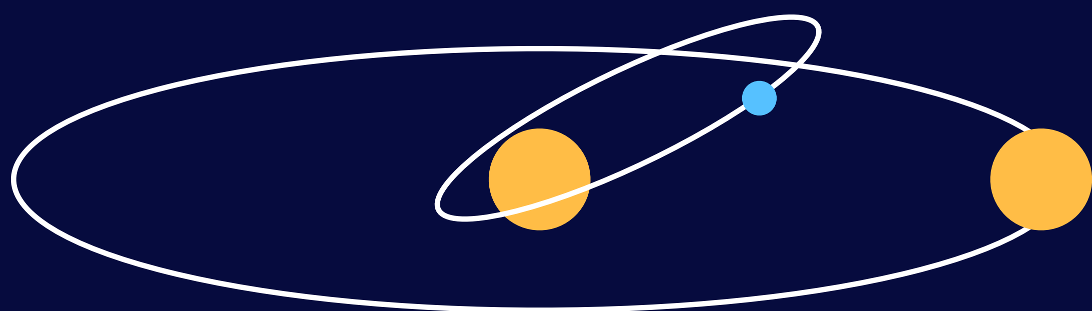
see e.g.
Wu & Murray 2003
Fabrycky & Tremaine 2007
Naoz et al. 2011
Naoz et al. 2012

Spin-orbit and orbit-orbit configurations in binary exoplanet-hosting systems



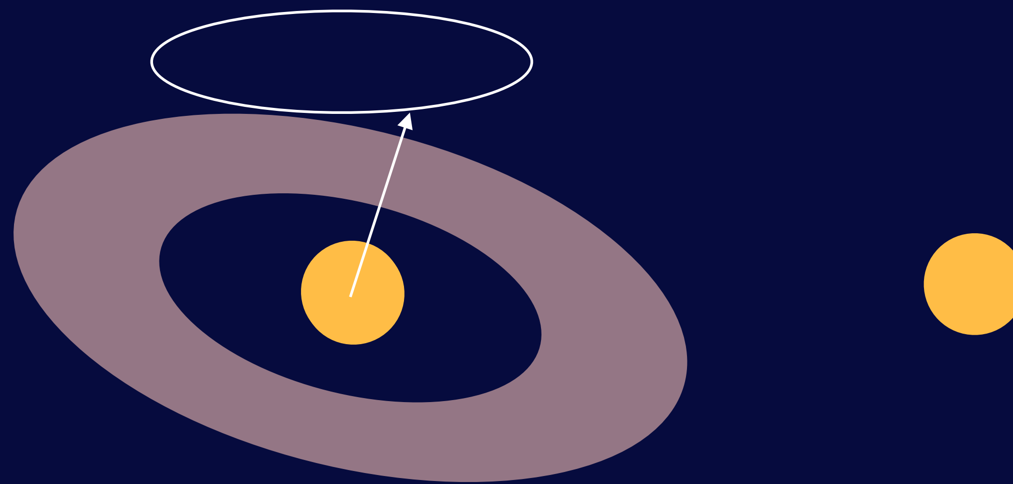
Rice, Gerbig, & Vanderburg 2024
Gerbig, Rice, Zanazzi ,et al. 2024

ZLK oscillations



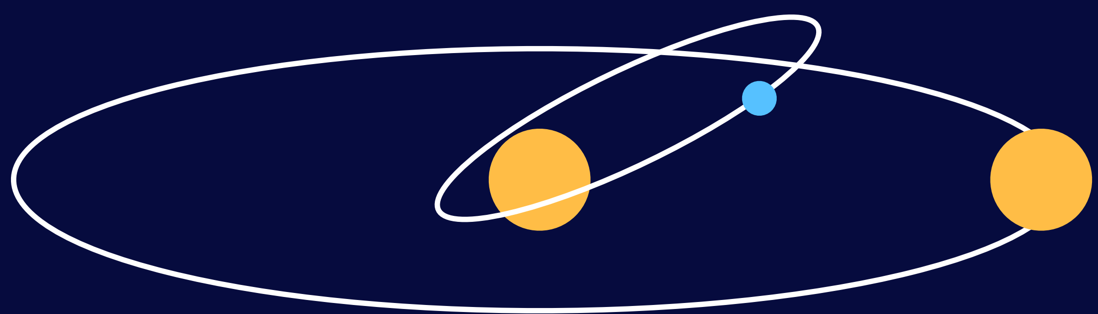
outcome: misalignment

Nodal recession +
dissipative precession



outcome: alignment

ZLK oscillations



outcome: misalignment

Nodal recession +
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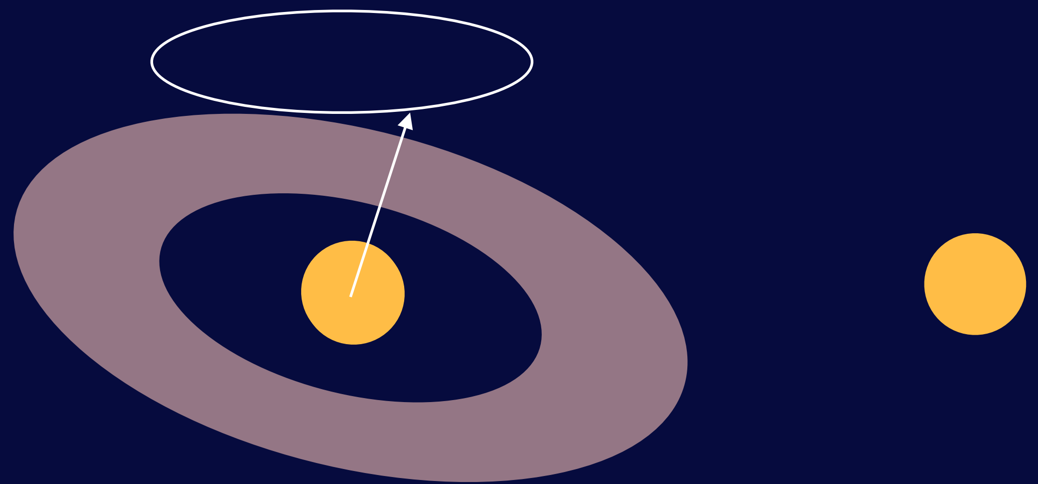


outcome: alignment

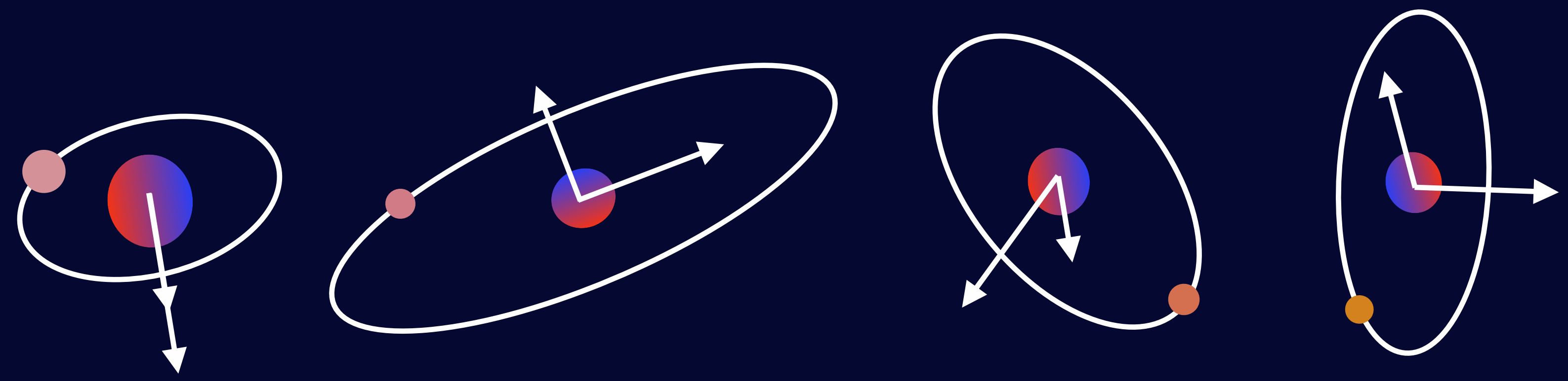
Toward clearer interpretations of the stellar obliquity distribution

Important factors to consider:

- Stellar type/temperature
- Orbital eccentricity
- Planet mass
- Planet-star separation
- Potential influences from stellar companions
- Potential influences from planetary companions
- System age

These parameters must be considered *jointly.*

Takeaways



We have constraints on spin-orbit orientations for hundreds of exoplanet orbits to date, and 3D orientations for several dozen. We don't generally know stellar obliquities.

In single-star systems, evidence suggests that inner protoplanetary disks are generally aligned with the stellar host's spin axis. Misalignments arise afterward, from post-disk dynamical evolution.

In binary star systems, spin-orbit misalignments can be excited through a broader range of mechanisms, including ZLK oscillations and dissipative precession.

While the census of spin-orbit measurements is generally biased toward hot Jupiters, it is rapidly expanding to new regimes of exoplanet and brown dwarf properties.