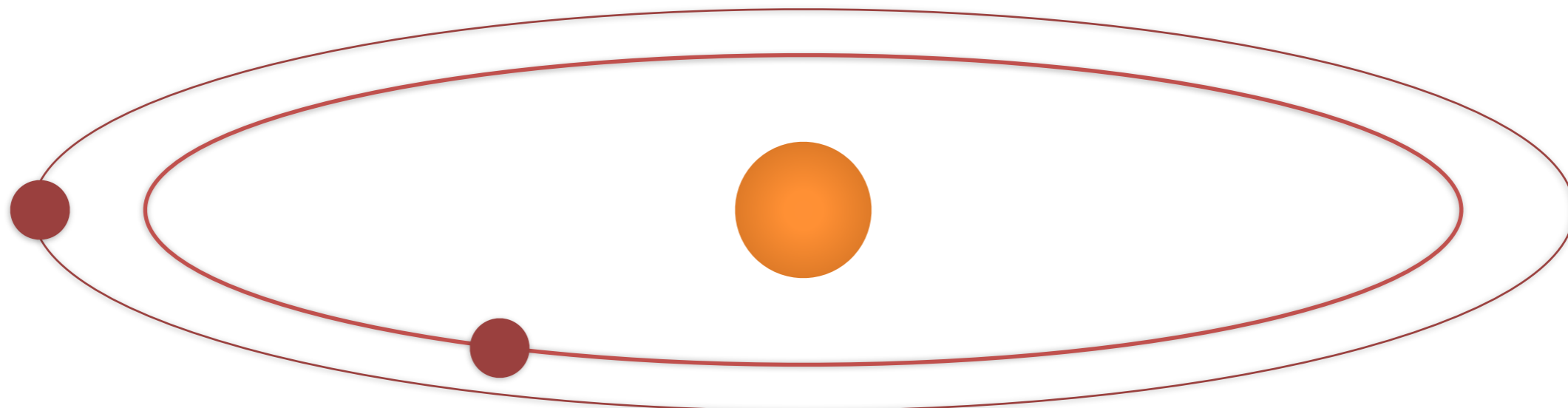
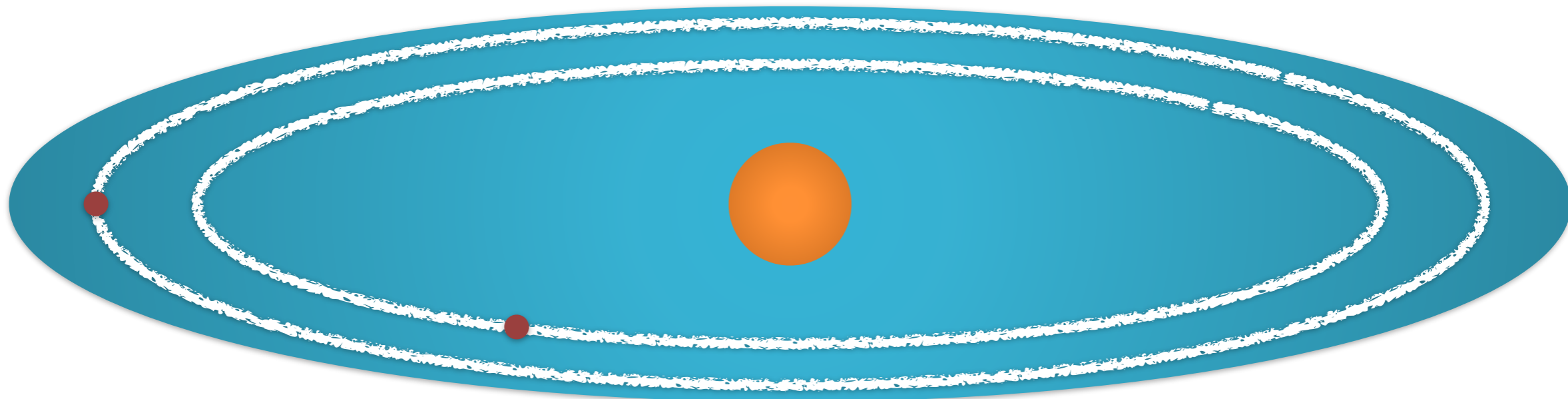
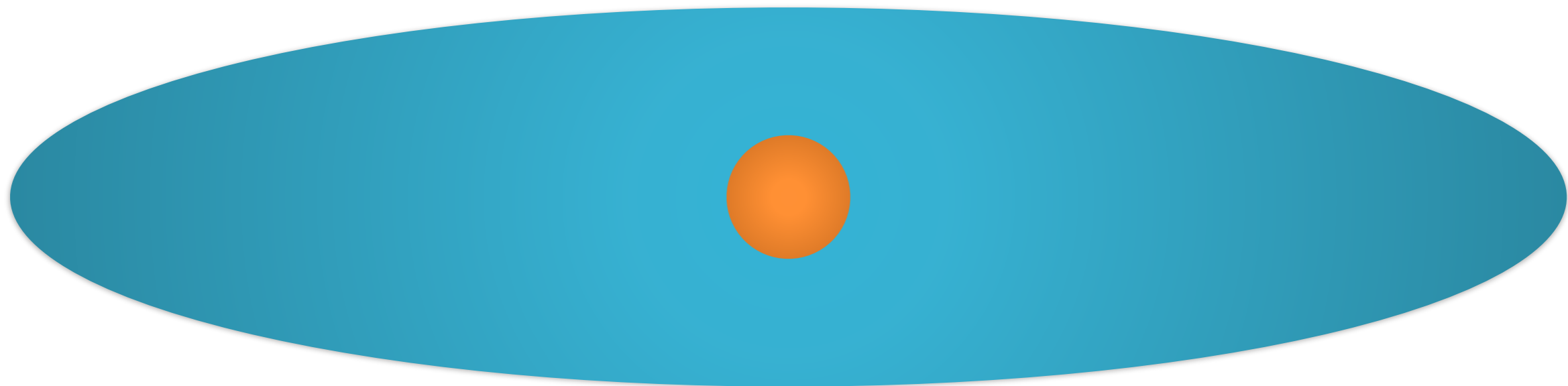
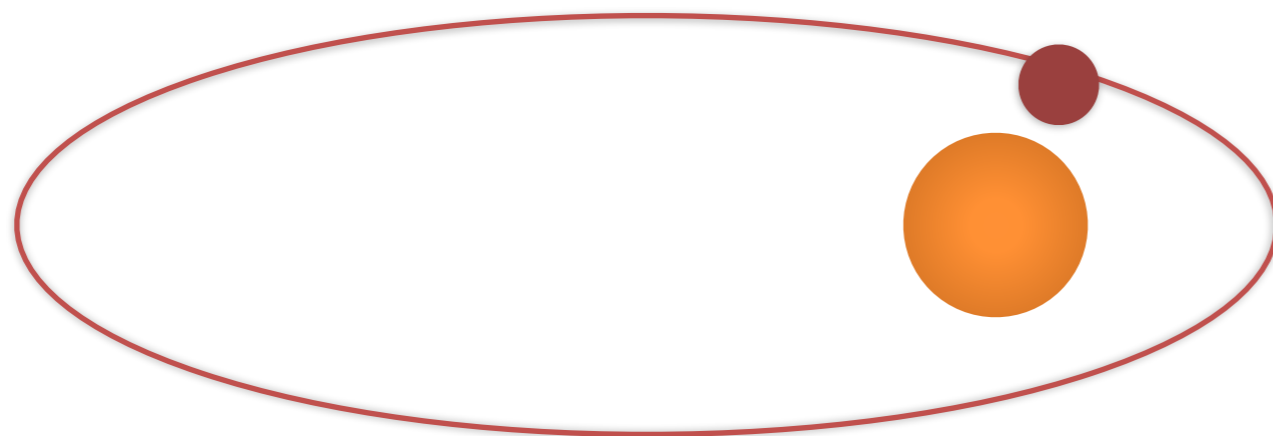
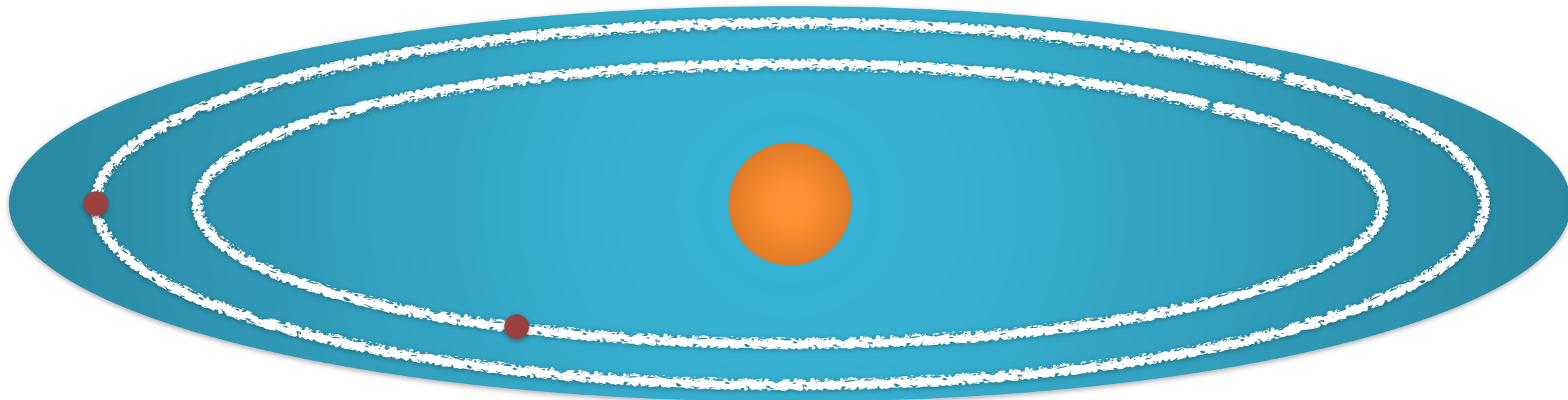
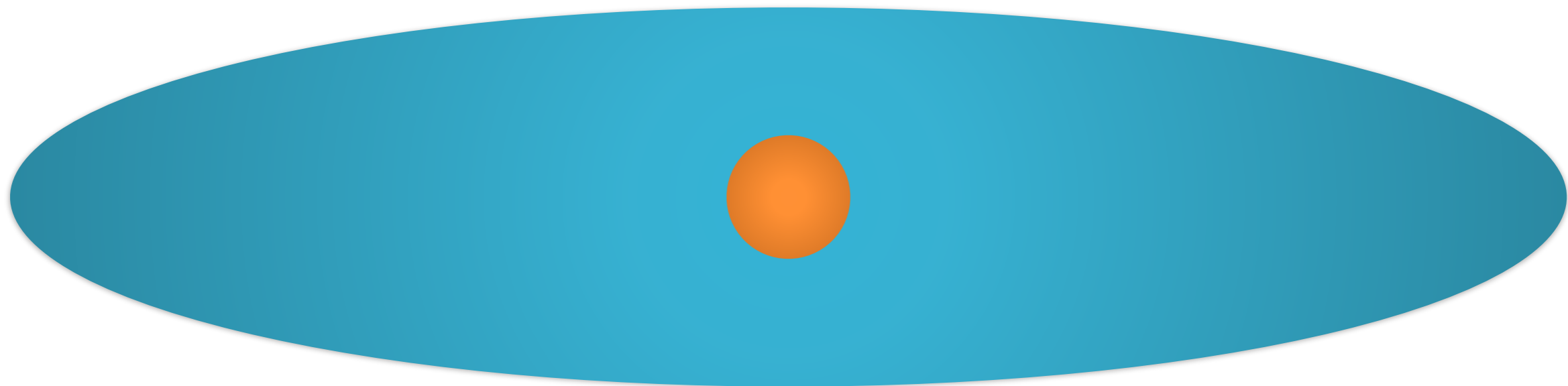
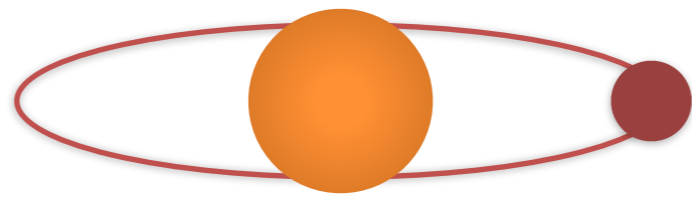
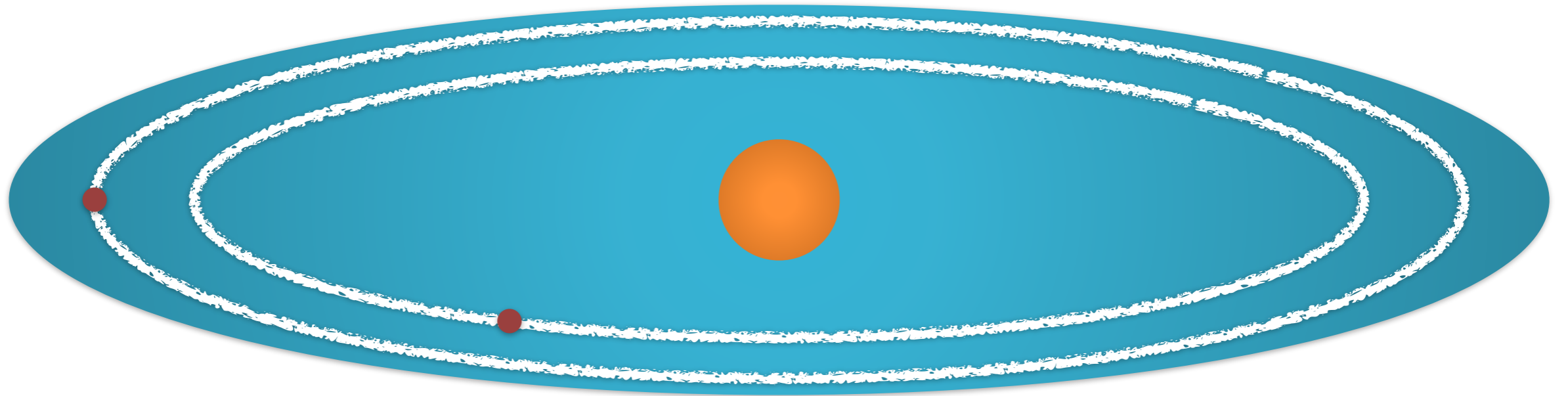
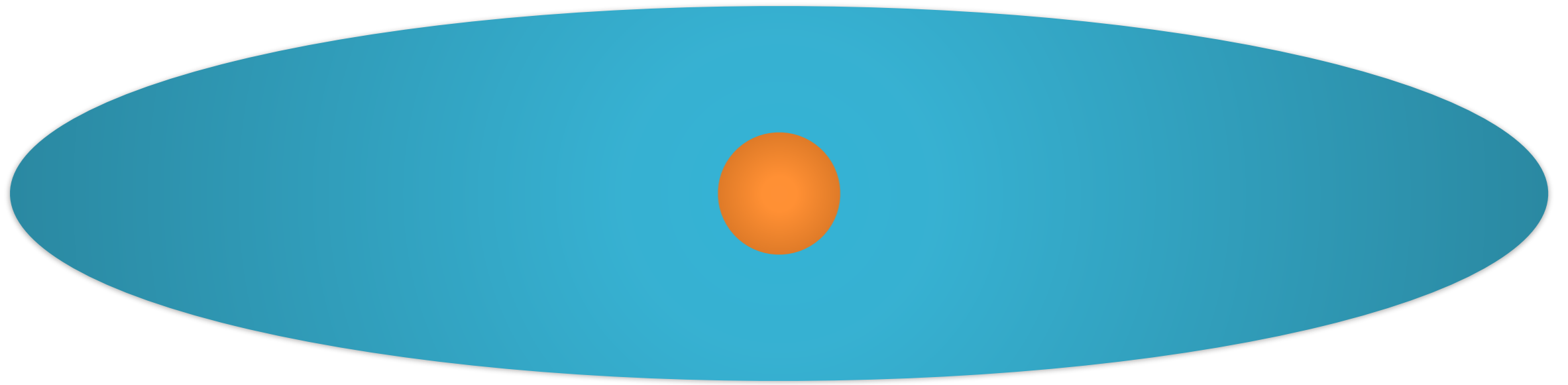


Tracing the origins of planets via their obliquities

George Zhou
Tatranská Lomnica







Gas Giants

Neptunes

Rocky

0.4 AU

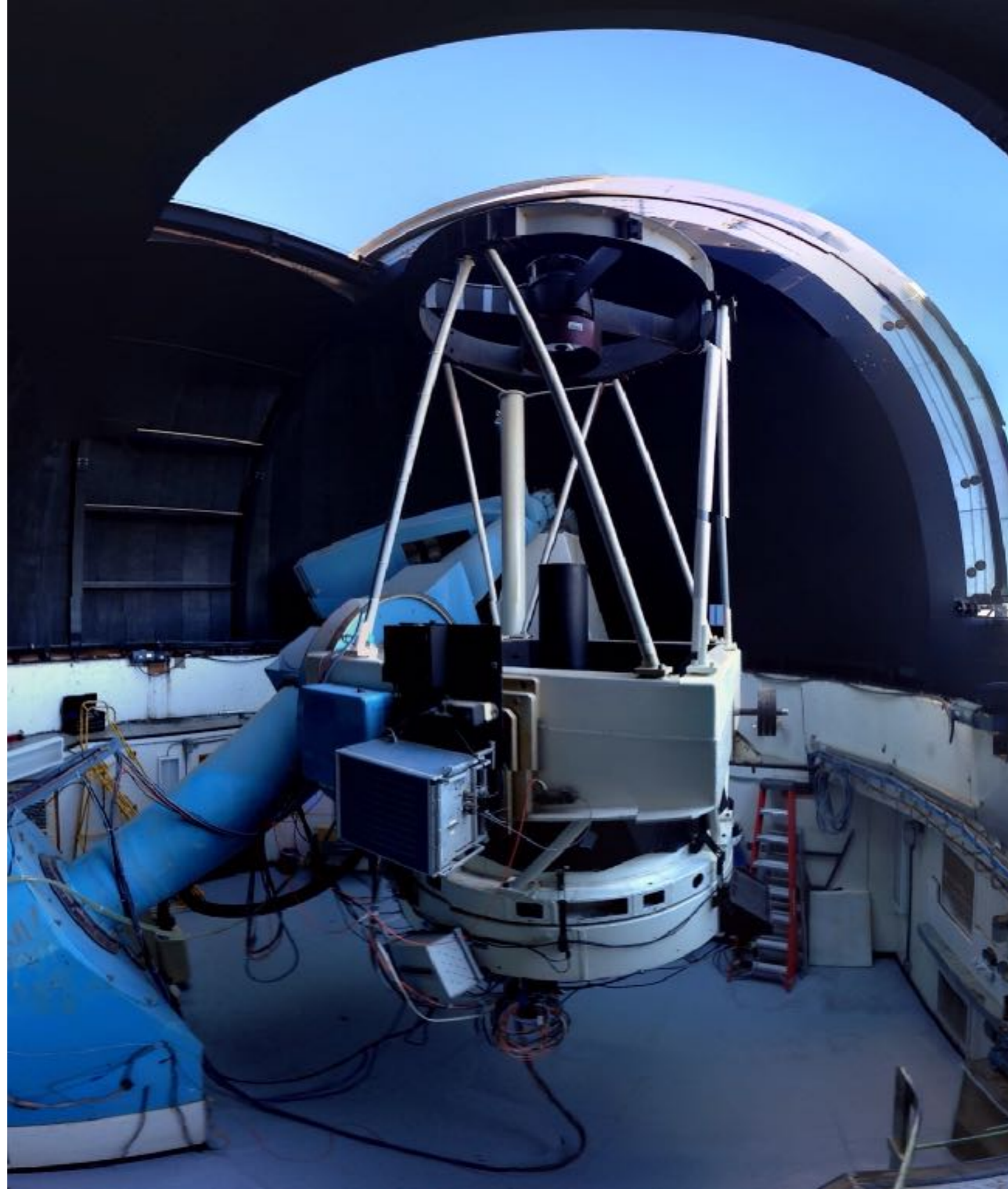
**Tillinghast Reflector
Echelle Spectrograph
(TRES)**

FLWO, Arizona, US

R=44000

3850-9100A

over 51 echelle orders



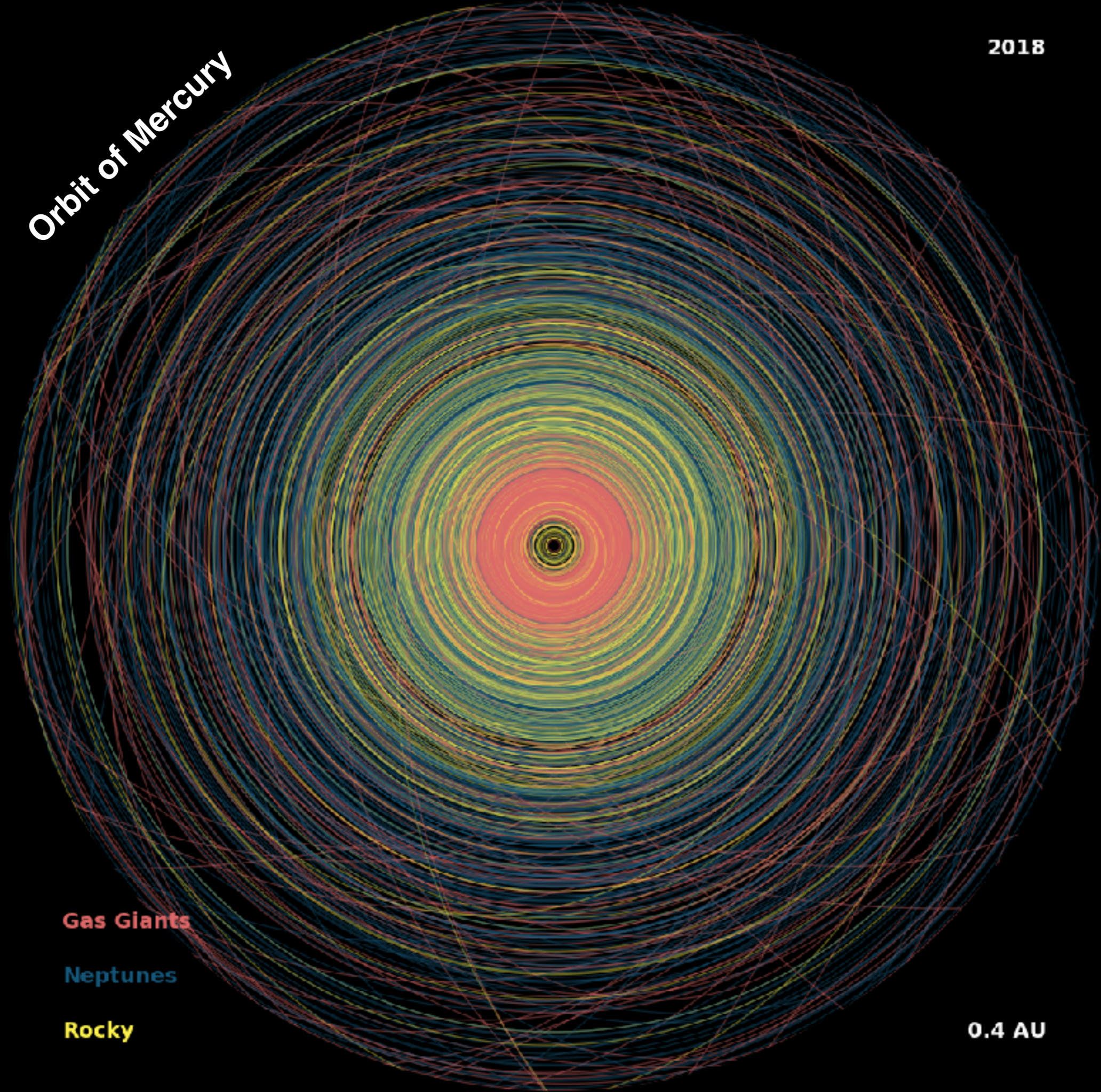
TRES observations since 2011

Project	Observations	Targets
HATNet	3350	1422
KELT	2863	1103
Qatar	2285	858
Kepler	6822	2385
K2	2263	745

Same story with CORALIE, FEROS, FIES, CHIRON, and many others

2018

Orbit of Mercury



Gas Giants

Neptunes

Rocky

0.4 AU

2018

Orbit of Mercury

Hot Jupiters

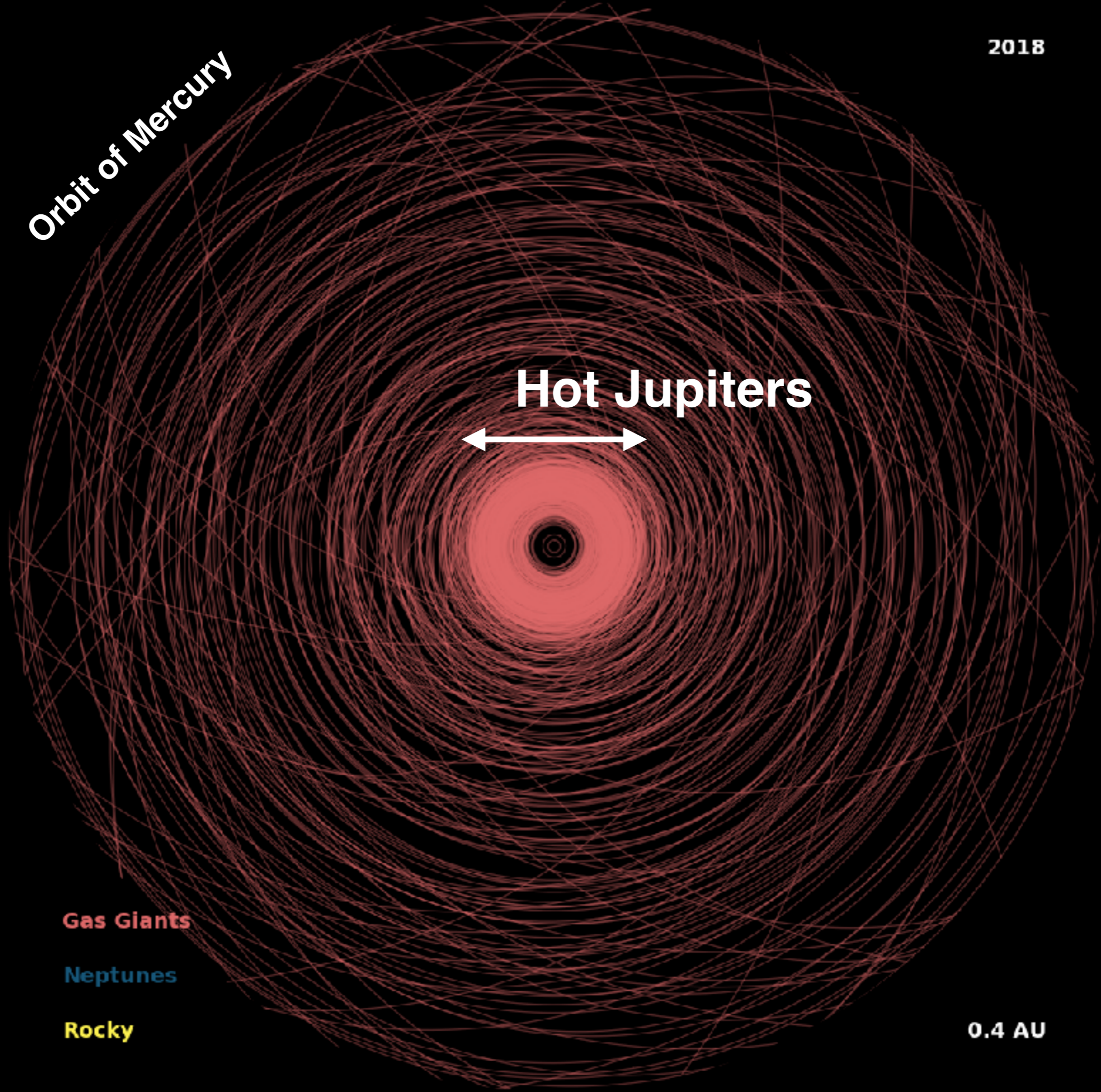


Gas Giants

Neptunes

Rocky

0.4 AU



2018

Orbit of Mercury

Warm Jupiters

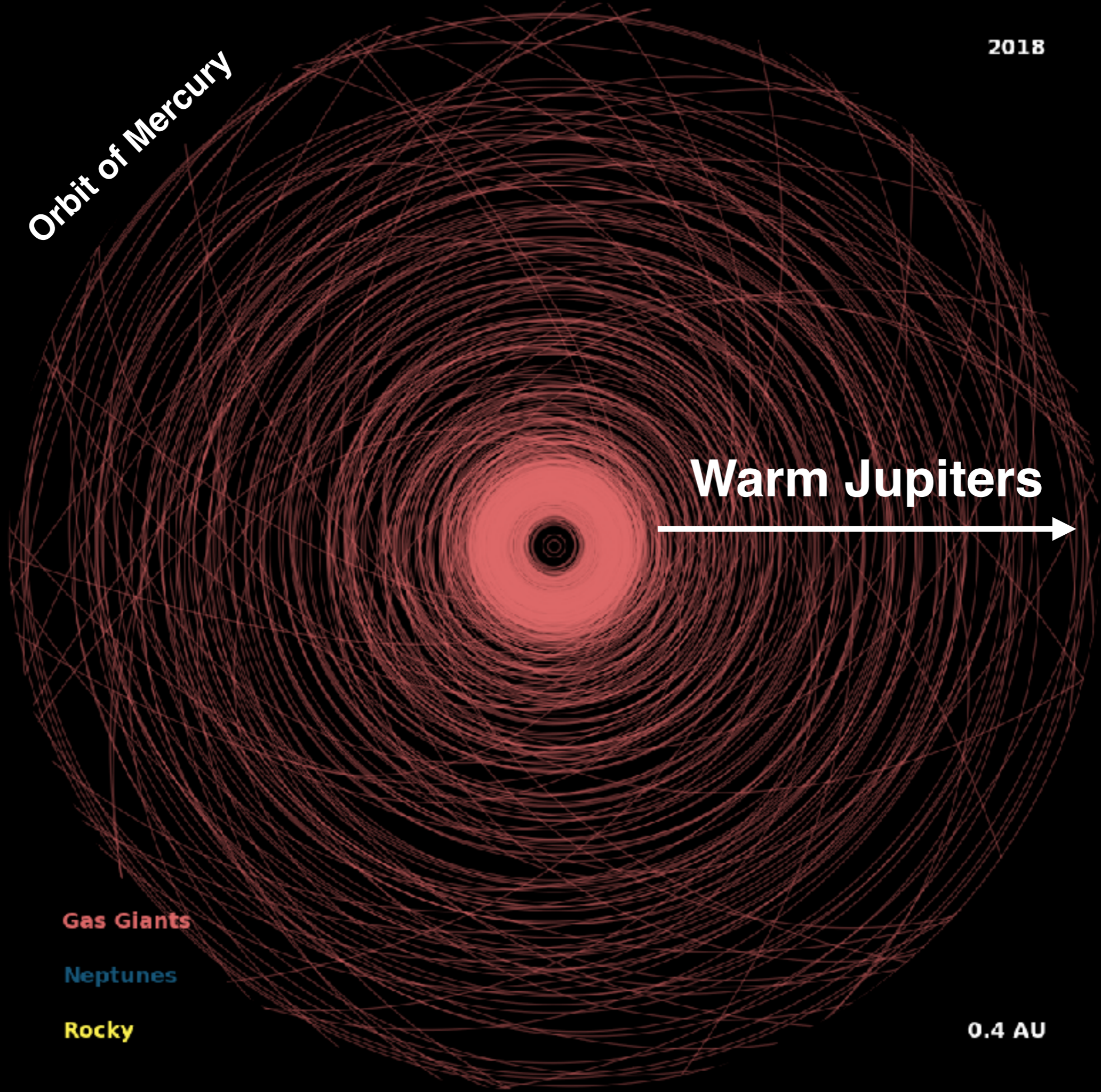


Gas Giants

Neptunes

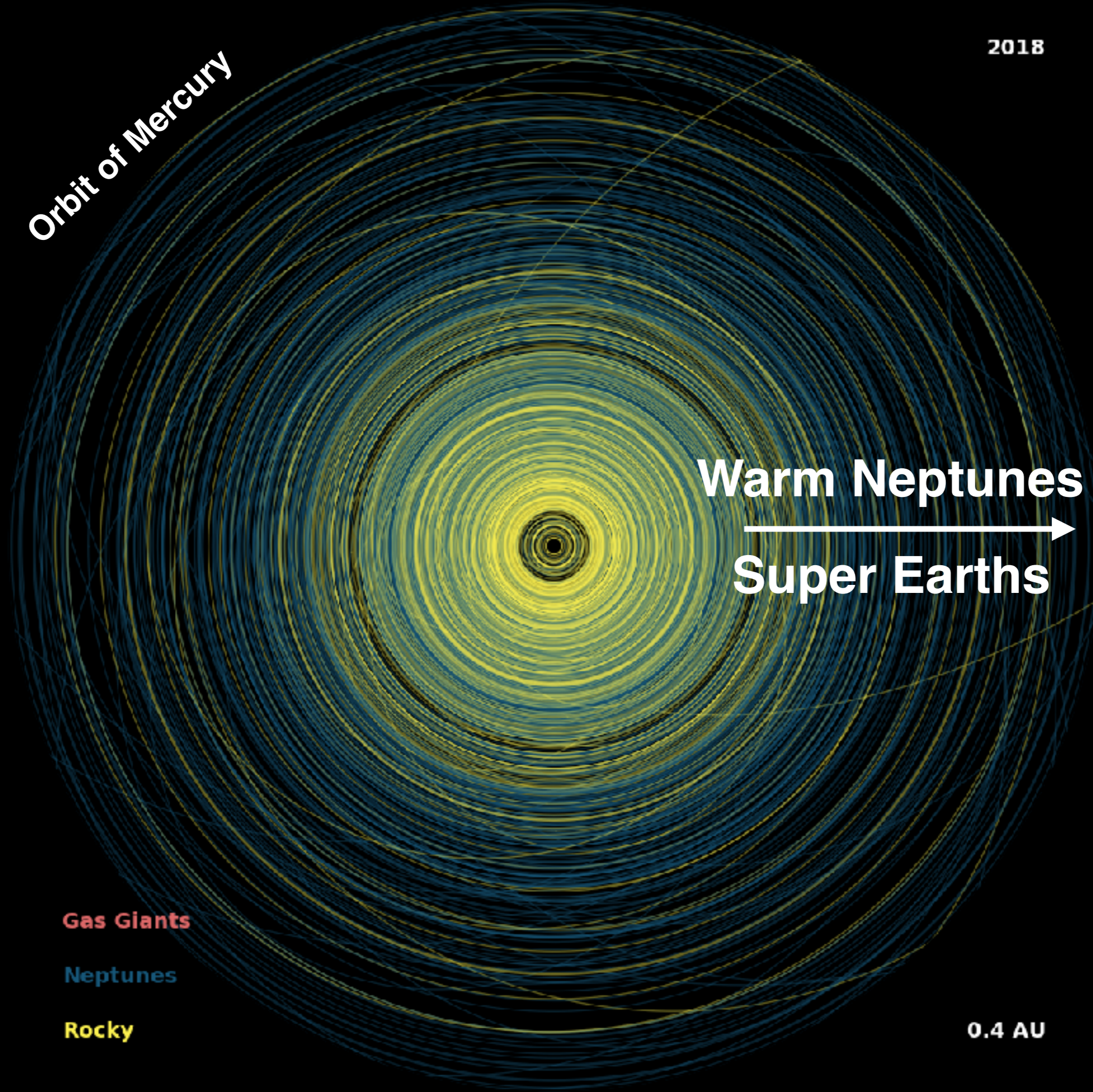
Rocky

0.4 AU



2018

Orbit of Mercury



Warm Neptunes



Super Earths

Gas Giants

Neptunes

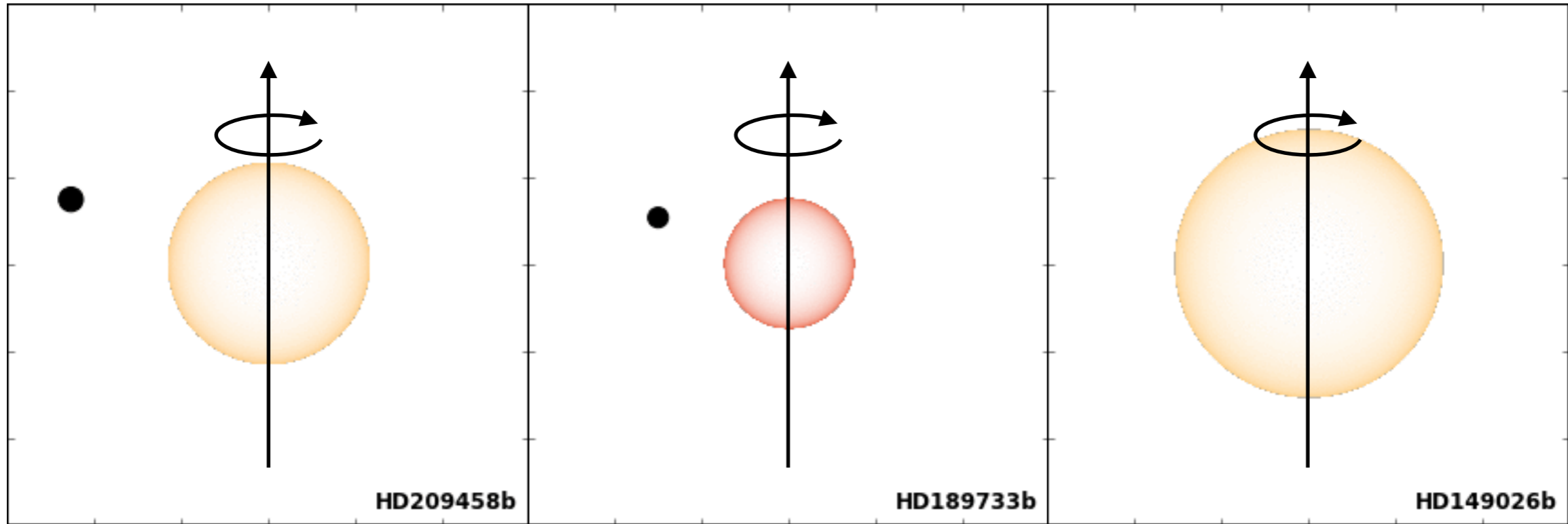
Rocky

0.4 AU

Winn+2005

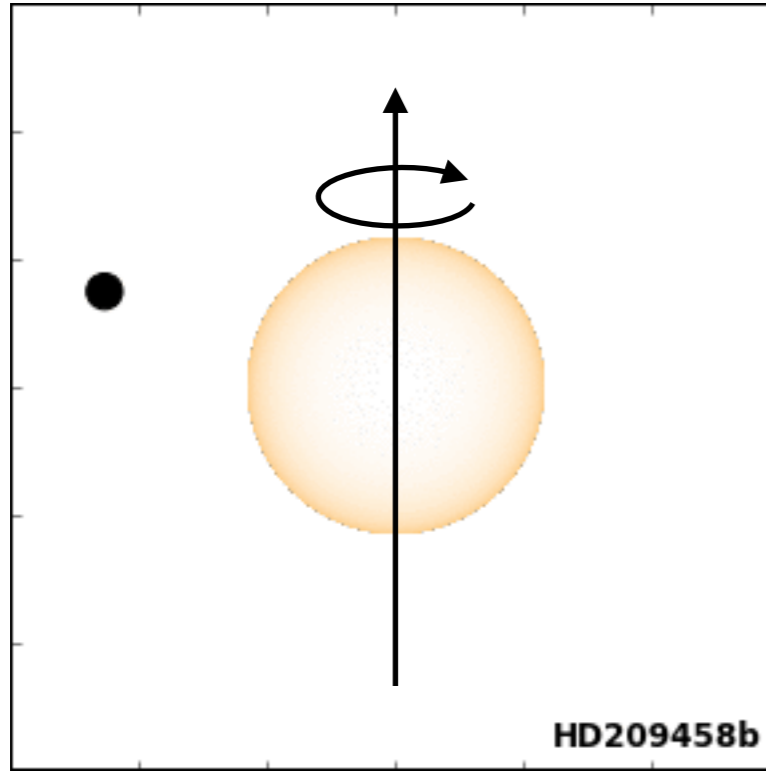
Winn+2006

Winn+2007

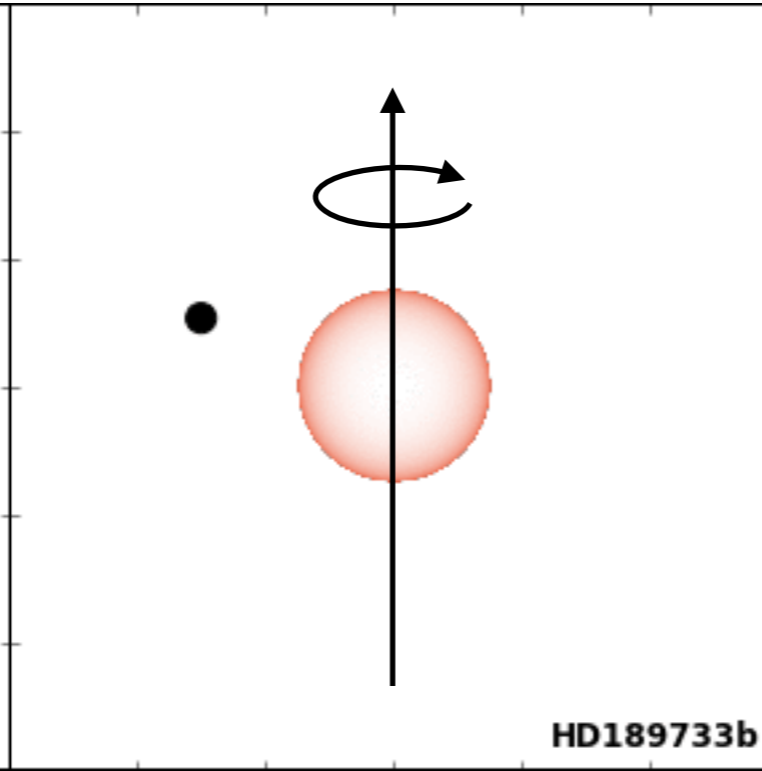


Orbital obliquities as tracers for evolution

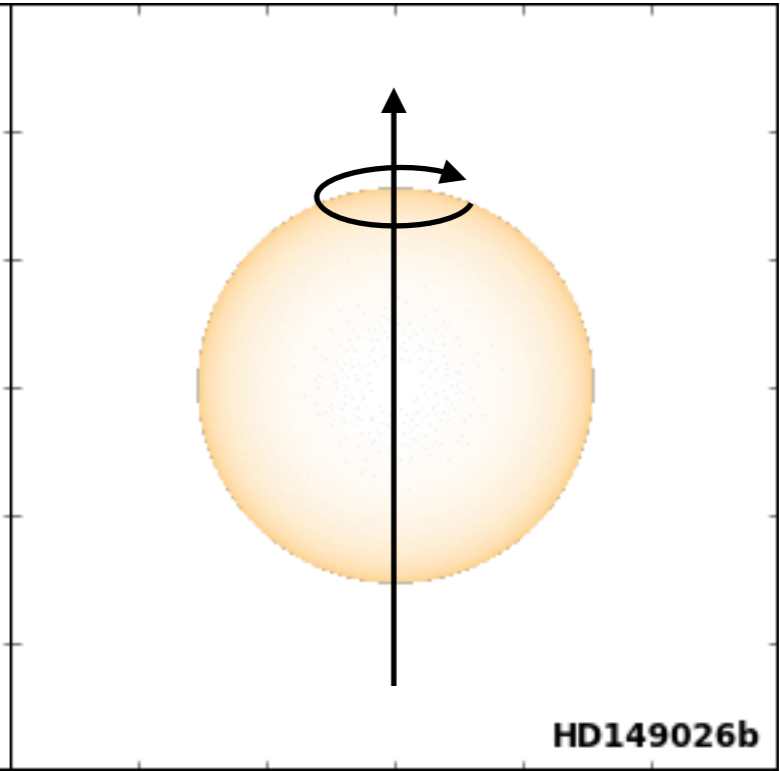
Winn+2005



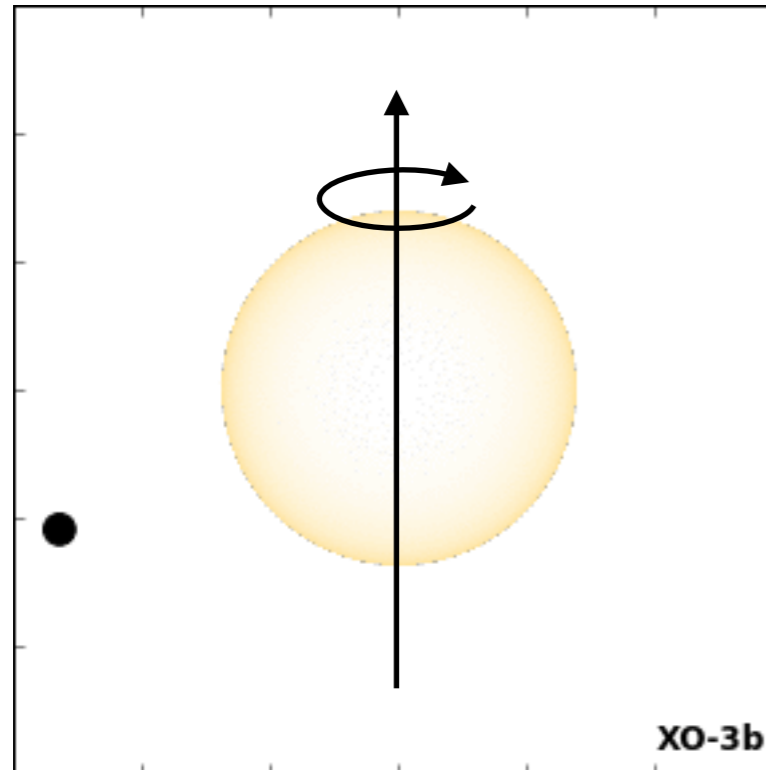
Winn+2006



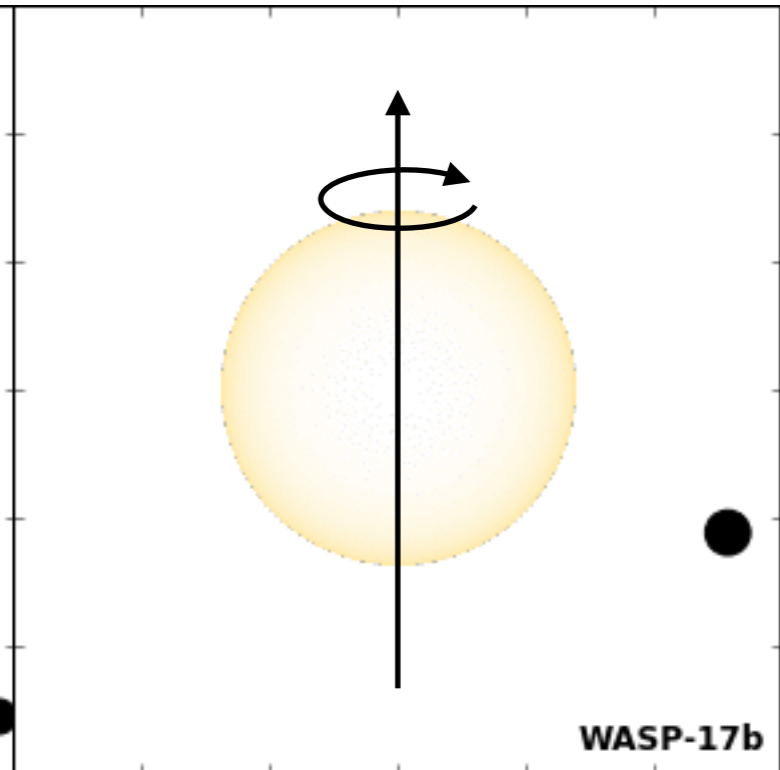
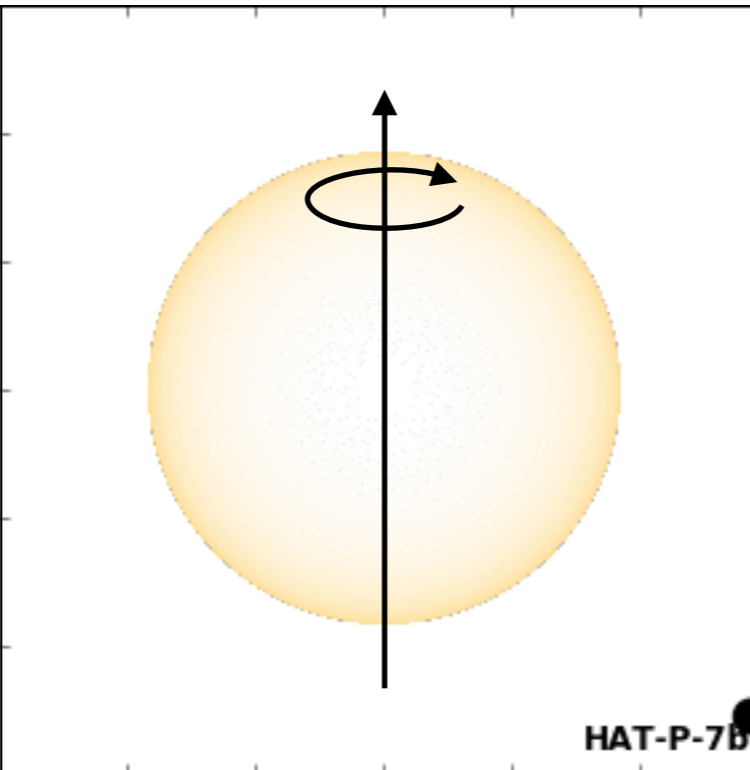
Winn+2007

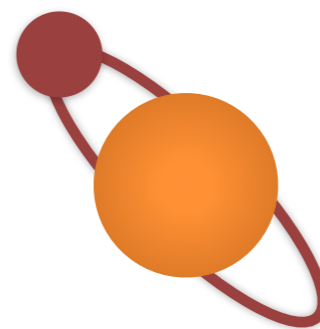
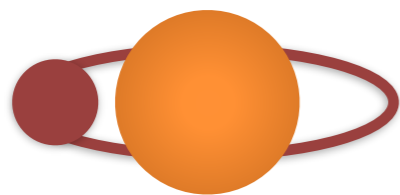
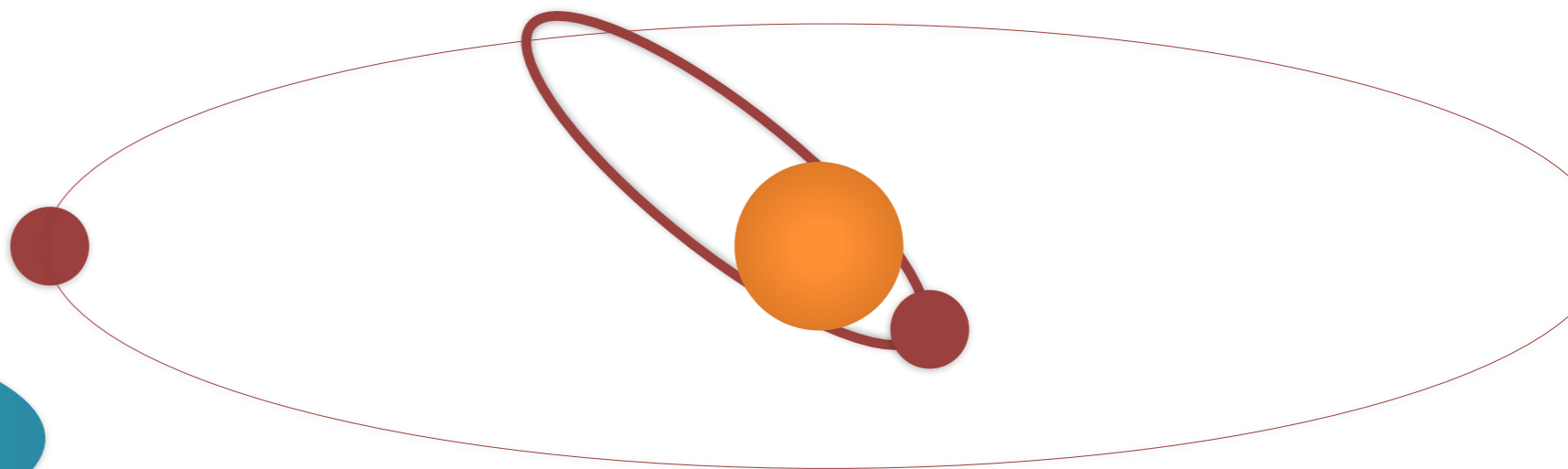
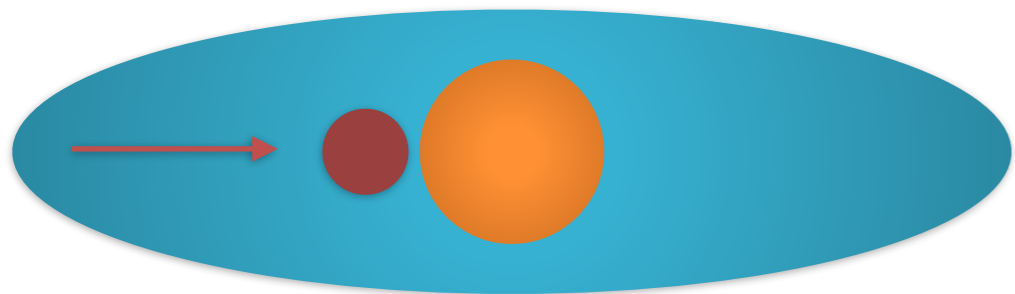
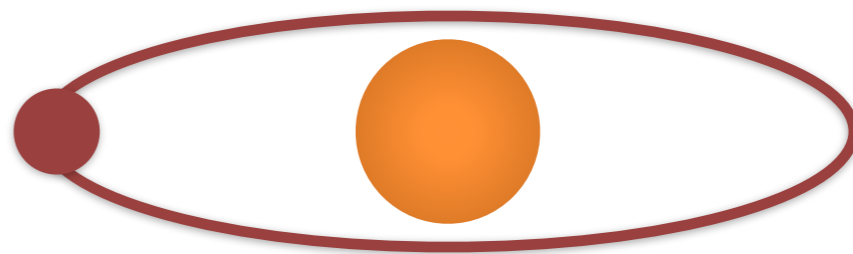
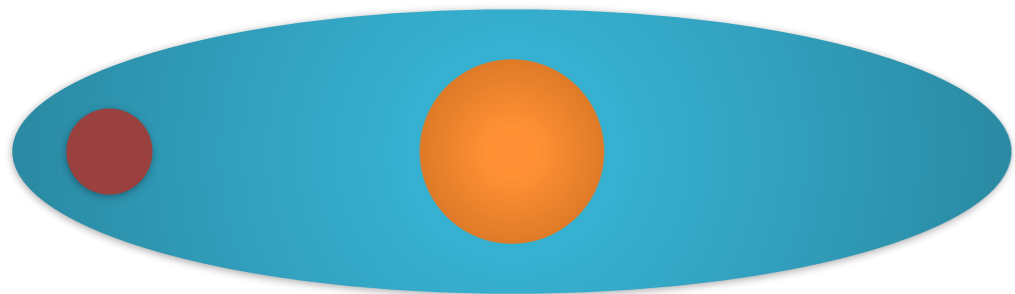


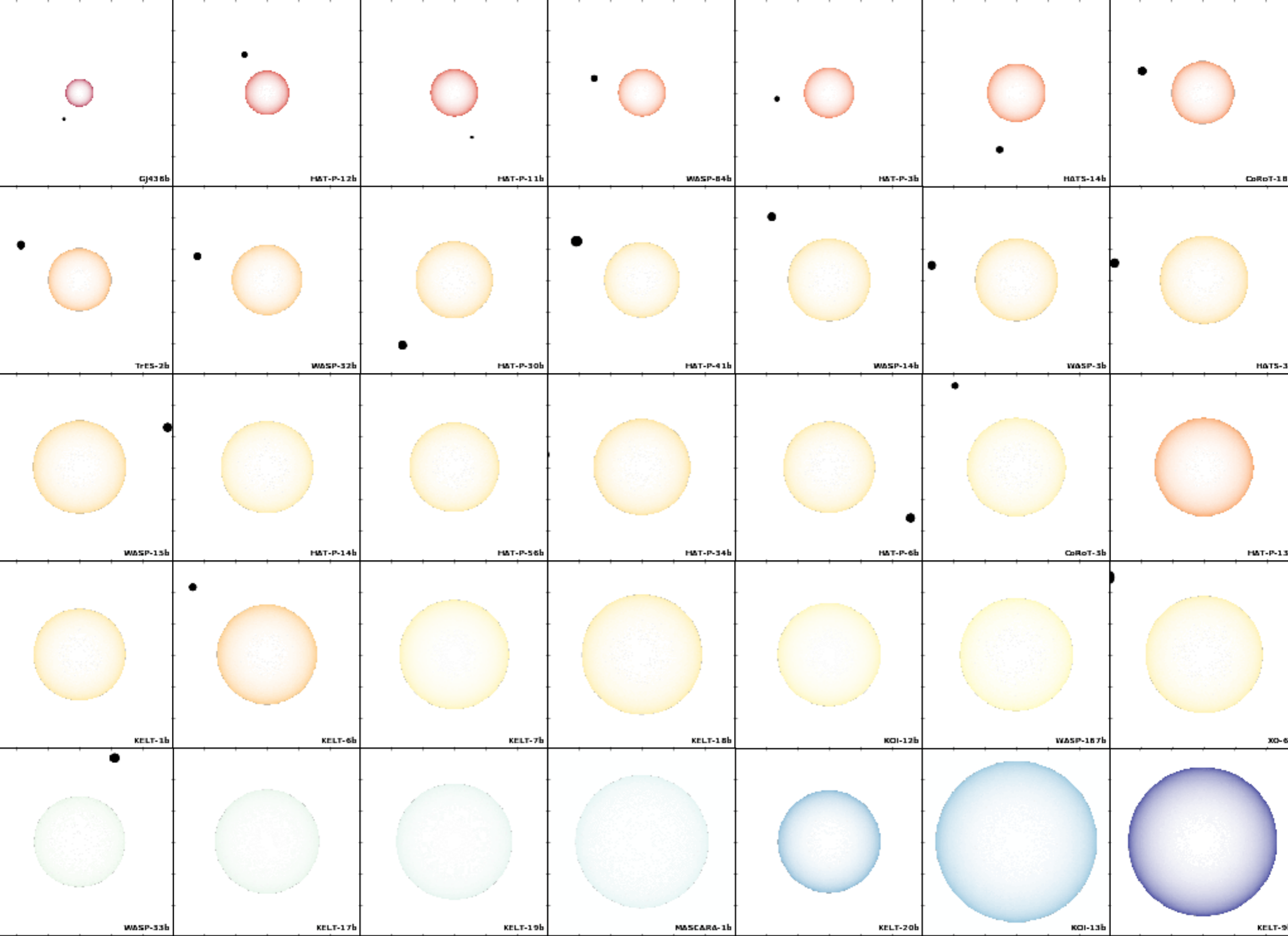
Winn+2009



Winn+2009, Narita+2009 Triaud+2009, Bayliss+2009

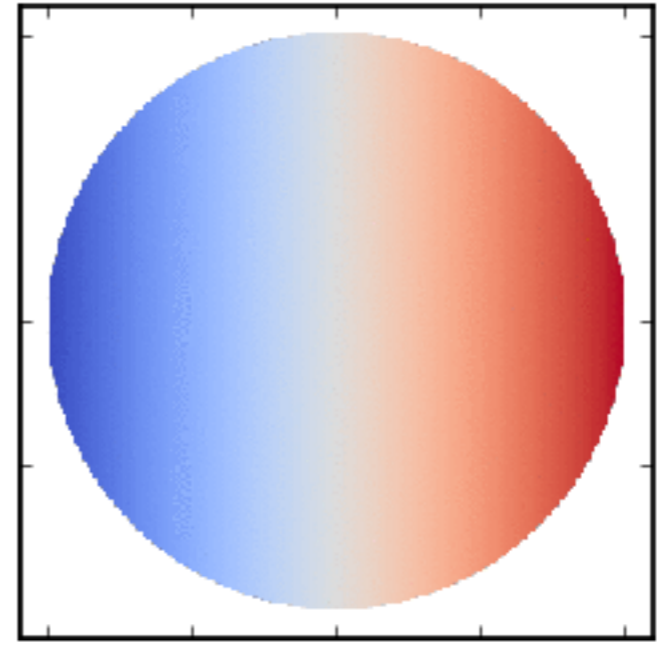
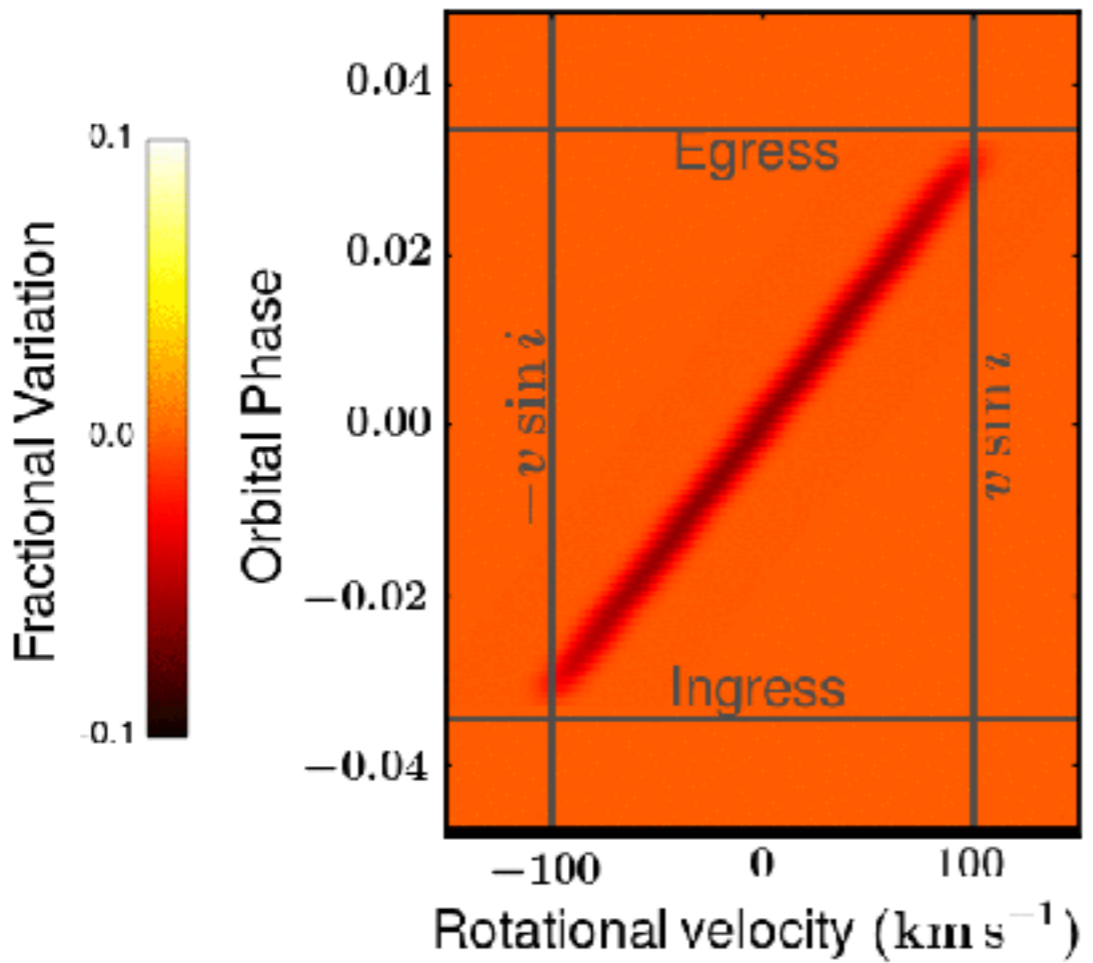
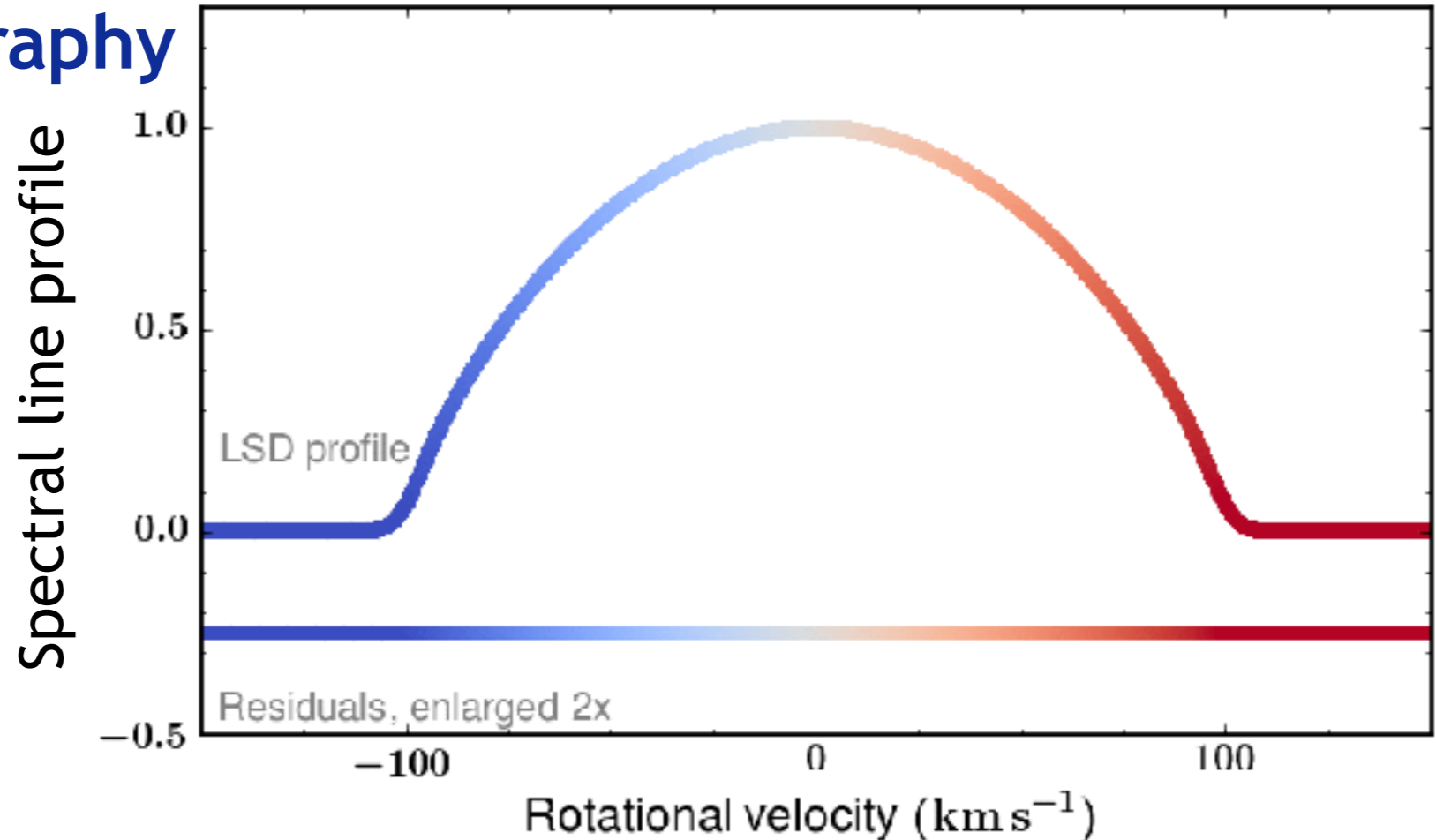






Doppler tomography

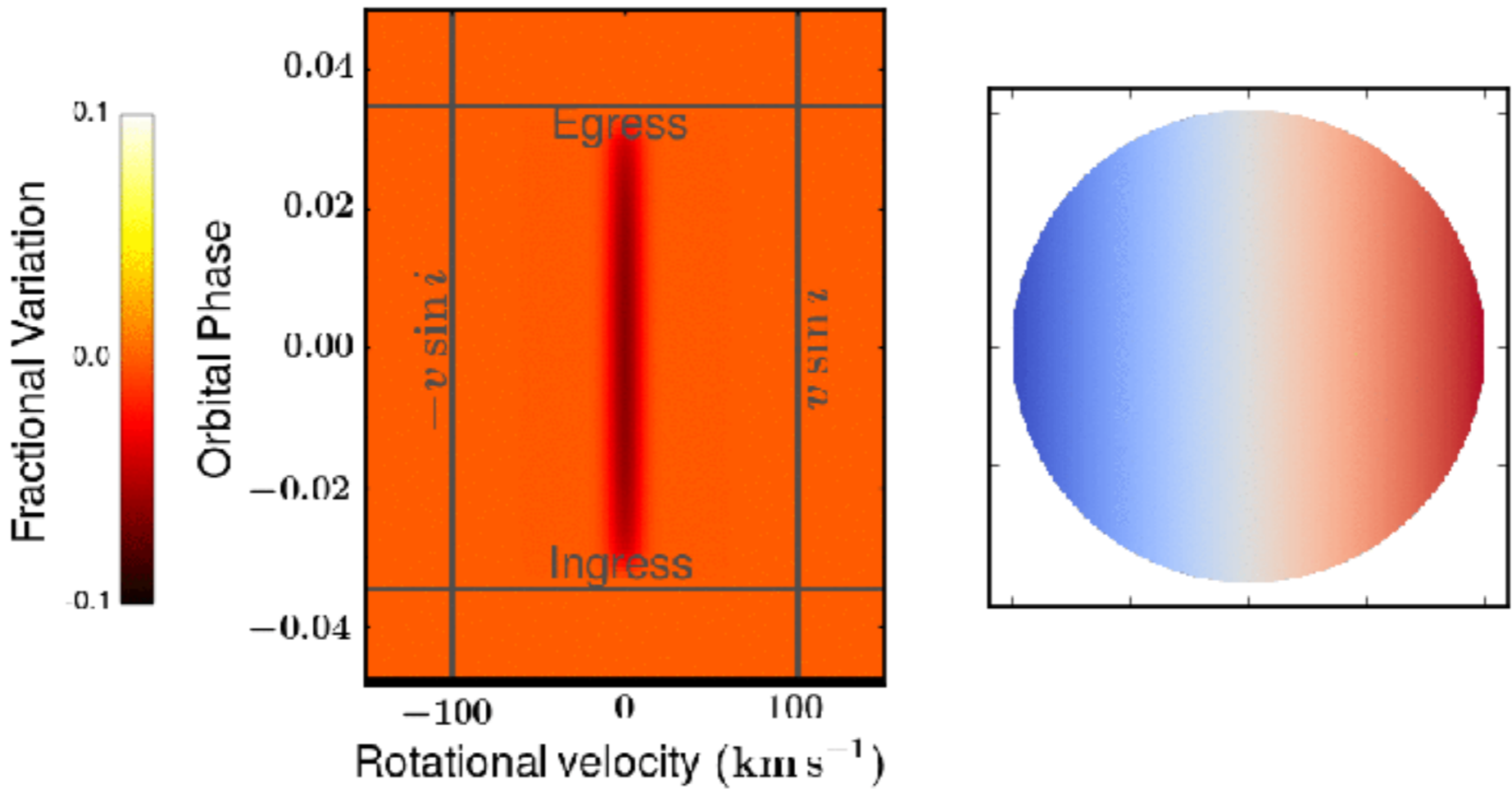
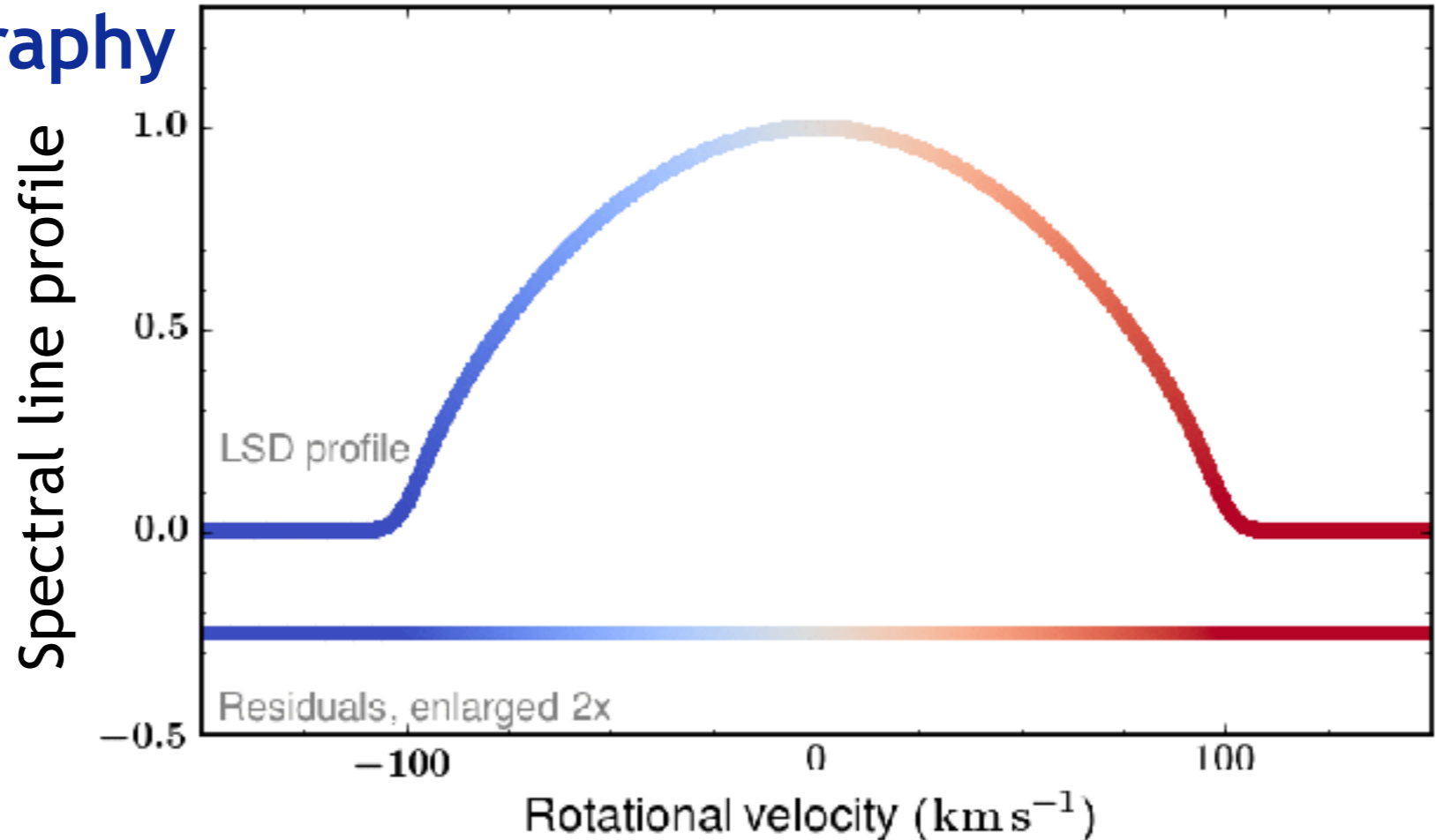
Prograde



See Donati+ 1997
Collier Cameron+ 2010

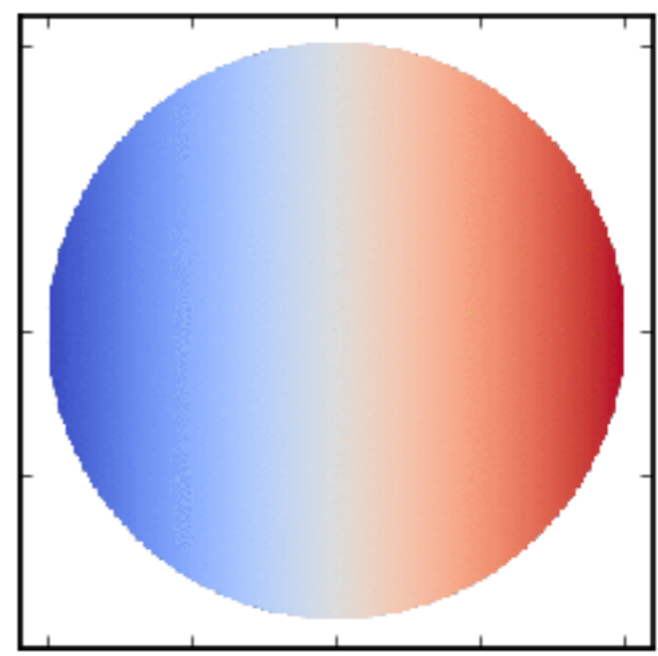
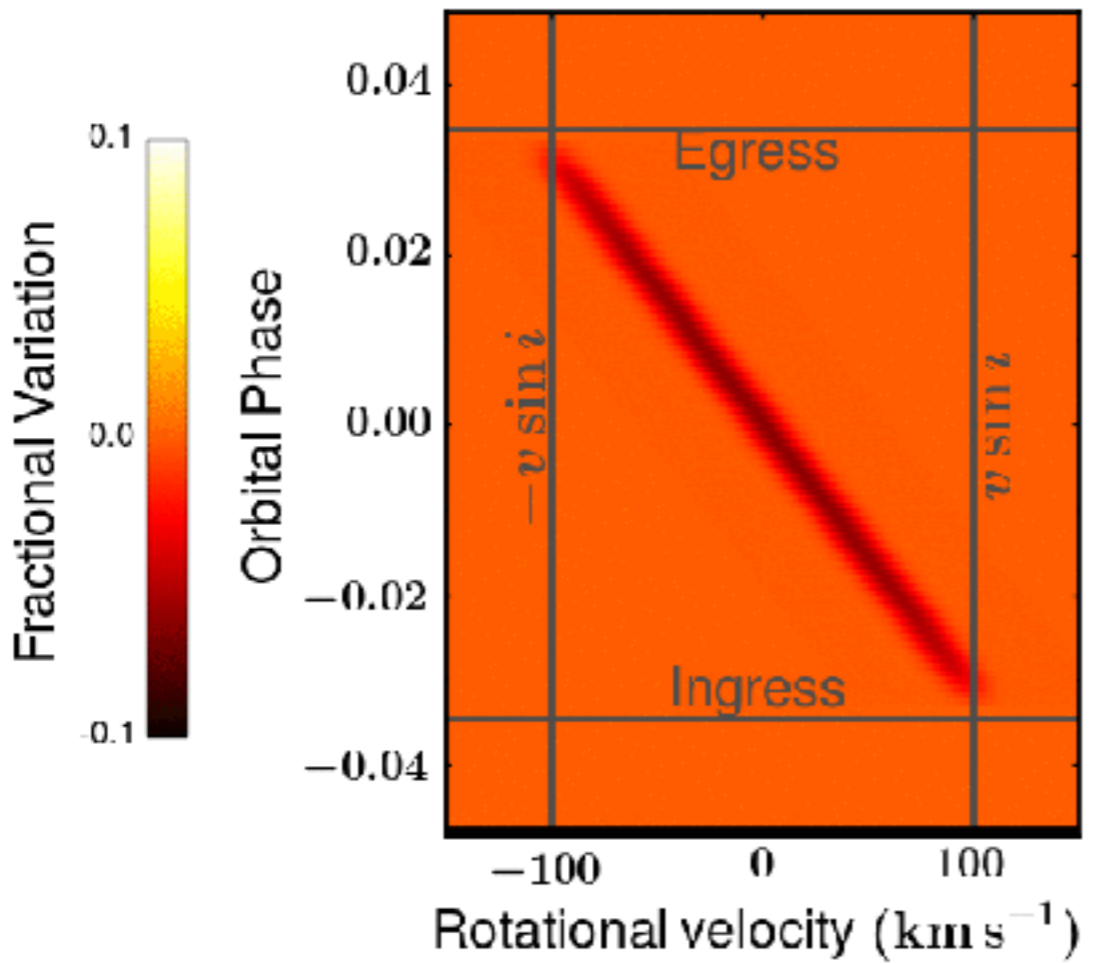
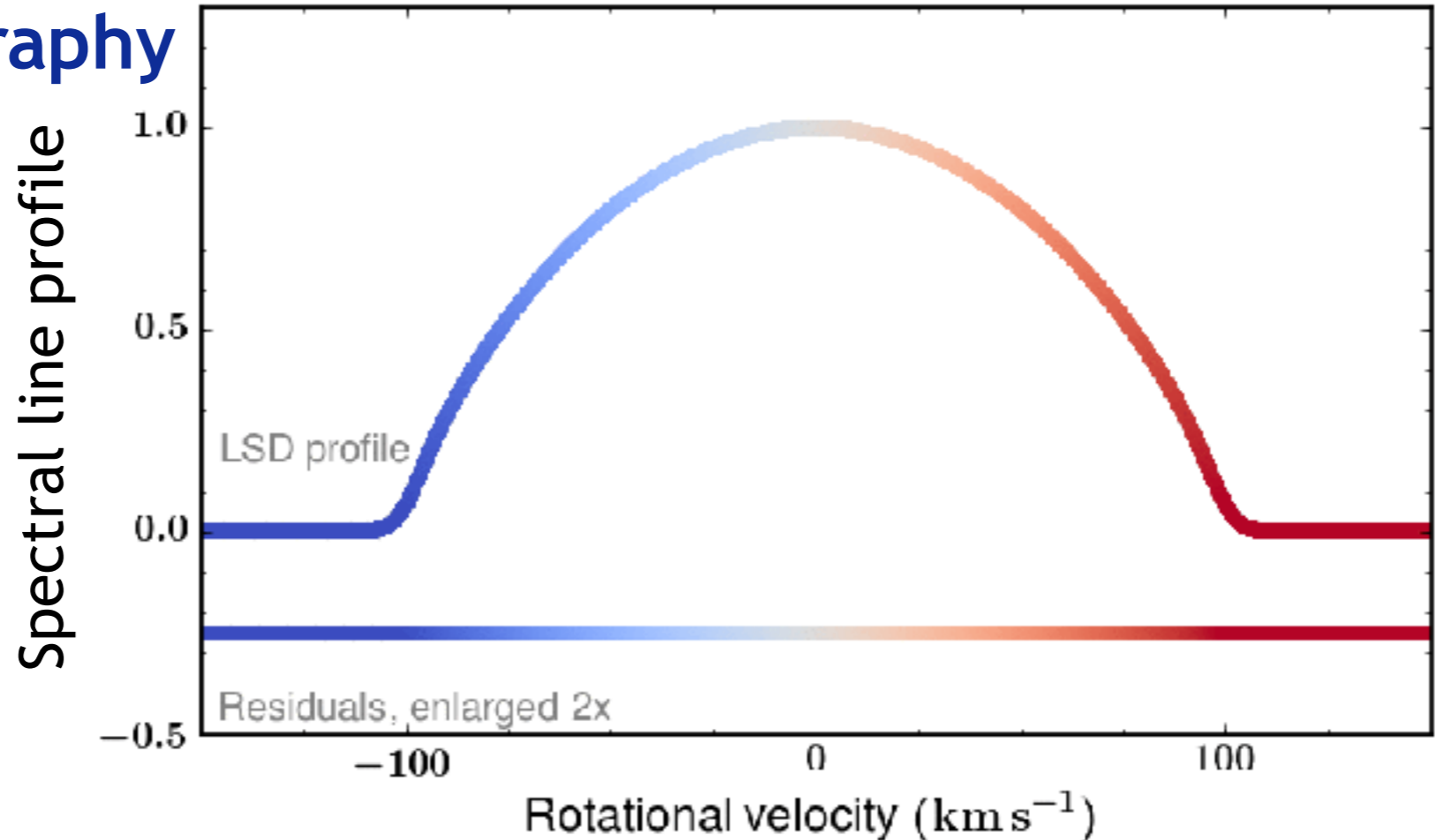
Doppler tomography

Polar



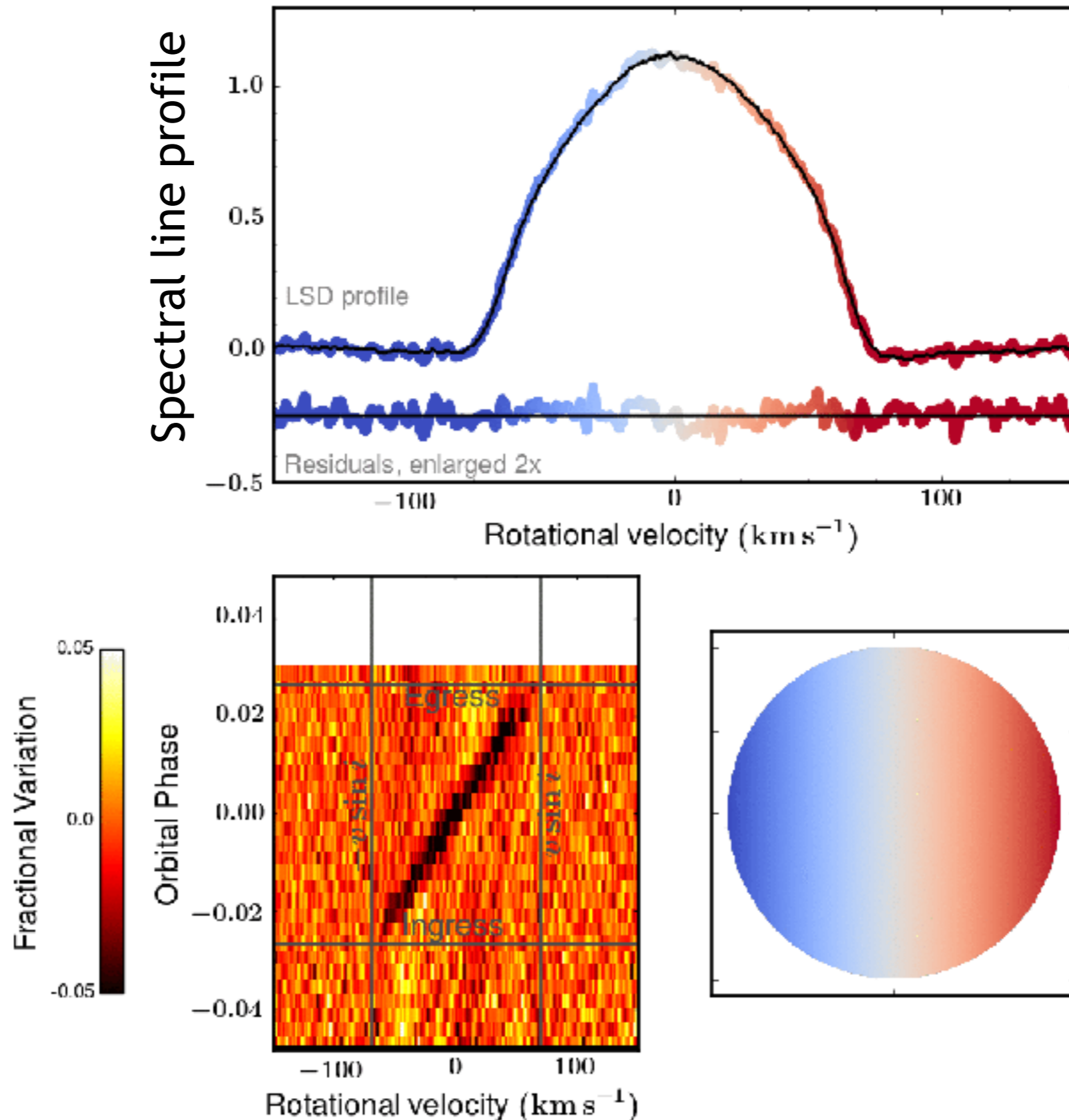
Doppler tomography

Retrograde



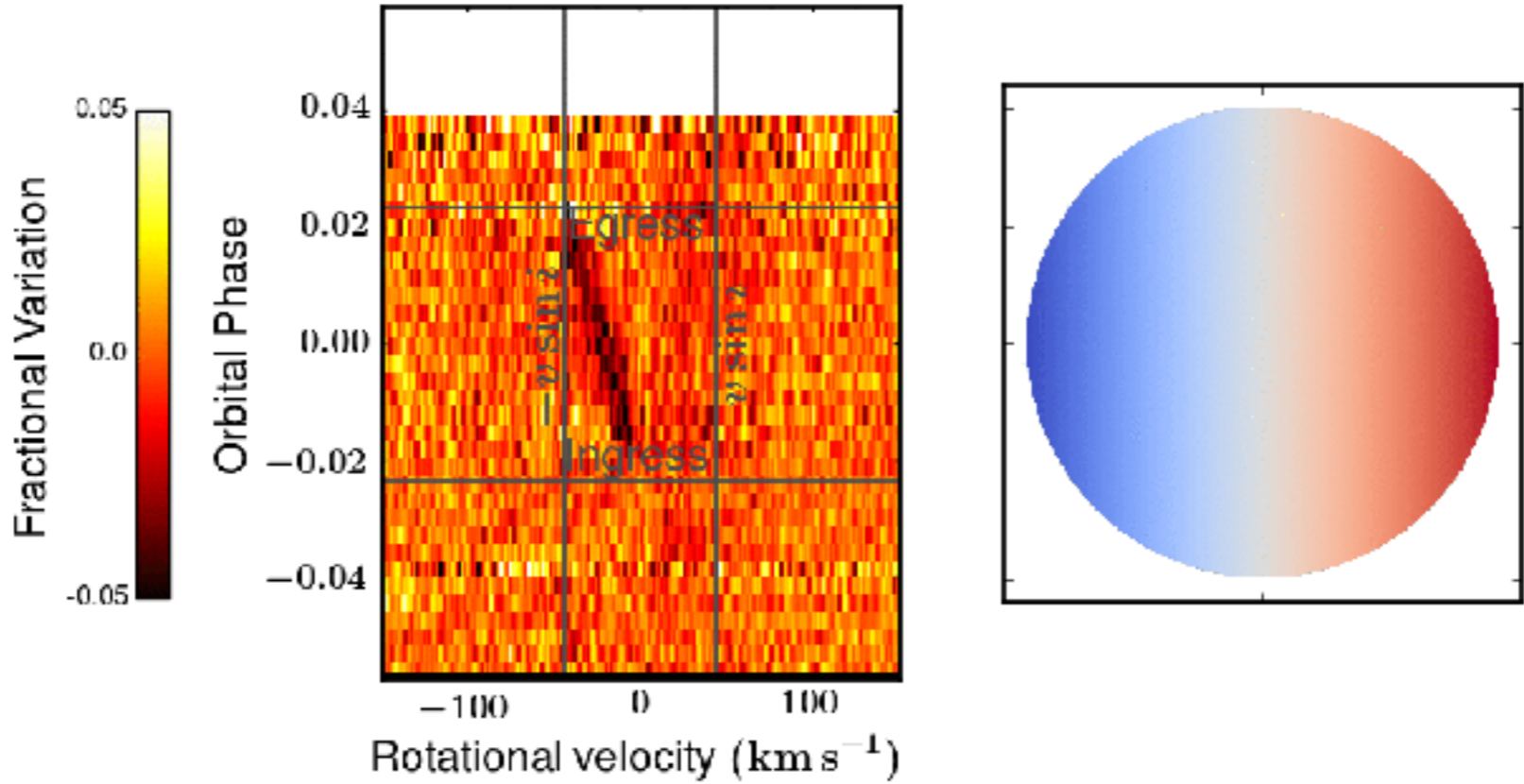
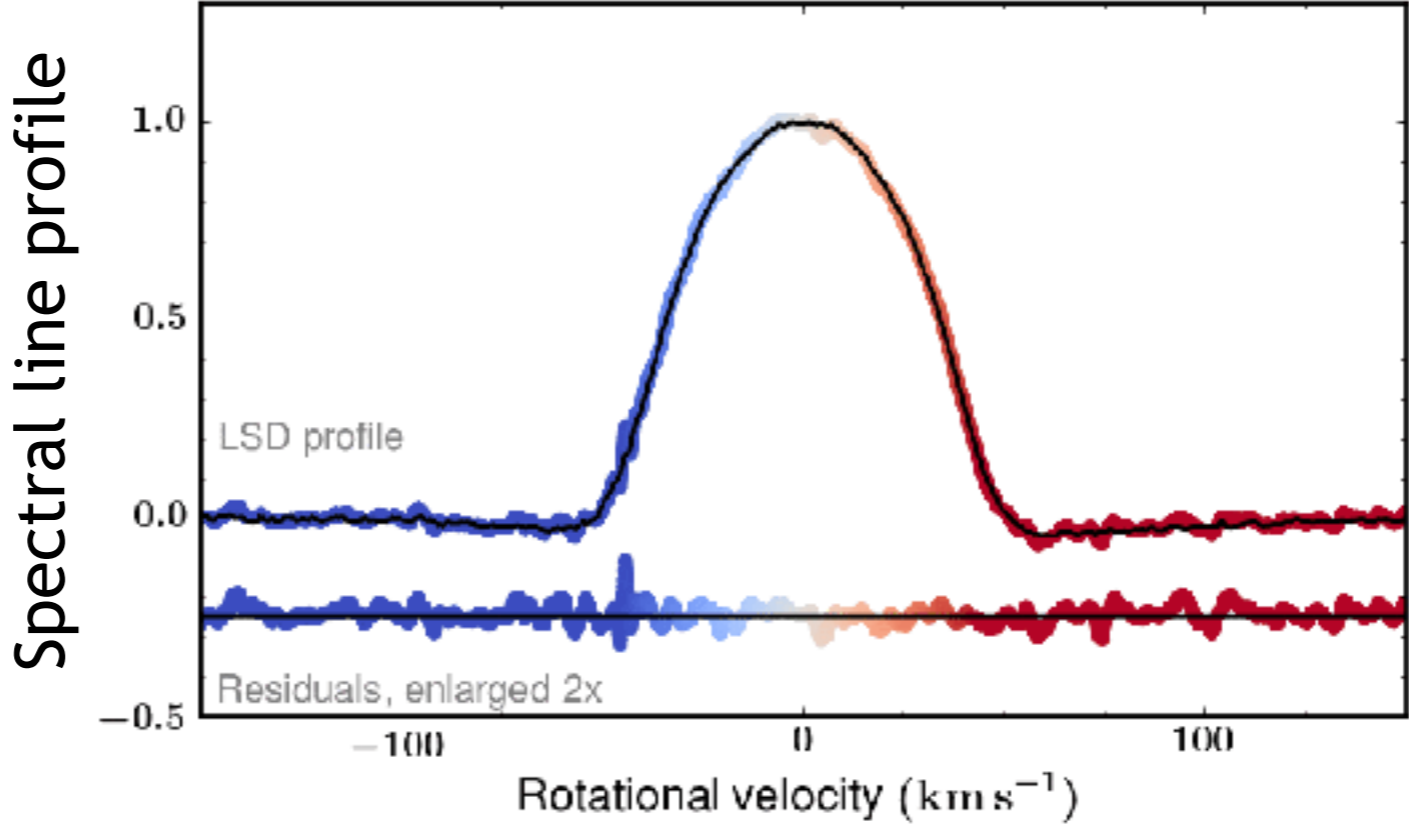
KELT-7b – a rapidly rotating F-star with a hot Jupiter

Bieryla+ 2015, Zhou+ 2016



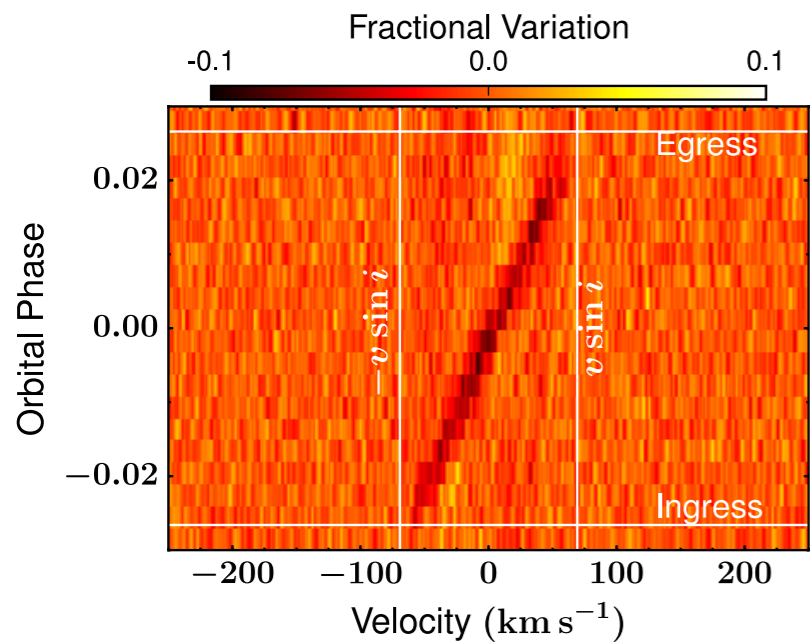
Doppler tomography, see Donati+ 1997, Collier Cameron+ 2010

KELT-17b – a polar hot Jupiter around an A star

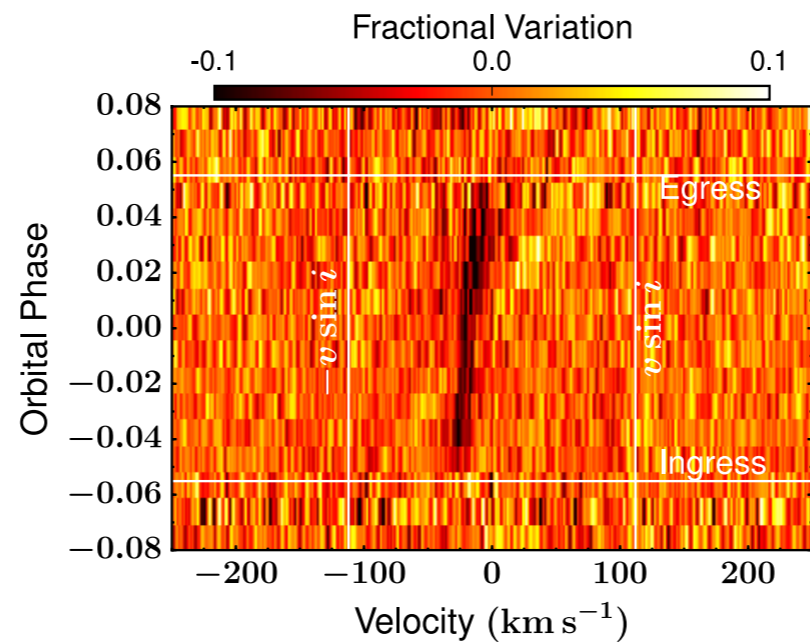


TRES Doppler tomography observations

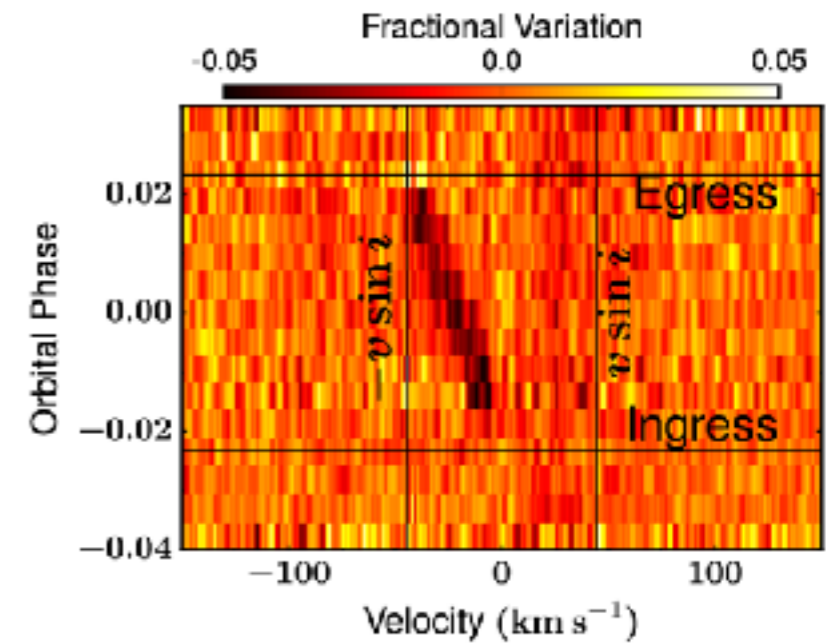
KELT-7b (Bieryla+15, Zhou+16a)



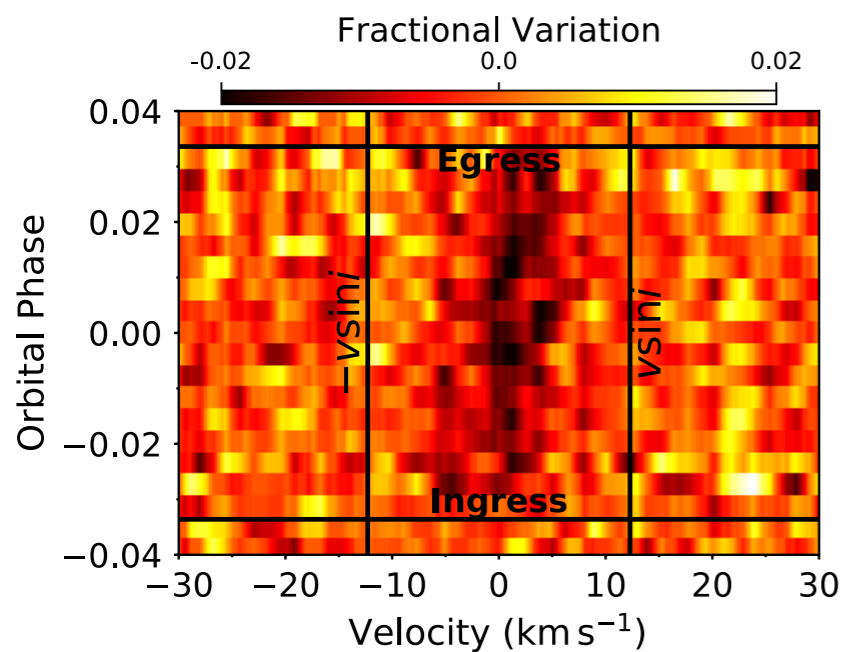
KELT-9b (Gaudi+17)



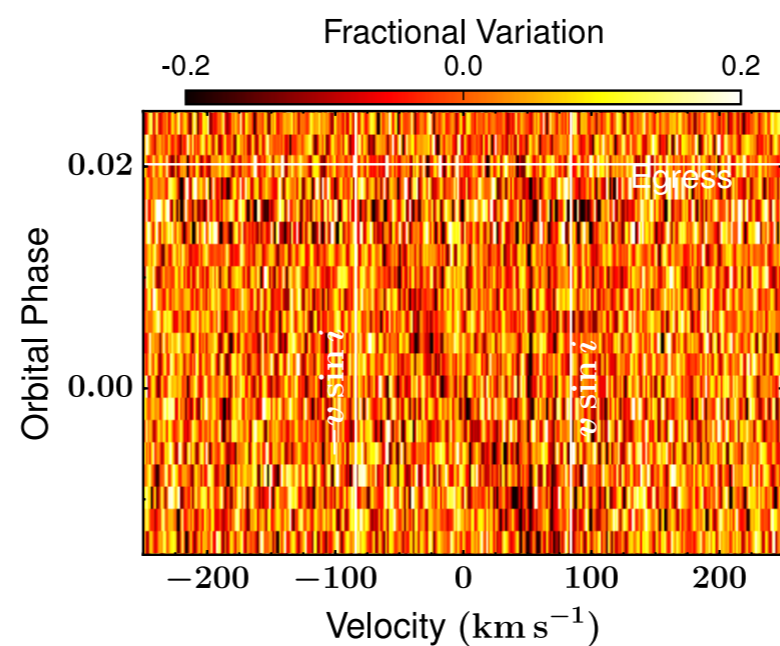
KELT-17b (Zhou+16b)



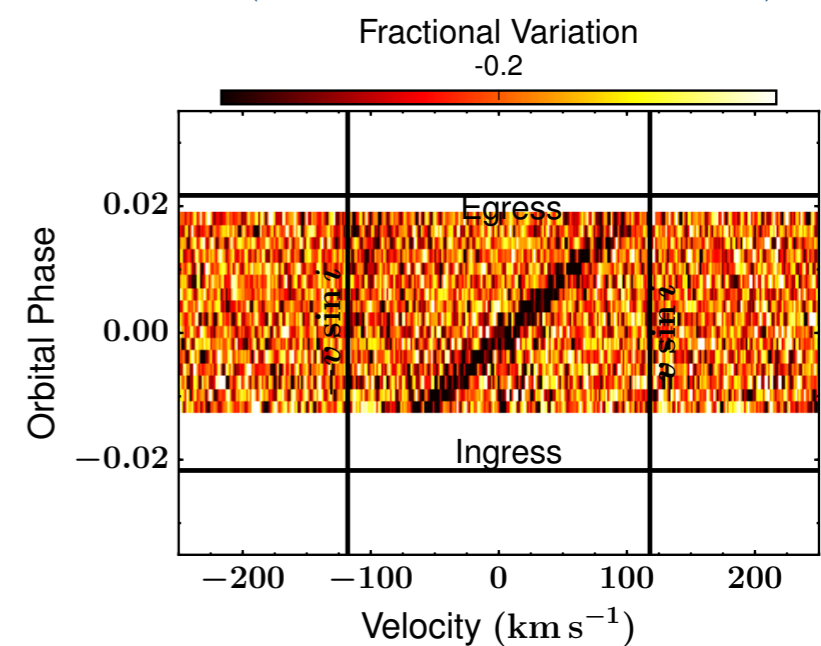
KELT-18b (Zhou+ in-prep)



KELT-19b (Siverd+17)

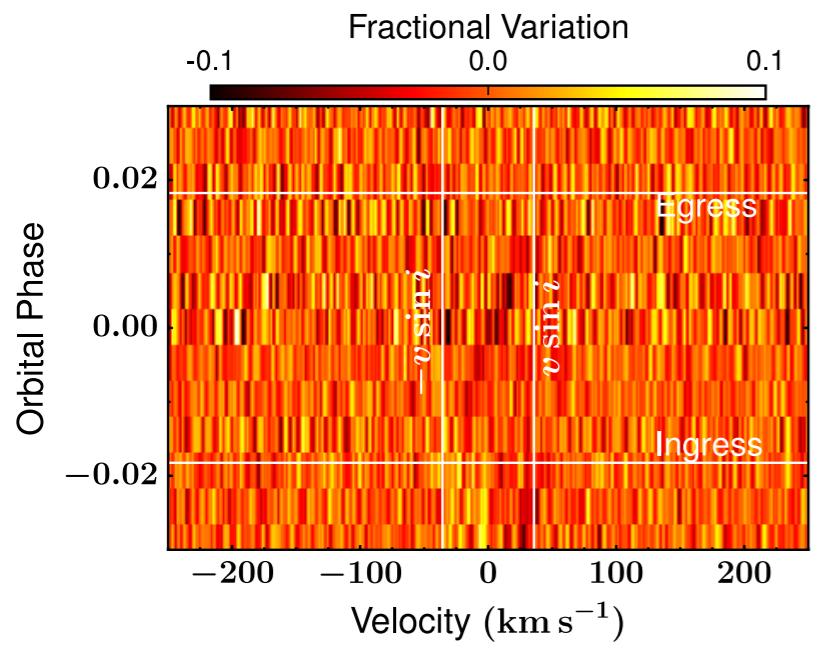


KELT-20b / MASCARA-2b (Lund+17, Talens+17)

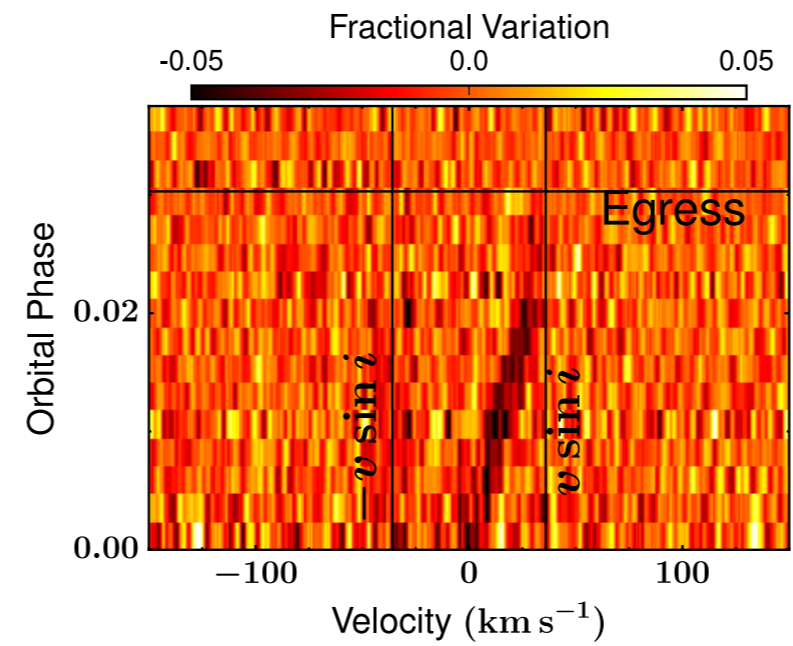


More TRES Doppler tomography observations

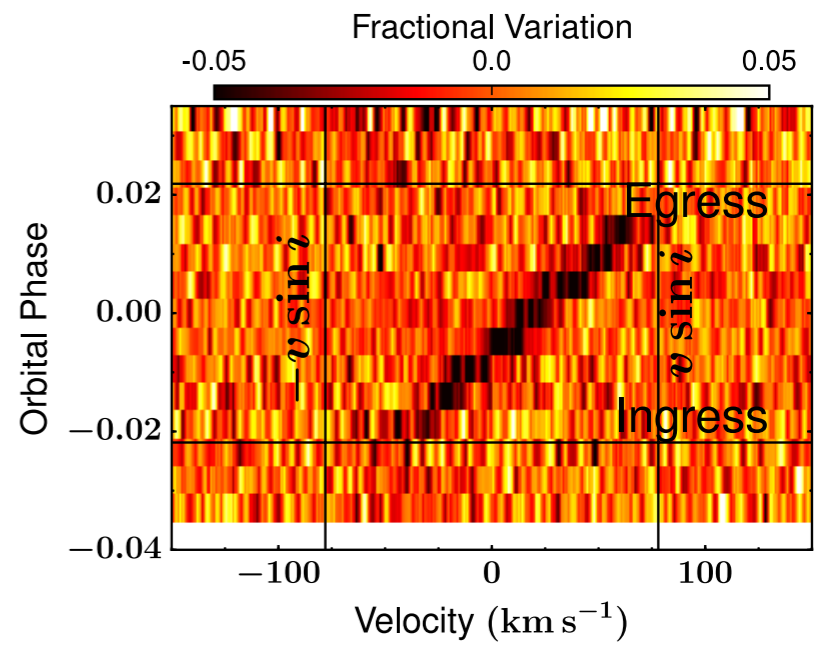
HAT-P-56b (Huang+15, Zhou+16)



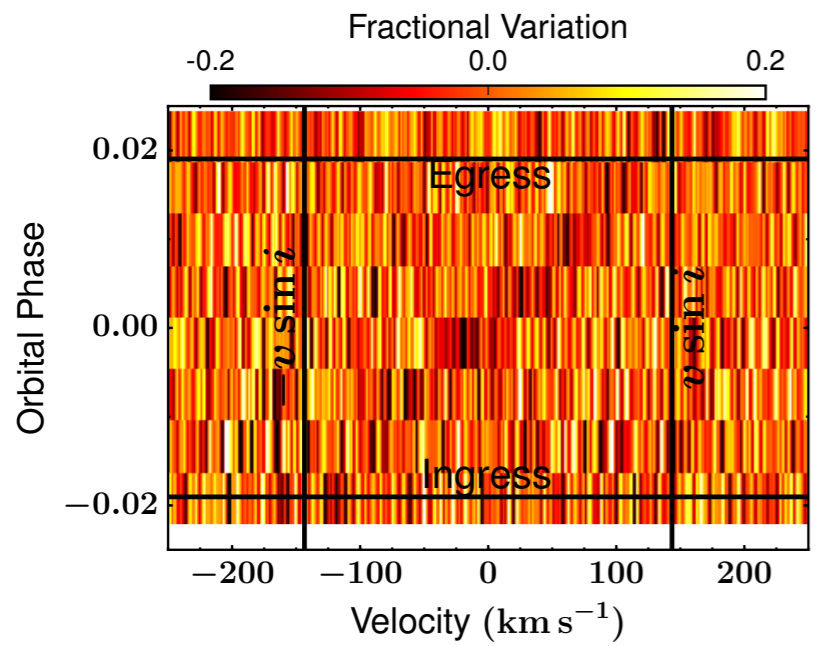
HAT-P-67b (Zhou+17)



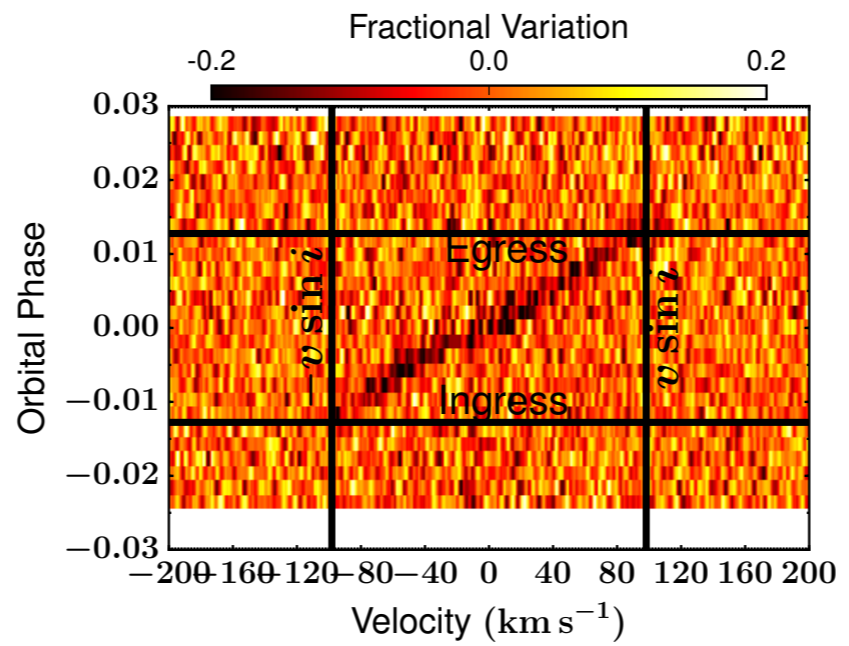
HAT Candidate (in-prep)



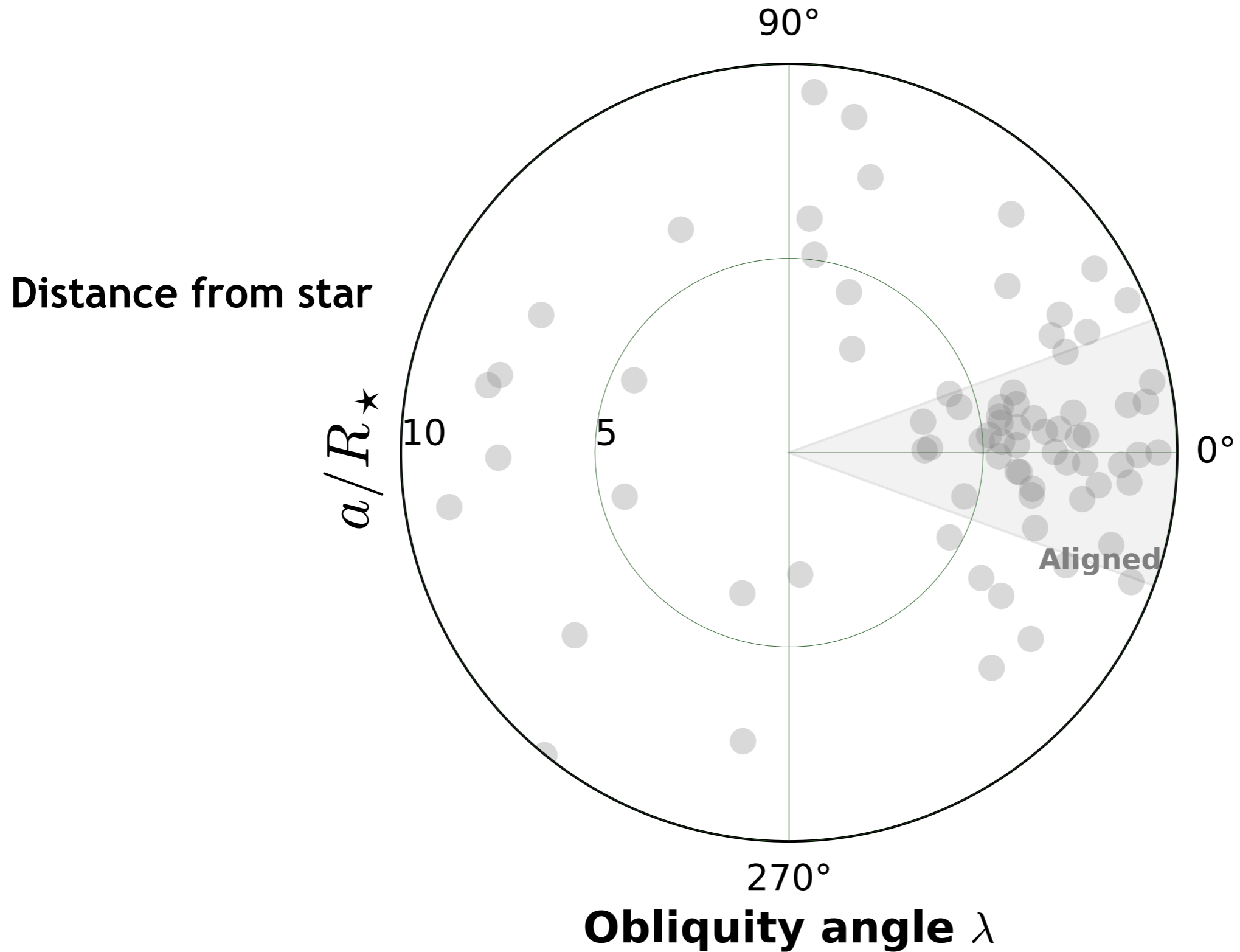
KELT-21 (Johnson+18)



KELT A-M binary (Stevens+ in-prep)

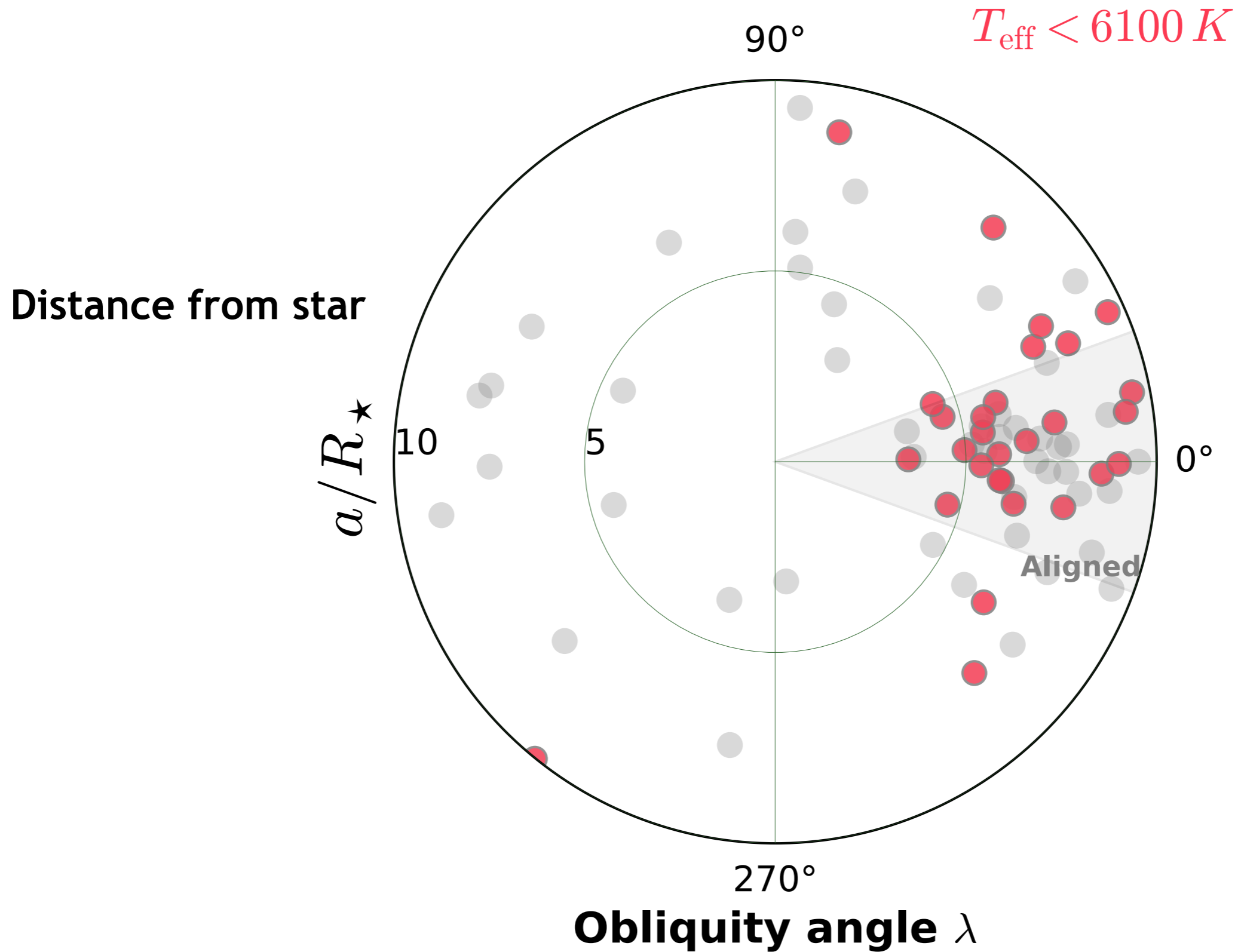


Obliquity as an origin for formation and migration

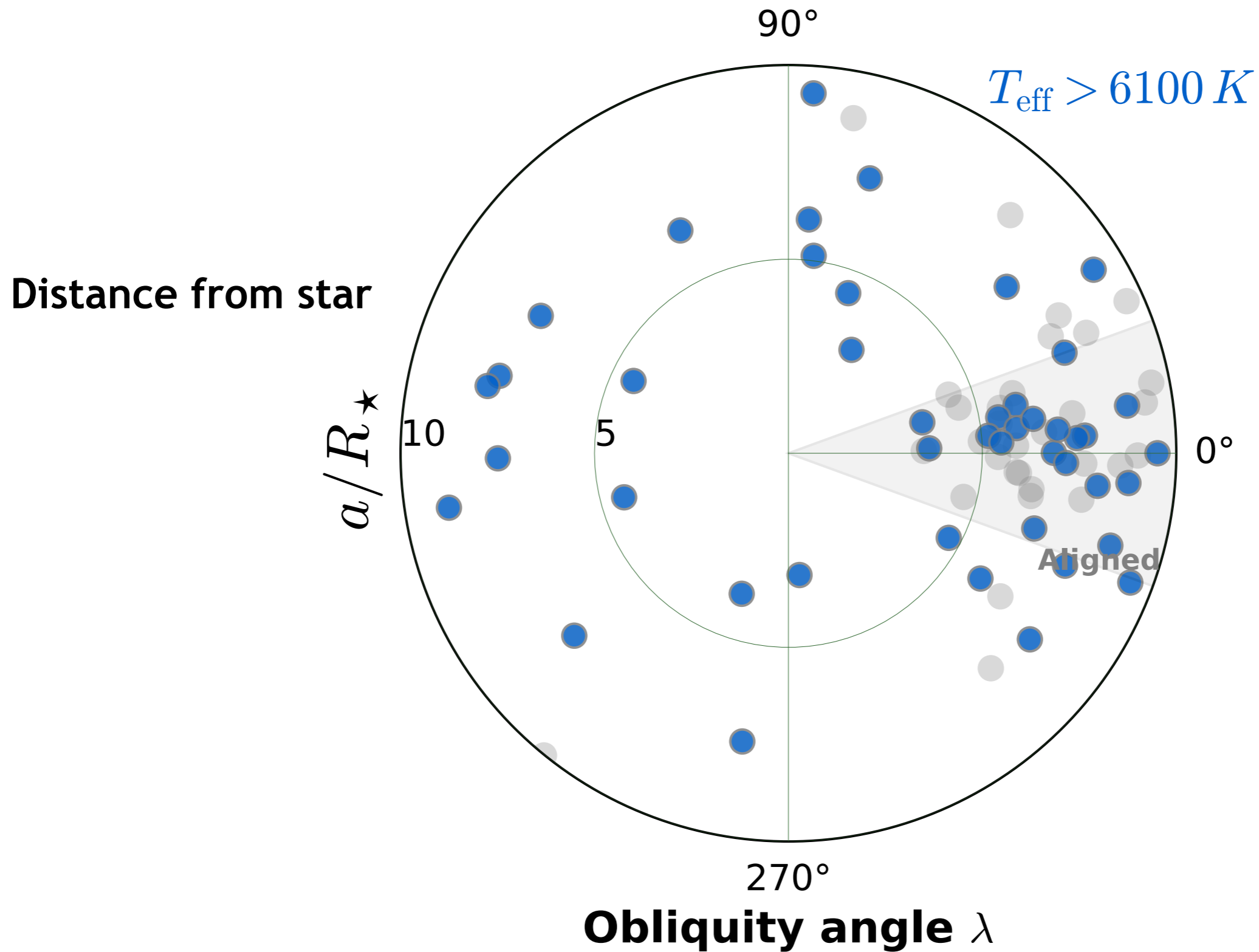


Inspired by plots from J Winn

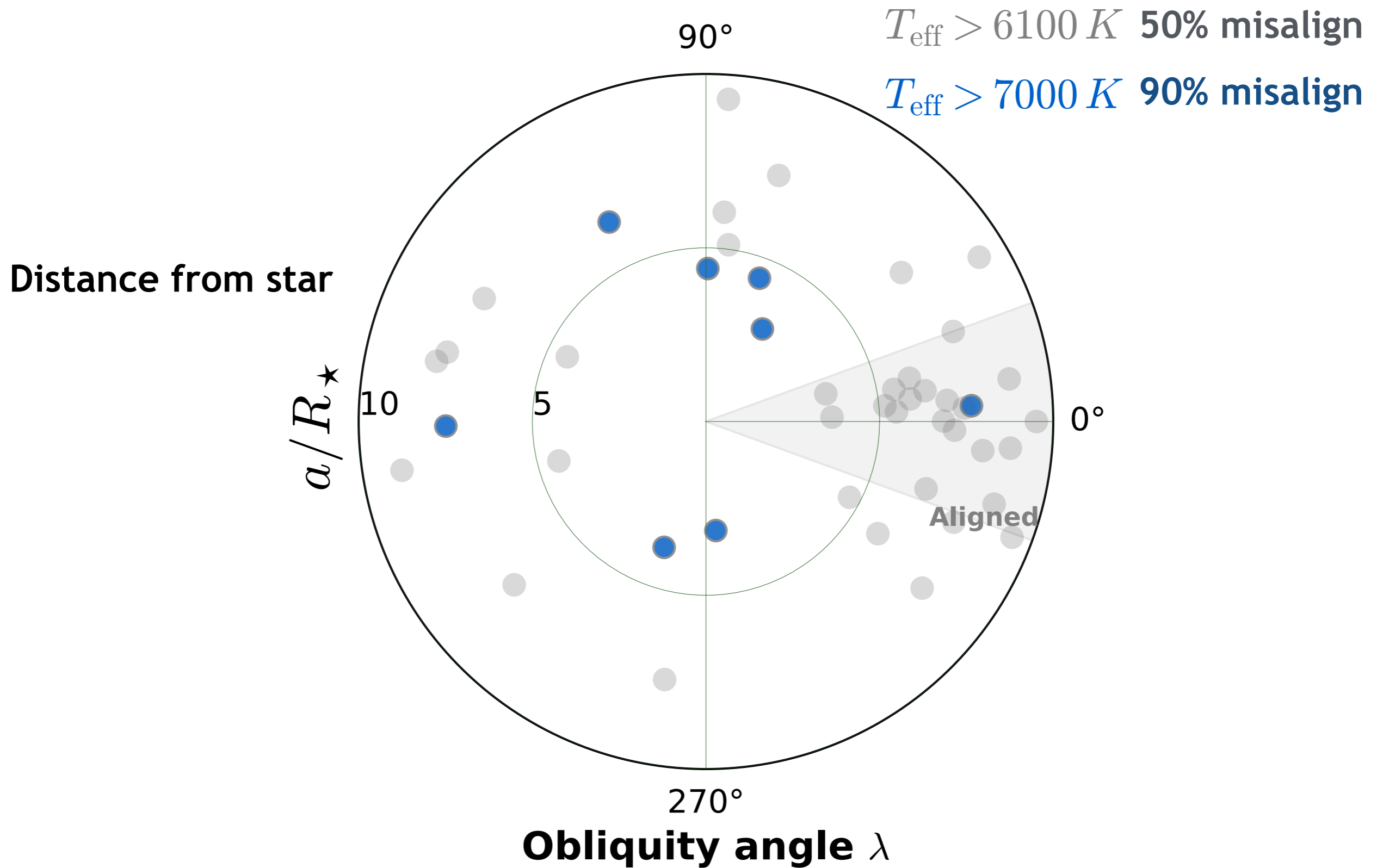
Dependence on effective temperature – Hot Jupiters



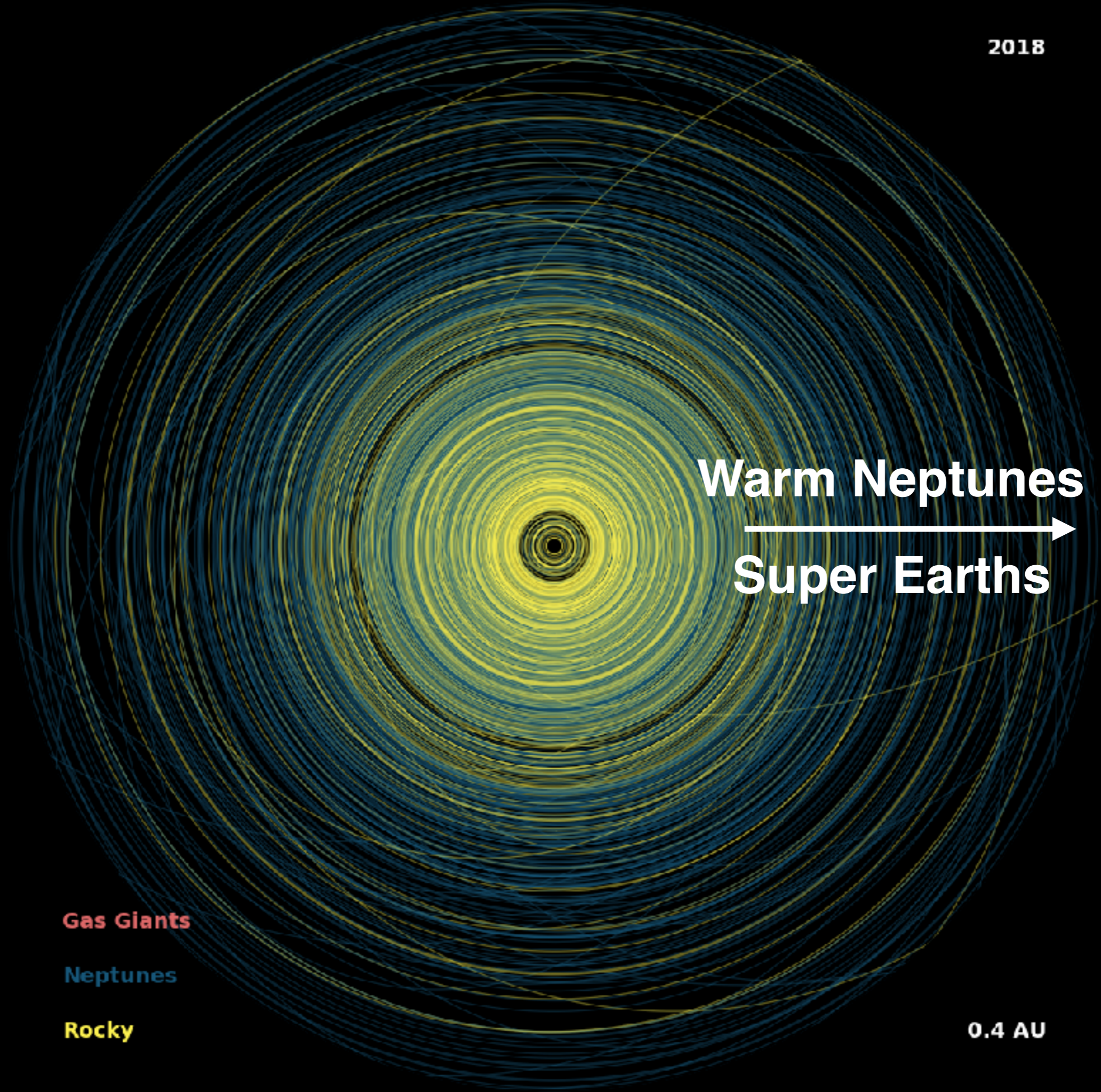
Dependence on effective temperature – Hot Jupiters



Dependence on effective temperature – Hot Jupiters



2018



Warm Neptunes
→
Super Earths

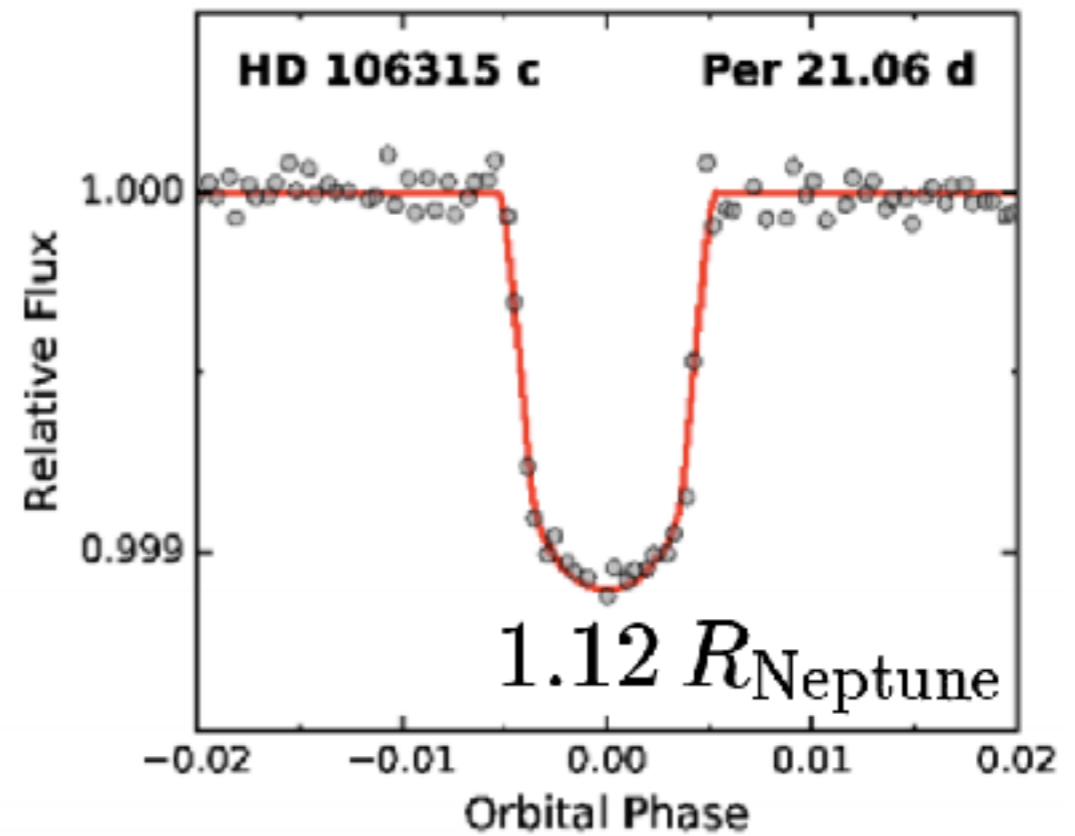
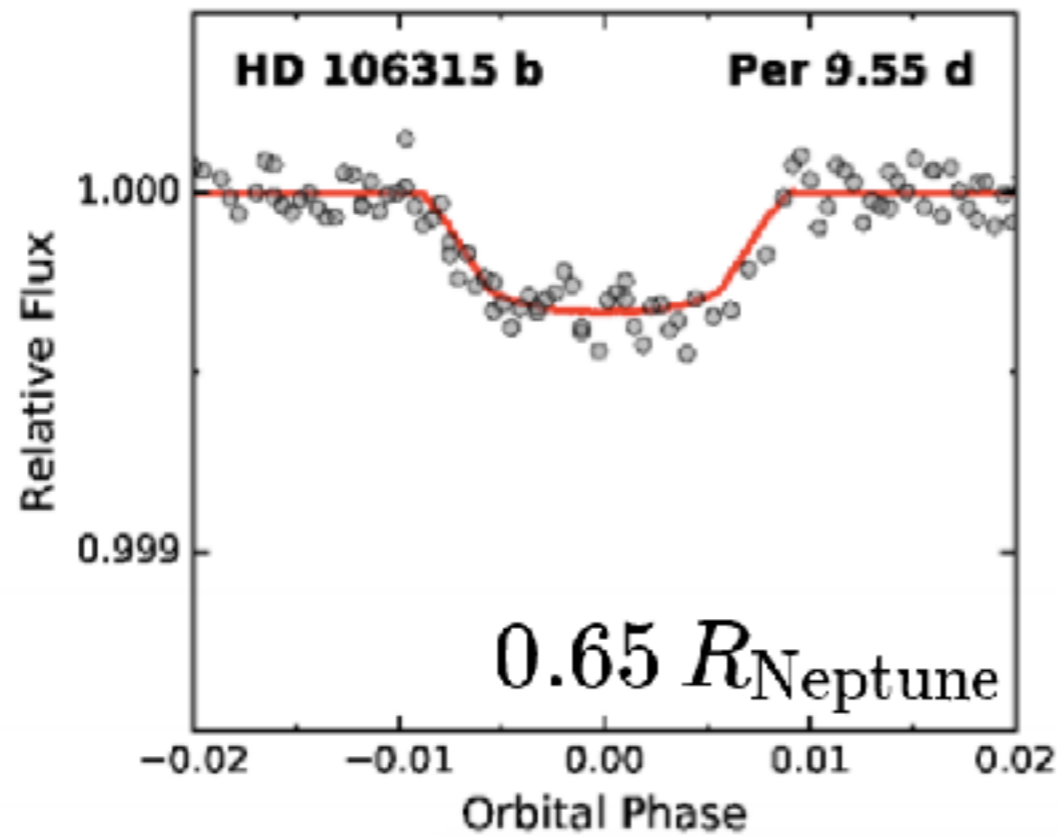
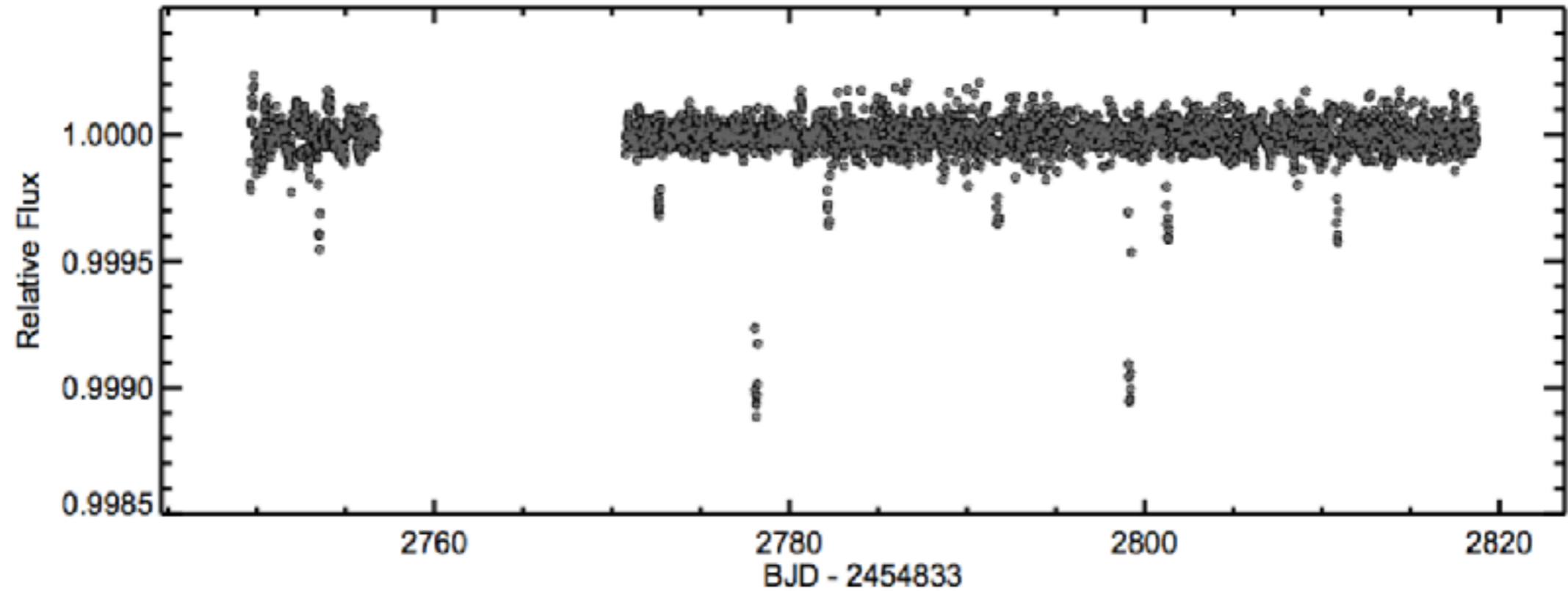
Gas Giants

Neptunes

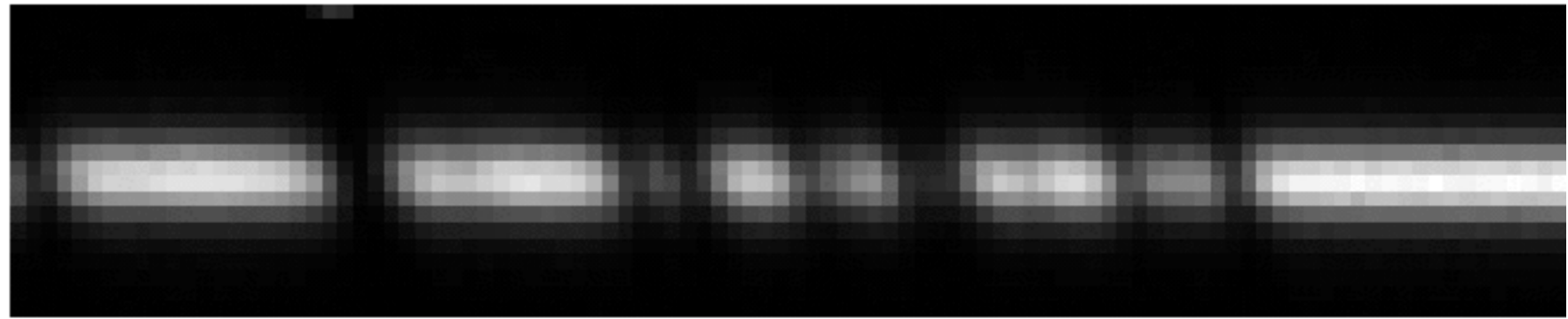
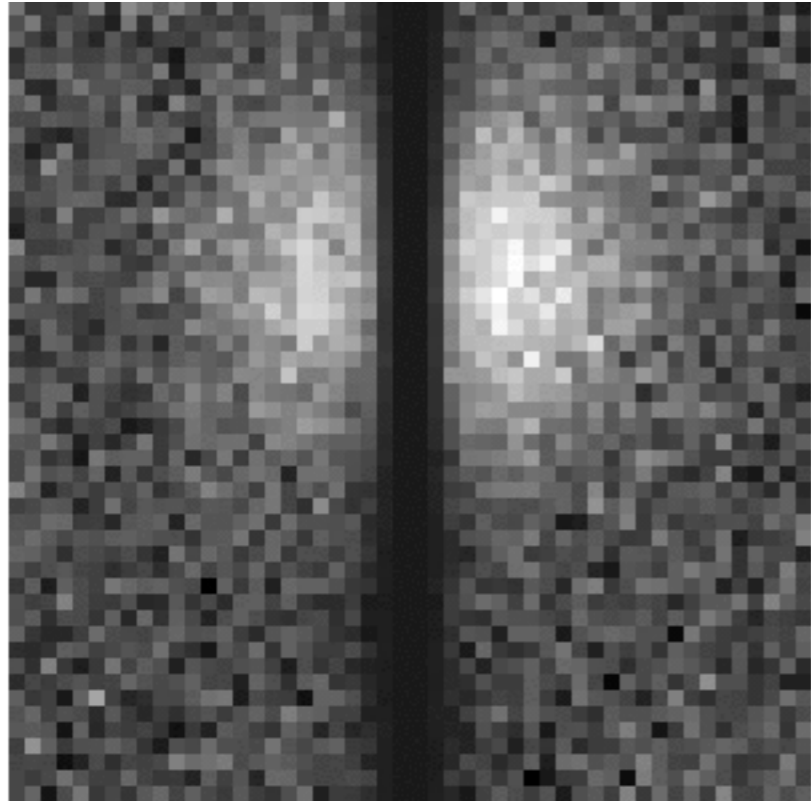
Rocky

0.4 AU

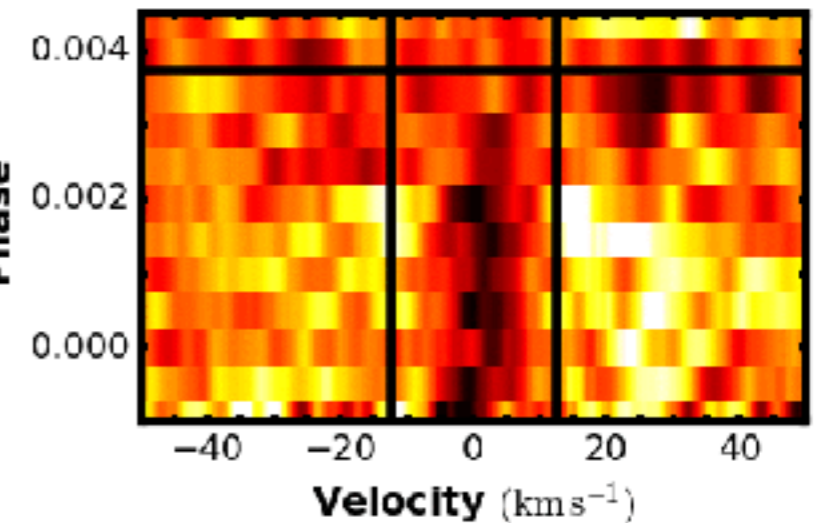
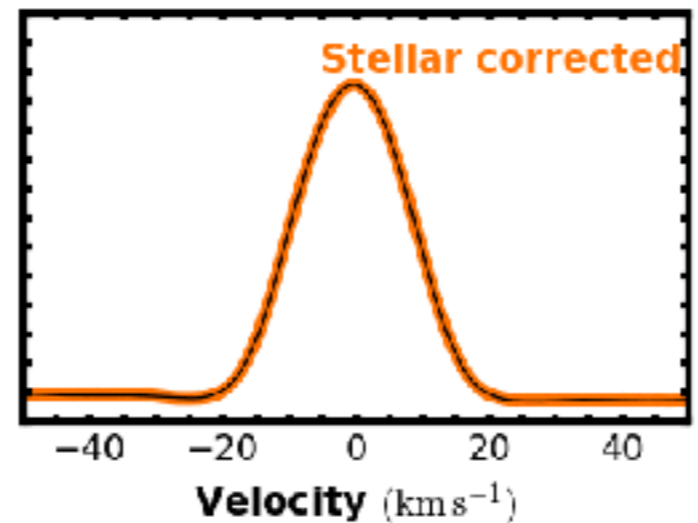
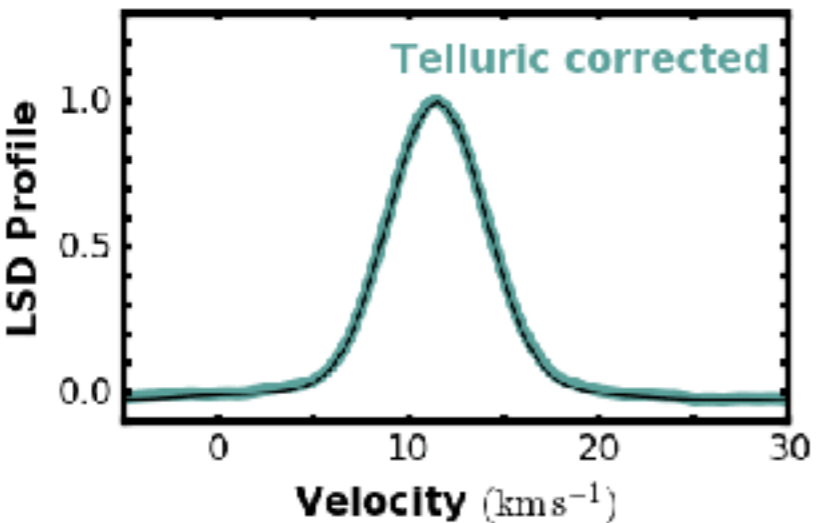
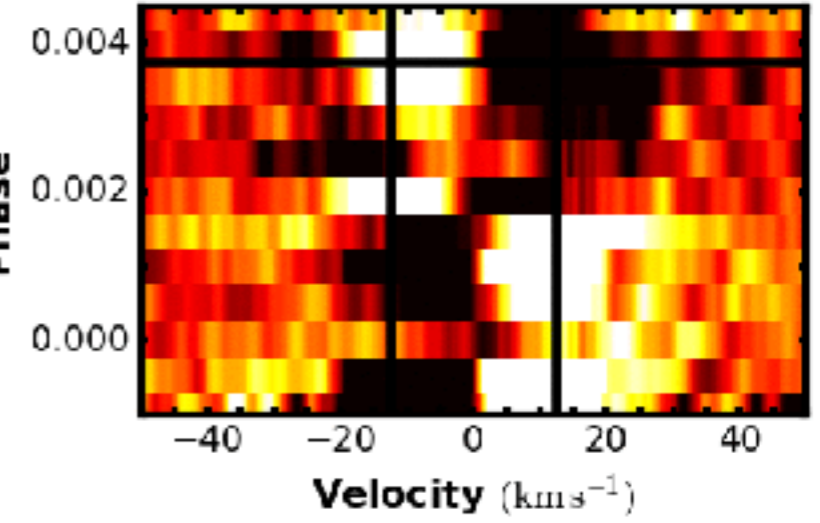
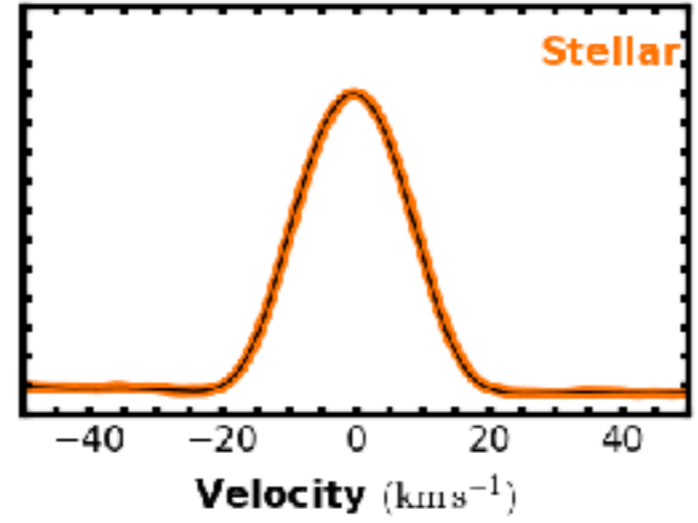
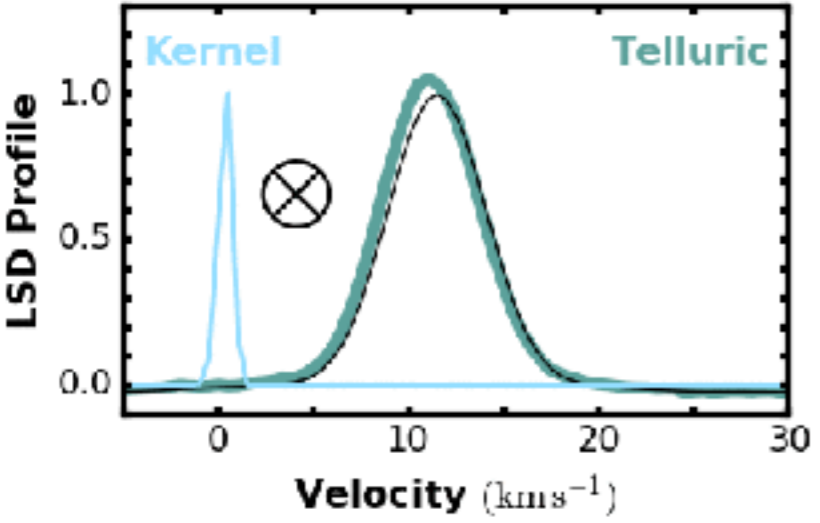
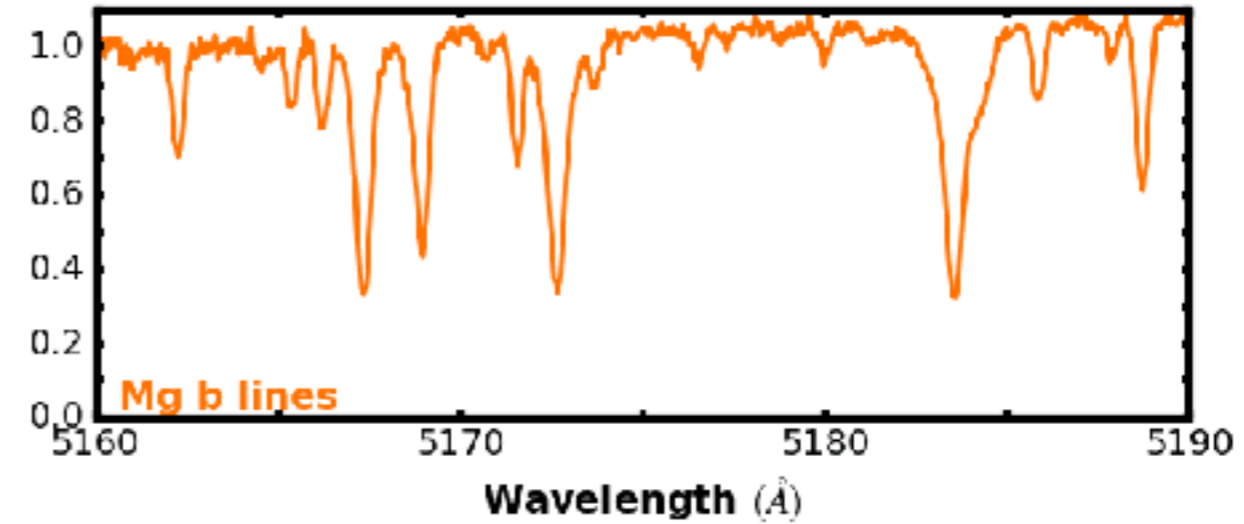
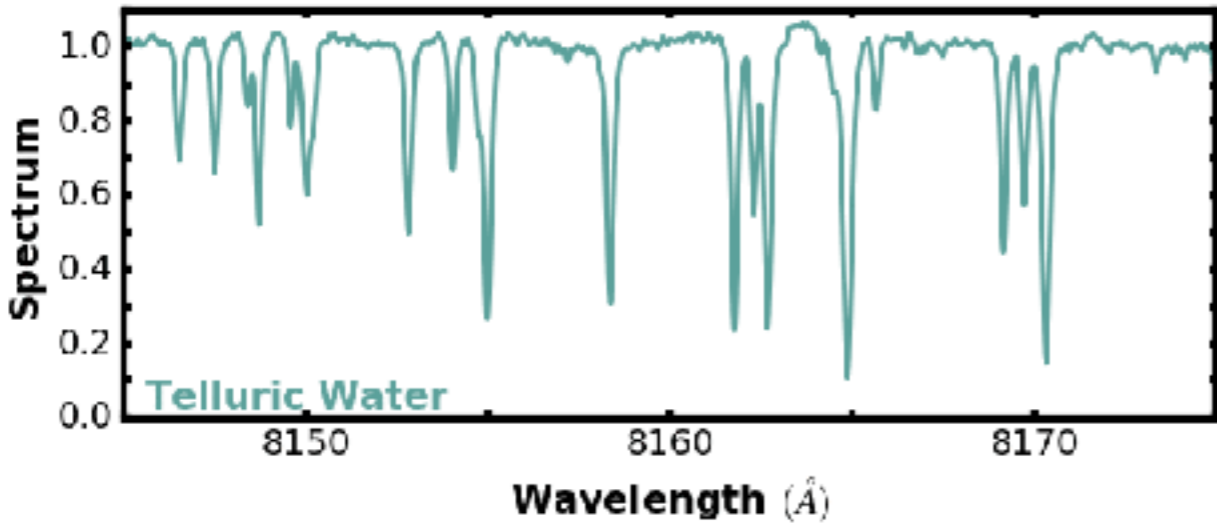
HD 106315 - Rapidly rotating V=9 F star



Slit-based variations!

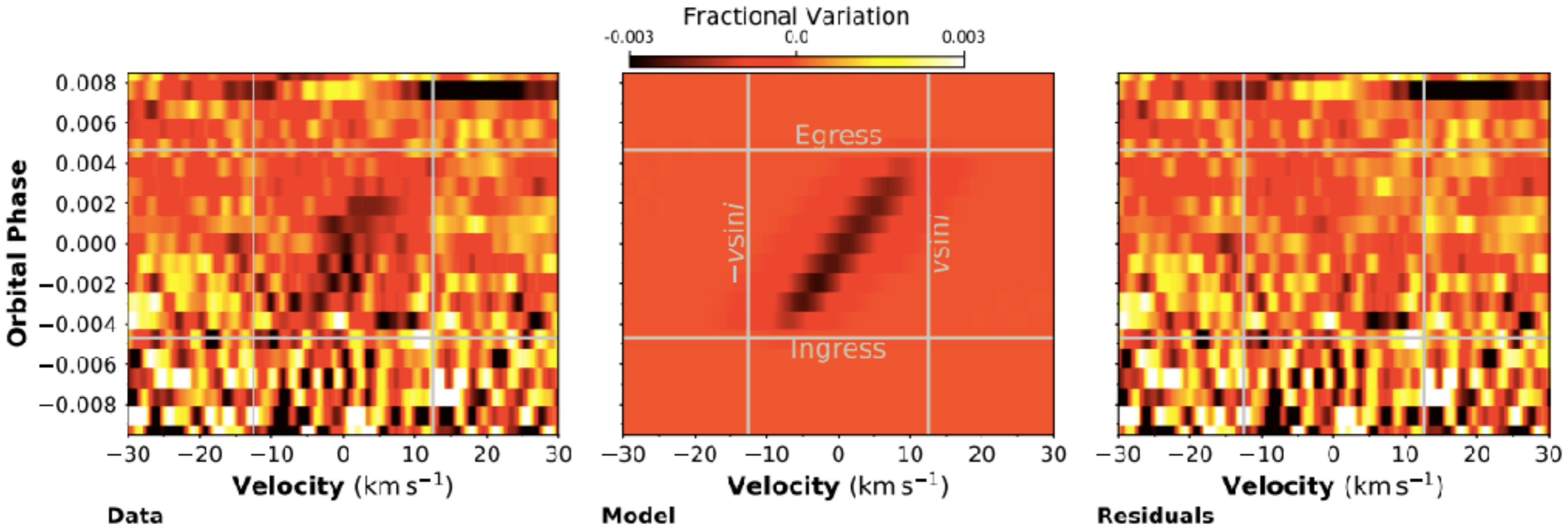


Correction with telluric lines



Even the obliquities of warm Neptunes – HD 106315c

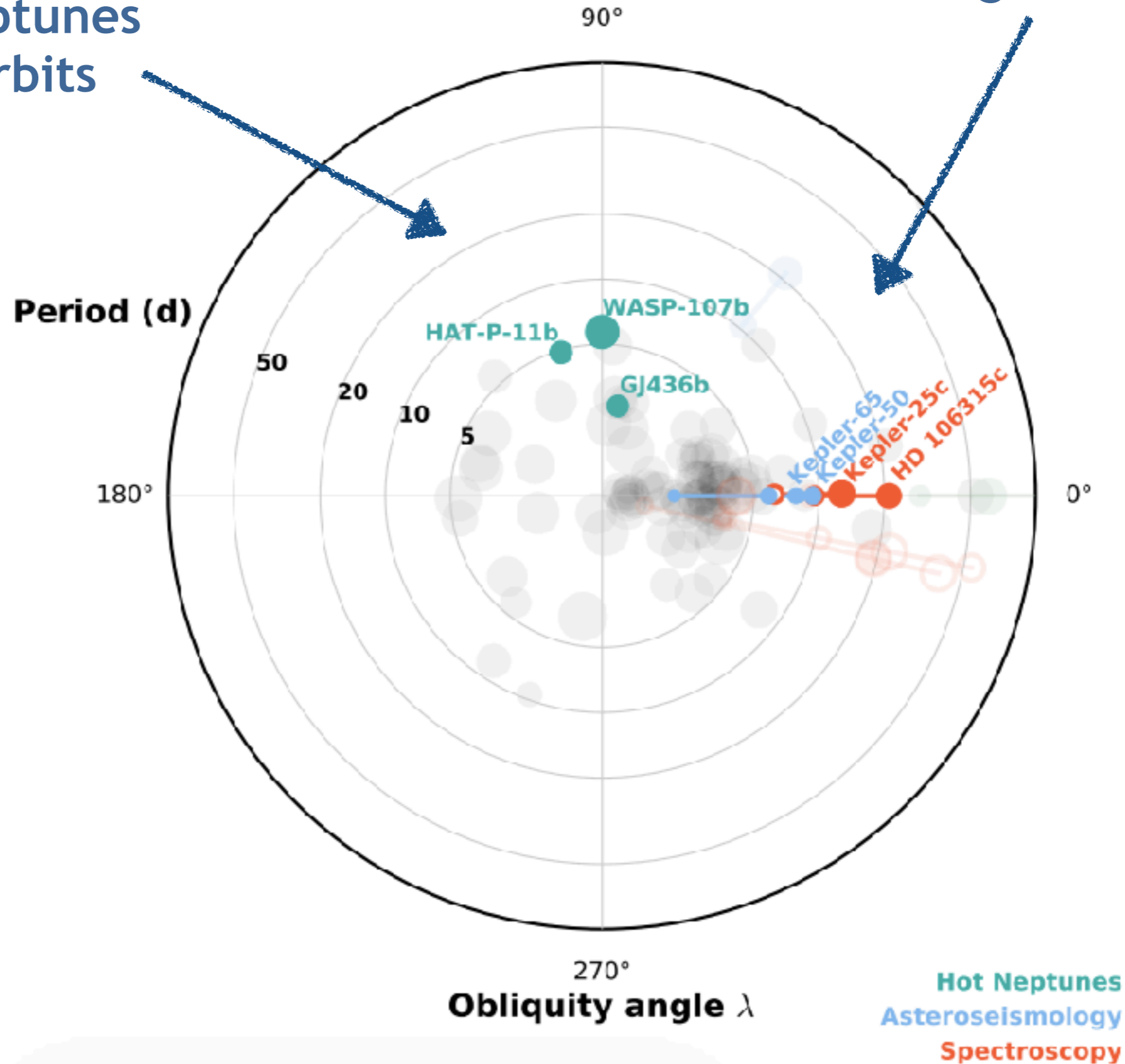
MIKE + TRES + HARPS



Dependence on planet mass – Neptunes

Warm Neptune systems well aligned

Single Neptunes in polar orbits



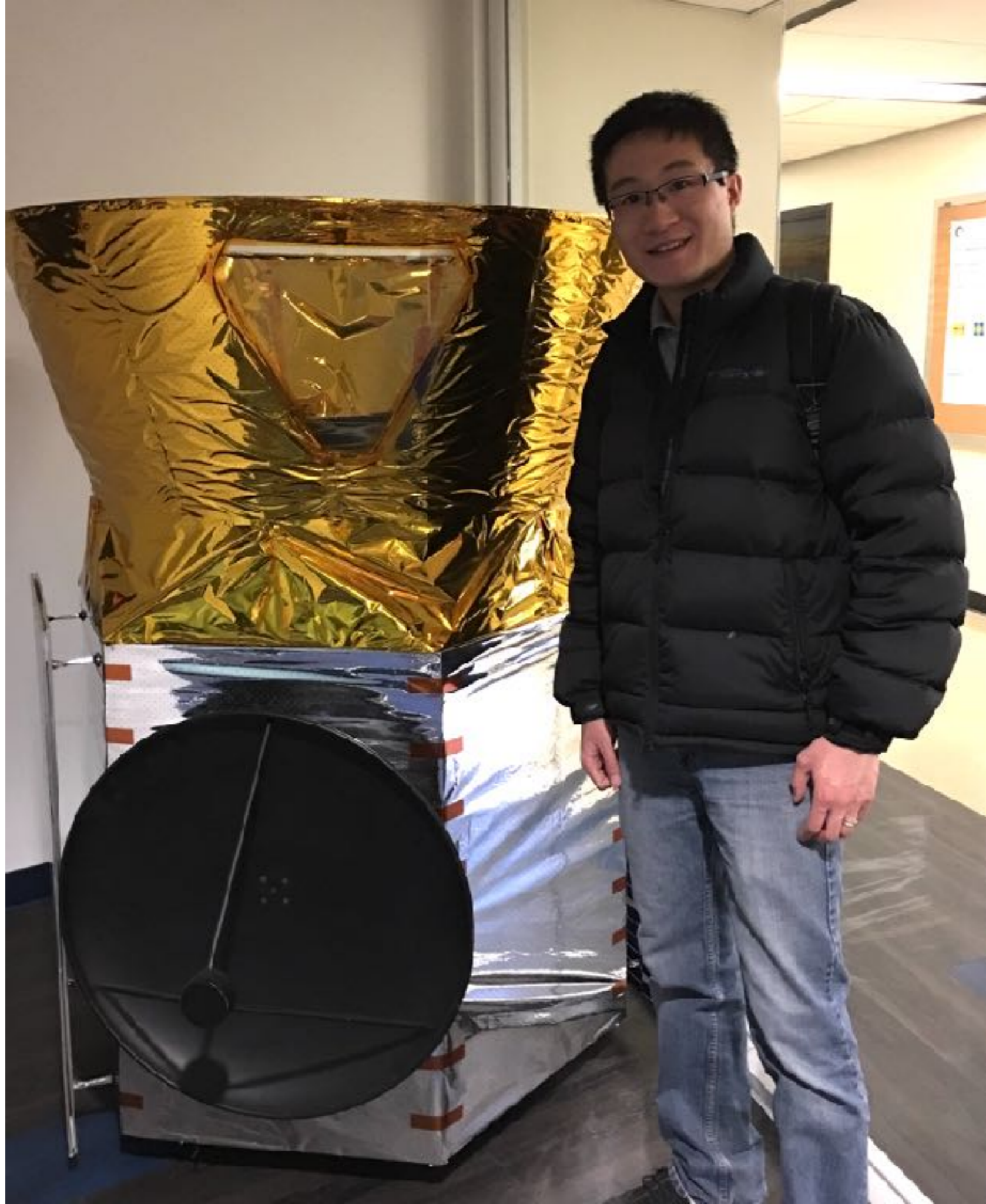
Transiting Exoplanet Survey Satellite

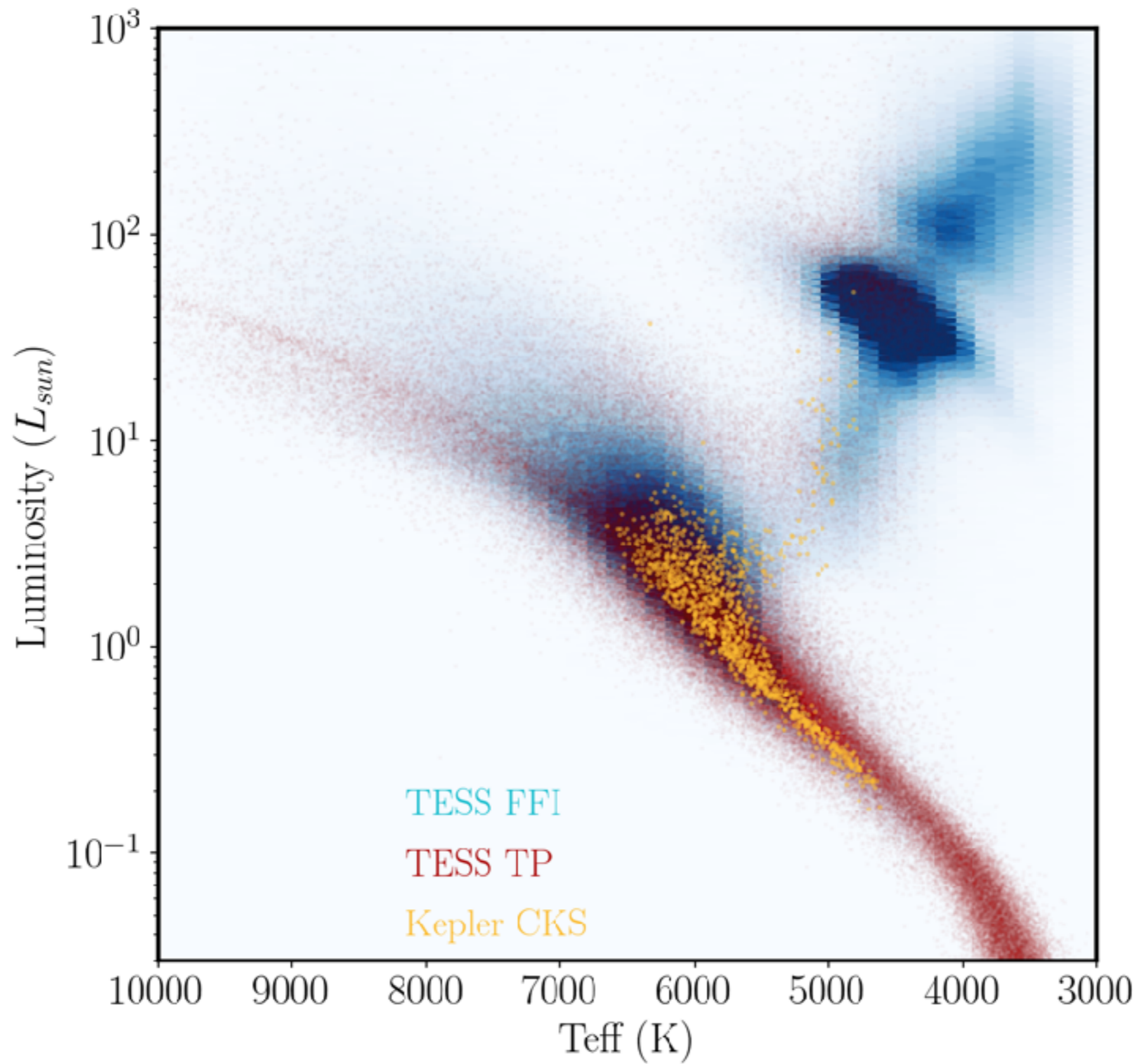




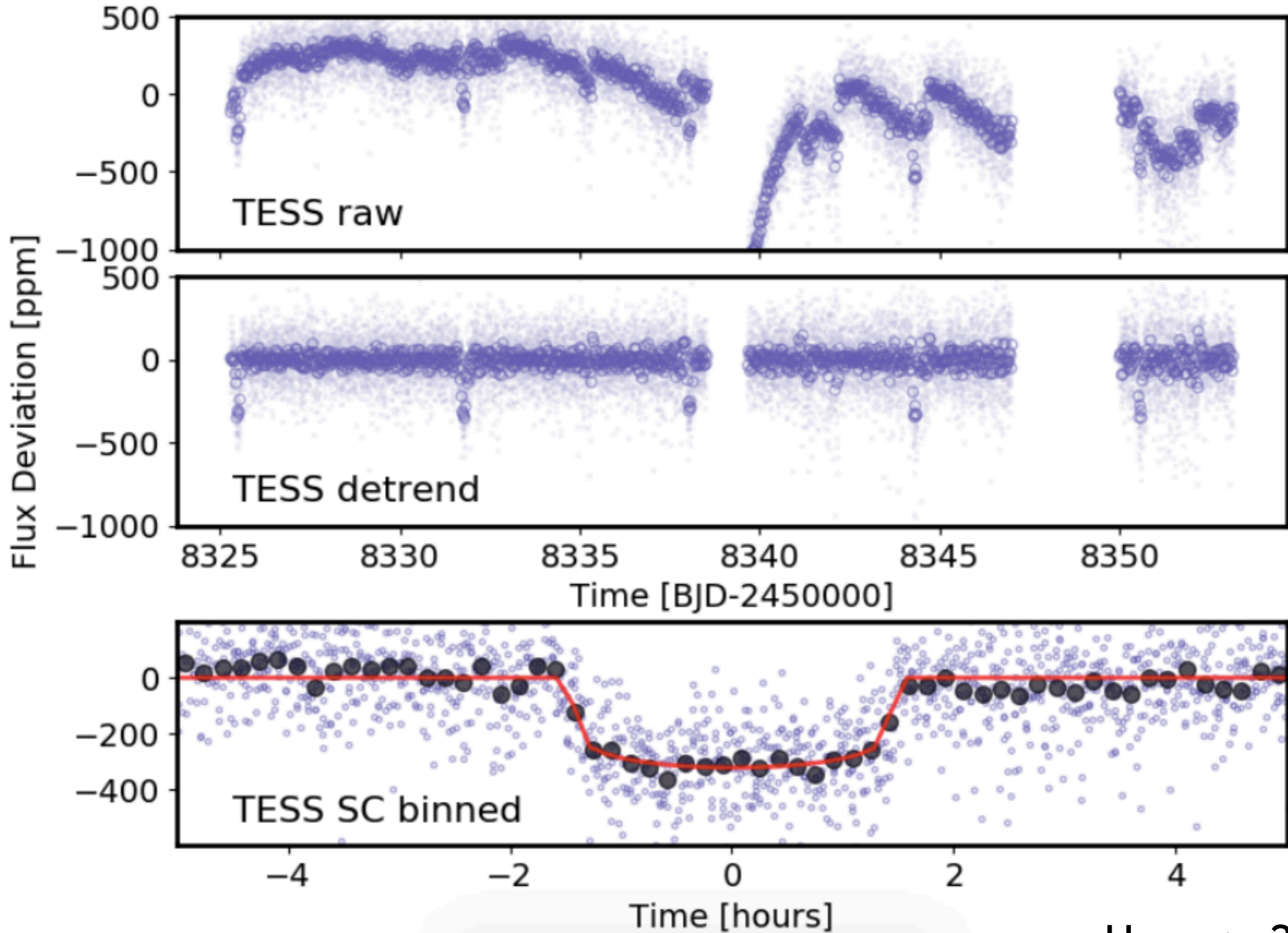




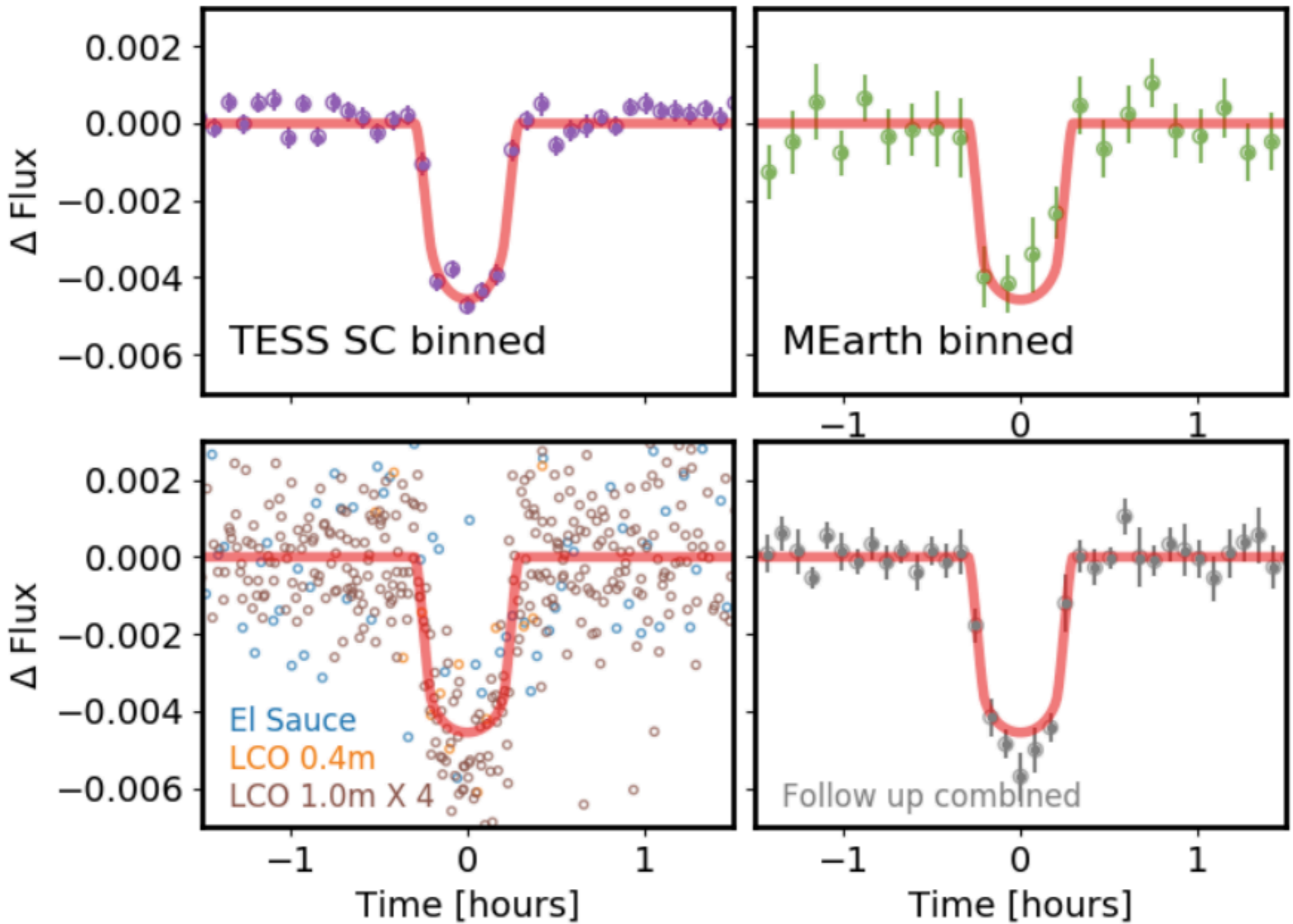




pi Mensae — a Vmag = 5.5 star with a super-Earth at 6 days

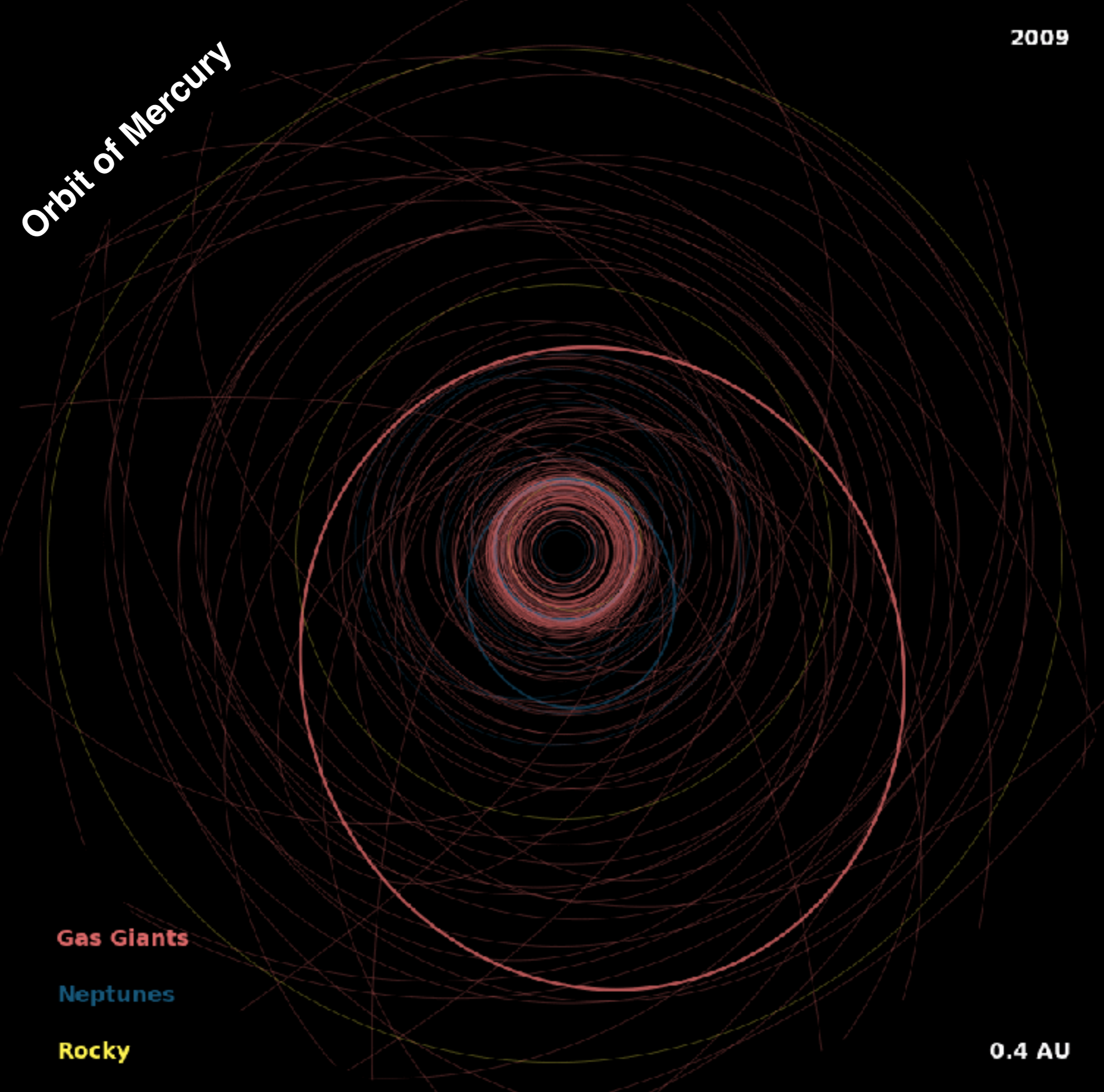


LHS 3844b – 1.3 Re planet in a 11hr orbit around an M-dwarf



Orbit of Mercury

2009



Gas Giants

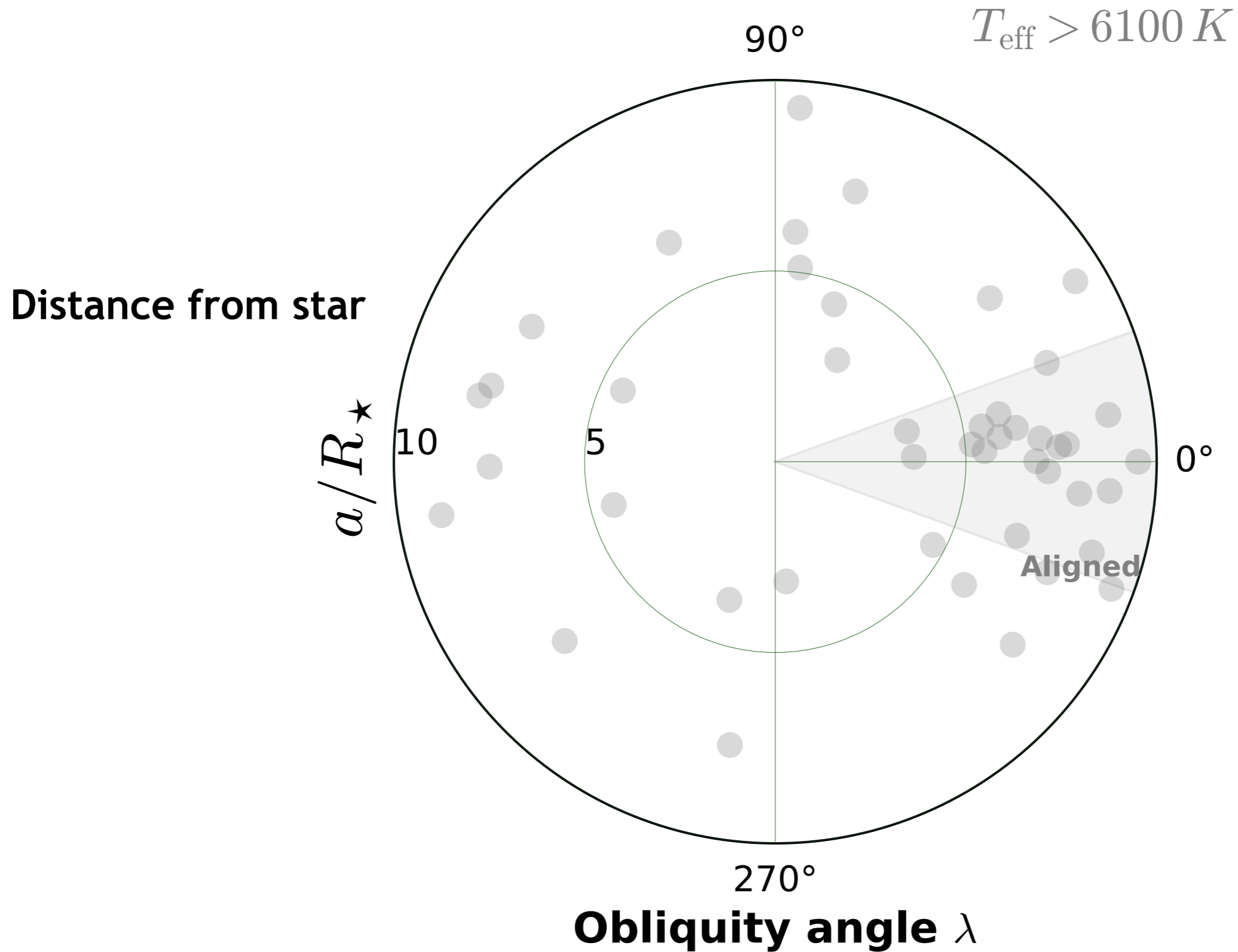
Neptunes

Rocky

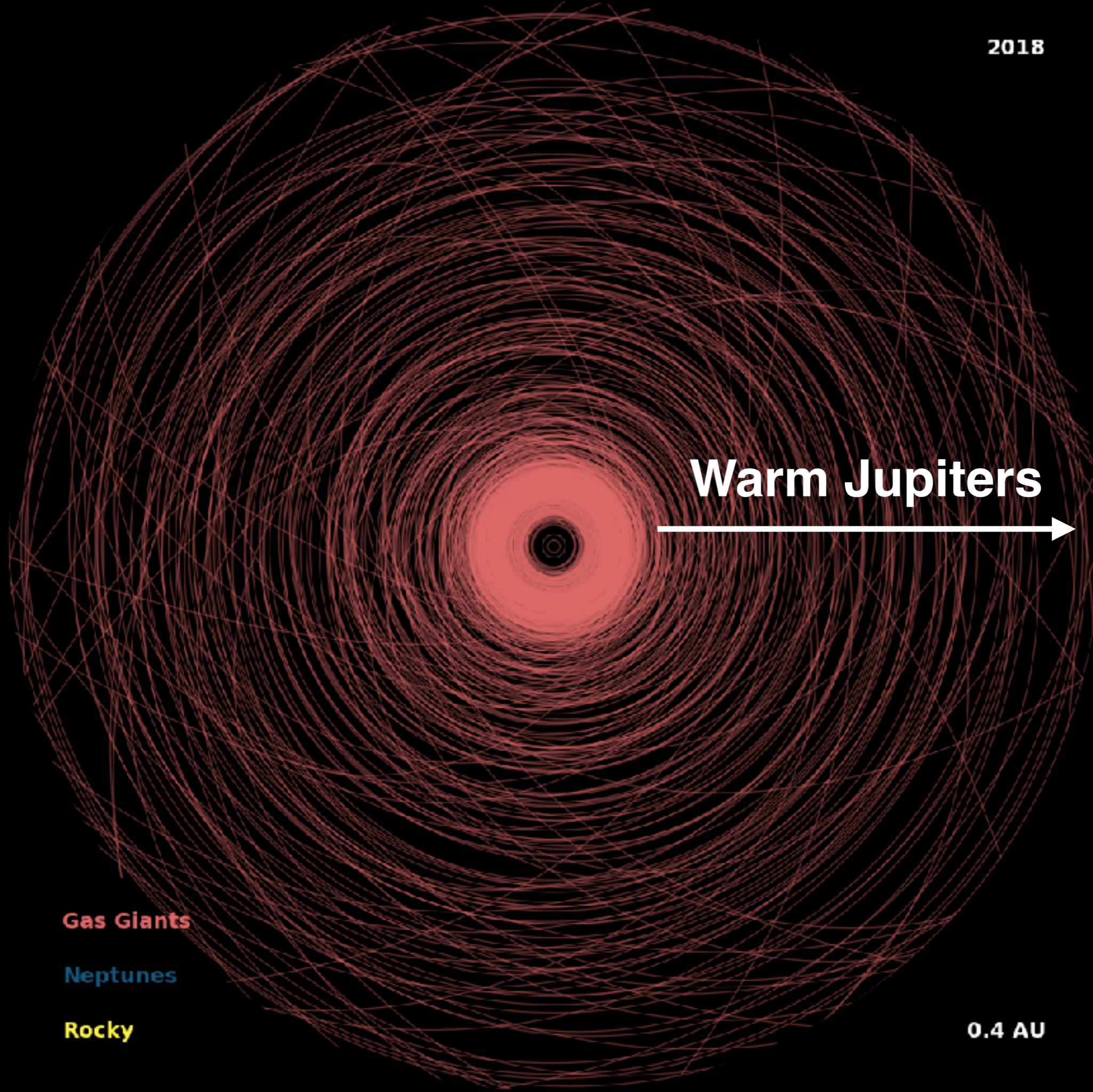
0.4 AU

Backup Slides

Dependence on effective temperature – Hot Jupiters



2018



Warm Jupiters

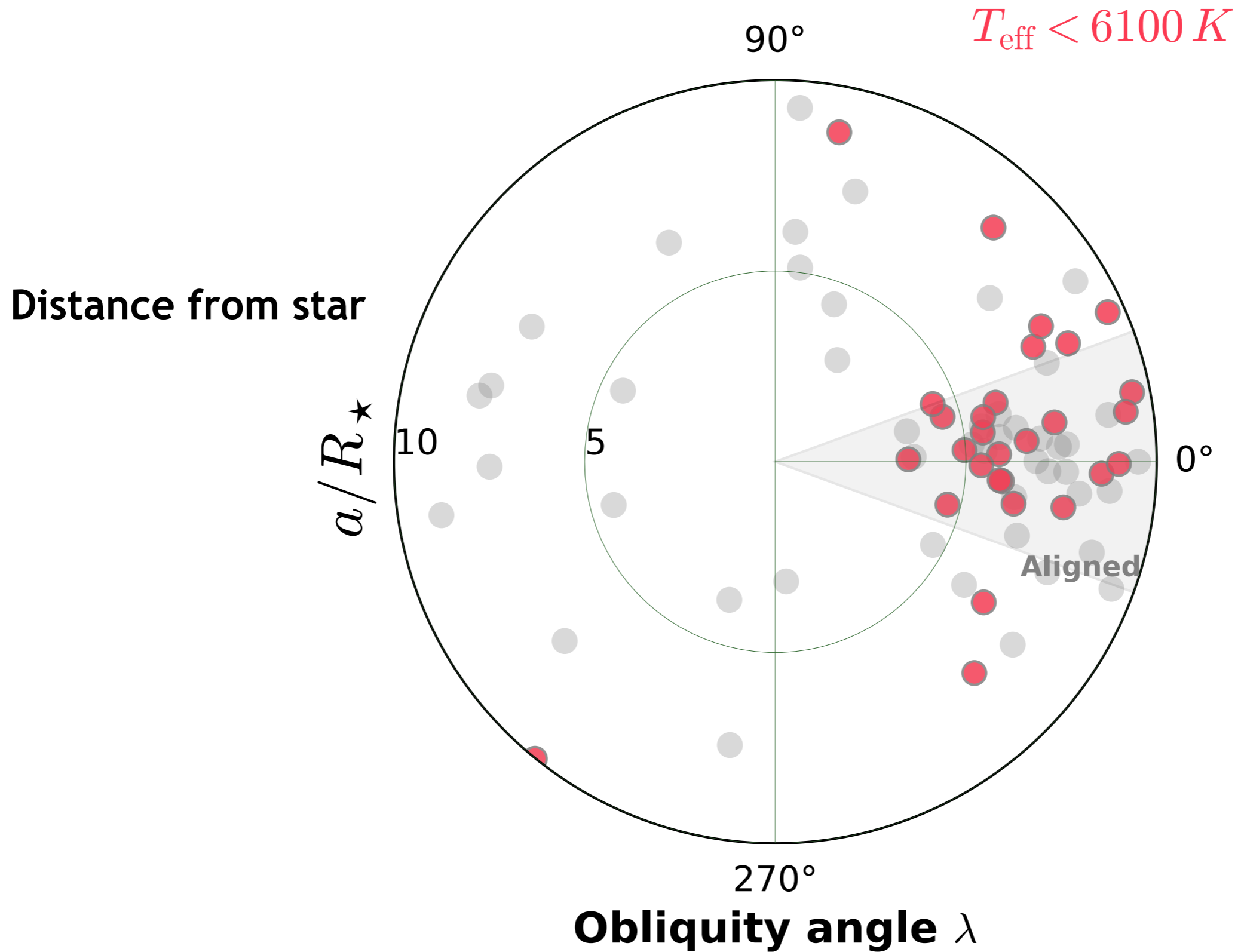
Gas Giants

Neptunes

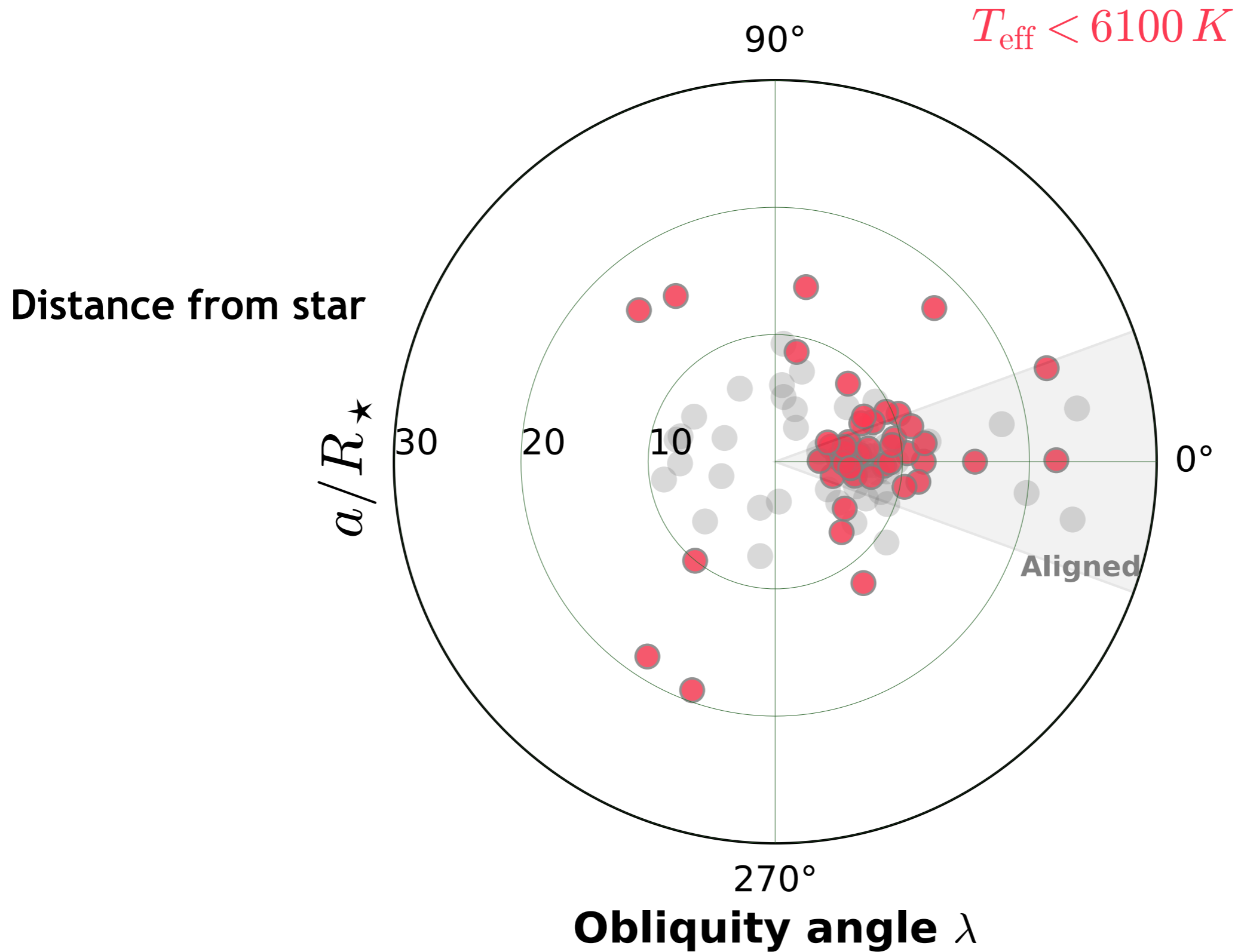
Rocky

0.4 AU

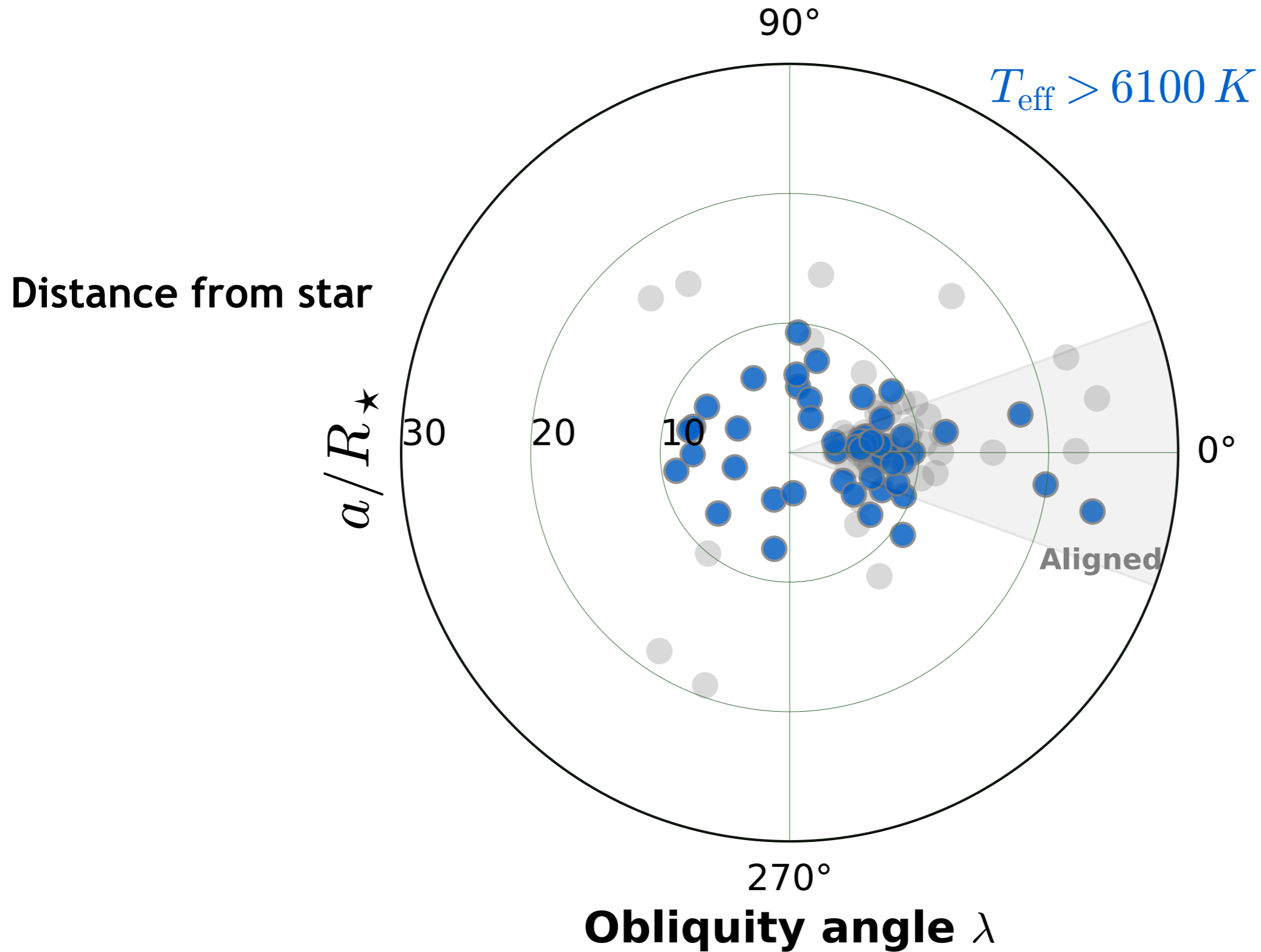
Dependence on effective temperature – Hot Jupiters



Dependence on host star – Warm Jupiters

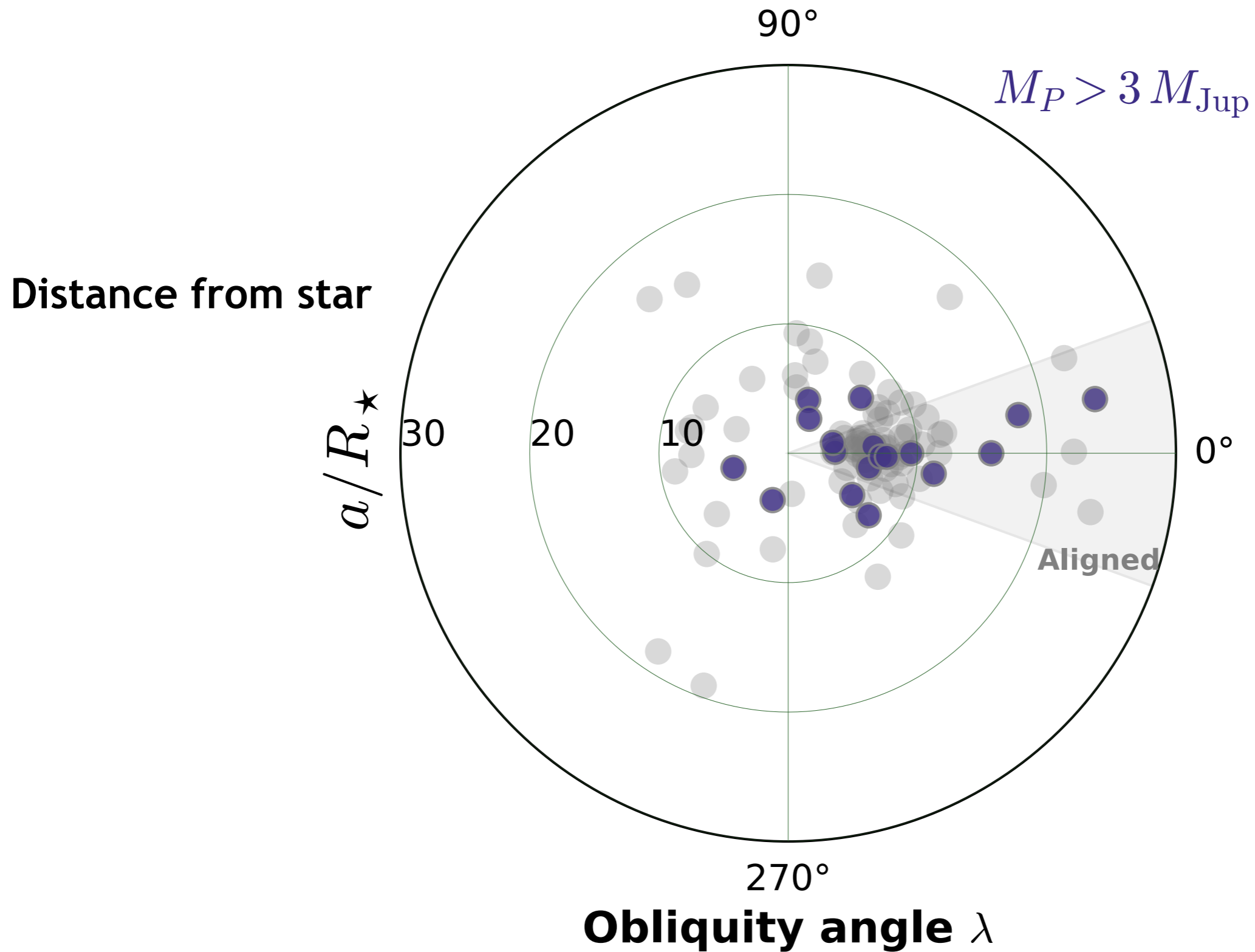


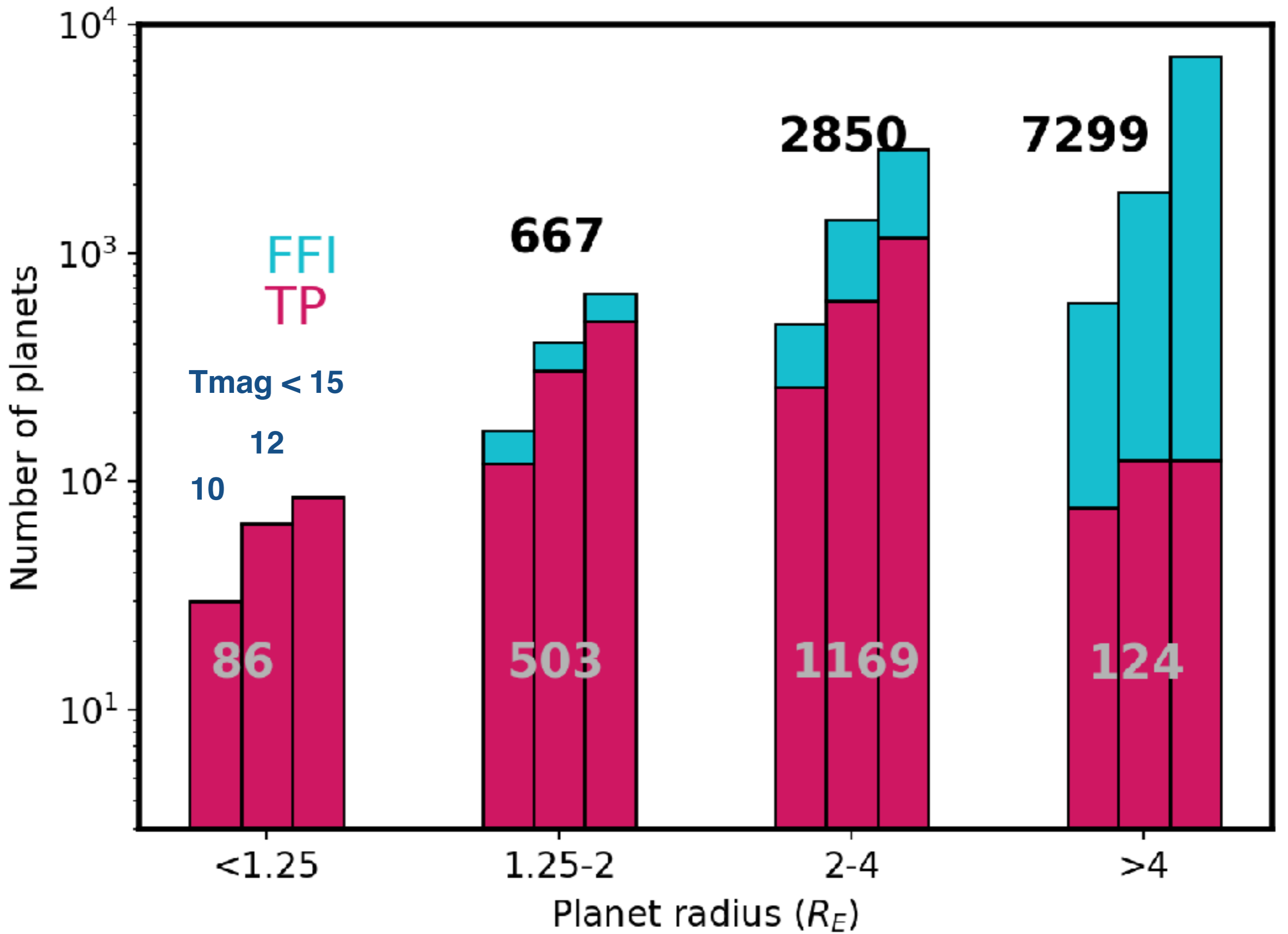
Dependence on host star – Warm Jupiters



Anderson+ 2015, Triaud+ 2017, Yu+ 2018

Dependence on planet mass – Massive Jupiters





pi Mensae – a Vmag = 5.5 star with a super-Earth at 6 days

