SUBARU TELESCOPE 20TH ANNIVERSARY

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Doppler Tomographic Analysis for Planetary Orbital Precession of WASP-33b

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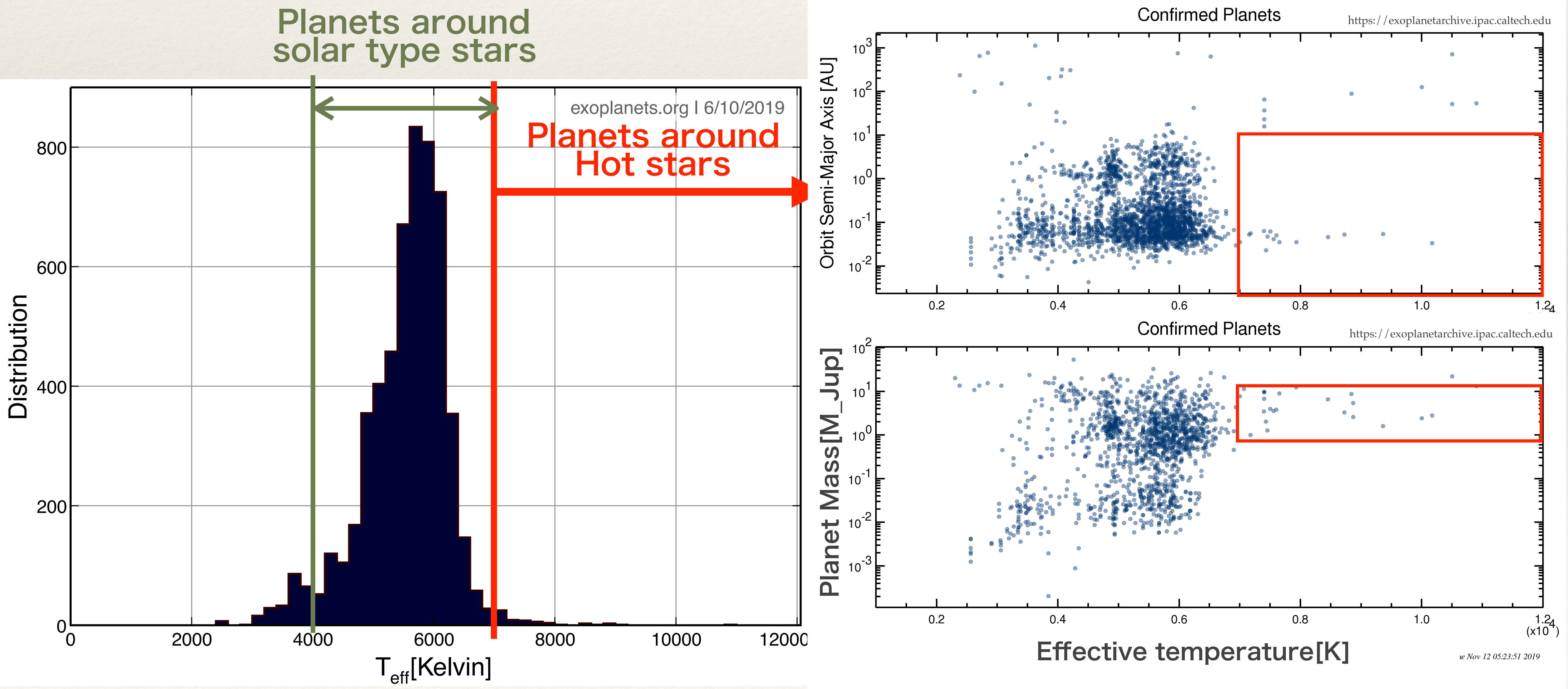
Watanabe et al. 2019 Submitted

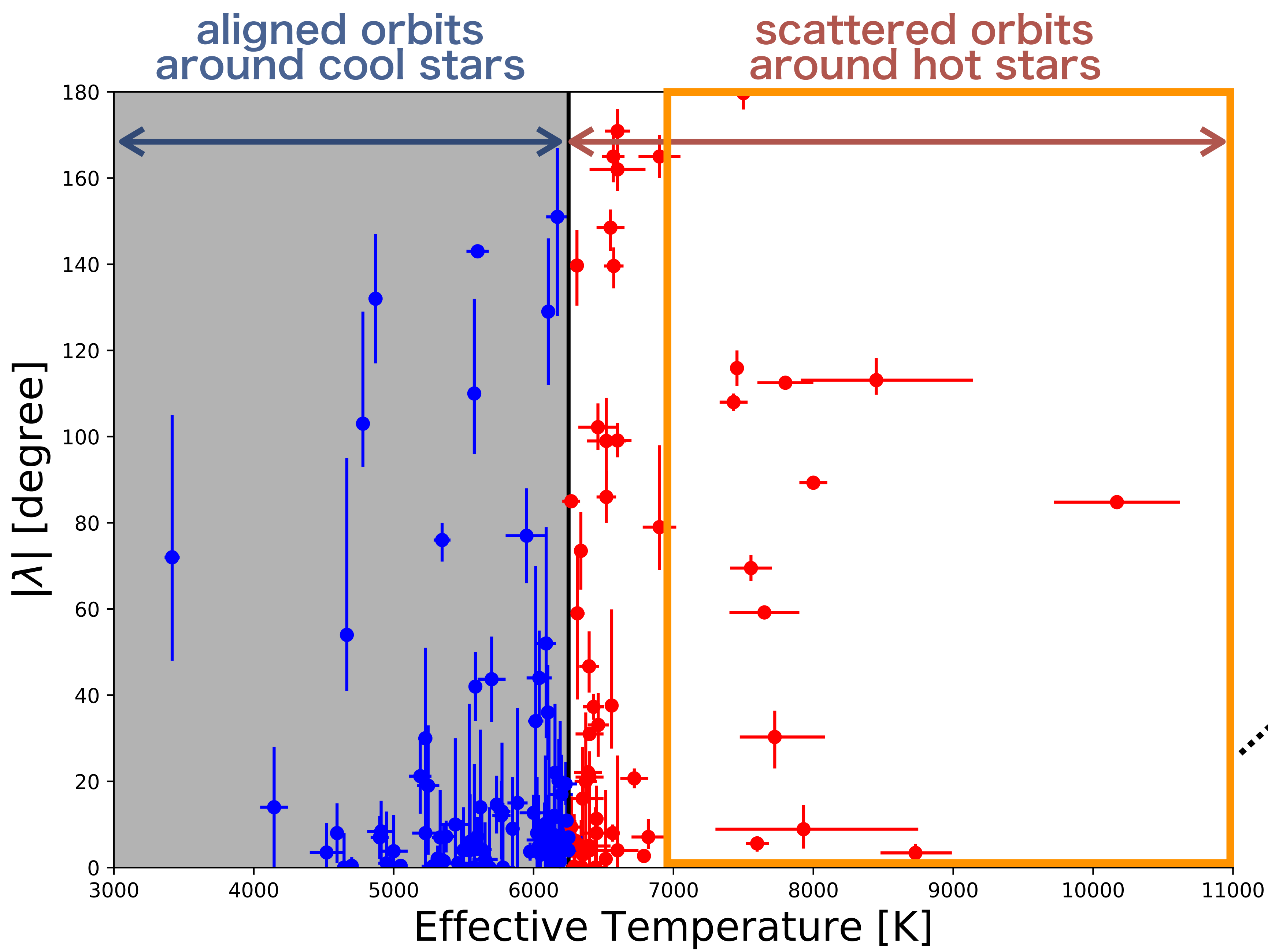
Exoplanets around Hot Stars

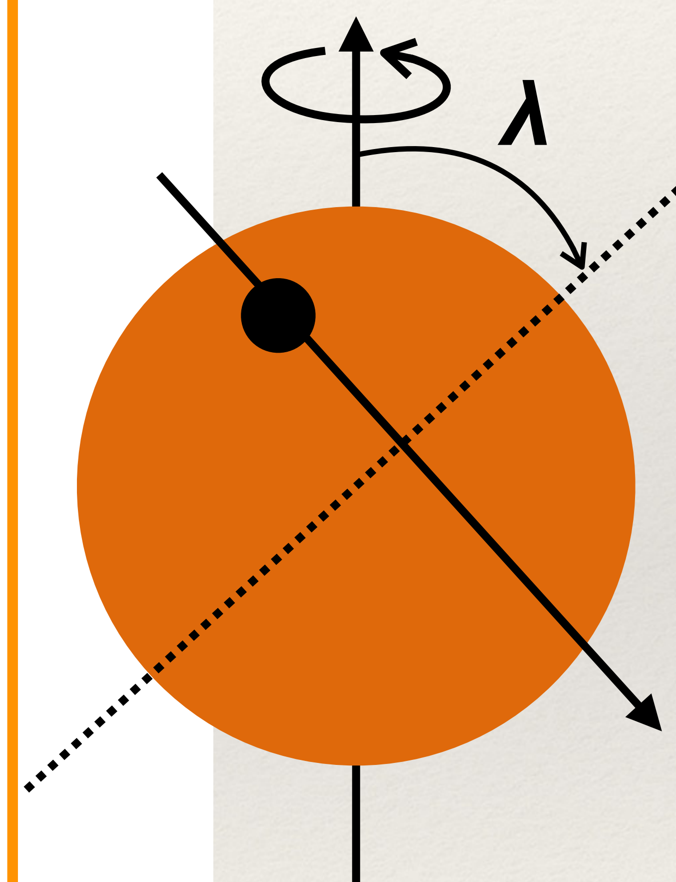
- More than 4,000 exoplanets have been confirmed.
- Confirmed planets around hot stars are few (~20 stars).
- Most of the known planets around hot stars are hot Jupiters.



Feature of HJ around Hot Star

- Wide range of projected spin-orbit obliquities

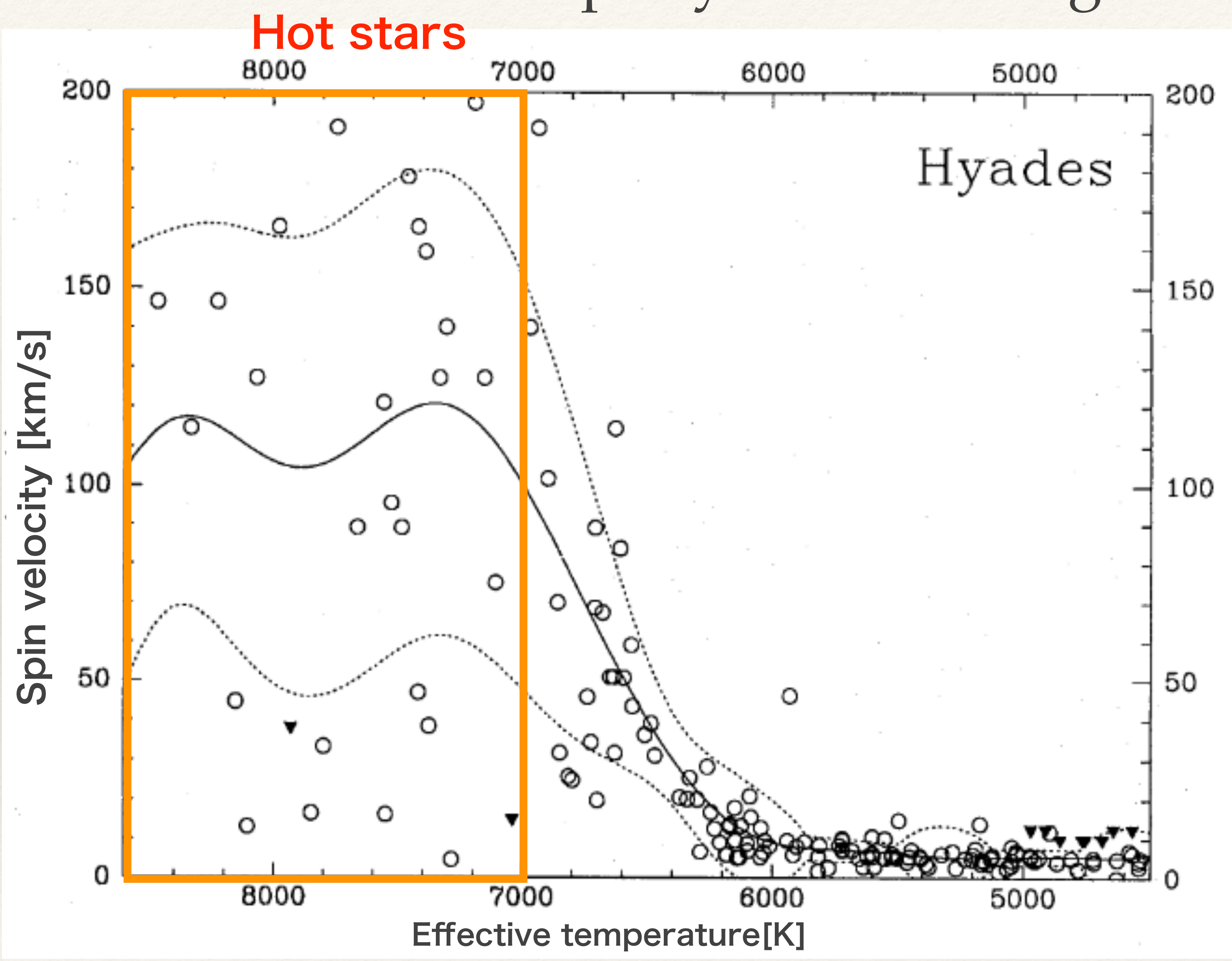


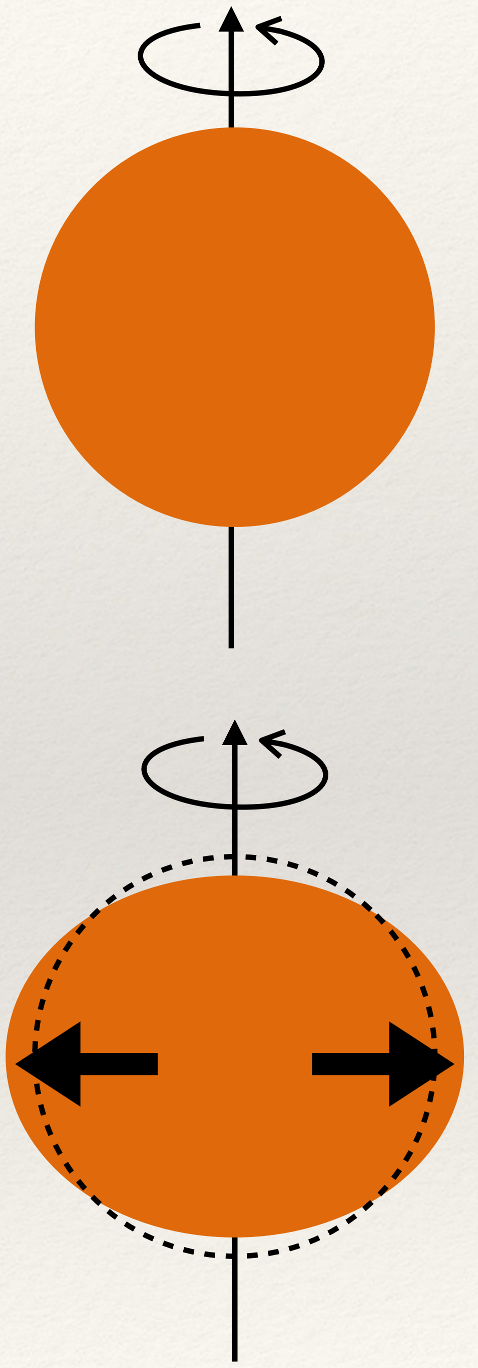


http://www.astro.keele.ac.uk/jkt/tepcat/

Features of Hot Star

- Hot stars rotate rapidly → Flattening themselves

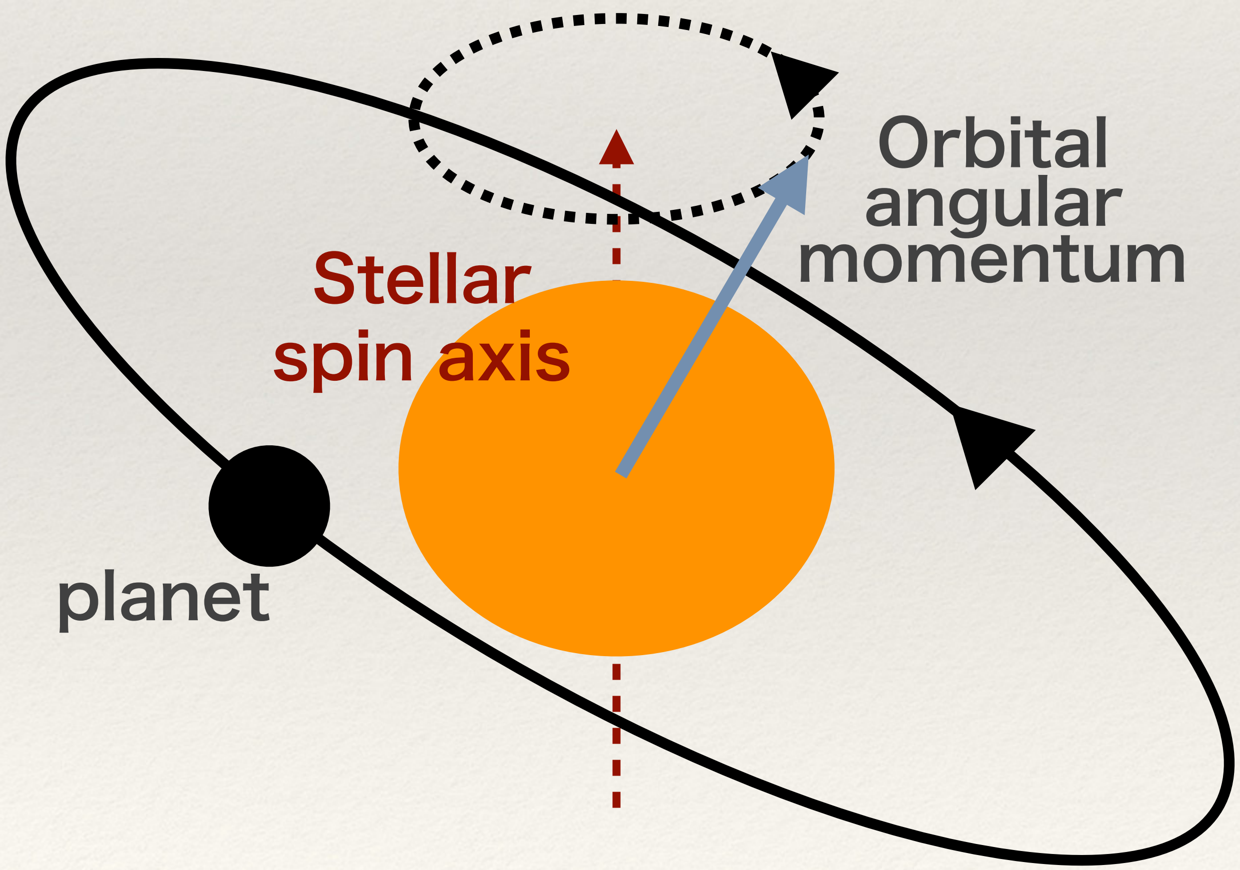


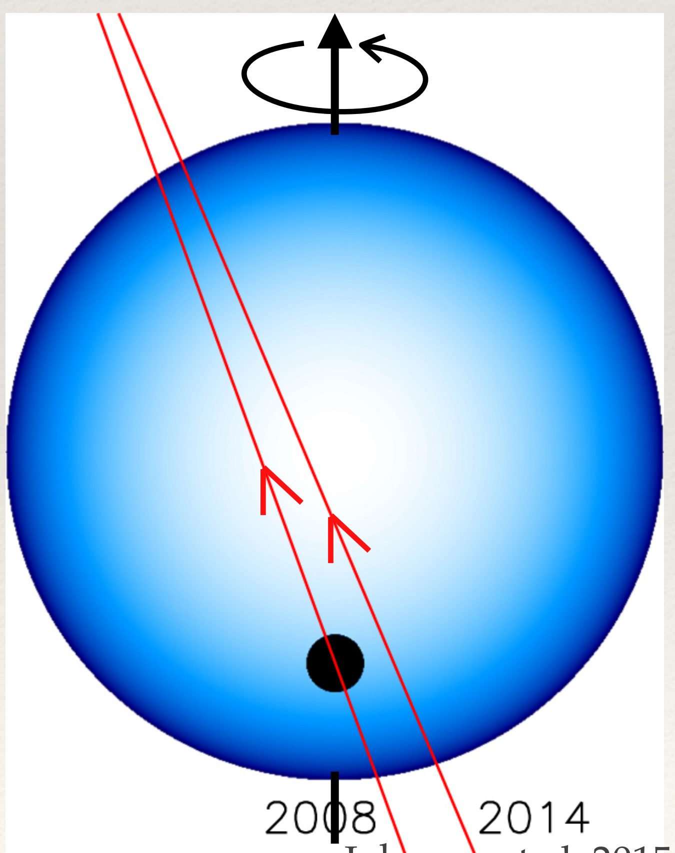


Gaige (1993)

Orbital Nodal Precession

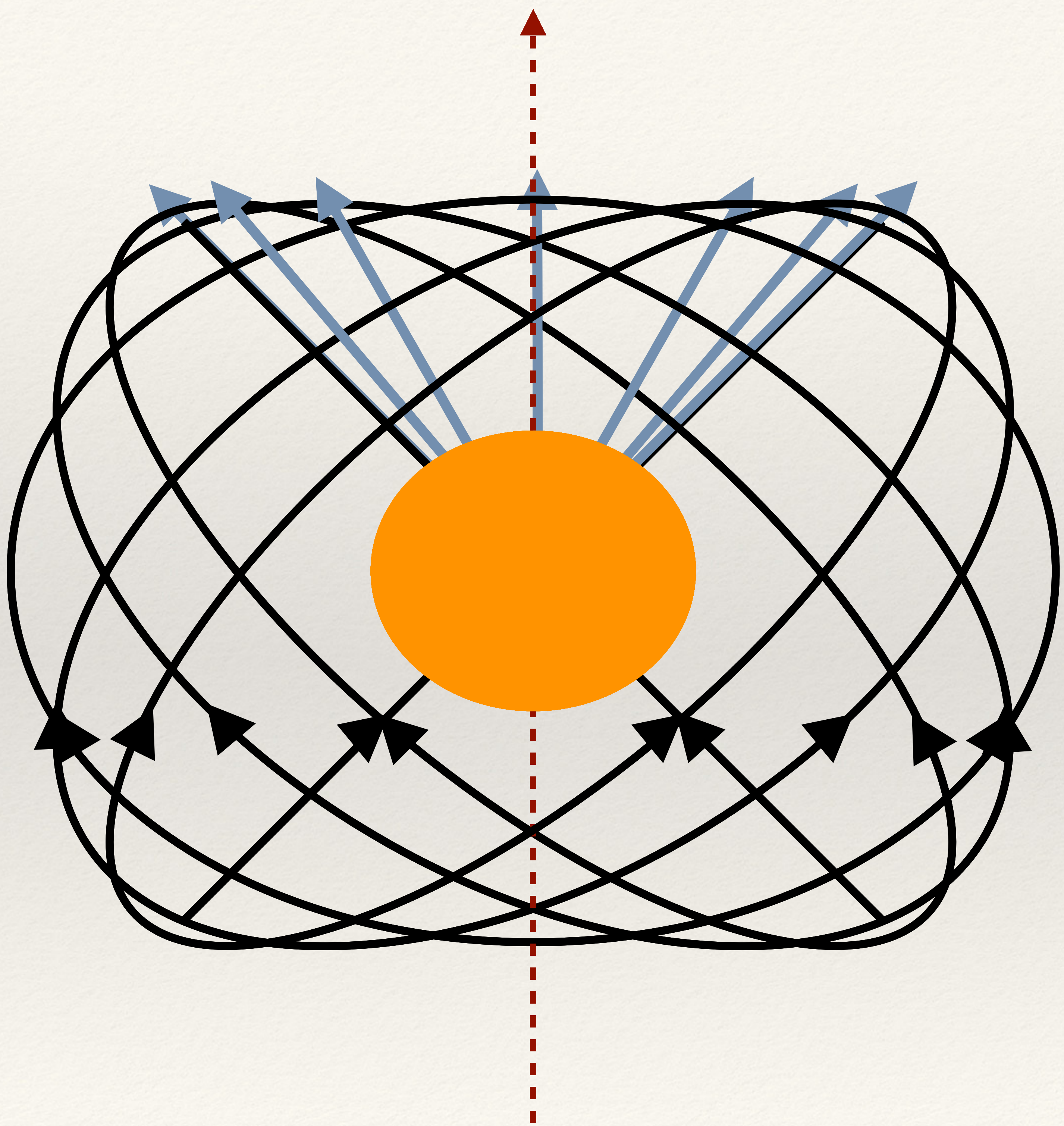
- This precession is caused by an interaction between a planet and a single flattened host star.
- Orbital nodal precession changes transit trajectory.
- Only two planets have been detected their nodal precession around each single star (Kepler-13Ab & WASP-33b).
  (Szabó et al. 2012) (Johnson et al. 2015)





Johnson et al. 2015

Orbital Nodal Precession



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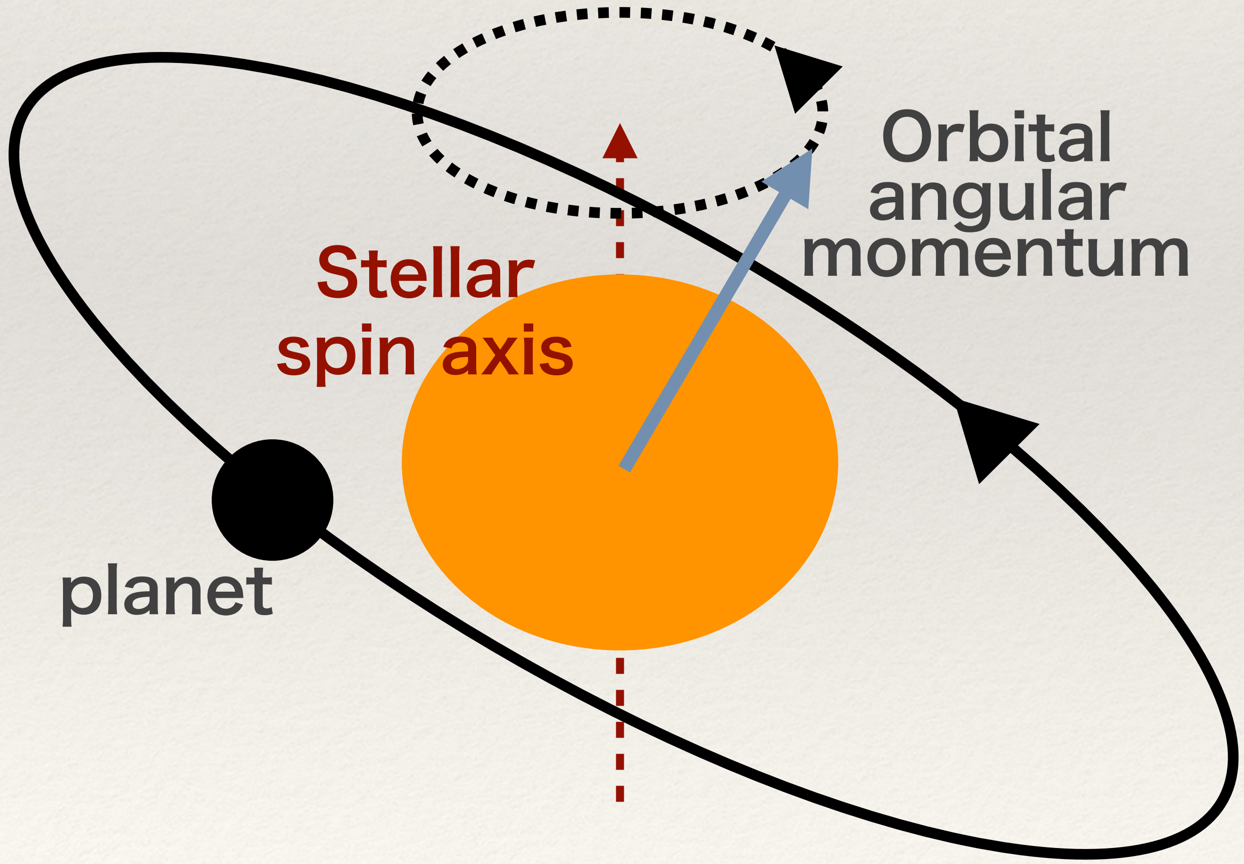
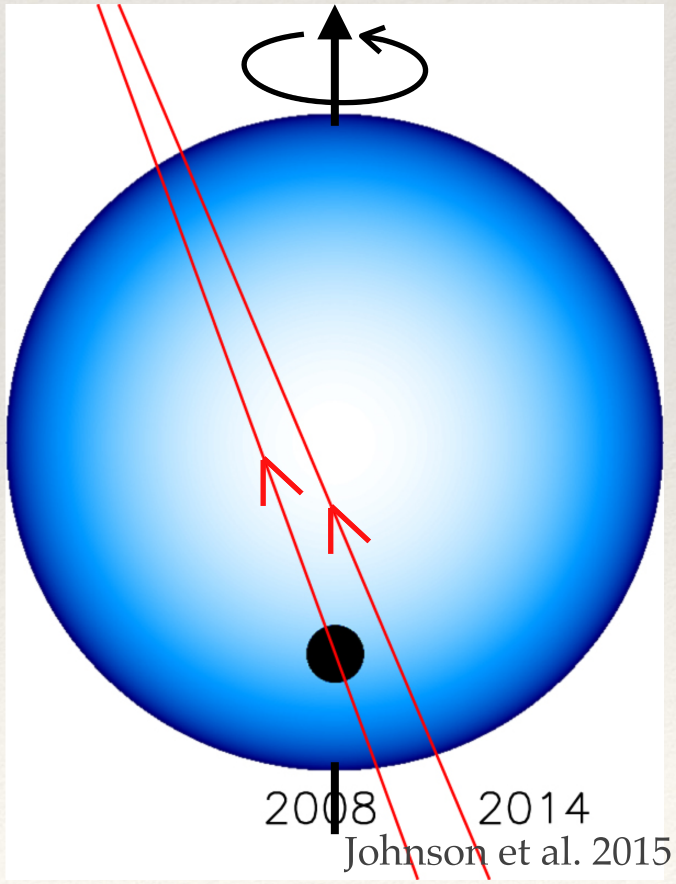
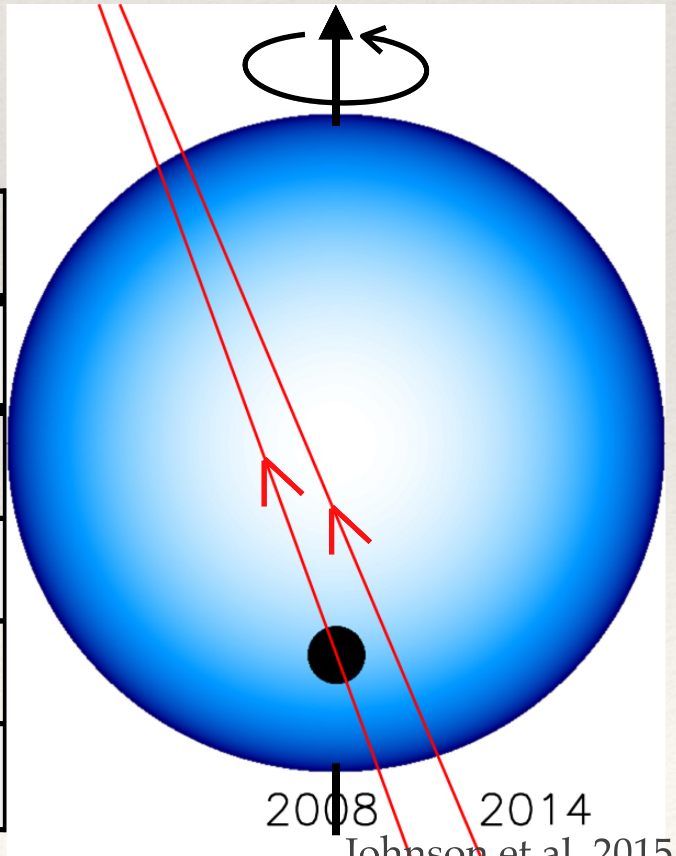




WASP-33b

- A hot Jupiter (P_{orb}~1.2day) around an A-type (T_{eff}~7430K) star
- Misaligned near-polar orbit.
- The host star rotates rapidly (VsinI ~90km/s) and exhibits pulsations. (Collier Cameron et al. 2010b)
- Nodal precession was detected by only 2 datasets (2008 & 2014) (Johnson et al. 2015)
- **Measure the precession more precisely using 2011 (HDS) data and previous ones.**

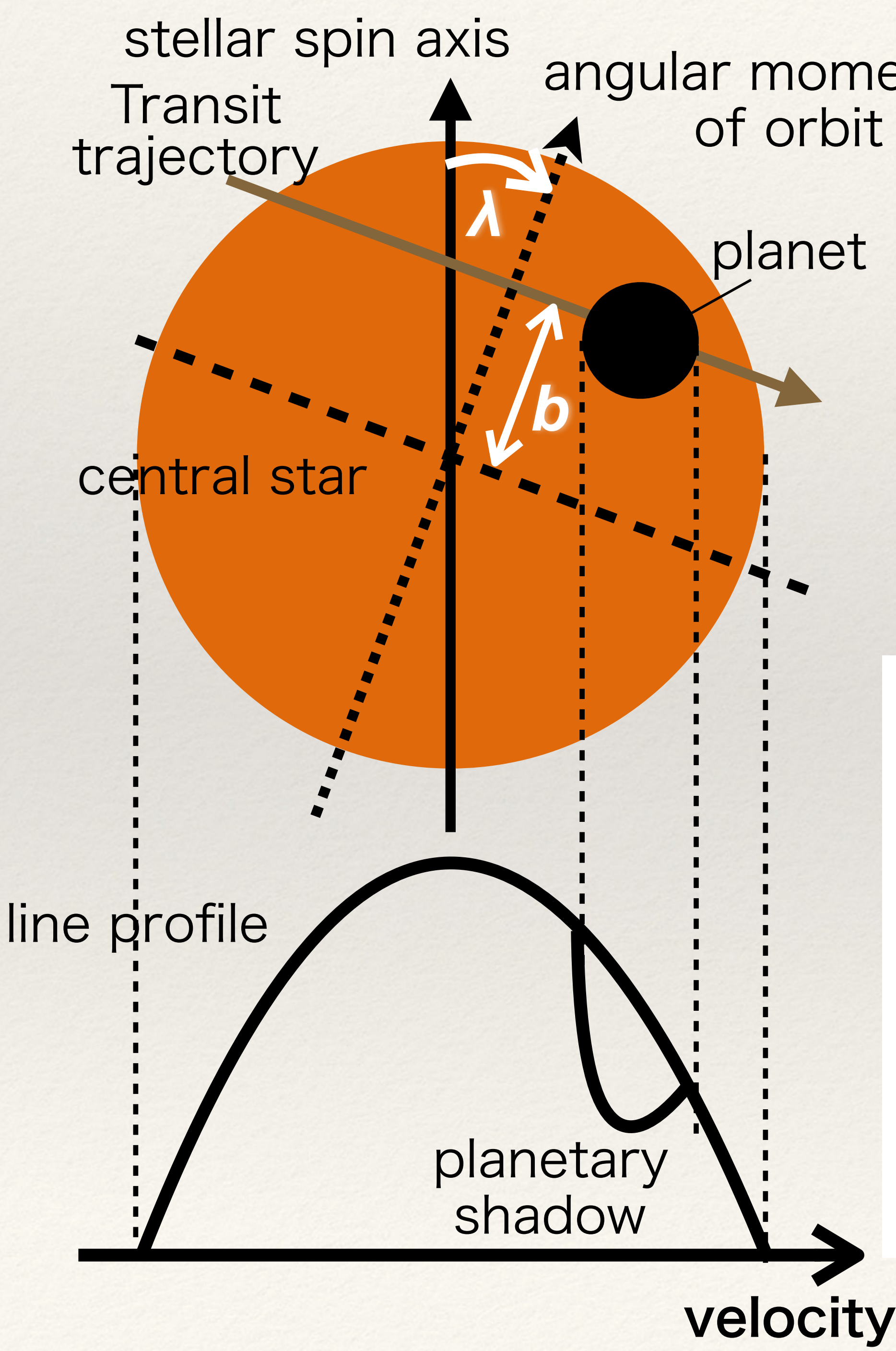
research	J+15	This study	J+15
date	2008 Nov 12	2011 Oct 19	2014 Oct 4
instrument	TS23/HJST	Subaru/HDS	TS23/HJST
resolution	60,000	110,000	60,000
SNR@5000Å	140	160	280
# of spectra	13 (10 in transit)	35 (16 in transit)	21 (10 in transit)

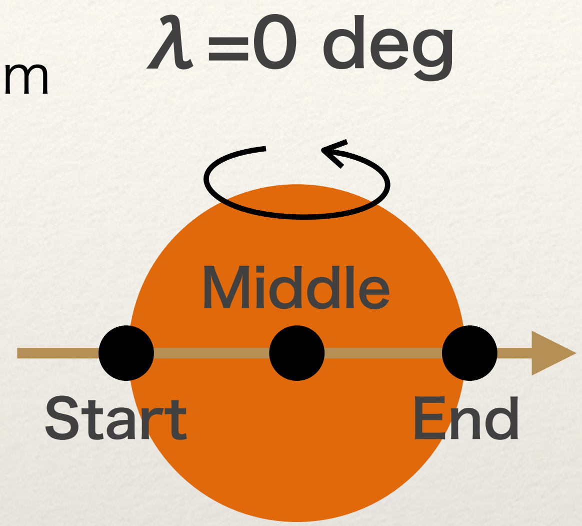


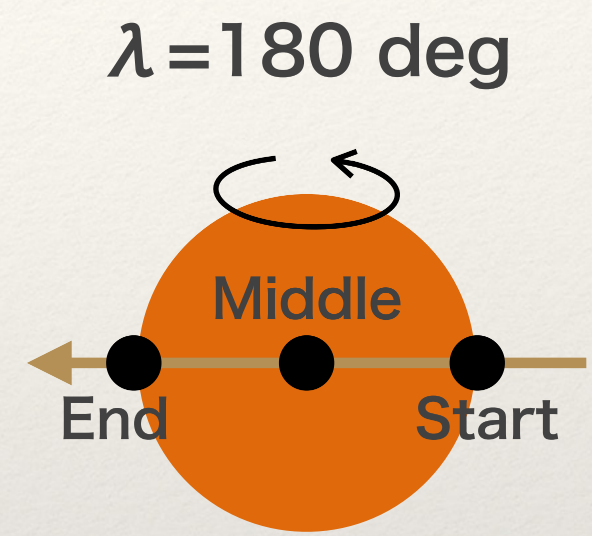
Johnson et al. 2015

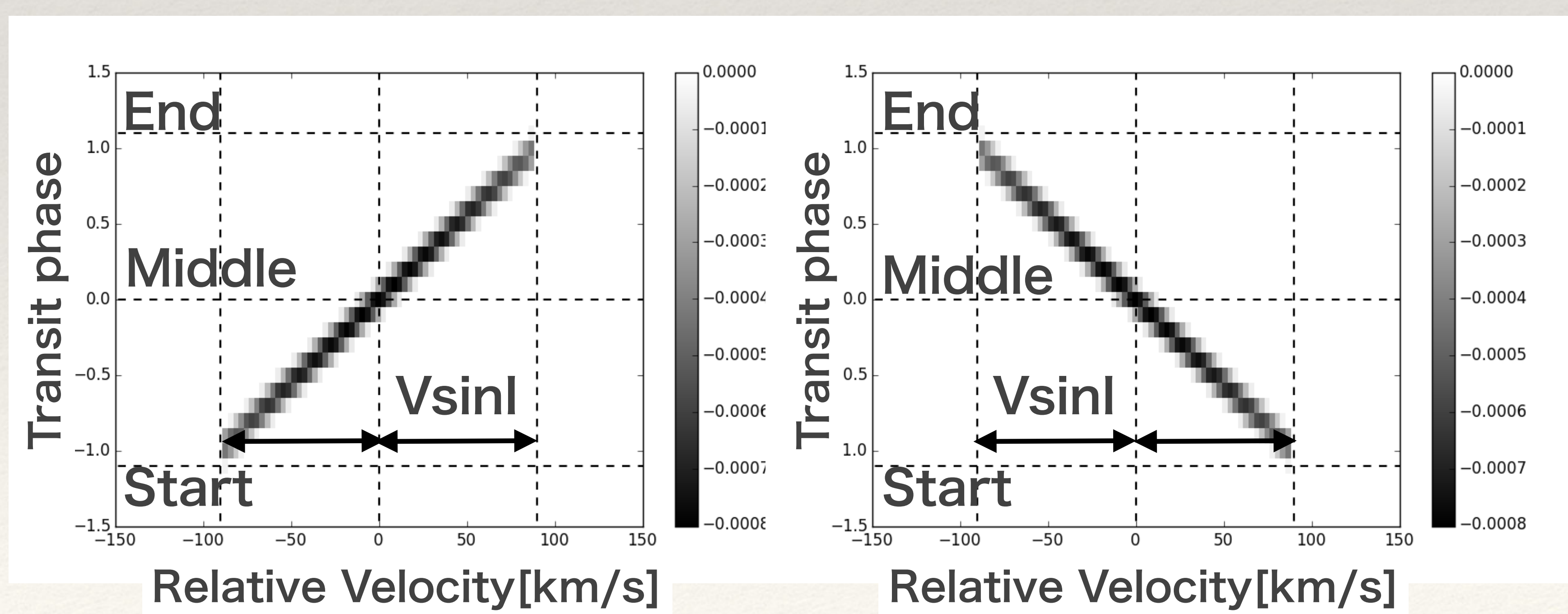
Doppler Tomography (DT)

- To measure spin-orbit obliquity (λ) & impact parameter (b)







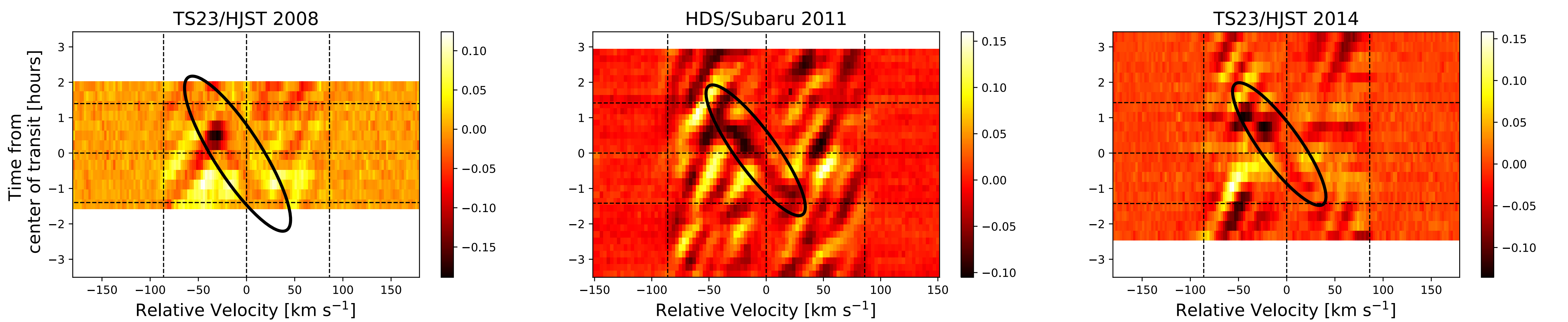


DT of WASP-33b

- There are **a planetary shadow** and pulsation components

Line profile residuals

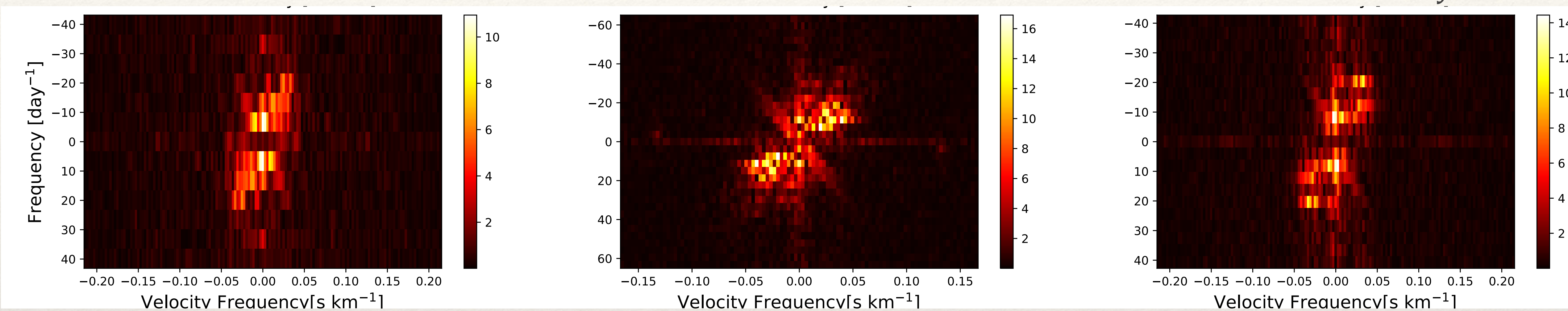
2008 Nov 12 HJST 2011 Oct 19 HDS 2014 Oct 4 HJST



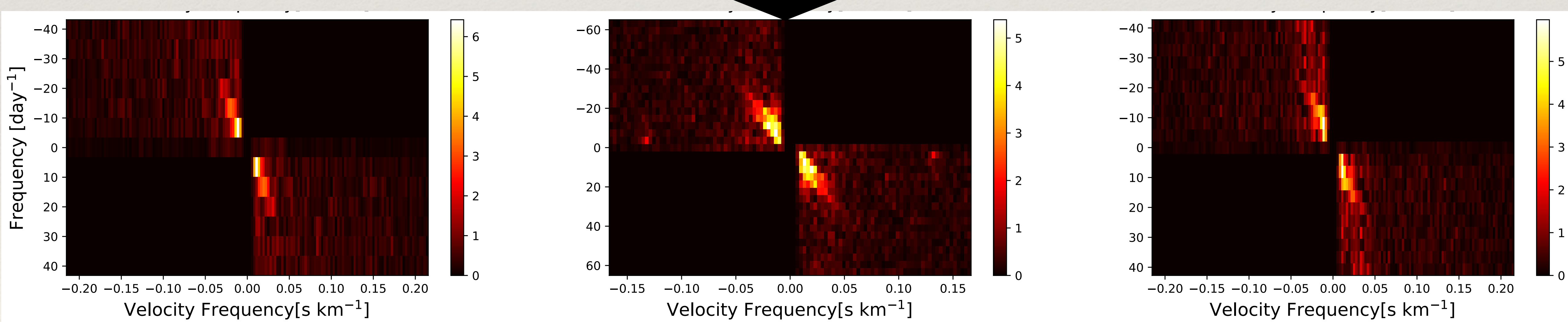
Fourier Filtering

- Fourier Filtering can extract only planetary shadow (Johnson et al. 2015)

2008 Nov 12 HJST
2011 Oct 19 HDS
2014 Oct 4 HJST



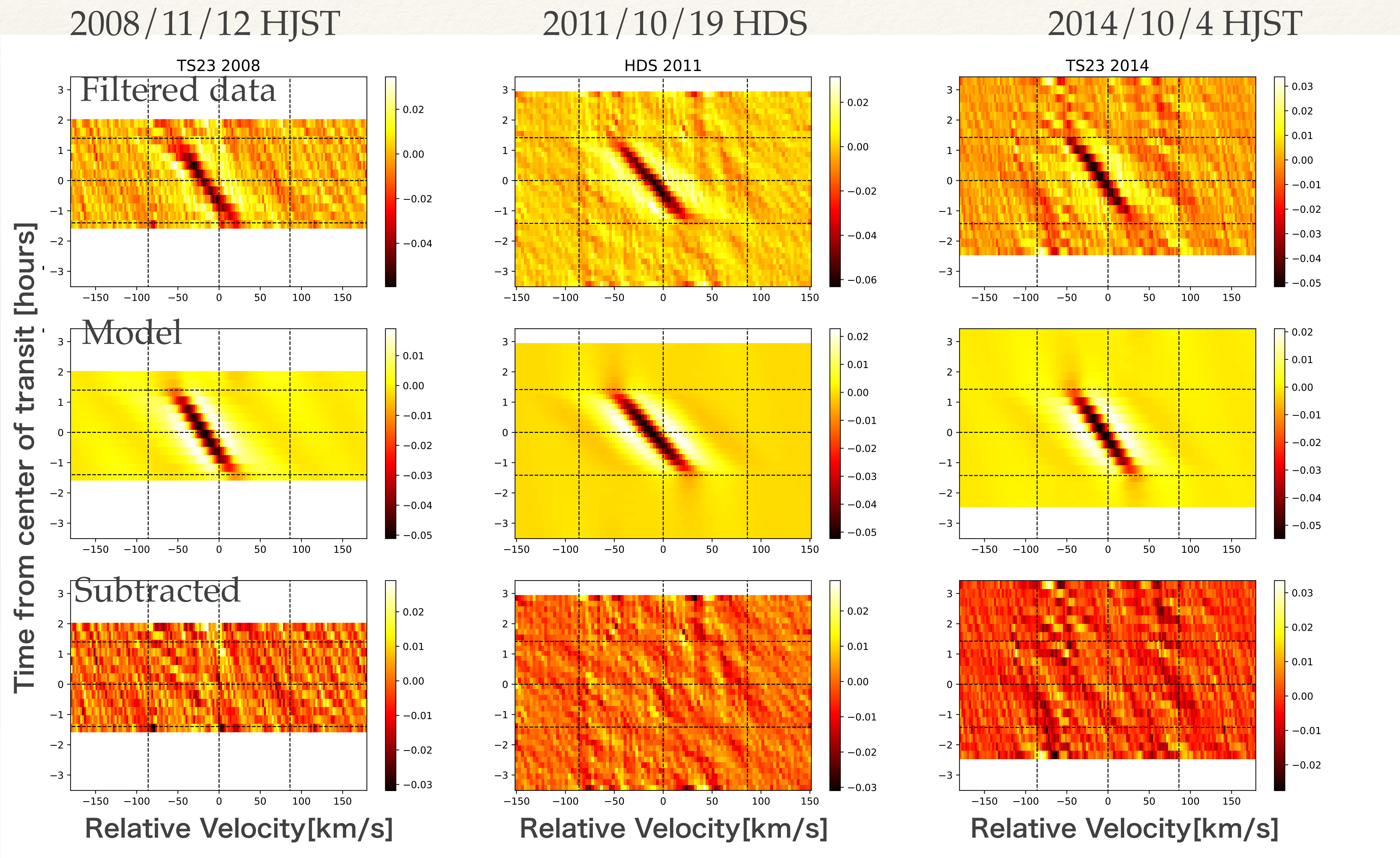
Masking



inverse Fourier transform

Fitting

- Measuring orbital parameters by MCMC fitting.

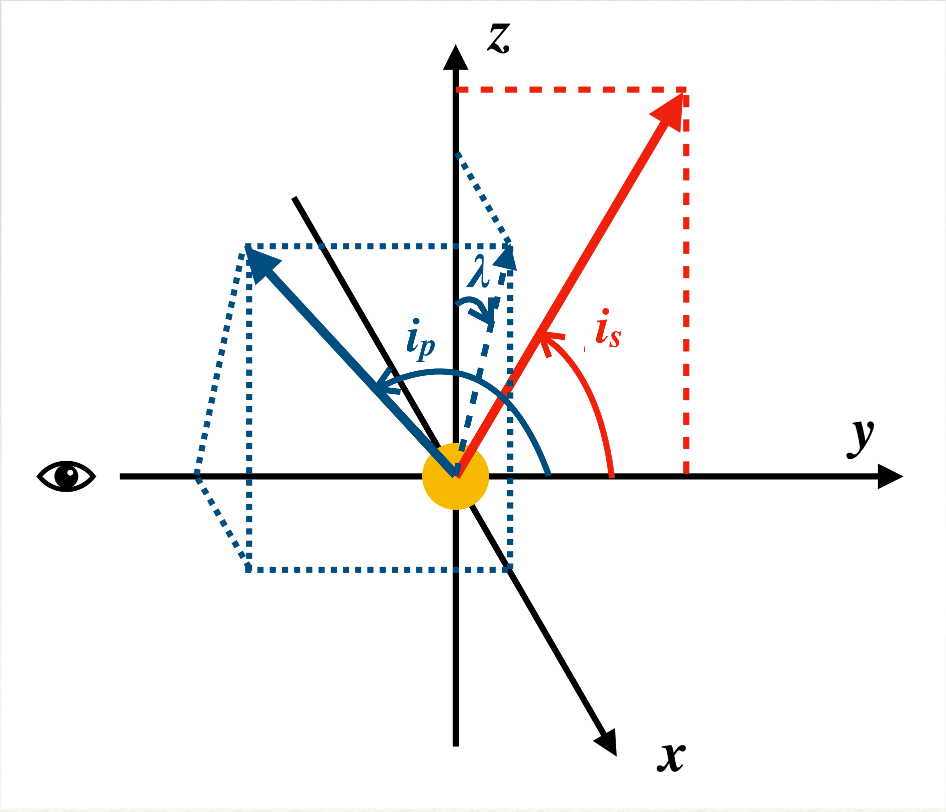


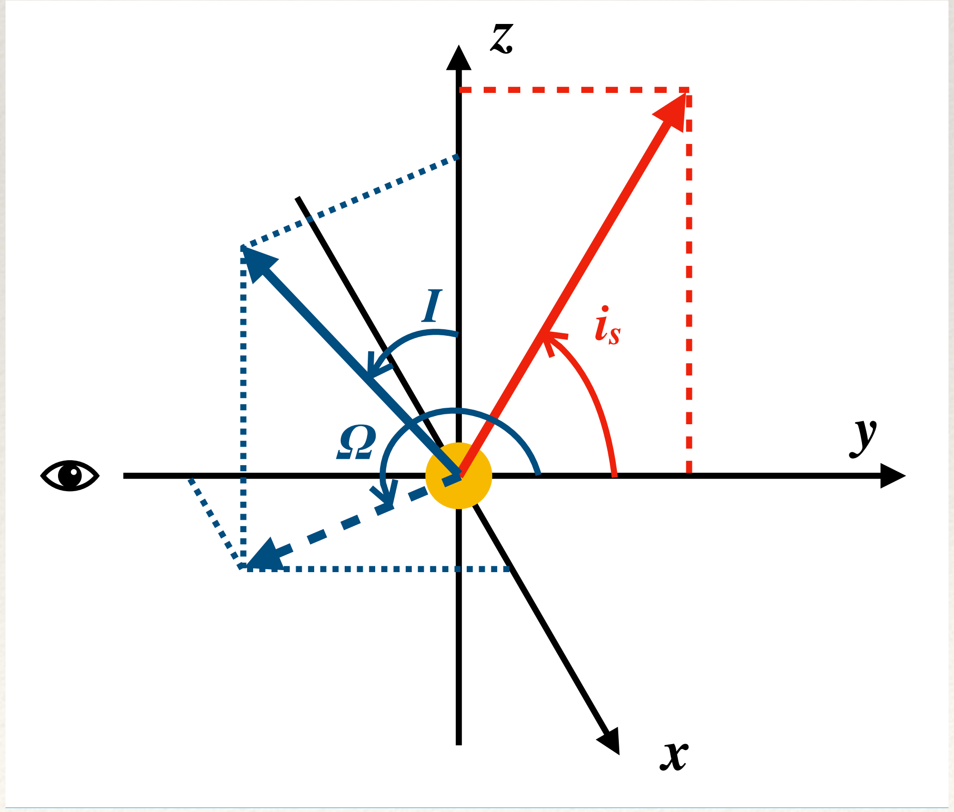
Result

date	2008 Nov 12	2011 Oct 19	2014 Oct 4
SNR	140	160	280
λ (deg)	$-111.28^{+0.47}_{-0.48}$	$-114.01^{+0.22}_{-0.20}$	-112.91 ± 0.24
b	$0.2397^{+0.0040}_{-0.0039}$	0.1571 ± 0.0020	$0.0856^{+0.0021}_{-0.0020}$
i_p (deg)	$86.275^{+0.070}_{-0.072}$	87.560 ± 0.037	$88.671^{+0.034}_{-0.036}$
Ω (deg)	$86.003^{+0.087}_{-0.091}$	87.329 ± 0.045	$88.557^{+0.039}_{-0.045}$
I (deg)	$111.23^{+0.48}_{-0.47}$	$113.99^{+0.20}_{-0.21}$	112.90 ± 0.24

Ω: ascending node
I: orbital inclination

$$\cos i_p = bR_s/a$$
$$\tan \Omega = -\sin \lambda \tan i_p$$
$$\cos I = \cos \lambda \sin i_p$$





Precession with model

- Fitting by weighted least square with long-term model.

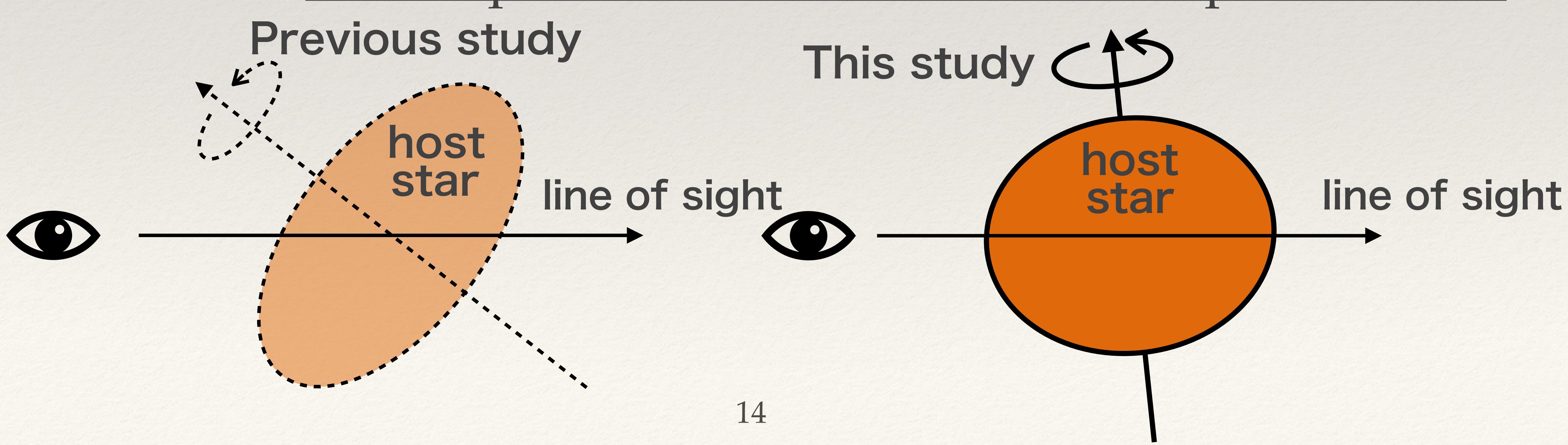
(Iorio 2016)

parameter	This study	Previous Studies
J_2	$(9.14 \pm 0.51) \times 10^{-5}$	$(2.1^{+0.8}_{-0.5}) \times 10^{-4}$ [I16]
i_s	96^{+10}_{-14} deg	142^{+10}_{-11} deg [I16]
$P_{precession}$	~840 years	~970 years [J+15]

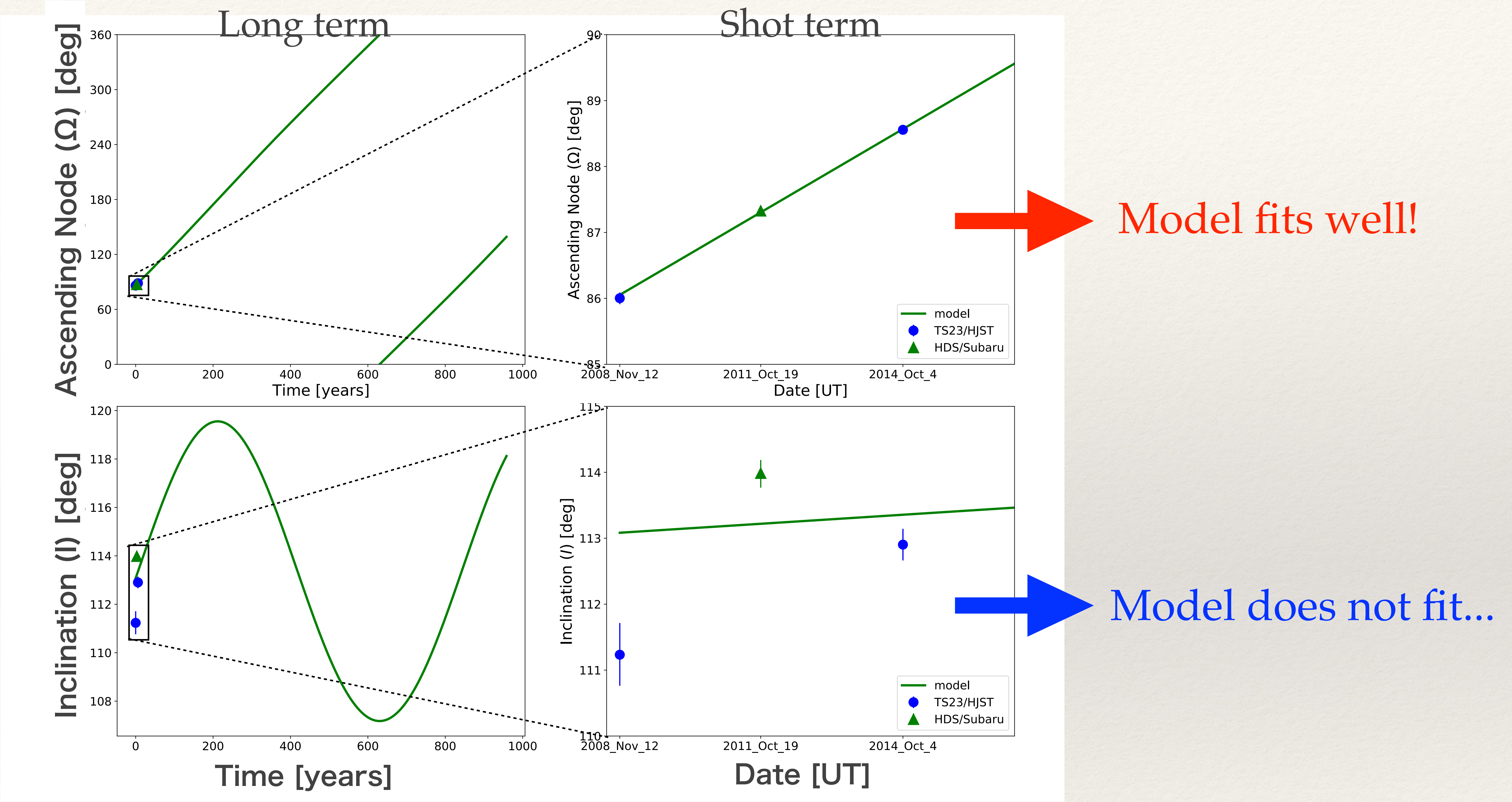
i.e. $J_{2,\,sun} = 2 \times 10^{-7}$

J_2: stellar gravitational quadrupole moment (oblateness)
i_s: angle between stellar spin axis and line of sight

- WASP-33b's orbital nodal precession is faster
- WASP-33 is more equator-on rotation and more spherical star



Precession with model

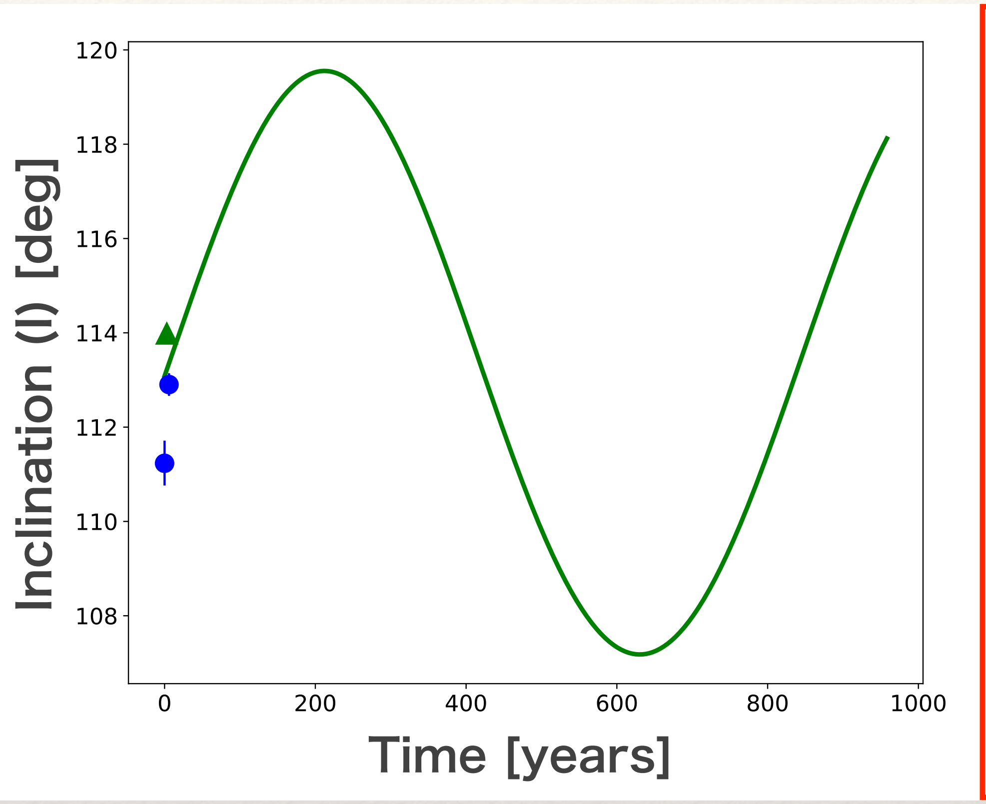


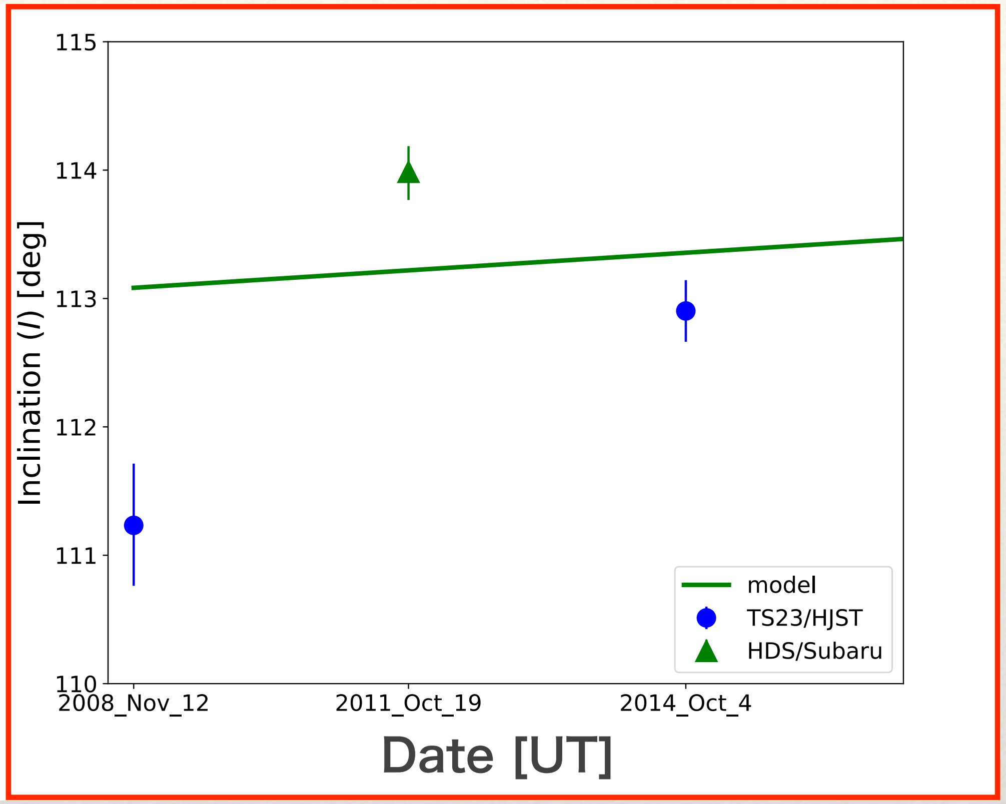
<u>WASP-33b's precession has short-term variation.</u>

or our measured uncertainties of inclinations are underestimated...

Future Work 1

- To clarify why the short-term change happens...





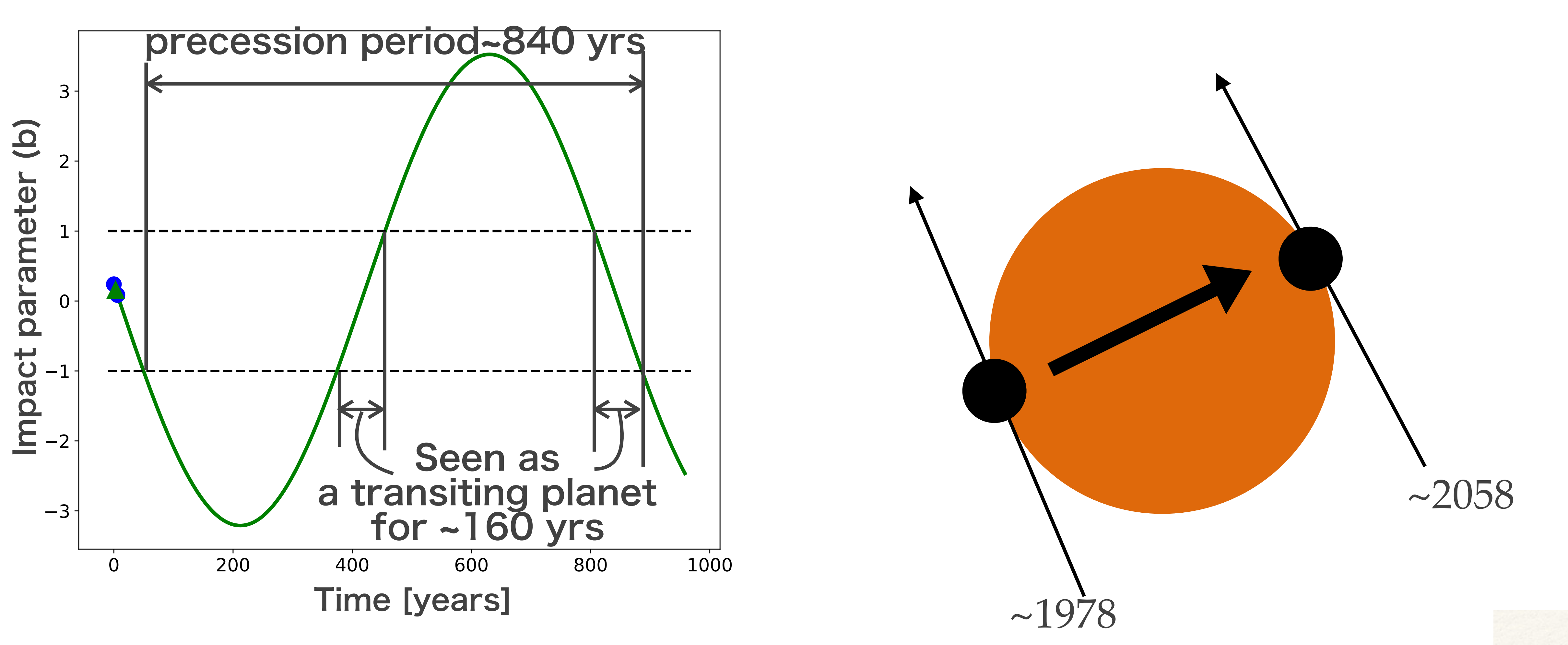
  - More follow-up observations of WASP-33b are needed.

Instrument	Resolution	Telescope	Location
HDS	110,000	Subaru 8.2m	Hawaii/US
HIDES	65,000	OAO 1.88m	Okayama/Japan

- We will get HIDES data this November.

Chance to See WASP-33b's Transit

- Period during transiting the host star is only ~20% of whole precession period.
- It is lucky to watch (detect) this transit.



Future Work 2

- To search orbital nodal precession…
  - Focusing other misaligned HJs around hot stars
    e.g. KELT-9b, Kepler-13Ab, exoplanets found by TESS, etc
  - Revealing the trend of the ratio of **period of transiting in front of the host star** to **precession period.**
- with transit spectral data

Instrument	Resolution	Telescope	Location
HDS	110,000	Subaru 8.2m	Hawaii/US
HIDES	65,000	OAO 1.88m	Okayama/Japan

- with transit photometry to measure impact parameter

Instrument	# of bands	Telescope	Location
MuSCAT	3 (g, r, z)	OAO 1.88m	Okayama/Japan
MuSCAT2	4 (g, r, i, z)	TCS 1.52m	Tenerife/Spain

Summary

- There are few exoplanets around hot stars (~20).
- Hot stars tend to have misaligned HJs and to rotate rapidly.
- Thus, the system makes orbital nodal precession.
- We detected precise orbital nodal precession of WASP-33b
  - One of models did not fit our values.
  - WASP-33b transits in front of theist star for only ~20% of nodal precession period.

- Observing nodal precessions of hot Jupiters, WASP-33b, KELT-9b and so on, by high dispersion instrument and photometry camera.