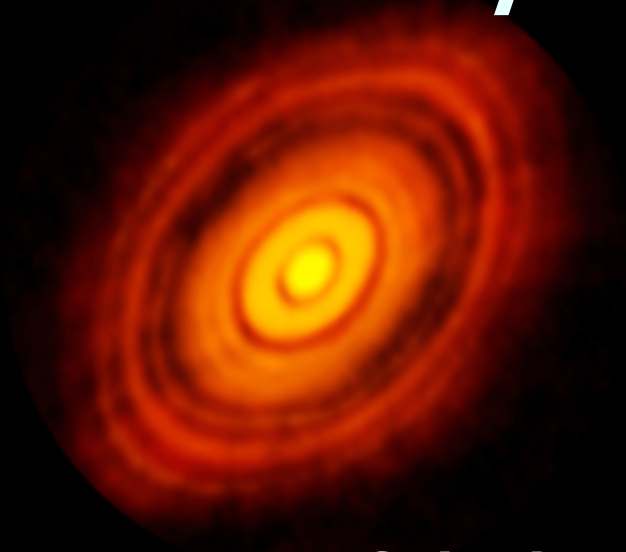
Simulating the spin-orbit architecture of planetary systems: *hydrodynamical simulation of turbulent proto-planetary disks and the fate of multi-planet systems via disk-planet migration in the HL Tau disk*



⇒

Yasushi Suto

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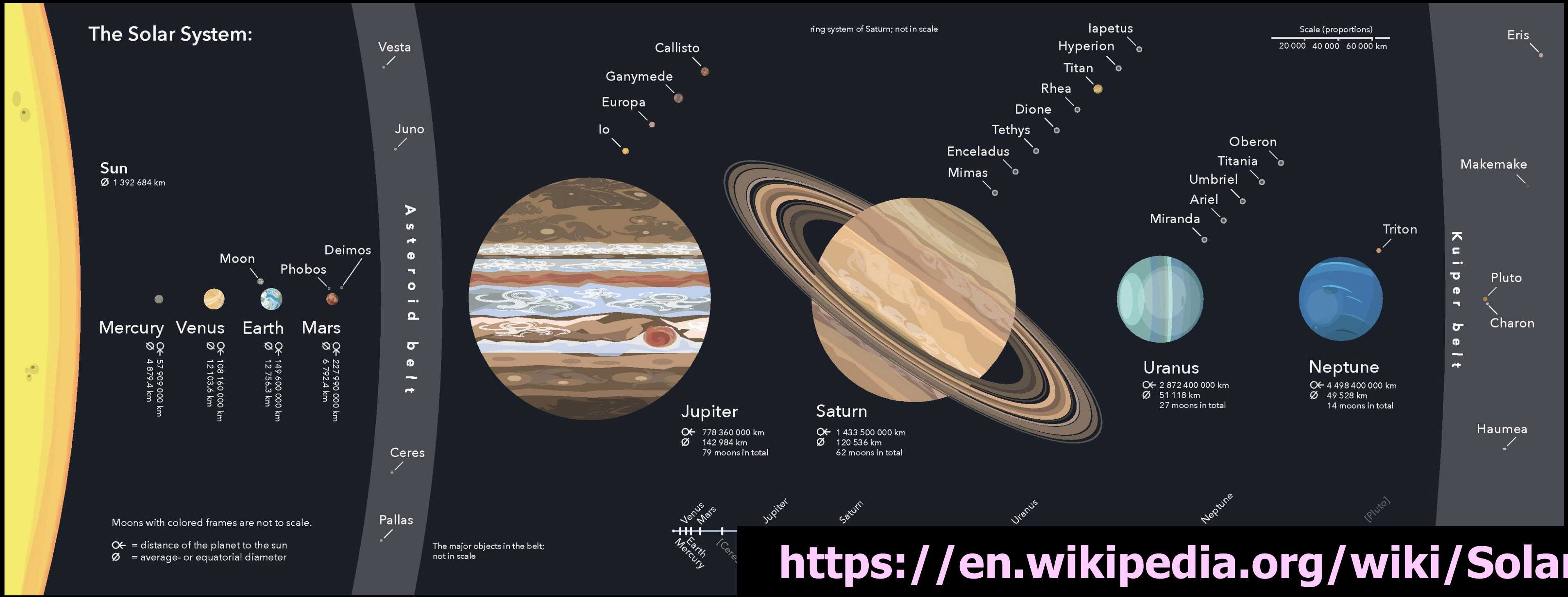
Daisuke Takaishi

Department of Physics, Kogoshima University

10:00-11:00 June 25, 2019 @ University of Bern

Architecture of the Solar system

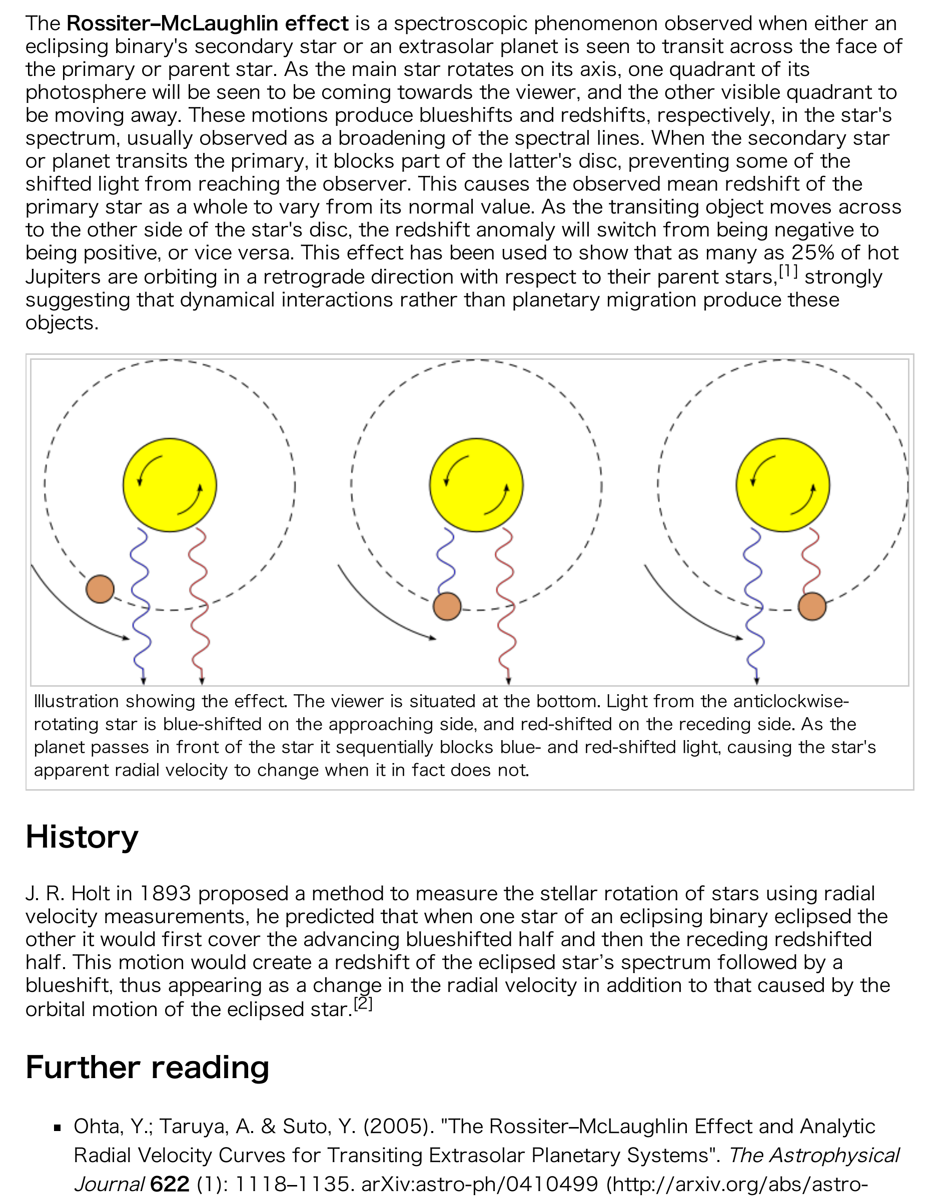


https://en.wikipedia.org/wiki/Solar_System

- Our Solar system is typical or atypical ?
  - *Very stable multiplanetary systems on nearly co-planar and circular orbits*
  - Rocky inner planets + Gaseous outer planets
  - satellites and rings are fairly common
  - A planet with life and (advanced) civilization

The Rossiter-McLaughlin effect

The Rossiter-McLaughlin effect @ Wikipedia



The **Rossiter–McLaughlin effect** is a spectroscopic phenomenon observed when either an eclipsing binary's secondary star or an extrasolar planet is seen to transit across the face of the primary or parent star. As the main star rotates on its axis, one quadrant of its photosphere will be seen to be coming towards the viewer, and the other visible quadrant to be moving away. These motions produce blueshifts and redshifts, respectively, in the star's spectrum, usually observed as a broadening of the spectral lines. When the secondary star or planet transits the primary, it blocks part of the latter's disc, preventing some of the shifted light from reaching the observer. This causes the observed mean redshift of the primary star as a whole to vary from its normal value. As the transiting object moves across to the other side of the star's disc, the redshift anomaly will switch from being negative to being positive, or vice versa. This effect has been used to show that as many as 25% of hot Jupiters are orbiting in a retrograde direction with respect to their parent stars,[1] strongly suggesting that dynamical interactions rather than planetary migration produce these objects.

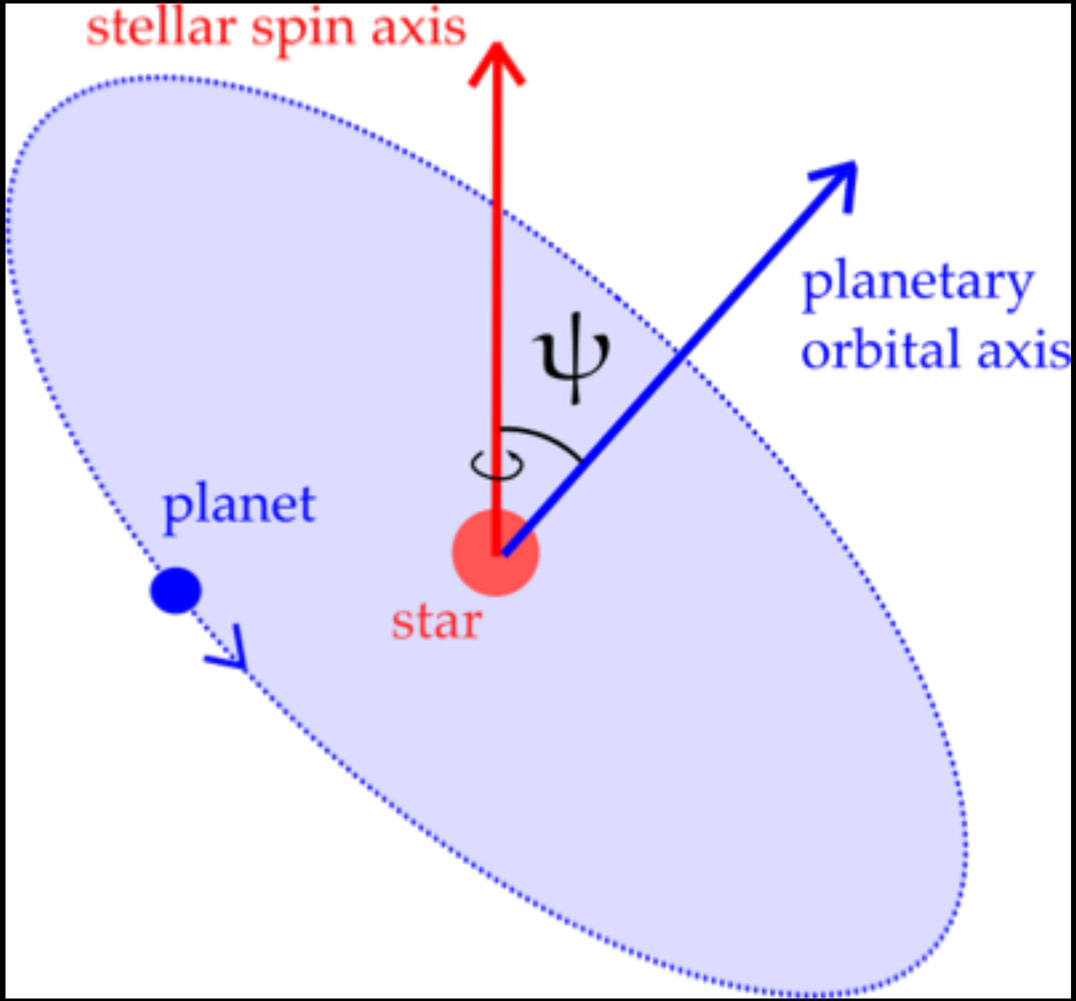
Illustration showing the effect. The viewer is situated at the bottom. Light from the anticlockwise-rotating star is blue-shifted on the approaching side, and red-shifted on the receding side. As the planet passes in front of the star it sequentially blocks blue- and red-shifted light, causing the star's apparent radial velocity to change when it in fact does not.

History

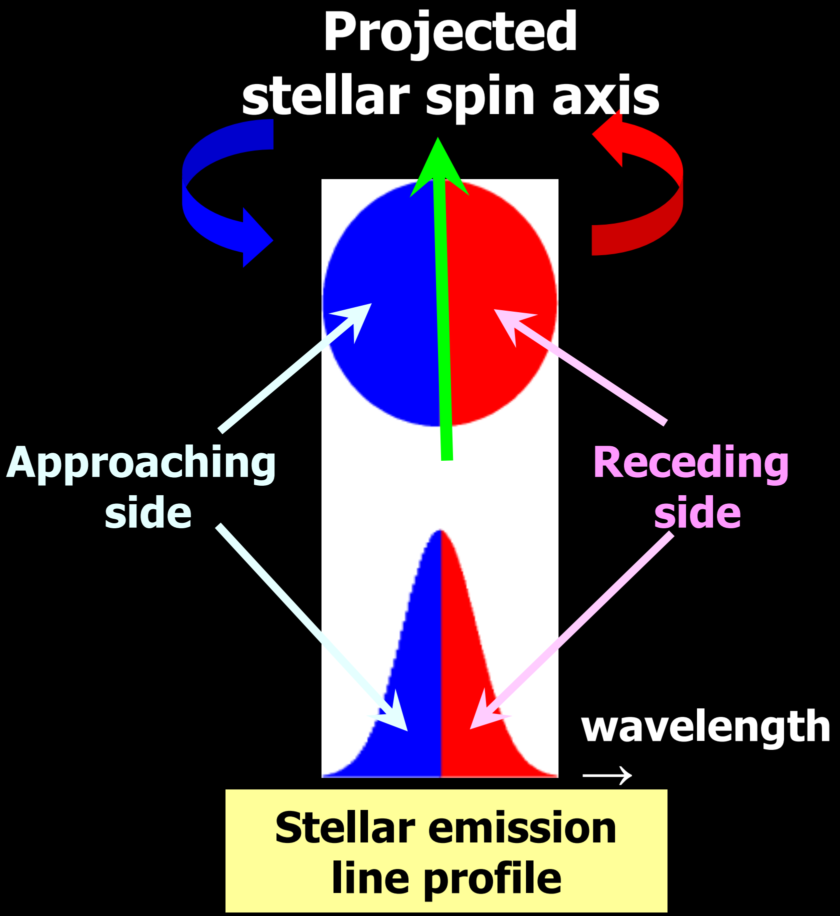
J. R. Holt in 1893 proposed a method to measure the stellar rotation of stars using radial velocity measurements, he predicted that when one star of an eclipsing binary eclipsed the other it would first cover the advancing blueshifted half and then the receding redshifted half. This motion would create a redshift of the eclipsed star's spectrum followed by a blueshift, thus appearing as a change in the radial velocity in addition to that caused by the orbital motion of the eclipsed star.[2]

Further reading

- Ohta, Y.; Taruya, A. & Suto, Y. (2005). "The Rossiter–McLaughlin Effect and Analytic Radial Velocity Curves for Transiting Extrasolar Planetary Systems". *The Astrophysical Journal* **622** (1): 1118–1135. arXiv:astro-ph/0410499 (http://arxiv.org/abs/astro-



Spectroscopic transit signature: the Rossiter-McLaughlin effect



Projected
stellar spin axis

Approaching
side

Receding
side

wavelength
→

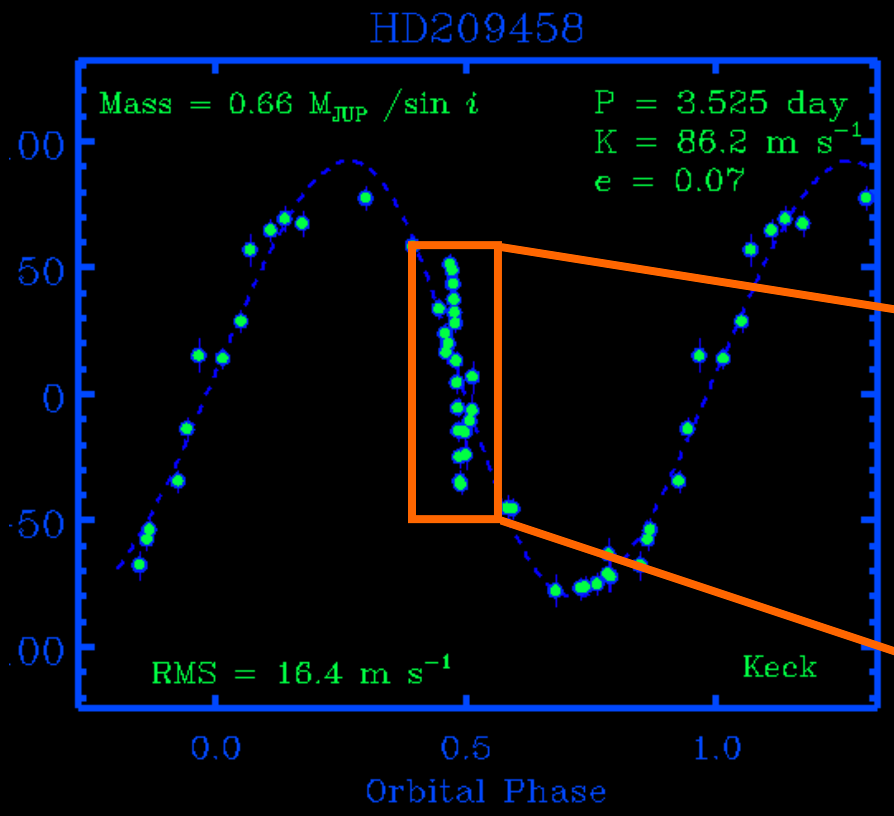
Stellar emission
line profile

- Time-dependent asymmetry in the stellar Doppler broadened line profile
  - apparent anomaly of the stellar radial velocity
- originally proposed for eclipsing binaries

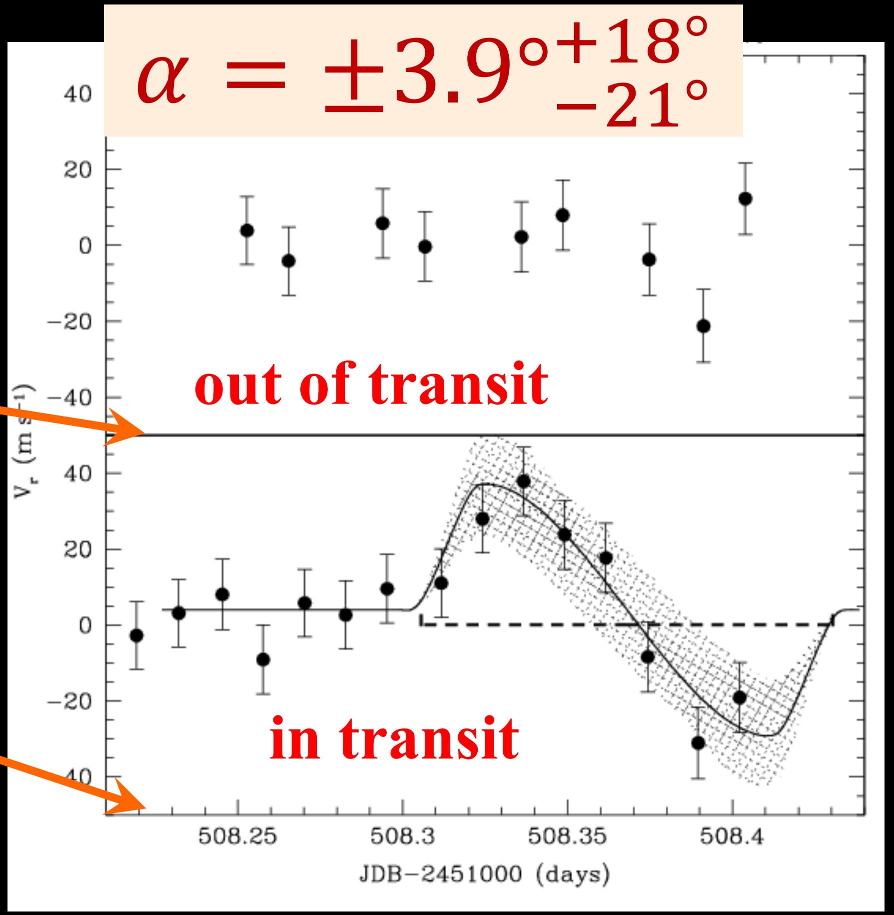
Holt, J.R. Astronomy and Astrophysics 12(1893)646
Rossiter, ApJ 60(1924)15; McLaughlin, ApJ 60 (1924)20
Hosokawa, PASJ 5(1953)88; Ohta, Taruya + YS, ApJ 622(2005)1118

The first detection of the RM effect: HD209458

HD209458 radial velocity data
http://exoplanets.org/



(This is not their original data in 2000)

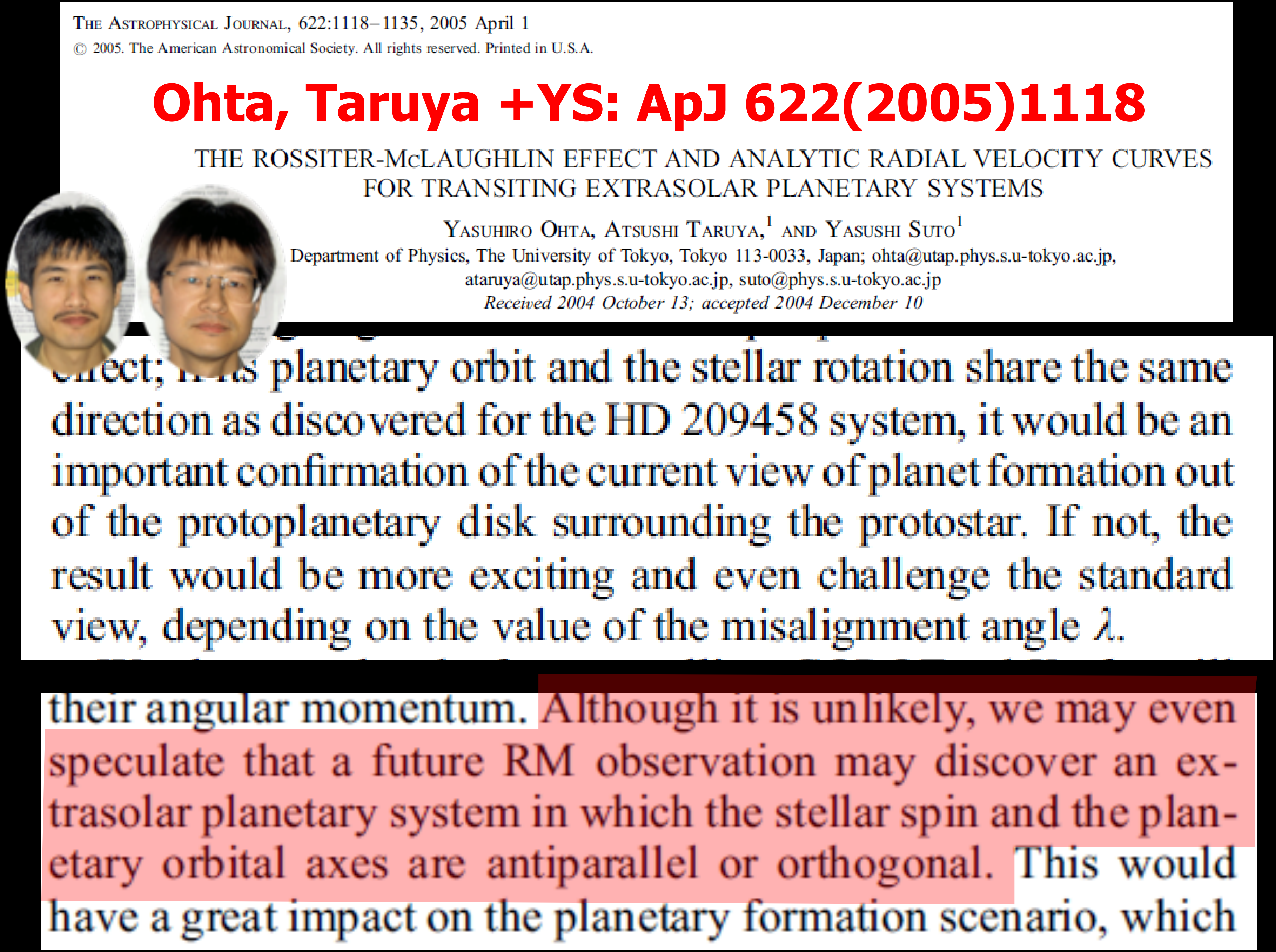


$$\alpha = \pm 3.9^{\circ}{}^{+18^{\circ}}_{-21^{\circ}}$$

out of transit

in transit

Stellar rotation and planetary orbit
Queloz et al. (2000) A&A 359, L13
ELODIE on 193cm telescope



The Astrophysical Journal, 622:1118–1135, 2005 April 1

Ohta, Taruya +YS: ApJ 622(2005)1118

THE ROSSITER-McLAUGHLIN EFFECT AND ANALYTIC RADIAL VELOCITY CURVES FOR TRANSITING EXTRASOLAR PLANETARY SYSTEMS

Yasuhiro Ohta, Atsushi Taruya,[1] and Yasushi Suto[1]
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Received 2004 October 13; accepted 2004 December 10

ect; its planetary orbit and the stellar rotation share the same direction as discovered for the HD 209458 system, it would be an important confirmation of the current view of planet formation out of the protoplanetary disk surrounding the protostar. If not, the result would be more exciting and even challenge the standard view, depending on the value of the misalignment angle λ.

their angular momentum. Although it is unlikely, we may even speculate that a future RM observation may discover an extrasolar planetary system in which the stellar spin and the planetary orbital axes are antiparallel or orthogonal. This would have a great impact on the planetary formation scenario, which

Evolution of my own prejudice 1

Spin-orbit misalignment for exoplanets is *unlikely*

- Queloz et al. (2000)
  - First RM result for HD209458

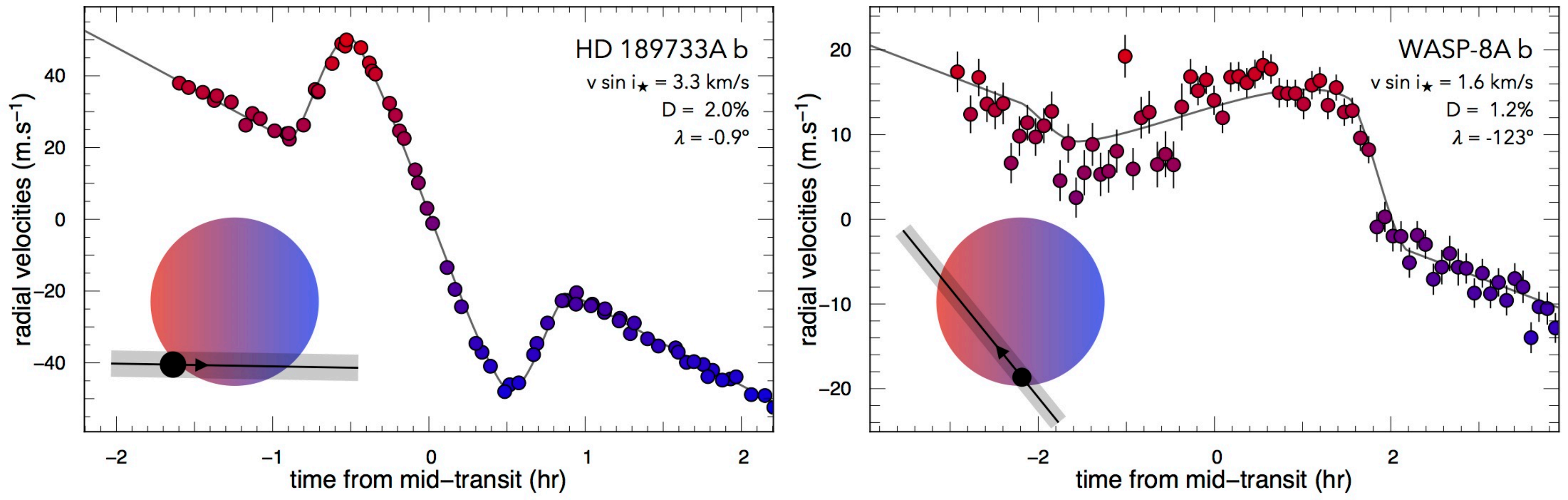
$$\alpha = \pm 3.9^\circ{}^{+18^\circ}_{-21^\circ}$$

- Ohta, Taruya + YS (2005)
  - Perturbative analytic formula for the RM effect
  - spin-orbit angle should be small according the standard planet formation (Hayashi) model
  - If not, it indicates a new non-standard formation channel for exoplanets
- Winn et al. (2005)
  - Significantly improved the RM measurement accuracy for HD209458 on the basis of OTS approach

$$\lambda = -4.4^\circ \pm 1.4^\circ$$

Examples of RM velocity anomaly

Aligned case **Misaligned case**



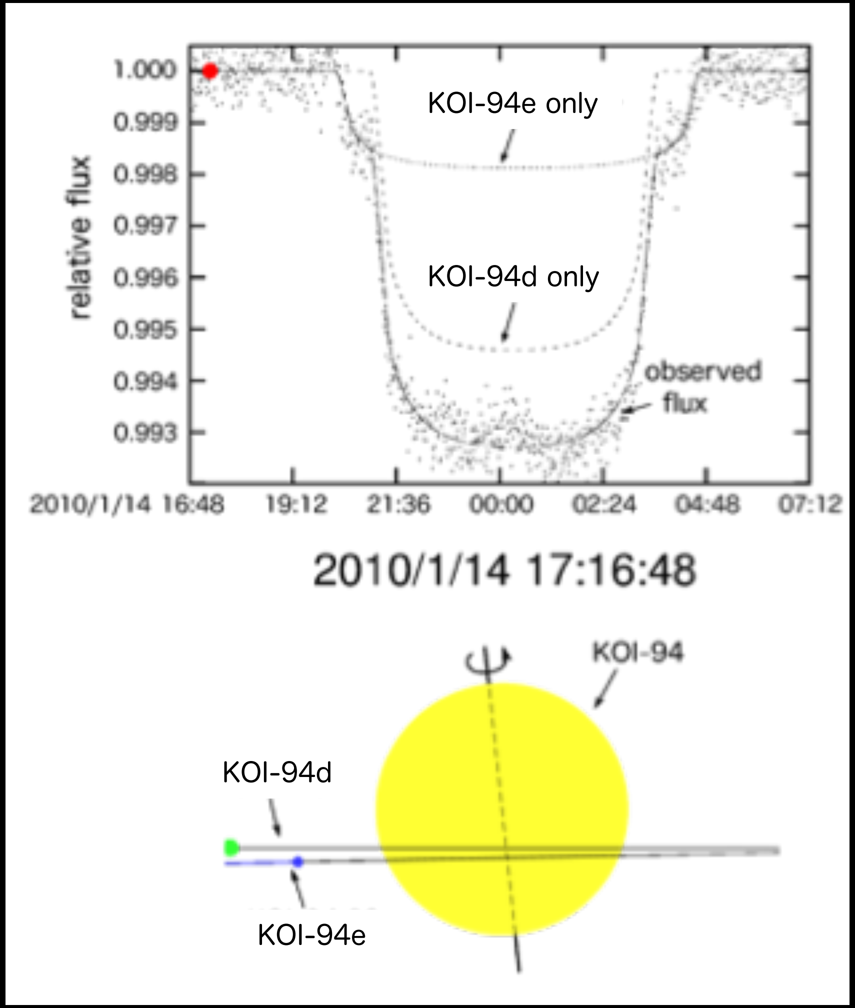
Ohta, Taruya, & YS, ApJ 622(2005)1118
Winn et al. ApJ 631(2005)1215
Fabrycky & Winn, ApJ 696(2009)1230
Winn & Fabrycky, ARA&A 53(2015)409
Triaud arXiv:1709.06376

Evolution of my own prejudice 2

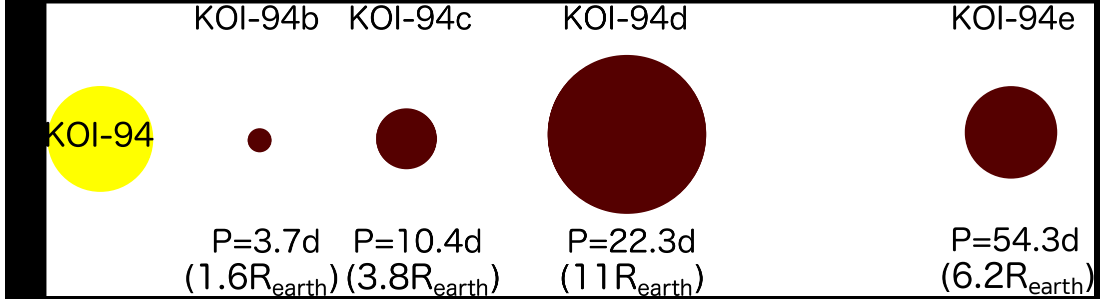
Spin-orbit misalignment may be common for Hot Jupiters, but should not for transiting multi-planetary systems

- Around 2010, it became clear that a fair fraction of the observed Hot-Jupiters exhibits large spin-orbit misalignment
- This *should* not happen, however, in transiting multi-planetary systems, which is unlikely to have suffered from significant dynamical disturbance, and thus should keep the initial condition (e.g., our Solar system aligned within several degrees)
- Let us test this prediction with the RM measurement for a transiting multi-planet system !

RM observation of KOI-94 with Subaru: a system with 4 transiting planets



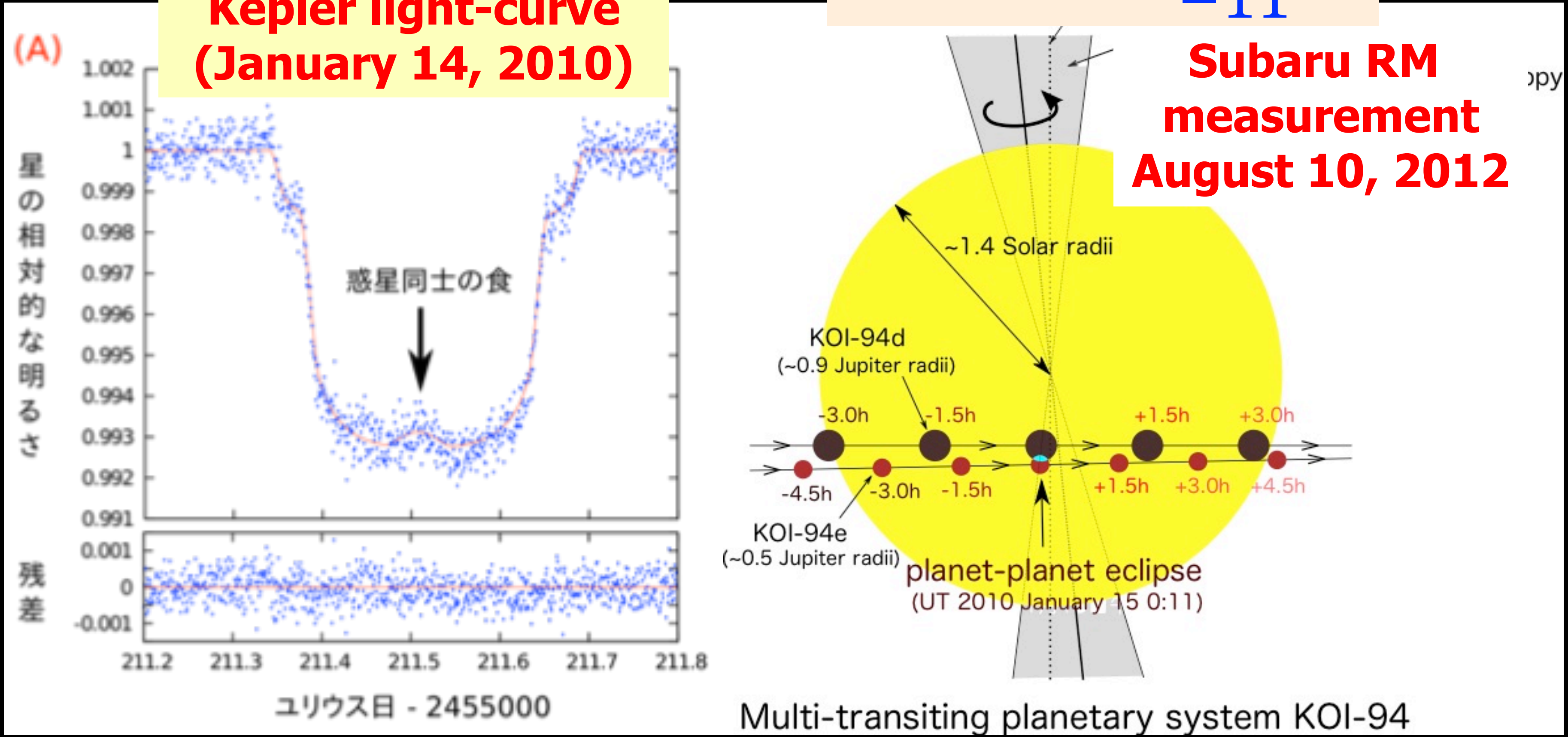
Hirano et al. ApJL 759 (2012)L36



- First detection of planet-planet eclipse !
  - Even before we conduct the RM measurement in August 2012, we found an anomalous transit signature from Kepler archive on January 14, 2010
  - The orbital planes of those planets are well-aligned

Spin-orbit alignment of KOI-94

$$\lambda = -6^{\circ}{}^{+13^{\circ}}_{-11^{\circ}}$$



Kepler light-curve (January 14, 2010)

Subaru RM measurement August 10, 2012

Multi-transiting planetary system KOI-94

Hirano et al. ApJL 759 (2012) L36
Masuda et al. ApJ 778 (2013) 185

Evolution of my own prejudice 3

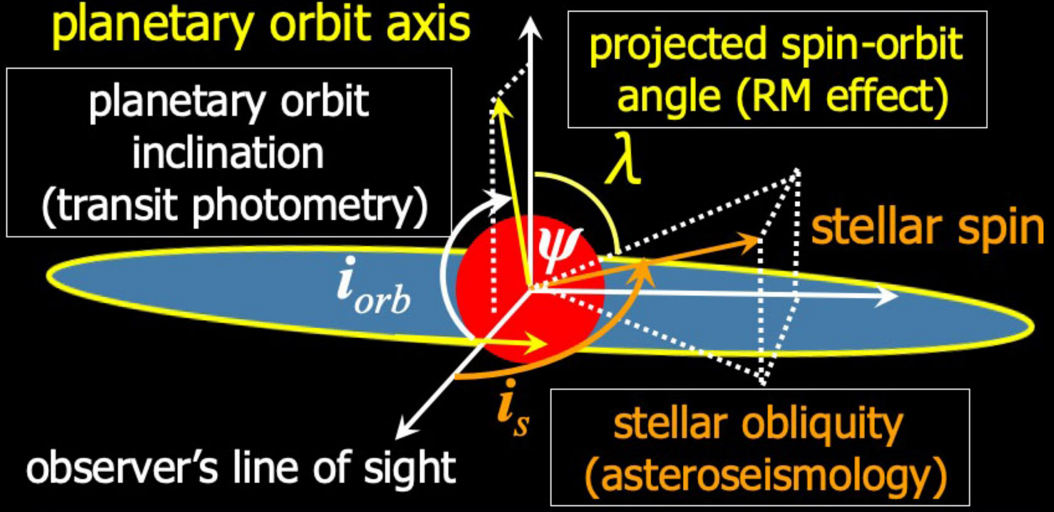
Spin-orbit misalignment should not exist for transiting multi-planetary systems

- Subaru spectroscopy + Kepler photometry of a transiting 4 planet system KOI 94 (Hirano et al. 2012, Masuda et al. 2013)
  - First measurement of RM effect for transiting multi-planet system
  - First discovery of planet-planet eclipse
  - KOI-94 was approved as Kepler-89
- Finally a reasonable picture established (?)

Evolution of my own prejudice 4

Stellar obliquity is another key

- Asteroseismology indicated the stellar obliquity of 47 ± 6 degree for Kepler-56
  - Kepler-56: red giant ($1.3M_s$, $4.3R_s$) + two transiting planets (10.5day, 20.4day)
  - Huber et al. Science 342(2013) 331



planetary orbit axis

projected spin-orbit angle (RM effect)

planetary orbit inclination (transit photometry)

stellar spin

stellar obliquity (asteroseismology)

observer's line of sight

- RM effect measures the *projected spin-orbit angle*
  - Is this also the case for other multi-planet systems, especially with a main-sequence host star ?

$$\cos\Psi = \sin i_s \sin i_{orb} \cos\lambda + \cos i_s \cos i_{orb}$$

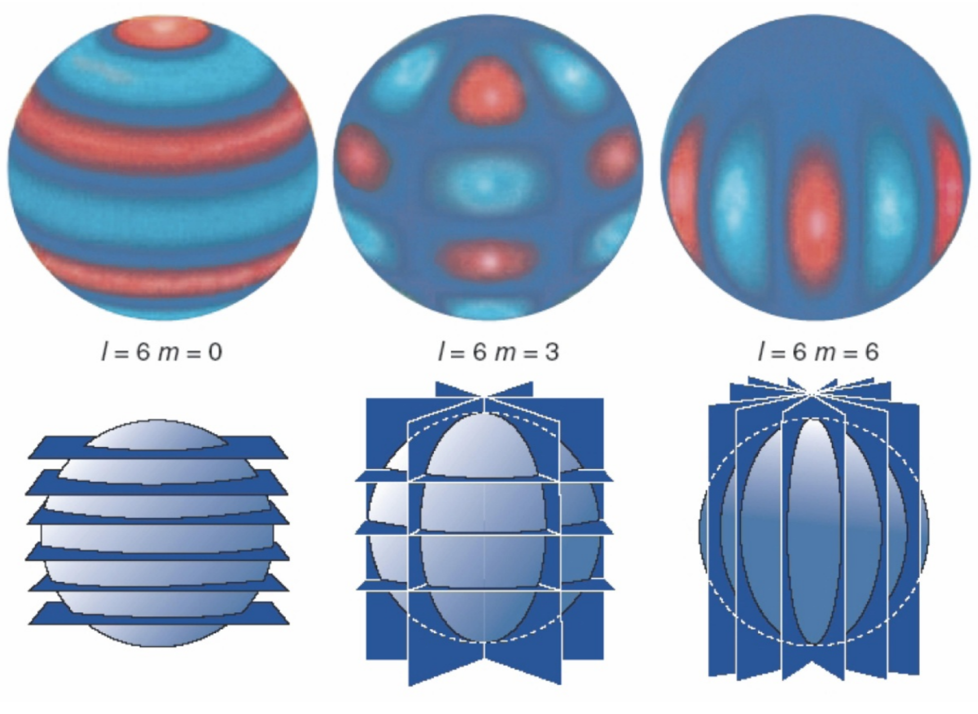
Asteroseismology

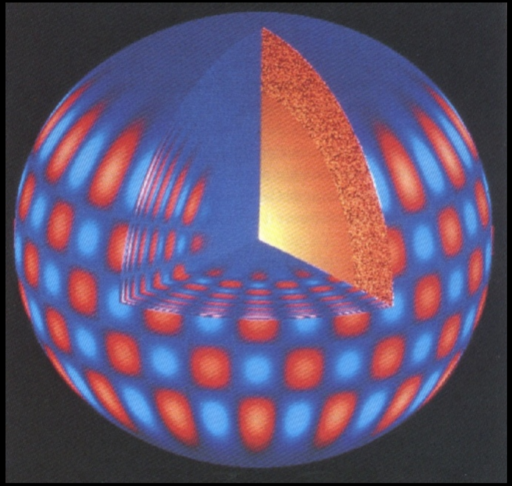
Characterizing the stellar pulsations

- Expansion in terms of spherical harmonics

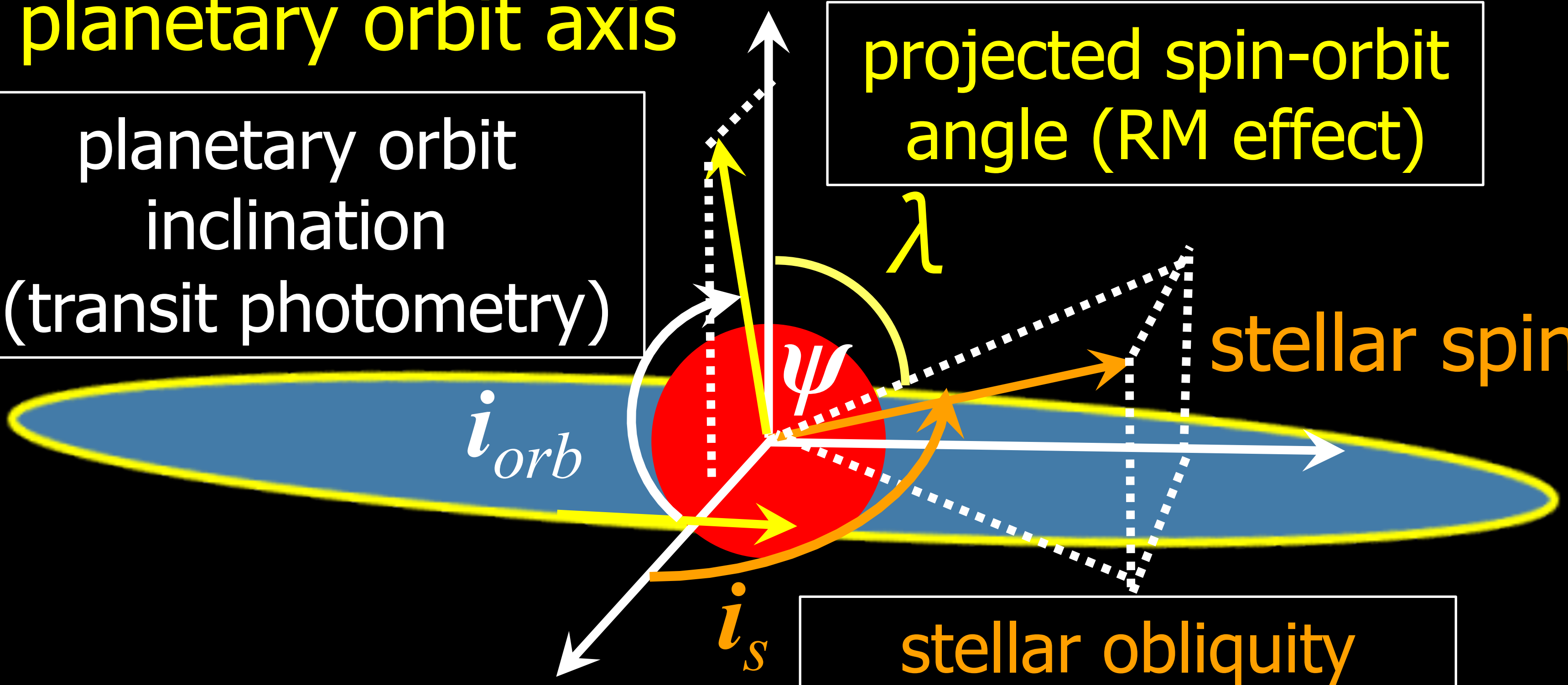
$$Y_{lm}(\theta,\varphi) \propto P_l^{|m|}(\cos\theta)e^{im\varphi}$$

- Three integers to characterize the mode
  - n radial order
  - l angular degree
  - m azimuthal order





Spin-orbit angles of a transiting planet



planetary orbit axis

planetary orbit
inclination
(transit photometry)

projected spin-orbit
angle (RM effect)

stellar spin

stellar obliquity
(asteroseismology)

observer's line of sight

$$\begin{aligned}\cos\Psi &= \sin i_s \sin i_{orb} \cos\lambda + \cos i_s \cos i_{orb} \\ &\approx \sin i_s \cos\lambda\end{aligned}$$

Asteroseismology can measure i_s

- **Oscillation in the corotating frame of the star**

$$\Psi_{nlm}(r,\theta,\varphi,t) = R_n(r)Y_{lm}(\theta,\varphi)e^{-iw_{nl}t} \propto e^{i(m\varphi - w_{nl}t)}$$

- **Oscillation frequency in the observer's frame**

$$\Psi_{nlm'}(r,\theta+i_*,\varphi-\Omega_* t,t) \propto e^{i(m'\varphi - m'\Omega_* t - w_{nl}t)}$$

- **Obliquity changes the amplitude of modes**

$$P(w) = \sum_{n,l}\sum_{m=-l}^{l} \frac{\mathcal{E}_{lm}(i_s)H_{nl}(w)}{1+4(\nu-\nu_{nlm})^2/\Gamma^2_{nlm}}$$

Toutain & Gouttebroze, (1993)
Gizon & Solanki (2003)
Kamiaka, Benomar & Suto (2018)

m-dependence of the mode amplitude

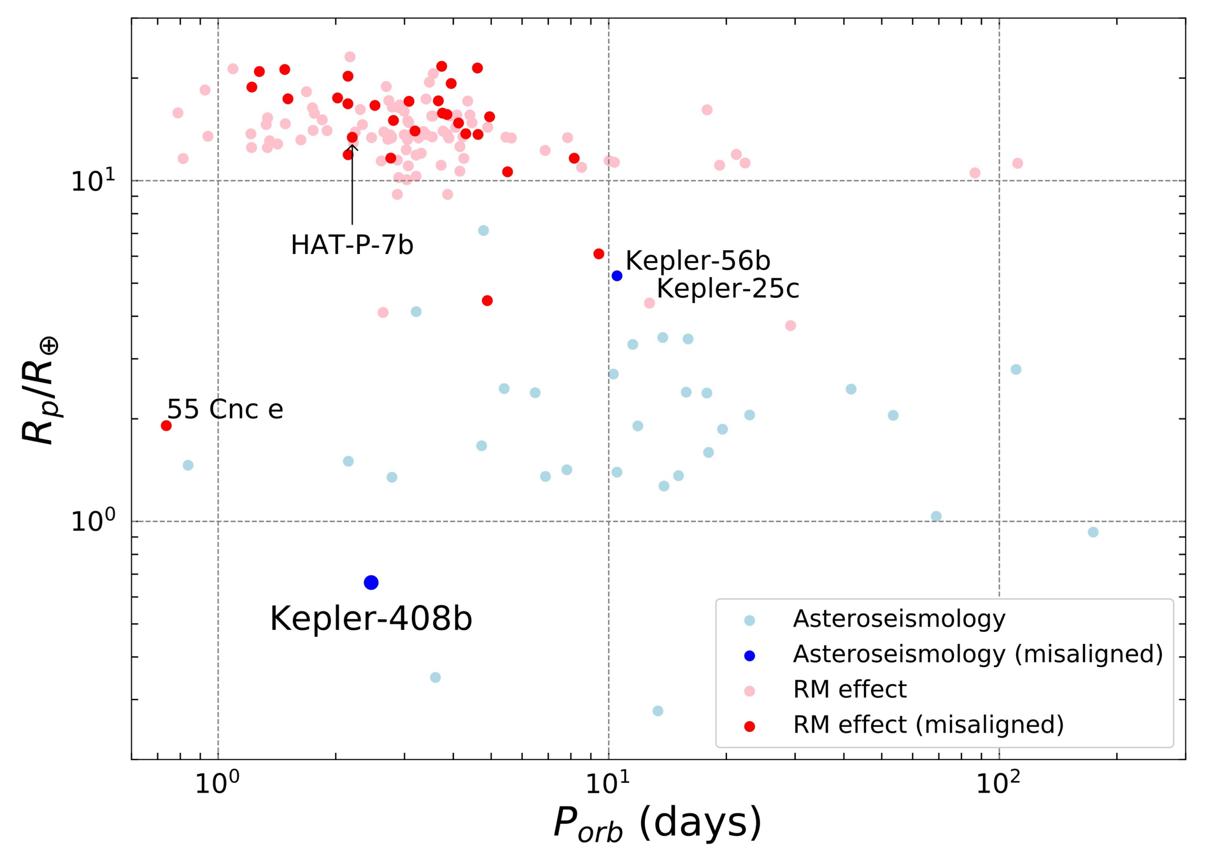
$$\mathcal{E}_{lm}(i_s) = \frac{(l-|m|)!}{(l+|m|)!}\left[P_l^{|m|}(\cos i_s)\right]^2$$

m-dependence of the mode frequency

$$\nu_{nlm'} = \nu_{nl} + m\boxed{\delta\nu_*}(1-\boxed{C_{nl}})$$

stellar rotation small correction factor

Complementarity of asteroseismology and RM effect for spin-orbit angle: λ and i_s

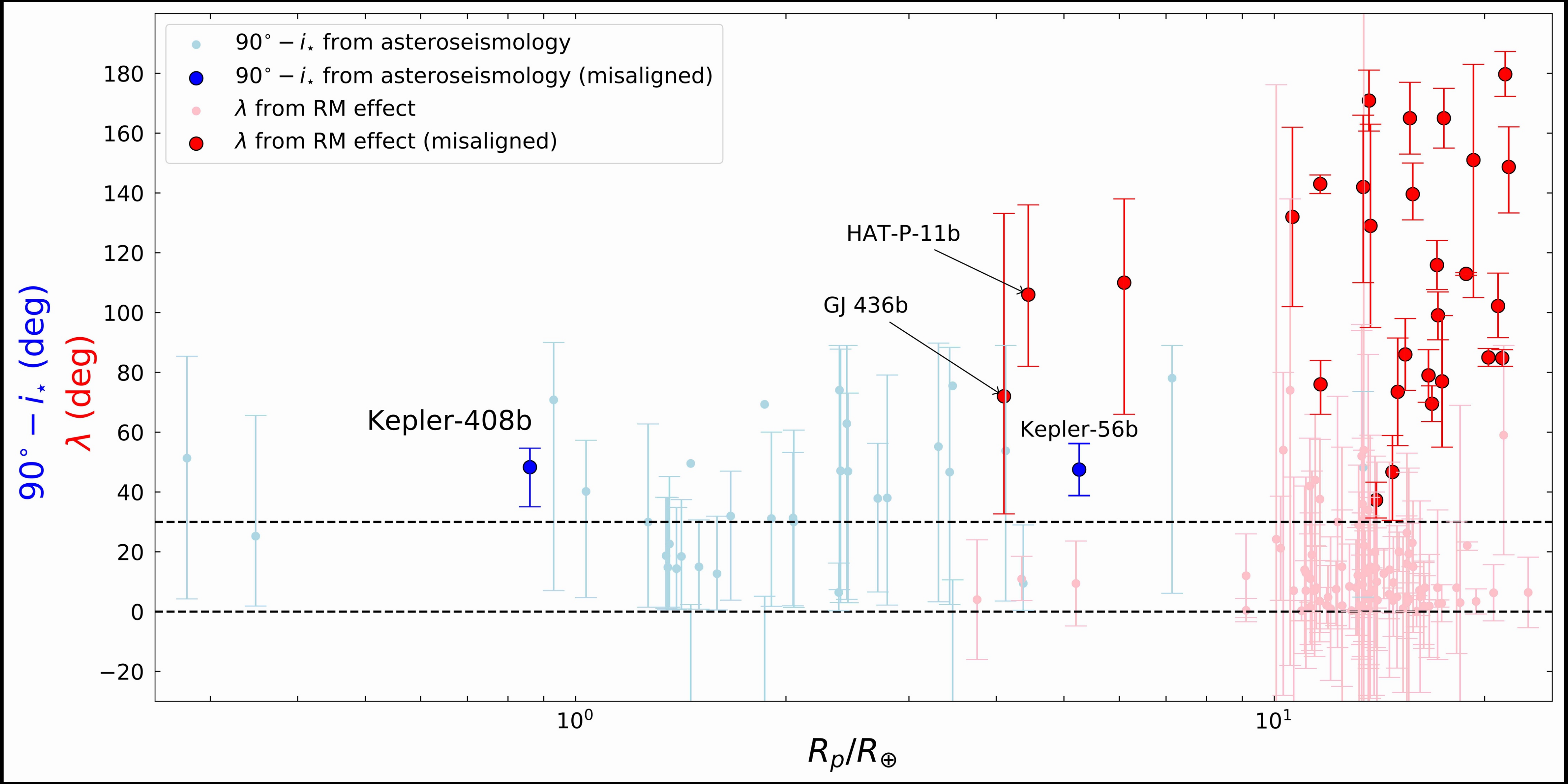


- RM effect
  - short-period and large planets
- Asteroseismology
  - independent of the properties of planets

Kamiaka, Benomar & YS
MNRAS(2018)
Kamiaka, Benomar, YS, Dai, Masuda, & Winn
AJ 157(2019)137
YS, Kamiaka & Benomar
AJ 157(2019)172

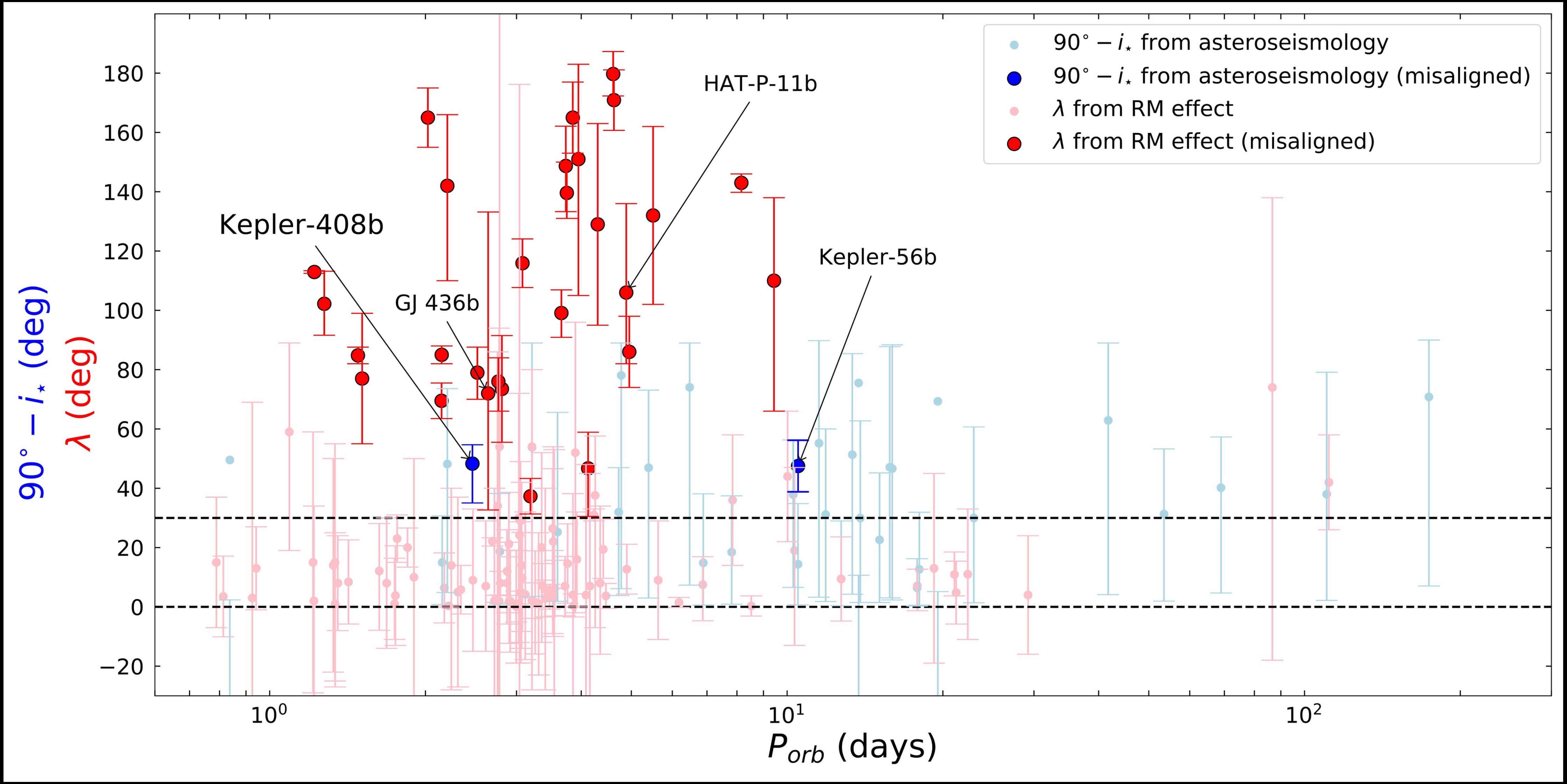
- Asteroseismology is based on various (non-trivial) assumptions, and required complicated and careful modeling

Spin-orbit angles against R_p



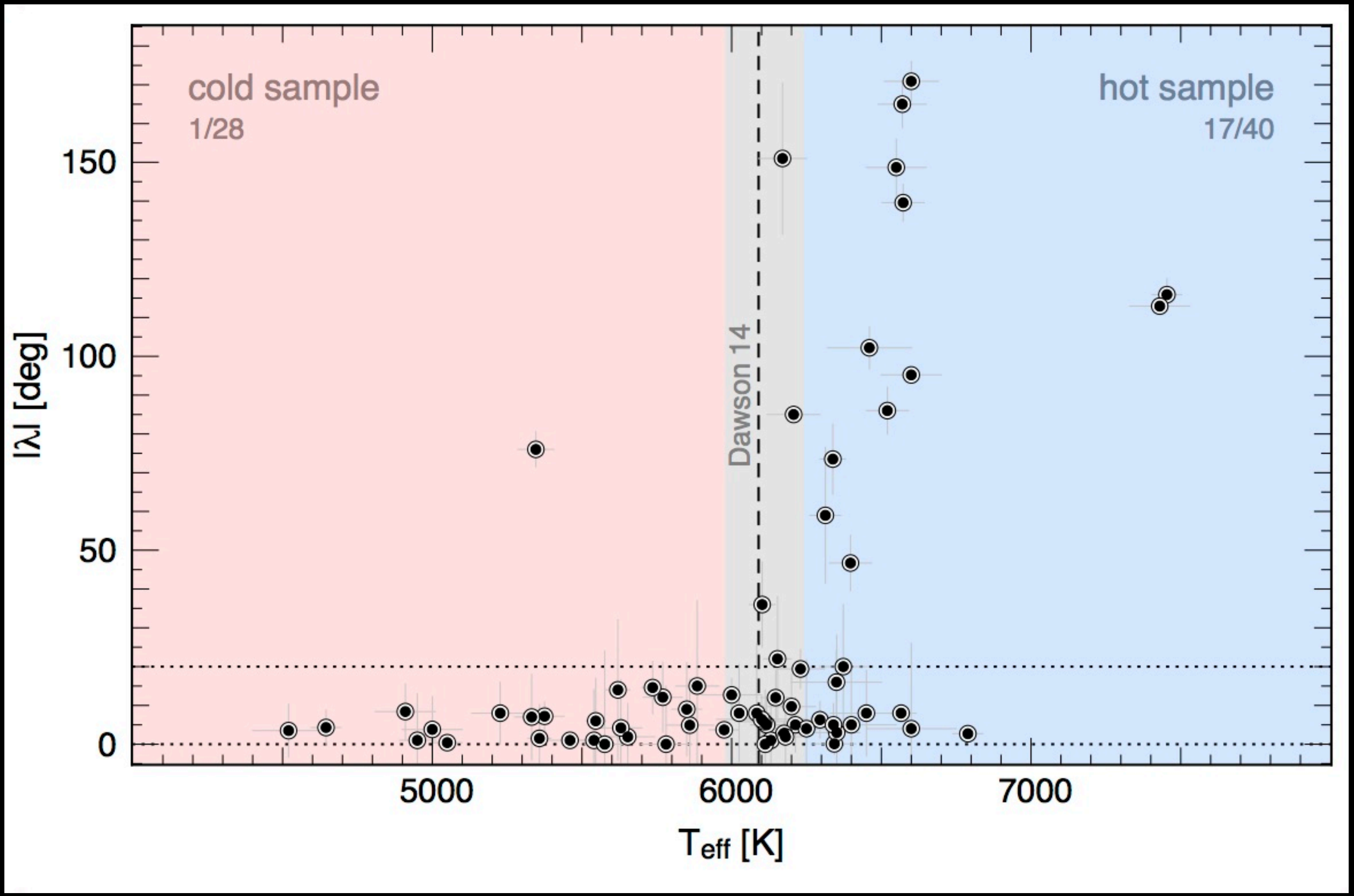
Kamiaka, Benomar, YS, Dai, Masuda, & Winn, AJ 157(2019)137

Spin-orbit angles against P_{orb}



Kamiaka, Benomar, YS, Dai, Masuda, & Winn, AJ 157(2019)137

λ vs. stellar effective temperature



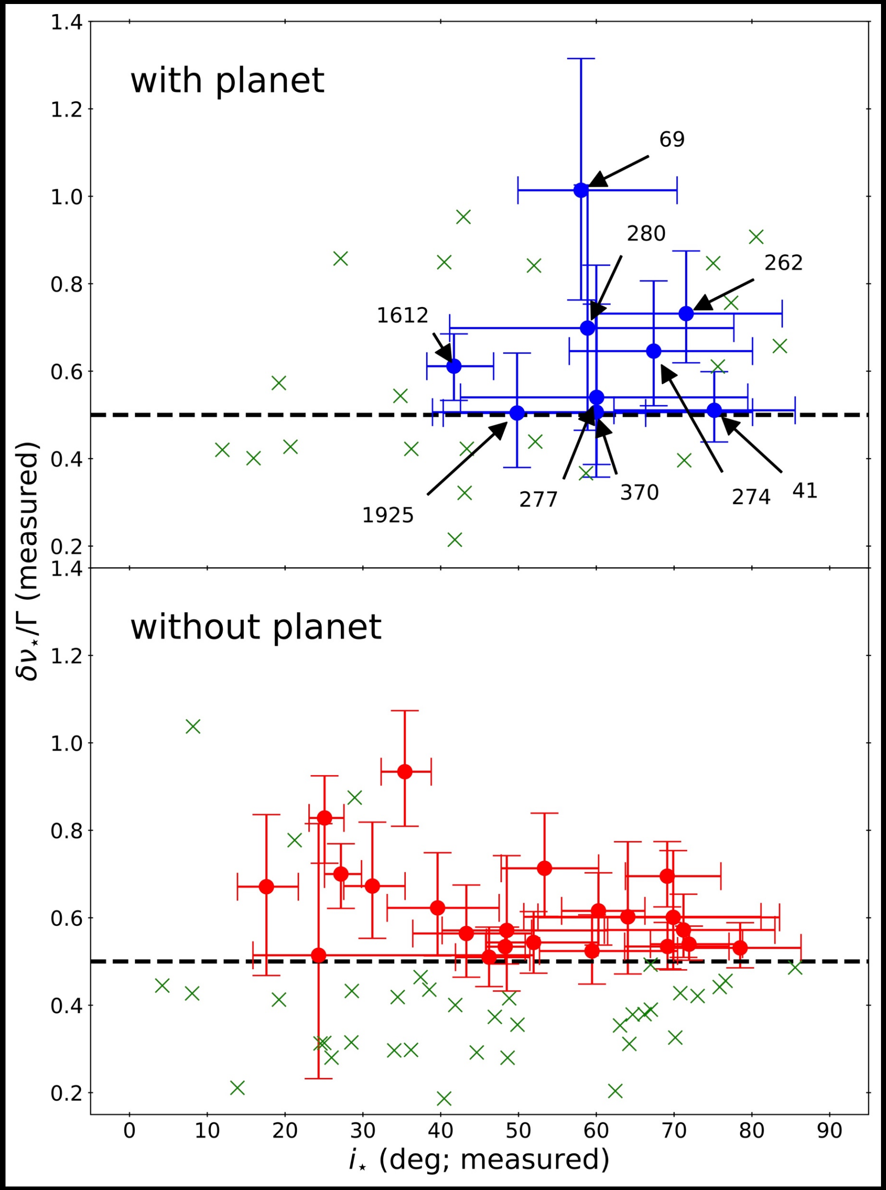
Triaud arXiv:1709.06376

More efficient spin-orbit “realignment” through star-planet tidal interaction due to the thicker convective zones of cool stars with T_{eff}<6100K ? (Winn et al. 2010)

Possible spin-orbit synchronization ?

i_s of Kepler stars from asteroseismology: with/without planets

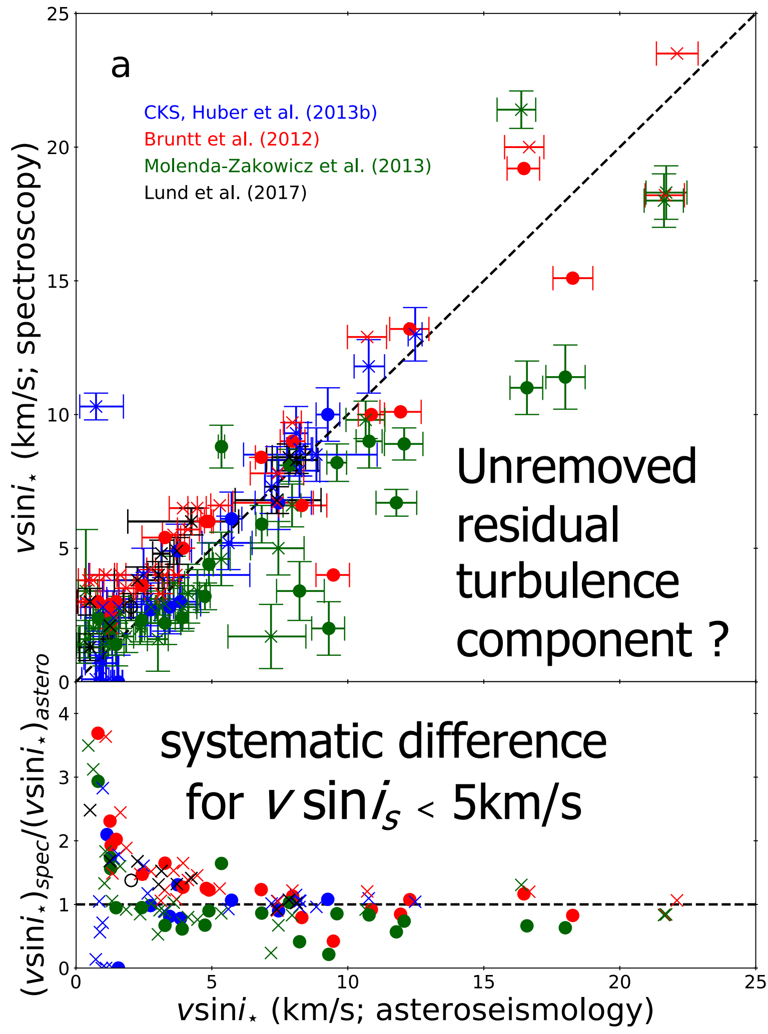
- 94 Kepler main-sequence stars
  - 33 with transiting planets
  - 61 with no known planets
- Transiting planet-host stars have systematically larger stellar obliquities (as expected)



Kamiaka, Benormar, and YS (2018)

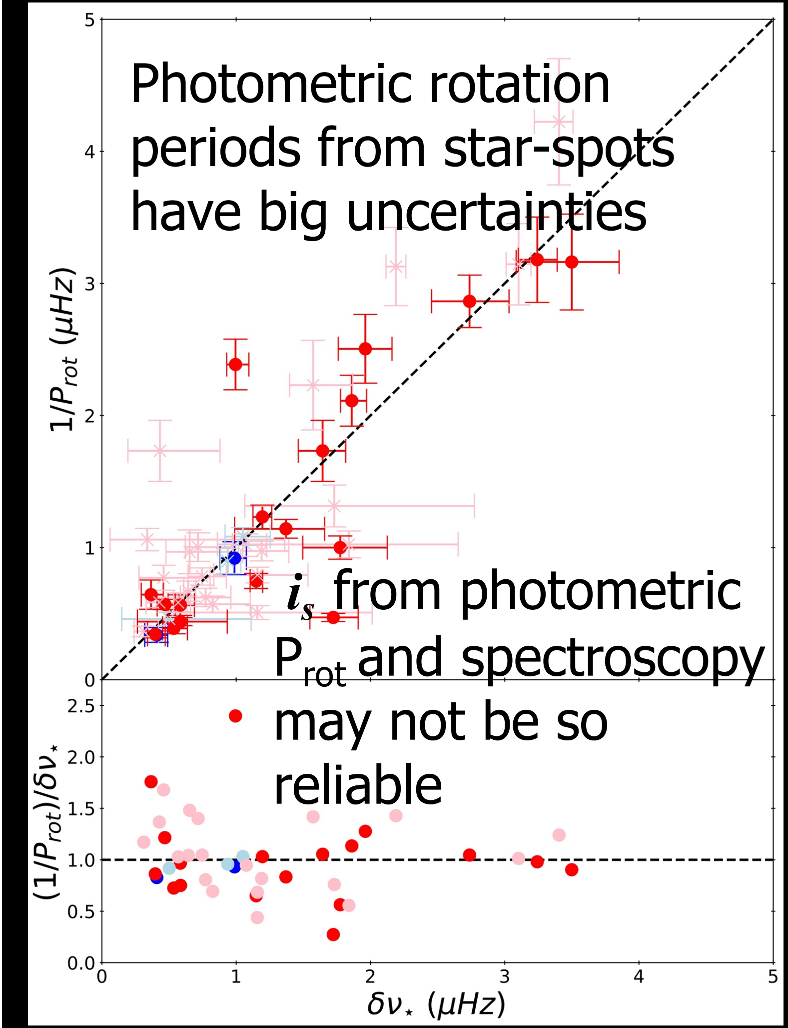
Comparison with independent observational estimates of $v\sin i_s$, P_{rot} and i_s

Kamiaka, Benormar, and YS (2018)



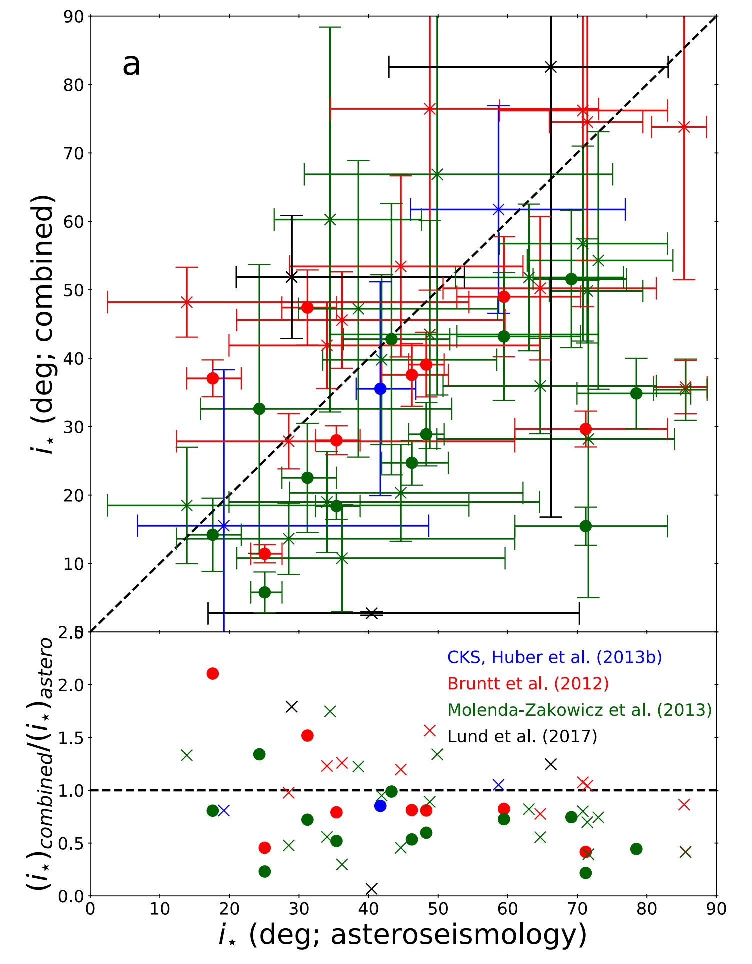
Unremoved residual turbulence component ?

systematic difference for $v\sin i_s$ < 5km/s

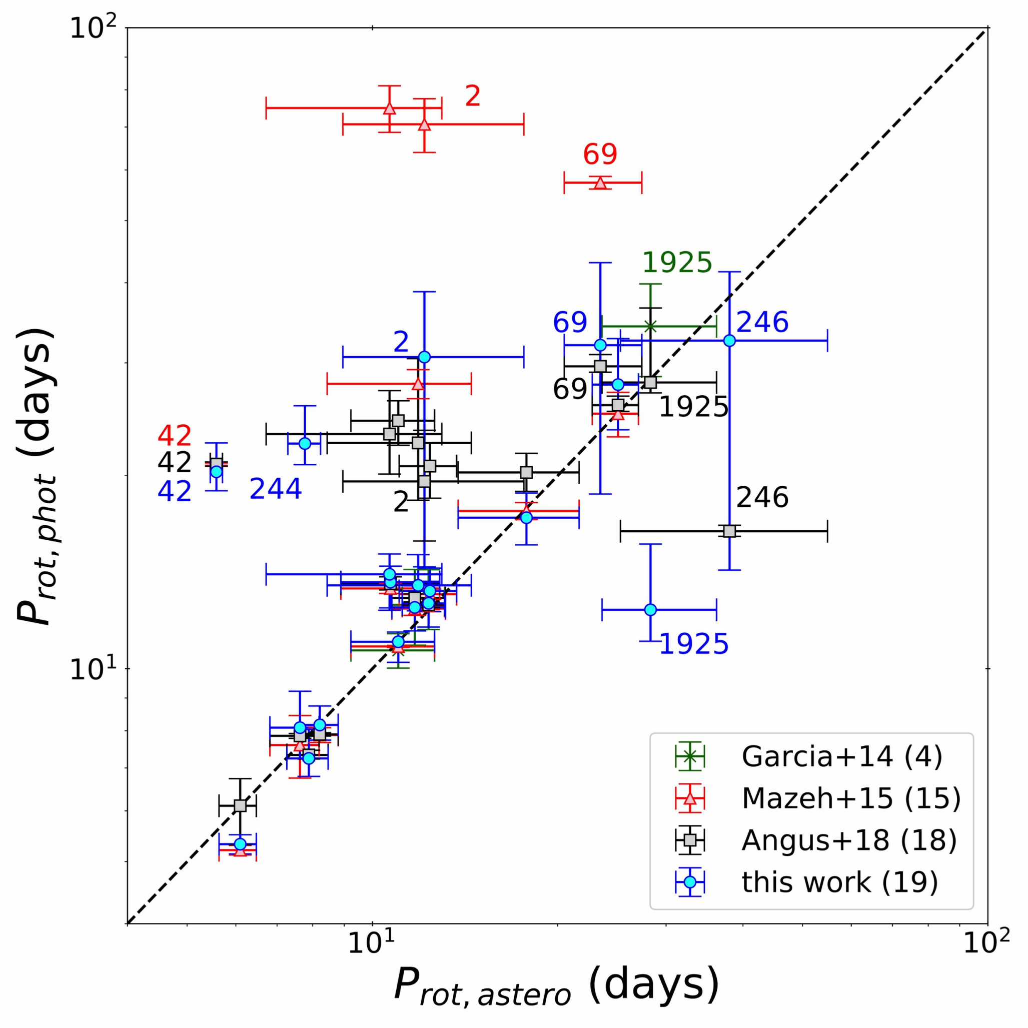


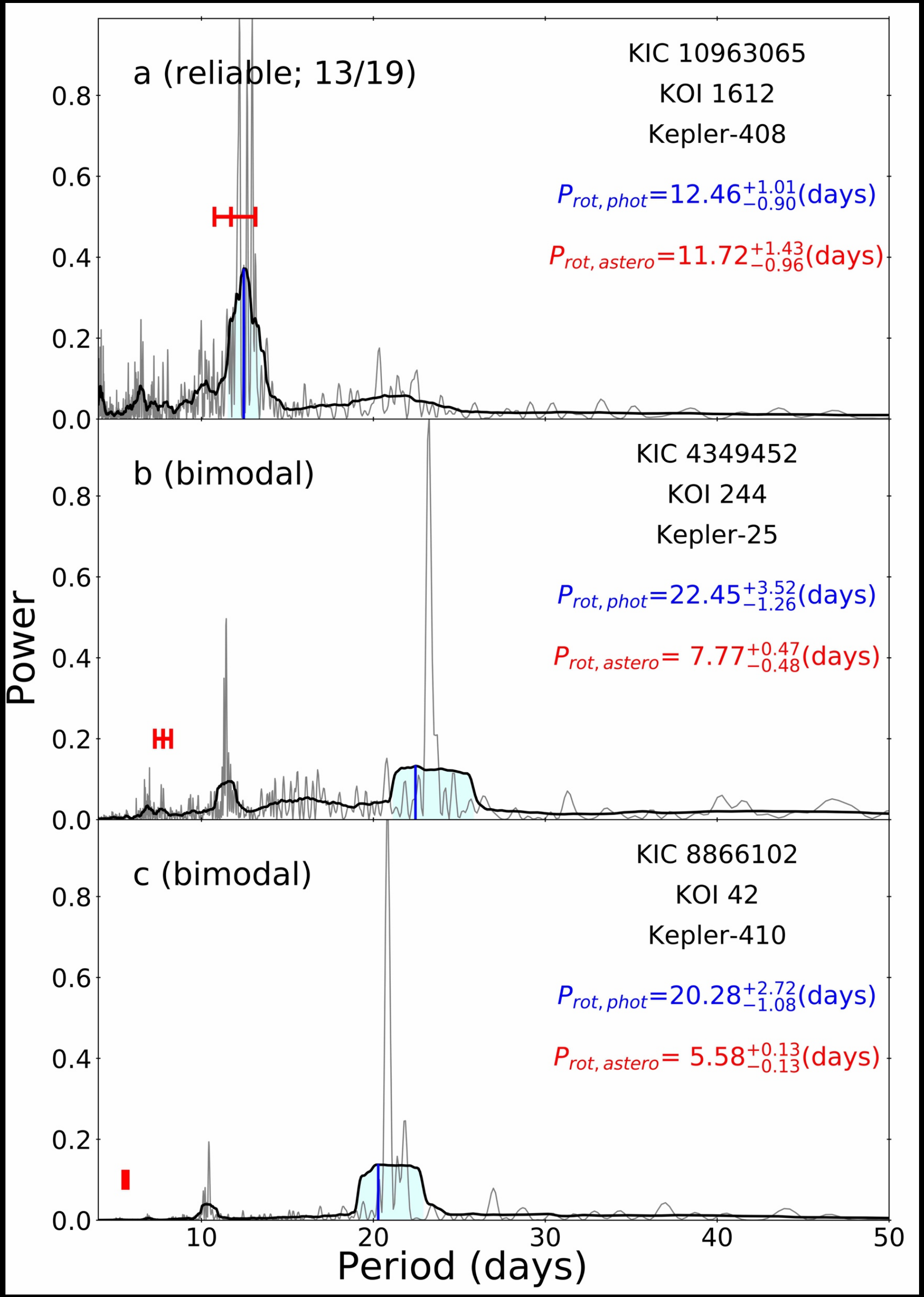
Photometric rotation periods from star-spots have big uncertainties

i_s from photometric P_{rot} and spectroscopy may not be so reliable



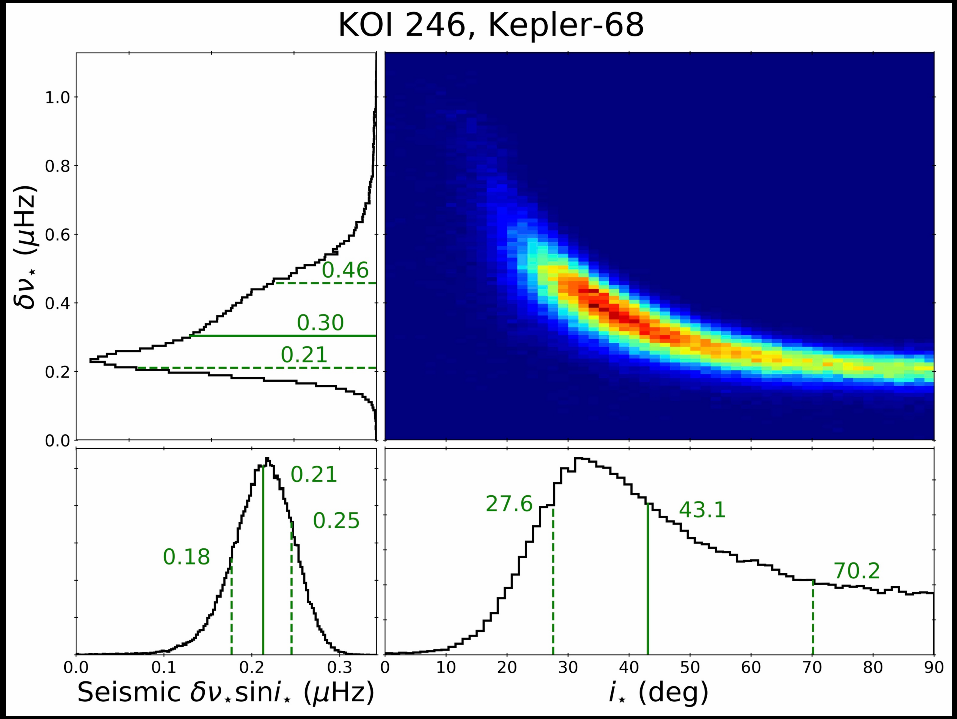
Photometric variation vs. asteroseismology

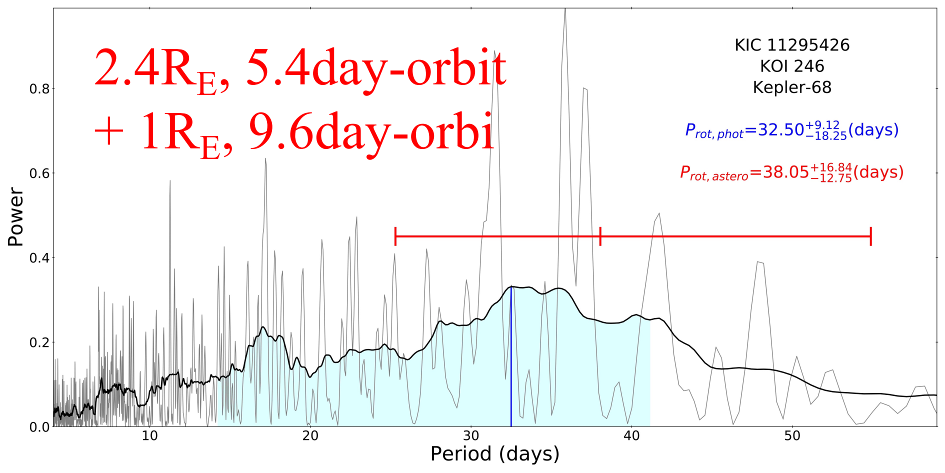




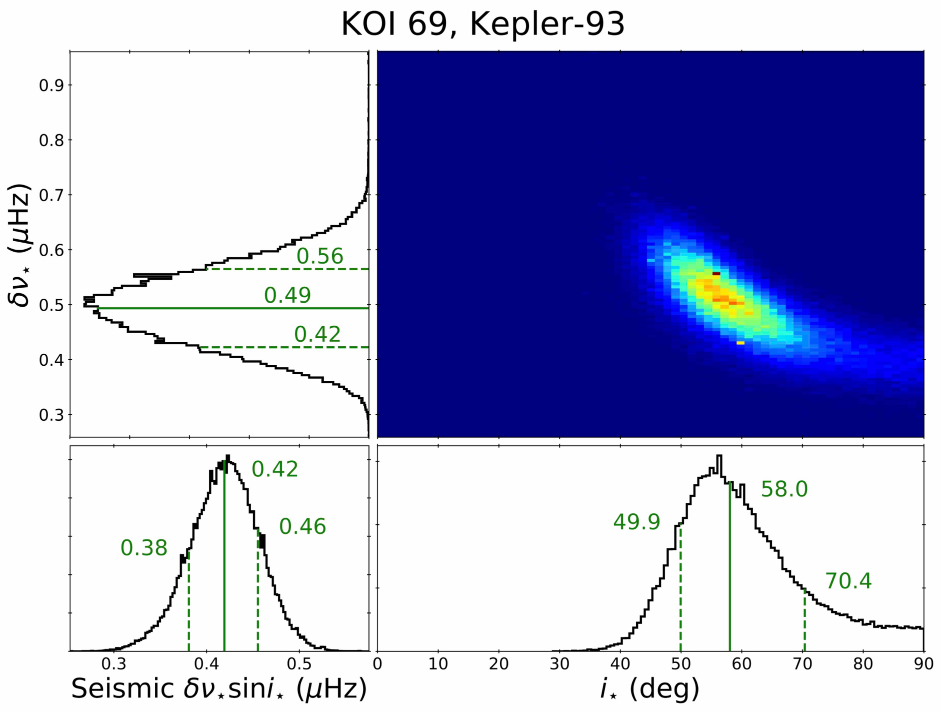
YS, Kamiaka & Benomar AJ 157(2019)172

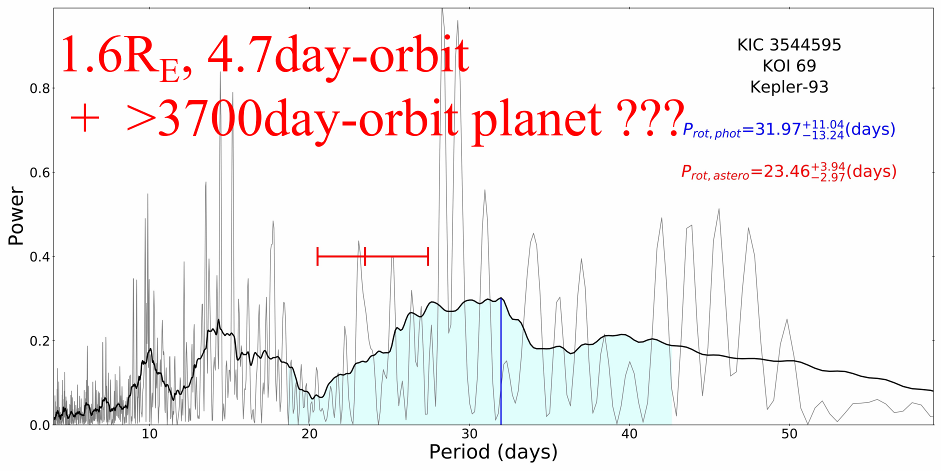
multi-planetary systems of possible interest





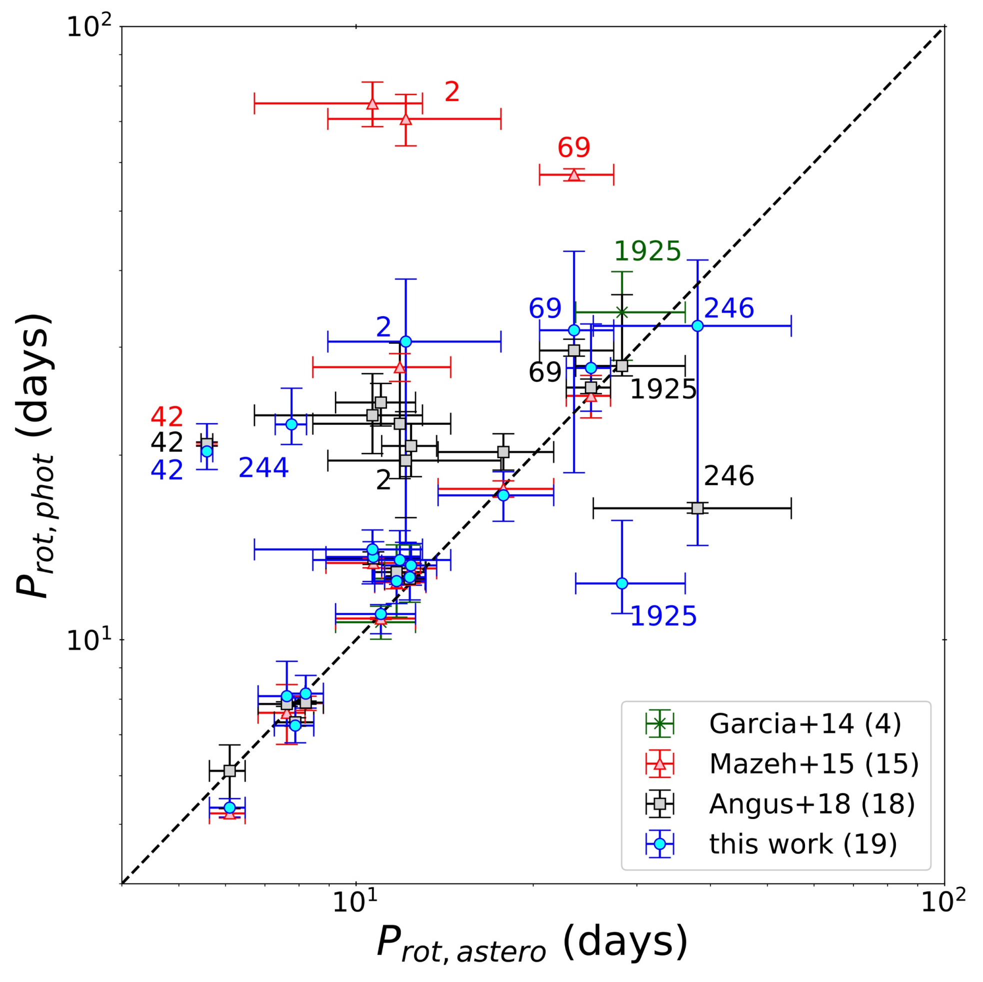
$2.4R_E$, 5.4day-orbit
+ $1R_E$, 9.6day-orbi





$1.6R_E$, 4.7day-orbit
+ >3700day-orbit planet ???

19 Kepler stars with transiting planets



- **Photometric spin rotation periods are not so reliable**
  - different methods (Lomb-Scargle periodogram, auto-correlation, wavelet, Gaussian process) often give very different resutls
- **Asteroseismic spin rotation period is independent**
  - nature of spots? latitudinal differential rotation?
  - radial differential rotation?

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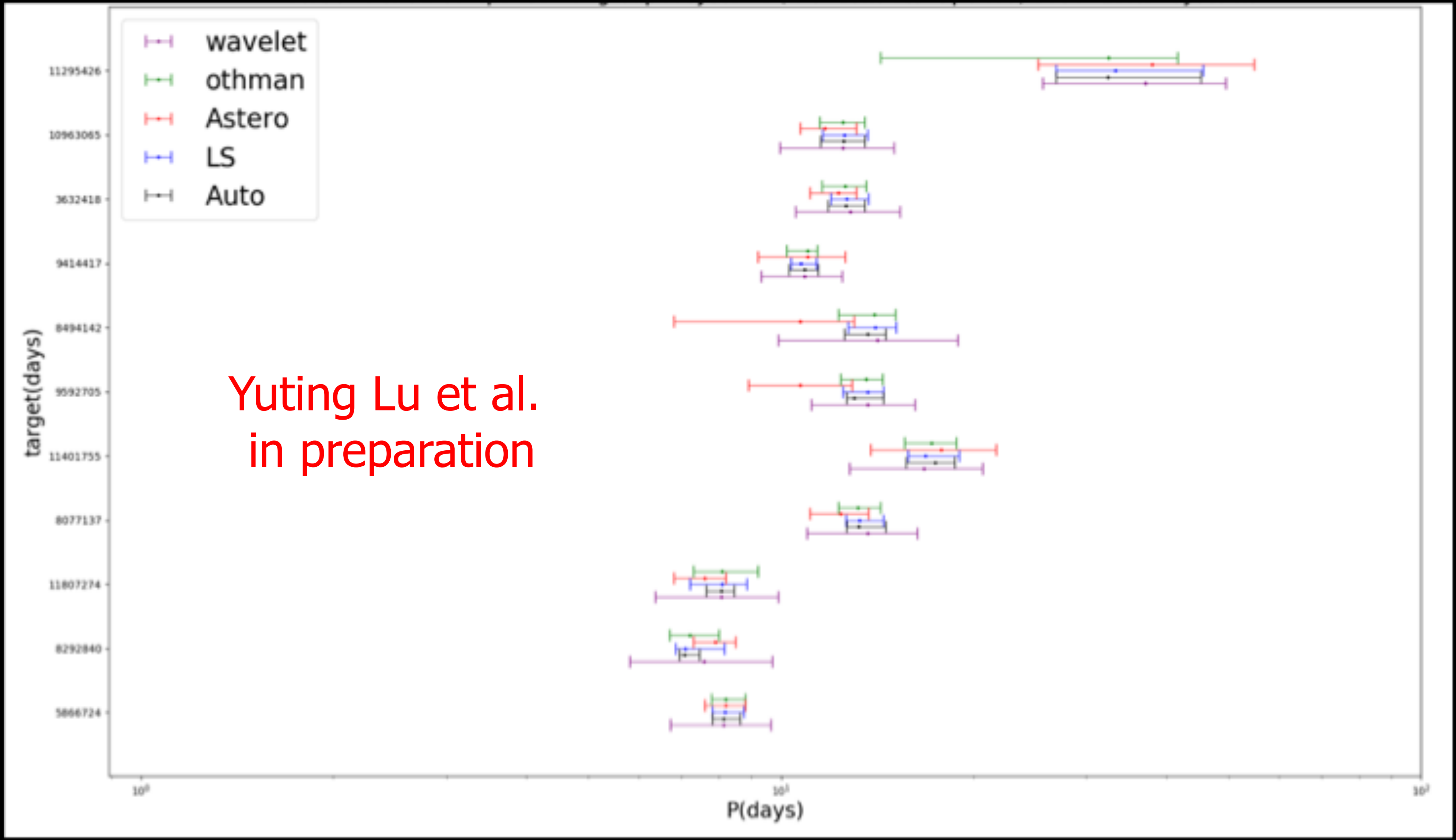
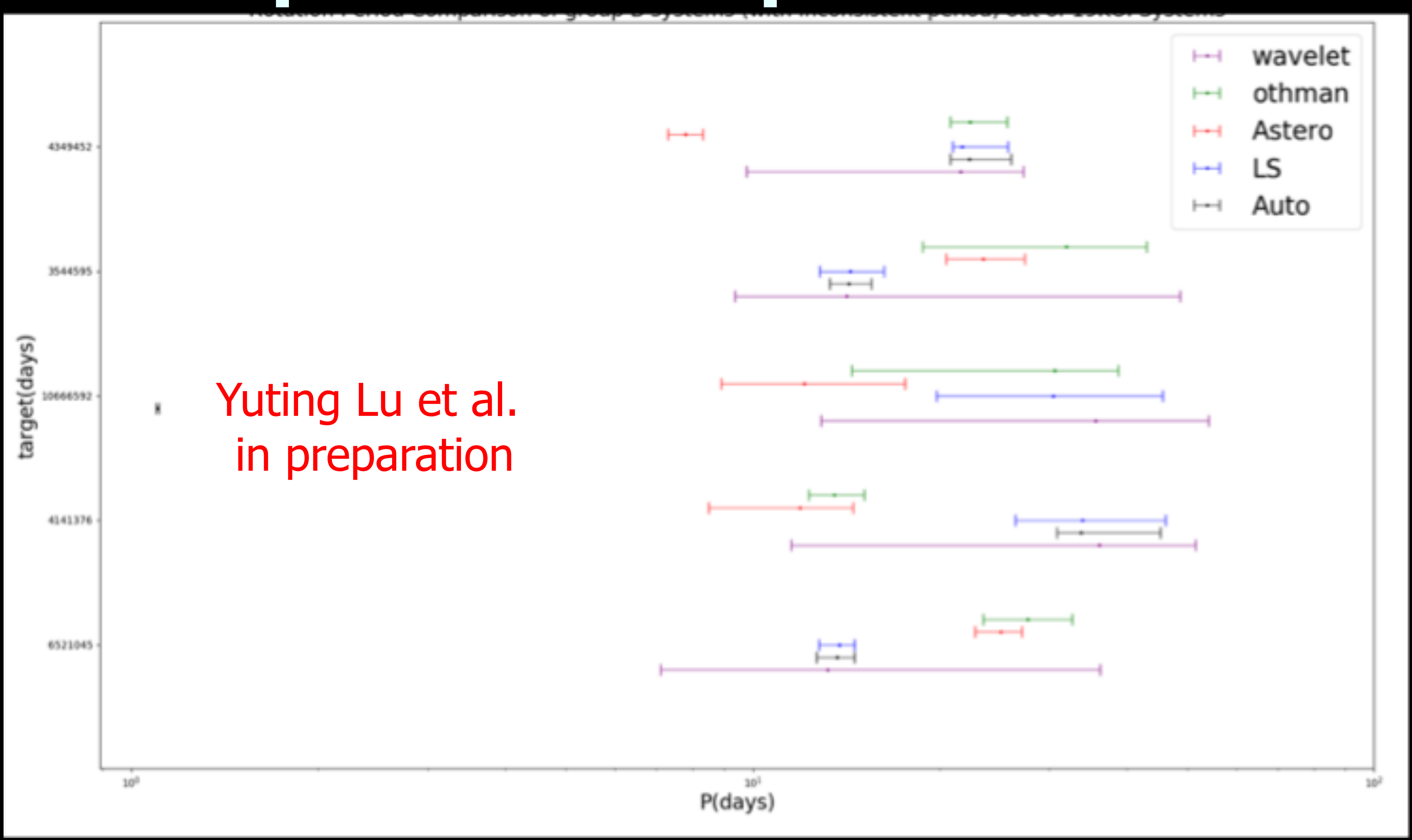
all spin periods are consistent: 11 out of 18



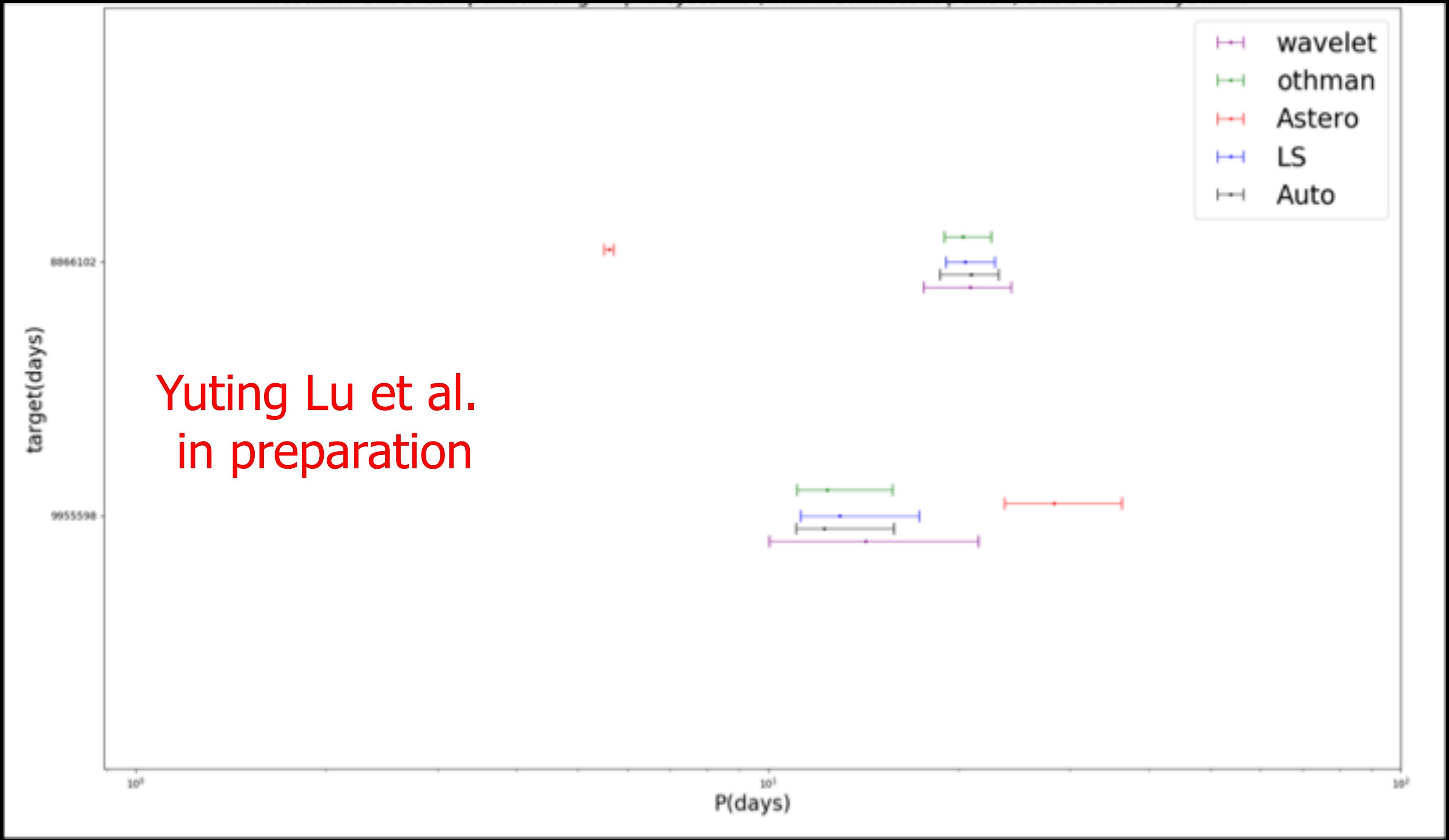
Yuting Lu et al.
in preparation

Different photometric periods: 5 out of 18



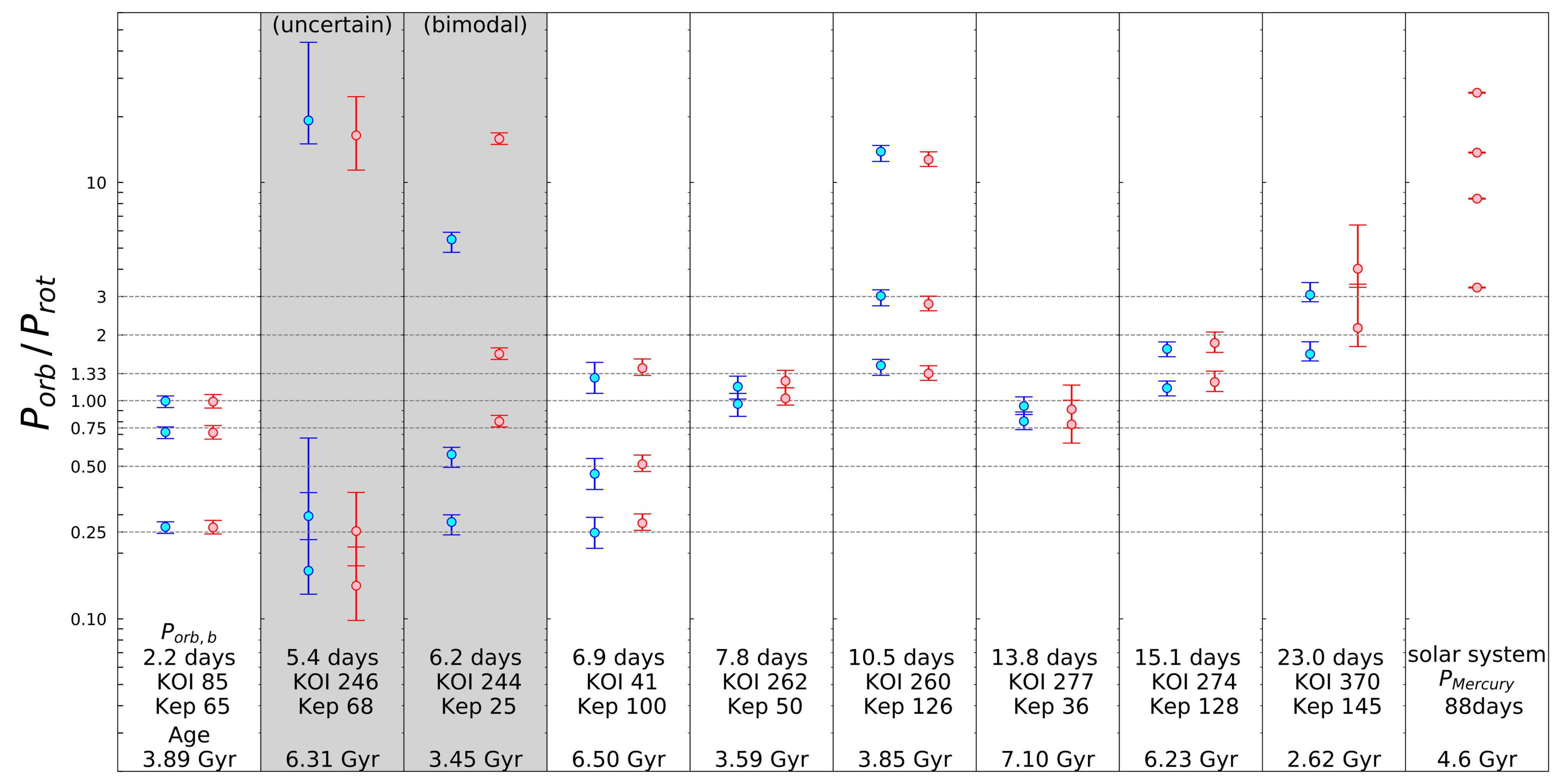
Yuting Lu et al.
in preparation

photometric ≠ asteroseismic: 2 out of 18



Yuting Lu et al.
in preparation

spin-orbit synchronization for multis ?



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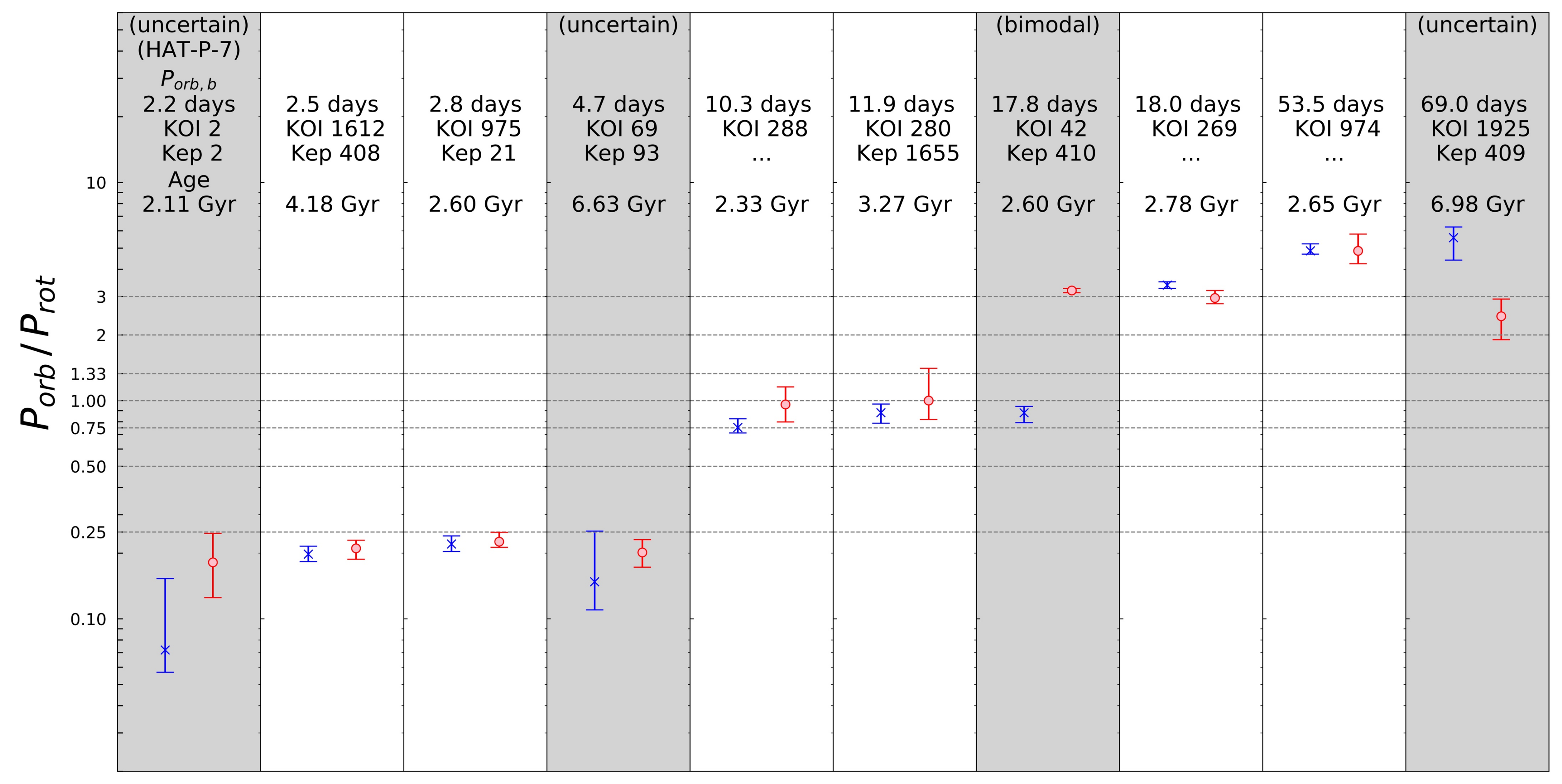
spin-orbit synchronization for singles ?



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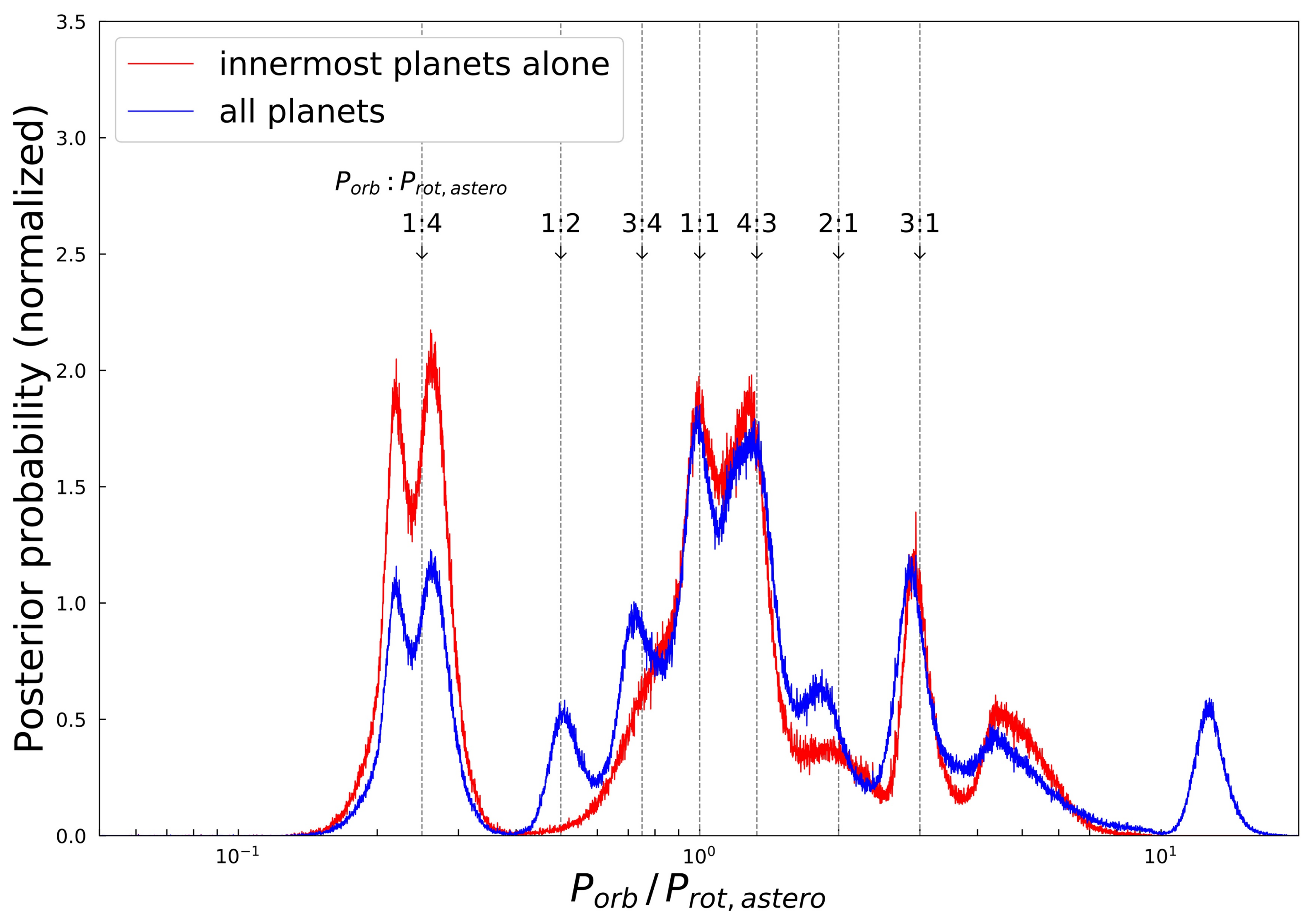
Posterior probability density



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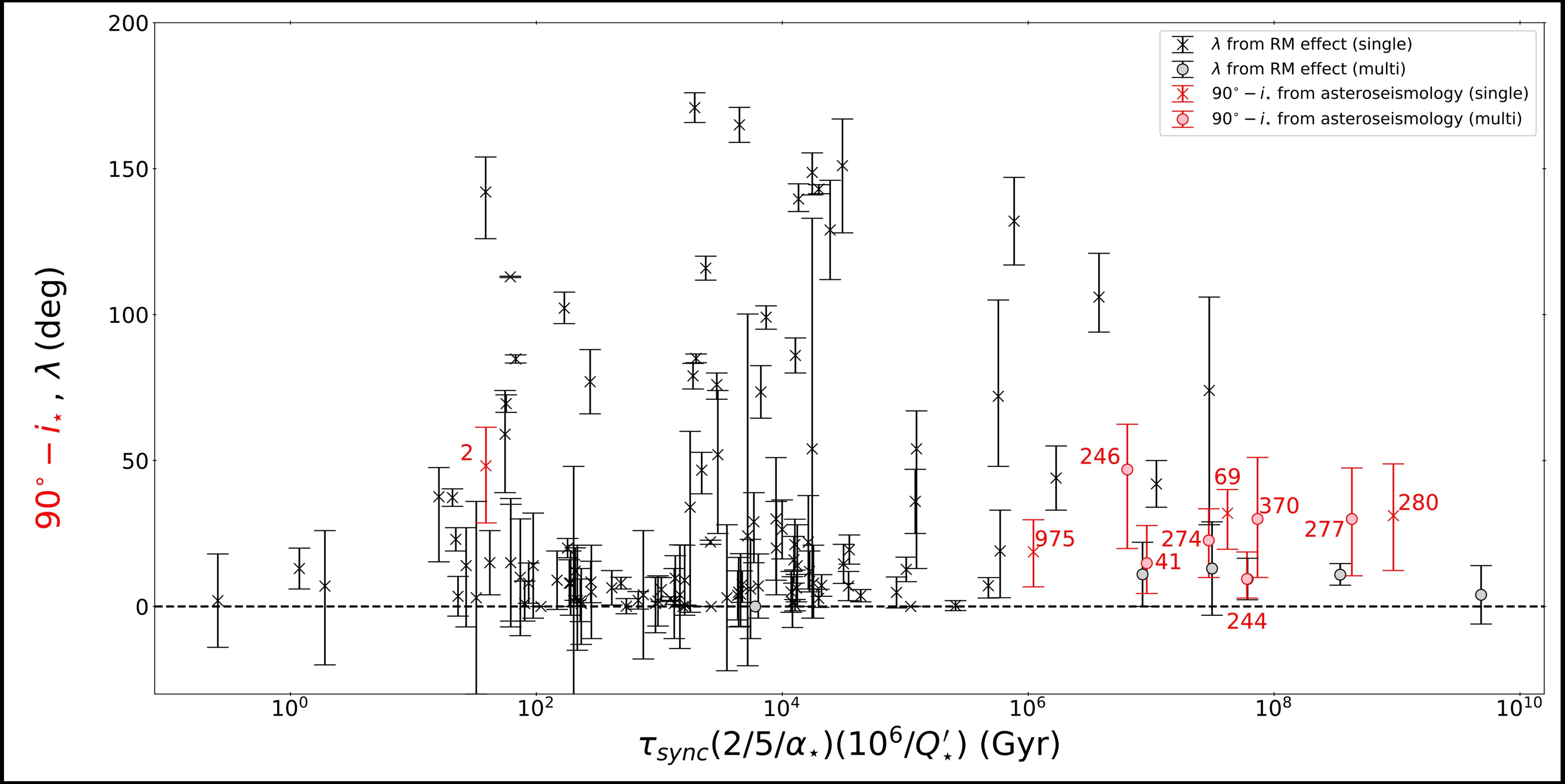
Spin-orbit angles against the tidal synchronization time-scale



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Summary of spin-orbit synchronization for Kepler transiting planetary systems

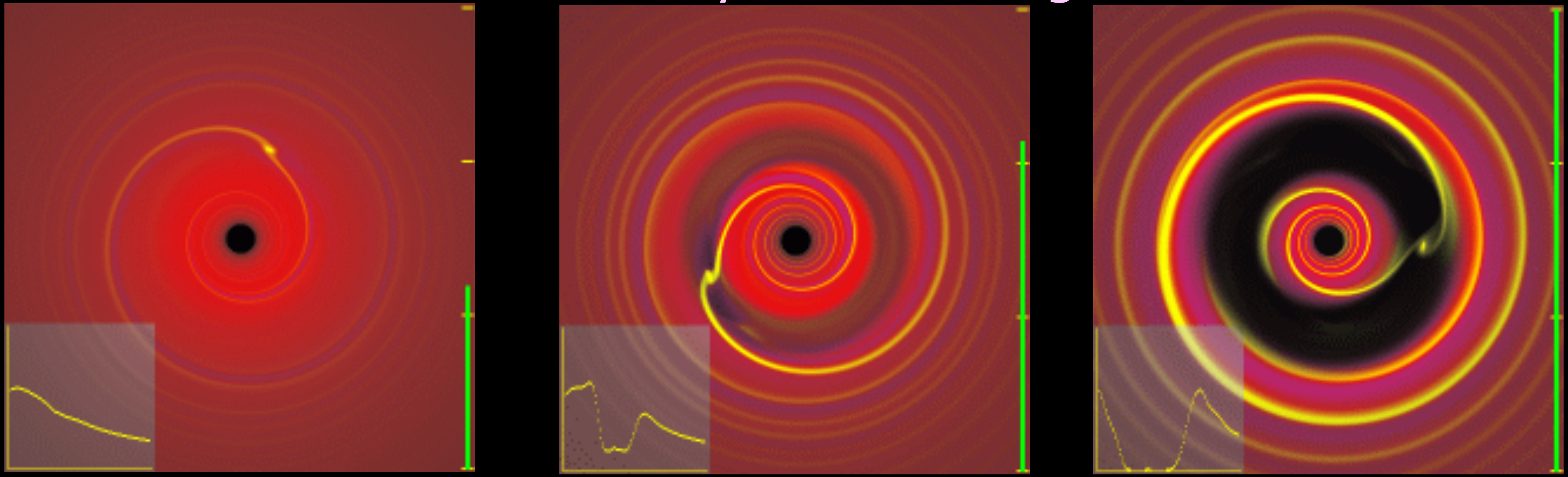
- Eclipsing binary stars often show spin-orbit resonance/synchronization (Lurie et al. 2017)
- Do exoplanetary systems show the similar spin-orbit resonance/synchronization ?
  - Photometrically estimated spin periods may not so reliable as thought before: spots evolution, latitudinal differential rotation
- Very preliminary indication for spin-orbit synchronization (?)
  - need more observational/theoretical work

Origin of spin-orbit misalignment

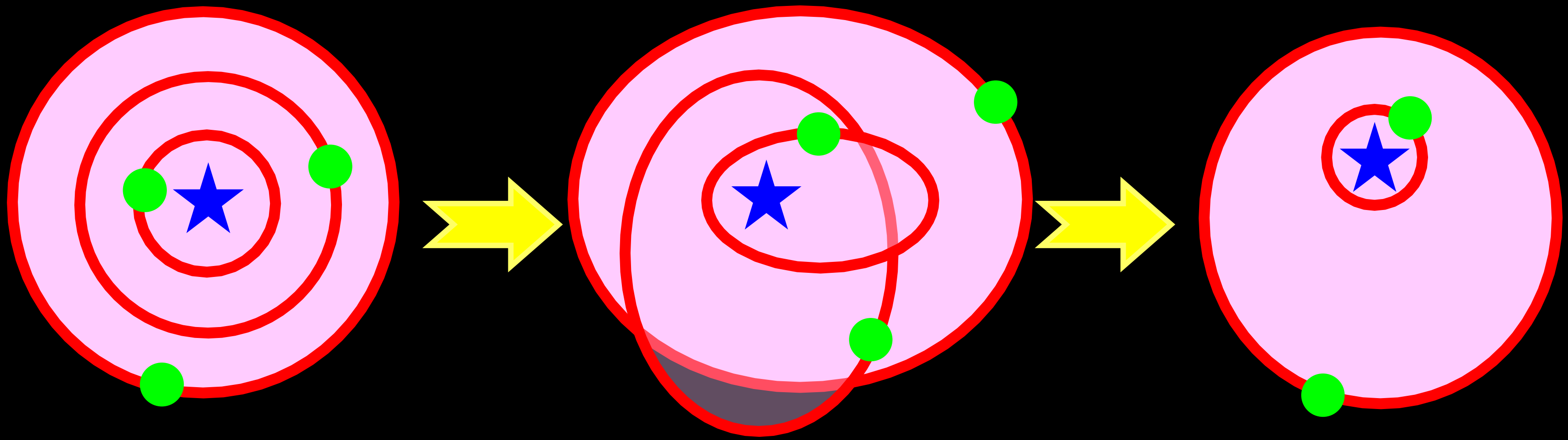
Planet migration channels

- Gravitational scattering
  - Planet - planet
- Type I migration
  - Low-mass planet - spiral wave in the gas disk
- Type II migration
  - High-mass planet - gap in the disk

Simulation by Phil Armitage



Planet-planet gravitation scattering + star-planet tidal interaction = circularized but misaligned Hot Jupiters



- Broad distribution of spin-orbit angles is generated due to planet scattering, tidal circularization, and the Lidov-Kozai effect (e.g., Nagasawa, Ida + Bessho 2008)

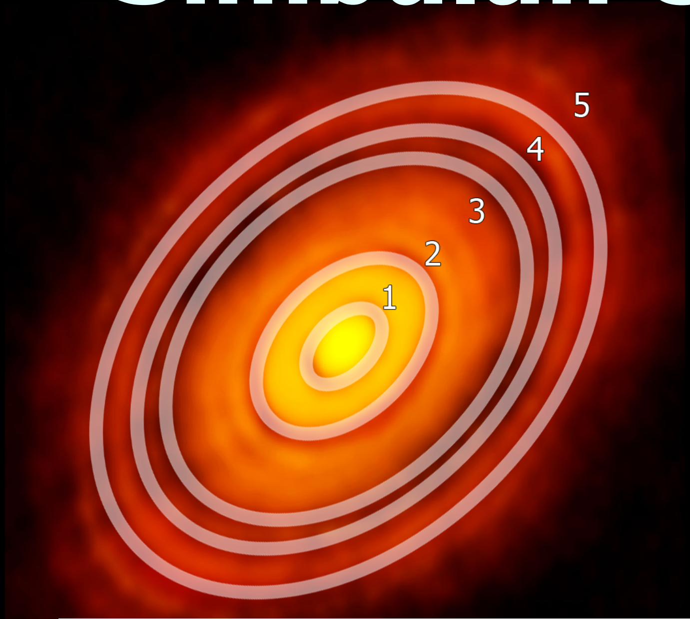
Origin of the spin-orbit misalignment ?

- Disk-planet migration is not so efficient to generate significant misalignment ?
- Planet-planet scattering may explain the observed misaligned systems (e.g., Nagasawa et al. 2008), but their initial condition is realistic ?
  - **Outcomes from the observed ALMA disks ?**
- Nearby stars and/or outer planets could perturb the dynamics of inner planets, but do they really exist ?
- Primordial misalignment in the proto-planetary disks
  - **Hydro-simulations of the primordial (mis)alignment ?**

Our on-going projects: Nature or Nurture

- **Daisuke Takaishi**, Y.Tsukamoto & YS (2019) in prep.
  - Collapse of turbulent isothermal clouds without magnetic field
  - SPH simulation + sink particles as proto-stars
  - Primordial (mis)alignment of star and disk rotation axes
- **Shijie Wang**, K.Kanagawa, T.Hayashi & YS (2019) in prep.
  - Populate proto-planets in the observed HL tau disk
  - Their orbital and mass evolution via disk-planet migration
  - Planet-planet interaction after the disk gas removal
  - What is the diversity in the resulting multi-planetary systems?

Simbulan et al. MNRAS 469(2017)3337



Very strong planet-planet scattering results in significant spin-orbit misalignment !
But too simplified modeling of disk-planet interaction and planet mass accretion ???

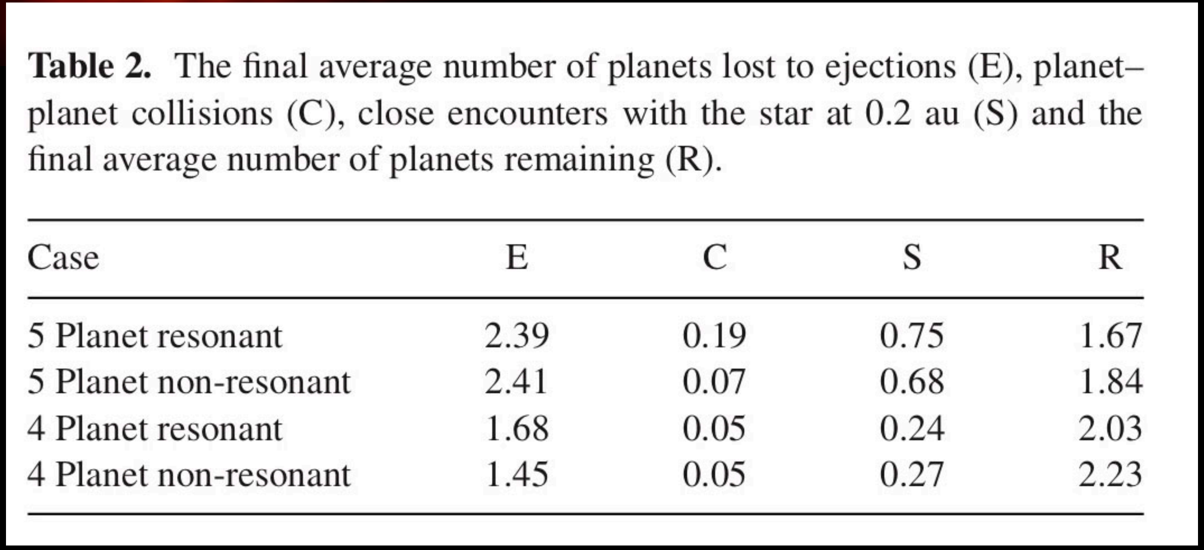
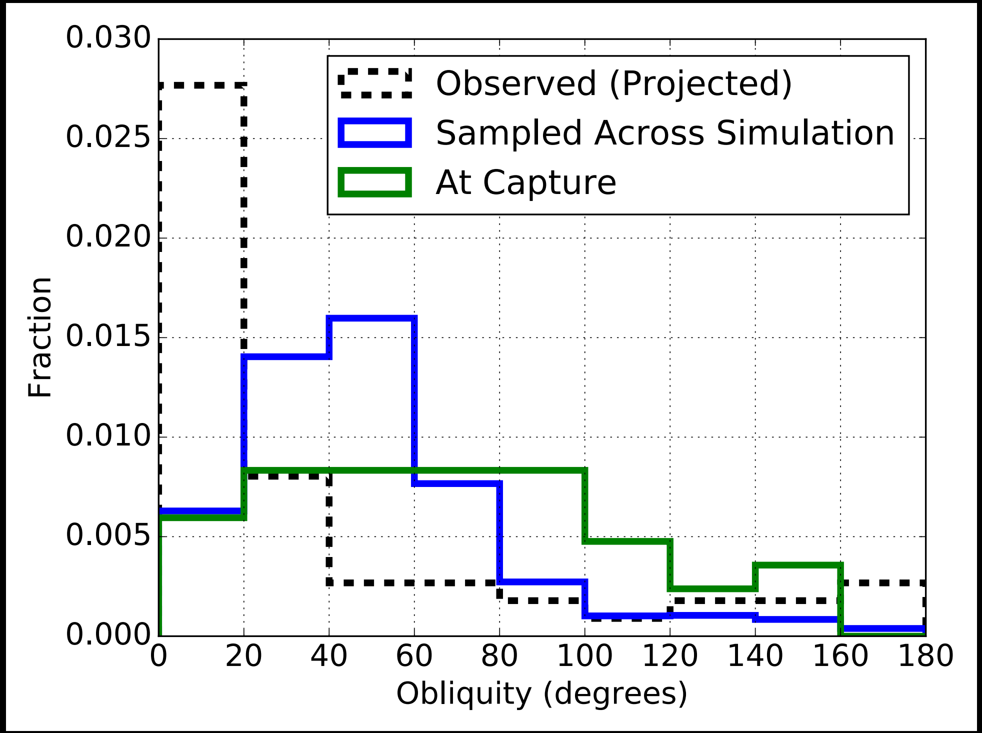


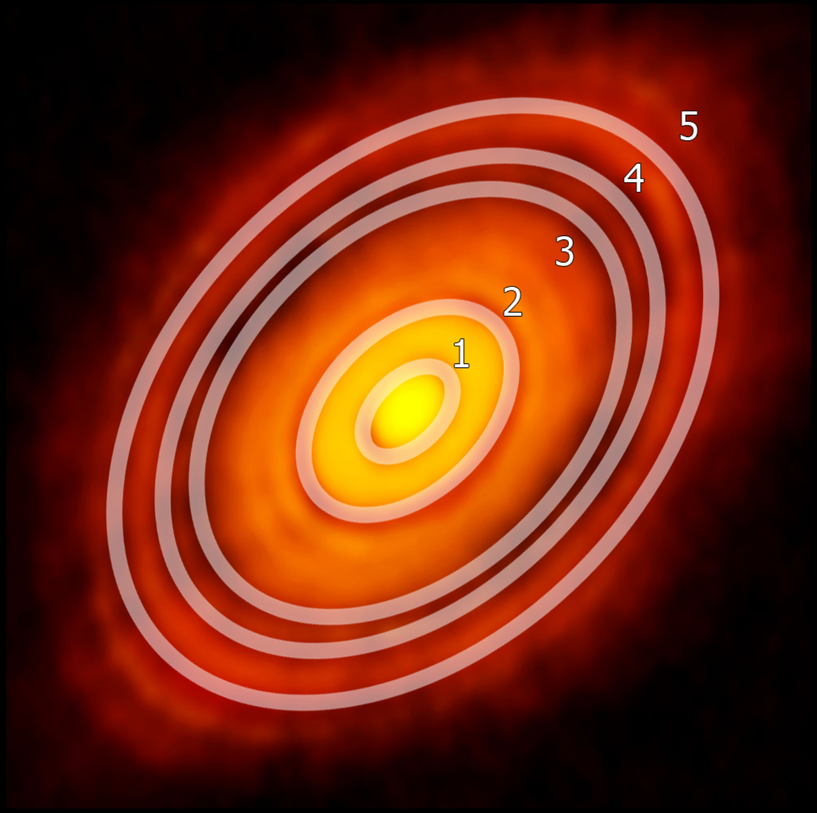
Table 2. The final average number of planets lost to ejections (E), planet–planet collisions (C), close encounters with the star at 0.2 au (S) and the final average number of planets remaining (R).

Case	E	C	S	R
5 Planet resonant	2.39	0.19	0.75	1.67
5 Planet non-resonant	2.41	0.07	0.68	1.84
4 Planet resonant	1.68	0.05	0.24	2.03
4 Planet non-resonant	1.45	0.05	0.27	2.23



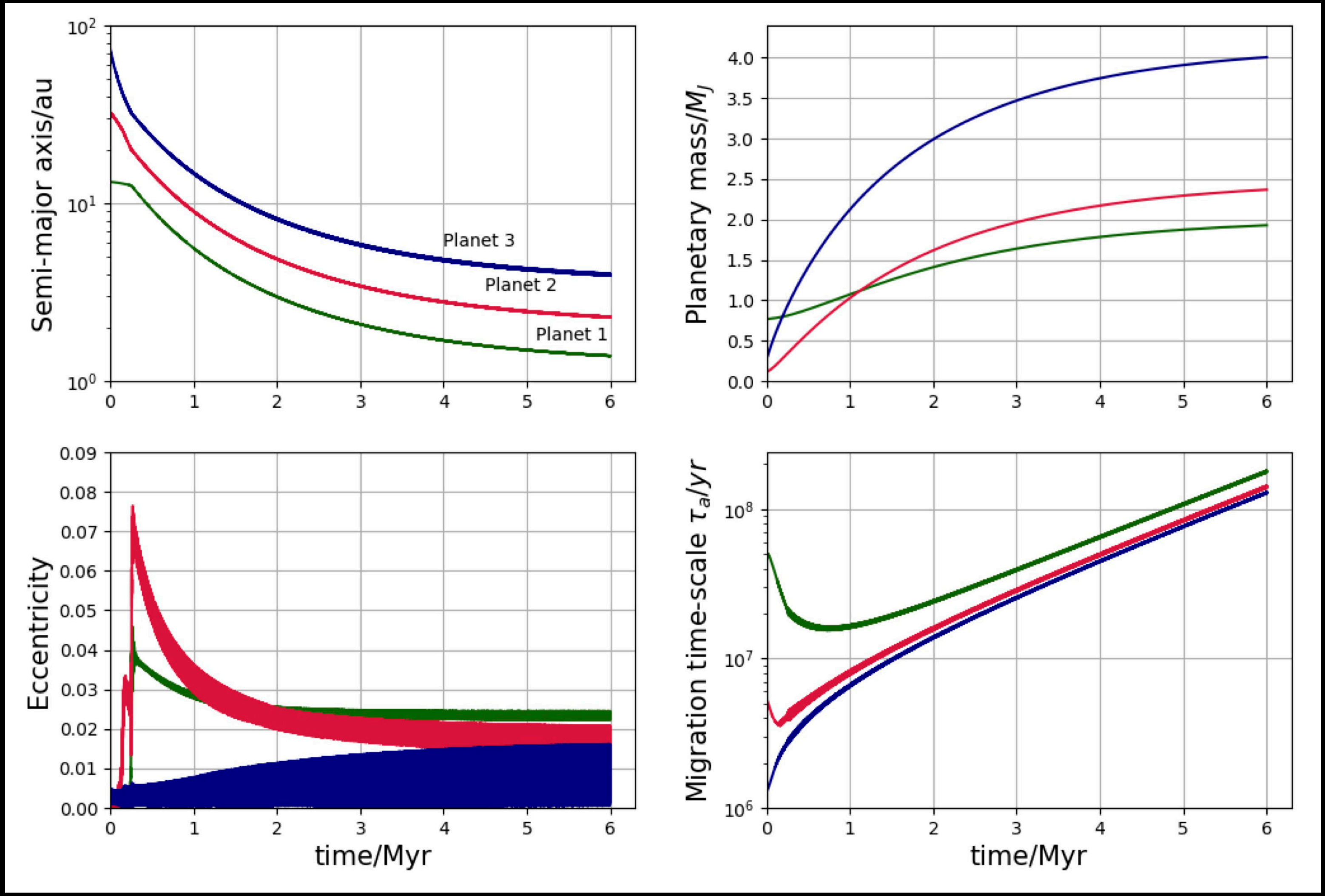
Improved disk-planet migration model

- Parameterization of the HL tau disk
  - disk viscosity α
  - flaring index f $(h \propto r^{f+1})$
  - gas dispersal time-scale τ
- Empirical migration model derived from 2D hydro-simulation by Kanagawa et al. (2018)
- Initially 3 planets are located at the major three gaps (1, 2, and 4) in the HL tau disk (Dipierro et al. 2015, Jin et al. 2016, Dong et al. 2017, 2018)



Wang, Kanagawa, Hayashi & YS (2019)

An example of the three-planet system



Wang, Kanagawa, Hayashi & YS (2019)

Fairly stable configuration ?

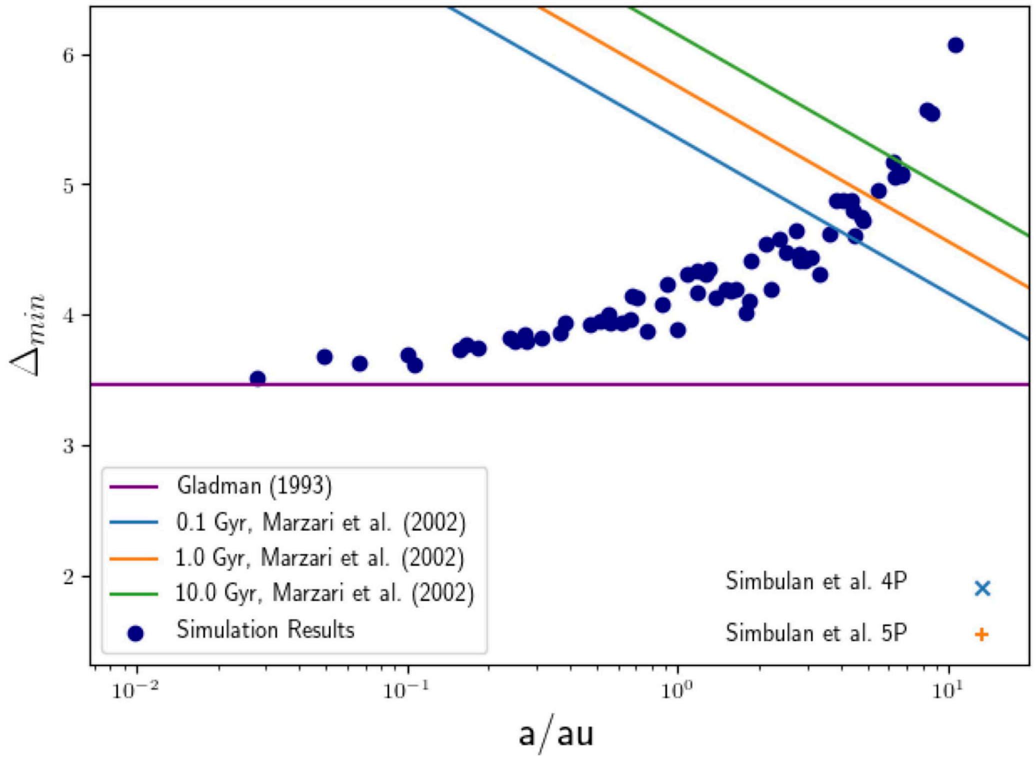
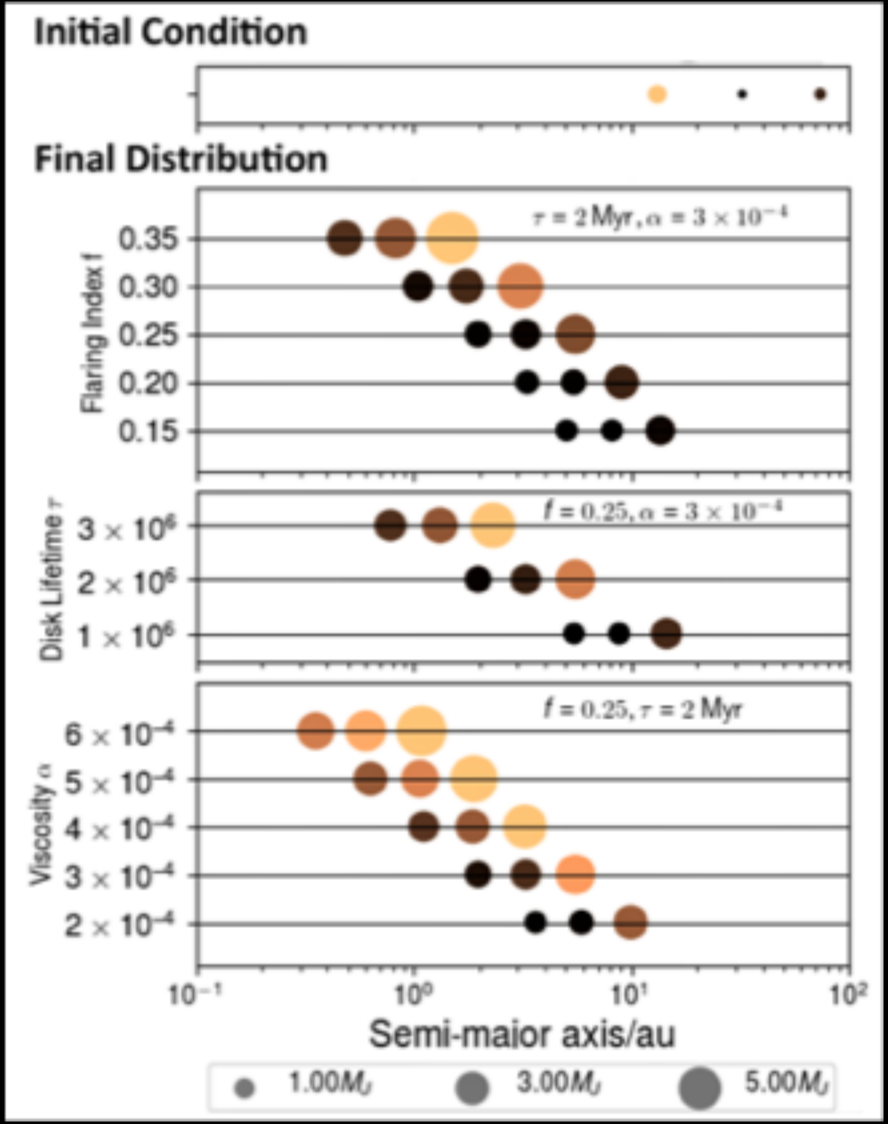


Figure 6. Minimum orbital separation of adjacent planet pairs in mutual Hill radius against the semi-major axis of the inner-most planet.



Wang, Kanagawa, Hayashi & YS (2019)

Fairly stable configuration ?

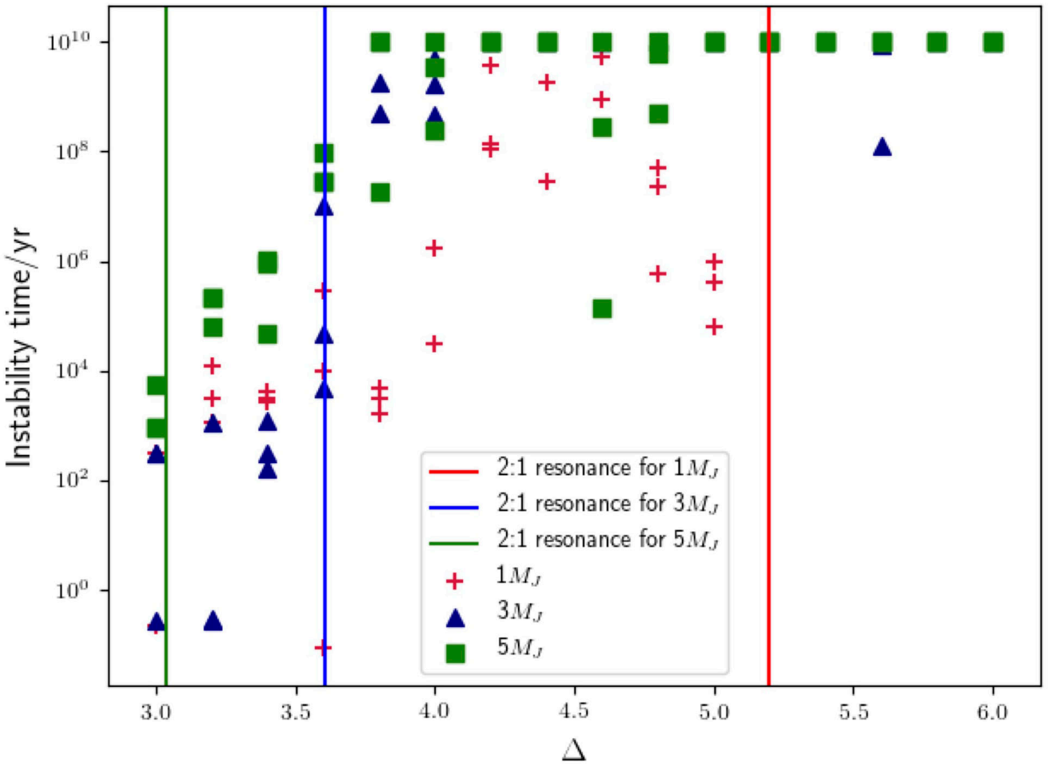
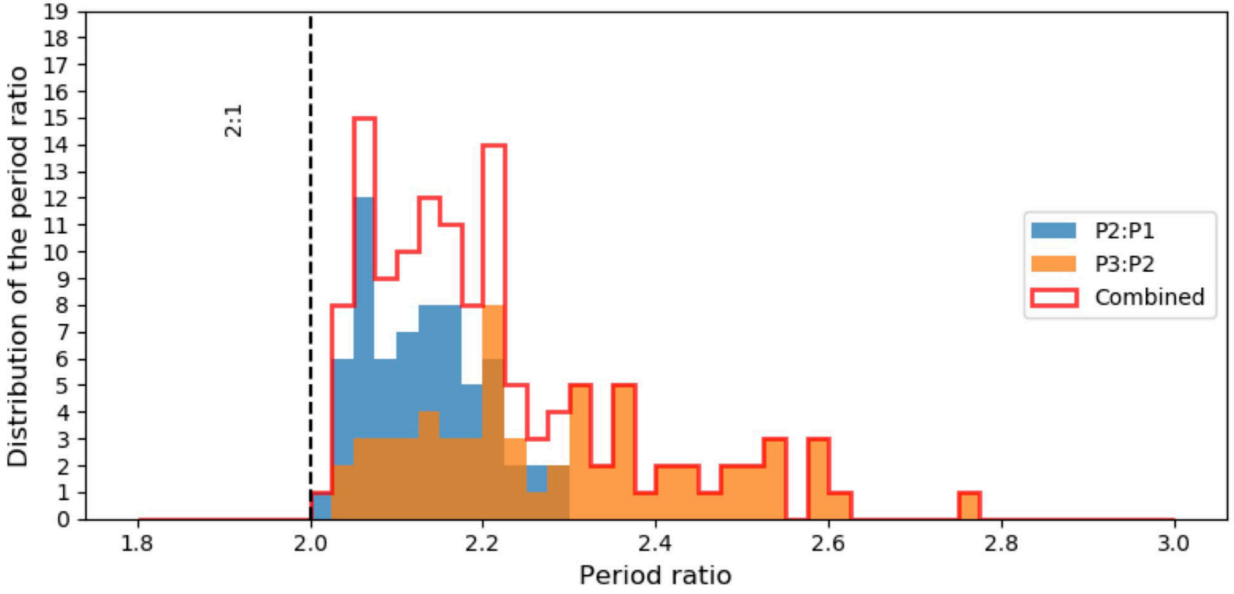


Figure 7. Instability time against the mutual Hill raidus for three planets in equal separation with equal mass.



Wang, Kanagawa, Hayashi & YS (2019)

Very preliminary summary

- Simulations starting from three planets located in HL tau protoplanetary disk
  - more realistic disk-planet migration modeling (Kanagawa et al. 2018)
- Almost all the systems are stable for ≫1 Gyr
  - very different from Simbulan et al. (2017) 's result
- incorrect/missing physics or initial condition ?
- HL tau is exceptional ?
- external perturbation ?