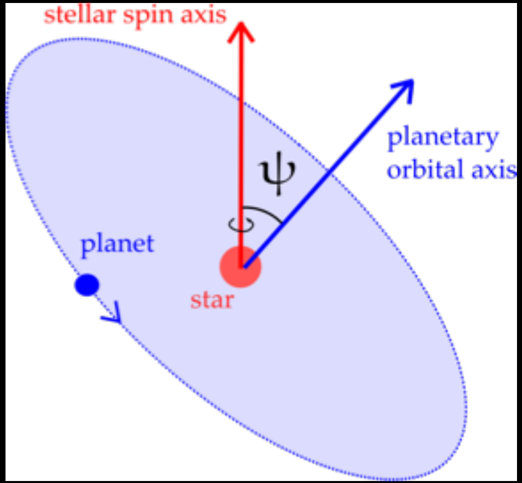
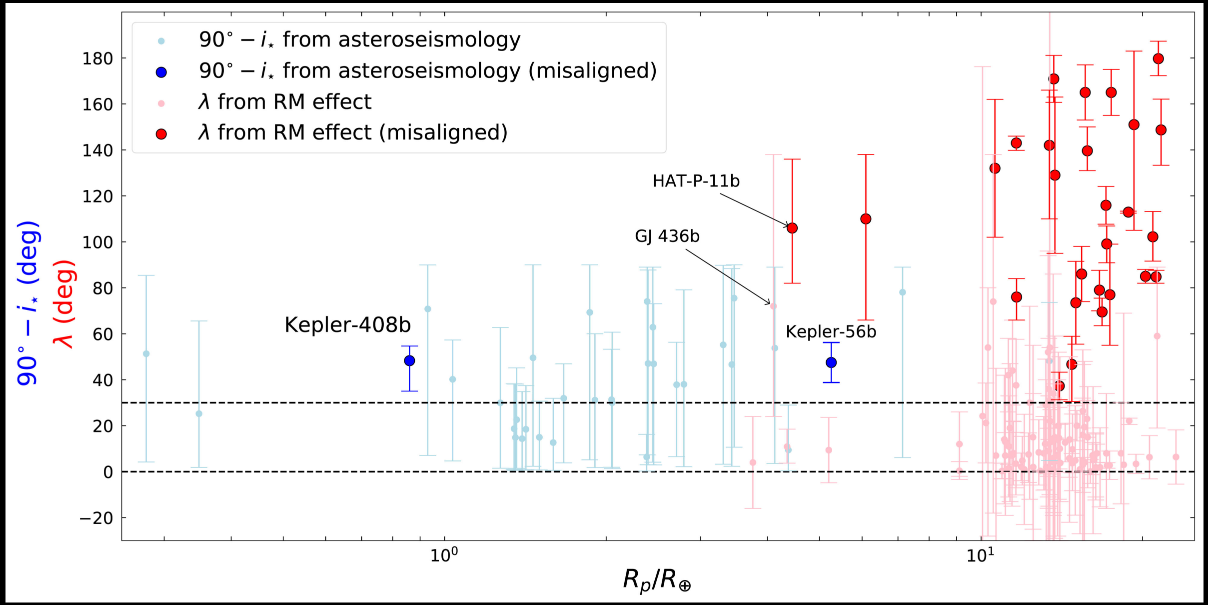
Spin-orbit architecture of planetary systems with the Rossiter-McLaughlin effect and asteroseismology





Core-to-Core Program

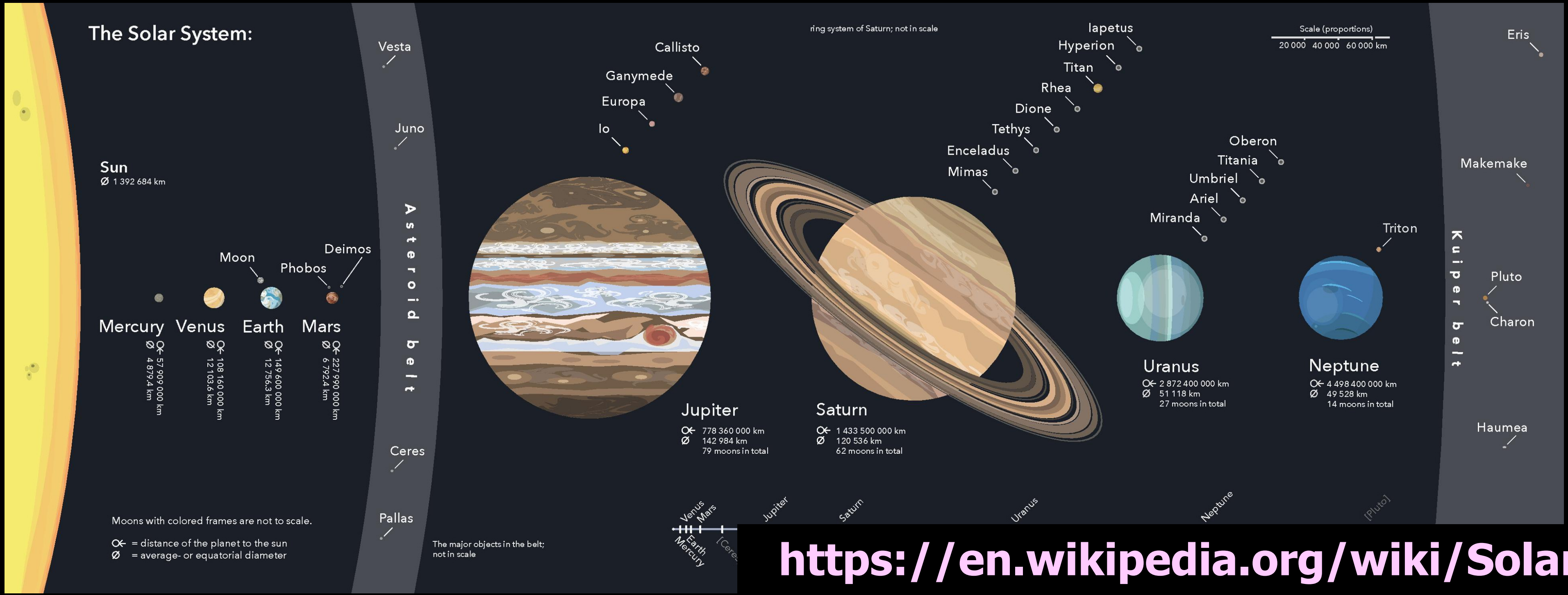
Yasushi Suto

Department of Physics and Research Center for the Early Universe
The University of Tokyo

JSPS core-to-core program Planet^2 & RESCEU workshop on exoplanets
10:00-10:30 August 27, 2019 @ Univ. of Tokyo

The Rossiter-McLaughlin effect

Architecture of the Solar system



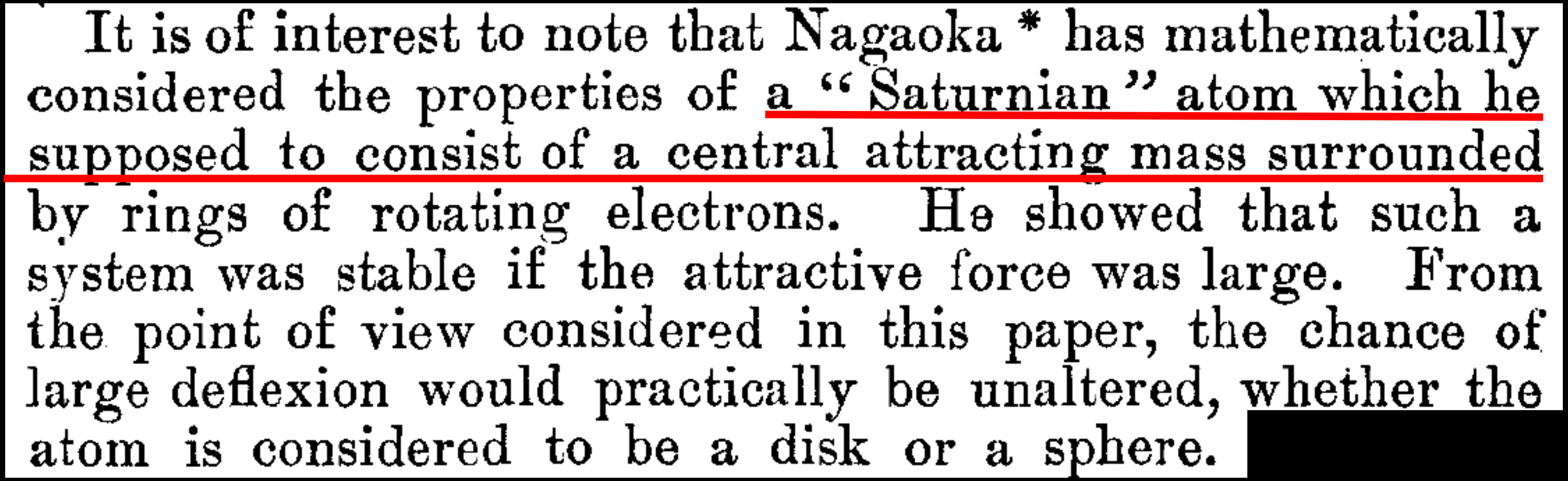
https://en.wikipedia.org/wiki/Solar_System

- Is our Solar system 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

From Saturnian model to atomic model

- Saturnian architecture inspired the model of atomic structure
  - H.Nagaoka: Phil. Mag. 7(1904) 445

Ernest Rutherford: *The Scattering of α and β Particles by Matter and the Structure of the Atom* Phil. Mag. 6(1911) 669

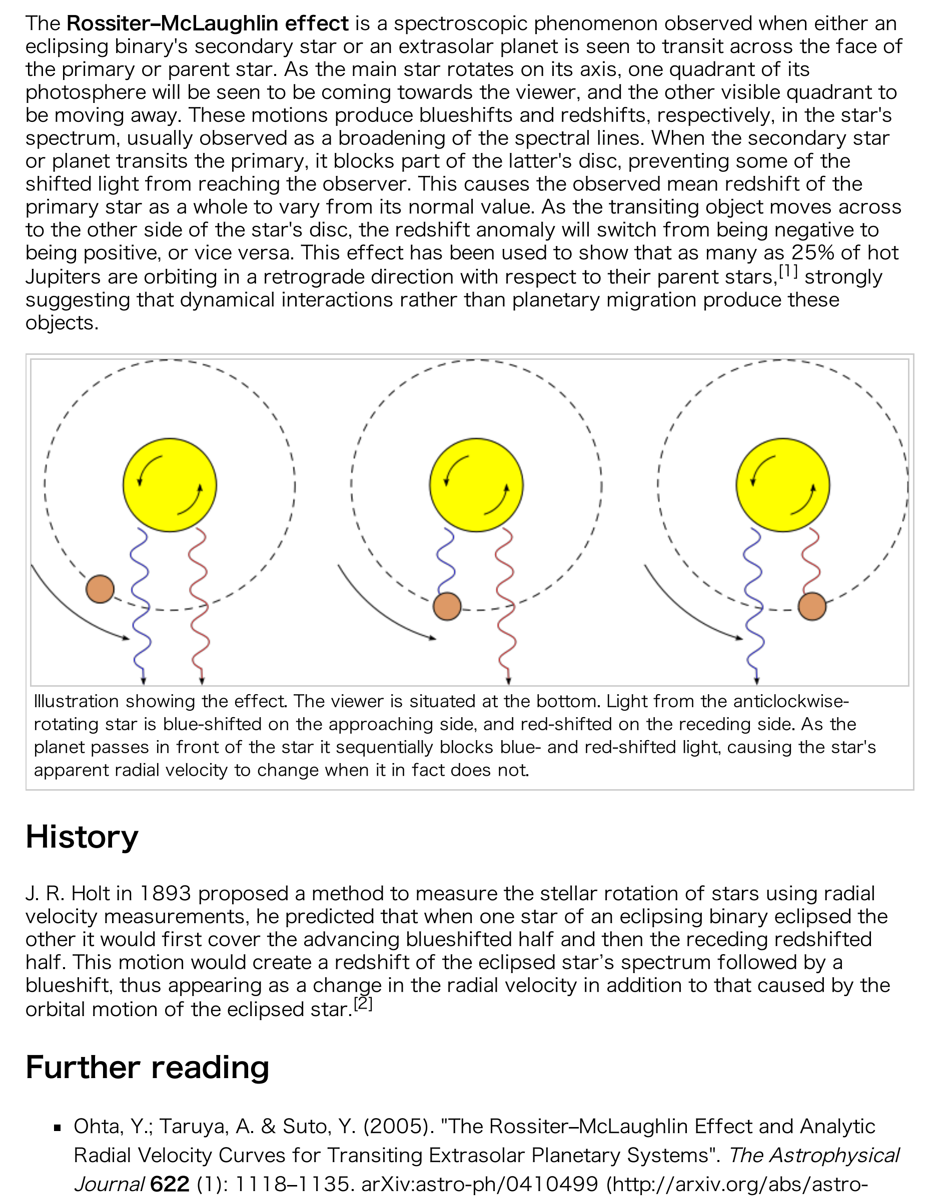


It is of interest to note that Nagaoka * has mathematically considered the properties of a "Saturnian" atom which he supposed to consist of a central attracting mass surrounded by rings of rotating electrons. He showed that such a system was stable if the attractive force was large. From the point of view considered in this paper, the chance of large deflexion would practically be unaltered, whether the atom is considered to be a disk or a sphere.

From atomic model to architecture of exoplanetary systems

Ang. Mom.	Atomic system	Exoplanetary system
L	Quantized energy levels Emission/absorption line transition	Spectroscopic radial velocity Transit photometry, Microlensing Orbital period, semi-major axis, eccentricity, planetary mass
S	Spin of nucleus Hyperfine structure splitting	Rossiter-McLaughlin effect Asteroseismology Stellar spin - planetary orbit angle Stellar spin obliquity
s	Spin of electrons Fine structure splitting	Tidal interaction between star and planet Planetary spin and obliquity planetary ring

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.

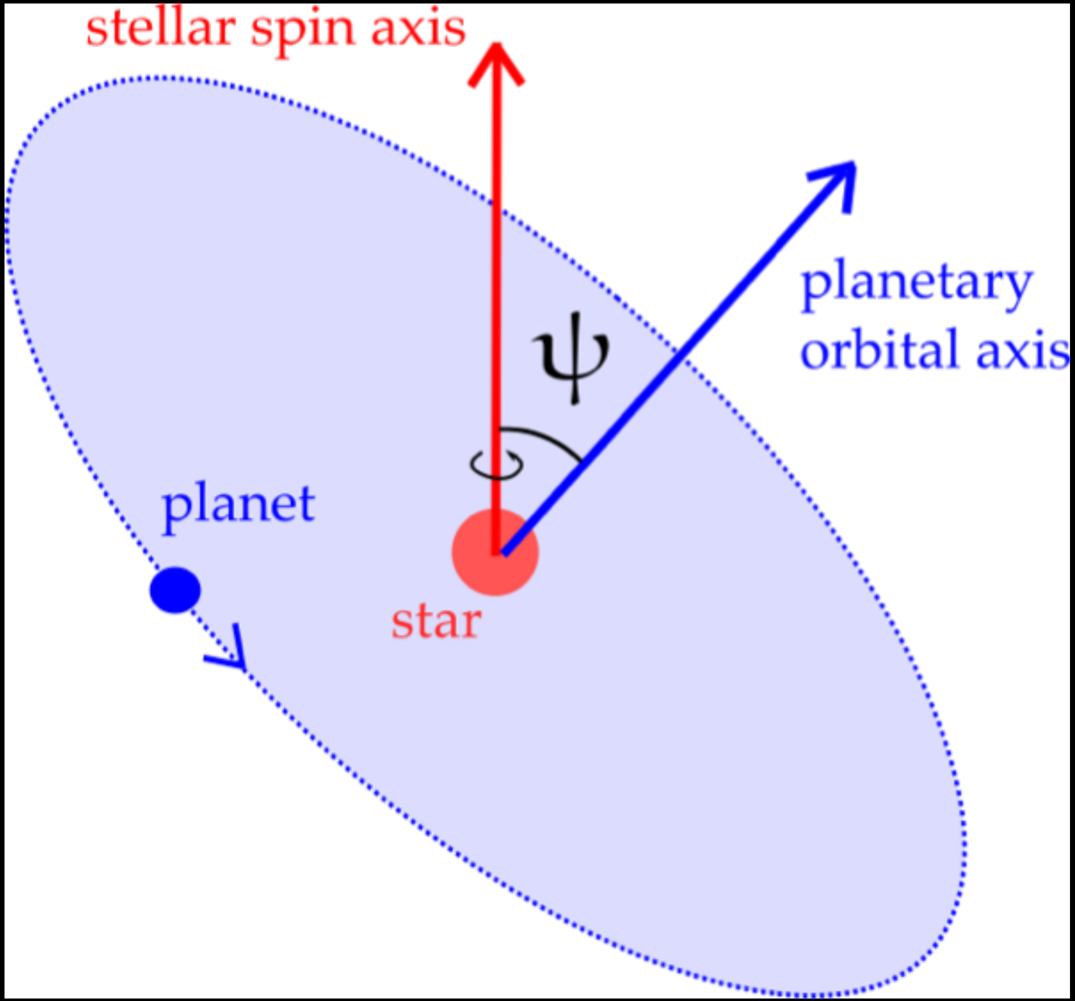
Illustration showing the effect. The viewer is situated at the bottom. Light from the anticlockwise-rotating star is blue-shifted on the approaching side, and red-shifted on the receding side. As the planet passes in front of the star it sequentially blocks blue- and red-shifted light, causing the star's 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]

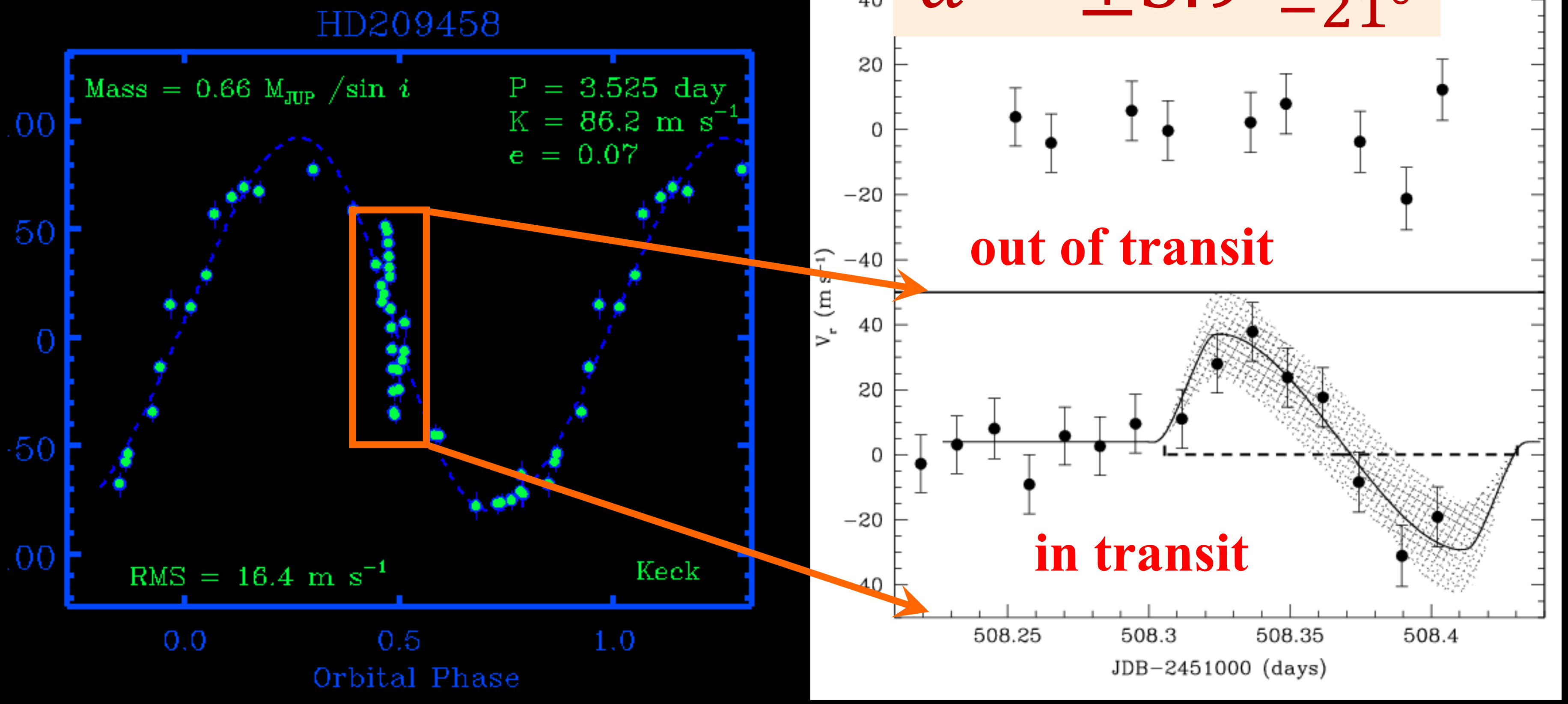
Further reading

- 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-



The first detection of the RM effect: HD209458

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



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

(This is not their original data in 2000)

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

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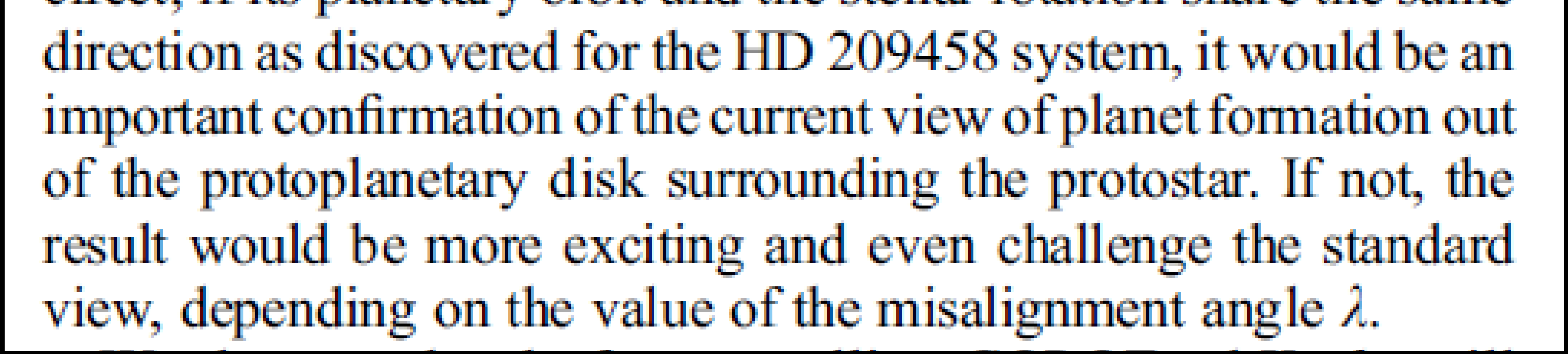
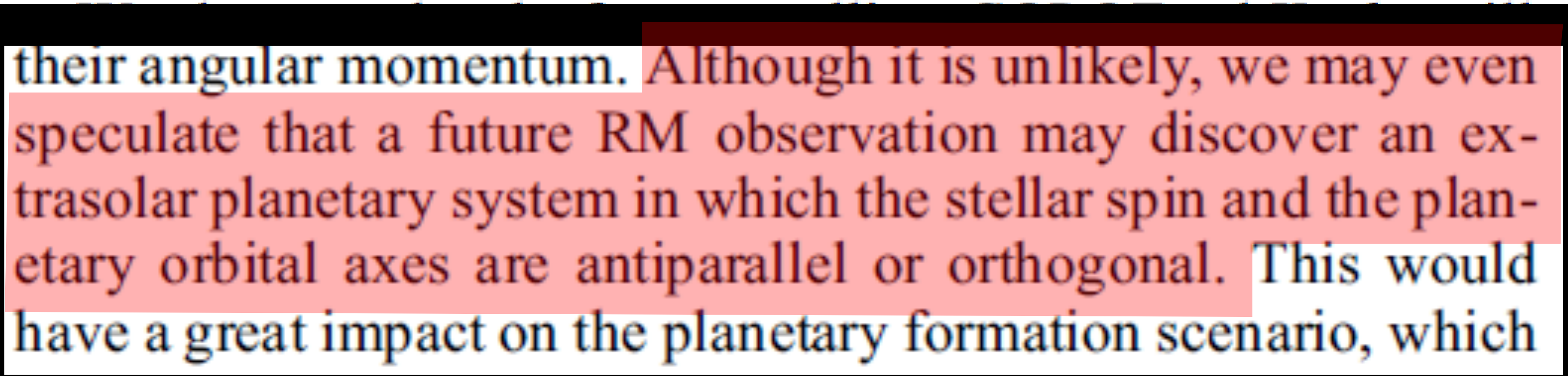
Received 2004 October 13; accepted 2004 December 10

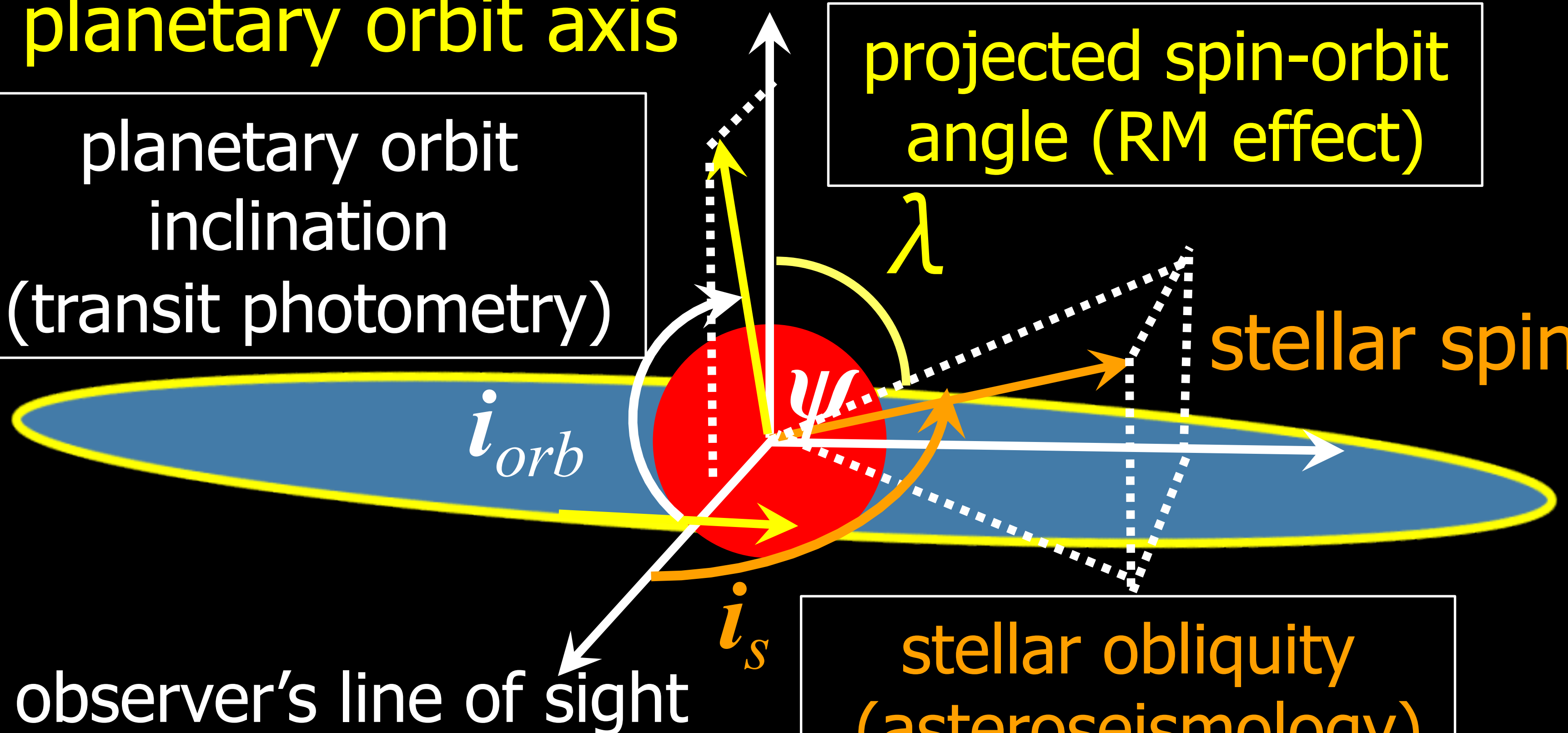


ect; ts planetary orbit and the stellar rotation share the same direction as discovered for the HD 209458 system, it would be an important confirmation of the current view of planet formation out of the protoplanetary disk surrounding the protostar. If not, the result would be more exciting and even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

Spin-orbit angles of a transiting planet



planetary orbit axis

planetary orbit inclination
(transit photometry)

projected spin-orbit angle (RM effect)

stellar spin

observer's line of sight

stellar obliquity
(asteroseismology)

true angle
ψ

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

Stellar inclination i_s **Projected angle λ**

History of my personal prejudice on the spin-orbit architecture of planetary systems

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)** introdcuced λ for spin-orbit angle
  - **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)**

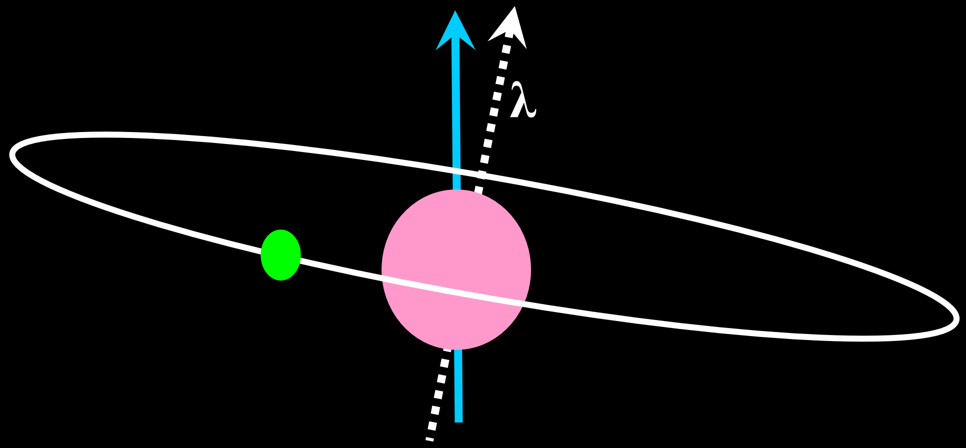
$$\lambda = -4.4^{\circ} \pm 1.4^{\circ}$$

  - Significantly improved the RM measurement accuracy for HD209458 on the basis of OTS approach

Measurement of spin-orbit alignment in an extrasolar planetary system

- Joshua N. Winn, R.W. Noyes, M.J. Holman, D.B. Charbonneau, Y. Ohta, A. Taruya, Y. Suto, N. Narita, E.L. Turner, J.A. Johnson, G.W. Marcy, R.P. Butler, & S.S. Vogt
  - ApJ 631(2005)1215 (astro-ph/0504555)

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



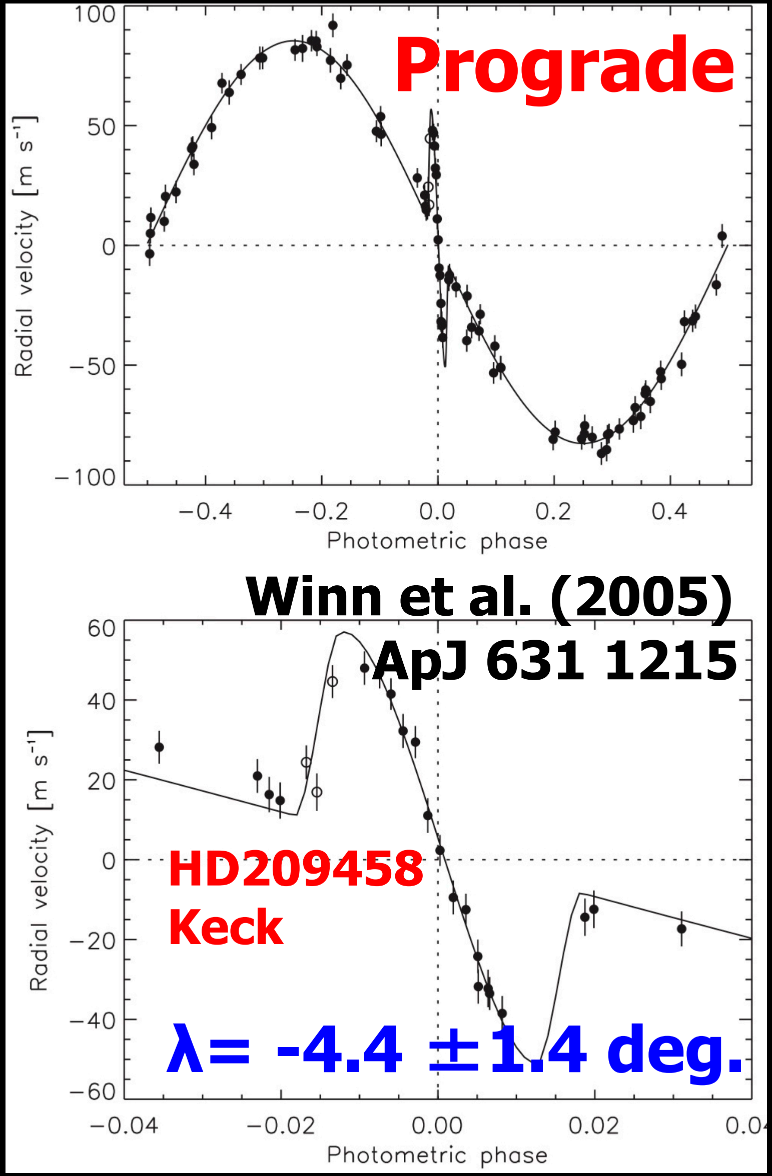
HD209458: Keck data + velocity anomaly template based on the perturbation formula by Ohta, Taruya & YS (2005)

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 “aligned” 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 !

Aligned and mis-aligned orbits

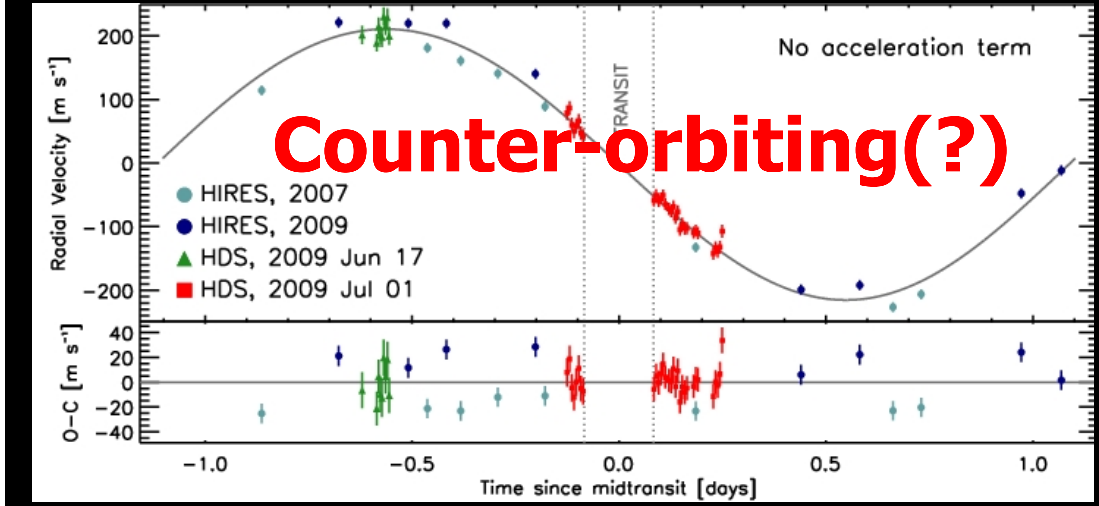


Prograde

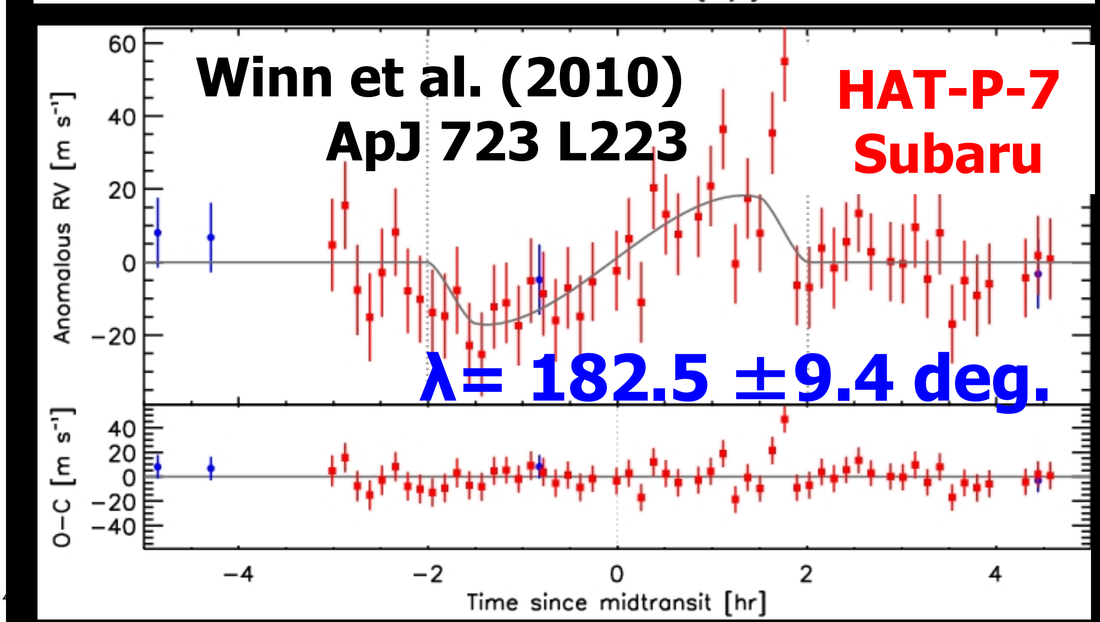
Winn et al. (2005)
ApJ 631 1215

HD209458
Keck

λ= -4.4 ±1.4 deg.



Counter-orbiting(?)

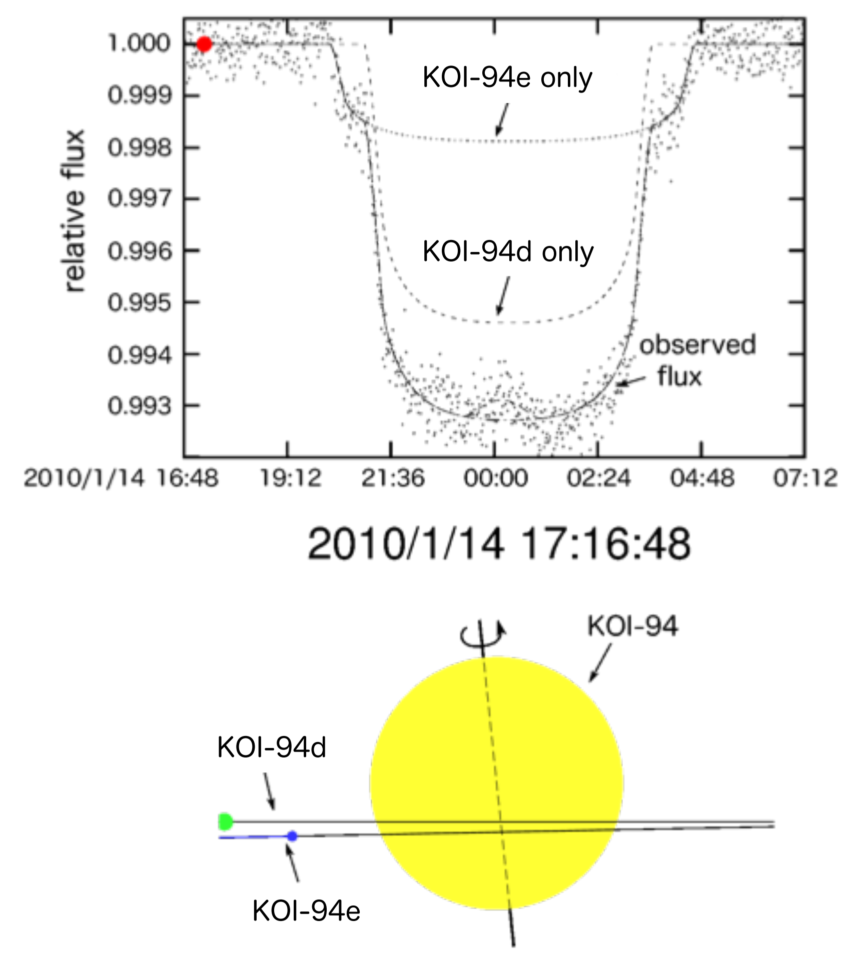


Winn et al. (2010)
ApJ 723 L223

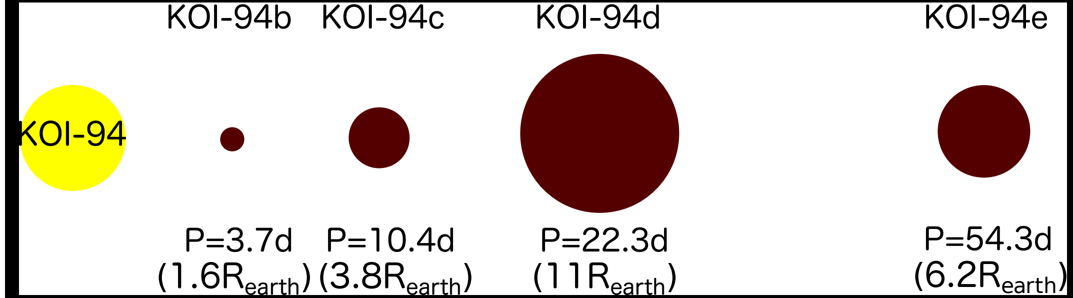
HAT-P-7
Subaru

λ= 182.5 ±9.4 deg.

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



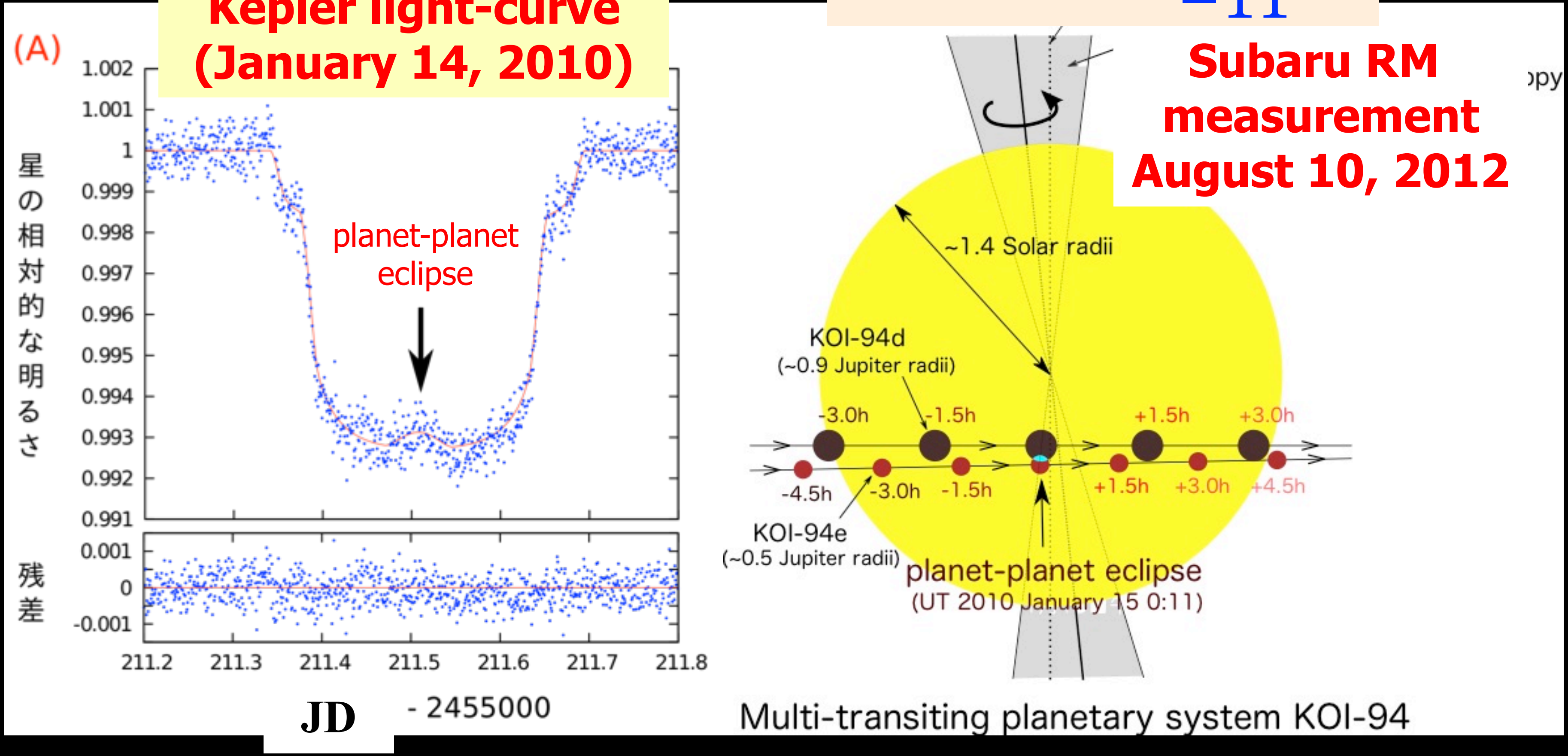
Hirano et al. ApJL 759 (2012)L36



- 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

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

Evolution of my own prejudice 3

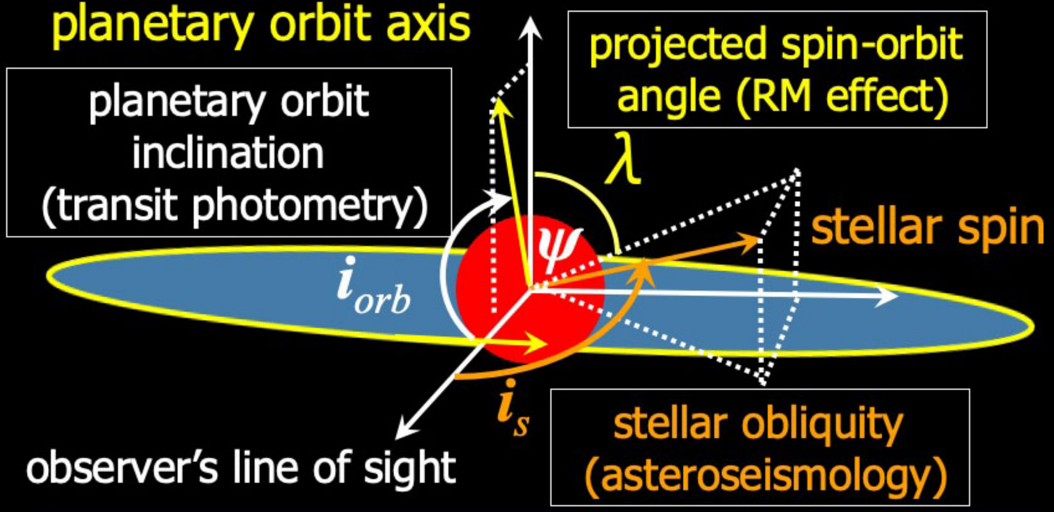
Spin-orbit misalignment should not exist for transiting multi-planetary systems

- 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 needed to determine the true angle

- ***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
- The 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 ?



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

Origin of the misalignment ?

- Primordial misalignment between the protostar and the protoplanetary disk ? (Bate, Lodato & Pringle 2010; Takaishi, Tsukamoto & YS 2019; talk by D.Takaishi)
- Precession of the protoplanetary disk due to the external perturber ? (Batygin 2012)
- Misaligned coplanar inner planetary systems due to outer-planet scattering ? (Huber et al. 2013; Gratia & Fabrycky 2017)
  - Are such initial conditions really consistent with the observed ALMA disk systems ? (talk by S.Wang)
- Reliability of asteroseismology ? (Kamiaka, Benomar & YS 2018; YS, Kamiaka & Benomar 2019; this talk + talk by Y.Lu)

Asteroseismology

Oscillations of Sun-like stars

$(0.8M_{\odot} < M < 2.5\ M_{\odot})$

- **Convection triggers oscillation waves inside stars**
- **The propagating waves form global standing waves with different eigenmode frequencies**

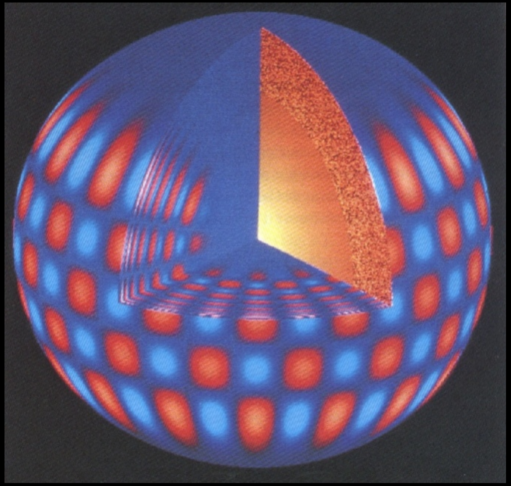
- The induced temperature perturbations are measured through the stellar photometric pulsation

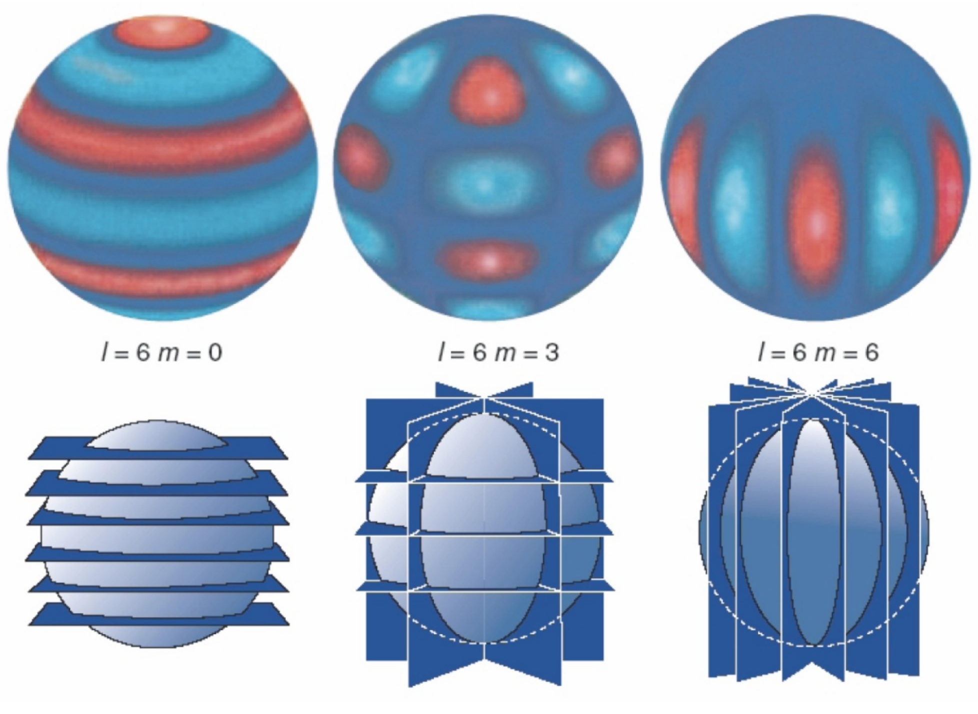
Characterizing the stellar pulsations

- Expansion in terms of spherical harmonics

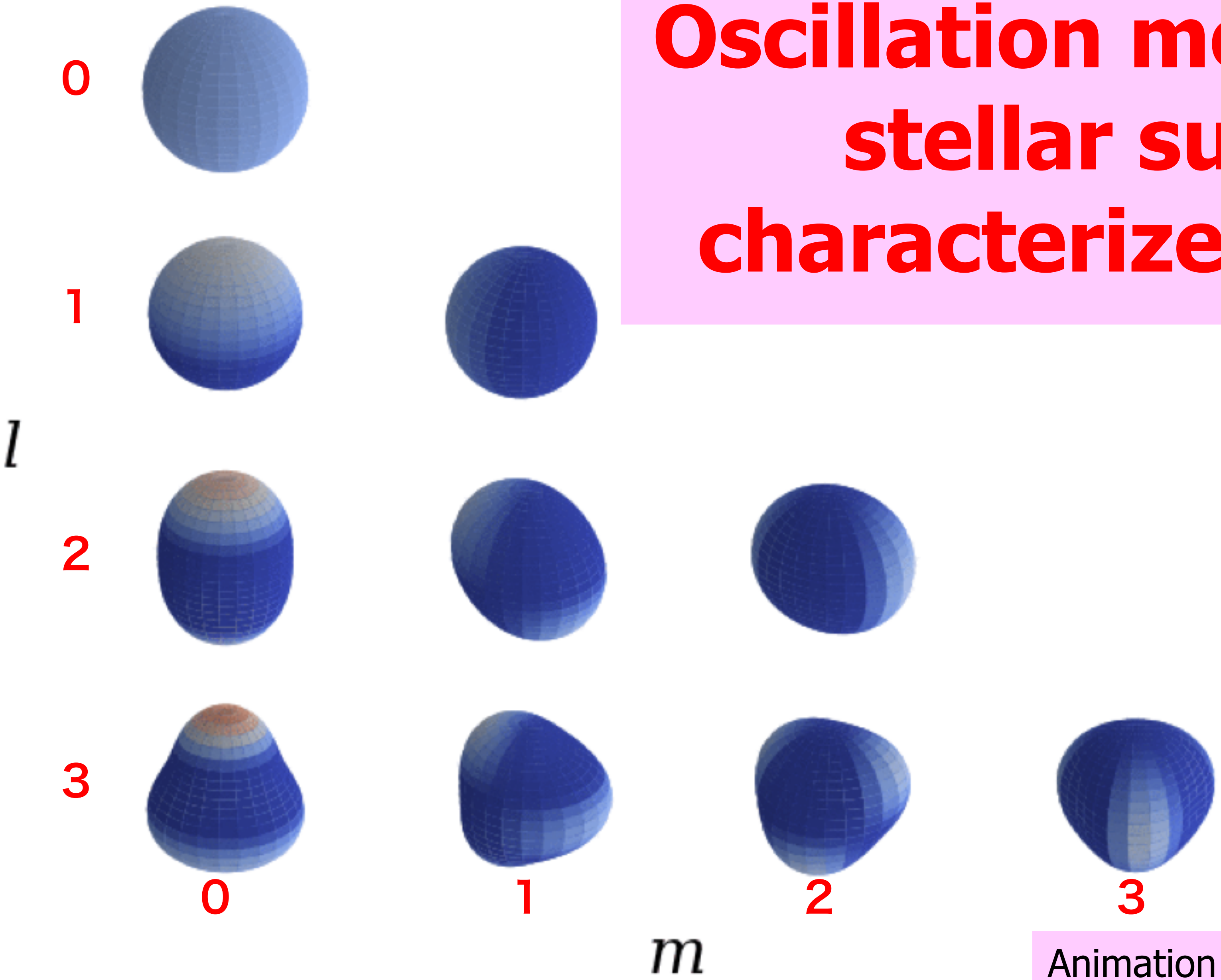
$$Y_{lm}(\theta,\varphi)\propto P_l^{|m|}(\cos\theta)e^{im\varphi}$$

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



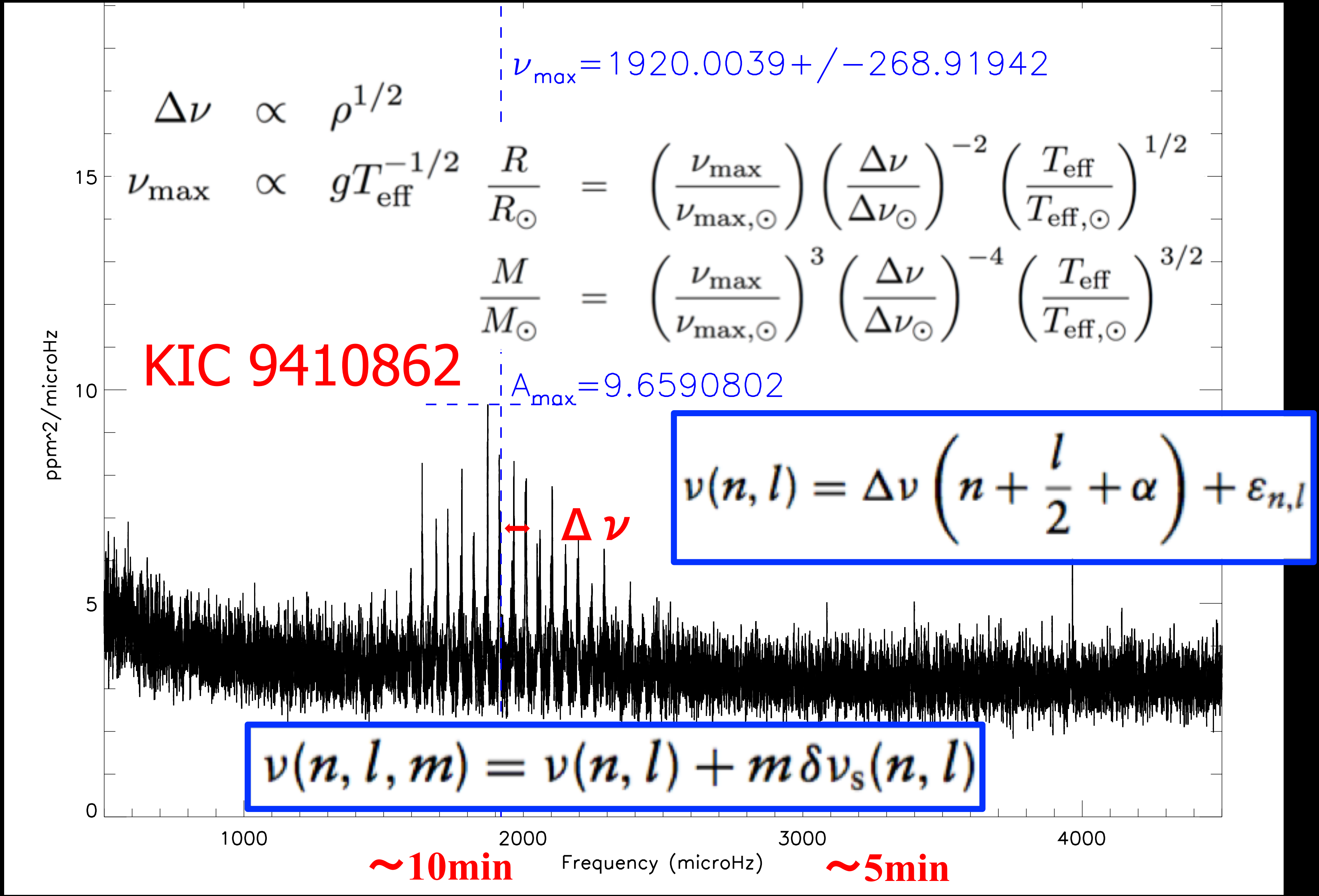


Oscillation modes of the stellar surfaces characterized by (l,m)



Animation by Martin B. Nielsen

Oscillation spectrum to stellar mass and radius



$$\Delta\nu \propto \rho^{1/2}$$

$$\nu_{\max} \propto g T_{\mathrm{eff}}^{-1/2}$$

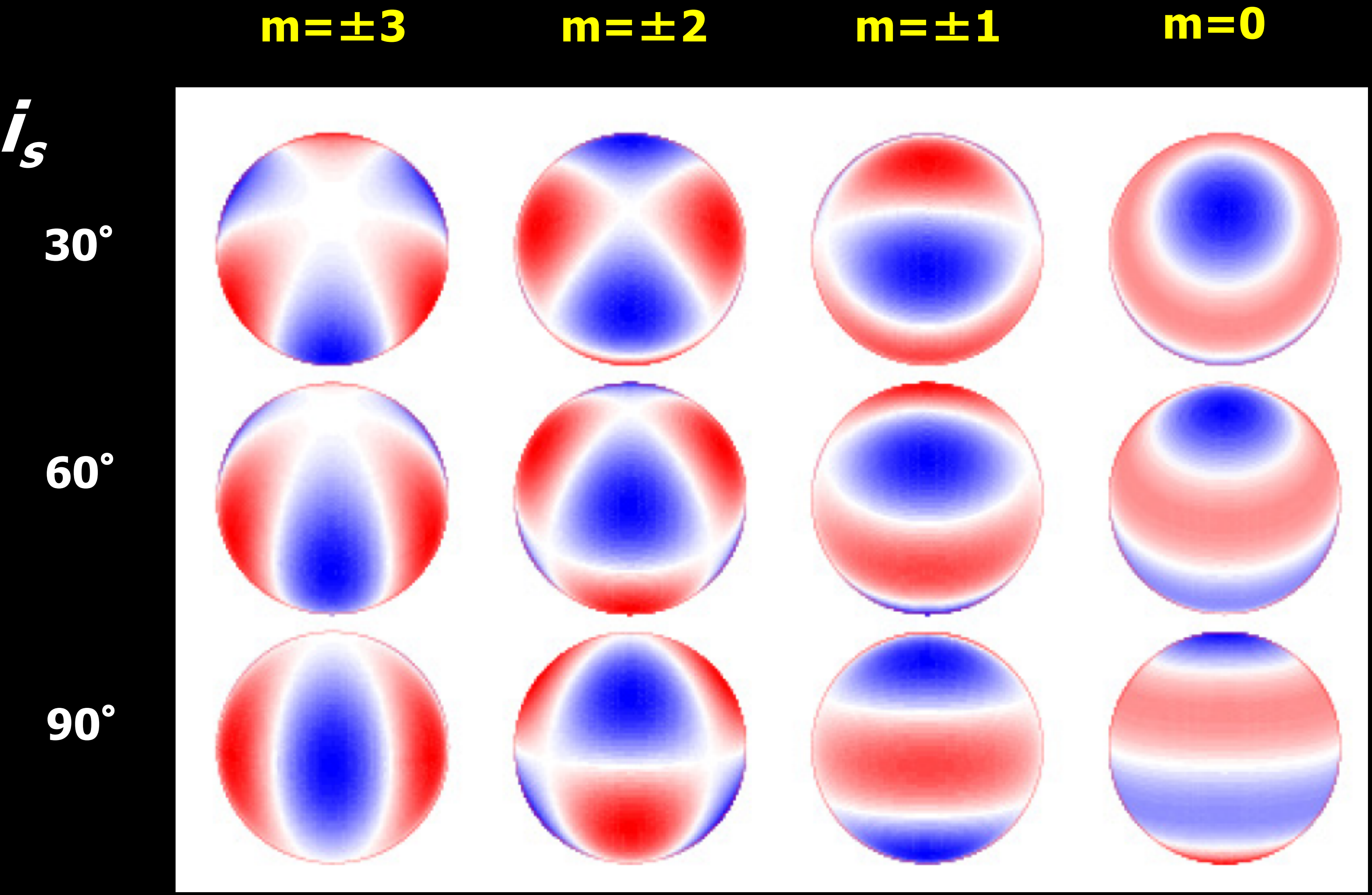
$$\frac{R}{R_\odot} = \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2}\left(\frac{T_{\mathrm{eff}}}{T_{\mathrm{eff},\odot}}\right)^{1/2}$$

$$\frac{M}{M_\odot} = \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)^{3}\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4}\left(\frac{T_{\mathrm{eff}}}{T_{\mathrm{eff},\odot}}\right)^{3/2}$$

$$\boxed{\nu(n,l) = \Delta\nu\left(n + \frac{l}{2} + \alpha\right) + \varepsilon_{n,l}}$$

$$\boxed{\nu(n,l,m) = \nu(n,l) + m\,\delta\nu_s(n,l)}$$

Dependence on the stellar obliquity (l=3)



T.L. Campante, arXiv:1405.3145

Stellar obliquity and power spectrum

- **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 $$\nu_{nlm'} = \nu_{nl} + m\,\underbrace{\boxed{\delta\nu_*}}_{\text{stellar rotation}}(1-\underbrace{\boxed{C_{nl}}}_{\text{small correction factor}})$$

c.f., Larmor’s theorem vs. the Zeeman effect

- Lagrangian for a particle of mass m and charge q under scalar potential φ

$$L = \frac{1}{2}mv^2 - q\varphi(r,z)$$

- frame rotation around z-axis with frequency Ω

$$L = \frac{1}{2}mv^2 - q\varphi(r,z) + m\Omega(xv_y - yv_x) + \frac{1}{2}m\Omega^2 r^2$$

- Homogeneous magnetic field B along z-axis

$$\begin{aligned} L &= \frac{1}{2}mv^2 - q\varphi(r,z) + q\boldsymbol{v}\cdot\boldsymbol{A} \\ &= \frac{1}{2}mv^2 - q\varphi(r,z) + \frac{qB}{2}(xv_y - yv_z) \end{aligned}$$

- Frame rotation is equivalent to magnetic field (B=2m Ω/q)
  - B breaks the degeneracy of m-level (Zeeman effect)
  - Classical asteroseimology ⇔ quantum Zeeman effect

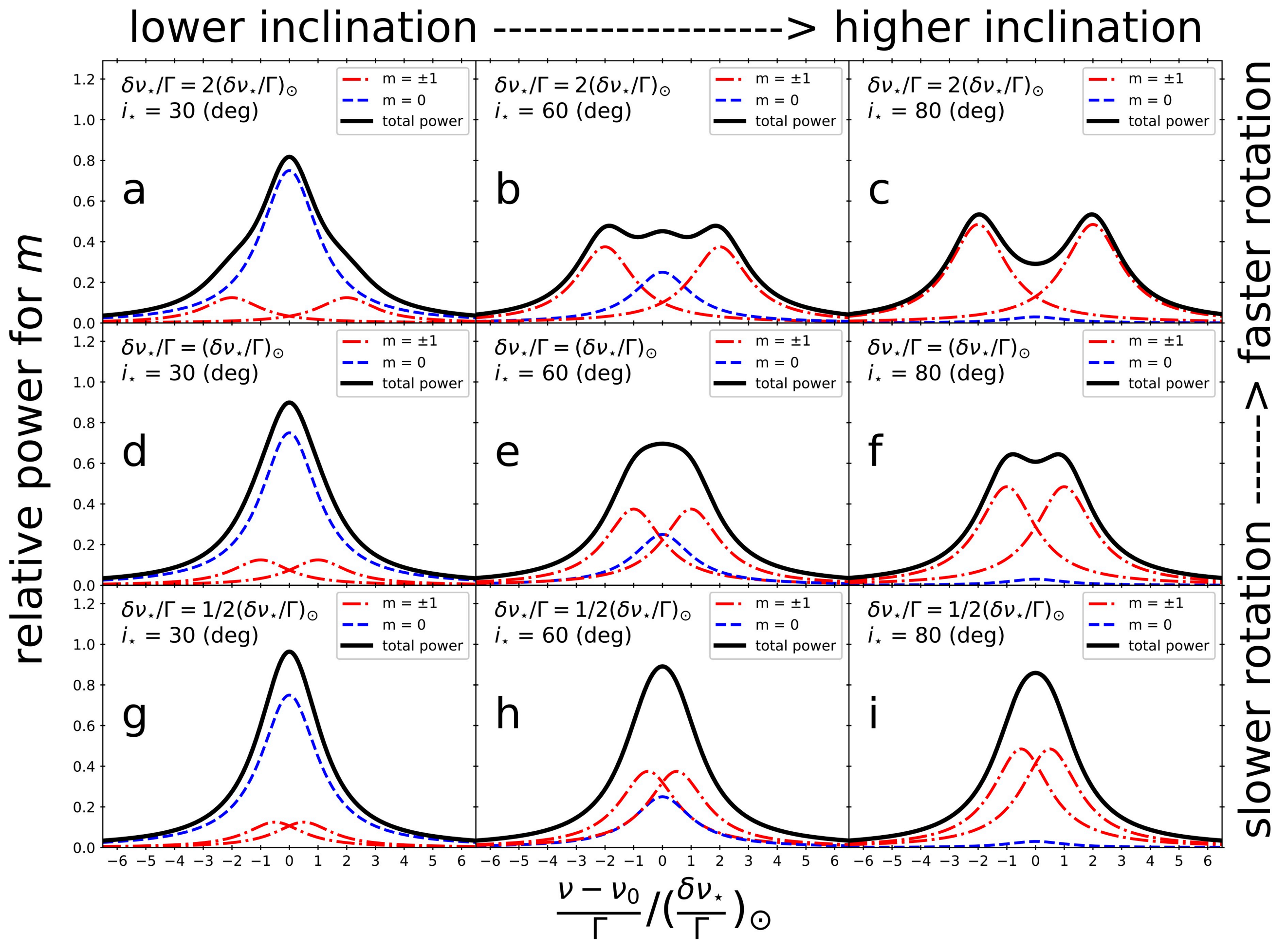
Stellar obliquity from asteroseismology

- Oscillation line mode profile: complementary probe of spin-orbit angles of exoplanetary systems

$\delta\nu_\star$: stellar rotation frequency

Γ: line width of the oscillation mode

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



True spin-orbit angles from RM effect + asteroseismology

- Only two systems have both measurements of λ (RM) and i_s (asteroseismology)
  - Kepler-25 (F-star+ planets with 6 and 13days)

$\lambda = 9.4^\circ \pm 7.1^\circ$ $i_s = 65.4^\circ{}^{+12.1^\circ}_{-7.4^\circ}$ $\Psi = 26.9^\circ{}^{+7.0^\circ}_{-9.2^\circ}$

  - see Campante et al. (2016) $i_s = 80.6^\circ{}^{+6.5^\circ}_{-9.3^\circ}$ $\Psi = 12.6^\circ{}^{+6.7^\circ}_{-11.0^\circ}$
  - HAT-P-7 (F-star + a single planet with 2.2 days)

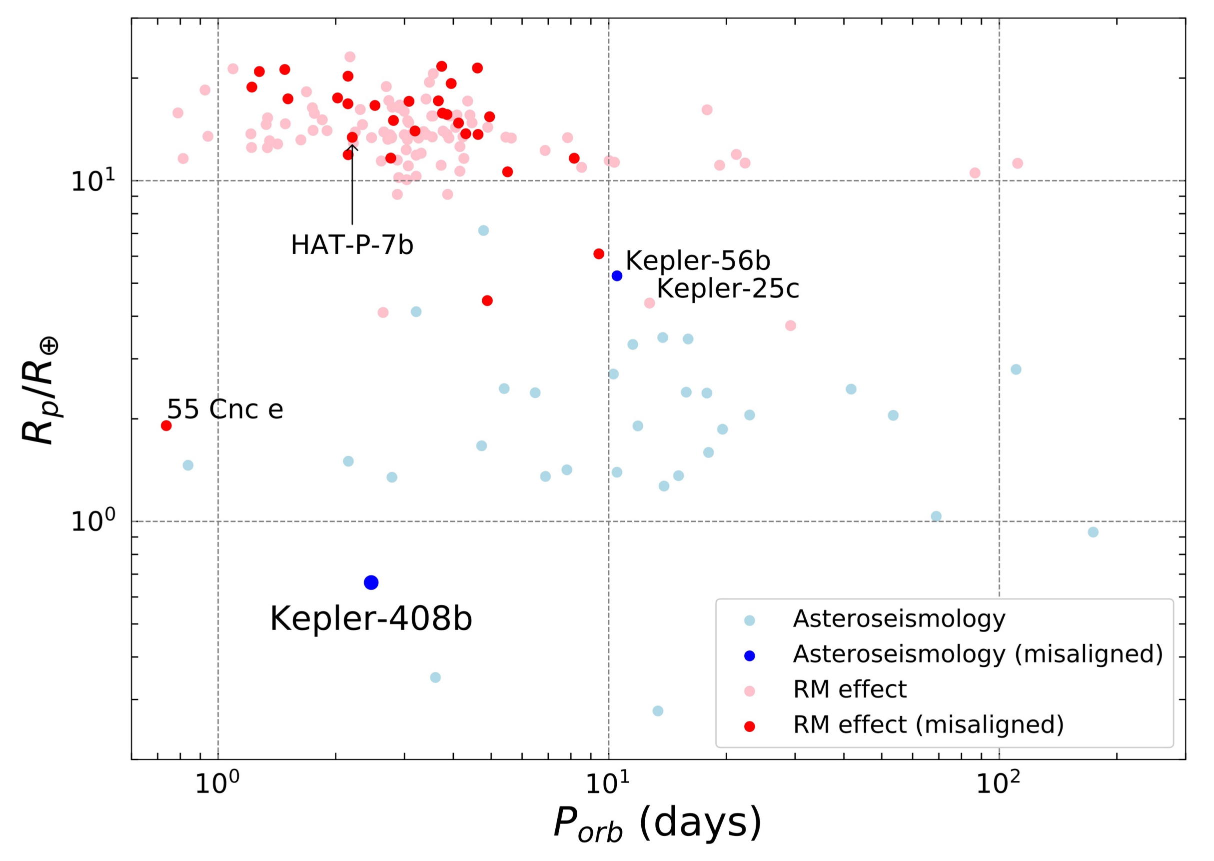
$\lambda = 186^\circ{}^{+10^\circ}_{-11^\circ}$ $i_s = 27^\circ{}^{+35^\circ}_{-18^\circ}$ $\Psi = 122^\circ{}^{+30^\circ}_{-18^\circ}$

Not a counter-orbiting planet

Benomar, Masuda, Shibahashi + YS, PASJ 66(2014) 9421
see also Huber et al. (2013) , Campante et al.(2016)

Evolution of my own prejudice 5

complementarity of asteroseismology ?



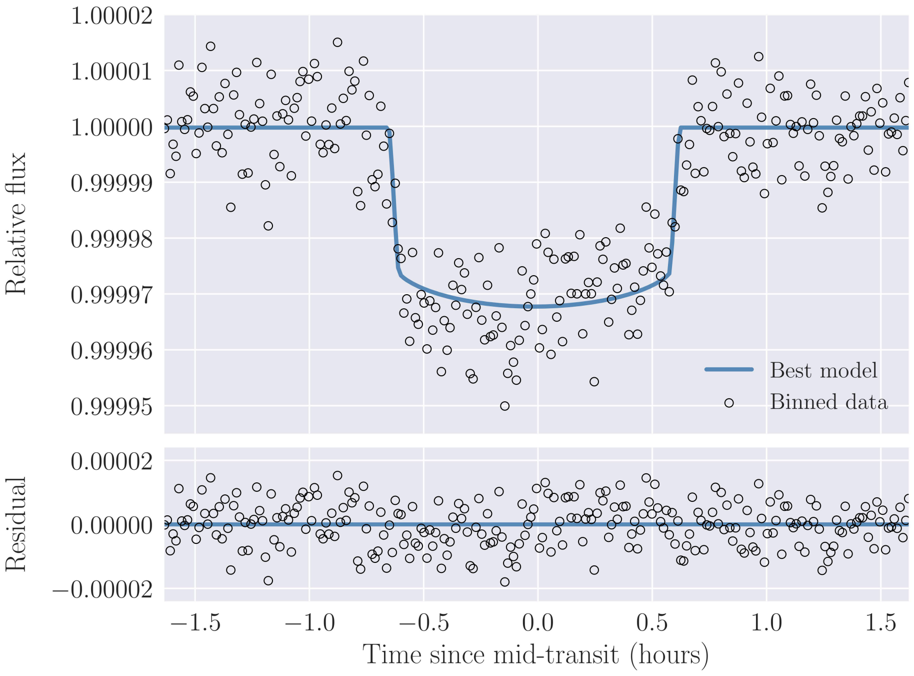
- RM effect
  - short-period and large planets
- Asteroseismology
  - independent of the properties of planets

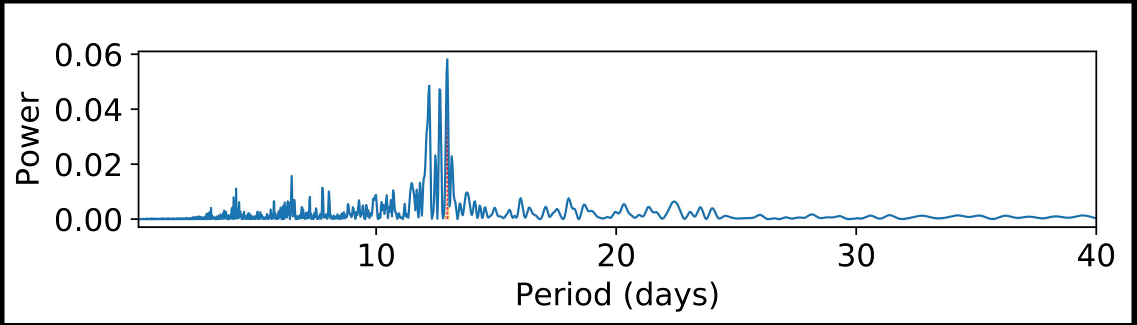
Kamiaka, Benomar & YS
MNRAS(2018)
Kamiaka, Benomar, YS, Dai,
Masuda, & Winn
AJ 157(2019)137
Suto, Kamiaka & Benomar
AJ 157(2019)172

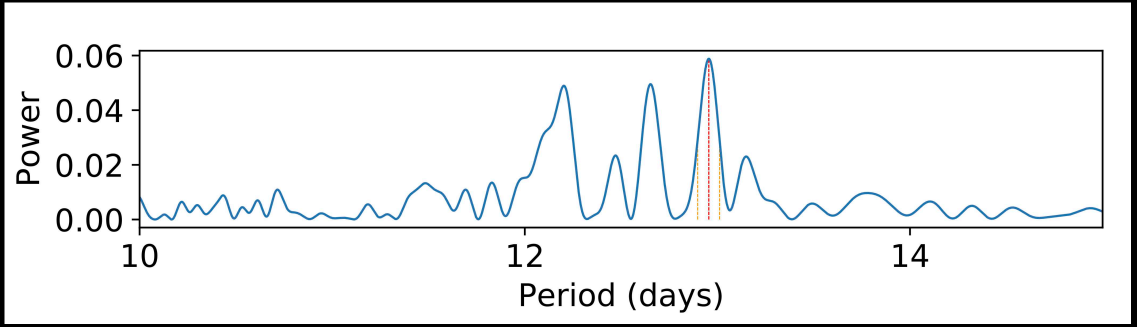
- Asteroseismology is based on various (non-trivial) assumptions, and required complicated and careful modeling

Transiting planetary system Kepler-408

- Kepler-408
  - Star: 6100K, 1.05M_{sun}, 1.25R_{sun}
  - Planet: sub-Earth size 0.86R_E, 2.5day orbital period



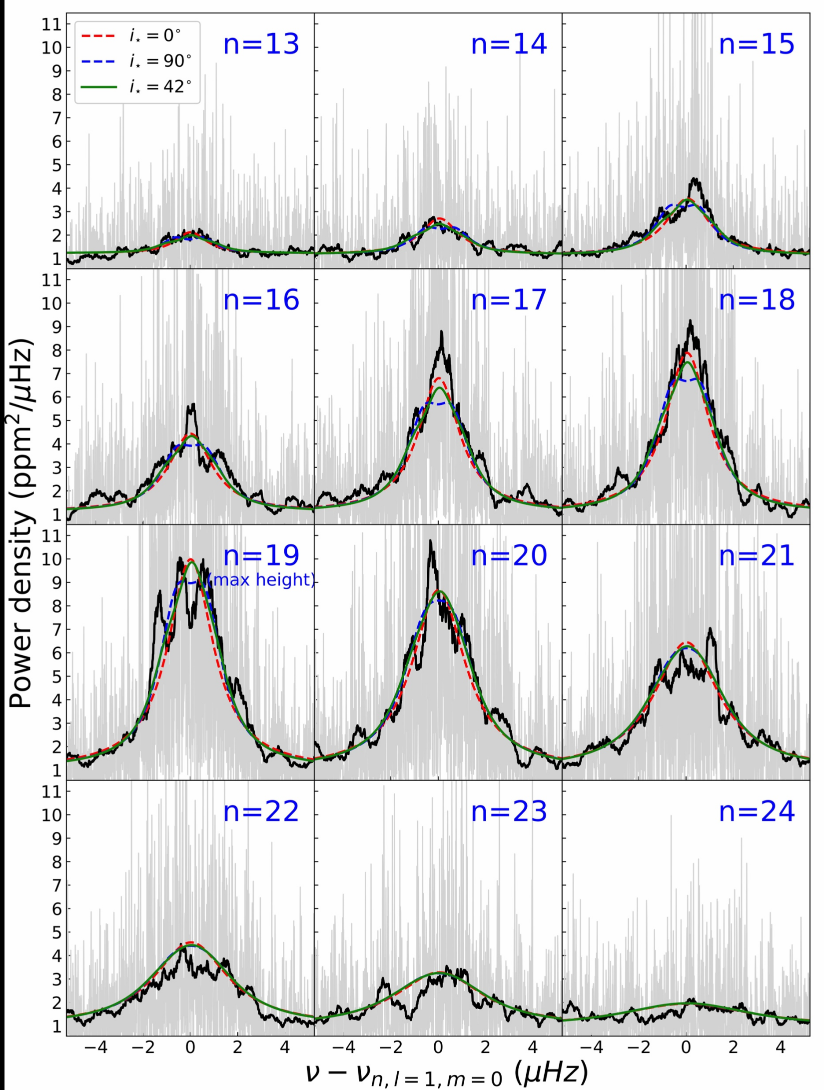


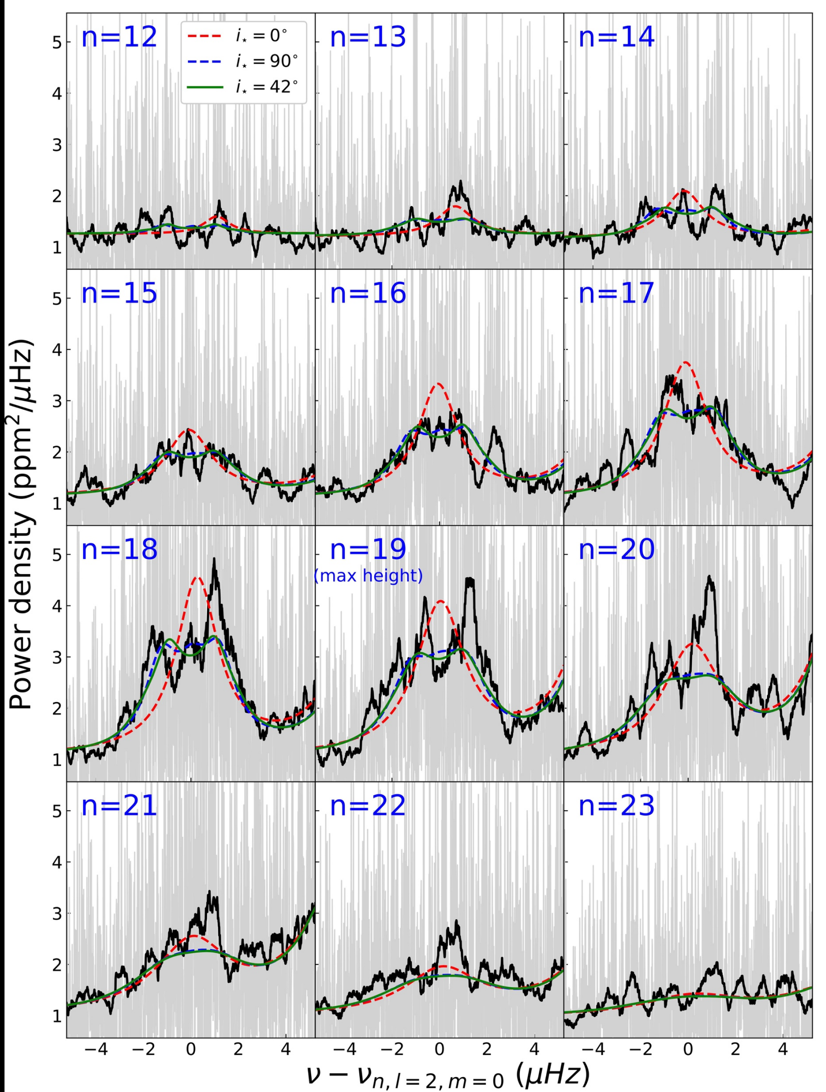


Kamiaka, Benomar, YS, Dai, Masuda & Winn, AJ 157(2019)137

Oscillation profiles (n,l) of Kepler-408

***l*=1**

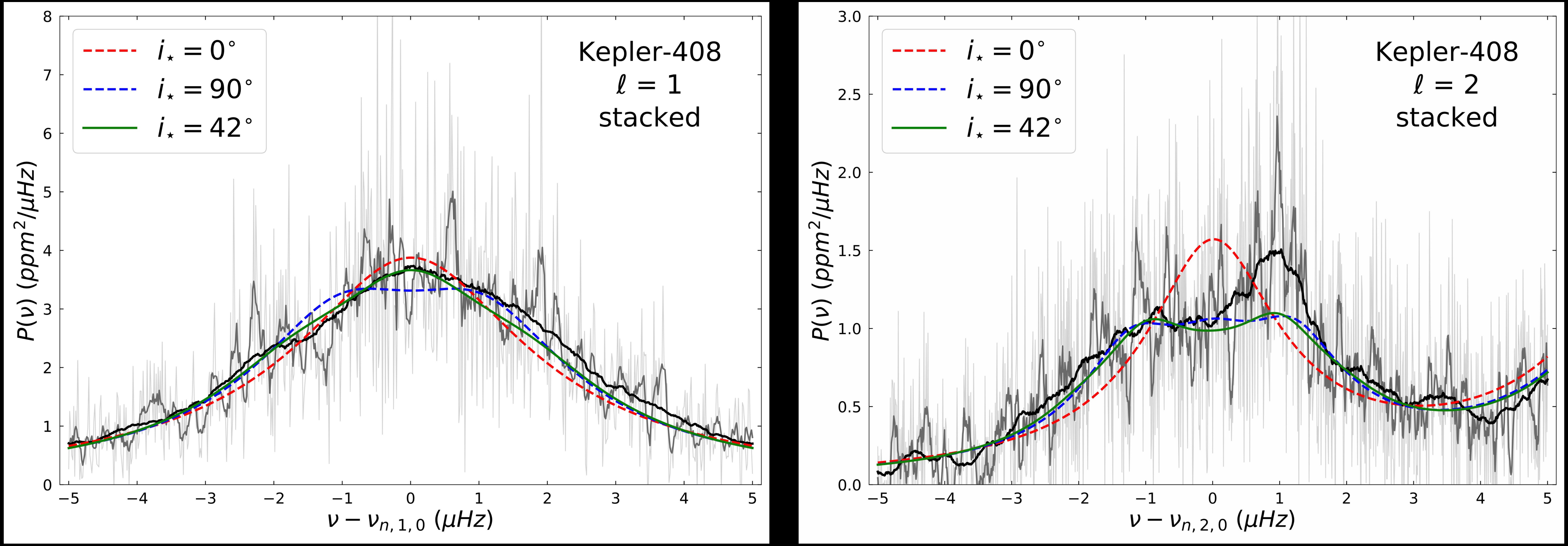




***l*=2**

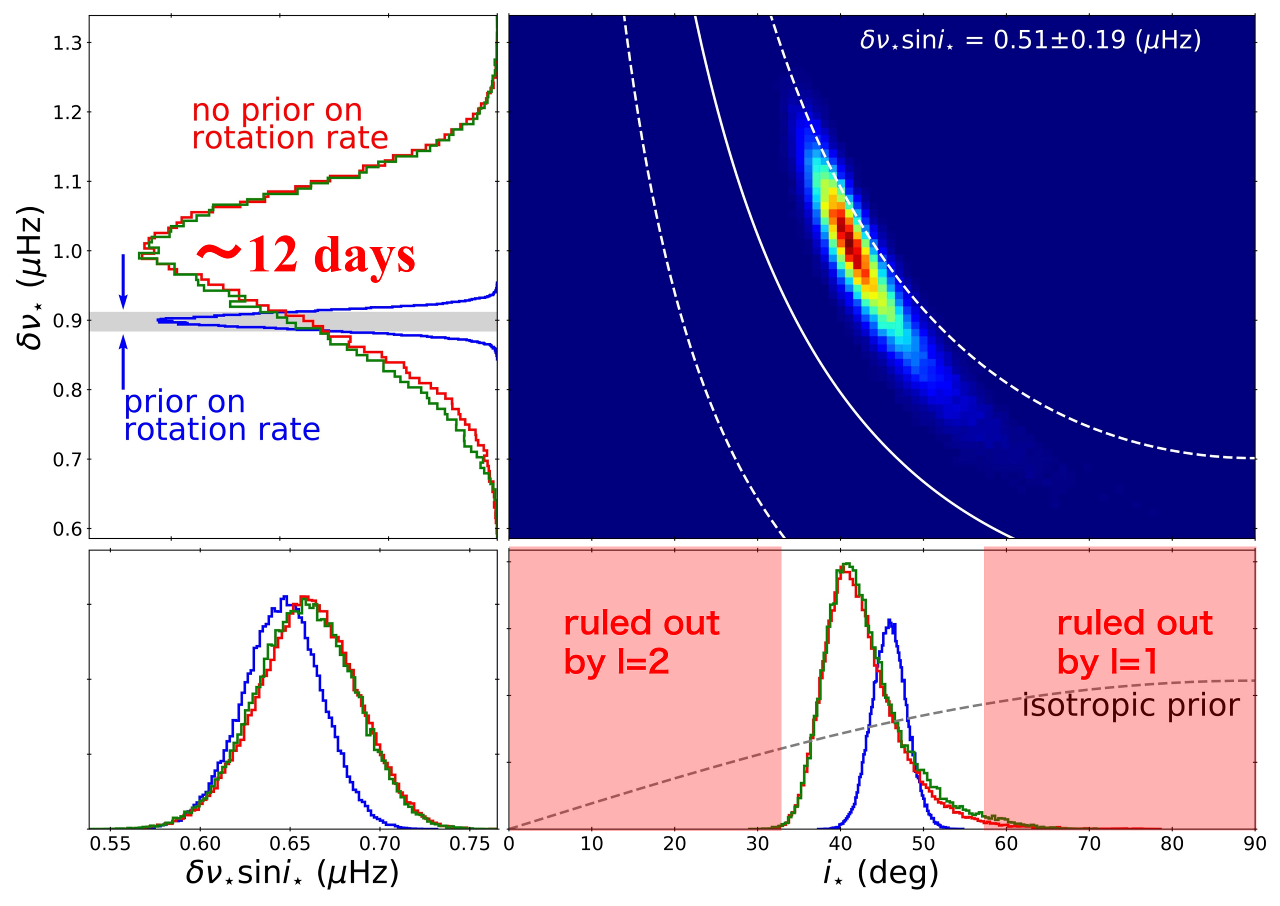
Kamiaka, Benomar, YS, Dai, Masuda, & Winn, AJ 157(2019)137

Stacked oscillation spectra of Kepler-408



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

Asteroseismic constraints on Kepler-408



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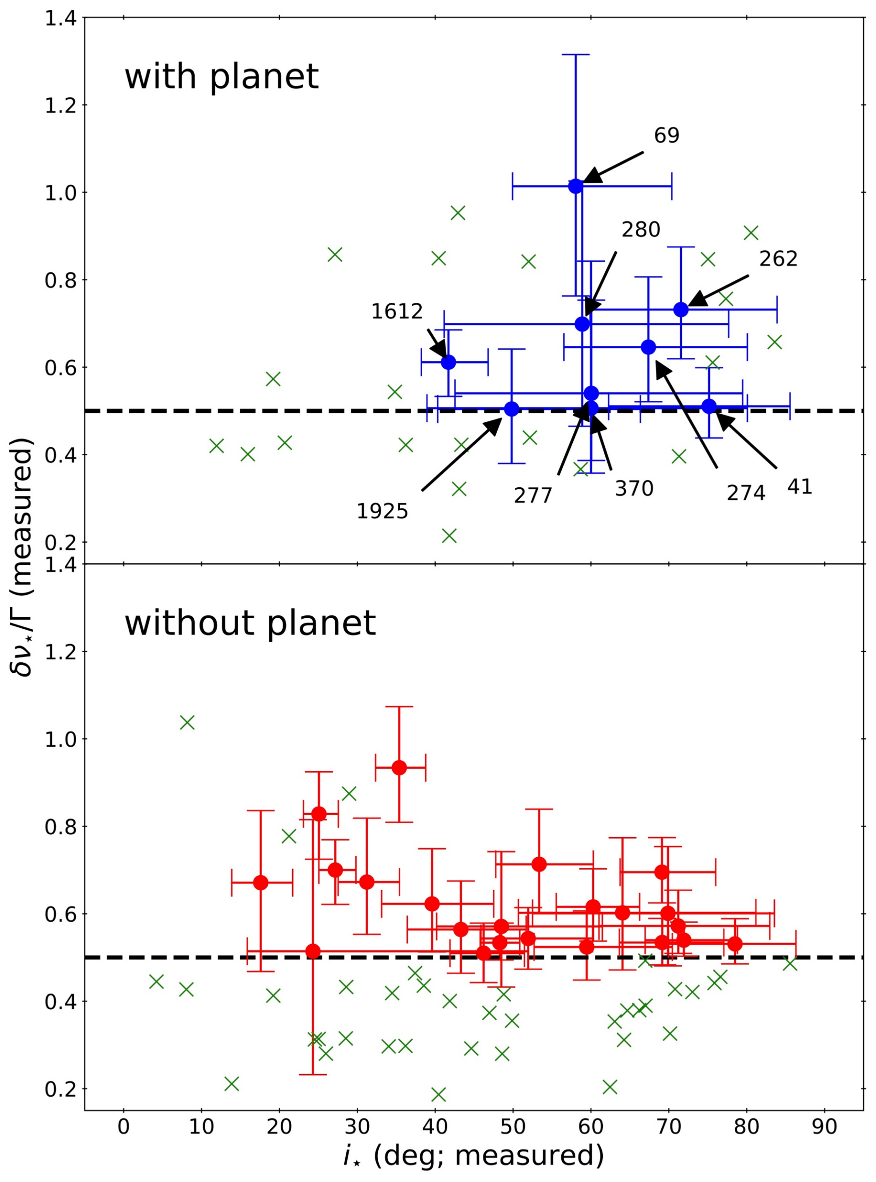
- Consistent with the other estimate
  - Photometric rotation period : P_{rot}
  - Doppler line broadening : $v_{rot} \sin i_\star$
- The smallest size planet in an oblique orbit

$$i_\star = \sin^{-1}\left(\frac{v_{\rm rot}\sin i_\star}{2\pi R_\star/P_{\rm rot}}\right) = 44^{+20}_{-15}\,(\rm deg)$$

i_s of Kepler stars from asteroseismology: with/without planets

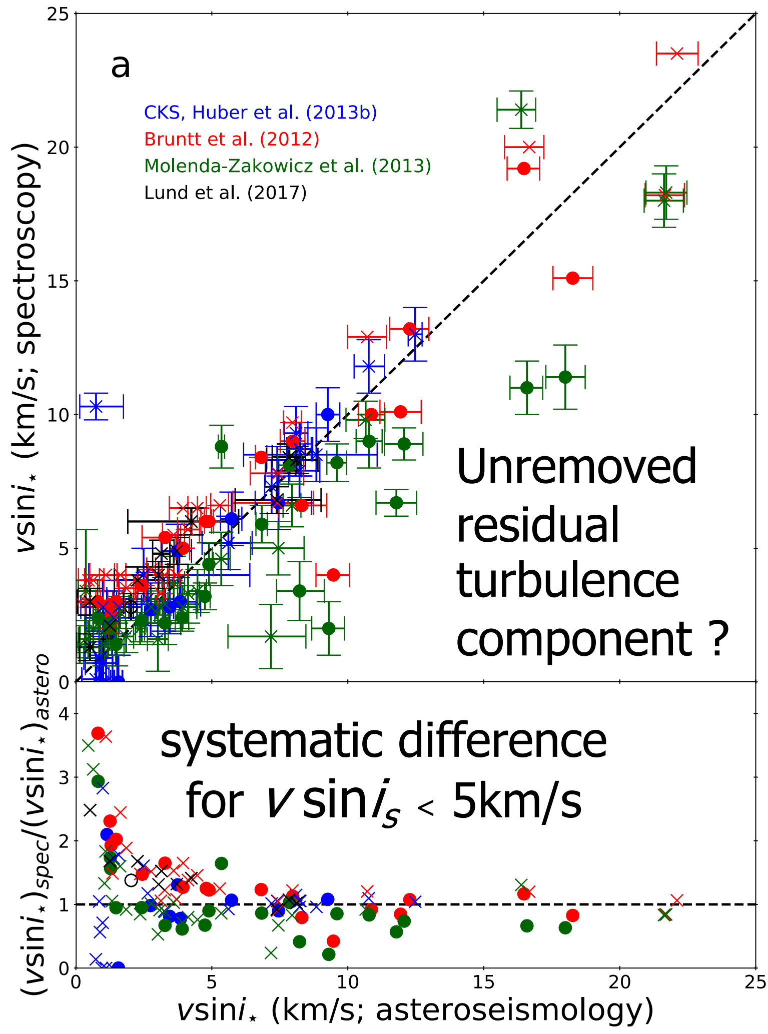
- 94 Kepler main-sequence stars
  - 33 with transiting planets
  - 61 with no known planets
- Transiting planet-host stars have systematically larger stellar obliquities (as expected)



Kamiaka, Benormar, and YS (2018)

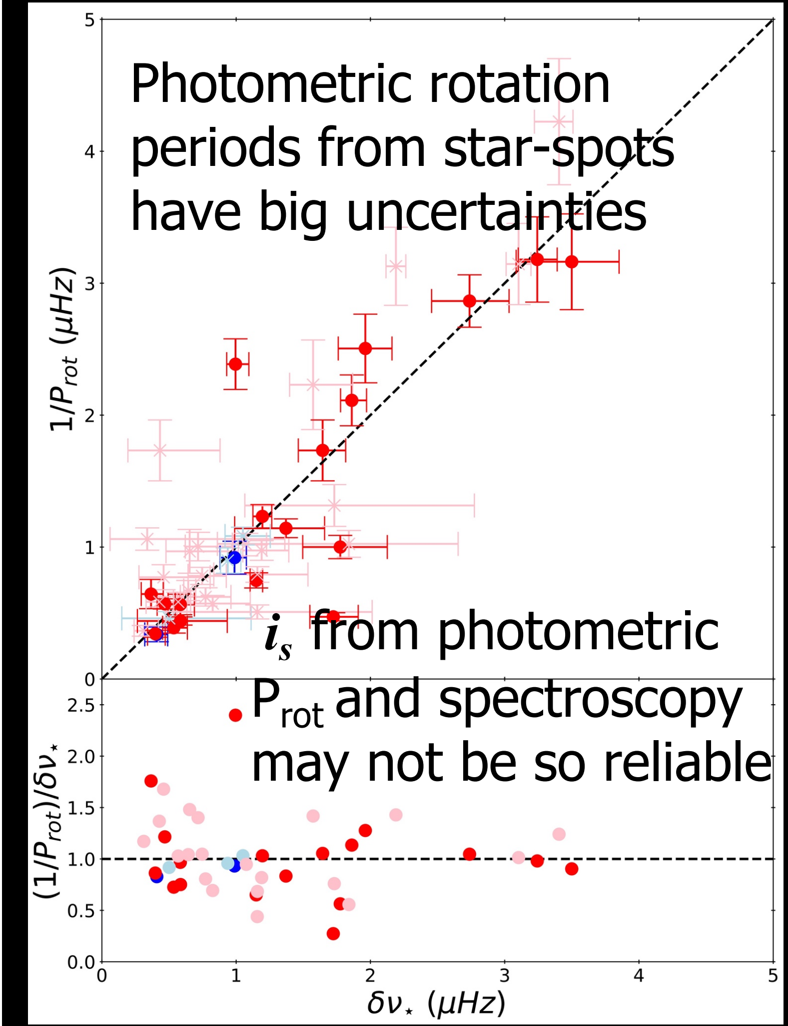
Comparison with independent observational estimates of $v\sin i_s$, P_{rot} and i_s

Kamiaka, Benormar, and YS (2018)



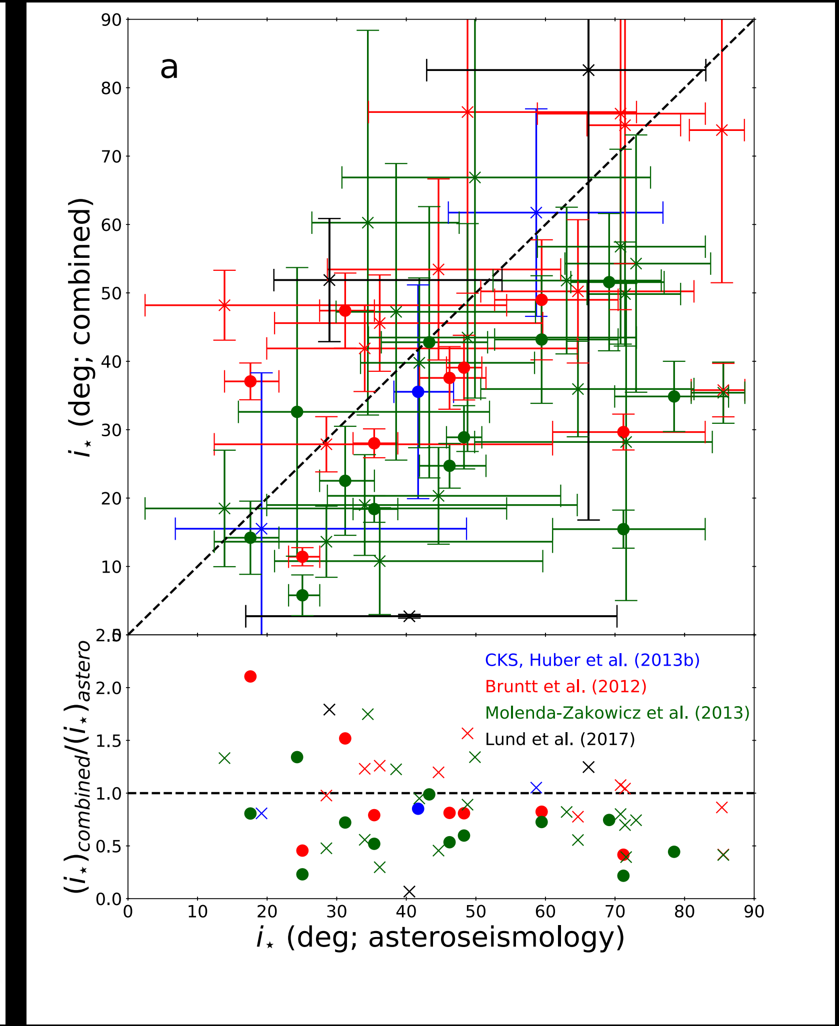
Unremoved residual turbulence component ?

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

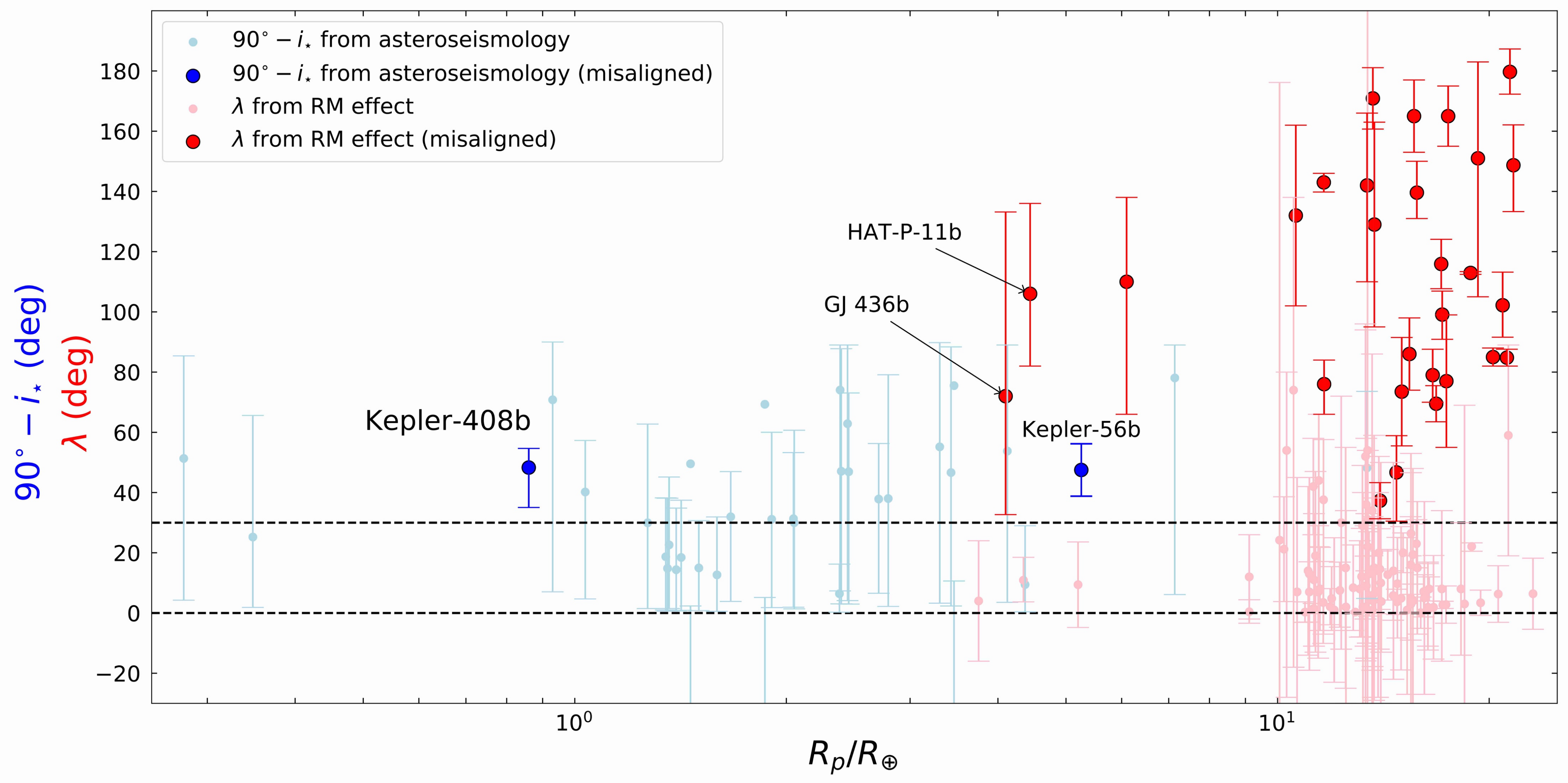


Photometric rotation periods from star-spots have big uncertainties

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



Spin-orbit angles against R_p



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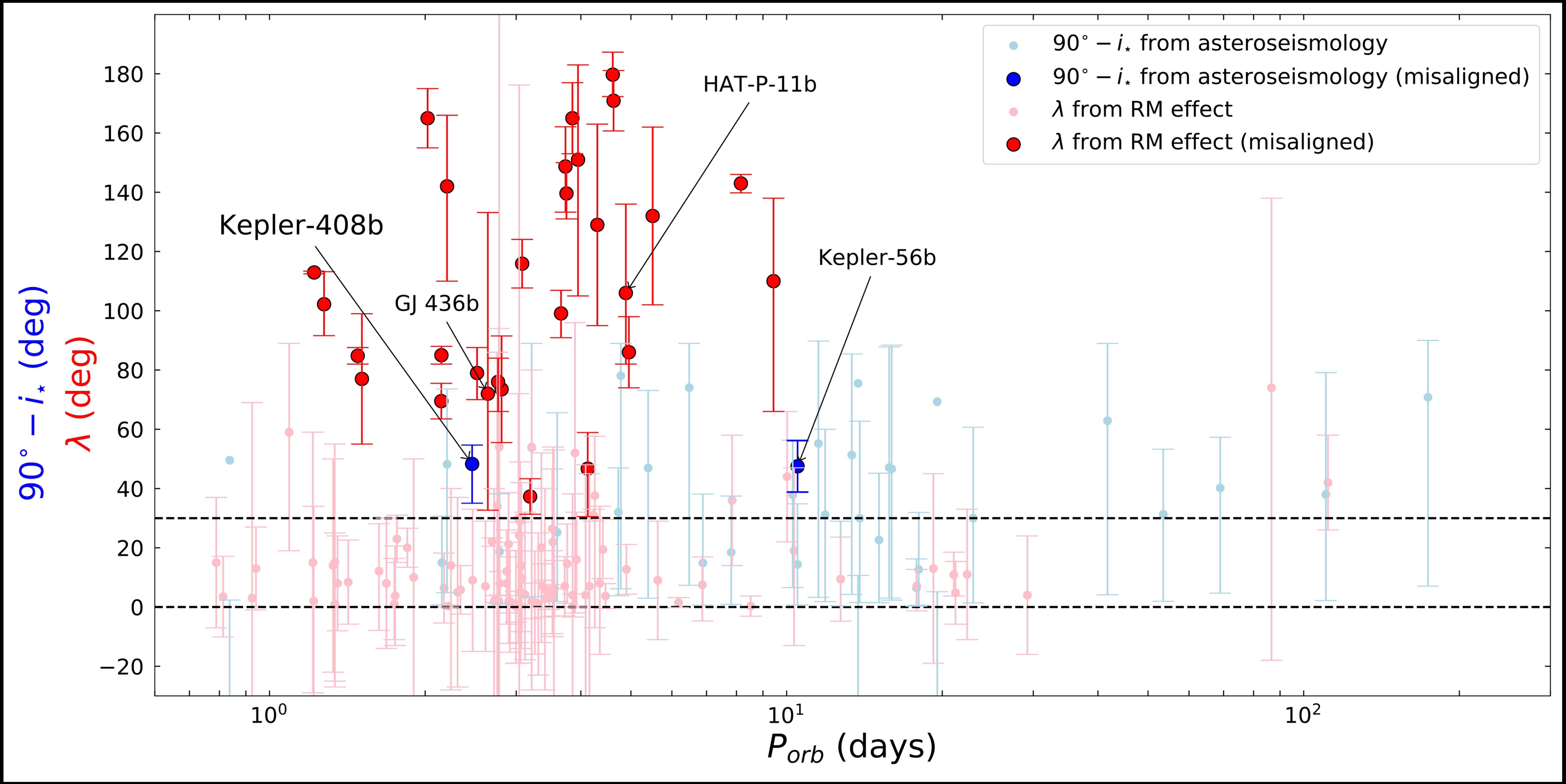
Spin-orbit angles against P_{orb}



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Summary

- The Rossiter-McLaughlin effect and asteroseismology revealed quite unexpectedly large diversities in the spin-orbit architecture of planetary systems (～30 percent of hot Jupiters are misaligned)
- The origin of the diversity is not well understood
  - Nature vs. Nurture ?
  - Initial condition imprinted in protoplanetary disks ?
  - Chaotic dynamics in planet-planet interaction ?
  - Tidal interaction between the host star and planets ?
- Numerical simulations with realistic initial conditions !